Transverse Energy Flow in the Underlying Event in the Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Calorimeter

by

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A Dissertation Submitted to the Faculty of the Department of Physics
In Partial Fulfillment of the Requirements For the Degree of Doctor of Philosophy
In the Graduate College
The University of Arizona

2012
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Signed: Chiara Paleari
ACKNOWLEDGEMENTS

I am especially thankful to Peter Loch and John Rutherfoord: this work would have not been possible without them. I thank you Peter for his passion, his immense knowledge in calorimetry and jets physics and for being a great teacher. I will never forget also the nice barbecues at his house and for welcoming Emanuele and I in his family! I’m thankful to John for his support and for helping me every time that I needed.

Many people in the ATLAS collaboration have helped me and this thesis would not have been possible without them. I would like to thank you Caterina for the help she gave me when I was at CERN and when she came to Tucson, Vincent, Frederic, and Marco for his help in the work in the ECAL team.

A special thanks goes to my officemates, and to all the friends in the UofA physics department, in particular Regina, for being a great friend and for babysitting the kids every time that I needed it, and Swati, for the beautiful friendship that was born studying together for the comprehensive exam. I will never forget all the non-physics Tucson friends: Julia, Doug and Marinella, Noe, Elizabeth, Monica and the Grecchi family, Marialina and Jeff, Steve and Quyen and their beautiful family, that has been our Tucson family in the past three years.

My adventures in particle physics started back in Milano, I would like to thank you Donatella for his friendship and support in all these years and Caterina, who also came to Tucson!

This work would not have been possible without all the help that my parents gave me during these years, coming to Tucson every time that I needed.

My family has been the greatest gift in these five years: thank you Manu for your love and your support, and thank you Maddi and Cate, you are the greatest gift God has given me.
DEDICATION

To Emanuele, Maddalena and Caterina
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Abstract

The European Organization for Nuclear Research (CERN) operates the world’s largest and highest energy proton-proton collider at a center of mass energy of $\sqrt{s} = 7$ TeV, the Large Hadron Collider (LHC). ATLAS is one of the four detectors operating at the LHC. The Underlying Event (UE), which is an unavoidable background at any hadron collider, includes particles from various sources generated in each proton collision. The particle flow in the underlying event is characterized by low transverse energies reflecting the long range character of the individual processes generating them. This regime cannot be described by the usual perturbative models provided by Quantum Chromodynamics (QCD), the theory of the strong force. To model this flow, phenomenological models have to be applied, as provided by Monte Carlo simulations. In this work I define new discriminating variables to constrain these UE models in the new kinematical regime available at LHC. Using calorimeter data from the ATLAS experiment, several Monte Carlo models are tested by comparing the data to these predictions for three different final states (minimum bias, di-jet and direct photon production). The experimental data are fully unfolded to the hadron level within the full acceptance of the ATLAS detector, thus for the first time including the forward direction in hadron collisions. The final results are presented in the context of previous measurements on the characteristics of the strong force in the proton, in deep inelastic lepton-proton scattering.
Chapter 1

Introduction

The European Organization for Nuclear Research (CERN) operates the world’s largest and highest-energy particle accelerator, the Large Hadron Collider (LHC), which is operating since November 2009. The LHC was built with the intention of providing new experimental knowledge to the Standard Model (SM) theory and of revealing the physics beyond the SM. ATLAS is one of the four detectors operating at LHC: it’s a general purpose detector designed to study a wide range of physics phenomenon.

The first months of proton-proton collisions at a center of mass energy of 7 TeV delivered by the LHC and recorded by the ATLAS experiment have provided data to probe quantum chromodynamics (QCD) at scales never reached before. In hadron-hadron collisions, besides the interaction between the two partons responsible for the hard scattering, there may be interactions involving low momentum transfer (underlying event). Perturbative QCD can not be applied and the underlying event has to be described by phenomenological models. Its contributions need to be well understood in order to provide precision measurements at ATLAS: QCD provides one of the main backgrounds to many new physics measurements.

In particular, underlying event contributions like additional low transverse momentum particle jets can reach into the signal region for new physics searches and thus limit the sensitivities for final states with rather low energetic signatures.

This thesis presents the definition of new discriminating variables, based on the signals reconstructed by the ATLAS calorimeter in data recorded in 2010. These variables are used to test the ability of current Monte Carlo (MC) models to describe the underlying event in minimum bias, di-jet and prompt photon events. Previous studies of the underlying event done by the ATLAS collaboration were based on charged particles signals reconstructed in the inner detector in minimum bias events only.
This work therefore extends the previous studies considering also the effects that the presence of a hard scattering in an event has on the energy flow in the underlying event, and it uses calorimeter topological clusters as input, the same signals used in ATLAS to reconstruct jets and missing transverse energy.

After an introduction of the LHC and the ATLAS detector in Chapter 1, in Chapter 2 the underlying event is defined with its main contributions. Chapter 3 is devoted to the definition of new variables that use the transverse energy deposited in the ATLAS calorimeter to study the underlying event. To increase the sensitivity to the underlying event several stripes along the pseudo-rapidity direction were defined and the azimuthal plane was divided in four regions: of particular interest are the two perpendicular to the direction of the hard scattering. The longitudinal correlations in the transverse energy flow were also used to validate the Monte Carlo generators. In Chapter 4 the results were unfolded to the hadron level to compare the measured quantities with the Monte Carlo predictions and to be able to compare the results with the ones obtained from other experiments.

Finally, in Chapter 5 measurements of the transverse energy flow in the ATLAS calorimeter are used to extend at a new energy scale studies performed by deep inelastic scattering experiments. Transverse energy measurements at HERA allowed a test of the different approaches used in Monte Carlo models, in particular for the evolution of the parton density functions. They also provided the first experimental evidence for the rise in the transverse energy density with $Q^2$. Similar studies are now possible with the ATLAS detector at a new energy scale.
Chapter 2

The Underlying Event

In hadron-hadron collisions, besides the interaction between the two partons responsible for the hard scattering, there may be soft interactions (named underlying event), involving low momentum transfer. Perturbative QCD cannot be applied and the underlying event has to be described by models. Contributions may come from additional gluon radiation, additional semi-hard interactions as well as interactions between the beam remnants.

The underlying event is an unavoidable background in hadron-hadron collisions and its contributions need to be well understood in order to provide precision measurements at ATLAS.

2.1 Phenomenology of proton-proton collisions

The cross section of each event of interest arising from the scattering of two protons can be expressed as:

\[
\frac{d\sigma}{dp_T^2} = \int_0^1 dx_1 \int_0^1 dx_2 f_1(x_1, p_T^2) f_2(x_2, p_T^2) \sigma(\text{process});
\]  

(2.1.1)

where \( f_1 \) and \( f_2 \) are the parton density functions for the gluons or quarks participating to the scattering: they express the probability that two partons with fraction of the momentum \( x_1 \) and \( x_2 \) of that of the initial proton participate to the scattering.

The cross section that appears is the one of the elementary scattering and can be theoretically computed.

The inelastic proton-proton cross-section at \( \sqrt{s} = 7 \) TeV has been measured by the ATLAS collaboration to be \( 60.3 \pm 2.1 \) mb [23]. Therefore the event rate \( R \), defined as the number of events produced per second by the \( pp \) interactions, is expected to be:

\[
R = \sigma \times L = 60 \text{mb} \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \sim 10^9 / \text{s},
\]  

(2.1.2)
when running at the nominal luminosity. These events belong to two classes:

- **Minimum bias events**
  Most events are due to large distance collisions between the two incoming protons. In this case the momentum transfer of the interaction is small (soft collisions) and therefore particle scattering at large angles is suppressed. The particles produced in the final state of such interactions have large longitudinal momentum but small transverse momentum ($p_T$) relative to the beam line ($p_T \leq 500$ MeV). Most of the collision energy escapes down the beam pipe. The final states arising from these soft interactions are called minimum bias events [24]. They represent the majority of the $pp$ collisions and, although they are not interesting for discovery analysis, they can be used for performance studies.

- **Hard scattering events**
  The proton beams can be seen as beams of partons (quark and gluons) with a wide band of energy. Head-on collisions may occur between two partons: these are interactions at small distances and therefore characterized by large momentum transfers. In this case particles in the final state can be produced at large angles with respect to the beam line. These are the interesting physics events, but they are rare compared to the soft interactions.

In the analysis presented in this thesis, in particular, together with minimum bias events, also di-jet and prompt photon events were studied.

**Di-jet events**
In some fraction of proton-proton collisions, two highly energetic quarks (or gluons) are among the outgoing particles. Each quark or gluon quickly evolves into a group of particles called a jet. An event with two jets is called a di-jet event.

**Prompt photon events at the LHC**
Direct photon events are events in which a photon emerges directly from a collision. For hadron collisions at leading order in perturbation theory there are two
subprocesses that contribute to the direct photon production: the annihilation process \( q\bar{q} \rightarrow \gamma g \) and the Compton process \( qq \rightarrow \gamma q \) (see Feynman diagrams in Figure 2.1). At NLO also diagrams with the emission of photons and gluons by the quark have to be considered.

In proton-proton collisions the Compton scattering is the dominant process over essentially all the momentum scale.

### 2.2 The underlying-event

All hadron collisions are accompanied by additional processes which collectively add to the hard scattering and which are named the underlying event (UE).

The UE may involve contributions from both hard and soft physics, where “soft” refers to interactions with low \( p_T \) transfer between the scattering particles.

The main contributions to the underlying event are: initial and final state radiation (particles that originate from the two partons participating to the scattering), particles that come from the breakup of the protons (“beam-beam remnants”), and multiple parton interactions (that are considered “semi-hard”).

It is impossible to uniquely separate the UE from the hard scattering process on an event-by-event basis. Also, the UE may involve contributions from both hard and soft physics and soft interactions cannot reliably be calculated with perturbative QCD
methods. They are generally described in the context of different phenomenological
models implemented in Monte Carlo (MC) event generators. These models contain
many parameters whose value is not \textit{a priori} known. Therefore to obtain insights on
the nature of soft QCD processes and to optimize the description of UE contributions
the model parameters must be fitted to experimental data.

2.3 The “transverse region” in the azimuthal plane

Since the underlying event involves contributions from both hard and soft physics,
the processes that contribute to it cannot reliably be calculated with perturbative
QCD models. Moreover, it is impossible to uniquely separate the UE from the hard
scattering. But it is possible to define and measure observables which are sensitive to
the underlying event and that can be used to test and tune the Monte Carlo models.
In particular, it is possible to define a region of interest in the azimuthal plane that
is the most sensitive to the soft QCD: the \textit{transverse} region.

The direction of the object (jet, track or cluster depending on the study done) with
the largest $p_T$ in the event - referred as the “leading” object - is used to define regions
in the $\eta$ - $\phi$ plane which have different sensitivities to the UE. The axis given by the
leading object is well defined in all events and it is highly correlated with the axis of
the hard scattering in high $p_T$ events.

The azimuthal angular difference from the leading object $\Delta \phi = |\phi - \phi_{\text{leading jet}}|$ is used
to define the following three azimuthal regions (see Figure 2.2) [25]:

- $|\Delta \phi| < \pi/3$, the “toward” region,
- $\pi/3 < |\Delta \phi| < 2\pi/3$, the “transverse” region, and
- $|\Delta \phi| > 2\pi/3$, the “away” region.

The transverse regions are the most sensitive to the underlying event, since they
are generally perpendicular to the axis of the hardest scattering and hence have the
Figure 2.2: Definition of regions in the azimuthal angle with respect to the leading object (leading track in this picture).
lowest level of activity from this source. However, the hard scattering can of course also emit particles perpendicular to the event axis: the regional division is not an exact filter.

In ATLAS several studies have been made of variables sensitive to the underlying event in the “transverse” region, using both charged particles (inner detector tracks) and calorimeter signals.

Previously the underlying event has been measured in di-jet and Drell-Yan events at CDF in Run I [25] and Run II [26].
Chapter 3

The ATLAS detector at the LHC

ATLAS (A Toroidal LHC ApparatuS) is one of the four main experiments at the Large Hadron Collider (LHC) at CERN. In this chapter a brief introduction to the LHC collider and its physics environment is given, together with a description of the ATLAS detector. The methods for the reconstruction and identification of physics objects of interest for this work are reported, and some relevant performance results of the detector with \(pp\) collisions at \(\sqrt{s} = 7\) TeV are reviewed.

3.1 The LHC collider

The LHC is designed to provide proton-proton \(pp\) as well as heavy ions collisions. When running in \(pp\) mode the design luminosity is of \(10^{34} cm^{-2} s^{-1}\) and the center-of-mass energy of 14 TeV, providing almost an order of magnitude increase in the maximum attainable collision energy previously reached by the Tevatron.

The production cross sections of important processes at proton-proton colliders are given in Figure 3.1. The cross section for Higgs boson production at the LHC is of particular interest, since in the case of large Higgs mass it can increase of many orders of magnitude with respect to the Tevatron. In general the increase in collision energy from the Tevatron to the LHC results in a huge increase in the production cross section for any new particle in the mass range \(500\) GeV \(\leq m \leq 5\) TeV. This provides sensitivity to a large region of parameters space (including many theories beyond the Standard Model) that was inaccessible to the Tevatron.

The LHC is located at CERN in the existing 26.7 km long tunnel built for the Large Electron-Positron (LEP) collider. The proton beams are kept in orbit by superconducting magnets, operating at a temperature of 1.9 K and providing magnetic fields
Figure 3.1: Cross section vs. collision energy ($\sqrt{s}$) for physics processes at proton-(anti)proton colliders [1].
above 8 T. They are accelerated by a 400 MHz superconducting cavity system.

The LEP tunnel has eight possible interaction points of which four are active at LHC. Two general purpose experiments, ATLAS and CMS, are positioned at Point 1 and Point 5, which focus on the discovery of new physics. LHCb is designed to study B-physics, while ALICE is a dedicated experiment for the study of quark-gluon plasma, which is expected to be produced in Pb-Pb collisions. A schematic layout of the LHC is shown in Figure 3.2.

The LHC started operations on 10 September 2008, but immediately after, during the commissioning phase, a major accident imposed a one year stop. During fall 2009 operations started again with the first 900 GeV collisions, recorded on November 23 2009, and followed shortly after by collisions at 2.36 TeV, the highest energy ever reached before. For machine safety reasons it was decided to limit the maximum center-of-mass energy to 7 TeV, and the first collisions at this world record energy
took place on March 30, 2010. In this thesis data recorded in 2010 at 7 TeV are analyzed.

3.1.1 Running conditions at the LHC

The physics program at the Large Hadron Collider includes searches for rare physics processes, such as the Higgs boson and supersymmetric particles: it is therefore important to maximise the delivered luminosity in order to be able to observe such events.

An increase in the luminosity can be achieved by squeezing the beams and reducing their transverse size, or by increasing the number of colliding protons per bunch or the number of bunches. The first two effects lead to an increase of proton-proton interactions within the same bunch (in-time pile-up), while the latter two lead to multiple interactions from different bunches during the time taken for the detector to process a single event (out-of-time pile-up). Out-of-time pile-up can also be produced by the circulation of multiple subsequent bunches (bunch train). The very first data delivered by the LHC had a negligible number of multiple interactions until May 2010, when the accelerator optics was optimised to decrease the size of the beams at the interaction point: this lead to an increase in the number of events with more than a single proton-proton interaction to about 10%. The number of protons per bunch was increased throughout the course of the summer, leading to a rise in the fraction of events with in-time pile-up that continued up to November 2010, when the average number of interactions was more than three [5]. This is shown in Figure 3.3.

