A study of QCD processes at low momentum transfer in hadron-hadron collisions

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Chapter 1

Introduction

Significant progress in particle physics has been achieved in the last century. The construction of particle accelerators permitted an exceptional precise test of the Standard Model, which describes the fundamental particles and the interactions among them. At the moment this model incorporates all observations best, and its validity has been widely tested over the last years.

QCD (Quantum Chromodynamics) [1, 2, 3] describes the strong interactions of quarks and gluons. It has been developed during the 1970s on the basis of QED, the theory of the electromagnetic interactions of lepton and quarks. Since its formulation, QCD has been tested in many particle physics experiments. Difficulties arise from the fact that quarks and gluons have never been freely observed, but always confined together in hadrons (like protons, neutrons, pions, ..). In detectors at particles accelerators quarks and gluons show up as a bunch of collinear hadrons (jet), the characteristics of which permit the study of the original constituents and their interaction.

At hadron colliders, precision calculations of QCD are inherently difficult to accomplish. However most of the interesting physics aspects, like the search of particles beyond the Standard Model, electroweak precision measurements, study of heavy quarks, are connected to the interaction of quarks and gluons at large transferred momentum, and therefore rely on the accuracy of QCD descriptions. Today, the highest energetic hadron collider in the world is the Tevatron [4], situated at the National Fermi Laboratory in Batavia (Chicago). During four years, starting in 1992, it collided protons on antiprotons at a center of mass energy of 1.8 TeV, with the exception of one month when the center of mass energy was 630 GeV. A new run at center of mass energies of 2 TeV has just started. Of enormous interest for the scientific community is the construction of the LHC [5], the Large Hadron Collider at CERN, in Geneva. It will collide protons on protons at a center of mass energy of 14 TeV, and it will start to be operated at the beginning of 2006.

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Since protons consist of quarks and gluons, a collision between them can be explained in terms of a collision between their constituents (partons), which carry only a fraction of the energy of the original hadrons. Most of the times a hadron collision is soft, involving low transferred momentum, but sometimes partons can interact hardly, at large transferred momentum, and their interaction can be described by perturbative QCD. Usually the remnant partons can also interact, or partons can radiate gluons before they collide (initial state radiation). These contributions, which come from sources different from the partons responsible for the hard interaction, designate the underlying event and should not be taken into account when testing perturbative QCD. The processes involved in the underlying event usually happen at low transferred momentum, therefore perturbative calculation cannot be applied and they have to be described by models.

The underlying event is the subject of this thesis. The actual assumption is that the underlying event energy is similar to the energy found in soft events (minimum bias events). We will analyze data of the CDF [6] experiment at the Tevatron accelerator, in order to test this assumption. Future experiments will benefit from a precise implementation of physics processes in Monte Carlo simulation programs, which are usually used to test the theory or to make predictions. In order to examine how well soft models are implemented in such programs, we will compare data to the simulation. Finally, results will be extended to the LHC, where a good understanding of soft dynamics will be of extreme importance, since a large number of soft interactions will superimpose on each hard scattering.

In the second chapter, we will briefly introduce the Standard Model of particle physics and the theory of the strong interactions. Some of the models for soft physics implemented in Monte Carlo simulation programs, will be illustrated.

The third chapter contains a description of the Tevatron accelerator and the CDF experiment. In the fourth chapter the CDF data used in the analysis will be described, and the applied cuts will be motivated.

The fifth chapter contains the analysis performed at the CDF detector on both jet and minimum bias data. The method used to calculate the underlying event energy in jet events will be illustrated and comparison with minimum bias events will be carried out. Monte Carlo simulations will be used in order to test their validity.

The sixth chapter describes the LHC and the ATLAS [7] experiment. In the last chapter both the fast and the full ATLAS detector simulation will be used in order to estimate the contribution of the underlying event at the future LHC accelerator. The results are summarized in chapter 8.
Chapter 2

Introduction to the Standard Model

2.1 Matter

The Standard Model of elementary physics describes the properties of the particles and the interactions between them. In our understanding, the matter is made of spin one-half particles called fermions, while the interactions are mediated by integer spin particles called bosons. There are four kinds of known interactions: electromagnetic, weak, strong and gravity.

Fundamental particles which constitute the matter are leptons and quarks. They are grouped into three generations, each containing a doublet of quarks or leptons as shown in table 2.1. The three generations differ only for their mass. Quarks and leptons are characterized by different quantum numbers such as spin, charge, baryon number, lepton number, isospin, mass. Indeed quarks have an additional quantum number, called colour, because they are subject to the strong interaction. To each particle corresponds an antiparticle with same spin and mass, but opposite charge, lepton and baryon number. The lepton number is 0 for quarks and 1 for leptons. The baryon number is $+1/3$ for quarks and 0 for leptons. Quarks have only been observed bound together in hadrons.

Hadrons are subdivided in two categories: mesons and baryons. Both types of hadrons are colourless configurations of respectively a pair of a quark and an antiquark or a triplet of quarks or antiquarks, bound together by the strong interaction via the exchange of coloured gluons. Baryons are fermions (half-integer spin particles) characterized by a baryon number equal to 1, while mesons are bosons (integer spin particles) with a baryon number equal to 0.
# Chapter 2. Introduction to the Standard Model

## Generation

| Generation | 1st | 2nd | 3rd | charge | $|e|$ |
|------------|-----|-----|-----|--------|-----|
| Quarks     | u   | c   | t   | $+2/3$ |     |
|            | d   | s   | b   | $-1/3$ |     |
| Leptons    | e   | $\mu$ | $\tau$ | -1 |     |
|            | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ | 0 |     |

Table 2.1: Elementary constituents of the matter

## Forces

The fundamental forces acting in the Standard Model are the electromagnetic, weak, strong interactions and gravity. The electromagnetic force binds the electrons to the nucleus to make atoms, and atoms together to create molecules. Weak interactions allow neutrons to turn into protons through the $\beta$ decay. Both interactions are unified by the model of electroweak interactions. The strong force acts at very small distance and is responsible for binding the quarks inside the hadrons. Table 2.2 resumes the properties of these interactions [8].

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediators</th>
<th>Range</th>
<th>Typical lifetime</th>
<th>Typical coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>8 gluons</td>
<td>$1 fm \approx 1/m_\phi$</td>
<td>$10^{-23}$</td>
<td>1</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>$\infty$</td>
<td>$10^{-20} \sim 10^{-16}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm, Z^0$</td>
<td>$1/M_W$</td>
<td>$10^{-12}$ or longer</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Gravitational</td>
<td>$G$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$10^{-38}$</td>
</tr>
</tbody>
</table>

Table 2.2: Forces and their interactions. The lifetime is referred to particles decaying via strong, electromagnetic and weak interactions.

The electromagnetic, weak and strong interactions are described by gauge theories, which require the Lagrangian of the Standard Model to remain invariant under local gauge transformations of a symmetry group. The importance of symmetry in physics is emphasized by the Noether theorem, which affirms that if an action is invariant under a group of transformations, there must exist quantities associated to these transformations which stay invariant. I.e. symmetries imply conservation laws [9].
2.3 Gauge theory

The idea of gauge invariance permits us to describe the origin of the forces themselves. In a gauge theory the fields are described by a representation of an abstract symmetry group. The interaction between the fields, mediated by the gauge bosons, is induced by the requirement that the Lagrangian is invariant under local transformation of the field. The formulation of theories as QED (Quantum Electrodynamics) and QCD (Quantum Chromodynamics), which illustrate respectively the electromagnetic and the strong interactions, follows this principle [10].

QED explains the interaction of charged particles in a way that the electric charge is always conserved. This means that the Lagrangian must be invariant under a group of symmetry $G$:

$$G \mathcal{L}(\psi) \rightarrow \mathcal{L}'(\psi')$$ (2.1)

the group of transformation is simply U(1). To keep the invariance under local gauge transformation we need to introduce an electromagnetic field (the photon):

$$G \mathcal{L}(\psi, A) \rightarrow \mathcal{L}'(\psi', A')$$ (2.2)

$A$ indicates a four vector which describes the electromagnetic potential. Its propagation and interaction with other electrons cancel the terms in the Lagrangian due to the local transformation and restores the symmetry. The assignment of a mass to the photon would break the symmetry.

The same method can be used to describe the force acting on a nucleus. In this case we can consider the nucleons as two components of the same isospin and require invariance in the isospin space. Now the Lagrangian should be invariant under the gauge group of isospin transformation SU(2). Exactly as for the simple case of U(1) transformation, we have to introduce gauge particles and a covariant derivative which describes their propagation to assure invariance under local transformation. Now the gauge particles can interact with each other. In fact, contrary to U(1), SU(2) is a non-abelian symmetry group.

2.4 Standard model of electroweak interactions

The model is also known under the name of Glashow-Weinberg-Salam model [11]. In 1962 Glashow noticed that to explain both electromagnetic and weak interactions with gauge theory the group SU(2) $\otimes$ U(1) could be used. The bosons that mediate the interactions are introduced via their coupling to the matter fields (quarks and leptons). Three gauge bosons ($W_1, W_2, W_3$)
are associated to SU(2) and a neutral field ($B$) is associated to U(1). The charged weak bosons ($W^+, W^-$) are linear combinations of $W_1$ and $W_2$, while the photon $A$ and a neutral weak boson $Z^0$ are both given by a mixture of $W_3$ and $B$ regulated by the electroweak mixing angle $\theta_W$ which determines the mixing between the two theories. The three bosons which govern weak interactions must be massive in order to reproduce the short range of the force. On the other hand, the gauge formalism does not predict mass terms for the gauge bosons. In 1967 Weinberg and independently Salam (1968) implemented the idea of spontaneous symmetry breaking and the Higgs mechanism to give mass to the weak bosons. Essentially a scalar potential is added to the Lagrangian to generate the vector-boson masses in a gauge invariant way. In this way the theory predicts one more boson: the Higgs boson. Contrary to the electroweak gauge bosons, the mass of the Higgs boson cannot be totally predicted by the theory, but only in terms of an unknown quantity. Its existence has not yet been proven and its search is one of the main challenges at modern colliders. The electroweak theory was later shown to be renormalizable by 't Hooft in 1971 [12], this means that the various unphysical contributions due to infinite terms can all be consistently eliminated.

2.5 QCD

QCD was first formulated in 1973 as a non-abelian gauge theory in order to describe the behaviour of quarks inside protons. The basic idea is to use a new charge called colour as the source of interactions between quarks (like the electric charge is the source of electromagnetic forces between electrically charged particles).

One motivation for the definition of colour came from the observation that particles like the $\Delta^{++}$ are made of 3 quarks of same flavour (up) and same spin (spin up), thus violating the Pauli exclusion principle which affirms that 2 fermions which carry the same quantum numbers cannot form a single system. A solution to this puzzle was the assumption that quarks carry an additional quantum number (colour), that can take on three distinct values (red, green, blue). All observed hadrons are colour singlets, i.e. combinations of colours mixed to render a baryon or a meson colourless. This implies that the colour is hidden and the quarks are confined inside the hadrons, though it has not yet been proven from first principles.

2.5.1 QCD Lagrangian

The formulation of QCD is remarkably similar to that of QED. Since hadrons are colour singlets under the SU(3) colour group, it was natural to choose
SU(3) as gauge symmetry group. The QCD Lagrangian can be written as:

\[ \mathcal{L}_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \sum_q \bar{q}_i (i \gamma^\mu D_\mu - m_q) q_j \]  

(2.3)

where

\[ F^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu \]  

(2.4)

and the covariant derivative \( D \) is given by:

\[ (D_\mu)_{ij} = \delta_{ij} \partial_\mu + ig T^a_{ij} G^a_\mu \]  

(2.5)

the sum over repeated double indices is assumed. \( f^{abc} \) are the structure constants, \( g \) is the coupling constant, \( T^a_{ij} \) are the SU(3) generators and \( G^a_\mu \) are the gluon fields.

The matrices \( T^a \) form a basis of traceless 3 \( \times \) 3 matrices in the fundamental representation of the group. There are 8 such matrices and therefore 8 gluons. The basis is chosen in such a way that \( Tr(T^a T^b) = \frac{1}{2} \delta_{ab} \). The structure constants are defined through the commutation relation:

\[ [T^a, T^b] = i f^{abc} T^c \]  

(2.6)

The QCD Lagrangian is indeed very similar to the QED Lagrangian, but the fermions carry a new quantum number: the colour (here the indices \( i, j = 1, 2, 3 \)). Also the gluons carry a colour related quantum number and therefore they are charged and can emit other gluons. This coupling is characteristic of a gauge theory based on a non-abelian group. The probabilities for a quark to radiate a gluon, or for a quark to split into a gluon or a quark pair are related to the coupling constant and some factors called colour factors which are indicated respectively by \( C_F, C_A, T_F \). As a standard normalization condition \( T_F = \frac{1}{2} \) is chosen, and it follows that \( C_A = 3 \) and \( C_F = \frac{4}{3} \) for SU(3). These factors have been experimentally measured as a test of QCD and gave results consistent with the predictions [13].

In order for the theory to be renormalizable and therefore to remove all ultraviolet divergences from a physical quantity, we must introduce a finite scale \( \mu \) in the redefinition of the coupling constant, \( \alpha_s \). The \( \mu \) dependence of \( \alpha_s \) is given by the renormalization group equation [14], the solution of which, at leading order, is [15]:

\[ \alpha_s(\mu) = \frac{1}{b_0 \ln \frac{\mu^2}{\Lambda^2}} \]  

(2.7)

\( \Lambda \) plays the role of an integration constant and its value has been experimentally measured to be of the order of few hundred MeV [16]. Indeed \( b_0 = \frac{11}{12\pi} C_A - \frac{1}{3\pi} T_F n_f \), with \( n_f \) the number of quark flavours, and is a positive quantity. Therefore, the definition of \( \alpha_s \) in equation (2.7) makes sense
only for $\mu \gg \Lambda$, for which the values of $\alpha_s$ are small and perturbation theory can be applied. The value of $\alpha_s$ decreases as $\mu$ increases. For this reason QCD is *asymptotically free*: when the quarks are close together the forces between them are weak, as the distance between them increases, so do the forces.

### 2.5.2 Kinematic variables in hadron collisions

This work concerns the analysis of processes in hadron collisions, i.e. with hadrons present in the initial state. The usual kinematic variables, for this kind of reactions, are defined as follows. We can consider the in and out going particles in a configuration as shown in figure 2.1.

![Kinematic variables in hadron scattering](image)

**Figure 2.1: Kinematic variables in hadron scattering**

The transverse momentum $p_t$ is the projection of the particle momentum on the plane orthogonal to the collision axis, the longitudinal momentum $p_l$ is the projection along the direction of the incident particle. The transverse energy, transverse mass and rapidity are defined, respectively, as:

\[
E_t = E \sin \theta \tag{2.8}
\]

\[
m_t = \sqrt{p_t^2 + m^2} \tag{2.9}
\]

\[
y = \frac{1}{2} \log \frac{E + p_t}{E - p_t} \tag{2.10}
\]

These variables are usually used in hadron collisions because the center of mass system for the process is boosted along the incident particle direction with respect to the hadron center of mass. The transverse momentum, energy and mass are invariant under longitudinal boosts and the rapidity is simply translated by the boost angle. Indeed, for particles of small masses the following approximation is valid:

\[
y \simeq -\log(\tan \frac{\theta}{2}) = \eta \tag{2.11}
\]
2.5. QCD

The quantity $\eta$ is called pseudorapidity.

2.5.3 Parton model and high momentum processes

In general, in hadron collisions, there are two classes of reactions. The first are soft interactions, which involve small momentum transfer and are sensitive to long-distance effects. The second involve hard scattering and are characterized by the presence of large momentum transfer as high transverse energy jets, heavy quarks, high mass lepton pair productions. Only for the second class of reactions, perturbative QCD can be directly applied and they will be illustrated first.

In general, we can study the collisions between two hadrons considering for example the exchange of gluons between only one of the constituents (called partons) of each initial hadron. All the other partons act as passive spectators (figure 2.2). For example a proton is composed of 3 valence quarks and other virtual constituents (gluons or $q\bar{q}$ pairs) into which it constantly dissociates. After the collision the 2 partons involved in the hard scattering may emerge sideways out of the hadrons. Because of the confinement mechanism, which keeps quarks in hadrons, they do not emerge as free particles, but the result is a collimated bunch of hadronic particles (jet) emerging along the directions of motion of the original parton.

In general, the cross section for the collisions of $h_1$, $h_2$ to produce particles $c$ and $d$ is given by:

$$d\sigma(h_1h_2 \to cd) = \sum_{ab} \int_0^1 dx_1 \int_0^1 dx_2 f_{h_1}^a(x_1, \mu)f_{h_2}^b(x_2, \mu)d\hat{\sigma}(ab \to cd)$$  \hspace{1cm} (2.12)

This formula is applicable for inclusive processes with large momentum transfer. By inclusive we mean that we do not care about the distribution of the final state hadrons. $x_1$ and $x_2$ are the fractions of the momenta of the partons involved in the hard scattering and the momenta of their parent hadrons. $f_{h_1}^a$ and $f_{h_2}^b$ are the parton distribution functions (PDF) evaluated at the scale $\mu$ of the process. They represent the probability to find the parton $a$ ($b$) with momentum fraction $x_1$ ($x_2$) inside the hadron $h_1$ ($h_2$). The sum is over all partonic subprocesses, which contribute to the production of $c$ and $d$. The partonic cross section $\hat{\sigma}(ab \to cd)$ is computable as a power series expansion in the QCD coupling $\alpha_s$:

$$\hat{\sigma}(ab \to cd) \equiv \hat{\sigma}_{ab} = \alpha_s^k(\mu)\{\hat{\sigma}_{ab}^{LO} + \alpha_s(\mu)\hat{\sigma}_{ab}^{NLO} + \alpha_s^2(\mu)\hat{\sigma}_{ab}^{NNLO} + \ldots\}$$  \hspace{1cm} (2.13)

with $k = 0, 2, \ldots$. The leading order (LO) term gives only an estimate of the cross section. NLO terms have been calculated and are available for many processes of interest [17].
CHAPTER 2. INTRODUCTION TO THE STANDARD MODEL

Figure 2.2: Schematic of a hadron-hadron reaction with a gluon exchange which gives rise to jets of hadrons in the final state.

Formula (2.12) is a direct result of the Factorization Theorem [18]: a large class of inclusive cross sections can be factorized into a short-distance part (process dependent but calculable by perturbative QCD) and a part (not calculable but universal) represented by a set of parton distribution functions (PDFs) which characterize long-distance hadron structure. The PDFs have a slight dependence on the scale $\mu$ determined by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation [19].

$$\mu^2 \frac{\partial}{\partial \log \mu^2} f^h_i(x, \mu) = \int_x^1 \frac{dy}{y} \sum_j P_{ij}(y) f^h_j\left(\frac{x}{y}, \mu\right) \tag{2.14}$$

The equations describe the evolution of a parton $i$ in the hadron $h$. $P_{ij}$ are called splitting functions and have a perturbative expansion in powers of $\alpha_s$. At leading order they can be interpreted as the probability to find a parton $i$ in the parton $j$ carrying a fraction $x$ of the longitudinal momentum of the parent parton and a transverse momentum squared $Q^2 \ll \mu^2$. Once these equations have been solved at a given energy, the solution can be evolved to other energies. Usually PDFs are extracted from measurements in lepton-nucleon scattering experiments at some scale and then used for calculations.
In a hadron collision, in addition to the hard subprocess such as hadronic scattering, we have an underlying event arising from the beam remnants. Usually it consists of a soft inelastic collision between parton remnants, therefore perturbation theory cannot be applied. Most of the produced soft particles have a limited transverse momentum and the main activity occurs at low angles with respect to the beam. However, it has been observed that there is an increased level of hadronic activity in hard events as compared to events where no hard scattering occurred. This suggests that more refined models are involved between the hard subprocess and the underlying event. Indeed, there is also the possibility that a second hard scattering occurs between the partons in the beam remnants, involving momentum transfer high enough to apply perturbation theory. Usually, in particle colliders, particles are accelerated in bunches. If the rate of collisions is high, there is a relevant probability that one single bunch crossing produces several separate events (pile-up events), resulting in an increase of the total particle production activity. Since the underlying event is the subject of this thesis, its implication will be described in more details in the next chapters.

2.5.4 Inelastic hadron collisions

Although we can describe events with a large momentum transfer in the reaction through perturbative QCD, most of the events in hadron collisions are soft. For the so called soft events, we intend that the characteristic momentum transfers are small in comparison to, say, the center of mass energy $\sqrt{s}$. Usually, events with high momentum transfer are rare compared to common low $p_t$ inelastic events [20]. The soft processes typically have a large cross section which grows logarithmically with the center of mass energy. The total $p\bar{p}$ cross sections at center of mass energies of $\sqrt{s} = 546$ GeV and 1800 GeV has been measured to be of $\sigma_T = 61.26 \pm 0.93$ mb and $80.03 \pm 2.24$ mb respectively [21]. Figure 2.3 shows the total cross section as a function of the center of mass energy for different $p\bar{p}$ experiments.

Perturbation theory cannot calculate the total cross section because it would be divergent at small momenta. Usually, phenomenological models based on optical models or Regge theory are used. The former is centered on the optical theorem which relates the total cross section to the imaginary part of the forward elastic scattering amplitude. The latter is based on the observation that resonances lay on straight lines in a graph of spin against mass squared (Regge trajectories). A collision between two hadrons is seen as the exchange of the content of one or more Regge trajectories between the two (reggeon exchange). I.e. a reggeon exchange represents the exchange of all these trajectories with differing masses and spin with...
an otherwise identical set of internal quantum numbers and the vacuum trajectories (Pomeron). It predicts that the total cross section for hadron collisions is constant over a wide range of energies (as observed in experiments). Regge theory can describe the charged multiplicity and many other features of experimental data, but from a theoretical point of view there are several open problems [22].

