
Measurement Of Inclusive Jet Cross-Section In Proton-Proton Collisions At $\sqrt{s} = 13\text{TeV}$ Using The CMS Detector At The LHC

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"The trouble with a kitten is that eventually it becomes a cat. "

Ogden Nash

Abstract

of

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The theory of Quantum Chromodynamics (QCD) is one of the fundamental underlying theories to describe interactions among quarks and gluons. In QCD, partons (quarks and gluons) are produced in hadron-hadron collision with large cross-sections. Partons, immediately after production, fragment and hadronize forming a cluster of collimated energetic colorless particles, hadrons. A clustering algorithm is applied on these particles to form a collection of particles which are called jets, the experimental analogue of partons and one of the key objects in the theory of QCD. However, formation of jets out of produced partons due to hadron-hadron collision is a very nontrivial phenomena. Hence Inclusive Jet cross-section measurement is an important and essential study at every new energy regime. The jets serve as the background for most other searches in a collider experiment. A detailed description of double differential inclusive jet cross-section measurement using proton-proton collision data from the CMS detector at CERN is presented. The center-of-mass energy is 13 TeV. The data used for this analysis correspond to 71.52 pb^{-1} . Measurement of the efficiencies of the triggers used is presented in detail. Jets are clustered with the Anti k_T clustering algorithm. The measured cross-section is unfolded to get rid of all detector effects. Various aspects of systematic uncertainties are discussed and estimated. Corrections for non-perturbative effects are also performed. Finally the cross-section is presented as a function of jet momentum in various rapidity bins. For the first time, super forward rapidity region is included in the measurement. The measured cross-section will be used to extract the value of the strong coupling constant and to study its scale dependence on a wider kinematic range than the one accessible at lower energies.

List of Publications

- Measurement of the double-differential inclusive jet cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV : Published in Eur. Phys. J. C (2016) 76:451 (doi:10.1140/epjc/s10052-016-4286-3)
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CMS Public and Internal Notes

- Measurement of the double-differential inclusive jet cross section at $\sqrt{s} = 13$ TeV : CMS-PAS-SMP-15-007
- Measurement of the inclusive jet cross section with the first data at $\sqrt{s} = 13$ TeV : CMS AN-15-154
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To my parents...

...and wife

Chapter 1

Introduction

We have measured the double differential cross-section of inclusive jets with the proton-proton collision data obtained from the CMS detector at CERN. The center-of-mass energy is 13 TeV. The data that we used for this analysis correspond to 71.52 pb^{-1} . Inclusive Jet cross-section measurement is important and essential at every new energy regime as the jets are the background for most other searches in a collider experiment. For the first time, the inclusive jet cross-section is measured in such a high center-of-mass energy. We have shown the variation of the cross-section with jet transverse momentum and pseudorapidity. The measured cross-section may be used to extract the value of the strong coupling constant or to study its scale dependence on a wider kinematic range than the one accessible at lower energies.

The thesis is divided into several chapters. Here is a brief description of the chapters:

Chapter 2 briefly discusses some essential aspects of the Standard Model of particle physics. Perturbative QCD along with Jet production at the LHC is also discussed in Chapter 2.

The LHC and the experiments are introduced in Chapter 3, focusing on the Compact Muon Solenoid (CMS). A brief description of detector design and layouts is presented.

Chapter 4 provides a description of how events are reconstructed in the CMS detector with an emphasis on the object of interest Jet. A brief description of the physics objects used for the analysis and of the requirements applied in the event selection is provided. Different clustering algorithms and energy corrections are also described here.

In Chapter 5, a detailed discussion on how we measured the efficiencies of all the triggers used in our analysis is presented.

Chapter 6 deals with the analysis inputs : the data and monte carlo. A description of the data used for the analysis is presented along with the monte carlo samples used. The monte carlo is compared to the data through various observables.

In Chapter 7 a study of the experimental resolution from simulated events is presented which helps to choose an appropriate binning for the measured distribution of the observables. At the end the response matrices were constructed, which connect detector and generator level quantities through studies of the detector resolution.

Chapter 8 presents a discussion on unfolding of experimental data. How experimental results are corrected for the detector effects are described. Some of the systematic

effects are also discussed here.

Various systematic effects which affect the inclusive jet cross-section measurements are discussed in detail and their impact is estimated on Chapter 9. A summary of the assigned uncertainties is provided.

Chapter 10 describes some essential aspects of non-perturbative effects and estimates the correction factors.

Chapter 11 summarizes the main results of double differential inclusive jet cross-section.

Chapter 2

The Standard Model of the Particle Physics

The Standard Model (SM) of Particle Physics [36], [37] is a unified theory which aims to describe the fundamental particles and interaction between them. The theory is proven to be amazingly successful, accurately describing almost all of the empirical data, though there are a few tiny discrepancies.

2.1 Particles in Standard Model

Elementary particles can be classified into two categories: fermions and bosons. Fermions are spin $\frac{1}{2}$ particles and follow Pauli exclusion principle, where no two fermions can have the same quantum state. Bosons are of integer spin and are allowed to be in same quantum state. Bosons act as the mediator of forces. There are in total of 12 known fermions, split in 6 leptons and 6 quarks, further categorized in 3 generations according to their masses.

Among the six leptons, $\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ is the first generation, $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ is the second generation and $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ is the third one. Similarly, the six quarks are divided into 3 generations as follows: $\begin{pmatrix} u \\ d \end{pmatrix}$, $\begin{pmatrix} c \\ s \end{pmatrix}$ and $\begin{pmatrix} t \\ b \end{pmatrix}$. Charged leptons and quarks can interact through electromagnetic interaction mediated by photon (γ). W and Z bosons are mediator of weak forces. Quarks which have color charge can participate in strong interaction mediated by gluons (g). Both γ and g are massless, whereas W and Z bosons are massive. Figure 2.2 illustrates the interactions of the SM particles. Two interacting particles are shown to be connected by a line, whereas the loops indicate a self coupling behavior of the particles. The field contents with mass, electric charge and spin are shown in 2.1

2.1.1 Gauge Symmetry Group of the Standard Model

In the Standard Model the unified interaction possesses an internal local gauge symmetry, consisting of three different gauge groups. A gauge theory is a quantum field theory with some internal symmetry that governs its dynamics. In the context of Quantum Field Theory, the Standard Model is described where every particle is represented as a dynamical field $\psi(x)$ in the four dimensional space time (x). The dynamical field must abide by the symmetry principles: spatial rotation, spatial translational and boosts of the reference frame. The gauge symmetry group of the Standard Model is represented by,

$$SU(3)_{color} \times SU(2)_{isospin} \times U(1)_{hypercharge} \quad (2.1)$$

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$ d down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ b bottom	0 0 1 γ photon	
	$0.511 \text{ MeV}/c^2$ -1 $1/2$ e electron	$105.7 \text{ MeV}/c^2$ -1 $1/2$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $1/2$ τ tau	$91.2 \text{ GeV}/c^2$ 0 1 Z Z boson	
LEPTONS	$< 2.2 \text{ eV}/c^2$ 0 $1/2$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$ ν_τ tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson	GAUGE BOSONS

FIGURE 2.1: Particle content of the Standard model. The mass, electric charge and spin of all the matter particles including Brout-Englert-Higgs (B-E-H) boson and the gauge bosons are shown [47]

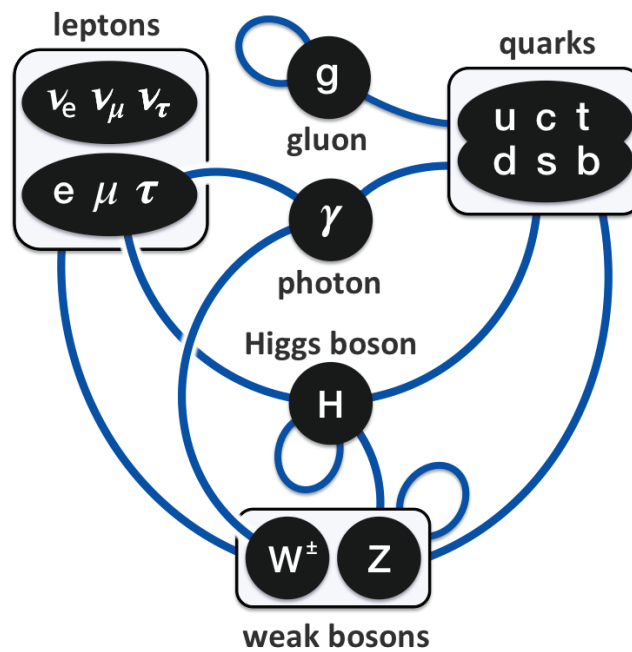


FIGURE 2.2: The SM Particles and their interactions [47]

Families				I_3	Y	Q
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	+1/2	-1	0
	e_R	μ_R	τ_R	-1/2	-1	-1
				0	-2	-1
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	+1/2	+1/3	+2/3
	u_R	c_R	t_R	-1/2	+1/3	-1/3
	d_R	s_R	b_R	0	+4/3	+2/3
				0	-2/3	-1/3

TABLE 2.1: The Standard Model: The Fermion Sector

Family		I_3	Y	Q
Scalars	$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	+1/2	+1/2	+1
		-1/2	+1/2	0

TABLE 2.2: The Standard Model: The Scalar Sector

Quantum Chromodynamics (QCD) describes the interactions of the colored quarks and gluons under the sub-group $SU(3)_{color}$. Gluons (g) are basically the 8 generators of the $SU(3)_{color}$ sub-group. The sub-group $SU(2)_{isospin} \times U(1)_{hypercharge}$ describes the electro-weak interactions, where SU(2) provides 3 generators corresponding to the weak nuclear interactions and U(1) provides 1 generator for electromagnetic interactions.

2.2 Quantum Chromodynamics

QCD Lagrangian density $\mathcal{L}_{QCD}$ is defined as

$$\mathcal{L}_{QCD} = \mathcal{L}_{quarks} + \mathcal{L}_{gluons} + \mathcal{L}_{gauge} + \mathcal{L}_{ghost} \quad (2.2)$$

where

- $\mathcal{L}_{quarks}$ describes the interaction of spin $\frac{1}{2}$ quark fields q_a of mass m_q with spin 1 gluon fields $\mathcal{A}_\mu^A$
- $\mathcal{L}_{gluons}$ represents the kinetic term of the gluon fields $\mathcal{A}_\mu^A$
- $\mathcal{L}_{gauge}$ defines the chosen gauge
- $\mathcal{L}_{ghost}$ is the so-called ghost term that is a remedy necessary in non-Abelian gauge theories to treat the degeneracy of equivalent gauge field configurations.

Spinor indices are suppressed, Greek letters $\mu, \nu, \dots \in \{0, 1, 2, 3\}$ represent space-time indices, and $a, b, c \in 1, \dots, 3$ and $A, B, C \in \{1, \dots, 8\}$ are the indices of the triplet and

octet representations, respectively, of the colour SU(3) gauge symmetry group. Summation over identical indices is implied. As in the QED, the first term can be written with the help of the covariant derivative $(\mathcal{D}_\mu)_{ab}$ as

$$\mathcal{L}_{quarks} = \sum_{q \in \{u, d, s, c, b, t\}} \bar{q}_a (i\gamma^\mu (\mathcal{D}_\mu)_{ab} - m_q) q_b \quad (2.3)$$

where the sum runs over all six quark flavours u, d, s, c, b, t and γ_μ are the Dirac matrices. Defining the diagonal metric tensor g as $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$, the γ matrices satisfy the anticommutation relation

$$\{\gamma^\mu, \gamma^\nu\} = 2g^{\mu\nu} \quad (2.4)$$

and the covariant derivative

$$(\mathcal{D}_\mu)_{ab} = \partial_\mu \delta_{ab} = ig_s \mathcal{T}_{ab}^A \mathcal{A}_\mu^A \quad (2.5)$$

not only exhibits colour indices a, b and the gauge coupling g_s of the strong interaction, but also, instead of one photon field for the sole generator of the U(1) group, eight gluon fields $\mathcal{A}_\mu^A$ with factors $\mathcal{T}_{ab}^A$ corresponding to the generators of the SU(3) gauge group of QCD. A representation of the generators is given via $\mathcal{T}^A = \lambda^A/2$ by the Hermitian and traceless Gell-Mann matrices λ^A :

$$\begin{aligned} \lambda_1 &= \begin{pmatrix} 0 & +1 & 0 \\ +1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, & \lambda_2 &= \begin{pmatrix} 0 & -i & 0 \\ +i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, & \lambda_3 &= \begin{pmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \lambda_4 &= \begin{pmatrix} 0 & 0 & +1 \\ 0 & 0 & 0 \\ +1 & 0 & 0 \end{pmatrix}, & \lambda_5 &= \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ +i & 0 & 0 \end{pmatrix}, & \lambda_6 &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & +1 \\ 0 & +1 & 0 \end{pmatrix}, \\ \lambda_7 &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & +i & 0 \end{pmatrix}, & \lambda_8 &= \frac{1}{\sqrt{3}} \begin{pmatrix} +1 & 0 & 0 \\ 0 & +1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \end{aligned}$$

The (2×2) sub-matrices of the first three λ_A can be recognized as Pauli matrices. The generator matrices $\mathcal{T}^A$ satisfy the commutation relations

$$[\mathcal{T}^A, \mathcal{T}^B] = if^{ABC} \mathcal{T}^C \quad (2.6)$$

where f^{ABC} are the corresponding structure constants of SU(3) with values of

$$f^{123} = 1 \quad (2.7)$$

$$f^{147} = -f^{156} = f^{246} = f^{257} = f^{345} = -f^{367} = \frac{1}{2} \quad (2.8)$$

$$f^{458} = f^{678} = \frac{\sqrt{3}}{2} \quad (2.9)$$

while all other f^{ABC} not related to these by index permutations are zero. The kinetic term of the gluons then reads

$$\mathcal{L}_{gluons} = -\frac{1}{4} \mathcal{G}_{\mu\nu}^A \mathcal{G}_A^{\mu\nu} \quad (2.10)$$

where

$$\mathcal{G}_{\mu\nu}^A = \partial_\mu \mathcal{A}_\nu^A - \partial_\nu \mathcal{A}_\mu^A - g_s f^{ABC} \mathcal{A}_\mu^B \mathcal{A}_\nu^C \quad (2.11)$$

being the field strength tensor. These two “classical” parts correspond to free quark and

gluon-field terms, and the quark-gluon interaction. They are depicted in the Feynman diagrams as shown in Figures 2.3, 2.4, 2.5, 2.6, 2.7.

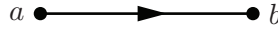
This classical QCD Lagrangian exhibits the property of local gauge invariance, i.e. invariance under a simultaneous redefinition of the quark and gluon fields. As a consequence of this internal symmetry, it is impossible to define the gluon field propagator without explicitly specifying a choice of the gauge. A popular choice is given as a generalization of the covariant Lorentz gauge $\partial^\mu \mathcal{A}_\mu^A = 0$ by the class of R_ξ gauges, imposed by adding the term

$$\mathcal{L}_{gauge} = -\frac{1}{2\xi}(\partial^\mu \mathcal{A}_\mu^A)^2 \quad (2.12)$$

to the classical Lagrangian. According to L. D. Faddeev and V. N. Popov [33] this must be accompanied by the ghost term

$$\mathcal{L}_{ghost} = \partial_\mu \eta^{A\dagger} (\mathcal{D}_{AB}^\mu \eta^B) \quad (2.13)$$

because of the non-Abelian character of the QCD gauge group. The ghosts η^A , with conjugate-transpose $\eta^{A\dagger}$, represent complex scalar fields that nevertheless obey Fermi–Dirac statistics. They do not have a physical meaning, but should be considered as a mathematical trick to cancel nonphysical degrees of freedom otherwise present in calculations with covariant gauges.



δ_{ab}

FIGURE 2.3: Free quark-field

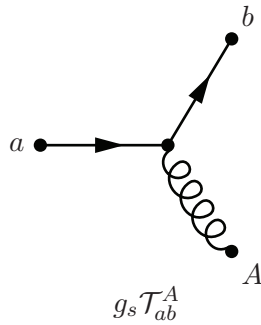


FIGURE 2.4: Quark-gluon interaction term

2.3 perturbative QCD

Perturbative QCD is necessary to describe the radiation of gluons off the primary quarks and the subsequent parton cascade due to gluon splitting into quarks or gluons, and radiation of gluons off secondary quarks. With the increase of center-of-mass energy, emission of hard gluons become increasingly important to determine the structure of

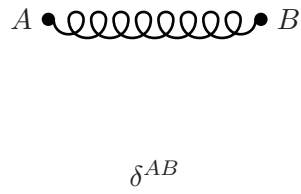


FIGURE 2.5: Free gluon-field

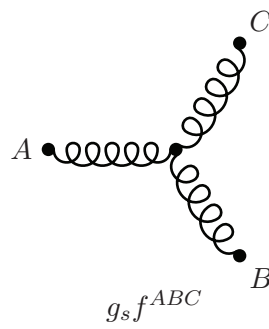


FIGURE 2.6: Cubic gluon self-interaction term

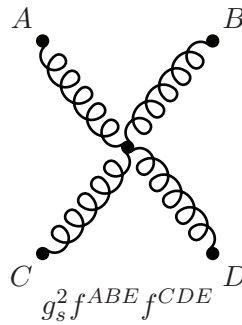


FIGURE 2.7: Quadratic gluon self-interaction term

event. To describe perturbative QCD, two complementary approaches can be taken : Matrix Element and Parton Shower.

2.3.1 Matrix Element

Here, Feynman diagrams are calculated order by order. For higher order diagrams, the calculation becomes increasingly difficult. Therefore, Matrix Element calculations exist only up to second order in coupling constant α_s .

The matrix element approach takes into account exact kinematics, the full interference and helicity structure. The string coupling constant α_s has a well defined meaning in this approach. The matrix element approach is required to determine α_s and to study QCD in 3 jet and 4 jet events.

2.3.2 Parton Showers

The parton shower approach is derived within the framework of the leading logarithm approximation. Only the leading terms in the perturbative expansion are kept and re-summed. Sub-leading corrections, which are down in order by factors of $\ln Q^2$ or $\ln z(\ln(1 - z))$, or by powers of $1/Q^2$, are thus neglected. Nevertheless, different schemes have been devised to take into account some sub-leading corrections like next to leading order terms.

2.4 Jet Production at the Large Hadron Collider

In the hard scattering process, $p + p \rightarrow \text{jets} + X$, the coloured partons, immediately after production, fragment and hadronize forming a cluster of collimated energetic colorless particles, hadrons. A clustering algorithm is applied on these particles to form a collection of particles which are called jets, the experimental analogue of partons and one of the key object in the theory of QCD. The Figure 2.9 shows a schematic diagram of jet formation in a typical $p - p$ collision at the LHC. Although jets are formed out of the fragmentation of colored partons, nevertheless it is colorless and a very robust observable in QCD measurement. However, formation of jets out of produced partons due to hadron-hadron collision is a very nontrivial phenomena. The produced partons first fragment and then hadronize to form a spray of color neutral energetic particles, which collectively form a jet. In Figure 2.8 a jet from generation at parton level to detection at the detector is shown. The color neutralization of jets, originating from a colored parton, happens through a non-perturbative dynamics. If Q is the hard scale involved in the hard scattering process, then the time scale associated with hard scattering $t_{hard} \sim \frac{1}{\sqrt{Q^2}}$. The

typical size of a light hadron is $R_0 \sim m_{hadron}^{-1} \sim \Lambda_{QCD}^{-1} \sim 1 fm$, which is the time scale of hadronization in the rest frame of the hadron. Hence in the lab frame, after applying the boost, the typical time scale of hadronization is $t_{had} \approx \gamma \cdot R_0 = \frac{E}{m} \cdot R_0 \sim \frac{Q}{R_0} \cdot R_0 = QR_0^2$.

In a typical fragmentation process if an initial parton of energy E emits a gluon of energy k , at an angle θ to the original direction of motion, then time-scale of such process is determined by the lifetime of the virtual gluon emitter. If q be the four-momentum of the recoiled parton and if we assume the recoil angle θ to be small, then

$$q^2 = 2Ek(1 - \cos \theta) \approx Ek\theta^2 = \frac{E}{k}k_{\perp}^2 \quad (2.14)$$

where $k_{\perp} = k\theta$, the transverse momentum of the emitted gluon. Applying the basic uncertainty relations and boost factor, the time scale of such a gluon emission from a

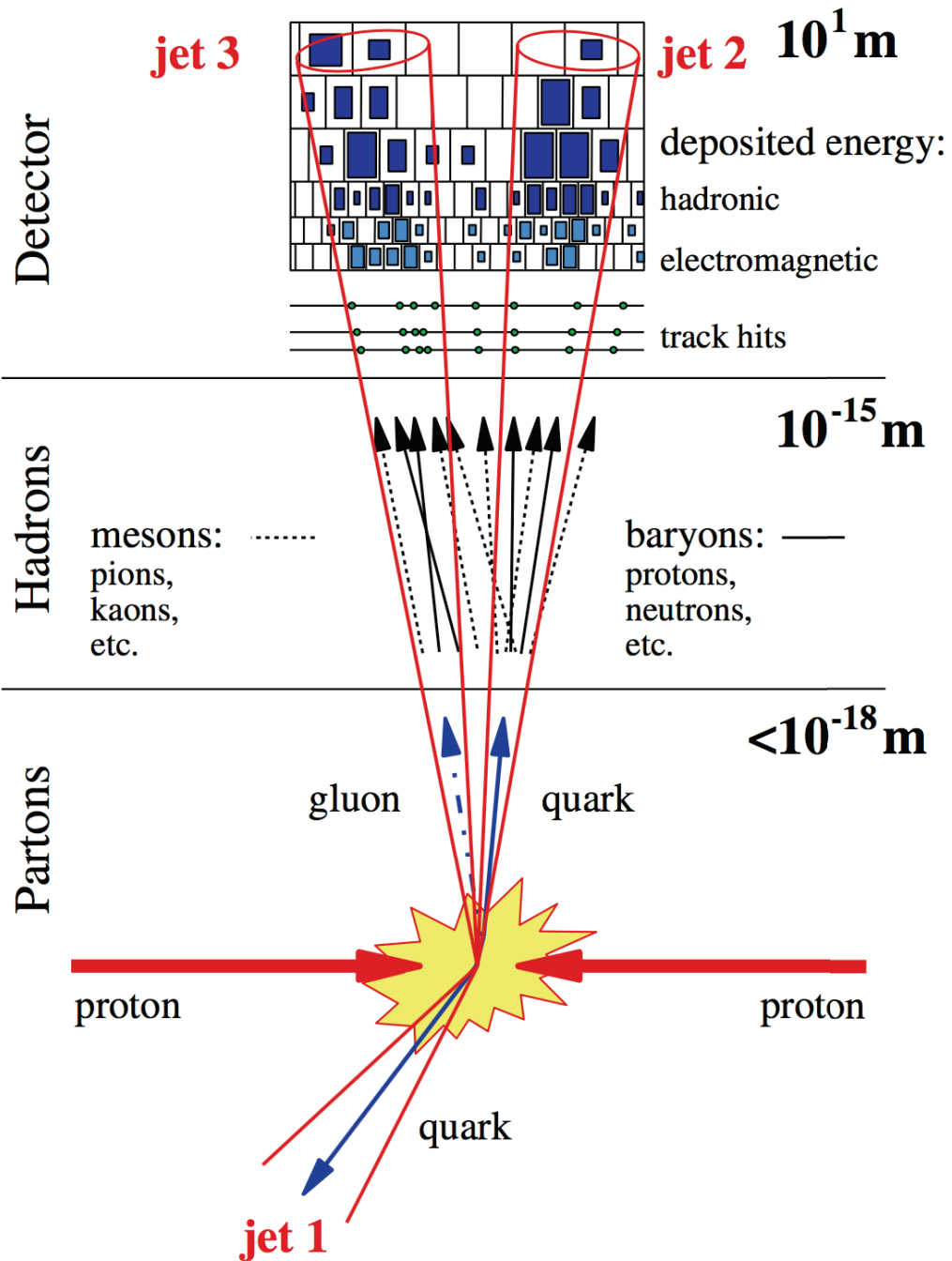


FIGURE 2.8: Illustration of a jet to which can consist of bundles of partons or hadrons, or detector measurements. (Taken from Ref. [32])

parton can be estimated as :

$$t_{form} \sim \frac{q_0}{\sqrt{q^2}} \cdot \frac{1}{\sqrt{q^2}} = \frac{E-k}{q^2} = \frac{E-k}{E} \frac{k}{k_{\perp}^2} \approx \frac{k}{k_{\perp}^2} \quad (2.15)$$

There is a second time-scale associated with the kinematics, the time taken by the gluon to reach a transverse separation R_0 from the emitter. As the transverse separation becomes $\geq R_0$, the effect of strong-interaction between the emitter and the emitted gluon gets diminished. The separation time is given by

$$t_{sep} \sim \frac{R_0}{\theta} = \frac{R_0 k}{k_{\perp}} \quad (2.16)$$

Comparing the time scales of gluon formation, separation and hadronization for the fragmentation process discussed above, we get :

$$t_{form} : t_{sep} : t_{had} = \frac{k}{k_{\perp}^2} : \frac{R_0 k}{k_{\perp}} : k R_0^2 = 1 : (k_{\perp} R_0) : (k_{\perp} R_0)^2 \quad (2.17)$$

In the above discussion, the physical picture we have in our mind is following :

- The initial parton emits a soft gluon and scatters at an angle θ . This process is a very fast process and takes a time t_{form} .
- The emitted gluon flies away for sometime such that its transverse distance from the emitter parton becomes $> R_0$ and hence this gluon is free from strong-dynamics effect of the emitter parton. This process happens over a time scale t_{sep} .
- The emitted gluon then undergoes non-perturbative strong interactions and much later hadronizes to form a colorless hadron, over the time-scale t_{had} .

In order to hold this picture, it is required to satisfy $t_{form} < t_{sep} < t_{had}$, which is true if $k_{\perp} > R_0^{-1}$. At such scales $\alpha_S(k_{bot}) < 1$ and hence prescription of pQCD is valid which ensures the viability of such process. If $k_{\perp} < R_0^{-1}$, no picturization as above can be made. In the intermediate energy range, there exist quantas with momentum scale $k_{\perp} = \theta k = R_0^{-1}$. These quantas feel the strong force and hold the hadron together and to distinguish them from perturbative gluons, they are denoted by a separate name 'gluers'. In a fragmentation process, at time scale R_0 , first gluers are formed with momenta $k \sim k_{\perp} \sim R_0^{-1}$. Whenever a primary parton is formed due to fragmentation, the gluers blanch their color fields, leaving two fast, color neutral system separate away. Since gluers have low momenta, it blanch the color fields of slower partons first and thus the slowest hadrons form first, close to the interaction point, forming an inside-out pattern. This is the process in which a colored parton showers and finally forms colorless hadrons at much later times. The set of collimated color neutral hadrons are combined to form jets and hence jets are also colorless objects. A more detailed discussion of the above mentioned phenomena can be found in [30], [5]. The color neutralization process itself is non-perturbative and different models exist for them [8], [52]. All the features of QCD, mentioned above, can be experimentally tested by studying observables constructed out of jets. These aspects are tested in various experiments very accurately.

