

Jet energy resolution measurement of the ATLAS detector using momentum balance

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs
in partial fulfillment of the requirements for the degree of

Master of Science

in the subject of

Particle Physics

Department of Physics

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Abstract

During 2015 to 2017, the ATLAS detector at the CERN Large Hadron Collider has recorded 80 fb^{-1} of proton-proton collisions at centre-of-mass energy of 13 TeV. By far, the most common final state objects procured in these collisions are collimated showers of hadronic particles known as jets. In addition to their abundance, jets play key roles in many physics phenomena of interest at the LHC. Thus, accurate understanding of the detector's jet measurements is essential.

In this thesis, the jet energy resolution of the ATLAS detector is measured. Two novel techniques are developed to improve on precision of previous measurements. First, different sets of triggers are combined to increase the amount of useable data. Second, a new statistical fitting procedure based on convolution is implemented to determine the detector response. These methods are demonstrated to accurately measure the jet energy resolution.

Statement of originality

As the author, I certify that this thesis presents my original work and attributes due credit to external sources.

I was primary analyser of the ATLAS detector jet energy resolution measurement using dijet events. The following is a brief overview of the my research activities done for this task.

Dijet data collection strategy

I improved the trigger procedure based on the so-called inclusion method. I formulated the mathematical implementation in close collaboration with Robert Hankache, whose focus was on the the so-called jet energy calibration using dijet events (so-called η -intercalibration). Then, I evaluated efficiencies of all triggers used in the analysis to optimize their configuration.

Jet energy resolution measurement

I established the analysis procedures, validated results, and finally evaluated their systematics. Existing procedures from previous measurements were revised, as well as

new techniques—for example, the extraction of detector response based on convolution—designed and implemented. In addition, I performed several topical studies in support of relevant experimental efforts. The results of one such study—of the impact of reduced data collection rates on the dijet jet energy calibration and resolution analyses—informed the experiment’s new trigger settings from 2018 and onwards. Throughout the analysis, I presented regular progress reports at the research group meetings to receive and address feedback from senior researchers.

Analysis code maintenance and development

The jet energy resolution measurement codebase received significant updates and developments. Initially, I updated the code from previous measurements was updated to utilise more modern experiment infrastructure. Afterwards, I developed code to implement improvements and new procedures. After the successful completion of the analysis, I added detailed documentation to the code and hosted it on the experiment-wide repository to be made available for all future analysers. The development received major contributions from Tanja Holm, who added code for measurement of the jet energy resolution using dijet events based on alternative assumptions about the momentum balance (so-called bisector method).

Acknowledgements

First of all, to my supervisor Dag Gillberg: thank you for showing me what it means to be not just a physicist, but also a great human being. Needless to say, my work at Carleton University would not have been possible without your unending support. I am lucky to have met a mentor with such keen insight and passion; you will be a tough benchmark for me to strive towards in my career.

I extend my gratitude to the faculty members and post-doctoral fellows I have had the pleasure to meet and work with at Carleton University. The graduate chair and the ATLAS team leader Manuella Vincter, always made sure my visits to CERN, among many other things, went well. The grizzled postdoc Ioannis Nomidis, handed out unrefined but genuine advice for me.

My ATLAS colleagues—Alex Bachiu, Graham Cree, Robert Hunter, Andre Hupe, Alexandre Laurier, Steven Lee, David Di Valentino, and Stephen Weber—have been great companions to share the office with; some have been valuable mentors, while others trusty comrades. A special mention goes out to Dylan Linthorne in theoretical physics, who has always been willing to descend from his armchair to grab coffee or beer with me, depending on the occasion.

Finally, I would like to send sincere gratitude and love to my family: I know only little of the tremendous sacrifices they make for me. My grandmother, who has been

my caretaker since childhood, is always eager to hear from me. Mom and dad: your love for me has shaped me to be the person I am today. My older brother pretends to hate the responsibility of looking after me, but never fails in it. I am also grateful to all other family members who have supported me along the way.

Contents

1	Introduction	1
2	Theoretical background	3
2.1	Standard Model	3
2.1.1	Quantum chromodynamics	5
2.2	Proton-proton collisions	6
2.2.1	Dijet production	7
3	Experimental setup	10
3.1	Large Hadron Collider	10
3.2	ATLAS detector	12
3.2.1	Coordinate system	13
3.2.2	Tracking	14
3.2.3	Calorimetry	16
3.2.4	Trigger system	19
4	Data and simulation	21
4.1	2015-2017 ATLAS dataset	21
4.2	Monte Carlo samples	24
5	Jet reconstruction	25

5.1	Jet clustering algorithm	25
5.1.1	Ghost particles	27
5.2	Constituent inputs	27
5.2.1	Topological calorimeter cell clustering	28
5.2.2	Particle-flow	30
5.3	Energy calibration	31
5.3.1	Pileup correction	32
5.3.2	Absolute MC-based calibration	33
5.3.3	Global sequential calibration	35
5.3.4	Residual <i>in situ</i> calibration	37
5.4	Trigger-level jets	39
6	Analysis	40
6.1	Overview	40
6.2	Trigger strategy	43
6.2.1	Efficiency calculation	44
6.2.2	Luminosity calculation	47
6.2.3	Trigger combination	48
6.3	Dijet event selection	50
6.4	Truth-level asymmetry	52
6.5	Detector response convolution	53
6.6	Systematic uncertainties	56
7	Results	61
8	Conclusions	68
A	2015+2016 jet energy resolution	70

List of Figures

2.1	Fundamental particles of the Standard Model (black) and their interactions (blue). [1]	4
2.2	Feynman diagrams of the basic QCD interaction vertices (a) quark-gluon, (b) three-gluon, and (c) four-gluon QCD interaction vertices	5
2.3	Anatomy of an inelastic proton-proton collision, comprised of a hard scatter process (red) between two partons and the proton remnants forming the underlying event	7
2.4	Example (a) LO and (b) NLO QCD hard scatter processes.	8
2.5	A parton undergoes showering and hadronisation to form a jet, where the collimated trajectories of hadronic particles can be visualised to be contained inside a cone.	8
2.6	Illustration of a QCD hard scatter in a pp collision, resulting in dijet production.	9
2.7	Production cross sections of various pp processes measured by ATLAS at centre-of-mass energies $\sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV}$. Results are in excellent agreement with SM predictions. [2]	9

3.1	Layout diagram of the CERN Accelerator Complex. Protons are accelerated through the LINAC2, PSB, PS, and SPS accelerators. They are split into two beams as they enter LHC, where they are circulated in opposite directions to reach a total energy of 6.5 TeV per beam. Finally, they are brought into collision at four major experiments: ATLAS, ALICE, CMS, and LHCb.	11
3.2	Cross-sectional view of the ATLAS detector, revealing its major components. [4]	12
3.3	ATLAS coordinate system. The detector silhouette is visualised as a grey cylinder, viewed from (left) a side of the detector, and (right) the beam axis.	13
3.4	Detector pseudorapidity marks different detector regions. Central regions approach $\eta_{\text{det}} = 0$, while $ \eta_{\text{det}} \gg 0$ for forward regions.	15
3.5	Cross-sectional view of the ATLAS Inner Detector, consisting of the Pixel Detector, Semiconductor Tracker, and Transition Radiation Tracker. [5]	16
3.6	Cross-sectional view of the ATLAS calorimeters, consisting of the Liquid Argon, Tile, and Forward Calorimeters. [8]	17
4.1	Total integrated luminosity in 2015–2017 pp collision data recorded by ATLAS detector at 13 TeV centre-of-mass energy. [12]	23
4.2	(left) Luminosity-weighted distribution of the mean number of interactions (μ) per bunch crossing crossing. (right) ATLAS detector event display of a pp collision recorded in 2017 containing a candidate $Z \rightarrow \mu\mu$ hard scatter on top of additionally reconstructed vertices from pileup interactions: the left shows the transverse plane, right the longitudinal plane, and the bottom zoomed in on the interaction region, the reconstructed vertices (squares) and tracks (lines). [12] [13]	23

5.1	Jets defined from hadronic particles by the (a) k_t and (b) anti- k_t clustering algorithm. Different colours represent the area occupied by the jet.	26
5.2	Stages of topo-cluster formation in the first module of the Forward Calorimeter (FCAL0) in a simulated dijet event with at least one jet entering this calorimeter, under no pileup and modelled electronic noise conditions [16]. All topo-clusters in (c) either have a seed cell in (a), or are seeded by one in another module. [16]	29
5.3	Particle-flow algorithm track matching and topo-cluster removal procedure in the second layer of the Barrel EM LAr calorimeter (EMB2) in the vicinity of a 30 GeV truth jet (ellipse). Tracks are extrapolated to the calorimeter (asterisks), where the cells are clustered into topo-clusters (blue rectangles). The tracks selected for particle-flow jet reconstruction (dark purple) are ones matched to the nominal hard-scatter primary vertex and clustered into the jet. Topo-clusters are matched to tracks (red), associated to neutral particles (green), or discarded as pileup (blue). [17]	31
5.4	Calibration procedures applied to the reconstructed jets. [18]	32
5.5	Per-event average p_T density at $N_{PV} = 10$ (solid) and $N_{PV} = 20$ (dotted) for $24 < \mu < 25$ as found in MC simulation, to be taken as ρ for the area-based correction factor. [18]	33
5.6	Dependence of jet p_T on N_{PV} (left) and μ (right) as a function of jet $ \eta_{det} $ for $p_T^{\text{true}} = 25$ GeV before any pileup corrections (blue circle), after the area-based correction (violet square), and after the residual correction (red triangle). The values of the linear-fitted dependence after the area-based correction in 4 $ \eta_{det} $ regions (purple band) are taken as the residual correction factors α and β	34

5.7	(a) The average energy response as a function of η_{det} for jets with a truth energy of 30, 60, 110, 400, and 1200 GeV, and (b) the signed difference between the truth jet η^{truth} and the reconstructed jet η^{reco} due to biases in the jet reconstruction. [18]	35
5.8	Average p_{T} response with respect to w^{track} of jets in $0.3 \leq \eta < 1.3$ several p_{T} bins (above) and the underlying w^{track} distributions (below) before (left) and after (right) application of GSC. [18]	36
5.9	Relative jet response as a function of probe jet η_{det} for in dijet events with $85 < p_{\text{T}}^{\text{avg}} < 115$ GeV. [18]	38
5.10	Combined <i>in situ</i> calibration of jets using $Z/\gamma + \text{jet}$ and multijet events. [18]	38
6.1	A dijet event viewed from the centre-of-mass (left) and detector (right) frame.	41
6.2	A dijet system forming a transverse momentum balance, with one jet in the well-measured reference region (green) and the other in a probe region (white) being studied	42
6.3	Trigger efficiency calculated using Equation 6.9 as a function of $p_{\text{T}}^{\text{avg}}$ in a given $\eta_{\text{det}}^{\text{probe}}$ bin. Neither single-jet trigger reaches full efficiency individually, but their combination does.	46
6.4	Turn-on point of HLT_j110 OR HLT_j110_320eta490 trigger combination set to across $\eta_{\text{det}}^{\text{probe}}$ bins	46
6.5	Dijet visual cross section versus (left) $p_{\text{T}}^{\text{avg}}$ with different colours indicating different trigger combinations used in their respective turn-on regions and (right) asymmetry with (01,10,11) denoting the categories explained in Equation 6.14.	49

6.6	Distributions of dijet topology kinematic variables $p_T^{j_3}/p_T^{\text{avg}}$ (left) and $\Delta\phi(j_1, j_2)$ (right) before (red) and after (blue) selections for events with $(55 \leq p_T^{\text{avg}} < 80 \text{ GeV}, 0.2 \leq \eta_{\text{det}}^{\text{probe}} < 0.7)$	51
6.7	Illustration of a QCD process with both ISR and FSR emission. This event can still be considered a dijet event if their effects are sufficiently insignificant such that the event passes the dijet topology selection described in Section 6.3.	52
6.8	Distributions of dijet asymmetry calculated from truth-level jets (blue) and reconstructed jets (black)	53
6.9	The truth asymmetry distribution (blue markers) fitted by the functional form of Equation 6.15 (blue line). Fits performed through χ^2 -minimization.	54
6.10	The reconstructed asymmetry distribution (black markers) fitted the functional form of Equation 6.16 (black line). Fits performed through χ^2 -minimization.	55
6.11	Different shapes of the truth-level asymmetry observed in the reference (left) and probe (right) regions fitted by the exponential power + Gaussian function, and the reconstructed-level asymmetry fitted by their Gaussian convolutions. Fits performed through χ^2 -minimization.	55
6.12	Expected in-situ jet energy resolution measurement in PYTHIA8 dijet events compared to the true quantity as a function of p_T and η_{det} . The lower panels show the ratio of desired over measured, which quantifies the non-closure of the method. The larger relative non-closure at high- p_T is identified to be due to the parametrisation of the true quantity.	56
6.13	Discrepancies in dijet asymmetry observed in MC simulation (coloured lines) versus data (dotted circles) for $400 \leq p_T^{\text{jet}} < 550 \text{ GeV}$	58

6.14	Gaussian fit (solid red line) to the core of the jet p_T response simulated in MC, extrapolated (dashed red line). The fits describe the entire shape of the response distribution for low- p_T jets, but non-Gaussian tails are observed for high- p_T jets.	59
6.15	Total systematic uncertainties on the jet energy resolution, obtained by adding uncorrelated sources in quadrature	60
7.1	Jet energy resolution of the ATLAS detector measured in 2017 data of calorimeter (left) and particle-flow (right) jets.	64
A.1	Jet energy resolution of the ATLAS detector measured in 2015+2016 data of calorimeter (left) and particle-flow (right) jets.	72

List of Tables

4.1	Configurations of MC generators used in the analysis	24
6.1	Trigger combination turn-on p_T^{avg} regions. Each trigger combination is specified a p_T^{avg} region in which it is fully efficient and is applied the lowest prescale.	49
6.2	Remaining number of events after requirements.	51
6.3	Summary of the sources of systematic uncertainties assessed.	56
7.1	Fit results of (Noise, Stochastic, Constant) parametrisation of jet energy resolution extracted from 2017 data. Neighbouring terms (N, S) and (S, C) tend to be strongly correlated, while the noise and constant terms (N, C) tend to be strongly anti-correlated. The parametrization used only has theoretical justification for calorimeter jets. The results shown for particle flow jets are not very meaningful; future work is needed to find an appropriate functional form for this resolution. . . .	63

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Chapter 1

Introduction

The ATLAS experiment explores a variety of unresolved questions as well as searches for new phenomena in particle physics from inelastic collisions of protons occurring at the CERN Large Hadron Collider. Its detector, correspondingly named the ATLAS detector, measures countless collision products to be studied by physicists. A striking phenomenon observed in high-energy inelastic proton-proton collisions is showers of hadronic particles called jets. Jets are the most common products from the collisions, and serve as important probes of many studies conducted at the experiment.

Due to the complex nature of the hadronic particles of a jet in the detector, however, they are also one of the most challenging objects for the detector to measure. Therefore, it is crucial for physics analyses to be able to correct for any detector effects in their jet measurements based on an accurate understanding of the detector.

The goal of this thesis is to determine the resolution of the ATLAS detector's jet energy measurements. A technique exploiting the momentum balance between two jets is used to extract a measurement of the resolution from collisions data collected by the detector.

Chapter 2 briefly introduces the Standard Model of particle physics that underpins the theoretical framework of physics discussed throughout the thesis, as well as the mechanism by which jets are produced in inelastic proton-proton collisions.

Chapter 3 and 4 present the setup of the experimental apparatus and datasets used in the study.

Chapter 5 outlines the how jets are measured in the ATLAS experiment. The methods used to of define jets out of detector signals is outlined, and the experimental procedures in calibrating jets is explained.

Chapter 6 details the analysis procedures. It contains the main research carried out for the measurement, with emphasis placed on novel techniques.

Chapter 7 and 8 present the results and conclusions on the measurement of the jet energy resolution of the ATLAS detector. Improvements brought to the measurement with respect to previous iterations are highlighted, and implications of the updated results are discussed.

Chapter 2

Theoretical background

2.1 Standard Model

The Standard Model of particle physics (SM) describes the fundamental particles and interactions of the universe. Its development began with the formulation of the electroweak theory in 1961, and culminated into its complete form known today by the experimental discovery of the Higgs Boson in 2012. Figure 2.1 shows a summary of all SM particles.

There are three generations of spin-1/2 fermions, the first of which make up all stable matter in the universe. They classify into two families, leptons and quarks. The electron (e^-), muon (μ^-), and tau (τ) are charged leptons, whereas their corresponding neutrinos — electron-neutrino (ν_e), muon-neutrino (ν_μ), and tauon-neutrino (ν_τ) — are neutral. The up (u), charm (c), and top (t) quarks have electric charges of $+2/3$ times the elementary charge, while the down (d), strange (s), and bottom (b) quarks are $-1/3$ charged. Quarks also possess an additional property, colour, which the strong nuclear force acts on. Each particle has an anti-particle, a mirror-image

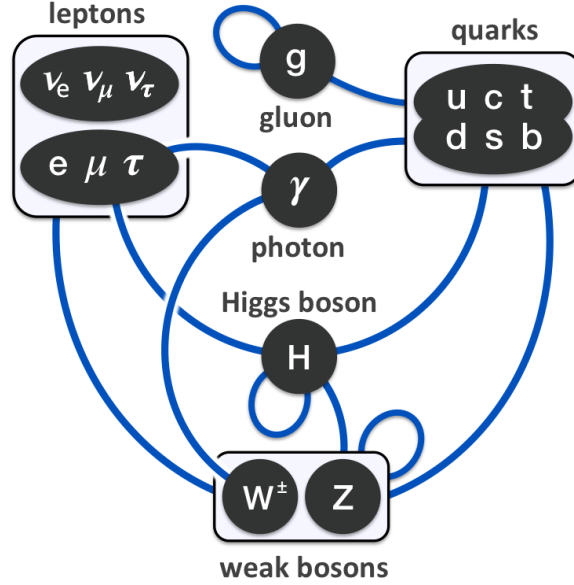


Figure 2.1: Fundamental particles of the Standard Model (black) and their interactions (blue). [1]

with the same mass but reversed electric charge and colour.

Matter particles interact with one another via gauge bosons, which are carriers of the fundamental forces. Under Quantum Field Theory (QFT), the theoretical framework on which the SM works, all particles, including gauge bosons, are excitations of their respective quantum fields. Respectively, the photon (γ) is the mediator of the electromagnetic, gluon (g) of the strong, and $W^\pm$ and Z bosons of the weak nuclear force. Lastly, the Higgs boson (H) is a mediator of the Higgs field, which gives mass to all SM particles, including itself.

The SM has withstood every experimental test conducted so far, several of which can be seen in Figure 2.7. As successful as it is, however, it is not a complete theory of the universe. In the case of neutrinos, the SM does not require them to be massive, and yet they have been observed to be so from neutrino oscillations. It is also possible that they are their own anti-particles, the so-called Majorana fermions. Gravity, which is the fourth force of the universe, is not part of the SM: its strength is so weak compared to others that it is more or less completely negligible given the precision of

current experiments. These aspects, while important in their own rights, are of little consequence in the context of this thesis.

2.1.1 Quantum chromodynamics

Quantum chromodynamics (QCD) is the theory of the strong nuclear force describing quarks and gluons. An important property of QCD is *asymptotic freedom*: as the energy (length) scale of the interaction increases (decreases), its strength becomes asymptotically weaker. Consequently, quarks and gluons interacting over short distances behave as free particles. The gluon can also carry colour, resulting in three ways in which quarks and gluons can interact with one another, as shown through *Feynman diagrams* in Figure 2.2.

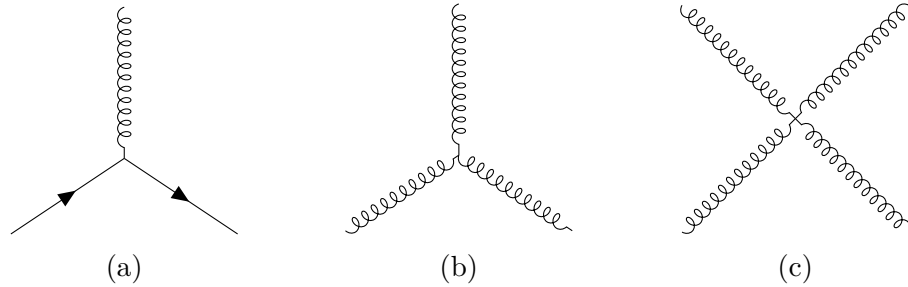


Figure 2.2: Feynman diagrams of the basic QCD interaction vertices (a) quark-gluon, (b) three-gluon, and (c) four-gluon QCD interaction vertices

But bare quarks and gluons, collectively termed *partons*, have never been observed. In fact, they bind together to form composite, colourless particles called *hadrons*. This phenomenon is called *colour confinement*. Qualitatively, the interactions between a quark-antiquark pair in a hadron is described as a string comprised of gluons. Trying to pull the quarks apart results in a corresponding increase in their interaction strength up to a certain point at which it becomes energetically favourable for the string to form an additional quark-antiquark pair. Thus, instead of the quarks being

freed, the system splits into a pair of hadrons.

2.2 Proton-proton collisions

A proton is a hadron, consisting of three valence quarks bound together by gluons, as well as sea quarks that arise spontaneously from vacuum fluctuations. Most high centre-of-mass energy ($\sqrt{s}$) proton-proton (pp) collisions result in inelastic scattering, in which individual partons of the protons interact, shown in Figure 2.3.