Usually, inelastic processes are quite complicated to describe. The usual quantities which describe the properties of these events are the charged multiplicity, the transverse momentum and rapidity distribution of the hadrons.

The multiplicity distribution is the frequency of the production of a final state with a given number of hadrons. Usually only charged hadrons are considered because they are the only ones to be individually measured by most experiments. The measured average multiplicity increases as $\log^2(s)$ [23].
The fluctuations between different events are of the order of 100%.

The transverse momentum distribution of the produced particles falls exponentially with increasing $p_t$. It has an average value of a few hundred MeV, which rises as $\log^2(s)$.

The rapidity distribution is flat at small $\eta$ and falls off rapidly at higher rapidity. The multiplicity density, $dN/d\eta$, at $\eta = 0$ has been measured at hadron colliders at different center of mass energies. It also increases faster than $\log(s)$ as it is shown in figure 2.4 [24].

Generally, the properties of the soft particles show only weak dependence on the center of mass energy of the colliding hadrons.

2.6 Hadron collisions and Monte Carlo generators

Monte Carlo generators are very useful in simulating high energy collisions and can be used to test theory predictions. They are programs which simulate collisions and calculate final states with the help of theory and models, using a random number generator to determine the kinematics of the collision. The behaviour of a hadron-hadron collision can be illustrated as in figure 2.5.

The collision is seen as the scattering between two partons (each from a different hadron). The processes due to the remnant partons are difficult to describe because they happen at relatively low momentum transfer,
where perturbation theory cannot be applied, thus, we have to rely on models. Several of these models, which are implemented in the event generator programs used in this analysis, will be described in section 2.6.2.

In general, the hadron-hadron scattering process can be separated into different subprocesses:

- **Initial state radiation (I.S.R.).** A parton from the incident hadron radiates gluons and consequently decreases its energy to a fraction of that of the initial hadron.

- **Hard scattering.** It consists of subprocesses that can be perturbatively calculated.

- **Parton Shower.** The outgoing partons radiate gluons.

- **Hadronization.** Partons are converted into hadrons. Since the energy involved in this process is less than a GeV, perturbative calculations cannot be performed and models must be used in order to describe this process.
In our analysis we will use two Monte Carlo generators: Herwig [25] and Pythia [26]. They both have $2 \to 2$ matrix elements for jet production, i.e. for processes with 2 incoming particles and 2 outgoing partons, and employ parton showering in the initial and final state and models to simulate events at low momentum transfers. The hard scattering matrix elements are implemented at leading order (LO). Higher order effects are approximated in Pythia’s parton shower at leading logarithmic approximation (LLA). The Herwig’s parton shower reproduces next-to-leading logarithmic approximation (NLLA) calculations [27].

2.6.1 Hadronization models

Different models have been defined to describe the mechanism of hadron formation. The two main ones are the cluster and string models. They are respectively implemented in Herwig and Pythia.

The cluster model [28]: after the parton shower, all gluons are split non-perturbatively into quark-antiquark or diquark-antidiquark pairs. Colour singlet clusters are formed from nearby quark-antiquark pairs. Clusters have a mass distribution and spatial size that peaks at low values and falls rapidly for large cluster mass and size. Hadrons are chosen according to the density of states with appropriate quantum numbers. Clusters with mass too large for isotropic two body decay are fragmented using an iterative fission model until the masses of the products are below a certain limit. One advantage of this model is that it has few parameters. But it does have problems with the decay of very massive clusters and in the suppression of baryon and heavy quark production [29].

The Lund string model [30]: the colour field lines between the partons outgoing the hard scattering, can be imagined as concentrated in a colour flux tube, stretched between the partons. This tube acts like a string with a constant tension $k$. The potential energy inside the string is of the form: $V = kr$ with $k \simeq 1$GeV/fm. When the partons move apart, the potential energy increases and when there is enough energy to create a hadron, the string breaks to produce a $q\bar{q}$ pair. Now the system consists of two colour singlets $q\bar{q}$ and $q\bar{q}$. If one of them has enough energy, the fragmentation process continues. If a gluon is emitted, i.e. $qqg$ events, a string is stretched from $q$ to $\bar{q}$ via the gluon which becomes a kink on the string and carries an energy and a momentum. Although with some problems, the model can describe baryon production better than the cluster model [27].
2.6.2 Soft collisions models

Aside from the two partons which give rise to the hard scattering, in hadron-hadron collisions, there is also the energy emerging from beam remnants. This underlying event is usually represented by a soft collision between the beam clusters, but there is also the possibility for the beam remnants to interact in a semi-hard fashion and generate multiple interactions. Due to the softness of the interaction and to the limited understanding of non-perturbative QCD, models must be implemented in Monte Carlo generators in order to reflect the properties of the data. Since soft processes have the largest cross section in hadron-hadron collisions, their importance should not be underestimated. There are different approaches to describe soft hadronic interactions. There are geometrical models which are based on the dynamics in the impact parameter space, hard scattering models which use perturbative QCD, and soft interaction models based on the chain topology\footnote{Particles are produced in 2 chains which extend between partons of different or same hadrons} [31]. Here, we will shortly explain how Herwig and Pythia describe soft interactions.

Herwig has a model for the underlying event description based on that of the UA5 collaboration [32], which took data at a center of mass energy of 546 GeV. The model is readapted to make use of the usual Herwig fragmentation model. As a first step the number of charged particles in the event is chosen by using a negative binomial distribution:

\[
P(n) = \frac{\Gamma(n + k)(\bar{n}/k)^n}{n!(\bar{n}/k)^{n+k}}
\]  

(2.15)

where \(\bar{n}\) is the mean charged multiplicity and \(k\) describes the shape of the distribution. Both parameters depend on the center of mass energy and have been derived from fits to data. The cluster masses are chosen from the distribution:

\[
P(M) \propto (M - M_0)e^{-a(M-M_0)}
\]  

(2.16)

with \(M_0 = 1\) GeV and \(a=2\) GeV\(^{-1}\). The transverse momentum distribution of a soft cluster has the form:

\[
P(p_t) \propto p_t e^{-b\sqrt{p_t^2 + M^2}}
\]  

(2.17)

\(b\) gives the slope of the distribution and its value is chosen according to the flavour of the quark or diquark pair created when the cluster is produced.

The Pythia model for the underlying event [33] is more complicated. The philosophy at the basis of the model is founded on the description of multiple interactions. In Pythia each beam remnant is identified, and energy and
mass are assigned to it. If they are above a certain cut-off, multiple interactions are generated. Each interaction is assumed to be independent from the other and the number of interactions per event is given by a Poissonian distribution. Perturbative QCD describes the total rate of parton-parton interactions at large transverse momentum. Here the perturbative framework is extended to the low $p_t$ region, but a regularization of the divergence in the cross section for $p_t \to 0$ has to be introduced. This is the main free parameter of the underlying event model in Pythia. The parameter has been obtained from fits to charged multiplicity distribution data. Indeed, as hadrons are extended objects, the collisions range from very central to rather peripheral ones. This scenario is considered in Pythia which can be run with the option of varying impact parameter.
Chapter 3

The Tevatron accelerator and the CDF detector

The Tevatron collider \cite{ref4} is currently the highest energy accelerator in the world. Proton-antiproton collisions take place at a center of mass energy of up to 2 TeV. The accelerator is located at the Fermi National Laboratory founded in Batavia, about 70 km far from Chicago and began operation in 1983. CDF, the Collider Detector at Fermilab, is a multipurpose detector at the Tevatron.

Starting from 1992 to 1996 (run1), CDF collected data at a center of mass energy of 1800 GeV during three different data taking periods: run1a (from 1992 to 1993), run1b (from 1994 to 1995) and run1c (from 1995 to 1996). For a short period during run1c, the Tevatron was operated at a center of mass energy of 630 GeV. Since in this analysis we are interested in data collected in run1b and at a center of mass energy of 630 GeV, the characteristics of the accelerator and the CDF detector during these periods of data taking will be illustrated.

3.1 The accelerator

Protons (and antiprotons) are accelerated through different stages. The accelerator complex is shown in figure 3.1.

The first stage of acceleration is provided by the Cockcroft-Walton electrostatic generator. Here electrons are added to hydrogen atoms resulting in negative ions consisting of two electrons and one proton. The $\text{H}^-$ ions are attracted and accelerated by a positive voltage to an energy of 750 keV.

After leaving the Cockcroft-Walton, the negative hydrogen ions enter the Linac, a linear accelerator 150 m long. The Linac consists of a series of 9
Figure 3.1: View of the accelerator complex

radio-frequency cavities. The H\(^-\) ions, which leave the Linac, pass through a carbon foil which removes the electrons, leaving only the protons.

The third stage of acceleration is the Booster, a synchrotron of 151 m in diameter located approximately 6 m underground. Magnets are used to bend the protons in a circular path and RF cavities to accelerate them.

After revolving about 20000 times, the protons leave the Booster with an energy of 8 GeV in bunches of \(10^{10}\) particles and enter the Main Ring, a synchrotron located in the same tunnel as the Tevatron, also 6 m underground, and of approximately 1 km radius. The Main Ring accelerates the protons to 150 GeV before injecting them into the Tevatron. Some of the protons in the Main Ring are extracted and sent to a nickel target to make antiprotons. The particles are focused through a lithium lens and a magnetic field bends only negative charged particles along the beam. The pions decay quickly and the remaining antiprotons come off the target in bunches 20 ns apart. About 1 antiproton is created for every \(10^5\) protons. After that, the antiprotons are stored in the Accumulator Ring where they are stochastically cooled to reduce their transverse momentum and spatial dispersion. When enough antiprotons are accumulated, they are injected into the Main Ring and then into the Tevatron.

The Tevatron is a synchrotron composed of a ring of superconducting
3.2. THE CDF DETECTOR

The Collider detector at Fermilab (CDF) is a 5000 t magnetic detector. It is approximately 27 m long and 10 m high. Event analysis is based on charged particle tracking, magnetic momentum analysis and fine-grained calorimetry [6]. Its various components are shown in a cut-away view of a quarter of the detector in figure 3.2. The CDF coordinate system is also shown. The $z$ axis points east along the direction of the protons, the $x$ axis points outside the accelerator ring and the $y$ axis points upwards. The detector is made up of a solenoidal magnet, steel yoke, tracking chambers, electromagnetic shower counters, hadron calorimeters and muon chambers and two identical forward/backward detectors consisting of time-of-flight counters. Its basic goal is to measure the energy, momentum and possibly the identity of particles produced in $p\bar{p}$ collisions at the Tevatron.

The detector covers $2\pi$ in azimuth ($\phi$) and -4.2 to 4.2 in pseudorapidity ($\eta$). There are three main divisions of the detector in $\eta$ space:

<table>
<thead>
<tr>
<th>Run</th>
<th>Year</th>
<th>Total luminosity</th>
<th>Instantaneous luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>run1a</td>
<td>1992-93</td>
<td>$19.65 \pm 0.71 pb^{-1}$</td>
<td>$\simeq 3 \times 10^{30} cm^{-2}s^{-1}$</td>
</tr>
<tr>
<td>run1b</td>
<td>1994-95</td>
<td>$86.34 \pm 3.52 pb^{-1}$</td>
<td>$\simeq 9 \times 10^{30} cm^{-2}s^{-1}$</td>
</tr>
<tr>
<td>run1c (630 GeV)</td>
<td>1995</td>
<td>$0.576 \pm 0.025 pb^{-1}$</td>
<td>$\simeq 2 \times 10^{30} cm^{-2}s^{-1}$</td>
</tr>
</tbody>
</table>

Table 3.1: Total integrated and average instantaneous luminosity measured by CDF.

Magnets directly below the Main Ring. Superconducting magnets produce a larger magnetic field at a lower operating cost than the conventional magnets and allow the protons to be accelerated up to 900 GeV. The two beams of protons and antiprotons collide in two different points: D0 and B0 where, respectively, the two main detectors D0 and CDF are located.

The luminosity is given by:

$$L = \frac{N_p N_\bar{p} B f}{4\pi \sigma^2}$$  \hspace{1cm} (3.1)

where $B$ is the number of bunches, $f$ is the revolution frequency, $N_p$ and $N_\bar{p}$ are the number of protons/antiprotons per bunch and $\sigma$ is the transverse cross sectional area of each bunch. The average luminosity during different data taking periods from 1992 to 1996 has been measured by CDF and is summarized in table 3.1 [34].
Figure 3.2: A quarter view of the CDF detector
3.3 Tracking

In the central region $|\eta| < 1.1$, which is of interest to our study, the tracking system consists of:

- a silicon vertex detector (SVX$'$)
- a vertex tracking chamber (VTX)
- a central tracking chamber (CTC)

The SVX$'$ was installed for the run1b and is a radiation-hard version of the previous silicon detector system (SVX), installed in 1992. It is located immediately outside the vacuum chamber and is composed of four concentric cylindrical layers of silicon microstrip detectors radially located respectively.

Figure 3.3: View of a barrel of the SVX$'$
at 2.9, 4.2, 5.7 and 7.9 cm from the beam line. It consists of two symmetric barrels 51 cm in length placed at $z = 0$ and separated by 2.5 cm to provide tracking on the $r - \phi$ plane. A barrel is shown in figure 3.3.

The SVX' provides a single-hit reconstruction resolution of 13 $\mu$m and an impact parameter\(^1\) resolution of 17 $\mu$m. The main goal of the SVX' is to reconstruct secondary decay vertices from precise measurements of tracks, in order, for example, to identify b-quarks decay (b-tagging). The SVX' provides a measurement of the impact parameter of the traversing particles.

The VTX provides information in the $r - z$ plane. It has a total outer radius of 22 cm and is made out of 28 drift modules which give full coverage in $\phi$ and in the pseudorapidity region $|\eta| < 3.25$. Each module is composed of 8 octants divided in two regions each 5 cm long. The active medium is a mixture of Argon and Ethane gas. The outer 10 modules contain 24 sense wires. The inner 18 modules contain 16 parallel drift wires in the $r - \phi$ plane, to allow the SVX' to fit inside the VTX. Each module is rotated by 15° with respect to the previous one to obtain a better coverage. Its main use is to reconstruct primary event vertices with a precision of 1 mm in the $z$ direction.

---

\(^1\)distance of closest approach to the main interaction point
The CTC is located outside the VTX chamber and inside the solenoidal magnet. This is the main tracking device in CDF and is 3.2 m long. Its inner radius is 277 mm and the outer radius 1380 mm. Its main goal is to identify secondary vertices from long lived particles and to measure the transverse momentum of charged particles. It provides a precise momentum measurement in the angular region $40^\circ < \theta < 140^\circ$ with a momentum resolution better than $\delta p_t / p_t^2 \leq 0.002$ (GeV/c)$^{-1}$. It is composed of 84 layers of sense wires arranged in 9 superlayers (figure 3.4).

There are 5 axial superlayers, in which the sense wires are parallel to the beam direction, which reconstruct the tracks in the $r-\phi$ plane. The axial superlayers are interspersed with 4 stereo superlayers, in which the angle between the sense wires and the beam line alternates by $\pm 3^\circ$. Stereo superlayers allow track reconstruction in the $r-z$ plane. Both axial and stereo superlayers are divided into cells. The maximum drift distance is 40 mm, which correspond to about 800 ns drift time. Superlayers are tilted by $45^\circ$ with respect to the radial direction to correct for the Lorentz angle of the electron drift in the magnetic field.

### 3.4 Solenoid magnetic coil

The CTC is immersed in a 1.41 T magnetic field in order to provide precise information on the transverse momentum of charged particles. The magnetic field is produced by a superconducting solenoidal coil of 3 m diameter and 5 m length. It is made of 1164 turns of an aluminium-stabilized NbTi/Cu superconductor, cooled by liquid helium. The radial thickness of the solenoid is 0.85 radiation length.

### 3.5 Calorimeters

Calorimeters are the only efficient way to measure neutral particles. All the CDF calorimeters are sampling calorimeters which, contrary to total absorption calorimeters, sample only a fraction of the energy deposited by an incoming particle. There are two types of calorimeters: electromagnetic and hadronic. In CDF, both alternate layers of absorbing material and active material. CDF calorimeters are non compensating. This means that their response to hadronic energy is smaller than their response to electromagnetic energy.

Due to the importance of jets in hadron collisions, CDF chose a tower geometry for both hadronic and electromagnetic calorimeters. The towers point to the interaction region (projective towers) and their coverage is $2\pi$.
in azimuth and from -4.2 to 4.2 in pseudorapidity. The size of the towers is \(0.11 \times 15^\circ (\Delta \eta \times \Delta \phi)\) in the central region and \(0.11 \times 5^\circ\) in the plug and forward region. This corresponds to a spatial size of the towers which ranges from about \(24.1 \text{ cm} \times 46.2 \text{ cm}\) (in \(\eta\) and \(\phi\) directions respectively) in the central region to about \(1.8 \text{ cm} \times 1.8 \text{ cm}\) in the very forward region. The \(\eta - \phi\) coverage and the size of the towers are shown in figure 3.5.

Figure 3.5: Hadron and electromagnetic towers coverage.

Every region (central - endplug - forward) has different calorimeters for a total of seven calorimeters systems: Central Electromagnetic Calorimeter (CEM), Central Hadron Calorimeter (CHA), Endplug Electromagnetic Calorimeter (PEM), Endplug Hadron Calorimeter (PHA), Wall Hadron Calorimeter (WHA), Forward Electromagnetic Calorimeter (FEM) and Forward Hadron Calorimeter (FHA). The WHA is a hadronic calorimeter which covers the gap between the central and the plug calorimeters. For this analysis we only used the Central Electromagnetic and Hadronic Calorimeters. The properties of the different CDF calorimeters are shown in table 3.2.

### 3.5.1 Central Calorimeters

The central calorimeter consists of 48 wedges, divided symmetrically at \(\eta = 0\). Each wedge is made of an electromagnetic and hadronic part and is divided in 10 towers with \(\Delta \eta = 0.11\).
3.5. CALORIMETERS

<table>
<thead>
<tr>
<th>Calorimeter properties</th>
<th>Central EM</th>
<th>HAD</th>
<th>Endwall EM</th>
<th>HAD</th>
<th>Endplug EM</th>
<th>HAD</th>
<th>Forward EM</th>
<th>HAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>η coverage</td>
<td>0-1.1</td>
<td></td>
<td>0-0.9</td>
<td></td>
<td>0.7-1.3</td>
<td></td>
<td>1.1-2.4</td>
<td>1.3-2.4</td>
</tr>
<tr>
<td>tower size</td>
<td>∼0.1 × 15°</td>
<td>∼0.1 × 15°</td>
<td>∼0.1 × 15°</td>
<td>∼0.1 × 15°</td>
<td>∼0.1 × 15°</td>
<td>∼0.1 × 15°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>active medium</td>
<td>polystrene</td>
<td>acrylic</td>
<td>acrylic</td>
<td>prop. tube</td>
<td>prop. tube</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>scint. thickn.[cm] or prop. tube size[cm²]</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.7 × 0.7</td>
<td>1.4 × 0.8</td>
<td>1.0 × 0.7</td>
<td>1.5 × 1.0</td>
<td></td>
</tr>
<tr>
<td>absorber</td>
<td>Pb</td>
<td>Fe</td>
<td>Fe</td>
<td>Pb</td>
<td>Fe</td>
<td>Pb</td>
<td>94% Pb</td>
<td>6% Sb</td>
</tr>
<tr>
<td>absorber thickness [cm]</td>
<td>0.32</td>
<td>2.5</td>
<td>5.1</td>
<td>0.27</td>
<td>5.1</td>
<td>0.48</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>energy (σ/E) res. at 50 GeV [%]</td>
<td>2</td>
<td>11</td>
<td>14</td>
<td>4</td>
<td>20</td>
<td>4</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>position res. at 50 GeV [cm²]</td>
<td>0.2 × 0.2</td>
<td>10 × 5</td>
<td>10 × 5</td>
<td>0.2 × 0.2</td>
<td>2 × 2</td>
<td>0.2 × 0.2</td>
<td>3 × 3</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Properties of CDF calorimeters

In the electromagnetic calorimeter [35], each wedge contains 31 layers of polystrene scintillator (5mm thick) alternated with 30 layers of lead absorber (3.2mm thick), clad on both sides with aluminium. Plastic light guides collect light from the scintillator. Each tower is connected to two photomultipliers tubes which read the signal. A proportional strip chamber (CES) is located between the eighth lead layer and the ninth scintillator layer to determine the shower position and profile at shower maximum.

The calibration of each module was performed at Fermilab by exposing the towers to 50 GeV/c electrons, sent to the center of the towers. The energy resolution for electrons centered in towers is described by:

\[
\frac{\sigma(E)}{E} = \frac{13.5\%}{\sqrt{E\sin\theta}} \oplus 2\%
\]

where E is in GeV. The position resolution is typically ±2mm.

