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*Medición de la producción de eventos con muchos jets
en colisiones protón-protón en el detector ATLAS*

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Measurement of the production of events with many jets in proton-proton collisions in the ATLAS experiment

Abstract

The work presented in this thesis has been carried out in the frame of the ATLAS experiment at the Large Hadron Collider. It is centred around the study of jets, their properties, their measurement in the calorimeter, and their production cross section. One of the main aspects of this thesis is the measurement of the differential cross section for the production of events with many jets, using the dataset collected by the ATLAS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV delivered by the LHC. The event selection requires that the four anti- k_t $R = 0.4$ jets in the event with the largest transverse momentum (p_T) within the rapidity range $|y| < 2.8$ are well separated ($\Delta R_{4j}^{\min} > 0.65$), all have $p_T > 64$ GeV, and include at least one jet with $p_T > 100$ GeV. The measurement considers a wide variety of variables, including distributions of jet momenta, invariant masses, minimum and maximum opening angles and other kinematic variables. At the same time, these variables were binned in regions of momenta and mass in order to probe more diverse kinematic regimes. The presented cross sections are corrected for detector effects and compared to some of the leading-order calculations of most widespread use in experimental physics, as well as next-to-leading-order theoretical predictions.

Other aspects of the work regarded the measurement of the momentum resolution of jets, and the design and assembly of new scintillator detectors in the calorimeter. The first subject involves the study of jet properties related to its energy resolution. This is an important measurement within the collaboration, as many analysis have jets in their final state. The resolution is affected by the data taking conditions, and it can worsen considerably when the instant luminosity and the energy of the collisions are increased. Consequently, the improvement of the jet resolution is one of the main goals in the corrections applied in jet calibration, which in turn need to be tested and validated through in situ methods.

The work related to scintillator detectors was carried out during the period in which data taking was halted, between 2013 and 2014, to allow for the repair and upgrade of the accelerator and the experiments. The irradiated scintillators used during Run 1 were removed for study, in order to make an improved design and assembly new detectors.

KEY WORDS: mutli-jet, QCD, jets physics, jet resolution, hadron-hadron scattering

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Introduction

Quantum Chromodynamics (QCD) is the theory that describes strong interactions within the Standard Model, and is one of the three fundamental blocks in the description of the interactions and components of matter. It has its historical roots in nuclear physics experiments, carried out with the aim of describing ordinary matter and its interactions. In a more modern perspective, the understanding of QCD is fundamental in the context of hadron colliders, as it describes the generation of the objects of highest cross section and one of the main sources of background in searches for new physics.

In the framework of QCD, jet production is interpreted as the final result of the fragmentation of quarks and gluons in a hard scatter collision and their subsequent hadronization. The calculations to describe this process can be performed at high energies via perturbative approximations of QCD theory (p QCD). But for lower energy ranges and wider production angles phenomenological input and modelling is fundamental, because this regime cannot be calculated from first principles. Both the theoretical calculations and the complimentary modelling benefit largely of high-precision jet cross-section measurements.

The work presented in this thesis was carried out between 2012 and 2016, within the ATLAS experiment at the European Centre for Nuclear Physics Research (CERN) in Geneva, Switzerland. The institute is home to some of the most relevant high energy physics experiments in the world, and in particular to the Large Hadron Collider (LHC) [68]. The LHC is the largest hadron collider ever built, boasting a 27 km ring that can accelerate protons to collide at a centre of mass energy of up to 14 TeV.

Particle jets are one of the main products in hadronic collisions. The primary subject of this thesis is the measurement of multijet production; these measurements are motivated by the need of stringent testing of the theoretical descriptions available for QCD processes. To this aim a thorough study was done in a particularly extensive variety of variables, and in a wide kinematic range. The need of well validated simulations that combine the theoretical predictions and the low energy/wide angle additions is present not only in this kind of study, but also in search analyses, as jets are one of the main components in many searches for new physics. Even though the large cross sections of jet production can provide the high statistics necessary for such tests, there is also the question of the large amount of noise generated in the high instant luminosity environment at the LHC. Studies to improve the jet measurement performance in order to accurately determine their energy and diminish the measuring fluctuations are of clear relevance in this context. This thesis presents the determination of jet energy resolution.

A brief theoretical frame is presented in chapter 1. It is divided in two parts: section 1.1 introduces the Standard Model theory, while section 1.2 discusses the modelling

of hadron collisions. Given that the Standard Model is a well known theory, it is not the aim of this chapter to be extensive, but to present a summary of the basic parts of the theory on which the work in this thesis relies. The theoretical description of events at a hadron collider is presented in a more thorough way, and the calculations and modelling needed to reproduce an event are specified. This last section is of particular relevance to the next chapter because it describes how the Monte Carlo simulations used throughout this thesis are obtained. In section 1.3 the various simulations used are specified and briefly described.

The ATLAS detector, as well as the surrounding LHC complex, are described in chapter 2. As well as providing a brief description of the accelerating process and of each component of the detector, information is given about the data taking conditions (section 2.2) and particular characteristics of hadronic events (section 2.3).

Chapter 3 is also related to the detector, but is considered separately as it describes the intervention in hardware upgrade activities. These activities took place during a period with no data taking, in which several repairs and upgrades were done to both the accelerator system and the experiment. In collaboration with the group in charge of the Tile Calorimeter in ATLAS, a contribution was made in the replacement of two different groups of scintillator detectors. This is the first contribution of its kind in the Buenos Aires ATLAS group.

In chapter 4 the jet performance activities are presented. Firstly, the reconstruction and calibration are described as they are carried out within the experiment for analysis using data collected during 2012. Then the jet energy resolution measurement is presented: the measurement methods are described, as well as the preliminary resolution results and performance studies.

Lastly, the multijet cross-section measurement is described in chapter 5. The motivation for this analysis is first presented, followed by the information pertaining the data selection and the simulations used. The analysis procedure is presented as well, with some additional studies that were necessary added as appendices. The results show the unfolded data distributions compared to several theoretical prediction, for ten different kinematic variables.

A brief summary of the work and an evaluation of the results is presented in the conclusions.

Chapter 1

Theoretical Introduction

This chapter is dedicated to describe the theoretical background behind the work presented in this thesis. The subject of the first section 1.1 is the Standard Model theory, which describes matter's interaction and composition. A brief introduction is given on how the different interactions are described within this framework. The second section 1.2 is dedicated to the description and modelling of events in hadron colliders. Although the Standard Model can successfully describe an interaction between any two particles, there are limitations to what can actually be calculated, both due to technical limitation and to the fact that more complex phenomena cannot be deduced from first principles. Consequently, most of what happens in a collision needs to be described using models, which are presented here.

1.1 The Standard Model

The Standard Model (SM) of particle physics [70, 92, 87] is the theoretical framework that so far best describes the composition and interactions of matter at a subatomic scale. Since its development the 1960's, it has been thoroughly tested and has been very successful in describing experimental observations. In addition, all the predicted phenomena have found experimental confirmation, the last one being the observation of the Higgs boson at the Large Hadron Collider in July 2012 [25, 61].

The SM is a renormalisable quantum field theory based on the total invariance under the gauge group:

$$SU(3)_C \otimes SU(2)_L \otimes SU(1)_Y \tag{1.1}$$

where $SU(3)_C$ is the symmetry group of the strong interaction and $SU(2)_L \otimes SU(1)_Y$ corresponds to the electroweak interaction. It describes the interactions between the constituents of matter, *fermions*, through the exchange of force mediators, *bosons*. Fermions can be separated into quarks and leptons, which are organized into three families or generations. The structure is repeated within each generation, but the masses of the particles vary from the lighter first generation to the heavier third one. Each quark and lepton has an additional anti-particle, with the same mass but opposite quantum numbers, thus doubling the number of fermions. A summary of the fermion family is provided in table 1.1. Fermions are described as spin-1/2 Dirac fields,

Generation	Name	Mass	Electric charge
Quarks			
1^{st}	Up (u)	2.3 MeV	+2/3
	Down (d)	4.8 MeV	-1/3
2^{nd}	Charm (c)	1.275 GeV	+2/3
	Strange (s)	95 MeV	-1/3
3^{rd}	Top (t)	173.5 GeV	+2/3
	Bottom (b)	4.65 GeV	-1/3
Leptons			
1^{st}	Electron (e)	0.51 MeV	-1
	Electron neutrino (ν_e)	< 2 eV	0
2^{nd}	Muon (μ)	105.66 MeV	-1
	Muon neutrino (ν_μ)	< 2 eV	0
3^{rd}	Tau (τ)	1.77 GeV	-1
	Tau neutrino (ν_τ)	< 2 eV	0

Table 1.1: Classification of fermion families with their masses and charges.

satisfying the lagrangian

$$\mathcal{L} = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi \quad (1.2)$$

where ψ is the fermion field, γ^μ are the Dirac matrices and m is the mass of the fermion.

Imposing the lagrangian to be invariant under local transformations of a given symmetry group requires the introduction of gauge fields (boson fields). The number of associated boson fields is equal to the number of generators of the symmetry group. The bosonic mediators of the SM can account for three out of the four fundamental interactions in Nature. Gravitational interactions are not described by the SM, which is one of the main motivations to look for physics beyond the SM (BSM). A summary of the boson classification is presented in table 1.2

Mediator	Mass [GeV]	Interaction	Electric charge	Spin
Gluon $\times 8$ (g)	0	strong	0	1
Photon (γ)	0	electromagnetic	0	1
Z	91.19	weak (neutral)	0	1
$W^\pm$	80.39	weak (charged)	± 1	1
Higgs (H)	125.7	-	0	0

Table 1.2: Summary of the boson classification in the Standard Model.

The study of the SM can be carried out separately for each type of interaction, dividing the lagrangian into two parts, one describing electroweak interactions and the other strong interactions. An additional term needs to be added to account for masses, and is called the Higgs sector:

$$\mathcal{L}_{SM} = \mathcal{L}_{EW} + \mathcal{L}_{QCD} + \mathcal{L}_H \quad (1.3)$$

1.1.1 Electroweak theory

The electroweak theory unifies the forces in the last two groups of equation 1.1, and describes the weak and electromagnetic interactions. The gauge group corresponding to weak interactions is $SU(2)_L$, and the state is described by the isospin (T). The generators of the group are the weak isospin operators $\hat{T} = \frac{\sigma_i}{2}, (i = 1, 2, 3)$, where σ_i are the three Pauli matrices. The subscript L comes from the fact that the weak interaction only affects left handed particles (right-handed anti-particles). Thus, when the fermion field is projected onto right and left components, the left-handed fermions transform as doublets, while the right-handed fermions as singlets:

$$\begin{aligned} f_L^i &= \begin{pmatrix} \nu_L^i \\ l_L^i \end{pmatrix}, \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix} \\ f_R^i &= l_R^i, u_R^i, d_R^i \end{aligned} \quad (1.4)$$

where i is the family (generation) index. The hypercharge, Y , is the property conserved through the second part of the term, $U(1)_Y$. The electric charge is related to the combination of T_3 and Y through the Gell-Mann Nishijima formula

$$\hat{Q} = \hat{T}_3 + \hat{Y}/2 \quad (1.5)$$

In order to respect local invariance under both symmetry groups, the covariant derivative is introduced in the lagrangian, in equation 1.2.

$$D_\mu = \partial_\mu - ig \vec{T} \vec{W}_\mu - ig' \frac{Y}{2} B_\mu \quad (1.6)$$

where g and g' are the coupling constants of the weak and hypercharge groups respectively, and W_μ^a and B_μ are the four corresponding gauge bosons. Self interaction should also be taken into account, which is why terms corresponding to interactions within the W_μ and B_μ fields are added as well. The electroweak lagrangian can then be written as the sum of the fermion and the gauge lagrangian:

$$\mathcal{L}_{EW} = \mathcal{L}_f + \mathcal{L}_{gauge} = \sum_{f=l,q} \bar{f} i \gamma^\mu D_\mu f - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \quad (1.7)$$

where $W_{\mu\nu}^i$ and $B_{\mu\nu}$ are the field tensors of the $SU(2)_L$ and $U(1)_Y$ groups respectively.

The introduction of mass terms for either the fermion or gauge fields break the local $SU(2)_L$ gauge invariance of the lagrangian. This is not in agreement with experimental measurements of their masses, which were indicated in tables 1.1 and 1.2. A mechanism was therefore introduced in order to generate non-zero masses while preserving the consistency of the theory at high energies. This is the Higgs-Englert-Brout mechanism, in which a new spinless boson - the Higgs boson - is defined.

1.1.2 The Higgs mechanism

This mechanism was proposed as a solution to the fact that gauge fields, as presented in equation 1.7, are massless. It postulates an elementary spin zero Higgs boson, whose coupling to other particles determines their masses. It consists of a scalar field with 4 real components, arranged into a complex scalar $SU(2)_L$ isospin doublet, $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$. The field is included in the lagrangian through its covariant derivative and a potential, where the covariant derivative D_μ is as defined in equation 1.6 and the potential, as well as the lagrangian is shown below.

$$\begin{aligned}\mathcal{L}_H &= |D_\mu \phi|^2 - V(\phi) \\ V(\phi) &= \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2\end{aligned}\tag{1.8}$$

The potential $V(\phi)$ depends on two parameters, μ and λ , and if their values are such that $\mu^2 < 0$ and $\lambda > 0$ the minimum of the ϕ field potential is degenerated. In other words, the fundamental vacuum state is no longer $SU(2)_L \otimes U(1)_Y$ invariant, and acquires a non-zero vacuum expectation value (VEV). The Goldstone theorem [74] states that a massless scalar (called Goldstone boson) appears when a continuous symmetry is spontaneously broken. These bosons can then be absorbed by a gauge field as a longitudinal polarization component and therefore, the gauge field acquires mass. In this case the gauge fields are those corresponding to the $W^\pm$ and Z^0 bosons, the photon being massless, taking three out of the four scalar field components. The remaining scalar field is the one with zero electric charge, and its value can be expanded around the minimum to obtain

$$\phi_0(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}\tag{1.9}$$

where $H(x)$ represents ground state fluctuations around the vacuum expectation value and corresponds to the massive electrically-neutral Higgs boson predicted in 1964.

The same Higgs isospin doublet is necessary for the generation of fermion masses. A term of the form $y_i \bar{\psi}_i \psi_j \phi$ is added to the lagrangian to account for interactions between the Higgs field and the fermionic field, where y_i is the coupling constant of Yukawa. Combining the resulting lagrangian terms and the scalar field expansion presented in 1.9, the additional terms for the fermion masses are obtained.

1.1.3 Quantum Chromo Dynamics

Quantum Chromo Dynamics (QCD) is the theory that describes strong interactions in the SM. It was developed as a way to describe the behaviour of the quarks being held together by the strong force, carried by gluons. It describes the state of a quark with a quantum number called *colour*, which can take three possible values, and corresponds to the $SU(3)_C$ group in equation 1.1 which is the starting global symmetry. The global gauge symmetry is promoted to a local one by introducing the covariant derivative

$$D_\mu = \partial_\mu - i4\pi\alpha_s T_a G_\mu^a\tag{1.10}$$

where α_s is the strong coupling constant, T_a are the $SU(3)_C$ generators (with $a=1 \dots 8$) and G_μ^a are the gluon fields. After introducing this term and a kinematic term for the gluon fields, the QCD lagrangian is given by:

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu)q - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.11)$$

where γ^μ are the Dirac matrices and q is a three-component vector corresponding to the different colour states of a quark type. Gluons transform under the adjoint representation, while quarks are in the fundamental representation of the $SU(3)_C$ group. The interactions between quarks and gluons are enclosed in the definition of the covariant derivative in equation 1.10: an interaction between a quark and a gluon will rotate the quark's colour in $SU(3)_C$ space. The field tensor $G_{\mu\nu}^a$ is given by:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - 4\pi\alpha_s f_{abc} G_\mu^b G_\nu^c \quad (1.12)$$

where f_{abc} are the structure constants of the $SU(3)_C$ group. The third term of the tensor describes the gluon self-interaction and is responsible for the non-abelian nature of QCD.

The value of the strong coupling constant α_s varies with the square of the scale of the interaction, Q^2 . In the high energy regime its value is sufficiently small so that it can be calculated using perturbation theory, giving the QCD theory good mathematical properties and predictive power. Its value vanishes for infinitely large energies, so that in this limit quarks can propagate freely, a property known as *asymptotic freedom*. In the opposite direction, the value of α_s increases for lower energy, to the point of diverging. This results in the *confinement* of quarks and gluons, which cannot appear as free particles. This means that when partons charged with colour start to separate from one another, the potential energy increases to the point that is energetically convenient to create a quark-antiquark pair with opposite charge from the first one from the vacuum. As a consequence, coloured partons produced in high-energy interactions will give place to a shower of hadrons, forming a *jet*. The importance of jet measurements rely in their direct relation to the scattering of quarks and gluons.

QCD interactions are dominant at the LHC because the colliding particles carry colour charge, and α_s is much larger than the electroweak coupling constants. Jets are, therefore, one of the most produced objects at the LHC.

1.2 Events in Hadron Colliders and their Modelling

Simulations are widely used in experimental high energy physics, and make one of the most important tools used in analyses. The aim of this section is to briefly describe how they are produced. In order to do so, however, it is also necessary to give a summarized explanation of what models and calculations can be used to describe the different components of a collision. Since the work in this thesis is mostly related to jet physics, particular attention will be placed in QCD simulations and jet generation.

1.2.1 Partons and Hadrons

The internal structure of particles such as protons and neutrons was experimentally inferred using deep inelastic scattering tests. In one of these experiments, for example, the internal structure of protons was probed by bombarding a hydrogen target with electrons. The results showed a larger number of large-angle deflected electrons than was expected, and it was then concluded that protons and neutrons were, unlike electrons, composite objects. They belong to the group of particles called *hadrons*, which are formed by point-like particles called *partons*. These partons were identified as the quarks and gluon fields described in section 1.1.3, which cannot be observed in isolation due to confinement. It is the hadronic cross section that is directly available through experiments, while the partonic cross sections have to be embedded within the hadronic environment.

In order to describe a collision, the partons can be considered to be free within the hadrons, so that it is valid to consider the interaction between them as a rapid interaction between two of their constituting partons. This interaction happens at a timescale much faster than the one at which interactions of partons within the hadron occur, so that both types of interactions can be separated in the hadronic cross section. This is known as factorization, and results in one part that corresponds to the parton cross section, which is process dependant and can be calculated with perturbative QCD theory (pQCD), and a second part that corresponds to the universal functions that describe the partonic content of the proton. These universal functions are called the Parton Distribution Functions, or PDFs, and describe how the hadron's momentum is distributed amongst its constituents. They are usually determined combining information from deep inelastic scattering experiments and hadron colliders.

The cross section for a proton-proton collision can therefore be expressed as

$$\sigma_{pp \rightarrow X} = \sum_{a,b} \int dx_a dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \hat{\sigma}_{ab \rightarrow X}(x_a p_a, x_b p_b, \mu_F^2, \mu_R^2) \quad (1.13)$$

where $f_i(x_i, \mu_F^2)$ is the PDF of a parton type i carrying a momentum fraction x_i , and μ_F is the factorization scale. The cross section for the partonic process, $\hat{\sigma}_{ab \rightarrow X}$, can be computed explicitly using perturbation theory to a fixed order, which introduces a dependence on the renormalization scale μ_R^2 (usually chosen equal to μ_F^2 and close to the process scale Q^2). This step is usually referred to as the Matrix Element (ME) calculation, because it involves the calculation of the scattering matrix relating the initial and final state particles of the process (initial state corresponds to the moment before the collision, and final to the moment after it). The ME can be expressed schematically for a given process as

$$\hat{\sigma}_{ab \rightarrow X} \sim \sum_{k=0}^{\infty} d\Phi_{X+k} \left| \sum_{l=0}^{\infty} \mathcal{M}_{X+k}^l \right|^2 \quad (1.14)$$

where the sum over k represents the additional ‘real emission’ corrections, called legs, and the sum over l represents the virtual corrections, or loops. Φ_{X+k} is the phase space for process X , with k legs.

By limiting the nested sums in equation 1.14 to include only specific values of k and l one can compute the ME to a fixed order in pQCD.

- $k = 0, l = 0$ corresponds to leading order (LO) for inclusive X production.
- $k = n, l = 0$ implies leading order for $X + n$ jets
- $k + l \leq n$ corresponds to a next-to-leading order, $N^n\text{LO}$, calculation for X (includes $N^{n-1}\text{LO}$ for $X + 1$ jet, $N^{n-2}\text{LO}$ for $X + 2$ jets, etc up to LO in $X + n$ jets)

In perturbation theory, the divergencies originated in the loops exactly cancel out with those from the real emissions, order by order. However, in a fixed order calculation the integration over the full momentum phase space will include configurations in which one or more of the k partons become collinear or soft, thus leading to singularities in the integration region. The integration needs to be modified, so that the calculation is done only for ‘hard, well separated’ momenta. The remaining part of the phase space is modelled by the *parton shower*, together with the higher order contributions that are not included in the ME calculation.

1.2.2 Parton Shower

Parton shower (PS) generators simulate the successive emission of quarks and gluons from the partons either in the final or initial state. It is an approximation, since it considers the parton emissions to be independent and does not consider virtual corrections. In the almost collinear splitting of a parton, the $n + 1$ -parton differential cross section can be related to the n -parton cross section before splitting through the probability that a parton will split into two at a virtuality scale, or invariant mass, q^2 , the outgoing parton carrying a fraction z of the original parton’s momentum:

$$d\sigma_{n+1} \approx d\sigma_n dP_i(z, q^2) \approx d\sigma_n \frac{\alpha_s}{2\pi} \frac{dq^2}{q^2} dz P_{ij}(z) \quad (1.15)$$

This relation can be applied to any process involving n partons in order to estimate σ_{n+1} . The probability diverges in the soft ($q = 0$) and collinear ($z = 0, 1$) regions, which is related to the non-perturbativity of QCD at low scales. But in practice this is unimportant, since partons so close together would not be identified by detectors, introducing an effective cut-off.

The implementation of the PS in Monte Carlo generators is done through the Sudakov form factors:

$$\Delta_i(q_1^2, q_2^2) = \exp \left(- \sum_j \int_{q_2^2}^{q_1^2} \int_{z_{min}}^{z_{max}} dP_i(z, q^2) \right) \quad (1.16)$$

The Sudakov form factor $\Delta_i(q_1^2, q_2^2)$ represents the probability for a parton to evolve from an initial scale q_1^2 to lower scale q_2^2 without splitting.

The showering is performed differently, and separately, for *initial* and *final-state radiation*. Final state radiation consists of partons produced by the outgoing partons in the interaction. Given an initial scale q_1^2 , radiation is emitted at a lower scale q_2^2

with a probability determined by the factors from equation 1.16. Unless q_2^2 becomes lower than the hadronization scale (see section 1.2.4), which is usually ~ 1 GeV, the process is repeated.

The *initial state radiation* consists of particles, mostly gluons and photons, radiated from the incoming hadrons in the collision. In this case there is an additional complication in the modelling of the shower, since the remaining energy will be the one entering the hard interaction. As a solution, Monte Carlo generators implement a *backward evolution* that starts by setting the correct parton momentum for the hard scatter, and then develop the shower backwards, with ancestor partons gaining energy at each emission.

1.2.3 Matrix Element and Parton Shower Matching

The introductions to ME calculations and PS modelling presented in the previous sections show that each is not sufficient on its own to describe a collision, but need to be combined for an accurate description of the final state. ME calculation will fail to describe the final state on their own, and need additional models to reproduce higher orders of the interaction. On the other hand the PS approach will produce poor results in configurations with wide angular distributions.

However this combination is not straight forward, due to the presence of overlaps in the phase space regions considered in both procedures. A given final state with one additional emission is generated both as the ME term of $X + 1$ parton, and the first radiation of the PS starting from the $X + 0$ parton state.

To remove this overlap the phase space covered by each method needs to be separated. This procedure is called *matching*; the two matching schemes most widely used are the Catani-Krauss-Kuhn-Webber (CKKW) [59] and the MLM method by Michelangelo Mangano [81].

The CKKW method bases the separation between ME and PS on a resolution scale y_{ini} determined using the k_t clustering algorithm [58] (clustering algorithms are described in detail in section 4.1). At a scale larger than y_{ini} , the cross sections and distributions are given by the ME, which is reweighted using the values of α_s in every vertex and the Sudakov form factors from every line between them. If the scale is lower than y_{ini} then the PS is used, but a veto is applied in order to cancel the dependence on y_{ini} . In this case, hard emissions in the shower evolution are vetoed if they have enough transverse momentum to produce a separate jet, according to the k_t algorithm.

The MLM matching method separates events generated from the ME into exclusive samples of n partons in the final state, and then develops the showering of each event. A clustering algorithm (the k_t algorithm mentioned above, or the cone algorithm) is used to group the event's clusters into jets of a certain radius, R_{jet} . The jets are then matched to the original partons in the event if $\Delta R(jet, parton) < R_{jet}$. Events with different numbers of jets and partons, or where some jets could not be matched, are discarded. If k is the maximum number of partons generated, an exception is made in the group of k partons, where events with k or more jets are accepted. The resulting groups, which originally had n partons, now have n jets, and are recombined in a single sample.

The part of an event that is accounted for in the parton shower (PS) depends on the order to which the ME was calculated. For example, in a 4-jets event generated

with a LO ME with $k = 2$, two out of the four jets will correspond to the PS. If, on the other hand, $k = 4$, then all the partons that generated the jets come from the ME. Most of the soft radiation added to the jets will come from the parton shower as well.

1.2.4 Hadronization

As the PS evolves, the QCD running coupling increases as the energy decreases below the hadronization scale of $Q_0 \approx 1$ GeV. At this point the confinement effect of QCD becomes relevant, as dynamics enter a phase in which the partons combine to form the hadrons observed in the final state. This process follows non-perturbative physics, and therefore requires a phenomenological approach based on general features of QCD. The most commonly used hadronization models are the string fragmentation and the cluster hadronization models.

In the string model [12, 88], the confinement between partons induced by the colour force is represented by a gluonic string. For a quark-antiquark pair, as the colour charges move apart, the string is stretched, and its potential energy grows. When the energy becomes of the order of hadron masses, it becomes energetically favourable for the string to break and create a new quark-antiquark pair. The two segments of string will stretch and break again, until all the energy has been converted into quark-antiquark pairs connected by short strings.

The cluster model [91, 82] relies on groupings of partons to form colourless clusters, after forcing the final state gluons to split into quark-antiquark pairs. The heaviest clusters can decay and split into smaller clusters. Most clusters will have masses below 3 GeV, and their decay into hadrons is simulated with three-body models with intermediate resonances.

1.2.5 Underlying Event

The full final state of a hadronic collision contains additional particles other than those corresponding to the process of interest, namely the hard interaction between two partons. They can be the product of different processes and are, in general, referred to as the *underlying event* (UE).

The UE can be considered to englobe multiple parton interactions (MPI) and beam remnant interactions (some definitions consider initial state radiation as part of the UE too). Due to the composite nature of hadrons, when two of these particles collide multiple simultaneous parton interactions can occur. This process usually occurs at a lower energy scale so that its accurate descriptions relies on models implemented in MC generators. These generators combine a perturbative description in terms of multiple scatterings with phenomenological models for soft, non-perturbative physics. Recently, the implementation of MPI effects in Monte Carlo models has quickly progressed through an increasing level of sophistication and complexity that has deep general implications for the LHC physics.

1.3 Monte Carlo Generators

Throughout this thesis, different Monte Carlo generators were used for the description of events; since the focus of the work was in jet physics, the generators used were those specialized in generating QCD. The availability of calculations both at LO and next-to-leading order (NLO) was exploited. A brief description of the main generators used is presented in this chapter, summarizing the way in which they reproduce the several steps of an event mentioned in the previous chapter. Additional tuning and corrections are also applied to these simulations, which are particular to the ATLAS experiment.

A complete simulation in the ATLAS experiment is based in a MC generator, that provides the ME calculation, the PS and the hadronization models. The PDF used to generate an event is usually either the NLO CT10 [78] or the LO distributions of CTEQ6L1 [85]. The simulations are complemented with information based on previous measurements, or on other simulations, such as pile up interactions and minimum bias events. The parameters that cannot be calculated from first principles, like the cut-off values for the matching, are determined via a set of *tunes* [19].

1.3.1 Leading Order Predictions

Leading order generators were the first available, and are still widely used in experimental high energy physics. Their lower computational cost allows for large datasets to be generated.

Pythia [90] is a general purpose MC generator of which two versions have been used, PYTHIA 6 and PYTHIA 8. The second is a complete rewrite in $C++$ of the previous FORTRAN version, in addition of containing new physics aspects. It is one of the generators of most widespread use, and has been available for more than 30 years. It can simulate $2 \rightarrow n$ ($n \leq 3$) processes between elementary particles such as $e, e+, p, \bar{p}$, in various combinations. It uses leading-logarithmic PS models which are based in p_T order evolution to generate initial and final state radiation. It can also provide MPI, fragmentation and decay. Hadronization is based on the Lund string fragmentation framework. PYTHIA 8 is used here to generate pp collisions in $2 \rightarrow 2$ processes including PS, hadronization and UE. PYTHIA 6 is used interfaced to another generator as will be detailed next.

Herwig++ [45] is also a general purpose MC generator for the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron collisions, with special emphasis on the accurate simulation of QCD radiation. It can generate either lepton or hadron collisions as $2 \rightarrow 2$ processes computed at LO in perturbation theory. The PS model used to generate initial and final state radiation is ordered by angular opening of the successive emissions. It used to be necessary to interface HERWIG with another generator in order to simulate MPI; these have now been incorporated through an eikonal multiple scattering model. The hadronization is done using the cluster model.

MadGraph [8] is a multi-leg generator that has the capability of computing tree-level and one-loop amplitudes for arbitrary processes. These computations are then com-

bined in different ways depending on the physical observable requested, with different perturbative accuracies and final-state descriptions. It has the interesting characteristic of being open source, and written in Python. MADGRAPH can generate the ME involving $2 \rightarrow n$ processes for up to $n = 6$ outgoing partons, which can then be interfaced with PYTHIA for the PS evolution, via an MLM matching scheme. The hadronisation therefore is the same as in PYTHIA. In this case MADGRAPH5 v1.5.12 was used with $n = 4$, with a PS provided by PYTHIA 6.427 [89], which is why the sample used will be referred to as MADGRAPH+PYTHIA. The jet-parton matching scale is set to 20 GeV.

1.3.2 Higher Order Predictions

The current state-of-the-art theoretical predictions for multi-jet events were put to the test in this work. The higher order calculations applied are computationally expensive, and it is therefore interesting to see how much of an improvement they present. They have only recently been combined with PS simulations [76], and in this case the simulations produced were not matched to PS or hadronisation.

BlackHat [50, 51] presents a stable and efficient computer program to compute experimentally-relevant cross sections through fixed order NLO calculation. It performs one-loop virtual corrections using the unitarity method and on-shell recursion, doing all the computations numerically. On-shell methods are one of the technologies that was developed with the aim of coping with the increasing computational difficulty of loop-amplitude calculations for increased number of outgoing particles. The remaining terms of the full NLO computation are obtained with AMEGIC++ [77, 73], part of SHERPA [71], which is why this simulation will be referred to as BLACKHAT/SHERPA. The simulation used in the multijet analysis was provided by the authors, and was not matched to PS.

NJet [43, 42] makes a numerical evaluation of the one-loop virtual corrections to multi-jet production in massless QCD. It implements an on-shell unitarity algorithm to construct primitive gluon amplitudes, with the additional feature of having the ability to compute amplitudes with an arbitrary number of external and internal quarks. The simulation used in the multijet analysis was provided by the authors of NJET. The Born matrix elements are evaluated with the COMIX generator [72] within SHERPA. SHERPA also performs the phase-space integration and infra-red subtraction via the Catani-Seymour dipole formalism. Therefore this sample is also a combination with SHERPA and will be referred to as NJET/SHERPA.

HEJ [9, 10, 11] is a perturbative framework that presents a different approach to the simulation of processes than the fixed order calculations that can be combined with PS presented before. It is based on the simplification of perturbative corrections in the case for large invariant mass between all emissions, seeking to correctly reproduce the part of the perturbative correction that controls the production of additional jets. The approximation is exact in the limit of large separation in rapidity between partons. It allows to build and approximate to all orders the hard-scattering ME for each exclusive parton multiplicity, for more than two outgoing jets. The resulting approximation

captures the hard, wide-angle emissions missed in the PS approach, focusing specifically on the part that is not done in a parton shower.

1.3.3 ATLAS Simulation

Monte Carlo simulations are sometimes compared directly to measured data, and can be used in some cases to estimate the effect the detector has in it. This information is not directly accessible in measured events, and sometimes the best approximation is provided by the difference between the *truth* information from the MC generators, and the *reconstructed* event in which detector effects have been included.

The interaction of particles with the ATLAS experiment is simulated using a GEANT4-based program [6]. It is a complex process in which the detector is built as accurately as possible, which requires the use of more than 300 different materials and 316k individual building blocks. The materials and the physical interactions are used as described by the Geant4 collaboration. Final-state particles with a mean lifetime $c\tau > 10$ mm are considered stable and propagated through the detector. Additional effects are combined with the input simulation, such as information about different placements of the interaction vertex, factors that take into account properties of the proton beam, and additional interactions between other protons in the the same event. In this way the amount of energy deposited by the particles in the detector is simulated. This serves as input to the next step, the digitization, which consists in the emulation of the signals that such energy deposits would produce in the detector. As of this point, the simulated event is completely equivalent to a real event, and can undergo the same reconstruction process as the data. It is in this step that the physical objects -electrons, muons, jets, etc...-are built. The particular reconstruction process for jets is presented in detail in chapter 4. A full account on the ATLAS simulation process can be found in ref. [18].

Chapter 2

The ATLAS Experiment

This chapter presents a short introduction to the accelerator complex and measuring devices. First a brief description of the accelerator complex is presented. Next the ATLAS experiment is described, with emphasis in the detector regions most relevant to this thesis.

2.1 The Large Hadron Collider

The Large Hadron Collider [68] at CERN is currently the largest hadron accelerator in the world. It is located in the border between France and Switzerland, and was built in the same 27-kilometre, 100 m below ground tunnel that housed the Large Electron Positron Collider (LEP) until the year 2000. Since it began its operation in 2009, it has provided the experiments around it with proton-proton, proton-lead and lead-lead collisions at energies ranging between 45 GeV and 13 TeV. With its unprecedented high energy and luminosity, it has been the basis for the discovery of the Higgs boson, an astounding amount of new and high-precision measurements, and leads the search for new physics.

Before entering the LHC, protons are accelerated from rest using a sequence of various pre-accelerators. They are extracted from a simple bottle of hydrogen gas, which is stripped from its electrons with an electric field, and directed into Linac2. This first step is a linear accelerator, and the resulting 50 MeV beam is injected into the Proton Synchrotron Booster (PSB), which accelerates the protons to 1.4 GeV. Then, the Proton Synchrotron (PS) further increases the energy to 25 GeV, and finally the Super Proton Synchrotron (SPS) produces the beam which will be injected into the two LHC beam pipes at 450 GeV. The accelerated protons are injected into the two beam pipes grouped into *bunches*, containing around 10^{11} protons each. The picture shown in Fig. 2.1 presents the accelerators previously mentioned, as well as other accelerators that are connected to the LHC complex and the many experiments which rely on the complex for data-taking. In particular, the four main LHC experiments can be found at the points at which the proton beams are focused and made to intersect. ATLAS [15] and CMS [60] are the two larger multi-purpose experiments, while LHCb [80] and ALICE [7] are focused in b-physics and lead-ions collisions respectively.

The LHC was originally designed to achieve collisions of two proton beams circulating in opposite directions, at a centre of mass $\sqrt{s}$ of 14 TeV. Due to a malfunction

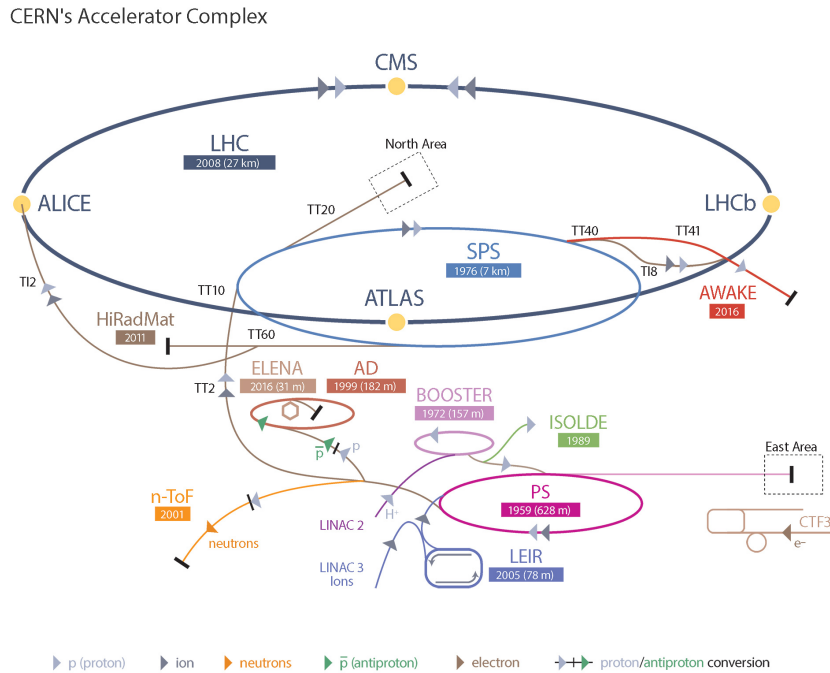


Figure 2.1: Schema of the CERN accelerator complex, showing the LHC together with its pre-acceleration stages, as well as other independent projects. The first year of operation and the length of each accelerator is indicated under its name, and the type of particle is indicated by the colour. Several experiments are indicated as well, in particular the four main experiments at the LHC.

in 2008, it was forced to delay its start up for a year, and the energy of the beam was temporarily reduced, reaching a maximum of $\sqrt{s} = 8$ TeV in 2012. This first data-taking period in 2010-2012 is referred to as Run 1. The following two years, 2013-2014, were dedicated to upgrade and maintenance activities, both for the accelerator and the experiments in it. This first long shutdown (LS1) was a period of intense activity, in which the necessary changes in the LHC were made in order to safely achieve the design luminosity and energy during Run 2, which began in 2015 and is on-going.

The second defining characteristic of the LHC is the luminosity $\mathcal{L}$, mentioned before. It connects the rate of events to the cross section of a given process:

$$R = \frac{dN}{dt} = \mathcal{L}\sigma$$

The LHC was set to achieve a design instant luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with the beams containing around 2000 bunches within 25 ns of one another.

2.2 Run 1 Data

Due to the 2008 incident mentioned before, the first run of the LHC was performed at lower energies than its design stipulated. Energy was ramped up during 2010, and

in 2011 data was collected at $\sqrt{s} = 7$ TeV. During 2012 the LHC delivered the largest dataset of Run 1, at $\sqrt{s} = 8$ TeV.

Fig. 2.2 presents the integrated luminosity as a function of time for both 2011 and 2012. There is a small difference when comparing the delivered luminosity in green and the recorded one in yellow. This is because the first counts from the start of the stable beam until the LHC requests ATLAS to put the detector in *safe standby mode*, before the beam dump or to perform beam studies, while the second excludes the time it takes ATLAS to be ready for data taking after the beam is stable, as well as reflecting data acquisition inefficiencies. There is a third reduction in the available data when applying data quality criteria, such as the one that will be described in section 5.2. However it can be seen that the final data acquisition for ATLAS during this period was highly efficient, and the figure presented reflects the excellent performance for both the LHC and ATLAS. The total integrated luminosity for physics was $\mathcal{L} = 4.51 \text{ fb}^{-1}$ for 2011 and $\mathcal{L} = 20.3 \text{ fb}^{-1}$ for 2012, determined with uncertainties of $\pm 1.8\%$ [28] and $\pm 2.8\%$ respectively.

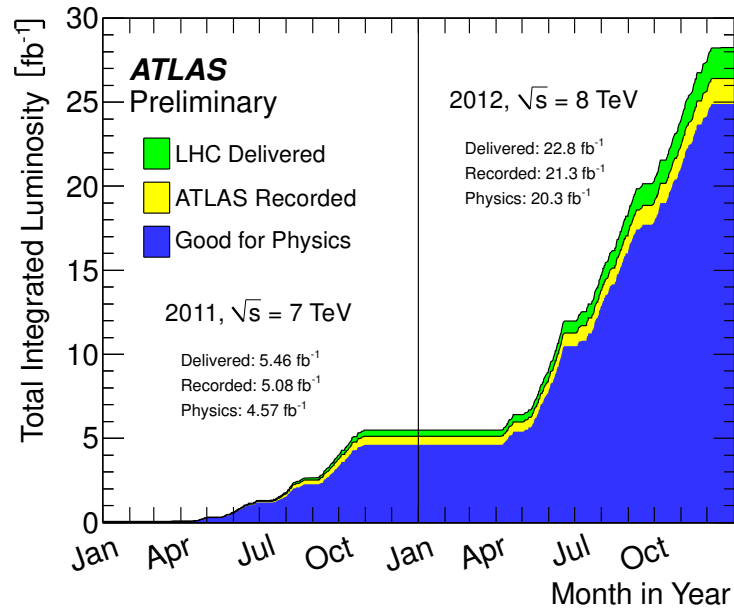


Figure 2.2: Cumulative luminosity as a function of time which was delivered by the LHC (green), recorded by ATLAS (yellow) and certified to have good data quality (blue), for 2011 and 2012.

The design luminosity goal was achieved and surpassed during Run 2, but during Run 1 the peak instant luminosity was $7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, with the beams containing up to 1380 bunches, such that collisions were produced every 50 ns. These parameters: the instant luminosity, the number of protons per bunch, and the spacing between bunches, determine some of the noise characteristics of the registered collisions. Since a pp collision is in essence a stochastic process, high luminosities enhance the probability of more than one pp scattering processes occurring at a bunch crossing. The expected average number of inelastic collisions per bunch crossing is referred to as $\langle \mu \rangle$. This variable follows a Poisson distribution whose mean is proportional to $\mathcal{L}_0$. The

characteristics of this distribution is sensitive to many other factors, such as beam optics and impact parameters; all factors combined produce clearly different $\langle\mu\rangle$ distributions for different data-taking periods, as can be appreciated in figure 2.3, where the distributions for 2011 and 2012 data are shown separately.

2.3 Pile-up

In general, *pile-up* is the effect that causes energy from other proton collisions to be measured within the hard scatter of interest, interfering with its correct energy measurement. The first type of pile up is a direct consequence of the high instant luminosity, and therefore the increased probability that more than one pair of protons will interact in each event. The pile-up arising from the multiple pp collisions happening in the event is referred to as *in-time pile-up*. In-time pile-up conditions can be reasonably estimated by the number of primary vertices (N_{PV}), which are the different pp interactions measured in an event using the tracking system in ATLAS. The second form of pile-up is a consequence of the short time separation between subsequent bunches. Although reasonably fast, the signal generated by each collision has a longer decay time than the bunch spacing, depending on the sub-detector in question. As a result the signal from a bunch crossing can affect the shape and level of the one that comes next. This case is called *out-of-time pile-up*.

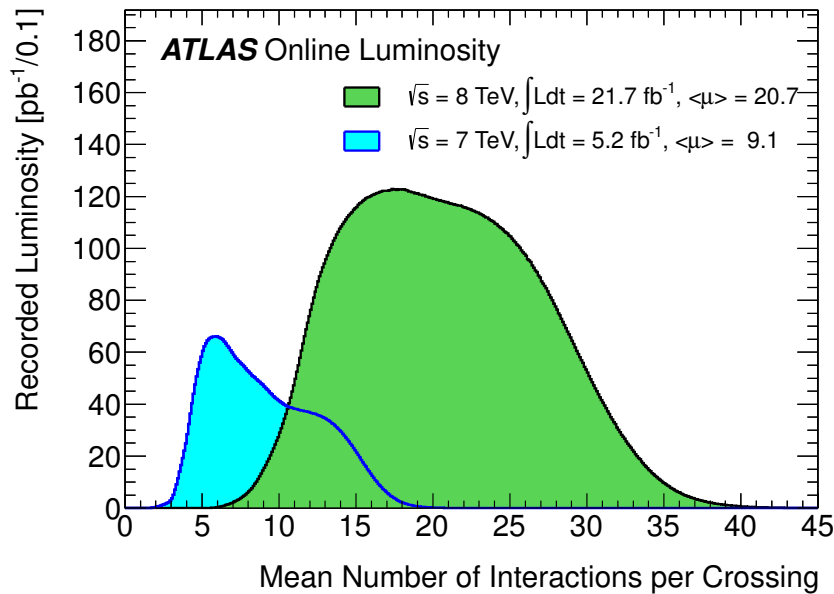


Figure 2.3: Distribution of the mean number of interactions per bunch crossing for the full 2011 and 2012 pp runs.

2.4 The ATLAS Detector

The ATLAS experiment (A Toroidal LHC ApparatuS) [15] is a multi-purpose particle physics detector located in one of the intersection point at the LHC. The high interaction rates, radiation doses, particle multiplicities and energies, as well as the requirements for precision measurements, set the standards to which this detector was designed. It is the biggest detector of its kind ever built (about 46 m long, 25 m wide and weights 7000 t), and presents a forward-backward symmetric cylindrical geometry with nearly 4π coverage in solid angle. A brief description of general aspects of the experimental setup, such as relevant materials, coverage and resolution, will be presented in this section. A complete description of the experiment can be found in the technical design report [15].

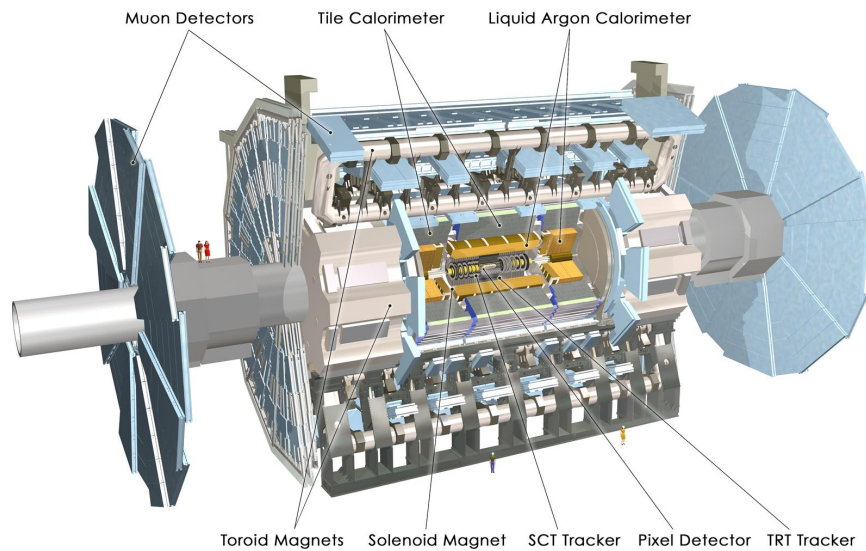


Figure 2.4: Computer generated sketch of the ATLAS detector. The different subdetectors and magnet systems are labelled, and two persons are presented for scale.

The layout of the detector is based on four superconducting magnet systems; the different detector subsystems are layered concentrically one after the other, as can be appreciated in figure 2.4. The subdetectors can be grouped into three main systems, ordered by their distance to the beam pipe:

- The Inner Detector is the closest system to the interaction point, and is immersed in a magnetic field generated by the superconducting solenoid that surrounds it. It constitutes a tracking system used to identify and measure the momenta of charged particles, as well as identifying the interaction vertices, by reconstructing their tracks
- The Calorimeters are used to measure the energy of neutral and charged particles. To this purpose they are designed to stop most of the particles generated in the collisions, except muons and neutrinos.

- The Muon Spectrometer is the outermost layer, and the largest component of ATLAS. It is designed to measure the properties of muons.

2.4.1 Coordinate System and Nomenclature

The coordinate system and nomenclature used to describe the ATLAS detector and the particles emerging from the pp collisions are briefly summarised here, since they will be used repeatedly in this document. The nominal interaction point of the protons is defined as the origin of a right-handed Cartesian coordinate system. The beam direction defines the z -axis, and the $x - y$ plane is the transverse direction. The positive x -axis is defined as pointing from the interaction point (IP) to the centre of the LHC ring and the positive y -axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z . The azimuthal angle ϕ is measured as usual around the beam axis, and the polar angle θ is the angle from the beam axis and has a range $0 - \pi$.

Since the momentum of the colliding partons along the z -axis is unknown, it is useful to define the transverse component of variables of interest, like energy and momentum, defined as the projection on the $x - y$ plane, which are boost-invariant along the z -axis:

$$E_T = E \sin \theta \quad p_T = p \sin \theta$$

Accordingly, another commonly used variable is the rapidity (y), because it is boost invariant along the z -axis. It is an angular variable dependent on θ as

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

which for vanishing particle mass is equal to the pseudorapidity (η)

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right)$$

Another commonly used variable is the angular distance ΔR , defined in the pseudorapidity-azimuthal angle space as

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \quad (2.1)$$

or in the rapidity-azimuthal angle space as

$$\Delta R_{i,j} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \quad (2.2)$$

2.4.2 Magnet System

The measurement of charged particles' momenta is based on their deflection in a magnetic field. The magnet system depicted in a sketch in figure 2.5 represents a particular characteristic of the ATLAS experiment, largely defining its size and layout. It is composed of four large superconducting magnets, a central solenoid and three open-air toroids, designed to provide a field mostly orthogonal to the particle trajectory.

The central solenoid surrounds the Inner Detector and provides a magnetic field parallel to the beam axis bending charged particles in the ϕ direction. At the IP the value of the magnetic field is 2 T and it remains constant in the radial direction. As

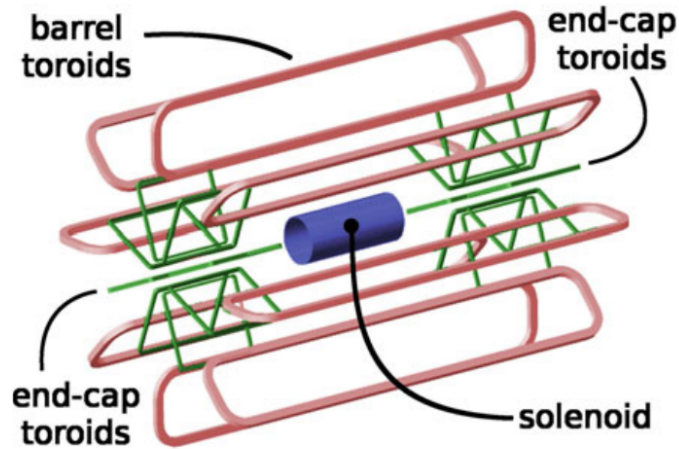


Figure 2.5: Simple sketch depicting the magnet system in ATLAS.

the distance from the IP increases in the z direction, the field strength decreases as a result of the finite size of the solenoid.

The toroid system produces the field needed by the muon spectrometer to deflect particles in the η direction: two end-cap toroids at the two extremes of the detector and a barrel toroid centrally located around the calorimeters. Each toroid is composed of eight independent coils equally distributed in the azimuthal plane. The barrel toroid generates a magnetic field of 3.9 T while the end-cap produces a field of 4.1 T.

2.4.3 Inner Detector

The Inner Detector (ID) [17], the closest sub-detector to the IP, is a complex high precision tracking system aimed at reconstructing the tracks of charged particles and the various interaction vertices of the collision. It has full ϕ coverage and reaches up to $|\eta| < 2.5$. It is divided in three different concentric subdetectors, as can be seen in the sketch in figure 2.6. The detector design required fast response electronics, good radiation resistance and reducing to a minimum the amount of material to be placed in front of the calorimeters to avoid degrading the energy measurement.

Silicon Pixel Detector The part of the detector closest to the IP is the silicon pixel, composed of three concentric layers of $50\text{ }\mu\text{m}$ by $400\text{ }\mu\text{m}$ semiconducting pixels. An additional 3 layered disc is placed at each end-cap. A very fine granularity is achieved, with a spatial resolution of $10\text{ }\mu\text{m}$ in the $R - \phi$ plane and $115\text{ }\mu\text{m}$ in the z direction (which corresponds to R in the end-caps). The very first layer, called the B-layer, is only 50.5 mm away from the IP, and it allows for the reconstruction of secondary vertices associated with the production of long-lived particles such as b-hadrons. This information is very useful to identify jets originating from the fragmentation of b-quarks.

Semi-Conductor Tracker (SCT) The following layer is the semi-conductor tracker (SCT). It is a silicon microstrip detector consisting of 4 layers of detectors in

the central barrel and 9 discs in the end-caps, allowing coverage up to $|\eta| < 2.5$. In the barrel, silicon strips are arranged parallel to the beam line, while in the disks, the strips are oriented radially. The spatial resolution achieved is $17\text{ }\mu\text{m}$ in $R - \phi$ and $580\text{ }\mu\text{m}$ in z (R) in the barrel (end-cap) region.

Transition Radiation Tracker (TRT) Lastly one finds the transition radiation tracker (TRT). It consists of 4 mm-diameter gaseous straw tubes interleaved with transition radiation material, enabling tracking for $|\eta| < 2$. The space between the tubes is filled with plastic material (polyethylene) in order to produce the transition radiation. The emission of photons depends on the Lorentz boost $\gamma(E/m)$ of the particles and, in the energy range of interest, is present only for electrons. The TRT is only segmented in $R - \phi$, and it provides a resolution of $130\text{ }\mu\text{m}$ per straw.

Using the combined information from this three types of tracking detectors tracks are built with a high precision, which translates to a resolution of 1.6% for tracks with $p_T \sim 1\text{ GeV}$ and of about 50% for $p_T \sim 1\text{ TeV}$.