The primary interaction of interest in a collision is the *hard scatter*, shown in Figure 2.3, while the rest of the proton-proton system form the *underlying event* (UE). The total pp production cross section of some state X ($\sigma_{pp \rightarrow X}$) contains contributions from all possible partonic hard scatter process cross sections ($\hat{\sigma}_{ab \rightarrow X}$):

$$\sigma_{pp \rightarrow X} = \sum_{a,b} \int dx_1 \int dx_2 f_a(x_1; \mu_F^2) f_b(x_2; \mu_F^2) \hat{\sigma}_{ab \rightarrow X}, \quad (2.1)$$

where $f_a(x_1; \mu_F^2)$ is the *parton distribution function* (PDF), which can be interpreted as the probability for a parton a to be carrying fraction x_1 of the total proton longitudinal momentum at an energy scale μ_F at which the proton is being probed. In turn, the cross section of an arbitrary partonic process $ab \rightarrow 1 \dots n$ is

$$\hat{\sigma}_{ab \rightarrow 1 \dots n} = \frac{1}{2\mathcal{F}(p_a, p_b)} \int \prod_{m=1}^n \frac{d^3 \mathbf{p}_m}{(2\pi)^3 2E_m} (2\pi)^4 \delta^{(4)}(p_a + p_b - \sum_{i=1}^n p_i) |\mathcal{M}_{ab \rightarrow 1 \dots n}|^2, \quad (2.2)$$

where $p_i = (\mathbf{p}_i, m_i)$ is the 4-momentum of particle i , $\mathcal{F}(p_a, p_b) = \sqrt{(p_a \cdot p_b)^2 - (m_a^2 m_b^2)}$ the Møller flux factor, and $\mathcal{M}_{ab \rightarrow 1 \dots n}$ is the *matrix element* of the process.

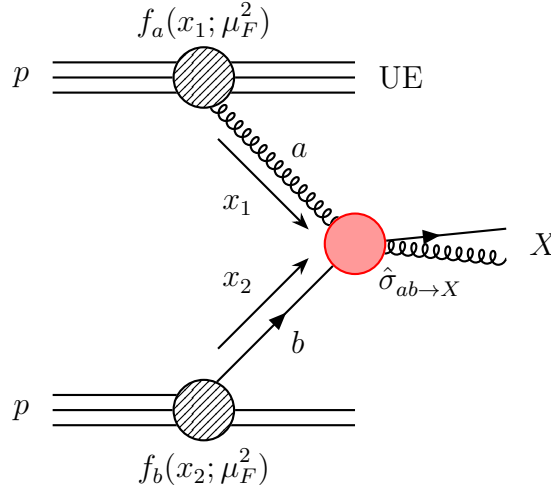


Figure 2.3: Anatomy of an inelastic proton-proton collision, comprised of a hard scatter process (red) between two partons and the proton remnants forming the underlying event

2.2.1 Dijet production

The most common hard scatter processes are QCD scattering, represented through Feynman diagrams in Figure 2.4: leading-order (LO) diagrams are $2 \rightarrow 2$ processes, while next-to-leading-order (NLO) contributions include initial state radiation (ISR), final state radiation (FSR), or virtual loop corrections. The total matrix element evaluation of a process of all possible Feynman diagrams, using the Feynman rules encoded in them.

The partons produced in collisions undergo a process called *parton showering*: gluons can split into two gluons or a quark-antiquark pair ($g \rightarrow gg, g \rightarrow q\bar{q}$), and quarks can emit gluons ($q \rightarrow qg$). The former case occurs with such small opening angles that result in both partons travelling approximately the same direction (collinear), while gluon emissions in the latter case carry only a small amount of energy away from the original parton (soft). Subsequently, the partons evolve into hadrons due to colour-confinement, a process called *hadronisation*. In summary, partons evolve into collimated showers of hadronic particles, known as a *jets*.

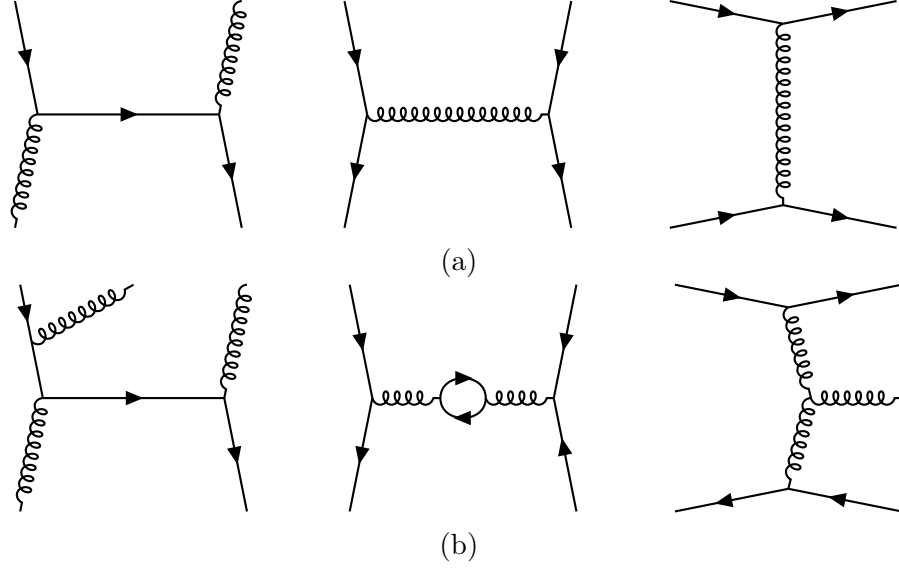


Figure 2.4: Example (a) LO and (b) NLO QCD hard scatter processes.

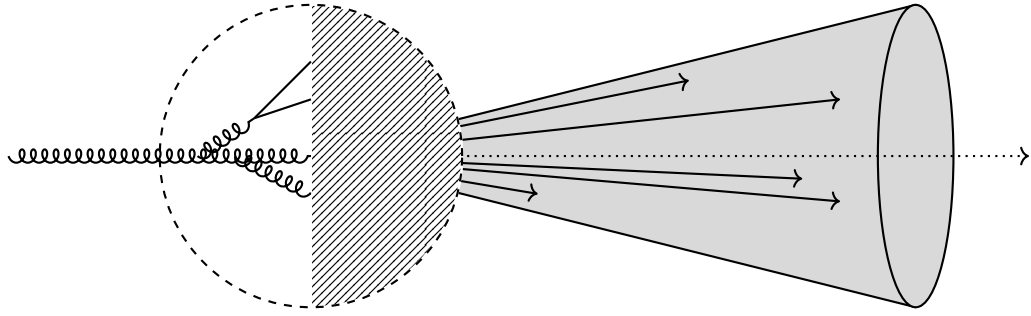


Figure 2.5: A parton undergoes showering and hadronisation to form a jet, where the collimated trajectories of hadronic particles can be visualised to be contained inside a cone.

Figure 2.7 [2] summarises the production cross section of several pp processes measured by the ATLAS experiment, detailed further in Chapter 3. As explained, QCD processes, which dominate the pp cross section, produce jets; thus, they are the most common final state objects seen at the LHC, and serve as important probes of the underlying parent partons. A pp collision in which two jets are produced are called *dijet* events, shown in Figure 2.6.

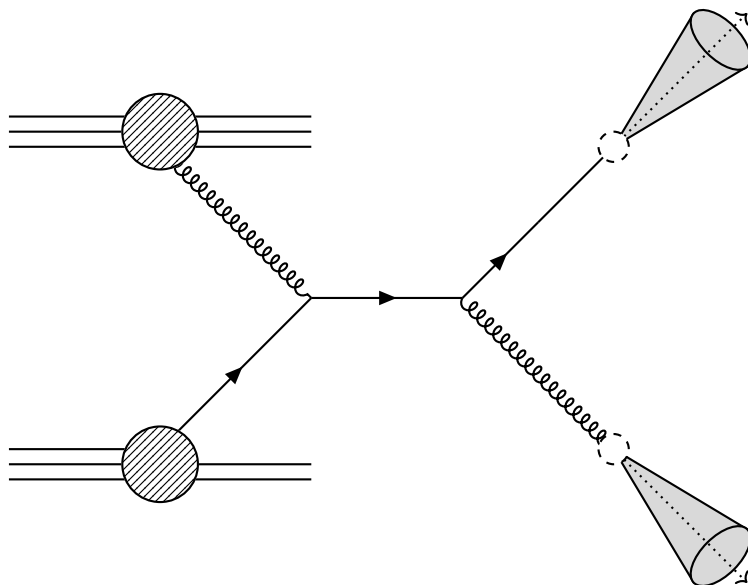
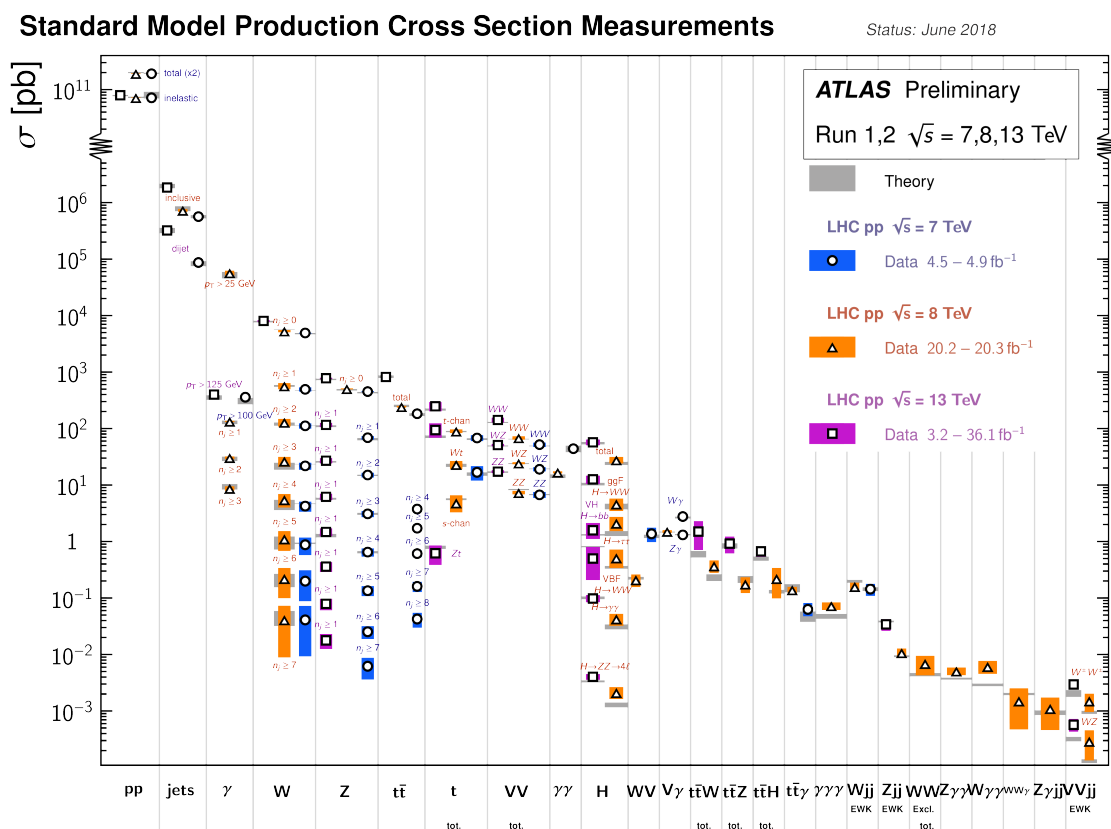


Figure 2.7: Production cross sections of various pp processes measured by ATLAS at centre-of-mass energies $\sqrt{s} = 7, 8$, and 13 TeV. Results are in excellent agreement with SM predictions. [2]



Chapter 3

Experimental setup

3.1 Large Hadron Collider

The Large Hadron Collider (LHC) [3] is a hadron accelerator and collider located at the European Centre of Nuclear Research (CERN) near Geneva, Switzerland. A layout diagram of the CERN Accelerator Complex, which includes the LHC, is shown in Figure 3.1. It is the most powerful particle accelerator in the world, designed to accelerate protons up to kinetic energy of 7 TeV. Two kinds of particle beams — protons and heavy-ions — can be circulated at the LHC. Two beams are circulated in opposite directions and brought into collision at four experiments on the LHC ring: ATLAS, ALICE, CMS, and LHCb. As introduced in Chapter 2, the collisions of focus in this thesis will be inelastic pp physics at the ATLAS experiment.

The acceleration of protons take place through a multi-stage process. First, protons are stripped from hydrogen atoms and accelerated through a linear accelerator aptly called Linear Accelerator 2 (LINAC2). Then they are further accelerated through three synchrotrons, also straightforwardly named Proton Synchrotron Booster (PSB),

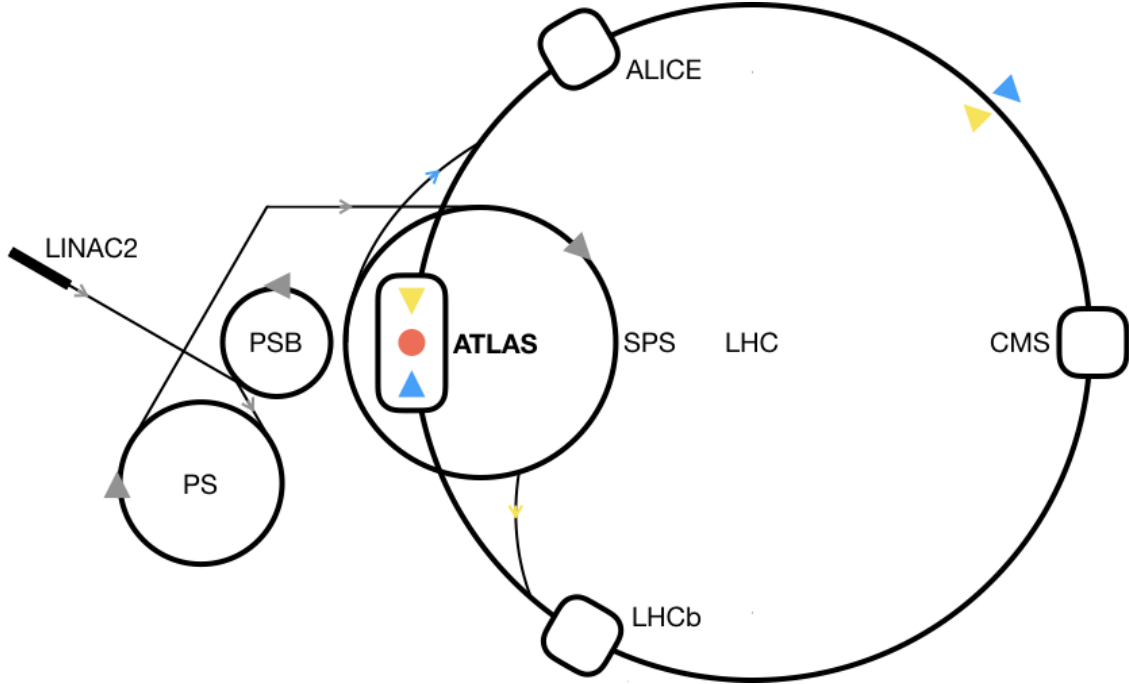


Figure 3.1: Layout diagram of the CERN Accelerator Complex. Protons are accelerated through the LINAC2, PSB, PS, and SPS accelerators. They are split into two beams as they enter LHC, where they are circulated in opposite directions to reach a total energy of 6.5 TeV per beam. Finally, they are brought into collision at four major experiments: ATLAS, ALICE, CMS, and LHCb.

Proton Synchrotron (PS), and Super Proton Synchrotron (SPS). As they are successively fed from one accelerator to the next, the protons reach kinetic energies of 50 MeV, 1.5, 25, and 450 GeV, respectively, until they reach the LHC.

A synchrotron refers to a type of accelerator that uses a circular ring beam path, such as the LHC. Particles are accelerated at a specific site of the ring, while being curved by a perpendicular magnetic field to loop around. The acceleration-loop process repeats until the maximum beam energy is reached. Radiofrequency (RF) cavities, which contain oscillating electromagnetic fields, are used to accelerate particles. Protons at nominal energy that arrive exactly on timing inside a cavity do not experience acceleration, while those with slightly less or more that arrive later or faster, respectively, are accelerated closer to the nominal energy. As a result, protons are packed into discrete “bunches”. The bunches are spaced by 25 ns; as a result, they

cross at the collision point at a rate of 40 MHz.

3.2 ATLAS detector

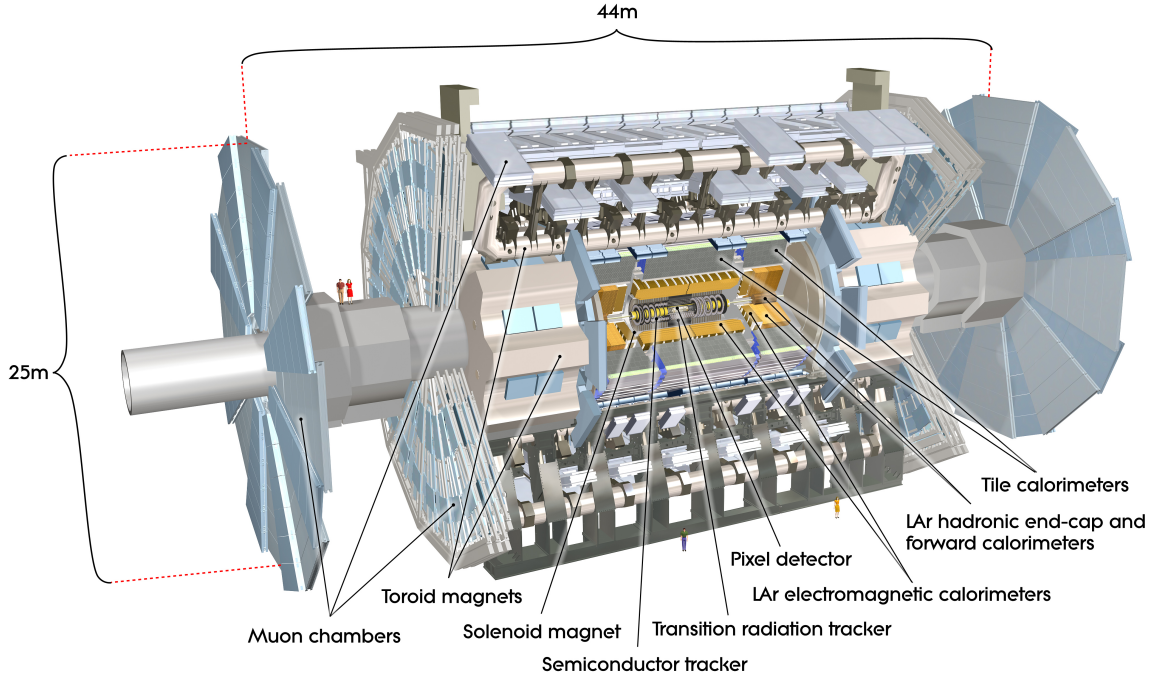


Figure 3.2: Cross-sectional view of the ATLAS detector, revealing its major components. [4]

The ATLAS detector [4] is a general-purpose particle detector primarily designed to study a broad range of pp physics interests at the LHC. It has a cylindrical design around the nominal collision point with nearly 4π sr of solid angle coverage, spanning 44 m and standing 25 m tall with 7000 t of detector components. A labeled diagram is shown in Figure 3.2 [4].

The complete detector is comprised of several components that provide complementary functionalities in identification and measurement of various collision products. The innermost layers of the detector consist of charged particle trackers. Calorime-

ters are placed behind to measure the energy of electrons, photons, and hadrons. Finally, the Muon Spectrometer System envelops the calorimeters for muon measurements. Separate barrel and endcap region sub-detectors specialise in measurements of particles travelling away from (central) and closely along (forward) the beam-line, respectively.

3.2.1 Coordinate system

The ATLAS detector is specified under right-handed Cartesian coordinates with its origin at the nominal point of interaction at the centre of the detector, the x -axis pointing towards the centre of the LHC ring, and the z -axis, also referred to as the beam axis, travelling through the beam pipe. The polar angle (θ) measures from the beam axis. Cylindrical coordinates are used in the xy -plane, also called the transverse plane, with the radial distance (r) from and the azimuthal angle (ϕ) around the beam axis. Figure 3.3 shows the orientation of the detector with respect to these coordinates.

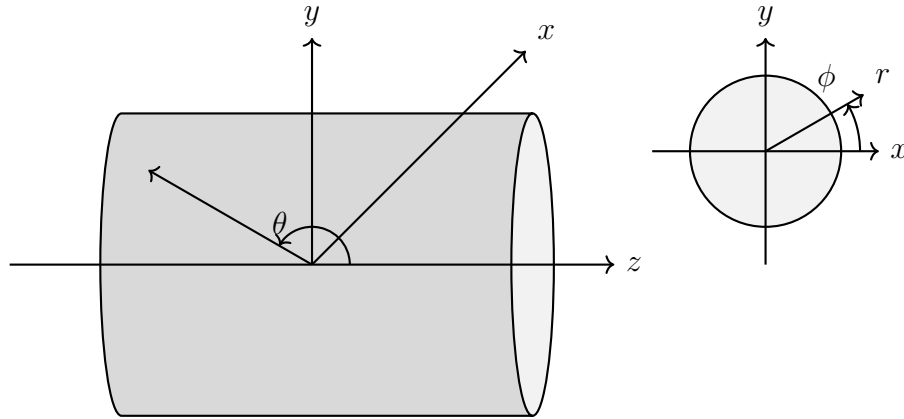


Figure 3.3: ATLAS coordinate system. The detector silhouette is visualised as a grey cylinder, viewed from (left) a side of the detector, and (right) the beam axis.

The *rapidity* of a particle is defined in particle physics as

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (3.1)$$

where p_z is the magnitude of the momentum component along the beam axis. Conversely, the *transverse momentum* (p_T) of a particle is the magnitude of the momentum projected onto the xy -plane orthogonal to the beam axis.

In the relativistic limit, the rapidity converges to a spatial coordinate measuring the angle of the particle with respect to the beam axis, called *pseudorapidity* (η):

$$\eta \equiv -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (3.2)$$

For reasonably light, high-energy particles, pseudorapidity is a good approximation of the true rapidity. The detector pseudorapidity (η_{det}), measured at the detector centre¹, marks the angular position of different detector regions, as shown in Figure 3.4. Central regions correspond to η_{det} close to zero, and forward regions to high $|\eta_{\text{det}}|$ values.