The LHC designed luminosity of $10^{34} \, cm^{-2} \, s^{-1}$ will lead to 22 simultaneous proton-proton interactions and to more than 1000 particles being produced within one event in the central detector region.
3.2 Physics at the LHC

The LHC physics program is very ambitious and covers a variety of topics in particle and nuclear physics. The main objectives are:

- The discovery of particles giving rise to the spontaneous symmetry breaking in the Standard Model (SM). The search for a standard Higgs boson extends for masses from the LEP exclusion limit of 114.4 GeV [3] up to about 1 TeV. If the Higgs boson is found its mass and couplings will be determined.

- Test of the validity of the SM, with precision measurements of the W and top-quark masses and couplings, B physics and CP violation.

- Search for signature beyond the Standard Model, in particular of particles predicted by various Supersymmetry models.

- Study of the properties of hadronic matter under extreme conditions, and possibly the transition to a state in which quarks and gluons are deconfined, called
quark-gluon plasma. This will allow an insight of the behavior of matter at the
dawn of time shortly after the Big Bang.

The very high luminosity of the LHC is needed to pursue these objectives, since
the cross sections of these processes of interest are very low. But a high luminosity
regime introduces some difficulties as well. One of them is the presence of pileup,
that is the superposition of high cross section inelastic events over the candidates for
new physics. At design luminosity 23 pileup events per bunch crossing are expected.
Another difficulty due to the nature of proton-proton collisions is that QCD processes
will dominate over the processes we are more interested in. This imposes strong
demands on the integrated luminosity needed and on the capability of the detector
to identify experimental signatures characteristic of the processes under study. The
physics goals therefore translate into requirements the LHC detectors have to face:

- **Fast response, high granularity and resistance to radiations.**
  The rate of events requires fast and sophisticated electronics, able to discrimi-
ninate events and minimize the effect of pileup. A high granularity of the detector
  is necessary to handle the high particle fluxes as well.

- **Trigger.** The output bandwidth of the detector is limited, and therefore the
  40 MHz interaction rate must be reduced to 200 Hz to be written to tape.
  The capability of triggering efficiently on interesting events with a very high
  background rejection is therefore crucial.

- **Full coverage.** The study of missing transverse energy ($E_{\text{miss}}$) is fundamental
  for the accomplishment of the physics goals. That requires a coverage over
  $2\pi$ in the azimuthal angle and pseudo-rapidity $|\eta| < 5$ (for the definition of
  pseudo-rapidity see section 2.3.1).

- **Particle identification.** The capability to precisely reconstruct and identify
electrons, muons, photons, tau leptons and jets is an essential requirement for
  the LHC experiments.
3.3 The ATLAS detector

The ATLAS detector surrounds the interaction region at Point 1 of the LHC collider, it was completed in 2008 after five years of assembly works. ATLAS is a multipurpose detector: even though its performances are aimed at the Higgs search it can cope with the study of a variety of phenomena.

The general layout and nominal performances are briefly reported, together with a brief description of the main subsystems. A complete description of the detector can be found in [4].

3.3.1 The coordinate system

To aid with the description of the detector, a brief summary of the coordinate system and nomenclature is given.

- The nominal interaction point (IP) is defined as the origin of the coordinate system.
- The positive $x$-axis is defined as pointing from the IP to the center of the LHC ring.
- The positive $y$-axis is defined as pointing upward from the IP.
- The $z$-axis is parallel to the beam and the $x$ and $y$ axes are perpendicular to the beam forming a right-handed Cartesian coordinate system. The $x$-$y$ plane is called the transverse plane.
- The azimuthal angle $\phi$ is measured around the $z$ axis and the polar angle $\theta$ is measured from the $z$ axis.
- The pseudo-rapidity, defined as $\eta = -\ln \tan(\theta/2)$, is often preferable as a polar coordinate as it distributes the transverse energy roughly evenly.
In case of massive objects the rapidity is often used

\[ y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}. \]  

(3.3.1)

The distance \( \Delta R \) in \( \eta - \phi \) space is defined as \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \).

Particles are often described by their transverse momentum \( p_T \) and transverse energy \( E_T \) as these variables are a better indicator of interesting physics than the standard energy and momentum and because they are conserved in the collision.

### 3.3.2 General layout

The general layout of ATLAS is shown in Figure 3.4. The detector has a cylindrical symmetry. Its dimensions are 25 m height and 44 m in length, while the overall weight is approximately 7000 metric tons.

Each of the ATLAS sub-detectors plays an important role in the reconstruction of particles. The sub-detectors are arranged in layers leading out from the interaction...
Detector component | Required resolution | η coverage
---|---|---
Tracking | $\sigma_{p_T}/p_T = 0.05\%p_T \oplus 1\%$ | $\pm 2.5$
EM calorimetry | $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$ | $\pm 3.2$
Hadronic calorimetry | $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ | $\pm 3.2$
Hadronic forward calorimeter | $\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$ | $3.1 \leq |\eta| \leq 4.9$
Muon spectrometer | $\sigma_{p_{T}}/p_T = 10\%$ at $p_T = 1$ TeV | $\pm 2.7$

Table 3.1: Nominal detector performance goals and coverage for the ATLAS detector [4].

Closest to the beam pipe is the tracking chamber, used to reconstruct the trajectory of charged particles. It is enclosed by a solenoid magnet, which provides a magnetic field in the chamber that bends the charged particles, thus allowing a measurement of their momentum and charge. The electromagnetic calorimeter encloses the tracking system and it measures the energy of electrons and photons. Outside the electromagnetic calorimeter is the hadronic calorimeter, which measures the energy of hadronic particles. Finally the calorimeters are enclosed by the muon spectrometer designed to reconstruct and identify muons. The spectrometer houses large toroidal magnets to deflect the path of muons. Combined with the tracking chambers it provides precise measurements of momentum and charge. They will be described in the next section together with the trigger system.

The efficiency of signal selection in analysis is highly dependent on the spatial coverage and sensitivity of the detector. The detector acceptance is a commonly used term to quantify this coverage and it’s defined as the efficiency to reconstruct a given event-type due to the coverage of the detector. To maximize the acceptance each sub-detector comprises a central cylindrical barrel region, closed off at each end by end-caps. The acceptance of the calorimeters is particularly important for an accurate measurement of $E^\text{miss}_T$, so their coverage is extended as close to the beam pipe in the forward and backward directions as possible.

The general requirements for the LHC experiments translate into nominal detector performance goals for the ATLAS detector as reported in Table 3.1.
3.3.3 Inner detector

The inner detector [6] is devoted to the measurement of charged particles tracks. This task is essential for the reconstruction of charged particles and momentum measurement, reconstruction of secondary vertices, and particles identification. Since the environment at nominal conditions is expected to be very busy the granularity of the detector has to be very fine.

The tracker is the system nearest to the beam pipe, and is immersed in a 2 T solenoidal magnetic field, provided by a solenoid placed around the tracker. The overall dimensions of the tracking system are 2.1 m in diameter and 6.2 m in length. The system consists of three sub-detectors: the Pixel Detector, the Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT), as shown in Figure 3.5. The innermost sub-detector is the Pixel detector, which is made up by three cylindrical layers of silicon pixels in the barrel region and three disks in each end-cap. The granularity is
very fine, with a pixel size of 50 x 400 $\mu m^2$, allowing for an intrinsic accuracy of 10 $\mu m$ ($R - \phi$) and 15 $\mu m$ ($\eta$). This detector allows high precision measurements, with three hits per track expected, the inner layer one as close as $\sim 2$ cm to the beam pipe. The pixel technology provides very high quality measurements, but its usage is limited to the most internal region, where a better track resolution is needed.

Behind the pixel detector the SCT completes the high precision tracking, with eight hits per track expected. The barrel comprises 4 cylindrical layers on modules of silicon micro-strips, each made up by two sensors at a 40 mrad stereo angle in order to measure both coordinates. The pitch of the strip is about 40 $\mu m$. The end-cap is made up by 9 disks. The intrinsic accuracies of the SCT are 17 $\mu m$ ($R - \phi$) and 580 $\mu m$ ($\eta$) and the total number of channels is approximately 6.3 million.

The TRT is made up by 4 mm straw tubes, arranged parallel to the beams in the barrel region and radially in the end-cap. Only $R - \phi$ is provided, with an intrinsic accuracy of 130 $\mu m$ per straw. A large number of hits per track is expected in this detector, about 36, and the total number of channels is about 351,000.

The TRT contributes both to tracking and particle identification. Its tubes are interleaved with layers of polypropylene fibers and foils: a charged particle that passes through the boundary region between materials with a different refraction index emits X-ray radiation whose intensity is proportional to the relativistic $\gamma$ factor. The TRT works with two threshold levels, the ratio of the high threshold hits versus all the hits can be used to discriminate electrons and pions.

### 3.3.4 Calorimetry

The studies presented in this thesis are done using the ATLAS calorimeter system. It consists of a number of different sampling calorimeters with full $\phi$-symmetry and $\phi$-coverage around the beam axis. The sampling calorimeter consists of active and passive medium and the signal is generated in the active medium only.

The ATLAS calorimeter system is very important for the measurements of many
Figure 3.6: ATLAS calorimeter layout [4]

physics channels. The energy and direction of electrons and photons, as well as jets are measured here. The calorimeter system consists of different electromagnetic (EM) and hadronic calorimeters divided into barrel and two end-cap regions to ensure good containment of EM and hadronic showers in $\eta$ and $\phi$. A general view of ATLAS calorimeter is presented in Figure 3.6.

The inner part of the calorimeter system consists of a high granularity liquid-argon (LAr) sampling calorimeters with excellent energy and position measurement resolution, covering the pseudo-rapidity range $|\eta| < 3.2$. These calorimeters are the closest to the beam-line and are housed in three cryostats, one barrel and two end-caps. The barrel cryostat contains the EM barrel calorimeter. Each end-cap cryostat contains EM and end-cap calorimeter (EMEC), a hadronic end-cap calorimeter (HEC) and forward calorimeter (FCal). End-cap calorimeters are used to cover the outer limits of $|\eta| < 1.5$. The LAr FCal calorimeters provide EM and hadronic measurements and extend the pseudo-rapidity range to $|\eta| = 4.9$. 
LAr calorimeters are surrounded by the hadronic scintillator-tile (so-called Tile) calorimeter in the range $|\eta| < 1.7$. The tile calorimeter is divided into a large central barrel part and two smaller extended barrel cylinders in each side of barrel. Calorimeters must provide good containment for EM and hadronic showers, hence the calorimeter depth is an important design consideration. The total thickness of the EM calorimeter is $> 22X_0$ in the barrel and $> 24X_0$ in the end-cap regions.

In the next section the various ATLAS calorimeter systems are described. The detail technical design of the LAr calorimeters is given in [7] and for Tile calorimeters in [8].

**LAr EM Calorimeter**

The EM calorimeter is divided into a barrel calorimeter ($|\eta| < 1.475$) and two end-caps calorimeters ($1.375 < |\eta| < 3.2$). These calorimeters are lead-liquid argon detectors with accordion shape absorbers and electrodes: readout electrodes and lead absorbers are laid out radially and folded so that particles cannot cross the calorimeter without being detected. The electrodes work as transmission lines as well, so that no dead region must be introduced. This geometry has been chosen to have several active layers in depth and provides a full coverage in $\phi$ without any crack. In the barrel region the accordion waves are axial and run in $\phi$, and the folding angles of the waves vary with radius to keep the LAr gap of active medium constant. All these features lead to uniform performance in linearity and resolution as a function of $\phi$.

The first layer of EM calorimeter is segmented very fine along $\eta$. This is the precision measurement region, where an accurate position measurement is obtained. The second layer collects the largest fraction of the energy of the EM shower, and the third layer collects only the tail of EM shower and is less segmented in $\eta$.

The absorber are made of lead plates. The read-out electrodes are located in the gaps between the absorbers and consist of three conductive copper layers separated by insulating polymide sheets.

The barrel EM calorimeter [9] is made from two half barrels centered around the $z$-
axis, one in positive $z$ and one in negative $z$. The length of a half barrel is 3.2 m and the inner and outer diameters are 2.8 m and 4 m. The region $|\eta| < 1.8$ is equipped with a presampler, in order to correct for the energy lost upstream in the tracker, in the calorimeter cryostat and the solenoid magnet.

A half barrel is made of 1024 accordion-shaped absorbers, interleaved with read-out electrodes. The size of the drift gap on each side of the electrode is 2.1 mm, which corresponds to a total drift time of about 450 ns for an operating voltage of 2000 V. The total thickness of a module is at least 33 radiation lengths ($X_0$), increasing from 22 to 30 $X_0$ in the region $0.8 < |\eta| < 1.3$. A module (shown in Figure 3.7) has three layers: front, middle and back. While most of the energy of electrons and photons is collected in the middle, the fine granularity of the front strips is necessary to improve the $\gamma - \pi^0$ discrimination, and the back measures the tails of highly energetic electromagnetic showers, and helps to distinguish electromagnetic and hadronic deposits.

The EM end-cap calorimeter (EMEC) consists of two co-axial wheels. Each wheel is
further divided into eight wedge-shaped modules without any discontinuity along the azimuthal angle. The total active thickness of EMEC is greater than 24 $X_0$ except for $|\eta| < 1.475$.

**Tile calorimeter**

The hadronic tile calorimeter [8] is placed behind the EM calorimeter and is divided into central barrel ($|\eta| < 1$) and two extended barrels ($0.8 < |\eta| < 1.7$). Each barrel consists of 64 modules. The tile calorimeter is a sampling calorimeter using steel as the absorber and plastic scintillator as the active medium. The total detector thickness at the outer edge of the tile-instrumented region is $9.7 \lambda$ at $\eta = 0$.

The signal in the tile calorimeter is generated in scintillator tiles. Tiles are radially oriented and normal to the beam line.

The gap between the barrel and the extended barrel is instrumented with special steel-scintillator sandwich modules which partially allow recover the energy lost in the crack.

**Hadronic end-cap calorimeter**

The HEC [10] is a copper-LAr sampling calorimeter with a parallel plate design, which covers the range $1.5 < |\eta| < 3.2$. It consists of a two cylindrical wheels - a front wheel (HEC1) and a rear wheel (HEC2). Each wheel is constructed of 32 identical wedge-shaped modules, as shown in figure 3.8. The sampling fractions of HEC1 and HEC2 are 4.4% and 2.2%.

The granularity of read-out cells is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ for $|\eta| < 2.5$ and $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$ for $|\eta| > 2.5$. The shower containment in HEC is $11 \lambda$.

**Forward Calorimeter**

The forward calorimeters (FCal) provides coverage in the region $3.1 < |\eta| < 4.9$ and are placed in the same cryostat as the HEC and EMEC calorimeters. The FCal consists of one EM (FCal1) and two hadronic modules (FCal2 and FCal3). As the FCal modules are located very close to the beam line at high $\eta$ regions, they are exposed to high fluxes of particles. This has brought to a special design for
the electrode structure, different from the readout geometries used in other ATLAS calorimeters. The thickness of active medium has to be very small and the density of absorption material very high. The very small liquid-argon gaps are obtained by using an electrode structure of small-diameters rods, which are centered in tubes oriented parallel to the beam direction. The copper was chosen as the absorber material for FCal1, optimal for electromagnetic measurements, and mainly tungsten for the FCal2 and FCal3, aimed at the energy measurements of hadrons.

The read-out cells size for the FCal1 is $\Delta x \times \Delta y = 3.0 \times 2.6 \text{ cm}^2$, FCal2 cells size is $\Delta x \times \Delta y = 3.3 \times 4.2 \text{ cm}^2$ and FCal3 $\Delta x \times \Delta y = 5.4 \times 4.7 \text{ cm}^2$.

The containment of FCal is approximately $10 \lambda$.

### 3.3.5 Muon system

Muons are the only particles that can traverse the calorimeters. They are measured by a large air-core muon spectrometer [12], whose layout is shown in Figure 3.9.