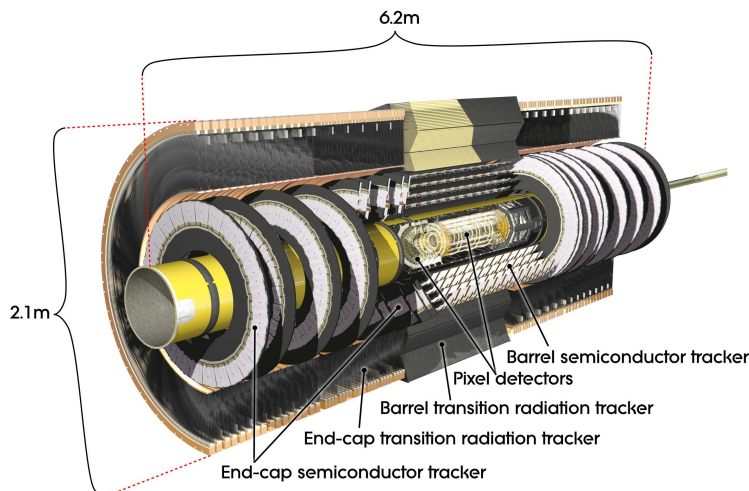


Figure 2.6: Computer generated sketch of the ID, with cut-offs that allow to appreciate its internal structure and its various layers.

2.4.4 Calorimeters

The ATLAS calorimeter is the central piece of the detector. It has full coverage in ϕ and reaches $|\eta| < 4.9$; the wide coverage allows for the correct reconstruction of the energy of the event, and in particular helps to accurately determine the missing energy in physics processes where weakly interacting particles are expected. The calorimetry system is divided into two subdetectors, an electromagnetic and a hadronic calorimeter, both divided into a central barrel with finer granularity and two symmetric, more coarse end-caps, as shown in figure 2.7. They are *sampling* calorimeters, meaning that intercalated layers of absorber and active materials are used so as to stop the arriving particles, absorbing most of its energy and producing a signal proportional to the deposited energy. They are also *non-compensating* calorimeters, which means that hadrons, which interact strongly with the nuclei in the active material, will have a lower

response than particles of the same energy that have a predominantly electromagnetic interaction.

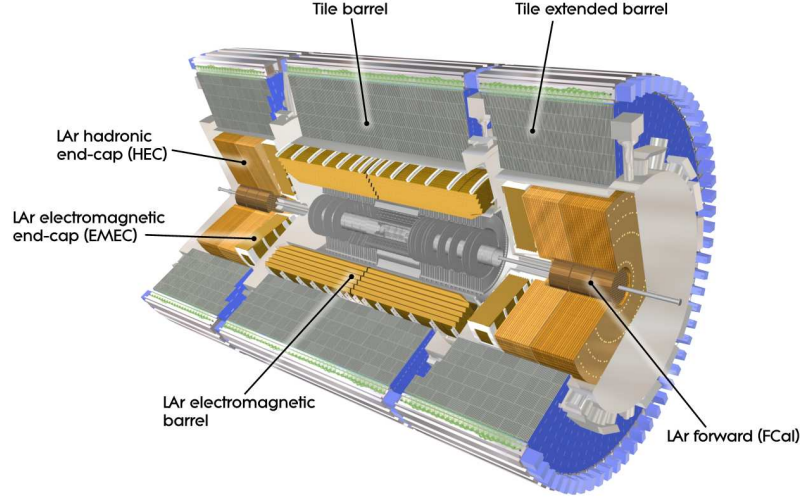


Figure 2.7: Computer generated sketch showing the different subsystems of the calorimeter system.

Electromagnetic Calorimeter The innermost type of calorimeter is the electromagnetic calorimeter (ECAL). The central barrel covers the range up to $|\eta| < 1.475$, and the end-caps extend it to $1.375 < |\eta| < 3.2$. It uses liquid argon (LAr) as active material, and thus must be contained within cryostats kept at 80 K using liquid nitrogen. LAr was chosen for its intrinsic linear behaviour, high ionization yield, stability and radiation hardness. The absorber material is lead both in the central barrel and end-caps (EMB and EMEC). The absorber plates are shaped into accordions and oriented in the radial direction, as shown in the sketch in figure 2.8a, which allows for a full symmetric coverage without cracks in the azimuthal direction.

The ECAL is segmented into 3 layers and spans a total thickness of 22 to 33 radiation lengths (X_0), increasing with η ; the span in the end-caps is $24\text{--}38 X_0$. This allows to fully contain electrons of energies up to a few TeV. The first layer, with a thickness of $4.3 X_0$, is finely divided into segments of $\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$ in order to measure precisely the direction in pseudorapidity of the particles. The strip layer is of particular importance for photon and electron identification and, combined with the information from the second layer, can be used to obtain precise information on the photon's production vertex. The second layer is $16X_0$ thick, represents most of the thickness of the calorimeter and absorbs about 80% of the energy in electromagnetic showers. It is divided into towers, each of size $\Delta\eta \times \Delta\phi = 0.25 \times 0.25$ forming a 3×7 matrix. The third layer is just $2X_0$ thick, and has coarser granularity, as the towers measure $\Delta\eta \times \Delta\phi = 0.05 \times 0.0245$. It is mainly used to estimate the amount of energy lost beyond the ECAL. In the central region an additional pre-sampler layer is present. The information from this layer can be used to estimate the energy lost by the electron

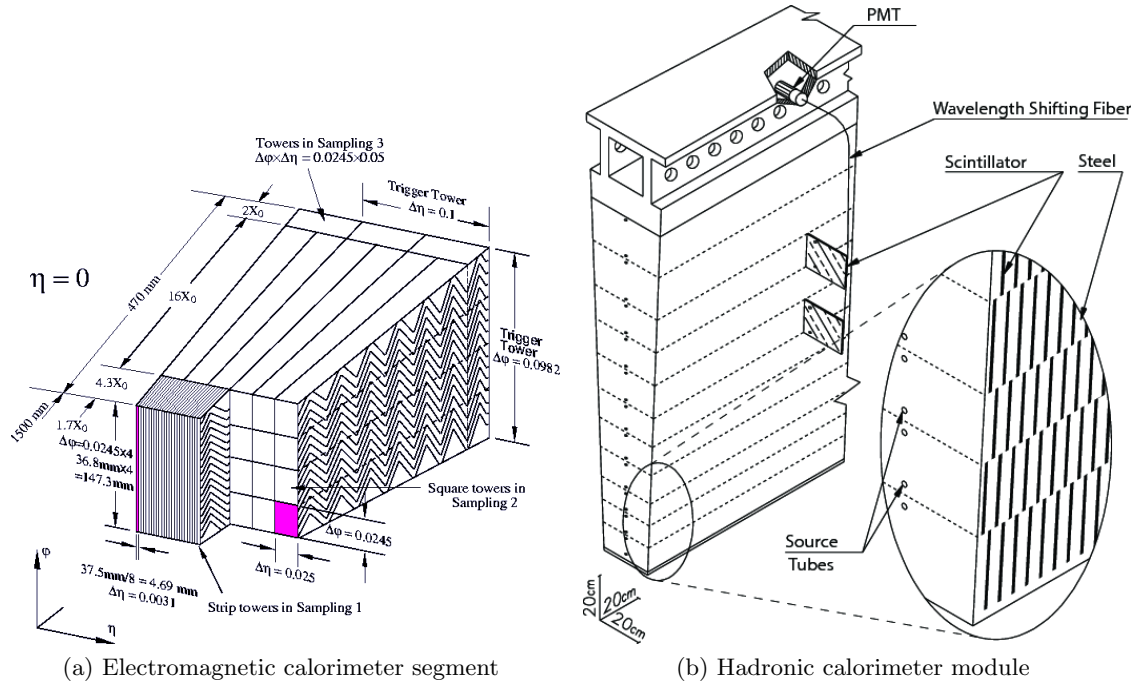


Figure 2.8: Sketches that detail the design of (a) a part of the barrel electromagnetic calorimeter and (b) a module of the tile calorimeter.

or photon in the passive material of the solenoid (and cryostat) that surrounds the ECAL.

The target energy resolution for the ATLAS electromagnetic calorimeters as specified in the technical design report [13] is:

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{17\%}{E} \oplus 0.7\%$$

Hadronic Calorimeter The hadronic calorimeter surrounds ECAL, and comprises 3 different types of calorimeter according to the different radiation conditions and resolution requirements. In the central area one finds the Tile Calorimeter (Tile-Cal) [14]. It consists of a central barrel section (LB) covering the region $|\eta| < 1.0$ and two extended barrels (EB) covering the region $0.8 < |\eta| < 1.7$ which use a polystyrene scintillator tile as the active material and steel plates as the absorber medium. Each structure is divided into 64 wedges of $\Delta\phi \sim 0.1$ for full azimuthal coverage, that go from 2 m from the IP to 4 m, measuring 2 m in the radial direction. A wedge is in itself divided into different sized cells, going from 0.1×0.1 to 0.2×0.2 as the distance to the IP increases. The sketch in figure 2.8b shows the structure of one of these TileCal modules. The photomultiplier tubes (PMTs) used to collect the signal can also be appreciated on the top of the module, in the electronics rack. The signal is collected by wavelength-shifting (WLS) fibres that run on each side of every scintillator tile, and are then grouped so that each cell is read by two PMTs; the PMT is then linked to one read-out channel.

The region between the LB and the EBs has a gap through which cooling and power supply services pass, and therefore is less instrumented. Some special detectors are located there in order to estimate the energy loss in this region. The gap scintillators cover the region of $1.0 < |\eta| < 1.2$, while the crack scintillators are installed on the front of the LAr end-cap and cover $1.2 < |\eta| < 1.6$. More information on these last detectors can be found in chapter 3.

There are two remaining hadronic calorimeters, both aimed at covering higher rapidity regions: the Hadronic End-Cap (HEC) and the Forward Calorimeter (FCal). They both use LAr as the active medium, like ECAL, but the absorber is copper in HEC and copper-tungsten in FCal. The material choice is due to the high radiation exposure in the region. HEC covers the range of $1.5 < |\eta| < 3.2$, with a granularity that increases with η . For $|\eta| < 2.5$ its first two layers are divided into $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ cells, while the third one is 0.2×0.1 . For $2.5 < |\eta| < 3.2$ all the layers have the latter cell size. The Forward Calorimeter covers the most forward region, $3.1 < |\eta| < 4.9$, giving the ATLAS calorimeter its high hermeticity which allows to minimize energy loss.

The coverage in η can be better appreciated in figure 2.9, where cell divisions are shown for the EB and LB.

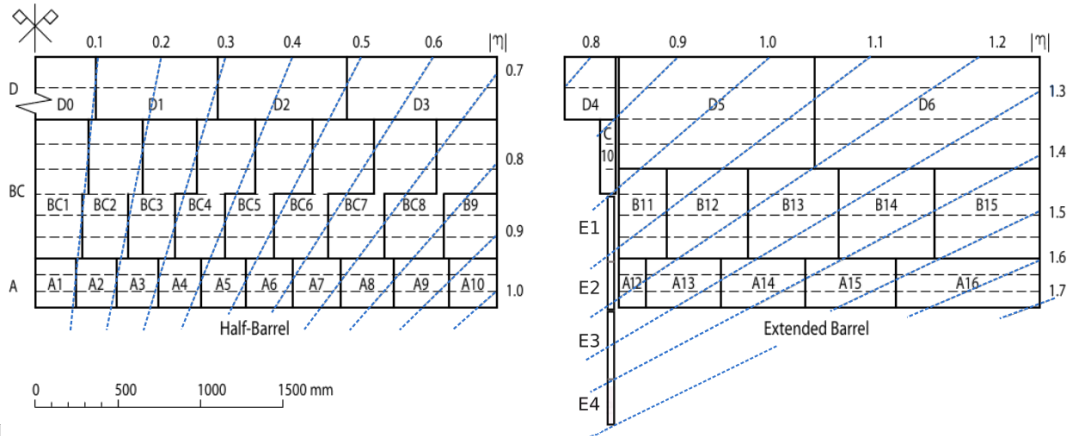


Figure 2.9: Sketch of a transverse cut in the hadronic calorimeter, showing the division into cells and the corresponding η range.

The hadronic calorimeter is fundamental when measuring the jet energy. A more detailed description of its performance can be found in chapter 4

2.4.5 Muon Spectrometer

The muon spectrometer is the most outer layer of subdetectors [16]. The precision chambers that conform it combine with the magnetic field generated by the toroids to provide the measurement of the muon momentum for $|\eta| < 2.7$. It has been built using four different types of detector chambers, which are distributed differently in the barrel and end-cap regions, as can be seen in figure 2.10: the barrel consists of three cylindrical layers around the beam axis, one within each other and one on the inside of the toroid magnet; in the end-caps the chambers are arranged perpendicular

to the beam, into discs. The different technologies were chosen following the resolution and timing requirements for precise measurements and triggering, as well as the large variation in particle flux with rapidity. Thus, the four types of chambers can be divided into precision chambers and trigger chambers.

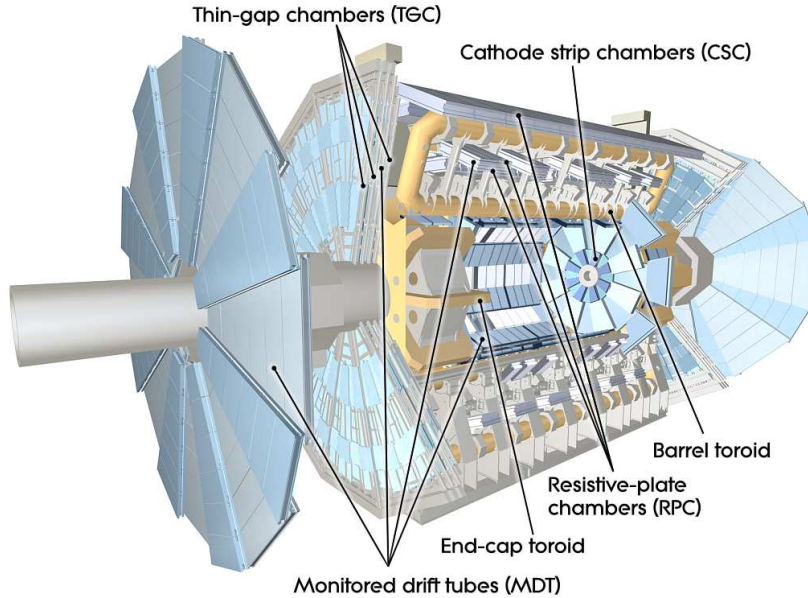


Figure 2.10: Computer generated sketch showing the different components of the calorimeter system.

Precision Chambers One of the precision-type chambers are the monitored drift-tube chambers (MDT). Each chamber contains 6 to 8 drift tubes filled with a mixture of argon and carbon dioxide, while the wire within them is made of tungsten and rhenium that generates a radial electric field. A muon passing through a tube will ionize the gas, and the resulting electrons will drift towards the wire due to the potential applied. The spatial resolution achieved is $80\text{ }\mu\text{m}$ for each tube, $40\text{ }\mu\text{m}$ for a complete chamber, and $30\text{ }\mu\text{m}$ when the three layers of MDTs are taken into account; this allows for very good track reconstruction and low number of fake tracks. These chambers are used to cover the largest area, of $|\eta| < 2.7$ (2.0 in the inner layer). But around the area of $|\eta| < 2.0$ in the end-caps the counting rate exceeds the MDTs operation limit of 150 Hz cm^{-2} , which is why the first layer is conformed of cathode strip chambers (CSC). Their operation limit is 1000 Hz cm^{-2} . They are multi-wire proportional chambers, with wires oriented in the radial direction within 2.5 mm of one another, and use the same gas mixture as the MDTs. The spatial resolution of the four layers of CSCs is $40\text{ }\mu\text{m}$ in the bending plane and 5 mm in the non-bending one. The maximum drift time for signal collection is 40 ns compared to the 700 ns of the MDTs, which gives the possibility to achieve higher acquisition rates.

Trigger Chambers A different, faster design is needed in the triggering chambers. The Resistive Plate Chambers (RPCs) follow a different concept, consisting of two resistive Bakelite plates and a gas mixture in the middle ($94.7\%C_2H_2F_4$, $5\%Iso$ –

C_4H_{10} , 0.3% SF_6). The electron avalanches are collected by two sets of orthogonal strips that provide position and time resolutions of 1 cm and 1 ns. The small time resolution allows for individual bunch-crossing discrimination, and these chambers provide the ϕ coordinate for the muon tracks since the MDTs can only measure the position in η .

Similarly to the CPCs, the Thin Gap Chambers (TGC) are multi-wire chambers, but the wire-to-cathode distance was made smaller than the wire-to-wire distance to achieve smaller drift times. They cover the region of $1.05 < |\eta| < 2.7$ (2.4 for triggering) in the end-cap wheels. Their timing resolution is comparable to the RPCs, and they provide the position with a resolution between 2 – 7 mm for both coordinates.

2.5 Trigger System

The LHC achieved its design goal of one bunch crossing every 25 ns, and collisions were delivered at a rate of ~ 40 MHz. Storing the information for every event produced in ATLAS would require to read and register the information provided by approximately 100 million readout channels from all subsystems, taking around 1.5 MB in disk space each time. But it is highly unlikely that every one of these events contains interesting physics; even if they did, the amount of disk space and speed required are unfeasible with current technology. The aim of the ATLAS trigger system is to quickly scan the event for signs of interesting physics (where the interesting characteristics must be carefully decided), and only record events which containing, reducing the event rate from the one received to its readout capacity of 200 Hz.

The trigger for Run 1 data is divided into three consecutive stages, or levels. Each level examines more information, in a more detailed way, in order to decide whether or not to keep an event. For an event to be saved, it has to pass one of the *trigger chains*, consisting of a Level 1 (L1), Level 2 (L2) and event filter (EF) trigger. A set of trigger chains conforms a *trigger menu*, which must be set for each run.

L1 triggers are the hardware-based triggers that make the first decision, based on coarse measurements from the calorimeters and the muon detectors. Mainly, they look for events that contain objects with a transverse energy larger than some threshold, and/or hits in the muon detector consistent with a track. The L1 trigger reduces the output rate to a maximum of 75 kHz, and also defines regions in $\eta - \phi$ that contain features of interest, called regions of interest or RoIs, to be analysed in the next stage.

The following two levels are software-based, and combined are usually referred to as the high level trigger, or HLT. The L2 trigger adds tracking information to the RoIs selected in L1 to build candidate objects (electrons, muons, photons), and calculates their energy and position. By applying a tighter selection on these objects it achieves an output rate close to 3 kHz. The events passing this selection reach the EF trigger, which will make a decision using objects built with the same event reconstruction software that is used offline. This means the entire event information is used, and the different triggers select for events containing objects, or combinations of objects, that pass certain thresholds; the thresholds can now be in energy or other characteristics, such as isolation or quality. For example, one could require at least four jets with $p_T > 45$ GeV, or two isolated high quality electrons with $p_T > 15$ GeV. The choice of these combinations is done carefully, to cover the needs of as many analysis as possible while taking into account the limited band width available for storage.

The most important characterization that needs to be made of a trigger chain before it is used is its efficiency as a function of the variable of interest; this is usually the object's momentum, i.e. the jet momentum in a jet trigger. It is evaluated by considering the full sample of events that should activate the trigger, and then checking what percentage is actually saved. Trigger inefficiencies have many sources, such as the differences between online and offline event reconstruction, calibrations, etc. It is desirable to use triggers in a way that they are close to the 99% efficiency point in order to avoid biases in the event selection. This is attained by choosing angular and momentum cuts higher than the values that are associated to the trigger.

One way to achieve a large variety of event selections while still maintaining the rates within the possible limits is to apply prescales at any point in the trigger chain. When a prescale of P is applied to a trigger, it means that one in every P events that pass this trigger will be randomly discarded. This is a useful resource that allows the experiment to keep similar quantities of data for events that have very different production rates.

Chapter 3

Scintillator Detectors Hardware

The Minimum Bias Trigger Scintillator and the Crack and Gap Scintillators are two groups of thin scintillator detectors managed within the calorimetry groups. They are located in the area between the central barrel and the extended barrel, and although similar in construction have two very different functions. The aim of this chapter is to briefly describe the work done during the shutdown LS1 in these systems.

The Crack Scintillators As mentioned in the previous chapter, section 2.4.4, the areas between the central and the extended barrels of the calorimeter are poorly instrumented. With the aim to recover some of this energy loss, special tile cells and scintillators were put in place. Since these areas are referred to as the gap and crack, these scintillators have been called the *gap cells* and *crack scintillators*. Their placement within ATLAS is more easily identified when looking at the sketch in figure 2.9. The gap cells are actually normal TileCal cells, officially labelled D4 and C10. The crack scintillators on the other hand are placed on the inner face of the calorimeter EB modules, and are labelled E1 through E4 as they approach the beam axis. They consist of a thin tile of scintillator plastic placed within a rectangular aluminium casing. The work was focused on the E3 and E4 counters, which are both placed in the same case, and are connected to two specially designated PMTs in the corresponding EB module. Figure 3.1 is provided to help to understand this layout: the sketch on the right depicts how these counters are placed surrounding the MBTS; the picture on the left shows the counters on the side of the EB (as seen from LB; LB and EB can be separated during shutdown to enable access). The red rectangle is highlighting one E3E4 counter. There is one counter placed on each EB module, therefore having a total of 64 counters on each side. But not all of them were installed for Run 1, since 16 PMTs were needed for the MBTS readout (8 on each side). These counters had been assembled but left in storage. Additionally, two counters had a poor signal during Run 1 and were removed for replacement, giving a total of 18 counters to be installed. In fact, the picture from figure 3.1 was taken when some of these counters were still missing.

Each E3E4 counter consists of a rectangular case made with aluminium less than a mm thick, within which the E3 and E4 scintillator tiles are placed. It is around 84 cm long, with 22.7 cm in its wider point. The tile plastic is based on polyvinyl toluene. Each tile is only 6 mm thick, and is wrapped in an envelope made of Tyvek[®] paper because its highly reflective surface helps to re-direct the light back into the tile in

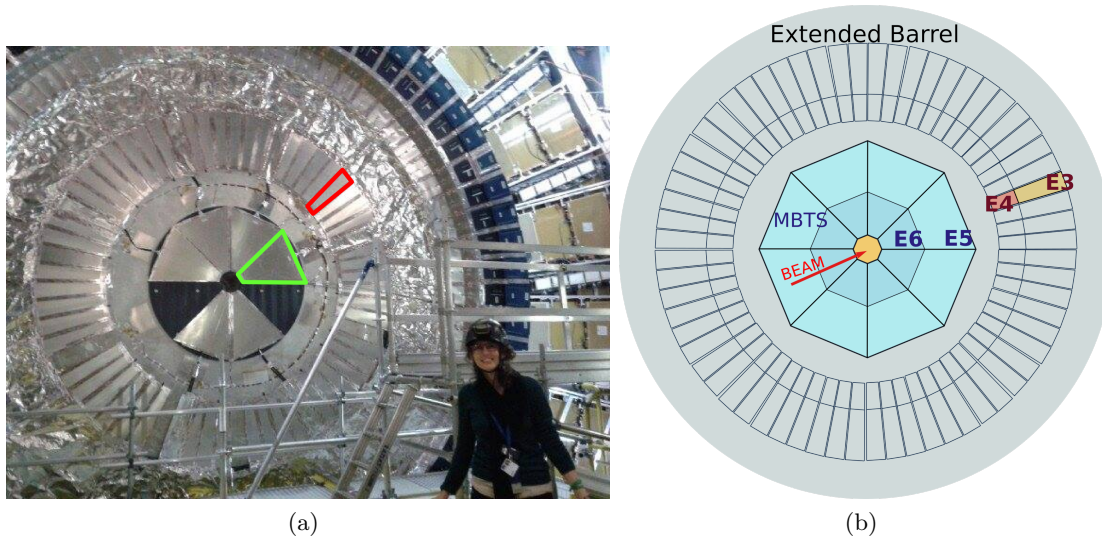


Figure 3.1: Picture of the inner side of the EB (as seen from the LB) where the MBTS is seen in the middle, with two missing octants and one marked in green. The E3E4 counters can be appreciated around it (also with some missing counters); one of them has been marked in red. On the right a sketch shows the position of the counters and the separate scintillators within them.

order to increase the yield at the edges, where the wavelength shifting (WLS) fibres are placed. A group of six fibres is used for each tile, pressed flatly on one edge within the Tyvek wrapping; the fibres of the E4 counter run on the outside of the wrapping of the E3 counter in order to reach the connector at the outer base of the case. Dark material is placed between the tiles and between the E3 counter and the E4 fibres in order to reduce cross-talk, which happens when signal that is produced by one counter can be registered by the other one. The connectors are placed at the end of E3, and point outwards in the ring formed by all the E3E4 counters. In the picture in figure 3.1, that part is covered in a thick aluminium foil to protect it from light contamination and dirt. A design of the counter can be found in figure 3.2.

Since the crack scintillators are very thin and receive a high dosage of radiation, a full replacement is to take place in the next shutdown. But any variation in the scintillator plastic composition causes different responses, which is why LS1 proved an excellent opportunity to install counters made with tiles of different origins. Two different makers were chosen for the test: Eljen¹ and Bicron^{®2}. Eight new counters were assembled using tiles provided by both makers, making four counters with each material. The same criteria as the pre-existing counters was followed, and they checked for errors before installation. Their different performance is to be assessed during Run 2.

The MBTS A *minimum bias* event is one in which a hard scatter, or non-diffractive inelastic interaction, has occurred between two protons in the bunch crossing.

¹Eljen Technologies website: <http://www.eljentechnology.com>

²Bicron Electronics website: <http://www.bicronusa.com>

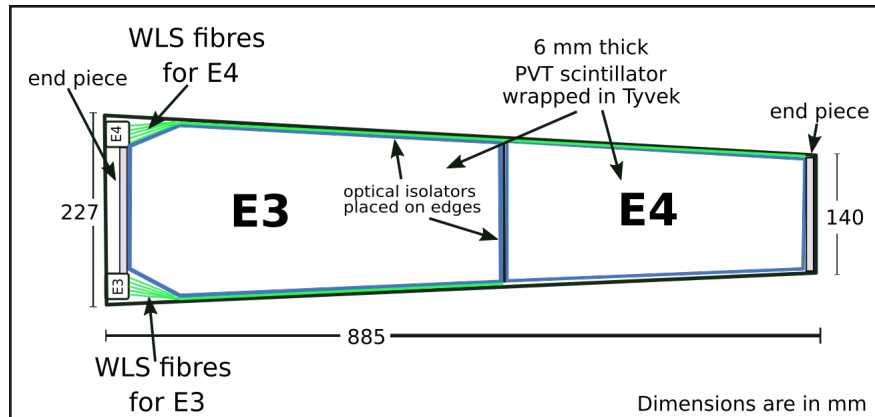


Figure 3.2: Design of the E3E4 counters. The smaller counter closer to the beam axis is E4, and the larger counter on the connector side is E3. The E3 tile needs to have its corners cut to allow the fibres to fan out more loosely as they are attached to the connectors in the base. Distances are expressed in mm.

The Minimum Bias Trigger Scintillator (MBTS), was commissioned as a first-level trigger detector aimed at detecting such events. Minimum bias events are dominated by soft interactions, and therefore constitute an important background to any physics that can be studied in ATLAS. This trigger is almost 100% efficient, and was only intended to be used during the first year of data taking since it could be assumed, after some running time, that every bunch crossing would eventually contain a hard-scatter. However, this trigger proved useful to a number of additional background and performance studies [22, 21], both in normal pp and heavy-ion runs [24]. As a result, the MBTS continued to operate throughout Run 1. During the shutdown, it was decided that the MBTS should be re-built in order to operate during as much time as possible during Run 2. This chapter describes the work done in order to study the effect that radiation had in the MBTS that was used during Run 1 (MBTS-1), and make a new design for the MBTS that would be installed for Run 2 (MBTS-2).

The MBTS consists of two octagonal counters located around the beam pipe, fixed to the inner side of each EB in the centre of the E4E4 ring, as can be seen in figure 3.1. They produce a signal when a coincidence is detected among both counters. Each octet consists of a large aluminium box, one of which is marked in green in the picture in figure 3.1. The radius is around 90 cm, they have 73 cm at its widest point, and are 2 cm thick; its inner border is only 15.3 cm away from the beam. Within each aluminium box two tiles can be found wrapped in Tyvek[®] paper, the same way as in the crack scintillators. Their naming convention continues the one in the crack scintillator, so that the larger, outer trapezoid is E5, and the inner one is E6. The scintillator plastic is polystyrene based. The light produced when a particle reaches a tile is collected by WLS fibres placed into grooves within the plastic, very small superficial channels which were polished to maximize light transmission. The fibres are connected to longer clear fibres at the outer edge of the counter, which take the signal to a PMT. These fibre bundles can also be seen leaving the MBTS-1 octants in picture 3.1 (they are wrapped in black plastic for protection). The electronics used to record the signal of the MBTS are actually from the surrounding TileCal modules. Initially there were 16

channels available for readout for each side, allowing the MBTS-1 to have two PMTs per counter, one for E5 and another for E6. For MBTS-2 only 12 channels were made available for each side, which is why it was decided that the E5 trapezoids should be read in pairs.

The main effect that radiation has on both the scintillator plastic and the fibres is the reduction of its capacity to produce and conduct light; i.e. it makes them more opaque. The passage of time contributes to the ageing of the material too. The MBTS signal is therefore expected to be reduced with time, and one of the key points in this study was to evaluate the radiation effect in the used scintillator plastic extracted from MBTS-1, by comparing its yield with the one of a non-irradiated plastic that would be used to build MBTS-2.

The most important way to optimize light yield is the placing of the grooves within which the fibres run. Another aspect of these studies was to optimize the way the grooves would be placed to accommodate a higher uniformity and light yield, and the reduced number of channels for readout available.

3.1 Scanning Methods

Two types of tests were performed in order to study the scintillators. The first one was used on the plastic pieces alone, without the cases and connectors. It consisted in generating a response from the scintillator by placing a Sr^{90} source close to its surface, and collecting the light using WLS fibres that go into a PMT. This way one can know, for a given setup, the light yield when particles (electrons in this case) arrive in a certain area. A picture accompanied by a sketch of the measuring device can be found in figure 3.3. In order to test a scintillator, the fibres connected to the PMT were attached to it and everything was placed inside the dark box (the PMT as well). The box also contained a device that allowed to move the source horizontally, parallel to the surface of the scintillator. The fibres, PMT and electronics are of the same kind that are used in TileCal, and therefore the same that would be used to read out the crack scintillators and the MBTS. The motor that moved the source could be controlled via software installed in a computer, and the distance between two consecutive measured points could be varied to obtain more or less measurements per unit of area. The computer also recorded the PMT signal, providing full control of the xy scan of the tiles.

One should note that this type of scan does not provide an absolute measurement of the plastics response, since the output signal depends on the characteristics of the source, its distance to the surface, the placement of the fibres, light and temperature conditions that affected the PMT, and other factors that could vary between one scan and another. It does provide information on the uniformity of the light yield and, when done appropriately, can be used to compare the yield between two scintillators scanned simultaneously.

Before explaining the second testing method, it is necessary to refer briefly to the TileCal calibration system. The ATLAS hadronic calorimeter is equipped with three complementary systems intended to debug issues in any point of the signal collection. It provides an almost daily report of the status of each acquisition channel, which is an important part of the data quality assessment. The first, and most simple one, is the

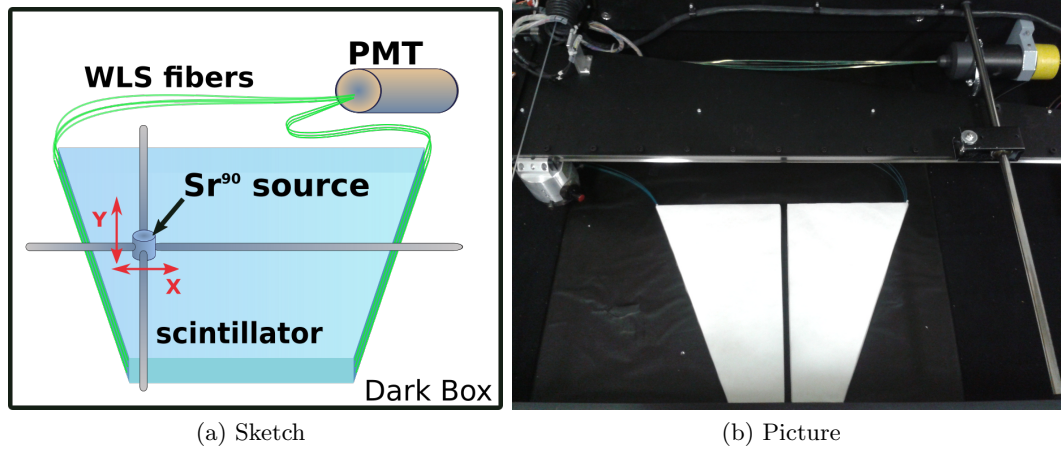


Figure 3.3: Setup used to scan scintillator tiles with a Sr^{90} source. The picture (a) shows the inside of the dark box with a small MBTS tile wrapped in Tyvek. Fibres can be seen attached to both sides. The source is in the aluminium cylinder on the left, and the PMT in the black cylinder on the top. The sketch (b) shows the basic components, with a similar tile, fibres placed on the left edge that go towards the PMT. The source and its moving mechanism is also depicted.

emission of a TTL pulse that is given as input to the acquisition electronics and should be reproduced by the data acquisition system. The second one is the laser, which sends pulses of light directly into the PMTs, so that if the TTL pulse of one channel was properly detected but the light pulse was not, it can be assumed that there is a problem in the PMT. Lastly one finds the cesium calibration system, the most complex of the three. Its purpose is to detect any problem between the cells and the PMT, usually coming from broken fibres or bad connectors. It consists of a set of small tubes (1.5 cm in diameter approximately) placed across every cell in the module, through which a cesium radioactive source (Cs^{137}) is directed using an hydraulic system. The tubes are marked in the drawing in figure 2.8b. When the source's emission reaches the scintillator tiles, they react as they would if reached by particles coming from an event, emitting a light signal. The difference is that the expected signal is well known in this case, the source being tested almost every day. Also, the timing is well known, as the speed of the source as it goes through the tube is precisely set.

The second kind of scan took advantage of the availability of a fully operational TileCal module, named EBA65, which is used for tests in the laboratory. Within the module one finds the cesium calibration system, the same that is used in the ATLAS hadronic calorimeter. In order to scan a tile, the counter would be hanged from the side of EBA65, as can be seen in the pictures in figure 3.4. The height at which it was hanged was chosen with respect of the inner tube's position. Given the scanning conditions, this test could only be performed on the full assembled counters, which were additionally protected with a black cover to make the measurements more independent from the room lighting conditions.

A set of typical signals collected from several scanned counters is presented in figure 3.5. There is a base noise signal, or pedestal, from which the counter's signal can

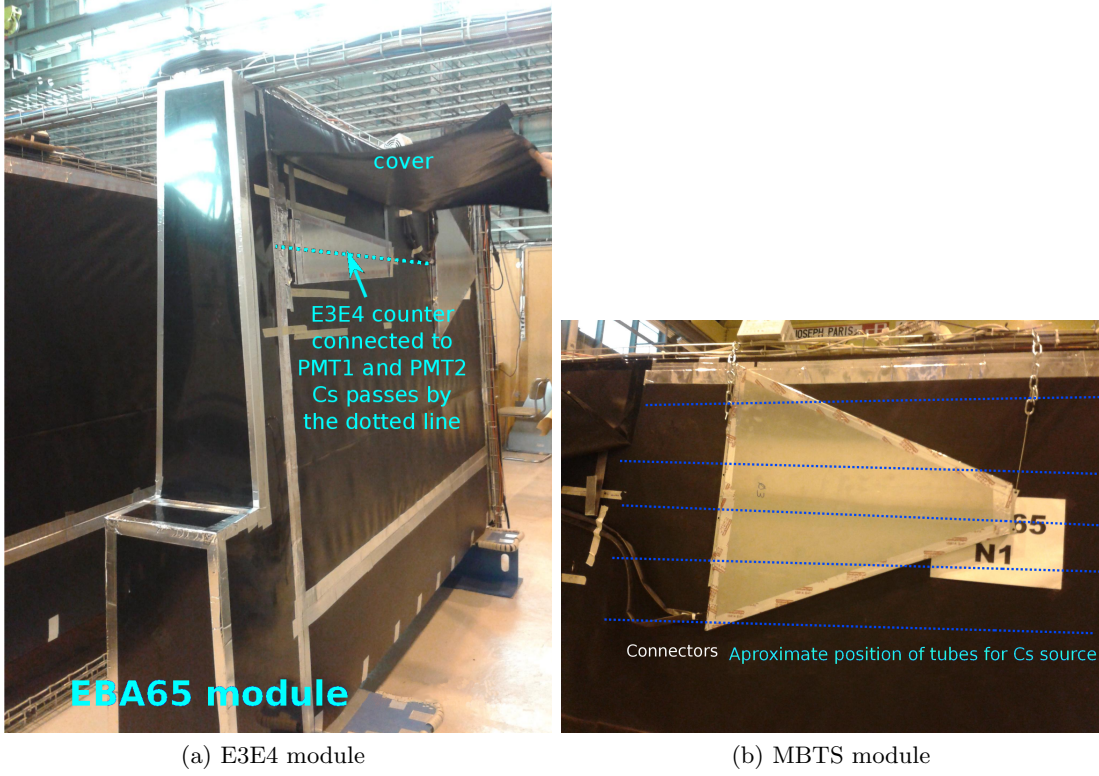


Figure 3.4: The pictures show two different counters placed on the side of EBA65 module in the TileCal testing facility. The picture on the left shows the setup, with an E3E4 counter and the cover used to shield from ambience light and protect the PMTs. A dotted line indicates the position of the Cs source tube within the module. The picture on the right shows an MBTS module also placed on the side of EBA65. Since this counter is larger, it covers several tubes of the Cs system, which are marked in dotted lines. The fibres that connect it to the PMTs can be seen on the bottom left.

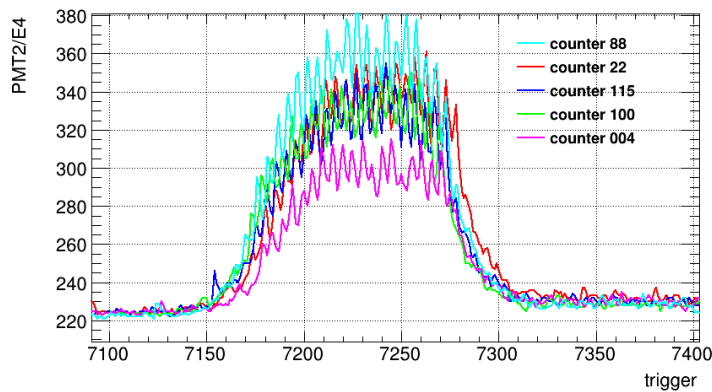


Figure 3.5: Typical signal for several measurements performed with the cesium scan of E4 tiles within different E3E4 counters. The x axis corresponds to a time unit, while the y axis is the signal of the PMT.

be easily distinguished when the source passes beside it. The signal presents several oscillations, which reflect the alternation between absorber and scintillator material inside the TileCal cells (more particles reach the counter when the source passes by a scintillator tile, since the iron plates absorb the emission). The emission reaches the counter in a diffuse way, after going through half of the cell, but as long as the counters are placed approximately in the same position, the measurements can be compared to one another and the level of the signal registered can be used to evaluate the expected performance of a counter. These scans are highly consistent in time, but as a precaution a reference counter was measured repeatedly every few measurements. In summary, this kind of scan was performed to evaluate the signal yield of fully assembled counters, and can be used to compare the signal level between counters.

3.2 Measurements and New Designs

The Crack Scintillators In the case of these counters the studies were aimed at evaluating the new tiles received from the different makers, and checking the integrity of the counters after building them. In addition, the pre-existing counters that needed to be installed were evaluated, to check their integrity before installation and as a resource for future performance evaluations.

Since some counters were removed for testing, it was possible to compare irradiated and non-irradiated tiles from the same maker, as well as the ones from Eljen and Bicron. The first mean of comparison used were the scans using the Sr^{90} source. Figure 3.6 shows an example plot of the scan of a non irradiated E4 tile: this tile comes from the counters that had been left in storage since the construction of ATLAS. It is placed next to an irradiated E3 tile, from a counter that had been used during Run 1. The PMT voltage is plotted using a colour scale as a function of the position in which the source was placed. The E4 tile can be distinguished in a red-orange colour against the blue background where no material was placed. The lighter area on the right corresponds to the irradiated E3 tile. The edges of the tiles show some border effects due to the diameter of the source. The darker red colour towards the bottom (top) of the E4 (E3) tile indicates the signal is slightly higher in this area, and is due to the fibres being placed along this edge.

A first interesting characterization would be then to know the attenuation length of the tile material, both in the direction parallel and orthogonal to the fibres. In order to evaluate it, an exponential fit was performed to the signal in both directions. An example of this fit can be found in figure 3.7a. Taking the data shown in figure 3.6, the signal values for a fixed position in the horizontal coordinate were fit with an exponential, to obtain an approximate value of attenuation length of 60 cm. The large uncertainty of around 50% is due to the much shorter distance evaluated. Similar or larger values were obtained for all the other non-irradiated tiles that were scanned, as well as for an irradiated tile that was tested. The tiles provided by Bicron and Eljen had a much larger value, above 2 m. It must be noted that this large values are somewhat inaccurate, since the tile width is only 15 cm, but the point was made that signal attenuation towards the fibre was not an issue in this kind of counter. A similar test was attempted in the radial direction, which has a higher symmetry and did not

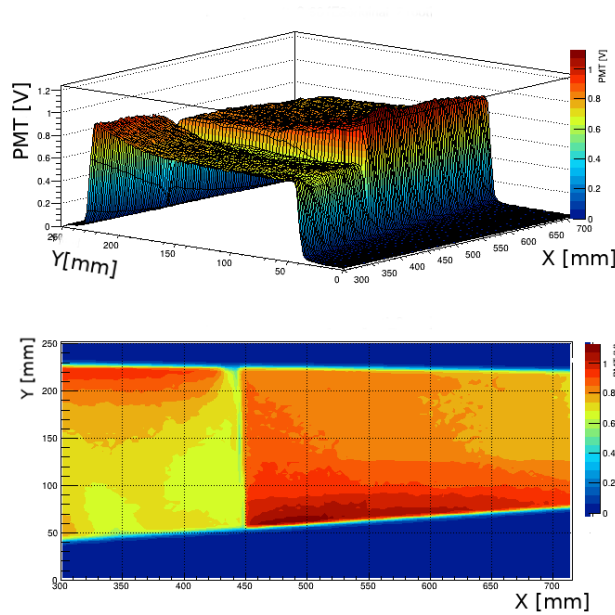


Figure 3.6: Spatial distribution of the PMT signal as a function of the position of the Sr^{90} source inside the scanning box for E4 non-irradiated tile, where an irradiated E3 tile was placed on the side for comparison. The colour reflects the level of the signal, red being a higher value. The graph on the bottom is a projection on the xy plane of the one on the top.

appear to have any measurable attenuation effect. Therefore, in order to evaluate the signal attenuation in this direction, linear fits to the signal were performed, obtaining a slope of some μV per mm (this plot can be found in appendix A).

A second possible characterization of the tiles is their uniformity, which is obtained through the ratio of the RMS and the mean of the signal distribution. This distribution is shown in figure 3.7b for the same E4 tile. The design of the tile and fibre layout gives a high uniformity, resulting in an $RMS/mean$ ratio of $\sim 6\%$ in this case. Similar values were obtained for all the tiles, both irradiated, non-irradiated, Eljen and Bicon, as expected.

Complementary information was obtained through the cesium scans after the counters were assembled. Every counter was hanged in the same position, so that the tube within the EBA65 module ran lengthwise, through the middle of both tiles, as can be appreciated in the picture in 3.4a. The source would then make its course through the tubes first in one direction towards the end of the circuit, then in the opposite direction back to its storage box. Each scan thus provides two sets of measurements. The fibres for the tiles were connected to different PMTs, and the obtained signal is shown in figure 3.8 after the mean noise value has been estimated and subtracted. The mean signal value for each counter is evaluated considering the part of the signal that is above half of the maximum. The level of cross-talk can be extracted from the plots such as this one too, by considering the average signal in one tile while the source is going passing next to the other one. The ratio of the mean signal of both tiles for a counter can be used to cancel some of the convoluted effects. One of such effects that

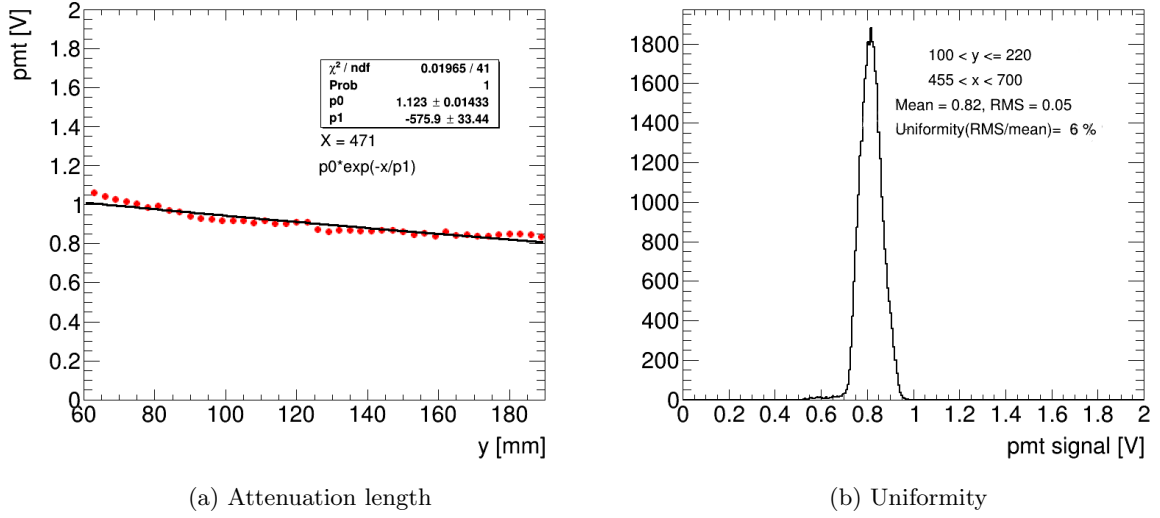


Figure 3.7: Distributions used to estimate the attenuation length and the uniformity of an E4 tile. The plot on the left shows the signal values in a direction orthogonal to the fibres, for a fixed x position. An exponential fit was performed to give an estimate value of the attenuation length. The plot on the right shows the signal value distributions for the entire tile.

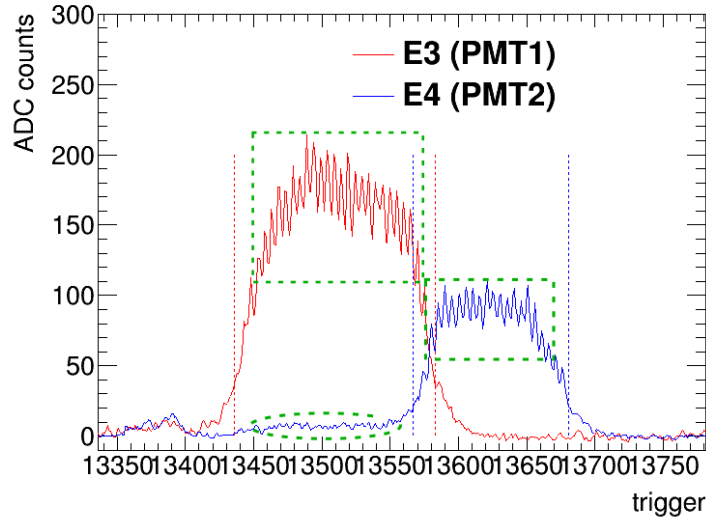


Figure 3.8: Signal of the E3 (red) and E4 (blue) tiles as a function of time, when the Cs^{147} source passes next to them. The vertical dashed lines indicate point where the signal equals a fifth of its maximum value. The dashed green squares surround the values considered when estimating the mean value of the signal. The dashed green ellipsis shows the cross-talk signal measured in the E4 counter when the source was within the E3 tile.

must be kept in mind is the different response of the PMTs used, as well as the different connection quality of the tiles.

Tables containing detailed information for each counter are presented in appendix A, and a summary per counter type is presented here. In general the E3 tiles, being larger, presented a bigger mean signal value. The ratio was calculated as the mean of $E4/E3$. The given signal values are in arbitrary units which consist of the PMT signal level minus the mean noise value.

Original counters : large differences were found between the counters. The E3 tiles have a mean signal of 160 au., with an 8% dispersion. The E4 tiles have 90 au $\pm 23\%$. There is no cross-talk signal measured in the E3 tile, and the one measured in E4 is below 5% of the measured mean. There were no significant differences between irradiated and non-irradiated counters.

Eljen and Bicron counters : the most interesting features are the much larger signal values (50% above the original counters) and the better similarity between counters. This could indicate ageing of the pre-existing counters, and/or an improvement in the new material used. Although these are only eight counters, it could also indicate a more uniform production scheme when building the counters. An additional feature was a larger level of cross-talk in the E4 counter, around 10%.

The MBTS In the MBTS-1, each trapezoid was actually separated into two halves, each of them with 4 fibres placed within a superficial groove. The grooves were sigma-shaped in E6, s-shaped in E5, and were placed in opposite sides in each half. Thus, in total, the inner and outer trapezoids had 16 fibres (8 each) for readout. A sketch of the MBTS-1 assembly can be seen in figure 3.9a.

An initial assessment showed that some improvements could be made in the assembly of MBTS-2. First, it was found that there was enough space within the case to increase the height of E6 by 2 cm, after making the top and bottom edges smaller and removing additional material found within the case. Secondly, the inner and outer tile were within the same Tyvek envelope and would be now wrapped individually, with an additional black strip between both tiles to diminish cross-talk. Lastly, the WLS fibres had been fixed to the clear fibres using a technique called *splicing*, and then wrapped in black plastic; for MBTS-2 the fibres were fixed to special connectors, which were glued to the case for increased rigidity. These differences, as well as the ones that will be described in this section, can be appreciated in the sketch in figure 3.9b.

The scans with the Sr^{90} were a valuable source of information, since the placement of the fibres needed to be determined. The plot in figure 3.10a corresponds to the scan of both halves of an E6 of MBTS-1. The darker red shape in the tile on the right correspond to the fibres placed within the groove, which was facing upwards and closer to the source, while the grooves of the tile on the left were facing downwards. It can be seen that the signal yield on the top section of the trapezoid is considerably smaller: the light produced on the outer curvature of the groove was collected with 50% less efficiency. It was concluded that the groove design caused a high non-uniformity, as the $RMS/mean$ of the signal plotted in figure 3.10b was around 18%. Similar

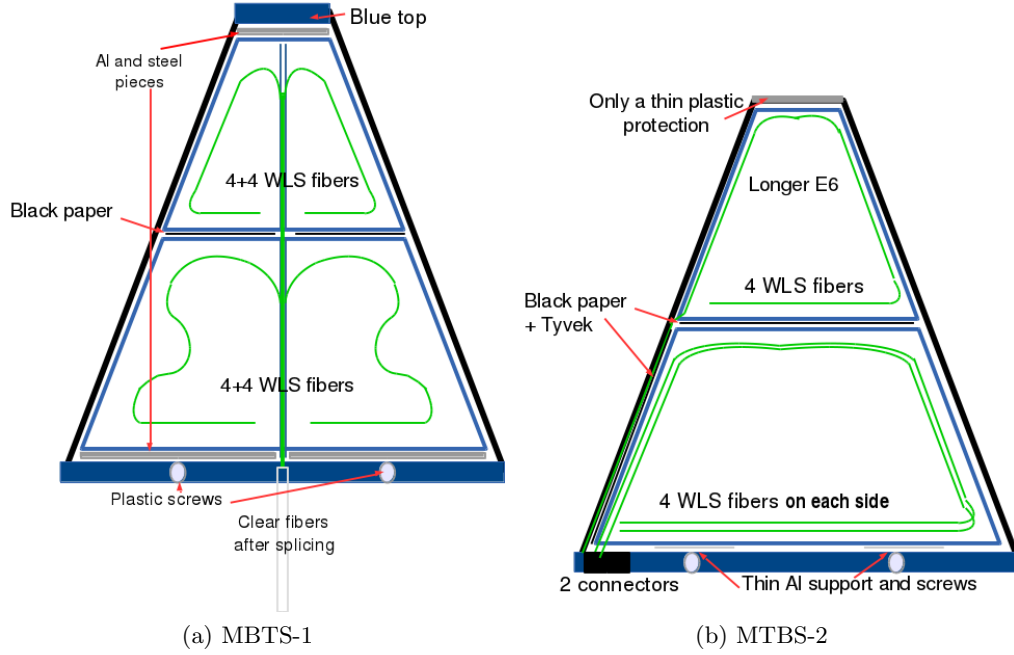


Figure 3.9: The pictures show the design of the old (left) and new (right) MBTS. Some of the modifications in the casing are pointed out, as well as the different placing of the tiles in light blue and the fibres in green.