3.2.2 Tracking

Trackers utilise “hit” signals resulting from the passage of a charged particle as indications of its presence at a specific site in the detector. These hits are traced across different layers of trackers to reconstruct the trajectory of the particle. Under a magnetic field, curvature of the trajectory enables measurements of the particle’s momentum. The Inner Detector (ID), shown in Figure 3.5, consists of three charged

¹It is implicit that the pseudorapidity of an object is defined with respect to the object’s origin point, i.e. jet pseudorapidity to the interaction point and detector pseudorapidity to the detector centre. In cases of ambiguity, η_{det} is used to explicitly denote the detector pseudorapidity.

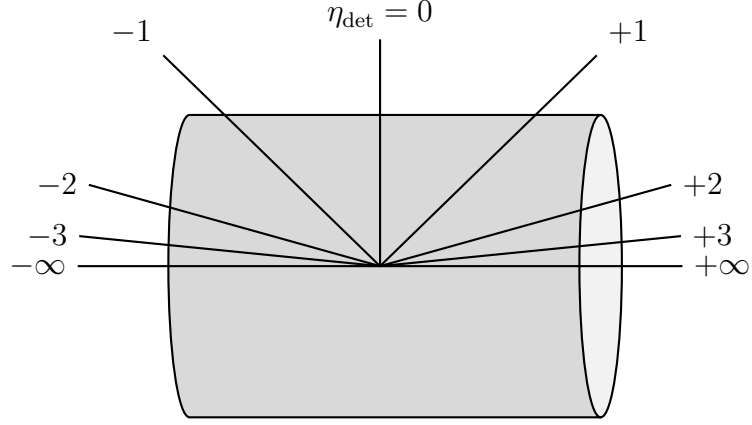


Figure 3.4: Detector pseudorapidity marks different detector regions. Central regions approach $\eta_{\text{det}} = 0$, while $|\eta_{\text{det}}| \gg 0$ for forward regions.

particle trackers immersed in a 2 T longitudinal magnetic field applied by an enveloping solenoid.

The Pixel Detector (PD) [6] and Semiconductor Tracker (SCT) [5] use silicon semiconductor sensors. Electron-hole pairs are created in the semiconductor, and the electrons travel toward the anode sites under a bias voltage applied across the semiconductor. The PD is the innermost tracker, consisting of four barrel layers and three disk layers on each of the two endcaps. Individual silicon pixel sensor modules line each layer side-by-side to cover the entire layer plane. The SCT uses modules segmented in one-dimensional strips rather than pixels. There are four barrel and nine disk layers, each of which has two layers of strip modules back-to-back at a stereo angle of 40 mrad to provide space point measurements. Together, they provide high precision tracking up to $|\eta| < 2.5$ with at least 8 and 12 hits per track in the barrel and endcaps, respectively.

The Transition Radiation Tracker (TRT) [7] is a proportional drift tube system. The Ar/CO₂/O₂ gas mixture inside 4 mm-diameter “straw” tubes is ionised by the transition radiation of relativistic charged particles and the charges are collected by an anode wire running across centre of the tube and a cathode wall lining. The

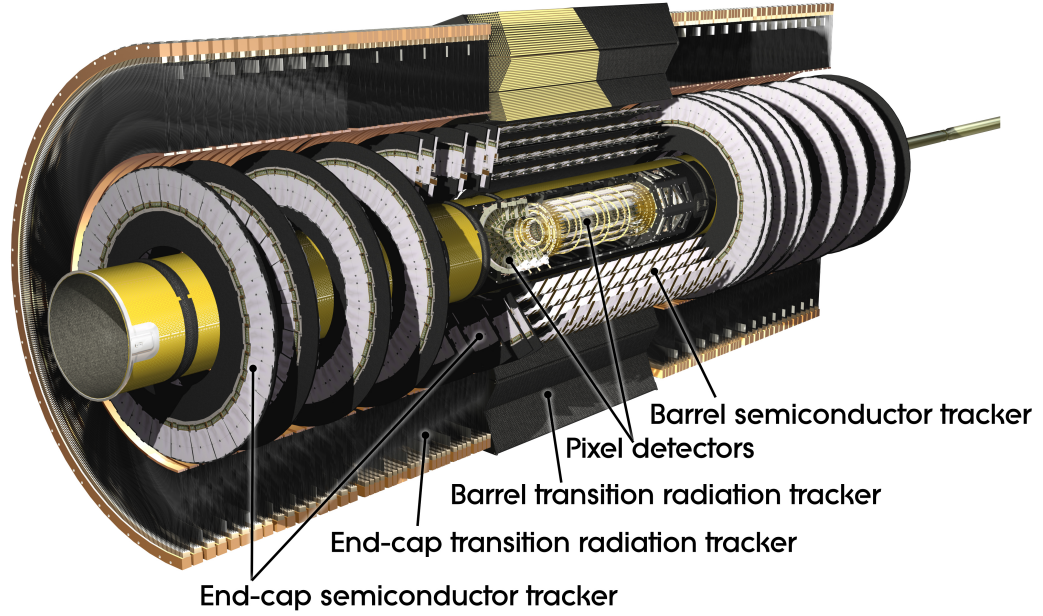


Figure 3.5: Cross-sectional view of the ATLAS Inner Detector, consisting of the Pixel Detector, Semiconductor Tracker, and Transition Radiation Tracker. [5]

barrel has straws running parallel to the beam-line, while the two endcaps arrange them radially, perpendicular to the beam-line. Despite only the $r - \phi$ information being available up to $|\eta| < 2.0$ from the TRT, its large number of more than 30 hits per track on average and optimised TR thresholds to distinguish particles contribute significantly to particle identification and momentum measurement of the ID.

3.2.3 Calorimetry

High-energy particles traversing through a dense medium undergo *showering* as they interact with the medium as produce cascades of secondary particles. The ATLAS calorimeters [8], shown in Figure 3.6, uses sampling calorimeters, which have alternating layers of absorber and active materials. The dense absorber material induces

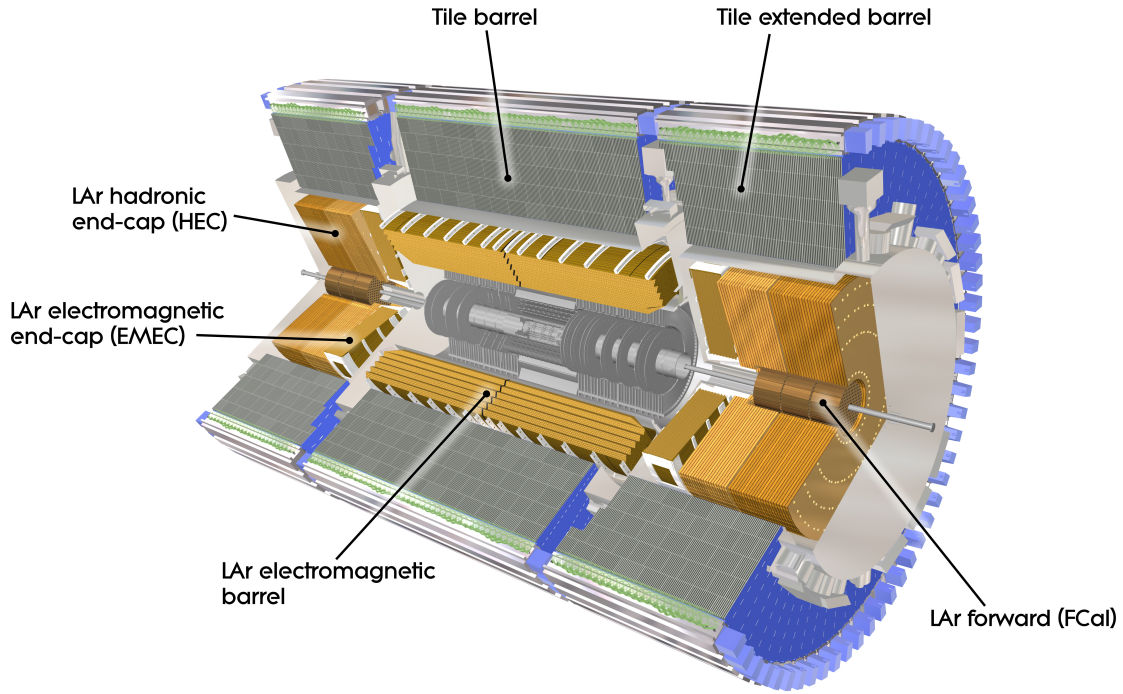


Figure 3.6: Cross-sectional view of the ATLAS calorimeters, consisting of the Liquid Argon, Tile, and Forward Calorimeters. [8]

showering of particles, while the active material produces an output signal proportional to their energies. Particle showering is classified into two categories by the incident particle—electromagnetic and hadronic—for which ATLAS deploys separate specialised calorimeter designs and technologies.

Electromagnetic calorimeters

Electromagnetic (EM) showers mainly consist of cascades of bremsstrahlung of electrons and pair-production from photons. The electromagnetic calorimeters are dedicated for measuring these processes from high energy electrons and photons.

The Liquid Argon (LAr) electromagnetic calorimeters use lead as absorber and LAr as active materials (lead-LAr). The barrel calorimeter (EMB) is a pair of halves joined

around the centre with a 4 mm gap, covering $0 \leq |\eta| < 1.475$. The endcaps (EMEC), one placed on each side, extend the coverage to $1.375 \leq |\eta| < 3.2$. An innovative design of the absorber-active material geometry, called the “accordion-shape”, allows for several active layers in depth without any cracks in ϕ -coverage. Calorimeters are also divided into several layers of $\Delta\phi \times \Delta\eta$ granularity, starting from 0.1×0.1 in the coarsest layer and becomes more finely segmented closer to the interaction region.

Hadronic calorimeters

Hadronic showers are inherently more complicated to measure than EM showers, in that hadrons can also interact through the weak and strong interactions (non-EM). A part of the the shower component interacting with the detector material in these non-EM processes may not produce an output signal. ATLAS hadronic calorimeters are *non-compensating*, meaning this “invisible” energy of the shower is not measured. As a result, they have a lower energy response to hadrons than to electrons and photons.

The Tile Calorimeter (TileCal) [9] is a steel/scintillator calorimeter. Plastic scintillator tiles are arranged in the plane perpendicular to the colliding beams and are radially staggered in depth. Scintillation light is guided out by wavelength-shifting (WLS) fibres to be measured by photomultiplier tubes (PMTs) at the outer radius. The innovative orientation of the tiles allows the WLS fibres to run straight to the PMTs without any bends, enabling the TileCal to have full ϕ -coverage.

The Forward Calorimeter (FCal) [10] is designed to provide electromagnetic and hadronic energy measurements in the most forward regions of the detector ($3.1 < |\eta| < 4.9$). The first module closest to the interaction point (FCal1) uses LAr/copper

to optimise for electromagnetic showers, while the other two (FCal2&3) are LAr/tungsten modules.

3.2.4 Trigger system

As explained in Section 3.1, proton bunches cross at a rate of 40 MHz. Due to the high bandwidth and computation resources necessary for the full detector readout and reconstruction of a collision event, it is impossible for every crossing to be fully processed. The ATLAS trigger system [11] reduces this down to a feasible rate of about 1 kHz. A *trigger* is a set of requirements that, if fulfilled, would signal an event of interest to be studied. Each event is checked from a pre-defined list of triggers and only those passing at least one trigger is allowed to be fully processed. The system is divided into two levels: Level 1 and High-Level Trigger.

The Level 1 (L1) system is hardware-based, using custom design electronics that processes detector signals received immediately from the front-end pipelines. It uses coarse calorimeter and muon system information to identify a physics signature of potential interest, called a Region-of-Interest (RoI). Only events containing RoIs that satisfy requirements of a trigger item are passed on to be further processed, which reduces the event rate to 100 kHz.

The High-Level Trigger (HLT) system is software-based, using sophisticated algorithms that process events using full detector information in the L1 RoIs or, for some signatures, the entire event. HLT accepts events at around the target rate of 1 kHz, after which they are written to data disks for full reconstruction.

Still, a trigger's requirements, if too broad and/or non-restrictive, may be passed at too high of a rate. Then, it must also undergo a secondary rate reduction in which,

probabilistically, only one out of a number of the events, called the *prescale* of the trigger, passing the trigger requirements will finally pass. This forces the trigger to pass events within its allowed rate budget.

Chapter 4

Data and simulation

4.1 2015-2017 ATLAS dataset

In particle physics, the event rate of a given process measured by a detector is given by:

$$\frac{dN}{dt} = \epsilon A \sigma L, \quad (4.1)$$

where ϵ and A are respectively the detector efficiency and acceptance factors, σ is the process cross section, and L is the instantaneous beam luminosity. The cross section has units cm^2 and the instantaneous luminosity $\text{s}^{-1}/\text{cm}^2$. Then, for a specified process, the integrated luminosity ($\mathcal{L}$) is a measure of the total amount of data collected over a data taking period:

$$\mathcal{L} = \int L dt, \quad (4.2)$$

usually expressed in unit $\text{fb}^{-1} = 1 \times 10^{39} \text{cm}^{-2}$. The ATLAS data acquisition system operates in discrete time intervals of about 1 min, called a luminosity block, in which the the system is dynamically adjusted according to the beam and detector conditions.

From 2015 to 2017, ATLAS has recorded about 80 fb^{-1} of inelastic pp collision physics data at $\sqrt{s} = 13 \text{ TeV}$.

From year to year, the LHC has delivered significantly increased luminosities, which has recorded by the ATLAS detector with high efficiency, as shown in Figure 4.1. The increase in the amount of collected data from year to year was achieved by focusing more protons into each bunch. This increases the chance of a hard scatter process occurring per bunch crossing, but at a cost of also increasing the number of undesired additional inelastic interactions called *pileup interactions*. The amount of pileup interactions is quantified by the mean number of interactions per bunch crossing (μ). Figure 4.2 shows the amount of pileup interactions seen by the ATLAS detector during the 2015–2017 period, and an event display with pileup interactions occurring on top of a hard scatter. The effects of pileup on this analysis is detailed in Chapter 6.

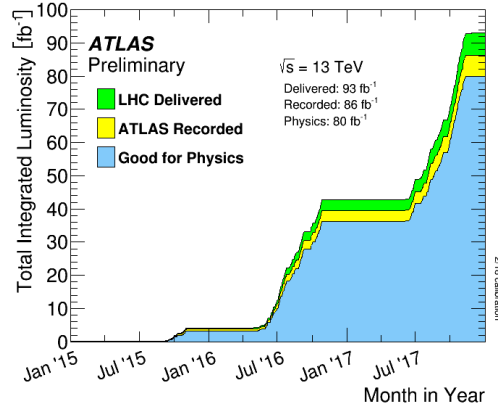


Figure 4.1: Total integrated luminosity in 2015–2017 pp collision data recorded by ATLAS detector at 13 TeV centre-of-mass energy. [12]

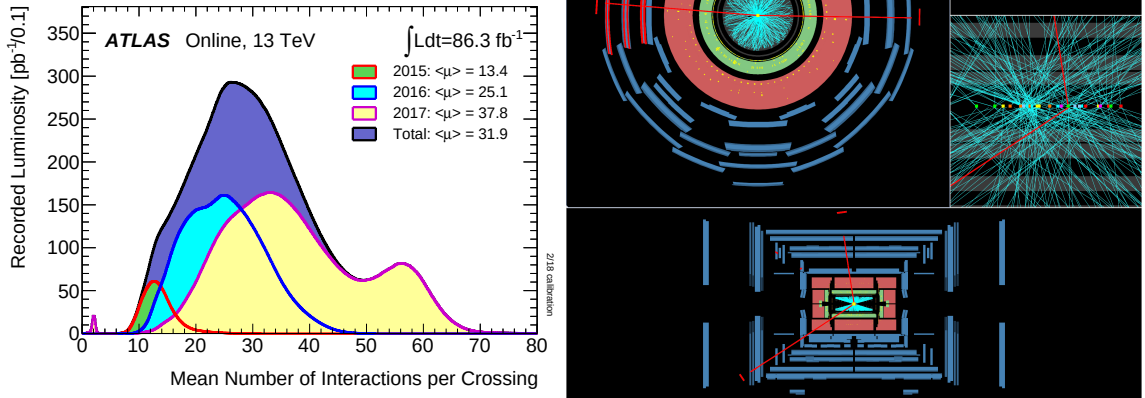


Figure 4.2: (left) Luminosity-weighted distribution of the mean number of interactions (μ) per bunch crossing crossing. (right) ATLAS detector event display of a pp collision recorded in 2017 containing a candidate $Z \rightarrow \mu\mu$ hard scatter on top of additionally reconstructed vertices from pileup interactions: the left shows the transverse plane, right the longitudinal plane, and the bottom zoomed in on the interaction region, the reconstructed vertices (squares) and tracks (lines). [12] [13]

4.2 Monte Carlo samples

Theoretical predictions of all physics processes in an inelastic pp collision, as described in Section 2.2, are necessary for them to be tested against experimental data. They are produced using Monte Carlo generation of events, shown in ???. All generators used in this analysis are accurate to leading-order calculation of the matrix element. Parton showering and hadronisation processes are emulated through phenomenological models. These three components are interfaced to PDFs produced from fits of previous experimental data. Configuration parameters of these generators that affect other aspects of the event, such as UE, are tuned to optimise modelling of observed data. The event generators used in this analysis are summarised in Table 4.1 — for brevity, they will be referred to as PYTHIA8, SHERPA, and HERWIG7.

The full detector response to all generated particles in the event record is simulated by a framework based on the GEANT4 toolkit [14]. Pileup activity is merged into the event during the digitization of hit signals. Finally, the digital readout of the detector is processed through the same reconstruction procedures used for real data.

Since both the physics and detector response in an event are fully dictated by simulation, MC samples constitute pseudo-datasets with two layers of information: (1) the true kinematics of particles according to theoretical predictions, called *truth-level*, and (2) the reconstruction of these events simulated from expected detector conditions and performance, called *reconstructed-level*.

Generator	PDF	Tune
PYTHIA 8.186	NNPDF2.3LO	A14
SHERPA 2.1.1	CT10	SHERPA
HERWIG 7.0.4	NNPDF3.0NLO	MMHT2014lo68cl

Table 4.1: Configurations of MC generators used in the analysis

Chapter 5

Jet reconstruction

5.1 Jet clustering algorithm

The purpose of a *jet clustering algorithm* is to define jets out of the observed particles in an event. The algorithms used by default in ATLAS are based on a sequential recombination procedure called *inclusive k_t* [15]. It starts from the list of the particles' four-momenta, each of which are “jet candidates”. First, distance measures between candidates i and j (d_{ij}), and a candidate i from the beam (d_{iB}) are defined as

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (5.1)$$

$$d_{iB} = k_{ti}^{2p} \quad (5.2)$$

where $\Delta_{ij} = (y_i - y_j) \oplus (\phi_i - \phi_j)$ is the angular distance between i and j and k_t is the transverse momentum¹². R is the jet radius parameter and p is a power parameter.

¹ $a \oplus b = \sqrt{a^2 + b^2}$

²For historical reasons, the transverse momentum is denoted as k_t in this algorithm. In all other cases, p_T will be used.

For all (i, j) combinations in the list, d_{ij} and d_{iB} are computed and the minimum is determined. If it is a d_{ij} , then (i, j) are merged into one candidate by summing their four-momenta. If it is a d_{iB} , then (i) is defined as a jet and removed from the list. The list is re-computed after either step. The algorithm repeats until no individual candidates remain.

There are two important requirements to be satisfied in order for a clustering algorithm to produce jets whose definitions are consistent and well-defined. First, the presence of additional particles with infinitesimal energies must not alter the jet's four-momentum. Second, collinear emissions from a single hard particle must not alter the jet's four-momentum, i.e. at some point in the algorithm, they are clustered into a single candidate with the four-momentum of the original parent. By construction, the inclusive k_t algorithms possess both of these properties, respectively called *infrared safety* and *colinear safety*.³ The $p = 1$ and -1 cases are respectively called

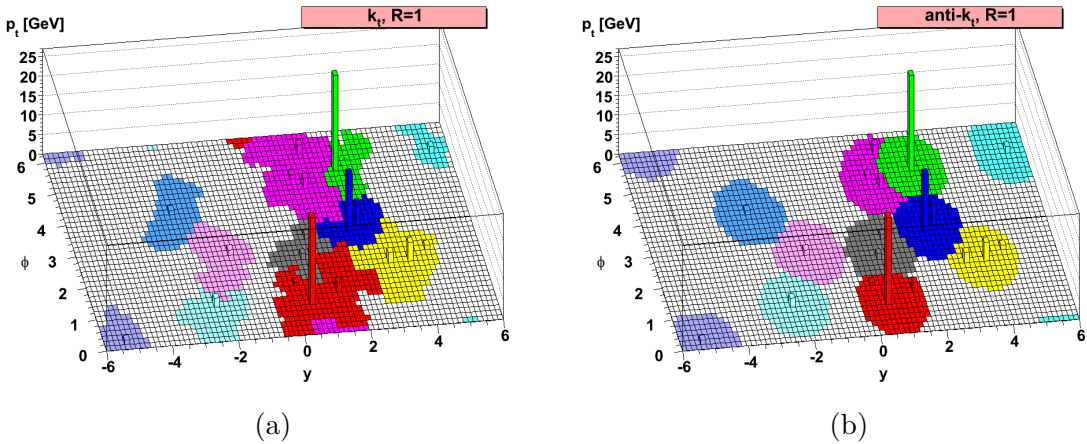


Figure 5.1: Jets defined from hadronic particles by the (a) k_t and (b) anti- k_t clustering algorithm. Different colours represent the area occupied by the jet.

k_t and anti- k_t . As shown in Figure 5.1 and explained further in Section 5.1.1, different algorithms exhibit differences from one another in their jet definitions. The k_t algorithm tends to be sensitive to soft radiation activity, often resulting in irregular

³In particle physics, the term *infrared* refers to low-energy, or equivalently long-distance, scales.

jet boundaries. The anti- k_t algorithm forms circular boundaries around the hardest particles, resulting in cone-shaped jets. In ATLAS, the anti- k_t with $R = 0.4$ is the primary clustering algorithm used to define jets, which are referred to as *small- R* jets.