The large volume magnetic field necessary to bend the particle trajectories is provided by the large barrel toroid in the region $|\eta| < 1.4$, by two smaller end-cap
magnets in the $1.6 < |\eta| < 2.7$ region and by a combination of the two in the transition region ($1.4 < |\eta| < 1.6$).

There are two different functions that muon chambers must accomplish: triggering and high precision tracking. The trigger system covers the region up to $|\eta| < 2.4$ and is composed by Resistive Plate Chambers (RPCs) in the barrel and Thin Gap Chamber (TGC) in the end-caps. The triggering system provides bunch-crossing identification, well defined $p_T$ thresholds and a measurement of the muon coordinate in the direction orthogonal to the chambers dedicated to precision tracking.

The tracking is performed by the Monitored Drift Tubes and by Cathod Strips Chambers at large pseudorapidities. High precision mechanical assembly techniques and optical alignment systems provide the essential alignment of the chambers, while the magnetic field measurement relies on sensors distributed throughout the spectrometer volume.
3.3.6 Luminosity detectors

An essential task for the detector is to determine precisely the luminosity recorded by the experiment. This is accomplished by a set of measurements taken by three very forward detectors: the LUCID (LUminosity measurement using Cerenkov Integrating Detector), ALFA (Absolute Luminosity for ATLAS) and ZDC (Zero Degree Calorimeter). The principal monitor is LUCID, that detects inelastic $pp$ scattering events. In addition the Minimum Bias Trigger Scintillators (MBTS), mounted in front of the electromagnetic end-caps, can be used as luminosity detectors in early data analysis, beyond providing a minimum bias trigger signal.

Figure 3.10 shows the luminosity delivered by the LHC and collected by ATLAS during stable beams and for $pp$ collisions in 2010.

3.3.7 Trigger

The ATLAS trigger system must be able to trigger on interesting events while keeping the background rate low in order to cope with high luminosity, corresponding to a
rate of $\sim 10^9$ Hz at nominal conditions, low cross sections of interesting processes and limited output bandwidth of 200 Hz.

The system is implemented in three levels, each step providing a refinement of the decision by more sophisticated algorithms and lower rates. The first level (L1) is hardware-based and makes an initial decision based on timing from an electrostatic beam pick-up (BPTX), coarse detector information from muon trigger chambers and tower calorimeter cells, together with multiplicity information from the MBTS and very forward detectors. The L1 provides regions of interest to the two further levels, that make up the high level trigger (HLT). The signatures the L1 looks for are high $p_T$ electrons and photons, jets, hadronic tau decays, and large missing transverse energy. The L1 nominal output rate is $\sim 100$ kHz. The High Level Trigger is composed by the second level trigger (L2) and the Event Filter (EF) and runs on a dedicated processor farm. The L2 uses more detector information, then the EF has access to the complete event and uses reconstruction algorithms similar to the ones used offline. The various working trigger chains that make a decision on whether to record an event or not constitute the trigger menu.

Not all the available trigger chains are allowed to make a decision, since some of them have a too high output rate when the luminosity is high. When this happens the trigger chain is prescaled: only a certain fraction of the events that fire the trigger is actually recorded.

### 3.4 Calorimeter Signal Objects

The energy in the calorimeter is deposited in single read-out cells. They provide many information: energy, time, signal quality and gain. They are primarily set at the so-called electromagnetic (EM) scale, that has been determined by electron test beams and simulations. Individual cell signals are hard to use because they can be negative due to noise effects and because it’s difficult to determine the source of signal without signals from neighbors. Cells are then collected into larger objects: tower or
3.4.1 Calorimeter towers

In the case of towers the cells are projected into fixed grid in pseudo-rapidity ($\eta$) and azimuthal direction ($\phi$). The tower bin size is $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in the whole acceptance region of the calorimeters, i.e. in $|\eta| < 4.9$ and $-\pi < \phi < \pi$, with $100 \times 64 = 6,400$ towers in total. Projective calorimeter cells which completely fit inside a tower contribute their total signal to the tower signal. Non-projective cells and projective cells larger than the tower bin size contribute a fraction of their signal to several towers, depending on the overlap fraction of the cell area with the towers. Thus the tower signal is the sum of possibly weighted cell signals (all cells included). As the cells signal are on the EM energy scale, the resulting tower signal is on the same scale.

3.4.2 Topological clusters

The alternative representation of the calorimeter signals are topological cell clusters, which are basically an attempt to reconstruct three-dimensional energy deposits representing the showers development for each particle entering the calorimeter.

The basic idea for topological clustering is to group into clusters neighboring cells that have significant energies compared to the expected noise. Thus the clusters will have a variable number of cells. Cluster growth starts at seed cells that have an energy significance, defined as the ratio signal to noise, above a threshold $t_{\text{seed}} = 4$. All directly neighboring cells of these seed cells in all the three dimensions are collected into a cluster. If any of the neighboring cells have a signal-to-noise ratio of above $t_{\text{seed}} = 2$, their neighbors are also added to the cluster. Finally a ring of guard cells with significance above 0 is added to the cluster, see Figure 3.11.

After the initial clusters are formed, they are analyzed for local signal maximums by a splitting algorithm [14].
Figure 3.11: Topological clustering in the Forward Calorimeter according to the “4,2,0” scheme. In Figure (a) cells with a signal-to-noise ratio greater than 4 are highlighted; in Figure (b) cells with a signal-to-noise ratio greater than 2 are added. In Figure (c) neighbor cells are added.
3.5 Calibration procedures

Calorimeters are the crucial detectors at ATLAS: they provide measurements of energy and position of electrons, photons and jets as well as measurement of the missing transverse energy.

Particles incoming the calorimeter typically initiate a shower of particles: energy of this shower is deposited by interactions of shower particles with medium of the calorimeter and is converted to electronic signals by the interaction with the active media of the calorimeters. The electronic signals of different detector subsystems are combined and the physics objects are derived by offline reconstruction algorithms.

An electromagnetic shower begins when a high-energy electron, positron or photon enters a material. At high energies (above a few MeV, below which photoelectric effect and Compton scattering are dominant), photons interact with matter primarily via pair production that is, they convert into an electron-positron pair, interacting with an atomic nucleus or electron in order to conserve momentum. High-energy electrons and positrons primarily emit photons, a process called bremsstrahlung. These two processes continue in turn, until the remaining particles have lower energy. Electrons and photons then lose energy via scattering until they are absorbed by atoms.

Hadronic showers, on the other hand, are developed by strong interactions between the incoming hadrons and the nucleons in the matter. One of their most important property is the invisible energy. In EM showers all the energy is eventually detectable and could be measured. However, in hadronic showers a certain fraction of energy in fundamentally undetectable due to strong interactions. Hadronic showers could be divided into a particle and a nuclear sector. In the nuclear sector the spallation reactions play a role, when a high-energy hadron strikes an atomic nucleus. In these reactions a nucleon may be released from the nuclei. The binding energy of this nucleon is lost for the calorimeter, is invisible. Hadronic showers are also considerably broader than the electromagnetic ones.
3.5.1 Signal Reconstruction

The ATLAS calorimeter is non-compensating, i.e. the response for EM showers ($e$) and hadronic showers ($h$) of the same energy is different. The ratio is $e/h > 1$ for non-compensating calorimeters, which means that the response for hadronic showers is lower.

In hadronic showers some of the dissipated energy is fundamentally undetectable, as it is invested into nuclear processes, including fusion and fission, which typically follow the direct interaction of the hadrons with nucleons. A typical example are binding energy losses, which do not generate a signal in the detector. Other contributions are from neutrinos and stopped decaying particles created in the hadronic shower development.

Hadronic showers are often considerably larger than electromagnetic showers, as their typical lateral and longitudinal extension is driven by the average length of a high energetic charged or neutral hadron generated in a hadron-nucleon collision (that is much larger than the free path length of high energetic photons and electrons in most materials).

The aim of hadronic calibration of calorimeter is to correct for these losses. In ATLAS two approaches are used: the global methods, where reconstructed hadronic final state objects (jets) are subjects to calibration and local methods where the weights are derived to calibrate

**Local hadron calibration**

This calibration scheme uses properties of clusters to calibrate them individually. Cluster shape variables are used to classify clusters as EM or hadronic. The hadronic clusters receive cell weights [15] to compensate for the lower response. The weights are based on detailed GEANT4 simulations of charged and neutral pions.

The particular steps are:

- classification of clusters as EM or hadronic,
• application of weights to clusters classified as hadronic,

• corrections for the energy deposited out of clusters, the so-called out-of-cluster corrections (part of the shower energy is deposited in cells which do not pass the selection criteria and remains out of the cluster, these cells belong to the tails of the hadronic showers),

• corrections for the energy deposited in dead material: these account for energy deposited in the passive part of the calorimeters (upstream material, crack regions, and leakages behind the calorimeter system).

Global cell energy-density weighting calibration scheme (GCW calibration)

This calibration scheme attempts to compensate for the different calorimeter response to hadronic and electromagnetic energy depositions in the calorimeters. The weights are determined by minimizing the energy fluctuations between the reconstructed and particle jets in Monte Carlo simulations. The weights also compensate for energy losses in the dead material, which is considerably different from losses for electrons. Jets are found from uncalibrated clusters and towers, then cells are weighted and a final $p_T$ and $\eta$ dependent correction is added to ensure that the jet energy is properly reconstructed.

3.6 Hadronic Jets at ATLAS

A jet is reconstructed from energy depositions in calorimeter cells and charged particle track momenta, and is corrected for detector response and hadronization effects so that the resultant 4-vector corresponds to that of the sum of the original hadrons of the jet.

In order to actually reconstruct a jet and make comparisons between data and theoretical predictions, a precise jet definition including the jet algorithm and its configuration, is required. For a precise comparison of experiment to theory, it is advantageous
for a jet algorithm to provide a similar description of a hard scattering event at the hadron/parton level or at the detector level.

Various jet algorithms have been formulated. They cluster partons, particles, or calorimeter towers or clusters based on their proximity in coordinate space or in momentum space. For some scattering events the jets structure is pretty clear, in some others the complexity of the energy deposition has as a consequence that different algorithms would assign in a different way detector towers or clusters to the various jets.

### 3.6.1 The iterative cone algorithm

The first step in the algorithm consists in the identification of the sublists of objects corresponding to the jets. These are determined through a simple sum over all the objects within a cone centered at a certain rapidity and azimuthal angle \( y_C \) and \( \phi_C \).

\[
k \subset C \quad \text{if} \quad \sqrt{(y_k - y_C)^2 + (\phi_k - \phi_C)^2} \leq R_{\text{cone}}
\]  

In ATLAS the values \( R = 0.4 \) and \( R = 0.6 \) are used.

Using the objects inside the cone it is possible to define a \( p_T \) weighted centroid combining the four-momenta. If the centroid does not coincide with the geometrical center of the jet \( (y_J, \phi_J) \neq (y_C, \phi_C) \) a cone is placed in the \( p_T \) weighted centroid and the calculation is repeated.

The calculation is iterated until a ‘stable’ cone is found.

From this definition of the algorithm it comes out that a single particle (parton or calorimeter cluster/tower) may belong to two or more cones. So a procedure must be included in the cone algorithm to look for possible overlaps and to define when to merge or not two jets. Cones whose shared \( E_T \) is larger than a fixed fraction of the energy of the cone are merged. Otherwise the shared particles are split between the two jets and assigned to the cone that is closer in space. This implies that despite the use of a fixed radius for the cone, a jet can include particles at angles greater than \( R \).
from its direction.

In the definition of the jet algorithm an important request is that the observables derived (for example the jet cross section) need to be infrared and collinear safe.

The formal definition of infrared safeness is as follows: an observable is infrared safe if, for any n-parton configuration, adding an infinitely soft parton does not affect the observable at all.

The formal definition of collinear safeness is similar: an observable is collinear safe if, for any n-parton configuration, replacing any massless parton by an exactly collinear pair of massless partons does not affect the observable at all.

An algorithm can be safe up to a certain order in perturbation theory. The cone algorithm is fully safe at NLO, to become almost unsafe at higher order in perturbation theory: cross sections can be calculated order by order in perturbation theory but can be unreliable. This arises from the fact that the particles pass through a calorimeter with finite cell size and minimum energy trigger and that the parameters $E_0$ (energy threshold) and $\delta_0$ (minimum separation between two particles so that they can be resolved in the calorimeter) are introduced.

The cone algorithm is not infrared safe at NNLO: it gives a different classification depending on whether there is or not emission of a soft parton. This introduces in the calculation of the inclusive cross section a logarithmic dependence on the energy threshold [16].

Different solutions have been tried like the formulation of seedless algorithms and the MidPoint algorithm.

### 3.6.2 The KT algorithm

Here are the main steps of the $k_T$ algorithm (also called successive combination jet algorithm [17]):

- The starting point is a list of protojets (these can be individual partons or particles) each with 4-momentum $p_t^\mu$. 
• For each protojet and for each pair of protojets we define

\[ d_i = p_{T_i}^2 \]  

(3.6.2)

\[ d_{ij} = \min(p_{T_i}^2, p_{T_j}^2) \left\{ \left[ (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \right] / R^2 \right\}. \]  

(3.6.3)

• We label the smallest of all the \( d_i \) and \( d_{ij} \) as \( d_{\text{min}} \).

• If \( d_{\text{min}} \) is a \( d_{ij} \) we merge protojets \( i \) and \( j \) into a new protojet \( k \) combining the four-momenta.

• If \( d_{\text{min}} \) is a \( d_i \) we consider the jet as done and we remove it from the list of protojets.

The \( k_T \) algorithm does not need a split/merge prescription as it is infrared safe and implements collinear stability [18]. The distance parameter \( R \) controls the spatial resolution and jet size.

### 3.6.3 The Anti-\( k_T \) algorithm

In the \( Anti - k_T \) algorithm in equation 3.6.3 \( p_T^2 \) becomes \( p_T^{-2} \). This means that in the vicinity \( \Delta R < R \) of a hard object, all softer objects will be merged with the harder object in order of their closeness in \( \Delta R \). Thus the jet boundary is unaffected by soft radiation. If two comparably hard objects are within \( R < \Delta R < 2R \) of each other, energy will be assigned to one of them depending upon their relative \( k_T \) and distance. For hard objects within \( \Delta R < R \) of each other, a single jet will be formed containing both hard objects and the soft objects within their vicinity. The ordering of the merging is not meaningful for this algorithm.

In ATLAS \( Anti - k_T \) has been adopted as default with \( R = 0.4 \) or \( R = 0.6 \).
3.7 ATLAS reconstruction and performance

In this section a brief overview of the ATLAS reconstruction of the different physics objects used in the analysis of this thesis is presented. Clusters, photons and jets are the main objects used in this work.

3.7.1 Photons

The ATLAS electromagnetic calorimeter is designed to be able to identify efficiently electrons and photons within a large energy range (5 GeV - 5 TeV) and to measure their energy with a linearity better than 0.5%.

The reconstruction of photons follow in its main aspects that of electrons [19]. Although the definition of an electron is rather straightforward, relying entirely on the presence of a track matching an electromagnetic cluster, that of a photon is a little bit more involved due to the fact that we have converted and unconverted photons.

A sliding window algorithm is used to identify and reconstruct electromagnetic clusters. Rectangular clusters are formed with a fixed size, in such a way that their position corresponds to the maximum amount of energy deposited inside them (a minimum energy of 3 GeV is required). The optimal cluster size depends on the particle type and the calorimeter region. Electrons need larger clusters than photons due to their larger interaction probability in the upstream material and also to the fact that they bend in the electromagnetic field, radiating soft photons.

The reconstruction of converted photons includes the initial reconstruction of the conversion vertices inside the tracker, followed by the association of conversion vertices to an electromagnetic cluster.

Any cluster that does not have any track matched to it is considered to be an unconverted photon candidate; calibration corrections are applied to the cluster energy. At this stage almost all converted photons are treated also as electrons candidates.