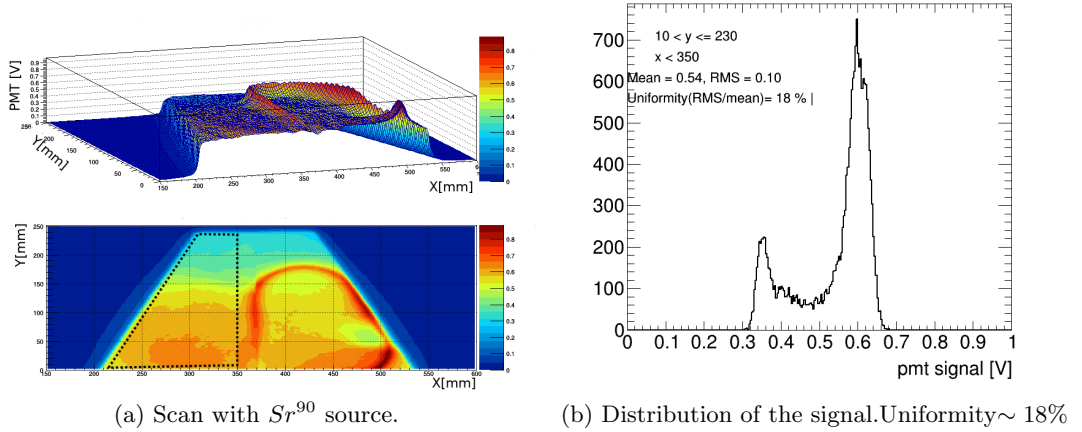


Figure 3.10: Scan of an inner tile of MBTS-1 using the Sr^{90} source (left), the colour scale represents the signal value, red corresponds to higher signal. The dotted lines around the left tile indicate the area considered to estimate the uniformity, of 18%, from the distribution of the signal value (right).

measurements were made of an E5 scintillator, reaching the same conclusion (figure A.2 in appendix A).

An additional aspect to take into account was the attenuation length. It was evaluated in a new piece of trapezoid-shaped tile, by placing four fibres on one edge using

plastic guides. Similarly as to what was found in the E3E4 counters, the attenuation length in the direction perpendicular to the fibres was larger than the tile width, around 1.4 m. When placing fibres on both sides, there was no significant reduction of the signal strength towards the centre of the tile, indicating fibres could be placed close to the borders without risking signal loss. There was however a radial dependence, due mainly to the tile's shape, which should be reduced if fibres were placed also on the upper and lower edge. These scans can be found in appendix A, in figures A.3 and A.4..

Evaluation of this information led to the conclusion that both E5 and E6 should consist of a single trapezoid-shaped tile each. Mechanical stability would also be improved in this way. The grooves should be as straight and close to the borders as possible in a sigma shape of large curvature radius. The resulting design can be seen in the sketch of figure 3.9b, and a scan of a final E6 tile is presented in figure 3.11a. The scan was performed placing 4 fibres in the groove; the $RMS/mean$ value can be seen to be significantly reduced, to only 5%, in figure 3.11b.

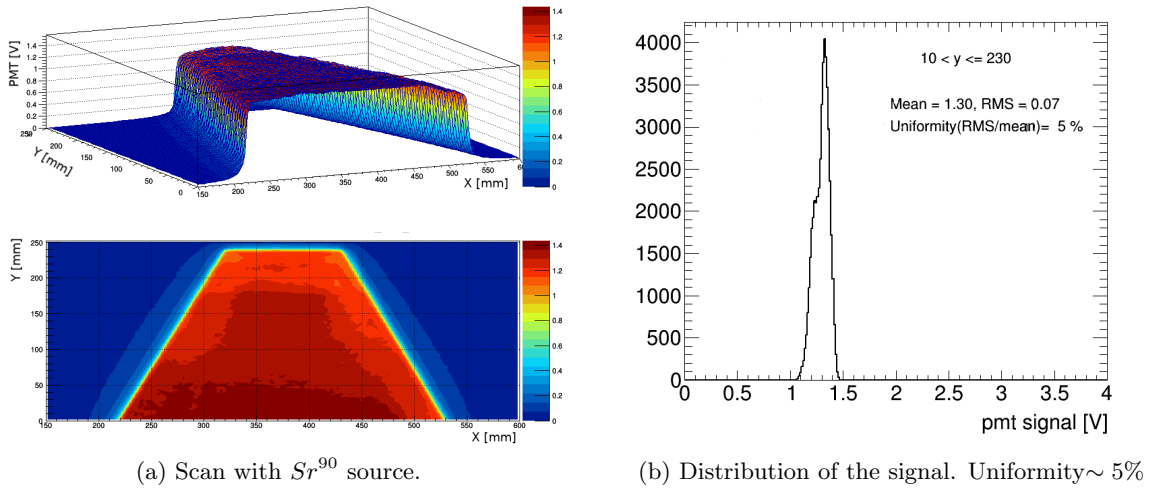


Figure 3.11: Scan of an inner tile of MBTS-2 using the Sr^{90} source(left), the colour scale represents the signal value, red equals higher signal. The signal values distribution is presented (right), estimating a uniformity value of 5%.

It should be noted that the grooves are made to accommodate only 4 fibres, reducing the light collection capabilities of the tiles in half with respect of the previous version. In the case of E6, the improved design and new scintillator material were expected to compensate for this, since the scans showed that the new tiles had more than twice the light yield of the irradiated ones. But the E5 tiles would be larger, and although at present showed similar yields as the old ones, it was feared that irradiation and age would reduce the signal too much to be used. As a precaution, it was decided to do grooves on both sides, so as to have 4 additional, spare fibres, that could be connected if the signal dropped below the detection threshold. A scan was performed on a test tile, grooved on both sides, to check what effect a second groove would have. It was found that light yield was reduced by less than 10% due to the presence of this groove, but uniformity was not affected. As expected, when connecting fibres from both sides,

the light yield almost doubled.

It was also interesting to evaluate the effect that radiation had in the tiles. Both new and irradiated tiles were scanned at the same time, and the light yield was around 50% smaller in the tile coming from MBTS-1 (it would be later confirmed using the cesium scans). This could be due to both irradiation and ageing. The same comparison served to show that there was no increase in the radial dependence of the light yield: both the new and old tiles had a similar radial dependence due to its shape.

The new counters were built by dismantling the MBTS-1 and using the same cases, and were checked using the Cs^{137} scan. Only one MBTS-1 counter was left assembled for reference. There were several characteristics that made the analysis of these scans less straight forward than was the case for the crack scintillators. To start with, due to the large size of the counters, there were four tubes passing at different positions of the tiles, as marked in the picture in figure 3.4b; therefore, each scan showed several peaks, as can be seen in figure 3.12a. Each pair of peaks had a different signal ratio between E5 and E6, as can be appreciated by comparing figures 3.12b and 3.12c.

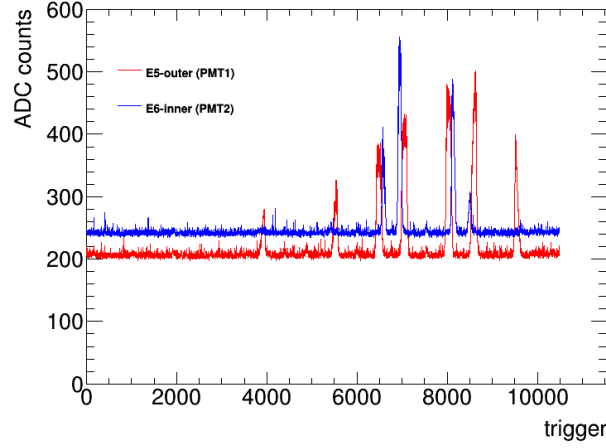
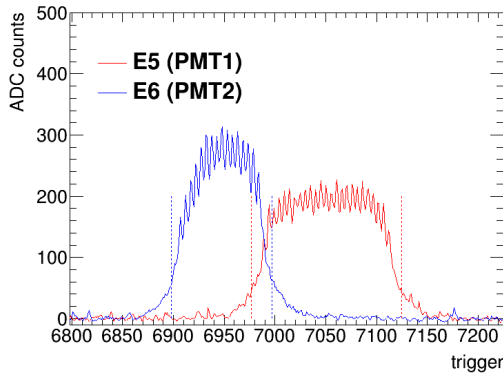
A second complication was the way the counters were connected to the PMTs. While the counter from MBTS-1 had its own 1.5 m of clear fibres attached to it (and they were aged and irradiated), the MBTS-2 counters needed a clear fibre extension to be connected. A bundle of 1.4 m long fibres was hand-made for the tests, and it was found that this connection could generate 50% signal loss in average. A second set of scans was later made using a 2.1 m bundle of fibres, the kind of which would be used in the installation. In addition, connecting the tiles to the different PMTs seemed to have different effects on each.

A large number of cross checks measurements were carried out in an attempt to reduce the effect of these caveats, such as cross measuring PMTs and fibres in all possible combinations, and adding and removing fibres to check for effects. Most importantly, it was found that all assembled counters were functioning correctly, without crucial flaws. Additionally:

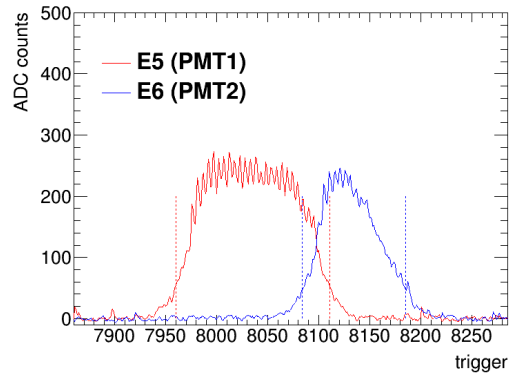
- The signal of the installed E6, with a 4-fibre readout, should be larger than the MBTS-1 version by around 30%.
- The signal of each installed E5, read by 4 fibres, would be reduced by 30-35% in average. But it should be taken into account that E5 tiles will be read in pairs, therefore the total signal would be increased by 40% with respect of MBTS-1.

Detailed information of these scans is presented in appendix A.

Final Comment The installed scintillator detectors have already been in operation for 2 years. Regarding the crack scintillators, no special impact was expected from their installation. As for the counters with new materials, when they are removed in the next shutdown it will be possible to use the information presented here to evaluate the performance of the different tiles. The fully functional MBTS-2 has already ran through 2015 and 2016 successfully. It was used to measure the update to the measurement of the inelastic pp cross section, published in reference [39].

(a) Scan with Cs^{137} source.

(b) Second peak



(c) Third peak

Figure 3.12: Signal from the E5 (red) and E6 (blue) counters when scanned using the Cs^{137} source. The full signal is shown in (a), the peaks correspond to the moments the source passed close to the counters. The second and third peaks are shown more closely and after pedestal subtraction in the plots (b) and (c) respectively. The vertical lines mark the point at which the signal equals a fifth of the maximum.

Chapter 4

Measurement of the Jet Energy Resolution

And jet I thought the only lonely
place was on the moon

Jet - Paul McCartney

One of the main focuses of this thesis is the performance study of jets for their use in analyses, as a continuation of the work done in jet resolution in 2010-2011 [29, 86]. The first part of this chapter describes the experimental aspects of working with jets, how they are built and calibrated. The second part is dedicated to the Jet Energy Resolution (JER), its definition, measurement methods, performance studies and improvement.

Jets originate in the decay of a parton, which evolves into a shower, and the decay products combine into hadrons (as was described in sections 1.1.3 and 1.2). In addition, section 1.3 described briefly how these components are simulated. There is one more point of view to analyse, that is the way in which the signal from these particles is collected and the jet is built.

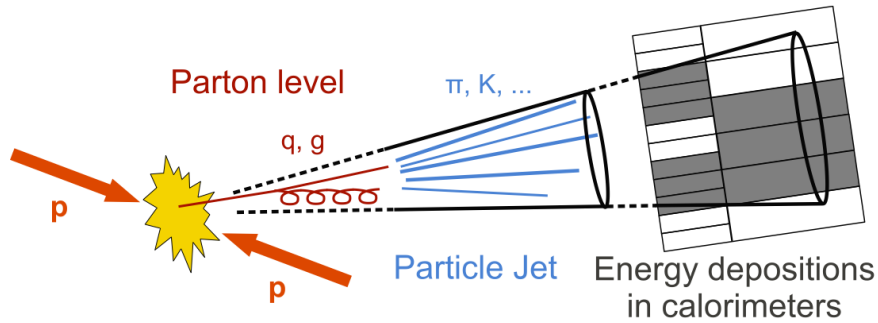


Figure 4.1: Sketch of a jet evolution.

The particles with longer life time enter the detector; as they go through the inner detector, those that are charged may leave a trace so that their track may be reconstructed. Then both charged and neutral particles deposit their energy in the calorimeters. The sketch in figure 4.1 shows the evolution of a jet. The read-out channels in the calorimeters are split into cells of variable sizes depending on the region

of the detector, as described in section 2.4.4. Particles often deposit their energy in more than one cell, which is why clustering algorithms were designed to group these cells together and sum the total energy deposited. There are different possible ways to group these cells, but the jets that were used throughout this thesis are made up of *topological clusters* [79], which start off with a seed cell and proceed to add neighbouring cells in three dimensions. The algorithm in ATLAS begins with seed cells with a signal that is at least four times the expected noise level, so that $|S/N| > 4$; the noise is defined as the RMS of the electronics noise for the current detector conditions plus the contribution of pile-up (introduced in section 2.3), added in quadrature. Any neighbouring cell is added in an iterative way if their signal is such that $|S/N| > 2$, and lastly all direct neighbour cells on the outer perimeter are included. This is known as the 4-2-0 strategy.

In order to recombine the parton's decay into the jet, it is necessary to define a recipe. Jet algorithms determine the way in which jet constituents are combined in order to reconstruct a jet, and they are categorized by the kind of input over which the algorithm is ran:

- *truth jets*: are built by running the algorithm over particles generated in a MC simulation. These are sometimes also called *particle jets*.
- *reconstructed jets* are those where the input constituents are topological clusters, either from data or from a MC sample that has gone through detector simulation and signal digitisation. Equivalent names for these are *reco jets*, or *calorimeter/calor jets* since their components come from calorimeter signals.
- *track jets* are jets built from the reconstructed tracks of the particles (either in real or simulated data); these have not been used here.

The different types presented above can be distinguished in figure 4.1.

4.1 Jet Algorithms

A jet algorithm is defined by the rule that decides how the components of an event are evaluated and combined with each other, and in which order. They usually depend on a radius parameter R which determines the approximate size of the jets. Different decisions result in jets with very different characteristics, such as their roundness, how they are separated when they are close to each other, and their sensitivity to noise. ATLAS currently uses sequential recombination algorithms, which work in an iterative way recombining the input components through the evaluation of a distance parameter. They were specifically designed to be resilient to infrared/soft and collinear radiation (a feature referred to as IRC safety). The distance parameter between two objects i and j is defined as a function of the momentum and the angular distance between them (with ΔR_{ij} as specified in equation 2.2):

$$d_{ij} = \min \left(p_{Ti}^{2p}, p_{Tj}^{2p} \right) \frac{\Delta R_{ij}^2}{R^2} \quad (4.1)$$

$$d_{iB} = p_T^{2p} \quad (4.2)$$

Equation 4.2 applies to the case where one of the objects is the beam, in which case the distance is evaluated only through the object's momentum. The parameter p regulates the evolution of the clustering, and its value results in very different jet algorithms. An algorithm following these rules identifies the pairs of objects with the smallest distance between them in order to cluster them together; if the smallest distance is d_{ij} , it recombines the constituents i and j by adding their four-momenta, while if the smallest distance is d_{iB} , the algorithm calls i a jet and removes it from the list of constituents. This procedure is repeated until all constituents are clustered. However, the actual results may vary depending on the value of p . In the case of the Cambridge/Aachen ($p = 0$) and the k_t ($p = 1$) methods, the reconstruction is done in a way that reverses shower history. The first relies solely on the angular order of emissions, which results in a large dependence on experimental conditions. The second introduces a direct dependence on the momentum, and combines the softer radiations first, again introducing sensitivity to small energy fluctuations in the shower.

The anti- k_t algorithm [56] is defined by setting $p = -1$. The resulting metric implies that soft particles will cluster with the ones with larger momentum first. If a hard particle has no hard neighbours within a distance $2R$, then it will simply accumulate all the soft particles within a circle of radius R , resulting in a perfectly conical jet in the $(y - \phi)$ plane. If, on the other hand, two hard particles are close by (but with $\Delta R_{ij} > R$), there will be two jets and their final shape will depend on the relative momenta. There is also the possibility of two hard particles being within $\Delta R_{ij} < R$, in which case they will be clustered together to form a jet centred on the one with larger p_T . The resulting key feature is that the shape of the jets is defined by the presence of hard particles, and is not affected by the soft radiation surrounding them. The jet boundary in this algorithm is thus resilient with respect to soft radiation.

An example of these three different jet reconstruction techniques can be found in figure 4.2; when applied to the same simulated event, some algorithms give more rounded jets than others, indicating less sensitivity to the surrounding low energy deposits. For example, the jets resulting from the anti- k_t method (figure 4.2b) have quite rounded areas, and is both resilient to soft and hard radiation surrounding the particles. It can also be appreciated that close-by jets are separated with different criteria, and have diverse sizes in spite of having the same value of R parameter.

The anti- k_t jet algorithm [56] is the default jet finding algorithm at the LHC experiments. Alternative jet algorithms such as the k_t and the Cambridge/Aachen methods are also widely used in jet performance, since their recombination order is closer to the shower development and allows to deconstruct the jets into smaller subjets. All algorithms are used here as implemented in the FastJet [57] package.

4.2 Jet Calibration

The calibration of the jet energy scale (JES) is fundamental to determine in an accurate way how much energy was actually deposited by the particles in the detector. The calibration procedure requires a first instance of cluster calibration, a combination of corrections and a final jet level calibration [34]. A diagram of the calibration scheme applied to the jets in the dataset of 2012 is shown in figure 4.3

The input clusters have a preliminary calibration, either to an electromagnetic scale

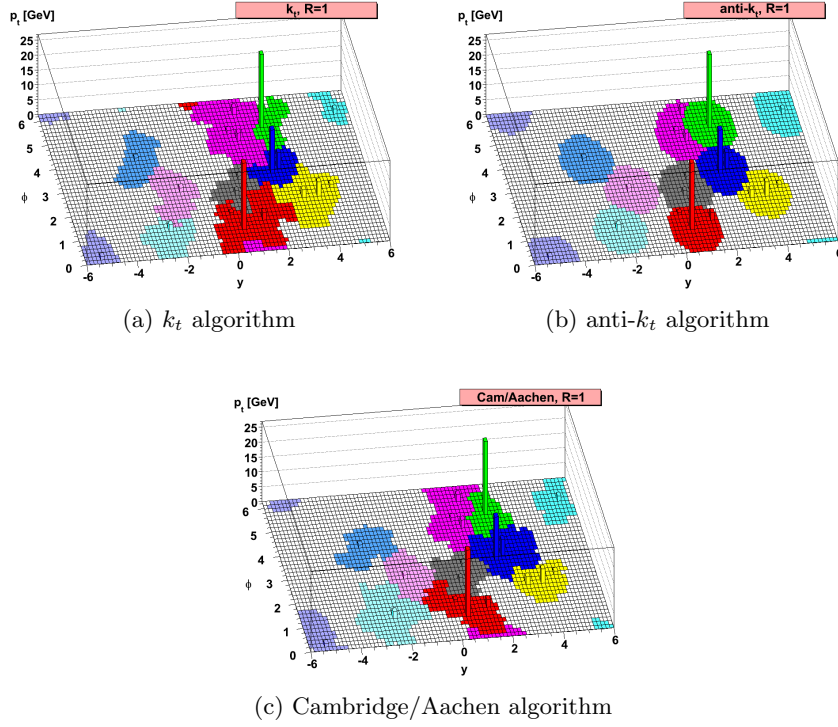


Figure 4.2: Jet distributions for different jet algorithms [56] applied on the same simulated event.

(EM) or to a scale that compensates for the lower hadronic response (LCW scale, for *local cell weighting*). The EM-scale correctly describes the energy deposited by an electromagnetic shower, and was determined through test beam studies. This means that the detector signal is converted to energy using a scale that best describes energy deposits of electromagnetic particles. A second kind of topological clusters is built using the LCW [47] technique. In the procedure clusters are first classified as either electromagnetic or hadronic, primarily based on the measured energy density and the longitudinal shower depth. The cells are then accordingly weighted, so that the response of the calorimeter to hadrons is correctly represented. The use of this kind of cluster significantly improves the energy resolution, as it reduces fluctuations in the measured energy due to the non-compensating nature of the calorimeter.

The four-step procedure sketched in figure 4.3 is then applied to the jets reconstructed with the anti- k_t algorithm using either the EM or LCW topological clusters.

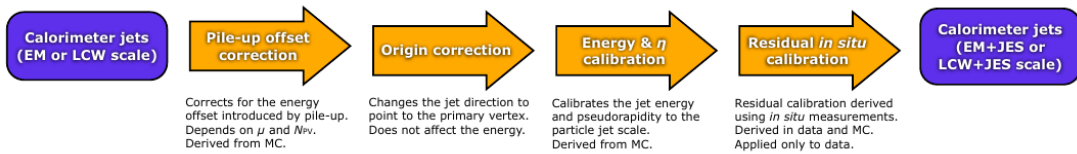


Figure 4.3: Overview of the jet calibration scheme applied to jets in ATLAS [34].

The aim of these corrections is to restore the energy scale of the reconstructed jet to that of the truth jet. The corrections are:

1. **Pile-up:** this effect generates additional energy deposits as was previously explained in section 2.3, that contribute to jets coming from the hard scatter (and can even form new jets, called pile-up or fake jets). These deposits need to be subtracted from the jets. A correction is derived from MC simulations as a function of the number of reconstructed primary vertices (N_{PV} , measuring the number of actual collisions in a given event) and the average number of interactions ($\langle\mu\rangle$, which is sensitive to out-of-time pile-up) in bins of the jet's y and p_T .
2. **Origin Correction:** the direction of the jet is adjusted so that it points back to the interaction vertex instead of the nominal centre of the ATLAS detector. The interaction vertex is the one with the largest value of $\sum (p_T^{track})^2$, where the scalar sum is taken over all tracks associated to the vertex.
3. **Jet calibration based on MC simulation:** the calibration of the energy and pseudorapidity of a reconstructed jet is a simple correction derived from the relation of these quantities to the corresponding ones of the matching truth jet in MC simulations (the closest in angular distance). It can be applied to jets formed from topological clusters at EM or at LCW scale with the resulting jets being referred to as calibrated with the EM+JES or with the LCW+JES scheme. This first JES correction uses isolated jets from an inclusive jet MC sample including pile-up events. The energy response

$$\mathcal{R}^{EM/LCW} = E_{jet}^{EM/LCW} / E_{jet}^{truth} \quad (4.3)$$

is the inverse of the jet energy calibration function, and is determined in bins of jet energy and η .

4. **Residual in-situ corrections:** using data-based methods that exploit the balance of the transverse momentum in different ways (such as the dijet balance method that will be explained in section 4.3.2), a residual correction is derived to be applied to the reconstructed jets in data. This technique is also used to calibrate forward jets using the central ones as reference. The application of this correction reduces the possible impact of MC mismodelling.

The uncertainty associated to jet calibration are derived as a function of p_T and $|\eta|$. The largest uncertainty comes from the use of MC simulation and the need to account for the possible mismodelling of the generator used; it is derived from the comparison of results obtained using different generators. Another relevant uncertainty component is due to pile-up. Its impact is assessed by deriving the calibration in datasets that have been separated in high and low $\langle\mu\rangle$, and in high and low N_{PV} , and comparing the results. Then there are some additional components due to the way jets are selected. For example, given that well separated jets are used in order to estimate the response, an additional uncertainty is estimated to account for event topology by varying the minimum angle required between jets. The total systematic uncertainty is obtained as the quadratic sum of the various components. The uncertainties have a strong pseudorapidity dependence, increasing with $|\eta|$. The dependence on p_T is weaker, and decreases with increasing jet transverse momentum.

4.3 Jet Energy Resolution

This section describes the procedure and results corresponding to the measurement of the jet momentum resolution in the first part of the 2012 dataset. This measurement is of key importance in a large variety of analyses, both in searches and in precision measurements such as the inclusive jet, dijet [37, 41], and multijet cross-sections [20, 36] such as the one presented in this thesis, as well as having a direct impact in the determination of missing transverse energy in an event. A brief description of the methods will be presented first, followed by the results obtained. A more thorough explanation of the measuring techniques as well as a complete account on the results can be found in references [29, 33]. The data-taking conditions to this year presented some differences with respect of the previous ones: in particular, the pile-up contributions were significantly increased, which prompted additional studies on the validity of the methods. The obtained results are combined to provide the uncertainty of the jet resolution to the analyses in ATLAS with jets in their final state. Lastly, the resolution was studied as a function of $\langle\mu\rangle$ in order to estimate its value for higher luminosities (and therefore higher pile-up).

The jet energy resolution is, as its name implies, the quantity that measures the precision with which the detector provides the jet energy measurement. It is therefore closely linked to the performance of the calorimeters. By definition, one should estimate it by comparing the original energy of the jet at truth level with the energy of the reconstructed jet (the two kinds of jets as defined in the introduction of this chapter). Instead of looking at the energy variable, the transverse momentum was chosen as a probe to the resolution. This is because the in-situ methods available are better parametrised as a function of p_T , and also because it is a variable more widely used in the experiment due to its nice balancing properties. The resolution thus measured, i.e. using truth information, is referred to as *truth resolution*, and the method is explained in the next section.

The use of methods that rely solely on calorimeter-level observables is fundamental as a way to validate the resolution results with data. The input to these methods can be both reconstructed simulations or data, so that in this way the MC simulation is validated as well through the comparison with data. Two in-situ approaches are presented here: the *dijet balance* and the *bisector* methods; they exploit the p_T balance in *dijet events*, where two of the jets have much larger momenta than the rest. The resolution is measured as a function of the average p_T of the bin, and in rapidity bins that follow the division of the calorimeter into a central barrel, the extended barrel, end-caps and forward region, plus a bin containing the less instrumented *crack* region, as explained in section 2.4.4.

4.3.1 Truth Momentum Resolution

The *truth resolution* is the resolution measured in MC simulation, using the information available from the generated particles. It is defined as:

$$\frac{\sigma(p_T)^{truth}}{p_T} = \frac{\sigma\left(\frac{p_T^{reco}}{p_T^{truth}}\right)}{\left\langle\frac{p_T^{reco}}{p_T^{truth}}\right\rangle} \quad (4.4)$$

where $\frac{\sigma(p_T)}{p_T}$ is the expression for the jet momentum resolution, and p_T^{reco} and p_T^{truth} are the transverse momentum of the reconstructed and the truth jet respectively. It is measured from the width of the *momentum response* distribution (ρ). As in the case of the energy response (equation 4.3), it is defined as the ratio between the momentum of the truth and reconstructed jets:

$$\rho = \frac{p_T^{\text{reco}}}{p_T^{\text{truth}}} \quad (4.5)$$

where the jets have been geometrically matched with $\Delta R(\text{truth}, \text{reco}) < 0.3$. This is the fundamental variable when probing detector effects, either for the resolution or calibration measurements. A bias in the reconstruction could cause the mean of the response distribution to be different from the expected value of 1, which is why the width is divided by the mean ($\langle \frac{p_T^{\text{reco}}}{p_T^{\text{truth}}} \rangle$) in equation 4.4 in order to obtain the resolution. The truth resolution is measured in bins of p_T^{truth} , and the results are presented as a function of the average value of each bin, $\langle p_T \rangle$.

Figure 4.4 shows two examples of response distributions for two different ranges of p_T^{truth} . The distributions have a Gaussian core, with non-Gaussian tails clearly visible through the use of logarithmic scale in the y -axis. The effects that cause these tails are not directly related to the calorimeter's performance (pile-up, jet punch-through, among others), which is why when a Gaussian fit is performed to estimate the width of the distributions through the standard deviation σ , only the core is included. The tails are mostly asymmetric, with a tendency to be larger on the right side of the distribution, indicating that it is more common for p_T^{reco} to be larger than p_T^{truth} , specially for lower jet momenta. Nonetheless, the tails in themselves are not too large, being at least 2 orders of magnitude below the core. A second noticeable feature is how the width is reduced as p_T^{truth} increases, showing that the resolution is much better for more energetic jets.

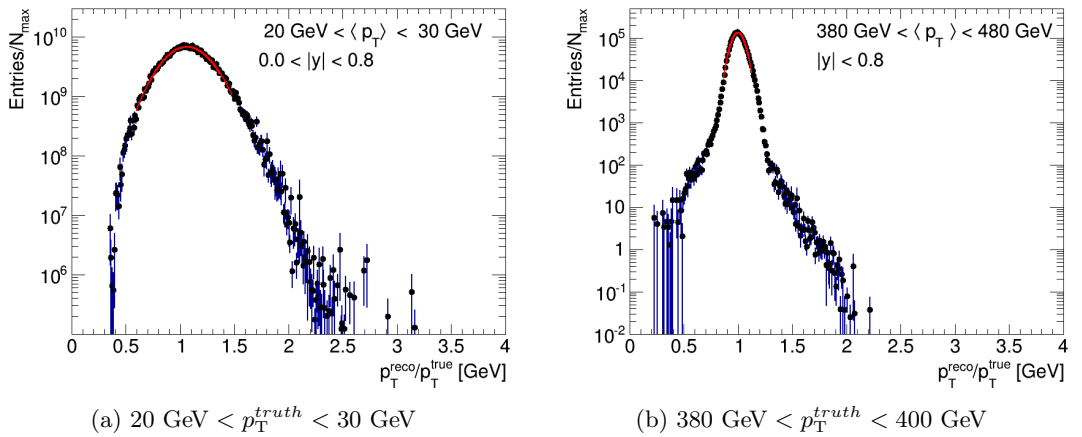
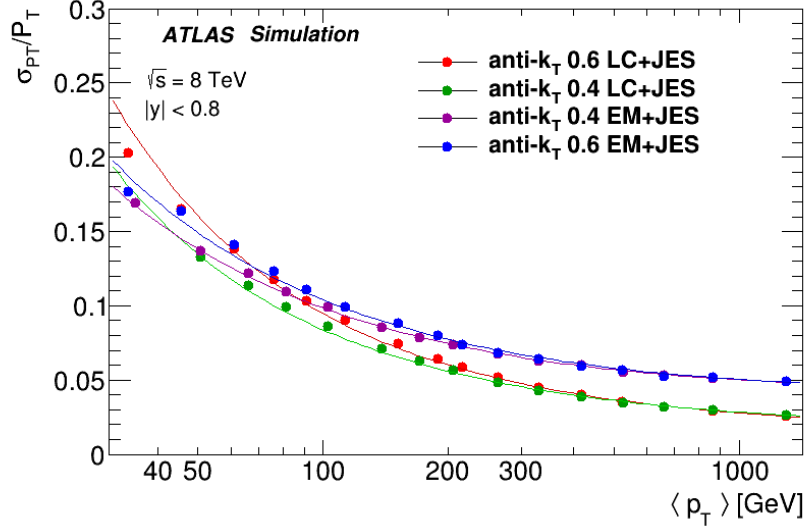


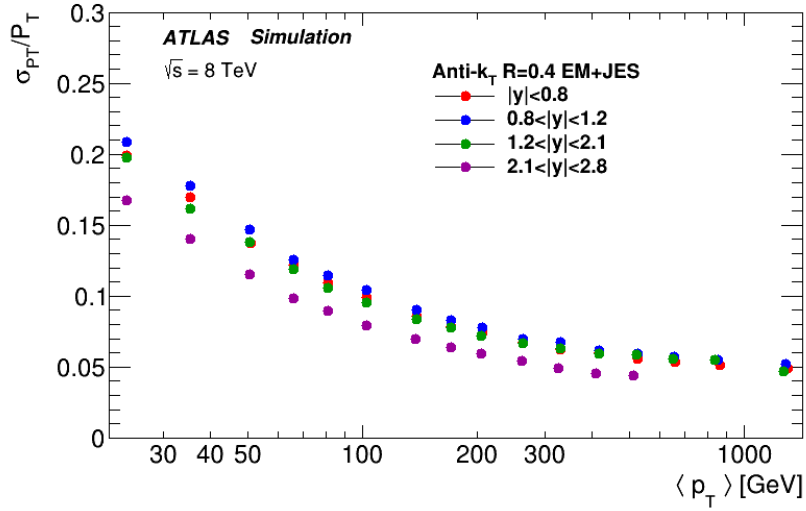
Figure 4.4: Distribution of the momentum response in anti- k_t $R=0.4$ jets calibrated to the EM+JES. A Gaussian fit has been performed to the core of the distributions, with $\sigma_{20-30} = (0.213 \pm 0.001)$ and $\sigma_{380-400} = (0.0604 \pm 0.0001)$.

Clearly, a smaller value of resolution is desirable, and indicates that the measured

momenta do not fluctuate too much with respect to the real ones. Figure 4.5a shows the truth resolution measured for events simulated using PYTHIA with anti- k_t $R=0.4$ and 0.6 jets calibrated using EM+JES and LCW+JES. The improvement in resolution expected for LCW+JES can be clearly appreciated for high- p_T jets. This is shown only for the central region of the detector ($|y| < 0.8$), while figure 4.5b shows the resolution for the different calorimeter regions compared.



(a) All calibrations, $|y| < 0.8$



(b) EM+JES anti- k_t $R = 0.4$, all regions

Figure 4.5: Truth resolution as measured using PYTHIA MC simulation, for (a) different jet calibrations and (b) different calorimeter regions. The resolutions in (a) have been fitted with the function expressed in equation 4.6.

The standard functional form expected from calorimeter resolutions is parametrised though three independent contributions which are combined through their sum in

quadrature:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{N^2}{p_T^2} + \frac{S^2}{p_T} + C^2} \quad (4.6)$$

These are the effective noise (N), the stochastic (S) and the constant (C) term. N represents external noise contributions that are independent of the momentum, or only depend weakly, such as the electronic noise and pile-up. It is expected to be predominant at lower energies, up to $p_T \sim 30$ GeV. Parameter C accounts for fluctuations that can be modelled as a constant fraction of the jet momentum, such as the signal loss in passive material or due to non-uniformities in the detector. It is expected to be the predominant effect for higher energies, $p_T > 400$ GeV. S accounts for the predominant effects in the intermediate values of p_T , namely event-by-event physical fluctuations of the jet shower related to the sampling nature of the calorimeter. The resolution results are usually fitted with this function.

The fit results are mostly used as a way to record the value of the resolution as a function of p_T to be used as input to the systematic uncertainties in other analysis, as will be described in section 4.3.7. The values of N , S and C can also be useful to estimate the impact of particular effects that worsen the resolution, or of the implementation of corrections that should improve it. However, the error assigned to N and S is usually rather large, given that different combinations of their values can yield equally good fits. A particular strategy was devised with the aim of estimating N as accurately as possible in the studies presented in section 4.3.6. The resolutions presented in figure 4.5a have been fitted using the expression in equation 4.6, resulting in similar noise and stochastic contributions between all calibration schemes, and two clearly different constant terms for the EM+JES and LCW+JES calibrations. The values of N range between 3 and 6 GeV², S is $\sim 0.6 - 0.7$ GeV, while $C = 0.42$ and 0.17 for the EM+JES and LCW+JES calibrations respectively.

The truth resolution thus measured has an evident dependence on the MC generator used for the simulation, and on the detector simulation software as well. An uncertainty is estimated by running the same algorithm on simulations from different MC generators, the effects never exceeding 5%.

4.3.2 Dijet Balance Method

The *dijet balance* method is based on momentum conservation in the transverse plane. It works on the approximation that there are only two jets in the event, and that they have the same truth p_T . The dijet asymmetry is defined as

$$A(p_{T,1}, p_{T,2}) \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}. \quad (4.7)$$

where $p_{T,1}$ and $p_{T,2}$ refer to the randomly ordered transverse momenta of the two leading jets.

Under the assumption of only two jets in the event, both in the same rapidity region, the standard deviation $\sigma(A)$ of a Gaussian fit to $A(p_{T,1}, p_{T,2})$ can be shown to be related to the relative jet resolution via

$$\frac{\sigma(p_T)}{p_T} = \sqrt{2} \sigma(A) \quad (4.8)$$

A detailed description of how this relation is derived and the approximations involved is presented in section 4.3.5. If one jet is in the rapidity bin being probed (y_j) and the other one is in the central reference region (y_i), the fractional jet p_T resolution is given by

$$\frac{\sigma(p_T)}{p_T} \Big|_{(j)} = \sqrt{4\sigma^2(A_{(i,j)}) - 2\sigma^2(A_{(i,i)})} \quad (4.9)$$

where $A_{(i,j)}$ is the asymmetry measured in a topology with one jet in region y_i and one jet in region y_j . Because $A_{(i,j)}$ involves two jets in the event, its distribution is measured in bins of the average momentum of the two leading (reconstructed) jets

$$\bar{p}_T = (p_{T,1} + p_{T,2})/2 \quad (4.10)$$

as it is the best approximation to the p_T of both jets.

In order to enrich the sample in dijet events, the leading jets are required to be almost back-to-back, with a cut of $\Delta\phi(1,2) > 2.8$. In addition, the third leading jet's momentum should be small, such that $p_{T,3}^{EM} < p_T^{cut}$. The cut on the third jet momentum is placed at the EM-scale to be independent of calibration effects and to have a stable reference for all calibration schemes.

An example asymmetry distribution is shown in figure 4.6a for jets in the central region and $\bar{p}_T$ between 185 and 240 GeV. The asymmetry is obtained for both data and MC, with anti- k_t $R = 0.4$ jets calibrated to EM+JES. The distributions show good data-MC agreement.

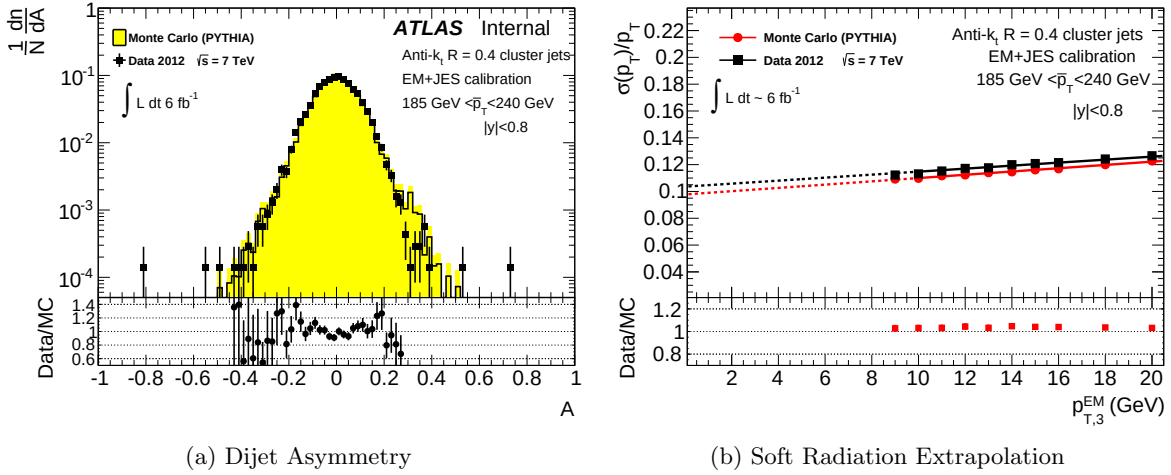


Figure 4.6: Distributions of the asymmetry (left) and soft radiation extrapolation (right) for $185 \text{ GeV} < \bar{p}_T < 240 \text{ GeV}$ for EM+JES, anti- k_t $R = 0.4$ jets. The filled area in the asymmetry distribution corresponds to simulated events while the black dots are data. In the SR plot black dots represent asymmetry values measured in data and red dots in MC; both show linear fits extrapolated to $p_{T,3}^{EM} \rightarrow 0$. The lower panel in both figures shows the Data/MC ratio.

In order for the Dijet Balance method to strictly apply, one should be able to select

events with exactly two particle jets that satisfy the hypothesis of exact momentum balance in the transverse plane. However, and in spite of the $\Delta\phi$ and $p_{T,3}^{EM}$ cuts, it is impossible to completely exclude the presence of additional soft particle jets not found at calorimeter level due to reconstruction inefficiencies at low p_T . A soft radiation (SR) correction is therefore implemented, in which $\sigma(A)$ is computed for a series of increasing cuts in $p_{T,3}^{EM}$, between 9 and 20 GeV. For each $\bar{p}_T$ bin, the jet energy resolutions obtained with the different $p_{T,3}^{EM}$ cuts are fitted with a straight line and extrapolated to $p_{T,3} \rightarrow 0$. Such extrapolation is presented in figure 4.6b for both data and MC simulated events. Note that resolutions are systematically broader as the $p_{T,3}^{EM}$ cut increases, a clear indication that the jet resolution determined from two jet topologies depends on the presence of a third jet. The bottom plot shows the ratio of data and MC, which is below 5% and flat, showing that data and MC have similar SR behaviour. It was found that for cuts of order ~ 25 GeV (depending on the $\bar{p}_T$ bin), SR saturates, and the resolution becomes flat. A soft radiation correction factor, $K_{soft}(p_T)$, is obtained from the ratio of the value of the linear fit at 0 GeV over the value at 10 GeV:

$$K_{soft}(p_T) = \frac{\left(\frac{\sigma(p_T)}{p_T}\right)_{p_{T,3} \rightarrow 0}}{\left(\frac{\sigma(p_T)}{p_T}\right)_{p_{T,3}^{EM} < 10 \text{ GeV}}} \quad (4.11)$$

This correction is applied as a multiplicative factor to the resolution values obtained from the distributions where a $p_{T,3}^{EM} < 10$ GeV cut was required. It can be a rather large correction, of almost 30% in the lowest $\bar{p}_T$ bins, and decreases in higher bins.

So far the method assumes that if it is applied in two-jet events, any resolution effect measured through the asymmetries comes solely from detector effects. However there can be an imbalance between the leading jets also at truth level. This is accounted for by introducing the truth asymmetry A^{truth} , defined as in equation (4.7) but with truth jets, as a correction to the reconstructed level asymmetry A^{reco} . The relation between the resolution and the asymmetry defined in equation 4.8 is then redefined as:

$$\left(\frac{\sigma(p_T)}{p_T}\right)^2 = 2[\sigma^2(A^{reco}) - \sigma^2(A^{truth})] \quad (4.12)$$

The particle imbalance $\sigma(A^{truth})$ is measured using the dijet method with truth jets as inputs. Regarding the SR correction, although ideally it would not be necessary to apply it, in practice only truth jets with $p_T^{truth} > 9$ GeV are saved in the simulation, making it necessary to extrapolate the truth asymmetries values to $p_{T,3} \rightarrow 0$.

The systematic uncertainties associated with this method correspond to the requirement of $\Delta\phi > 2.8$ and the application of the SR correction. The first is evaluated by varying the $\Delta\phi$ cut between 2.6 and 3.0; the uncertainty is found to be largest in the lower $\bar{p}_T$ bin, with values between 2-3% for 30-60 GeV. As for the SR correction, the $K_{soft}(p_T)$ values are plotted against $\bar{p}_T$ and fitted, which yields a correction function that takes into account all the values of $K_{soft}(p_T)$ obtained. The difference between the resolutions corrected by the independent $K_{soft}(p_T)$ and by the SR function correction is taken as the uncertainty.

4.3.3 Bisector Method

The *bisector method* is based on the definition of an imbalance (transverse) vector, $\vec{P}_T$, which is defined as the vector sum of the two leading jets in a dijet event, $\vec{P}_T = \vec{p}_{T,1} + \vec{p}_{T,2}$. This vector is projected along an orthogonal coordinate system in the transverse plane, denoted as (ψ, η) ¹, where η is chosen in the direction that bisects $\Delta\phi_{12} = \phi_1 - \phi_2$, the angle formed by $\vec{p}_{T,1}$ and $\vec{p}_{T,2}$. Figure 4.7 illustrates how this coordinate system and the projections are defined.

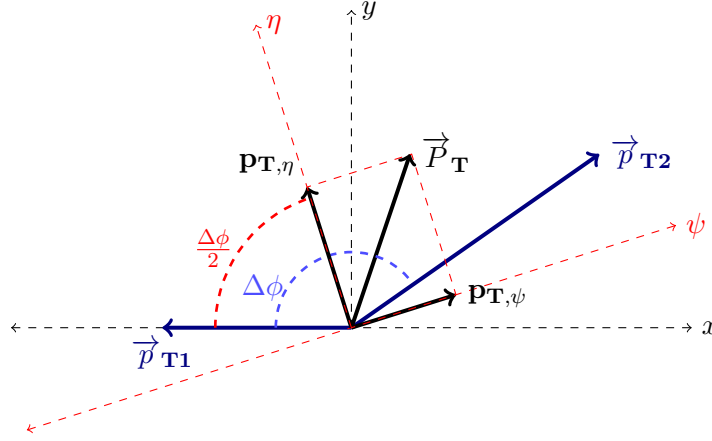


Figure 4.7: Diagram of the jet momenta (arrows in blue) in the transverse plane, and how they are projected onto the bisecting coordinates (arrows in black) in order to obtain the variables of the bisector method.

In a perfectly balanced dijet event, $\vec{P}_T = 0$. However, both instrumental effects and particle imbalance ones contribute to it, causing a dispersion in its ψ and η components. The ψ component, $p_{T,\psi}$, has greater sensitivity to the energy resolution because it is the difference between two large transverse momenta while $p_{T,\eta}$ is the sum of two small component. In order to measure the resolution, the distributions of $p_{T,\psi}$ and $p_{T,\eta}$ are obtained in bins of $\bar{p}_T$ (where $\bar{p}_T$ is used instead of p_T for the same reason as in the dijet method). Also as in the dijet method, in order to enrich the sample in dijet events, a cut is applied on the momentum of the third jet at EM scale, asking for $p_{T,3}^{EM} < 10$ GeV. The $\Delta\phi$ cut however is not applied, since the method relies on this angle and the cut would create a bias towards smaller resolutions.

Examples of the distributions of $p_{T,\psi}$ and $p_{T,\eta}$ are presented in figure 4.8 for the $\bar{p}_T$ bin (125-160) GeV. Both distributions show good agreement between data and MC simulation, and it can be appreciated that the $p_{T,\psi}$ distribution is wider than the one for $p_{T,\eta}$ due to the higher sensitivity to resolution effects of this component.

The variances of these projections are approximated by the standard deviations obtained from Gaussian fits to the distributions such as the ones shown in figure 4.8, so that $\sigma_\psi^2 \simeq \text{Var}(p_{T,\psi})$ and $\sigma_\eta^2 \simeq \text{Var}(p_{T,\eta})$ respectively. The values of σ_ψ and σ_η as a function of $\bar{p}_T$ are shown in figure 4.9, measured both in data and MC simulation; the good agreement seen in figure 4.8 is reflected for the whole range of $\bar{p}_T$. As expected,

¹The names of the axes of this new coordinate system have been historically chosen like this. The η direction has not relation, and is not be confused, with the pseudorapidity (defined in section 2.4.1).

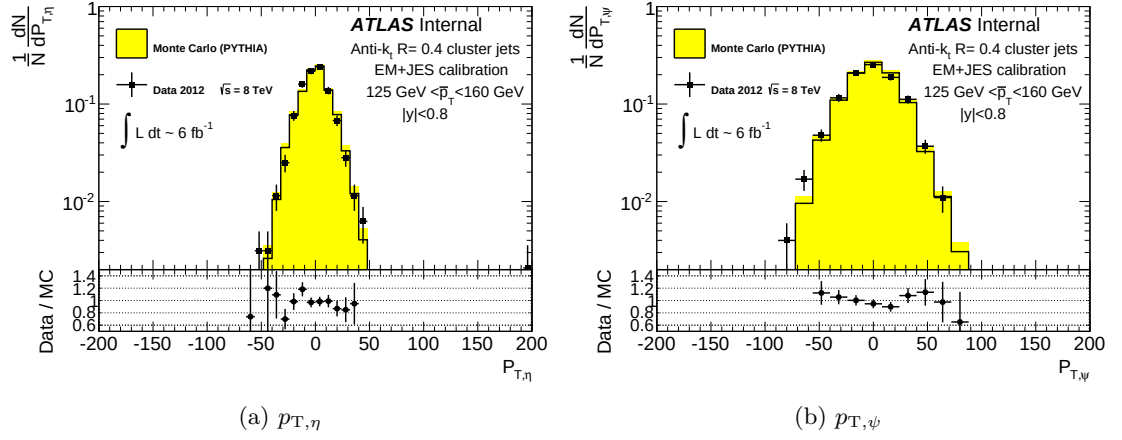


Figure 4.8: Normalised distributions of the η (left) and ψ (right) projections of the momentum in the bisector method. The filled area corresponds to simulated events while the black dots to the data. The lower panel in both figures shows the Data/MC ratio.

the value of σ_η remains constant in $\bar{p}_T$, while that of σ_ψ increases due to the increase in the absolute values of the jet momentum variations due to resolution effects.

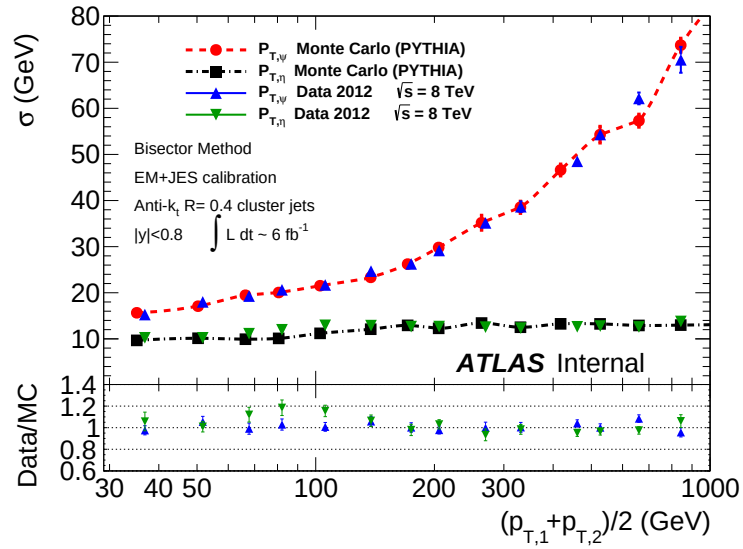


Figure 4.9: The values of σ_ψ and σ_η are shown as a function of $\bar{p}_T$ for both data and MC simulation (PYTHIA 8). The lower panel shows the Data/MC ratio for each of the projections (blue for σ_ψ and green for σ_η).

It can be shown [83] that the measured σ^2 are related to the detector resolution via:

$$\begin{aligned}\sigma_\psi^2 &\simeq \sigma_\psi^{2,truth} + 2\sigma^2(p_T) \sin^2(\Delta\phi_{1,2}/2) \\ \sigma_\eta^2 &\simeq \sigma_\eta^{2,truth} + 2\sigma^2(p_T) \cos^2(\Delta\phi_{1,2}/2)\end{aligned}\quad (4.13)$$

where $\sigma_\psi^{2,truth}$ and $\sigma_\eta^{2,truth}$ are the part of the widths due to truth-level effects. By subtracting the two expressions one arrives to the resolution expressed in terms of the standard deviations:

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{(\sigma_\psi^2 - \sigma_\eta^2) - (\sigma_\psi^{2,truth} - \sigma_\eta^{2,truth})}{2p_T^2 |\cos(\Delta\phi_{1,2})|}} \quad (4.14)$$

where the term $(\sigma_\psi^{2,truth} - \sigma_\eta^{2,truth})$ is directly linked to the truth-level contributions to $\vec{P}_T$. These contributions come from initial state radiation and, to a lesser extent, from the intrinsic transverse momentum of the partons in the protons and from out-of-cone parton showering, i.e. when the jet radius is not large enough to contain the entire particle shower. They are expected to be isotropic and thus should affect equally the distributions of $p_{T,\psi}^{truth}$ and $p_{T,\eta}^{truth}$. In this sense, the bisector method has an intrinsic particle imbalance cancellation, which in fact had been, until now, the basic assumption of the method (as reference [29] explains). However, it has been found that $p_{T,\psi}^{truth}$ tends to be more sensitive to the truth level fluctuations, thus leaving a small contribution from particle imbalance that needs to be accounted for. MC simulation is used to estimate the value of $(\sigma_\psi^{2,truth} - \sigma_\eta^{2,truth})$, which is found to be constant within uncertainties as a function of $\bar{p}_T$. This is shown in figure 4.10 for anti- k_t R=0.4 and R=0.6 jets. This figure shows that the size of the imbalance depends on the jet size, its value being smaller for larger jets ($\sim 25 \text{ GeV}^2$ and $\sim 49 \text{ GeV}^2$ for R=0.6 and 0.4 respectively). This favours the hypothesis that the imbalance could be mostly due to out-of-cone radiation.

Lastly, the expression in equation 4.14 assumes that both of the leading jets in the event belong to the same rapidity region. As with the dijet balance method, the resolution is measured in rapidity bins, where the central region of $|y| < 0.8$ is used as the reference (region i) to be subtracted to obtain the resolution in region j :

$$\left. \frac{\sigma(p_T)}{p_T} \right|_{(j)} = \sqrt{\left. \frac{(\sigma_\psi^2 - \sigma_\eta^2) - (\sigma_\psi^{2,truth} - \sigma_\eta^{2,truth})}{2p_T^2 |\cos(\Delta\phi_{1,2})|} \right|_{(i,j)} - \left. \frac{\sigma(p_T)^2}{p_T} \right|_{(i)}} \quad (4.15)$$

The systematic uncertainty corresponding to this method arises from the assumption of isotropy of the soft radiation. Although the particle level imbalance is subtracted as a correction to the method, there is still the matter of whether its value is independent of the cut in $p_{T,3}^{EM}$. For this reason $(\sigma_\psi^2 - \sigma_\eta^2)$ is evaluated as a function of the cut in $p_{T,3}^{EM}$, and the systematic uncertainty is derived from the difference between the maximum and minimum values found:

$$\Delta \left(\frac{\sigma(p_T)}{p_T} \right)_{bisector} = \frac{1}{2} \frac{\sqrt{(\sigma_\psi^2 - \sigma_\eta^2)_{max}} - \sqrt{(\sigma_\psi^2 - \sigma_\eta^2)_{min}}}{p_T \sqrt{2 \cos(\Delta\phi_{1,2})}} \quad (4.16)$$

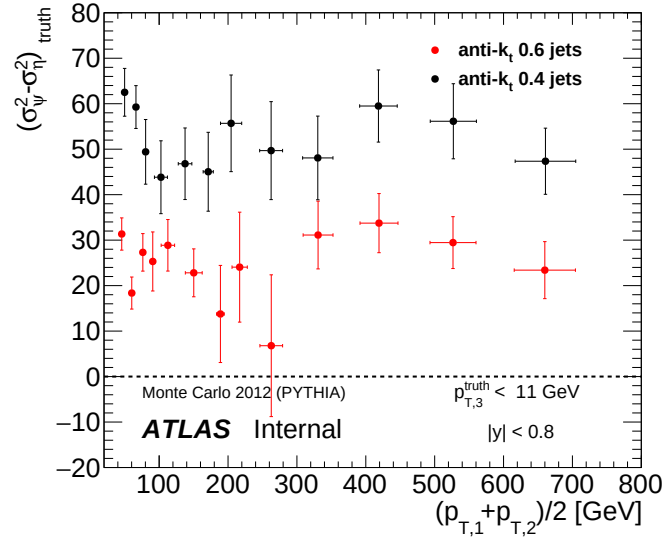


Figure 4.10: The truth-level imbalance ($\sigma_{\psi}^{2,truth} - \sigma_{\eta}^{2,truth}$) measured in MC PYTHIA 8 as a function of $\bar{p}_T$. The values are shown for anti- k_t $R=0.4$ (black) and $R=0.6$ (red) jets.