In this thesis, we present our study on the measurement of double differential cross-sections for the production of inclusive jets as a function of transverse momentum and rapidity at the center of mass energy $\sqrt{s} = 13$ TeV. The analysis considers two different cone widths for the clustering algorithm used for the jets. A larger cone width of 0.7 makes possible to evaluate the ratio of differential cross-sections at different energies. This ratio,

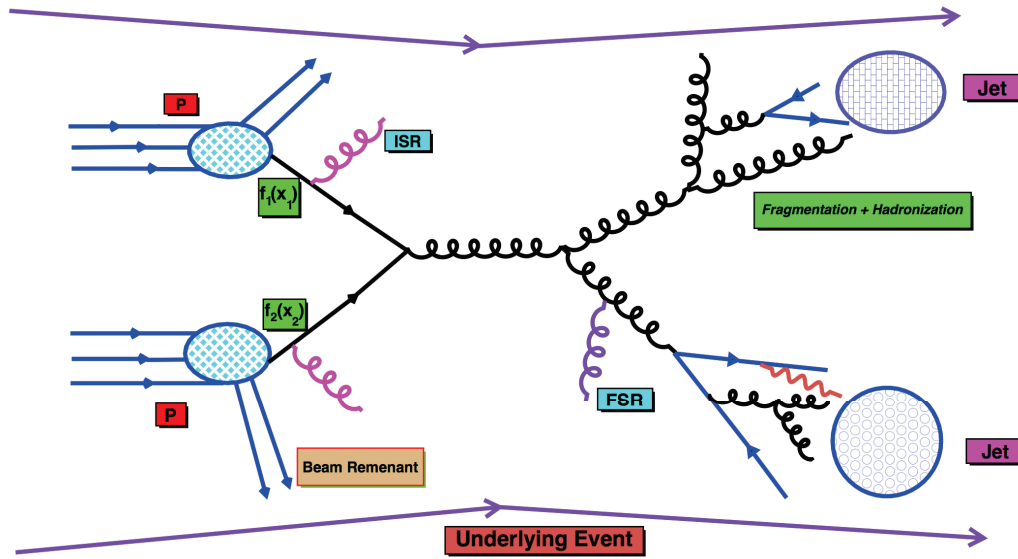


FIGURE 2.9: A schematic diagram of hard interaction in a $p - p$ collision, showing the phenomena of parton scattering, fragmentation of partons, hadronization and finally giving jets in the final state.

with a reduced sensitivity to scale uncertainties, may constitute a powerful constraint for parton density function (PDF) determination for further analyses. The measured cross-section may be used to extract the value of the strong coupling constant or to study its scale dependence on a wider kinematic range than the one accessible at lower energies. The measurement with the smaller cone width of 0.4, which is going to be the default one for CMS, aims for being the baseline for further jet analyses.

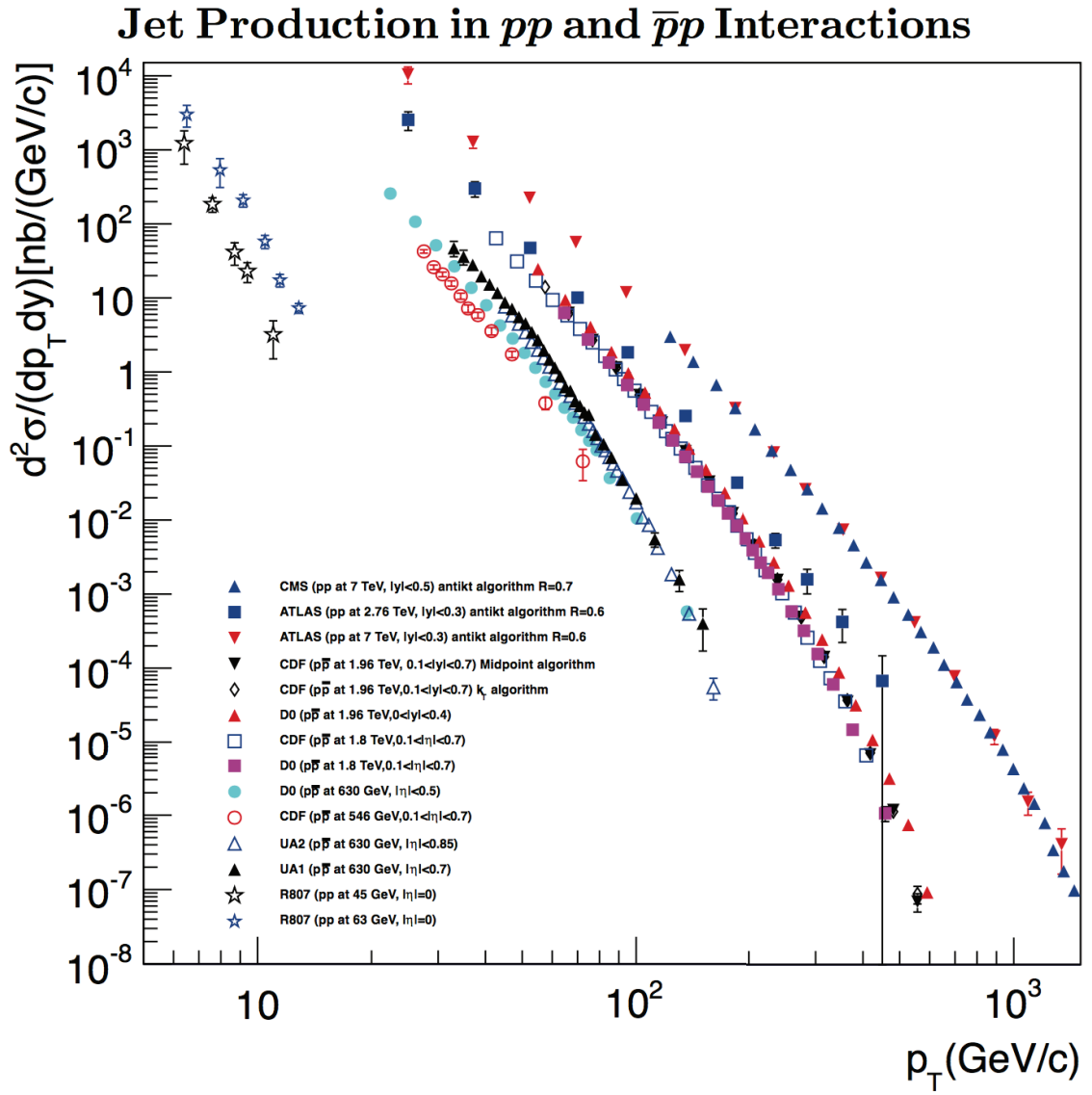


FIGURE 2.10: Inclusive differential jet cross-sections, in the central rapidity region, plotted as a function of the jet transverse momentum [1]

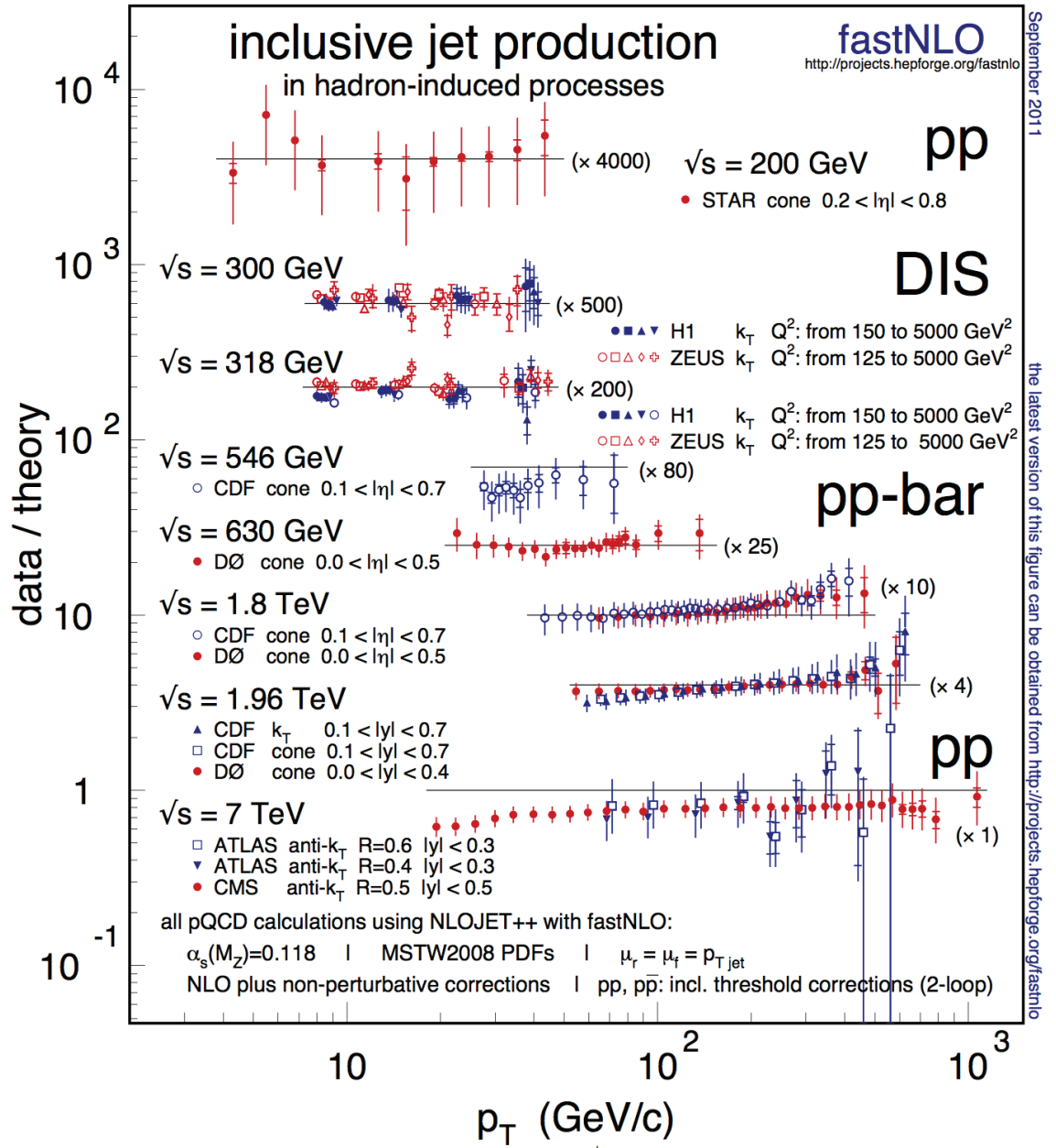


FIGURE 2.11: Data/Theory curves for Inclusive-Jet cross-section vs jet p_T using MSTW2008 PDF set [13].

Chapter 3

The Large Hadron Collider and the Compact Muon Solenoid Detector

3.1 The Large Hadron Collider (LHC)

The LHC, operating at CERN near Geneva in Switzerland, is a super-conducting storage ring collider. It is installed inside the 27 Km underground tunnel which was the former home of the Large Electron-Positron (LEP) collider on the France-Switzerland border. It is designed to provide proton-proton collisions of up to 14 TeV center-of-mass energy. A diagram of the LHC complex is shown in Figure 3.1.

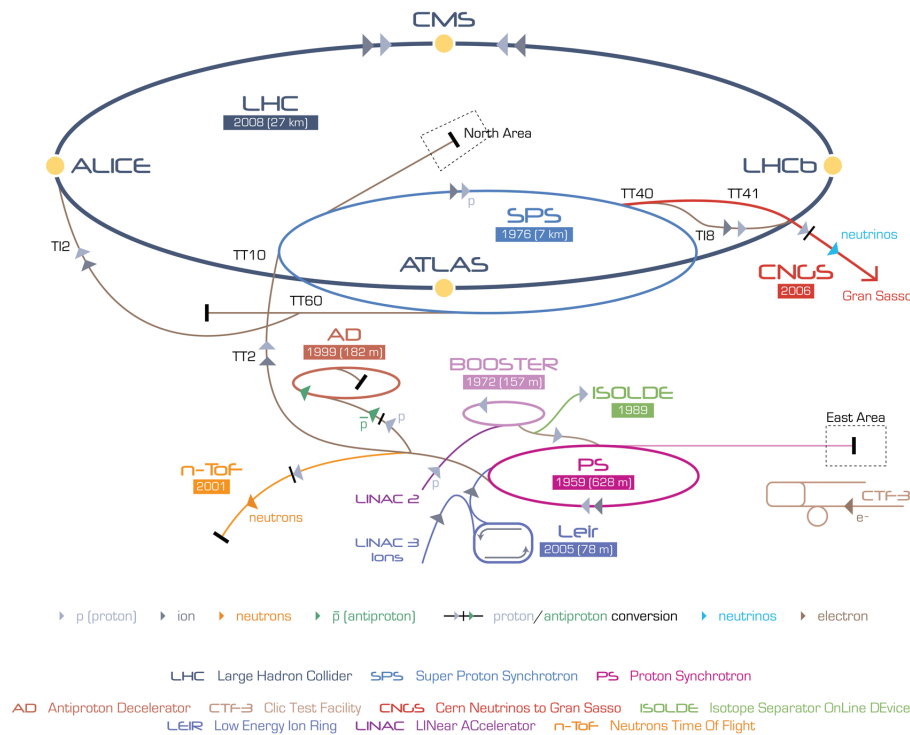


FIGURE 3.1: The Large Hadron Collider Complex at CERN

Particles are accelerated through multiple stages before being injected as proton bunches into the main accelerator ring. The acceleration process is done through the following steps:

- Hydrogen atoms, stored in a gas cylinder, are injected at a precisely controlled rate to a small chamber of the Linear Accelerator 2 (LINAC2) where the atoms are stripped of their electrons through electric discharge. The resulting protons are then accelerated in the LINAC2 to 50 MeV.

- b. In order to maximize the intensity of the beam, the stream of protons are then divided into four parts before they enter the booster ring PSB (Proton-Synchrotron Booster) of 157 meter circumference. The protons are accelerated to reach an energy of 1.4 GeV.
- c. The PSB is followed by the 628 meter circumference Proton Synchrotron (PS), where the energy is further increased to 25 GeV and the protons attain a speed of 99.9% of the speed of light.
- d. The protons then go to the Super Proton Synchrotron (SPS) (7 km in circumference) where they are accelerated to 450 GeV.
- e. The protons are injected into the two beam pipes of the LHC, where their energy is increased to 6.5 TeV. Eight radio frequency (RF) resonating cavities are used to accelerate the proton beams to this center of mass energy through a field gradient of 5.5 MV/m increasing the energy of the beams by 16 MeV per turn.

The two fully accelerated bunches, one moving clockwise and the other anticlockwise, are then made to collide at the center of detectors located around the four straight sections of the LHC ring:

- 1. ALICE (A Large Ion Collider Experiment) is a detector aiming to study strongly interacting matter at very high energy densities. The nature of a new phase of matter, the quark-gluon plasma, is studied here. The detector has a very efficient tracking system, consisting of a time projection chamber (TPC) and a transition radiation detector. This detector is highly efficient in a high multiplicity environment.
- 2. ATLAS (A Toroidal LHC ApparatuS) is a general purpose detector, aiming at searches of New Physics and precise measurements of the Standard Model, primarily in the Higgs sector. Its structure comprises of a tracking and a calorimetry system, immersed in a toroidal magnetic field of 2 T intensity, and an external muon detector. It is the largest detector at the LHC, with a length of 44 m and a diameter of 25 m.
- 3. CMS (Compact Muon Solenoid) is the other general purpose detector at the LHC, with smaller dimensions and different technologies with respect to ATLAS; a detailed description is provided in the coming section.
- 4. LHCb (Large Hadron Collider beauty) is a single-arm spectrometer detecting particles going in the forward direction with a very precise tracking system, provided by a magnetic field of 4T for the measurement of the momentum of the charged particles along with an electromagnetic and hadronic calorimetric structure. The detector specializes on measurements in the heavy flavour sector, particularly focusing on rare decays of charm and bottom hadrons and the parameters of the CP violation, in searches for New Physics and insights on the primordial matter-antimatter asymmetry.

3.2 The Compact Muon Solenoid Detector

The Compact Muon Solenoid is one of the two general purpose detectors at the LHC, the other one being ATLAS, located at one of the interaction points near the village of Cessy in France. It detects particles emerging from proton-proton and heavy ion collisions. This detector is designed to measure the properties of these particles, like momentum, energy,

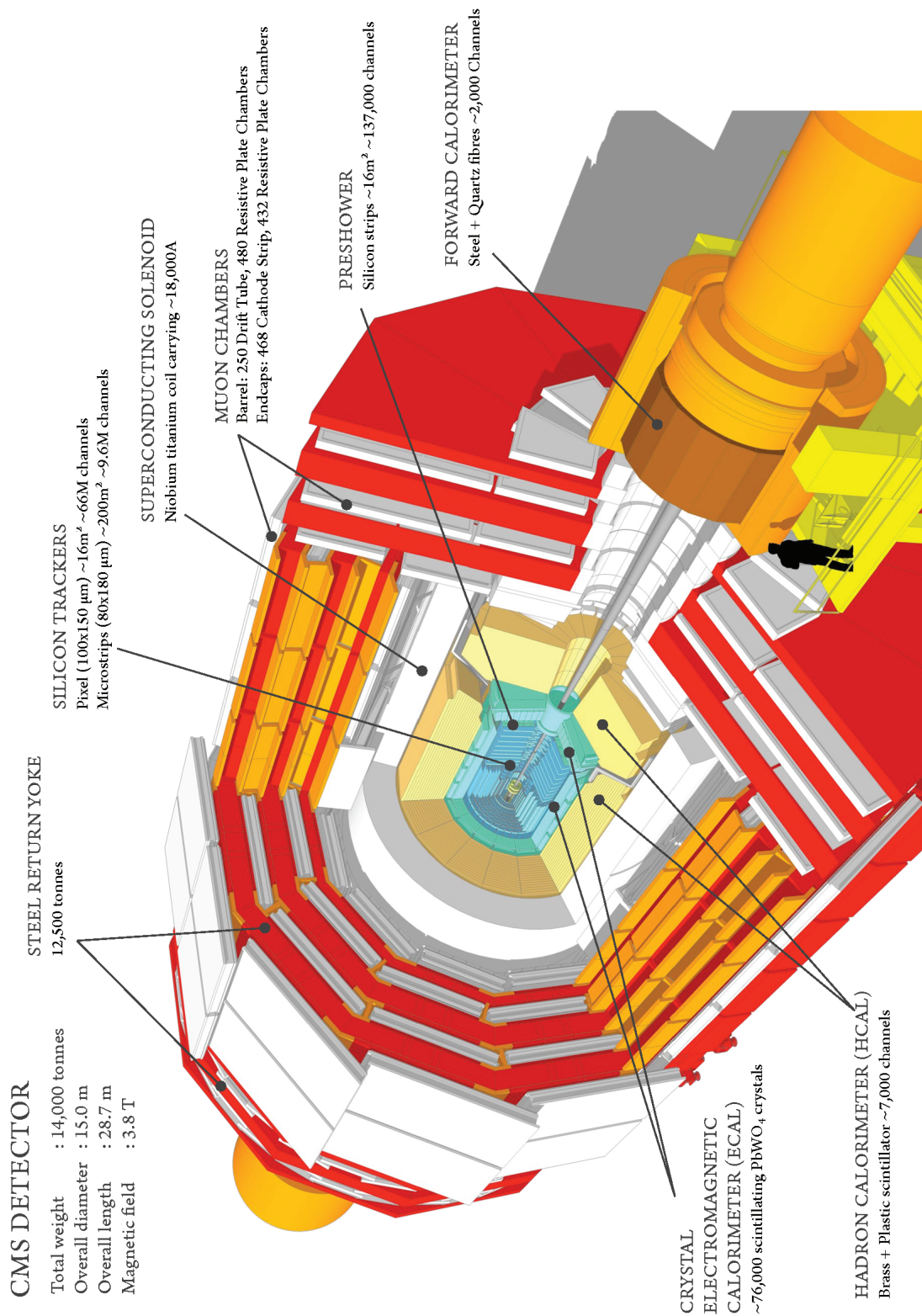


FIGURE 3.2: A schematic diagram of CMS detector showing the individual sub-detector components.

charge etc. with high precision. The name emphasizes three of the most important features, compact design, the particular design for muon measurement and the solenoid, providing a homogeneous magnetic field in the inner detector. Figure 3.2 shows the individual sub-detector components of the detector.

3.2.1 Experimental Coordinate System

The CMS coordinate system is chosen such that the x -axis points towards south with respect to the center of the LHC ring, the y -axis points vertically upward and the z -axis towards the direction of the beam to the west. The azimuthal angle ϕ is measured from the x -axis in the xy plane and the radial coordinate in this plane is denoted by r . The polar angle θ is defined in the rz plane with respect to z -axis (which is along the beam pipe). It is sometimes preferred to use a quantity, called pseudorapidity, because, for massless particles, differences between pseudorapidities are Lorentz-invariant under boost along the z -direction (which is also the direction of the beam). Pseudorapidity is defined as:

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right) \quad (3.1)$$

The relation between θ and η is illustrated in Figure 3.3, which links together values of the two quantities in the rz plane. The particle production can also be assumed as constant per unit of pseudorapidity. The momentum transverse to the beam direction, denoted by p_T , is computed from the x - and y -components, while the transverse energy is defined as $E_T = E \cdot \sin \theta$. In hadron colliders, the transverse quantities become important: in fact, in the transverse plane, the sum of all momenta should be equal to 0, assuming that the incoming protons have no transverse component at the moment of interaction. In the described analyses, the p_T , ϕ and η quantities will be considered to identify and select the physics objects. The physics objects, selected approximately with $|\eta| < 2.5$ are referred to as “central”, while the ones in $|\eta| > 2.5$ are called “forward”.

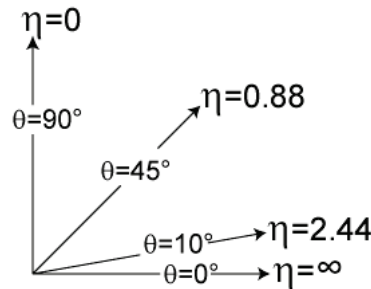


FIGURE 3.3: Variation of η with θ . The horizontal axis is the z -axis, while the vertical one is any direction in the xy plane

3.2.2 The Tracking System

The CMS tracker is an all-silicon detector with a sensitive area of over 200 m². The sensors are arranged in concentric cylinders around the interaction region of the LHC beams and are placed in a 3.8 Tesla magnetic field. The purpose of the detector is to provide high precision measurement points in three dimensions along the curved trajectories of charged particles up to pseudorapidities $|\eta| < 2.5$. The best tracking efficiency is achieved in the barrel region, $|\eta| < 0.9$. The charged particle tracks are used to reconstruct the positions of the primary interaction and secondary decay vertices. The tracker allows

for rapid and precise measurements with temporal and spatial resolutions that fulfill the challenges posed by the high luminosity LHC collisions, which occur at a frequency of 40 MHz. The high particle fluence induces radiation damage, which also presents a challenge for the operation and data-reconstruction in the inner layers of the tracker.

The CMS tracker is comprised of two sub-detectors with independent cooling, powering, and read-out schemes. The inner sub-detector, the pixel detector, has a total surface area of 1.1 m^2 . It is segmented into 66 million pixels of size $100 \mu\text{m}$ by $150 \mu\text{m}$ implanted into n -type bulk with thickness of $285 \mu\text{m}$ and p -type back side. The detector has three layers in the barrel region at radii of 4.3 cm, 7.2 cm, and 11 cm, respectively, and two disks on either side of the barrel (the endcap regions) at 34.5 cm and 46.5 cm from the interaction point. The pixel detector contains 15840 read-out chips (ROC), each reading an array of 52 by 80 pixels. The ROCs are arranged into modules which transmit data via 1312 read-out links.

The sub-detector surrounding the pixels, the strip detector, is segmented into 9.6 million $p+$ strips which are implanted into n -type bulk with thickness of $320 \mu\text{m}$ ($500 \mu\text{m}$) in the inner (outer) layers or disks and n -type back side. The pitch of the strips varies from $80 \mu\text{m}$ to $205 \mu\text{m}$. The detector has 10 tracking layers in the barrel region that span radii from 25 cm to 110 cm and along the z axis up to 120 cm: 4 layers in the inner barrel (TIB) and 6 in the outer barrel (TOB). It also has 12 disks in the endcap region with radii up to 110 cm and in z up to 280 cm: 3 inner disks (TID) inside and 9 endcap disks (TEC) outside the TOB as shown in figure 3.4. Four layers in the barrel and multiple layers in the endcap regions of the strip detector are equipped with stereo modules allowing for 2D measurement. These modules have two silicon sensors mounted back-to-back with their strips aligned at a 100 mrad relative angle. Both sub-detectors are read out via a chain of analog electronic and optical links which are able to transmit absolute pulse height. In the pixel detector, the pixel coordinates are also transmitted. For the strips, all data-processing happens in off-detector electronics.

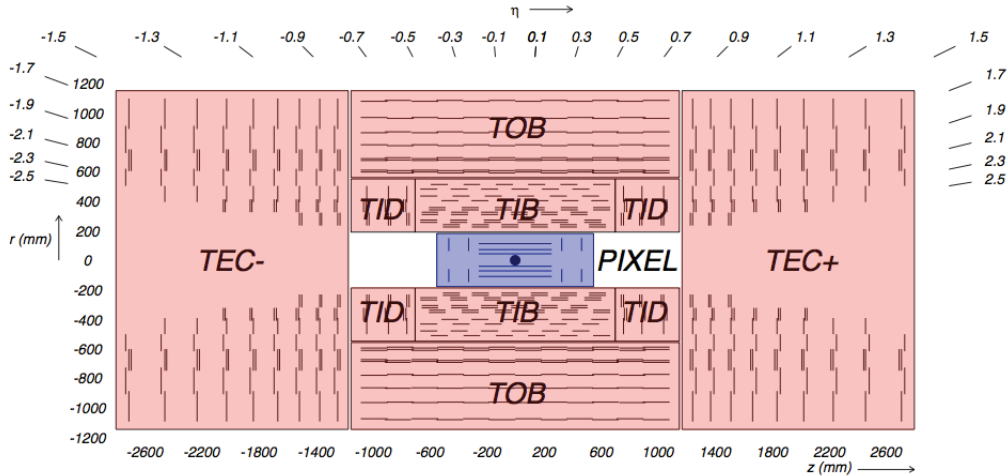


FIGURE 3.4: A schematic diagram of the tracker in the CMS experiment. The figure shows two quadrants of a longitudinal section of the inner tracking detector of CMS along the rz plane. The strip detector comprises four components: the Tracker Inner Barrel (TIB) is complemented by the Tracker Inner Disks (TID). These two are surrounded by the Tracker Outer Barrel (TOB). High η ranges are covered by the Tracker End Cap (TEC) up to $|\eta| = 2.5$.