A recovering process allows the identification of converted photons: for an electron
Figure 3.12: Overall photon reconstruction efficiencies before and after recovery as a function of true $\eta$ (left) and true $p_T$ (right) [20].

candidate with an associated conversion vertex, if the matching track to the electron coincides with the associated conversion vertex, then this electron is considered as a photon candidate. The photon reconstruction efficiency expected at ATLAS is reported in Figure 3.12 (photons from $H \to \gamma\gamma$ with $m_H = 120$ GeV with transverse momentum $p_T > 20$ GeV are used), and it reaches 99%.

Calorimetric variables have also been defined to further improve the photon identification. They can be grouped in three main categories: hadronic leakage, variables using the second longitudinal compartment (middle layer) of the EM calorimeter, and variables using the first longitudinal compartment (strips). Two sets of cuts (loose and tight) are available.

- Loose cuts are used for triggering purposes. This set of cuts performs a simple photon identification based only on limited information from the calorimeters. Cuts are applied on the hadronic leakage and on the shower-shape variables derived from the middle layer of the EM calorimeter only. This set of cuts provides excellent identification efficiency, but poor background rejection.

- Tight cuts are instead optimized to provide a good rejection of the most dangerous background, consisting of $\pi^0$ (strips are used for their fine granularity).

On top of the photon identification isolation cuts are also applied using calorimeter
and tracking based variables.

Photon identification efficiency is defined as:

\[ \epsilon = \frac{N_{\gamma}^{\text{reco}}}{N_{\gamma}^{\text{truth}}} \]  

(3.7.1)

where \( N_{\gamma}^{\text{truth}} \) is the total number of truth photons having \( E_T \) greater than a threshold, and \( N_{\gamma}^{\text{reco}} \) the number of reconstructed photon candidates associated with a true photon and with \( E_T \) greater than the same threshold. The total photon reconstruction and identification efficiency is shown in Figure 3.13.

### 3.7.2 Clusters

Clusters are the main objects used in the analysis presented in this thesis. Many physics processes to be studied at ATLAS require precision measurements of jets and missing transverse energy obtained from the calorimeter system: therefore it’s important to have good energy and position measurements with calorimeter clusters.

Figure 3.14 shows the multiplicity of topological clusters with \( p_T > 0.5 \text{ GeV} \) and \(|\eta| < 2.5\), versus the number of stable particles (charged and neutral) and tracks in interaction and simulated events (PYTHIA). A strong correlation is observed between the number of topological clusters and the number of stable particles, indicating that clusters are a good representation of the particle activity in \( pp \) events.

Figure 3.15 shows the distributions of \( p_T \) and \( \eta \) for topological clusters in data and simulated events. The distributions are normalized to the number of entries. The plots show a good agreement between data and PYTHIA, with 20% discrepancies in some phase-space regions.

Charged particles are deflected in the magnetic field of the solenoid. Their trajectories are extrapolated to the calorimeter using a Monte Carlo simulation which includes a detailed field map as well as the effect of the material in front of the calorimeter. An essential issue is the accuracy with which the simulation reproduces the energy reconstruction in the calorimeter. For charged particles the energy scale
Figure 3.13: Total photon efficiency (reconstruction and identification) vs true $\eta$, Figures (a) and (c), and true $E_T$, Figures (b) and (d). Unconverted photons are used in (a) and (b), while converted photons are used in (c) and (d) [20].
Figure 3.14: Correlations between the multiplicities of (a) topological clusters and stable particles in simulated events, (b) topological clusters and primary reconstructed tracks from interaction events, (c) topological clusters and primary reconstructed tracks from simulated interactions [21].

Figure 3.15: A comparison between data and MC simulation for topological clusters $p_T$ (a) and $\eta$ (b) [21].
Figure 3.16: The average $E/p$ in different $\eta$ bins for isolated topological clusters matched to tracks for track momentum $p$ larger than 0.5 GeV [21].

was studied using isolated tracks by extrapolating tracks to the calorimeter surface and matching them to topological clusters. The average value of the ratio $E/p$ was reconstructed, where $E$ is the cluster energy in the calorimeter and $p$ is the track momentum. Figure 3.16 shows the average response $E/p$ for calibrated topological clusters. Data and MC agree within 5% except for the transition region between barrel and end-cap ($1.5 < |\eta| < 1.8$).

3.7.3 Jet energy scale

ATLAS has developed several jet calibration schemes with different level of complexity and different sensitivity to systematic effects.

**Simple $p_T$ and $\eta$ dependent calibration scheme: EMJES calibration.**

Presently ATLAS uses a simple calibration scheme that applies jet-by-jet corrections as a function of the jet energy and pseudo-rapidity to jets reconstructed at the electromagnetic scale. This calibration scheme (called EM+JES) allows a direct eval-
uation of the systematic uncertainty.

The EM+JES calibration scheme consists of three steps:

- The average additional energy due to pile-up is subtracted from the energy measured in the calorimeters using correction constants extracted from an in-situ measurement. The correction is derived from minimum bias data and takes into account the average additional energy deposited in a fixed grid of $0.1 \times 0.1$ in $\eta - \phi$.

- The position of the jet is corrected such that the jet direction points to the primary vertex of the interaction instead of the geometrical center of the ATLAS detector. This correction improves the angular resolution, while the jet energy is unaffected.

- The jet energy and position as reconstructed in the calorimeters are corrected using constants derived from the comparison with truth Monte Carlo jets. The calibration is derived using isolated calorimeter jets that have a matching truth jet. The EM-scale energy response $R = \frac{E_{\text{calo}}^{EM}}{E_{\text{truth}}}$ for each calorimeter-truth pair is measured in bins of the truth energy and calorimeter jet pseudo-rapidity. For each $E_{\text{truth}} - \eta_{\text{reco}}$ bin the response is defined as the peak position of a Gaussian fit to the $\frac{E_{\text{calo}}^{EM}}{E_{\text{truth}}}$ distribution. In each bin a response function is obtained and its inversion gives the jet energy scale correction.

The JES systematic uncertainty is derived combining information from in-situ and single pion test-beam measurements, the description of the electronic noise and the Monte Carlo modeling. Dedicated Monte Carlo simulations test samples are generated with different conditions with respect to the nominal Monte Carlo sample. These variations are expected to provide an estimate of the systematic effects. The contributions to the JES systematics are: the uncertainty due to the JES calibration method, the uncertainty due to the calorimeter response, the uncertainty due to the detector simulation and the parameters used in Monte Carlo generators.
Figure 3.17: Fractional jet energy scale systematic uncertainty: (a) in the pseudo-rapidity region $0.3 < |\eta| < 0.8$ [49], (b) in the pseudo-rapidity region $2.1 < |\eta| < 2.8$ [49].

Figure 3.17 shows the final fractional jet energy scale systematic uncertainty as a function of the jet momentum. For $p_T > 60$ GeV the fractional JES uncertainty is between 2 and $4\%$. 

Chapter 4

Measurement setup and selections

Studies of the underlying event have already been made at ATLAS and the results are briefly presented in this chapter. In this thesis new variables are defined that may allow a deeper understanding of the underlying event contribution to the transverse energy flow at ATLAS, using minimum bias, di-jet and prompt photon event. Measuring the transverse energy flow in \( pp \) collisions and its correlations in the underlying event can be an interesting tool to validate Monte Carlo (MC) generators used to model these collisions.

A comparison between data collected by the ATLAS detector and predictions based on two different Monte Carlo generators are presented.

4.1 Measurements of underlying event characteristics using charged particles at ATLAS

ATLAS has performed measurements of primary charged particle multiplicities in soft “minimum bias” events [27] [28]. While these minimum bias studies are an important ingredient to constrain the phenomenological models used to describe soft hadron interactions, underlying event studies allow to exploit fully the topological structure of hadron-hadron collisions.

Studies have been done with the ATLAS detector of UE observables constructed from primary charged particles [29]. At the detector level charged particles are observed as tracks in the inner tracking system. The direction of the track with the largest \( p_T \) is used in each event to define the “transverse” region.

The most common UE observable is a “profile” plot of the mean value of charged particles \( p_T \) or multiplicity as a function of the \( p_T \) of the leading object in the event. The distributions are unfolded at the hadron level and compared to model predictions.
Figure 4.1: ATLAS data at 7 TeV corrected back at particle level showing the density of the charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ as a function of $p_T^{lead}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty [29].

The transverse, toward and away regions each have an area of $\Delta \phi \times \Delta \eta = \pi/3 \cdot 10$ in the $\eta - \phi$ space, so the density of the particles and transverse momentum sum are constructed by dividing the mean values by the corresponding area.

The data show a higher underlying event activity than that predicted by Monte Carlo models to which is compared (PYTHIA and PHOJET).

In Figure 4.1 is the charged particles multiplicity measured at ATLAS compared with several Monte Carlo models. Data were collected between 30 March and 27 April 2010 at $\sqrt{s} = 7$ TeV. The number density in the transverse region appears to be independent of the energy scale defined by $p_T^{lead}$ once it reaches the plateau. All the pre-LHC MC tunes considered show at least 10-15% lower activity than the data in the transverse region plateau.

In Fig. 4.2 the charged particles scalar $\Sigma p_T$ density is shown as a function of $p_T^{lead}$. The summed charged particles $p_T$ in the plateau characterized the mean contribution.
Figure 4.2: ATLAS data at 7 TeV corrected back at particle level showing the scalar \( \Sigma p_T \) density of the charged particles with \( p_T > 0.5 \text{ GeV} \) and \(|\eta| < 2.5 \) as a function of \( p_T^{\text{lead}} \). The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty [29].

of the underlying event to jet energies. All the MC tunes considered show 10-15 % lower \( \Sigma p_T \) than the data in the plateau part of the transverse region.

The angular distributions with respect to the leading charged particle of the charged particles number were also plotted (see Fig. 4.3), with the leading charged particle taken to be at \( \Delta \phi = 0 \).

These distributions show a significant difference in shape between data and MC predictions. With the increase of the leading charged particle \( p_T \) data show a sharper rise in the transverse region compared to MC. This discrepancy was also observed at Tevatron by the CDF collaboration [30].

All these plots show significant differences between Monte Carlo models and the measured distributions. These observables are particularly important for constraining the energy evolution of multiple partonic interaction models, since the plateau heights for the UE profiles are highly correlated to multiple parton interaction activity.
Figure 4.3: ATLAS data at 7 TeV corrected back at particle level showing the $\phi$ distribution of charged particle densities with respect to the leading charged particle, for $p_T > 0.5$ GeV and $|\eta| < 2.5$. The leading charged particle is excluded [29].
4.2 Measurements of underlying event characteristics using neutral and charged particles at ATLAS

A study of the underlying event using calorimeter clusters has been performed at ATLAS. As in the case for charged particles, the number density of the clusters and their transverse energy density in this region are sensitive observables for UE studies. Many physics processes to be studied with the ATLAS detector require precision measurements of jets and missing transverse energy obtained principally from the calorimeter system. Therefore it is important that the UE measurements are performed using the same reconstructed objects: calorimeter clusters.

The analysis using calorimeter clusters has several important features. Firstly, its results are sensitive to the entire hadronic final state, including neutral particles. Secondly, the analysis based only on calorimeter clusters has completely independent experimental uncertainties compared to the corresponding analysis using tracks. Finally, since jet reconstruction is based almost entirely on energy deposition in the calorimeter, the results of this UE analysis can be used directly to estimate the effect of the underlying event on any jet-based measurement.

Figure 4.4 shows the mean number of particles (clusters) per event per unit interval in $\eta$ and $\phi$ in the transverse region. None of the Monte Carlo predictions describe the data well.

Figure 4.5 shows the mean scalar $p_T$ sum for stable particles in the transverse region as a function of $p_T^{lead}$. Again, the Monte Carlo predictions do not fully describe the data.

Figure 4.6 shows the density distribution of stable particles as a function of the distance in azimuthal angle between the leading particle and the other particles in an event. The shape of the distribution is similar to the one observed in track based studies. The particle densities measured using topological clusters are higher than the charged-particle densities measured using tracks, due to neutral particles contribution.
Figure 4.4: ATLAS data at 7 TeV corrected back at particle level showing the density of the charged and neutral particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ as a function of $p_T^{lead}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty [21].
Figure 4.5: ATLAS data at 7 TeV corrected back at particle level showing the scalar $p_T$ density of the charged and neutral particles with $p_T > 0.5$ GeV and $|\eta| < 2.5$ as a function of $p_T^{\text{lead}}$. The error bars show the statistical uncertainty while the shaded area shows the combined statistical and systematic uncertainty [21].
Figure 4.6: ATLAS data at 7 TeV corrected back at particle level showing the average number of particles per unity of pseudorapidity as a function of the azimuthal separation between the leading particle and other particles [21].
4.3 Data and Monte Carlo

The results presented in this Chapter have been obtained from 7 TeV data samples collected during stable periods of pp collisions with nominal magnetic field conditions in 2010 by the ATLAS detector.

For each run only those luminosity blocks (periods corresponding to about two minutes of data-taking) satisfying data quality criteria for calorimeters and jet and missing transverse energy reconstruction were analyzed [32].

Data have been compared to Monte Carlo minimum bias, di-jet and prompt photon events; all Monte Carlo events pass through a full Geant 4 [33] detector simulation with a detailed description of geometry and material.

Events generated using different Monte Carlo programs have been analyzed, in particular PYTHIA, HERWIG [37] and events generated using the Perugia2010 [35] tune for PYTHIA. The spread between different generators can be used to give some impression of the uncertainties involved.

4.3.1 Monte Carlo generators

Monte Carlo generators are used to produce high-energy physics events. Since an exact description of strong interaction is not available, Monte Carlo generators are based on a combination of analytical results and various QCD-based models. Models are used to describe initial and final state parton showers, underlying events (UE), beam remnants, hadronization and decays. Since different models have been developed, different Monte Carlo generators are also available.

In these models the event is “factorized” in different components and the hard process is separated from the rest of the event.

These are the main physical aspects involving non perturbative QCD that need to be modeled:
• Parton Distributions
  A parton distribution function \( f_i^a(x) \) describes the probability of finding a parton \( i \) inside beam particle \( a \) carrying a fraction \( x \) of the momentum. MRST LO* parton density functions are used in Monte Carlo generators for ATLAS [36].

• Initial and Final State Radiation
  One shower initiator parton starts off a sequence of branchings. Because of the largeness of the strong coupling constant QCD emission of quarks and gluons is very prolific.
  Initial and final state radiation are described in both PYTHIA and HERWIG with the parton shower approach in a \( p_\perp \)-ordered shower algorithm [34]: starting from some maximum scale \( Q^2_{\text{max}} \) an original parton is evolved downwards in \( Q^2 \) until a branching occurs. The selected \( Q^2 \) value defines the \( p_\perp \) of the branching parton. The “Perugia” tunes are a different set of tunes (respect to PYTHIA) of the \( p_T \)-ordered shower and underlying events [35].

• Beam Remnants and Multiple Interactions
  In a hadron-hadron collision where only one parton-parton interaction occurs the participating parton only takes a fraction of the initial hadron momentum, leaving behind a beam remnant that is color-connected to the hard interaction. Moreover in hadron-hadron collisions the beams contain a multitude of partons and so several different interactions are possible. The understanding of multiple interactions is still very primitive [34].

• Hadronization
  Hadronization or fragmentation is the process in which the colored partons are transformed into colorless hadrons. Two main models are available: string fragmentation and cluster fragmentation.
  String fragmentation (or “Lund model”) is the default model in PYTHIA [34].
According to this model, the energy stored in the color dipole field between a charge and an anti-charge increases linearly with the separation between the charges (this assumption is supported by lattice QCD). As \( q \) and \( \bar{q} \) move apart from their common production vertex, the physical picture is that of a color flux tube. The potential energy stored increases, and the string may break producing a new \( q'\bar{q}' \) pair. The original system therefore splits into two color-singlet systems \( qq' \) and \( \bar{q}\bar{q}' \). Further breakings may occur if the invariant mass of either of these string pieces is large enough. The string break-up process proceeds until only on-mass-shell hadrons remain.