The relative uncertainty is then estimated with respect to the measured resolution, and yields values between 1-7%. The uncertainty is found to be larger in anti- k_t $R=0.4$ jets, of 7% up to 150 GeV, decreasing to 1% at 600 GeV. In the case of $R=0.6$ jets the range of the uncertainty is 1-3%.

4.3.4 Jet Resolution Results 2012

The measurement of the jet energy resolution was carried out in the first part of the 2012 dataset using approximately 6 fb^{-1} of data corresponding to proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$, delivered by the LHC and collected by the ATLAS experiment. Data is compared to Monte Carlo simulations of jets at high transverse momentum. The baseline simulation samples were produced with the PYTHIA 8.160 event generator described in section 1.3. The ATLAS AU2 underlying event tune and the CT10 PDF set are used.

Pile-up is simulated by overlaying additional unbiased pp collisions generated with PYTHIA 8. These extra events are overlaid onto the hard scattering events according to the measured distribution of the average number of pp interactions per bunch crossing, $\langle\mu\rangle$. The simulated proton bunches are organised in four trains of 36 bunches with a 50 ns spacing between them, so that the simulation also contains effects from out-of-time pile-up. Simulated events are reweighted such that the MC distribution of $\langle\mu\rangle$ agrees with the data. The present dataset has $\langle\mu\rangle$ values ranging from 6 to 40, with a mean of 20. The generated events are passed through the full detector simulation, subsequently processed using the same reconstruction software as the data, and put through the trigger simulation package of the experiment.

Events selected for this analysis are required to satisfy several basic quality criteria in order to reject significant contamination from detector noise, non-collision beam

anti- k_t jets p_T bin [GeV]		Trigger
$R = 0.4$	$R = 0.6$	Runs 200804 - 205113
(30,45)	(40,55)	EF_j15_a4tchad OR EF_fj15_a4tchad
(45,60)	(55,70)	EF_j25_a4tchad OR EF_fj25_a4tchad
(60,75)	(70,85)	EF_j35_a4tchad OR EF_fj35_a4tchad
(75,90)	(85,100)	EF_j45_a4tchad OR EF_fj45_a4tchad
(90,125)	(100,135)	EF_j55_a4tchad OR EF_fj55_a4tchad
(125,160)	(135,180)	EF_j80_a4tchad OR EF_fj80_a4tchad
(160,185)	(180,200)	EF_j110_a4tchad OR EF_fj110_a4tchad
(185,240)	(200,240)	EF_j145_a4tchad OR EF_fj145_a4tchad
(240,300)	(240,300)	EF_j180_a4tchad OR EF_fj180_a4tchad
(300,380)	(280,380)	EF_j220_a4tchad OR EF_fj220_a4tchad
(380,480)	(380,480)	EF_j220_a4tchad OR EF_fj220_a4tchad
(480,600)	(480,600)	EF_j360_a4tchad
> 600	> 600	EF_j460_a4tchad

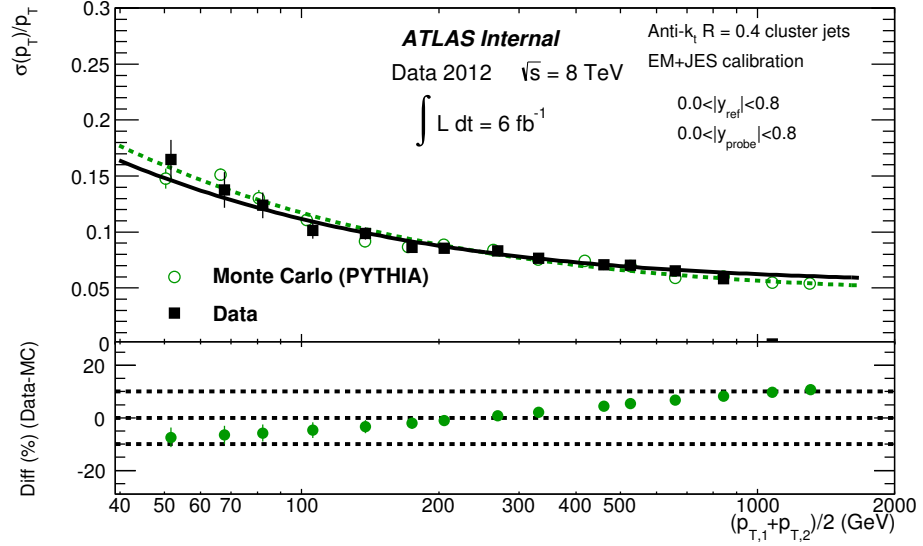
Table 4.1: Description of the inclusive combination of jet triggers used for each p_T bin

backgrounds, and other spurious effects. For every event, the reconstructed interaction vertex position is required to be consistent with the beam-spot, to have a z position within 200 mm of the ATLAS geometrical centre and to have at least 5 reconstructed tracks associated with it. The event selection requires at least two jets with momentum larger than a series of cuts determined by the trigger. A series of single jet and forward jet triggers is used in an inclusive OR combination. The full list of triggers is presented in table 4.1, where the technical denomination of the triggers is given. ‘EF’ stands for event filter, the high-level trigger presented in section 5.2.1; ‘j25’ and ‘fj25’ indicate that the triggers require at least one jet or forward jet with a momentum above 25 GeV. The jet momentum at which each trigger becomes 99% efficient depends on the jet radius, which is why the range of p_T in which each trigger combination is applied is indicated in separate columns for anti- k_t $R=0.4$ and $R=0.6$ jets. The combinations were chosen such that the trigger efficiency, for a specific region of p_T , was greater than 99%.

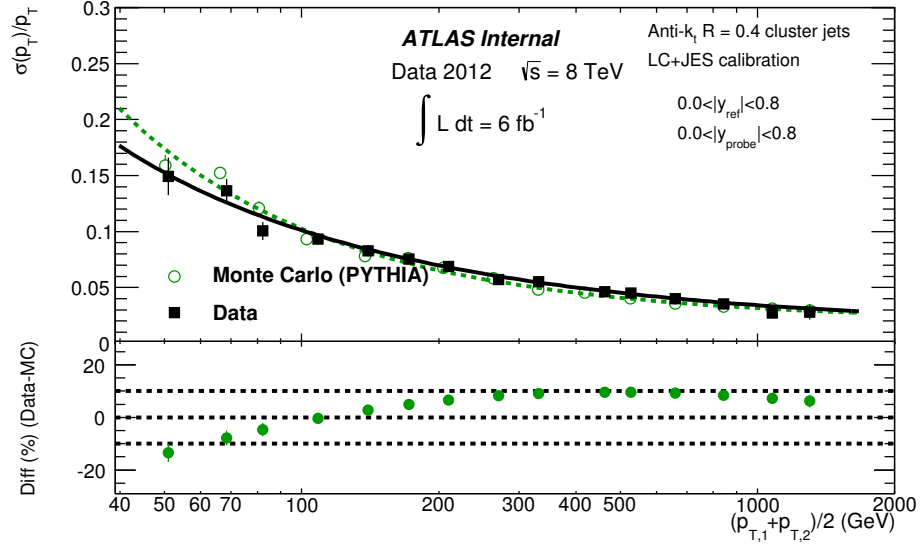
The resolution is studied using the in-situ methods presented above for the EM+JES and LCW+JES calibrations, in four bins of rapidity, for the jet collections corresponding to $R=0.4$ and $R=0.6$. The results corresponding to both calibrations in the central region ($|y| < 0.8$) for anti- k_t $R=0.4$ jets are presented in figure 4.11. For reasons that will be explained in the next section (4.3.5), only the bisector method was used in this case. The measured values of resolution are expressed with the corresponding statistical uncertainty.

The resolutions are fitted with the function presented in equation 4.6, and the relative difference between the fits is shown in the bottom part of each plot. Excellent agreement is observed between data and MC. Similar results are obtained for the other rapidity regions; they are included in appendix B.

The validation of the in-situ methods as observables that measure the resolution



(a) EM+JES



(b) LCW+JES

Figure 4.11: Jet momentum resolution for the bisector technique as a function of $\bar{p}_T$ for anti- k_t jets with $R = 0.4$ (a) and $R = 0.6$ (b). Only statistical uncertainties are shown. The lower part shows the relative difference between data and Monte Carlo results. The black dotted lines indicate a relative difference of $\pm 10\%$. The bisector method is found to be in agreement for both Monte Carlo simulation and data.

is done through the comparison with the truth resolution. This is called the *closure test*, in which the MC in-situ results are plotted against the truth resolution, as shown in figure 4.12 for the EM+JES calibration. To this aim the p_T^{truth} bins in which the truth resolution has been measured are converted into p_T^{reco} bins. Previous results had seen good agreement (within 10%) between the dijet, the bisector and the truth resolution. In the plots shown here, however, a larger disagreement can be appreciated; in particular it is $\sim 20\%$ for the dijet method up to 200 GeV. This indicates that the observable thus measured is close, but not quite equal to, the jet resolution.

The failure of the closure test leads to the conclusion that probably one, or some, of the assumptions on which the method relies to relate the calorimeter observables to the resolution is no longer valid. The studies concerning the dijet non-closure are detailed in section 4.3.5, and it was found that the assumption that the variance could be replaced by the standard deviation of the Gaussian fit did not hold; i.e the distributions were not Gaussian, or had too large non-Gaussian tails. This seemed to be the main failure of this method, that led to issues with the SR correction and consequently a measurement considerably larger than the resolution.

It should be mentioned that the measurement with both in-situ methods encountered obstacles due to the non-Gaussianity of the different distributions, specially in the lower $\bar{p}_T$ bins. This is a direct consequence of the presence of fake jets (jets with no truth counterpart) and pile-up, related to the increase in energy and luminosity of the beam. Such changes were accordingly incorporated into the MC simulations, therefore affecting both the measurements in data and MC. Issues like these are the ones that prompt improvements in the JES and jet selection, as well as in the measurement itself. During 2014 and 2015 many improvements were made in the JES and event selection that allowed to work past the issues found in this measurement. The updated version of the results shown here can be found in reference [33], where new JES corrections are described, and the JER is measured using these methods only above 300 GeV; below this, the balance between jets and photons, or jets and the Z boson is exploited in a new generation of in-situ methods.

4.3.5 Closure Study of the Dijet Method

The studies described in this section were prompted by the results shown in figure 4.12, where the resolution measured in MC simulation using the in-situ dijet and bisector methods was 10-20% above the truth resolution measured in the same simulation. Both methods rely on a series of approximations that allow them to relate calorimeter observables to the momentum resolution. Given the more approachable derivation of the dijet method, a study is presented where each step of the method is revised, with the aim of finding which approximation(s) are no longer valid.

Events for this study were selected with the same criteria as for the actual dijet method, requiring $\Delta\phi_{1,2}^{\text{truth}} > 2.8$. Additionally, the three leading reconstructed jets have been matched to a truth jet geometrically, requiring $\Delta R(\text{truth}, \text{reco}) < 0.3$, and where $p_T^{\text{truth}} > 20$ GeV. The jets are calibrated with the EM+JES scheme, and use the anti- k_t clustering algorithm with radius parameter $R=0.4$. Both leading jets in the event are required to be in the central calorimeter region ($|y| < 0.8$). The variables in each step were measured in the same $\bar{p}_T$ bins as in the normal dijet method.

The derivation of the method starts by establishing this somewhat obvious, but

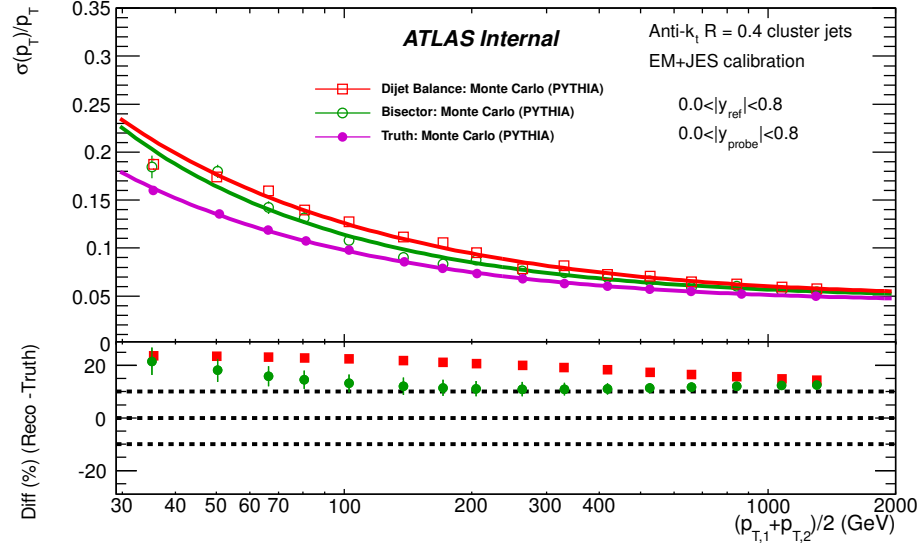
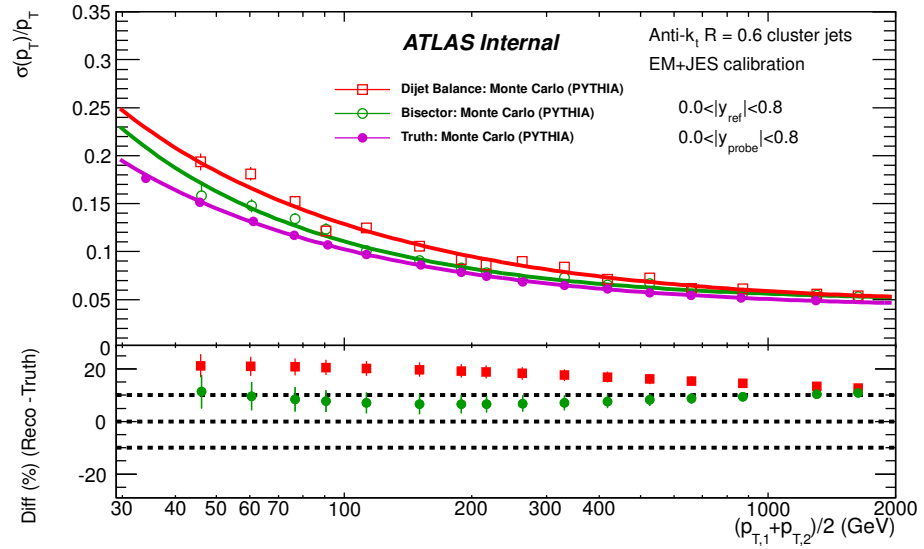
(a) anti- k_t $R=0.4$ (b) anti- k_t $R=0.6$

Figure 4.12: Comparison between the Monte Carlo simulation truth resolution (magenta) and the results obtained from the bisector (green) in-situ technique for anti- k_t 0.4 (a) and 0.6 (b) in MC simulation. Only statistical uncertainties are shown. The black dotted line indicates a relative uncertainty of $\pm 10\%$.

mathematically exact, relation between the leading jets in an event:

$$p_{T,1}^{reco} - p_{T,2}^{reco} = (p_{T,1}^{reco} - p_{T,1}^{truth}) + (p_{T,2}^{reco} - p_{T,2}^{truth}) + (p_{T,1}^{truth} - p_{T,2}^{truth}) \quad (4.17)$$

where $p_{T,1}$ and $p_{T,2}$ are the momenta of the two leading jets (randomized, as is done in the dijet method). This shows the relation between the imbalance of the leading reconstructed jets with the resolution fluctuations and the truth jet imbalance due to out-of-cone showering and the presence of more than two jets in the event.

For a given bin of the average p_T of the leading jets at truth level ($\bar{p}_T^{truth}$) one can take the variance of the terms in equation 4.17; since the three terms on the right hand side are statistically independent, the variance can be applied to each one separately. Furthermore, it is valid to consider $Var(p_{T,1}^{reco} - p_{T,1}^{truth}) = Var(p_{T,2}^{reco} - p_{T,2}^{truth}) \equiv Var(p_T^{reco} - p_T^{truth})$. This is because the variance of the difference between the reconstructed and the truth jet (i.e. the resolution) should be similar for the two leading jets if they are in the same region of the calorimeter and the third leading jet is required to be sufficiently small. These considerations result in the following expression:

$$2Var(p_T^{reco} - p_T^{truth}) = Var(p_{T,1}^{reco} - p_{T,2}^{reco}) - Var(p_{T,1}^{truth} - p_{T,2}^{truth}) \quad (4.18)$$

which relates the resolution fluctuations to the imbalances at reconstructed and truth level. The variance is not a robust magnitude, due to its sensitivity to the tails of the distribution. Under the assumption that the fluctuations are predominantly normal, a Gaussian fit is performed on the distributions in the range of ± 2 RMS around the mean in order to approximate the variance with the more robust standard deviation:

$$2\sigma^2(p_T^{reco} - p_T^{truth}) = \sigma^2(p_{T,1}^{truth} - p_{T,2}^{truth}) - \sigma^2(p_{T,1}^{reco} - p_{T,2}^{reco}) \quad (4.19)$$

The terms in equation 4.19 can be divided by average momentum of each bin, $\langle \bar{p}_T^{truth} \rangle$, in order to bring this one step closer to the resolution, without affecting the agreement between the two sides of the expression. The three resulting terms go through different approximation procedures that relate them to either the width of the asymmetries as defined for the dijet method or the JER. The first term is related to the resolution:

$$2 \frac{\sigma^2(p_T^{reco} - p_T^{truth})}{\langle \bar{p}_T^{truth} \rangle^2} \simeq 2\sigma^2 \left(\frac{p_T^{reco} - p_T^{truth}}{p_T^{truth}} \right) = 2\sigma^2 \left(p_T^{reco} / p_T^{truth} \right) \quad (4.20)$$

where the average momentum is approximated by taking $\bar{p}_T^{truth} \sim p_T^{truth}$ and considered within the expression for the distribution. This part is thus related to the width of the response, i.e. the resolution. The next two terms follow similar procedures. In the case of the one corresponding to reco-level variables, $\bar{p}_T^{truth} \sim \bar{p}_T^{reco}$ is the first step, and the second is to take this from the average of the bin to an event-by-event variable, resulting in the standard deviation of the dijet method's asymmetry:

$$\frac{\sigma^2(p_{T,1}^{reco} - p_{T,2}^{reco})}{\langle \bar{p}_T^{truth} \rangle^2} \simeq \frac{\sigma^2(p_{T,1}^{reco} - p_{T,2}^{reco})}{\langle \bar{p}_T^{reco} \rangle^2} \simeq 4\sigma^2 \left(\frac{p_{T,1}^{reco} - p_{T,2}^{reco}}{p_{T,1}^{reco} + p_{T,2}^{reco}} \right) \equiv 4\sigma^2(A^{reco}) \quad (4.21)$$

In a similar way, although without the need of approximating $\bar{p}_T^{truth}$, the second term

is written as the width of the truth level asymmetry:

$$\frac{\sigma^2(p_{T,1}^{truth} - p_{T,2}^{truth})}{\langle p_T^{truth} \rangle^2} \simeq 4\sigma^2 \left(\frac{p_{T,1}^{truth} - p_{T,2}^{truth}}{p_{T,1}^{truth} + p_{T,2}^{truth}} \right) \equiv 4\sigma^2(A^{truth}) \quad (4.22)$$

The results of the approximations expressed in equations 4.20, 4.21 and 4.22 can now be inserted into equation 4.19 to obtain the expression of the dijet method corrected by the particle imbalance (equation 4.12).

In order to test the assertions stated in equations 4.18 and 4.19, the sides of the equivalences are calculated and plotted separately in figure 4.13. The bottom part of the plot shows the ratio for each equation: the differences for the variances is found to be much smaller, around 10%, than for the width of the Gaussian fits.

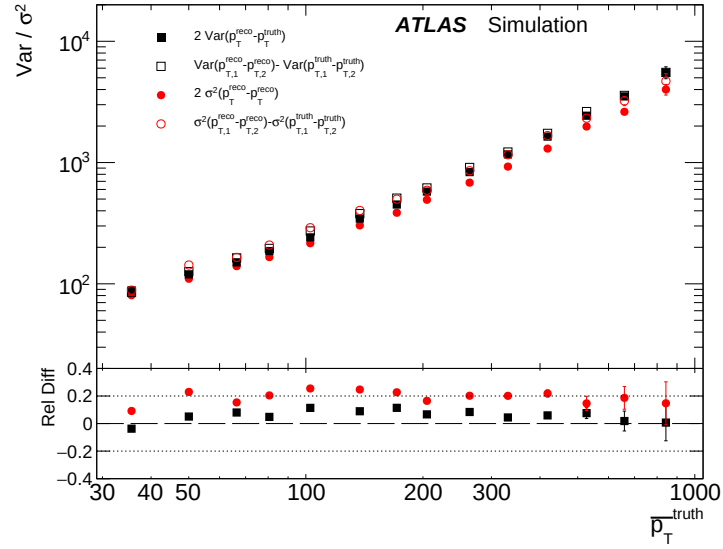


Figure 4.13: Closure test for equations 4.18 (black) and 4.19 (red). The resolution side of the expression (in full markers) is compared to the other side of the equation (in empty markers) through the relative ratios shown in the bottom plot. The variances show better agreement than the Gaussian fits for the entire p_T^{truth} range.

Since this step appears to contribute to the non closure, each term was tested separately, comparing its variance and its standard deviation, as presented in figure 4.14. This shows that, as expected, the variances yield larger values than the standard deviations for all the terms. However the differences appear to be much larger for the distribution of $(p_{T,1}^{truth} - p_{T,2}^{truth})$. The fact that the difference between the variance and σ^2 is not compensated accordingly in both sides of the equations leads to non-closure.

The remaining steps in the procedure to arrive to the dijet balance equation do not show major inconsistencies. Figure 4.15a shows the difference between dividing a each term by $\langle p_T^{truth} \rangle$ and the width of the corresponding asymmetry (as done through equations 4.21 and 4.22). The same is shown for the resolution as obtained through equation 4.20, in this case showing a small discrepancy for high p_T^{truth} . The last step is the closure test for the method, presented in figure 4.15b. The purpose is to compare

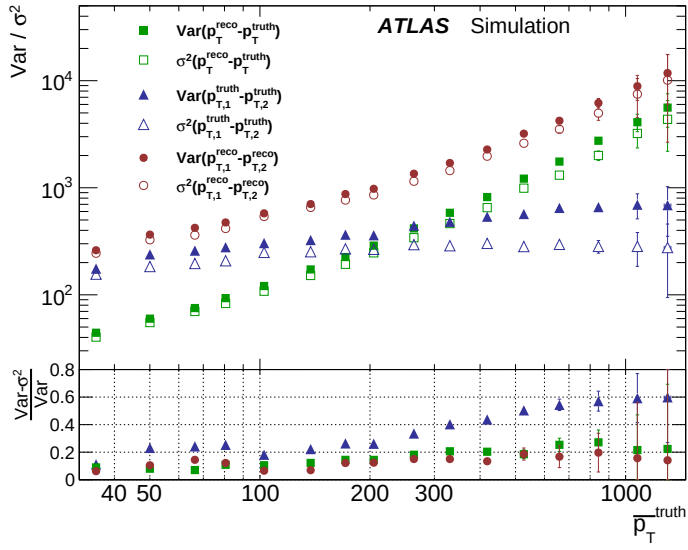
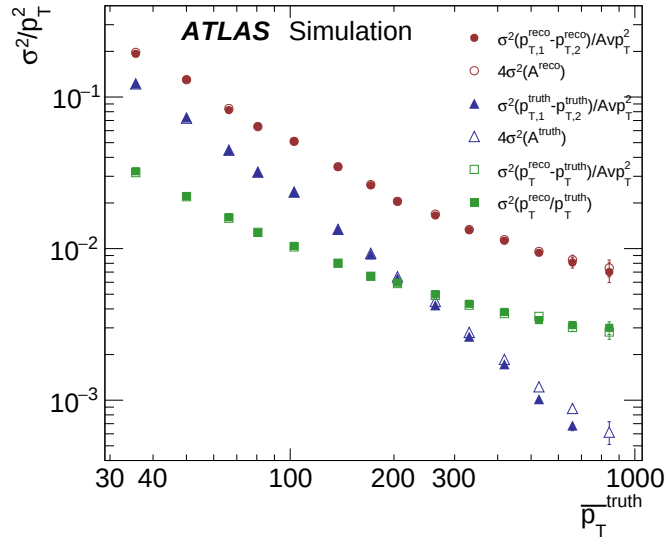
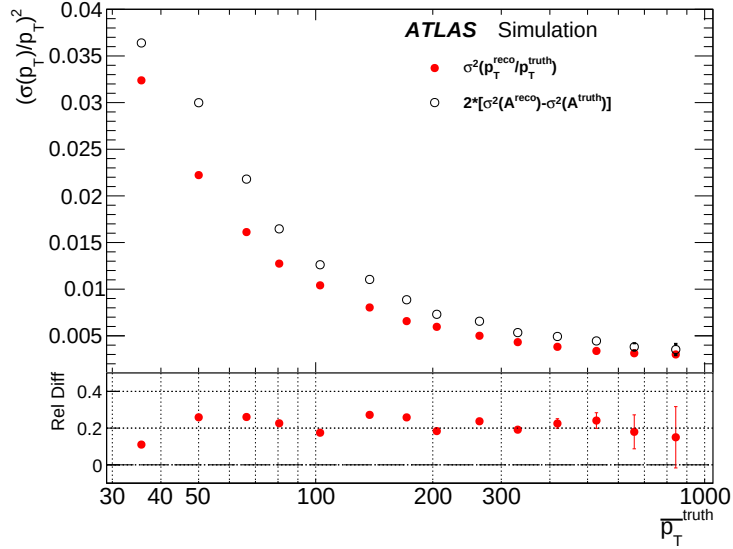


Figure 4.14: Comparison of the variance and the standard deviation of the Gaussian fit for the three terms in equations 4.18 (full markers) and 4.18 (empty markers). The bottom plot shows the relative difference between variances and σ^2 . The variances are larger than the σ^2 in all cases, in particular for $(p_{T,1}^{truth} - p_{T,2}^{truth})$.

both sides of equation 4.12 using the values obtained in this study, expecting to see a similar non closure as in figure 4.12a.



(a)



(b)

Figure 4.15: The approximations of equations 4.22(blue), 4.21(red) and 4.22(green) are tested separately, showing no major disagreements (a). The final equivalence that leads to the dijet method shows the total non-closure (b).

4.3.6 Jet Resolution Prospects for High Luminosity

This section describes the study of the resolution in different simulated pile-up environments. The aim was to evaluate the jet calibration and resolution performance in scenarios with increased noise with respect of the situation in 2011, so as to demonstrate the possibility of jet calibration in the 2012 data-taking conditions. The studies were then used to evaluate the performance of the jet areas correction. In addition,

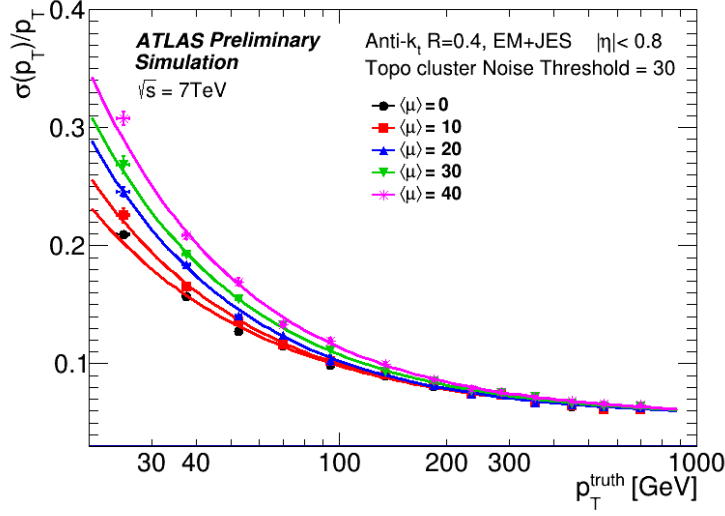


Figure 4.16: The jet energy resolution ($\frac{\sigma_{p_T}}{p_T}$) measured for anti- k_t jets with $R = 0.4$ within $|\eta| < 0.8$, versus the true jet p_T , in the EM+JES calibration. The data points are fit with the function in equation 4.6 to obtain the values of the N,S and C parameters. The resolution is measured for samples with different values of $\langle\mu\rangle$. The noise term increases with $\langle\mu\rangle$, while the fitted value for S is constant within errors and C is kept fixed to its value for $\langle\mu\rangle = 0$.

they were used to extrapolate the resolution in extreme pile-up conditions such as the ones expected in a future upgraded ATLAS detector in the projected High Luminosity LHC. The complete results are included in references [33, 65].

The increase in luminosity and energy of the LHC beam leads to higher pile-up environment. Some of the effects of pile-up have already been described, for example the difficulties they imply in the resolution measurement with in-situ methods. In addition, pile-up interactions add an energy offset (of the order of 1 GeV per additional vertex for jets reconstructed with the anti- k_t algorithm with $R=0.6$), making jet performance highly dependent on the pile-up varying conditions. Furthermore, the resolution is much degraded by event-by-event fluctuations of pile-up contributions. This type of contributions are of the kind that is independent of the jet momentum, thus considered mostly through the noise term (N) from equation 4.6. Pile-up fluctuations also lead to the presence of pile-up jets (also called fake jets), which consist of random combinations of soft particles from multiple vertices that fluctuate above the minimum jet p_T threshold as well as hard jets originating from additional pile-up interactions.

Calorimeter clusters were described at the beginning of this chapter as the basic components of reconstructed jets. Their defining characteristic is the noise threshold applied, which is determined from the RMS of the noise. The noise is noticeably increased in higher pile-up conditions, indicating that the noise threshold should be modified in order to make the minimum detectable signal remain above the typical pile-up induced energies. The modification of the noise threshold thereby reduces the impact that pile-up has in jet reconstruction.

To investigate the effects of pile-up and cluster threshold a series of MC simulations

were generated with varying values of $\langle\mu\rangle$ and threshold. The number of additional interactions per bunch crossing is sampled from a Poisson distribution with mean μ of the same values. The values chosen were 0, 10, 20, 30 and 40. The cluster thresholds were tuned accordingly for each case, and are denominated through their corresponding value of $\langle\mu\rangle$. As shown in section 2.2, in the 2012 data-taking conditions $\langle\mu\rangle = 20.7$.

The measured truth resolution using anti- k_t R=0.4 jets calibrated using the EM+JES scheme is presented in figure 4.16. The different curves correspond to the different values of $\langle\mu\rangle$, where the cluster threshold was kept constant (to the value for $\langle\mu\rangle = 30$). Each plot was fitted with the function expressed in equation 4.6. The complementary case in which $\langle\mu\rangle$ is kept constant and the cluster threshold is varied was evaluated separately, without finding any significant impact in the resolution.

It was of particular interest for these studies to be able to extract the noise term to the fits of the resolution measured for different $\langle\mu\rangle$ samples. In theory N , S and C account for different effects, so that in the current test only N should be modified with varying $\langle\mu\rangle$. However the three parameters are correlated in the fit, and S and C vary as well. This was particularly problematic in the forward regions, where the resolution dependence on p_T is flatter and thus the shape of N and S at intermediate p_T are very similar. A fitting procedure was hence established, in which first the resolution for $\langle\mu\rangle = 0$ was fitted, and the value of C obtained was fixed; when fitting the resolution measured with $\langle\mu\rangle > 0$, only N and S were allowed to fluctuate. In the forward regions the value of S was fixed as well. This first approximation showed that the noise parameter could not be well determined through the fit to the resolution. An independent estimation was later designed, through the use of Minimum Bias data (Zero Bias data), as was done in reference [33]. The results from the fit for the central region ($|\eta| < 0.8$) are presented in table 4.2.

$\langle\mu\rangle$	N [GeV ²]	S [GeV]	C
0	3.1 ± 0.2	0.76 ± 0.01	0.055
10	3.7 ± 0.2	0.74 ± 0.02	0.055
20	4.8 ± 0.2	0.72 ± 0.01	0.055
30	5.1 ± 0.2	0.78 ± 0.02	0.055
40	5.8 ± 0.2	0.81 ± 0.02	0.055
150	13 ± 2	0.8	0.55

Table 4.2: Values of the fit parameters corresponding to figure 4.16. The value of C has been fixed to the one corresponding to no pile-up. The value of N was extrapolated for $\langle\mu\rangle = 150$ using a linear fit, while S and C were kept from the previous results.

Having the values of N as a function of $\langle\mu\rangle$ allowed to see that through a linear fit the value of N could be extrapolated to even higher pile-up, for a value of $\langle\mu\rangle = 150$. The purpose of this was to have an estimation of the resolution in an hypothetical upgraded ATLAS detector at the High Luminosity LHC. The result is presented in table 4.2 too.

The last subject of this section is the performance test of a correction that would be implemented in the JES as an improvement to deal with increased pile-up. The default correction for 2012 was the so-called ‘offset correction’, described in section 4.2, and

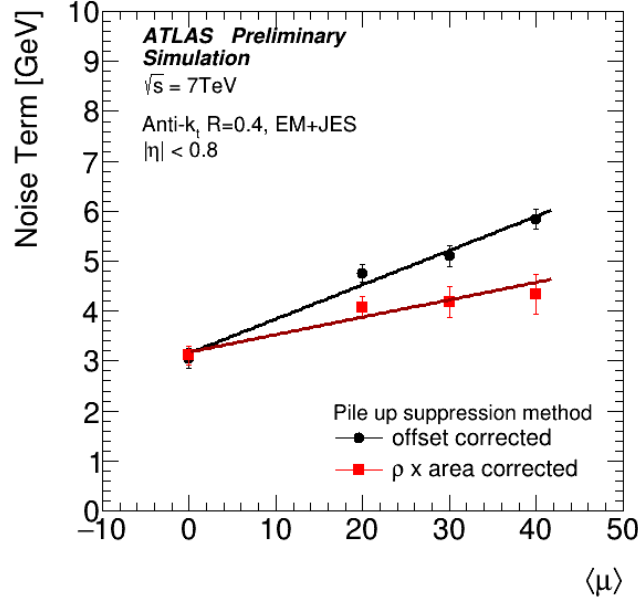


Figure 4.17: Noise term (N) of the jet energy resolution versus the mean number of pile-up interactions per bunch crossing ($\langle\mu\rangle$). N is obtained from the fits to the jet energy resolution measured on anti- k_t jets of $R = 0.4$ within $|\eta| < 0.8$ in the EM+JES calibration. The value of N is reduced by applying the jet areas correction.

that can be seen as the first step in figure 4.3. The *jet areas* correction has since replaced it, as can be seen in [33]. It estimates pile-up on an event-by-event and jet-by-jet basis, subtracting from each jet the product of the pile-up p_T density (ρ) and the area of the jet (A^{jet}). A typical value for the event p_T -density in the 2012 ATLAS data is ~ 10 GeV, which for a $R = 0.4$ jet corresponds to a subtraction in jet p_T of $\rho A^{jet} \sim 5$ GeV. A test of this correction is shown in figure 4.17, where the value of N is shown as a function of $\langle\mu\rangle$ for jets calibrated using the default JES with the offset correction (in black) and the new JES with the jet areas correction (in red).

4.3.7 Use of the JER in Physics Analyses

An important purpose of the measurement of the jet energy resolution is to provide the many analyses in ATLAS that use jets with an estimation of the systematic uncertainty due to JER. The impact of this uncertainty depends on the specific analysis, and needs to be established in each case. In order to achieve this, the most common procedure is to compare the distributions obtained using the default JES calibration with a new set of distributions in which the energy and momentum of the jets has been smeared. This means that it has been multiplied by a random factor obtained from a Gaussian of mean equal to 1 and a width that will depend on the p_T and $|y|$ of the jet. This width is obtained from information extracted from the results presented in section 4.3.4.

In order to describe the JER uncertainty, it is convenient to first define:

- $\frac{\sigma(p_T)}{p_T}^{truth}$ as the truth resolution

$$\bullet \frac{\sigma(p_T)}{p_T}^{data} = \frac{\sigma(p_T)}{p_T}^{truth} + \left(\frac{\sigma(p_T)}{p_T}^{in-situ}_{data} - \frac{\sigma(p_T)}{p_T}^{in-situ}_{MC} \right)$$

The non-closure between the truth resolution and the in-situ methods makes it necessary to estimate the resolution measured in data in an alternative way. This is achieved through the combination of the data-MC agreement measured in in-situ methods with the truth resolution. A conservative estimation of the uncertainty was settled upon:

$$\Delta \frac{\sigma(p_T)}{p_T} = \sqrt{\Delta(Data - MC)^2 + \Delta(in - situ)^2} \quad (4.23)$$

where the components combined in quadrature are defined as:

- $\Delta(Data - MC) = \frac{\sigma(p_T)}{p_T}^{data} - \frac{\sigma(p_T)}{p_T}^{truth}$ using the previous definitions
- $\Delta(in - situ)$ is the sum in quadrature of the systematic uncertainty of the resolution measured in data and MC using the bisector method.

Finally, the smearing factor is obtained by combining the truth resolution with the resolution uncertainty in the following way:

$$SF = \sqrt{\left(\frac{\sigma(p_T)}{p_T}^{truth} - \Delta \frac{\sigma(p_T)}{p_T} \right)^2 - \left(\frac{\sigma(p_T)}{p_T}^{truth} \right)^2} \quad (4.24)$$

where all the values have been obtained as a function of p_T and in bins of $|y|$, therefore making it possible to provide the smearing factor with this dependence.

An example of $\frac{\sigma(p_T)}{p_T}^{truth}$ and $\frac{\sigma(p_T)}{p_T}^{data}$ is shown in a descriptive way in figure 4.18. The uncertainty is also shown.

This strategy was implemented in a package to be used throughout the collaboration. An example of the actual results included in this package can be found in figure 4.19, where the smearing factor is plotted as a function of p_T for the different rapidity bins. Only the factors corresponding to anti- k_t R=0.4 jets calibrated with the EM+JES scheme are shown, but the same information was available for the LCW+JES calibration, and for R=0.6 jets. These results were used in the collaboration by analysis using 2012 data until they were updated in the beginning of 2015.

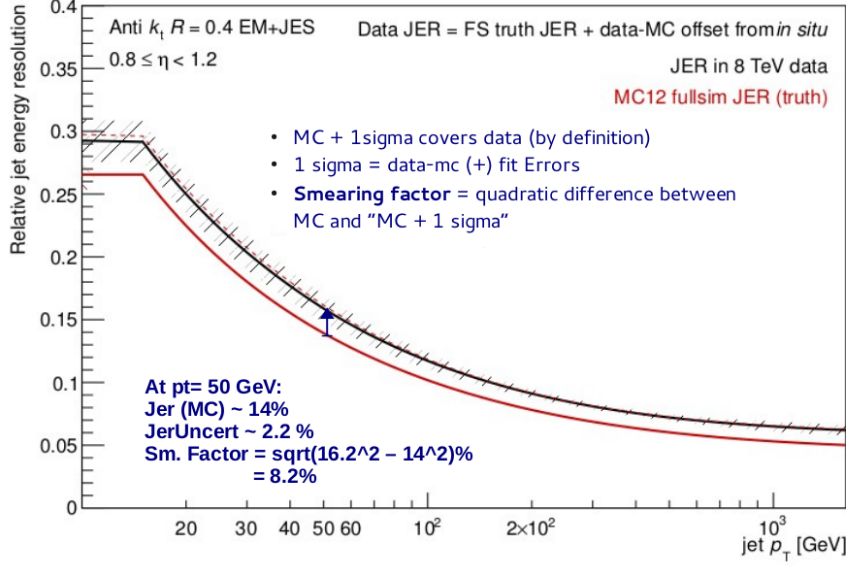


Figure 4.18: Explicative plot showing the truth jet resolution, $\frac{\sigma(p_T)}{p_T}^{truth}$, and $\frac{\sigma(p_T)}{p_T}^{data}$ as defined in this section. An example case is depicted in which a 50 GeV jet would be smeared according to a factor of $\sim 8\%$.

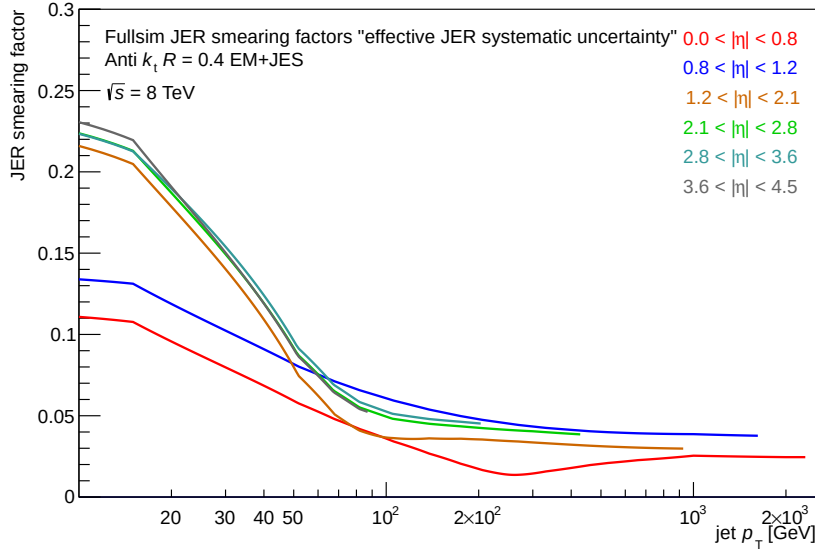


Figure 4.19: Values of the smearing factor stored in the JER provider package to be used (and measure in) anti- k_t $R=0.4$ jets calibrated in the EM+JES scheme. The results are shown as a function of p_T , and the different plots correspond to the various rapidity regions.

Chapter 5

Measurement of the Production of Four-Jet Events

This analysis [36] studies events in which at least four jets are produced in a hard-scatter process. These events are of particular interest as the corresponding Feynman diagrams require several vertices even at LO in α_s . The last few years have seen significant improvements in the simulation of such events, first with the availability of NLO p QCD calculations of the ME (one of the first of which was BLACKHAT [50]), and more recently with their combination to PS [76]. But these high-end predictions have not been incorporated to the everyday work of analysers, but rather remain a more exclusive resource. Instead, it is the more manageable LO MC simulations that have a widespread use, most frequently producing only two outgoing partons and generating additional legs via PS (this is the case for PYTHIA and HERWIG). But this type of approach has well known shortcomings in some kinematical regions. Alternatively, LO generators that can provide more outgoing partons are sometimes used. MADGRAPH or SHERPA can provide as much as six outgoing partons and give an adequate description in some of the cases where the others fail. While the computational cost of such improvements can sometimes be a limitation, they are still less expensive than the more advanced NLO predictions. As it was briefly hinted in the introduction, the experimental needs and the development of more advanced theoretical predictions drive each other towards improvement, and thus arises the need to put both the currently used predictions and their possible successors to the most stringent tests.

Another relevant motivation for this analysis is the study of the QCD backgrounds. Many analyses, some of which search for new physics, select processes with several jets in the final state. While it is common to use data-driven methods as a way to estimate the expected contribution from events in which QCD is the predominant interaction, as was done for example in ref. [30], such methods need to be tested using MC simulations. Hence the importance of the level of accuracy of the predictions is affirmed.

This chapter describes the measurement of the differential cross sections for events with at least four jets. This is the first study where differential cross sections are analysed as a function of a large variety of kinematical and topological variables related to the momenta, angular distances and masses of the jets. These variables were binned either in the p_T of the leading jet or the total invariant mass, allowing to test separately different kinematic regimes and jet configurations. The event selection was carefully

defined so as to take maximum advantage of the available dataset, probing jet variables in a wide p_T and angular range. It required the four most energetic anti- k_t $R = 0.4$ jets in the event within the rapidity range $|y| < 2.8$ to have a $p_T > 64$ GeV and be well separated. Additionally the leading jet should have $p_T > 100$ GeV. The resulting measurements are sensitive to the diverse mass scales in the event, the presence of forward jets and the azimuthal distribution of the four leading jets.

Similar measurements to the one presented here have been performed before. The multi-jet production was measured in ATLAS at $\sqrt{s} = 7$ TeV [20]. Incidentally, it was found that predictions may differ from data by $\sim 30\%$ even at NLO [44]. The differential cross section for three-jet events was measured by many experiments. In fact it was this that led to the discovery of the gluon [53, 46, 48, 84]. A more recent measurement of the three-jet cross section was done in ATLAS [38] and CMS, where the ratio of three to two jet events was used to measure α_S [62]. Motivation to test a wide variety of kinematic variables comes from their previously tested sensitivity to higher-order p QCD effects in refs. [23, 63]. Although there are many previous multi-jet measurements from various experiments, this is the first performed on such a large dataset and in so many variables, allowing the deeper understanding of multijet production. The previous measurements were done by ATLAS [20], CMS [64], CDF [4, 3] and D0 [1, 2]. The ATLAS result, for example, was performed on a dataset 10 thousand times smaller, and focused on the test of several LO predictions with different tunes to the PS, the matching and the detector simulation. Also, it is a common characteristic that only momentum variables were used, like the p_T of the leading jets and H_T .

In this chapter the analysis will be described in detail. The MC simulations and data selection applied are explained briefly, given that the main characteristics of the simulations and the experimental conditions have been presented in detail in chapters 1.3 and 2 respectively. In the case of the simulations, the aim is to specify the generator versions and other details pertaining the samples used in the analysis. The cross section definitions are presented afterwards, accompanied by a motivation for the choice of the variables. The unfolding procedure, through which detector effects are removed from data, and the estimation of uncertainties are described too, before providing the final results.

5.1 Monte Carlo Samples

The MC samples used in this analysis can be separated into two groups. The first one is composed of LO simulations, widely used throughout different analysis and performance studies in ATLAS. The second one is a set of three NLO and all-order approximation simulations which were compared to the unfolded data. The specific information for each simulation is summarized in table 5.1.

Three LO simulations were used as an aid to estimate the experimental uncertainties which will be described in section 5.5, in the unfolding procedure (of which details are presented in 5.4) as well as being compared to the unfolded data. PYTHIA 8.160 [90] and HERWIG++ 2.5.2 [45] were employed to obtain two LO $2 \rightarrow 2$ samples. A third LO sample was generated using MADGRAPH5 v1.5.12 [8], which being a multi-leg generator could provide larger parton multiplicities at ME level ($2 \rightarrow 4$). The three samples have parton shower (PS) and underlying event (UE) simulation, including multiple

Name	Hard scattering	LO/NLO	PDF	PS/UE	Tune	Factor
Pythia	PYTHIA 8	LO ($2 \rightarrow 2$)	CT10	PYTHIA 8	AU2-CT10	0.6
Herwig++	HERWIG++	LO ($2 \rightarrow 2$)	CTEQ6L1	HERWIG++	UE-EE-3-CTEQ6L1	1.4
MadGraph	MADGRAPH	LO ($2 \rightarrow 4$)	CTEQ6L1	PYTHIA 6	AUET2B-CTEQ6L1	1.1
HEJ	HEJ	All [†]	CT10	—	—	0.9
BlackHat	BLACKHAT/SHERPA	NLO ($2 \rightarrow 4$)	CT10	—	—	—
NJet	NJET/SHERPA	NLO ($2 \rightarrow 4$)	CT10	—	—	—

Table 5.1: The generators used for comparison against the data are listed, together with the parton distribution functions (PDFs), PS algorithms, underlying event (UE) and parameter tunes. Each MC prediction is multiplied by a normalisation factor (last column) as described in section 5.1.1, except BLACKHAT/SHERPA and NJET/SHERPA. (†) The HEJ sample is based on an approximation to all orders in α_s .

parton interactions (MPI); this was provided by the generator itself in the case of PYTHIA and HERWIG++, while MADGRAPH needs to be interfaced to PYTHIA 6.427 [89]. The generators are ran using PDFs from different groups, the NLO CT10 [78] is used in PYTHIA while the LO distributions of CTEQ6L1 [85] is used in the other two. The parameter tunes employed are the ATLAS tunes AU2 [26] and AUET2B [19] for PYTHIA and MADGRAPH respectively, and the HERWIG++ tune UE-EE-3 [69]. In all cases pile up is simulated using PYTHIA 8.

The second group is composed of the theoretical predictions that are compared to the unfolded data. Two of these were calculated at NLO, using BLACKHAT/SHERPA [50, 51] and NJET/SHERPA [43, 42]. The third one was generated using an approximation to all orders in HEJ [9, 10, 11]. The distributions corresponding to these datasets were provided by their respective authors. Neither of these predictions include PS and UE simulation, which is why the results are presented at particle level. As a consequence, they do not need the ATLAS tune packages (and are clearly not put through detector simulation). They all use the same NLO PDF that was used for the PYTHIA sample.

One should note that the use of higher order simulations is not so straight forward: while it is currently possible to generate tenths of millions of events using the LO $2 \rightarrow 2$ generators within the ATLAS computing infrastructure, the inclusion of additional partons in a LO simulation increases the computational cost greatly, and the time required for the addition of NLO terms could be prohibitively nowadays.

5.1.1 Normalisation

A large disagreement was found when comparing the total normalisation of the LO MC samples and the data. This was not unexpected, since in LO calculations the size of the error in the cross section depends on the NLO term, which is known to be fairly large at some scales. Logically, it was not the purpose of this analysis to evaluate this aspect of the predictions; their performance when describing the shape of the jet variables chosen was deemed more important. Given this, it was decided to apply a scale factor to each of the LO samples, which is presented in the last column in table 5.1.

The factors were obtained from the distributions of the leading jet p_T at reconstructed level, presented in figure 5.5a. It is such that the integrated number of events

in the region $500 \text{ GeV} < p_T^{(1)} < 1.5 \text{ TeV}$ which satisfy the inclusive analysis cuts described in section 5.3 is equal to the corresponding number in data. It is important to emphasise that the value of the factor must not be regarded as an estimation in the level of disagreement between data and MC, as the disagreement has large variations depending on the momentum range and the variables; this particular range was chosen somewhat arbitrarily. A smaller disagreement was found in the HEJ sample, so a scale factor was also applied.

No scale factor is ascribed to BLACKHAT/SHERPA and NJET/SHERPA as in their case it is relevant to assess cross section discrepancies in light of the theoretical uncertainties.

5.1.2 Theoretical Uncertainties

These uncertainties have been computed for the NLO predictions and HEJ. The central value of the renormalisation and factorisation scales used in the NJET/SHERPA and BLACKHAT/SHERPA samples was chosen to be $H_T/2$. H_T is a commonly used variable to this purpose and is obtained as the scalar sum of the transverse momentum of the events' components. It is also one of the measured variables in this analysis and is thus defined in section 5.3. Scale uncertainties are evaluated for NJET/SHERPA by simultaneously varying both scales by factors of 1/2 and 2. Figure 5.1 exemplifies the dependence of the cross section on the fraction of H_T chosen as scale in a multijet simulation of higher multiplicity, both for a LO and NLO calculation. The dependence close to $H_T/2$, to the left of which a rapid drop in σ can be observed, results in large and asymmetric uncertainties in the NLO predictions. As a results this is the dominating component of the theoretical uncertainty. PDF uncertainties are obtained by reweighting the distributions for all the PDF error sets using LHAPDF [54], following the recommendations from ref. [52]. The additional PDF sets include variations in the value of α_S . The sum in quadrature of the resulting scale and PDF variations defines the total NLO theoretical uncertainty.

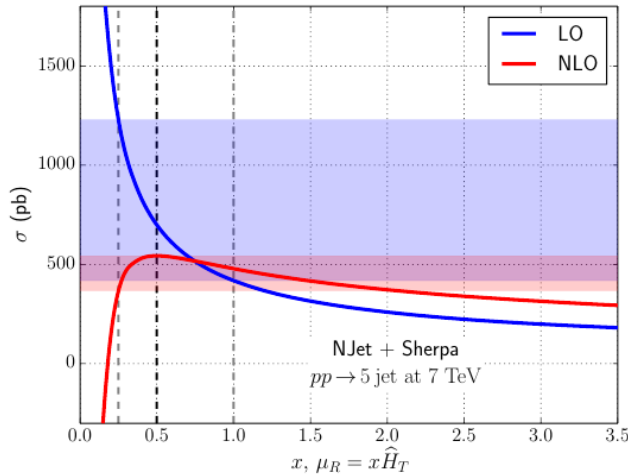


Figure 5.1: Residual scale dependence of the 5-jet cross section in LO (blue) and NLO (red) for an NJET/SHERPA sample [44].

The sensitivity of the HEJ calculation to higher-order corrections was determined by the authors of the calculation by varying independently the renormalisation and factorisation scales by factors of $\sqrt{2}$, 2, $1/\sqrt{2}$ and $1/2$ around the central value of $H_T/2$. The total uncertainty is the result of taking the envelope of all the variations. The typical size of the uncertainty is $^{+50\%}_{-30\%}$.