3.2.3 The Electromagnetic Calorimeter

The CMS electromagnetic calorimeter is a homogeneous calorimeter composed by 61200 lead tungstate (PbWO_4) crystals in the barrel region and 7324 ones in each of the two end-caps. This material was chosen because of its high density (8.28 g/cm^3), short radiation length (0.89 cm) and small Moliere radius (2.2 cm), fast response time and good radiation tolerance. Signal from the scintillation (and Cerenkov) light, produced by electrons and positrons of the shower, is transmitted through total internal reflection and is detected by avalanche photo-diodes in the barrel region and vacuum photo-triodes in the endcaps. The barrel section has an inner radius of 129 cm and its structure is organized with 20deg “supermodules”, each covering $|\eta| < 1.479$ region; a supermodule is a collection of four modules, equipped with five pairs of crystals each. Every crystal covers 0.0174 in both ϕ and η (corresponding to 1deg in θ) angular region and has a length of 230 mm corresponding to $25.8 X_0$. The endcaps are at a distance of 314 cm from the interaction point and close the barrel part on both sides; they cover a pseudorapidity range of $1.479 < |\eta| < 3.0$ and are contained inside two semi-circular aluminum plates with basic units of 5×5 crystals. The endcaps are also equipped with a preshower sampling calorimeter in front of the whole system, composed of lead radiators and silicon strip detectors in order to identify neutral pions in the forward region and to have a better determination of the position for electrons and photons. An overview of the ECAL sub-detector is sketched in Figures 3.5 and 3.6.

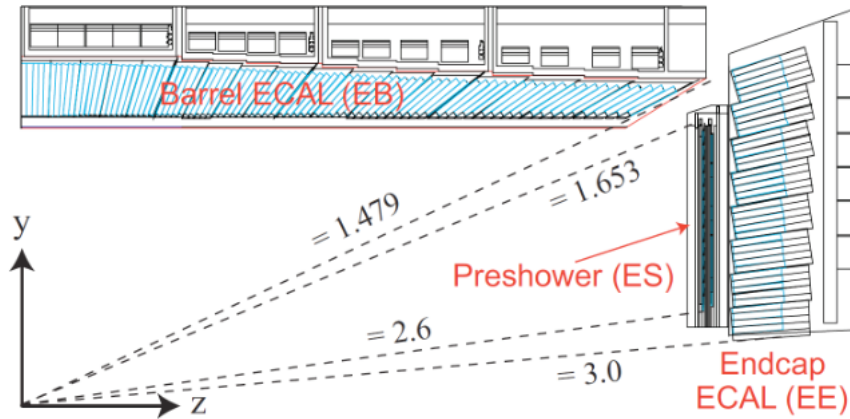


FIGURE 3.5: Sketch of the ECAL barrel and endcap regions represented in the longitudinal plane

The energy resolution measured during calibration is parametrized by:

$$\left(\frac{\sigma_E}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12\%}{E}\right)^2 + (0.30\%)^2 \quad (3.2)$$

The first term refers to the stochastic contribution due to fluctuations in the lateral shower development and in the energy released in the preshower; the second term quantifies the noise, due to electronics, digitization and pile-up, and finally the third term is a constant due to calibration errors, energy leakage or non-uniformity in the light collection.

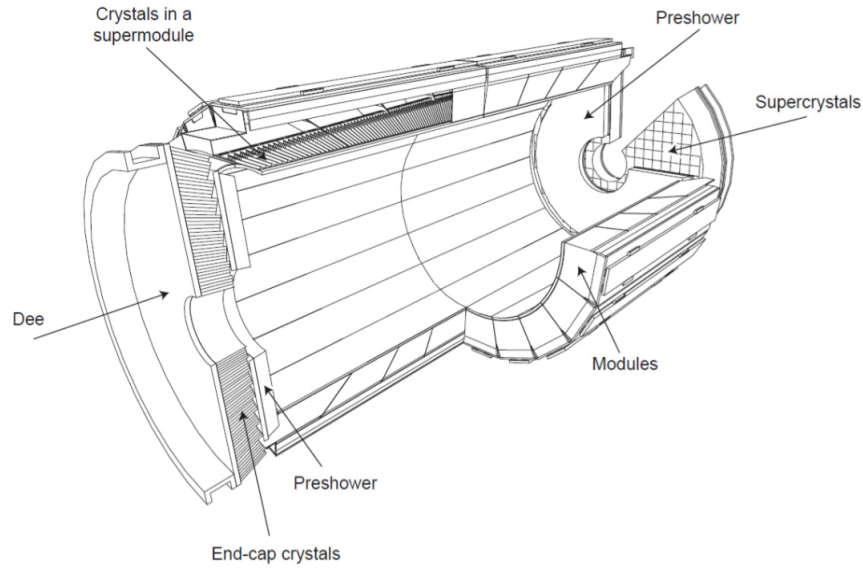


FIGURE 3.6: A schematic diagram of ECAL sub-detector showing the individual components

3.2.4 The Hadron Calorimeter

The CMS Hadron Calorimeter is a sampling calorimeter, relevant for measuring the jet energy and for providing information used for photon and lepton identification. Its structure is not totally contained inside the magnet coil because of the small space left empty between the solenoid and the ECAL. The hadron calorimetry system is, therefore, organized in four parts: an inner hadron barrel (HB), an outer detector (HO), an endcap part (HE) and a forward calorimeter (HF).

The hadron barrel part consists of 36 wedges covering the pseudorapidity region $|\eta| < 1.3$, segmented into four azimuthal sectors each, and made out of 14 flat brass absorber layers, enclosed between two steel plates. An additional segmentation in pseudorapidity of plastic scintillators provides an overall division in $\phi \times \eta = 0.087 \times 0.087$ angular regions. Due to the limited space between the ECAL and the solenoid, the effective thickness ranges from only $5.82 \lambda_I$ at the center ($\eta \sim 0$) to $10.6 \lambda_I$ at the edges ($|\eta| \sim 1.3$). However, hadrons traversing HB have already passed ECAL which provides an additional $1.1 \lambda_I$ of material.

The hadron outer detector contains scintillators with the same angular segmentation and lies outside the solenoid. The solenoid is used as absorber and the thickness of the scintillators depends on the angle, resulting in $1.4 \lambda_I / \sin \theta$. This is achieved by adding one layer of scintillator in the extreme forward part and two layers of scintillators in the central part of the calorimeter. The HO covers the region $|\eta| < 1.26$ and works as a tail catcher, sampling the energy from penetrating hadron showers leaking through the back part of the barrel calorimeter. The information from the HO serves to improve the energy resolution, by increasing the total thickness of the calorimeter to $11.8 \lambda_I$.

The hadron endcaps consist of 14 towers in η on either side of the barrel with segmentation in ϕ of about 5° for the lower pseudorapidities inside the range $1.3 < |\eta| < 1.6$ and of 10° for the higher ones, inside $1.6 < |\eta| < 3.0$. The HE includes 18 layers made of alternating 79 mm brass plate and 9 mm scintillator. Similar to the HB, each endcap is organized as a collection of 18 wedges. A drawing of the HCAL is shown in Figure 3.7,

for both barrel and endcap parts.

The energy resolution is parametrized for single pions by the function:

$$\frac{\sigma_E}{E} = \frac{84.7\%}{\sqrt{E}} + 7.4\% \quad (3.3)$$

where the first term includes the effects of leakage and sampling fluctuations, while inhomogeneities and shower leakages contribute to the second one. However, the response and resolution of the CMS calorimetry system depends on both ECAL and HCAL, since most particles start showering in the ECAL. The ECAL and the HCAL fractions of the energy deposited in each calorimeter do not vary linearly with energy and, as a result, the raw energy measurements require substantial corrections.

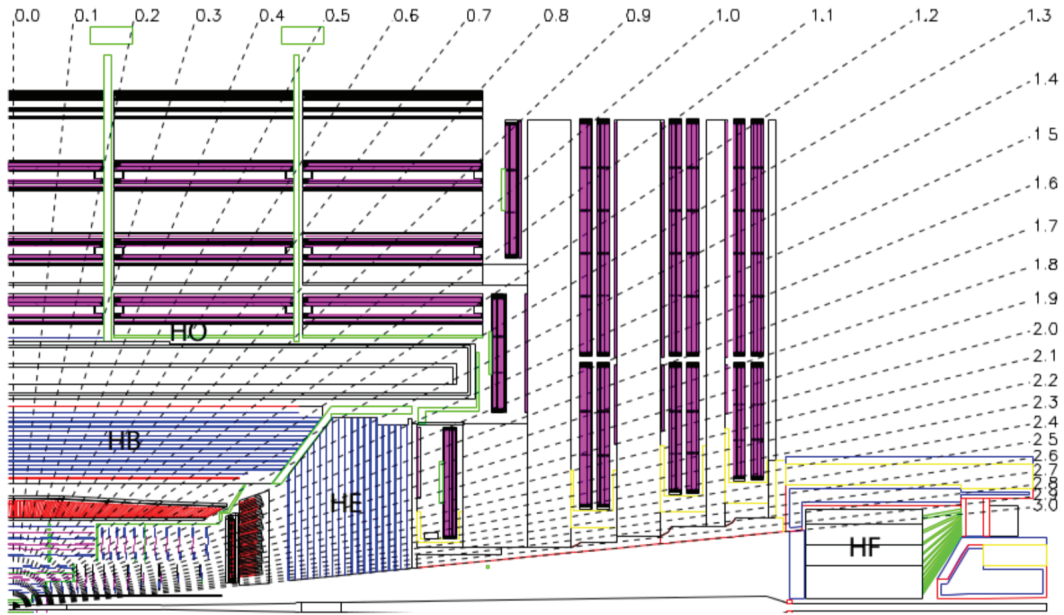


FIGURE 3.7: Longitudinal view of the CMS showing different parts of the hadron calorimeter: HB, HE, HF and HO

Finally, the hadron forward calorimeter assures a coverage up to $|\eta| = 5$ and, because of the high flux of particles in this region, is provided with a sandwich of different layers of steel as absorber and quartz fibre as active material. This design leads to narrower and shorter showers for electrons and photons which allows to distinguish electromagnetic and hadronic showers. The absorber-fiber layers are arranged in 864 towers (on either side of the interaction point) that run parallel to the beam line, at a distance of 11.2 m from the interaction point. The signal originates from Cerenkov light emitted in the quartz fibres, which is then channeled towards photomultipliers that produce the electric signal. An outline of the sub-detector is shown in Figure 3.7. The performance of the HF is described in [6], together with the whole calibration and compensation procedure. The energy resolution can be parametrized as:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} + b \quad (3.4)$$

where values of the two parameters are listed in 3.1 for different particles. In general, the

coefficient a is around 200% for electromagnetic particles and 300% for hadrons, while b is around 10% for both types.

Parametrization	$a[\%]$	$b[\%]$
$\left(\frac{\sigma_E}{E}\right)_{EM} = \frac{a}{\sqrt{E}} + b$	208.4 ± 1.3	10.7 ± 0.4
$\left(\frac{\sigma_E}{E}\right)_{HAD} = \frac{a}{\sqrt{E}} + b$	313.5 ± 2.9	11.2 ± 0.9

TABLE 3.1: The electromagnetic and hadronic energy resolutions for single particles are summarized here. The values are quoted in percent, while E is in GeV

The calorimetry system is completed by CASTOR, an electromagnetic and hadronic calorimeter installed in the very forward region.

3.2.5 CMS Solenoid

Magnetic field is an essential component for an experiment at colliders. By measuring the curvature of a charged particle in a magnetic field, a measurement of its transverse momentum is possible. The CMS magnet [49], which provides a magnetic field up to 4 Tesla, is a superconducting solenoid, 220 tons in weight and 3.9 radiation lengths thick. The field is closed by a 10,000 tons of iron return yoke made by five barrels and two endcaps of three layers each. The yoke is instrumented with four layers of muon stations and the coil is cooled down to 4.8 K by a helium refrigeration plant; the whole structure is kept isolated by two pumping stations providing vacuum on the 40 m³ of the cryostat volume. Such a strong magnetic field enables a very compact layout and an efficient muon detection.

3.2.6 Muon Detectors

The CMS muon system [50] forms the outer part of the CMS layout; this is because the muons are able to travel through the whole solenoid with minimal energy loss inside the inner detectors. The muon system is composed of three types of gaseous detectors, located inside the empty volumes of the iron yoke and therefore arranged in barrel and endcap sections. In the barrel region where the muon flux is quite low, standard drift chambers with rectangular cells are used. They are arranged in four stations inside the return yoke and cover the region of $|\eta| < 1.2$. Since the muon and background flux is higher in the forward region, the choice for muon detectors fell upon cathode strip chambers (CSC) because of their fast response time, fine segmentation and radiation tolerance. Each endcap is equipped with four stations of CSCs that cover in total the region of $0.9 < |\eta| < 2.4$. They are arranged in concentric rings, three in the innermost stations and two in the last one. In total, the muon system contains about 25,000 m² of active detection planes and nearly one million electronic channels. For the muon reconstruction, the tracking system is used in addition to the muon detectors. The reconstruction performance has been measured in [26]: the identification efficiency for muons with a transverse momentum of more than a few GeV is greater than 95% in all detector regions, while the misidentification rate lies only between 0.1% and 1%, depending on the selection. For muons with p_T between 20 and 100 GeV, the relative p_T resolution is between 1.3% and 2% in the barrel and slightly higher than 6% in the endcaps. Even for high-energetic muons with $p_T > 1$ TeV, the resolution is still better than 10%.

3.2.7 Trigger System

The task of a trigger system is to select interesting events inside a huge multiplicity of non-interesting interactions, and to suppress background as efficiently as possible. High bunch crossing rates and high values of the luminosity at the LHC correspond to a total of 10^9 events/s to be recorded by CMS. This large amount of data is impossible to store and process with the current technology of data storage and processing. Therefore, a dramatic rate reduction has to be achieved. Fortunately, interesting events are rare (with a frequency of about 1 Hz) and hence, it is possible with an efficient trigger system to retain most of the interesting physics events and reject background events. In case the condition of rarity of the examined process is not fulfilled, *e.g.* for Minimum Bias samples or events with jets at low p_T , a prescaling is applied: this procedure consists of storing only a fraction of events of the same type. The events that are effectively recorded are probabilistically chosen, *e.g.* the first event out of ten is recorded while the others are rejected. The decision of recording or dropping an event has to be performed very quickly and it is based on signals of certain physics objects inside the detector.

CMS achieves this condition in two steps: the Level 1 (L1) Trigger [19] and the High Level Trigger (HLT) [18], [3]. The Level 1 trigger is based on custom and programmable electronics (FPGA, ASICs and LUTs), while the HLT is a software system implemented on a ~ 1000 processor farm. The overall trigger is designed to reduce the rate at least 10^6 times. The maximum allowed output rate for L1 is 100 kHz. It uses rough information from coarse segmentation of calorimeters and muon detectors and keeps data in a pipeline until the acceptance/rejection decision is made. HLT exploits the full amount of collected data for each bunch crossing accepted by L1 Trigger and is capable of complex calculations such as the offline ones. Configuration and operation of the trigger components are handled by a software system, called Trigger Supervisor. Currently, the transmission of data from the L1 to the HLT is handled with optical links. The size of each event is about 1 MB and the total rate of data to be passed to HLT is ~ 100 GB/s.

The L1 Trigger involves the calorimetry and muon systems, as well as some correlation of information between the two. The L1 decision is based on the presence of particle candidates such as photons, electrons, muons and jets above set E_T or p_T thresholds. It also employs sums of E_{miss} and E_T . The total allowed latency time for the L1 Trigger is $3.2 \mu\text{s}$.

All events that pass the L1 Trigger are sent to a computer farm (Event Filter), that performs physics selections, using faster versions of the offline reconstruction software, to filter events and to achieve the required output rate. The HLT is able to reduce the rate of recorded events down to 200 Hz and only these events are stored and processed by the Data Acquisition (DAQ). The whole trigger chain is outlined in Figure 3.8, where the different trigger operations are shown, together with hardware and software parts used in each step and rate of events, until the data storage.

3.3 Luminosity Measurement and cross-section

Luminosity is the parameter which relates the rate of events for a certain type of process to the cross-section of that process. It can be expressed in terms of the number of particles in the beam crossing the collision point per time and the effective area of the crossing region. The quantity measures the ability of a particle accelerator to produce the required number of interactions.

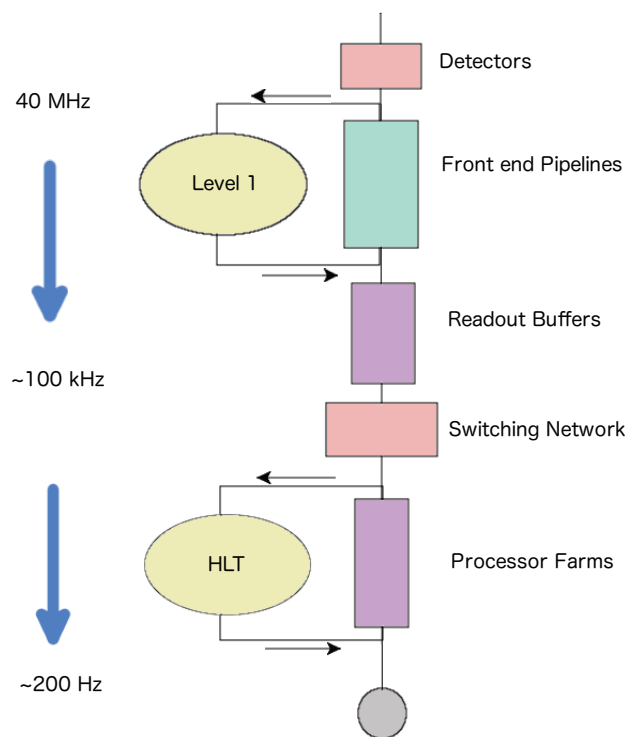


FIGURE 3.8: A schematic view of the CMS trigger system

The instantaneous luminosity L is proportional to the rate $\frac{dN}{dt}$ of a certain process of cross-section σ :

$$L = \frac{dN}{dt} \cdot \frac{1}{\sigma} \quad (3.5)$$

In reality, luminosity is measured as :

$$L = \frac{N_p^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (3.6)$$

where

- N_p is the number of protons per bunch,
- n_b is the number of bunches per beam,
- f_{rev} is the revolution frequency,
- γ_r is the relativistic gamma factor,
- ϵ_n is the normalized transverse beam emittance,
- β^* is the value of the beta function at the collision point which relates to the transverse size of the beams at the interaction point,
- F is the geometric factor due to the crossing angle of the two beams.

The LHC has been designed to produce pp collisions at a center-of-mass energy of 14 TeV with a peak instantaneous luminosity $L = 10^{34} cm^{-2} s^{-1}$, a nominal bunch spacing $T_b = 25$ ns and a number of bunches equal to 2808, 7.5 m apart from each other. This brings a fraction of bunches in the ring of the order of $2808 \times 7.5 \text{ m} / 27 \text{ km} = 0.78$. Table 3.2 summarizes the beam parameters at the LHC. The expected collision rate is 40 MHz. Figure 3.9 shows the growth of instantaneous luminosity with time at the LHC.

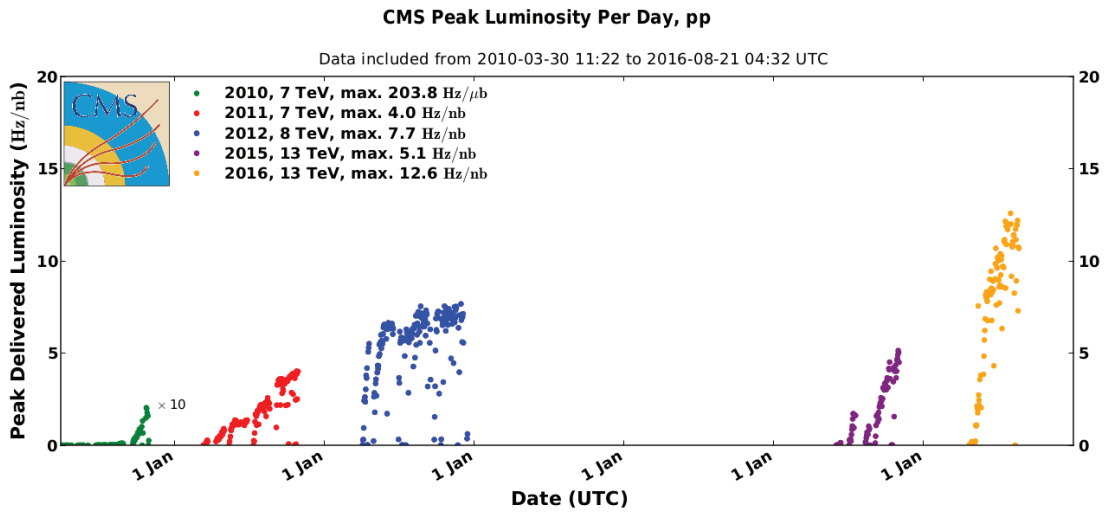


FIGURE 3.9: Growth of instantaneous luminosity with time

The integrated luminosity is the integral of the instantaneous luminosity over time. It is usually expressed in units of barn^{-1} to give a direct indication of the number of produced events for a process. For instance, an integrated luminosity of 30 pb^{-1} means that 30 events of a process with cross-section equal to 1 pb are produced. Figure 3.10

Parameters	Units	Effective value(2015)
Number of bunches	n_b	2076
Bunch spacing	T_b [ns]	25
Protons per bunch	$N_b [\times 10^{11}]$	1.18
Norm. tr. emittance	$\epsilon_n [\mu\text{m}]$	2.6
R.M.S. bunch length	σ_S [cm]	1.05
β at IP	β^* [m]	0.4 / 10 / 0.4 / 3
Luminosity lifetime	τ_L [h]	24
Peak luminosity	$L_{peak} [\times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}]$	1.05

TABLE 3.2: Main parameters of the accelerator machine and proton beams at the LHC, This is only a snapshot as some parameters varied over the run periods.

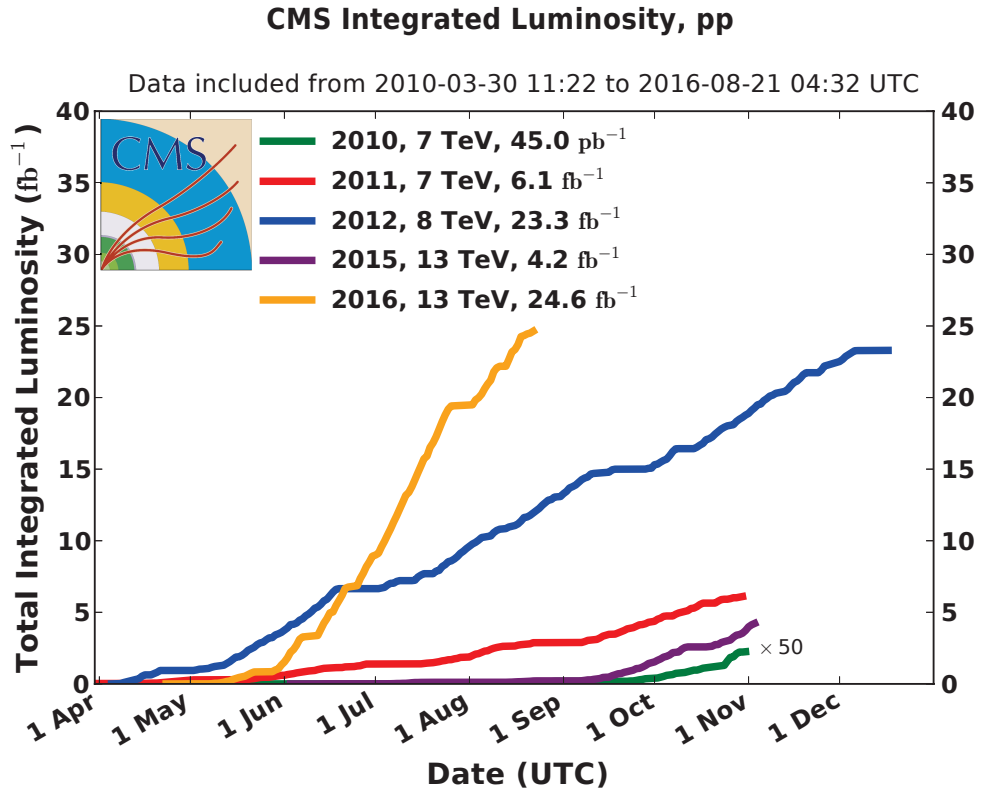


FIGURE 3.10: Total integrated luminosity delivered to the CMS experiment during the year 2010-2016.

shows the integrated luminosity delivered to the CMS experiment during the year 2010-2016 as a function of time.

Chapter 4

Physics Object Reconstruction

This chapter provides a description of how events are reconstructed in the CMS detector. While CMS collects huge amount of data over time, one needs to extract compact information from these data which is relevant to a given analysis. This information needs to be small in size, related to the generated signal information created by particles interacting with the detector material. The data are processed to create physics objects and the selection cuts are applied to these physics objects. The aim of the event reconstruction is to build well calibrated physics objects. A brief description of the physics objects used for the analysis and of the requirements applied in the event selection is provided. Details of the reconstruction and energy correction of jets are also described here.

4.0.1 Particle Flow Algorithm

The CMS experiment utilizes a technique, called Particle-Flow (PF), which is able to identify and reconstruct individually each particle in an event, by combining information from all the sub-detectors [11]. In CMS, the PF algorithm relies on an excellent tracking efficiency in the high magnetic field and a very fine calorimeter granularity. This type of reconstruction leads to an improved performance for the detection of all physics objects and it is used in the analyses described in this thesis. The ingredients for an efficient PF algorithm arise from the following principles: to maximise the separation between charged and neutral hadrons. A large field integral and very high calorimeter granularity are of primary importance to enable this. An efficient tracking is a key item as well as very small material budget in front of the calorimeters. The CMS detector [27] fulfills several of these conditions with a field integral more than twice larger than in other past or existing experiments; an electromagnetic calorimeter with an excellent resolution and granularity, and a tracker system fully exploited with the iterative tracking algorithm.