The cluster hadronization model is instead used in HERWIG [37]. After the perturbative parton branching process, all the outgoing gluons are splitted into light quark-antiquark or diquark-antidiquark pairs. Quarks are then combined with their nearest neighbors to form color singlet clusters. The clusters formed in this way are fragmented into hadrons following some prescriptions. A similar cluster model is also used to model soft and underlying hadronic events.

### 4.4 Data and Monte Carlo Selection

In order to suppress cosmic-ray and beam-related backgrounds, events were required to contain at least one primary collision vertex.

Collision events were triggered using different criteria for the different final states. Minimum Bias Trigger Scintillators (MBTS) were used for minimum bias events. Timing criteria based on calorimeter measurements were applied to reject residual beam background by requiring the MBTS\(_1\) trigger to record one or more hits on either side of the calorimeter.

Due to the fast increase in luminosity over the data taking period different triggers were applied to photon-jet events, see Table 4.1. The Event Filter (EF) was used: this is the last element of the ATLAS trigger system. The EF uses offline physics and event reconstruction algorithms accessing the full event data.
### PROMPT PHOTON TRIGGERS

<table>
<thead>
<tr>
<th>Data Period</th>
<th>Trigger Name</th>
<th>Trigger Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-D</td>
<td>EF_g10_loose</td>
<td>At least one photon with $p_T &gt; 10$ GeV</td>
</tr>
<tr>
<td>E</td>
<td>EF_g17_etcut</td>
<td>At least one photon with $E_T &gt; 17$ GeV</td>
</tr>
<tr>
<td>F-I</td>
<td>EF_g20_loose</td>
<td>At least one photon with $p_T &gt; 20$ GeV</td>
</tr>
</tbody>
</table>

Table 4.1: Description of the trigger requirements applied to prompt photon events.

### DI-JET TRIGGERS

<table>
<thead>
<tr>
<th>$p_T$ average</th>
<th>Trigger</th>
<th>CutApplied</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$ average &lt; 50 GeV</td>
<td>L1_MBTS_1</td>
<td>At least one hit recorded by MBTS_1 trigger.</td>
</tr>
<tr>
<td>50 GeV &lt; $p_T$ average &lt; 80 GeV</td>
<td>L1_J5</td>
<td>At least one jet with $p_T &gt; 5$ GeV at EM scale.</td>
</tr>
<tr>
<td>$p_T$ average &gt; 80 GeV</td>
<td>L1_J15</td>
<td>At least one jet with $p_T &gt; 15$ GeV at EM scale.</td>
</tr>
</tbody>
</table>

Table 4.2: Description of the trigger requirements applied to di-jet events.

Three trigger selections were used for di-jet events to study a wide $p_T$ range with enough statistics. The trigger requirements are reported in Table 4.2 according to the average $p_T$ between the leading and sub-leading jets [47].

Monte Carlo events were simulated with in-time pileup, and only events with only one primary vertex were considered (for both data and Monte Carlo). Moreover it is required $|z| < 100$ mm for the primary vertex, so that the measured positions are compatible with the ATLAS coordinate system.

Further selection cuts were applied to prompt photon and di-jet events. Only events where the two jets (jet and photon in photon-jet events) with the highest transverse momentum were in the central pseudo-rapidity region ($|\eta| < 0.8$) and had $p_T > 20$ GeV were considered.

The two leading hard objects were also required to be in opposite pseudo-rapidity hemispheres (one with positive $\eta$ and one with negative $\eta$) and to be back-to-back.
(\Delta \phi > 2.9). Requiring that the two leading objects are in opposite \( \eta \) hemispheres allowed to study the correlation coefficients between the transverse energy deposited in the \( \eta \) hemisphere where the leading jet lies and the \( \eta \) hemisphere of the sub-leading jet (or leading photon).

4.4.1 Jets Selection

Jets were reconstructed with the Anti-\( k_T \) algorithm with a distance parameter \( R = 0.6 \) and full four momentum recombination.

Three selection criteria were applied to identify jets caused by noise or by out-of-time energy deposition in the calorimeters, or jets associated with real energy deposition but in regions where the measurement is not accurate (e.g. problematic calorimeter regions).

The cleaning cuts were not applied to Monte Carlo events since most of the cleaning variables are not very well modeled.

- Fake jets caused by sporadic noise burst in the HEC were identified by requiring that the fraction of the jet energy in the HEC is larger than 0.8, and that 90\% of the jet energy is distributed over less than 6 calorimeter cells. An additional cut was also applied based on the correlation between the jet energy fraction in HEC and the jet quality, defined on the basis of the fraction of jet energy from LAr calorimeter cells flagged as problematic (low signal quality).

- Fake jets caused by very few noise burst in the electromagnetic calorimeter causing large coherent noise in neighboring cells were identified by requiring the fraction of jet energy from LAr calorimeter cells flagged as problematic to be greater than 0.8, and the fraction of energy in only the electromagnetic calorimeter to be greater than 0.95.

- Jets reconstructed from large out-of-time energy deposits in the calorimeter (for example those due to photons produced by cosmic ray muons overlaid on a
minimum bias collision event) were identified if the time of the jet is more than 25 ns different from that of the average event time.

For this study di-jet events in which the leading and sub-leading jet in \( p_T \) fell into any of the category above were rejected. For photon-jet events the leading jet was considered.

### 4.5 The playing field

For this study all hard final state objects were reconstructed in the central detector region denoted by \( \eta_{\text{signal}} \) in Figure 4.7. The two leading objects were required to be in different \( \eta \) hemispheres: \( \eta_{\text{signal},1} \times \eta_{\text{signal},2} < 0 \). The \( \eta \) hemisphere in which the leading jet lies is called the “toward” region, while the “away” region is the \( \eta \) hemisphere where the sub-leading jet (or leading photon) lies.

The \( \eta-\phi \) plane was divided in ten \( \eta \) strips. With the requirement for a central signal region the underlying event measurement focuses on the more forward regions of the
final state from $pp$ scattering. The strips were named as $\tau_0$, $\tau_1$, $\tau_2$, $\tau_3$ and $\tau_4$ in the “toward” region and $\alpha_0$, $\alpha_1$, $\alpha_2$, $\alpha_3$ and $\alpha_4$ in the “away” region. This view of the event make the study of the forward transverse energy and its correlations easy.

4.5.1 Regions in the azimuthal direction

Along the azimuthal direction the plane was divided in four regions in order to select the regions that are more sensitive to the soft QCD processes responsible for the underlying event.

The azimuthal angular distance between a leading jet (at cluster or particle level) in transverse momentum and other clusters (particles) is given by $\Delta \phi = \phi - \phi_{\text{lead}}$, where $\phi$ is the azimuthal angle of the cluster (particle) and $\phi_{\text{lead}}$ the azimuthal angle of the leading jet. The transverse region, defined as $\pi/3 < |\Delta \phi| < 2\pi/3$ is the most sensitive to the underlying event since it is perpendicular to the axis of the hardest scattering, approximated by the direction of the leading jet. The transverse energy of clusters (particles) in this region is a sensitive observable for UE studies. Moreover in each event “Phi-TransMAX” is defined as the transverse region (in the positive or negative $\eta$ hemisphere) where the transverse energy of clusters (particles) is greater, while the one in the other $\eta$ hemisphere will be “Phi-TransMIN”. The azimuthal region containing the leading jet ($|\Delta \phi| < \pi/3$) is instead defined as the “Phi-Toward” region, and the one opposite in $\phi$ “Phi-Away”.

4.6 Transverse energy scale evaluation

Figure 4.9 shows the transverse energy profile per event as function of the pseudo-rapidity for calibrated clusters and clusters at the electromagnetic scale in collision data and Monte Carlo (PYTHIA) minimum bias events. The lower part of the figure shows the relative ratio between the MC simulation prediction and collision data; the errors are obtained from the statistics error of the upper histogram. Apart from the
Figure 4.8: A schematic representation of regions in the azimuthal angle $\phi$ with respect to the leading object (shown with an arrow).
two bins closest to the beam remnants, clusters in the Monte Carlo simulation are overestimating the real energy deposit: the relative difference is about 20%.

In Fig. 4.10 is the same plot for prompt-photon events and in Fig. 4.11 the same histograms according to the transverse momentum of the leading jet of the event. The events were divided in four $p_T$ regions: in the first one are events where the leading jet has $p_T$ between 20 GeV and 40 GeV, in the second one between 40 GeV and 80 GeV, in the third one between 80 GeV and 160 GeV, and in the forth one the transverse momentum is greater than 160 GeV. In these plots the negative $\eta$ hemisphere is the $\eta$ hemisphere where the sub-leading (in $p_T$) object lies, while the positive $\eta$ hemisphere is associated to the leading jet.

The inclusive plot shows a bigger discrepancy between data and MC prediction in the central $\eta$ region, in Fig. 4.11 the relative difference is about 20-30%. Monte Carlo predictions here are underestimating the transverse energy deposition in the lower $p_T$ regions, and overestimating it in the forth $p_T$ region in the bins close to the leading objects.

For each of the four $p_T$ regions the same histograms were also made in the four azimuthal regions: the “Phi-Toward” (where the leading object lies), the “Phi-Away” (where the sub-leading object lies), and the two transverse regions: “Phi-TransMAX” and “Phi-TransMIN”. The results are shown in Figures 4.12, 4.13, 4.14 and 4.15. In the “Phi-TransMIN” region the Monte Carlo expectations are even lower than the energy reconstructed at the electromagnetic scale.

The same plots were made for di-jet events, see Fig. 4.16.

Due to statistics problems plots in only two of the $p_T$ regions are presented, corresponding to the leading jet transverse momentum belonging to the intervals $80 \text{ GeV} < p_T < 160 \text{ GeV}$ and $p_T > 160 \text{ GeV}$, Fig. 4.17, 4.18 and 4.19. The difference between data and Monte Carlo predictions reaches 40 % in the pseudo-rapidity bins closer to the protons beam remnants.
Figure 4.9: Transverse energy distribution in minimum bias events for calibrated and uncalibrated clusters in real data and Monte Carlo.

Figure 4.10: Transverse energy distribution in prompt photon events for calibrated and uncalibrated clusters in real data and Monte Carlo.
Figure 4.11: Transverse energy distribution in photon-jet events in different $p_T$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) $20 \text{ GeV} < p_T^{\text{leading jet}} < 40 \text{ GeV}$, (b) $40 \text{ GeV} < p_T^{\text{leading jet}} < 80 \text{ GeV}$, (c) $80 \text{ GeV} < p_T^{\text{leading jet}} < 160 \text{ GeV}$, (d) $p_T^{\text{leading jet}} > 160 \text{ GeV}$.
Figure 4.12: Transverse energy distribution in photon-jet events where the leading jet has $p_T$ between 20 GeV and 40 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region.
Figure 4.13: Transverse energy distribution in photon-jet events where the leading jet has $p_T$ between 40 GeV and 80 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo.
Figure 4.14: Transverse energy distribution in photon-jet events where the leading jet has $p_T$ between 80 GeV and 160 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region
Figure 4.15: Transverse energy distribution in photon-jet events where the leading jet has $p_T$ greater than 160 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region
Figure 4.16: Transverse energy distribution in di-jet events for calibrated and uncalibrated clusters in real data and Monte Carlo.

### 4.7 Systematic uncertainty

The systematic uncertainty on the transverse energy deposition can be calculated from the topoclusters energy scale uncertainties.

These uncertainties can be estimated from comparisons between data and MC simulation using the $E/p$ response from single track, that has also been used in ATLAS for the estimate of the calorimeter jet energy scale (JES).

#### 4.7.1 Calorimeter response to single isolated hadrons

The ratio between the energy $E$ deposited by an isolated charged particle in the calorimeter and the track momentum $p$ is the observable used in ATLAS to assess the calorimeter response [48].

The track momentum measurement is very precise and accurate and it can therefore allow to assess the calorimeter response to hadrons. A calorimeter energy deposit is
Figure 4.17: Transverse energy distribution in di-jet events in two \( p_T \) regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) 80 GeV < \( p_T \) leading jet < 160 GeV, (b) \( p_T \) leading jet > 160 GeV.
Figure 4.18: Transverse energy distribution in di-jet events where the leading jet has $p_T$ between 80 GeV and 160 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo.
Figure 4.19: Transverse energy distribution in di-jet events where the leading jet has $p_T$ greater than 160 GeV in the four $\phi$ regions for calibrated and uncalibrated clusters in real data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region
associated to an isolated track and the energy in the calorimeter is compared to the track momentum reconstructed by the inner detector.

A cone of a given size is opened around the extrapolated impact point of the track at the calorimeter entrance, and the energy associated to the hadron is the one deposited inside that cone. The energy is computed making use of topological clusters at the electromagnetic scale and using all the calorimeter layers. The value of the radius around the track is chosen trying to both maximize the particle shower but also minimize the background contribution coming from neutral particles produced close to the track. The $E/p$ distribution has been studied in different bins of momentum and pseudo-rapidity.

The average measured $E/p$ is compared to the predictions of the Monte Carlo simulation. In general the agreement between data and MC is very good. The ratio between MC and data fluctuates around one, with a maximum deviation that is well within 5% (in the transition region between the barrel and end-cap EM calorimeters).

Using this method the jet calorimeter JES and its systematics can also be derived by correlating a particle jet to a reconstructed jet and then propagating the response and uncertainty of the particles that make the jet [49].

### 4.7.2 Topoclusters energy scale uncertainties

Uncertainties on the topoclusters energies have been derived from the study on isolated hadrons.

The shift in the topocluster energy scale is applied by multiplying the topocluster energy by the function [51]:

$$1 \pm a \times (1 + b/p_T)$$

(4.7.1)

with $a = 3(10)\%$ for $|\eta| < (>) 3.2$, $b = 1.2$ and $p_T$ is expressed in GeV.

Equation 4.7.1 is based on the results shown in Ref. [49] but with updated measurements, as reported in [50]. To go from the response from single isolated particles to the cluster energy scale possible effects from the noise thresholds in the configuration
Figure 4.20: Transverse energy distribution in minimum bias events using calibrated clusters in collision data and Monte Carlo. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.

with nearby particles are taken into account (two close-by particles can have a higher response than the sum of two isolated particles [52]).

4.7.3 Results

The systematic uncertainty for the transverse energy were found and compared with the difference between Monte Carlo and data using two different event generators. In Figure 4.20 is the plot for minimum bias events: the black error bars are found using formula 4.7.1. Both PYTHIA and HERWIG are overestimating the transverse energy deposition.

The same plot for prompt photon events in Fig. 4.21 and in the different $p_T$ regions in 4.22. While in the inclusive plot the data points in the lower histogram are
Figure 4.21: Transverse energy distribution in prompt photon events using calibrated clusters in collision data and Monte Carlo. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.

well above the error band (especially in the central pseudo-rapidity region), Monte Carlo gives good results in Fig. 4.22. HERWIG seems to perform slightly better than PYTHIA in the low $p_T$ regions.

The systematic uncertainty is about 30 % in the $\eta$ bins close to the beam remnants, and 10 % in the central region.

In Fig. 4.23, 4.24, 4.25 and 4.26 the histograms are done in the four azimuthal regions. As the transverse momentum of the leading jet increases HERWIG seems to perform better than PYTHIA, especially in the two transverse regions.

The inclusive plot for di-jet events is in Fig. 4.27. In Fig. 4.28 are the histograms for the two $p_T$ regions.