5.1.1 Ghost particles

A powerful technique often used with jet clustering algorithms is adding particles with infinitesimal p_T , called *ghost particles*, in the jet candidate list. As explained in Section 5.1, adding ghost particles into a jet does not change the jet finding results or its four-momentum.

This technique can be used in various ways to quantify properties of the jet. One intuitive but powerful example is the aforementioned determination of a jet’s area and boundary. Ghost particles are added uniformly in (y, ϕ) -space, forming a grid. Tracking which ghost particles are clustered into a jet then reveal the area in which real particles, if they did exist within its boundary, would have been clustered together.

5.2 Constituent inputs

The anti- k_t algorithm clusters particles to form jets. In MC simulation, stable particles produced by the hadronisation can be used directly. This corresponds to what a “perfect” detector would measure; therefore, jets defined from such particles are referred to as *truth jets*. At the reconstructed-level, the detector signals of particles are processed into clustering algorithm inputs; jets defined from these signals are called *reconstructed jets*. Two types of reconstructed jets—calorimeter and particle-flow—are studied in this thesis.

5.2.1 Topological calorimeter cell clustering

Calorimeter cell signals are collected into three-dimensional topologically connected clusters, called topo-clusters [16], to reconstruct particle showers in the calorimeter. More generally, jets defined from topo-clusters are called calorimeter jets.

The cell signal significance ($\varsigma_{\text{cell}}^{\text{EM}}$) is defined as the ratio of the cell signal ($E_{\text{cell}}^{\text{EM}}$) to the average noise ($\sigma_{\text{noise,cell}}^{\text{EM}}$) at the electromagnetic scale.

$$\varsigma_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}} \quad (5.3)$$

The seeding, growth, and boundary of a topo-cluster is controlled by three respective cell significance threshold parameters ($S > N \geq P$).

$$\left| \varsigma_{\text{cell}}^{\text{EM}} \right| > \begin{cases} S & : \text{primary seed} \\ N & : \text{growth control} \\ P & : \text{boundary threshold} \end{cases} \quad (5.4)$$

ATLAS uses the ($S = 4, N = 2, P = 0$) configuration by default. The formation of topo-clusters follows a seed-and-collect followed by a splitting procedure. First, $\varsigma_{\text{cell}}^{\text{EM}}$ is computed for all cells. Starting from the seed cell with the highest $\varsigma_{\text{cell}}^{\text{EM}}$, neighbouring cells (adjacent in same sampling layer, or (η, ϕ) -overlapping in adjacent sampling layers) that satisfy either the growth or boundary thresholds are added until those whose neighbours satisfy the boundary threshold, but not the growth threshold, are collected. The clusters undergo a splitting procedure if they contain multiple local signal maxima ($E_{\text{cell}}^{\text{EM}} > 500 \text{ MeV}$) with at least four neighbours, all with less energy than the local maximum cell. This procedure is illustrated in Figure 5.2 [16]

Each topo-cluster is assigned a four-momenta with energy equal to the sum of its

associated cells, (y, ϕ) from the energy-weighted average of the cells, and mass equal to zero. Since they are designed to reconstruct the energy signatures of particle showers in the calorimeter rather than the particles themselves, individual topo-clusters can be from the full or fractional shower of a particle, or a combination of full and fractional showers from multiple particles.

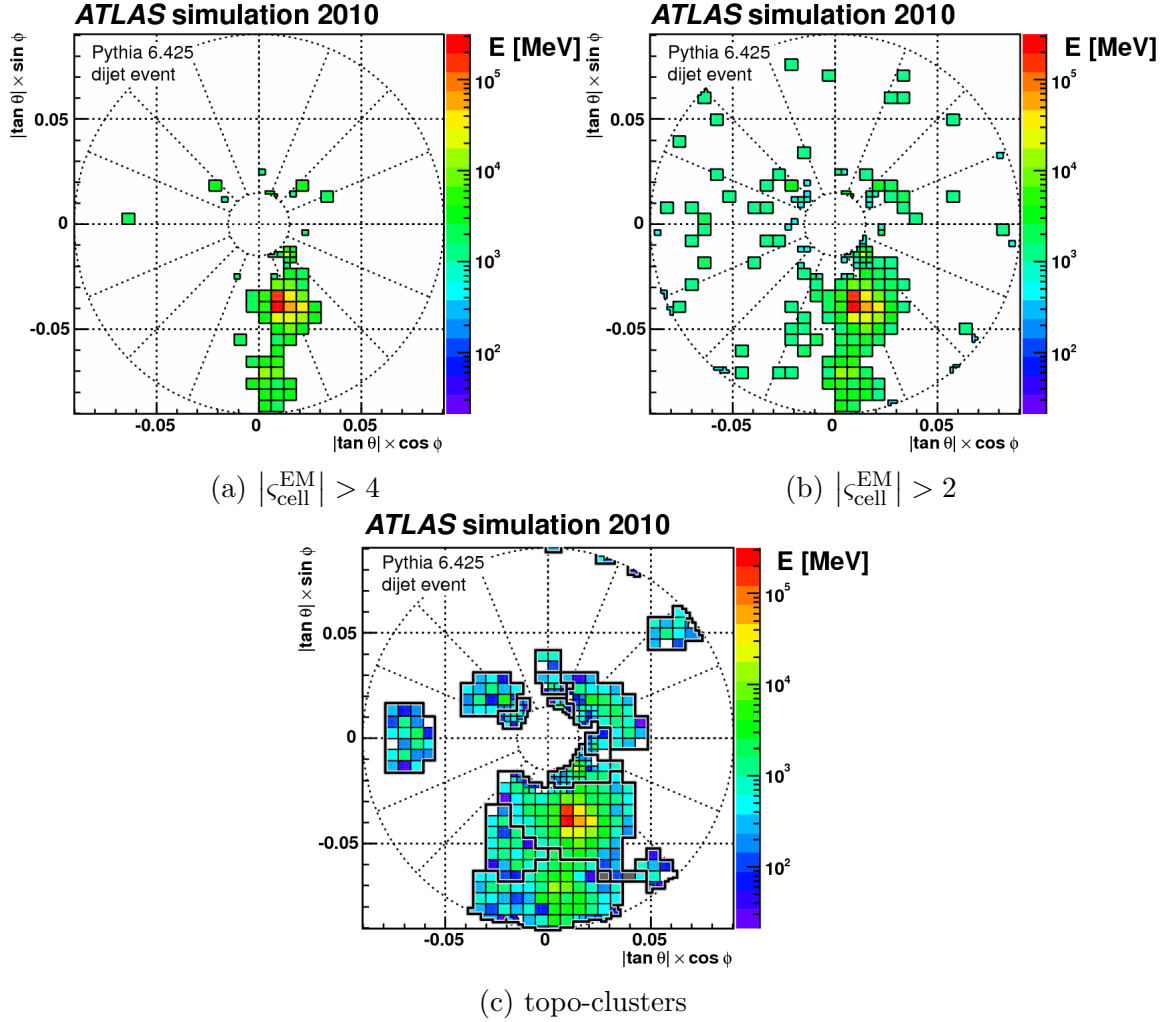


Figure 5.2: Stages of topo-cluster formation in the first module of the Forward Calorimeter (FCAL0) in a simulated dijet event with at least one jet entering this calorimeter, under no pileup and modelled electronic noise conditions [16]. All topo-clusters in (c) either have a seed cell in (a), or are seeded by one in another module. [16]

5.2.2 Particle-flow

The particle-flow algorithm [17] combines calorimetric and tracking information remove overlap between the energy and momentum measurements of the respective sub-detectors. As a result, the energy measurements of soft jets are more reliable due to better tracking performance relative to calorimetric measurements for low- p_T hadrons. The angular resolution obtained through tracks is also far superior to that from calorimeters. Finally, it provides intrinsic suppression of pileup jets, since tracks that do not originate from the hard scatter, along with their matched topo-clusters, can be entirely removed from the input list prior to clustering.

First, each charged particle track is matched to a set of topo-clusters based on the positions of the topo-clusters and the track extrapolated to the calorimeter layers. Additional topo-clusters are added until they contain the full expected shower energy of the particle, assumed to be a charged pion. Then it subtracts away the energy from topo-clusters based on the momentum measurement of the track. In the case that the energy deposited in the topo-cluster is consistent with being entirely from the single particle, it is removed. Otherwise, a cell-by-cell subtraction is performed to take away the particle's contribution to the topo-cluster. This procedure is illustrated in Figure 5.3. The removed topo-cluster information is then replaced by the tracking information.

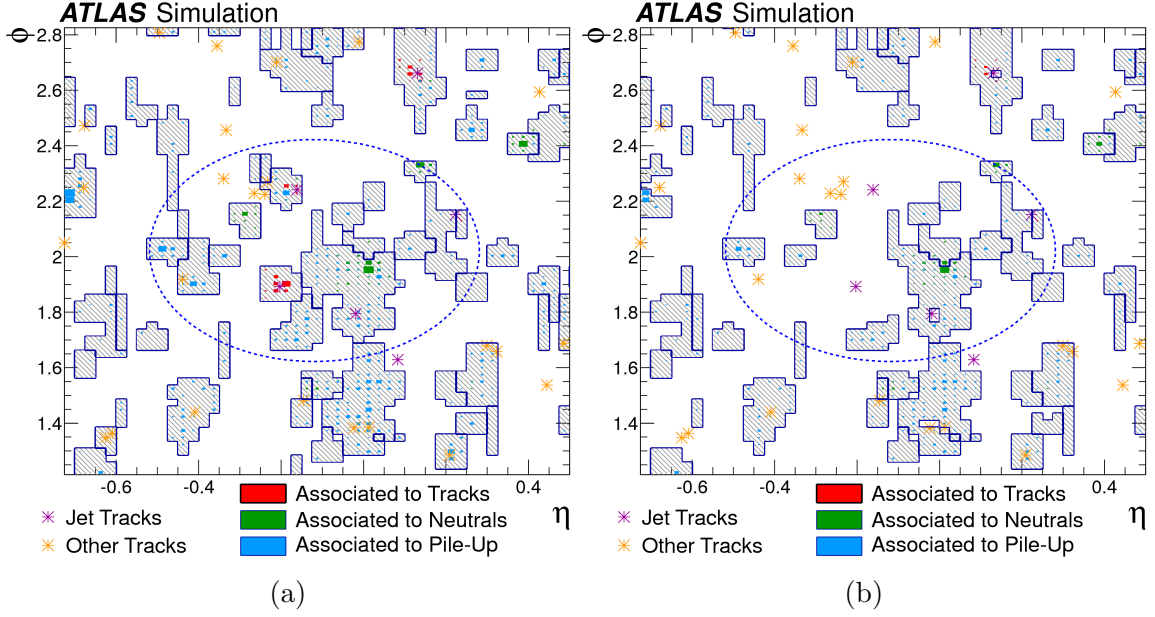


Figure 5.3: Particle-flow algorithm track matching and topo-cluster removal procedure in the second layer of the Barrel EM LAr calorimeter (EMB2) in the vicinity of a 30 GeV truth jet (ellipse). Tracks are extrapolated to the calorimeter (asterisks), where the cells are clustered into topo-clusters (blue rectangles). The tracks selected for particle-flow jet reconstruction (dark purple) are ones matched to the nominal hard-scatter primary vertex and clustered into the jet. Topo-clusters are matched to tracks (red), associated to neutral particles (green), or discarded as pileup (blue). [17]

5.3 Energy calibration

A reconstructed jet obtained immediately from the clustering algorithm has four-momentum equal to the sum of its constituents' four-momenta, and is referred to be at *constituent scale*.

$$p^{\text{const}} = \sum_{i=1}^{N_{\text{const}}} p_i^{\text{const}} = (E^{\text{const}}, \mathbf{p}^{\text{const}}) \quad (5.5)$$

Jet calibrations are derived as multiplicative scale factors to the components of the constituent scale four-momentum, with the exception of the pseudorapidity correc-

tion, which is applied as an offset:

$$(E, \eta, \phi, m) = (c_{\text{calib}} E^{\text{const}}, \eta^{\text{const}} + \Delta\eta, \phi^{\text{const}}, c_{\text{calib}} m^{\text{const}}) \quad (5.6)$$

$$c_{\text{calib}} = \prod_{i=1}^N c_{\text{calib},i} = c_{\text{PU}} \cdot c_{\text{JES}} \cdot c_{\text{GSC}} \cdot c_{\text{insitu}}, \quad (5.7)$$

where each $c_{\text{calib},i}$ corresponds to one of the calibration steps shown in Figure 5.4.

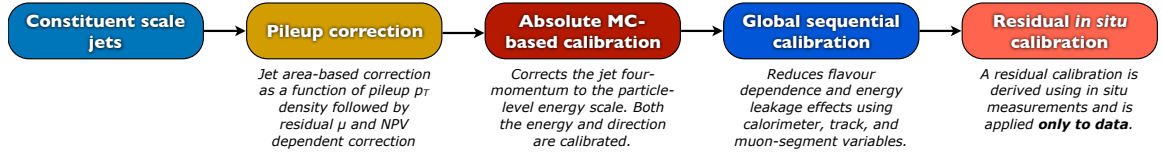


Figure 5.4: Calibration procedures applied to the reconstructed jets. [18]

5.3.1 Pileup correction

Two separate corrections are applied to correct the reconstructed jet p_T to mitigate effects in energy deposits from particles produced in pileup interactions [18].

The first correction approximates and then subtracts the expected pileup contribution to any given jet. This is done by first estimating event-by-event the pileup p_T density (ρ) using jets within $|\eta| < 2.0$ built from k_t algorithm due to its sensitivity to soft radiation background. Then, the area (A) of anti- k_t jets (A^{jet}) in (η, ϕ) -space are calculated using ghost particles, as explained in Section 5.1.1.

If the area-based subtraction was perfect, the jet p_T should be independent on the pileup activity. However, it is observed to have a residual dependence on pileup activity, as shown in Figure 5.6. Therefore, pileup activity is further parametrised by N_{PV} , the number of reconstructed primary vertices, and μ . Additional piecewise-

linear subtraction factors α and β are derived for these:

$$c_{\text{PU}} p_{\text{T}} = p_{\text{T}} - \rho A - \alpha(N_{\text{PV}} - 1) - \beta \mu. \quad (5.8)$$

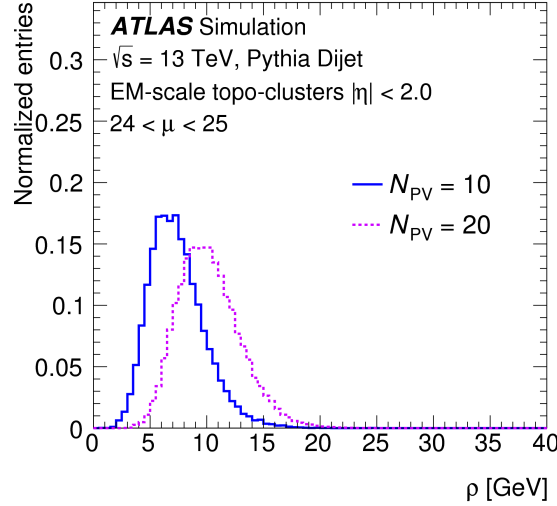


Figure 5.5: Per-event average p_{T} density at $N_{\text{PV}} = 10$ (solid) and $N_{\text{PV}} = 20$ (dotted) for $24 < \mu < 25$ as found in MC simulation, to be taken as ρ for the area-based correction factor. [18]

5.3.2 Absolute MC-based calibration

Due to the non-compensation, the measured EM-scale energy of a jet will tend to be lower than the true energy. As well, there are many other factors that also affect the reconstructed jet energy. An baseline calibration derived from MC simulation is applied to correct for all of these effects [18].

A truth jet and a reconstructed jet are defined to match if the two are within angular distance $\Delta R = \Delta\eta \oplus \Delta\phi < 0.3$ of each other. Then, the jet energy response ($\mathcal{R}$) is

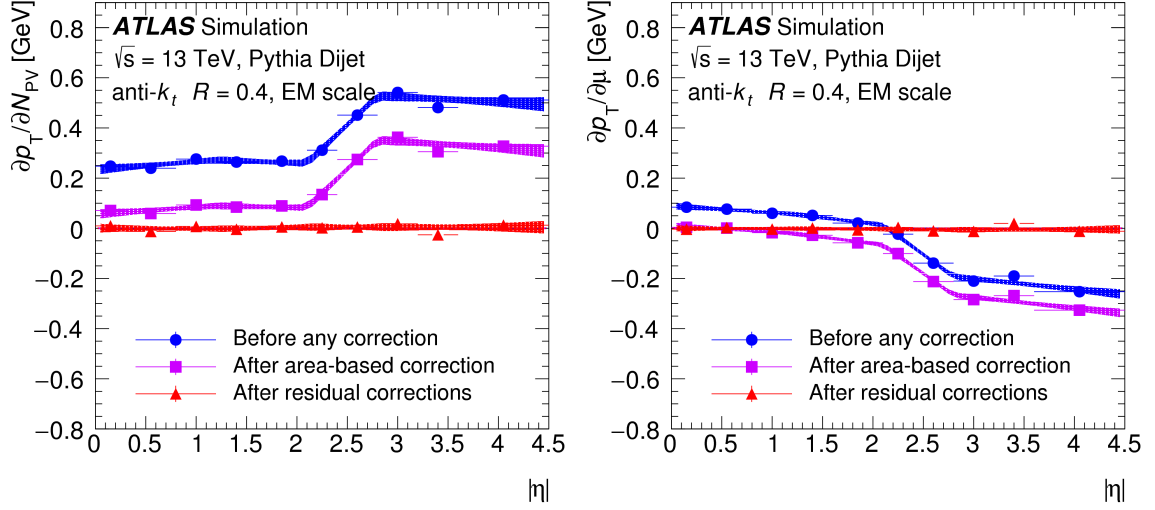


Figure 5.6: Dependence of jet p_T on N_{PV} (left) and μ (right) as a function of jet $|\eta_{\text{det}}|$ for $p_T^{\text{true}} = 25 \text{ GeV}$ before any pileup corrections (blue circle), after the area-based correction (violet square), and after the residual correction (red triangle). The values of the linear-fitted dependence after the area-based correction in 4 $|\eta_{\text{det}}|$ regions (purple band) are taken as the residual correction factors α and β .

determined as

$$\mathcal{R} = \frac{E_{\text{reco}}}{E_{\text{truth}}}, \quad (5.9)$$

where E_{reco} is the reconstructed jet energy after pileup correction, and E_{truth} is the energy of its matching truth jet.

The calibration is derived as the inverse of the average response,

$$c_{\text{JES}} = \frac{1}{\langle \mathcal{R} \rangle}, \quad (5.10)$$

in narrow bins of E_{truth} and the reconstructed jet η_{det} . It is then parametrised as a function of E_{reco} in each η_{det} bin such that the jet response is close to unity in each $(E_{\text{truth}}, \eta_{\text{det}})$ bin. An offset $\Delta\eta$ to the reconstructed jet pseudorapidity is applied to correct for biased direction reconstruction, notably in transition regions of the detector. These calibrations are shown in Figure 5.7.

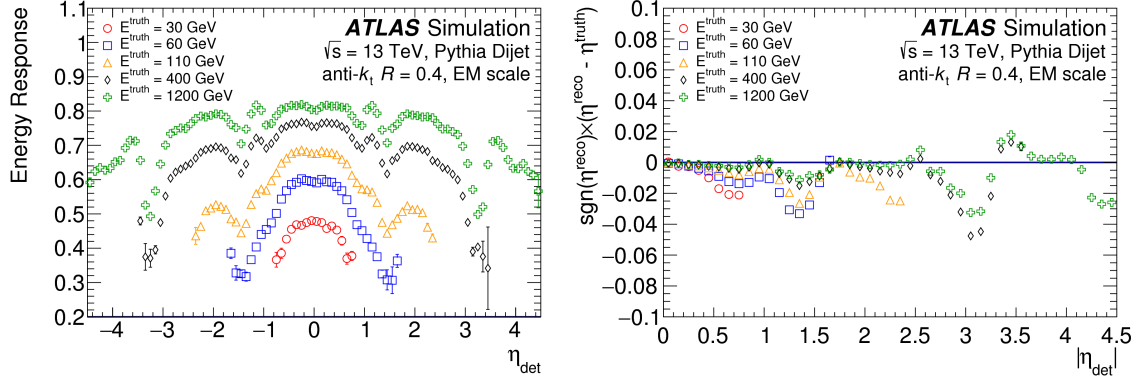


Figure 5.7: (a) The average energy response as a function of η_{det} for jets with a truth energy of 30, 60, 110, 400, and 1200 GeV, and (b) the signed difference between the truth jet η^{truth} and the reconstructed jet η^{reco} due to biases in the jet reconstruction. [18]

5.3.3 Global sequential calibration

The global sequential calibration (GSC) [19] improves precision of the jet calibration using features of a jet's shower development. For each detector variable x that characterises the jet shower, a correction factor $c(x)$ stabilises the jet response with respect to the variable, as shown in Figure 5.8:

$$c(x) = k \frac{1}{\langle \mathcal{R}(x) \rangle}, \quad (5.11)$$

where k is a constant chosen such that the overall response stays constant, and $\mathcal{R}(x)$ is the jet energy or p_{T} response. It is parametrised as a function of p_{T} and jet property x , $c(p_{\text{T}}, x)$, in η_{det} bins that reflect changes in response between different detector regions. Several calorimeter energy deposit and tracking variables are used:

1. f_{LAr3} , fraction of jet energy deposited in the third electromagnetic calorimeter layer.
2. f_{Tile0} , fraction of jet energy deposited in the first tile calorimeter layer.

3. n_{track} , number of reconstructed tracks matched to calorimeter clusters.
4. w^{track} , the tracks' p_{T} -weighted average distance from the jet axis.
5. n_{segments} , the number of muon segments with track activity behind the jet.