5.2 Data Sample and Event Selection

The data sample considered in this analysis was recorded by the ATLAS detector in proton-proton collisions at a centre of mass energy of $\sqrt{s} = 8$ TeV between March and December 2012, and is part of the Run 1 dataset described in section 2.2. After the application of data-quality requirements the total integrated luminosity amounts to 20.3 fb^{-1} .

There are different elements related to the selection of events for analysis. The first one is the choice of a group of triggers that will be combined in order to acquire data. Then there is the object reconstruction; in this case, the objects used were jets, and their calibration process has been described in detail in section 4.2. Thus, only a brief specification is given below. Lastly the data needs to be ridden of events that have a questionable quality through a procedure that is common to most ATLAS analyses.

5.2.1 Trigger

The choice of triggers in this analysis was motivated by the goal of comparing distributions in a wide range of jet momentum; it was equally relevant to provide information in the high and the low p_T range, as they are associated to different physics aspects. Furthermore, wide angle and multiple jet radiations were put to the test, making it more necessary to reach lower values in p_T . The main constraint in order to achieve this were the trigger prescales that were put in place for the lower momentum triggers during data taking; since jet cross sections are among the largest in LHC experiments, it is clear that events with low p_T jets would take up too large a portion of the available bandwidth and only a few of the total should be kept.

Nominal 4-jet triggers	L1 Item	L2 Chain	Stream	Luminosity
EF_4j45_a4tchad_L2FS	L1_4J15	L2_4j15_a4Ttem	JetTauEtmis	95.2 pb^{-1}
EF_4j65_a4tchad_L2FS_delayed	L1_4J15	L2_4j20_a4Ttem	HadDelayed	17.4 fb^{-1}
Nominal single-jet triggers				
EF_j280_a4tchad_delayed	L1_J75	L2_j165_c4cchad	HadDelayed	17.4 fb^{-1}
EF_j360_a4tchad	L1_J75	L2_j165_c4cchad	JetTauEtmis	20.3 fb^{-1}
Reference single-jet triggers				
EF_j80_a4tchad_delayed	L1_J30	L2_j75_c4cchad	HadDelayed	2.3 pb^{-1}
EF_j45_a4tchad	L1_J10	L2_j40_c4cchad	JetTauEtmis	0.04 pb^{-1}

Table 5.2: Triggers used for the analysis and reference triggers used to calculate the efficiencies of the former.

A decision was made to combine four triggers in an exclusive way, which would allow to span the range of $p_T > \sim 60$ GeV. Two of the triggers select events with at least four jets, and are called 4j45 and 4j65 because they require them all to be

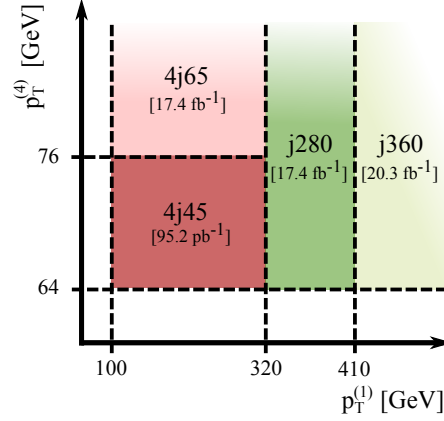


Figure 5.2: Schematic of the kinematic regions in which the four different jet triggers are used, including the total luminosity that each of them recorded. The term 4j45 (4j65) refers to a trigger requiring at least four jets with $p_T > 45$ GeV (65 GeV), where the p_T is measured at the EF level of the triggering system. The term j280 (j360) refers to a trigger requiring at least one jet with $p_T > 280$ GeV (360 GeV) at the EF level. The horizontal and vertical axes correspond to $p_T^{(1)}$ and $p_T^{(4)}$ respectively, both calculated at the offline level (i.e., including the full object calibration).

above a p_T threshold of 45 and 65 GeV respectively. The remaining two are single jet triggers, which put the momentum requirement (of 280 for one and 360 GeV for the other) only in the leading jet of the event. The list of used triggers is presented by their technical name in table 5.2. The full chain (L1,L2 and EF) is indicated, as was described in section 5.2.1, as well as the single jet triggers used as reference to estimate the efficiencies.

As mentioned before, the four triggers were combined in an exclusive way. This means that each trigger was applied in a region that would not overlap with another - no event can fall in two regions at the same time-, as shown in figure 5.2. The regions are defined by cuts in the momentum of the leading and the fourth leading jets in the event, when sorted by $p_T(p_T^{(1)}$ and $p_T^{(4)}$ respectively). The cuts were chosen so as to select events in the 99% efficiency region of each trigger. The trigger efficiencies were measured using reference triggers of either lower jet multiplicity or lower momentum, detailed at the bottom of table 5.2. They are shown for the four-jet triggers as a function of $p_T^{(4)}$ in figure 5.3 for both data and MC. In the case of the 4-jet triggers, the efficiency is both dependent on the momentum of the four jets in the event and on the angular separation between them. It was found that in order for them to be highly efficient a cut in the minimum angular separation between the four leading jets in the event had to be applied. The small residual loss of data due to trigger inefficiency is corrected as a function of jet p_T using the techniques described in section 5.4.

It can be noted that the value of the total integrated luminosity detailed for three out of the four triggers is smaller than 20.3 fb^{-1} , as a result of these being prescaled. It is for this reason that higher p_T triggers were needed, instead of only using 4j45 for example. The lowest single jet trigger available without a prescale was j360. The data collected through the other three needed to be scaled in order to be combined correctly.

Although the value of the prescale factor may vary from one run to another, the scaling was done considering the data taking periods as a unit, for two reasons. Firstly it was more practical, as there were 10 periods for which the integrated luminosity of each trigger was evaluated and compared, and was less prone to error than using a run-by-run approach. But the main reason was the fact that part of the data came from a so-called *delayed stream*. This part of the data is saved unprocessed, a trick that allows the experiment to record more data than could be processed at once. There is a small caveat, which is that this cannot be done in the first part of each run, in which the instant luminosity is too high. The prescale in 4j45 and 4j65 is then not only a fluctuating number below 1 that could be corrected in a run-by-run way, but also is set to -1 for some time, which translates to the triggers being deactivated at that moment, and the run-by-run approach could not take this into account: there are no events to re-scale.

5.2.2 Jet Reconstruction and Calibration

The jets in this analysis follow the reconstruction and calibration process described in chapter 4. In particular, the anti- k_t jet algorithm was applied using a radius parameter $R = 0.4$. The jet calibration scheme chosen was the one followed by most analysis, which is the LCW calibration. This calibration improves the jet resolution, and therefore is a sensible choice in jet cross section analyses.

The jet energy scale and resolution applied here were measured in pp collision data as described in references [34, 35, 33]. The jet areas based correction [55], that was first tested as presented in section 4.3.6 was applied as a part of the calibration procedure to account for the effects of pile-up on jet energies.

The minimal jet acceptance requirement applied prior to any event selection to all the jets in the event were $p_T > 20$ GeV and $|y| < 2.8$. The momentum cut stems

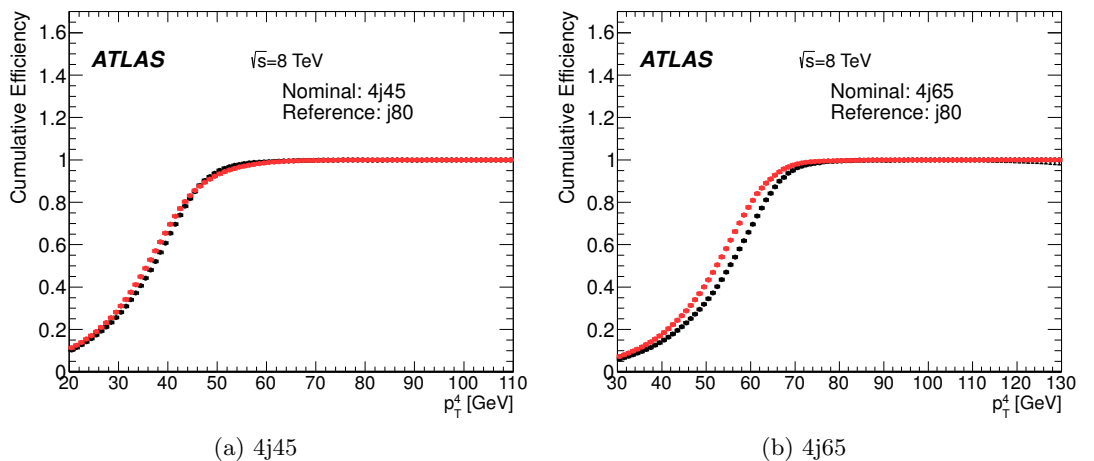


Figure 5.3: Cumulative efficiencies of the four-jet triggers for the nominal event selection, integrated over values of $p_T^{(4)}$ greater than the value indicated on the x-axis. The efficiencies are plotted relative to a single-jet trigger for data (in black) and for the PYTHIA sample (in red).

from the minimum value for which an energy calibration exists. The rapidity cut is associated to the detector structure, and an increase in the granularity for rapidity values larger than this.

5.2.3 Data Quality Criteria

A series of quality cuts are applied to the data prior to the kinematic cuts that are analysis specific. These cuts are used throughout ATLAS with few exceptions, and are tested and suggested by different dedicated working groups. In some occasions it is necessary to evaluate more specifically the impact that a recommendation has. In addition, some of these cuts need to be emulated in the MC simulations. The cuts adopted for the multi-jet analysis are listed below, indicating if they were applied only to data or to both MC and data; a study that complemented their implementation has been included in appendix C. The cleaning cuts described have different impacts upon the event count in both data and MC. The cutflow for this analysis is presented in table 5.3.

Good Run List (GRL) The Data Quality group in ATLAS provides a list of the sections of recorded data that are apt for use in analysis, based on a careful record kept by each subdetector of their performance. The fraction of data considered as ‘good’ is $\sim 95\%$.

Vertex Requirement The vertex with the largest value of $\sum (p_T^{track})^2$ is required to have at least 2 associated tracks, both in data and MC.

Corrupted Tile Data During a short period of time the Tile Calorimeter system registered fake high energy readings in one cell. The cell was not masked, meaning that it was not removed from the event before reconstruction, causing the affected events to show high, and fake, missing energy. A veto is applied to events in data where this happens.

LAr and Tile Errors Global noise bursts appear and disappear in the LAr and Tile calorimeters on a time scale smaller than a luminosity block, so that the events cannot be excluded via the GRL. Events taken during improper function of the LAr and Tile calorimeters are rejected.

Incomplete data events As the name indicates, data events that have been improperly recorded or the data was corrupted have to be removed.

Hot Tile Cleaning During a short period of time another tile showed permanent high readings. Since it was not removed before reconstruction, events in data were vetoed if one a jets overlapped with the problematic cell and deposited more than 60% of its energy in it.

Jet Cleaning is a general quality criteria defined for jets both in data and MC. It evaluates the fraction of energy deposited in the different parts of the calorimeter and pre defined quality coefficients to decide if this is a *good* or *bad* jet; if the event contains a bad jet it is discarded.

Masked Tile Module Cleaning Tile Cal modules fail either temporarily or permanently for a variety of reasons. During 2012 there was one module that was permanently off, while some others had periods in which they malfunctioned. In most cases these modules are masked prior to reconstruction; but the technique was designed for masking particular cells and did not handle full modules well. High p_T jets are particularly sensitive, since being more collimated makes it possible for them to be

completely, or almost completely, contained within the affected module. The way in which events with these jets are treated depends on the sensitivity of an analysis, which is why the final strategy was determined after evaluating how the application of the cleaning modified the variables shapes and the agreement between data and MC. Since the malfunctioning modules were also masked in MC simulations, it was important to implement the same strategy in these samples and to avoid incorporating differences between data and MC. More details on these studies are presented in appendix C.

The studies led to the decision to evaluate the five leading jets in the event to see if they overlapped with the problematic region. A *medium* quality requirement was applied (see appendix C), and if any of these jets was flagged as bad the event was discarded. The reason to look at five jets instead of only four is related to the possibility that the fourth and fifth jet might be swapped.

Cut	Data	Data %	MC	MC %
Total	1259141793	100%	26900195	100%
Passed GRL	1187928633	94.34431%	26900195	100%
Passed Trigger	24496542	1.9455495 %	3198697	11.8909807%
Vertex Cut	24496406	1.9454843 %	3198696	11.8909770%
Corrupted Tile Data	24496392	1.9454832 %	3198696	11.8909770%
LAr/Tile Errors	24431139	1.9403009 %	3198696	11.8909770%
Corrupted Data	24431098	1.9402976 %	3198696	11.8909770%
Hot Tile	24430683	1.9402646 %	3198696	11.8909770%
Jet Cleaning	24391868	1.9371820 %	3196014	11.8810068%
Masked Tile Module	23078593	1.8328828 %	2945679	10.9504002%
Global cleaning	23078593	1.8328828 %	2945679	10.9504002%

Table 5.3: Cutflow of the event selection. The left column shows the remaining number of events after each cut in data, while the right column shows the equivalent information in PYTHIA 8. The percentage that each number represents is also shown (in some cases the % change being very small).

5.2.4 Analysis Cuts

Events are selected if they contain at least four jets within the rapidity range $|y| < 2.8$. In addition, the leading one must have $p_T > 100$ GeV, while the next three must have $p_T > 64$ GeV. The jets are requested to be well separated from one another, with a minimum distance of $\Delta R_{4j}^{\min} > 0.65$, where $\Delta R_{4j}^{\min} = \min_{\substack{i,j \in [1,4] \\ i \neq j}} (\Delta R_{ij})$ and ΔR_{ij} is as defined in equation 2.2. The subindexes i and j refer to any of the four leading jets. This set of cuts that defines the analysis is referred to as the ‘inclusive analysis cuts’ to differentiate them from the cases where additional requirements are made, for example on the invariant mass of the four leading jets. As was detailed in section 5.2.1, this selection is mainly motivated by the triggers used to select the events.

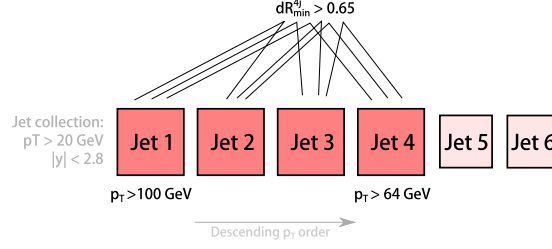


Figure 5.4: Sketch of the event selection.

5.2.5 Signal Contamination

Leptons and Photons Although some (fake) jets could result from leptons or photons impacting the calorimeter, they are not excluded from this analysis. Neither were the contributions from these signatures corrected for. This was decided based on the estimation that events containing such jets are expected to contribute less than 0.1% to the cross sections under study.

This estimation was obtained through a simple MC-based study. The MC samples chosen should contain events with at least one photon or at least one τ lepton. In addition, it only made sense to use samples that would be able to generate at least 4 jets, resulting in a sample selection consisting of:

- $t\bar{t} \rightarrow \tau lhad$
- $W \rightarrow \tau\nu$ divided into various possible additional jets
- $\gamma + jet$ also divided into possible energies of the γ

Each sample was scaled to the total luminosity of the analysis's dataset and the analysis cuts were applied. The event yield after the cuts was compared to the one obtained in data in order to estimate the contribution.

Double Parton Scattering An additional mention should be made of the possibility that the four jets measured in an event come from different hard scatters. This is generally called Multiple Parton Interactions (MPI), and more specifically to this case Double Parton Scattering (DPS). DPS interactions have not been investigated independently up to this point, so the measurement is inclusive in this respect. The fraction of events coming from DPS (f_{DPS}) can be estimated by

$$f_{DPS} = \frac{1}{\sigma_{eff}} \frac{\sigma_{2j}^A \sigma_{2j}^B}{\sigma_{4j}} \quad (5.1)$$

where σ_{eff} is the effective cross section of DPS and is an energy dependant parameter taken in this case as $\sim 15nb$; σ_{4j} is the inclusive four jet cross section obtained here, and $\sigma_{2j}^{A/B}$ are the two jet cross sections corresponding to the different possible combination in this analysis ($p_T^{(1)} > 100$ GeV and $p_T^{(2)} > 64$ GeV or both $p_T^{(1)}, p_T^{(2)} > 64$ GeV). A quick estimation of the values of these variables allowed to infer an expected contribution of 1% or less to the results. A later result published in [40] found that the contribution was in fact much smaller than this.

5.3 Binning and Variable Definition

Following the motivation to understand how well multi-jet events are described by QCD calculations and approximations, cross sections are measured differentially as a function of a set of ten selected variables. The only jets used in all cases are the four leading ones in p_T . The group is composed mainly of event level jet variables, the value of which may be directly related to a certain characteristic. The distributions of the momentum of each of the leading jets are considered as well. The complete list of variables is presented in table 5.4, accompanied by the mathematical definition of each of them and a brief comment. The binning of each variable must be determined as well; the criteria adopted to decide the binning is described in the first of the next two sections, while a more detailed description of the measured variables is presented next.

Name	Definition	Comment
$p_T^{(i)}$	Transverse momentum of the i th jet	Sorted descending in p_T
H_T	$\sum_{i=1}^4 p_T^{(i)}$	Scalar sum of the p_T of the four jets
m_{4j}	$\left(\left(\sum_{i=1}^4 E_i \right)^2 - \left(\sum_{i=1}^4 \mathbf{p}_i \right)^2 \right)^{1/2}$	Invariant mass of the four jets
$m_{2j}^{\min}/m_{4j}$	$\min_{\substack{i,j \in [1,4] \\ i \neq j}} \left((E_i + E_j)^2 - (\mathbf{p}_i + \mathbf{p}_j)^2 \right)^{1/2} / m_{4j}$	Minimum invariant mass of two jets relative to invariant mass of four jets
$\Delta\phi_{2j}^{\min}$	$\min_{\substack{i,j \in [1,4] \\ i \neq j}} (\phi_i - \phi_j)$	Minimum azimuthal separation of two jets
$\Delta y_{2j}^{\min}$	$\min_{\substack{i,j \in [1,4] \\ i \neq j}} (y_i - y_j)$	Minimum rapidity separation of two jets
$\Delta\phi_{3j}^{\min}$	$\min_{\substack{i,j,k \in [1,4] \\ i \neq j \neq k}} (\phi_i - \phi_j + \phi_j - \phi_k)$	Minimum azimuthal separation between any three jets
$\Delta y_{3j}^{\min}$	$\min_{\substack{i,j,k \in [1,4] \\ i \neq j \neq k}} (y_i - y_j + y_j - y_k)$	Minimum rapidity separation between any three jets
$\Delta y_{2j}^{\max}$	$\Delta y_{ij}^{\max} = \max_{i,j \in [1,4]} (y_i - y_j)$	Maximum rapidity difference between two jets
$\Sigma p_T^{\text{central}}$	$ p_T^c + p_T^d $	If $\Delta y_{2j}^{\max}$ is defined by jets a and b , this is the scalar sum of the p_T of the other two jets, c and d ('central' jets)

Table 5.4: Definitions of the various kinematic variables measured. Only the four jets with the largest p_T are considered in all cases.

An additional clarification should be made concerning the difference between cuts applied to *truth*-level events and to *reconstructed*-level ones. This is a brief reminder of these concepts from chapter 4:

- *Truth-level* refers to the information of an event where experimental effects are not taken into account. It is most commonly used for MC simulated events prior to reconstruction, but it also applies to unfolded data. At truth level, only the inclusive analysis cuts defined above are applied.
- *Reconstructed-level* (abbreviated *reco*-level) refers to event information resulting from the interaction between particles and the detector, and can be either data, or simulation. The trigger and cleaning cuts detailed in the previous section are applied to these before the inclusive analysis cuts.

5.3.1 Binning

The optimization of the binning of the variables has to be done in perspective of the unfolding procedure that they will undergo in order to be compared to the theoretical predictions. The difference between the value of the reconstructed observables and their counterpart at truth level can result in migrations between bins that complicate the unfolding of detector effects. Larger bins mitigate the migration, but also dilute the shape of the variable. The optimal binning is defined in terms of the *purity* (P) and the *stability* (S):

$$P = \left[\frac{\# \text{ events that stay in same bin}}{\# \text{ events that pass reco cuts}} \right]_{\text{Passed truth}}$$

$$S = \left[\frac{\text{N. events that stay in same bin}}{\text{N. events that pass truth cuts}} \right]_{\text{Passed reco}}$$

The purity is a property of the reco-level bins, and represents the fractional number of events per bin which do not migrate to other bins after the detector simulation, calculated with respect to the number of events which pass the truth-level cuts. The stability is a property of the truth-level events, and represents the fraction of truth events that don't migrate to another bin due to reconstruction.

The binning of the variables was determined with the aim of having an average $P \sim 80\%$ for each bin, with a minimum allowed value of 70%. The stability was used as a cross check. The statistical uncertainty should also be taken into account, and the limit is set to 10% for the predicted uncertainty in data. For most variables a constant binning gives approximately similar values of purity. Variables with steeply falling spectra require variable-width bins to maintain the purity above the desired threshold; when this happened, bins were re adjusted in order to keep the purity and stability flat above 70%. The bin edges were rounded to the significant figure in each case, and the final binning for each variable is presented in table 5.5.

Observable	Bin edges
$p_T^{(1)}$	100, 155, 235, 325, 420, 530, 650, 790, 950, 1130, 1350, 1630, 4000 [GeV]
$p_T^{(2)}$	64, 145, 255, 385, 535, 715, 930, 1175, 1460, 3000 [GeV]
$p_T^{(3)}$	64, 120, 205, 305, 425, 570, 740, 2000 [GeV]
$p_T^{(4)}$	64, 85, 135, 190, 255, 330, 415, 515, 1500 [GeV]
H_T	290, 485, 705, 950, 1225, 1530, 1875, 2265, 2705, 3205, 7000 [GeV]
m_{4j}	100, 545, 735, 935, 1150, 1375, 1620, 1880, 2160, 2460, 2780, 3115, 3460, 3810, 7000 [GeV]
$m_{2j}^{\min}/m_{4j}$	0.0, 0.04, 0.08, 0.13, 0.17, 0.23, 0.3, 0.4
$\Delta\phi_{2j}^{\min}$	0.0, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2, 1.35, 2.5
$\Delta y_{2j}^{\min}$	0.0, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.05, 1.2, 1.35, 1.5, 2.5
$\Delta\phi_{3j}^{\min}$	0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.5
$\Delta y_{3j}^{\min}$	0.0, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3.5, 3.75, 4.0, 5.0
$\Delta y_{2j}^{\max}$	0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, 3.6, 4.0, 4.4, 4.8, 5.2, 5.6
$\Sigma p_T^{\text{central}} \Delta y_{2j}^{\max} > 1$	120, 170, 240, 315, 395, 480, 575, 680, 795, 930, 1085, 1260, 1465, 1705, 1980, 2300, 3075, 5000 [GeV]
$\Sigma p_T^{\text{central}} \Delta y_{2j}^{\max} > 2$	120, 185, 270, 365, 465, 575, 700, 845, 1005, 1195, 1410, 1665, 1960, 2305, 5000 [GeV]
$\Sigma p_T^{\text{central}} \Delta y_{2j}^{\max} > 3$	120, 190, 285, 385, 490, 605, 735, 880, 1040, 1225, 1430, 1655, 1905, 2790, 5000 [GeV]
$\Sigma p_T^{\text{central}} \Delta y_{2j}^{\max} > 4$	120, 190, 285, 385, 490, 605, 730, 865, 1010, 1170, 1340, 1525, 2165, 5000 [GeV]

Table 5.5: Bin edges defined for the different variables in the analysis.

5.3.2 Variables of Interest

The variables presented in table 5.4 have been separated into three types: first, the momentum variables, directly related to the jet momentum. Second, the mass variables, derived from the combined masses of either two or four of the leading jets. Thirdly there are the angular variables, obtained from the angular distances between jets. There is actually a fourth variable that is both related to momentum and angles and is therefore treated separately.

In order to probe different phase-space regions, additional cuts are applied to the measured cross-section. Depending on the variable, a binning was defined by either a lower bound in $p_T^{(1)}$ or in the combined mass of the four leading jets, m_{4j} . A summary of the additional cuts applied for each measured variable is shown in table 5.6. The purpose of some of these cuts will be explained for each variable separately.

The variables selected were additionally tested for their resilience to varying pile-up conditions. It has been seen that the shape of some variables could be modified by additional pile-up, and this would not be desirable for the variables in this analysis. No dependence was found for any variable on the value of $\langle\mu\rangle$, thus concluding that the variables are well behaved in this aspect. The corresponding study is presented in appendix D.

Observable	$\Delta R_{4j}^{\min} > \dots$	$p_T^{(4)} > \dots$ [GeV]	$p_T^{(1)} > \dots$ [GeV]	$m_{4j} > \dots$ [GeV]	$\Delta y_{2j}^{\max} > \dots$
$p_T^{(i)}$			100	-	-
H_T			100	-	-
m_{4j}			100	-	-
$m_{2j}^{\min}/m_{4j}$			100	500, 1000, 1500, 2000	-
$\Delta\phi_{2j}^{\min}$			100, 400, 700, 1000	-	-
$\Delta y_{2j}^{\min}$	0.65	64	100, 400, 700, 1000	-	-
$\Delta\phi_{3j}^{\min}$			100, 400, 700, 1000	-	-
$\Delta y_{3j}^{\min}$			100, 400, 700, 1000	-	-
$\Delta y_{2j}^{\max}$			100, 250, 400, 550	-	-
$\Sigma p_T^{\text{central}}$			100, 250, 400, 550	-	1, 2, 3, 4

Table 5.6: Summary of the analysed phase-space regions, including the $p_T^{(1)}$, m_{4j} and $\Delta y_{2j}^{\max}$ bins into which each of the differential cross-section measurements is split (a dash indicates when the cut is not applied on a variable). The $\Delta R_{4j}^{\min}$ and $p_T^{(4)}$ requirements, specified in the second and third columns respectively, apply to all variables. The observables are defined in table 5.4.

Momentum Variables

Jet Momentum The distributions of the jet p_T are studied individually for each of the four leading jets in the event. They are interesting in themselves, as they are the most often revised variables in data and MC validation. They are often the input to other, more complex variables such as the ones that are presented next. Two of the four distributions are presented in figure 5.5 as an example. Data is compared to the LO simulations, which are here used at reconstructed level, scaled by the factors presented previously. The different slopes of the simulations can be better appreciated in the ratios between MC and data shown below.

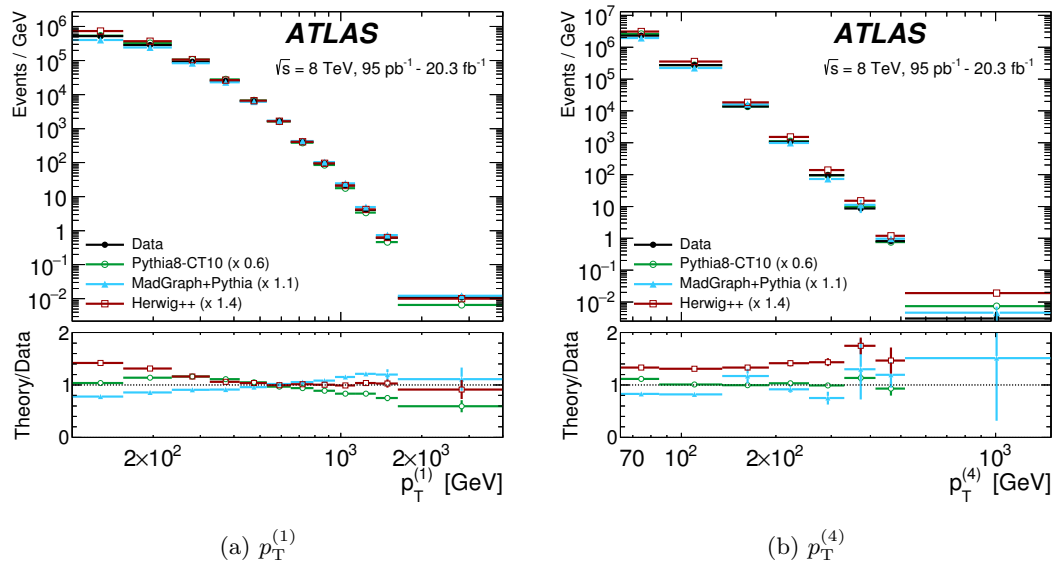


Figure 5.5: Detector-level distributions of the $p_T^{(1)}$ and $p_T^{(4)}$ for data and for example MC predictions. The MC predictions have passed through detector simulation, and are scaled to the total luminosity. The lower panel in each plot shows the ratios of the MC predictions to data. For better comparison, the predictions are multiplied by the factors indicated in the legend. The statistical uncertainties are shown but cannot be appreciated in the plot.

H_T is defined as the sum of the four leading momenta in the event, so it is not affected by how these are ordered. At its lower value it is related to events where jets have similarly lower p_T , while the higher values are dominated by very boosted jets. Incidentally, H_T is often used to set the scale of multi-jet processes too. As stated in section 5.1.2, the NLO simulations included in this analysis have the renormalisation and factorisation scales set to $H_T/2$. The H_T distribution at reconstructed level is presented in figure 5.6.

Mass Variables

m_{4j} is the combined mass of the four leading jets in the event and, being an inclusive variable like H_T , is not affected by their ordering either. The motivation to include

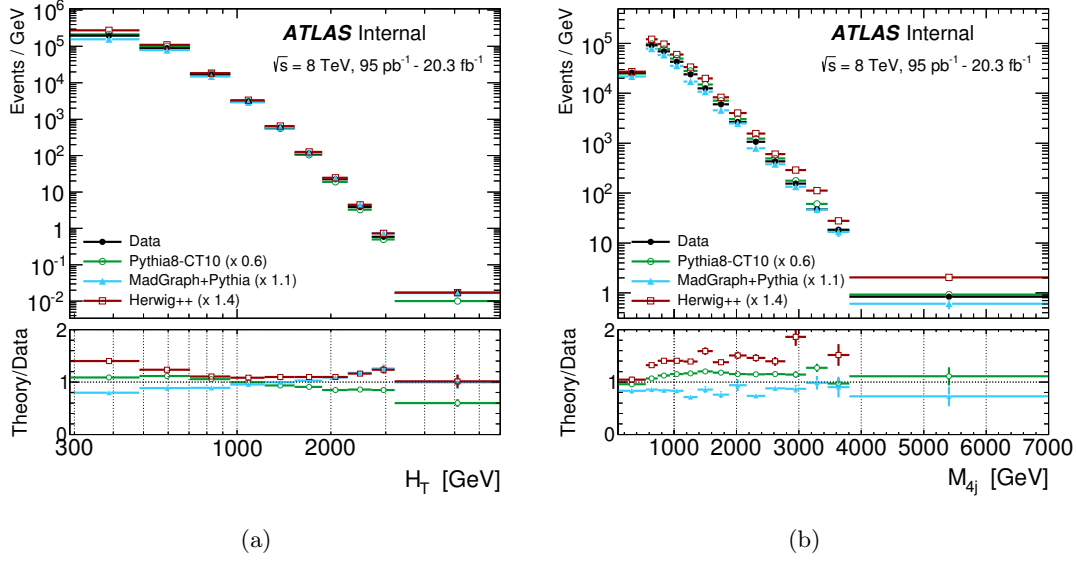


Figure 5.6: Detector-level distributions of H_T (left) and m_{4j} (right) for data and for LO MC predictions. The details are as in figure 5.5.

it is that mass variables are widely used in physics searches and they are sensitive to events with large separation between jets. This variable is representative of the largest energy scale in the event. An example of an event with a large value of this variable, $m_{4j} = 3.49$ TeV, is presented in figure 5.9. The illustration shows a real data event, where the detector is drawn showing the energy depositions from two different perspectives.

$m_{2j}^{\min}/m_{4j}$ is the ratio of the minimum invariant mass between any pair of jets in the event ($m_{2j}^{\min}$), and m_{4j} . While $m_{2j}^{\min}$ is sensitive to the smallest splitting scale in the event, the hardest scale is set by m_{4j} , so that their ratio probes the different splitting scale regimes. The cross section for this variable has been measured differentially in m_{4j} , using the four lower mass cuts presented in table 5.6. These cuts will allow to assess how MC behaves in different mass regimes.

Angular Variables

$\Delta\phi_{2j}^{\min}$ and $\Delta y_{2j}^{\min}$ are the minimal angular distance between any pair of jets in the event, in the azimuthal angle and in rapidity respectively. These distributions are slightly affected by the $\Delta R_{4j}^{\min}$ cut applied. These variables are capable of testing the description of events with small angle radiation. The cross sections for these variables have been measured differentially in inclusive $p_T^{(1)}$ bins as defined in table 5.6.

$\Delta y_{2j}^{\max}$ is the maximum rapidity distance between any pair of jets in the event. It complements the two previous variables, since it is sensitive to any large rapidity interval in the event. There is additional interest to include it in the measurement given that it has been used as the binning variables of $\Sigma p_T^{\text{central}}$.

$\Delta\phi_{3j}^{\min}$ and $\Delta y_{3j}^{\min}$ are more complex, three-jet angular distances used for further angular testing. They measure the minimum angular distance between any three jets

in the event, either in ϕ or in rapidity, by finding the jet that has the minimum distance to any other two. The case of $\Delta\phi_{3j}^{\min}$ is particularly interesting, as it gives a description of the event in the transverse plane. Given that the jets are expected to approximately balance in the transverse plane, small values of this variable correspond to a configuration where three jets are recoiling against one. The larger values, then, correspond to configurations where two jets recoil against the other two. A sketch of how these configurations yield different $\Delta\phi_{3j}^{\min}$ values is presented in figure 5.7a. The red and green arcs show the two angles taken into account to calculate $\Delta\phi_{3j}^{\min}$ in each case. The drawing on the left yields a lower value of the variable, and the one on the right a higher value. The distributions in figure 5.7 correspond to two different cuts in $p_T^{(1)}$. One can appreciate how two-against-two events are predominant at lower p_T . $\Delta\eta_{3j}^{\min}$ works in a similar way. The event displays presented in figures 5.10 and 5.11 show real data events with small and large values of $\Delta\phi_{3j}^{\min}$ respectively. The corresponding jet distribution in the transverse plane can be appreciated.

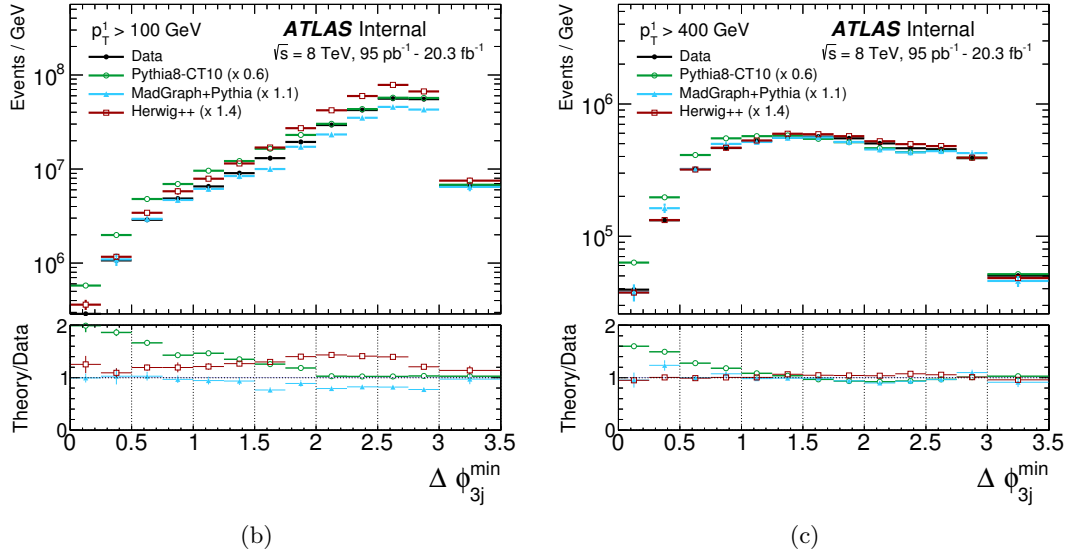
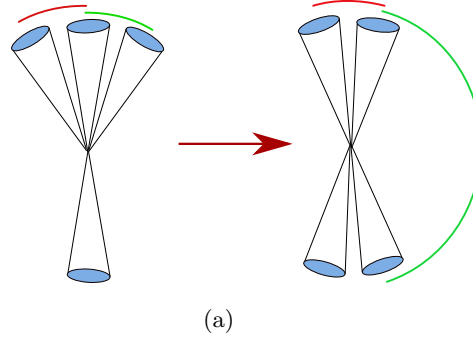


Figure 5.7: Detector-level distributions of $\Delta\phi_{3j}^{\min}$ for data and for the LO MC predictions, for two different $p_T^{(1)}$ cuts. The details for plots in (b) and (c) are as in figure 5.5. Figure (a) shows a sketch of the changing predominant jet configurations as the value of the variable increases.

Sum of the central p_T

$\Sigma p_T^{\text{central}}$ was designed to study the kinematics of jets as a function of the largest rapidity interval in the event, therefore being sensitive to events with forward jets. The two most separated jets in rapidity in the event are first identified, and then the scalar sum of the p_T of the remaining two jets is calculated. These two jets are, in fact, the more 'central' jets. The variable is binned both in $p_T^{(1)}$ and in the rapidity distance of the two most separated jets, $\Delta y_{2j}^{\text{max}}$. The cut in $p_T^{(1)}$ affects the shape of the distributions, as can be seen in the histograms presented in figure 5.8: for the lower cut of $p_T^{(1)} > 100$ GeV the distribution is smooth whereas for $p_T^{(1)} > 400$ GeV it presents a kink at 464 GeV. This value marks a transition: below it, only configurations in which the leading jet in the event is not central (as in the left sketch in figure 5.8a) can be found; above this value, the leading jet is allowed to be central, thus having an increased contribution from events such as the one sketch on the right in figure 5.8a. The splitting of this variable has therefore the property of tracking the position of the leading jet with respect of the central pair.

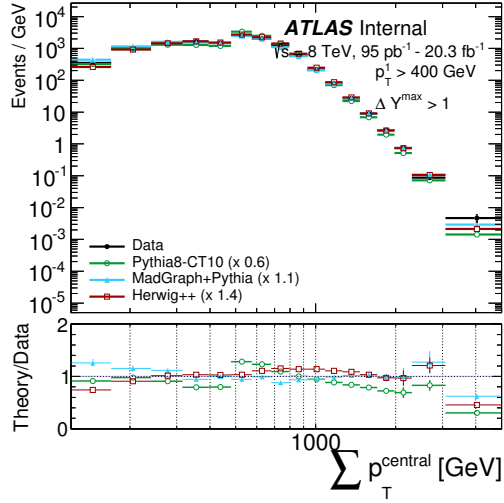
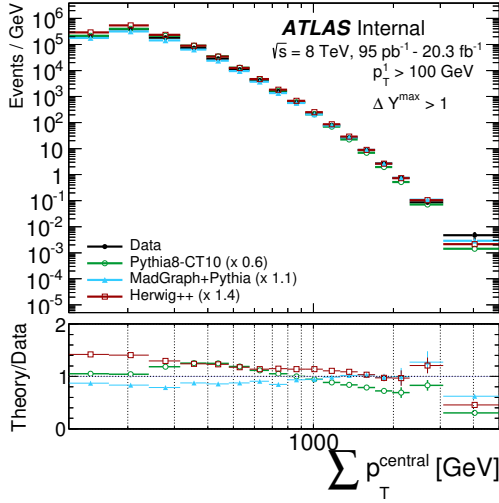
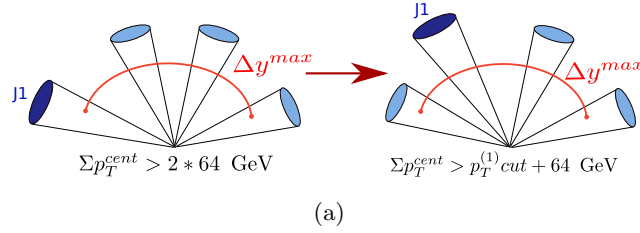


Figure 5.8: Detector-level distributions of $\Sigma p_T^{\text{central}}$ for data and for the LO MC predictions. The distributions shown here correspond to $\Delta y_{2j}^{\text{max}} > 1$ and $p_T^{(1)} > 100$ GeV (left) and $p_T^{(1)} > 400$ GeV (right). The details are as in figure 5.5. The sketch presented above shows the possible jet configurations that contribute to the distribution differently depending on the position of the leading jet (J1).

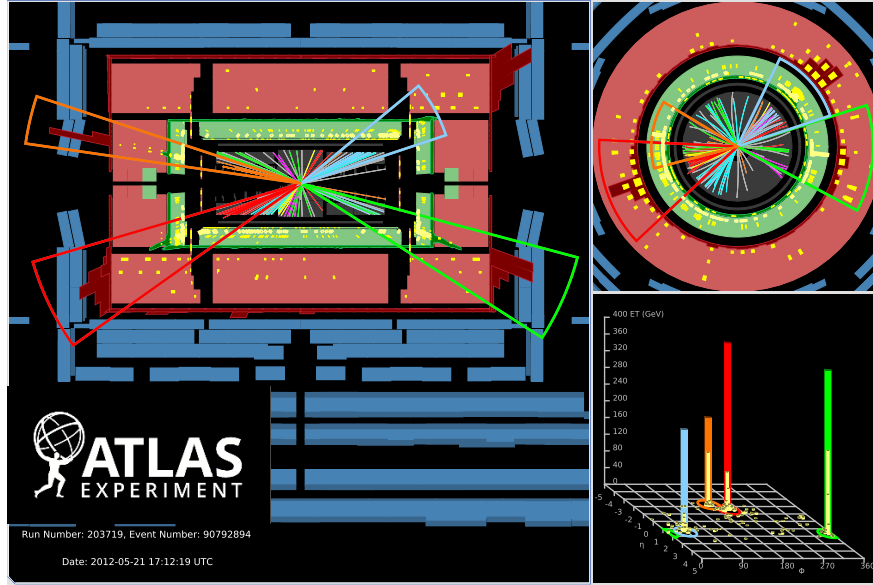


Figure 5.9: Event display for Run 203719, Event 90792894. This shows an example of an event with $m_{4j} = 3.49$ TeV. A cut of 60 GeV was applied on the jets shown, which are drawn in different colours for better distinction. The tracks are colour coded according to their corresponding jet, while the energy deposits in the calorimeters are all the same. Only jets and clusters are shown in the lego plot.

5.3.3 Expected Performance of the MC Simulations

The different predictions tested are expected to display various levels of agreement in different kinematic configurations. The generators which combine $2 \rightarrow 2$ parton MEs with PSs are in principle not expected to provide a good description of the data, particularly in regions where the additional jets are neither soft nor collinear. A previous measurement of multi-jet cross sections at 7 TeV by the ATLAS Collaboration [20] found that the cross section predicted by MC models typically disagreed with the data by $\mathcal{O}(40\%)$, and could differ from data by $\sim 30\%$ even at NLO [44]. It also found disagreements of up to 50% in the shape of the differential cross section measured as a function of $p_T^{(1)}$ or H_T . Nevertheless, there are also examples of exceptional cases where these calculations perform well, which adds interest to the measurement; for example, the same 7 TeV ATLAS paper observed that the shape of the $p_T^{(4)}$ distribution was described by PYTHIA within just 10%. It is also interesting to test whether PSs based on an angular ordering perform better in angular variables such as $\Delta\phi_{2j}^{\min}$ or $\Delta\phi_{3j}^{\min}$ than those using momentum ordering. In contrast to PS predictions, multi-leg matrix element calculations matched to parton showers (ME+PS) were seen at 7 TeV to significantly improve the accuracy of the cross-section calculation and the shapes of the momentum observables. In the present analysis, such calculations are expected to perform better in events with additional high- p_T jets and/or large combined invariant masses of jets. This is also the type of scenario where HEJ is expected to perform well, since it provides an all-order description of processes with more than two hard jets, and it is designed to capture the hard, wide-angle emissions which a standalone PS

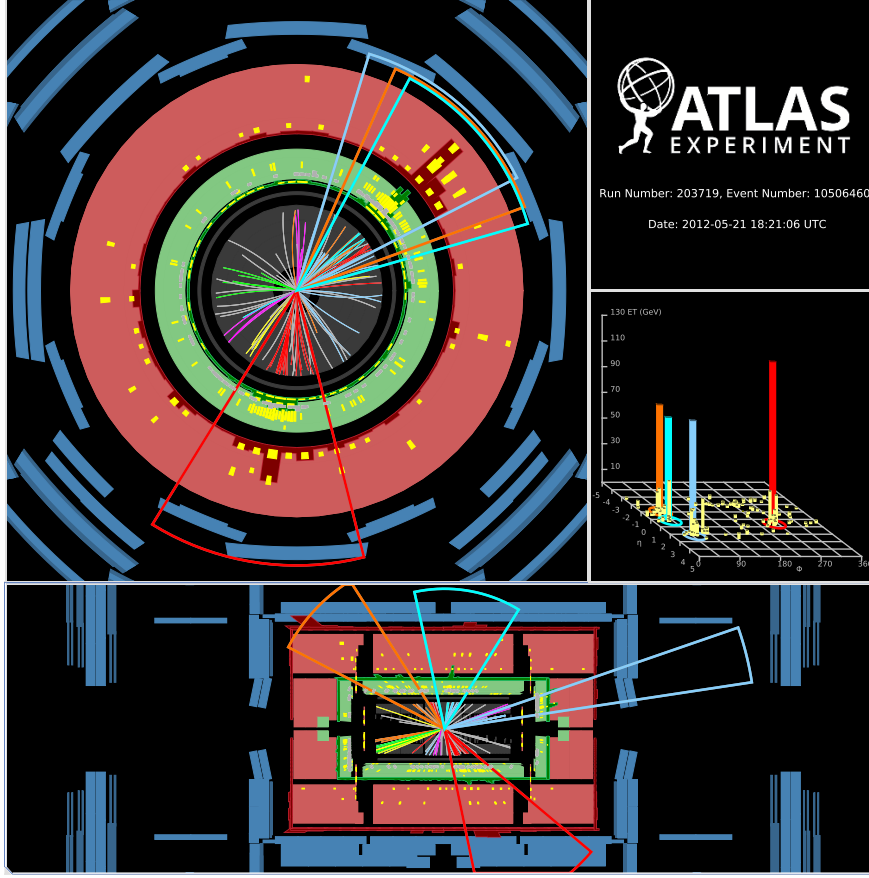


Figure 5.10: Event display for Run 203719, Event 105064604. This shows an example of an event with small $\Delta\phi_{3j}^{\min} = 0.2$, which corresponds to a topology where one jet recoils against three in the transverse plane. A cut of 60 GeV was applied on the jets shown, which are drawn in different colours for better distinction. The tracks are colour coded according to their corresponding jet, while the energy deposits in the calorimeters are all the same. Only jets and clusters are shown in the lego plot.

approach would miss. Variables such as $\Delta y_{2j}^{\max}$, $\Delta y_{3j}^{\min}$ or $\Sigma p_T^{\text{central}}$ were included in the analysis with this purpose in mind. Finally, the fixed-order, four-jet NLO predictions are expected to provide a better estimation of the cross sections than the LO calculations. Interestingly, studies at 7 TeV found that the NLO cross section for four-jet events was $\sim 30\%$ higher than the data [44].

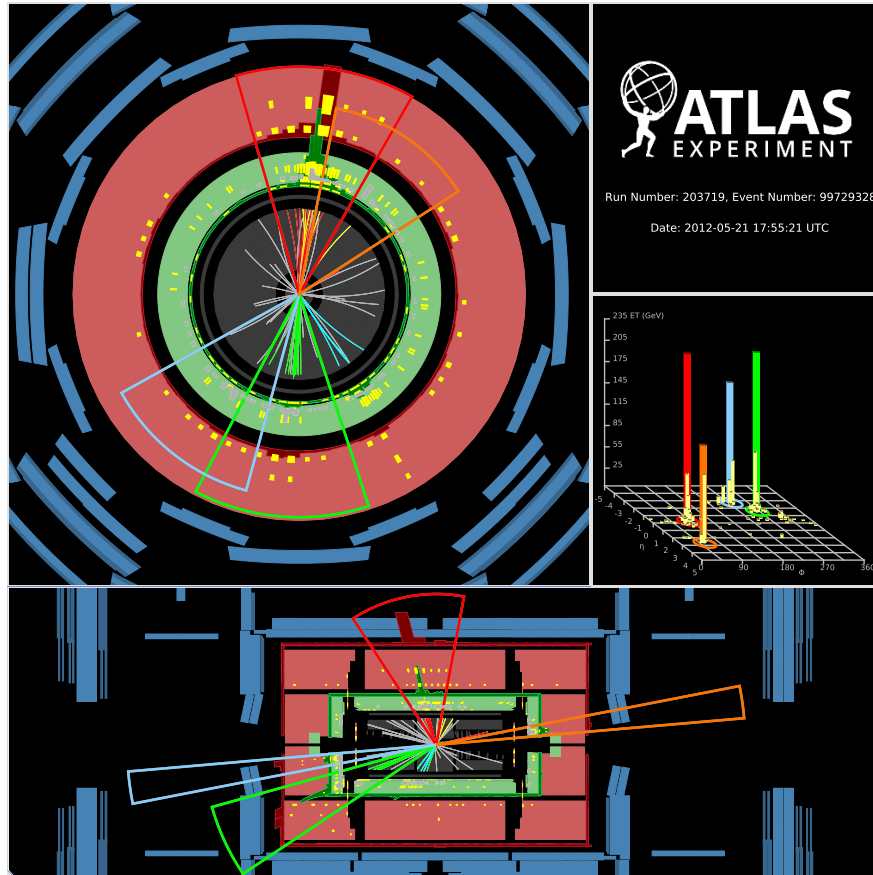


Figure 5.11: Event display for Run 203719, Event 99729328. This shows an example of an event with large $\Delta\phi_{3j}^{\min} = 3.1$, which corresponds to a topology with two pairs of close-by jets in the transverse plane. A cut of 60 GeV was applied on the jets shown, which are drawn in different colours for better distinction. The tracks are colour coded according to their corresponding jet, while the energy deposits in the calorimeters are all the same. Only jets and clusters are shown in the lego plot.

5.4 Data Unfolding

In order for the data to be compared to theoretical predictions it is necessary to remove any effect caused by its detection or reconstruction. In any experiment, the characteristics of the measured objects are different from the ones of the truth object. Many of the reasons for this have been described in chapter 4 for jets in particular. Although a large effort goes into correcting these effects through the jet energy scale and complementary corrections, it is still necessary to take reconstructed data to the truth level in order to compare it. The procedure applied to deconvolve detector effects from the measured differential cross sections is called *unfolding*. The method takes into account migrations between bins, which results from fluctuations in the variables due to reconstruction effects. It also corrects the results for the presence of events which pass the selection at reconstructed level but not at the particle level; and for detector inefficiencies, which have the opposite effect. This section presents a general explanation of the Bayesian Iterative unfolding method used in this analysis, and then more specific information of its implementation. The related uncertainties will be presented in section 5.5 together with the full account of the systematic errors. The resulting unfolded distributions are presented in chapter 5.6.

5.4.1 The Bayesian Iterative Method

The type of unfolding chosen is the Bayesian Iterative method [66, 67], and is applied as implemented in the `RooUnfold` package [5]. It is based on Bayes' theorem, which can be stated in terms of *causes* and *effects*. Effects ($\bar{E} = E_1..E_j..E_{n_E}$) in this case are the reco-level observables, while the causes ($\bar{C} = C_1..C_i..C_{n_C}$) are the truth-level ones.

The number of observed events of a given effect ($n(E_j)$) can be related to the number of events of each cause ($n(C_i) = P(C_i)N_{true}$) through the *transfer matrix*, also sometimes referred to as the *smearing or response matrix*, as expressed in equation 5.2. $P(C_i)$ is the probability distribution of cause C_i , and is such that $\sum_{i=1}^{n_C} P(C_i) = 1$.

$$n(E_j) = \sum_{i=1}^{n_C} P(E_j|C_i)P(C_i)N_{true} \quad (5.2)$$

But, of course, what is available in data is $n(E_j)$, while the goal is to estimate the real cross section determined by $n(C_i)$. A naive approach would be to attempt to use the inverse of the transverse matrix, which is possible in some cases and is called a 'bin by bin' unfolding, but the inversion process is mathematically unstable. Mostly, one would like to obtain an estimation of $n(C_i)$ as:

$$\hat{n}(C_i) = \sum_{j=1}^{n_E} n(E_j)P(C_i|E_j) \quad (5.3)$$

Using Bayes' theorem one can express the values of $P(C_i|E_j)$ as a function of $P(C_i)$ and of the transfer matrix values:

$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_C} P(E_j|C_l)P_0(C_l)} \quad (5.4)$$

It is possible to argue that the knowledge of $P(C_i)$ can be limited, but one should

note at this point that it is possible to increase the knowledge on this distribution through iteration, so that even a uniform distribution could be the departing point. Thus equation 5.4 is stated as a function of the *initial probability* of C_i , $P_0(C_i)$. On the contrary, $P(E_j|C_i)$ are not updated by observation. They have to be estimated using Monte Carlo methods, and if there were any ambiguities as to their value their *systematic effects* should be evaluated.

The normalisation of $P(C_i|E_j)$ is deduced from 5.4 as $\sum_{i=1}^{n_C} P(C_i|E_j) = 1$, and implies that all causes of a certain effect must be included in the model. Therefore all background events - or *fakes* - with non-negligible contributions must be taken into account. Unlike the inverse case, where not every cause must have a measurable effect (and if $P(C_i) = 0$ it means that the experiment is not sensitive to this cause). This is related to the *efficiency* of detecting cause C_i , $\epsilon_i = \sum_{j=1}^{n_E} P(E_j|C_i)$.