In Figures 4.29 and 4.30 are the plots in the four azimuthal regions. The Monte
Figure 4.22: Transverse energy distribution in prompt photon events in different $p_T$ regions using calibrated clusters in collision data and Monte Carlo: (a) $20 \text{ GeV} < p_T^{\text{leading jet}} < 40 \text{ GeV}$, (b) $40 \text{ GeV} < p_T^{\text{leading jet}} < 80 \text{ GeV}$, (c) $80 \text{ GeV} < p_T^{\text{leading jet}} < 160 \text{ GeV}$, (d) $p_T^{\text{leading jet}} > 160 \text{ GeV}$. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.23: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ between 20 GeV and 40 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.24: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ between 40 GeV and 80 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.25: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ between 80 GeV and 160 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.26: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ greater than 160 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.27: Transverse energy distribution in di-jet events using calibrated clusters in collision data and Monte Carlo. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.28: Transverse energy distribution in di-jet events in different $p_T$ regions using calibrated clusters in collision data and Monte Carlo: (a) $80 \text{ GeV} < p_T^{\text{leading jet}} < 160 \text{ GeV}$, (b) $p_T^{\text{leading jet}} > 160 \text{ GeV}$. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Carlo prediction seems to work better in the low $p_T$ region (Fig. 4.29), where the relative difference shown in the lower plot is smaller, or very close, to the error for both PYTHIA and Perugia. In the high $p_T$ region (Fig. 4.30), instead both the simulations do not seem to reconstruct properly the transverse energy associated with the hard component of the event, while they have a better performance in the “Phi-TransMIN” region.

4.8 Selection on the clusters $p_T$

The transverse energy flow was also studied with additional cuts on the transverse momentum of the clusters to study how the soft clusters impact the distributions. The clusters were selected with a transverse momentum higher than 100 MeV, 250 MeV, 500 MeV, 750 MeV or 1 GeV.

In Fig. 4.31, 4.32 are the results for prompt photon events. The cuts do not have a big impact on the energy distributions: the energy flow behaviour is governed by the high $p_T$ clusters.

In Fig. 4.33, 4.34 are the results for di-jet events.
Figure 4.29: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ between 80 GeV and 160 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.30: Transverse energy distribution in prompt photon events where the leading jet has $p_T$ greater than 160 GeV in the four $\phi$ regions using calibrated clusters in collision data and Monte Carlo: (a) “Toward” region, (b) “Trans-MIN” region, (c) “Away” region and (d) “Trans-MAX” region. The error is the systematic error. In the lower part of the figure is the relative difference between data and Monte Carlo. The black error is the systematic one, while the yellow error bars are obtained combining statistics and systematic uncertainties.
Figure 4.31: Transverse energy distribution in prompt photon events using calibrated clusters with different $p_T$ thresholds.
Figure 4.32: Transverse energy distribution in prompt photon events using calibrated clusters with different $p_T$ thresholds in the four $p_T$ regions: (a) $20 \text{ GeV} < p_T \text{ leading jet} < 40 \text{ GeV}$, (b) $40 \text{ GeV} < p_T \text{ leading jet} < 80 \text{ GeV}$, (c) $80 \text{ GeV} < p_T \text{ leading jet} < 160 \text{ GeV}$, (d) $p_T \text{ leading jet} > 160 \text{ GeV}$.
Figure 4.33: Transverse energy distribution in di-jet events using calibrated clusters with different $p_T$ thresholds.

Figure 4.34: Transverse energy distribution in di-jet events using calibrated clusters with different $p_T$ thresholds in two $p_T$ regions: (a) $80 \text{ GeV} < p_T^{\text{leading jet}} < 160 \text{ GeV}$, (b) $p_T^{\text{leading jet}} > 160 \text{ GeV}$.
4.9 Transverse Energy Correlations

Measuring the longitudinal correlations in the transverse energy flow can be an interesting tool to validate Monte Carlo generators. Correlation coefficients of the $E_T$ in various $\eta$ regions have been computed for minimum bias, di-jet and prompt photon events.

4.9.1 Correlation Coefficients

In statistics correlation coefficients are a measure of the dependence between two variables $X$ and $Y$, giving a value between $+1$ (when a linear equation describes the relationship between $X$ and $Y$, for which $Y$ increases when $X$ increases) and $-1$ (if $Y$ decreases when $X$ increases). A value of 0 means that there is no linear correlation between the two variables.

Given two pseudo-rapidity regions out of the ten in which the $\eta$ axis has been divided, $i$ and $j$, if $E_{T,i}$ and $E_{T,j}$ correspond to the transverse energy in an event in the regions $i$ and $j$, the correlation coefficient is then defined as:

$$c_{i,j} = \frac{\langle E_{T,i}E_{T,j} \rangle - \langle E_{T,i} \rangle \langle E_{T,j} \rangle}{\sqrt{\langle E_{T,i}^2 \rangle - \langle E_{T,i} \rangle^2 \sqrt{\langle E_{T,j}^2 \rangle - \langle E_{T,j} \rangle^2}}}, \quad (4.9.1)$$

where the average is computed over the total number of events $N$.

It is possible to associate a statistics error to the correlation coefficient [31]:

$$\sigma(c_{x,y}) = \frac{1 - c_{x,y}^2}{\sqrt{N}}. \quad (4.9.2)$$

Correlation coefficients can be calculated from calorimeter signals reconstructed at various energy scales, and from particles from MC generators. The imminent advantage of this quantity is that to first order it is independent on calorimeter energy scales.

Short range correlations in the central region, like $(\alpha_1, \alpha_2)$ or $(\tau_1, \tau_2)$ (see Fig. 4.7 for the naming convention), likely suffer from hadronic shower leakage.
Considering instead the long range correlations (between regions of different $\eta$ hemispheres), they are introduced by the proton remnants and the underlying event and pile-up and we expect them to be small. Indeed these long range correlations are mostly independent from the hard scattering and they should therefore be independent of the number of additional proton collisions in the same bunch crossing. This has been proven by looking at the shapes of the correlations as function of the number of reconstructed vertices. Also, if the correlations are independent on the hard scattering they should also not change with the $p_T$ of the hardest jet. Moreover, they should be very similar for minimum bias, di-jet and photon-jet events. The only difference could be the presence of diffractive processes in minimum bias events, where the protons are actually not destroyed.

Correlation coefficients in the forward regions of $pp$ scattering could be used to study the color flow between the hard scattering and the proton remnants. Beam-beam remnants are indeed color connected to the hard scattering and we can imagine the hadronization process as happening along these colored strings. Here it is expected that there are differences in the color flow, and thus in the particle flow, between the quark (coming out from the interaction in di-jet events) and the photon (in prompt photon production).

The correlation coefficients of the transverse energy for each event in each of the ten pseudo-rapidity regions with the other nine were computed. Again for each event a leading object hemisphere and a sub-leading object hemisphere were defined. For each $\eta$ region in one of the two hemispheres the correlations with the other nine were reported in three different plots.

- For a region $i$ belonging to the sub-leading (leading) hemisphere one plot is filled with the correlations with the regions belonging to the same hemisphere on the “beam remnants side” (i.e. that are closer to the remnants than $i$).
- A second plot is filled with the correlations with the regions belonging to the same hemisphere on the “leading object side”.
• A third plot is filled with the “cross correlations”: correlations with the regions belonging to the other hemisphere.

In Figure 4.35 are the correlations in the sub-leading object hemisphere with the regions closer to the remnants in prompt photon events compared with Monte Carlo (PYTHIA) predictions. The value of the coefficients decreases going from the central region to the remnants, indication that in the high pseudo-rapidity regions the energy flow is independent from the hard scattering. In Fig. 4.36 the correlations with the regions closer to the sub-leading object and in 4.37 the ones with the regions in the leading object hemisphere: the values of the coefficients are close to zero, there is no cross correlation between the two hemispheres. In Fig. 4.38 and 4.39 are the correlation coefficients for regions in the leading object hemisphere.

The same plots for di-jet events are in Fig. 4.40, 4.41, 4.42, 4.43, 4.44.
Figure 4.35: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the remnants for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.36: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the sub-leading object for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.37: Correlation Coefficients in the sub-leading object hemisphere with the regions in the leading object hemisphere for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.38: Correlation Coefficients in the leading object hemisphere with the regions closer to the remnants for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.39: Correlation Coefficients in the leading object hemisphere with the regions closer to the leading jet for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.40: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the remnants for di-jet events in the two $p_T$ regions: (a) the leading jet has $80 < p_T < 160$ GeV, (b) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.

Figure 4.41: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the sub-leading object for di-jet events in the two $p_T$ regions: (a) the leading jet has $80 < p_T < 160$ GeV, (b) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.42: Correlation Coefficients in the sub-leading object hemisphere with the regions in the leading object hemisphere for di-jet events in the two $p_T$ regions: (a) the leading jet has $80 < p_T < 160$ GeV, (b) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.

Figure 4.43: Correlation Coefficients in the leading object hemisphere with the regions closer to the remnants for di-jet events in the two $p_T$ regions: (a) the leading jet has $80 < p_T < 160$ GeV, (b) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
Figure 4.44: Correlation Coefficients in the leading object hemisphere with the regions closer to the leading jet for di-jet events in the two $p_T$ regions: (a) the leading jet has $80 < p_T < 160$ GeV, (b) the leading jet has $p_T > 160$ GeV. Filled bullets are for data, the empty ones are for the Monte Carlo predictions. Errors are computed from 4.9.2.
In any experiment the distribution of a measured observable differs from the one of the corresponding true physical quantity, due to detector effects. Unfolding is the procedure of estimating the “truth-level” spectrum of an observable, i.e., the spectrum that would be measured with an ideal detector and infinite event statistics. This requires a good knowledge of the overall effect of the distortions on the true physical quantity.

In many problems it’s not necessary to unfold the measured distribution; in most of the cases it’s easier to modify the prediction of the theory to include the distortions of the detector. Without unfolding, however, the measurement cannot be compared with the results of other experiments. Unfolding it’s not used at ATLAS in searches for new physics, for example, where it can not be assumed that the data are consistent with the MC prediction, but it’s useful when the distribution itself of the measured quantity is the object of interest that we want to compare with the theory, as in this case for the $E_T$ distribution.

In this chapter the results of unfolding the transverse energy distribution will be shown: the correction will include contributions from the event selection, detector effects, trigger requirements, efficiency, and bin-by-bin migration [65].

Several unfolding methods have been studied. As of 2011, ATLAS has used two unfolding methods [63]: bin-by-bin correction factors and an iterative method by D’Agostini [64].

5.1 Bin-by-bin correction

When dealing with only one physical variable the unfolding method mostly used is the so called bin-by-bin correction: one evaluates with a Monte Carlo simulation a set
of correction coefficients calculating for each bin of a distribution the ratio between
the value of the reconstructed variable and the one of the true one (the hadron level
in our case). This efficiency is then used to estimate the true value from the one
measured with real data.

Clearly this method requires the same subdivision in bins of the true and experimental
variable. It cannot take into account migrations of events in different bins and it
neglects correlations between adjacent bins.

The correction is reliable only if the amount of migration is negligible and if the
standard deviation is smaller than the bin size.

For a given Monte Carlo sample, let \( T_i \) be the expected content of bin \( i \) of the truth-
level spectrum of a certain variable. Detector simulation is not involved in the truth-
level spectrum. Let \( R_i \) be the expected value in bin \( i \) of the measured spectrum, and
\( D_i \) the actually measured value. Then

\[
C_i \equiv \frac{T_i}{R_i} \quad (5.1.1)
\]
is the correction factor corresponding to bin \( i \) of the observed spectrum. After bin-
by-bin correction

\[
U_i \equiv C_i \cdot D_i \quad (5.1.2)
\]
is the estimator of \( T_i \).

### 5.2 Iterative unfolding

A different approach to unfolding is based on Bayes theorem.

#### 5.2.1 Bayes’ theorem

Considering several different causes \( (C_i, i = 1, 2, ..., n_c) \) that can produce one effect
\( E \), if \( P(C_i) \) is the initial probability of the causes and \( P(E|C_i) \) the probability that
\( C_i \) produces the effect \( E \), Bayes’ theorem states that:

\[
P(C_i|E) = \frac{P(E|C_i)P(C_i)}{\sum_{i=1}^{n_c} P(E|C_i)P(C_i)}. \quad (5.2.1)
\]
The probability that a measurement $E$ is due to the $i$th cause is proportional to the probability of the causes times the probability of the causes to produce the effect.

If one has no a priori idea on the $P(C_i)$ distributions the iteration can be started with a uniform distribution.

As the outcome of a measurement there are usually several possible effects $E_j$ for a given cause $C_i$ (in this case all the possible values for the energy).

If one observes $n(E_j)$ events with effect $E_j$, the expected number of events assignable to each of the causes is

$$n(C_i) = n(E_j)p(C_i|E_j).$$  \hfill (5.2.2)

Bayes’ theorem can then be rewritten as:

$$P(C_i|E_j) = \frac{P(E_j|C_i)P(C_i)}{\sum_{i=1}^{n_c} P(E_j|C_i)P(C_i)}.$$  \hfill (5.2.3)

The unfolding is then done iteratively starting from an initial distribution $P_0(C_i)$; in case of complete ignorance $P_0(C_i)$ will just be a uniform distribution.

### 5.2.2 Bayes unfolding for the Transverse Energy Distributions

Bayes method has been used to unfold the transverse energy distributions to the true level. To have a result that is as model independent as possible two different Monte Carlo have been used for each datasets: PYTHIA and HERWIG for minimum bias and photon-jet events, PYTHIA and Perugia for di-jet (where a HERWIG sample is not available).

The transverse energy distribution in each of the ten $\eta$ regions has been unfolded.

Let $E_{\text{true}}$ be the true energy of a particle: this is the truth-level quantity and it corresponds to one of the “causes” $C_i$ mentioned in formula 5.2.3.

Let $E_{\text{reco}}$ be instead the reconstructed energy after detector smearing: it corresponds to one of the “effects” in 5.2.3.

Then formula 5.2.3 can be re-written as:

$$P(E_{\text{true},i}|E_{\text{reco},j}) = \frac{P(E_{\text{reco},j}|E_{\text{true},i})P(E_{\text{true},i})}{\sum P(E_{\text{reco},j}|E_{\text{true},i})P(E_{\text{true},i})}.$$  \hfill (5.2.4)
The iteration is done using an initial set of probabilities $P(E_{true})$ (in this case the truth information of the Monte Carlo sample) and is then repeated using as the new probabilities the solution at the previous step [65]).

5.2.3 The ROOT RooUnfold Package

To unfold the $E_T$ distributions the RooUnfold package in ROOT [66] has been used. RooUnfold is a framework for unfolding that currently implements three methods: iterative (or Bayesian) method, bin-by-bin correction, and the inversion of the response matrix.

The RooUnfoldBayes algorithm uses the method described by D’Agostini [64]: repeated application of Bayes’ theorem is used to invert the response matrix. The algorithm requires a regularisation parameter: the number of iterations. Too many iterations result in bin-by-bin fluctuations in the unfolded spectrum, while too few iterations increase too much the influence of the initial distribution on the final answer. In principle, the parameter has to be tuned according to the sample statistics and binning. In practice it has been shown [66] that four iterations are usually sufficient. The optimal regularisation parameter would be selected by finding the largest value up to which the systematic errors remain reasonable (i.e. do not become much larger than the previous values).

RooUnfoldBayes takes the truth distribution as its initial probability, rather that a flat distribution as described by d’Agostini [64]. This should not bias the result with the iterations, but could reach an optimum after fewer iterations.

5.3 Unfolding for the Transverse Energy Distributions

The unfolding correction for the transverse energy distribution was found in each of the $\eta$ regions using the RooUnfold package and it was applied to the data: results are shown in Appendix A.