They are applied sequentially, with each step derived from the calibrated energy up to the previous step:

$$c_{\text{GSC}} = \prod_{i=1}^N c_i(p_{\text{T}}^{i-1}, x_i). \quad (5.12)$$

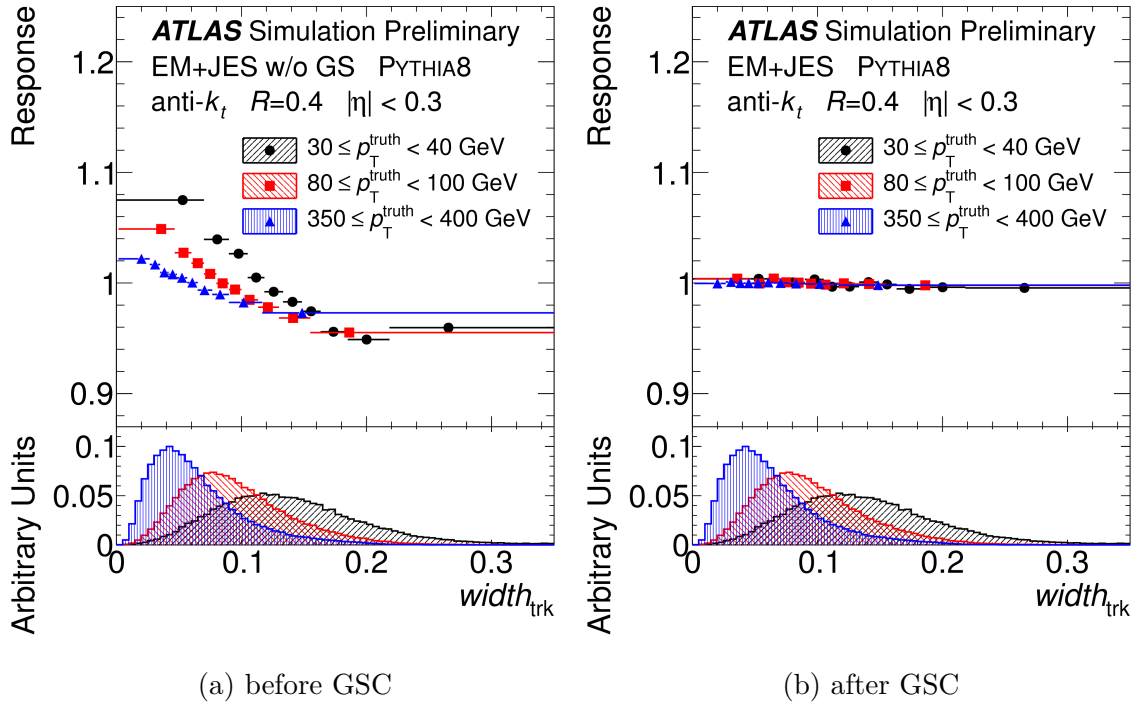


Figure 5.8: Average p_{T} response with respect to w^{track} of jets in $0.3 \leq |\eta| < 1.3$ several p_{T} bins (above) and the underlying w^{track} distributions (below) before (left) and after (right) application of GSC. [18]

5.3.4 Residual *in situ* calibration

The MC-based calibration corrects for the EM-scale response to bring the jet energy to the particle-jet level. Biases that may be present from mismodelling effects in MC simulation are determined using events with topologies in which the jets are expected to be balanced in momentum with respect to a well-measured reference object. A residual *in situ* correction is derived as the p_T response ratio between MC and data, and only applied to data [18]:

$$\frac{1}{c_{\text{insitu}}} = \frac{\mathcal{R}_{\text{data}}}{\mathcal{R}_{\text{MC}}} = \frac{\langle p_T^{\text{jet}}/p_T^{\text{ref}} \rangle_{\text{data}}}{\langle p_T^{\text{jet}}/p_T^{\text{ref}} \rangle_{\text{MC}}}. \quad (5.13)$$

Relative η -intercalibration

If the absolute MC calibration had a perfect description of the detector in simulation, the jet energy response is expected to be flat as a function of η . However, it is observed to be non-uniform, notably in transition regions of the detector that are difficult to model, as well as due to discrepancies in the distribution of dead material. η -intercalibration calibrates the jet response of the forward detector region ($0.8 < |\eta| < 4.5$) with respect to the well-calibrated central region ($|\eta| < 0.8$). Figure 5.9 shows the relative response of the forward jet with respect to the central reference jet.

Absolute Z/γ +jet and Multijet balance

Photons and electrons, which deposit all their energy in electromagnetic showers in the calorimeters, and muons, which produce tracks both in the ID and Muon Spectrometers, can all be measured much more precisely than jets. Thus, events in

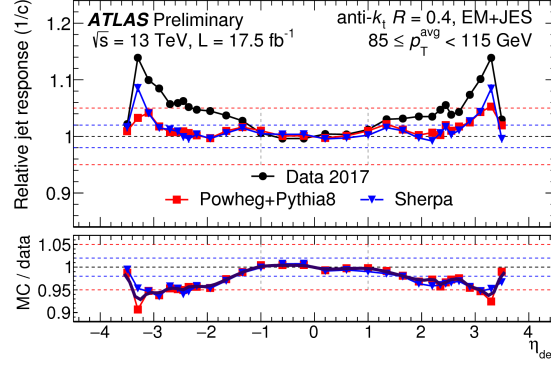


Figure 5.9: Relative jet response as a function of probe jet η_{det} for in dijet events with $85 < p_T^{\text{avg}} < 115 \text{ GeV}$. [18]

which a jet recoils against a Z boson, which decays via $Z \rightarrow ee/\mu\mu$, or a photon provide a precise, independent reference to measure the jet energy response [18]. These topologies are statistically limited to be effective in the central detector region ($|\eta| < 0.8$) for jets with $30 \leq p_T < 950 \text{ GeV}$. Subsequently, the recoil system of well-calibrated jets against a single high- p_T jet is used to extend the calibration up to $p_T < 2000 \text{ GeV}$. The three calibrations are combined into one, as shown in Figure 5.10.

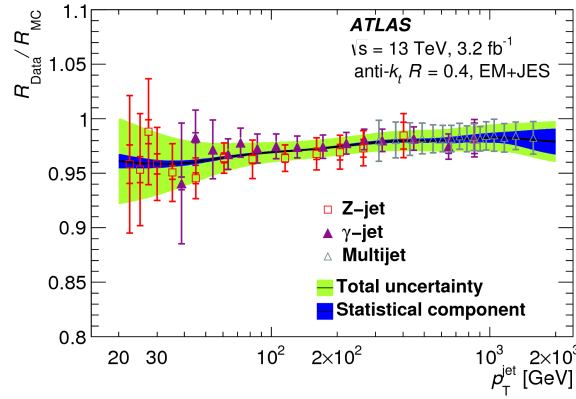


Figure 5.10: Combined *in situ* calibration of jets using $Z/\gamma + \text{jet}$ and multijet events. [18]

5.4 Trigger-level jets

As explained in Section 3.2.4, the trigger system must make near-instantaneous judgments on whether or not an event contains an interaction of interest or not. Jets are reconstructed very coarsely at the trigger-level to serve as valuable inputs in making these decisions.

At L1, a jet RoI is defined using a sliding window algorithm on the EM calorimeter trigger towers. A 2×2 local maximum in granularity of $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ is located, and it is deemed a RoI if the surrounding 8×8 region has total E_T from the EM and hadronic calorimeters that exceeds a predefined noise threshold. The local maximum core defines the coordinates of the jet RoI [20].

At HLT, jets are defined from anti- k_t $R = 0.4$ using topo-clusters. Then, they are calibrated following a customised version of the procedures used in full calibration. Pileup subtraction and MC-based absolute calibration are applied⁴. As of 2017, GSC using only calorimeter-based variables, as well as residual *in situ* calibrations, have also become available [21].

⁴Though equivalent in procedures, trigger-level calibrations often use older and carefully validated data.

Chapter 6

Analysis

6.1 Overview

The *jet energy resolution* quantifies the amount of fluctuations in the measurement of a reconstructed jet's energy at a fixed particle-level energy. The ATLAS calorimeters were designed to give a Gaussian energy response, which is observed both in simulation and data to a good approximation [18][8]. Hence, the relative jet energy resolution is defined to be the standard deviation of energy measurements over the mean, denoted by:

$$\frac{\sigma_E}{E}. \tag{6.1}$$

Due to the negligible contributions of the mass and angular resolution in small- R anti- k_t jets, the transverse momentum resolution is approximately synonymous with energy resolution, and colloquially taken to be as such:

$$\frac{\sigma_E}{E} \approx \frac{\sigma_{p_T}}{p_T}. \tag{6.2}$$

This is the quantity measured in this thesis.

An *in situ* calibration technique introduced in Chapter 5—momentum balance between two jets in dijet events—can also be used in the jet energy resolution measurement. Momentum is conserved from the initial system of incoming partons to the final system of outgoing particles. In the centre-of-mass frame of a dijet event, the outgoing jets’ transverse momenta and rapidities are balanced. The transformation in rapidity for a boost along the beam axis is additive:

$$y \xrightarrow{\beta=v/c} y - \tanh^{-1} \beta. \quad (6.3)$$

In the detector frame, the rapidities of the jets are boosted by the initial system’s momentum along the beam axis, meaning the jets can shower into different regions (η_{det}) of the detector, as shown in Figure 6.1. Meanwhile, the transverse momenta of the jets will remain invariant with respect to the longitudinal boost between the two frames:

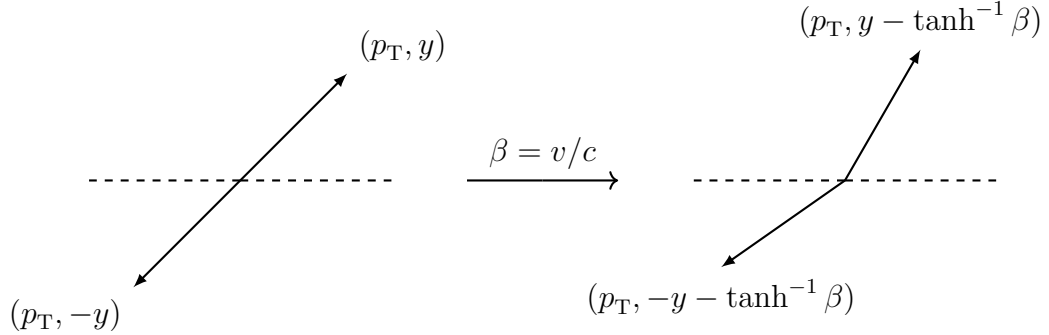


Figure 6.1: A dijet event viewed from the centre-of-mass (left) and detector (right) frame.

Define *asymmetry* of the dijet system as

$$\mathcal{A} = \frac{p_T^{\text{probe}} - p_T^{\text{ref}}}{p_T^{\text{avg}}}, \quad (6.4)$$

where p_T^{ref} is the transverse momentum of the jet in a well-measured reference region, p_T^{probe} is of the jet being studied in detector region $\eta_{\text{det}}^{\text{probe}}$, and $p_T^{\text{avg}} = (p_T^{\text{probe}} + p_T^{\text{ref}})/2$. For dijet events produced at a fixed particle-level $(p_T^{\text{ref}}, p_T^{\text{probe}})$, the widening of the

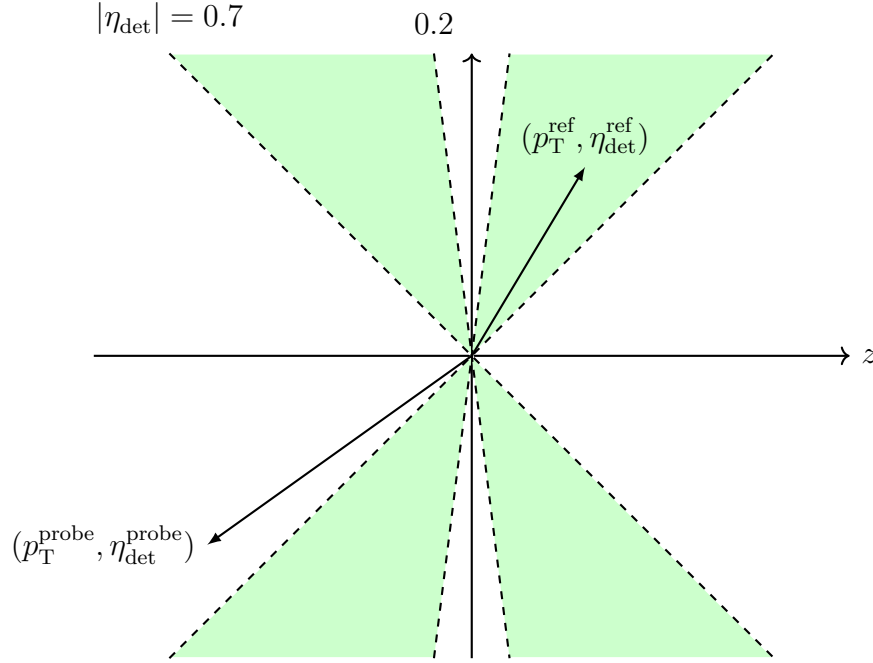


Figure 6.2: A dijet system forming a transverse momentum balance, with one jet in the well-measured reference region (green) and the other in a probe region (white) being studied

asymmetry due to the detector resolution ($\sigma_{\mathcal{A}}^{\text{det}}$) can be expressed in terms of the jet energy resolutions of the reference and probe jets as

$$\sigma_{\mathcal{A}}^{\text{det}} = \left(\frac{\sigma_{p_T}}{p_T} \right)^{\text{ref}} \oplus \left(\frac{\sigma_{p_T}}{p_T} \right)^{\text{probe}}. \quad (6.5)$$

The reference region is defined to be $0.2 \leq |\eta| < 0.7$, which is considered the region of the ATLAS calorimeters with the best energy resolution.¹ The jet energy resolution is studied as a function of p_T^{avg} and $\eta_{\text{det}}^{\text{probe}}$. For events in which both jets fall in the reference region, they have the same resolution. Subsequently, the probe region jet energy resolution is obtained by subtracting the reference jet energy resolution from

¹This is based on recent, unpublished studies in MC simulation, but also consistent with the results presented herein.

the asymmetry resolution:²

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^{\text{ref}} = \frac{\sigma_{\mathcal{A}}^{\text{ref}}}{\sqrt{2}}, \quad (6.6)$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^{\text{probe}} = \sigma_{\mathcal{A}}^{\text{probe}} \ominus \left(\frac{\sigma_{p_T}}{p_T}\right)^{\text{ref}}. \quad (6.7)$$

The asymmetry resolution is measured in discrete bins of p_T^{avg} , which constrains both the reference and probe jet p_T scale.

6.2 Trigger strategy

Single-jet triggers, which search for individual jets in the detector, are used in this analysis. Because there is a significant transition in calorimetry from EMEC/HEC to FCal around $3.1 \leq |\eta_{\text{det}}| < 3.2$, two separate chains of HLT(L1) single-jet triggers, central and forward, search for jets in $|\eta_{\text{det}}| < 3.2(3.1)$ and $|\eta_{\text{det}}| \geq 3.2(3.1)$, respectively. Multiple triggers exist in each chain, defined by a threshold requirement on the *transverse energy* (E_T) of the trigger-level jet:

$$E_T = \frac{E}{\cosh(\eta)}. \quad (6.8)$$

As will be shown, using a logical-OR combination of a central and forward single-jet trigger at each E_T threshold yields significant benefits over using either one individually in collecting dijet event data.

² $a \ominus b = \sqrt{a^2 - b^2}$

6.2.1 Efficiency calculation

The efficiency of the trigger is the fraction of events of interest accepted by the trigger:

$$\epsilon^{\text{trig}} = \frac{N^{\text{pass}}}{N^{\text{all}}}, \quad (6.9)$$

where N^{all} is the total number of events of interest, and N^{pass} is the number of the subset of these events passing the trigger requirements. Usage of an inefficient trigger without dedicated correction factors can introduce severe biases in measurements performed with the collected data; therefore, it is important to have a trigger selection that is fully efficient, i.e. $\epsilon = 1$ to a good approximation.

When using single-jet triggers to collect dijet events, there are four possible scenarios:

1. Neither trigger nor forward trigger requirements pass (00).
2. Only central trigger requirements pass (10).
3. Only forward trigger requirements pass (01).
4. Both central and forward trigger requirements pass (11).

The set of events collected by the chosen trigger strategy is given by:

$$N^{\text{pass}} = \begin{cases} (\sigma^{10} + \sigma^{11})\mathcal{L}^{\text{ctr}} & : \text{central trigger only} \\ (\sigma^{01} + \sigma^{11})\mathcal{L}^{\text{fwd}} & : \text{forward trigger only} \\ (\sigma^{10} + \sigma^{01} + \sigma^{11})\mathcal{L}^{\text{comb}} & : \text{trigger combination} \end{cases} \quad (6.10)$$

where σ^{ab} are the cross sections of the trigger scenarios $ab = (00, 10, 01, 11)$, and $\mathcal{L}^{\text{trig}}$ for $\text{trig} = (\text{ctr}, \text{fwd}, \text{comb})$ are respectively the luminosities collected by the central,

forward, and their combined triggers, explained in Section 6.2.2. Meanwhile, the total to be collected also includes the inefficient case in which events do not pass either trigger's requirements.

$$N^{\text{all}} = (\sigma^{00} + \sigma^{10} + \sigma^{01} + \sigma^{11})\mathcal{L}^{\text{comb}} \quad (6.11)$$

First, the trigger usage must be restricted to a kinematic region in which the event must pass the requirements of at least one of the triggers ($\sigma^{00} = 0$). However, as shown in Equation 6.10, events that pass the requirements of only one of the central or forward triggers cannot be collected by the other, which means using either one trigger may still be inefficient. The only way to guarantee full efficiency is to combine both triggers to collect the data.

Trigger efficiencies are calculated using the so-called *tag-and-probe* technique. First, an unbiased sample of events containing jets is obtained using an already fully efficient *tag* trigger with a less stringent requirement than the *probe* trigger being studied. Then, the probe trigger is emulated in these events to determine those that pass its requirements. Finally, the efficiency of the probe trigger is estimated by the fraction of events passing its requirements out of the total. Lowest E_{T} threshold triggers are tagged by pass-through triggers, which fire randomly per bunch crossing and are thus fully efficient by construction. Since the main requirement of a trigger is the jet E_{T} threshold, one that reaches full efficiency at some $p_{\text{T}}^{\text{avg}}$ should remain so for higher $p_{\text{T}}^{\text{avg}}$; therefore, it can be used to probe another with higher E_{T} threshold. This process is performed successively for all triggers to be used.

As shown in Figure 6.3, neither the central nor forward single-jet trigger becomes fully efficient for events in which the probe jet falls in the $3.5 \leq |\eta_{\text{det}}| < 4.5$ region of the detector. Their combination, on the other hand, is fully efficient for $p_{\text{T}}^{\text{avg}} \geq 115 \text{ GeV}$.

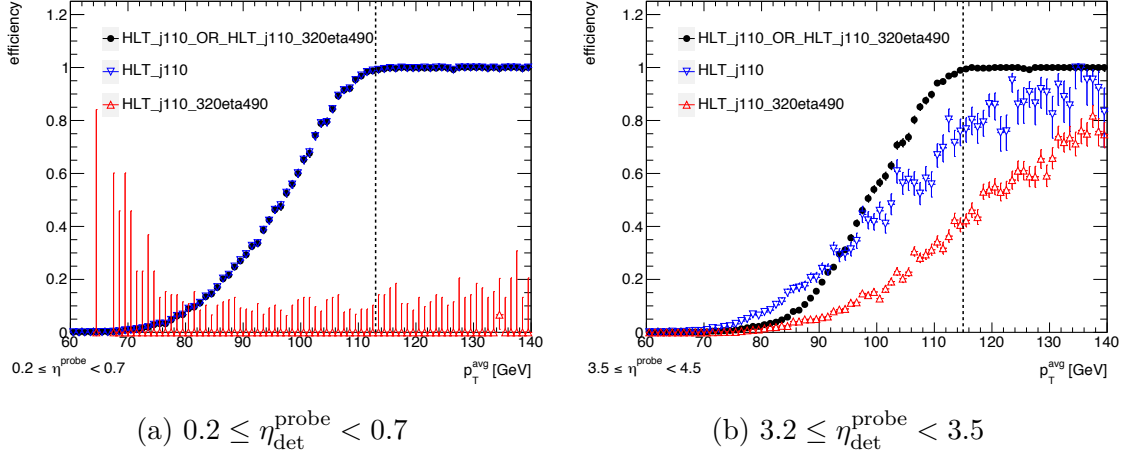


Figure 6.3: Trigger efficiency calculated using Equation 6.9 as a function of p_T^{avg} in a given $\eta_{\text{det}}^{\text{probe}}$ bin. Neither single-jet trigger reaches full efficiency individually, but their combination does.

Consequently, trigger combination allows the data collected in this kinematic region, which would have otherwise been discarded, to be used.

Finally, the lowest p_T^{avg} point at which a trigger reaches full efficiency, called the trigger's *turn-on* point, is identified for all triggers. The turn-on point of a trigger is estimated to be the lowest p_T^{avg} point to reach and retain at least 99% efficiency across $\eta_{\text{det}}^{\text{probe}}$ plus some conservative safety margin, as shown in Figure 6.4.

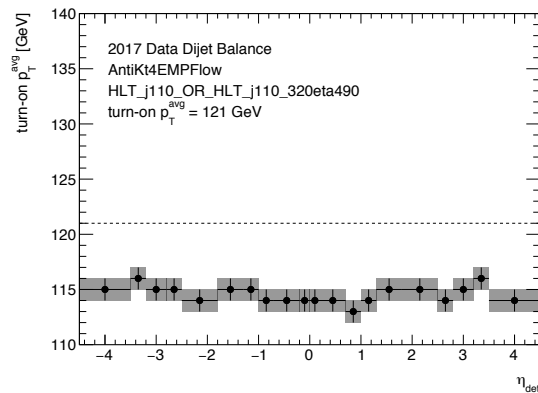


Figure 6.4: Turn-on point of HLT_j110 OR HLT_j110_320eta490 trigger combination set to across $\eta_{\text{det}}^{\text{probe}}$ bins

6.2.2 Luminosity calculation

As explained in Section 3.2.4, the prescale of a trigger (s^{trig}) probabilistically passes only a fraction of events passing requirements of the trigger that would otherwise pass events at too high of a rate:

$$s^{\text{trig}} = \frac{1}{P(a^{\text{trig}} = 1 \mid r^{\text{trig}} = 1)}, \quad (6.12)$$

where r^{trig} and a^{trig} are booleans indicating whether or not the trigger's requirements have been passed and has passed the prescale, respectively. As a result, the luminosity collected by the trigger from a dataset is given by:

$$\mathcal{L}^{\text{trig}} = \sum_{\text{lbn}} \frac{\mathcal{L}_i^{\text{tot}}}{s_i^{\text{trig}}}. \quad (6.13)$$

where in each luminosity block i , respectively, $\mathcal{L}_i^{\text{tot}}$ is the total collected luminosity and s_i^{trig} is the trigger prescale.