If from each cause one should measure a certain number of events $\hat{n}(C_i)$, the best estimate one can make of this number is given by

$$\hat{n}(C_i) = \frac{1}{\epsilon_i} \sum_{j=1}^{n_E} n(E_j) P(C_i|E_j) = \sum_{j=1}^{n_E} M_{ij} n(E_j) \quad (5.5)$$

where M_{ij} are the values of the *unfolding matrix*. These are the unfolded events, from which the total number of events, the probability distribution of the causes, and the efficiency can be estimated.

$$\hat{N}_{true} = \sum_{i=1}^{n_C} \hat{n}(C_i) \quad (5.6)$$

$$\hat{P}(C_i) \equiv P(C_i|n(E)) = \frac{\hat{n}(C_i)}{\hat{N}_{true}} \quad (5.7)$$

$$\epsilon_i = \frac{N_{obs}}{\hat{N}_{true}} \quad (5.8)$$

From the three previous results an iterative procedure can be established, as described by d'Agostini in ref. [66].

1. $P_0(C_i)$ is taken from the truth distribution of MC, and $P(E_j|C_i)$ is built from comparing truth and reconstructed information. This determines the expected number of events $n_0(C_i) = P_0(C_i)N_{obs}$.
2. By obtaining $P(C_i|E_j)$, estimate $\hat{n}(C_i)$ and $\hat{P}(C_i)$.
3. Make a χ^2 comparison between $n_0(C_i)$ and $\hat{n}(C_i)$
4. Replace $n_0(C_i)$ by $\hat{n}(C_i)$ and $P_0(C_i)$ by $\hat{P}(C_i)$, repeating the steps 2-4 until the value of χ^2 is 'small enough'.

5.4.2 Building of the Unfolding Matrix

The transfer matrix is the fundamental input to the unfolding algorithm. It is built using MC simulation, and one matrix is defined for each of the analysis variables, in each of the $p_T^{(1)}$ or m_{4j} bins. Its axes correspond to the truth- and reco-level values

of the variable in question, and it allows to see how the reconstruction process smears the observable. Due to this smearing, an event in which the truth level observable is within certain limits, might not be so at reconstructed level. This is referred to as *bin migration*. The most important sources of migrations between bins are:

- *Jet energy scale and resolution*: the correction applied by the jet energy scale rectifies the average energy of the jets, resulting in a spread around this value that is the jet energy resolution.
- *Jet swapping*: a jet may be reconstructed with an energy larger or smaller than its corresponding truth jet. Jets of similar energy at truth level may fluctuate so that the p_T ordering of the reconstructed jets can differ from the one for truth jets.
- *Merging and splitting of jets*: it occurs when two truth jets with a small angular separation between them are merged into one reconstructed jet, or vice-versa. This effect has no incidence in the analysis thanks to the $\Delta R_{4j}^{\min}$ cut applied.

The variables most affected by jet swapping are the angular ones, since a small change in energy can result in different jets, with very different angular positions, being used. Some of the variables like H_T or m_{4j} are not sensitive to the p_T ordering of the four leading jets, so they are not affected by jet swapping between them. However a non-leading jet at truth level could become leading at reconstructed level. It was found that in 6% of the events the 5th truth jet matches one of the four leading reconstructed jets, indicating swapping occurred; the same happens in 0.5% of the events for the 6th jet and 0.1% for the 7th.

In order to first evaluate the variables for their sensitivity to reconstruction effects, a correlation matrix is built. Small and regular binning is used to better verify how diagonal they are. All variables were found to present a strong linear correlation, and even the angular ones have an order of magnitude difference between the bins along the diagonal and the off-diagonal ones. Hence the chosen variables are not overly sensitive to reconstruction effects and should not hinder the unfolding process.

The binning defined in section 5.3.1 is then applied equally at truth and reco level to build the transfer matrix. However, as will be explained in section 5.5.2, an additional column is added to account for the events that pass the cuts at reconstructed but not at truth level. No spatial matching is performed between reconstructed and truth jets. However, events are required to pass the analysis cuts at both reconstructed and truth level, as defined in section 5.2.4. For observables requiring additional kinematic cuts, these are also applied both at the reconstructed and particle levels. Events that pass the cuts at reconstructed level but not at truth level (previously defined as fakes) are also included in the matrix in a column for events with no well defined truth cause. On the other hand, events that pass the truth-level cuts but not the ones at reconstructed level are translated into a bin-by-bin inefficiency correction. Figure 5.12 shows two examples of the transfer matrices used in the unfolding of H_T and $\Delta\phi_{2j}^{\min}$. The wider spread of the events along the diagonal mentioned previously can be appreciated when comparing this angular variable with H_T .

Ideally, the transfer matrix should be independent of the MC used to construct it, as it represents detector effects. However, there are a number of reasons why different

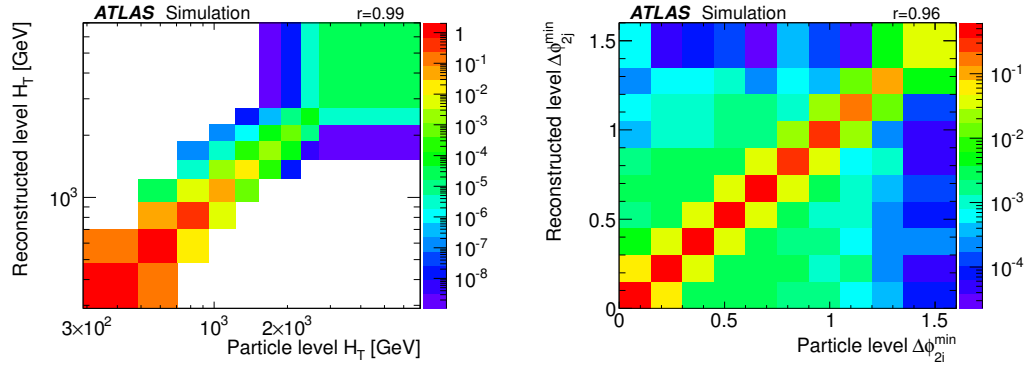


Figure 5.12: The transfer matrices are shown between truth-level and reco-level predictions for the H_T (left) and $\Delta\phi_{2j}^{\min}$ (right) distributions, using the PYTHIA MC calculation. The events plotted are required to satisfy the minimum kinematic requirements of section 5.2.4 both at truth- and reconstructed-level.

MC will produce different matrices. For example, they can populate the phase space differently or have diverse flavour compositions that result in different jet responses. The choice of the MC generator to be used for constructing the transfer matrix is based on three main aspects:

- Detector response (as defined in equation 4.5) was checked for the four leading reconstructed jets by matching them to their truth counterparts. The PYTHIA and MADGRAPH samples were found to agree within 1%, while HERWIG++ shows a slightly larger discrepancy at low p_T .
- Shape differences at reconstructed level were evaluated from the distributions shown in section 5.3, in figures 5.5-5.8, by comparing the MC samples to data. No bias was found due to shape differences in any of the variables.
- The number of generated events, as larger samples will produce smaller statistical uncertainties. Among the available samples, PYTHIA has the largest statistics.

Consequently, the sample chosen to construct the inputs to the unfolding procedure was the one with largest statistics, generated with PYTHIA, as it didn't present any major differences in the other aspects with respect to the other two.

The number of iterations needs optimization as well, but is usually set between 1 and 3. Two iterations are used in this analysis. The more iterations are performed, the closer the unfolded distribution will be to the truth one. However, each additional iteration increases the statistical uncertainties.

5.5 Systematic Uncertainties

5.5.1 Statistical Uncertainty

The statistical uncertainties are calculated with pseudo-experiments using the bootstrap method. For each pseudo-experiment, the data and MC distributions are reweighted event by event following a Poisson distribution centred at one. Each resulting Poisson

replica of the data is unfolded using the corresponding fluctuated unfolding matrix. The random numbers for the pseudo-experiments are generated using unique seeds, following the same scheme used by the inclusive jet [37], dijet [31] and three-jet [38] measurements at $\sqrt{s} = 7$ TeV, to allow for possible future combination of results with the same dataset used for this analysis.

5.5.2 Unfolding Uncertainties

The unfolding method presented in section 5.4 allows to remove the detector effects from the data in an iterative way that makes the results independent of the choice of prior for $P(C_i)$. However it does rely heavily on the construction of the transfer matrix, and thus on the choice of MC generator to build it. It is therefore imperative to evaluate the robustness of the unfolding to the differences between the MC generators, assess the effects and estimate the associated uncertainties.

The evaluation was first made by taking a simulation both statistically and systematically independent from the one used to build the unfolding matrix. HERWIG++ was selected for this because it showed the largest difference in response with respect to PYTHIA. The $p_T^{(1)}$ spectrum generated with HERWIG++ was unfolded as would be done with data, and compared to its corresponding truth spectrum, finding differences below 10%. Several variations were performed on the unfolding to test different effects, and an improvement in the agreement was found when using only events that pass both reconstructed- and truth-level cuts, which is equivalent to removing inefficiencies and fakes. Thus one concludes that the sources of systematic uncertainties to be evaluated are the differences in the reconstruction (related to the different shapes) and the different modelling of the efficiencies and inefficiencies. It should be mentioned that the differences in the response of the various MC generators mentioned in the previous chapter is covered by the JES uncertainties to be described in the next section.

The shape differences are therefore one of the sources of systematic uncertainty in the unfolding, and the possible presence of biases due to this is evaluated using a data-driven closure test. In this study, only events that pass both reconstructed and truth level cuts are used, and the data is reweighted to account for the additional truth-level cuts. The MC distributions are reweighted to match the shape of those obtained from the reweighted data, and then unfolded using the same unfolding matrix as for the data. The reweighted reconstructed MC is unfolded and compared to the reweighted truth, and the ratio between them yields the systematic uncertainty. The statistical uncertainty for this systematic is evaluated using the bootstrap method, and then used to determine if the systematic is significant. It is found that the systematic is consistent with 0 within 2σ in all bins, and therefore is not considered in the total uncertainty.

The most relevant unfolding uncertainty is related to the different modelling of the event selection inefficiencies. In order to evaluate it, two efficiency curves are measured for the MC samples generated with PYTHIA and HERWIG++:

- The inefficiency is studied with respect of the truth-level variable by selecting events passing the cuts at both levels with respect to the ones passing only the truth-level cuts.
- The fake rate is studied with respect of the reconstructed-level variable by selecting events passing the cuts at both levels with respect to the ones passing only

the cuts at reconstructed level.

For each efficiency curve the ratio between the two samples is taken. The envelope of these two ratios defines the final uncertainty. The statistical uncertainties were evaluated and propagated through the ratios considering the fact that both samples are completely uncorrelated. The resulting uncertainty is found to be subdominant in most cases, with typical sizes of 2–10%. The uncertainty is rebinned and smoothed, such that its statistical uncertainty is smaller than 40%.

5.5.3 Experimental Uncertainties

This section presents the uncertainties which arise from the jet energy scale (JES), jet energy resolution (JER), jet angular resolution and integrated luminosity. The effect from trigger and cleaning inefficiencies is negligible, and therefore no systematic uncertainty is associated with them. The dominant source of uncertainty in this measurement is the JES.

The uncertainty in the JES calibration is determined in the central detector region by exploiting the transverse momentum balance in Z +jet, γ +jet or multi-jet events, which are measured in situ. The uncertainties in the energy of the reference object are propagated to the jet whose energy scale is being probed. The uncertainty in the central region is propagated to the forward region using dijet systems balanced in transverse momentum. The procedure is described in detail in ref. [34].

The total JES uncertainty is decomposed into eighteen components, that account for the uncertainties arising from the several components of the calibration procedure:

- 6 are in fact a reduction of a larger set that accounts for the uncertainty in the in-situ methods used in the jet energy scale calibration itself
- 4 components are related to the pile-up subtraction procedure
- 3 are related to possible parton flavour differences between samples and to the b -jet energy scale
- 2 correspond to the eta-intercalibration used to propagate uncertainties to forwards jets
- 1 from the behaviour of high- p_T jets
- 1 to account for jets not completely contained within the calorimeter, or punch-through.

Each of these uncertainties is incorporated as a coherent shift of the scale of the jets in the MC simulation. The energies and transverse momenta of all jets with $p_T > 20$ GeV and $|y| < 2.8$ are varied up and down by one standard deviation of each uncertainty component, before the events go through the selection. The components are sometimes asymmetric, i.e. the values of the upwards and downwards variations are different. There are then 34 shifted distributions for each variable, four of which are shown for two example variables in figure 5.13. Each plot shows the nominal MC distribution at reconstructed level, and the upwards and downwards shifted distributions for two of the JES uncertainty components. In the case of H_T the ratio plot

in the bottom shows that in these two cases the shifts are symmetric, and that the upward (downward) shift results in a shifted distribution that is above (below) the nominal. The behaviour of the shifted distributions however is less coherent in the case of $\Delta\phi_{2j}^{\min}$ where the upwards and downwards shifted distributions are not symmetric with respect of the nominal, and the second JES component can be seen to yield ratios that are positive for some bins and negative for others.

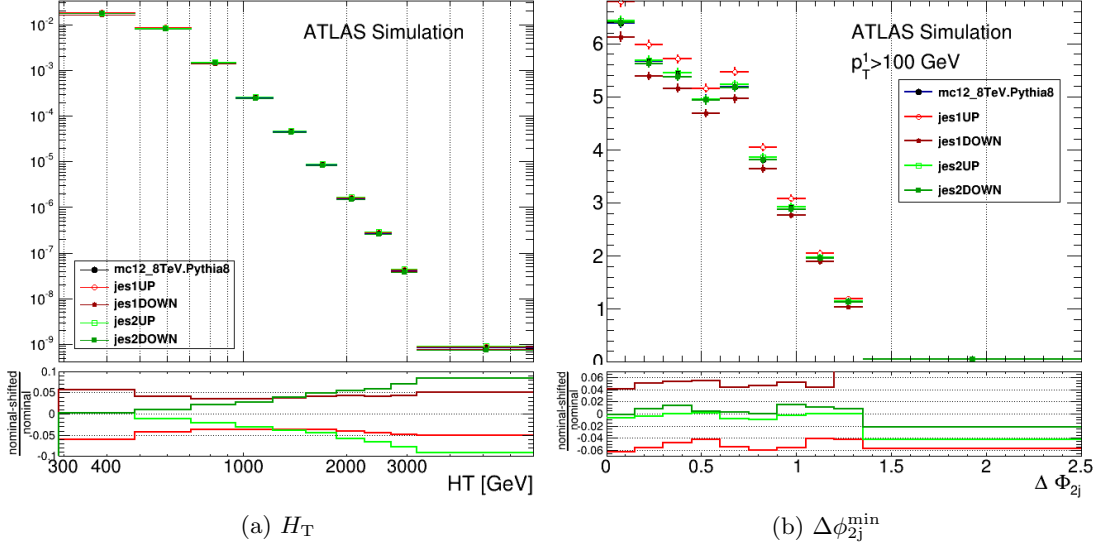


Figure 5.13: Distributions of (a) H_T and (b) $\Delta\phi_{2j}^{\min}$ in PYTHIA. The nominal distribution is shown in black, while the red and green distributions have been shifted with respect of the nominal with the two of the JES components. The lighter (darker) shade of each colour corresponds to the upward (downward) shift in energy and momentum. The bottom plot shows the ratio between the nominal and the shifted distributions.

These distributions are all propagated through the unfolding. The unfolded distributions corresponding to the systematically varied spectra are compared one by one to the nominal ones, and the difference taken as the unfolded-level uncertainty due to that JES uncertainty component. The resulting positive and negative variations are combined respecting their sign, and independently of whether they resulted from an upwards or downwards variation, by summing the contributions quadratically.

Statistical uncertainties on each of the JES uncertainty components are obtained by using the same boots-strap method as explained in the first part of this section. Such statistical uncertainties are used to evaluate the significance of the uncertainty for each component and for each bin of all the differential distributions. As in the case of the unfolding uncertainty, the unfolded-level uncertainty due to each JES component is then rebinned and smoothed using a Gaussian kernel regression in order to get statistical uncertainties smaller than 40% in all bins. The typical size of the JES uncertainty is 4–15%.

Jets may be affected by additional energy originating from pile-up interactions. This effect is corrected for as part of the jet energy calibration. The distributions were binned in different ranges of the average number of interactions per bunch crossing in

order to test the possible presence of residual effects. No significant deviations were observed, therefore no uncertainty associated with pile-up mismodelling was considered beyond the pile-up uncertainty already included in the jet calibration procedure.

The JER has been measured in data using dijet events [29], chapter 4, and an uncertainty was derived from the differences seen between data and MC prediction. In general, the energy resolution observed in data is somewhat worse than that in MC simulations. The uncertainty on the observables can therefore be evaluated by smearing the energy of the reconstructed jets in the MC simulation. But unlike what was done for the JES, an alternative unfolding matrix is constructed using the smeared distribution and is used to unfold the nominal MC prediction. The MC distribution is also unfolded using the nominal matrix, and the difference between the distributions unfolded with different matrices is symmetrised and taken as the JER systematic uncertainty. The typical size of this uncertainty is 1–10% of the cross section.

The jet angular resolution was estimated in MC simulation for y and ϕ by matching spatially jets at the reconstructed and particle level, and found to be below $\lesssim 2\%$. The procedure and results are further explained in appendix E. The results are in agreement with in-situ measurements that have been presented before [75], so no systematic uncertainty is assigned.

Finally, the uncertainty on the integrated luminosity is $\pm 2.8\%$. It is derived following the same methodology as that detailed in ref. [27].

Two examples of the values of the total experimental systematic uncertainty are shown in figure 5.14 for two representative variables, namely H_T and $\Delta\phi_{2j}^{\min}$. The jet energy scale and resolution uncertainties dominate in the majority of bins, being larger at the high and low ends of the H_T spectrum. The unfolding uncertainty is nearly as large at low values of the jet momenta, and it is therefore an important contribution in most of the $\Delta\phi_{2j}^{\min}$ bins.

5.6 Results

The results presented in this section consist in various differential cross sections measured in events with at least four jets built with the anti- k_t algorithm with $R = 0.4$. Events are cleaned following guidelines recommended within ATLAS, as listed in section 5.2, after which the analysis cuts defined in 5.2.4 are applied. The observables used for the measurements have been defined and described in section 5.3, and the measured cross sections are shown in figures 5.15 to 5.30. They present a wide range of jet transverse momenta, from 64 GeV to several TeV, spanning two orders of magnitude in p_T and over seven orders of magnitude in cross section. They have been corrected for all detector effects using the unfolding procedure described in section 5.4. The theoretical predictions described in 5.1 are compared to the unfolded results. The aim is to provide a thorough description of the performance of the different predictions in the variables, highlighting in which areas they provide a good description or show their limitations.

The unfolded cross sections are presented in two plots each, one in comparison to the LO simulations generated with PYTHIA, HERWIG++ and MADGRAPH, the other one opposed to HEJ and the NLO predictions BLACKHAT/SHERPA and NJET/SHERPA. The ratio between the unfolded data and the predictions is presented too; in the case of the LO plot the total experimental systematic uncertainty is shown, while the total

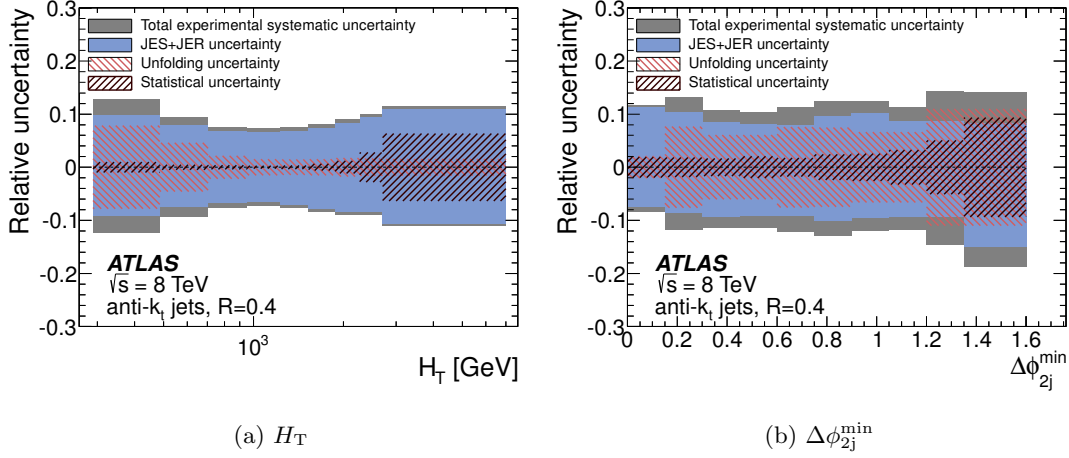


Figure 5.14: Total systematic uncertainty in the four-jet cross section measurement for anti- k_t $R = 0.4$ jets as a function of (a) H_T and (b) $\Delta\phi_{2j}^{\min}$. In both cases the event selection corresponds to the inclusive analysis cuts, namely $p_T^{(4)} > 64$ GeV, $p_T^{(1)} > 100$ GeV and $\Delta R_{4j}^{\min} > 0.65$. Separate bands show the jet energy scale (JES) and resolution (JER), and the unfolding uncertainty, as well as the combined total systematic uncertainty resulting from adding in quadrature all the components. The total statistical uncertainty of the unfolded data spectrum is also shown. The luminosity uncertainty is not shown separately but is included in the total uncertainty band.

theoretical uncertainty is added in the other. The latter is drawn centred in the ratio of NJET/SHERPA to data, and can be seen to be highly asymmetric. In the variables where additional kinematic cuts have been applied in $p_T^{(1)}$ or m_{4j} the corresponding ratios are presented separately.

Summary of the results The cross sections predicted by the LO generators were found to differ from the data to an extent that obstructs the comparison and made it preferable to apply scale factors. The scale factors, found to vary between 0.6 and 1.4, are applied as anticipated in section 5.1.1. Their values are shown in the figure next to the reference for each distribution. Not all generators describe the shape of $p_T^{(1)}$ correctly, so these scale factors should not be seen as a measure of the level of agreement between MC simulation and data, which may vary as a function of the cuts in $p_T^{(1)}$ and m_{4j} .

The cross section predicted by BLACKHAT/SHERPA and NJET/SHERPA is larger than that measured in data, but overall the difference is covered by the scale and PDF uncertainties evaluated using NJET/SHERPA, with only a few exceptions. BLACKHAT/SHERPA and NJET/SHERPA give identical results within statistical uncertainties; therefore only one of the two (NJET/SHERPA) is discussed in detail, for simplicity. It is nevertheless interesting to compare experimental results with two different implementations of the same NLO p QCD calculations as an additional cross-check.

In general, an excellent description of both the shape and the normalisation of the variables is given by NJET/SHERPA. The small differences found are covered by theoret-

ical and statistical uncertainties in almost all cases; only the tails of $p_T^{(4)}$ and $\Delta y_{2j}^{\max}$ hint at deviations from the measured distribution. HEJ also provides a good description of most variables; the most significant discrepancy occurs for the angular variables $\Delta y_{2j}^{\min}$ and $\Delta y_{2j}^{\max}$ when $p_T^{(1)}$ is small. However when $p_T^{(1)}$ is large, HEJ describes $\Delta y_{2j}^{\max}$ better than NJET/SHERPA, which highlights one of the strengths of this calculation. MADGRAPH+PYTHIA describes the data very well in most regions of phase space, the most significant discrepancy being in the slopes of $p_T^{(1)}$ and $p_T^{(2)}$ and variables derived from the jet momentum. The $2 \rightarrow 2$ ME calculations matched to parton showers provide different levels of agreement depending on the variable studied; the only variable whose shape is reasonably well described by both PYTHIA and HERWIG++ is H_T .

The following discussion is based on the results obtained after applying the particular choice of normalisation of the theoretical predictions as explained at the beginning of this section. Therefore in relation to this approach, the results of the LO predictions will be evaluated for discrepancies in shape description, and not in their size. Having applied scale factors makes it irrelevant to evaluate if the differences are within the uncertainties or not. NJET/SHERPA, which generally gives very good agreement with the data, is only discussed for those cases where some deviations are present.

Momentum variables The momentum variables comprise the p_T of the four leading jets and H_T . Part of the importance of these variables lies in their wide use in analyses, alone or as inputs to more complex observables. They are also interesting in themselves: it has been shown that the ratio of the NLO to the LO predictions is relatively flat across the $p_T^{(1)}$ spectrum with a maximum variation of approximately 25% [44]. Perhaps surprisingly, the PS description of $p_T^{(4)}$ was found to be better than that of $p_T^{(1)}$ in the 7 TeV multi-jet measurement published by ATLAS [20].

Figures 5.15 to 5.18 show the p_T distributions of the leading four jets. All the LO generators show a slope with respect to the data in the leading jet p_T (figure 5.15). PYTHIA's slope changes for lower $p_T^{(1)}$ values. The ratios of HERWIG++ and HEJ to data are remarkably flat above ~ 500 GeV and ~ 300 GeV respectively. MADGRAPH+PYTHIA is within the experimental uncertainties above ~ 300 GeV, and it is the only one with a positive slope in the ratio to data, and thus the only one to produce a harder spectrum (PYTHIA and HERWIG++ being softer). The subleading jet p_T (figure 5.16) is well described by HEJ, while the LO generators show similar trends to those in $p_T^{(1)}$. In particular, HERWIG++ seems again flatter than PYTHIA for $p_T^{(2)}$ above ~ 300 GeV. MADGRAPH+PYTHIA describes both $p_T^{(3)}$ and $p_T^{(4)}$ well, as shown in figures 5.17 and 5.18. As the 7 TeV results suggested, PYTHIA gives a good description of the distribution of $p_T^{(4)}$. HERWIG has a small variation in the $p_T^{(3)}$ ratio, but overestimates the number of events with high $p_T^{(4)}$. This last remark also applies to HEJ, which shows an upward trend at the tails of $p_T^{(4)}$. NJET/SHERPA shows a similar trend at high $p_T^{(4)}$, but the discrepancy is mostly covered by the theoretical uncertainties. H_T , shown in figure 5.19, exhibits features similar to those in $p_T^{(1)}$.

In summary, PYTHIA and HERWIG++ tend to describe the p_T spectrum of the leading jets with similar levels of agreement, whereas PYTHIA is better at describing $p_T^{(4)}$. MADGRAPH+PYTHIA does a reasonable job for all of them, while HEJ and NJET/SHERPA

are very good for the leading jets and less so for $p_T^{(4)}$. This difference points both at the excellent capability of the PS models to correctly reproduce the spectrum of non leading jets, and to the fact that the NLO prediction's description could perhaps be improved by matching the calculations to PSs.

Mass variables Mass variables are widely used in physics searches, and they are also sensitive to events with large separations between jets, which puts the HEJ and MADGRAPH+PYTHIA predictions to the test, as they are expected to be especially accurate in this regime.

The distribution of the total invariant mass m_{4j} is studied in figure 5.20. PYTHIA and MADGRAPH+PYTHIA describe the data very well. Both PYTHIA and HERWIG++ appear to have a slight slope below ~ 1 TeV, which is more marked for the latter. However HERWIG++ describes the shape of the data well above this value. HEJ is mostly compatible with the measurement, but the ratio to data has a bump structure in the region of approximately 1 to 2 TeV. This feature is also shared by NJET/SHERPA, but the differences with respect to the data are covered by the NLO uncertainties. The results of the predictions for higher values of the variable fluctuate, but appear to show NJET/SHERPA overestimating the number of events with larger m_{4j} .

The description of different splitting scales is tested in figure 5.21 through the variable $m_{2j}^{\min}/m_{4j}$. This distribution is well described by PYTHIA, whereas HERWIG++ gets worse with increasing m_{4j} , consistently overestimating the two ends of the $m_{2j}^{\min}/m_{4j}$ spectrum. MADGRAPH+PYTHIA provides a very good description, with a flat ratio for all the m_{4j} cuts. The HEJ prediction shows trends similar to those of HERWIG++ at higher values of m_{4j} , but a better agreement for the first bins. These differences are covered in all cases by the large associated scale uncertainty. NJET/SHERPA consistently overestimates the number of events in the very first bin for all the cuts in m_{4j} , but otherwise agrees with the data within the theoretical uncertainties. The overestimation in the tail of m_{4j} mentioned before could lead to this effect, but there could also be hidden discrepancies in $m_{2j}^{\min}$. The lack of matching to PS can again be related to the discrepancies of the NLO prediction.

Overall, MADGRAPH+PYTHIA provides the best description of mass variables.

Angular variables Similarly to mass variables, angular variables are able to test the description of events with small- and wide-angle radiation. In addition, they can also provide information on the global spatial distribution of the jets. High- p_T , large-angle radiation should be well captured by the ME+PS description of MADGRAPH+PYTHIA, or the all-orders approximation of HEJ – particularly the rapidity variables $\Delta y_{2j}^{\min}$, $\Delta y_{2j}^{\max}$ and $\Delta y_{3j}^{\min}$. PS generators are expected to perform poorly at large angles, given that they only contain two hard jets, and the rest is left to the soft- and collinear-enhanced PS. The fixed-order NLO prediction of NJET/SHERPA should provide a very good description of these variables too, as long as they are far from the infrared limit. This is indeed the case, and therefore no detailed comments about its performance are given here.

Figure 5.22 compares the distributions of $\Delta\phi_{2j}^{\min}$ for different cuts in $p_T^{(1)}$. PYTHIA has a small downwards slope with respect to the data in all the $p_T^{(1)}$ ranges, indicating it tends to have more jets closer together. MADGRAPH+PYTHIA also shows a small slope.

The other generators, both LO and NLO, reproduce the data very well. HERWIG++, in particular, provides a very good description of the data.

The $\Delta\phi_{3j}^{\min}$ spectrum is shown in figure 5.23; this variable is particularly interesting, as it is clearly related to the distribution of the jets in the events: the smaller values correspond to event configurations where one jet recoils against three, while large values reflect two jets recoiling against two. The different $p_T^{(1)}$ cuts change which of this configurations is predominant, so that it can be seen that at low $p_T^{(1)}$ most events are of the latter kind, while at high $p_T^{(1)}$ the first dominate. In general, the description of the data improves as $p_T^{(1)}$ increases. For PYTHIA, the number of events where one jet recoils against three (low $\Delta\phi_{3j}^{\min}$) is significantly overestimated when $p_T^{(1)}$ is low; as $p_T^{(1)}$ increases, the agreement improves such that the $p_T^{(1)} > 1000$ GeV region is very well described. MADGRAPH+PYTHIA, HERWIG++ and HEJ are mostly in good agreement with data.

Figure 5.24 compares the distributions of $\Delta y_{2j}^{\min}$ with data. This variable is remarkably well described by PYTHIA, showing no significant trend. MADGRAPH+PYTHIA mostly underestimates high $\Delta y_{2j}^{\min}$ values, while HERWIG++ presents a slope that hints to a tendency to underestimate the low values. HEJ overestimates the number of events with high $\Delta y_{2j}^{\min}$ values at low $p_T^{(1)}$, but describes the data very well at larger values of $p_T^{(1)}$.

For the variable $\Delta y_{3j}^{\min}$, presented in figure 5.25, the predictions provided by PYTHIA and HERWIG++ show in general a positive slope with respect to the data, more marked in the second. MADGRAPH+PYTHIA reproduces the shape of the data well, as does HEJ for $p_T^{(1)} > 400$ GeV. However, for smaller values of $p_T^{(1)}$ HEJ overestimates the number of events at the end of the spectrum, as was the case for $\Delta y_{2j}^{\min}$.

The variable $\Delta y_{2j}^{\max}$, shown in figure 5.26, is very well described by HEJ in events with $p_T^{(1)} > 400$ GeV. The ratios to data in both PYTHIA and HERWIG++ have upwards slopes in all $p_T^{(1)}$ bins. MADGRAPH+PYTHIA provides mostly a good description of the data, with a tendency to underestimate the extremes of the distribution. Interestingly, NJET/SHERPA seems to overestimate the number of events in the tail, although it is a statistically limited region and the comparison with BLACKHAT/SHERPA is not conclusive.

In summary: NJET/SHERPA mostly agrees with the data within the uncertainties, but its ratio to data has an upwards trend in the tail of $\Delta y_{2j}^{\max}$. HEJ provides a very good description of all angular variables for the region $p_T^{(1)} > 400$ GeV, as expected, but shows significant discrepancies with respect to the data in all the rapidity variables for lower $p_T^{(1)}$ values. It is important to keep in mind, though, that the associated scale uncertainties are large. MADGRAPH+PYTHIA describes all the data well, apart from the tail of $\Delta y_{2j}^{\min}$ and the extreme values of $\Delta y_{2j}^{\max}$, which it underestimates. HERWIG++ gives good descriptions of the ϕ variables, but fails at describing the rapidity variables. PYTHIA has some problems describing both three-jet variables, as well as $\Delta y_{2j}^{\max}$. These variables highlight the need to combine four-jet ME calculations with parton showers.

$\Sigma p_T^{\text{central}}$ variables The variables setting a minimum forward–backward rapidity interval and measuring the total p_T of the central jets ($\Sigma p_T^{\text{central}}$) were defined to test

the framework of HEJ. HEJ has been designed to describe events with two jets significantly separated in rapidity with additional, central, high- p_T radiation. These variables are also useful to describe the spatial configuration of the events, as they represent the forward–backward rapidity span of the jets, and whether the leading jet is among the two central ones or not. The NLO predictions and MADGRAPH+PYTHIA are also expected to be successful in this regime, whereas the $2 \rightarrow 2$ generators with PSs are expected to be less suitable.

The variable $\Sigma p_T^{\text{central}}$ is studied for values of $\Delta y_{2j}^{\text{max}}$ larger than 1, 2, 3 or 4, and for different cuts in $p_T^{(1)}$. In most cases, the description of the observable worsens significantly with increasing $\Delta y_{2j}^{\text{max}}$ and $p_T^{(1)}$. Figures 5.27 to 5.30 correspond to the results for $\Delta y_{2j}^{\text{max}} > 1, 2, 3, 4$, and the cuts in $p_T^{(1)}$ are shown in separate ratios in each case.

This variable has a threshold value where the contribution from different jets changes; given a certain cut in $p_T^{(1)}$, only after this cut plus 64 GeV will there be contributions from events where the leading jet is central. The generators with $2 \rightarrow 2$ MEs have problems describing the data around such thresholds, which appear as kinks in the ratio distributions around this points. For $p_T^{(1)} > 400$ GeV, this happens at $\Sigma p_T^{\text{central}} > 464$ GeV, at which point there is a major jump in PYTHIA in the second ratio plot of figure 5.27. PYTHIA gives in general the most discrepant prediction, with kinks in the ratio to data at the transition points that reach differences of 70% at high $p_T^{(1)}$, as well as global slopes. HERWIG++ describes the data very well at lower $\Delta y_{2j}^{\text{max}}$ values, but as $\Delta y_{2j}^{\text{max}}$ grows its normalisation worsens, as well as the shape – particularly at high $p_T^{(1)}$.

MADGRAPH+PYTHIA provides an excellent description of the $\Sigma p_T^{\text{central}}$ variables, especially at low $p_T^{(1)}$. The agreement deteriorates at high $p_T^{(1)}$, but it is not very much affected by the changes between different jet configurations, providing overall a very good description of the shapes. Most distributions are well described by HEJ, especially the high $\Sigma p_T^{\text{central}}$ region; the low $\Sigma p_T^{\text{central}}$ region shows more shape differences, which get worse at large $\Delta y_{2j}^{\text{max}}$. This is compatible with similar observations made in previous ATLAS measurements performed with 7 TeV data [32], where it was also shown that the agreement was significantly improved after interfacing HEJ with a PS generator. NJET/SHERPA has a tendency to overestimate the number of events with very low $\Sigma p_T^{\text{central}}$, which may be correlated with the $p_T^{(4)}$ discrepancy discussed earlier. It provides a very good description of the data otherwise.

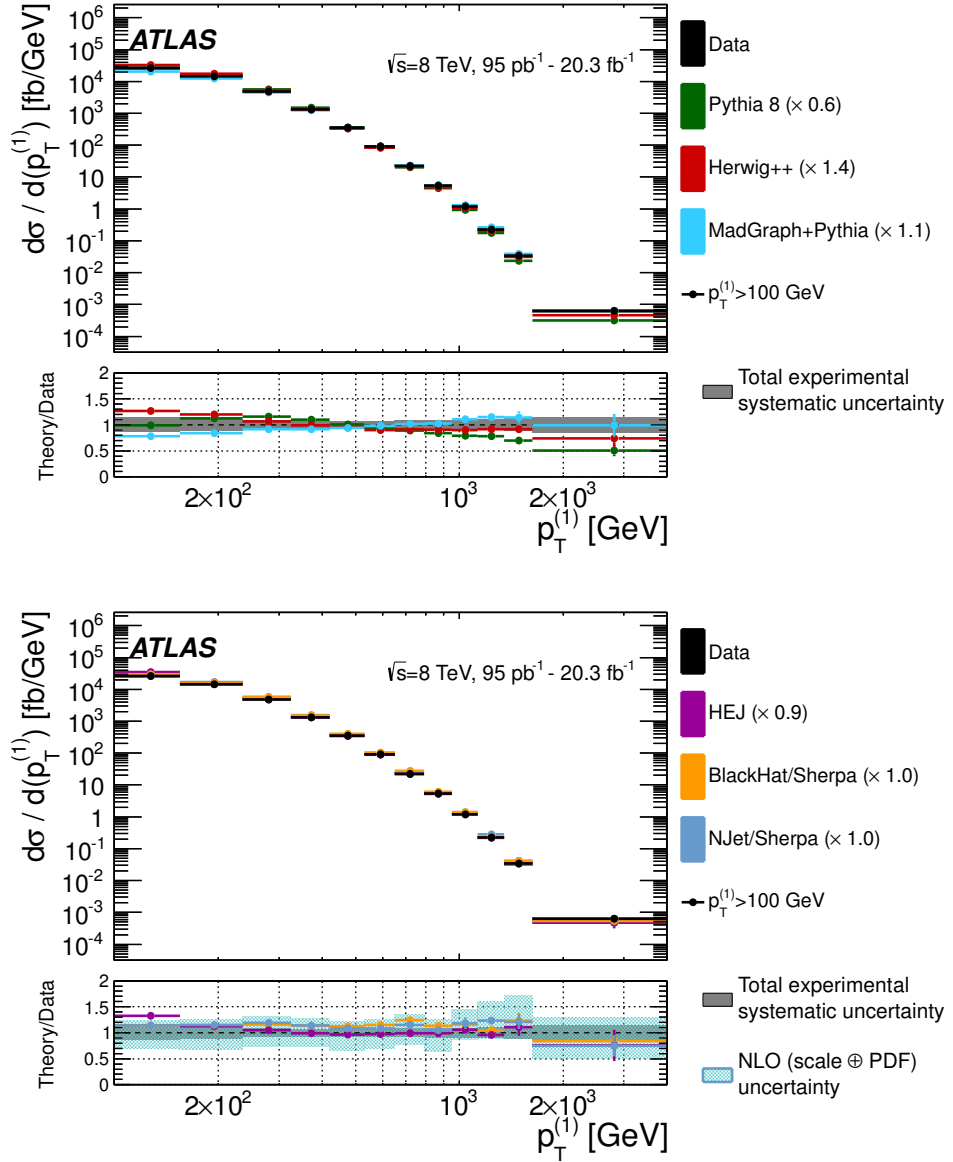


Figure 5.15: The four-jet differential cross section as a function of leading jet $p_T(p_T^{(1)})$, compared to different theoretical predictions: PYTHIA, HERWIG++ and MADGRAPH+PYTHIA (top), and HEJ, NJET/SHERPA and BLACKHAT/SHERPA (bottom). For better comparison, the predictions are multiplied by the factors indicated in the legend. In each figure, the top panel shows the full spectra and the bottom panel the ratios of the different predictions to the data. The solid band represents the total experimental systematic uncertainty centred at one. The patterned band represents the NLO scale and PDF uncertainties calculated from NJET/SHERPA centred at the nominal NJET/SHERPA values. The scale uncertainties for HEJ (not drawn) are typically $+50\%$ -30% . The ratio curves are formed by the central values with vertical uncertainty lines resulting from the propagation of the statistical uncertainties of the predictions and those of the unfolded data spectrum.

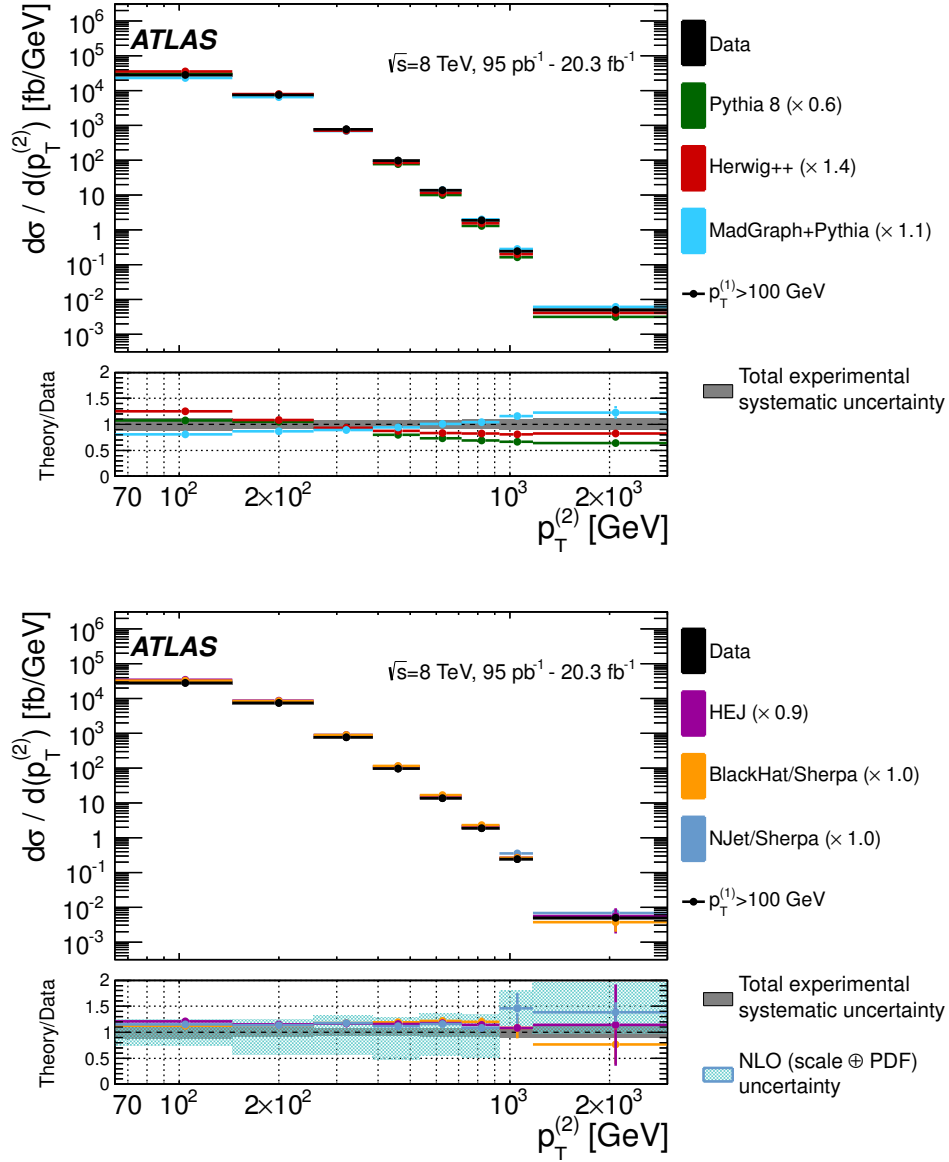


Figure 5.16: Unfolded four-jet differential cross section as a function of $p_T^{(2)}$, compared to different theoretical predictions. The other details are as for figure 5.15.

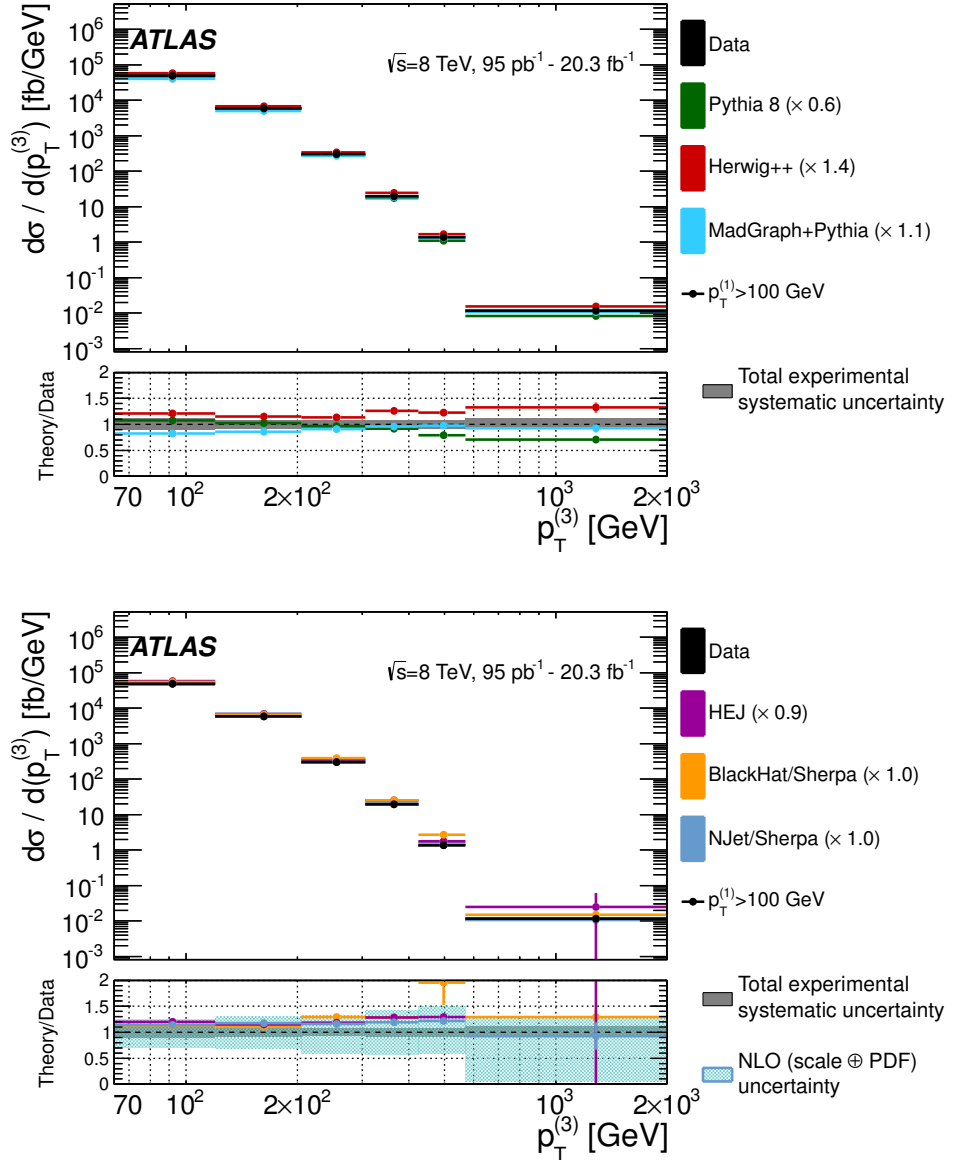


Figure 5.17: Unfolded four-jet differential cross section as a function of $p_T^{(3)}$, compared to different theoretical predictions. The other details are as for figure 5.15.

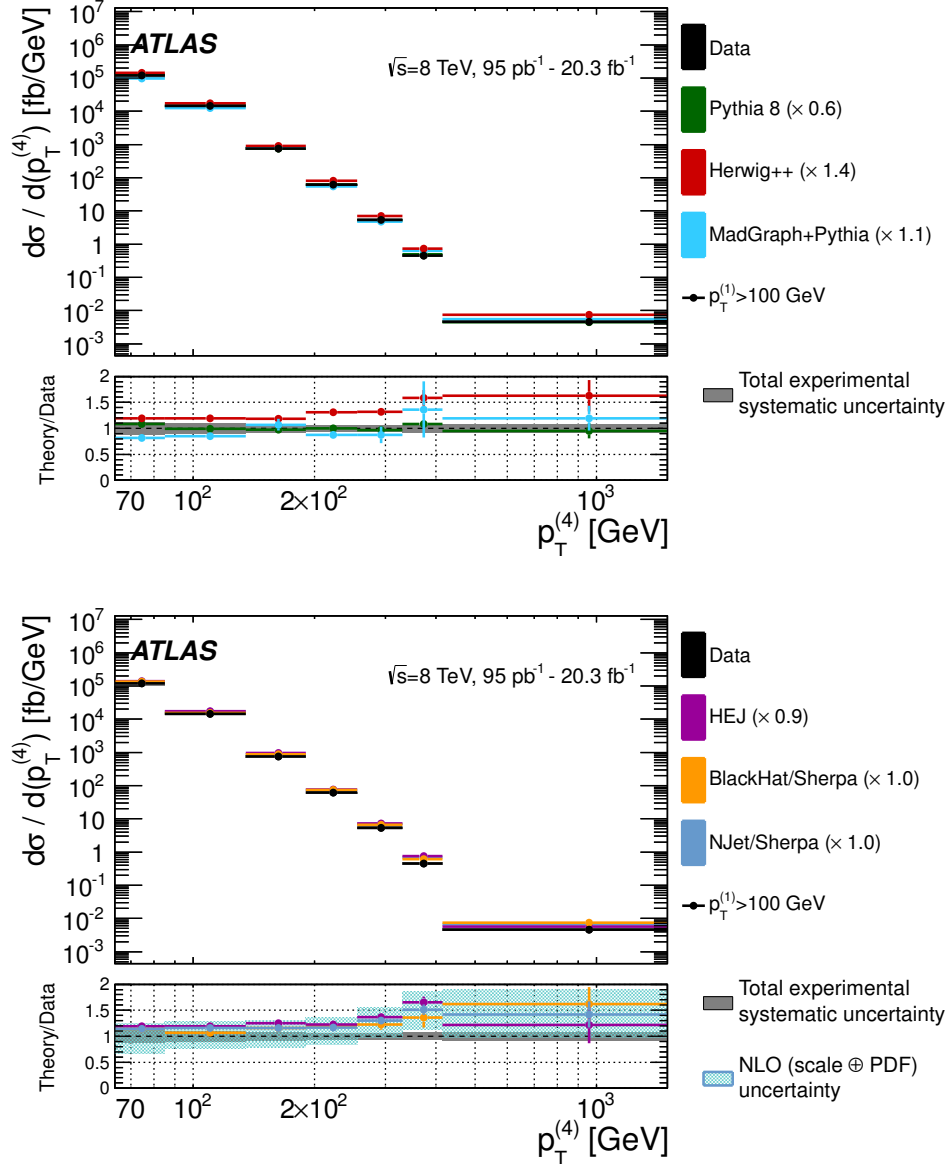


Figure 5.18: Unfolded four-jet differential cross section as a function of $p_T^{(4)}$, compared to different theoretical predictions. The other details are as for figure 5.15.

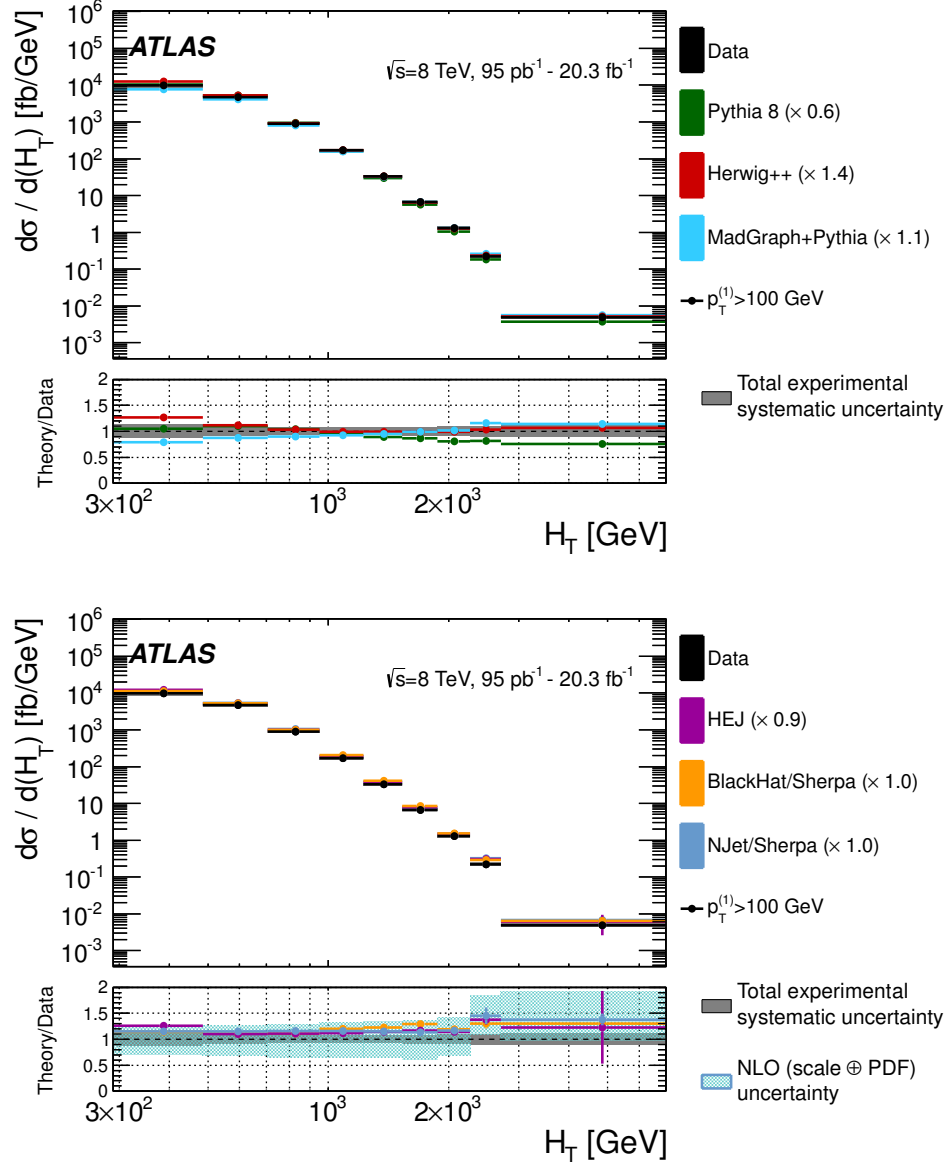


Figure 5.19: Unfolded four-jet differential cross section as a function of H_T , compared to different theoretical predictions. The other details are as for figure 5.15.