Each Monte Carlo event has been weighted according the real data distribution, to
avoid in the Monte Carlo distributions peaks given by the effect of the generator. The errors of the unfolded distributions are calculated by the RooUnfold package with error propagations from the equation

\[ n(C_i) = \sum_j n(E_j) P(C_i|E_j) \]  \hspace{1cm} (5.3.1)

taking into account the dependence on the input measurements (the default assumption is an uncertainty \( \sqrt{N} \) in each bin).

From the unfolded \( E_T \) histograms the mean of the transverse energy as a function of \( \eta \) was obtained using two different Monte Carlo for each type of event: PYTHIA and HERWIG for prompt photon and minimum bias events, while PYTHIA and Perugia for di-jet events. In each rapidity region the mean value of the \( E_T \) distribution was used as the entry in each bin of the transverse energy “profile” along \( \eta \).

The corrections coming from the two Monte Carlo samples were very similar (see Appendix B). The results obtained from the two Monte Carlo samples were combined using a weighted mean. In each event, in each bin of the “profiles” the unfolded energy coming from each of the two Monte Carlo were combined according to the formula:

\[ E_{\text{average}}^T = \frac{E_{T \text{MC1}} + E_{T \text{MC2}}}{\frac{1}{\sigma_{\text{MC1}}} + \frac{1}{\sigma_{\text{MC2}}}} \]  \hspace{1cm} (5.3.2)

where \( E_{T \text{MC1}} \) and \( E_{T \text{MC2}} \) are the unfolded energy according to the Monte Carlo MC1 (PYTHIA) and MC2 (HERWIG or Perugia), and \( \sigma_{\text{MC1}} \) and \( \sigma_{\text{MC2}} \) are the uncertainties associated to \( E_{T \text{MC1}} \) and \( E_{T \text{MC2}} \), obtained combining statistics and systematic errors.

The systematic uncertainty was determined from the specific unfolding method used in this analysis. The unfolding corrections are in general influenced by the number of particles and \( E_T \) distributions so there will be some dependence on the event generator model. In order to estimate this error it is necessary to compare different event generator models.

The error was defined in each bin as the biggest between \( |E_{\text{average}}^T - E_{T \text{MC1}}^T| \) and
Figure 5.1: $E_T$ mean as a function of $\eta$ before and after (yellow) the unfolding correction for di-jet events compared with PYTHIA (red) or Perugia (blue) at the truth level.

$|E_{T}^{\text{average}} - E_{T}^{MC}|$. Since this uncertainty is independent of any efficiency systematics it is summed in quadrature with the cluster energy systematic uncertainty and the statistical uncertainty.

In Figure 5.1 is the transverse energy distribution along $\eta$ before and after the unfolding correction for di-jet events. And in Figures 5.2 are the profiles according to the transverse momentum of the leading jet. In Figure 5.3, 5.4 are the results for prompt photon events.
Figure 5.2: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for di-jet events in the two $p_T$ regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level: (a) $80 \text{ GeV} < p_T \text{ leading jet} < 160 \text{ GeV}$; (b) $p_T \text{ leading jet} > 160 \text{ GeV}$. 

(a) 

(b)
The same plots were done for photon-jet events, Fig. 5.3, 5.4. The unfolding correction has a very small effect when considering events belonging to the same $p_T$ region.

A correction has also been found for events belonging to different regions in the $\phi$ direction. As for the results shown in Chapter 3, for each event a “Toward”, “Away”, “TransMIN” and “TransMAX” regions in the $\phi$ plane have been defined from the direction of the leading jet.

For each $p_T$ region the results are shown in Figures 5.5 and 5.6 for di-jet events in all the four $\phi$ regions, and in Fig. 5.7, 5.8, 5.9 and 5.10 for photon-jet.

In each $\eta$ bin the ratio between the transverse energy before and after the unfolding is between 0.9 and 1.1 in the toward and away regions, while the correction is higher in the transverse regions: it reaches 1.4 in the Trans-MAX region and 1.8 in the Trans-MIN region.

The unfolding correction is similar in photon-jet and di-jet events and it has a bigger effect in the two transverse regions (especially in the “TransMIN” region). There the energy deposited comes from the soft part of the interaction, it’s more sensitive to the underlying event, and therefore the calorimeter does not reconstruct the signal as
Figure 5.4: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for photon-jet events in the four $p_T$ regions compared with PYTHIA (black) and HERWIG (red) simulations at the truth level: (a) 20 GeV $< p_T$ leading jet $< 40$ GeV, (b) 40 GeV $< p_T$ leading jet $< 80$ GeV, (c) 80 GeV $< p_T$ leading jet $< 160$ GeV, (d) $p_T$ leading jet $> 160$ GeV.
well as for the hard objects. So the unfolding correction has a bigger effect.
Figure 5.5: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for di-jet events where the leading jet has $p_t$ between 80 GeV/$c$ and 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level.
Figure 5.6: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for di-jet events where the leading jet has $p_T$ greater 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (balck) and Perugia (red) simulations at the truth level.
Figure 5.7: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for photon-jet events where the leading jet has $p_T$ between 20 GeV/$c$ and 40 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level.
Figure 5.8: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for photon-jet events where the leading jet has $p_T$ between 40 GeV/$c$ and 80 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level.
5.4 Unfolding of the correlation coefficients

New correlation coefficients were also computed after the unfolding correction. This allows a direct comparison with the predictions given by Monte Carlo generators at the hadron level.

For each event, in the pseudo-rapidity bin $i$ the correction to the transverse energy $E_T(i)$ is given by the ratio $r = \frac{E_{T, \text{unfolded}}(i)}{E_{T, \text{average}}(i)}$, where $E_{T, \text{unfolded}}(i)$ and $E_{T, \text{average}}(i)$ are the average $E_T$ after and before the unfolding in bin $i$ (obtained from the plots in Chapter 4.3). New coefficients were found applying this correction to the transverse energy.

Again, as in chapter 3.7, for each pseudo-rapidity bin considered the correlation coefficients were reported in three different plots according to whether the compared $\eta$ is on the beam remnants side, in the hard object side, or in the opposite $\eta$ hemisphere. In Figure 5.11 are the correlations in the sub-leading object hemisphere with the regions closer to the remnants in prompt photon events compared with Monte Carlo (PYTHIA) predictions. In Fig. 5.12 the correlations with the regions closer to the sub-leading object and in 5.13 the ones with the regions in the leading object hemisphere: the values of the coefficients are close to zero, there is no cross correlation between the two hemispheres. In Fig. 5.14 and 5.15 are the correlation coefficients for regions in the leading object hemisphere.

The unfolded correlation coefficients show a similar behaviour than the one they had before the correction was applied.
Figure 5.9: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for di-jet events where the leading jet has $p_t$ between 80 GeV/$c$ and 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level.
Figure 5.10: $E_T$ mean as a function of $\eta$ before (dashed line) and after (yellow) the unfolding correction for di-jet events where the leading jet has $p_T$ greater than 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions compared with PYTHIA (black) and Perugia (red) simulations at the truth level.
Figure 5.11: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the remnants for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data before the unfolding corrections, the empty ones are the corrected coefficients. Errors are computed from 4.9.2.
Figure 5.12: Correlation Coefficients in the sub-leading object hemisphere with the regions closer to the sub-leading object for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data before the unfolding correction, the empty ones are the corrected coefficients. Errors are computed from 4.9.2.
Figure 5.13: Correlation Coefficients in the sub-leading object hemisphere with the regions in the leading object hemisphere for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data before the unfolding correction, the empty ones are the corrected coefficients. Errors are computed from 4.9.2.
Figure 5.14: Correlation Coefficients in the leading object hemisphere with the regions closer to the remnants for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data before the unfolding correction, the empty ones are the corrected coefficients. Errors are computed from 4.9.2.
Figure 5.15: Correlation Coefficients in the leading object hemisphere with the regions closer to the leading jet for prompt photon events in the four $p_T$ regions: (a) the leading jet has $20 < p_T < 40$ GeV, (b) the leading jet has $40 < p_T < 80$ GeV, (c) the leading jet has $80 < p_T < 160$ GeV, (d) the leading jet has $p_T > 160$ GeV. Filled bullets are for data before the unfolding correction, the empty ones are the corrected coefficients. Errors are computed from 4.9.2.
Transverse energy measurements at HERA allowed a test of the different approaches used in Monte Carlo models, in particular for the evolution of the parton densities. For example it was shown that early Monte Carlo models tended to produce insufficient transverse energy in the region near the proton remnant.

They also provided the first experimental evidence for the rise in the transverse energy with $Q^2$ in the central pseudorapidity region.

Similar studies are possible with the ATLAS detector at a new energy scale, the results are presented in this chapter.

6.1 Deep Inelastic Scattering experiments

In deep inelastic scattering experiments a high-energy charged lepton scatters off a hadron target. Deep inelastic scattering experiments have been a very powerful instrument to investigate the structure of the proton.

The SLAC-MIT experiment [53] was built at the Stanford Linear Accelerator Center, in the late 1960s: a 20GeV electron beam was scattered from a hydrogen target. The BCDMS (Bologna-CERN-Dubna-Munich-Saclay) apparatus at CERN in the 1980s collided muons into hydrogen and deuterium atoms [54], while the more recent experiments H1 [55] and ZEUS [56] at HERA had a high energy electron-proton collider.

The data collected at the SLAC-MIT experiment showed a reaction rate comparable to what would have been expected if the proton were an elementary particle. However, only in rare cases did a single proton emerged from the scattering [57]. Bjorken and Feynman explained these results with the so-called parton model: it assumes that the proton is made of loosely bound particles (charged fermions named quarks and bosons that bind them together). According to this model, when the electron hits the
proton only one of the partons participates to the scattering, while the rest hadronize in a jet. A given parton inside the proton can be characterized by the fraction $x$ of the proton’s momentum that it carries. The Parton Density Functions $f_i(x)$ then will express the probability that the parton $i$ will participate to the scattering carrying a fraction $x$ of the momentum. Deep inelastic scattering experiments thus gave the first experimental evidence of the existence of the quarks, already predicted in the Standard Model.

HERA (Hadron-Electron Ring Accelerator) operated at DESY from 1992 to 2007. It was the first electron-proton collider in the world: 27.5 GeV electrons collided with 820 GeV protons at a center of mass energy of 300 GeV.

At HERA a new kinematic region became accessible for deep inelastic lepton scattering, with value of the momentum transfer square $Q^2$ reaching $4 \times 10^4$ GeV$^2$, an increase of two order of magnitude from previous experiments [58].

6.2 The parton evolution equations

Transverse energy measurements by the H1 collaboration allowed a test of the different approaches used in Monte Carlo models, in particular for the evolution of the parton densities.

Electron-proton scattering for values of $Q^2$, the virtuality of the exchanged boson, significantly above 1 GeV$^2$ is usually considered as a deep inelastic scattering (DIS) process, where the exchanged boson directly couples to a parton in the proton. This approach gives a good description when appropriate parton distribution functions are used to describe the partonic content of the proton and its evolution. Several approaches, based on the DGLAP (Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) [38] [39] [40], BFKL (Balitsky-Fadin-Kuraev-Lipatov)[41] and CCFM (Ciafaloni-Catani-Fiorani-Marchesini) [42] equations have been derived in the Leading-Log-Approximation and are expected to be valid in certain regions of Bjorken $x$.

At lowest order the BFKL and DGLAP evolution equations effectively resum the
Figure 6.1: Parton kinematic regions in deep inelastic experiment. The red arrows indicate where the BFKL and DGLAP evolution equations are respectively significant.

leading logarithmic $\alpha_s \ln(1/x)$ or $\alpha_s \ln Q^2$ contributions respectively [43].

Experimental data are well described by the DGLAP equation in the limit $\ln Q^2 \gg \ln \frac{1}{x}$ (when $Q^2$ is large the leading terms need to be resummed to subtract divergences). When the “small-x limit” is reached, other resummations should be applied, terms in $\ln(1/x)$ are dominant and need to be resummed: in this limit the BFKL equation operates. In Figure 6.1 is the phase space available at HERA and ATLAS with indications of where the DGLAP and BKFL evolution equations are respectively significant.

In an axial gauge this amounts to a resummation of ladder diagrams of the type
shown in Fig. 6.2. This shows that before a quark is struck by the virtual photon, a cascade of partons may be emitted. The fraction of the proton momentum carried by the emitted partons, $x_1$, and their transverse momenta, $k_{T1}$, are indicated in the figure.

In the leading log DGLAP scheme this parton cascade follows a strong ordering in transverse momentum $k_{Tn}^2 \gg k_{Tn-1}^2 \ldots \gg k_{T1}^2$, while there is only a soft (kinematical) ordering for the fractional momentum $x_n < x_{n-1} < \ldots < x_1$. In the BFKL scheme the cascade follows a strong ordering in fractional momentum $x_n \ll x_{n-1} \ll \ldots \ll x_1$, while there is no ordering in transverse momentum. The transverse momentum follows a kind of random walk in $k_T$ space: the value of $k_{T1}$ is close to that of $k_{T1-1}$, but it can be both larger or smaller. As a consequence, BFKL evolution is expected to produce more transverse energy $E_T$ than DGLAP evolution [44] in the region between the struck quark and the remnant for low $x$ events.

### 6.3 Results of the Transverse Energy studies at HERA

Measurements of the transverse energy flow at HERA have proven useful in discriminating between the different approaches used in different Monte Carlo models.
Figure 6.3: $E_T$ flow as function of pseudorapidity. CDM is Monte Carlo generator based on the BFKL approximation, while MEPS uses DGLAP [62].
It was shown that early Monte Carlo models based on DGLAP evolution tended to produce insufficient transverse energy in the region near the proton remnant for values of the Bjorken scaling variable $x$ less than about $10^{-3}$ [60], see Fig. 6.3.

**The hadronic center of mass system**

The deep inelastic $ep$ scattering may be viewed in the rest frame of the proton. In this frame the photon can be considered to fluctuate into a hadronic object which subsequently interacts with the proton.

The virtual photon can convert in a quark-antiquark pair. For values of $x$ of less than $10^{-2}$ (in agreement with the HERA phase space) the virtual photon can fluctuate into and exists as a hadronic object over a distance of 10 to 1000 fm, which is far larger than the size of the proton. Therefore, at low $x$, a virtual photon can stay in a hadronic state for a long time and interact with the target strongly, leading to a final state similar to the one in a hadron-hadron collision. This approach was tested by the H1 collaboration in [61], where it was demonstrated that the average transverse energy flow in the central rapidity region in the hadronic centre of mass system showed no significant $Q^2$ dependence. This is consistent with observations made in hadron-hadron scatterings.

Whereas in the laboratory frame a sizable contribution to the transverse energy is produced by the kinematic recoil from the scattered lepton, in the hadronic center of mass system (hCMS) the transverse energy is due largely to perturbative QCD and fragmentation effects. The Lorentz transformation from the laboratory into hCMS therefore serves to isolate the physically interesting part of the $E_T$ flow. Moreover, it allows a direct comparison with the $E_T$ flow studies performed with ATLAS.

The amount of transverse energy depends on the shower algorithms and hence the expected levels of $E_T$ are sensitive to the different evolution schemes and can be used to test them.
Figure 6.4: Variation of the mean $E_T$ in the central pseudorapidity bin and the photon fragmentation bin with $Q^2$. The data are compared with three QCD based models [62].

The $E_T$ flow was studied at HERA in two pseudorapidity regions: the central region and the so-called photon fragmentation bin (the chosen bin is expected to be dominated by the fragmentation of the hadronic fluctuation of the photon). These studies provided the first experimental evidence for a rise in the transverse energy with $Q^2$ in the central region, as can be seen in Figure 6.4. All of the QCD based models used described correctly the rise with $Q^2$ of the measured transverse energy, although RAPGAP predicted too much transverse energy in the central pseudorapidity range.