The CDF central hadron and endwall calorimeters cover respectively the pseudorapidity regions |η| < 0.9 and 0.7 < |η| < 1.3, so that they overlap in the 0.7 < |η| < 0.9 region [36]. The hadron calorimeter has a tower structure such that there is a one-to-one correspondence between the CEM and the CHA towers. The CHA consists of 32 layers of 2.5 cm thick steel plate interspersed with 1 cm of plastic scintillator. The WHA consists of 15 layers of 5 cm thick steel plates interspersed with 1cm of plastic. The light is collected by wavelength shifter strips which lie against the long sides of
the scintillator sheets and which are read out from the multiplier tubes. The calibration of the hadronic wedges were performed using 50 GeV charged pions. For pions of energy in the range $10 - 150$ GeV the energy resolution was found to be:

$$\frac{\sigma(E)}{E} = \frac{75.5\%}{\sqrt{E \sin \theta}} \oplus \pm 3\%$$  \hspace{1cm} (3.3)

where $E$ is in GeV. Aging studies were made on each wedge by using a $^{137}\text{Cs}$ source placed in the scintillator and reading out the signal.

Because of the necessity of support structure and of the presence of readout cables, there are uninstrumented regions in the detector (cracks). The energy of a particle traveling through these regions is poorly measured. These cracks appear at $\theta = 10^\circ, 30^\circ, 90^\circ$, but only the crack at $\theta = 90^\circ$ affects our studies. Here the CEM modules are bound by 2.5 cm steel endplates that are separated from the scintillators by a support gap of 1.6 cm. The steel endplates of the two symmetric modules that are joined at $z = 0$, are separated by an air gap of 0.5 cm.

### 3.6 Muon detection

Muons are very penetrating particles. For this reason the muon system is located in the outer region of the CDF detector. The muon detection is made by matching a track in the CTC with a response in one of the muon detector systems. There are 4 muon systems in CDF.

The Central muon drift chambers (CMU) and the central muon upgrade (CMP) cover the pseudorapidity region $|\eta| < 0.6$. Both detectors consist of 4 layers of wire drift chambers. The CMP was installed in 1992 to reduce the backgrounds from hadrons that pass through the calorimeter.

The Central Muon extension (CMX) covers the pseudorapidity region of $0.6 < |\eta| < 1.0$ and is also constructed from single wire drift chambers.

The Forward Muon detector (FMU) covers the pseudorapidity region of $1.9 < |\eta| < 3.6$. It consists of three sets of drift chambers in between two 1 m thick steel magnets with outer and inner diameter of 7.8 m and 0.9 m respectively.

### 3.7 The beam-beam counters

The beam-beam counters (BBC) consist of a plane of scintillation counters located on the front face of the forward electromagnetic calorimeters at ± 5.8 m in the $z$ direction from the interaction point. The scintillators provide
3.7. THE BEAM-BEAM COUNTERS

A time resolution of 200 ps. Each set of scintillators has 16 counters which are arranged in a rectangle around the beam pipe (figure 3.6).

The smallest counter is directly on the beam pipe, while the largest is at 47 cm from the beam pipe. They cover a pseudorapidity range of $3.24 < |\eta| < 5.90$. The BBC provides a minimum bias trigger for the detector requiring at least a signal from one counter in each plane within 15 ns from the beam crossing time. A minimum bias trigger indicates that some inelastic physics took place. The BBCs are also used as the primary luminosity monitor.

![Figure 3.6: A beam-beam counter plane seen from the beam direction.](image)
3.8 Data acquisition and trigger system

At the Tevatron, the rate of bunch crossing is 286 kHz (3.5 $\mu$s between crossing). With a typical total $p\bar{p}$ inelastic cross section of 50 mb and instantaneous luminosity of $10^{31}$ cm$^{-2}$s$^{-1}$ we expect a proton-antiproton interaction rate of about 500 kHz, i.e. almost two interactions per bunch crossing. Since the rate at which CDF can write events on disk is less than 10 Hz, CDF needs to select one event out of 30 000. This is accomplished by the trigger system which consists of three levels of increasing sophistication and trigger time requirement. The first two triggers are hardware triggers. Since the detector cannot see other crossings during the trigger decision, it is very important to try to reach a decision in a small time. In this way dead times are reduced.

At Level 1 the decision is taken in less than the bunch crossing time of 3.5 $\mu$s. The decision is based on beam-beam counters information. In addition, the hadronic and electromagnetic calorimeters towers are grouped in such a way to divide the entire detector in a 42 (in $\eta$) by 24 (in $\phi$) grid. If the sum of $E_t$ for all towers above a certain threshold is greater than 30 – 40 GeV the crossing is accepted. Presence of muons in the muon chambers and tracks in CTC are also taken into account for the decision. If an event is not accepted by the Level 1 trigger, a reset will be sent in time for the next crossing and no dead times are added, otherwise the Level 2 trigger starts. The acceptance rate of the Level 1 trigger is of few kHz.

The Level 2 trigger takes a decision in about 20 $\mu$s. During this time about 7 – 10 beam crossings are lost since the data have not been buffered. Level 2 searches for clusters of total or electromagnetic energy, calculates the total transverse energy in the detector, matches clusters to tracks from the CTC and identifies muons. The final trigger is a selection on muons, electrons, photons, jets and missing $E_t$. At this level the trigger is prescaled to reduce the acceptance rates to 20 Hz for Level 3 because this is the maximum rate that it can accept. This means that some events are rejected even if they passed the above cuts. The trigger can be dynamically prescaled, in this case the prescale factors depend on the instantaneous luminosity.

When the Level 2 accepts a crossing, all detector information are read out and passed to the third level for processing. The data acquisition (DAQ) takes about 3 ms to read the information and this corresponds to a loss of about 1000 crossings. Once the event readout is completed, the Level 1 and Level 2 trigger systems are reenabled.

The Level 3 trigger decides if an event must be recorded on tape for the off-line analysis. This is a software trigger written in Fortran running a reduced version of the CDF off-line software. A Silicon Graphics Farm is used for this purpose. This trigger reconstructs physics jets and tracks.
from raw data. It searches for electrons, muons, taus, heavy quarks. Level 3 rejects about $60 - 80\%$ of the events from Level 2. The data are recorded in different streams. For the run1b events were stored in two formats: a fast one (PAD) containing essential triggers that can be quickly analyzed, and another format (DST) which contains triggers with looser requirements at Level 3.
Chapter 4

Data sample

In this analysis we use CDF data from run1b, at a center of mass energy of 1800 GeV, and data collected in December 1995 from run1c, when the Tevatron was operated at a center of mass energy of 630 GeV. We use jet and minimum bias data set at both energies. For the analysis we only use runs classified as good. The list of these runs is in [34].

4.1 Jet trigger at $\sqrt{s} = 1800$ GeV

During run1b four triggers were used to collect jet data: Jet_{20}, Jet_{50}, Jet_{70} and Jet_{100}. The triggers require at Level 2 at least one jet with transverse energy bigger than respectively 20, 50, 70 and 100 GeV.

Jet_{100} was not prescaled. Jet_{70} was prescaled by a factor 8 at Level 2. Jet_{50} was prescaled by 40 at Level 1 and Jet_{20} was prescaled by 40 at Level 1 and by 25 at Level 2, for a total prescaling factor of 1000. At Level 1, prescaling factors are applied on events which pass the cuts on the energy of single towers in the electromagnetic and hadronic calorimeters.

To increase the jet trigger efficiency, we require one jet in the central rapidity region $0.1 < |\eta_{\text{detector}}| < 0.7$ with transverse energy (E_t) greater than 40, 75, 100, 130 GeV respectively for the four samples. The jet trigger efficiency was studied in [38]. Jet_{100} is found to be 100% efficient for E_t greater than 130 GeV, Jet_{70} is 96.7% efficient at 100 GeV, Jet_{50} is 94.7% efficient at 75 GeV and Jet_{20} is 94.3% efficient at 40 GeV.

4.2 Jet trigger at $\sqrt{s} = 630$ GeV

Two triggers were used at $\sqrt{s} = 630$ GeV to collect jet data: Jet_{5} and Jet_{15}. The two triggers require at Level 2 at least one jet with transverse...
energy bigger than 5 and 15 GeV respectively. \textit{Jet\_15} requires the towers in the electromagnetic calorimeter inside the jet to have transverse energy greater than 0.5 GeV. \textit{Jet\_5} trigger requires at Level 2 a single tower in the central calorimeter with transverse energy bigger than 4 GeV and a coincidence in the beam-beam counters.

\textit{Jet\_15} was not prescaled, while \textit{Jet\_5} was dynamically prescaled by a factor in the range 100 to 600, according to the instantaneous luminosity, with an average value of 151.3.

We require at least one jet in the central region with \( E_T > 10, 30 \) GeV respectively for \textit{Jet\_5}, \textit{Jet\_15} trigger, so that the trigger efficiency is bigger than 90\% [39].

### 4.3 Minimum Bias trigger

The minimum bias trigger requires a coincidence in the West and East beam-beam counters. During run1b and run1c, a dynamical prescale was used. The minimum bias trigger selects events from diffractive and inelastic non-diffractive interactions from beam-beam collisions. Minimum bias events are studied as an approximation to the underlying event in hard scattering events (jet events).

### 4.4 Cosmic rays rejection

Additional energy can be found in the detector coming from cosmic rays or from beam gas events that must be rejected in order to study beam-beam interactions. In CDF this is achieved using the COSFLT filter module.

COSFLT rejects events with cosmic rays and beam gas events by examining the leading cluster in the event. The criteria used to determine if an event is due to a cosmic ray are able to reject them in the central region. Since cosmic rays are rarely in time with the bunch crossing, measures of out of time energy in the central hadron calorimeter are used to estimate irreducible background.

### 4.5 Vertex reconstruction

The vertex reconstruction is done using information from the VTX and the CTC, most importantly the \( z \) position of the vertices. Only vertices with at least two segments in the VTX are used. Segments with a \( z \) coordinate
bigger than 150 cm or an estimated error bigger than 2 cm are not used. The number of hits must be bigger than 24, unless there is only one vertex for which there is no restriction. The vertex is classified according to the number of hits and segments associated with the vertex. Table 4.1 shows the criteria to assign the class to the vertex. The decision whether a vertex is primary is made on class, hit segments and asymmetry\(^1\) consideration.

Class 5 vertex are classified as beam-gas vertex and will be excluded from our analysis.

We require \(p\bar{p}\) interactions to occur within \(|z| < 60\) cm of the geometrical center of the detector. The \(z\)-vertex cut efficiency calculated from the minimum bias sample is \((93\pm2)\%\).

### 4.6 Event selection

In our analysis we use data stored in the compressed PAD format\(^2\). Besides the cuts on the \(E_t\) of the jet, in jet events, described in this chapter, and the use of the COSFLT module for cosmic ray rejection, our final jet and minimum bias samples consists of events which passed the following cuts:

- \(\sum E_t < 1800,630\) GeV (run1b, run1c) where \(\sum E_t\) is the total transverse energy in the event. This cut removes cosmic rays which passed the COSFLT filter module
- **for jet events:**
  \[ E_t / \sqrt{\sum E_t^2} < 6\sqrt{3}\) GeV \] where \(E_t\) is the missing transverse energy,

---

1. Asymmetry considers the difference in the number of forward and backward segments.
2. The data streams used at \(\sqrt{s} = 1800\) GeV were QJ0B\(_5\)P, QJ7B\(_5\)P, QJ5B\(_5\)P, QJ2B\(_5\)P in jet analysis and XMBB\(_5\)P in minimum bias. At \(\sqrt{s} = 630\) GeV we used JT1B\(_6\)P for jets and XMBB\(_6\)P for minimum bias.
Table 4.2: Cuts applied on the CDF data sample.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$\sqrt{s} = 1800$ GeV jet</th>
<th>$\sqrt{s} = 630$ GeV jet</th>
<th>$\sqrt{s} = 1800$ GeV m.b.</th>
<th>$\sqrt{s} = 630$ GeV m.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{LeadJet}}$ (GeV)</td>
<td>&gt; 130, 100, 75, 40.</td>
<td>&gt; 25.</td>
<td>&gt; 30, 20.</td>
<td>&gt; 25.</td>
</tr>
<tr>
<td>$\sum E_t$ (GeV)</td>
<td>&lt; 1800</td>
<td>&lt; 1800</td>
<td>&lt; 630</td>
<td>&lt; 630</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{\text{LeadJet}}</td>
<td>$</td>
<td>&lt; 0.7</td>
<td>-</td>
</tr>
<tr>
<td>$z_{\text{vtx}}$ (cm)</td>
<td>&lt; 60</td>
<td>&lt; 60</td>
<td>&lt; 60</td>
<td>&lt; 60</td>
</tr>
<tr>
<td>$E_t$ (GeV)</td>
<td>&lt; 6/$\sum E_t$</td>
<td>&lt; 20</td>
<td>&lt; 6/$\sum E_t$</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>COSFLT</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

defined as the vector sum of all the transverse energy in the event [40]. This cut is also used to reject cosmic rays.

• **for minimum bias events:**
  $E_{t,\text{LeadJet}} < 25$ GeV. This cut rejects events in which a hard scattering occurred.
  $E_t < 20$ GeV. It removes events with cosmic rays which passed the previous cuts.

Table 4.2 summarizes the cuts applied on the jet and minimum bias samples.

### 4.6.1 Track selection

Once the tracks in the CTC have been reconstructed, we use a cut (TRK-SEL) on the number of layers\footnote{At least four hits in each of the two axial superlayers and hits in one stereo superlayer.} and wires hit in the CTC to choose high quality tracks and to remove ghost tracks.

We apply geometrical cuts on the reconstructed tracks to remove particles coming from decays of secondary interactions:

• $d_0 = |\sqrt{x_0^2 + y_0^2} - c| \leq 5$ mm. $d_0$ is the track impact parameter, $x_0$ and $y_0$ are the transverse coordinates of the center of the helix and $c$ is the curvature of the track.

• $|z_0 - z_{\text{vtx}}| \leq 5$ cm. $z_0$ is the value of closest approach of the track to the vertex along the $z$ axis and $z_{\text{vtx}}$ is the $z$ coordinate of the $p\bar{p}$ vertex.
4.7 SOURCES OF SYSTEMATIC UNCERTAINTIES

The track pattern recognition was optimized for high \( p_t \) tracks. If \( p_t < 0.21 \) GeV/c the particles spiral inside the solenoid [41]. To avoid the effects due to misconstructions, we require \( p_t \geq 0.4 \) GeV/c. The CTC pattern recognition efficiency for tracks in run1b calculated using axial and stereo wires was found to be \( 92.0 \pm 2.6\% \) for negative charged particles and \( 91.7 \pm 3.0\% \) for positive charged particles with \( p_t \geq 0.4 \) GeV/c [42]. The dependence of the efficiency on the transverse momentum for positively and negatively charged tracks in run1(a+b) is shown in figure 4.1. We use a fit to this function to correct our track sample [43]. Since the deterioration of the tracking performance is mainly due to the increase of instantaneous luminosity and only slightly depends on aging effects [44], we use the run1a efficiency parameterization to correct track related observables at \( \sqrt{s} = 630 \) GeV.

![Figure 4.1: Efficiency for positively (solid line) and negatively (dashed line) charged tracks in run1(a+b).](image)

4.7 Sources of systematic uncertainties

The advantage of using phototube based calorimeters results in a very low level of noise. The noise is of about only 10 – 20 MeV per tower. Since
the threshold that we apply on the calorimeter towers in order to reject the noise is 50 MeV, the probability that the noise contributes to the signal is negligible [46].

At very low energies, which are relevant to our studies, the calibration of the calorimeter plays an important role on the results. The CDF calorimeter resolution has been already discussed in section 3.5. Since the most of the energy in the calorimeter, is due to particles which interact in the electromagnetic portion of the calorimeter, we use equation 3.2 to estimate the energy resolution of observables which will be used in our analysis. Particularly, we are interested in the energy resolution in a cone of radius $R = \sqrt{\Delta \eta^2 + \Delta \phi^2}=0.7$ in the calorimeter. We leave out the constant term in the equation, because at very low energies the first term, which depends on the transverse energy, is dominant. In the worst situation (very low energy), we find about 0.2 GeV per tower and 4 towers in a cone of radius 0.7, which corresponds to an energy resolution of about 13%. However, the uncertainty on that energy is larger than it would be if all of the energy were deposited by electrons or photons. In fact, there are larger fluctuations in the energy deposited by hadrons.

Other sources of uncertainties come from the track reconstruction. Tracks have been corrected for the CTC pattern recognition efficiency. The statistical and systematic errors on the calculation of the tracking efficiency were found to be below 5% [42].

The main source of systematic uncertainties on the track reconstruction results from the cut on the impact parameter [45]. The relative error $\frac{\delta P_{\text{syst.}}}{P}$ has been estimated as:

$$\frac{\delta P_{\text{syst.}}}{P} = \frac{|P_{\text{no-cut}} - P_{d_0 \leq 0.5}|}{P_{d_0 \leq 0.5}}$$

where $P_{d_0 \leq 0.5}$ refers to the sum of the transverse momentum of the tracks inside a cone of radius $R$, calculated with a cut on the impact parameter: $d_0 \leq 0.5$ cm. $P_{\text{no-cut}}$ refers to the same quantity without the cut on the impact parameter. The error $\frac{\delta P_{\text{syst.}}}{P}$ is found to be below 10%. Other cuts, such as the one on the transverse momentum of the tracks, or on the distance between the value of closest approach of the track to the $z$ axis and the $z$ coordinate of the interaction vertex, are much smaller.

### 4.8 Simulated data

CDF data are analyzed and compared to Monte Carlo predictions. Both Herwig and Pythia Monte Carlo programs are used and some of their characteristics have already been illustrated in section 2.6. Most of the simu-
4.8. SIMULATED DATA

<table>
<thead>
<tr>
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<th>$\sqrt{s} = 1800$ GeV</th>
<th>$\sqrt{s} = 630$ GeV</th>
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<td>jet m.b.</td>
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<td>426347</td>
</tr>
<tr>
<td></td>
<td>30683</td>
<td>1842892</td>
</tr>
<tr>
<td>Herwig+QFL</td>
<td>42393</td>
<td>399645</td>
</tr>
<tr>
<td></td>
<td>59039</td>
<td>86786</td>
</tr>
<tr>
<td>Pythia+QFL</td>
<td>23951</td>
<td>397101</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.3: Final number of events which passed the required cuts.

simulation is done with Herwig because its parton shower reproduces next-to-leading logarithmic approximation (NLLA) calculations which provides the best available implementation of perturbative QCD effects.

Pythia version 6.115 is used for jets and minimum bias simulation in its default version for the CDF software. Two older versions, 5.6 and 5.7, are used for comparisons. Herwig 5.6 was also used with its default parameters, but the parton distribution function is set to be CTEQ3L [47].

The output from both Monte Carlo programs consists of the 4-vectors of the final state hadrons. The results can be quoted at the three levels:

- **parton level**, where partons are considered before they undergo the hadronization process;
- **hadron level**, based on final stable particles as seen from an ideal detector;
- **detector level**, where the stable particles are passed through the detector simulation.

In our analysis, we used the fast CDF detector simulation program, QFL [48], which gives an answer based on a parameterization of the detector response. The parameterization has been tuned to data from $p\bar{p}$ collisions and to data from test beam on the different components of the detector.

In conclusion, the number of events in data and in the simulation which passed the previously illustrated cuts are shown in table 4.3. Jet data are required to have one and only one class 10 or 11 or 12 vertex, minimum bias data are required to have one and only one class of any class except class 5. We generated 2 800 000 jet events at $\sqrt{s} = 1800$ GeV with Herwig and 2 000 000 with Pythia, but because of the cut on the leading jet energy, most of the events are refused and the final sample consists of only 1% of the original sample.
Chapter 5

Underlying events at CDF

Jets are the result of hard quarks and gluons interactions and therefore they can provide an important test of perturbative QCD. At LO ($O(\alpha_s^2)$) one parton per proton takes part in the hard scattering resulting in two outgoing partons. Each outgoing parton emerges as a bunch of hadrons in the detector where it releases its energy. This energy must be clustered in order to reconstruct the initial parton and to compare data with theory.

Figure 5.1 shows an event in the CDF calorimeter with two jets in the central rapidity region. The tower height is proportional to the $E_t$ deposited in the tower. The oval around each clump of energy indicates the jet clustering cone. The transverse energy of the most energetic jet is 101.1 GeV and of the second jet 81.5 GeV. Even if there are no additional jets in the event, some energy can be found in the calorimeter in the region between the two jets. This ambient energy may come from different sources as energy splashed out from one of the jets or fragmentation of partons not associated with the hard scattering.

5.1 Jets definition

Jets feel the effect of long-distance processes as showering and hadronization. As the initial parton carries a colour and the final hadrons are colourless objects, there cannot be an unique association of jets with the initial partons [49]. For this reason a suitable jet definition is important to minimize the effect of long distance physics. The first attempt to standardize jet definitions for different theories and experiments was given by the Snowmass accord [50]. Typically a jet contains tens of neutral and charged pions and a smaller amount of kaons which shower in different calorimeter cells. Usually at CDF a jet covers about 40 calorimeter cells [51]. According to
5.2 CDF jet algorithm

The CDF cone algorithm [52] used in this analysis is called JETCLU and makes use of a fixed opening angle cone to define a jet. The towers of the CDF calorimeters point to the interaction region, so that the fixed opening angle of the cone corresponds to a fixed radius \( R = 0.7 \) in our analysis. The steps followed by the algorithm are the following:

- A candidates list consisting of all the calorimeter towers with \( E_t > 1 \) GeV (seed towers) is created.
- Preclusters are formed starting from the tower with highest \( E_t \). Preclusters are defined as an unbroken chain of adjacent towers within a cone \( R \) from the seed tower with a continuously decreasing tower \( E_t \).
- The \( E_t \) weighted centroid of the cluster is found.
5.2. CDF JET ALGORITHM

- A fixed cone in $\eta - \phi$ space of radius $R$ is formed around the centroid and towers with $E_t > 100$ MeV inside this cone are merged in.