The algorithm can be described as follows: the tracks are extrapolated through the calorimeters. If they fall within the boundaries of one or several clusters, the clusters are associated to the track. The set of track and cluster(s) constitute a charged hadron and these building bricks are not considered anymore in the search of other charged hadrons during the rest of the pattern recognition algorithm. The muons are identified beforehand so that the corresponding tracks do not give rise to a charged hadron. The electrons are more difficult to deal with. Indeed, due to the frequent bremsstrahlung photon emission, a specific track reconstruction is needed as well as a dedicated treatment to properly attach the photon clusters to the electron and to avoid energy double counting. Once all the tracks are treated, the remaining clusters result in photons in case of the electromagnetic calorimeter (ECAL) and neutral hadrons in the hadron calorimeter (HCAL).

Once all the deposits of a particle are associated, its nature can be assessed, and the information from the sub-detectors is combined to determine optimally its four-momentum. In case the calibrated calorimeter energy of the clusters, which is simply a linear combination of the ECAL and HCAL energy deposits, associated to a track is found to be in excess with respect to the track momentum at more than one sigma, the

excess is attributed to an overlapping neutral particle (photon or hadron), carrying an energy corresponding to the difference of the two measurements. The resulting list of particles, namely charged hadrons, photons, neutral hadrons, electrons and muons, is then used to reconstruct the jets, the missing transverse energy (E_{miss}). The taus are reconstructed and identified from their decay products. The isolation of each of these particle candidates is also determined.

The performance of the algorithm is studied with simulated events. About 90% of the jet energy is carried by the charged hadrons and the photons while 10% of the energy is carried by the neutral hadrons. The energies of charged hadrons and photons are measured with a high precision by the tracker and the ECAL respectively, while the remaining energies are measured with the hadron calorimeter (HCAL) with a resolution of $120\%/\sqrt{E}$.

4.0.2 Physics Objects in CMS

Signals from different sub-detectors are reconstructed as several physics objects, depending on the type of signal left by the particle after interacting with detector material. In particular, it is important to combine information from the different sub-detectors in order to truly discriminate between particles which are produced during the hadron-hadron collision. In 4.1, a sketch of the CMS detector is provided with focus on the signals produced by the various particles crossing different sub-detectors. It can be seen that muons (light blue curve) are the most penetrating particles produced in a collision, able to cross all the sub-detectors and to reach the most external layers. A photon (dashed blue line) is just seen as energy deposit in the electromagnetic calorimeter, while an electron (red curve) has additionally a track in the tracking system. Hadrons deposit energies in both the electromagnetic and the hadronic calorimeters. The neutral ones (dashed green line) have no associated tracks, while the charged ones (solid green line) have corresponding hits in the tracker. These features are used by the event reconstruction to build the physics objects. The list of the reconstructed physics objects in CMS is given below, with a very brief description of their detection:

Jet

A jet is seen through a highly-collimated energy deposit in the calorimeters and a collection of tracks in the tracker in the same direction. Different techniques have been developed in CMS for a reliable and well calibrated jet reconstruction and they are described in 4.0.3;

Muon

A muon is detected with high probability because it is the only particle whose energy is not completely absorbed by the calorimeter system and can reach the muon system. Its reconstruction makes use of a combination of hits in the muon chambers and in the internal tracker, and also uses the minimum ionizing particle signature in the calorimeters.

Electron

Electrons are detected by searching for signals in the inner tracker and corresponding clusters in the electromagnetic calorimeter. Quality criteria are then applied to reject fake jets or converted photons.

Heavy flavour jet

The CMS detector is able to discriminate jets of different flavours, by identifying hadrons from the fragmentation of heavy-flavour quarks. This feature is particularly used for b-jets: their identification is based on the detection of a displaced secondary vertex from a long lived B-hadron decay, on the measurement of the jet mass or on the presence of high p_T leptons inside the jet cone.

Tau

The detector signature of τ leptons, decaying hadronically, is a collimated jet with low multiplicity (up to three charged hadrons) and constituents isolated from other particles; the reconstruction algorithm is quite complex and uses energy clusters in the calorimeters, together with tracker information, in particular a signal in one tracker strip.

Photon

A photon appears in CMS as an energy cluster in the ECAL. A prompt photon is a photon which is produced at the primary vertex, and not emitted, for example, via bremsstrahlung or decay of other particles, in general. The detection of a prompt photon requires the presence of energy deposit in many ECAL towers, due to its shower; this energy spread is collected in the so-called “electromagnetic super-cluster”. The super-cluster does not have a matching track in the Tracker and isolated with respect to other energy signals in the calorimeter. Furthermore, an upper threshold is also set to the energy present in the hadronic calorimeter along the photon direction.

Missing Transverse Energy

Since the initial state of hadronic collisions at the LHC has no transverse components, vector sum of transverse energy should be equal to 0 because of conservation laws. This is true for a completely hermetic and ideal experiment, namely an experiment which is able to measure every particle with infinite resolution. In real life, this is not true and the presence of neutrinos and effects due to detector resolution contribute to give a certain amount of E_{miss} . To measure it, all the energy deposits in the calorimeter acceptance are measured: in particular, $E_{miss} = -\sum_i E_{i,T}$, where i refers to each energy cluster in the event.

4.0.3 Jets in CMS

Jets in the CMS detector appear as energy deposits in both the calorimeters (ECAL and HCAL) in the same region, together with tracks pointing to the same direction. The PF jet algorithm utilizes the particle flow candidates obtained using an algorithm described before.

Other types of jet reconstruction are also used within CMS and are listed below:

- **Calo-Jets** : Jets are obtained by clustering the energy deposits in the ECAL and in the HCAL.
- **Jet Plus track(JPT)** : Jets are reconstructed from energy deposits in the ECAL and in the HCAL. The calorimetric energy value is then corrected by using the measured momentum of the charged particles in the jet. This reconstruction algorithm differs from the PF technique, since information from the different sub-detectors is just merged and not combined for a detailed particle identification as done in the case of PF.

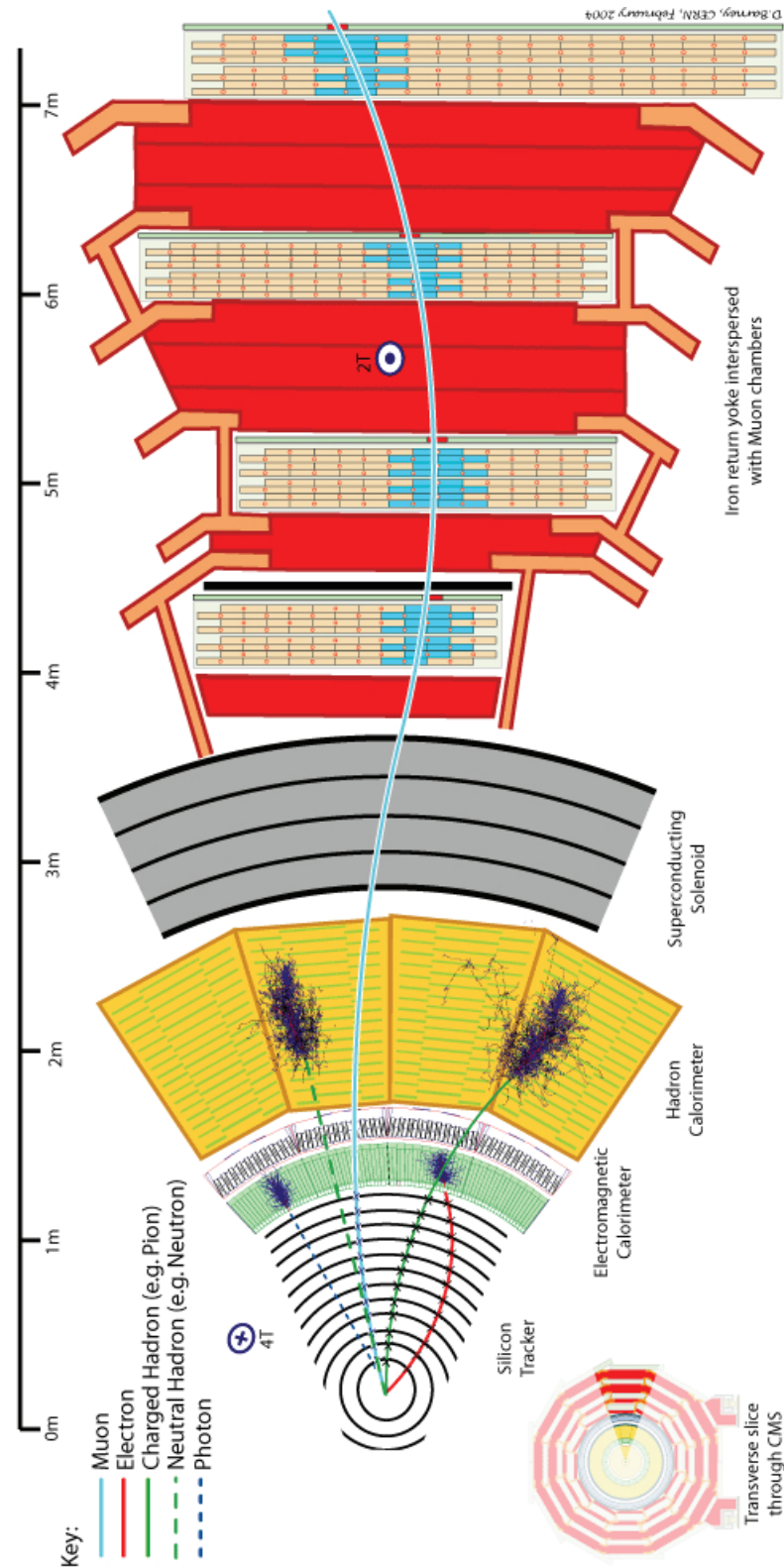


FIGURE 4.1: Sketch of a slice in the transverse plane of the CMS detector[27]: all the sub-detectors are drawn, along with the trajectories of particles hitting the detector. The flight of a muon, an electron, a charged and a neutral hadron, and a photon is represented in the detector, with a visualization of the signals released in the crossed sub-detectors

- **Track-Jets** : Jets are reconstructed from tracks of charged particles, independent of calorimetric information.

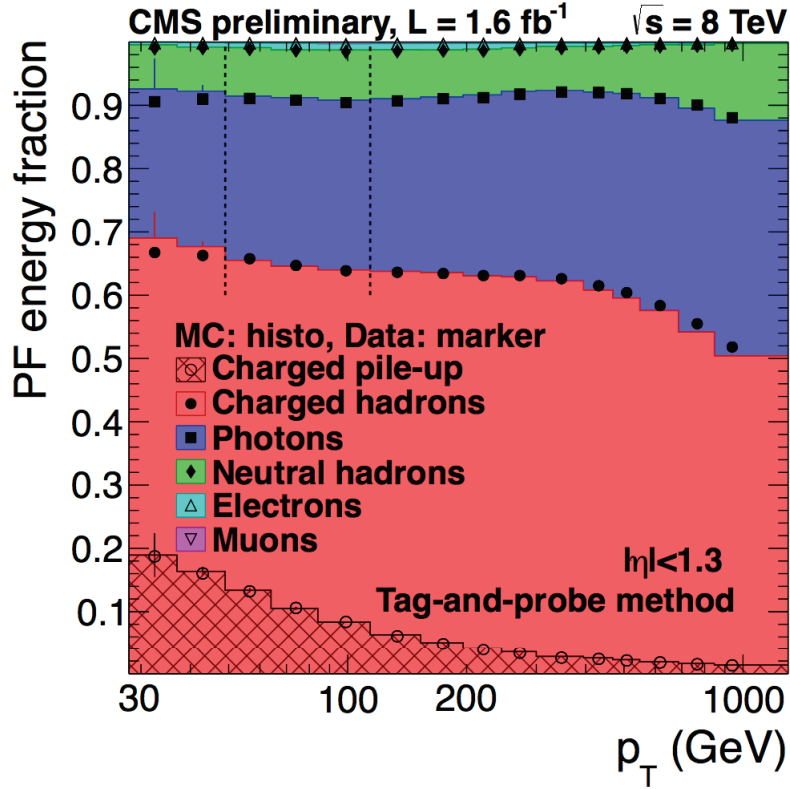


FIGURE 4.2: Jet composition as a function of the jet p_T for jets with $|\eta| < 1.3$ for data (histogram) and simulation (markers)

Since PF jets use the totality of the available information from the sub-detectors, while the others are reconstructed with only a part of it (namely the one measured either with the tracker or with the calorimeters), the performance of the PF algorithm is much better.

In particular, a PF jet has a p_T resolution of 15, 10 and 5% respectively at 20, 100 and 500 GeV, very similar in the barrel and in the endcap regions. The η and ϕ resolutions stay at values of 0.02–0.03 over the whole phase space.

Considering the jet performance, measurements of PF jets are considered reliable for p_T values down to 20 GeV in the entire η acceptance range. In case the p_T threshold needs to be decreased, a choice of Track-Jets would be more appropriate, since also the tracks of very small p_T , which do not hit the calorimeters due to the curvature in the magnetic field, would be considered and would improve the reconstruction performance. Spectra for jets are generally measured in a differential way: this means that the cross-section is measured as a function of jet observables. The most common ones are jet p_T , η and ϕ . The cross-section as a function of p_T is rapidly decreasing for increasing p_T . The decrease can be parametrized as a power law with an exponent between -3 and -4 . A flat distribution is observed as a function of jet ϕ , due to the perfect symmetry of the collision in the transverse plane, while the cross-section as a function of η is rather flat (for $p_T > 20$ GeV) in the more central region ($|\eta| < 3$) but starts to decrease for higher pseudorapidities, due to kinematical effects.

4.0.4 Jet Clustering Algorithms

As soon as all the particles have been correctly reconstructed and identified, they are grouped together to form a jet. Jet algorithms provide a set of rules for grouping particles into jets. They usually involve one or more parameters that indicate how close two particles must be for them to belong to the same jet. Additionally they are always associated with a recombination scheme, which indicates what momentum is to be assigned to the combination of two particles (the simplest is the 4-vector sum). Taken together, a jet algorithm with its parameters and a recombination scheme form a “jet definition”.

Several important properties that should be met by a jet definition are:

- simple to implement in an experimental analysis;
- simple to implement in the theoretical calculation;
- can be defined at any order of the perturbation theory;
- yields finite cross-sections at any order of perturbation theory;
- yields a cross-section that is relatively insensitive to hadronisation.

These are collectively called the “Snowmass accord”.

Different Jet Clustering Algorithms

There are different jet clustering algorithms. Jade algorithm, Iterative Cone Algorithm, SIScone Algorithm, Cambridge/Aachen Algorithm, k_T Algorithm and anti- k_T Algorithm are to name a few. Fig 4.5 shows simulated reconstruction of jets four of the algorithms. A good clustering algorithm must have the following properties :

Collinear Safety: A hard parton undergoes many collinear splittings as part of the fragmentation process. The non-perturbative dynamics also lead to collinear splittings, for example in the decay of energetic hadrons. For a collinear safe algorithm, the set of hard jets that are found in the event should remain unchanged even after these collinear splitting.

Infrared Safety: There is always some emission of soft particles in QCD events, both through perturbative and non-perturbative effects. The motivation for constructing jets is precisely that one wants to establish a way of viewing events that is insensitive to all these effects.

Here we discuss k_T and anti- k_T algorithm:

k_T and anti- k_T Algorithm: d_{ij} is the distance between entities (particles, particle flow candidates) i and j and d_{iB} is the distance between entity i and the beam (B). The (inclusive) clustering proceeds by identifying the smallest of the distances and if it is a d_{ij} recombining entities i and j , while if it is d_{iB} calling i a jet and removing it from the list of entities. The distances are recalculated and the procedure repeated until no entities are left. The extension relative to the k_T and Cambridge/Aachen algorithms lies in the definition of the distance measures:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \quad (4.1)$$

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

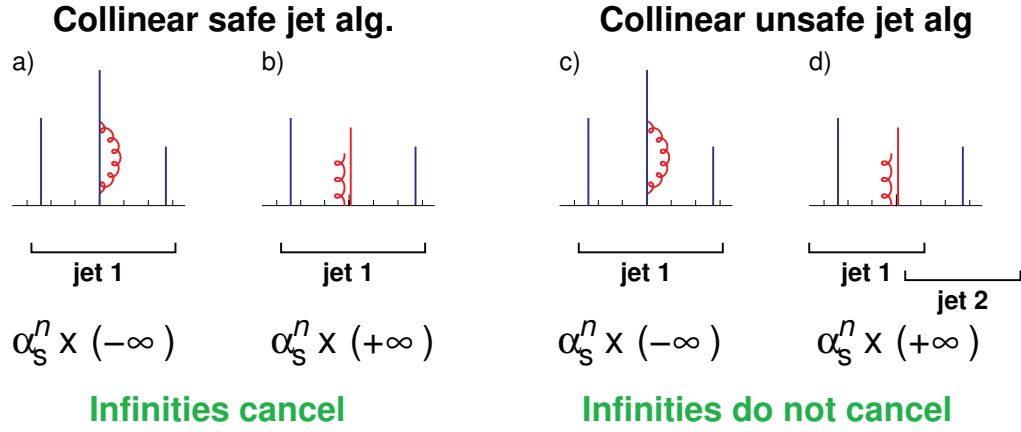


FIGURE 4.3: Illustration of collinear safety (left) and collinear unsafety (right). Partons are vertical lines, their height is proportional to their transverse momentum, and the horizontal axis indicates rapidity[45].

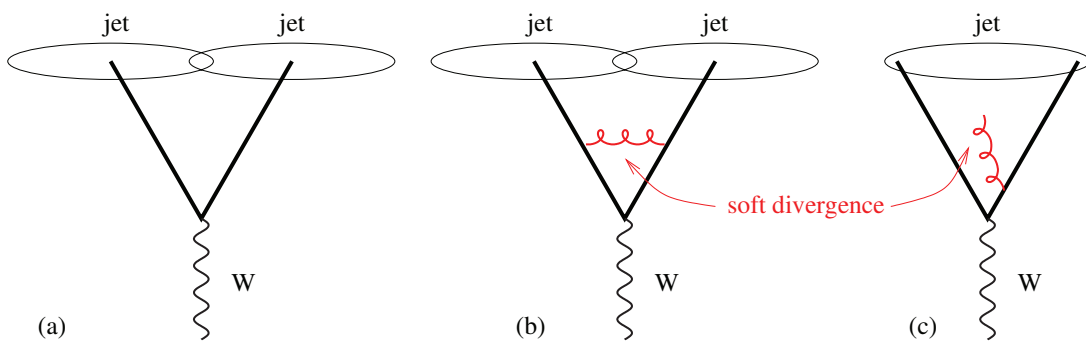


FIGURE 4.4: Configurations illustrating IR unsafety in events with a W and two hard partons. The addition of a soft gluon converts the event from having two jets to just one jet[45].

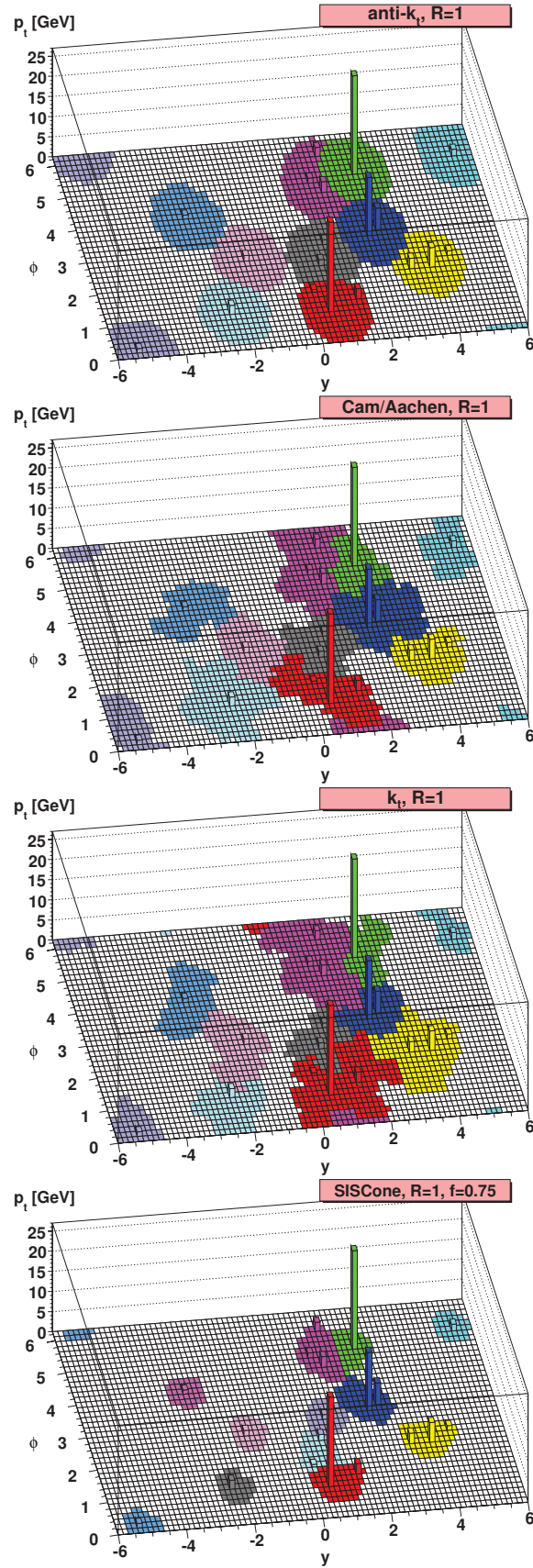


FIGURE 4.5: A sample parton-level event generated with Herwig clustered with four different jet algorithms[45]

where $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and k_{ti} , y_i and ϕ_i are respectively the transverse momentum, rapidity and azimuth of particle i . In addition to the usual radius parameter R , an additional parameter p is provided to govern the relative power of the energy versus geometrical (Δ_{ij}) scales.

For $p = 1$ one recovers the inclusive k_T algorithm, while for $p = -1$, it is the anti- k_T algorithm.

In CMS, the anti- k_T algorithm is generally used with a cone width of 0.4 or 0.7. For 0.4, it has been found that it is a good compromise between the amount of energy of the jet itself, which stays inside the cone and the amount of external energy, coming from pile-up or overlap with other jets, which are accidentally included in it. It is evident that too small cone widths would exclude some of the particles coming from the shower of the partons, while a too big cone width would include more external energy. After clustering, it is interesting also to investigate which particles constitute the jet itself. These studies have been performed by CMS. A jet is mainly composed by charged hadrons ($\sim 66\%$), photons ($\sim 20\text{--}25\%$, originating from π^0 decays), neutral hadrons ($\sim 8\text{--}10\%$) and electrons and muons ($\sim 1\%$, arising from hadron decays) 4.2. The jet composition does not change much as a function of the jet p_T , while the measured η constituents are different because, in the forward region, CMS can only use calorimeter information, and particle identification is not possible without the measurements from the tracker. Thus, in the forward region, the main part is composed by hadronic energy deposits in the HF, while a fraction of the energy is identified due to an electromagnetic component from the HF signals. The discrimination between hadronic and electromagnetic energy deposits in the HF, relies on the detection of the different profiles of the showers, produced inside the detector.

4.0.5 Jet reconstruction and event selection

The main physics objects are Particle Flow (PF) jets reconstructed with the anti- k_T clustering algorithm. The performance of the anti- k_T algorithm is discussed in [15]. It tends to cluster particles starting from the ones at highest p_T , and to produce jets preferably with circular area. Minor effects on the jet observables are observed in presence of soft particles. Values of cone width R are chosen usually between 0.4 and 1. Two different cone widths have been considered in this analysis: $R = 0.4$ (AK4) and $R = 0.7$ (AK7). The Particle flow (PF) jets are reconstructed by clustering the four-momentum vectors of PF candidates. The PF jet momentum and spatial resolutions are greatly improved with respect to calorimeter jets, as the use of the tracking detectors and of the high granularity of ECAL allows resolution and measurement of charged hadrons and photons inside a jet, which together constitute $\sim 85\%$ of the jet energy. In order to reduce pile-up contribution to the reconstructed jets, the novel technique of charged hadron subtraction (CHS) is considered. The presence of pile-up results in unwanted calorimetric energy depositions and extra tracks. The CHS reduces these effects by removing tracks identified as originating from pile-up vertices. The pile-up from charged particles is reduced by identifying which vertex the charged PF candidates originate from and removing those unambiguously associated to pile-up vertices before clustering jets and missing transverse energy. This method is referred to as charged hadron subtraction (CHS). The leading primary vertex (PV) is chosen based on the largest sum of squares of the track transverse momenta ($\sum |p_T^{track}|^2$) associated to the vertex. Subleading PVs are classified as pile-up vertices, and are required to pass further quality criteria on the compatibility with the luminous region and minimum number of degrees of freedom

$$N_{dof} = -3 + 2 \sum_{i=1}^{nTracks} w_i, \quad w_i \text{ in } [0, 1] \quad (4.3)$$

The minimum requirement $N_{dof} > 4$ corresponds to at least four tracks. Tracks are matched to vertices based on the chi-square per degree of freedom ($\chi^2/\text{d.o.f.}$). If $\chi^2/\text{d.o.f.} < 20$ for a protovertex, then the track is associated to this and only this vertex. If the track from a charged hadron is associated to a good pile-up PV, it is considered a pile-up track, and removed in the CHS procedure. All other tracks, including those not associated to any PV, are kept. The charged hadron subtraction can remove approximately 50% of pile-up within tracker coverage [20]. The remaining unassociated charged hadrons are either not pointing to any reconstructed vertex, are associated with a vertex that did not pass all the quality cuts, or have too large $\chi^2/\text{d.o.f.}$ for robust vertex association. The vertex reconstruction and identification inefficiency is about 30% for pile-up vertices, and responsible for a large proportion of the unassociated tracks from pile-up.

In the simulation, jets are considered at the generator level, which corresponds to the true level before the simulation of the detector response. Generator-level jets are clustered with, respectively, AK4 and AK7 algorithm for the two jet analysis, and are defined as the following. The MC particle level jets are built by applying the clustering procedure to all stable ($c\tau > 1$ cm) particles excluding neutrinos. The exclusion of neutrinos is a convention adopted by CMS, but it is not universally adhered to by all experiments at HEP. Indeed, neutrinos are often included at the particle level, but the response is measured from samples with negligible neutrino content, leading to almost no practical difference for inclusive JEC. The CMS convention allows to define response in a way that is experimentally accessible and significantly reduces response differences between heavy flavor (b, c) and light flavor (u, d, s, g) jets caused by neutrinos produced in semileptonic decays of heavy flavor hadrons. It should be noted that the neutrino fraction leads to an additional systematic in b and c jet fragmentation that is not included in JEC systematics, but should be considered in e.g. measurements of inclusive b-jet cross-section or top quark mass. The final results are unfolded to this level of generator jets, also referred to as “stable-particle level”.