In the case of a trigger combination, as prescribed by the *inclusion method* [22], its prescale is categorised based on the trigger requirements:

$$s^{\text{comb}} = \begin{cases} \frac{1}{P(a^{\text{ctr}} = 1 \mid r^{\text{ctr}} = 1)} = s^{\text{ctr}} & : (r^{\text{ctr}} r^{\text{fwd}}) = (10) \\ \frac{1}{P(a^{\text{fwd}} = 1 \mid r^{\text{fwd}} = 1)} = s^{\text{fwd}} & : (r^{\text{ctr}} r^{\text{fwd}}) = (01) , \\ \frac{1}{P(a^{\text{ctr}} + a^{\text{fwd}} = 1 \mid r^{\text{ctr}} = r^{\text{fwd}} = 1)} = \frac{s^{\text{ctr}} s^{\text{fwd}}}{s^{\text{ctr}} + s^{\text{fwd}} - 1} & : (r^{\text{ctr}} r^{\text{fwd}}) = (11) \end{cases} \quad (6.14)$$

where $\text{trig} = (\text{ctr}, \text{fwd}, \text{comb})$ respectively denote the central, forward, and their combined trigger. Consequently, combination effectively results in a lower applied prescale and a higher collected luminosity than individual triggers.

6.2.3 Trigger combination

The demonstrated efficiency and luminosity gains are compounded due to the steeply falling dijet cross section with respect to p_T^{avg} . A single-jet trigger with a lower E_T threshold requirement is applied a much higher prescale than their higher siblings. Therefore, it is desirable to use the trigger such that they are fully efficient, yet with the lowest E_T threshold requirement. Consequently, not only does trigger combination expand the kinematic region in which which lower E_T threshold triggers can be used with full efficiency, it also accepts more events than using either one individually within the region.

For each trigger combination, the p_T^{avg} range in which it is uniquely the fully efficient with the lowest applied prescale, called the *turn-on* range, is identified. As shown in Table 6.1 and Figure 6.5, trigger combinations are only used in their respective turn-on regions. Furthermore, correct categorised luminosity calculation should yield an unbiased distribution of asymmetry.

Trigger combination		Turn-on p_T^{avg} range
central	forward	[GeV]
HLT_j15	HLT_j15_320eta490	[25,35)
HLT_j25	HLT_j25_320eta490	[35,50)
HLT_j35	HLT_j35_320eta490	[50,65)
HLT_j45	HLT_j45_320eta490	[65,85)
HLT_j60	HLT_j60_320eta490	[85,110)
HLT_j85	HLT_j85_320eta490	[110,125)
HLT_j110	HLT_j110_320eta490	[125,195)
HLT_j175	HLT_j175_320eta490	[195,280)
HLT_j260	HLT_j260_320eta490	[280,380)
HLT_j360	HLT_j260_320eta490	[380,475)
HLT_j460	HLT_j260_320eta490	[475,1500)

Table 6.1: Trigger combination turn-on p_T^{avg} regions. Each trigger combination is specified a p_T^{avg} region in which it is fully efficient and is applied the lowest prescale.

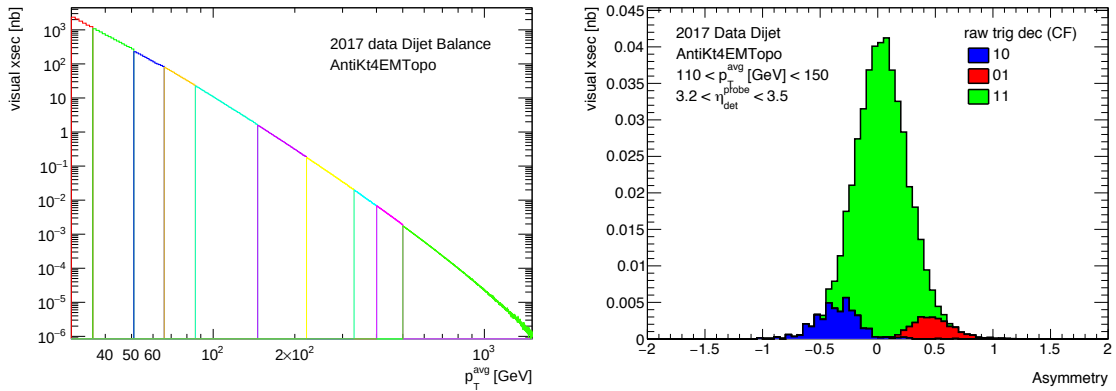


Figure 6.5: Dijet visual cross section versus (left) p_T^{avg} with different colours indicating different trigger combinations used in their respective turn-on regions and (right) asymmetry with (01,10,11) denoting the categories explained in Equation 6.14.

6.3 Dijet event selection

Throughout the data taking period, several factors can lead to degradation in quality of data recorded by the ATLAS detector. These include non-collision backgrounds, such as cascades from proton losses in the beam and cosmic-rays, as well as temporary detector errors, such as noise spikes. The detector is monitored around-the-clock and the recorded luminosity blocks passing data quality checks status are compiled into a good-runs-list (GRL) [23]. Only events marked to be of sufficient quality for physics analyses, as indicated by the GRL, are selected; events during which select detector components reported suboptimal operation are further vetoed.

In order to ensure that events contain a pp collision, they are required to have at least one reconstructed primary vertex along the beam axis ($N_{\text{PV}} \geq 1$) with at least two tracks pointing towards the hardest scatter vertex ($n_{\text{track}}^{\text{PV0}} \geq 2$). The trigger selection outlined in Section 6.2 is applied only on data passing these basic requirements.

Two requirements are placed on quality of reconstructed jets. First, jet cleaning [24] is a criteria to reject jets likely produced from non-collision backgrounds or during detector noise spikes. Second, the Jet Vertex Tagger (JVT) [25] is a likelihood discriminant based on tracks to identify jets that do originate from the hard scatter. It is applied on low- p_{T} jets ($20 \leq p_{\text{T}}^{\text{jet}} < 60 \text{ GeV}$) within tracking acceptance ($|\eta_{\text{det}}| < 2.4$) to reject *pileup jets* that originate from pileup interactions. Events are required to have the two leading—meaning highest p_{T} —jets pass both cleaning and $\text{JVT} > 0.59(0.2)$ for topo-cluster(particle-flow) jets. Also, the third jet in the event is defined to be the one that passes the same cleaning and JVT requirements as the leading two.

Kinematic criteria on jets in the event are applied to enforce dijet topology. Events are required to have a large azimuthal separation between the two leading jets ($\Delta\phi(j_1, j_2) >$

2.7) and a third jet, if one exists, that carries only a small fraction of the dijet system transverse momentum ($p_T^{j_3} < \max(25 \text{ GeV}, 0.25 \cdot p_T^{\text{avg}})$). The impact of this selection is shown in Figure 6.6.

The track record of the number of events remaining after each selection, called the cut-flow, is presented in Table 6.2.

Event selection	Number of events	
	calorimeter	particle-flow
All	338857664	
GRL	333621504	
LAr/TileCal quality	333369856	
Primary vertex	333364576	
Trigger strategy	271445888	
≥ 2 jets	270467200	264772928
Jet cleaning	269701664	264772928
JVT	235873520	252889024
Dijet topology	13469030	13301840

Table 6.2: Remaining number of events after requirements.

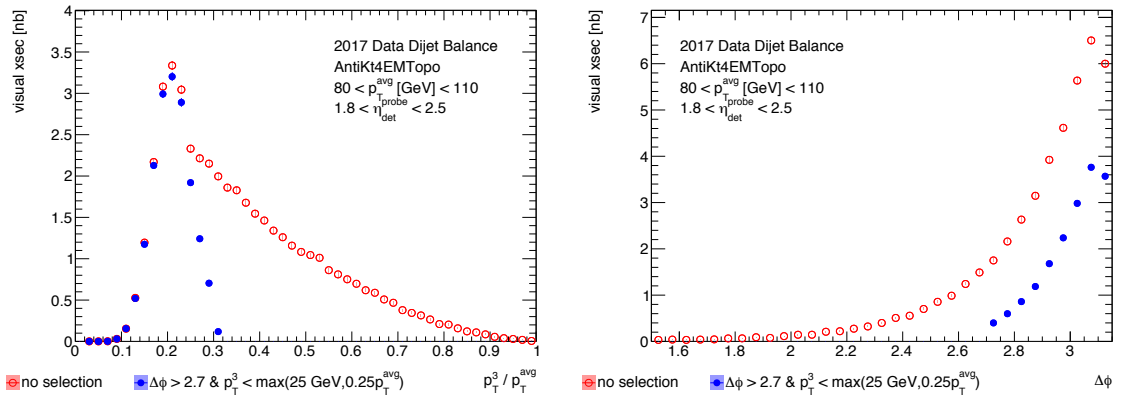


Figure 6.6: Distributions of dijet topology kinematic variables $p_T^{j_3}/p_T^{\text{avg}}$ (left) and $\Delta\phi(j_1, j_2)$ (right) before (red) and after (blue) selections for events with ($55 \leq p_T^{\text{avg}} < 80 \text{ GeV}$, $0.2 \leq \eta_{\text{det}}^{\text{probe}} < 0.7$)

6.4 Truth-level asymmetry

Perfect momentum balance only holds for an ideal, leading-order $2 \rightarrow 2$ parton system. In a realistic pp dijet event, as shown in Figure 6.7, the balance between the two jets will be spoiled by several factors. Though isotropic in ϕ on average, initial state radiation from incoming partons will boost the hard scatter centre-of-mass system to a non-zero initial- p_T state. As well, the full parton shower of an outgoing parton may not necessarily be fully captured by the clustering algorithm due to final state radiation from the parton, an effect called *out-of-cone* (OOC) radiation.

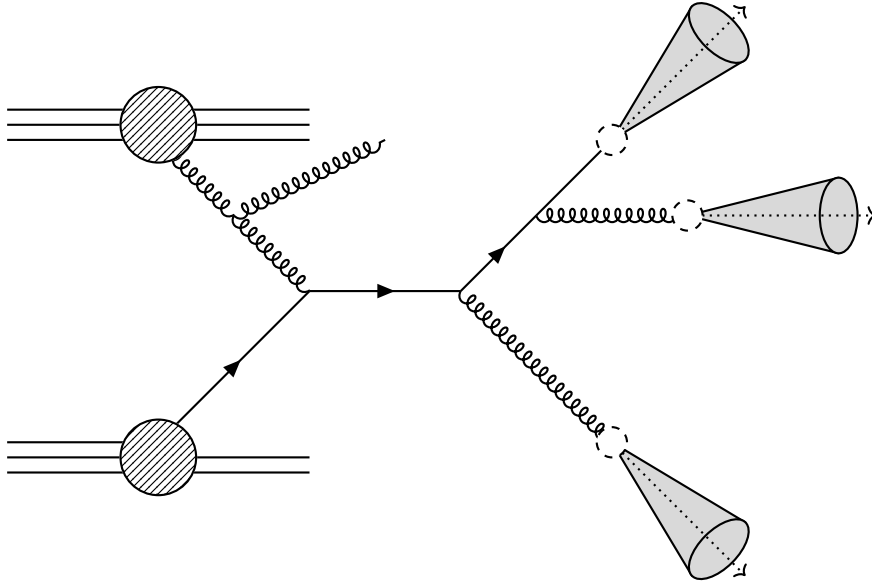


Figure 6.7: Illustration of a QCD process with both ISR and FSR emission. This event can still be considered a dijet event if their effects are sufficiently insignificant such that the event passes the dijet topology selection described in Section 6.3.

These effects can be verified in the distribution of truth-level asymmetry ($\mathcal{A}^{\text{truth}}$), calculated from truth jets in dijet events, as shown in Figure 6.8. The reconstructed-level asymmetry ($\mathcal{A}^{\text{reco}}$), calculated from reconstructed jets, then contains both physics and detector resolution effects.

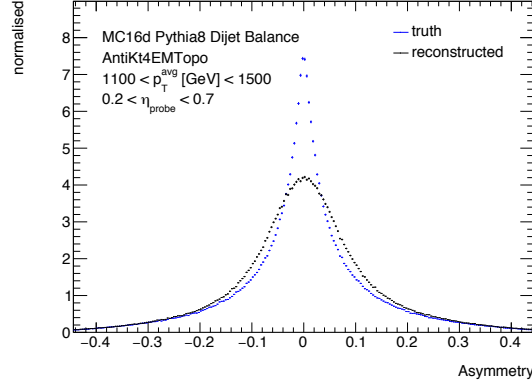


Figure 6.8: Distributions of dijet asymmetry calculated from truth-level jets (blue) and reconstructed jets (black)

6.5 Detector response convolution

In order to extract a measurement of the jet energy resolution, the detector response to the dijet asymmetry must be separated from the underlying physics in the reconstructed asymmetry distribution. The method outlined below describes a new procedure derived for this analysis.

First, the truth-level asymmetry is obtained from MC simulation, by requiring the truth matching between reconstructed and truth jets using the same method described in Section 5.3.2. As shown in Figure 6.9, this distribution is found to be well-described by the empirically derived form:

$$\begin{aligned}
 f(\mathcal{A}^{\text{truth}}) &= (c) \mathcal{E}(\mathcal{A}^{\text{truth}}; \mu, \sigma, n) + (1 - c) \mathcal{N}(\mathcal{A}^{\text{truth}}; \mu', \sigma'), \\
 \mathcal{E}(x; \mu, \sigma, n) &= \exp\left(-\frac{1}{2} \left| \frac{x - \mu}{\sigma} \right|^n\right), \\
 \mathcal{N}(x; \mu, \sigma) &= \exp\left(-\frac{(x - \mu)^2}{2\sigma^2}\right),
 \end{aligned} \tag{6.15}$$

where c is a parameter between 0 and 1, (μ, σ, n) are the mean, width, and power parameters of the exponential power function ($\mathcal{E}$), and (μ', σ') are the mean and width of the gaussian function ($\mathcal{N}$).

Next, as shown in Figure 6.10, the reconstructed-level asymmetry can be described by the convolution of the truth-level asymmetry with the detector response:

$$\begin{aligned}\Delta\mathcal{A} &= \mathcal{A}^{\text{reco}} - \mathcal{A}^{\text{truth}}, \\ g(\mathcal{A}^{\text{reco}}) &= (f \otimes \mathcal{N})(\mathcal{A}^{\text{reco}}) \\ &= \int_{-2}^2 f(\mathcal{A}^{\text{truth}}) \mathcal{N}(\Delta\mathcal{A}; \mu_{\mathcal{A}}^{\text{det}}, \sigma_{\mathcal{A}}^{\text{det}}) d\mathcal{A}^{\text{truth}}.\end{aligned}\tag{6.16}$$

where the detector response to the dijet asymmetry is posited to be Gaussian. Then the asymmetry resolution ($\sigma_{\mathcal{A}}^{\text{det}}$), the parameter of interest in Equation 6.5, is determined from the fit.

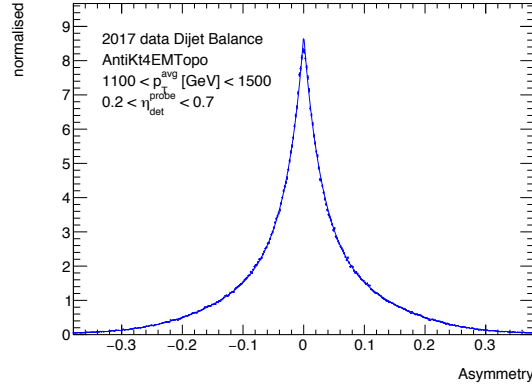


Figure 6.9: The truth asymmetry distribution (blue markers) fitted by the functional form of Equation 6.15 (blue line). Fits performed through χ^2 -minimization.

When both jets are in the reference region, the asymmetry distribution is symmetric around zero. In other probe regions, varying degrees of imbalance favouring central jets over forward jets (or vice versa) is predicted. In all cases, as shown in Figure 6.11, the chosen truth asymmetry function fits is verified to reliably describe their respective characteristic shapes.

The validity of this measurement method can be verified in MC simulation. The non-closure—also called method bias—is the difference between the measured and true jet

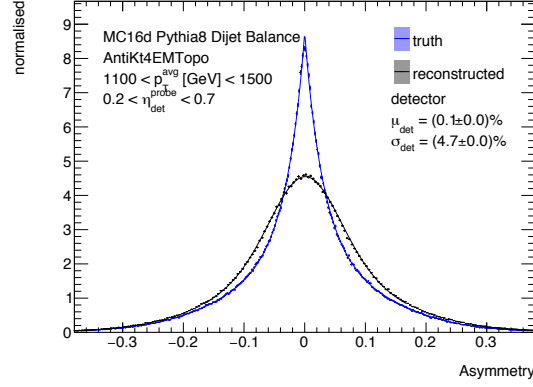


Figure 6.10: The reconstructed asymmetry distribution (black markers) fitted the functional form of Equation 6.16 (black line). Fits performed through χ^2 -minimization.

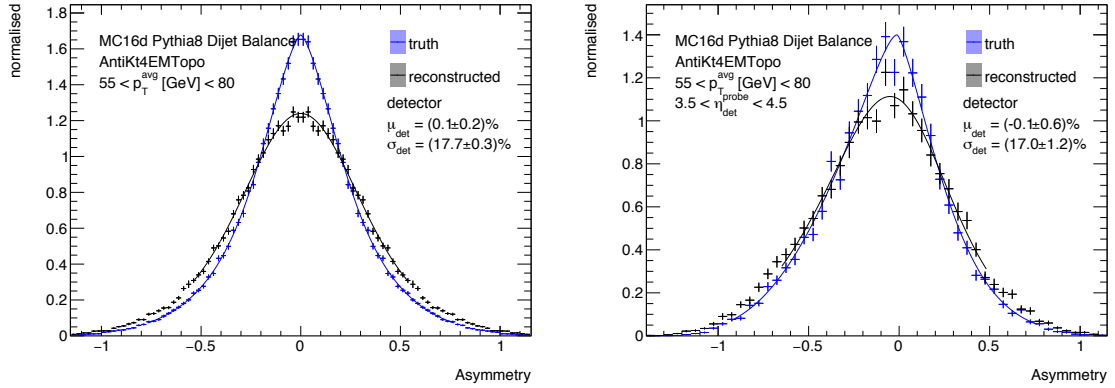


Figure 6.11: Different shapes of the truth-level asymmetry observed in the reference (left) and probe (right) regions fitted by the exponential power + Gaussian function, and the reconstructed-level asymmetry fitted by their Gaussian convolutions. Fits performed through χ^2 -minimization.

energy resolutions in MC simulation. The true jet energy resolution is obtained from the relative width of the jet p_T response distribution, parametrised by its Gaussian core, as shown in Figure 6.14. In an ideal scenario in which the *in situ* method works perfectly and the detector has an entirely Gaussian jet energy response, the two should yield identical jet energy resolution values. As shown in Figure 6.12, the measurements are within 10% of the true value, which is a convincing verification that the convolution fitting procedure is reliably extracting the detector resolution from the reconstructed asymmetry distribution.

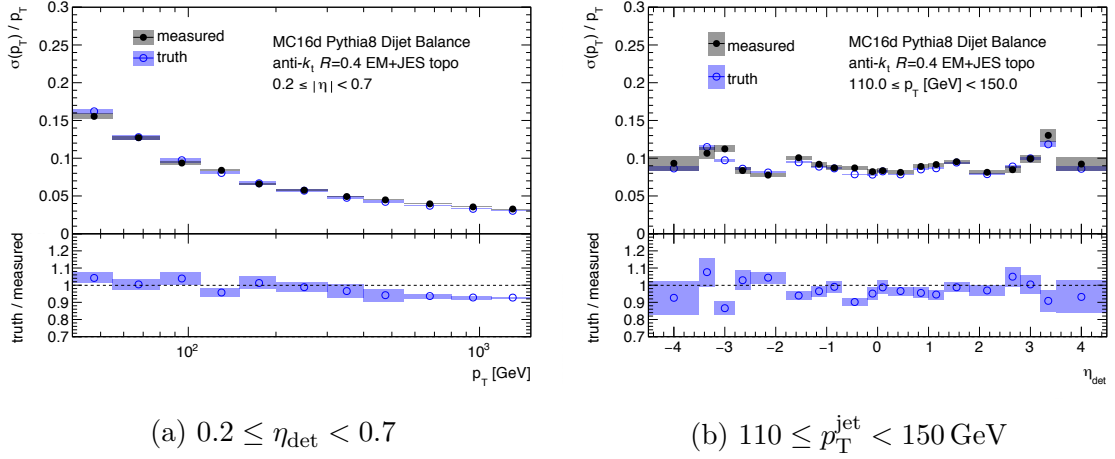


Figure 6.12: Expected in-situ jet energy resolution measurement in PYTHIA8 dijet events compared to the true quantity as a function of p_T and η_{det} . The lower panels show the ratio of desired over measured, which quantifies the non-closure of the method. The larger relative non-closure at high- p_T is identified to be due to the parametrisation of the true quantity.

6.6 Systematic uncertainties

The effects of various analysis choices and techniques applied in the measurement of the jet energy resolution are assessed to evaluate systematic uncertainties of the measurement. Table 6.3 summarises the sources of systematic uncertainties.

Source	Description
Jet energy scale	Potential jet energy miscalibration
Pileup jet rejection	Jet JVT requirement
Dijet topology	Dijet topology event selection
MC generator	Difference in physics modelling between MC generators
<i>In situ</i> non-closure	Bias of the measurement method

Table 6.3: Summary of the sources of systematic uncertainties assessed.