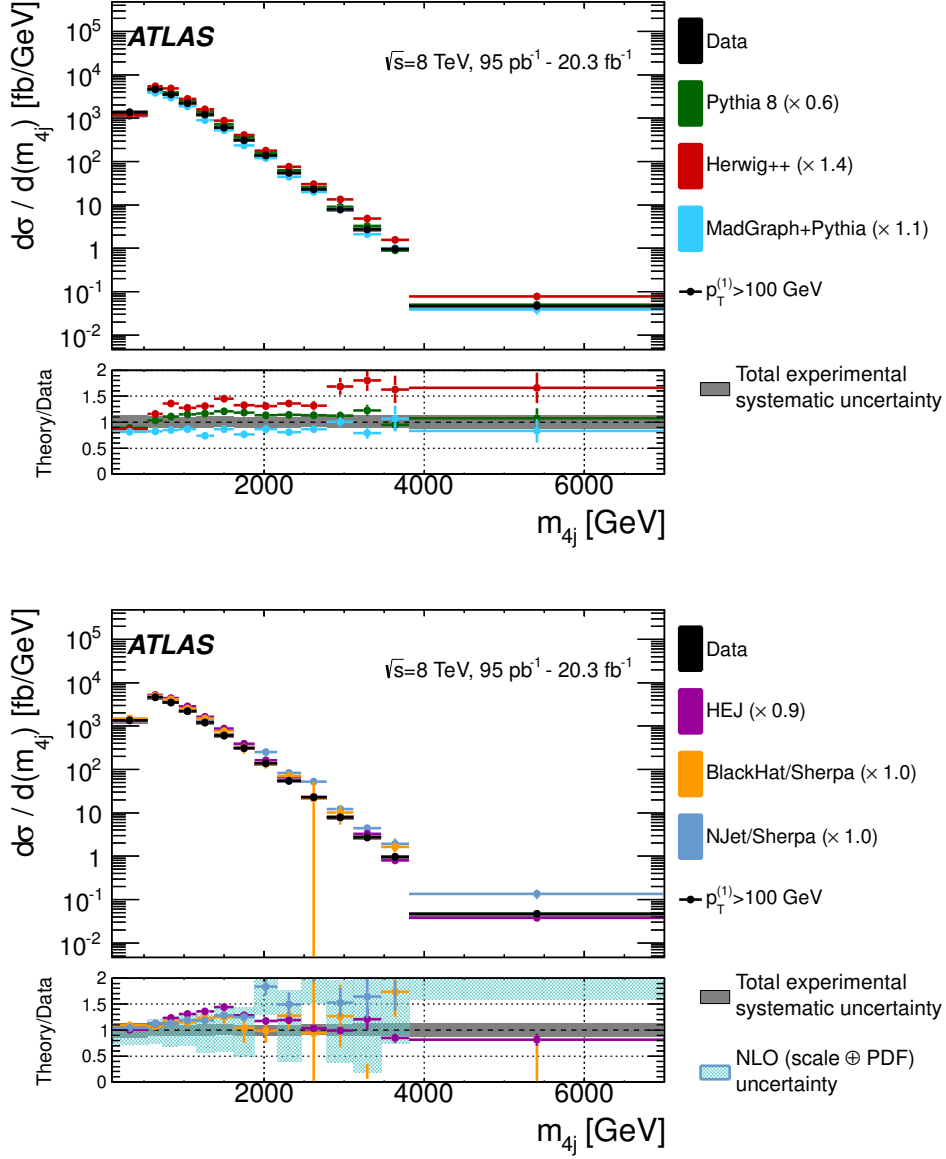


Figure 5.20: Unfolded four-jet differential cross section as a function of m_{4j} , compared to different theoretical predictions. The other details are as for figure 5.15. Some points in the ratio curves for NJet/SHERPA fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

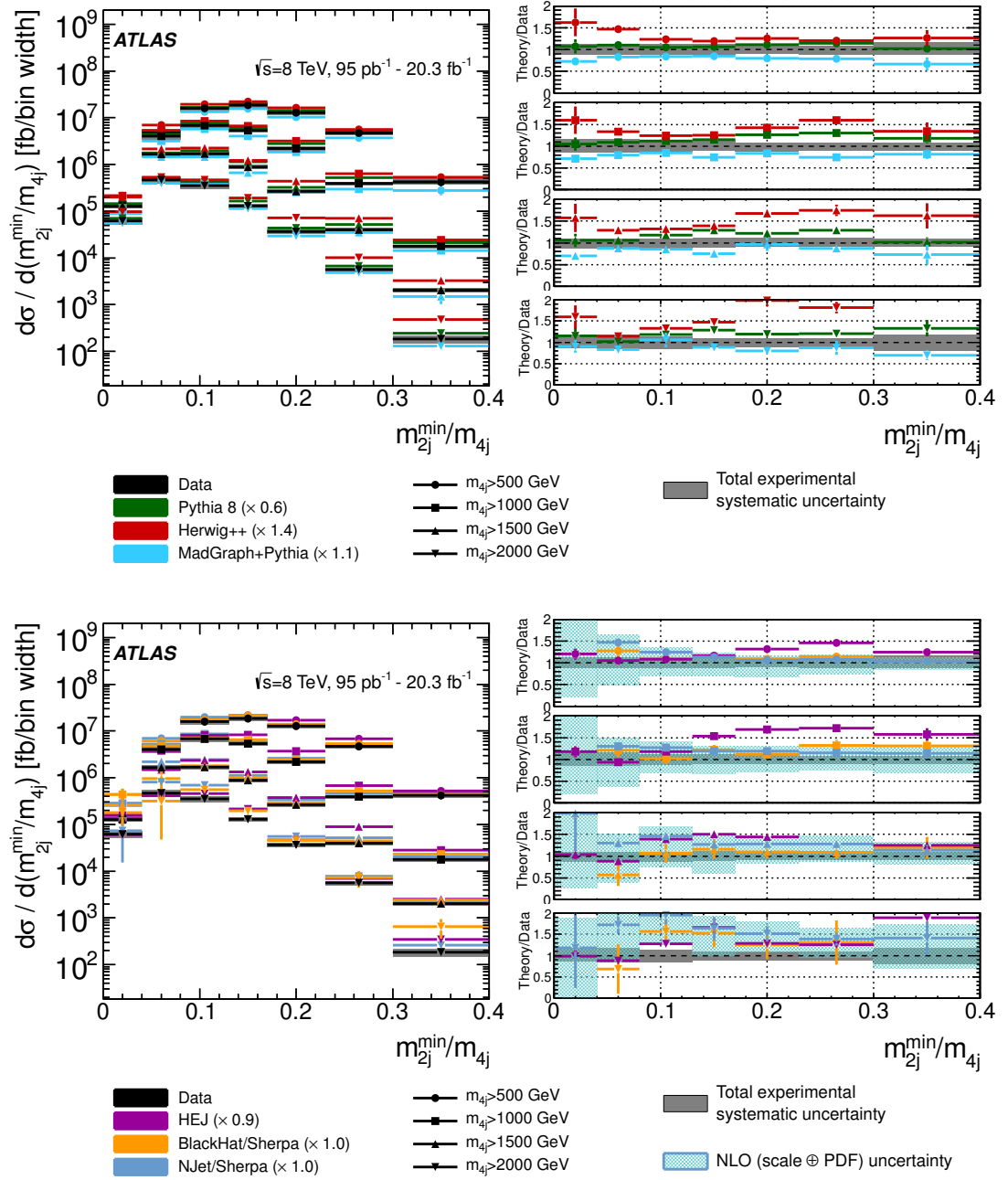


Figure 5.21: Unfolded four-jet differential cross section as a function of $m_{2j}^{\min}/m_{4j}$, compared to different theoretical predictions: PYTHIA, HERWIG++ and MADGRAPH+PYTHIA (top), and HEJ, NJET/SHERPA and BLACKHAT/SHERPA (bottom). For better comparison, the predictions are multiplied by the factors indicated in the legend. In each figure, the left panel shows the full spectra and the right panel the ratios of the different predictions to the data, divided according to the selection criterion applied to m_{4j} . The solid band represents the total experimental systematic uncertainty centred at one. The patterned band represents the NLO scale and PDF uncertainties calculated from NJET/SHERPA centred at the nominal NJET/SHERPA values. The scale uncertainties for HEJ (not drawn) are typically $+50\%$ -30% . The ratio curves are formed by the central values and vertical uncertainty lines resulting from the propagation of the statistical uncertainties of the predictions and those of the unfolded data spectrum.

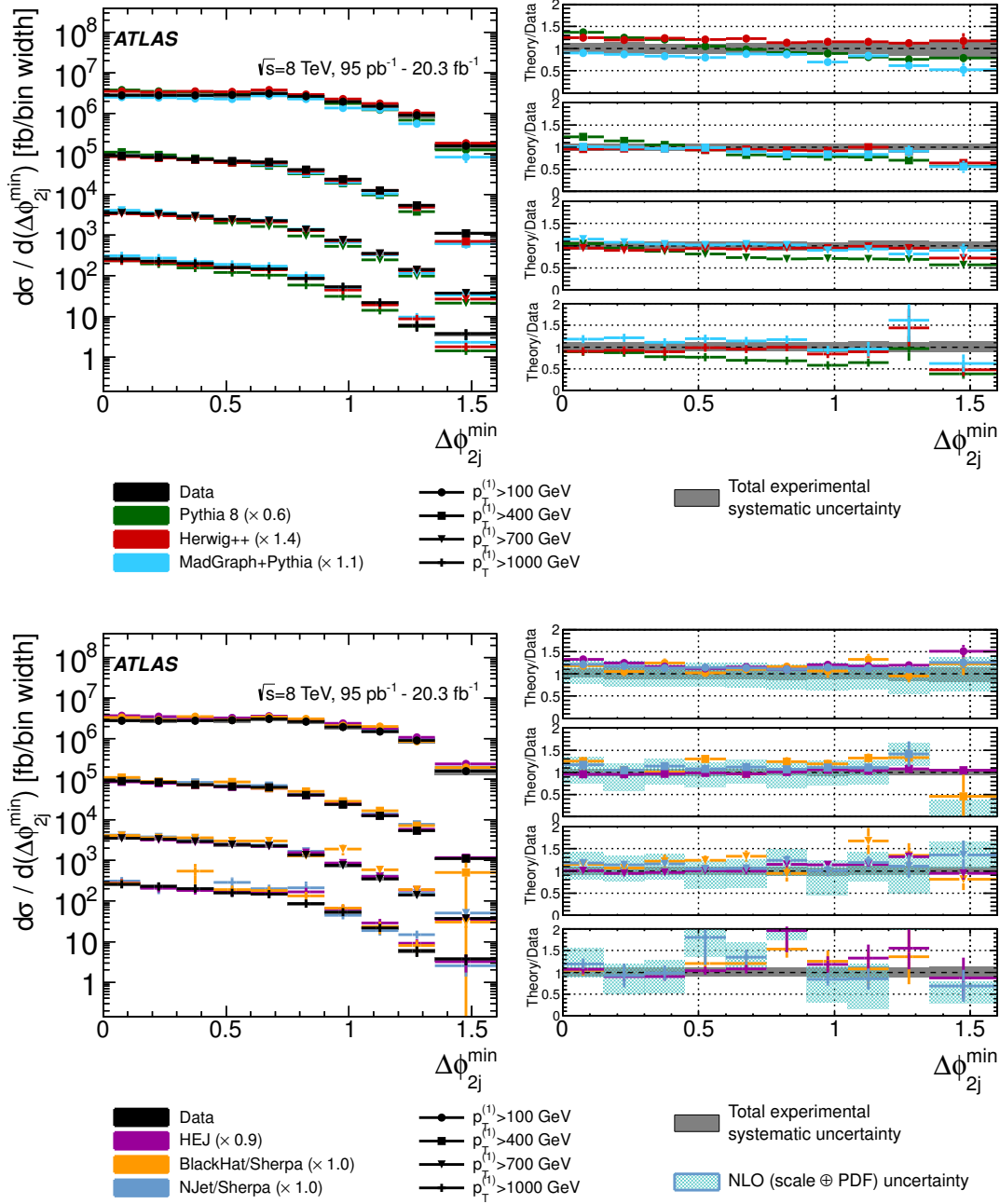


Figure 5.22: Unfolded four-jet differential cross section as a function of $\Delta\phi_{2j}^{\min}$, compared to different theoretical predictions. The other details are as for figure 5.21, but here the multiple ratio plots correspond to different selection criteria applied to $p_T^{(1)}$. Some points in the ratio curves for NJet/Sherpa fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

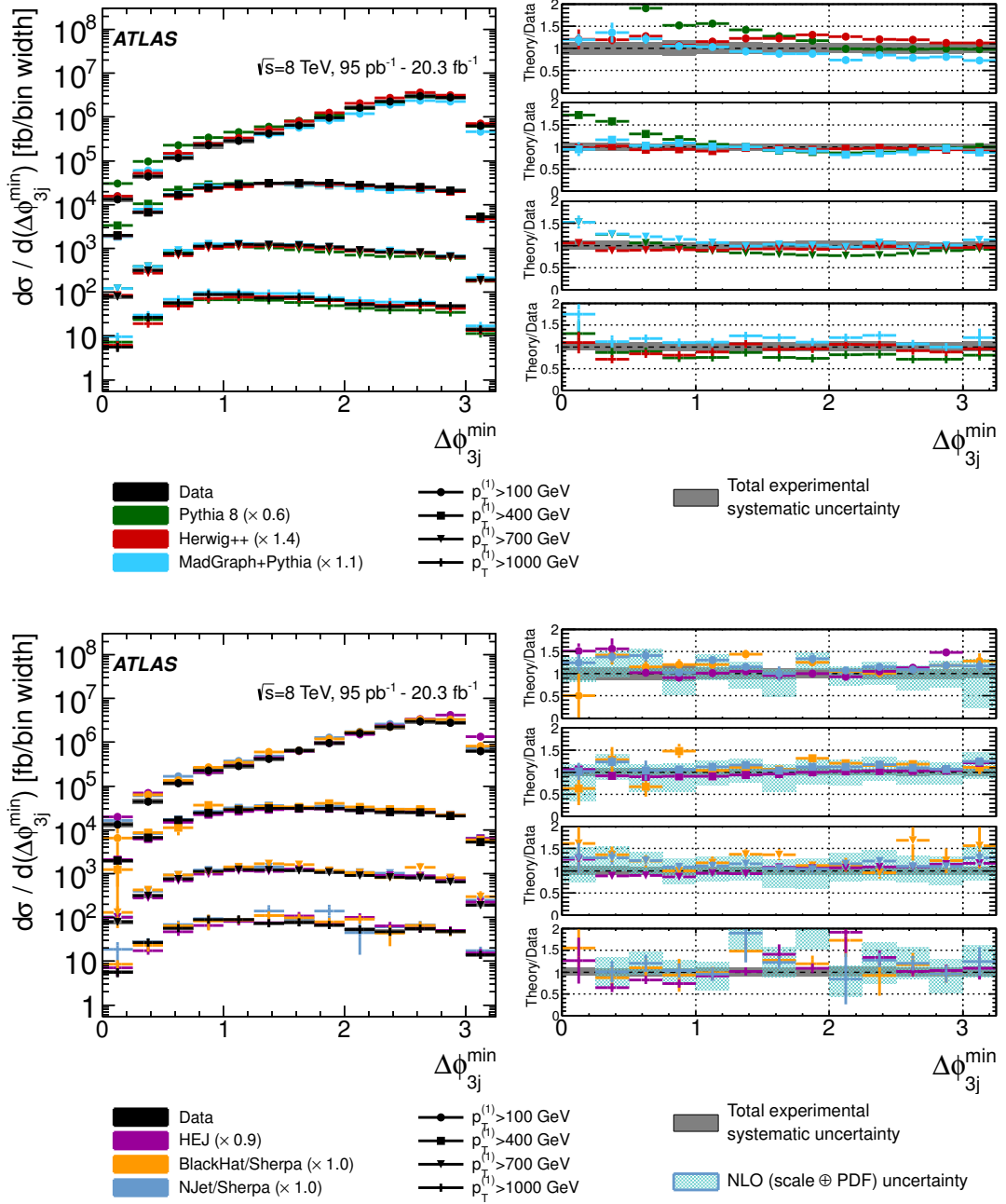


Figure 5.23: Unfolded four-jet differential cross section as a function of $\Delta\phi_{3j}^{\min}$, compared to different theoretical predictions. The other details are as for figure 5.22. Some points in the ratio curves for NJET/SHERPA fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

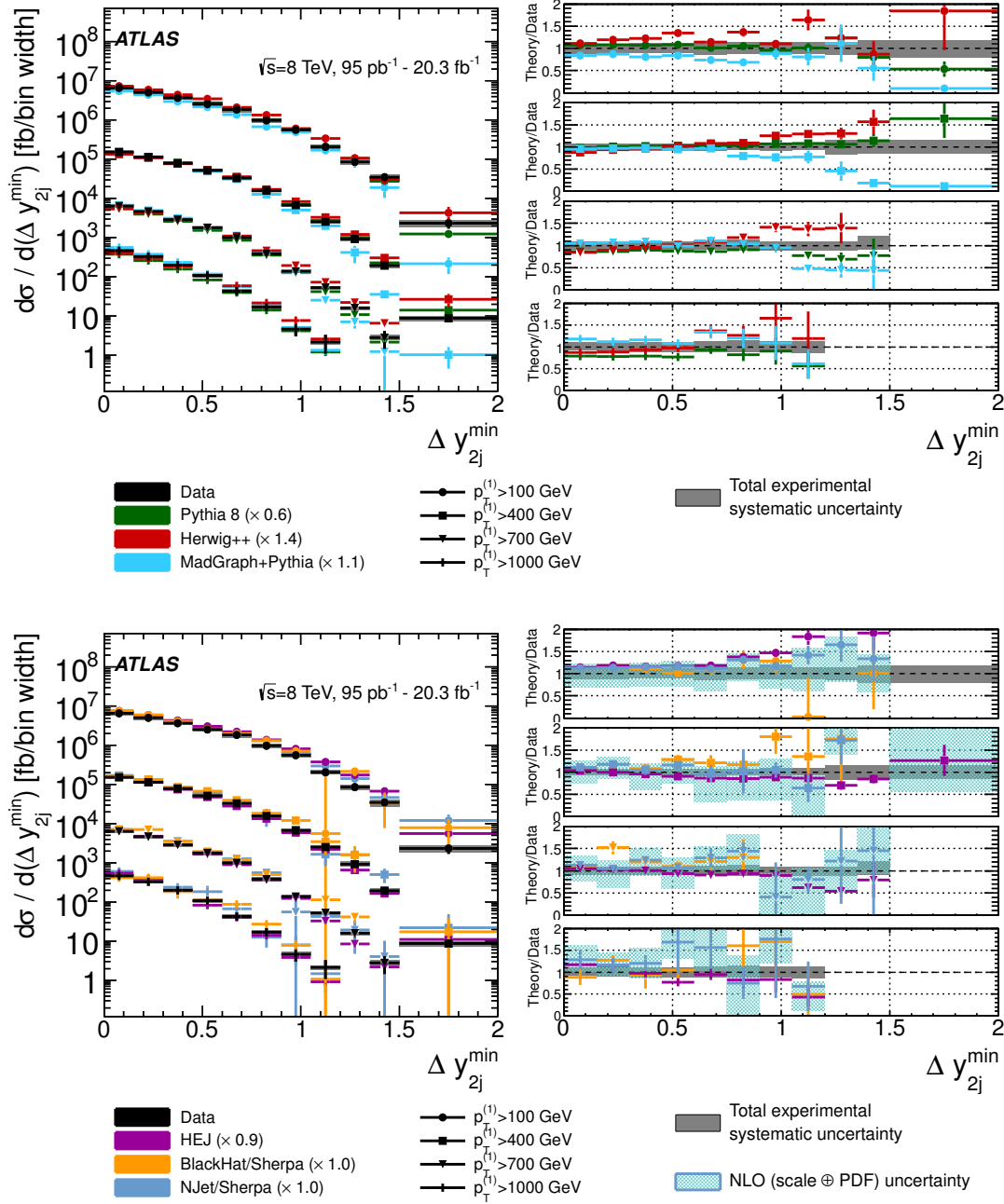


Figure 5.24: Unfolded four-jet differential cross section as a function of $\Delta y_{2j}^{\min}$, compared to different theoretical predictions. The other details are as for figure 5.22. Some points in the ratio curves for NJet/SHERPA fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

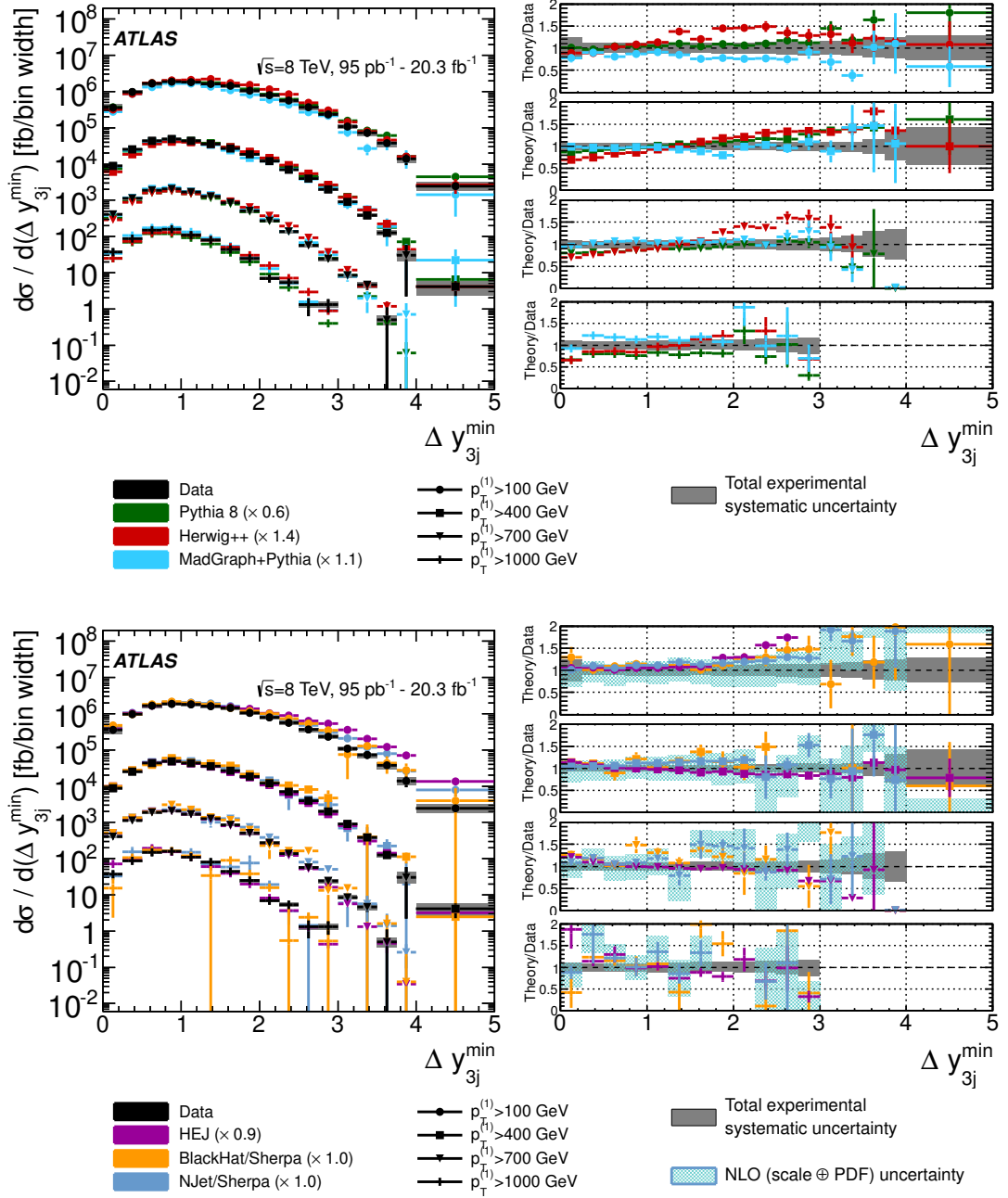


Figure 5.25: Unfolded four-jet differential cross section as a function of $\Delta y_{3j}^{\min}$, compared to different theoretical predictions. The other details are as for figure 5.22. Some points in the ratio curves for NJet/Sherpa fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

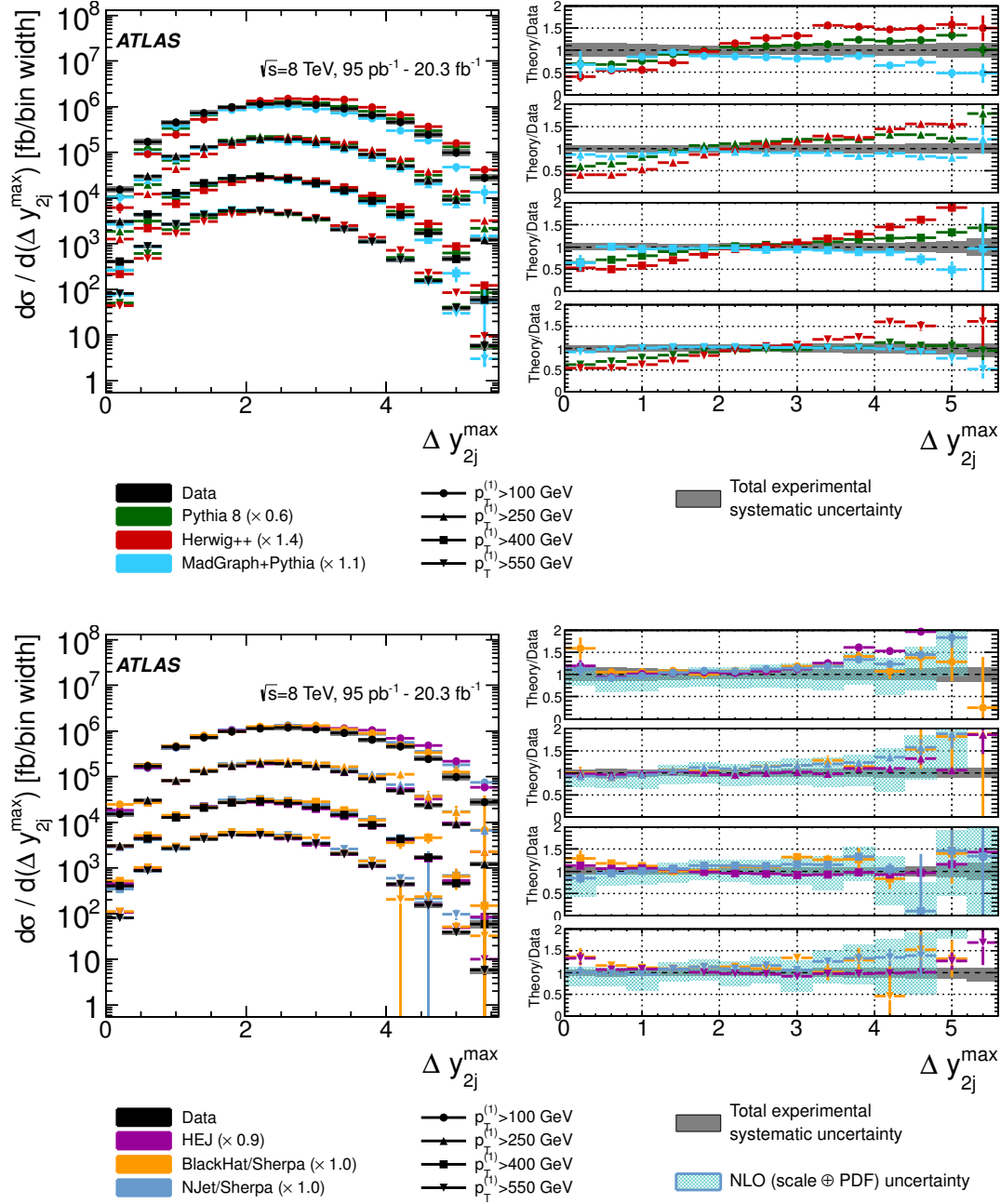


Figure 5.26: Unfolded four-jet differential cross section as a function of $\Delta y_{2j}^{\max}$, compared to different theoretical predictions. The other details are as for figure 5.22. Some points in the ratio curves for NJet/SHERPA fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

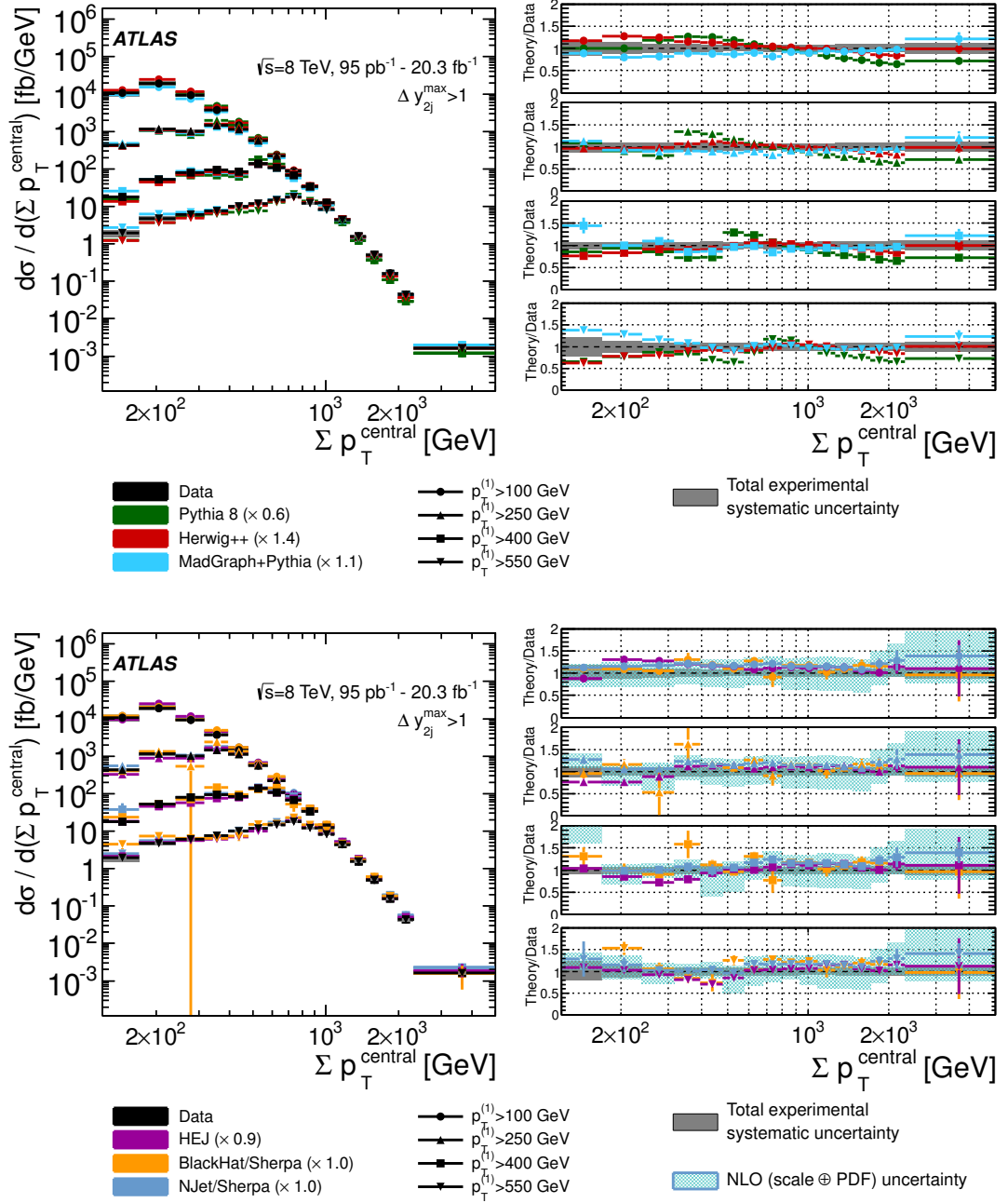


Figure 5.27: Unfolded four-jet differential cross section as a function of $\Sigma p_T^{\text{central}}$ with $\Delta y_{2j}^{\text{max}} > 1$, compared to different theoretical predictions. The other details are as for figure 5.22.

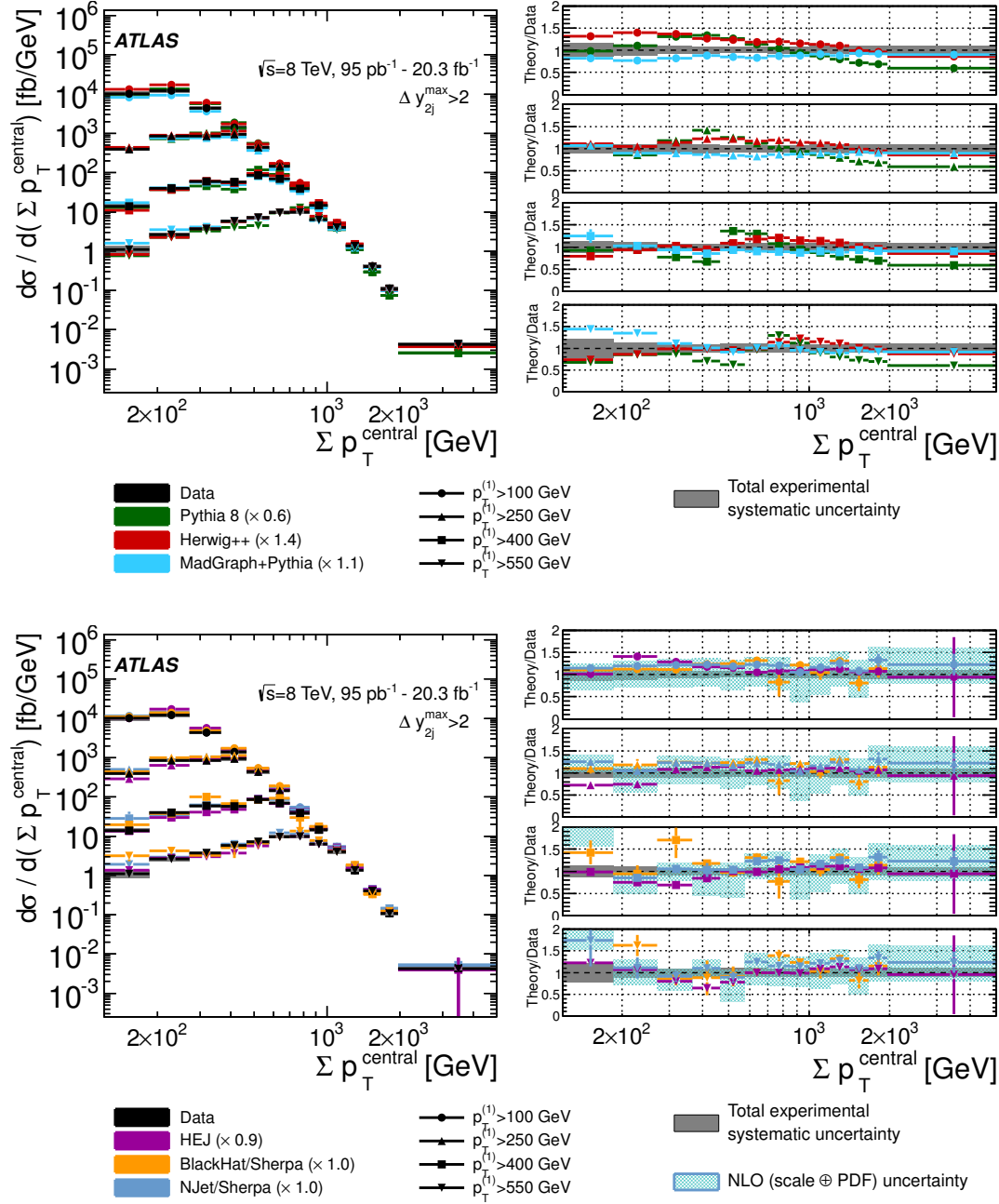


Figure 5.28: Unfolded four-jet differential cross section as a function of $\Sigma p_T^{\text{central}}$ with $\Delta y_{2j}^{\text{max}} > 2$, compared to different theoretical predictions. The other details are as for figure 5.22.

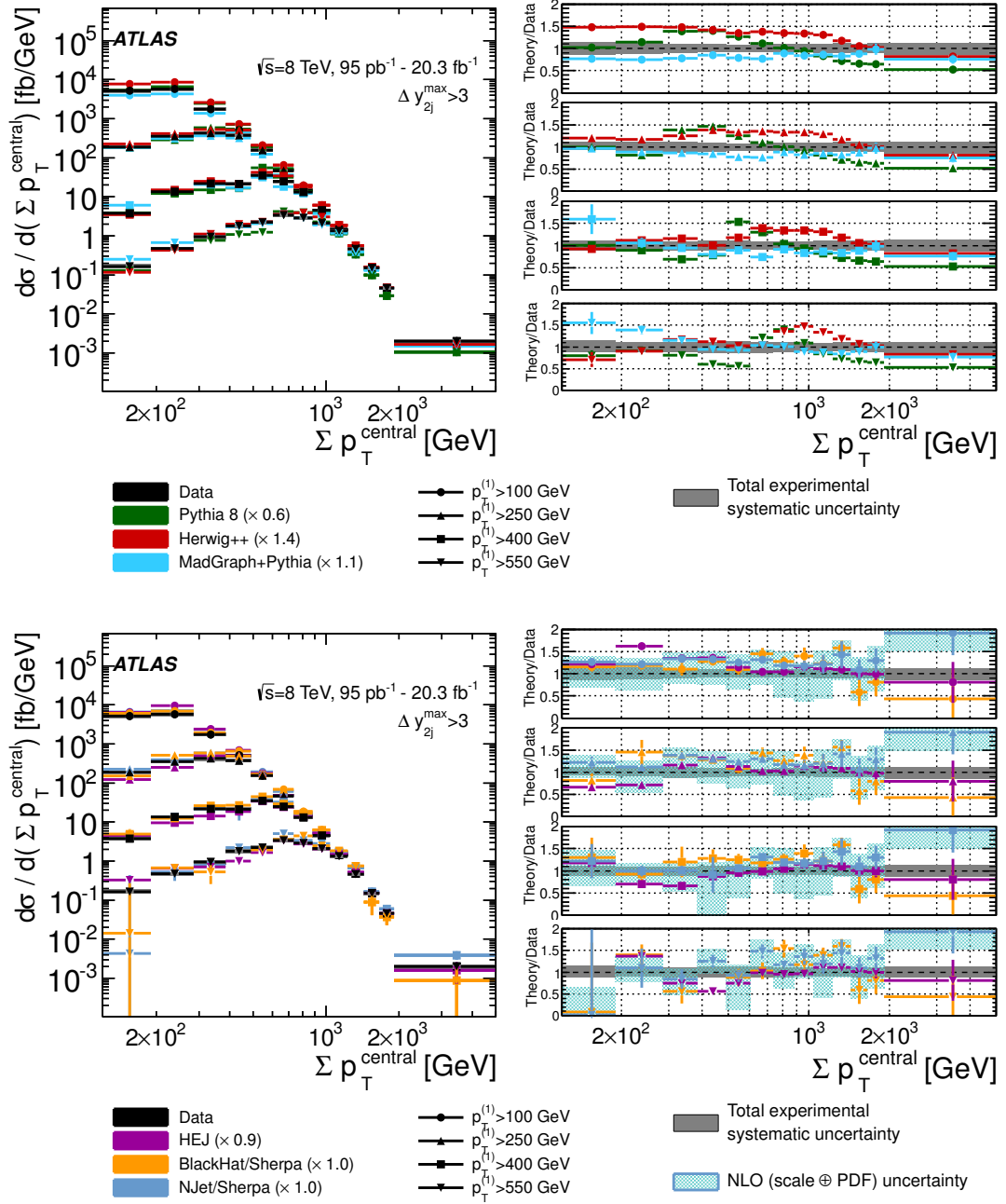


Figure 5.29: Unfolded four-jet differential cross section as a function of $\Sigma p_T^{\text{central}}$ with $\Delta y_{2j}^{\text{max}} > 3$, compared to different theoretical predictions. The other details are as for figure 5.22.

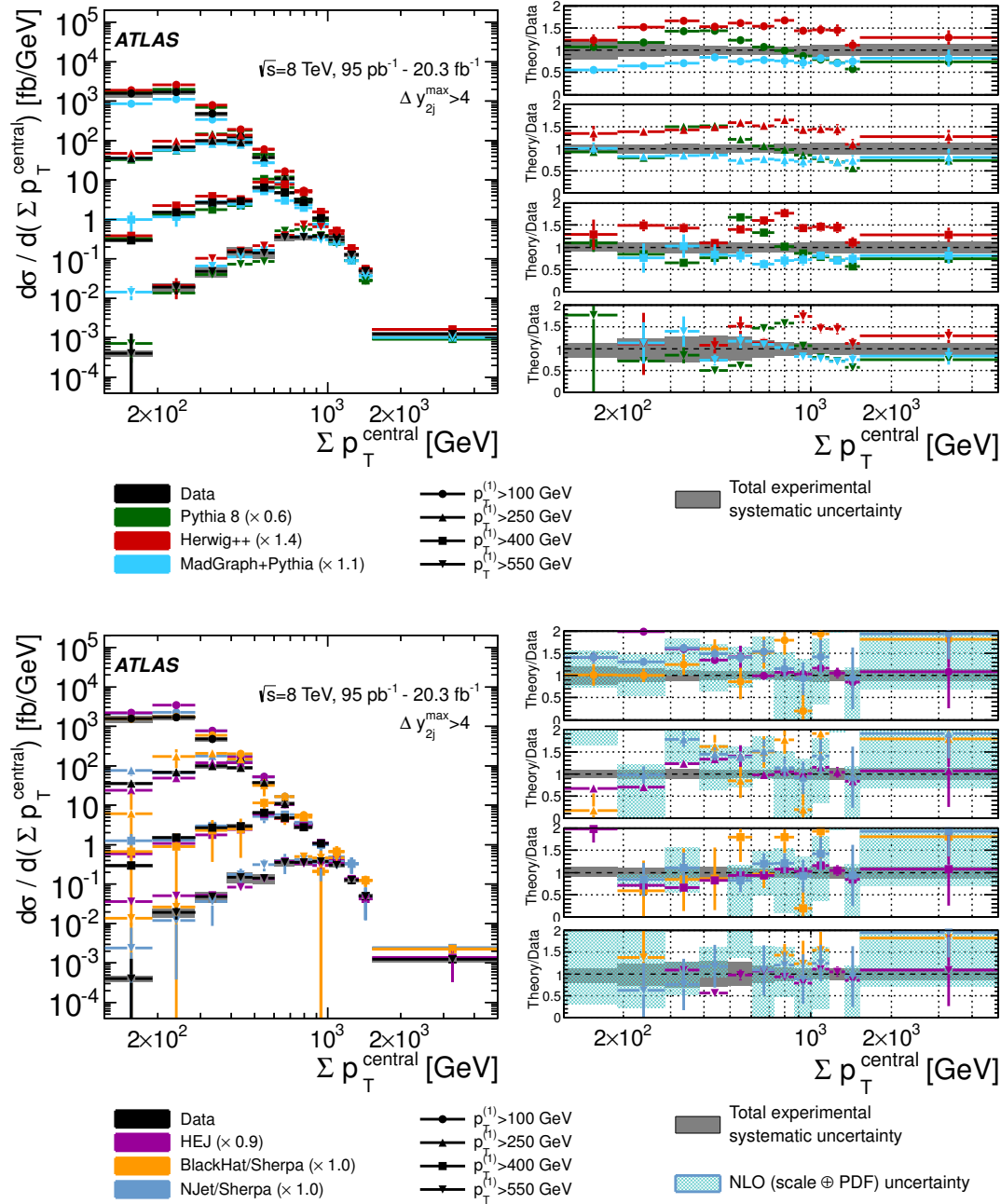


Figure 5.30: Unfolded four-jet differential cross section as a function of $\Sigma p_T^{\text{central}}$ with $\Delta y_{2j}^{\text{max}} > 4$, compared to different theoretical predictions. The other details are as for figure 5.22. Some points in the ratio curves for NJET/SHERPA fall outside the y -axis range, and thus the NLO uncertainty is shown partially, or not shown, in these particular bins.

Conclusion

The study of jets from different perspectives has been presented in this thesis. As part of the collaboration with the ATLAS Tile Calorimeter group, scintillator detectors that are important for jet performance measurements were replaced, as described in chapter 3. Chapter 4 was dedicated to the description of jet performance studies, in particular the estimation of the jet resolution. Lastly, the measurement of the multijet cross section was presented in chapter 5.

The evaluation of the impact of radiation in scintillator detectors and their design and assembly was described in chapter 3. This collaboration with the Tile Calorimeter group took place during the shut-down period LS1. The Minimum Bias Trigger Scintillator was commissioned for replacement, after its usefulness in performance analyses and ion collisions was proved to extend beyond expectation. The detector used during Run 1 was removed in order to assess the impact that radiation had had in its components, and this information was used in the implementation of a new design for its successor. The new detector needed to be adapted to both the harsher data-taking conditions expected in Run 2, and the diminished availability of photomultipliers to collect its signal. The assembly and installation was very successful: the MBTS counters were all functioning as expected by the beginning of Run 2. Already there have been published results based on this triggers, such as the update to the measurement of the inelastic pp cross section [39], and performance studies to estimate the noise level due to pile-up [49]. The above mentioned photomultipliers that would no longer collect the signal of the MBTS were destined to complete the group of thin scintillator detectors placed on the side of the calorimeter end-caps. The missing detectors were installed, and a new set was assembled as part of a long term study to determine the best material to be used in a future replacement. Also as part of these studies, the performance of all the counters was carefully assessed and recorded for future comparisons.

The jet resolution arises from the functioning principles of the calorimeter, and is therefore a magnitude closely related to the way the detector was constructed, and also largely affected by the data taking conditions. Such sensitivity of the resolution to the increased number of interactions in the event was evaluated in a dedicated study [65]. The measurement of the jet energy resolution presented in chapter 4 for the first data collected during the year 2012 was greatly affected by the increased instantaneous luminosity and energy of that year with respect of the previous one. The first attempts at the measurement showed a $\sim 20\%$ non-closure between the in-situ and the truth measurement, and that the usual soft radiation corrections did not perform as expected. A more detailed study showed that indeed the dijet method's assumptions could not be upheld in those conditions, which is why the decision was made to temporarily only provide in-situ results from the bisector method. For this case very good agreement was

observed between the data and the MC measured resolutions. In the central calorimeter region the agreement was below 10%, while in the forward regions it was below 20%. The presented results were provided to the collaboration as the input to the analyses that use jets, which is the vast majority in ATLAS. These were the default resolution inputs used for measurements presented in the Moriond 2013 and 2014 conferences. The final resolution for the year 2012 [33] is a result of the continuation of the work presented here and the implementation of various jet calibration corrections that aided to diminish the issues encountered. The prospect of one of these corrections, the jet areas correction, was shown as well. It is now a default part of the calibration scheme. Lastly, a new generation of in-situ methods has been implemented to measure the JER in the lower p_T ranges where the bisector and dijet methods could no longer be used due to the higher pile-up conditions.

The measurement of the multijet cross section [36] has been presented in chapter 5. The unfolded differential cross sections were measured in events with at least four jets in pp collisions at 8 TeV centre-of-mass energy, obtained from the full dataset collected by the ATLAS detector at the LHC in 2012. This corresponds to a total integrated luminosity of 20.3 fb^{-1} . Events were selected if the four anti- k_t $R = 0.4$ jets with the largest transverse momentum within the rapidity range $|y| < 2.8$ were well separated ($\Delta R_{4j}^{\min} > 0.65$), all had $p_T > 64$ GeV, and included at least one jet with $p_T > 100$ GeV. The cross sections were studied as a function of a wide variety of kinematic and topological variables which include momenta, masses and angles. The total experimental systematic uncertainty is typically of the order of 10%, and it is dominated by the jet energy scale calibration uncertainty.

The measurements were compared to NLO p QCD predictions provided by BLACKHAT/SHERPA and NJET/SHERPA, as well as the all-orders calculation provided by HEJ. Three leading-order calculations are also considered, including two $2 \rightarrow 2$ PS samples (PYTHIA and HERWIG++) and a multi-leg calculation with up to four partons in the ME matched to a PS generated by PYTHIA (MADGRAPH+PYTHIA).

The LO cross sections and HEJ are normalised by fixed factors to facilitate the comparison of the spectra in the kinematic regions of interest; these factors vary between 0.6 and 1.4 for the different samples, where the MADGRAPH+PYTHIA and HEJ samples are the ones that need the smallest corrections. The NLO predictions, BLACKHAT/SHERPA and NJET/SHERPA, are almost always compatible with the data within their theoretical uncertainties, which are found to be large ($\mathcal{O}(30\%)$ at low momenta) and asymmetric. Within the normalisation scheme used, MADGRAPH+PYTHIA also provides a good description of the data, as does HEJ, especially at high leading jet p_T . The $2 \rightarrow 2$ PS calculations generally describe the data relatively poorly, although they are found to provide good predictions in some particular cases: PYTHIA gives a very good prediction of $p_T^{(4)}$ and $\Delta y_{2j}^{\min}$, while HERWIG++ performs well in the azimuthal angle variables.

Looking at the individual distributions of the differential cross section, the description of the jet momenta is compatible with previous measurements of the multi-jet cross sections. It should be noted that HEJ, NJET/SHERPA and BLACKHAT/SHERPA give a very good description of the distributions of the leading jets but show some discrepancy with the data for $p_T^{(4)}$. For variables that are particularly sensitive to wide-angle configurations and high- p_T radiation, such as masses or angles, BLACKHAT/SHERPA, NJET/SHERPA and MADGRAPH+PYTHIA do a remarkable job overall. HEJ also provides a good de-

scription of the data, the main exception being that it disagrees with the rapidity measurements in events with low $p_{\text{T}}^{(1)}$. At high $p_{\text{T}}^{(1)}$ the prediction is very good. These measurements expose the shortcomings of $2 \rightarrow 2$ parton ME+PS predictions in a variety of scenarios and highlight the importance of the more sophisticated calculations.

Appendix A

Additional Information for Scintillator Detectors

This appendix contains additional information pertaining the scans of the crack scintillators, or E3E4 counters, and the MBTS scintillators.

A.1 Information for E3E4 counters

The E3E4 counters were scanned using a Sr^{90} source in a setup specially assembled to this purpose, and with a Cs source. The information was used to evaluate the integrity of each detector. It will also be a useful record in the long term study of the materials.

Figure A.1 shows the signal for a Sr scan for a fixed Y value, therefore evaluating the radial direction. Three tiles of different origin are compared: a new one provided by Eljen, an old one taken from an unused counter that had been in storage, and another one from the same production batch that had been used during Run 1 and was therefore irradiated. The linear fit shows very small slopes, meaning the signal dependence in this direction is minimal. Although the signal level for both older tiles is of ~ 0.8 V, and noticeably smaller than the one of the new tile, this difference has to be considered with care due to the fact that these scans are not very consistent from one to another, as was explained before. A more adequate comparison of signal level is obtained from the Cs scans.

Table A.1 shows the information of the average signal obtained in the CS scans of each of the original counters, and the ratio between the signals of each scintillator within the case. The last columns details where the counter was installed (which EB module, on side A or side C) or if it was refurbished to contain new scintillator tiles. The newly made counters with Eljen and Bicron tiles were also scanned and installed, the related information is presented in tables A.2 and A.3 respectively.

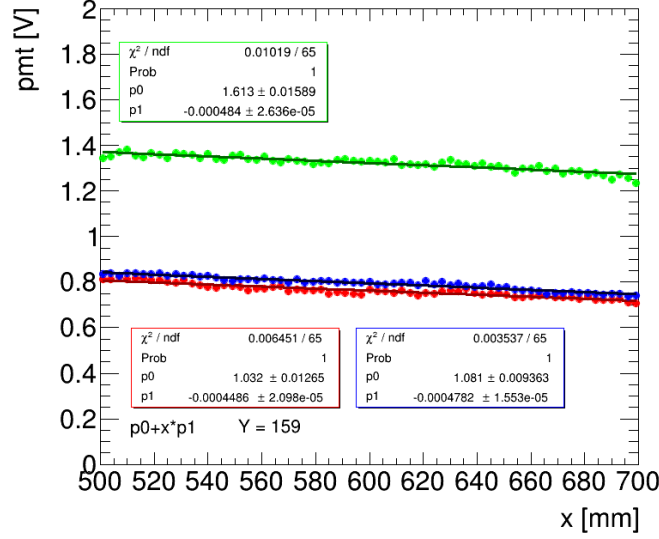


Figure A.1: Signal profile from a scan with a Sr^{90} source as a function the position in the tile. The values correspond to a fixed Y value in the scans. The signal of different tiles is compared: new (Eljen material, green), non-irradiated old tile (blue) and an irradiated tile (red). A linear fit is applied, obtaining a slope of $\sim 0.5 \cdot 10^{-5} \frac{V}{mm}$.

Counter	E3 signal [au]	E4 signal [au]	E4/E3 ratio	installed
#004	165	70	0.42	Bicron
#022	146	126	0.63	EBC-28
#061	141	102	0.72	EBA-60
#063	154	97	0.63	EBA-35
#064	160	74	0.47	Bicron
#067	168	87	0.52	EBC-37
#068	155	103	0.67	EBC-61 ¹
#069	174	98	0.57	EBC-49
#071	171	76	0.45	Bicron
#074	166	88	0.53	not installed
#088	146	126	0.87	EBC-20
#109	163	43	0.27	Bicron
#100	182	98	0.54	EBC-04
#115	176	98	0.56	EBC-13

Table A.1: For each of the original counters tested, mean signal of the E3 and E4 tiles, the ratio, and the information concerning the installation of the counter.