Events are selected by requiring at least one good primary vertex. A primary vertex is identified by a collection of tracks, measured in the tracker with a good fit quality between the hits and compatible with the beam line. The tracks are clustered according to the z -coordinate of their point of closest approach to the beam axis. A primary vertex candidate is obtained through a three-dimensional fit. Primary vertices are retained only if their z -coordinate stays at a distance less than 24 cm from the beam spot. The goodness of the vertex refers to the following requirements:

- the number of degrees of freedom (NdF) of the fit is required to be greater than 4: NdF is related to the free parameters of the fit and the number of associated tracks;
- fake vertices are discarded: they may be produced by weak decays, secondary interactions with the detector material, or by tracks coming from the beam-spot or with poor momentum resolution.

Jets are selected by starting from $p_T = 114$ GeV and grouped in seven different rapidity (y) bins: from $0 < |y| < 3.0$, they go in steps of 0.5, while the last rapidity bin includes the region between 3.2 and 4.7 in absolute value. Only jets with tight identification requirements are selected. These are based on the number of constituents inside the reconstructed jets and aim for rejection of non-physical jets arising from noise. The following cuts need to be fulfilled by the jets:

- Neutral Hadron Fraction(NHF) < 0.90 , Neutral ElectroMagnetic Fraction(NEMF) < 0.90 and number of constituents > 1 for $|\eta| < 3.0$
- Charged Hadron Fraction(CHF) > 0 , Charged Hadron Multiplicity(CHM) > 0 and Charged Electromagnetic Fraction(CEMF) < 0.99 for $|\eta| < 2.4$
- NEMF < 0.90 and number of neutral particle > 10 for $|\eta| > 3.0$

The performance for these tight ID cuts can be found in [23]. The efficiency of this new set of criteria is greater than 99% and the background rejection is 84% using a Minimum-Bias sample.

The binning chosen for the measurement is the following in each considered rapidity bin:

- 114, 133, 153, 174, 196, 220, 245, 272, 300, 330, 362, 395, 430, 468, 507, 548, 592, 638, 686, 737, 790, 846, 905, 967, 1032, 1101, 1172, 1248, 1327, 1410, 1497, 1588, 1684, 1784, 1890, 2000, 2116, 2238, 2366, 2500, 2640, 2787, 2941, 3103, 3273, 3450, 3637, 3832, 4037, 4252, 4477, 4713, 4961, 5220, 5492, 5777, 6076, 6389, 6717, 7000;

4.1 Jet Energy Correction

All reconstructed objects need to be calibrated. Jets also need to be calibrated or corrected such that on average the correct energy can be assigned to them. Jet energy calibration or correction(JEC) procedure is performed in a series of steps as follows:

- The first step, accounts for extra energy caused by electronic noise or by PU collisions.
- In the second stage, major part of the correction is performed using detailed detector simulations.
- Unavoidable imperfections in the detector modelling through simulation are identified and corrected in phase three with data-based methods as a function of jet pseudorapidity and p_T .
- Finally MC-based corrections account for differences in the flavour compositions of signal and calibration samples, if necessary.

The JEC procedure is illustrated in Fig4.6

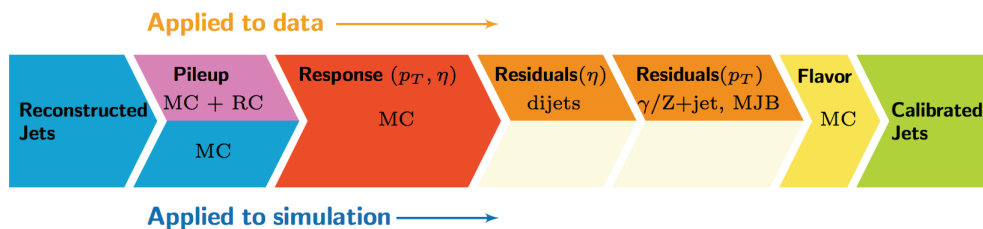


FIGURE 4.6: Consecutive stages of the jet energy calibration as performed in CMS. The upper half corresponds to corrections applied to data, while the lower half lists the ones applied to simulation.

Chapter 5

Trigger Efficiency Measurement

The CMS trigger system is introduced in Chapter (3). The triggers utilize physics objects like electrons, photons, muons, and jets. Triggers used in the analysis presented in the thesis make use of jets. It is important to determine efficiency of the triggers used as well as the corresponding thresholds to be used in the selection of events for the given trigger.

The jet triggers used in the analyses are identified by the name “HLT_JetX”, where X stands for the energy threshold, expressed in GeV, set for the HLT jets. For this work, triggers with values of X equal to 60, 80, 140, 200, 260, 320, 400, and 450 have been used. Jet multiplicity decreases with increasing p_T . So, to correctly identify jets above a particular p_T threshold, one jet trigger is not sufficient. Moreover, all the lower p_T triggers are prescaled properly in accordance with the bandwidth limitation. Trigger with a threshold of 450 GeV is the first unprescaled one; 500 GeV being the second. We kept the 500 GeV trigger as a backup unprescaled trigger in case 450 GeV trigger fails. As this never happened, the jet trigger with threshold 500 was not used for the analysis. The L1 and HLT thresholds for each of the triggers are listed in Table 5.1. For instance, an event is selected by the HLT_Jet60 trigger, in case a calorimeter cluster exceeds the energy of 40 GeV in $|\eta| < 5.2$ and the primitive jet, clustered with the jet finder algorithm, has an energy greater than 60 GeV. Note that the primitive jet needs a more accurate and complicated reconstruction with additional corrections, before being used for any analysis.

The trigger efficiency is measured in the data in two different ways which give compatible results. The two methods are:

Cross-section ratios: Differential jet cross-sections, as a function of η and p_T , are measured separately when the trigger under examination, trig_i , and a reference trigger, trig_{ref} , have fired. The reference trigger needs to be fully efficient, in the considered region of the phase space and it is normally a jet trigger with lower p_T threshold or a Minimum Bias trigger. The ratio of the two differential cross-sections constitutes the measured trigger efficiency, ϵ_{trig} , as defined by the equation:

$$\epsilon_{\text{trig}} = \frac{\left(\frac{d\sigma}{dO}\right)^{\text{trig}_i}}{\left(\frac{d\sigma}{dO}\right)^{\text{trig}_{\text{ref}}}} \quad (5.1)$$

with O , any kinematical jet observable (η , p_T , etc.). For instance, in order to measure the efficiency of HLT_Jet80, HLT_Jet60 has been used as reference, while for HLT_Jet140, cross-sections measured with HLT_Jet80 have been compared.

Trigger emulation: The trigger decision is emulated in the data by using the trigger elements of a reference trigger, trig_{ref} . In order to reproduce the trigger decision, two objects are needed, one for each of the two trigger levels. They are referred to as “L1” and “HLT” objects. For jet triggers, the L1 object consists of a broad energy deposit in HCAL and ECAL by using a coarse segmentation. Information obtained with the full calorimetric granularity is added to the L1 object to produce the HLT

one. In the assumption that the reference trigger is fully efficient, in the considered region of the phase space, the emulation method is expressed by the following equation:

$$\epsilon_{\text{trig}_i} = \frac{\text{InclusiveRecoJet}_O(\text{trig}_{\text{ref}} + \text{L1Object}_{p_T} > Z + \text{HLTObject}_{p_T} > Y)}{\text{InclusiveRecoJet}_O(\text{trig}_{\text{ref}})} \quad (5.2)$$

where Y indicates the p_T threshold of trig_i , and with Z , the threshold of the L1 object is identified. The quantity O is again any observable for which the trigger efficiency has to be measured. The denominator corresponds to the number of events for which the emulator trigger path trig_{ref} has fired. The numerator is the number of events for which trig_{ref} has fired and the p_T of the HLT-Object corresponding to the trigger path trig_i is $> Y$. For example, in order to obtain the turn on curve for HLT_Jet80, the HLT path threshold, used for HLT_Jet60, is chosen: the p_T cut on the L1-Object corresponding to this trigger path is 60 GeV. The complete list of measured triggers with the corresponding reference triggers are listed in Table 5.1, along with the values of the L1 and HLT thresholds.

The second method is preferred for efficiency measurements because it achieves a higher statistical accuracy, it is not affected by the high prescales which are applied to the lowest threshold triggers and it does not need any luminosity information of the triggers, which is usually the case when evaluating cross-section ratios. Hence, in the following, only results of the trigger emulation method are considered. The trigger emulation method has been also used in previous CMS analyses [17, 21]. In order to identify the regions of phase space where a correction needs to be applied, the efficiency, as a function of the leading jet p_T selected in $|\eta| < 4.7$, has been measured for the nine triggers under study. Two distinct studies are performed for jets clustered with anti- k_T charged hadron subtraction (CHS) $R = 0.7$ (AK7) and anti- k_T charged hadron subtraction (CHS) $R = 0.4$ (AK7). The results for AK7chs are shown in Figure 5.1, for inclusive jet scenarios, as a function of the leading jet p_T . The trigger efficiencies show a turn-on curve, with a rising part, where the trigger is partly inefficient, until a plateau region, corresponding to the region of full efficiency of the trigger. From these results, the jet p_T threshold, from which each trigger starts to become fully efficient, can be identified.

Trigger Path	Reference Trigger	L1 Threshold [GeV]	HLT Threshold [GeV]	Full efficiency threshold [GeV]
HLT_PFJet60	HLT_PFJet40	40	60	105.2
HLT_PFJet80	HLT_PFJet60	60	80	132.9
HLT_PFJet140	HLT_PFJet80	80	140	216.0
HLT_PFJet200	HLT_PFJet140	140	200	298.2
HLT_PFJet260	HLT_PFJet200	200	260	381.9
HLT_PFJet320	HLT_PFJet260	260	320	452.2
HLT_PFJet400	HLT_PFJet320	320	400	561.8
HLT_PFJet450	HLT_PFJet400	400	450	600.8
HLT_PFJet500	HLT_PFJet450	450	500	653.8

TABLE 5.1: List of the triggers available in jet analyses with corresponding reference triggers, and p_T threshold at L1 and HLT. The p_T threshold corresponding to the starting point of full efficiency is also specified for each trigger. Jets clustered with the anti- k_T algorithm are considered with $R = 0.7$.

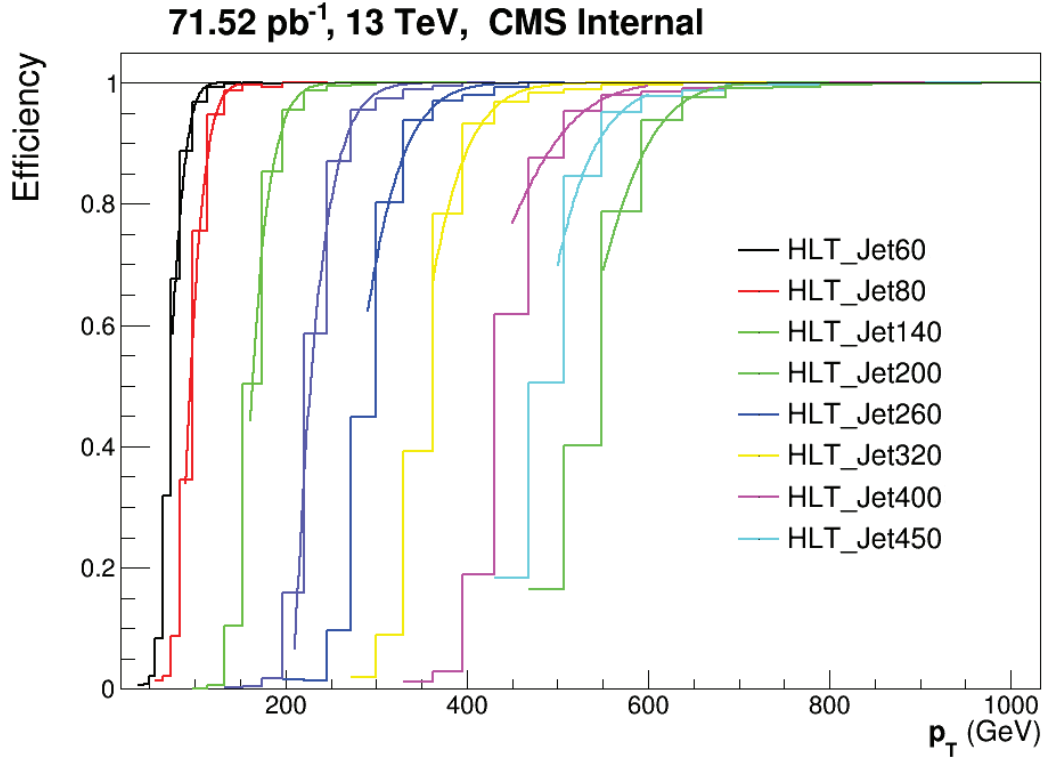


FIGURE 5.1: Trigger efficiency measurement as a function of the leading AK7chs jet p_T selected in $|\eta| < 4.7$ for the available triggers.

The trigger efficiency curves, shown in Figure 5.1, are fitted according to an error function with three free parameters, as the following:

$$\epsilon = a + 0.5 \cdot (1 - a) \cdot (1 + \text{erf}((p_T - \mu)/\sigma)) \quad (5.3)$$

The turn-on point corresponds to the value where the function takes the value of 0.99 and is considered as the point of full efficiency for the trigger. The turn-on point is obtained by inverting Equation 5.3, which yields:

$$p_T = \text{erf}^{-1}((2 * 0.98 - 1 - a)/(1 - a)) * \sigma + \mu \quad (5.4)$$

In Table 5.2, thresholds at L1 and HLT, reference trigger and full efficiency point are listed for each considered trigger for AK4chs jets. In Figure 5.2, the corresponding turn-on curves are shown. The shapes of the measured trigger efficiency curves are very similar for the two clustering algorithms, but the turn-on point obtained from the fits is systematically lower for AK4chs than for AK7chs. This shift ranges between 20 and 100 GeV and increases for increasing jet p_T thresholds. This effect is expected because the trigger seeds implement a clustering width $R = 0.4$ and are optimized for jets using this size. The difference mainly comes from gluon splitting processes which might be reconstructed as one jet in the case of AK7 clustering algorithm and as two separate jets for AK4 clustering algorithm. Since two separate analyses are presented for AK4 and AK7 jets, it was decided to use the same trigger strategy for both. The selected trigger regions are fully efficient for both AK4 and AK7 triggers.

It is also important to check the dependence of trigger efficiency on the considered rapidity regions. The evaluation of the trigger efficiency in steps of 0.5 in rapidity is not possible due to limited statistics. This is the reason why only three regions have been

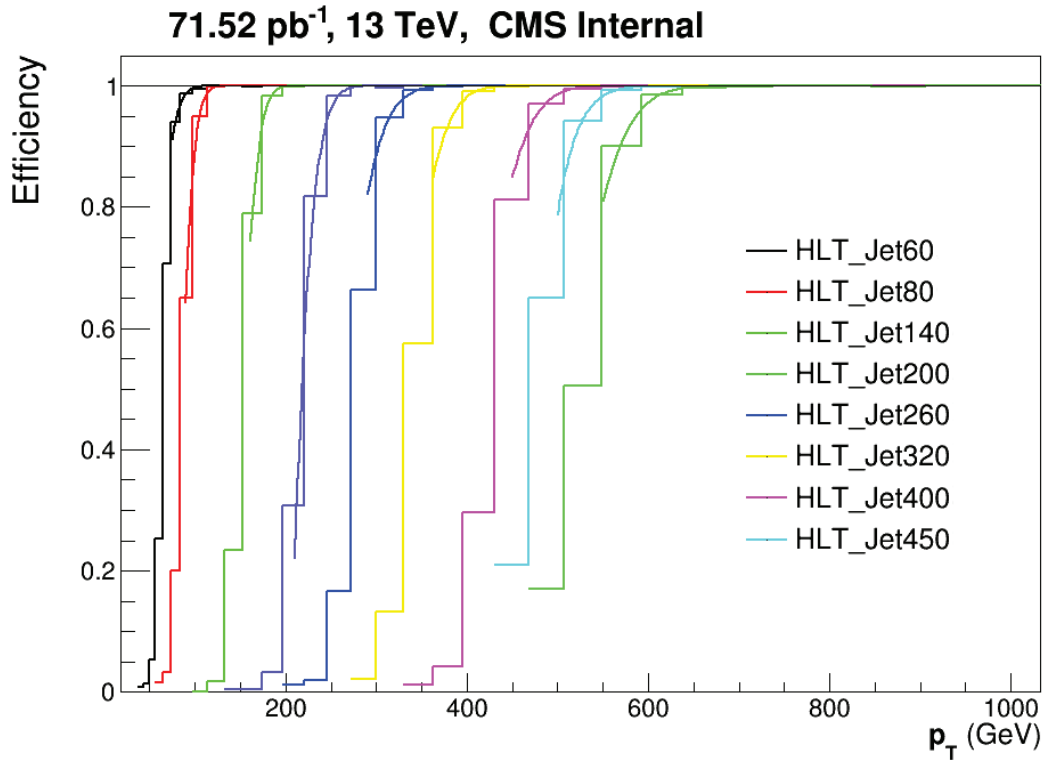


FIGURE 5.2: Trigger efficiency measurement as a function of the leading AK4chs jet p_T selected in $|\eta| < 4.7$ for the available triggers.

Trigger	Reference Trigger	L1 Threshold [GeV]	HLT Threshold [GeV]	Full efficiency threshold [GeV]
HLT_PFJet60	HLT_PFJet40	40	60	87.6735
HLT_PFJet80	HLT_PFJet60	60	80	111.236
HLT_PFJet140	HLT_PFJet80	80	140	183.822
HLT_PFJet200	HLT_PFJet140	140	200	257.09
HLT_PFJet260	HLT_PFJet200	200	260	331.50
HLT_PFJet320	HLT_PFJet260	260	320	399.874
HLT_PFJet400	HLT_PFJet320	320	400	494.961
HLT_PFJet450	HLT_PFJet400	400	450	547.823
HLT_PFJet500	HLT_PFJet450	450	500	608.266

TABLE 5.2: List of the triggers available in the jet analyses with corresponding reference triggers, and p_T threshold at L1 and HLT. The p_T threshold corresponding to the starting point of full efficiency is also specified for each trigger. Jets clustered with the anti- k_T algorithm are considered with $R = 0.4$.

separately considered for the leading jet. Results for leading jets in $|y| < 1.0$, $1.0 < |y| < 2.0$ and $|y| > 2.0$ are shown in Tables 5.3 and 5.4 for, respectively, AK7chs and AK4chs jets. A little dependence is observed of the turn-on point, when moving from the central to the forward region. In particular, as expected, the turn-on point tends to increase for more forward selections.

Trigger	Turn-on inclusive [GeV]	Turn-on $ y < 1.0$ [GeV]	Turn-on $1.0 < y < 2.0$ [GeV]	Turn-on $ y > 2.0$ [GeV]
HLT_PFJet60	105.259	102.488	102.824	114.175
HLT_PFJet80	132.927	128.483	130.72	140.238
HLT_PFJet140	216.041	215.2	208.748	221.519
HLT_PFJet200	298.272	296.542	287.571	298.653
HLT_PFJet260	381.993	389.078	376.953	373.188
HLT_PFJet320	452.227	454.308	445.918	456.486
HLT_PFJet400	561.8	558.842	567.528	566.931
HLT_PFJet450	600.812	595.85	602.083	617.654
HLT_PFJet500	653.809	651.475	652.906	685.825

TABLE 5.3: List of the triggers available in the AK7chs jet analyses with corresponding reference triggers, and p_T threshold at L1 and HLT. The p_T threshold corresponding to the starting point of full efficiency is also specified for each trigger.

Trigger	Turn-on inclusive [GeV]	Turn-on $ y < 1.0$ [GeV]	Turn-on $1.0 < y < 2.0$ [GeV]	Turn-on $ y > 2.0$ [GeV]
HLT_PFJet60	87.6735	78.4333	79.2786	96.402
HLT_PFJet80	111.236	102.771	107.758	118.463
HLT_PFJet140	183.822	172.06	175.855	190.404
HLT_PFJet200	257.09	246.306	252.216	269.315
HLT_PFJet260	331.50	312.59	321.831	351.323
HLT_PFJet320	399.874	388.914	394.942	426.14
HLT_PFJet400	494.961	483.452	492.94	535.773
HLT_PFJet450	547.823	536.515	548.65	592.945
HLT_PFJet500	608.266	593.825	615.188	665.516

TABLE 5.4: List of the triggers available in the AK4chs jet analyses with corresponding reference triggers, and p_T threshold at L1 and HLT. The p_T threshold corresponding to the starting point of full efficiency is also specified for each trigger.

The final choice of trigger regions according to the exclusive division method is summarized in Table 5.5.

This is how the data have been treated and in the plots shown in the following sections, the listed trigger requirements have been always applied according to the leading jet p_T . In Figures 5.3-5.9, the cross-sections obtained for the different triggers as a function of the jet transverse momentum are shown for the different rapidity regions.

In order to select events for the inclusive-jet analyses, the exclusive division method [39] is used. This consists of dividing the phase space in independent regions as a function of the leading jet p_T . In each region, only one trigger is used and one region has no overlap with the others, in order to avoid any double counting. The division is organized for the inclusive jet analysis in the following way:

- $114 \leq p_T^{\text{leading}} < 133 \text{ GeV} \rightarrow \text{HLT_Jet60}$

Trigger	Leading jet p_T
HLT_PFJet60_v2	114-133
HLT_PFJet80_v2	133-220
HLT_PFJet140_v2	220-300
HLT_PFJet200_v2	300-430
HLT_PFJet260_v2	430-507
HLT_PFJet300_v2	507-638
HLT_PFJet400_v2	638-737
HLT_PFJet450_v2	> 737

TABLE 5.5: Available triggers and regions of the phase space, where the single triggers have been used for event selection, according to the leading jet p_T .

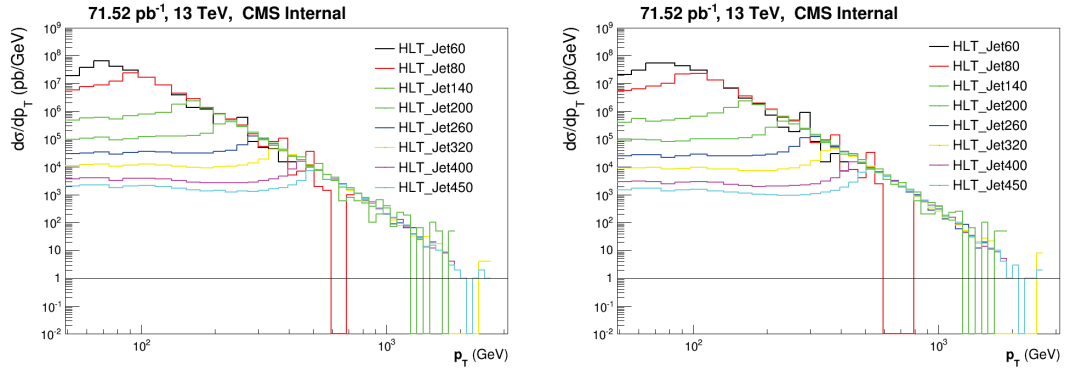


FIGURE 5.3: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $0.0 < |y| < 0.5$.

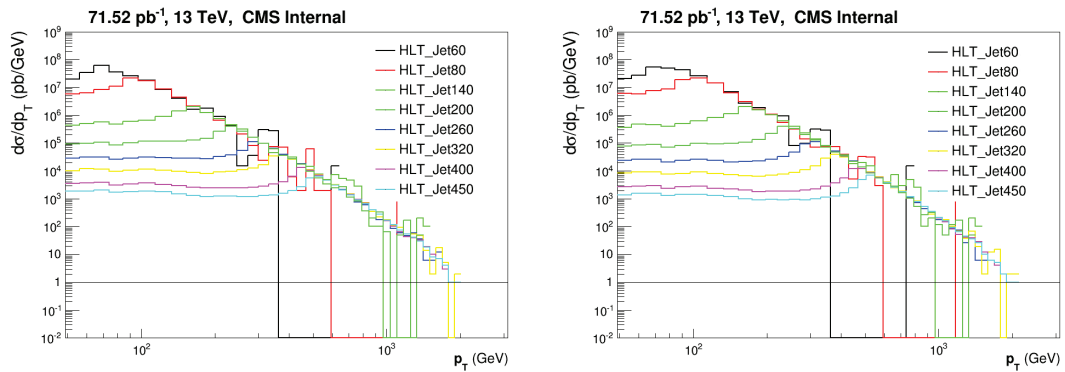


FIGURE 5.4: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $0.5 < |y| < 1.0$.

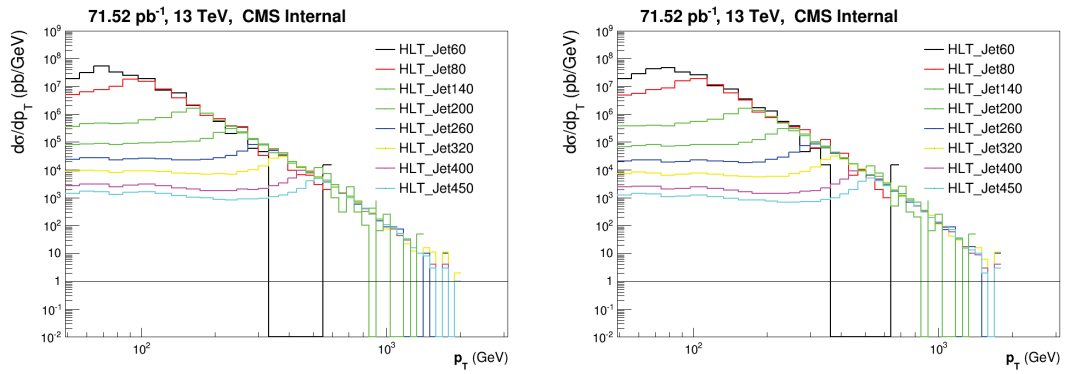


FIGURE 5.5: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $1.0 < |y| < 1.5$.

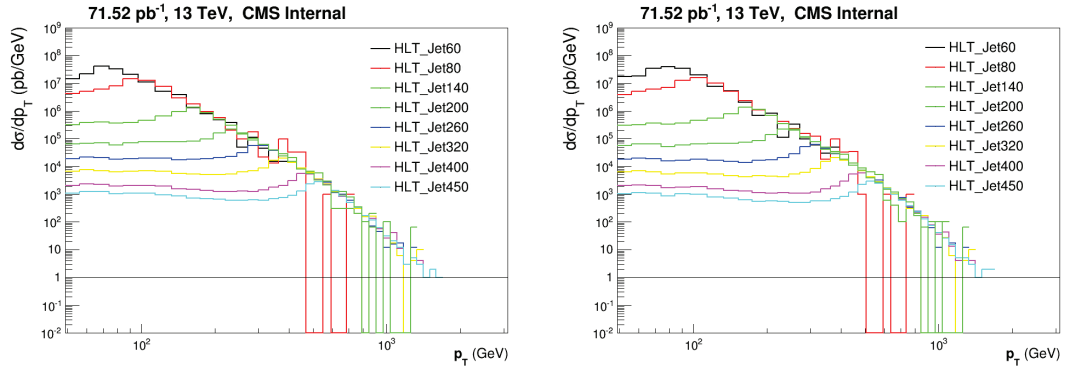


FIGURE 5.6: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $1.5 < |y| < 2.0$.