Jet energy scale

As explained in Section 5.3, the jet energy calibration is a multi-step procedure, each with an associated set of uncertainties [18]. The impact on the jet energy resolution measurement is evaluated following the standard procedure used at the ATLAS experiment: a given systematic source is propagated to all jets in MC simulation, resulting in adjusted four-momenta, and the full analysis is repeated. This is done separately for each JES systematic uncertainty source.

The jet energy scale is observed to be the most dominant source of systematic uncertainty in low- p_T regions, most heavily impacted by uncertainties in η -intercalibration. A localised feature at high- p_T is seen to arise from theoretical uncertainties in modelling of hadronic physics in GEANT4 [26], which is not expected to be representative of data; nevertheless, it is kept as a conservative estimate.

Pileup jet rejection

Contamination of pileup jets breaks the expected momentum balance between jets. The JVT requirement is tightened to $JVT > 0.91(0.5)$ for calorimeter(particle-flow) jets, which enhances the rejection of pileup jets. The impact of this variation is found to be negligible.

Dijet topology selection

The dijet topology selection, as explained in Section 6.3, enforces the ϕ -balance of the two leading jets and limits p_T -imbalance due to additional jets, modelled by parton showering in LO MC generators used and are not perfectly described. In past measurements, an extrapolation of the selection to perfect balance was performed

[27], which eliminated this systematic, but re-introduced a different one due to the parametrisation of the extrapolation fit. In this analysis, the selection is tightened and loosened around the nominal working point by $\Delta\phi(j_1, j_2) \geq 2.7^{+0.2}_{-0.2}$ and $p_T^{j_3} < \max(25^{+5}_{-5} \text{ GeV}, 0.25^{+0.05}_{-0.05} p_T^{\text{avg}})$.

MC generator

Differences in the physics modelling among MC generators lead to uncertainties in the underlying truth-level asymmetry distribution to be assumed. Since all MC generators are accurate to LO, there is no *a priori* reason to trust one over others. The MC sample using the same generator used to derive jet energy calibrations, PYTHIA8, is chosen as the nominal sample, while SHERPA and HERWIG7 are used as comparisons and to quantify the systematic uncertainty.

MC physics modelling is a significant source of systematic uncertainty in the forward regions of the detector $|\eta| > 3.2$. Usage of NLO generators, which should provide an accurate description of the third leading jet, remains an area for improvement.

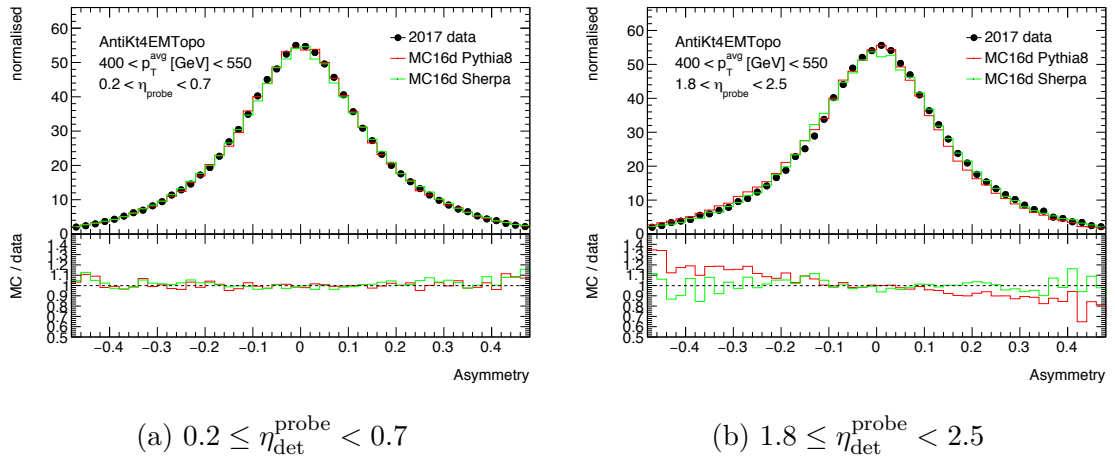


Figure 6.13: Discrepancies in dijet asymmetry observed in MC simulation (coloured lines) versus data (dotted circles) for $400 \leq p_T^{\text{jet}} < 550 \text{ GeV}$

Non-closure

The non-closure of the measurement method is within 1 %³. Its relative effect is the most significant in high- p_T regions, where non-Gaussian tails are observed in the jet p_T response, shown in Figure 6.14. The Gaussian core approximation is currently the standard procedure within the ATLAS experiment, and an improved parametrisation, currently under study, should result in better closure of the method.

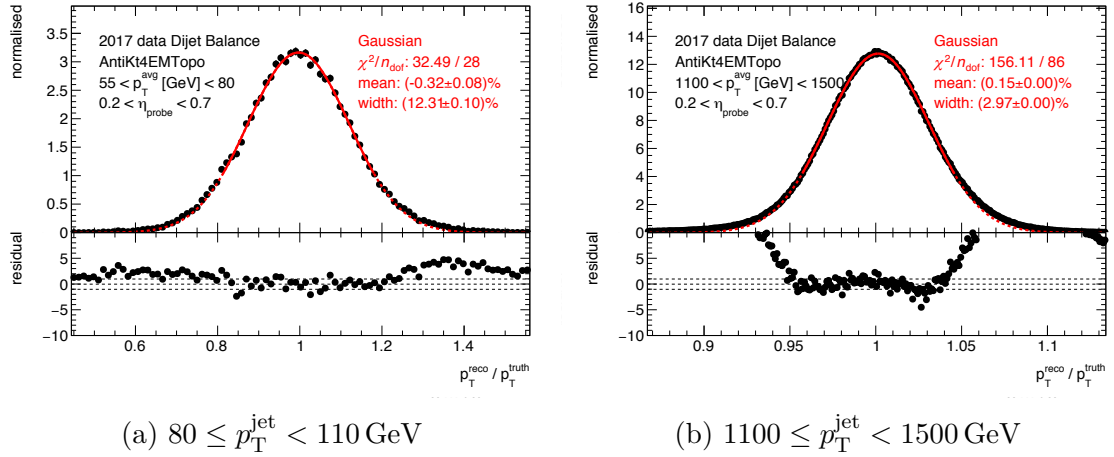


Figure 6.14: Gaussian fit (solid red line) to the core of the jet p_T response simulated in MC, extrapolated (dashed red line). The fits describe the entire shape of the response distribution for low- p_T jets, but non-Gaussian tails are observed for high- p_T jets.

Summary

Most systematic uncertainty sources assessed are evaluated by introducing variations that inject or remove events. Due to the limited statistics in the MC samples used, the resulting variations will both contain the actual systematic bias, but also statistical fluctuations. A Gaussian kernel smoothing procedure [28] is applied to estimate statistically significant effects as a continuous function over the (p_T, η) phase space.

³This is the absolute uncertainty on the relative jet energy resolution, which is itself expressed in %.

Total systematic uncertainties, shown in Figure 6.15, are obtained by addition in quadrature of uncertainties of the individual sources, which should be independent of one another.

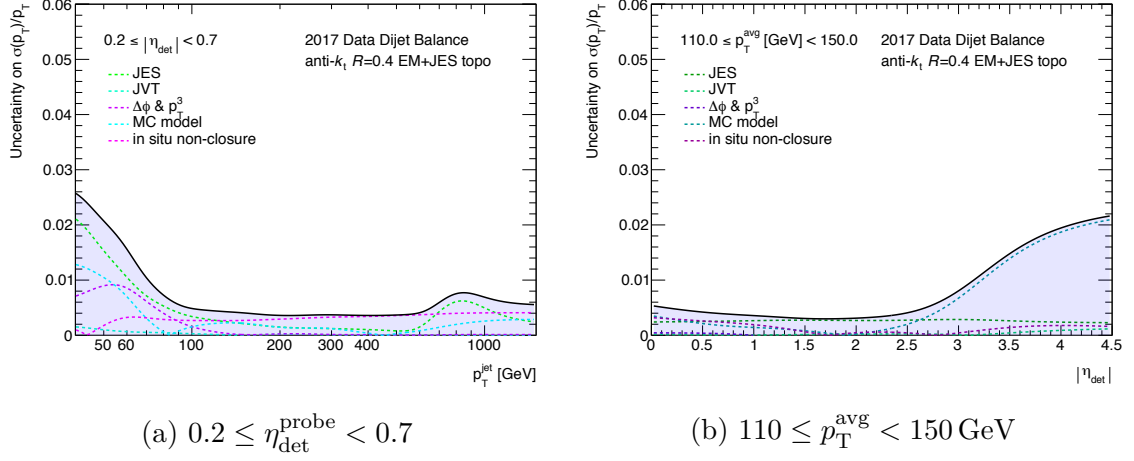


Figure 6.15: Total systematic uncertainties on the jet energy resolution, obtained by adding uncorrelated sources in quadrature

Chapter 7

Results

The jet energy resolution is measured in different η regions that reflect the transition regions of the ATLAS detector that are predicted to exhibit performance differences. No significant difference exists in the resolution between the the left ($\eta < 0$) and right ($\eta > 0$) halves of the detector, which is expected from its symmetric design. Therefore, $|\eta|$ bins are merged to increase statistics.

The p_{T} -dependent jet energy resolution is parametrised as a function of three terms [27]:

$$\frac{\sigma(p_{\text{T}})}{p_{\text{T}}} = \frac{N}{p_{\text{T}}} \oplus \frac{S}{\sqrt{p_{\text{T}}}} \oplus C, \quad (7.1)$$

where N characterises the electronic and pileup noise, S is the stochastic term due to the sampling nature of the calorimeters, and C is the constant term attributed to non-uniformities in the energy response and/or signal loss due to passive material in the detector. Results are fitted and compared to those obtained from the truth response simulation in MC. Although this parametrisation describes the observed functional form of the jet energy resolution well, it entails a high degree of (anti-)correlation between the parameters in fits, and it is not possible to unambiguously

disentangle individual contributions from a single set of measurements. Also, in the case of particle-flow jets, since the constituent input is not solely based on calorimetric information, this parametrisation cannot be expected to hold — for example, the CMS experiment, which has implemented a similar particle-flow algorithm, uses an ad hoc parametrisation, in which it is possible for the noise term contribution to be negative [29]. Therefore, the results of the fits, shown in Table 7.1, are not meant to be a conclusive determination of the parametrisation.

calorimeter			particle-flow		
N	S	C	N	S	C
$0.0 \leq \eta_{\text{det}} < 0.2$					
4.5 ± 2.2	0.85 ± 0.13	$(3.0 \pm 0.7)\%$	3.5 ± 3.1	0.92 ± 0.13	$(3.3 \pm 0.7)\%$
$0.2 \leq \eta_{\text{det}} < 0.7$					
5.1 ± 1.8	0.79 ± 0.12	$(2.6 \pm 0.7)\%$	0.00 ± 3.2	0.95 ± 0.04	$(2.6 \pm 0.5)\%$
$0.7 \leq \eta_{\text{det}} < 1.3$					
6.0 ± 1.6	0.82 ± 0.12	$(3.1 \pm 0.6)\%$	0.00 ± 5.8	1.05 ± 0.04	$(2.8 \pm 0.5)\%$
$1.3 \leq \eta_{\text{det}} < 1.8$					
0.00 ± 3.2	0.93 ± 0.04	$(3.8 \pm 0.4)\%$	0.00 ± 2.0	1.02 ± 0.04	$(4.0 \pm 0.4)\%$
$1.8 \leq \eta_{\text{det}} < 2.5$					
0.00 ± 1.4	0.72 ± 0.04	$(2.9 \pm 0.4)\%$	0.00 ± 5.9	0.80 ± 0.04	$(3.1 \pm 0.3)\%$
$2.5 \leq \eta_{\text{det}} < 3.2$					
7.6 ± 1.7	0.52 ± 0.30	$(4.6 \pm 0.8)\%$	0.00 ± 5.9	1.00 ± 0.06	$(2.3 \pm 0.8)\%$
$3.2 \leq \eta_{\text{det}} < 3.5$					
6.9 ± 5.2	0.72 ± 1.07	$(6.9 \pm 4.7)\%$	0.00 ± 11.5	1.08 ± 0.15	$(6.5 \pm 1.7)\%$
$3.5 \leq \eta_{\text{det}} < 4.5$					
6.4 ± 1.3	0.00 ± 2.26	$(6.0 \pm 1.6)\%$	0.00 ± 1.2	0.92 ± 0.18	$(1 \pm 15)\%$

Table 7.1: Fit results of (Noise, Stochastic, Constant) parametrisation of jet energy resolution extracted from 2017 data. Neighbouring terms (N, S) and (S, C) tend to be strongly correlated, while the noise and constant terms (N, C) tend to be strongly anti-correlated. The parametrization used only has theoretical justification for calorimeter jets. The results shown for particle flow jets are not very meaningful; future work is needed to find an appropriate functional form for this resolution.

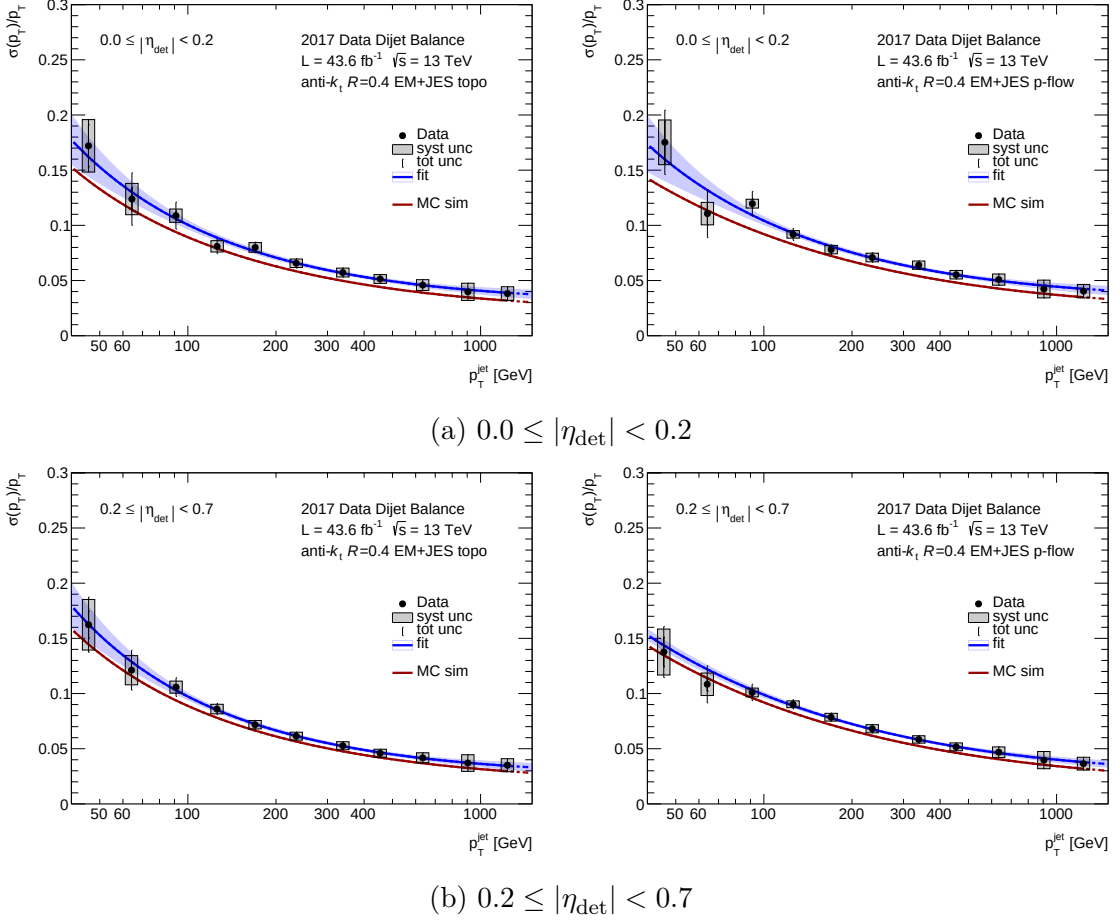


Figure 7.1: Jet energy resolution of the ATLAS detector measured in 2017 data of calorimeter (left) and particle-flow (right) jets.

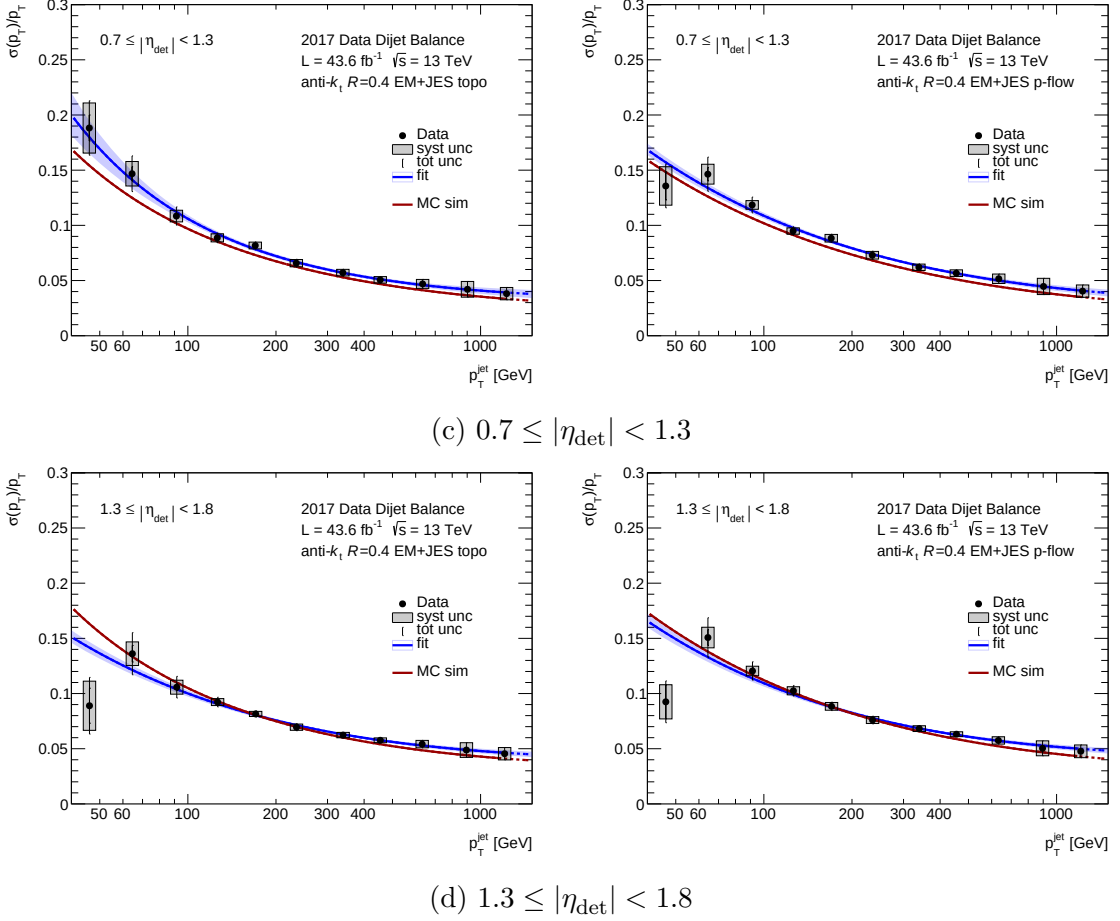


Figure 7.1: Jet energy resolution of the ATLAS detector measured in 2017 data of calorimeter (left) and particle-flow (right) jets.

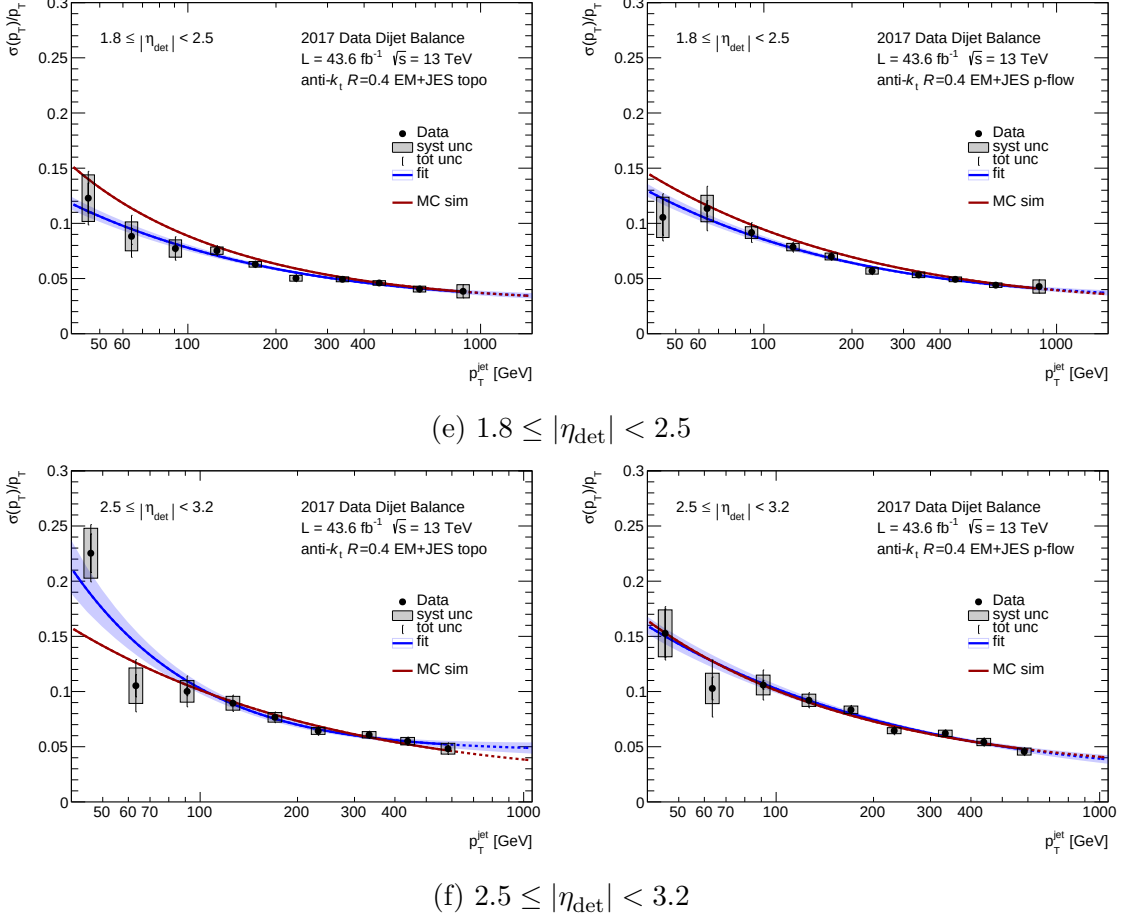


Figure 7.1: Jet energy resolution of the ATLAS detector measured in 2017 data of calorimeter (left) and particle-flow (right) jets.