- From this new set of towers a new centroid is calculated and all the candidate towers in a cone around the new centroid are merged in. This process is repeated until the tower list remains unchanged.

- A list of clusters, one for each seed cell is given. Some of them may be duplicated and are thrown away.

- Now every pair of clusters is considered. If two jets are distinct they are left alone. If one cluster is completely contained in another, the smaller of the two is dropped.

- If two clusters overlap for more than 75%, the two jets will be merged, otherwise the two cones are split and the energy will be divided up between the clusters, based on the proximity of the towers to the centroid. In this way every calorimeter tower belongs to only one jet.

The final jet energy and momentum are computed from the final list of towers:

\[
E_{\text{Jet}} = \sum_{i \in \text{jet}} E_i \quad (5.1)
\]

\[
P_x = \sum_{i \in \text{jet}} E_i \sin \theta_i \cos \phi_i \quad (5.2)
\]

\[
P_y = \sum_{i \in \text{jet}} E_i \sin \theta_i \sin \phi_i \quad (5.3)
\]

\[
P_z = \sum_{i \in \text{jet}} E_i \cos \theta_i \quad (5.4)
\]

\[
\sin \theta_{\text{Jet}} = \frac{\sqrt{P_x^2 + P_y^2}}{\sqrt{P_x^2 + P_y^2 + P_z^2}} \quad (5.5)
\]

\[
\phi_{\text{Jet}} = \tan^{-1}(P_y/P_x) \quad (5.6)
\]

\[
E_{t,\text{Jet}} = E_{\text{jet}} \sin \theta_{\text{jet}} \quad (5.7)
\]

One difference between the CDF and Snowmass algorithm is that the CDF jets have a mass ($E_t \neq P_t$).

The CDF jet algorithm is not without problems. It turns out that the preclustering and merging/splitting step make the algorithm infrared-unsafe, i.e. sensitive to the presence of soft gluons, and collinear-unsafe, i.e. sensitive to splitting and joining of collinear particles. Therefore the cross section for processes with four partons in the final state, such as 3 jets cross section to NLO, results negative infinite [53].
5.3 Underlying events

In hadron collisions, in addition to the hard interaction that produces the jets in the final state there is also an underlying event, originating mostly from soft spectator interactions. Because of its softness this contribution cannot be perturbatively calculated. There may also be a contribution due to semihard interactions between spectator partons, which create minijets at transverse momentum almost large enough for perturbative calculations, but much smaller than that of the primary interaction responsible for the highest $E_t$ jet in the event [54]. This process is known as double parton scattering. Both of the above processes contribute to the underlying event as well as higher order radiation from the $2 \rightarrow 2$ hard subprocess. The experimental cross sections are most commonly compared to theoretical calculations at next-to-leading order (NLO) in the coupling constant $\alpha_s$, such as JETRAD [55] or EKS [56]. At NLO, there can be at most 3 partons in the final state, leading to the presence of either 2 or 3 jets, depending on whether the third parton is present in the final state and whether it ends up being clustered with one of the other two partons. Since the jet clustering is based on a fixed size cone algorithm, the contribution due to the underlying event must be subtracted from the jet cone, in order to compare the results with NLO QCD calculations.

Although this contribution is small (of the order of few GeV) its effect on high $E_t$ jets is not negligible. In fact the perturbative jet spectrum falls very rapidly with $E_t$. Therefore, even if it is rare for a jet to have its energy increased by several GeV due to the underlying event activity, the small fraction of events at high energy is biased towards larger numbers due to low $E_t$ events with significant amount of underlying event energy.

Unfortunately the underlying energy in the jet cone is not well defined theoretically. The underlying event structure contains the fragments of the original hadronic system, hadrons arising from initial state radiation, and possibly hadrons resulting from multiple parton scattering.

By now the underlying event energy has been measured either by estimating the energy in a cone in soft collisions (i.e. minimum bias events) or by measuring the energy far away from the jets in jet events. The second method has been first proposed by Marchesini and Webber [57] and shows roughly a 30% variation in the energy perpendicular to the jet axis depending on the selection criteria. Since in a hadron collision with jets in the final state the beam impact parameter is usually small, the energy arising from beam remnants can be larger than in minimum bias interactions. CDF assumes an uncertainty of 30% on the underlying event subtraction in jet analysis. This is at the moment the dominant source of systematic error for the CDF inclusive jet cross section at low $E_t$ (figure 5.2). The energy in a
5.4 Analysis of the transverse energy distribution in minimum bias and jet events in CDF at $\sqrt{s} = 1800$ GeV

In every analysis which involves jets, the ambient energy (i.e. energy not coming from partons responsible for the hard scattering) must be subtracted from the energy inside the jet. Unfortunately the underlying event is not a well understood object and its definition is not precise. The current assertion is that the underlying event energy is similar to the energy found in minimum bias events. In order to investigate this statement we examine both the
underlying event energy in jet events and the energy in minimum bias events.

In jet events we consider the energy in the central rapidity region inside two cones of radius 0.7 at the same rapidity and at $\pm 90^\circ$ in azimuth from the most energetic jet in the events. The cone size is the same used to reconstruct jets in the inclusive jet cross section analysis at CDF. In figure 5.3 the calorimeter central region is shown unrolled: $\eta$ ranges are between -1 and +1, while $\phi$ goes from $0^\circ$ to $360^\circ$. The leading jet cone, i.e. the most energetic jet in the event, and the two cones under study are shown. The two cones are used to study the underlying event energy because they are supposed to be in a semi-quiet region, far away from the two leading jets, but still in the central rapidity region. Given the non-uniform response of the CDF detector as a function of rapidity, the latter criterion is essential. The $E_t$ distribution inside the two cones provides an idea of the contribution of the underlying event in the jet cone. For each event we label the cone which has the maximum energy ($max$ cone) and the cone with minimum energy ($min$ cone). This is useful because NLO perturbative corrections to the $2 \rightarrow 2$ hard scattering can contribute only to one of these two regions [57]. The difference between the $max$ and the $min$ cone provides information on this contribution, while the $min$ cone gives an indication of the amount of underlying event. The underlying event contribution should be suppressed...
5.4. TRANSVERSE ENERGY DISTRIBUTION AT $\sqrt{S} = 1800$ GEV

in the difference.

In minimum bias events we pick a random cone of radius 0.7 in the
central region and a cone at the same $\eta$, but at $+180^\circ$ in $\phi$ from the first
one. We look at the energy in both cones and separate them in a max and
min cone. If the underlying event energy would be similar to minimum bias
energy, the energy found in the random cone should be comparable to that
found in the min cone in jet events. In our analysis we are interested in
testing this assertion.

5.4.1 Underlying event in jet events at $\sqrt{s}=1800$ GeV

We analyze the energy in the calorimeter in jet events at CDF using inform-
ation from run1b. Ntuples\(^1\) were created from jet event data including
information on the energy, the position of the jets in the event, together
with the energy and the number of towers in two cones located at $\pm 90^\circ$ in $\phi$
and at the same $\eta$ as the leading jet. The jet data sample has been described
in the previous chapter.

We reproduced, with the help of the simulation, ntuples containing the
same information as found in the data ntuples. Jet events are generated
in four samples which have a minimum transverse momentum of the hard
scattering of 20, 40, 60, 80 GeV and we require $E_{t,\text{LeadJet}} > 40, 75, 100$ and
130 GeV respectively. The average $E_{t,\text{LeadJet}}$ in each sample is shown in
table 5.1 together with the statistical errors.

For each jet event we examine two cones of radius 0.7 at $\eta = \eta_{\text{LeadJet}}$
and $\phi = \phi_{\text{LeadJet}} \pm 90^\circ$. We look at the energy in each cone for two different
calorimeter tower thresholds: 50 and 100 MeV. A cut of 100 MeV on tower
energies is typically used for jet analyses. For most of the comparisons to
follow, we use a 50 MeV cut, though, since we are interested in possible
contributions to the tower energies from a number of sources. This lower

\(^1\)An ntuple is a list of identical data structure each corresponding to a single event

<table>
<thead>
<tr>
<th>DATA</th>
<th>$E_{t,\text{LeadJet}}$</th>
<th>$P_{T\text{min}}$</th>
<th>Herwig+QFL</th>
<th>Pythia6.115+QFL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\langle E_{t,\text{LeadJet}} \rangle$</td>
<td>$\langle E_{t,\text{LeadJet}} \rangle$</td>
<td>$\langle E_{t,\text{LeadJet}} \rangle$</td>
<td>$\langle E_{t,\text{LeadJet}} \rangle$</td>
</tr>
<tr>
<td>Jet_20</td>
<td>44.8 ± 0.1</td>
<td>20.</td>
<td>50.8 ± 0.1</td>
<td>50.8 ± 0.1</td>
</tr>
<tr>
<td>Jet_50</td>
<td>92.0 ± 0.1</td>
<td>40.</td>
<td>91.4 ± 0.2</td>
<td>91.7 ± 0.2</td>
</tr>
<tr>
<td>Jet_70</td>
<td>120.7 ± 0.1</td>
<td>60.</td>
<td>120.2 ± 0.2</td>
<td>120.3 ± 0.4</td>
</tr>
<tr>
<td>Jet_100</td>
<td>153.8 ± 0.1</td>
<td>80.</td>
<td>153.4 ± 0.2</td>
<td>153.5 ± 0.2</td>
</tr>
</tbody>
</table>

Table 5.1: $E_t$ of the leading jet in data and Monte Carlo jet samples in
run1b. Results are in GeV.
threshold is still well above the typical noise level of 10 – 20 MeV [46]. The leading jet is required to be in the central region, \(|\eta| < 0.7\), the same as in the inclusive jet analysis. No requirement is made on the location of the second jet.

The data are required to have one and only one vertex of class 10, 11 or 12 (primary vertex) in order to insure that there is only one interaction per event. The vertex classification has been previously illustrated in chapter 3. Since QFL does not simulate the VTX bank, we cannot compare the class of the vertices in the data with the simulation. In jet data the majority of primary vertices is class 12 (more than 99%), therefore including also vertices of class 10 or 11 does not affect the result of our study.

In figure 5.4 the transverse energy inside the two cones (max and min) is plotted as a function of the \(E_t\) of the leading jet. Only statistical errors are shown. Systematic errors have been discussed in section 4.7. It can be clearly observed that Herwig+QFL, Pythia6.115+QFL and the data have a similar behaviour for the max and min cone: the min cone stays flat while the max cone increases with the \(E_t\) of the leading jet. The increase of the max cone energy with increasing jet \(E_t\) is easily understandable from the contribution of a third jet associated with the hard scattering. What may be surprising is the flatness of the min cone energy as the transverse energy

![Figure 5.4: \(E_t\) inside the max and min cone as a function of the \(E_t\) of the leading jet. Data and Monte Carlo distributions are plotted. The center of mass energy is 1800 GeV.](image-url)
of the leading jet increases. Of course, the division into a max and min cone partially encourages this effect through selection. Nevertheless, the level of flatness is still somewhat surprising, since we would expect eventual NNLO contribution (i.e. a fourth jet in the event) to become evident at higher energies.

An offset between data and Monte Carlo simulations is also visible. Table 5.2 shows the amount of transverse energy inside the max and min cones and their difference, for the different jet samples. Herwig+QFL has about 800 MeV less than data in the max cone and 500 MeV in the min cone. If the tower threshold is increased from 50 to 100 MeV, the transverse energy decreases by about 180 MeV in the data (both cones), while in Herwig+QFL the transverse energy decreases by about 70 MeV in the max cone and 40 MeV in the min cone. Pythia6.115+QFL agrees within the statistical and

<table>
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<tr>
<th>Trigger</th>
<th>$E_t$</th>
<th>Thr=50</th>
<th>Thr=100</th>
<th>Thr=50</th>
<th>Thr=100</th>
<th>Thr=50</th>
<th>Thr=100</th>
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<tr>
<td>$Jet_{20}$</td>
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<td>.57</td>
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<td>1.81</td>
<td></td>
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<tr>
<td>$Jet_{50}$</td>
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<td>.75</td>
<td>.71</td>
<td>2.53</td>
<td>2.50</td>
<td></td>
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<tr>
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<td>.71</td>
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<td>.77</td>
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<th>Thr=100</th>
<th>Thr=50</th>
<th>Thr=100</th>
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<tr>
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<td>3.08</td>
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<td>$Jet_{50}$</td>
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<td>1.01</td>
<td>.96</td>
<td>3.23</td>
<td>3.20</td>
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<tr>
<td>$Jet_{70}$</td>
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<td>1.06</td>
<td>1.01</td>
<td>3.73</td>
<td>3.70</td>
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<td>.95</td>
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<td>4.30</td>
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<table>
<thead>
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Table 5.2: $E_t$ inside the max and min cone at $\eta = \eta_{\text{LeadJet}}$ and $\phi = \phi_{\text{LeadJet}} \pm 90^\circ$. $E_t$ differences between max and min cone are also shown. The center of mass energy is 1800 GeV. Tower thresholds are in MeV, energies are in GeV. Statistical errors are not shown, but they have been calculated to be below 5%.
systematic errors with data at the max cone level, but the energy found in the min cone is about 300 MeV less than in data.

The difference between the transverse energy in the max and in the min cones has a similar trend in both data and simulation (figure 5.5). There is still an offset but the offset decreases to about 300 MeV. Herwig+QFL is lower than data, while Pythia6.115+QFL is higher. It looks that the max – min distribution starts going down again at very high $E_T$, although the statistics becomes poor.

Besides Pythia6.115, two older versions of this generator were examined. The difference between version 5.6 and 5.7, which could influence our study, is the extension of the hadron parton distribution function in the low-$x$ and low-$Q^2$ region. From version 5.7 to version 6.115 some of the parameters which describe the parton shower have been changed. The parameter for the minimum gluon energy emitted in space-like shower is modified so that the amount of gluon radiation increases (light quarks are not affected). Another change consists in a cut on parton emission, the effect of which is to reduce the total amount of emission and it is mainly important for the hardest emission. The two effects are in opposite direction, but with the latter effect being dominant. Moreover some of the parameters which regularize the multiple scattering, such as the effective minimum transverse momentum or

Figure 5.5: Difference between $E_T$ inside the max and min cone as a function of the $E_T$ of the leading jet. Data and Monte Carlo distributions are plotted. The center of mass energy is 1800 GeV.
the regularization scale of the transverse momentum spectrum for multiple interactions, are made energy dependent. In fact, it has been observed that constant parameters lead to a much too fast increase in the multiple interaction rate at small $x$ [59].

Figure 5.6 shows the energy in the $\text{max}$ and $\text{min}$ cone as a function of the jet $E_t$ for the three different versions of Pythia. The main observed differences are between versions 5.6 and 5.7. The energy found in the $\text{max}$ cone in Pythia5.7 is smaller than in Pythia5.6 and its trend as a function of the $E_t$ of the leading jet differs between the two versions. The $\text{min}$ cone decreases by about $200 - 400$ MeV, depending on the $E_t$ of the leading jet. Recent studies on the underlying event energy [60] show how the Pythia ability to reproduce the data strongly depends on the choice of the parton distribution function. In fact the parameters which regularize the multiple interaction scattering are sensitive to the choice of the parton distribution function. If the structure function is not the default one in Pythia (for example we chose CTEQ3L), the default parameter for the multiple interaction should be re-adapted in order to agree with the experiments. In Pythia6.115 we keep the CDF software default structure function MRSG [61] and from now on we will use only this version for comparisons with data.

In figures 5.7, 5.8 and 5.9 the $E_t$ frequency distributions for data and simulation are compared. In each plot, the $E_t$ values in the $\text{max}$, $\text{min}$ and
Figure 5.7: Frequency distribution for $E_t$ in the $\text{max}$ cone. The center of mass energy is 1800 GeV. The calorimeter tower energy threshold is 50 MeV.

$max - min$ cone are plotted, for data, Herwig+QFL and Pythia6.115+QFL. The number of entries in the simulation is normalized to the number of entries in the data, to easily allow a direct comparison. Monte Carlo and data distributions differ: Pythia6.115+QFL falls too steeply with $E_t$, while Herwig+QFL is always below the data at middle $E_t$ values. In the $max - min$ cone, where the underlying event contribution should be removed, the difference between Herwig+QFL and data decreases.
Figure 5.8: Frequency distribution for $E_t$ in the min cone. The center of mass energy is 1800 GeV. The calorimeter tower energy threshold is 50 MeV.
Figure 5.9: Frequency distribution of $\max - \min E_t$. The center of mass energy is 1800 GeV. The calorimeter tower energy threshold is 50 MeV.
5.4.2 Energy in two more cones at opposite rapidity from the leading jet

The two cones at $\phi = \phi_{LeadJet} \pm 90^\circ$ and $\eta = \eta_{LeadJet}$ contain not only the energy coming from parton spectator interactions, but also a possible spillover from the two leading jets. The requirement for the leading jet to be in the central region ($|\eta| < 0.7$), forces us into a very tight region of phase space; therefore the two cones used to study the underlying event energy are relatively close to the jet cones. From figure 5.3 it is possible to get an idea of the size of the cones with respect to the size of the calorimeter region used in our analysis.

In order to trace the position of the second most energetic jet when the leading jet is in the central region, we plot its distance $d = \sqrt{\Delta \phi^2 + \Delta \eta^2}$ from the max and the min cone (figure 5.10). The second jet is always relatively far from the two cones; in fact most of the time it is at $\phi = \phi_{LeadJet} \pm 180^\circ$, as expected from momentum conservation in a two jet system, with a relatively uniform distribution along $\eta$.

To further check the level of energy that may end up in the two cones from the leading and second jet, we add two more cones at $\eta = -\eta_{LeadJet}$ and $\phi = \phi_{LeadJet} \pm 90^\circ$ and we examine the energy inside these cones in the Herwig+QFL sample. The two most energetic jets are required to be on

![Figure 5.10](distance.png)

Figure 5.10: Distance between the second most energetic jet in the event and max/min cone.
the same $\eta$ side of the detector (the leading jet being always in the central region). On average, the transverse energy decreases only by about 50 MeV inside the $\text{min}$ cone and by 100 MeV in the $\text{max}$ cone with respect to the situation where the cones are at $\eta = \eta_{\text{LeadJet}}$ and no restriction is placed on the rapidity of the second jet. Thus, we observed that the transverse energy inside the $\text{min}$ and $\text{max}$ cone is not substantially affected by spillover, in fact the transverse energy increases by a maximum of 6%.

### 5.4.3 Parton, hadron and detector level in Herwig

With Monte Carlo simulations (unlike the data), we have the advantage of being able to examine the energy distributions not only at the detector level, but also at the hadron and parton levels. Since in the Herwig model for interactions at low momentum transfer the energy contribution is calculated directly at the hadron level, we cannot study the underlying event at the parton level. In this section, in order to examine the differences between hadron, detector and parton level, we switch off the underlying event in Herwig.

Figure 5.11 shows the transverse energy inside the $\text{max}$ and $\text{min}$ cones at $\eta = \eta_{\text{LeadJet}}$ and $\phi = \phi_{\text{LeadJet}} \pm 90^\circ$ as a function of the leading jet energy.
transverse energy at the parton, hadron and detector level. The leading jet is always in the central rapidity region. Because of the degradation due to the detector response, the amount of energy is higher at the hadron level than at the detector level.

It is also interesting to note that the hadron level energy is larger than the parton level energy, by the order of several hundred MeV. This is due to hadronization effects of the partons produced in or near the leading and second jet cones. Most of the hadronization effects come from strongly decaying particles (resonances) and their subsequent decays. The hadronization effects from the partons inside the jet cone have been termed splash out. It is important to note that this splash out is not currently taken into account in either CDF jet analysis or that from D0. Both experiments implicitly assume that the hadron and parton levels produce the same energy in the jet cone. This is especially relevant for low $E_t$ jet production. In order to evaluate to what level resonance decays influence the energy inside the two cones at $\pm 90^\circ$ in $\phi$ from the leading jet, we switch off all resonance decays and then examine the energy in the cones both at the parton and at the hadron level. The difference of $E_t$ inside the min cone (between hadron and parton level) decreases from an average of 300 MeV to 100 MeV, while the difference in the max cone drops from 500 MeV to 100 MeV.

5.4.4 Minimum bias events at $\sqrt{s}=1800$ GeV

The minimum bias events generated with Herwig and Pythia6.115 are passed through QFL and the energy released in the calorimeter towers is saved in ntuples. Pythia6.115 is used with the option of varying impact parameter (MSTP(82)=4). We examine the amount of transverse energy in the caloiimeter in a random cone of radius 0.7, that we require to be in the central region ($|\eta|<0.7$).

In minimum bias data the number of class 5, 7, 8, 10, 11 vertices is larger than in jet events. There are about 7% class 7, 8% class 8, 5% class 10, 29% class 11, 49% class 12 vertices if only one interaction per event is required. Since the number of non primary vertices is high, the decision whether to accept them for comparisons with Monte Carlo simulations or not is significant. Vertices classified as class 5 originate from beam-gas interaction and should be rejected from physics analysis, therefore they will not further be accepted. From now on we refer to vertices of every class, when the class is 7, 8, 10, 11 or 12. The selection of a primary vertex enhances the transverse energy inside the random cone by about 150 MeV. In fact, the better the class of the vertex the higher the possibility that a hard or semi-hard interaction takes place, resulting in an increase of energy in the central rapidity region.
Figure 5.12: Transverse energy inside a random cone in minimum bias data and simulation. The center of mass energy is 1800 GeV. The tower threshold is 50 MeV.