### 6.4 $E_T$ flow studies at ATLAS

Similar studies can be performed with the ATLAS detector, exploring new regions of the phase space. In particular it is possible to investigate the mean $E_T$ in the central pseudorapidity region, adding a new data point (corresponding to the center of mass of 7 Tev) to the plot in Figure 6.4.
### PROMPT PHOTON: SUB-LEADING HEMISPHERE

<table>
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<th>$p_T^2$</th>
<th>$p_T^3$</th>
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Table 6.1: Average transverse energy per event in the central region per unity of pseudo-rapidity according to the $p_T$ of the leading jet, in prompt photon events, in the pseudo-rapidity hemisphere of the sub-leading object.

In Fig. 6.4 the transverse energy is summed in the central pseudorapidity region, where the jet fragmentation does not give contribution.

In the same way, it is possible to define a $\eta$ interval for ATLAS, far enough from the hard scattering products to determine the average $E_T$ contribution in di-jet and prompt photon events.

Events have been selected with the same cuts used in Chapter 3 and again a “sub-leading object $\eta$ hemisphere” and a ‘leading object $\eta$ hemisphere” have been defined. In the plot in 6.4 data were corrected bin-by-bin for QED radiation detector effects using the event generator DJANGO [46] together with a full simulation of the detector response. For the studies presented in this chapter ATLAS data were unfolded to the hadron level using the D’Agostini method (see Chapter 4).

In the present study the $E_T$ density has been calculated in the intervals $2 < \eta < 5$ in the leading object hemisphere and $-5 < \eta < -2$ in the sub-leading object hemisphere. In the tables 6.1, 6.2, 6.3 and 6.4 are reported the results.
<table>
<thead>
<tr>
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<tr>
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<td>2.7 ± 0.1 GeV</td>
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<tr>
<td>\text{“Trans-MAX”}</td>
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<tr>
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<td>2.7 ± 0.1 GeV</td>
<td>2.8 ± 0.4 GeV</td>
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</tbody>
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Table 6.2: Average transverse energy per event in the central region per unity of pseudo-rapidity according to the \( p_T \) of the leading jet, in prompt photon events, in the pseudo-rapidity hemisphere of the leading object.
### DI-JET: SUB-LEADING HEMISPHERE

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<tr>
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<td></td>
<td>$2.20 \pm 0.01$ GeV</td>
<td>$2.61 \pm 0.02$ GeV</td>
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</table>

Table 6.3: Average transverse energy per event in the central region per unity of pseudo-rapidity according to the $p_T$ of the leading jet, in di-jet events, in the pseudo-rapidity hemisphere of the sub-leading object.

### DI-JET: LEADING HEMISPHERE

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<td>$15.9 \pm 0.1$ GeV</td>
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<tr>
<td>“Trans-MIN”</td>
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<tr>
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<td>$2.09 \pm 0.01$ GeV</td>
<td>$2.57 \pm 0.02$ GeV</td>
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Table 6.4: Average transverse energy per event in the central region per unity of pseudo-rapidity according to the $p_T$ of the leading jet, in di-jet events, in the pseudo-rapidity hemisphere of the leading object.
Table 6.5: Systematic uncertainty on the transverse energy for prompt photon events in the sub-leading object hemisphere.

<table>
<thead>
<tr>
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<th>$P_{T3}$</th>
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Table 6.6: Systematic uncertainty on the transverse energy for prompt photon events in the leading object hemisphere.

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<td>3.5 GeV</td>
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<tr>
<td>“Trans-MAX”</td>
<td>0.3 GeV</td>
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<td>1.9 GeV</td>
<td></td>
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</tbody>
</table>

**Systematic error**

A systematic error on the value of the transverse energy in the central region has been determined using the $E_T$ deposited in the three bins closest to the remnants (both in the leading and sub-leading object hemisphere). The $E_T$ average between these three bins was found and for each of them the difference between the transverse energy and the average was computed. The systematic uncertainty for each hemisphere was defined as the biggest among the differences for the three bins closest to the remnants. This systematic accounts for the contribution to the $E_T$ in the central region coming from the hard component of the event (jet fragmentation).

The values of the systematic uncertainty are reported in Tables 6.5 and 6.6 for prompt photon events, and in 6.7 and 6.8 for di-jet events.
Table 6.7: Systematic uncertainty on the transverse energy for di-jet events in the sub-leading object hemisphere.

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<td>&quot;Trans-MAX&quot;</td>
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Table 6.8: Systematic uncertainty on the transverse energy for prompt photon events in the leading object hemisphere.

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<tr>
<td>&quot;Trans-MAX&quot;</td>
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<td>0.2 GeV</td>
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Results

The average $E_T$ per unit of pseudo-rapidity was found in minimum bias, prompt photon and di-jet events. In minimum bias events it amounts to $4.28 \pm 0.08$ GeV. In di-jet and prompt photon events the values found for the leading and sub-leading object hemisphere and for the four $p_T$ and $\phi$ regions are in good agreement, within the error bars. The results are in Figures 6.5, 6.6 and 6.7. Their average amounts to $15.6 \pm 1.2$ GeV.

The results are reported in Fig. 6.8 together with the values measured at HERA. The high $E_T$ value measured in di-jet and prompt photon events is due to the large phase space available at ATLAS, which produce a high number of jets with associated radiation phenomena. In Figure 6.8 a fit is done using the data points from HERA at $Q^2 = 8$GeV$^2$ and from the UA1 experiment. The minimum bias data point obtained by ATLAS shows
Figure 6.5: Transverse energy densities per unit of pseudo-rapidity for di-jet events in the leading jet hemisphere. The red line is the average and the yellow area its uncertainty.

a very good agreement with the logarithmic fit $\log^2(\sqrt{s})$ that was obtained using the data from the previous experiments. The same function is used in PYTHIA to model the transverse energy flow in the underlying event. In the same plot a fit is done using the average of the various entries for prompt photon and di-jet events and data collected at HERA at $Q^2 = 600\text{GeV}^2$. A logarithmic function $\log^k(\sqrt{s})$ is again used, with $k \sim 4.5$. This observation indicates that the presence of hard scattering in the final state both in deep inelastic scattering and in pp collisions changes the soft event shapes, likely due to increased gluon radiation at larger angles. As no theoretical guidance for this feature, which is strongly related to the parton shower, is available, the observed power law cannot be motivated further at this time.
Figure 6.6: Transverse energy densities per unit of pseudo-rapidity for di-jet events in the sub-leading jet hemisphere. The red line is the average and the yellow area its uncertainty.

Figure 6.7: Transverse energy densities per unit of pseudo-rapidity for photon-jet events in the sub-leading jet hemisphere. The red line is the average and the yellow area its uncertainty.
Figure 6.8: The data points from ATLAS are fitted with the results obtained by H1 and UA1 experiments.
Chapter 7

Conclusions

The analysis of the first ATLAS data collected from proton-proton collisions at a center of mass energy of $\sqrt{s} = 7$ TeV at the LHC is an opportunity to test the Standard Model of particle physics to scales never reached before and to discover new physics. The energy scale of the LHC is beyond any other particle accelerator.

In hadron-hadron collisions, besides the interaction between the two partons responsible for the hard scattering, there may be soft interactions (the underlying event), involving low momentum transfer. The underlying event is an unavoidable background in hadron-hadron collisions and its contributions need to be well understood in order to provide precision measurements at ATLAS. Perturbative QCD cannot be applied and the underlying event has to be described by models. These models contain many parameters whose values are not a priori known, therefore they must be fitted to experimental data.

In ATLAS several studies have already been done using variables sensitive to the underlying event, using both charged and neutral particles.

In this thesis the transverse energy flow in the ATLAS calorimeter and its correlations are used to validate Monte Carlo models in minimum bias, di-jet and prompt photon events. The results are unfolded to the hadron level to allow a comparison with the Monte Carlo predictions. A discrepancy of about 20% in the transverse energy distribution along the pseudo-rapidity direction is observed between real data and the Monte Carlo simulations. The systematic uncertainty on the transverse energy distribution is calculated from the calorimeter topoclusters energy scale uncertainties using the $E/p$ response from single isolated tracks. The systematic uncertainties amounts at about the 10% in the $E_T$ distribution.

Studies on the correlation coefficients have shown that the ATLAS calorimeter does
not allow to study the color flow patterns in di-jet and photon-jet final states. In particular, the brake in the color flow by the photon cannot be observed.

At HERA transverse energy measurements allowed a test of the different approaches used in Monte Carlo models to extrapolate the evolution of the parton density functions. They also provided the first experimental evidence for the rise in the transverse energy with $Q^2$ in the central pseudorapidity region. Similar studies are possible with the ATLAS detector at a new energy scale. The transverse energy density per unit of pseudorapidity has been found in minimum bias events. For di-jet and prompt photon events a pseudo-rapidity region far enough from the hard scattering products has been defined. The average transverse energy density per event amounts to $4.20 \pm 0.08$ GeV in minimum bias events, and $15.6 \pm 1.2$ GeV in di-jet and prompt photon events, due to the large phase space available at ATLAS, where many jets are produced with associated radiation phenomena. The minimum bias data point agrees with a logarithmic fit (the same function in used in PYTHIA to model the transverse energy flow in the underlying event) that interpolates also the HERA datapoint at $Q^2 = 8$ GeV$^2$. The extrapolation to higher center of mass energies, while in principle following a power law in the same scale, lacks more data points to be completely conclusive.

In future studies more Monte Carlo models could be tested in their ability to describe the transverse energy flow. Studies using more recent data, recorded by ATLAS in 2011, would be instead problematic, due to the high pile-up.
Appendix A

Unfolding results of the Transverse Energy Distributions

The unfolding correction for the transverse energy distribution was found in each of the $\eta$ regions using the RooUnfold package and it was applied to the data. Each Monte Carlo event has been weighted according the real data distribution, to avoid in the Monte Carlo distributions peaks given by the effect of the generator. In Figure A.1 are the $E_T$ distributions for di-jet in each $\eta$ region for true particles (generator level), Monte Carlo (PYTHIA) signals at detector level (clusters) and real data before the unfolding correction. In Figures A.2 and A.3 are the di-jet distributions according to the transverse momentum of the leading jet of the event. And in Figures A.4, A.5, A.6, A.7 and A.8 are the distributions for photon-jet events.
Figure A.1
Figure A.1
Figure A.1: Transverse energy distributions for di-jet events in the different $\eta$ regions: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.2
Figure A.2: Transverse energy distributions for di-jet events where the leading jet has $p_T$ between 80 GeV/c and 160 GeV/c: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.3
Figure A.3
Figure A.3: Transverse energy distributions for di-jet events where the leading jet has $p_T > 160$ GeV/$c$: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.4
Figure A.4
Figure A.4: Transverse energy distributions for photon-jet events: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.5
Figure A.5
Figure A.5: Transverse energy distributions for photon-jet events where the leading jet has $p_T$ between 20 GeV/$c$ and 40 GeV/$c$: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.6
Figure A.6
Figure A.6: Transverse energy distributions for photon-jet events where the leading jet has $p_T$ between 40 GeV/$c$ and 80 GeV/$c$: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.7
Figure A.7
Figure A.7: Transverse energy distributions for photon-jet events where the leading jet has $p_T$ between 80 GeV/$c$ and 160 GeV/$c$: for Monte Carlo and true particles in the upper histogram, and for real data in the lower one.
Figure A.8
Figure A.8
Figure A.8: Transverse energy distributions for photon-jet events where the leading jet has $p_T > 160$ GeV/$c$: for Monte Carlo and true particle in the upper plot, and for real data in the lower histogram.
The $E_T$ distributions have been unfolded following the Bayesian method. In Figures A.9, A.10 and A.11 is the comparison of the real data $E_T$ before and after the unfolding correction for di-jet events.

In Figures A.12, A.13, A.14, A.15 and A.16 are the same plots for photon-jet. Photon-jet events don’t have a high statistics in the two highets $p_T$ regions, thus the unfolding process gives bigger errors there.

The unfolding correction increases the population in the low $E_T$ bins, where due to detector effects and reconstruction thresholds particles are not reconstructed.
Figure A.9
Figure A.9: Transverse energy distributions for di-jet data before (black) and after (blue) the unfolding correction.
Figure A.10
Figure A.10: Transverse energy distributions for di-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ between 80 GeV and 160 GeV.
Figure A.11
Figure A.11: Transverse energy distributions for di-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ greater than 160 GeV.
Figure A.12
Figure A.12: Transverse energy distributions for photon-jet data before (black) and after (blue) the unfolding correction.
Figure A.13
Figure A.13: Transverse energy distributions for photon-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ between 20 GeV and 40 GeV.
Figure A.14
Figure A.14: Transverse energy distributions for photon-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ between 40 and 80 GeV.
Figure A.15
Figure A.15: Transverse energy distributions for photon-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ between 80 GeV and 160 GeV.
Figure A.16
Figure A.16: Transverse energy distributions for photon-jet data before (black) and after (blue) the unfolding correction in events where the leading jet has $p_T$ greater than 160 GeV.
Appendix B

Unfolding corrections

Here are presented the results obtained unfolding the transverse energy distributions using two different Monte Carlo sample for each event type. More than one Monte Carlo has been use to have a result as model indipendent as possible.

In Figure B.1 is the transverse energy distribution along $\eta$ before and after the unfolding correction for di-jet events. And in Figures B.2 and B.3 are the profiles according to the transverse momentum of the leading jet. In Figure B.4, B.5, B.6, B.7 and B.8 are the results for prompt photon events.
Figure B.1: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events using PYTHIA (red) or Perugia (blue).

Figure B.2: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ between 80 GeV/$c$ and 160 GeV/$c$ using PYTHIA (red) and Perugia (blue).
Figure B.3: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ greater than 160 GeV/$c$ using PYTHIA (red) and Perugia (blue).
Figure B.4: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events using PYTHIA (red) and HERWIG (blue).

Figure B.5: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_T$ between 20 GeV/$c$ and 40 GeV/$c$ using PYTHIA (red) and HERWIG (blue).

The same plots have been done for photon-jet events, Fig. B.4, B.5, B.6, B.7 and B.8.

The unfolding correction has a very small effect when considering events belonging to the same $p_T$ region.

A correction has also been found for events belonging to different regions in the $\Phi$ direction. As for the results shown in Chapter 3, for each event a “Toward”, “Away”, “TransMIN” and “TransMAX” regions in the $\Phi$ plane have been defined from the direction of the leading jet.
Figure B.6: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_t$ between 40 GeV/$c$ and 80 GeV/$c$ using PYTHIA (red) and HERWIG (blue).

Figure B.7: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_t$ between 80 GeV/$c$ and 160 GeV/$c$ using PYTHIA (red) and HERWIG (blue).
Figure B.8: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_t$ greater than 160 GeV/$c$ compared with PYTHIA (red) and HERWIG (ble).

For each $p_T$ region the results are shown in Figures B.9 and B.10 for di-jet events in all the four $\Phi$ regions, and in Fig. B.11, B.12, B.13 and B.14 for photon-jet. The unfolding correction is similar in photon-jet and di-jet events and it has a bigger effect in the two transverse regions (especially in the “TransMIN” region). There the energy deposited comes from the soft part of the interaction, it’s more sensitive to the underlying event, and therefore the calorimeter does not reconstruct the signal as good as for the hard objects. So the unfolding correction has a bigger effect.
Figure B.9: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ between 80 GeV/c and 160 GeV/c in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
Figure B.10: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ greater 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
Figure B.11: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_t$ between 20 GeV/$c$ and 40 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
Figure B.12: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for photon-jet events where the leading jet has $p_t$ between 40 GeV/$c$ and 80 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
Figure B.13: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ between 80 GeV/$c$ and 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
Figure B.14: $E_T$ mean as a function of $\eta$ before and after the unfolding correction for di-jet events where the leading jet has $p_t$ greater than 160 GeV/$c$ in the “Toward” (a), “TransMIN” (b), “Away” (c) and “TransMAX” (d) regions using PYTHIA (red) and Perugia (blue).
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