Counter	E3 signal [au]	E4 signal [au]	E4/E3 ratio	installed
#058	341	183	0.54	EBA-03
#059	331	191	0.58	EBA-30
#060	347	195	0.56	EBC-45
#062	318	180	0.58	EBA-53
#070	357	186	0.52	not installed

Table A.2: For each of the counters made with new Eljen tiles, mean signal of the E3 and E4 tiles, the ratio, and the information concerning the installation of the counter.

Counter	E3 signal [au]	E4 signal [au]	E4/E3 ratio	installed
#002	312	210	0.67	not installed ¹
#004	367	204	0.57	EBA-12
#064	377	204	0.54	EBA-23
#071	362	213	0.59	EBA-44
#109	388	194	0.5	EBC-12

Table A.3: For each of the counters made with new Bicron tiles, mean signal of the E3 and E4 tiles, the ratio, and the information concerning the installation of the counter.

A.2 Additional information on MBTS

The tiles extracted from the irradiated MBTS-1 were scanned with the Sr^{90} source in order to both assess the deterioration of the material and to evaluate new fibre placing possibilities. The scan of an E5 tile from MBTS-1 is presented in figure A.2, with the corresponding distribution of signal that allows to estimate the uniformity. The high value motivated the need of different fibre placement.

A second aspect to evaluate was the attenuation length. Given the large size of the new E5 tiles, it was important to be assured that placing the fibres on the edges would not cause signal loss from the central area. The plots in figure A.3 show the profiles obtained from the Sr^{90} of two new tiles, with fibres placed only on one side (a) and then on both sides (b). The first case shows an attenuation length much larger than the tile. The second shows that if fibres are placed on both sides the signal from the central area is not affected in any significant way by the distance to the fibres. The radial attenuation length was also evaluated and is presented in figure A.4 for both an irradiated and a new tile. A larger distance dependence is obtained, by comparison to the E4 counters: approximately 0.7 mV/mm. This is probably due to the trapezoidal shape of the tile and the fact that light collection was done from the sides for this test.

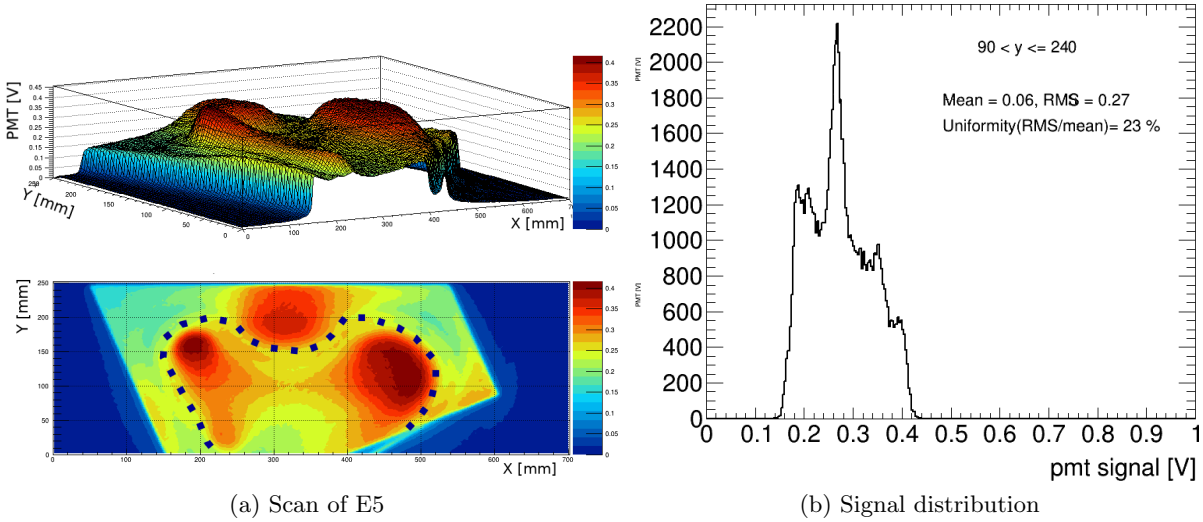
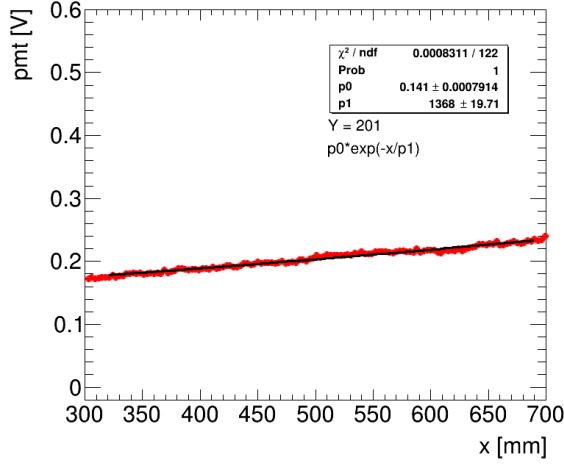


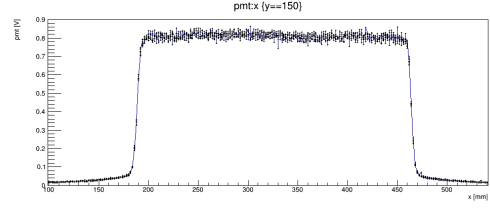
Figure A.2: Scan of an E5 tile of MBTS-2 using the Sr^{90} source (left), the fibres marked with a dashed line. The signal distribution is shown on the right, with a uniformity of 23%.

All MBTS-2 counters were scanned using the Cs^{137} setup before installation. In addition, one of the counters of MBTS-1 was scanned for reference before being dismantled. The information concerning this scan is:

- 8 fibres for E5 and 8 for E6
- 1.5m of clear fibre attached by splicing to WLS fibre.
- peak 2: E5 = 147 E6 = 125

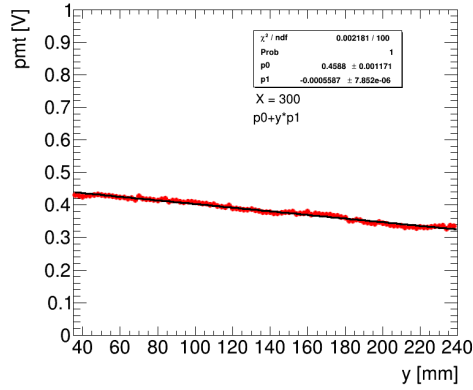


(a) Fit of attenuation length

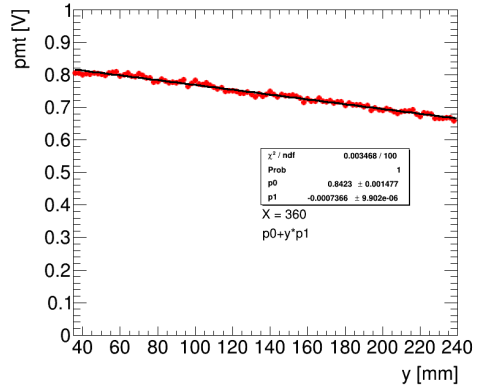


(b) Profile with fibres on both sides for E6

Figure A.3: Profile of the signal measured in a Sr^{90} scan with fibres on one side (left) and on both sides (right). The plots show the signal profile for new E5 and E6 scintillators respectively. The estimated attenuation length is 1.4 m when measuring from one side only, and the effect of attenuation is not significant enough to be measured when fibres are placed on both sides.



(a) MBTS-1



(b) MBTS-2

Figure A.4: Profile and fit of the signal measured using the Sr^{90} scan of an irradiated (a) and a new (b) tile of MBTS. The profile is taken in the direction parallel to the fibres in order to estimate the radial attenuation length, and a linear fit is performed. An attenuation of ~ 0.7 mV/mm is obtained for both cases.

- peak 3: E5 = 145 E6 = 82
- $\sim 34\%$ light loss in new E5 in average
- $\sim 26\%$ light increase in new E6 in average

The following tables present the information for the MBTS-2 counters. The values

Counter	E5 -p2 [au]	E6 -p2 [au]	E5 -p3 [au]	E6 -p3 [au]
#01	198	199	233	242
#02	226	188	272	137
#03	187	245	225	187
#04	183	229	211	162
#05	155	160	185	118
#06	199	263	239	187
#07	157	205	190	150
#08	180	223	222	176
#09	173	224	205	165
#11	181	221	217	171
#15	230	245	279	185

Table A.4: Mean value of the signal of Cs^{137} scans of MBTS-2 counters measured with old fibres 1.5 m long. The mean noise was subtracted. The first pair of columns correspond to the signal of the E5 and E6 tiles at the second peak, and the second pair to the third peak.

Counter	E5 -p2 [au]	E6 -p2 [au]	E5 -p3 [au]	E6 -p3 [au]
#01	98	138	119	96
#02	108	132	129	93
#03	90	157	105	122
#04	84	157	102	144
#05	76	118	93	85
#06	93	181	106	131
#07	76	142	91	103

Table A.5: Mean value of the signal of Cs^{137} scans of MBTS-2 counters measured with new fibres 2.1 m long. The mean noise was subtracted. The first pair of columns correspond to the signal of the E5 and E6 tiles at the second peak, and the second pair to the third peak.

presented in table A.4 were measured using a bundle of fibres 1.5 m long. It was hand made, and it was found it caused high losses. It had 4 fibres for E6 and 8 for E5. The values presented in table A.5 were measured with a newly made bundle of fibres, 2.1 m long. It provided 4 fibres for each tile.

Appendix B

Jet Energy Resolution: complete results

This section shows the complete set of results obtained for the JER measurement presented in section 4.3.

Results for the EM+JES calibration scheme

The results measured with the bisector technique for jets calibrated with the EM+JES scheme are presented here. The resolution was measured for jets reconstructed from calorimeter topological clusters using the anti- k_t algorithm with $R = 0.6$ and $R = 0.4$. The performance on data and Monte Carlo simulation are compared as a function of $\bar{p}_T$ and the results corresponding to the central calorimeter region of $|y| < 0.8$ are shown in figure B.1. Only statistical uncertainties are shown. It can be observed that the agreement for the Monte Carlo simulation and data is within 10%, through the ratio plots presented in the bottom part of each figure. In order to get the final jet p_T resolution, both data and the Monte Carlo simulation results are fitted using equation 4.6. The results corresponding to the remaining three rapidity regions are presented in figure B.2. The data-MC agreement is also within uncertainties. The number of events that pass the selection decreases with $|y|$, which is why the more forward plots show larger statistical errors and fluctuations. It is not possible to do an in-situ measurement for $|y| > 2.8$; by plotting the values of σ_ψ and σ_η as a function of $\bar{p}_T$ as was done in figure 4.9 for both data and MC, and fitting them, it is possible to obtain an estimation of the data-MC agreement for the more forward regions.

Results for the LCW+JES calibration scheme

The results obtained in the bisector method for jets calibrated with the LCW+JES scheme are shown below. Figure B.3 plots the resolution as a function of $\bar{p}_T$ in the central rapidity region, $|y| < 0.8$. It is observed that data and Monte Carlo simulation are in agreement within 10%.

Figure B.4 show the corresponding results for three non-central rapidity regions. It is found that at high $\bar{p}_T$ the MC simulation tends to underestimate the results from data by up to 20%, which motivated further studies.

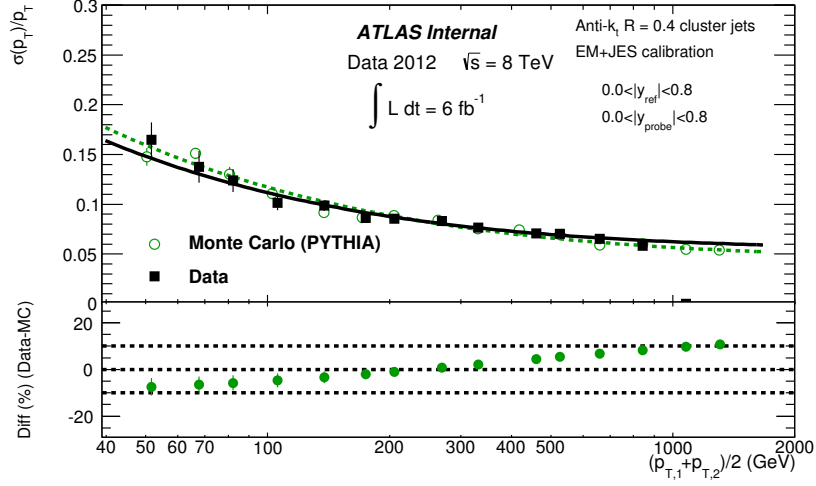
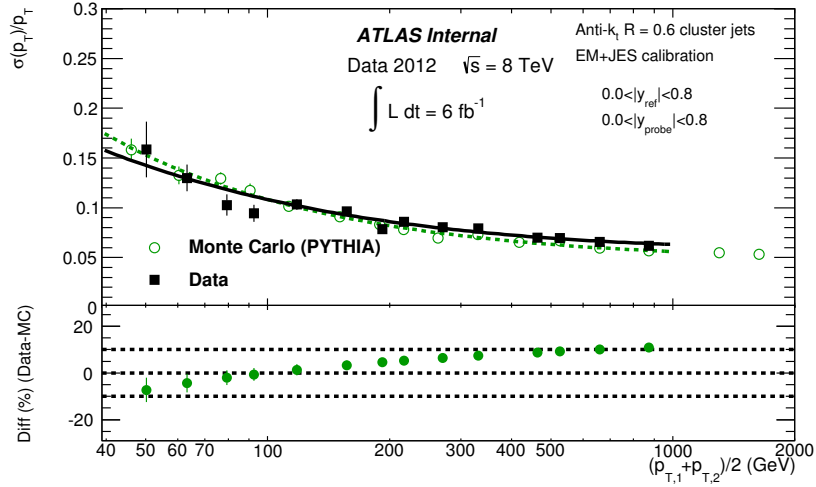
(a) anti- k_t $R=0.4$ (b) anti- k_t $R=0.6$

Figure B.1: Jet momentum resolution for the bisector technique as a function of the average jet transverse momentum for anti- k_t jets with $R = 0.4$ (a) and $R = 0.6$ (b). The lower part shows the relative difference between data and Monte Carlo results. The black dotted lines indicate a relative difference of $\pm 10\%$. The bisector method is found to be in agreement for both Monte Carlo simulation and data.

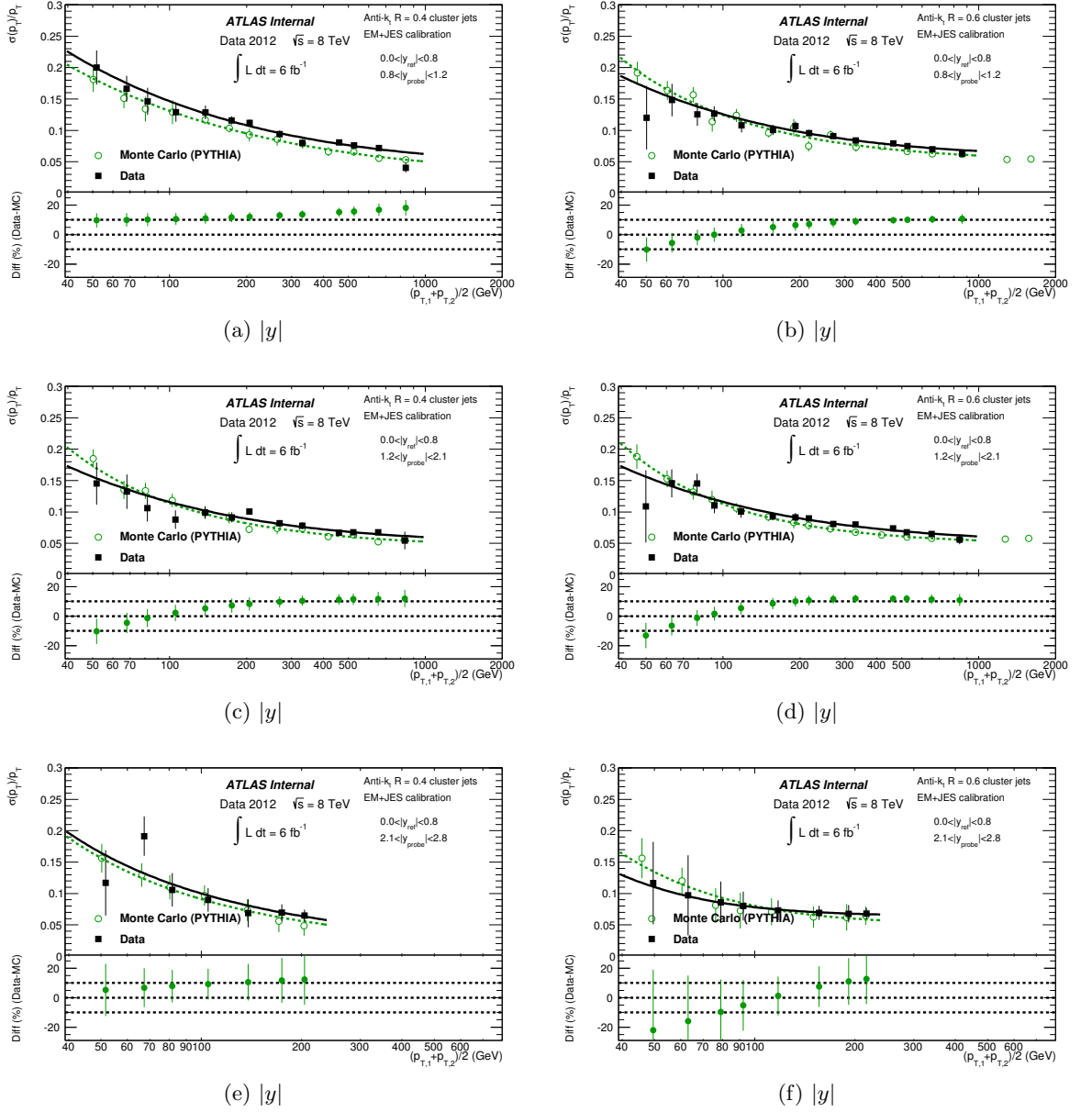


Figure B.2: Jet momentum resolution as a function of the average jet transverse momenta for anti- k_t jets with $R = 0.4$ (left) and $R = 0.6$ (right) for different rapidity regions using the bisector technique. In the lower part of each figure the relative difference between the Monte Carlo fit and the data results are shown. The black dotted line indicates a relative discrepancy of $\pm 10\%$.

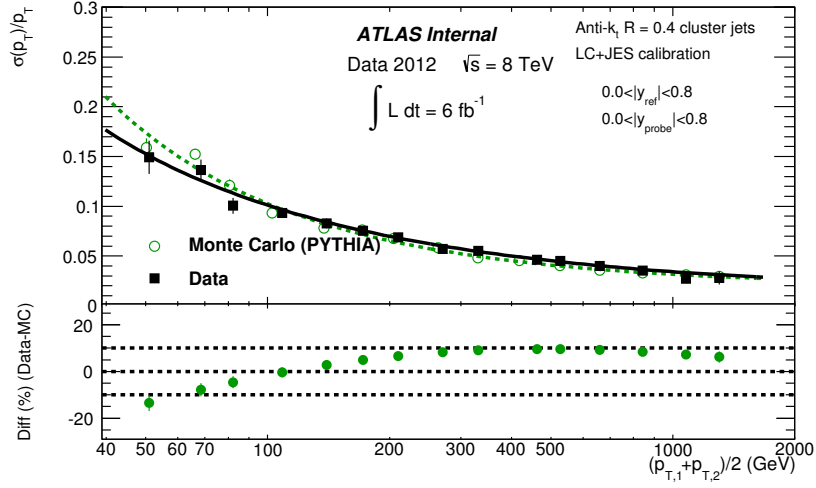
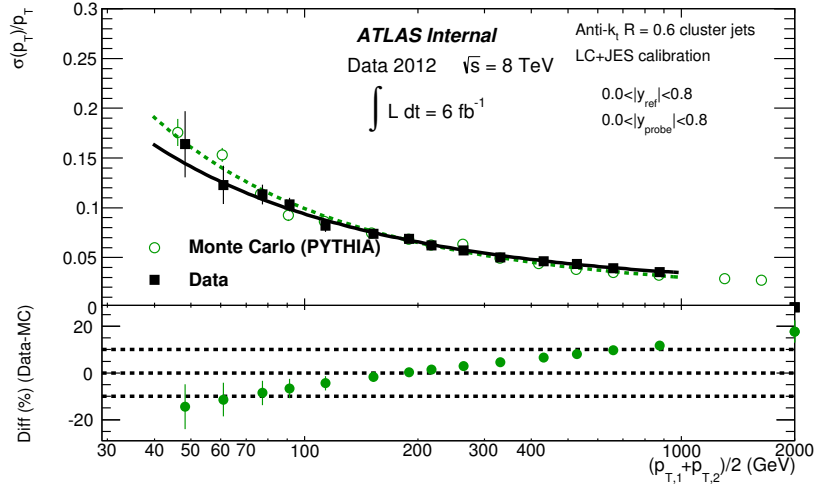
(a) anti- k_t $R=0.4$ (b) anti- k_t $R=0.6$

Figure B.3: Jet momentum resolution for the bisector technique as a function of the average jet transverse momentum for anti- k_t jets with $R = 0.4$ (a) and $R = 0.6$ (b). The lower part shows the relative difference between data and Monte Carlo results. The black dotted lines indicate a relative difference of $\pm 10\%$. The bisector method is found to be in agreement between Monte Carlo simulation and data.

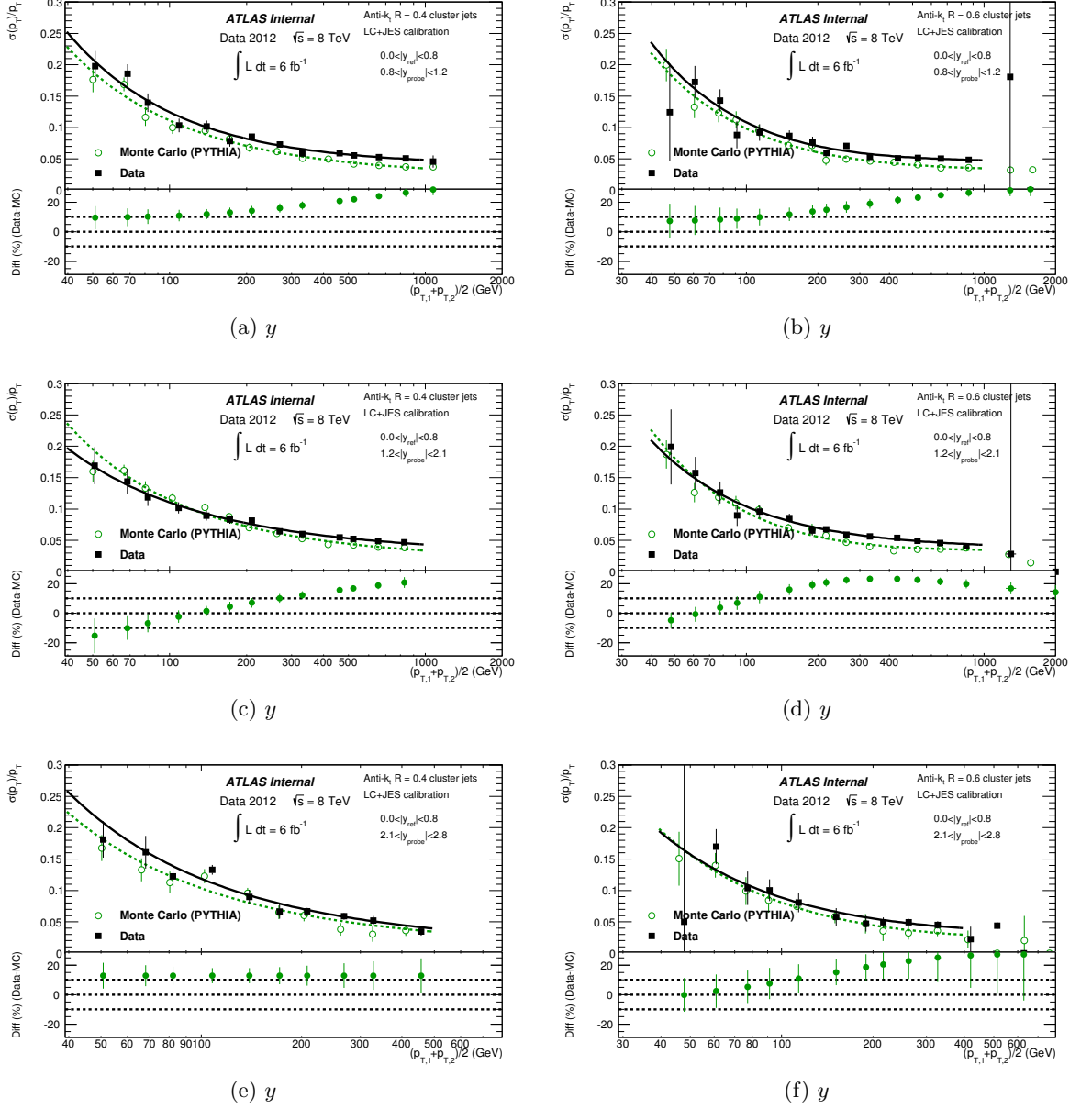


Figure B.4: Jet momentum resolution as a function of the average jet transverse momenta for $R = 0.4$ (left) and $R = 0.6$ (right) anti- k_t jets calibrated with the LCW+JES scheme. Results are obtained with the bisector technique for three different non-central rapidity regions. In the lower part of each figure the relative difference between the Monte Carlo fit and the data results are shown. The black dotted line indicates a relative discrepancy of $\pm 10\%$.

Appendix C

Quality Cuts: complimentary studies

The effect of different combinations of cleaning cuts related to the masking of failing calorimeter modules was tested on the variables of interest. The tool used to apply this cut provides 2 kinds of cuts:

Medium Cut all jets falling into the core of a masked region are flagged as bad, as well as jets falling into the edge of a masked region if they show a given combination of `emfrac/BCH.CORR_CELL`¹ proven to lead to MET tails and overestimated jet response.

Tight Cut all jets falling into the masked region are flagged as bad, whether they are at the edge or the core of the masked region.

The event would then be discarded if a bad jet was found, but there are several ways to apply this cuts, for example:

- apply the cut on the 4 leading jets
- apply the cut on 5 leading jets
- apply the cut on all jets with $p_T > 0.7 \times p_T^{min}$ in the event; in this analysis $p_T^{min} = 64$ GeV is the lowest cut on the 4th jet p_T .

The idea is to apply this cut to jets relevant to the analysis. Although only the 4 leading jets in each event will be used in the calculation of our variables, the cut should be applied on more jets to account for possible jet swapping (an estimation on the amount of jet swapping can be found in section 5.4.2).

Other factors to take into account are the loss in events and possible changes in the distribution shape in all cases. Regarding the first, when applying the medium cut looking at the 5 leading jets in each event, around 5% of the events are discarded. But when using the tight cut in the same way, the event loss goes up to 18%.

It is possible to distinguish small changes in the shapes of the distributions due to the application of the cut: the p_T spectrum is made slightly softer by it. Also, with a

¹emfrac is the fraction of the jet that is measured in the EM calorimeter. BCH.CORR_CELL indicates the value of the correction applied.

thin enough binning in the rapidity distribution, one can distinguish the larger event loss in the region corresponding to a masked module. Figure C.1 shows the leading jet p_T and rapidity distributions as example. Data and MC (Pythia) distributions are shown in separate plots. In each figure, the bottom plot shows the ratio between the distribution without the BCH cut and the ones with different cuts applied. One can see that the effect is highly increased with the tight cut, independently of how many jets are taken into account. The rest of the variables show a flat ratio.

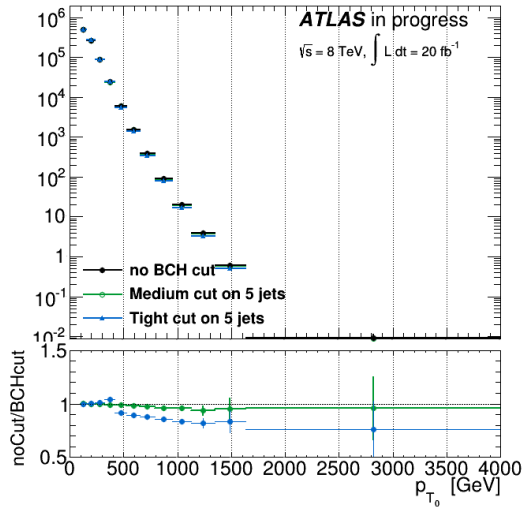
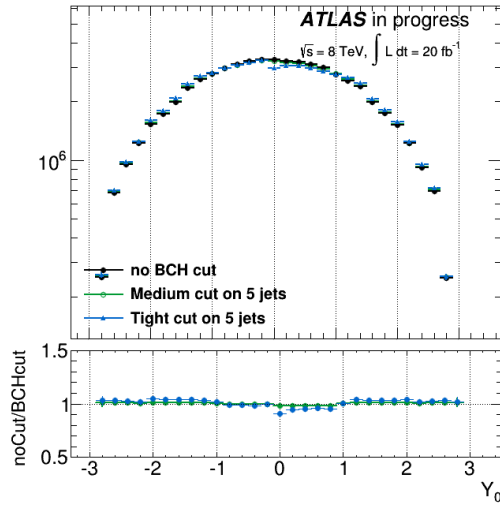
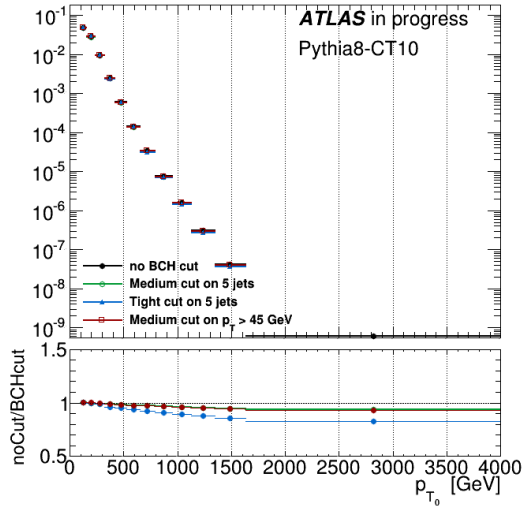
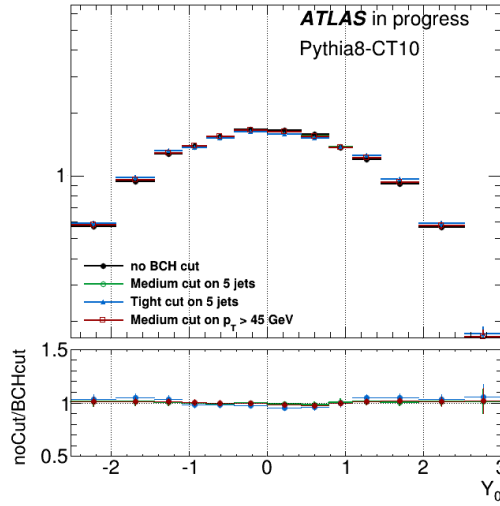
(a) Data - 1st jet p_T (b) Data - 1st jet y (c) PYTHIA- 1st jet p_T (d) PYTHIA- 1st jet $|y|$

Figure C.1: Leading jet p_T and rapidity distribution in data (top plots) and MC (bottom). Within each plot, the top panel shows the distributions with medium and tight cuts applied, on the 5 leading jets and on all the jets in the event with $p_T > 70\% p_T^{\min}$. The bottom panel shows the ratio with respect of the distribution without BCH cut.

Due to the high loss in events that the tight cut causes, it was decided to apply the medium version of the cut. No difference, except that of losing more events, was found when applying the medium cut on more jets, which is why it was subsequently applied only on 5.

It is interesting to see that the data-MC agreement is not affected by this cut: Figure C.2 shows the data and MC distributions for the leading jet p_T and rapidity without the BCH cut, with the medium cut applied on 5 jets, and the tight cut applied the same way. The bottom plots show not only the MC/data ratio corresponding to each of the cuts, but also the double ratio of each of these and the ratio without the cut, $(\frac{MC}{Data})^{noCut} / (\frac{MC}{Data})^{BCHcut}$. The lines (light blue for the medium cut and light green for the tight one) are very close to 1. This means that the cut is well reproduced in MC, and does not affect the data-MC agreement, specially when the medium cut is used.

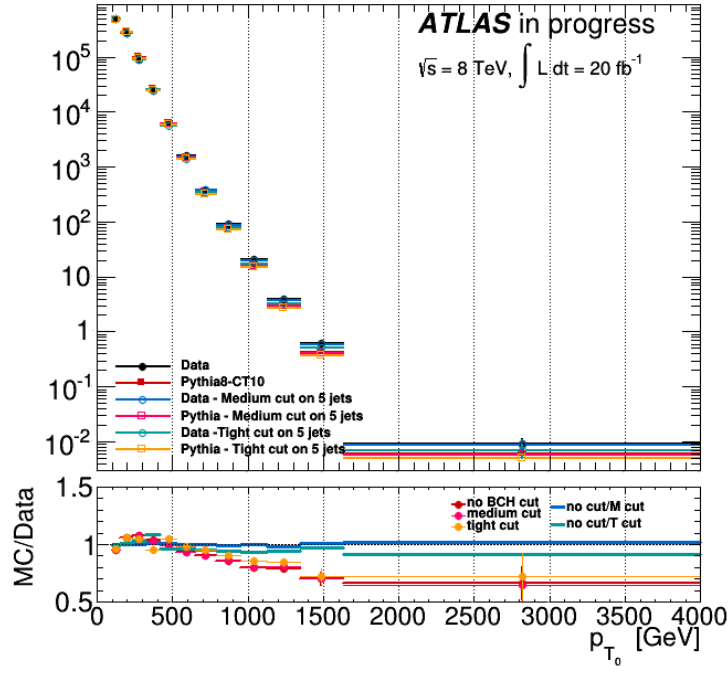
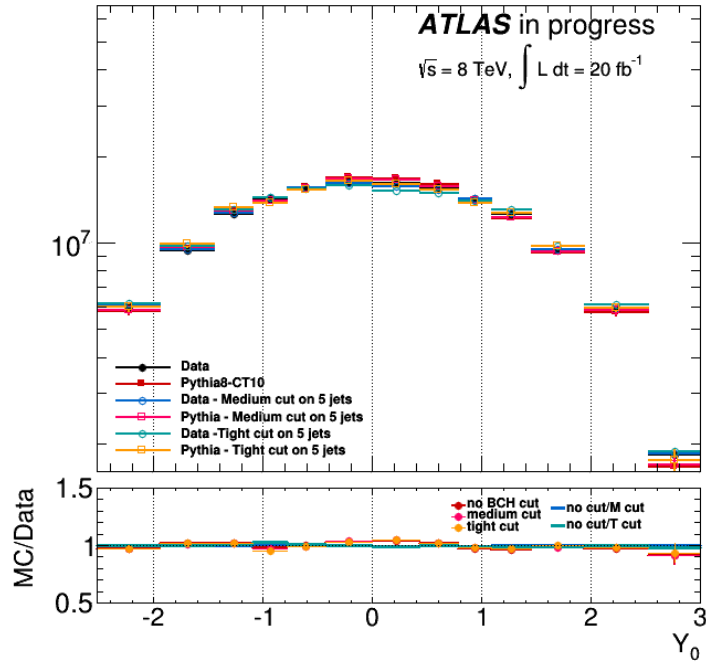
(a) 1st jet p_T (b) 1st jet y

Figure C.2: Leading jet p_T and rapidity distribution in data and Pythia8-CT10. The upper plots show the distributions without the cut and with a medium and tight cut applied on the 5 leading jets; distributions are scaled to the data without the cut applied. The bottom part shows the MC/data ratio for each pair of distributions; the blue and green lines show the double ratio of the MC/data ratio without and with the cut.

Appendix D

Sensitivity of the Variables to Pile-up

One of the characteristics of the variables presented in section 5.3 that needs to be studied is how they can be affected by pile-up. A short study conducted to this aim is presented in this appendix. It has been observed before that some event variables can be sensitive to pile-up, changing the shape of their distribution when the level of pile-up increases. In order to test if the variables selected were resilient to this effect, the dataset is divided into three parts for low, medium and high $\langle\mu\rangle$. The cuts chosen are $\langle\mu\rangle > 15$, $15 < \langle\mu\rangle < 25$ and $\langle\mu\rangle > 25$, respectively. These splitting does not separate the dataset in equal parts, causing some distributions to have more statistics than others. Therefore they are all scaled to the leading jet p_T cross section to facilitate the comparison (the goal being to find if the shape depends on $\langle\mu\rangle$ values).

In addition, it was observed that the distributions should be separated by trigger as well, given that otherwise the samples had to be weighted to account for the trigger prescale. This had been done correctly for the full dataset, but the corresponding information was not available for the dataset divided by $\langle\mu\rangle$.

Although, as mentioned, all the variables were evaluated in this way, two examples are presented here. Figure D.1 shows the distributions of $p_T^{(1)}$ for each of the momentum regions corresponding to the four triggers applied in the analysis. Each plot shows the distribution, at reconstructed level, for the full dataset, and the three $\langle\mu\rangle$ subsets. The bottom section shows the ratio between each $\langle\mu\rangle$ range and the full dataset, and they are equal to 1, with no tendencies whatsoever. The second variable chosen to exemplify this study is shown in figure D.2 and corresponds to $\Delta\phi_{2j}^{\min}$. The plots follow the same format as the previous ones and, in the same way, show no difference between the distribution corresponding to the full dataset and the ones made for each $\langle\mu\rangle$ range.

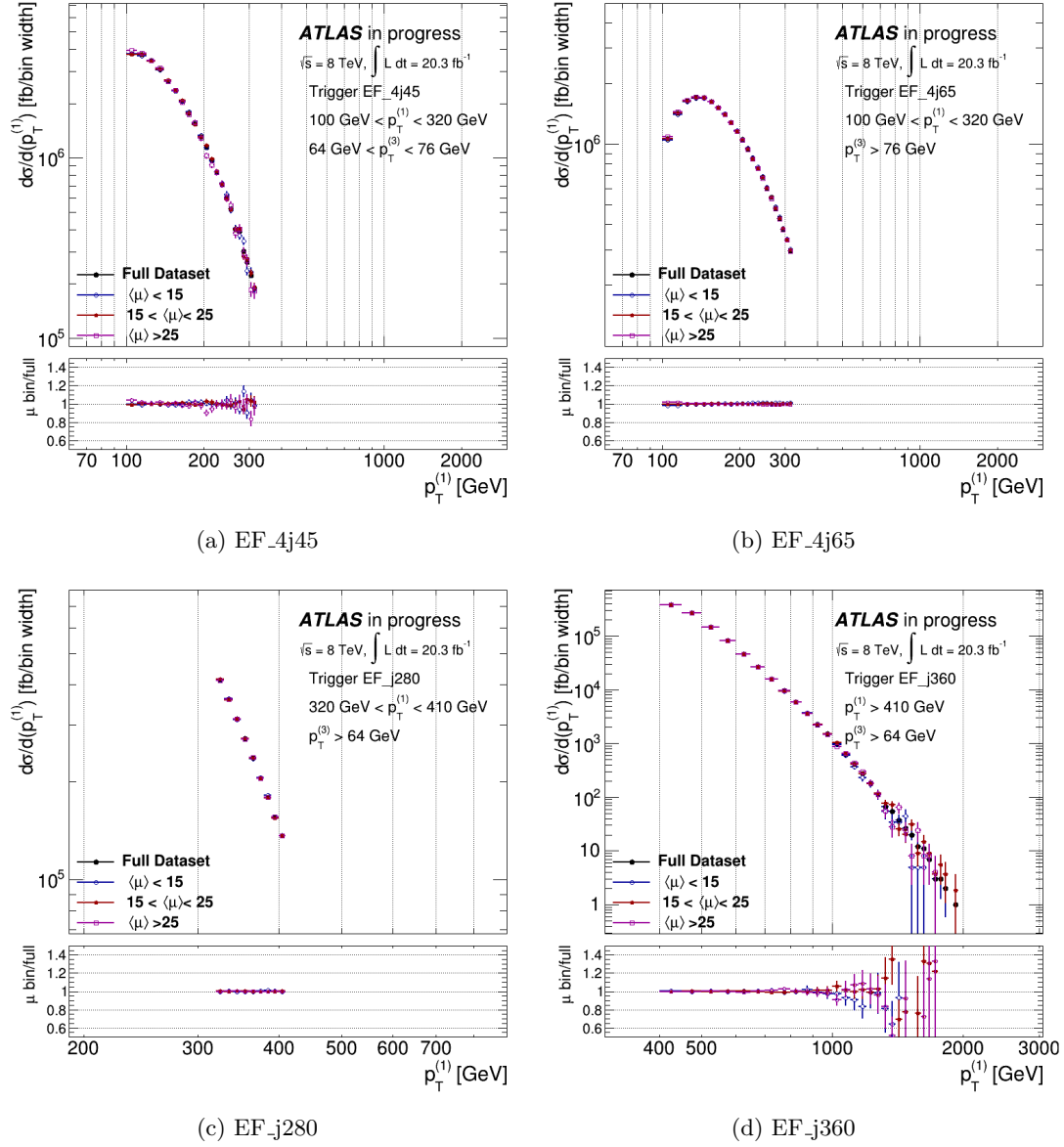


Figure D.1: $p_T^{(1)}$ distribution plotted separately for each exclusive trigger bin. Each plot compares the distribution in different $\langle \mu \rangle$ ranges and the full dataset; the bottom part of each plot shows the ratio with respect of the full dataset.

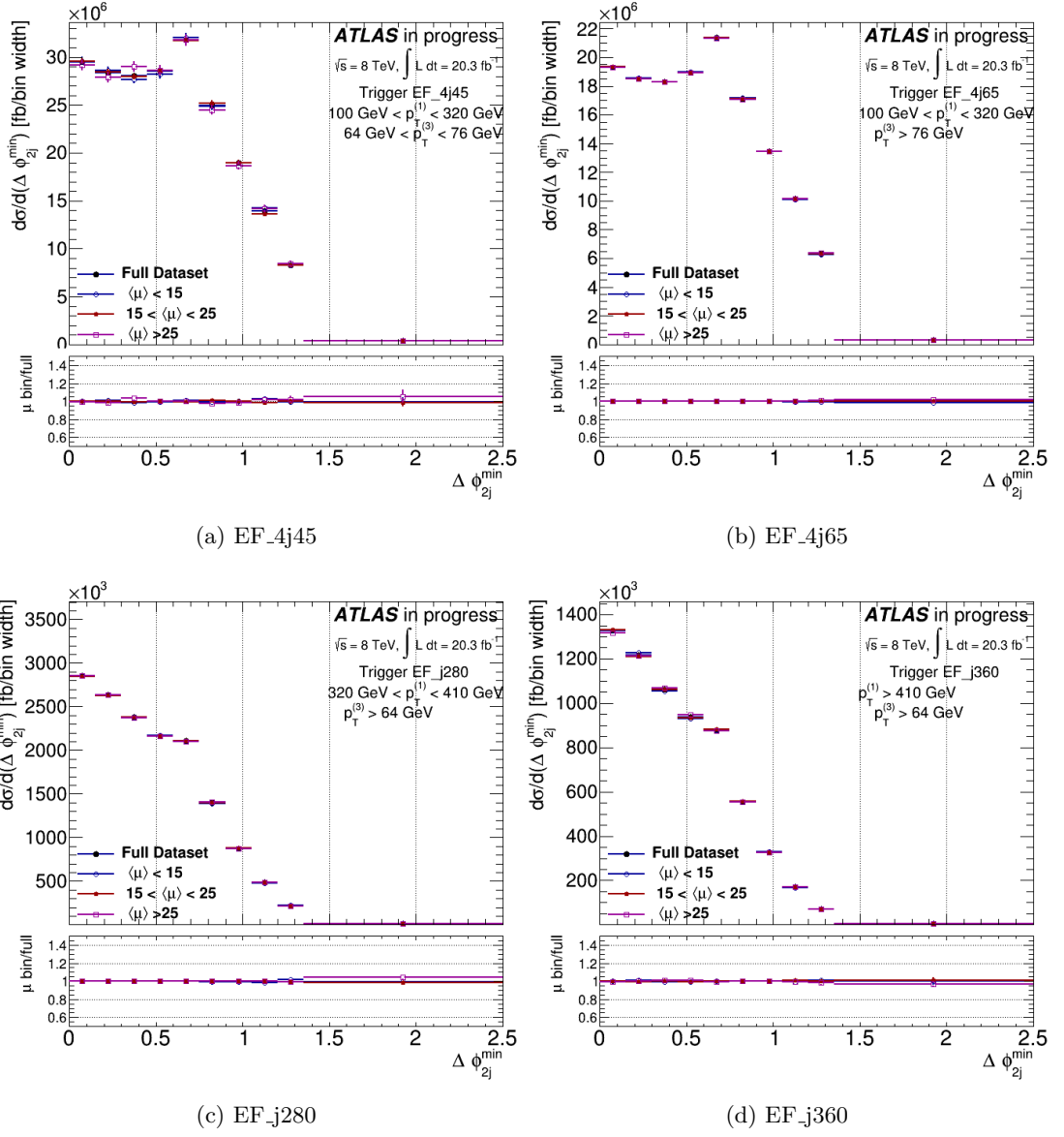


Figure D.2: $\Delta\phi_{2j}^{\min}$ distributions plotted separately for each exclusive trigger bin. Each plot compares the distribution in different μ ranges and the full dataset; the bottom part of each plot shows the ratio with respect of the full dataset.

Appendix E

Jet Angular Resolution Estimation

The Jet Angular resolution was estimated separately for ϕ and y in the PYTHIA sample. The four leading jets in the event are matched to the closest truth-level jet; if no jet within $\Delta R < 0.4$ is found then the jet is not considered. For the remaining jets, the difference between the reconstructed and truth-level angle was obtained, and split into y and p_T (truth-level) bins. Figure E.1 shows the $\Delta\phi$ and Δy values as a function of p_T^{truth} , presenting an apparently wider distribution for lower momenta of the jets. The range of p_T was divided into bins, for each of which the plots of $\Delta\phi$ and Δy were projected. Examples of these distributions are shown in figure E.2 for the bin of $100 < p_T^{truth} < 155$ GeV. The width of the distribution was obtained from a Gaussian fit in a range of $\pm 3RMS$, shown with a green line in the plots. Figure E.3 shows the width of the $\Delta\phi$ and Δy distribution as a function of p_T^{truth} for each rapidity region. The angular resolution is always below $\sim 2.5\%$, and more so for the momenta of interest for this analysis. In central rapidities, the ϕ resolution of jets above 250 GeV is smaller than 1%, whereas for more forward rapidities this happens at around 150 GeV. The rapidity resolution is always smaller than 2 %. It is smaller than 1% for truth jets with roughly $p_T > 150$ GeV.

These results are comparable to the JAR values obtained before in other studies [75] with similar methods. In this study the JAR was also measured in data using an in-situ method; for the p_T range of this analysis, the resolution measured in data is below 3% in both y and ϕ . The in-situ results are mostly found to be in agreement with the simulation ones, within systematic uncertainties (shown in Figures 5 and 6 in [75]).

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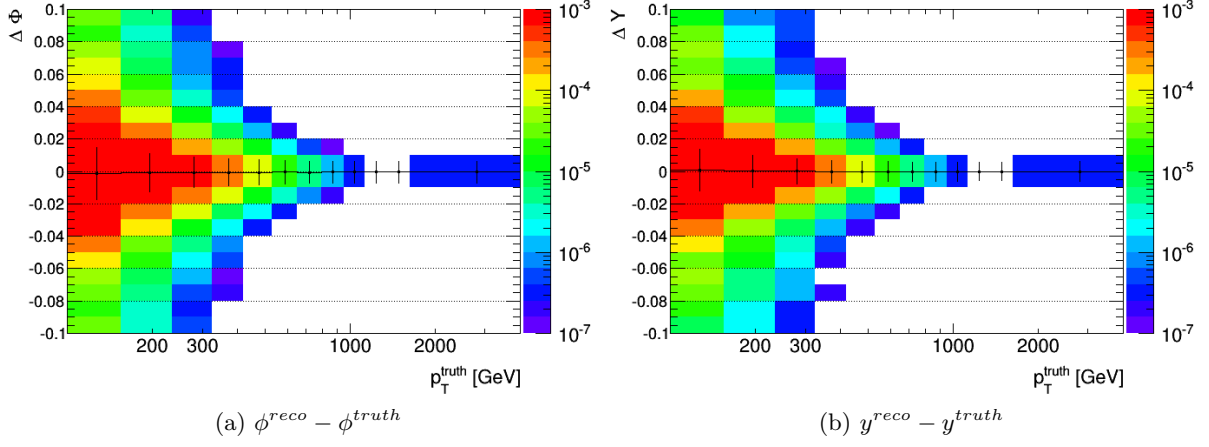


Figure E.1: $\Delta\phi$ and Δy distributions for $|y| < 0.8$ as a function of $< p_T^{\text{truth}} < \text{GeV}$.

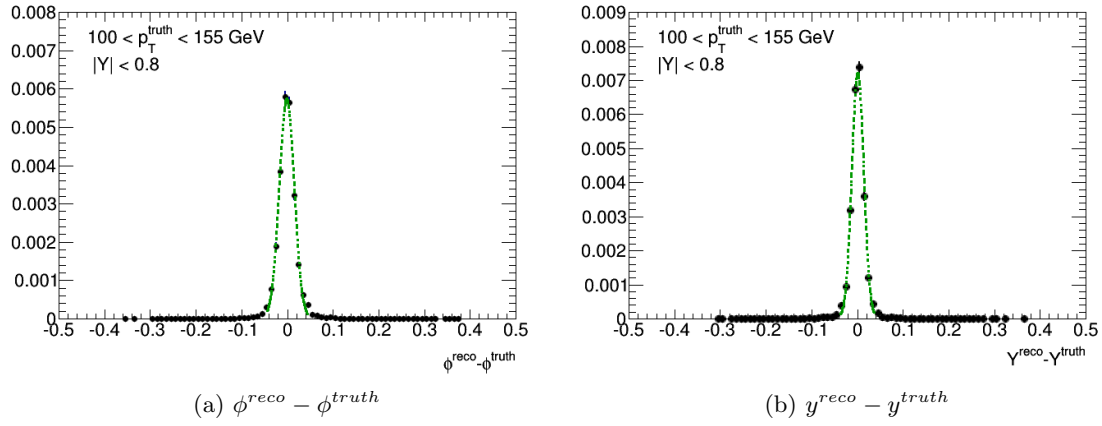
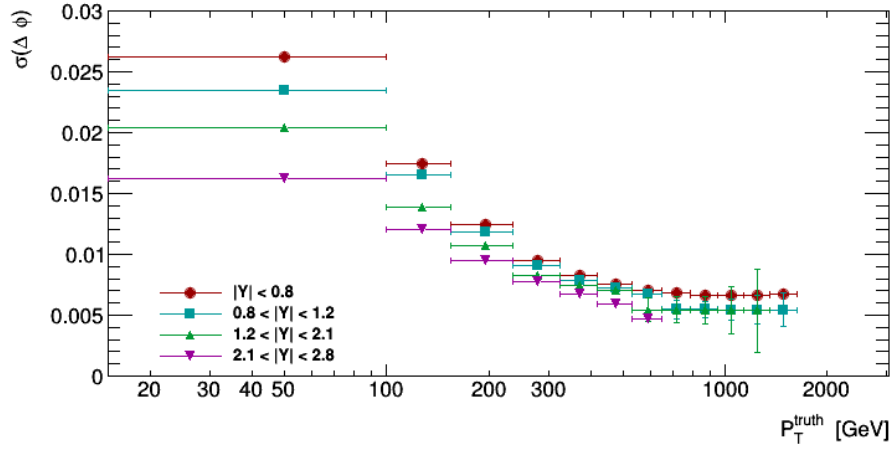
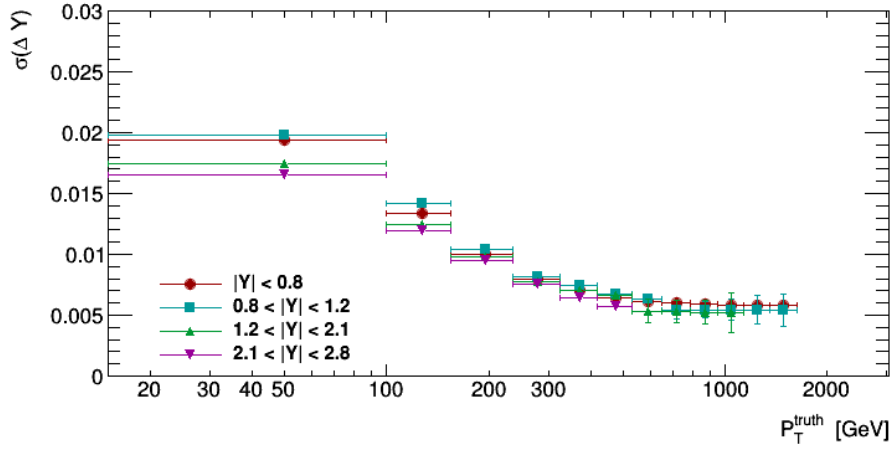


Figure E.2: $\Delta\phi$ and Δy distributions for $|y| < 0.8$ and $100 \text{ GeV} < p_T^{\text{truth}} < \text{GeV}$. The distributions are fitted with a Gaussian.

(a) $\phi^{\text{reco}} - \phi^{\text{truth}}$ (b) $y^{\text{reco}} - y^{\text{truth}}$ Figure E.3: Angular resolution as a function of p_T^{truth} for ϕ and rapidity.

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