The transverse energy distribution in the random cone when the energy threshold is set to 50 MeV, is shown in figure 5.12 for data and Monte Carlo simulations. Data are required to have one and only one vertex (of any kind of class) per event. The number of entries in the simulation is normalized to the number of entries in the data, to allow for a better shape comparison. Both Herwig+QFL and Pythia6.115+QFL do not reproduce the data, but Pythia6.115+QFL is better than Herwig+QFL which fails completely.

Beside the random cone, we also look at the transverse energy in a cone at $+180^\circ$ in $\phi$ and at the same $\eta$ with respect to the random cone. Again we consider the $\text{max}$ cone as the one with more energy between the two cones, and the $\text{min}$ cone as the one with less energy. Results are shown in table 5.3.

The difference between data and Herwig+QFL is bigger in the $\text{max}$ cone (420 MeV) than in the $\text{min}$ cone (220 MeV). This is an indication of the fact that the Herwig model for the minimum bias event does not give an unified description of soft and hard physics, but that only soft processes are included. Pythia6.115+QFL has a bigger $\text{hard}$ component and on average seems to better reproduce the data, although the shape of energy distribution differs from data.
5.4. TRANSVERSE ENERGY DISTRIBUTION AT $\sqrt{s} = 1800$ GEV

<table>
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Table 5.3: Data and simulation comparisons for minimum bias events. The averages of the maximum and minimum transverse energy in a random cone of radius 0.7 and in a cone at +180° in $\phi$ to the random cone are shown. The center of mass energy is 1800 GeV. Threshold are in MeV, results are in GeV. Statistical errors are negligible.

5.4.5 Sum of transverse energy in the central rapidity region (Swiss cheese) at $\sqrt{s} = 1800$ GeV

An experimental approach to study the underlying event which is complementary to the two cones in jet events examined in the previous sections has been investigated. This method considers the energy in the central calorimeter and excludes the energy due to the most energetic jets in the event.

For these comparisons, we sum the transverse energy in every calorimeter tower in the central region ($|\eta| < 1$), excluding the towers in a radius 0.7 from the center of the two (or three) most energetic jets in the event:

$$E_t^\text{sum} = \sum_{\text{towers}} E_t^{\text{towers}} - \sum_{2,3\text{jets}} \left[ \sum_{\text{towers}} E_t^{\text{towers,jet}} \right]$$  \hspace{1cm} (5.8)

where $E_t^{\text{towers,jet}}$ are all the towers in a radius 0.7 from the center of the jet. We require $E_t^{\text{jet}} > 5$ GeV. This configuration has been labelled Swiss cheese. The four different jet samples and the minimum bias event samples are considered. For the minimum bias level, we just sum the transverse energy in the central region. As shown in figure 5.13, there are on average between 2 and 2.5 jets in the central rapidity region, with this average having a slight slope as a function of the $E_t$ of the leading jet.

The Swiss cheese energy in the central region is plotted in figure 5.14 as a function of the $E_t$ of the leading jet and compared for data, Herwig+QFL and Pythia6.115+QFL. The approximate minimum bias level for simulation and data is shown with a flat line on the picture. In the simple picture presented earlier, on which the CDF and D0 jet analyses are based, the difference between the Swiss cheese energy with two jets subtracted and
Figure 5.13: Number of jets in the central rapidity region ($|\eta| < 1$) and in the whole detector ($|\eta| < 4.2$) in Herwig+QFL as a function of the $E_t$ of the leading jet. The center of mass energy is 1800 GeV.

The minimum bias level should be proportional to the NLO (third parton) and higher contributions. The Swiss cheese level with three jets subtracted should have little or no NLO contribution and can be directly compared to the minimum bias data level. The 3-jet subtracted Swiss cheese energy is larger than the minimum bias level and there is a small slope as a function of the $E_t$ of the leading jet (the offset varies from $8 - 10$ GeV over the $E_t$ range). This indicates perhaps that there is more complexity here than in the $max$ and $min$ cone picture. Other possible contributions to the Swiss cheese energy include hadronization from the jets (splash out), double parton scattering and higher order radiation effects.

The Swiss cheese transverse energy in the central region is summarized in table 5.4 for data, Herwig+QFL and Pythia6.115+QFL. Both Monte Carlo generators reproduce the behaviour of the data as a function of the $E_t$ of the leading jet, but the absolute energy value is not correctly simulated.

We can try to compare this result with the one we obtained with the method of the two cones in jet events. For example the $E_t$ offset found between data and Herwig+QFL was about 600 MeV (on average between the $max$ and $min$ cone). Taking this value we can estimate the energy offset
Figure 5.14: $E_{\text{sum}}$ of equation 5.8 is shown with statistical errors. The two (-2 jets) and three (-3 jets) most energetic jets in the events are subtracted from the total transverse energy in the central calorimeter region ($|\eta| < 1$). The center of mass energy is 1800 GeV.

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Table 5.4: $E_T$ summed in the central region. Both the two and the three most energetic jets are subtracted from the sum. The center of mass energy is 1800 GeV. Tower threshold = 50 MeV, results are in GeV. Statistical errors are below 5%.
between data and Herwig+QFL for the central region by:

\[
(E_{t_{\text{max cone}}} - E_{t_{\text{min cone}}}) \times \frac{[\Delta \eta \times \Delta \phi]_{|\eta|<1} - 2\pi R^2}{\pi R^2}
\]

where the area of the central region is \( \Delta \eta \times \Delta \phi = 2 \times 2\pi = 12.56 \) and the area of a 0.7 cone is \( \pi R^2 = 1.54 \). We get an amount of energy offset in the central region of about 3.6 GeV. Thus the differences between Herwig+QFL and the data are consistent.

As we did for the min and max cone studies, we switch off the underlying event in Herwig and we examine the hadron and parton level in the Swiss cheese plots when the resonances are not allowed to decay. Results are shown in figure 5.15 in the case for which the transverse energy of the two leading jets in the central region is subtracted from the total sum. At the hadron level, allowing resonances to decay, we find about 1.5 GeV more energy. This implies a 600 – 700 MeV contribution of splash out per jet (again at the detector level) to the Swiss cheese energy.

Figure 5.15: The two most energetic jets in the simulated events are subtracted from the total transverse energy in the central calorimeter region both when resonance decay in Herwig is on and off. The center of mass energy is 1800 GeV. Underlying events are switched off.
5.5 Analysis of transverse momentum of charged particles in minimum bias and jet events in CDF at $\sqrt{s} = 1800$ GeV

Since the underlying event consists of evenly spread energy deposits, we are forced to rely upon the QFL simulation of the detector response in order to compare Monte Carlo predictions to CDF data. So, of particular relevance is the accuracy of the QFL simulation of the detector response to the low energy particles that make up the bulk of the underlying event. Part of the discrepancies observed may come from inadequacies of QFL rather than an incorrect treatment of the underlying event in Monte Carlo generators. QFL is not the only source of uncertainties: inaccuracies in the calorimeter calibration could lead to discrepancies with the simulation.

This motivated the analysis of the charged particles, which leave tracks in the detector and therefore are less affected than the calorimeter by the subtleties of the detector simulation. For the track analysis we consider the same jet triggers and minimum bias samples that we have previously used for the analysis at the calorimeter level. To reconstruct the tracks we use information from the Central Tracking Chamber (CTC).

5.5.1 Underlying event in jet events at $\sqrt{s}=1800$ GeV

The procedure applied to study the underlying events in the CDF detector using charged particles is the same as in the analysis at the calorimeter level. We examine two cones in the detector region $|\eta| < 0.7$ at $\pm 90^\circ$ in $\phi$ and at the same $\eta$ as the leading jet. We sum up the transverse momentum of the tracks inside the two cones: $p_t = \sum_{i=1}^{N_{\text{track,cone}}} p_{t,i}$. The cuts and the corrections applied on the tracks have been described in section 4.6.1.

The results of the transverse momentum inside the max and min cones for data, Herwig+QFL and Pythia6.115+QFL are shown in table 5.5. The average values of $p_t$ for Herwig+QFL and data agree within the statistical and systematic errors at the track level in the max and min cone. The systematic errors on the track reconstruction have been already discussed in section 4.7. In the max cone we can think at one more source of error, since a third jet may end up in the cone. In fact, the track reconstruction efficiency is reduced in jets of energy larger than 50 GeV, because the high density of tracks increases the probability of tracks overlap. In the Jet,50 sample, for example, about 20% of the events have a reconstructed jet within a distance 0.7 from the max cone, the energy of which is on average only 11 GeV. Therefore the efficiency of the tracks inside the max cone is generally not affected by the presence of a jet. Figure 5.16 displays the max
CHAPTER 5. UNDERLYING EVENTS AT CDF

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<td>3.33</td>
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Table 5.5: $P_t$ inside the $max$ and $min$ cone at $\eta = \eta_{LeadJet}$ and $\phi = \phi_{LeadJet} \pm 90^\circ$. $P_t$ differences between the $max$ and $min$ cone are also shown. Momenta are in GeV/c. The center of mass energy is 1800 GeV. Statistical errors are found to be below 4%.

and $min$ cone transverse momentum and their difference as a function of the $E_t$ of the leading jet. Again the agreement of data with Herwig+QFL is good for the whole jet’s $E_t$ spectrum. On the other hand the agreement of Pythia6.115+QFL with the data at the track level is worse than at the calorimeter level. At the calorimeter level we found the $max$ cone to reproduce the data and the $min$ cone to be only 300 MeV softer. Now both $max$ and $min$ cone have more energy than the data.

Figure 5.16: $Max$ and $min$ cone transverse momentum $p_t$ (on the left) and their difference (on the right) as a function of the $E_t$ of the leading jet at $\sqrt{s} = 1800$ GeV.
5.5. DISTRIBUTION OF CHARGED PARTICLES AT \( \sqrt{s} = 1800 \text{ GeV} \)

It is interesting to observe that while the track and calorimeter levels do not differ much in the simulation, the track level for data is lower than the calorimeter level. Roughly one might expect the sum of the transverse momentum of charged particles to be similar to the sum of the energy at the calorimeter level. In fact charged particles carry about 2/3 of the total energy, but the energy in the calorimeter is reduced by about 1.6 (depending on the energy) due to detector response.

If we look at the \( p_t \) distribution of the tracks inside the \textit{max} and \textit{min} cones (figures 5.17 and 5.18), we see that Monte Carlo and data distributions

![Figure 5.17: \( p_t \) distribution of tracks inside the \textit{max} cone for data, Herwig+QFL and Pythia6.115+QFL at \( \sqrt{s} = 1800 \text{ GeV} \).](image)

Figure 5.17: \( p_t \) distribution of tracks inside the \textit{max} cone for data, Herwig+QFL and Pythia6.115+QFL at \( \sqrt{s} = 1800 \text{ GeV} \).
are similar, but the percentage of events without any track in the two cones is larger in data than in Herwig+QFL and Pythia6.115+QFL.

The average number of tracks found inside the two cones is shown in table 5.6 for the four jet samples and in figure 5.19 as a function of the $E_t$ of the leading jet. Pythia6.155+QFL yields a larger number of tracks than data. In Herwig+QFL, the number of tracks in the min cone is higher for the simulation than for the data. As the average $p_t$ sum in the min cone in data and Herwig+QFL is about the same, this is an indication that the tracks generated by Herwig are too soft.
5.5. DISTRIBUTION OF CHARGED PARTICLES AT $\sqrt{s} = 1800$ GeV

We also sum up the transverse momentum of all the tracks in the central detector region ($|\eta| < 1$) and subtract from this sum the two or three most energetic jets in the event (Swiss cheese). The only requirement is for the leading jet to be in the central region. The plot with both the 2 and 3 jet subtracted is shown in figure 5.20. Data and Herwig+QFL agree within the statistical and systematic errors. Pythia6.115+QFL does not reproduce the data: a larger momentum due to charged particles is generally found in the

![Graph showing the distribution of charged particles](image)

Figure 5.19: Number of tracks in the $\text{max}$ and $\text{min}$ cone as a function of the $E_t$ of the leading. Data, Herwig+QFL and Pythia6.115+QFL distributions are plotted at $\sqrt{s} = 1800$ GeV.

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<th>Pythia6.115+QFL</th>
</tr>
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Table 5.6: Number of tracks inside the $\text{max}$ and $\text{min}$ cone at $\eta = \eta_{\text{LeadJet}}$ and $\phi = \phi_{\text{LeadJet}} \pm 90^\circ$. The center of mass energy is 1800 GeV. Statistical errors are below 2%.
Figure 5.20: $P_{t}^{\text{sum}}$ (Swiss Cheese). The two and three most energetic jets in each event are subtracted from the total transverse momentum in the central calorimeter region. Data, Herwig+QFL and Pythia6.115+QFL results are shown at $\sqrt{s} = 1800$ GeV.

central rapidity region in Pythia.

5.5.2 Minimum bias events at $\sqrt{s} = 1800$ GeV

In minimum bias events we examine the sum of the transverse momentum $p_t$ and the number of tracks inside a random cone in the central region ($|\eta| < 0.7$) and in a cone at $+180^\circ$ in $\phi$ and at the same $\eta$ with respect to the random cone. We include vertices of every class (except class 5) in the data but always require only one vertex per event. The transverse momentum in a random cone in minimum bias data is about 100 MeV lower than the transverse momentum in the min cone in jet events. If we choose minimum bias events with only one primary vertex (class 10, 11 or 12), the $p_t$ in a random cone increases by about 50 MeV and if only class 12 vertex events are considered, the $p_t$ increases by 210 MeV. Table 5.7 summarizes the number of tracks and the momentum in the random cone in data with different cuts on the class of the vertex.

The simulation results are shown in table 5.8. The value of the average
5.5. DISTRIBUTION OF CHARGED PARTICLES AT $\sqrt{s} = 1800$ GEV

<table>
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<th>DATA (1vtx)</th>
<th>DATA (1vtx class 10, 11, 12)</th>
<th>DATA (1vtx class 12)</th>
</tr>
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<td></td>
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<td>$p_t$ no. of tracks</td>
<td>$p_t$ no. of tracks</td>
</tr>
<tr>
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<td>.41 .51</td>
<td>.57 .69</td>
</tr>
<tr>
<td>max</td>
<td>.61 .74</td>
<td>.68 .83</td>
<td>.94 1.10</td>
</tr>
<tr>
<td>min</td>
<td>.11 .16</td>
<td>.12 .18</td>
<td>.19 .27</td>
</tr>
</tbody>
</table>

Table 5.7: Minimum bias events data. The maximum and minimum average of transverse momentum (in GeV/c) and the number of tracks in a random cone of radius 0.7 are shown. The center of mass energy is 1800 GeV. Statistical errors are negligible.

track transverse momentum $p_t$ in a random cone in Herwig+QFL is slightly lower than in data (with 1 vertex of any class). The number of tracks is about the same. Pythia generates too many tracks and for this reason we find too much momentum inside the random cone.

Figures 5.21 and 5.22 show, respectively, the distribution of the number and the momentum of the tracks in the minimum bias sample. The number of entries in the simulation is normalized to the number of entries in the data, to match Monte Carlo and data. The distribution of the number of tracks shows that Herwig+QFL, in general, does not reproduce the data. Pythia, as we already observed, generates too many charged particles.

The transverse momentum distribution is generally not well reproduced. In Herwig we barely find any track with a $p_t$ larger than 4 GeV, while this does happen in the data. This is clearly an indication of a lack of a hard physics description in the Herwig model of minimum bias events. Pythia6.115 produces also particles with a higher momentum, as we find in data, but the form of the distribution differs from data. On the top of figure 5.22 we show the momentum distribution in a linear scale in the range

<table>
<thead>
<tr>
<th>cone</th>
<th>Herwig+QFL</th>
<th>Pythia6.115+QFL</th>
</tr>
</thead>
<tbody>
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<td>$p_t$ no. of tracks</td>
<td>$p_t$ no. of tracks</td>
</tr>
<tr>
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<td>.47 .64</td>
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<tr>
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<td>.73 .97</td>
</tr>
<tr>
<td>min</td>
<td>.10 .17</td>
<td>.20 .31</td>
</tr>
</tbody>
</table>

Table 5.8: Herwig+QFL and Pythia6.115+QFL in minimum bias events. The maximum and minimum average of transverse momentum (in GeV/c) and the number of tracks in a random cone of radius 0.7 are shown. The center of mass energy is 1800 GeV. Statistical errors are negligible.
Figure 5.21: Distribution of number of tracks at $\sqrt{s} = 1800$ GeV in the minimum bias sample.

Figure 5.22: $p_t$ distribution of tracks at $\sqrt{s} = 1800$ GeV in the minimum bias sample.
0.3 – 1. GeV to look at the difference at very low momenta. It is evident that both Herwig and Pythia generate too many low $p_t$ particles.

5.6 Analysis of minimum bias and jet events in CDF at $\sqrt{s} = 630$ GeV

In the previous sections, we have observed that, in jet events, Herwig reproduces the average transverse momentum of the charged particles at the Tevatron only at the track level, while Pythia, with the default tuning, fails at both energy and track level. Therefore, we intend to study if the observed agreement between data and Herwig, at the track level in jet events, remains at lower energy, with the goal of an extrapolation at higher energy at future colliders. Indeed, since the Herwig Monte Carlo model of minimum bias events is a parameterization of the UA5 charged multiplicity distribution at $\sqrt{s} = 546$ GeV, the data at $\sqrt{s} = 630$ GeV provide an opportunity to test the tuning.

We examine the $E_t$ distribution at $\sqrt{s} = 630$ GeV as well to determine if the reason for the discrepancy between data and simulation observed in the low $E_t$ distribution at 1800 GeV is due to the energy extrapolation, or must be attributed to detector effects.

5.6.1 Analysis of the transverse energy distribution in jet events at $\sqrt{s} = 630$ GeV

Two triggers were used at $\sqrt{s} = 630$ GeV to collect jet data. The jet data sample and the cuts applied have been described in details in the previous chapter. In jet events at $\sqrt{s} = 630$ GeV the vertex is class 12 in more than 80% of the cases. We always require one and only one vertex of a class larger than 10 for comparison with the simulation.

With Herwig we simulate two QCD 2 → 2 samples ($Jet_{05}$ and $Jet_{15}$) with minimum momentum of the hard scattering respectively of 10 and 18 GeV. We apply the same cuts as in the data. We find that the leading jet transverse energy is on average 25.1 and 36.1 GeV respectively in the $Jet_{05}$ and the $Jet_{15}$, while in the data these values are 25.2 and 37.1 GeV.

As in the 1800 GeV analysis, we consider two cones at ±90° in $\phi$ and at the same $\eta$ with respect to the leading jet. Figure 5.23 shows the max and min cone distributions and their difference as a function of the transverse energy of the leading jet, for both data and Herwig+QFL. The same results for the two jet triggers are summarized in table 5.9 at two calorimeter energy
Figure 5.23: $E_t$ inside the max and min cones (on the left) and their difference (on the right) as a function of the $E_t$ of the leading jet. Both data and Herwig+QFL distributions are plotted. The center of mass energy is 630 GeV. Calorimeter tower energy threshold is 50 MeV.

tower thresholds. Later on we will use 50 MeV as tower threshold (if not differently specified).

Data is observed to be always larger than Herwig+QFL, but at $\sqrt{s} = 630$ GeV, the differences decrease to 450 MeV in the max cone and to 350 MeV

<table>
<thead>
<tr>
<th>Jet</th>
<th>$E_t$</th>
<th>max</th>
<th>min</th>
<th>$E_t$</th>
<th>max</th>
<th>min</th>
<th>$E_t$</th>
<th>max</th>
<th>min</th>
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<td>Thr=50</td>
<td>1.63</td>
<td>.48</td>
<td>Thr=100</td>
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<td>.45</td>
<td>Thr=100</td>
<td>1.15</td>
<td>1.13</td>
</tr>
<tr>
<td>15</td>
<td>Thr=50</td>
<td>1.85</td>
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<td>Thr=100</td>
<td>1.79</td>
<td>.47</td>
<td>Thr=100</td>
<td>1.34</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 5.9: $E_t$ inside the max, min and max−min cone at $\eta = \eta_{\text{LeadJet}}$ and $\phi = \phi_{\text{LeadJet}} \pm 90^\circ$ at $\sqrt{s} = 630$ GeV. Thresholds are in MeV, energies are in GeV. Statistical errors are below 4%.
5.6. MINIMUM BIAS AND JET EVENTS AT $\sqrt{s} = 630$ GEV

Figure 5.24: Frequency distributions for $E_t$ in the $max$, $min$ and $max - min$ cones at $\sqrt{s} = 630$ GeV. Tower threshold is 50 MeV.

in the $min$ cone. In the difference of $max$ and $min$ cone, the agreement between data and Herwig+QFL improves remarkably. The distributions (in figure 5.24 with the number of entries in the simulation normalized to the number of entries in the data to compare the shapes) are similar, but Herwig+QFL has more entries at small $E_t$.

It is also interesting to examine the number of towers inside the $max$ and $min$ cones with a transverse energy larger than 50 MeV. Data have on average about two towers more than Herwig+QFL. The distributions are
CHAPTER 5. UNDERLYING EVENTS AT CDF

Figure 5.25: Number of calorimeter towers inside the max and min cones as a function of the $E_t$ of the leading jet at $\sqrt{s} = 630$ GeV.

Figure 5.26: Max and min cone transverse energy as a function of the $E_t$ of the leading jet. The upper plot shows data at both 1800 and 630 GeV. The lower plot shows the same in the Herwig+QFL simulation.
shown in figure 5.25 as a function of the \( E_t \) of the leading jet.