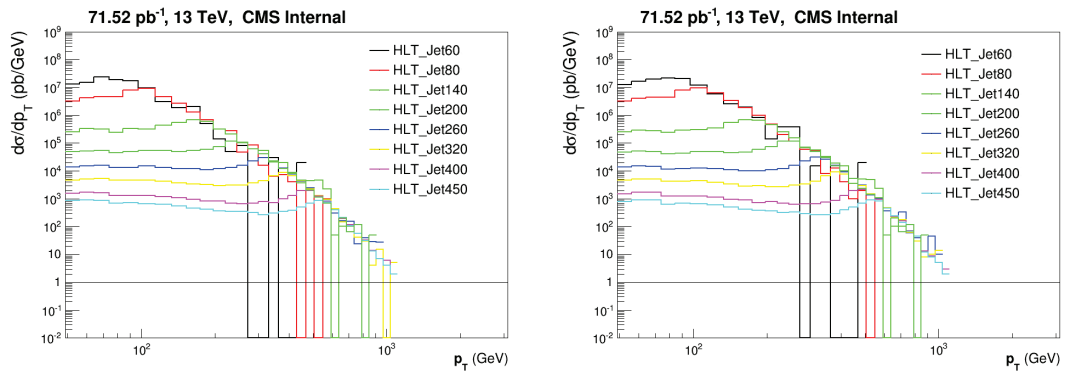


FIGURE 5.7: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $2.0 < |y| < 2.5$.

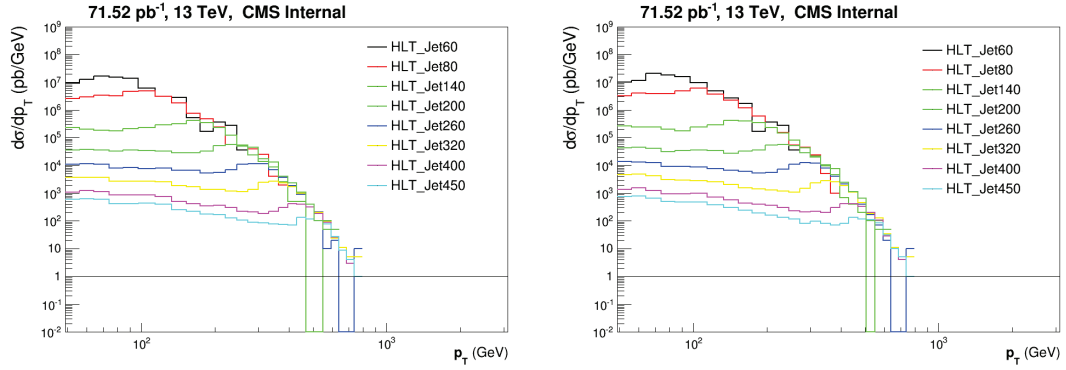


FIGURE 5.8: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $2.5 < |y| < 3.0$.

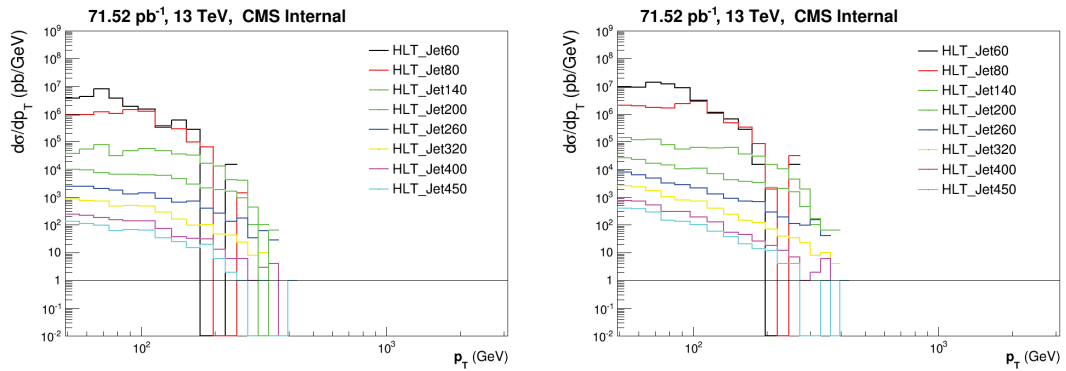


FIGURE 5.9: Cross-section measurement for the different triggers used in the analysis as a function of the jet transverse momentum for AK4chs (left) and AK7chs (right) jets in $3.2 < |y| < 4.7$.

- $133 \leq p_T^{\text{leading}} < 220 \text{ GeV} \rightarrow \text{HLT_Jet80}$
- $220 \leq p_T^{\text{leading}} < 300 \text{ GeV} \rightarrow \text{HLT_Jet140}$
- $300 \leq p_T^{\text{leading}} < 430 \text{ GeV} \rightarrow \text{HLT_Jet200}$
- $430 \leq p_T^{\text{leading}} < 507 \text{ GeV} \rightarrow \text{HLT_Jet260}$
- $507 \leq p_T^{\text{leading}} < 638 \text{ GeV} \rightarrow \text{HLT_Jet320}$
- $638 \leq p_T^{\text{leading}} < 737 \text{ GeV} \rightarrow \text{HLT_Jet400}$
- $p_T^{\text{leading}} \geq 737 \text{ GeV} \rightarrow \text{HLT_Jet450}$

where the specified triggers are the ones used in each region. The choice of these regions with the corresponding triggers is the result of a compromise between sufficiently high statistics for each of them and fully efficient trigger. Furthermore, the edges of the various trigger regions have been selected by taking the edges of p_T bins used for the inclusive jet cross-section, in order not to fill a p_T bin with two different triggers. In the following, the measurement of the trigger efficiency is shown in detail and the choice of the exclusive regions is motivated.

Chapter 6

Input to the Analysis : Data and Monte Carlo Sets

Data collected by the CMS experiment during 2015 with 50 ns bunch spacing are split in two periods. In this analysis the following data sets are used:

- /JetHT/Run2015B-PromptReco-v1/AOD
- /JetHT/Run2015C-PromptReco-v1/AOD
- recorded luminosity is 71.52 pb^{-1} .

The quantity H_T is the scalar sum of $p_{T\text{'s}}$ of all jets in the event. JetHT data set contains those events which are either triggered by single jet triggers with certain p_T threshold or by some high level jet trigger with a threshold on H_T . The first sample corresponds to an integrated luminosity of 45.04 pb^{-1} , while the second to an integrated luminosity of 26.48 pb^{-1} , according to the CMS Luminosity Calculation tool, BrilCalc [25]. The available data at 50 ns have then a total integrated luminosity of 71.52 pb^{-1} , which are used for this analysis. The used JSON file for selecting only good runs is the following:

- Cert_246908-255031_13TeV_PromptReco_Collisions15_50ns_JSON_v2.txt

and a summary of the two samples is provided in Table 6.1.

Data sample	Number of Events	Integrated luminosity (pb^{-1})
RUN2015B	671787	45.04
RUN2015C	286941	26.48

TABLE 6.1: The run period, number of events and integrated luminosity for the data used in this analysis

The skimmed ntuples are produced by the CMSSW release 7_4_0 with the global tag 74X_dataRun2_Prompt_v0.

Two MC samples are available with full detector simulation for comparison and study of detector effects. They have been centrally produced with the MC event generator PYTHIA 8 [46] Tune CUETP8M1 [24]. One uses a flat distribution in the transverse momentum of the outgoing partons, $\hat{p}_T$, in order to fill the whole region of phase space with sufficient statistical accuracy. The other sample is divided in multiple samples generating different bins of $\hat{p}_T$. The considered samples can be accessed through the following names:

- /QCD_Pt_*to*_TuneCUETP8M1_13TeV_pythia8/RunIISpring15DR74-Asympt50ns_MCRUN2_74_V9A-v*/AODSIM

- /QCD_Pt-15TTo7000_*-Flat_13TeV_pythia8/RunIISpring15DR74-Asympt50ns_MCRUN2_74_V9A-v1/AODSIM

where * refers to p_T ranges and version in the first, while it refers to tune in the second case.

The skimmed ntuples have been produced with the CMSSW release 7_4_0 using the MCRUN2_74_V9A global tag. The UE simulation, provided by the CUETP8M1 tune, is expected to reproduce well the processes accompanying the hard scattering at the new collision energy. The summary of the MC samples can be found in Table 6.2. In these samples, since no trigger information are available, the jet triggers have not been applied in the MC selection.

MC sample	Number of Events	Cross-section (pb)
PYTHIA8 Tune CUETP8M1	9754744	2022100000
PYTHIA8 Tune CUETP8M1 50-80	4993440	19204300
PYTHIA8 Tune CUETP8M1 80-120	3486569	2762530
PYTHIA8 Tune CUETP8M1 120-170	3496840	471100
PYTHIA8 Tune CUETP8M1 170-300	3479240	117276
PYTHIA8 Tune CUETP8M1 300-470	2995248	7823
PYTHIA8 Tune CUETP8M1 470-600	1997547	648.2
PYTHIA8 Tune CUETP8M1 600-800	1998579	186.9
PYTHIA8 Tune CUETP8M1 800-1000	1996832	32.293
PYTHIA8 Tune CUETP8M1 1000-1400	1498686	9.4183
PYTHIA8 Tune CUETP8M1 1400-1800	398928	0.84265
PYTHIA8 Tune CUETP8M1 1800-2400	199756	0.114943
PYTHIA8 Tune CUETP8M1 2400-3200	198870	0.00682981
PYTHIA8 Tune CUETP8M1 > 3200	199304	0.000165445

TABLE 6.2: List of Monte Carlo samples used for the inclusive jet cross-section measurement. The number of generated events and the total cross-section are also provided for each sub-sample.

Jets are corrected on the fly with the latest jet energy correction (JEC) available [23], for both data and MC. Jets clustered with AK4chs are corrected with the corresponding AK4chs corrections, while jets clustered with AK7chs are corrected with AK8chs corrections, since no corrections for AK7 are available. Resolution obtained for AK7chs jets obtained with AK8chs corrections are found to be higher and more reliable than AK4chs corrections and this is the reason why they are chosen for AK7chs jets. Only cuts on corrected jet p_T are applied and are considered in the following sections.

Comparisons between data and MC simulation at detector level are studied in detail. The absolute cross-sections, as well as the ones normalized to the total number of selected events, are shown as a function of jet p_T in seven different rapidity bins, in steps of 0.5 for $0.0 < |y| < 3.0$ and the last one in $3.2 < |y| < 4.7$. To investigate further how the simulation is able to reproduce the distributions obtained in data, different variables are considered, which are related to the jet constituents. These are the following:

Charged hadron fraction OR Charged hadron multiplicity: fraction of the total energy carried by charged hadrons in the considered jet OR number of charged hadrons in the considered jet;

Neutral hadron fraction OR Neutral hadron multiplicity: fraction of the total energy carried by neutral hadrons in the considered jet OR number of neutral hadrons in the considered jet;

Muon electromagnetic fraction OR Muon electromagnetic multiplicity: fraction of the total energy carried by muons in the considered jet OR number of muons in the considered jet;

Photon electromagnetic fraction OR Photon electromagnetic multiplicity: fraction of the total energy carried by photons in the considered jet OR number of photons in the considered jet;

Charged electromagnetic fraction OR Charged electromagnetic multiplicity: fraction of the total energy carried by charged electromagnetic particles in the considered jet OR number of charged electromagnetic particles in the considered jet;

Neutral electromagnetic fraction OR Neutral electromagnetic multiplicity: fraction of the total energy carried by neutral electromagnetic particles in the considered jet OR number of neutral electromagnetic particles in the considered jet;

To examine in more detail, a new variable is used instead of Neutral electromagnetic fraction OR Neutral electromagnetic multiplicity. This is called the Hadron Electromagnetic Fraction OR Hadron Electromagnetic Multiplicity. It is the fraction energy associated to hadrons of the considered jet and deposited in the ECAL OR number of hadrons of the considered jet which have decayed before reaching the ECAL. Jets clustered with the two examined algorithms, AK4chs and AK7chs, are considered in the following.

6.0.1 Comparisons at detector level for AK7chs jets

In this section, comparisons are provided between jets from data and simulation, when clustered with the AK7chs algorithm. Figure 6.1 and 6.2 shows the normalized cross-section as a function of p_T , rapidity and azimuthal angle of, respectively, the leading and sub-leading jets. A very good agreement is observed for all the distributions. Figures 6.3 and 6.4 show the inclusive jet cross-section as a function of jet p_T , normalized to the total number of events in the various rapidity bins considered. The simulation is able to reproduce very well the measured data points. In the central region, the agreement is very good with deviations of only up to 5-10%, while in the forward region, discrepancies between data and simulation increase slightly up to 30-40% but they are always within the jet energy scale uncertainty, which is the dominant uncertainty for jet measurements.

Figure 6.5 shows comparisons between data and simulation for various jet shape fractions, as defined in this Section. Jets in the whole rapidity region are considered for these comparisons. The simulation is able to reproduce quite well the measurements in the core of the distributions. Only in some regions of the considered variables, bigger differences are observed for neutral hadron and hadron electromagnetic multiplicities.

In Figure 6.6, fractions of the jet shapes are shown compared to the simulation. The description is better than the multiplicity variables. It is observed that the agreement between data and simulation tends to improve if only jets in the central region ($|y| < 2.0$) are considered in these comparisons. Further work is however needed for jets selected in the forward region.

The missing transverse energy (MET) and its corresponding fraction of the total event energy are also investigated in the selected events (see figure 6.7).

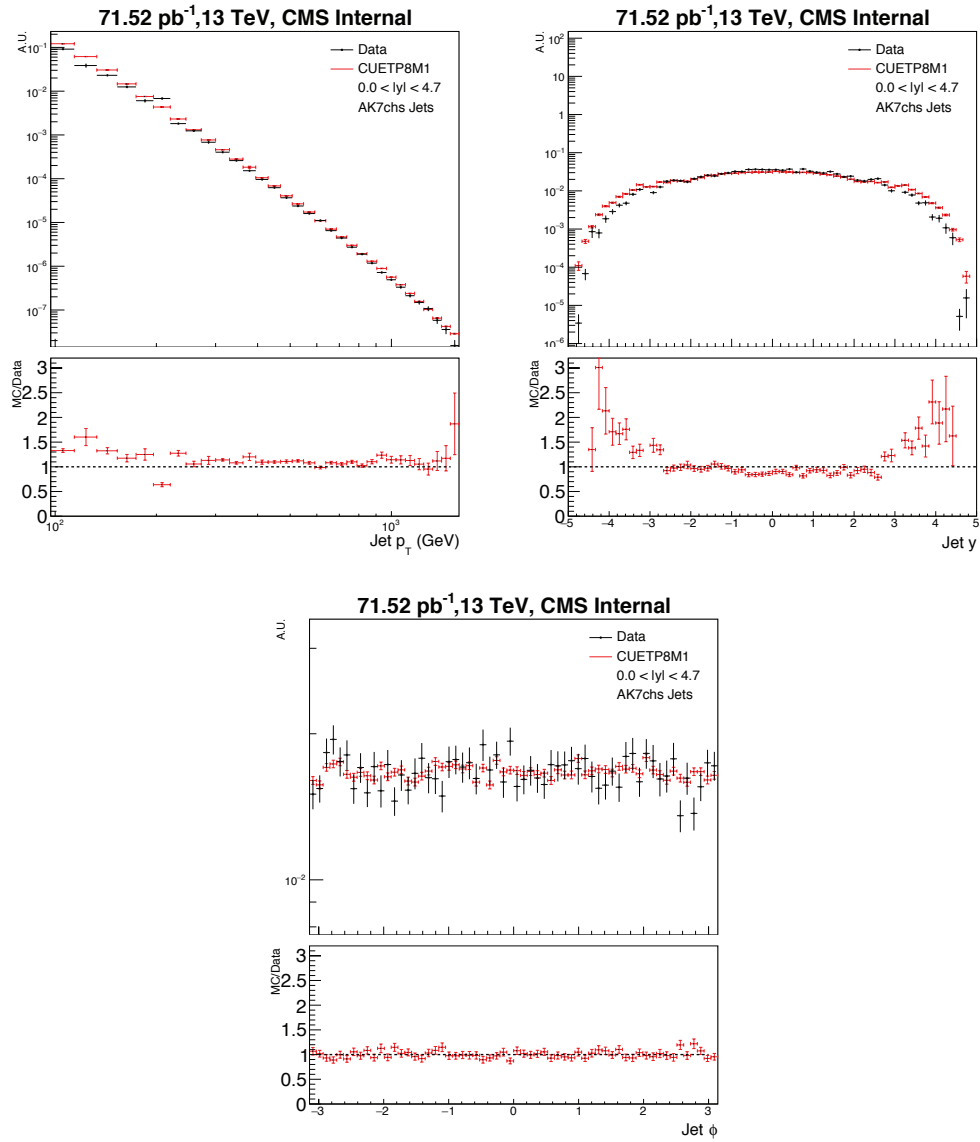


FIGURE 6.1: Control distributions at the detector level for AK7chs jets as a function of leading jet observables, compared to predictions from PYTHIA 8 Tune CUETP8M1: transverse momentum (left), rapidity (right) and azimuthal angle (bottom).

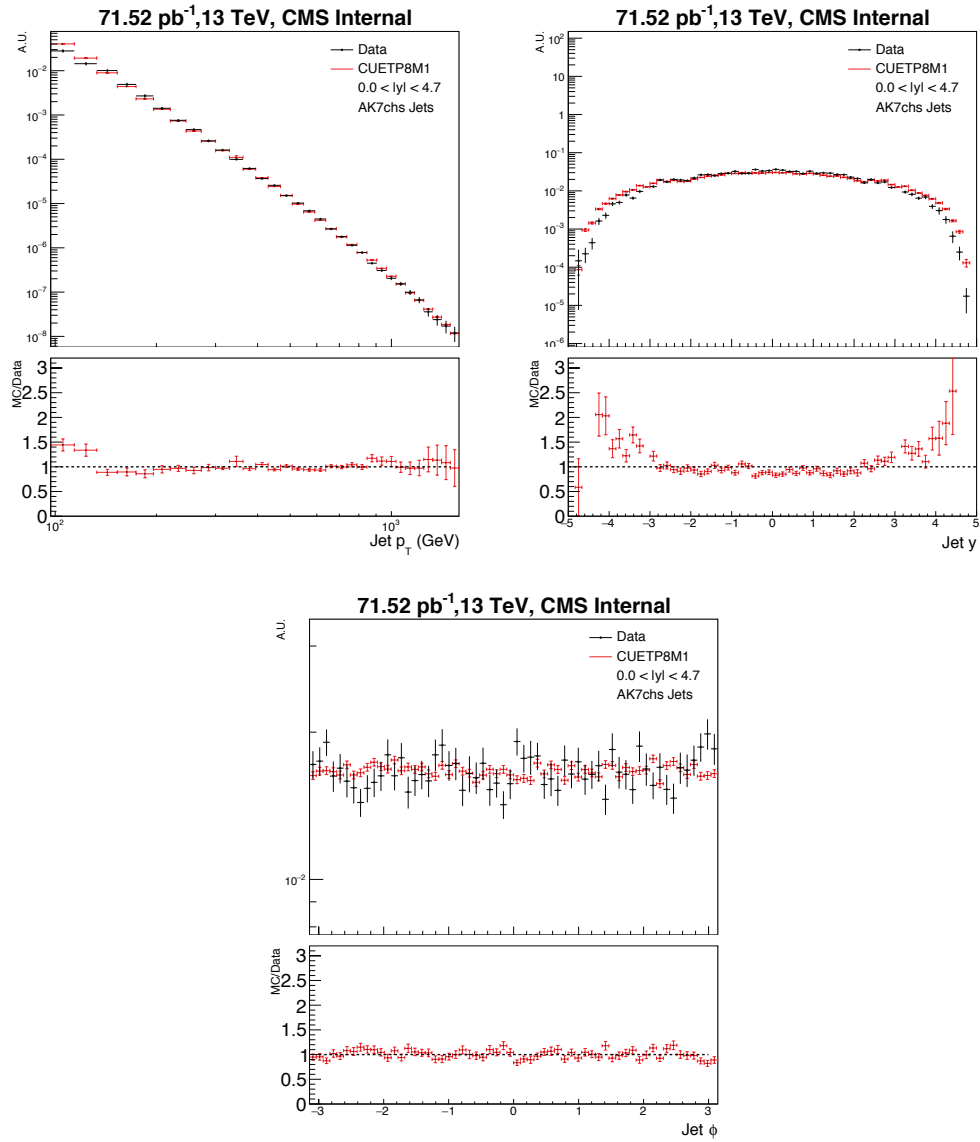


FIGURE 6.2: Control distributions at the detector level for AK7chs jets as a function of sub-leading jet observables, compared to predictions from PYTHIA 8 Tune CUETP8M1: transverse momentum (left), rapidity (right) and azimuthal angle (bottom).

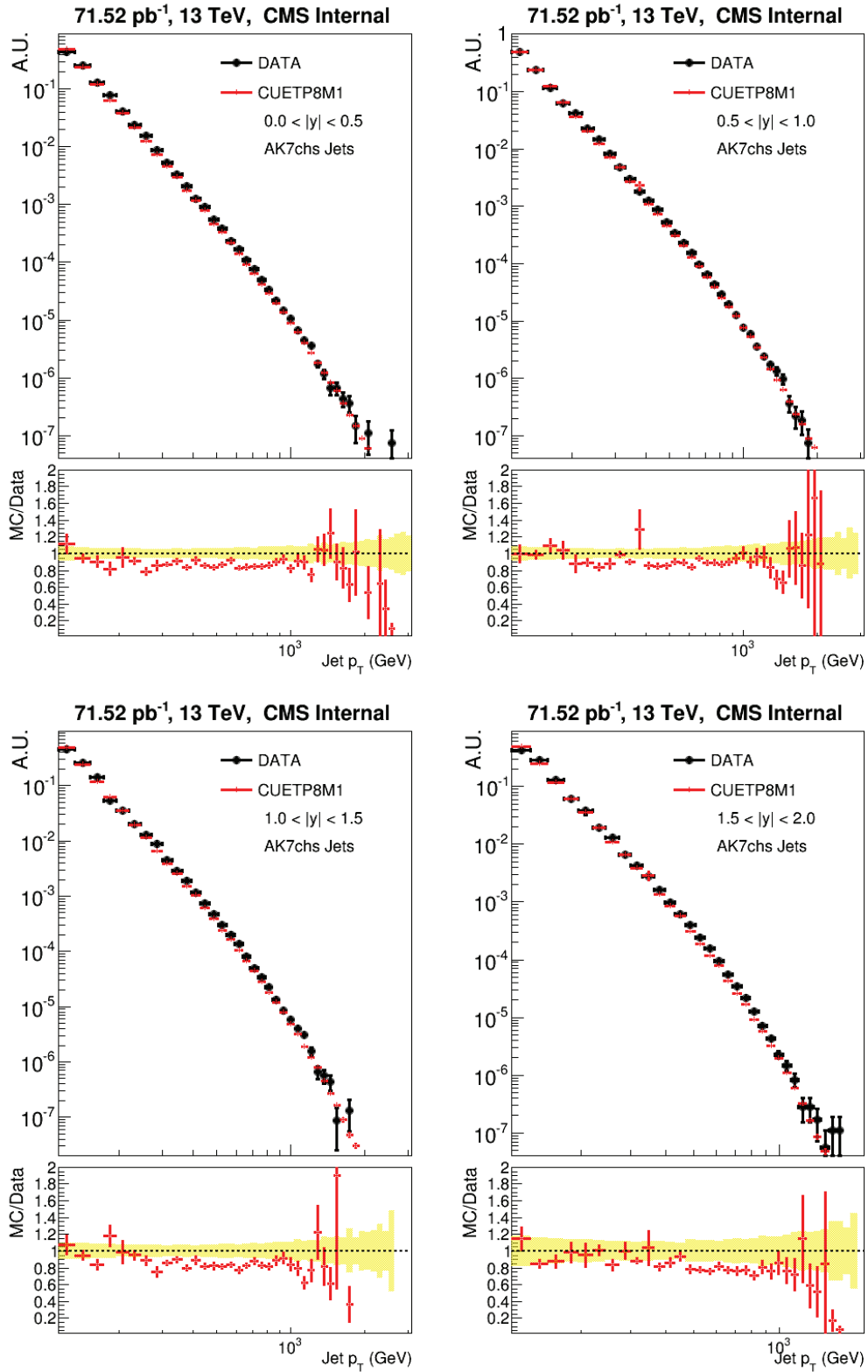


FIGURE 6.3: Control distributions at the detector level for AK7chs jets as a function of jet p_T compared with predictions from PYTHIA 8 Tune CUETP8M1 in different rapidity bins: $0.0 < |y| < 0.5$ (top left), $0.5 < |y| < 1.0$ (top right), $1.0 < |y| < 1.5$ (bottom left), $1.5 < |y| < 2.0$ (bottom right).