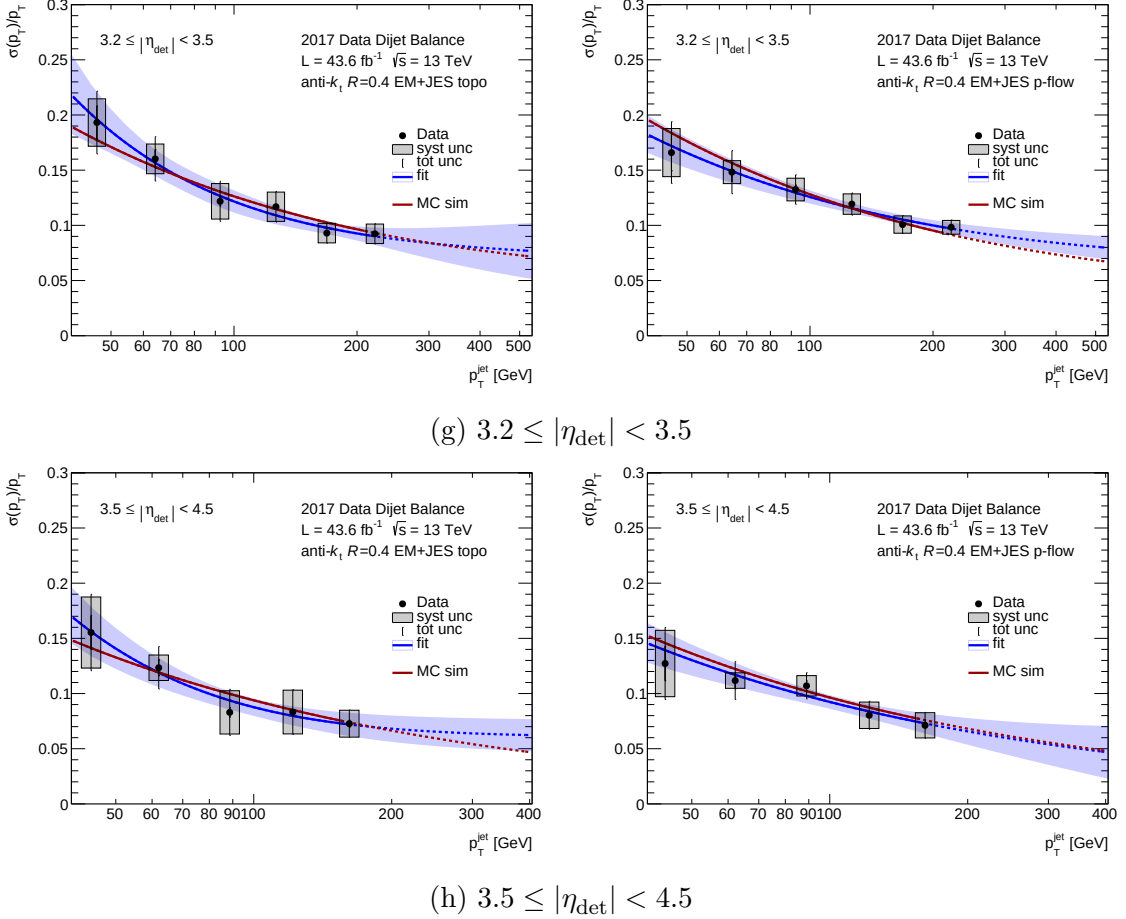


Figure 7.1: Jet energy resolution of the ATLAS detector measured in 2017 data of calorimeter (left) and particle-flow (right) jets.

Chapter 8

Conclusions

The jet energy resolution of the ATLAS detector during 2015 to 2017 data taking periods have been measured, and associated systematic uncertainties have been evaluated. For jets with transverse momenta of 45 GeV that fall in the central calorimeter region, the relative jet energy resolution is measured to be $(16.2 \pm 2.8)\%$ and $(13.8 \pm 2.7)\%$ for calorimeter and particle flow jets, respectively. The corresponding measurements for jets with transverse momenta of 1200 GeV are $(3.5 \pm 0.6)\%$ and $(3.6 \pm 0.6)\%$.

As the first jet energy resolution measurement to be done using 13 TeV collision data, these results will be important for all ongoing analyses within the experiment. In the near future, these results will be combined with those from other measurements using different event topologies ($Z/\gamma + \text{jet}$) and other specialised strategies. While these complementary methods are expected to provide much more precision in the low- p_T regions and/or constraints on the noise term, the results from the dijet *in situ* method alone has the widest reach in measurement phase space, reaching out to $p_T^{\text{jet}} > 500 \text{ GeV}$ as well as forward- η regions where other methods are statistically limited.

With the aid of increased amount of data and the new trigger strategy, enough statistics are available to measure the resolution in finer η -bins than ever before, which reveal detailed features of the detector. In particular, the endcap-to-forward transition ($3.2 \leq |\eta| < 3.5$) is observed, as expected, to have by far the worst resolution. As well, the seam region at which the LAr EM calorimeter half-barrels are joined together ($0.0 \leq |\eta| < 0.2$) exhibits degradation in resolution compared to the rest of the barrel region ($0.2 \leq |\eta| < 0.7$). This is the first time that these findings are being reported through an *in situ* measurement.

The systematic uncertainties of the measurement using the convolution fitting procedure are assessed to be at least as precise as or more than the previous measurement. Detailed investigations into each source, as discussed in Section 6.6, show promises of further precision improvements to be gained in future iterations.

Most importantly, the measurement clearly indicates discrepancies between the jet energy resolution simulated by MC versus observed in data. In particular, the detector performance in the central region up to $|\eta| < 1.8$, which is the the most sensitive region for many physics analyses, is consistently overestimated in simulation. These analyses rely on MC simulation to derive detector correction factors and evaluate systematic uncertainties, and the results presented reveal shortcomings in the MC simulation, which will now need to be adjusted to match the resolution observed in data. On a lower level, it may even be used as input to tune the GEANT4 model of the ATLAS detector itself.

The ATLAS experiment is a long-term physics project spanning multiple decades. Almost 10 years after its first recorded collision, the ATLAS detector continues to operate with excellent performance in jet energy measurements.

Appendix A

2015+2016 jet energy resolution

calorimeter			particle-flow		
N	S	C	N	S	C
$0.0 \leq \eta_{\text{det}} < 0.7$					
4.8 ± 1.9	0.79 ± 0.12	$(2.7 \pm 0.7)\%$	0.00 ± 6.1	0.96 ± 0.05	$(2.8 \pm 0.6)\%$
$0.7 \leq \eta_{\text{det}} < 1.3$					
5.3 ± 1.7	0.75 ± 0.12	$(3.4 \pm 0.6)\%$	1.8 ± 4.6	1.0 ± 0.1	$(3.1 \pm 0.7)\%$
$1.3 \leq \eta_{\text{det}} < 1.8$					
6.7 ± 1.4	0.93 ± 0.04	$(3.8 \pm 0.4)\%$	0 ± 15	1.3 ± 0.1	$(3.9 \pm 0.4)\%$
$1.8 \leq \eta_{\text{det}} < 2.5$					
5.4 ± 1.4	0.38 ± 0.21	$(3.9 \pm 0.4)\%$	0.0 ± 3.3	0.78 ± 0.04	$(3.2 \pm 0.3)\%$
$2.5 \leq \eta_{\text{det}} < 3.2$					
5.3 ± 2.0	0.54 ± 0.24	$(4.9 \pm 0.7)\%$	4.0 ± 2.3	0.76 ± 0.15	$(3.9 \pm 0.7)\%$
$3.2 \leq \eta_{\text{det}} < 3.5$					
0 ± 20	1.19 ± 0.15	$(3.1 \pm 4.1)\%$	4.9 ± 5.5	0.95 ± 0.61	$(5.6 \pm 4.3)\%$
$3.5 \leq \eta_{\text{det}} < 4.5$					
0.0 ± 1.2	0.64 ± 0.22	$(3.6 \pm 3.7)\%$	0 ± 16	0.54 ± 0.25	$(5.5 \pm 2.4)\%$

Table A.1: Fit results of (Noise, Stochastic, Constant) parametrisation of jet energy resolution extracted from 2015+2016 data. Neighbouring terms (N, S) and (S, C) tend to be strongly correlated, while the noise and constant terms (N, C) tend to be strongly anti-correlated. The parametrization used only has theoretical justification for calorimeter jets. The results shown for particle flow jets are not very meaningful; future work is needed to find an appropriate functional form for this resolution.

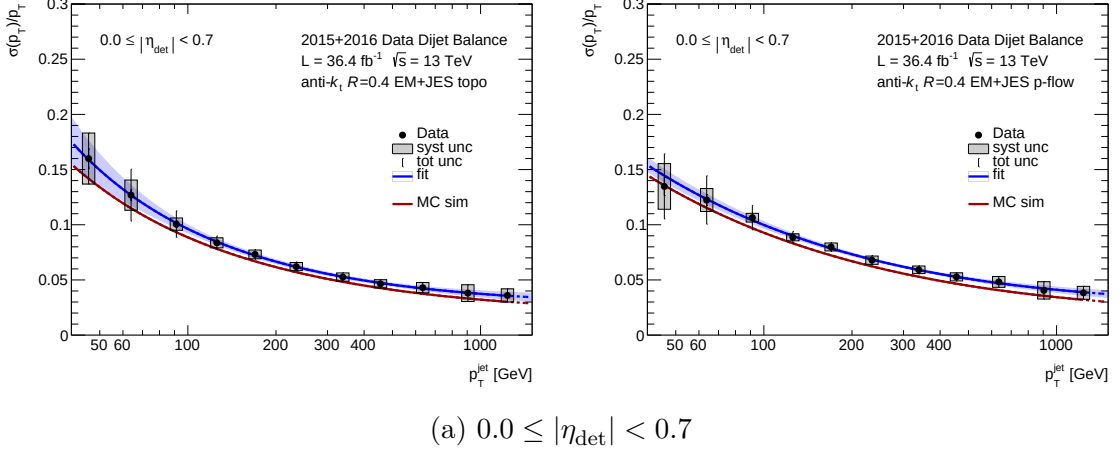


Figure A.1: Jet energy resolution of the ATLAS detector measured in 2015+2016 data of calorimeter (left) and particle-flow (right) jets.

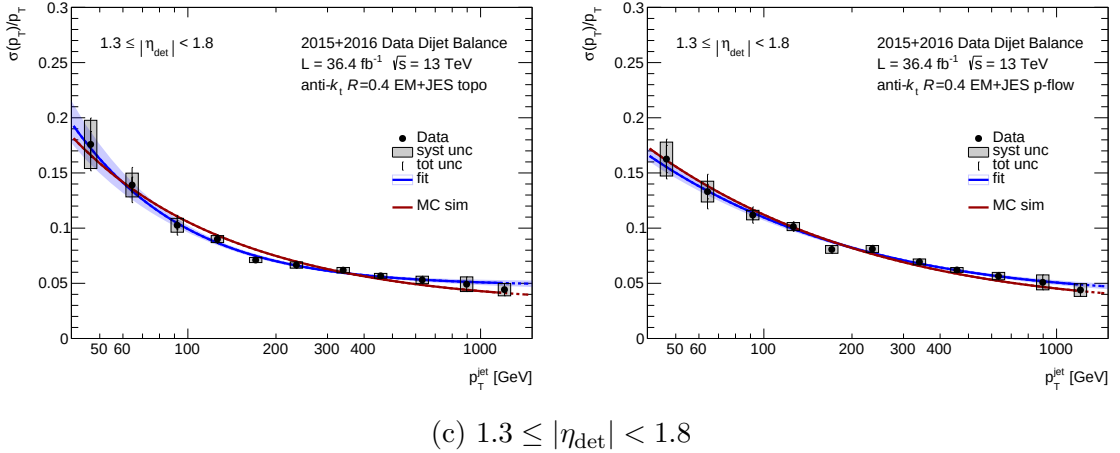
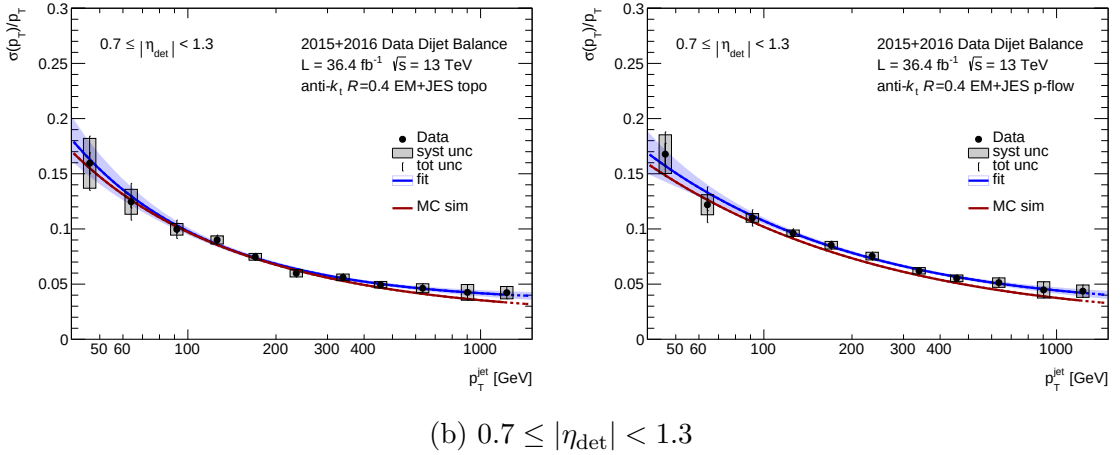


Figure A.1: Jet energy resolution of the ATLAS detector measured in 2015+2016 data of calorimeter (left) and particle-flow (right) jets.

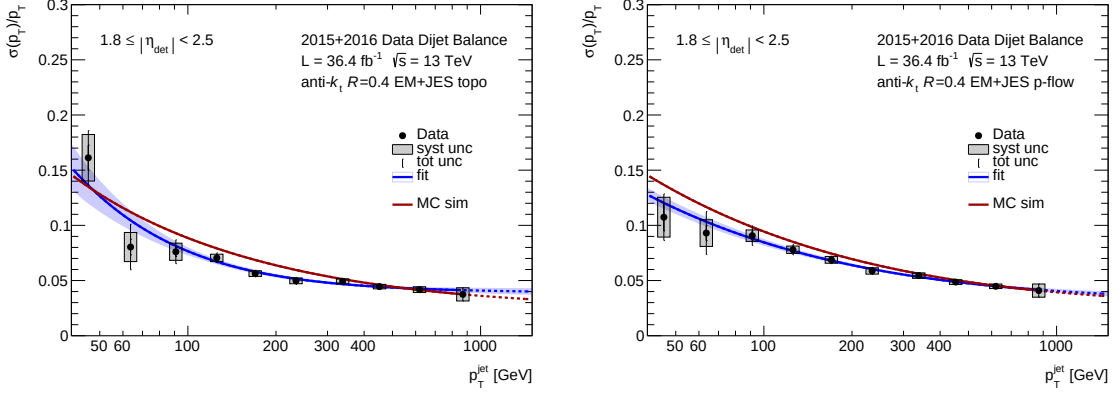
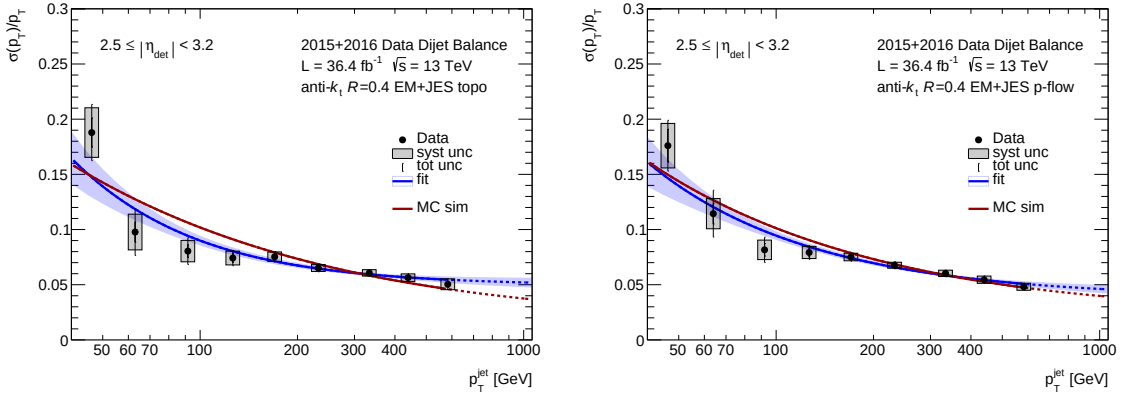
(d) $1.8 \leq |\eta_{\text{det}}| < 2.5$ (e) $2.5 \leq |\eta_{\text{det}}| < 3.2$

Figure A.1: Jet energy resolution of the ATLAS detector measured in 2015+2016 data of calorimeter (left) and particle-flow (right) jets.

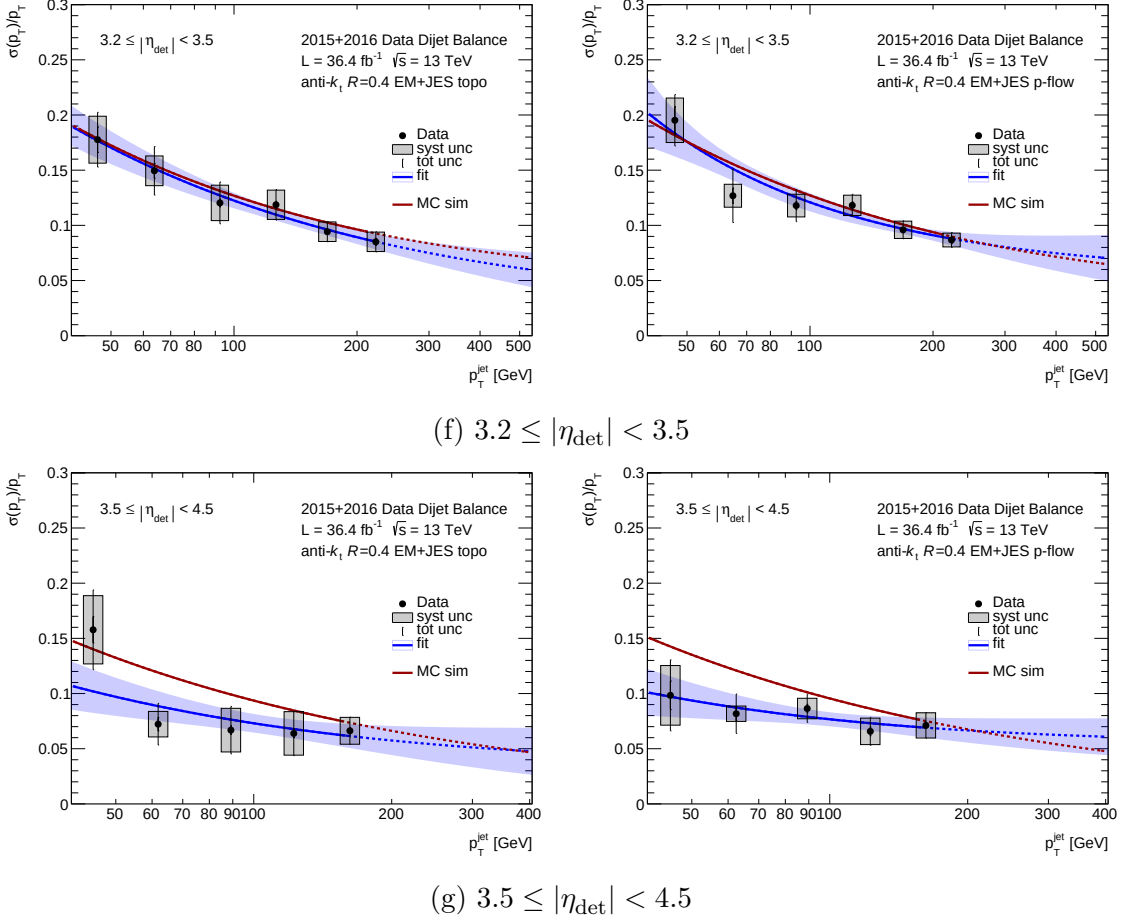


Figure A.1: Jet energy resolution of the ATLAS detector measured in 2015+2016 data of calorimeter (left) and particle-flow (right) jets.

Index

- anti- k_t , 26
- k_t , 26
- colour confinement, 5
- constituent scale, 31
- dijet asymmetry, 41
- ghost particle, 27
- hadron, 5
- hadronisation, 7
- hard scatter, 6
- jet energy resolution, 40
- matrix element, 6
- non-compensating, 18
- out-of-cone radiation, 52
- particle-flow, 30
- parton, 5
- parton showering, 7
- pileup interactions, 22
- pileup jet, 50
- prescale, 20
- pseudorapidity, 14
- rapidity, 14
- reconstructed, 27
- reconstructed-level, 24
- showering, 16
- single-jet trigger, 43
- small- R , 27
- toop-cluster, 28
- transverse energy, 43
- transverse momentum, 14
- trigger, 19
- truth, 27
- truth-level, 24
- turn-on, 48
- underlying event, 6

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