When going from 1800 to 630 GeV, the \textit{max} cone in data decreases by about 800 MeV and the \textit{min} cone by 400 MeV, but in Herwig+QFL the energy goes down only by about 300 MeV in the \textit{max} and 100 MeV in the \textit{min} cone. This can be observed in figure 5.26 which displays the \textit{max} and \textit{min} cone in data and Herwig+QFL as a function of the \( E_t \) of the leading jet at both 1800 and 630 GeV center of mass energies. Due to different jet \( E_t \) triggers, data below jet’s \( E_t \) of 40 GeV are displayed only at a center of mass energy of 630 GeV.

5.6.2 Analysis of the transverse energy distribution in minimum bias events at \( \sqrt{s} = 630 \) GeV

If we examine the class of the vertex in minimum bias data at \( \sqrt{s} = 630 \) GeV we find a large percentage of vertices of class below 12. About 35% of the vertices are class 12 and 34% are class 11. There is also a high number of class 7 and 8 vertices (about 24%). We choose to keep all the vertices that have a physical meaning (i.e. we exclude only class 5) because we expect the simulation to reproduce them.

Exactly as we did for the analysis at 1800 GeV, we pick a random cone of radius 0.7 in the central calorimeter region and examine the transverse energy inside the cone and inside another cone at \(+180^\circ\) in \( \phi \) and at same \( \eta \). The values of the transverse energy found inside the cones are shown in table 5.10.

According to Herwig+QFL, there are very few differences in the energy found in a random cone in the central region in minimum bias events at \( \sqrt{s} = 1800 \) GeV and at \( \sqrt{s} = 630 \) GeV, while the differences are larger in data. In the simulation, the transverse energy in a random cone increases,

<table>
<thead>
<tr>
<th></th>
<th>DATA</th>
<th>Herwig+QFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_t )</td>
<td>Thr=50</td>
<td>Thr=100</td>
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<tr>
<td>\textit{random}</td>
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<td>\textit{max}</td>
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<td>.69</td>
</tr>
<tr>
<td>\textit{min}</td>
<td>.28</td>
<td>.19</td>
</tr>
</tbody>
</table>

Table 5.10: Data and Herwig+QFL in minimum bias events at \( \sqrt{s} = 630 \) GeV. The averages of the maximum and minimum transverse energy in a random cone of radius 0.7 and in a cone at \(+180^\circ\) in \( \phi \) to the random cone are shown. Thresholds are in MeV, results are in GeV. The statistical errors are negligible in the simulation and below 1% in the data.
Figure 5.27: A comparison for both data and Herwig+QFL of the distribution of transverse energy inside the random cone at 1800 GeV with that at 630 GeV in minimum bias events.

Figure 5.28: Herwig+QFL and data transverse energy distributions in the max and min cone in minimum bias events at $\sqrt{s} = 630$ GeV.
on average, by about 5% when the center of mass energy increases. In data, we found about 25% more energy in a random cone at larger center of mass energies.

In Herwig+QFL, not only is the absolute value of the energy very similar at the two different center of mass energies, but the distribution as well, as can be seen in figure 5.27. The plot compares, for both data and Herwig+QFL, the distribution of the energy inside the random cone at 1800 GeV with that at 630 GeV. The number of entries at 630 GeV is normalized to the number of entries at 1800 GeV, in order to compare the shapes. However, the comparison of Herwig+QFL with data in transverse energy at $\sqrt{s} = 630$ GeV reveals noticeable differences, as can be seen in figure 5.28.

5.6.3 Analysis of transverse momentum of charged particles in minimum bias and jet events at $\sqrt{s} = 630$ GeV

An analysis of charged particles at $\sqrt{s} = 630$ GeV was conducted for both the jet and minimum bias samples. In the previous chapter we described the jet and minimum bias samples and the cuts that have been applied on the tracks.

Figure 5.29 shows the max and min cone $p_t$ in jet events and their difference as a function of the $E_t$ of the leading jet. Herwig+QFL reproduces

![Figure 5.29: Max and min cone transverse momentum $p_t$ (on the left) and their difference (on the right) at $\sqrt{s} = 630$ GeV as a function of the $E_t$ of the leading jet. Both data and Herwig+QFL are plotted.](image-url)
Figure 5.30: Track momentum at $\sqrt{s} = 630$GeV as a function of the number of tracks inside the max and min cone. Both data and Herwig+QFL are plotted.

In the min cone we find about 200 MeV less transverse momentum than at $\sqrt{s} = 1800$ GeV (see figure 5.16), corresponding to a decrease of about 45%.

Figure 5.30 shows the transverse momentum as a function of the number of tracks inside the max and min cone. Herwig+QFL lies always below the data. Again this is an indication that the momentum distribution is not well reproduced, only its average value.

For completeness we examine the Swiss cheese configuration (figure 5.31). We find a very good agreement between data and simulation when the momentum of the tracks inside the three most energetic jets in the event is subtracted from the sum of the total momentum in the central region. If only the two most energetic jets are subtracted, the simulation is slightly higher than data, though in agreement with data within the statistical and systematic errors.

In the minimum bias sample, we observe a slightly larger transverse momentum in the data than in Herwig+QFL. Table 5.11 shows the sum of the transverse momentum inside a random cone in the central region and in a cone at the same $\eta$ and at $+180^\circ$ in $\phi$ with respect to the random cone. We observe that data decrease by about 20% with respect to the $\sqrt{s} = 1800$
5.6. MINIMUM BIAS AND JET EVENTS AT $\sqrt{s} = 630$ GEV

Figure 5.31: $P^{\text{sum}}_t$ (Swiss Cheese) at $\sqrt{s} = 630$ GeV. The two and three most energetic jets in the events are subtracted from the total transverse momentum in the central calorimeter region. Both data and Herwig+QFL results are shown.

Table 5.11: Data and Herwig+QFL comparisons for minimum bias events at $\sqrt{s} = 630$ GeV. The maximum and minimum averages of the transverse momentum (in GeV) and the number of tracks in a random cone of radius 0.7 are shown. Statistical errors are below 1%.

<table>
<thead>
<tr>
<th>cone</th>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
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<td></td>
<td>$p_t$</td>
<td>no. of tracks</td>
<td>$p_t$</td>
<td>no. of tracks</td>
</tr>
<tr>
<td>random</td>
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<td>.37</td>
<td>.26</td>
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<td>.08</td>
<td>.12</td>
<td>.08</td>
<td>.13</td>
</tr>
</tbody>
</table>
CHAPTER 5. UNDERLYING EVENTS AT CDF

GeV sample, while the values in the simulation decrease by about 15%.

5.7 E over p in run1b

By examining the charged particles at low \( p_t \) we have observed that Herwig+QFL reproduces the average value of the sum of the track momentum in the central rapidity region in both jet and minimum bias samples. But the momentum distributions still reflect some discrepancies, due to the lack of any hard physics description in the minimum bias model in Herwig. On the other hand, if we examine the transverse energy in the central calorimeter, we find that Herwig+QFL does not reproduce the data at all: the energy found in the CDF calorimeter is always larger than the Monte Carlo predictions. Pythia6.115 seems to have a better model to describe minimum bias data, but we still find disagreement in the comparison of the momentum and energy distributions. Indeed, in jet events, the max cone energy at the calorimeter level reproduces the data, while at the tracks level it does not and Pythia becomes larger than data.

Figure 5.32 shows the transverse energy (calorimeter level) inside the \( \text{max} \) and \( \text{min} \) cones at \( \sqrt{s} = 1800 \) GeV as a function of the sum of the track transverse momenta, for data, Herwig+QFL, and Pythia6.115+QFL.

![Figure 5.32](image)

Figure 5.32: Transverse energy inside the \( \text{max} \) and \( \text{min} \) cone at \( \sqrt{s} = 1800 \) GeV as a function of the track momentum \( p_t \).
We observe that at low momentum the transverse energy is larger in data than in Herwig+QFL or in Pythia6.115+QFL. At momenta larger than 5 GeV this difference seems to decrease but statistics become poor.

In order to understand the reasons for these discrepancies we studied the $E$ over $p$ ($E/p$) distribution for low momentum single charged particles in data, Herwig+QFL and Pythia6.115+QFL. We utilize the run 1b minimum bias event sample and apply the following (standard) cuts on the tracks:

- $d_0 < 0.5$ cm
- $|z_0 - z_{vtx}| < 5$ cm
- $p_t \geq 0.5$ GeV/c

The usual minimum bias cuts are also applied, but we further restrict the primary vertex to be within 40 cm of the nominal interaction point.

We proceed in the following way. First we look at each single track in the event. We extrapolate the track to the calorimeter to find the calorimeter tower hit by the track. We require the charged particle to be isolated; if we find another track inside a calorimeter grid of $5 \times 5$ around the target tower we reject the track. Otherwise we keep it. Indeed, because the response of a calorimeter tower depends on the impact point of the charged particle, we

![Calorimeter towers used in the $E/p$ calculation.](image)
CHAPTER 5. UNDERLYING EVENTS AT CDF

require the particle to hit the inner 25% region of the tower. We define the following quantities:

\[ \frac{E}{p} = \frac{E_{\text{CEM}} + \sum_{n=1}^{9} E_{n}^{\text{CHA}}}{p_{\text{track}}} \]

\[ \frac{E}{8p} = \frac{\sum_{n=1}^{9} E_{n}^{\text{CEM}} - E_{\text{CEM}}^{\text{target}}}{8 \times p_{\text{track}}} \]

\[ \frac{E}{p(\text{corrected})} = \frac{E}{p} - \frac{E}{8p} \]

where CEM and CHA indicate respectively the energy in the electromagnetic and hadronic calorimeter. Figure 5.33 shows the towers involved in the definition.

The \( \frac{E}{8p} \) distribution is subtracted from the \( \frac{E}{p} \) distribution in order to correct for neutral particle contamination. This is also the reason to use the hadronic energy around the target cell and the electromagnetic energy only in the target cell: we try to reduce as much as possible the contribution of neutral particles which cannot be detected by the CTC.

On the left side of figure 5.34, we display \( \langle \frac{E}{p} \rangle \) for Herwig+QFL, Pythia6.115+QFL and data as a function of the track momentum for tracks

![Graph](image)

Figure 5.34: On the left side of the figure, \( \langle \frac{E}{p} \rangle \) as a function of the track momentum for data, Herwig+QFL, and Pythia+QFL is shown. On the bottom also \( \langle \frac{E}{8p} \rangle \) is shown as a function of track momentum. On the right side of the figure, the corrected \( \langle \frac{E}{p} \rangle \) distribution as a function of the track momentum is shown.
in the central rapidity region $|\eta| < 1$. On the bottom of the plot also the $\langle E/p \rangle$ distribution is plotted. In the data the corrections decrease as a function of $p$ from about 0.04 to 0.01 in the track momentum range 0.4 − 6. GeV. On the right side of figure 5.34 the corrected distribution is shown. Data are larger than Herwig+QFL or Pythia6.115+QFL but the discrepancies seem to decrease when the momentum increases. Unfortunately we can take into account only a very small momentum range because in Herwig we do not find tracks with a momentum larger than 4 GeV. Pythia6.115+QFL seems to reach the data level when $p > 3.5$ GeV, although the low statistics does not allow a precise comparison.

In general, $\langle E/p \rangle$ is larger in the very central region than in the forward one as can be seen from figure 5.35 showing the corrected $\langle E/p \rangle$ distribution as a function of momentum for $|\eta| < .5$ and $.5 < |\eta| < 1$. The reason for that is the presence of plastic embedded in the calorimeter. The number of plastic layers increases with increasing rapidity, therefore low momentum particles do not penetrate in the calorimeter if $|\eta| > .5$ [62].

If we look at the distribution of $E/p$ at different intervals of track momentum (figures 5.36 and 5.37) we observe that the data and Herwig+QFL differ in every momentum range. Herwig+QFL has a much larger number of entries at low momentum. Pythia+QFL improves its agreement with data when the momentum is larger than 3 GeV. Both Monte Carlo generators

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.35.png}
\caption{Corrected $\langle E/p \rangle$ as a function of the track momentum for data, Herwig+QFL, and Pythia6.115+QFL in the rapidity region $|\eta| < 0.5$ (on the left) and $0.5 < |\eta| < 1$ (on the right).}
\end{figure}
Figure 5.36: Distribution of $E/p$ for different intervals of $p$ of the track (in GeV). Both data and Herwig+QFL are shown for $|\eta| < 1$.

Figure 5.37: Distribution of $E/p$ for different intervals of $p$ of the track (in GeV). Both data and Pythia6.115+QFL are shown for $|\eta| < 1$. 
Figure 5.38: Fraction of zeroes as a function of momentum. Data, Herwig+QFL, and Pythia6.115+QFL are shown.

have a much larger number of zeroes, as it can be observed in figure 5.38 which shows the fraction of zeroes as a function of the momentum. We define a zero as a charged particle that passes all the cuts above but deposits less that 0.15·p of energy in the calorimeter towers under examination.

5.7.1 Single Pion production

For comparison with data, we generated with QFL 400 000 single π+ with momentum between 0.5 and 10. GeV. The track rapidity varies uniformly between -1 and +1 and the azimuthal angle between 0 and 360 degrees.

First, we employ the definition of $E/p$ of the previous section. On the left side of figure 5.39 we compare the results from QFL with data. At very low momentum QFL is substantially below the data. We therefore redefine for the QFL simulation:

$$E/p = \frac{\sum_{n=1}^{9} (E_{n}^{CEM} + E_{n}^{CHA})}{p_{track}}$$

i.e. we sum the energy in a $3 \times 3$ grid around the target cell in both the electromagnetic and hadronic calorimeters. We use this new definition in
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

P track (GeV/c)

$\langle E/p \rangle$

Data

QFL Ecem+Ehad3x3

0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

P track (GeV/c)

$\langle E/p \rangle$

Data

QFL Ecem3x3+Ehad3x3

Figure 5.39: $\langle E/p \rangle$ as a function of the track momentum. For QFL, the definition in section 5.7 is used on the left side of the figure and definition in section 5.7.1 is used on the right side of the figure.

QFL because here we do not have the problem of neutral particles contamination. On the right side of figure 5.39, we show the $\langle E/p \rangle$ distribution as a function of the track momentum in the central rapidity region $\eta < 1$. $E/p$ in QFL is calculated with the new definition. Now QFL and data get closer although the QFL simulation results become larger than data for track momenta above 7 GeV.

5.8 Conclusions on underlying event energy and minimum bias events at CDF

Comparison of ambient energy in CDF data and Monte Carlo simulation

In order to study the underlying event, we have considered two cones in the calorimeter far away from the leading jet and we have examined the energy inside the cones, in CDF data, Herwig+QFL and Pythia6.115+QFL. We have found that both data and Herwig+QFL exhibits a similar behaviour for the max and the min cone; the min cone stays flat, while the max cone increases as a function of the $E_t$ of the leading jet. At $\sqrt{s} = 1800$ GeV there is an offset, however, of about 500 MeV for the min and of 800 MeV for the max cone between data and Herwig+QFL. Pythia6.115+QFL agrees with
5.8. CONCLUSIONS

the data for the max cone, but has about 300 MeV less energy than data in the min cone.

In minimum bias, the Herwig model predicts a level of energy below the one found in minimum bias data (350 MeV compared to 670 MeV). Part of this difference is due to the lack of any kind of hard interaction in the minimum bias model. Pythia seems to better reproduce the average value, but the shape of the energy distribution in the calorimeter is in disagreement with data.

A comparison of the track momenta in the underlying event at 630 and 1800 GeV, for both minimum bias and jet events, leads to relatively good agreement in general between the CDF data and the Herwig+QFL simulated data in jet events. This is in contrast to the level of agreement observed when comparing similar quantities at the calorimeter level. Herwig’s minimum bias transverse momentum distribution is still too soft. On the other hand Pythia’s disagreement with data in jet events generally increases.

At $\sqrt{s} = 630$ GeV we compared data to Herwig+QFL. The disagreement between data and simulation, in the analysis of the transverse energy in jet events, decreases to 450 MeV in the max cone and 350 MeV in the min cone. The average energy found in data and in Herwig+QFL is smaller at 630 GeV than at 1800 GeV. The analysis of the transverse momentum of the charged particles in jet events shows a good agreement between Herwig+QFL and data.

Problem related to CDF calorimeter calibration

We examined the ratio of energy over momentum for isolated charged particles and found a disagreement between data and simulation for tracks below 4 GeV. The reason for this discrepancy is still being investigated but could be due to the method of calibration of the CDF calorimeters, which may underestimate low energy depositions by hadrons in the electromagnetic portion of the calorimeter [63]. CDF hadronic energy must be multiplied by a bigger factor to account for the fact that the calorimeter response to hadrons is intrinsically smaller than its response to electrons. The CDF calorimeter has been calibrated using electrons for the electromagnetic section and penetrating pions for the hadronic section. However, this method introduces some undesirable effects: The reconstructed hadronic energy depends on the starting point of the shower (about 60% of the pions begin to shower in the electromagnetic section of the calorimeter) and the calibration constants depend on the energy of the incident particle (since the electromagnetic content of the shower depends on this energy).
Underlying event energy in jet events and in minimum bias events at CDF

We observed that generally the energy in a cone in minimum bias events is lower than the energy in the \textit{min} cone in jet events. The minimum bias energy in a random cone depends on the choice of the vertex class. If we restrict the acceptance to higher class vertices, the energy in the central region increases. If we consider only charged particles in order to avoid calorimeter effects, the minimum bias transverse momentum inside a random cone in the central rapidity region of the CDF detector is about 20\% or 10\% lower than in the \textit{min} cone in jet events depending on whether we accept every vertex or restrict to a higher class vertex.

In conclusion, we have observed that for the same available energy the underlying event in a \textit{hard} scattering is considerable more active than in a \textit{soft} collision.

5.9 On the importance of an accurate calorimeter calibration

An improved energy resolution of the CDF calorimeter is required for a number of reasons. Many processes of interest are characterized by the presence of jets in the final state, which are usually reconstructed summing up the energy in electromagnetic and hadronic towers (see section 5.1). For example, the mass of the top quark or the discovery of the light Higgs boson are very sensitive to the jet’s energy resolution.

One of the possible decay channels of the top quark at the Tevatron is given by $qq \rightarrow tt \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (q\bar{q}'b)(l\nu\bar{b})$. Due to the presence of a lepton in the final state, this process is easier to reconstruct than when both W’s decay hadronically. If one requires the lepton to be an electron or a muon (since the tau rapidly decays hadronically), the branching ratio of this process is about 30\%. A jet emerges from each b-quark decay. Once the b’s are tagged, the energy of the jets must be reconstructed in order to obtain the mass of the top quark. Accurate values of the mass of the top quark and of the W boson are desired in order to provide limits on the mass of the Higgs. Since the mass of the Higgs depends logarithmically on the $M_W/M_{top}$ ratio, a small bias on the mass values corresponds to a large change of the limit on $M_H$ [64].

Indeed, one of the favourite decay modes of a light Higgs boson, is given by: $qq \rightarrow WH \rightarrow l\nu bb$ [65]. Since the Higgs particle should appear as a bump in the invariant mass of the two b-jets, a good energy resolution of

\footnote{for Higgs masses up to 130 GeV}
5.9. **ON THE IMPORTANCE OF AN ACCURATE CALORIMETER CALIBRATION**

the jet is important in order to distinguish the signal from the background. Previous studies [66] on the physics at the just started run (run2) at the Tevatron, show that an improvement of 30\% on the jet's energy resolution corresponds to an increase of the significance of the Higgs signal by almost 25\%, after 10 fb$^{-1}$ [67].

These results point out the importance of developing a new method of calibration for the CDF calorimeters in order to obtain a high energy resolution.
Chapter 6

LHC and ATLAS

The search for new particles and potential new physics requires the construction of more powerful accelerators. LHC [5], the future accelerator at the CERN laboratory in Geneva, will collide protons on protons at a center of mass energy never reached before. Figure 6.1 displays some cross sections of interest at the Tevatron and at LHC energies. For example, at LHC, the actual cross section for the production of a Higgs boson with a mass of 150 GeV is

\[ \sigma_{	ext{Higgs}}(M_{\text{Higgs}} = 150 \text{ GeV}) \]

Figure 6.1: Cross section for hard scattering versus \( \sqrt{s} \) [17].
GeV, will be up to $10^4$ times larger than at the Tevatron [17].

A crucial factor for the discovery of new particles is the achievement of a high luminosity, such that an average of 23 minimum bias events are expected to be superimposed on any hard event of interest. A precise understanding of the dynamics of minimum bias and of underlying event in hard scattering events, will be fundamental in order to correctly reconstruct jets at LHC. In this chapter we briefly describe the characteristics of the LHC and of ATLAS, one of the multipurpose detectors at LHC. In the next chapter we estimate the impact of the underlying event energy in jet events at ATLAS, with the help of Monte Carlo and detector simulation.

### 6.1 The Large Hadron Collider

The LHC is a proton-proton accelerator in construction which is planned to meet the first collision at the beginning of 2006. It is designed in order to reach a center of mass energy of 14 TeV and an instantaneous luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ after running some time in the start-up phase at a luminosity of $10^{33}\text{cm}^{-2}\text{s}^{-1}$. It will be housed in the already existing LEP [68] tunnel which has a circumference of 27 km. Beside its usage as a proton-proton collider, LHC will be used as a heavy ion collider (Pb-Pb). In our analysis we are only interested in the proton-proton mode of running.

There is a complex of different accelerators at CERN which will be used as injectors for the LHC and will allow the protons to reach energies of 7 TeV. The LHC injector complex and the LHC ring are shown in figure 6.2.