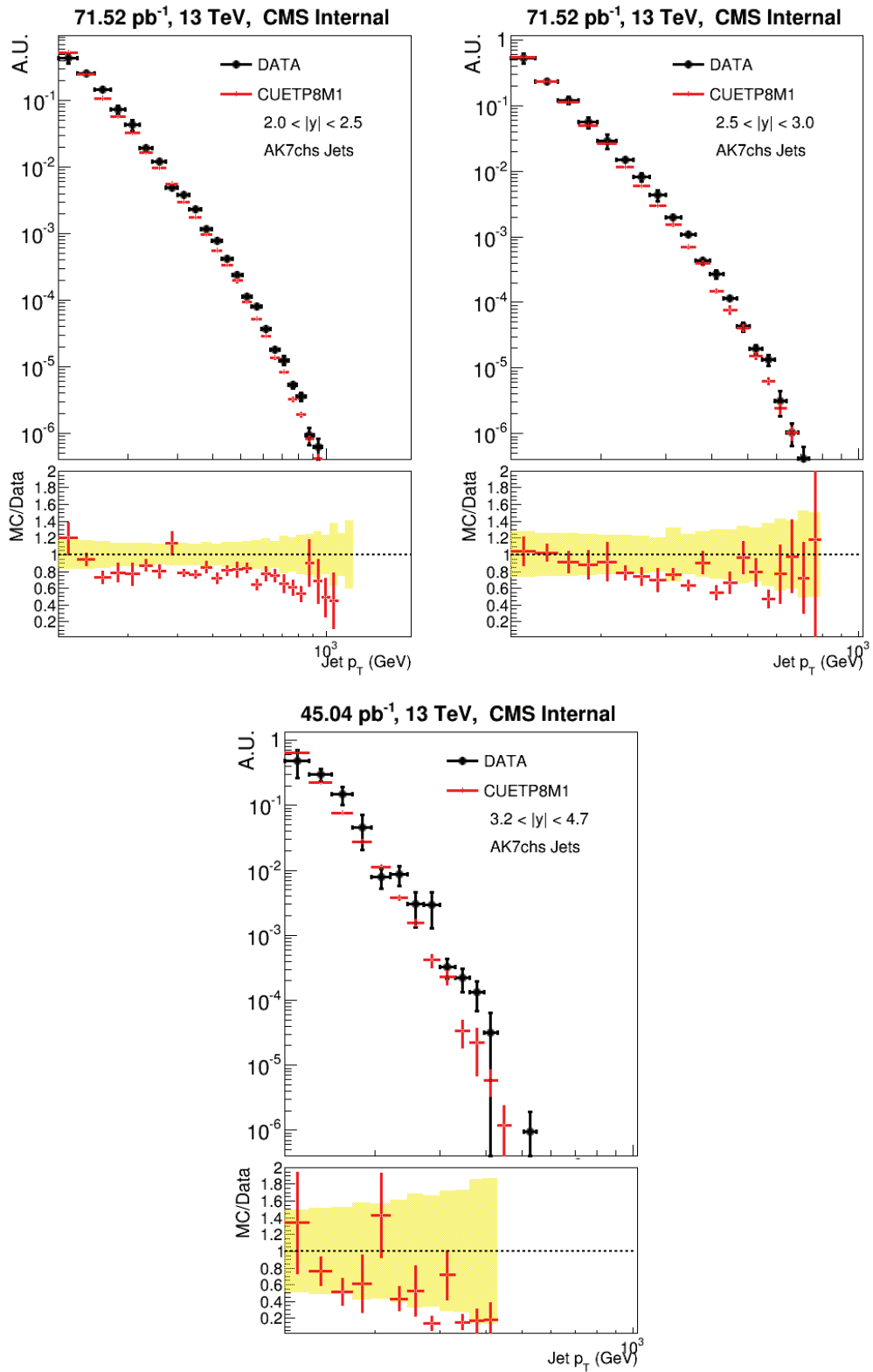


FIGURE 6.4: Control distributions at the detector level for AK7chs jets as a function of jet p_T compared with predictions from PYTHIA 8 Tune CUETP8M1 in different rapidity bins: $2.0 < |y| < 2.5$ (top left), $2.5 < |y| < 3.0$ (top right), $3.2 < |y| < 4.7$ (bottom).

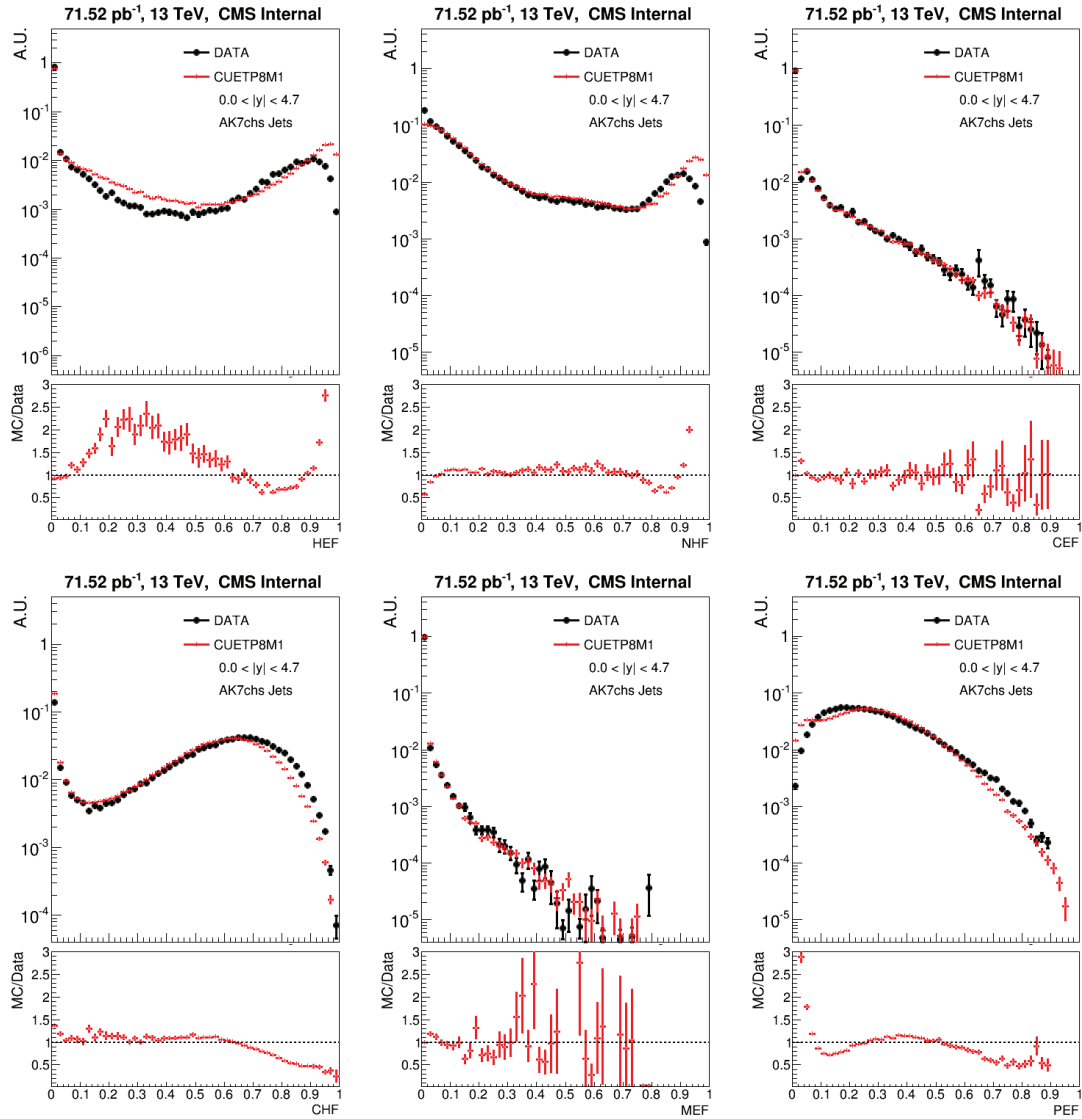


FIGURE 6.5: Control distributions at the detector level for AK7chs jets as a function of several jet constituent observables compared to predictions from PYTHIA 8 Tune CUETP8M1: hadron electromagnetic fraction:HEF (top left), neutral hadron fraction:NHF (top middle), charged electromagnetic fraction:CEF (top right) and charged hadron fraction:CHF (bottom left), muon electromagnetic fraction:MEF (bottom middle) photon electromagnetic fraction:PEF (bottom right).

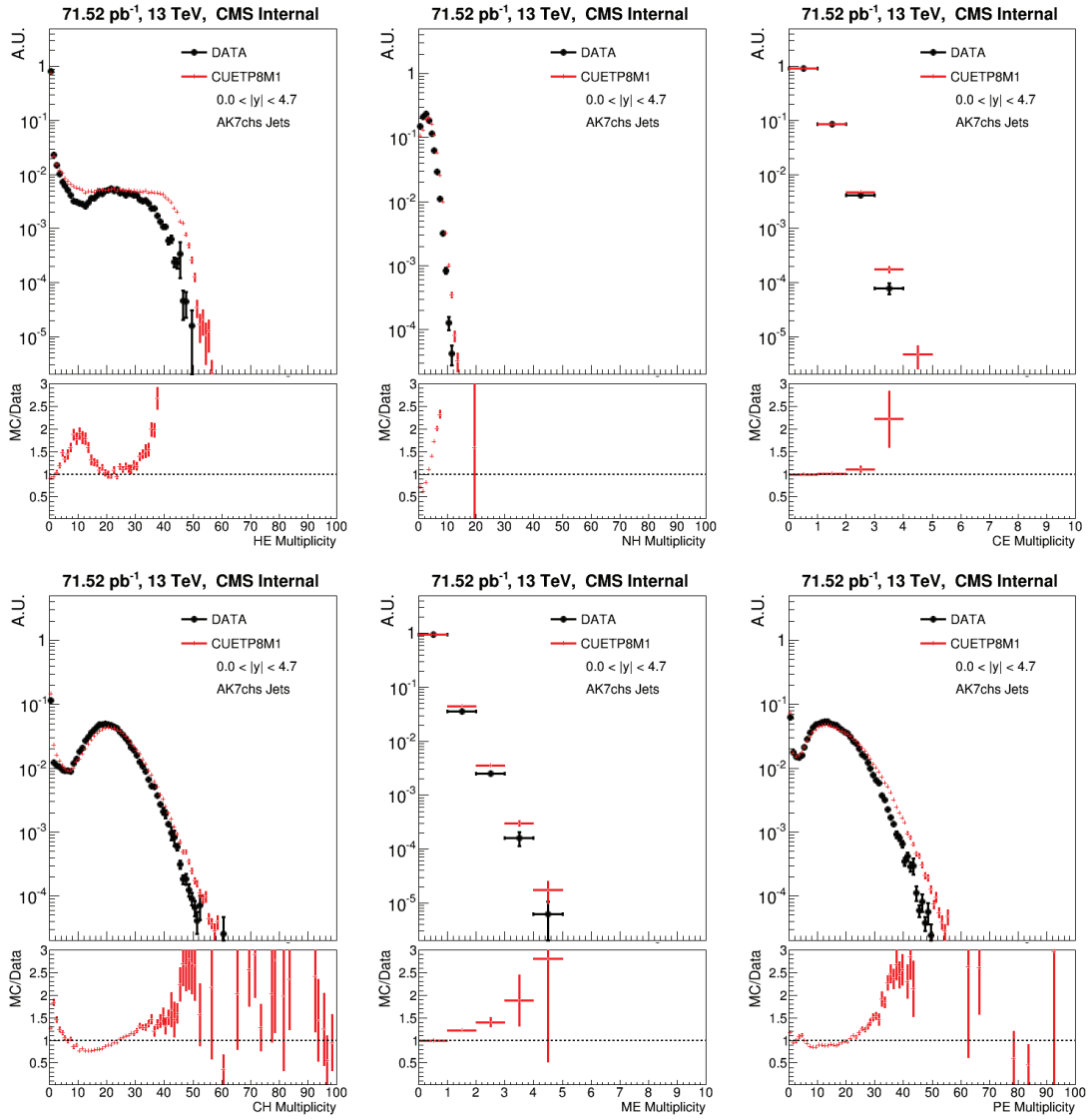


FIGURE 6.6: Control distributions at the detector level for AK7chs jets as a function of several jet constituent observables compared to predictions from PYTHIA 8 Tune CUETP8M1: hadron electromagnetic multiplicity (top left), neutral hadron multiplicity (top middle), charged electromagnetic multiplicity (top right) and charged hadron multiplicity (bottom left), muon electromagnetic multiplicity (bottom middle) photon electromagnetic multiplicity (bottom right).

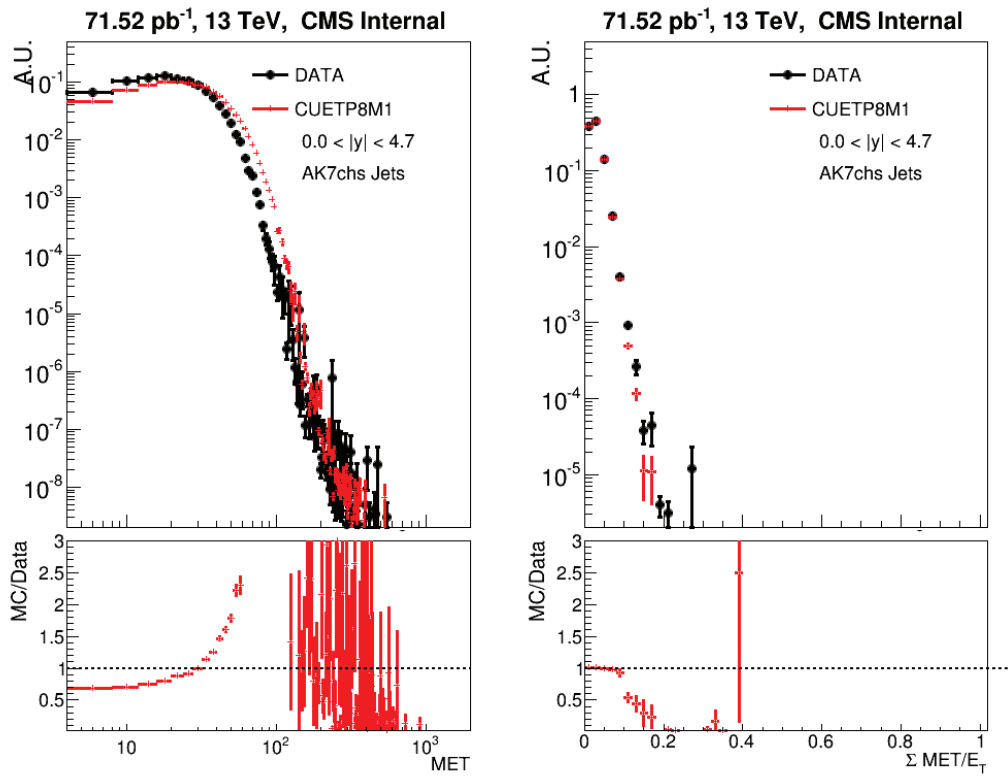


FIGURE 6.7: Control distributions at the detector level as a function of MET observables, compared to predictions from PYTHIA 8 Tune CUETP8M1: Missing transverse energy (left), fraction of MET with respect to the total hadronic energy (right).

6.0.2 Comparisons at detector level for AK4chs jets

In this section, comparisons are provided between jets from data and simulation, where the jets are clustered with the AK4chs algorithm. The same observables as done previously for AK7chs are considered. Figure 6.8 and 6.9 shows comparisons for leading and sub-leading jets, while in Figures 6.10 and 6.11 different rapidity regions are shown for inclusive jet cross-sections. In general, the simulation is able to reproduce the jet spectra at the same level of agreement, as observed for AK7. Figures 6.12 and 6.13 show, respectively, multiplicities and fractions for jets selected in the whole rapidity region. Similar conclusions as extracted for AK7chs are observed.

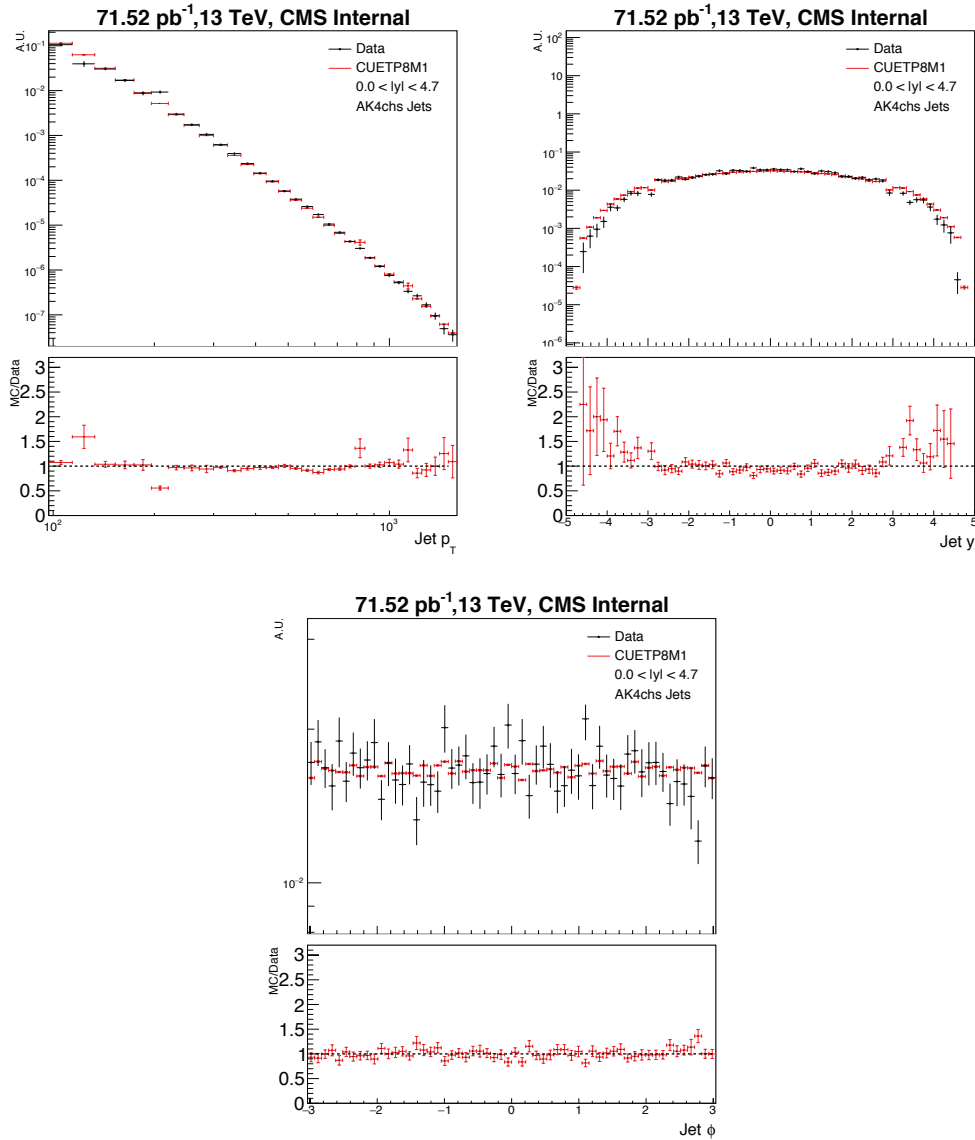


FIGURE 6.8: Control distributions at the detector level for AK4chs jets as a function of leading jet observables, compared to predictions from PYTHIA 8 Tune CUETP8M1: transverse momentum (left), rapidity (right) and azimuthal angle (bottom).

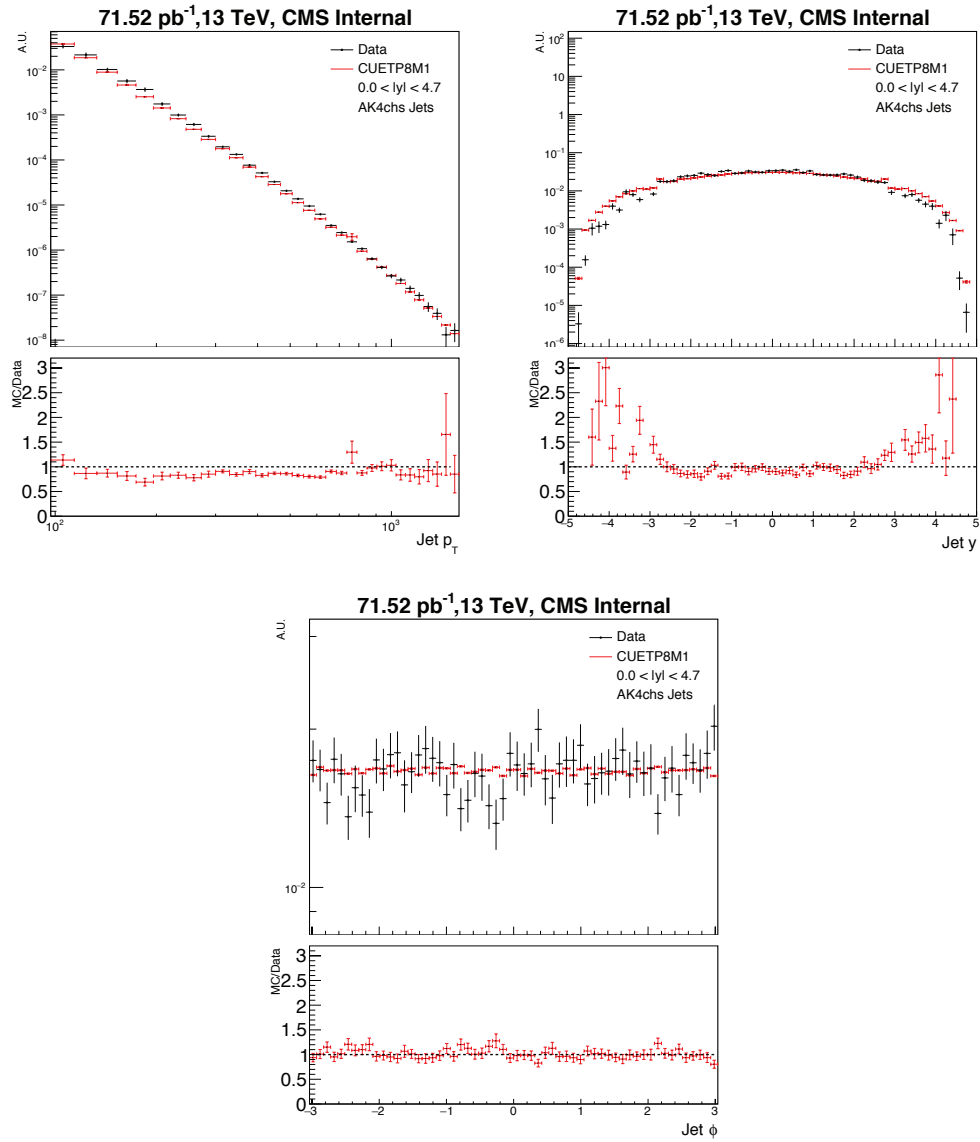


FIGURE 6.9: Control distributions at the detector level for AK4chs jets as a function of sub-leading jet observables, compared to predictions from PYTHIA 8 Tune CUETP8M1: transverse momentum (left), rapidity (right) and azimuthal angle (bottom).

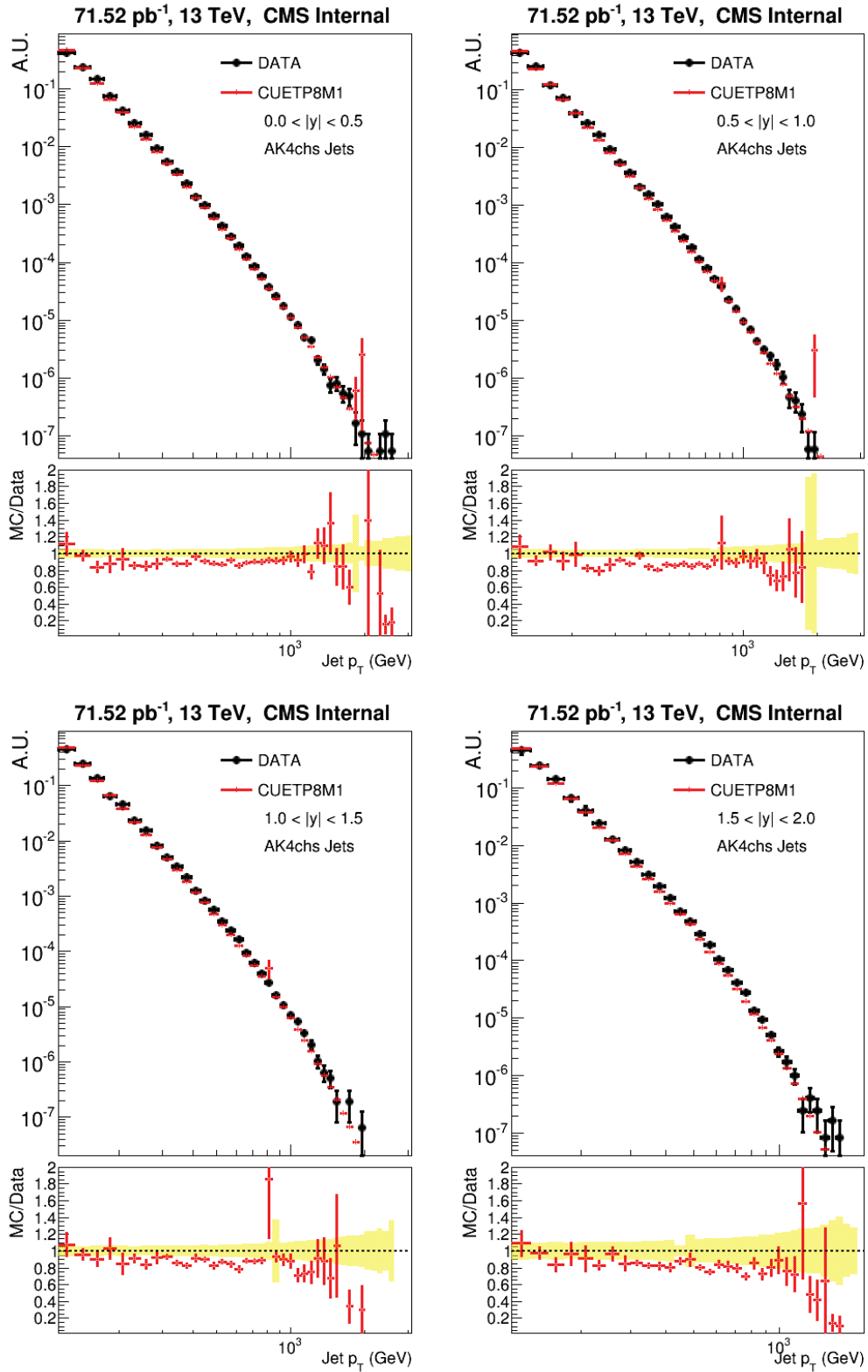


FIGURE 6.10: Control distributions at the detector level as a function of jet p_T for AK4chs jets compared with predictions from PYTHIA 8 Tune CUETP8M1 in different rapidity bins: $0.0 < |y| < 0.5$ (top left), $0.5 < |y| < 1.0$ (top right), $1.0 < |y| < 1.5$ (bottom left), $1.5 < |y| < 2.0$ (bottom right).