![Figure 6.2: View of the LHC and its injector complex.](image)
6.1. *THE LARGE HADRON COLLIDER*

<table>
<thead>
<tr>
<th>LHC general parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy at collision</td>
</tr>
<tr>
<td>Energy at injection</td>
</tr>
<tr>
<td>Dipole field</td>
</tr>
<tr>
<td>Coil inner diameter</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Bunch spacing</td>
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<td>Bunch separation</td>
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<td>Particles per bunch</td>
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<tr>
<td>Energy loss per turn</td>
</tr>
<tr>
<td>RF cavities</td>
</tr>
</tbody>
</table>

Table 6.1: General parameters for protons in the LHC

The protons will be produced and accelerated to 50 MeV by the LINAC. They will be injected in the Proton Synchrotron Booster (PSB) and further accelerated to reach the energy of 1.4 GeV. The Proton Synchrotron (PS) will bring them to energies of 26 GeV and finally the Super Proton Synchrotron (SPS) will inject protons in the LHC with an energy of 450 GeV. The LHC will subsequently accelerate the protons to 7 TeV in bunches and will allow a collision every 25 ns. The main LHC parameters are compiled in table 6.1.

Since the LHC will accelerate particles of the same charge in different directions in order to make the collision, it is necessary to have two different vacuum pipes and different magnets. A design will be used which combines the two beam lines in a single magnet with two coils and beam channels with the same mechanical structure and cryostat as shown in figure 6.3.

In order to accelerate the protons at the nominal energy and to bend them inside the LEP tunnel, the magnetic field needs to be of about 8.3 T. Such a strong magnetic field can be reached with the use of superconducting magnets which will be cooled to temperatures below 1.9 Kelvin by using superfluid Helium. At LHC there will be need of 1276 superconducting dipole magnets to bend the beam, 788 quadrupole magnets to focus the beam and 4952 small correctors to the main dipole, for a total of 7016 superconducting magnets.

General purpose detectors will be placed at two collision points: ATLAS [7, 69] and CMS [70]. Other interaction points will be used by ALICE [71], a heavy ions experiment and LHC-B [72], devoted to studies of CP violation and rare B hadron decays.
6.2 ATLAS

The ATLAS (A Toroidal LHC ApparatuS) detector is a general purpose detector to exploit the full discovery potential of the LHC. One of the main focus of study is the origin of mass at the electroweak scale. For this reason the detector should be sensitive to a large range of Higgs masses. Indeed studies of supersymmetry, compositeness of fermions, CP violation in B decay, and top quark will be of extreme importance. Because of the high rate of particle production at LHC, it is important for the detector to be sensitive to a large variety of signatures in order to perform many internal checks. The main design considerations for ATLAS can be summarized as follow:

- a good calorimeter will be necessary in order to identify precisely electrons and photons and to reconstruct jets and missing $E_T$;

- since muon spectrometry is of extreme importance for discoveries in the LHC high radiation environment, a high precision muon momentum reconstruction is required;

- an efficient tracking system, able to measure lepton momenta, tag $b$-quarks, identify electrons and photons and reconstruct $\tau$ leptons, and heavy flavour vertices, is needed;
6.3 INNER DETECTOR

- a trigger and measurement of particles at low $p_t$ and a large acceptance in $\eta$ coverage will optimize the exploitation of the LHC.

The ATLAS detector layout is shown in figure 6.4. The detector will be about 44 m long (including the last layer of the forward muon chambers) and about 35 m high.

![ATLAS Detector Layout](image)

Figure 6.4: Overall ATLAS detector layout

### 6.3 Inner detector

The density of tracks at LHC will be very large. For this reason it is necessary to have a tracking system able to reconstruct the vertex and the track momentum with very high precision. At ATLAS this is achieved by using
semiconductor tracking detectors, silicon microstrips (SCT) and pixels, and straw tube trackers (TRT) which combine high resolution at inner radii with continuous tracking elements at outer radii. Usually each track crosses three pixel layers, 8 strip layers and 36 straw tubes. The acceptance of the inner detector is $|\eta| < 2.5$. A picture of the inner detector [73] is shown in figure 6.5.

![Figure 6.5: View of the ATLAS inner detector](image)

The semiconductor pixels are located around the vertex region and provide a high granularity and high precision measurements, such as impact parameter and vertex position. The number of pixel layers must be limited because of the high costs and the amount of material they introduce. The pixels layers are segmented in $r-\phi$ and $z$ to give three dimensional information. They require the use of advanced electronic techniques for the readout. The readout chips have single connections to each pixel element and buffers to store the data during the level 1 trigger (LVL1) decision. Indeed the chips must be radiation hardened to survive the high amount of radiation close to the beam interaction. The mechanical design of the pixel system allows its replacement in case of radiation damage. The pixel system is both in the barrel and in the endcap region. It consists of three barrels at 4, 11, and 14 cm and four disks on each side between radii of 11 and 20 cm. Each pixel has dimensions of 50 $\mu$m (in $r$, $\phi$) and 400 $\mu$m (in $z$). In the barrel the pixel system provides a $r-\phi$ resolution of 12 $\mu$m and a $z$ resolution of 66$\mu$m.

The SCT system is located outside the pixel system. In the barrel it makes use of four double layers of silicon microstrip detectors located at radii 30, 37.3, 44.7 and 52 cm and provide information in the $r-\phi$ plane and in the $z$ coordinate. Each endcap is made of 9 disks. Each module
6.4. MAGNET SYSTEM

consists of four 6.36 × 6.40 cm² silicon detectors bonded together to form 12.8 cm long strips. Each double layer consists of strips aligned in the azimuthal direction and strips rotated by 40 mrad stereo angle with respect to the first set. Their position resolution in $r - \phi$ is 16$\mu$m and 580$\mu$m in $z$.

The TRT is based on straw tubes interspersed with a radiator to identify electrons from transition radiation photons created by the electrons during the crossing of the radiator. Straw tubes provide a continuous tracking over large distances at lower cost and avoid the introduction of large amount of material. There will be two endcap TRTs with radial straws for $r - \phi$ measurements, and one barrel TRT with axially oriented straws to measure $\phi$ and $z$ and indirectly $r$ through the particles entrance and exit position in the detector, determined by the first and last hit straws in the trajectory. Each straw is 4 mm in diameter and the maximum length is 144 cm. Each endcap consists of 14 disks. The barrel contains about 50,000 straws divided in two at the center and read out at each end. The barrel section is built from three layers, each with 24 modules, and covers the region between 56 and 107 cm. The position resolution of each straw is 170 $\mu$m.

6.4 Magnet system

The superconducting magnet system in ATLAS consists of three different sub-systems: a Central Solenoid (CS) which provides the inner detector with magnetic field, a Barrel Toroid (BT) which generates the magnetic field for the muon spectrometer, and two End-Cap Toroids (ECT). The Central Solenoid provides the required 2 T magnetic field with a peak of 2.6 T at the superconductor itself. It is 5.2 m long with an inner bore of 2.4 m. To reduce the amount of material the solenoid shares the cryostat with the liquid argon calorimeter. The Barrel Toroid consists of 8 flat coils each about 25 m long and 5 m wide, assembled radially and symmetrically around the beam axis. The inner bore of the BT is 9 m and the outer radius 20 m. The two End-Cap Toroids are placed before and behind the Central Solenoid. They also consists of 8 coils rotated by 22.5° with respect to the BT system to optimize the bending power in the interface region. Their length is about 5m, the inner bore is 1.6m and the outer diameter is 11 m. All the magnets are cooled by liquid Helium at about 4 K.

6.5 Calorimeters

The calorimeter system in ATLAS [74] consists of an electromagnetic barrel calorimeter, a hadronic barrel and an extended barrel calorimeter, an electromagnetic endcap calorimeter, a hadronic endcap calorimeter (1.5 < $|\eta|$ <
### 6.5.1 Electromagnetic calorimeter

The electromagnetic calorimeter consists of two identical half barrels separated by a 6 mm gap at $z = 0$ and two endcaps. In the region $|\eta| < 1.8$ the EM calorimeter is preceded by a presampling detector which is used to correct for the energy lost in the detector material in front of the calorimeter.

ATLAS will operate in a high luminosity environment and therefore it will be exposed to a very large amount of radiation. For this reason an important requirement in the calorimeter design is its radiation resistance which must allow data taking for more than ten years. In ATLAS, a design using liquid argon (LAr) sampling technique with accordion-shaped absorbers has
been chosen. This provides long-term response stability. Indeed, the choice of such a geometry permits the absence of azimuthal uninstrumented cracks because the connections to the preamplifiers come from the end of a tower. A basic cell which shows the accordion geometry is illustrated in figure 6.6 and consists of a lead absorber plate, a liquid argon gap, a readout electrode and a second argon gap. The argon acts as the active medium.

![Diagram of an ATLAS electromagnetic calorimeter cell](image)

Figure 6.6: View of an ATLAS electromagnetic calorimeter cell which shows the accordion geometry

The lead thickness in the absorber plates has been chosen as a function of the rapidity and vary from 1.5 to 1.1 mm, while the liquid argon gap has a constant thickness in the barrel of 2.1 mm. In the endcap, the shape of the electrodes is more complicated and the amplitude of the accordion waves increases with the radius. Since the absorbers have constant thickness, the LAr gap increases with radius.

In the $|\eta| < 2.5$ region which is dedicated to precision physics, the calorimeter is segmented into three longitudinal samplings. The first sampling is equipped with $\eta$-strips of much finer segmentation in $\eta$ with respect to that in $\phi$ because showers which start in front of the solenoid are smeared in $\phi$ by the magnetic field and therefore no attempt is made to measure their finer structure in $\phi$ but a precise position measurement in $\eta$ is provided. A picture showing the granularity of the electromagnetic barrel calorimeter and the absorption power in terms of absorption length is given in figure 6.7.
The energy resolution of the ATLAS electromagnetic calorimeter is:

$$\sigma(E) = \frac{10\%}{\sqrt{E\ (\text{GeV})}} \oplus 0.7\%$$

throughout the rapidity coverage except for the small barrel endcap transition region $\eta \simeq 2$.

### 6.5.2 Hadronic calorimeters

The hadronic calorimeter system consists of a tile calorimeter and an endcap calorimeter.

The tile calorimeter is composed of a barrel and extended barrel calorimeter. In the region between the barrel and the extended barrel at $|\eta| = 1$ there is a 68 cm gap for cables and services for the innermost detectors. The tile calorimeter is a sampling calorimeter using iron as absorber material and scintillating tiles as active material which are readout by wavelength shifting fibers (WLS) into photomultipliers. It has a cylindrical structure with an inner radius of 2.28 m and an outer radius of 4.25 m. The barrel is 5.6 m long and the two extended barrels are each 2.6 m long. Each of them is subdivided in azimuth in 64 modules. A module is shown in figure 6.8.

The modules are placed in planes perpendicular to the beam and staggered in depth. Radially the calorimeter is segmented in three layers of
Figure 6.8: Module of the ATLAS tile calorimeter.

approximately 1.5, 4.2 and 1.9 interaction lengths thickness at \( \eta = 0 \). The jet and missing \( E_t \) resolution is given by [74]:

\[
\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E \text{ (GeV)}}} \oplus 3\%
\]

The barrel calorimeter must provide good containment of the hadronic shower and reduce punch through of hadrons for the muon system. For this reason the thickness is an important design parameter. The total amount of material in front of the muon system, including also the calorimeter support, is 11 interaction lengths at \( \eta = 0 \).

### 6.6 Muon spectrometer

For the muon spectrometer [75] a very high momentum resolution over a \( p_t \) range from 5 GeV to over 1000 GeV is required in order to detect decays such \( H \to ZZ^* \to 4l \) or \( Z' \to \mu\mu \). The system is made of 3 superconducting air-core toroid magnets (which have been described in section 6.4), precision tracking detectors and a trigger system. For the precision measurements Monitored Drift Tube chambers (MDTs) and Cathode Strip Chambers (CSCs) are used, while for triggering Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) were chosen. The muon spectrometer can
be divided in 3 regions: the barrel region ($|\eta| < 1.05$), a transition region ($1.05 < |\eta| < 1.4$), and the endcap region ($|\eta| > 1.4$).

In the barrel region the chambers are arranged cylindrically concentric with the beam axis. There are three stations of chambers at radii of 4.5 m, 7 m and 10 m. Each chamber is made of two multilayers of high pressure drift tubes (MDT) mounted to either side of a support structure at a variable size between 150 and 350 mm, depending on the position of the chamber. Each multilayer consists of 3 or 4 layers of tubes. Each tube has an outer diameter of 30 mm and a length varying from 1.4 to 6.3 m. These chambers combine a high intrinsic spatial resolution ($\sigma \leq 80 \mu m$) with an internal monitoring system to track distortions of the chamber. For the triggering the RPCs are used. They are gaseous parallel plate detectors.

In the endcap region MDTs are used in smaller rapidity regions while at high rapidity, where a higher granularity is required, CSCs are preferred. Indeed aging consideration lead to this choice due to the high level of radiation in the region. Cathode Strip Chambers (CSCs) are multiwire proportional chambers with a distance between anode and cathode of about 2.5 mm.

In the transition region the muon track is measured in 3 vertical stations located inside or near to the barrel magnet, while in the endcap there are two chambers outside the cryostat. For the trigger TGCs are chosen for rapidities $1.05 < |\eta| < 2.2$ and for complementary coordinate measurement at $|\eta| > 2.2$ because here a good spatial resolution ($\sigma < 1 cm$) is needed, since the level of radiation is high. They are similar to multiwire proportional chambers with a distance between the wires larger than the cathode-anode distance.

6.7 Trigger and Data Acquisition

The very high rate of interactions at LHC is a challenge for the ATLAS trigger system [76]. Since the bunch crossing rate is 40 MHz, a decision whether to accept an event for further processing or not, must be taken every 25 ns. Indeed, at design luminosity, each bunch crossing provides about 23 interactions for a total rate of $10^9$ interactions per second. ATLAS uses three trigger levels in order to reduce the event rate: LVL1, LVL2 and event filter (EF) as it is illustrated in figure 6.9.

LVL1 trigger receives data at a rate of 40 MHz and has an output rate capability of about 75 kHz, extensible to 100 kHz. The time needed to collect the data, make a decision and distribute it (latency) is about 2 $\mu$s. The decision is based on reduced granularity data from a restricted number of detectors. The LVL1 trigger flags the so called region of interest (RoIs) which
6.7. TRIGGER AND DATA ACQUISITION

will be passed and further analyzed by the LVL2 trigger. LVL1 provides information such as position and $p_t$ threshold for jets, muons and electromagnetic clusters. The settings used at LVL1 at the muon and calorimeter level are based on a simplified reconstruction, in order to make fast decisions. During the time needed by LVL1 to process the data, data from all detector systems are held in pipeline memories. If an event is accepted, the data are read out and stored in readout buffers (ROBs) for use by the next trigger level.

At LVL2 each RoI is examined to see if it is confirmed as an interesting object. LVL2 searches also in detector regions not analyzed by LVL1, such as the inner tracking detectors. In this way more specialized trigger objects such as muons, electrons, photons, taus, jets and missing $E_t$, and B-physics objects are formed. The output rate of LVL2 is about 1 KHz and the latency is variable from event to event and is expected to be in the range $1 - 10$ ms.

After an event is accepted by LVL2, data are passed on to the event filter for the final selection. The full event is collected from the readout buffers and data are processed using a full granularity in order to make a final decision. The acceptance rate of the event filter is about 100 Hz and the latency is expected to be up to 1 s. The accepted events have an average size of 100 Mbyte and must be stored on permanent media for the offline analysis. During one year about $10^9$ Mbytes of raw data will be stored.
Chapter 7

Extrapolation to LHC energies

The underlying event of hard collisions and minimum bias events consist of low energy particles, the behaviour of which is usually difficult to simulate. In ATLAS, due to the magnetic field, charged particles with $p_t < 0.4$ GeV [77] do not reach the calorimeter and loop in the inner detector. At the calorimeter level, resolution problems arise from non-compensation, the presence of dead material and the different showering properties of hadrons and leptons in the electromagnetic and hadronic calorimeters [78, 79]. An accurate study would require the use of full detector simulation based on a GEANT description [80]. But since we are interested in determining the approximate amount of energy from the soft underlying event and how it will affect the jet energy measurement, we rely on the fast ATLAS simulation program ATLFAST [81]. For completeness we examine 5000 fully simulated minimum bias events generated for the studies presented in the ATLAS physics Technical Design Report [69], and compare them to the fast detector simulation.

7.1 Comparison of fast and fully simulated ATLAS minimum bias events

We analyze 5000 minimum bias events which were generated with DICE [82] program version 98.2 in the rapidity region $|\eta| < 3.2$ and written on tape [83]. DICE is the GEANT based ATLAS geometry description. Proton-proton events at a center of mass energy of 14 TeV were generated using Pythia5.7 and Jetset7.4 with the following settings:

- MSEL = 1 → minimum bias setting
• MSTP(2)=2 $\rightarrow$ second order running $\alpha_s$ at the hard interaction
• MSTP(33)=3 $\rightarrow$ inclusion of a K factor in the hard cross section for strong radiative corrections to the parton-parton scattering
• MSTP(81)=1 $\rightarrow$ multiple interactions required
• MSTP(82)=4 $\rightarrow$ running with varying impact parameter
• MSTJ(22)=2 $\rightarrow$ a particle is allowed to decay only if its average proper lifetime corresponds to over 10 mm flight distance.

For comparison we generate 15 000 events using the same settings and send them through the fast detector simulation ATLFAST.

The transverse momentum distribution of the generated stable particles in the two samples (full simulation/fast simulation) agree within the statistical errors. From now on we refer to generated particles to indicate Monte Carlo generated particles which did not undergo any energy smearing, but whose trajectory was corrected for magnetic field effects. In other words we speak about tracks and calorimeter cells before any energy correction due to detector effects is applied.

7.1.1 Charged particle detection

Tracks are reconstructed in the fully simulated events with XKALMAN [77], a package for global pattern recognition and track fitting in the ATLAS inner detector for charged particles with transverse momentum above 0.5 GeV. The algorithm starts by finding track segments in the TRT as possible track-candidate trajectories, each defined as an initial helix. The helices which pass quality criteria (based on the number of precision hits) are extrapolated back in the TRT. Charged particles are measured in the inner detector with a resolution which depends on their transverse momentum and rapidity. For example the momentum resolution $\sigma(Q/p_t)$ is about 30% (1/TeV) if the track transverse momentum is 0.5 GeV and 0.5% (1/TeV) if $p_t = 1$TeV [84].

In the central rapidity region the resolution is independent of the rapidity except for very low $p_t$ particles, whose resolution worsens if $|\eta| > 1$. These resolution values have been used in the fast detector simulation to smear the tracks.

In order to have a high track finding efficiency as well as a good resolution, we require the reconstructed impact parameter to be less than 1mm and we restrict the detection of charged particles to the central detector region ($|\eta| < 1.4$).
The sum of the transverse momentum in the central region is on average 7.08 GeV in the full simulation, 8.04 GeV in the fast simulation and 8.03 GeV using the generated particles. The transverse momentum distribution of the tracks compared at these three levels is shown in figure 7.1, where the number of entries in the fast simulation is normalized to the number of entries in the full simulation.

Figure 7.1: ATLAS transverse momentum distribution of charged particles in the central rapidity region in minimum bias events in the fast and full simulation. The statistics refers to the entries which have not been normalized yet.

The track momentum distribution is quite flat over the considered rapidity interval as it can be observed in figure 7.2 which shows the track momenta as a function of $\eta$ and $\phi$. The ratio between the fast and the fully simulated distributions (figure 7.3) is unity within the statistical errors over the entire $\eta$ and $\phi$ range.

### 7.1.2 Calorimeter simulations

The comparison between fast and full simulation at the calorimeter level is complicated by the high number of electromagnetic and hadronic calorimeters with different segmentation in $\eta$ and $\phi$ and from different degrees of non-compensation (cf. section 3.5). Another complication is due to dead material: a critical region is the corner where the electromagnetic accordion
Figure 7.2: The average ATLAS transverse momentum distribution of charged particles in minimum bias events as a function of $\eta$ and $\phi$.

Figure 7.3: Ratio between fast and fully ATLAS simulated transverse momentum distribution of charged particles in minimum bias events as a function of $\eta$ and $\phi$. 
7.1. ATLAS MINIMUM BIAS EVENTS

<table>
<thead>
<tr>
<th>Calorimeter</th>
<th>Central barrel($\eta = 0.3$)</th>
<th>Extended barrel($\eta = 1.3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile</td>
<td>0.056</td>
<td>0.047</td>
</tr>
<tr>
<td>EM barrel</td>
<td>0.164</td>
<td>0.098</td>
</tr>
<tr>
<td>Presampler</td>
<td>0.098</td>
<td>0.107</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.199</strong></td>
<td><strong>0.191</strong></td>
</tr>
</tbody>
</table>

Table 7.1: Electronic noise in electromagnetic scale in the tower of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ after digital filtering [69].

ends, at $|\eta| = 1.45$. To avoid that, we limit the analysis to $|\eta| < 1.4$ which defines the region of the barrel electromagnetic calorimeter.

For jet reconstruction, towers of $0.1 \times 0.1$ in $\eta$ and $\phi$ will be used in ATLAS. For this reason we group together the calorimeter cells in order to have 28 $\eta$ segments of $\Delta \eta = 0.1$ (within $-1.4 < |\eta| < 1.4$) and 64 $\phi$ segments of $\Delta \phi = 0.098$ (over the all azimuthal range). In the third longitudinal layer of the hadronic calorimeter where the segmentation is of 0.2 in $\eta$, we simply split each cell in two, each with half of the energy of the original tower.

In the region with $|\eta| < 1.4$ the ATLAS system of calorimeters consists of a presample, plus 3 longitudinal layers in the central barrel to detect electromagnetic energy and 3 longitudinal layers in the central barrel, plus 3 longitudinal layers in the extended barrel, plus 2 plugs and 2 scintillators to detect hadronic energy.

In the fast simulation every cell is smeared using formulas extrapolated from the full simulation results in order to reproduce properly the mass spectra resolution. These formulas have been validated from test beam results. The formulas used to smear the electromagnetic and hadronic cells in the central rapidity region are respectively [81]:

$$\frac{\delta E_e}{E_e} = 0.12 \frac{1}{\sqrt{E_e}} \oplus \frac{0.245}{E_e} \oplus 0.007 \quad (7.1)$$

$$\frac{\delta E}{E} = 0.50 \frac{1}{\sqrt{E}} \oplus 0.03 \quad (7.2)$$

The level of electronic noise in calorimeter towers of $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in electromagnetic scale (i.e. before any correction is applied to the hadronic energy for non-compensation effects) is shown in table 7.1 [69] and is always below 200 MeV.

ATLFAST simply smears the energy in the cell hit by the incoming particle but does not simulate showering effects in the calorimeter as the
full simulation does. This means that the energy of a single particle hitting
the calorimeter is concentrated only in one cell in the fast simulation but in
many different cells, each containing only a fraction of the initial energy, in
the full simulation.

We sum up the energy in cells of the entire central calorimeter as is
shown in figure 7.4. No energy threshold is applied on the cells. The energy
is the sum of the electromagnetic and hadronic portion. The energy in the
full simulation is on average less than in the fast simulation.

![Figure 7.4: Total energy in the ATLAS central (|η| < 1.4) calorimeter re-
region. The number of entries in the full simulation is normalized to the
number of entries in the fast simulation. Statistics refers to entries before
normalization.](image)

Figure 7.5 shows the sum of the energy in slices of ∆η = 0.1 or ∆φ = 0.1
as a function respectively of η and φ in the fast and full simulation. We
observe that the energy in the fast simulation is larger than in the full
simulation over the entire η and φ range.

The differences may be due to the fact that the sum in the slices is
only a rough attempt to pick up the energy of the initial particle after the
showing. But mainly it is due to the fact that the energy shown is simply
the energy deposit from the particles in the calorimeters, and it must be
corrected for calibration effects.

To obtain from the deposited energy the true energy, different calibra-
tion constants should be applied for different parts of the calorimeter. The best way to correct would be to study the energy dependence of every cell in the calorimeters and correct the energy in the cells. But this is not trivial at all considering that ATLAS has 214,000 electromagnetic cells and 20,000 hadronic cells. By now calibration constants have been calculated [78] grouping together detector compartments with a similar answer (presampler, EM barrel, tile barrel,..) and optimizing the weighted sum of these compartments:

\[
\min_{w_i} \sum_j \left( \sum_i w_i E_{i,j} - E_{\text{true},j} \right)^2
\]  

(7.3)

The weights have been calculated from di-jet and \(Z^0\)+jets events for energies between 50 and 1000 GeV and \(|\eta| < 3.05\) [85]. We use the factors calculated for jets of 20 GeV energy and with a cone algorithm of radius 0.7 to correct the energy in the calorimeter cells.

The energy summed up in the calorimeter slices as a function of \(\eta\) and \(\phi\) after the calibration is shown in figure 7.6. Before the calibration was applied, the total energy in the ATLAS central calorimeter was found to be 16.86 GeV (see figure 7.4). After calibration, the total energy increases to 21.47 GeV, in good agreement with the fast simulation.
CHAPTER 7. EXTRAPOLATION TO LHC ENERGIES

Figure 7.6: Energy in $\phi$ and $\eta$ slices as a function of $\eta$ and $\phi$. Fully simulated events are calibrated with weights determined using jets of 20 GeV energy and a clustering cone of 0.7.

The ratio of corrected fully and fast simulated energy is shown in figure 7.7. The use of calibration factors calculated for jets of 20 GeV energy is only an approximation, since calorimeter cells should be calibrated with factors calculated at lower energies. For this reason we study what happens if calibration constants for jets of higher energies, such as 50 GeV, are used. The differences are found to be below 1%, thus the employed approximation is useful.

The fast and full simulation (corrected with 20 GeV jets calibration constants) agree within the statistical errors over the full $\eta$ and $\phi$ range.

7.2 Comparison of ATLAS and CDF fast simulated events

Minimum bias and jet events are simulated at LHC energies with the help of the Herwig Monte Carlo generator, whose model for soft physics has been compared to data from the Tevatron (chapter 5) at two different center of mass energies: 1800 and 630 GeV.
7.2. FAST SIMULATION AT ATLAS AND CDF

Figure 7.7: Ratio between fast and fully simulated ATLAS energy in $\eta$ and $\phi$ slices as a function of $\eta$ and $\phi$. Fully simulated events are calibrated with weights for jets of 20 GeV energy and clustering cone of 0.7.

7.2.1 Minimum bias events

We generate 200 000 minimum bias events with Herwig 5.9 at a center of mass energy of 14 TeV and pass them through the fast ATLAS simulation ATLFAST. Default generation parameters are chosen. No changes regarding minimum bias and underlying event simulation have been performed between the 5.6 and 5.9 Herwig versions, which therefore behave identical in this respect.

From now on, we will refer to Herwig+ATLFAST for events generated with Herwig at a center of mass energy of 14 TeV and passed through the ATLFAST simulation of the ATLAS detector and to Herwig+QFL for events generated with Herwig at a center of mass energy of 1800 GeV and passed through the QFL simulation of the CDF detector.

The momentum of the charged particles is measured by tracking and for this reason has smaller detector related corrections than calorimetric measurements. The basic cuts applied on both the Herwig+ATLFAST and Herwig+QFL samples have already been previously described. Here we additionally require the tracks in both samples to pass the following cuts:

- $|\eta| < 1.4$
• $p_t > 0.5$ GeV

The comparison of the simulated momentum distribution of charged particles in minimum bias events in Herwig+ATLFAST and Herwig+QFL is shown in figure 7.8 with the number of entries in the Herwig+QFL simulation normalized to the number of entries in the Herwig+ATLFAST simulation.

Figure 7.8: Transverse momentum distribution of charged particles in minimum bias events in Herwig+ATLFAST and Herwig+QFL on a logarithmic and linear scale.

The two distributions look very similar except for a slight increment in the minimum bias activity at 14 TeV as pointed out by few tracks with momenta larger than 4 GeV. The average for the track momentum is about 790 MeV in both Herwig+ATLFAST and Herwig+QFL. If we sum up the transverse momentum in a random cone of radius 0.7 in the central region, to compare with the CDF results in chapter 5, we find in the cone about 370 MeV in Herwig+ATLFAST and 310 MeV in Herwig+QFL. The momentum distribution of the tracks as a function of the rapidity and of the azimuthal angle is shown in figure 7.9.

The energy distribution in the calorimeters (electromagnetic+hadronic) is much more difficult to compare in ATLAS and CDF because of its large dependence on detector simulations. In order to remove showering effects which are not simulated by ATLFAST, we do not compare tower by tower.
Instead we consider the energy inside a random cone of radius 0.7 in the central calorimeter region ($|\eta| < 1.4$) and apply a minimum energy cut on the towers of 50 MeV. As it is shown in figure 7.10 the Herwig+QFL and Herwig+ATLFAST transverse energy distributions inside the random cone look very different. We find on average 340 MeV inside the cone with Herwig+QFL and 780 MeV in Herwig+ATLFAST. The discrepancy is mainly due to the different response of the ATLAS and CDF calorimeters.

In order to avoid calorimeter effects we analyze the energy released by the simulated particles before they enter the CDF or ATLAS calorimeters. We find on average 750 MeV in a random cone at 1800 GeV and 690 MeV at 14 TeV, i.e. 60 MeV more if the center of mass energy is lower. The reason for that is mainly due to the fact that charged particles below 440 MeV do not reach the ATLAS calorimeter while they release energy in the CDF calorimeter. This can be easily observed in figure 7.11 which shows the distribution of the transverse energy in the cone at both center of mass energies. The main differences arise from energies below 500 MeV. In the small insert on the same picture the number of entries in the Herwig+QFL distribution is normalized to the number of entries in Herwig+ATLFAST starting from 500 MeV energies and their agreement is fairly good. If we restrict ourselves to tower energies larger than 500 MeV, we find about 10% more energy in a cone of radius 0.7 at 14 TeV than at 1800 GeV.
Figure 7.10: Distribution of the transverse energy summed up inside a random cone of radius 0.7 in Herwig+ATLFAST and Herwig+QFL.

Figure 7.11: Distribution of the transverse energy summed up inside a random cone of radius 0.7 in ATLAS and CDF simulations at the hadron level.
7.2. FAST SIMULATION AT ATLAS AND CDF

7.2.2 Underlying event in jet events

From Herwig simulations we observe that an increase of the center of mass energy from 1.8 to 14 TeV only slightly affects the minimum bias event activity. This is not the case for the underlying event energy in jet events, where we study the energy in a region far away from jets arising from the hard scattering.

We generate with Herwig+ATLFAST four jet samples with minimum transverse momentum of the hard scattering of 180, 500, 1000, 1380 GeV. To reduce inefficiencies we require the transverse energy of the leading jet in each sample to be larger than 260, 650, 1200, 1500 GeV respectively. The effect of charged particles with transverse momentum below 500 MeV as well as calorimeter towers with energies less than 50 MeV are neglected. Again we only consider the central rapidity region $|\eta| < 1.4$. We take two cones of radius 0.7 at the same $\eta$ but at $\pm 90^\circ$ in $\phi$ with respect to the most energetic jet in the event. We label, as before, the two cones $\text{max}$ (maximum) and $\text{min}$ (minimum), according to their energies.

![Figure 7.12: Transverse momenta of charged particles inside the max and min cone (on the left) and their difference (on the right) as a function of the $E_t$ of the leading jet in Herwig+ATLFAST and Herwig+QFL.](image)

First we sum up the transverse momentum of charged particles in the cones. Figure 7.12 shows the $\text{max}$ and $\text{min}$ cone $p_t$ and their difference as a function of the $E_t$ of the leading jet. Both Herwig+ATLFAST and Herwig+QFL are shown. The $\text{min}$ cone increases very slowly as a function of the jet $E_t$. The average values of the transverse momentum inside...
the \( max \) and \( min \) cones are shown in table 7.2 for the four jet samples. Stepping from jets of 50 GeV (Herwig+QFL) to jets of 1000 GeV (Herwig+ATLFAST) the transverse momentum in the \( min \) cone increases from 450 MeV to 1 GeV. So, it is up to 250 MeV bigger than in a random cone in minimum bias events. Looking at the transverse momentum distribution inside the \( max \) and \( min \) cone, one could expect a scaling behaviour, i.e. that the ATLAS and CDF distributions fall on top of each other if the \( E_T \) of the leading jet and \( p_t \) are scaled to the respective center of mass energy. However, we find the scaled distribution at 14 TeV to be lower than that at 1800 GeV. The way we proceeded is not completely correct, since the partons which take part to the hard scattering only carry a fraction of the energy of the original hadron. The higher is the center of mass energy, the higher is the probability that the partons responsible for the hard scattering carry a lower fraction, \( x_{Bj} \), of the initial energy. This reflects the growth of the gluon density in the proton towards small \( x_{Bj} \) \cite{86}.

As we already emphasized, the comparisons at the calorimeter level are complicated due to the details of calorimeter simulation. In figure 7.13 the transverse energy in the \( max \) and \( min \) cone and their difference as a function of the \( E_t \) of the leading jet are shown. There is no continuation between CDF and ATLAS simulation as we have observed for the track momenta.

<table>
<thead>
<tr>
<th>( E_t )</th>
<th>Herwig+ATLFAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>( max ) cone</td>
</tr>
<tr>
<td>( Jet_{180} )</td>
<td>12.17</td>
</tr>
<tr>
<td>( Jet_{500} )</td>
<td>19.25</td>
</tr>
<tr>
<td>( Jet_{1000} )</td>
<td>23.92</td>
</tr>
<tr>
<td>( Jet_{1380} )</td>
<td>26.14</td>
</tr>
</tbody>
</table>

Table 7.3: Transverse energy inside the \( max \) and \( min \) cone in Herwig+ATLFAST. Results are in GeV. Statistical errors are below 2%. 

### Table 7.2: Transverse momentum inside the \( max \) and \( min \) cone in Herwig+ATLFAST. Results are in GeV. Statistical errors are below 3%.

<table>
<thead>
<tr>
<th>( p_t ) Trigger</th>
<th>( max ) cone</th>
<th>( min ) cone</th>
<th>( max ) – ( min ) cone</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Jet_{180} )</td>
<td>6.62</td>
<td>.68</td>
<td>5.94</td>
</tr>
<tr>
<td>( Jet_{500} )</td>
<td>10.81</td>
<td>.92</td>
<td>9.89</td>
</tr>
<tr>
<td>( Jet_{1000} )</td>
<td>13.71</td>
<td>1.01</td>
<td>12.70</td>
</tr>
<tr>
<td>( Jet_{1380} )</td>
<td>14.48</td>
<td>1.04</td>
<td>13.04</td>
</tr>
</tbody>
</table>
7.3. CONCLUSIONS

The average values of the transverse energy in the max and min cones in ATLAS are shown in table 7.3. The min cone increases from 2.18 to 3.46 GeV. The transverse energy is up to 270 MeV bigger than in a random cone in minimum bias events.

Figure 7.13: Transverse energy inside the max and min cone (on the left) and their difference (on the right) as a function of the Et of the leading jet in Herwig+ATLFAST and Herwig+QFL.

7.3 Conclusions

We compared fully and fast ATLAS simulated minimum bias events at the track and calorimeter level and we found a good agreement between the two simulations. We therefore further relied on the fast detector simulation and we found that the momentum distributions of charged particles in minimum bias events at CDF center of mass energy (1800 GeV) and ATLAS center of mass energy (14 TeV) are very similar. The energy distribution is considerably affected by calorimeter simulation effects and therefore difficult to compare between the two experiments. In jet events we looked in regions possibly far away from the most energetic jets in the event (max and min cone at ±90° in azimuthal angle with respect to the direction of the leading jet). We found that at ATLAS the transverse momentum in the min cone, which is more sensitive to the underlying event energy, increases by up to 600 MeV with respect to CDF.
Chapter 8

Summary and conclusions

We examined both jet and minimum bias events using the CDF detector, in order to study the structure of the underlying event. We performed investigations at two center of mass energies: 1800 GeV and 630 GeV with the goal of an extrapolation to LHC energies. Data from both calorimeters and tracking chambers were analyzed and compared to simulations from two Monte Carlo programs: Herwig and Pythia, the results of which were passed through the CDF detector fast simulation QFL. An extrapolation of the CDF analysis to LHC energies has been done with the help of the Herwig simulation program.

Comparison of ambient energy with CDF data and Monte Carlo simulation

In order to study the underlying event in jet events, we considered two cones in the calorimeter far away from the leading jet in CDF data, Herwig+QFL and Pythia+QFL. The cone with more energy between the two was called $\text{max}$ cone, the one with less energy $\text{min}$ cone. The $\text{max}$ cone should be sensitive to both NLO perturbative corrections to $2 \rightarrow 2$ hard scattering and underlying event, while the $\text{min}$ cone is sensitive only to the underlying event contribution. In minimum bias events, we picked a random cone in the central rapidity region, the energy of which should be similar to the underlying event energy in jet events.

The study of the transverse energy in jet events showed that data, Herwig+QFL and Pythia+QFL exhibit a similar behaviour for the $\text{max}$ and the $\text{min}$ cone; the $\text{min}$ cone stays flat, while the $\text{max}$ cone increases as a function of the $E_t$ of the leading jet. However, none of the examined Monte Carlo programs with their default parameters was able to reproduce the data at the Tevatron in every respect.
Herwig fails in the minimum bias model: the generated tracks are too soft and semi-hard or hard interactions should be added to the minimum bias events in order to reproduce the data. On the other hand, the study of the charged particles at 630 and 1800 GeV, for jet events, leads to relatively good agreement in general between the CDF data and the Herwig+QFL simulated data.

Pythia has problems in both jet and minimum bias events, since the number of generated particles is too high. Pythia, however, reproduces better than Herwig the shape of the $p_t$ distribution of charged particles in minimum bias data, indicating that an adequate tuning of the parameters, which control the multiple interactions, could reproduce the jet and minimum bias event data. Due to the large number of parameters \(^1\) of this model, this is a non-trivial job.

**Problems related to CDF calorimeter calibration**

The level of agreement observed when comparing similar quantities at the calorimeter level, is in contrast with that at the track level. The discrepancies observed between data and simulation are related to detector effects, as the study of the ratio of energy found in the calorimeter over the momentum measured by the tracking chambers for isolated charged particles showed. The reason for this could be due to the method of calibration of the CDF calorimeters, which may underestimate low energy depositions by hadrons in the electromagnetic portion of the calorimeter.

An inaccurate calibration of the CDF calorimeter decreases the jet’s energy resolution. Since many physical processes of interest have quarks and gluons in the final state, and therefore jets, a high energy resolution of the jet is required in order, for example to reconstruct the top quark mass and to set a limit on the Higgs mass. Indeed, the discovery of a light Higgs at the run2 at Tevatron is also very sensitive to the jet’s energy resolution. For the new run, which started in March 2001, the problems related to the calorimeter calibration have been acknowledged and a better method to calibrate the CDF calorimeter is under study.

**Splash out**

By examining the hadron, parton, and detector level with Herwig+QFL, we observed that the hadron level in the $max$ and $min$ cone is higher than the parton level. This is mostly due to strongly decaying particles and the

\(^1\)For example, Pythia can be run with or without the impact parameter option, the mass distribution inside the hadrons can be interpreted as double or single gaussian, the cut on the minimum $p_t$ of the beam remnants in order to generate double parton scattering, can be modified and so on.
subsequent decays of the particles inside the jets, which end up outside the jet of fixed cone size (splash out). This effect has not actually been taken in account by CDF and D0 in run1, which assume the jet energy at the parton level to be equal to that at the hadron level. This effect can be especially relevant for low $E_t$ jet production.

**Underlying event energy in jet events and in minimum bias events at CDF**

We observed that for the same available energy the underlying event in a hard scattering is considerable more active than in a soft collision. Generally, the energy in a cone in minimum bias events is lower than the energy in the min cone in jet events. If we consider only charged particles, whose momentum measurement is not affected by the CDF calorimeter calibration, the minimum bias transverse momentum inside a random cone in the central rapidity region of the CDF detector is about 20% lower than in the min cone in jet events. So minimum bias events do not provide a precise estimate of the underlying event energy in jet events. Therefore, subtracting the minimum bias energy from the energy of a jet as the contribution due to the underlying event, causes a 20% uncertainty on the jet’s energy.

**Underlying event energy in jet events and in minimum bias events at LHC**

The analysis performed at the Tevatron was extrapolated to LHC energies. A comparison of the fast and full ATLAS detector simulation was accomplished. This proved the reliability of the ATLAS fast detector simulation for an investigation of the underlying event in jet events and minimum bias events at LHC energies for the ATLAS detector. The comparison of fully and fast ATLAS simulated minimum bias events at the track and calorimeter level showed a good agreement between the two simulations. We further employed the fast detector simulation and found that the momentum distribution of charged particles in minimum bias events at CDF center of mass energy (1800 GeV) and ATLAS center of mass energy (14 TeV) does not change significantly, according to Herwig’s implementation of this process. In jet events we found that in the ATLAS simulation the transverse momentum increases in the min cone by up to 600 MeV with respect to the CDF simulation.

**Conclusion towards LHC**

The reconstruction of jets at LHC will be a difficult task. LHC has to deal not only with underlying event energy, i.e. energy coming from beam...
remnants in a hard scattering, but also with energy coming from minimum bias events which are superimposed to the hard event. A precise definition of the underlying event will be indispensable.

From the Herwig simulation, we found about 70% more energy in the \( \text{min} \) cone in jet events than in a random cone in minimum bias events. In this case, the decision whether to assume the underlying event energy as the energy found in minimum bias events, or to derive it from jet events, would be significant. According to Herwig’s predictions, we expect, in minimum bias events, an energy contribution of 780 MeV in a cone of radius 0.7. Since at LHC about 23 minimum bias events on average are superimposed to a hard event and since we found about 2.8 GeV in the \( \text{min} \) cone in jet events, we could expect to find about 20 GeV in a jet of cone size 0.7, solely due to ambient energy.

The ability to detect additional low \( p_t \) jets, due to minimum bias events, is an important tool for the reduction of the background in many physics channels. For example, due to the additional jets generated in minimum bias events, in the search of a heavy Higgs signal at the LHC, the jet veto threshold has to be raised from 15 (low luminosity) to 25 (high luminosity) GeV to avoid a significant loss of efficiency for the signal [69].

In conclusion, an improved understanding of the underlying event at the Tevatron is desired for a number of reasons:

- The underlying event subtraction is the largest uncertainty for the jet cross section at low transverse energy (below 60 GeV). In order to have a good comparison of the data with theory, a better understanding of the proper level of this subtraction must be obtained. This uncertainty is especially important for the measurement of the jet cross section at 630 GeV, since most of the data points are below 60 GeV, and similar considerations also apply at 1800 GeV.

- The investigation of underlying events concerns the interface between perturbative and non-perturbative QCD, a field where a great deal of work still needs to be done.

- Every prediction of the environment for physics measurements at the LHC is vague without the proper understanding of what happens at the Tevatron.

Monte Carlo programs are an absolutely essential tool to understand the physics at LHC. So the authors of these programs have been informed. They acknowledged the results of this analysis [87] which they will use to substantially improve the implementation of soft processes in their programs.
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