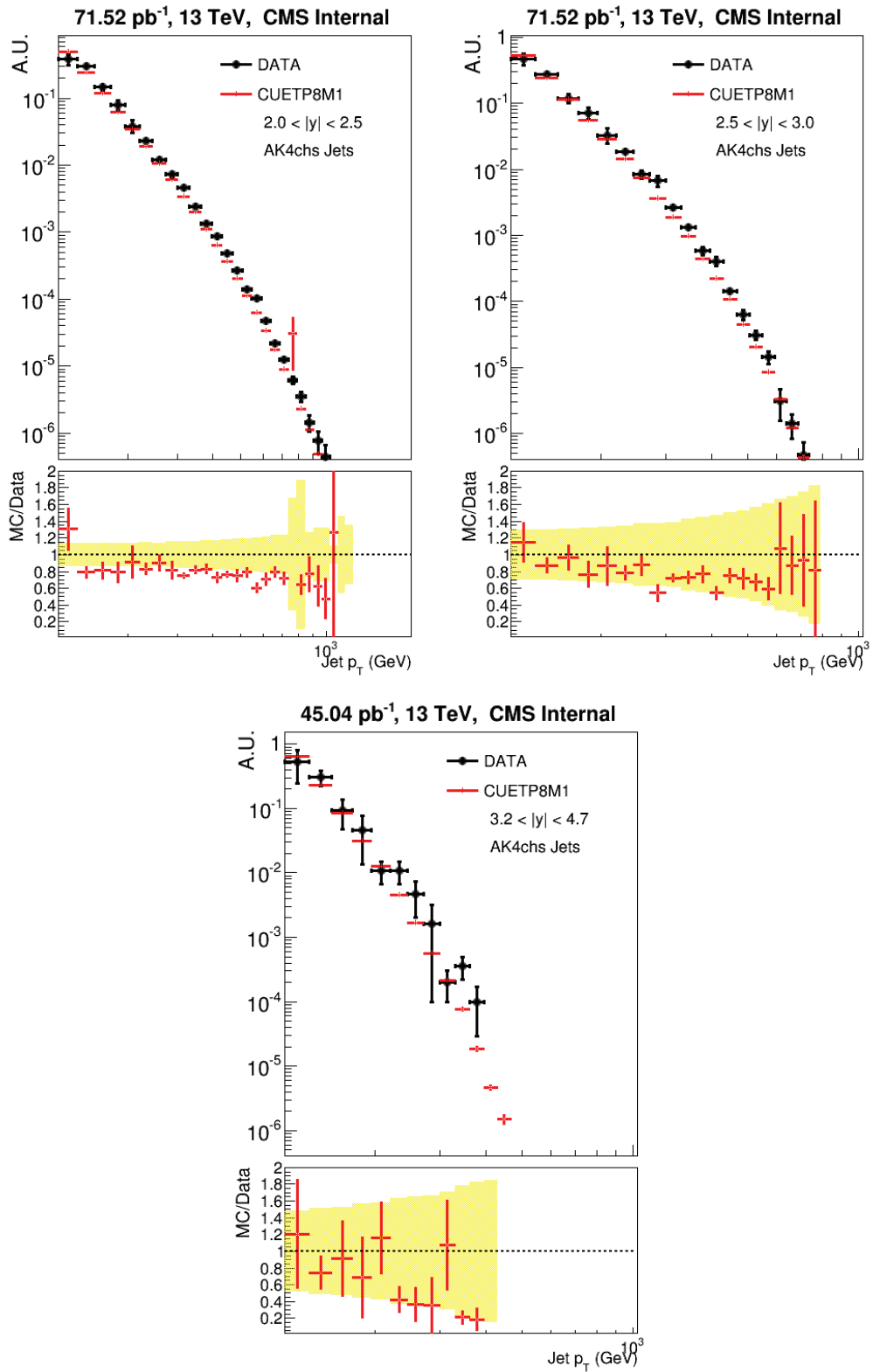


FIGURE 6.11: Control distributions at the detector level as a function of jet p_T for AK4chs jets compared with predictions from PYTHIA 8 Tune CUETP8M1 in different rapidity bins: $2.0 < |y| < 2.5$ (top left), $2.5 < |y| < 3.0$ (top right), $3.2 < |y| < 4.7$ (bottom).

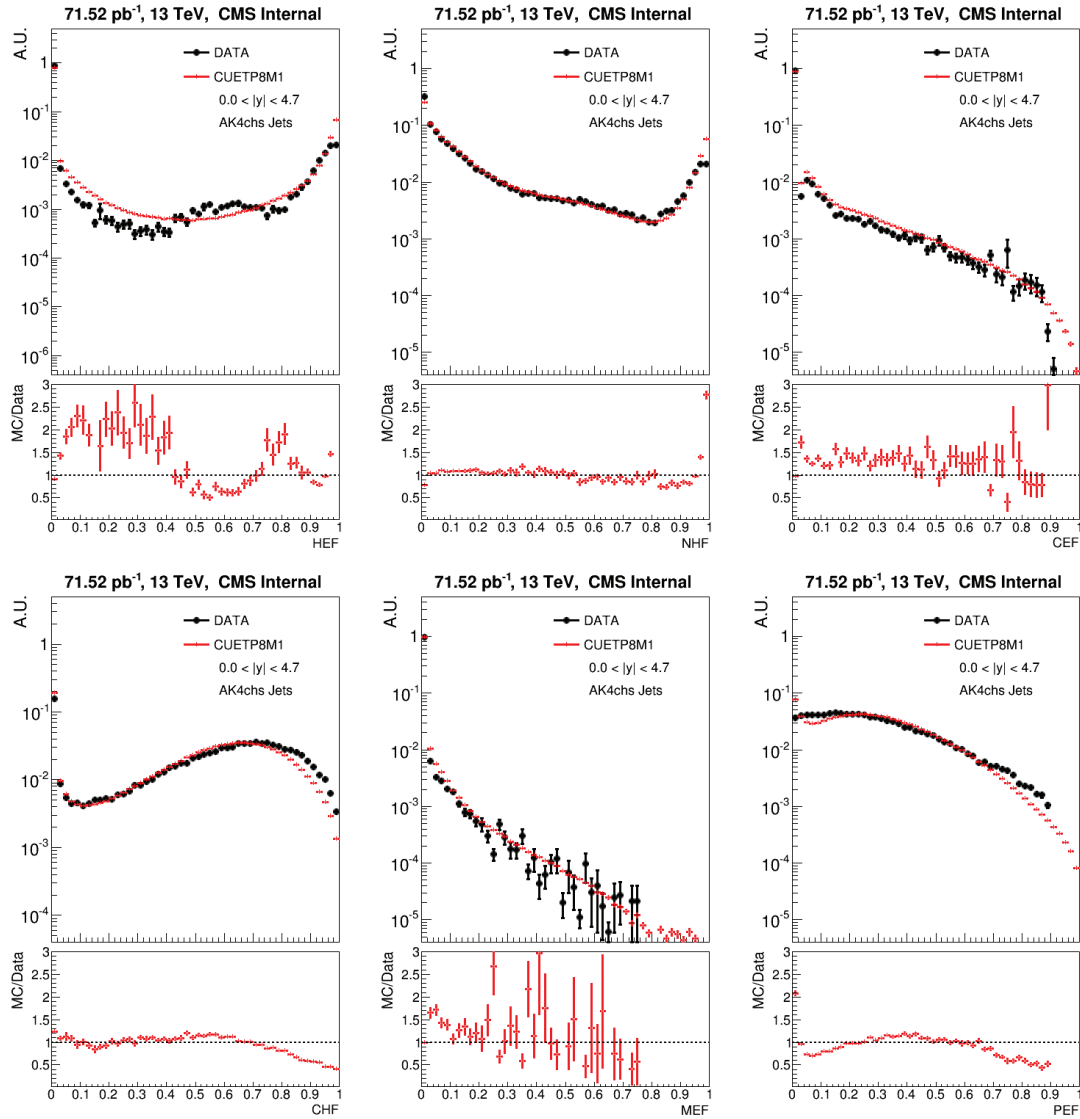


FIGURE 6.12: Control distributions at the detector level as a function of several jet constituent observables for AK4chs jets compared to predictions from PYTHIA 8 Tune CUETP8M1: hadron electromagnetic fraction:HEF (top left), neutral hadron fraction:NHF (top middle), charged electromagnetic fraction:CEF (top right) and charged hadron fraction:CHF (bottom left), muon electromagnetic fraction:MEF (bottom middle) photon electromagnetic fraction:PEF (bottom right).

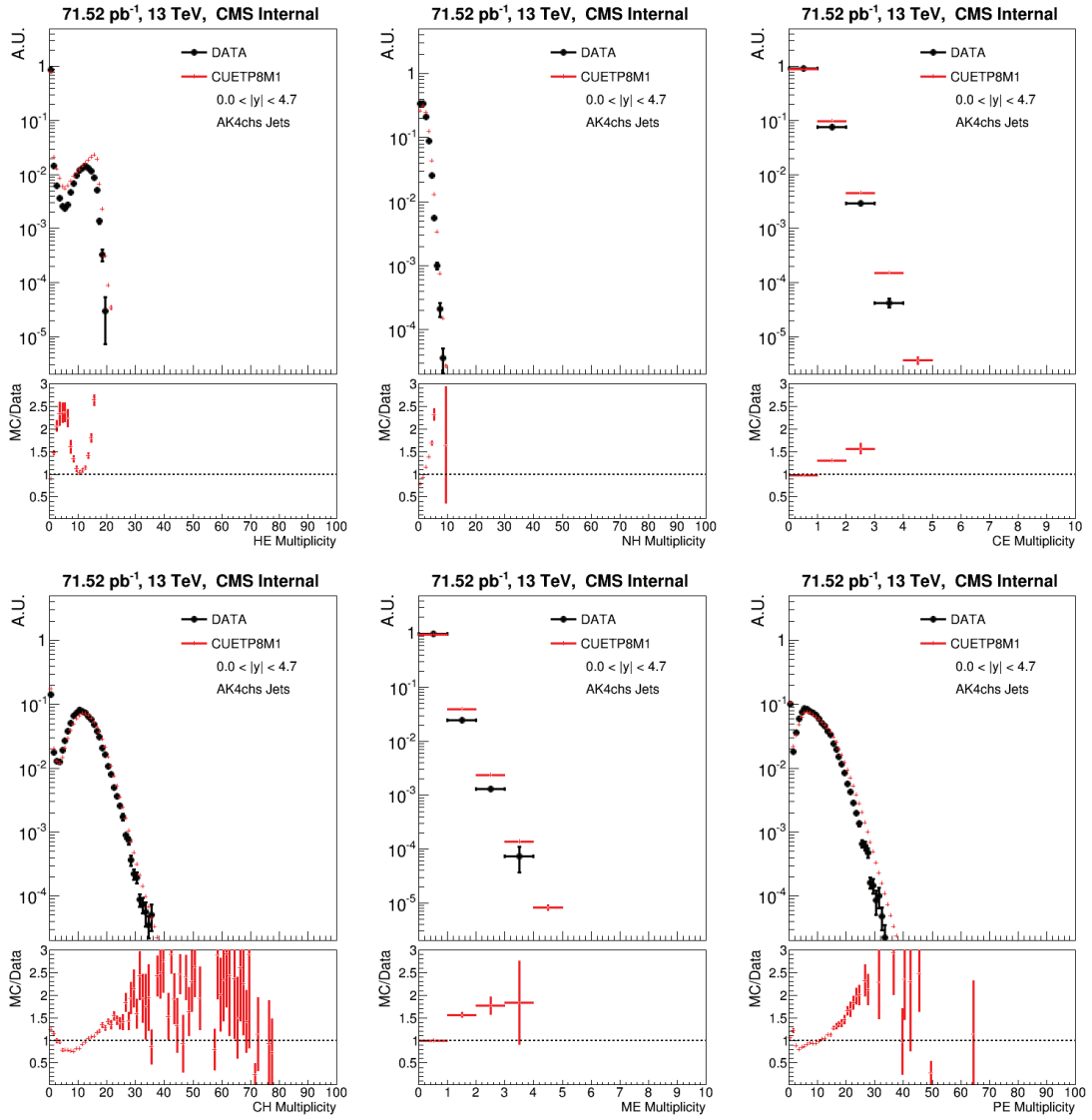


FIGURE 6.13: Control distributions at the detector level as a function of several jet constituent observables for AK4chs jets compared to predictions from PYTHIA 8 Tune CUETP8M1: hadron electromagnetic multiplicity (top left), neutral hadron multiplicity (top middle), charged electromagnetic multiplicity (top right) and charged hadron multiplicity (bottom left), muon electromagnetic multiplicity (bottom middle) photon electromagnetic multiplicity (bottom right).

6.0.3 Effect of pile-up in inclusive jet cross-sections

The effect of pile-up is studied by investigating the variation of the normalized cross-sections of inclusive jets distributions with the requirement of a different number of primary vertices. This study is based on distributions from simulation, since similar selections in data with low pile-up samples suffer from statistical inaccuracy. Figures 6.14 and 6.15 show the shapes of the inclusive jet cross-sections for the nominal selection without any requirement on the number of vertices and for a “low pile-up” selection, by requiring the number of primary vertices to be lower than 10. A selection with a lower number of vertices is found to be not statistically sufficient for extracting any conclusion.

The effect of the different selection of number of vertices is found to be not significant. Differences are observed only of the order of 5-10%.

6.0.4 Effect of pile-up reweighting in inclusive jet cross-sections

The effect of pile-up reweighting is also investigated. So far, there is no definitive recommendation on pile-up reweighting of the first data at 50 ns. However, to study the impact of the differences observed in pile-up distributions in data and simulation, the iterative reweighting method is applied to the simulation. This method consists of comparing the distributions of good reconstructed primary vertices obtained in the data and in the MC. In an ideal case, a good reconstructed primary vertex corresponds to a pp interaction. Since a pile-up event is separated in space and independent of the other interactions occurring in the same collision, one could think, as a first approximation, that the number of pile-up events is equal to the number of reconstructed vertices. Unfortunately, many detector effects spoil this identity: inefficiencies (a true vertex is not reconstructed), resolution issues (two vertices are too close to be resolved separately) and fake reconstructions (a primary vertex not corresponding to a pile-up event is reconstructed as such, because of track misidentification) determine a decrease or an increase in the number of reconstructed vertices. This is why an exact correspondence between the number of primary vertices and pile-up interactions, generally, does not hold.

The bin-by-bin ratios of the primary vertex distributions measured in the data and in the MC are considered for the iterative method. They are applied as weights to the true number of pile-up interactions¹ in the simulation. Provided that each pile-up interaction creates a separated primary vertex, the described procedure would give a perfect agreement between the primary vertex distributions in the data and in the MC after the application of the weights. This is in fact not true, because of the aforementioned effects and implies the fact that the reweighting procedure in the simulation as a function of the true number of pile-up interactions needs to be repeated (hence, the name “iterative”) several times. For high pile-up scenarios, it has been shown that this procedure has troubles to converge because at number of vertices around 10 there is no more one-to-one correspondence between number of pile-up events and number of reconstructed vertices. However, this procedure shows the impact of different pile-up scenarios, as observed in the default simulation and data. The normalized distribution of the good reconstructed primary vertices are shown in Figure 6.16 for MC before and after reweighting. In Figures 6.17 and 6.18, the normalized cross-sections as a function of jet p_T are shown in the different rapidity bins for distributions with and without pile-up reweighting. Practically, no effect on the inclusive jet cross-sections is observed. This gives confidence on the fact that a more detailed treatment of the pile-up in the analysis is not required. In the following, the MC is, hence, not reweighted as a function of the number of primary

¹In MC, the true number of pile-up events, namely how many interactions, overlapped to the hard scattering, are effectively simulated, is indeed available, while in the data it is not.

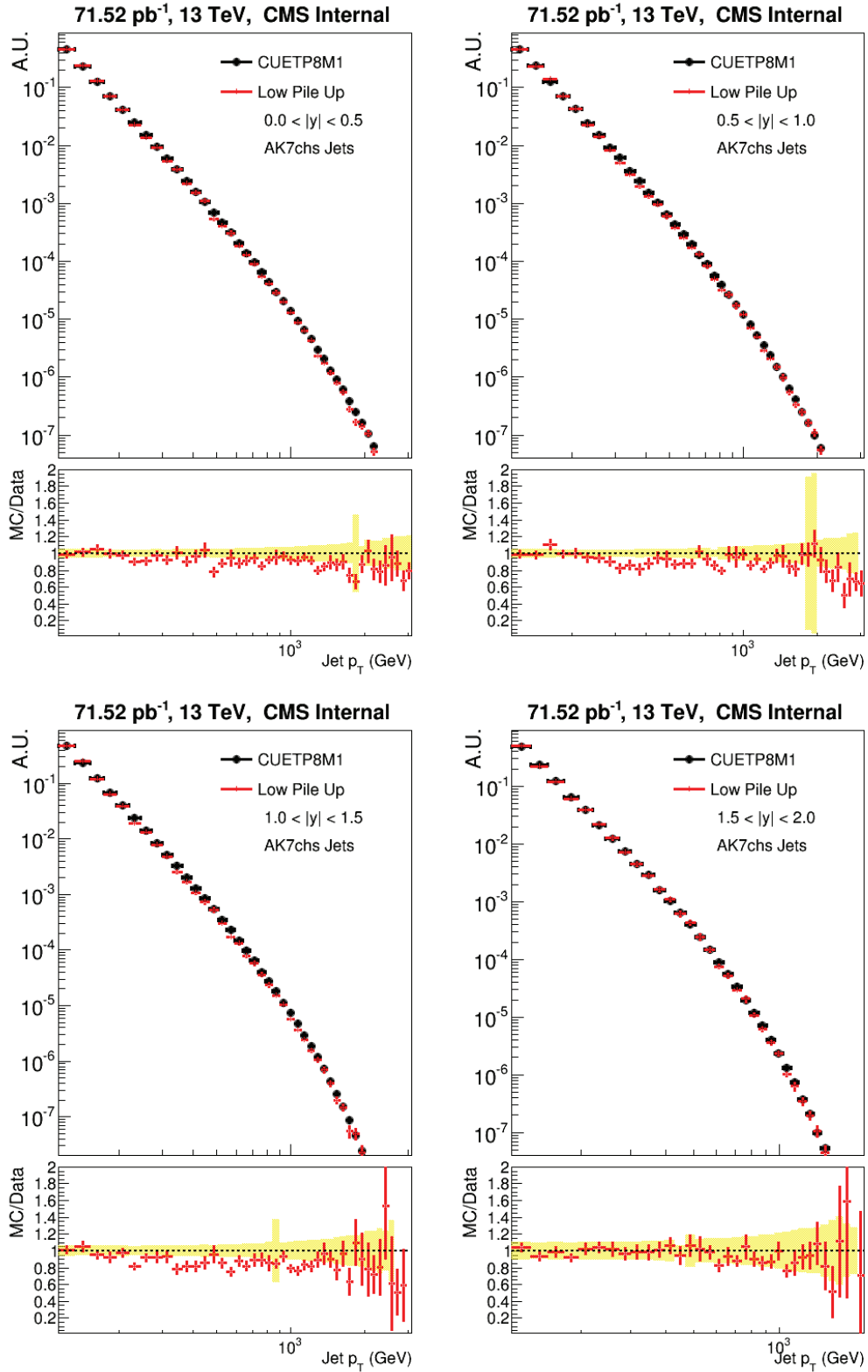


FIGURE 6.14: Control distributions at the detector level as a function of jet p_T from predictions of PYTHIA 8 Tune CUETP8M1 without any requirement in the number of primary vertices and with number of primary vertices less than 10 (“Low Pile-up”) in different rapidity bins: $0.0 < |y| < 0.5$ (top left), $0.5 < |y| < 1.0$ (top right), $1.0 < |y| < 1.5$ (bottom left), $1.5 < |y| < 2.0$ (bottom right).

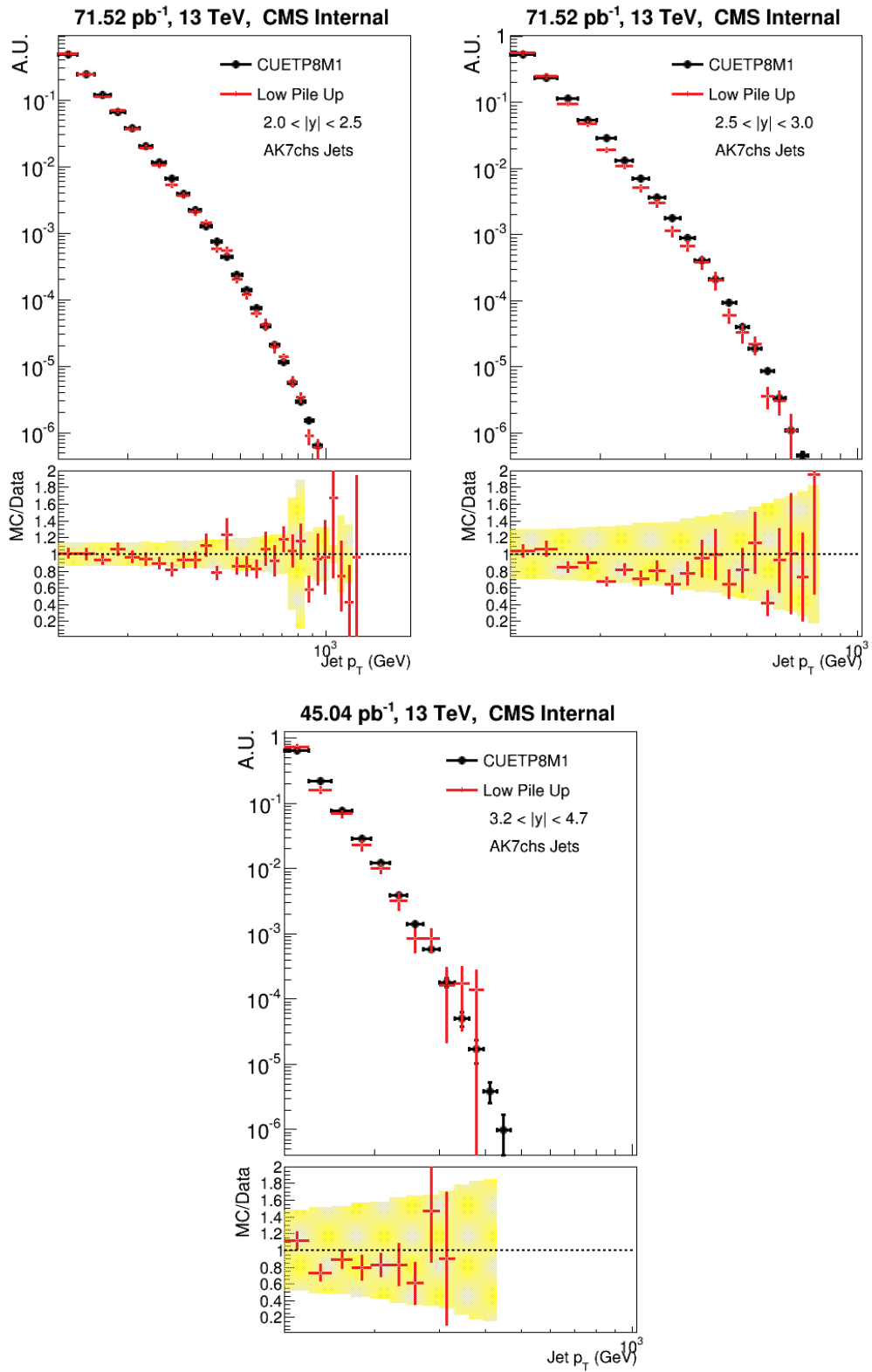


FIGURE 6.15: Control distributions at the detector level as a function of jet p_T from predictions of PYTHIA 8 Tune CUETP8M1 without any requirement in the number of primary vertices and with number of primary vertices less than 10 ("Low Pile-up") in different rapidity bins: $2.0 < |y| < 2.5$ (top left), $2.5 < |y| < 3.0$ (top right), $3.2 < |y| < 4.7$ (bottom).

vertices and taken with the simulated pile-up scenario (which anyway does not differ too much from the data distributions - see Figure 6.16).

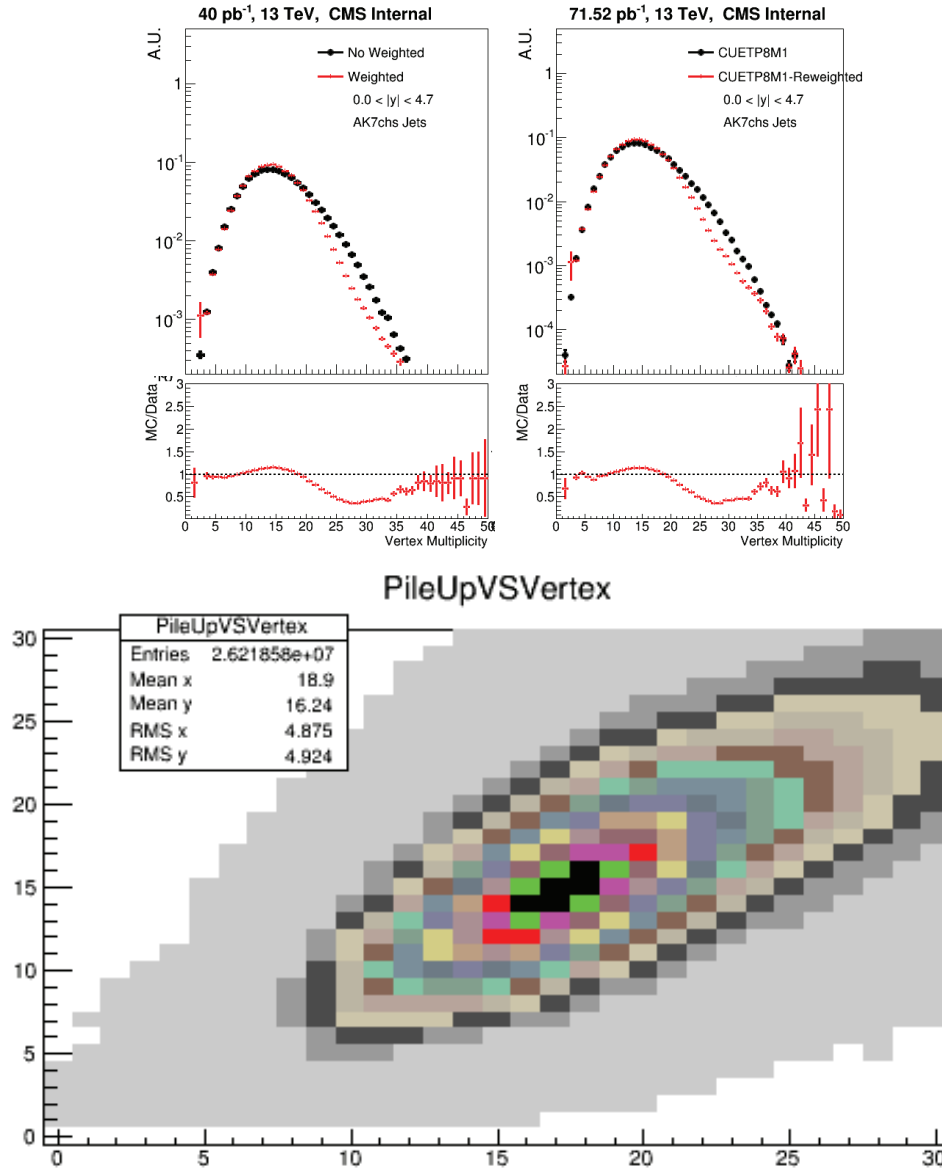


FIGURE 6.16: (Top Left) Normalized cross-section as a function of the number of primary vertices in the non-reweighted and reweighted scenario. (Top Right) Normalized cross-section as a function of the number of primary vertices in the reweighted and scenario and data. (Bottom) Scatter plot of number of pile-up events versus number of reconstructed primary vertices in the simulation.

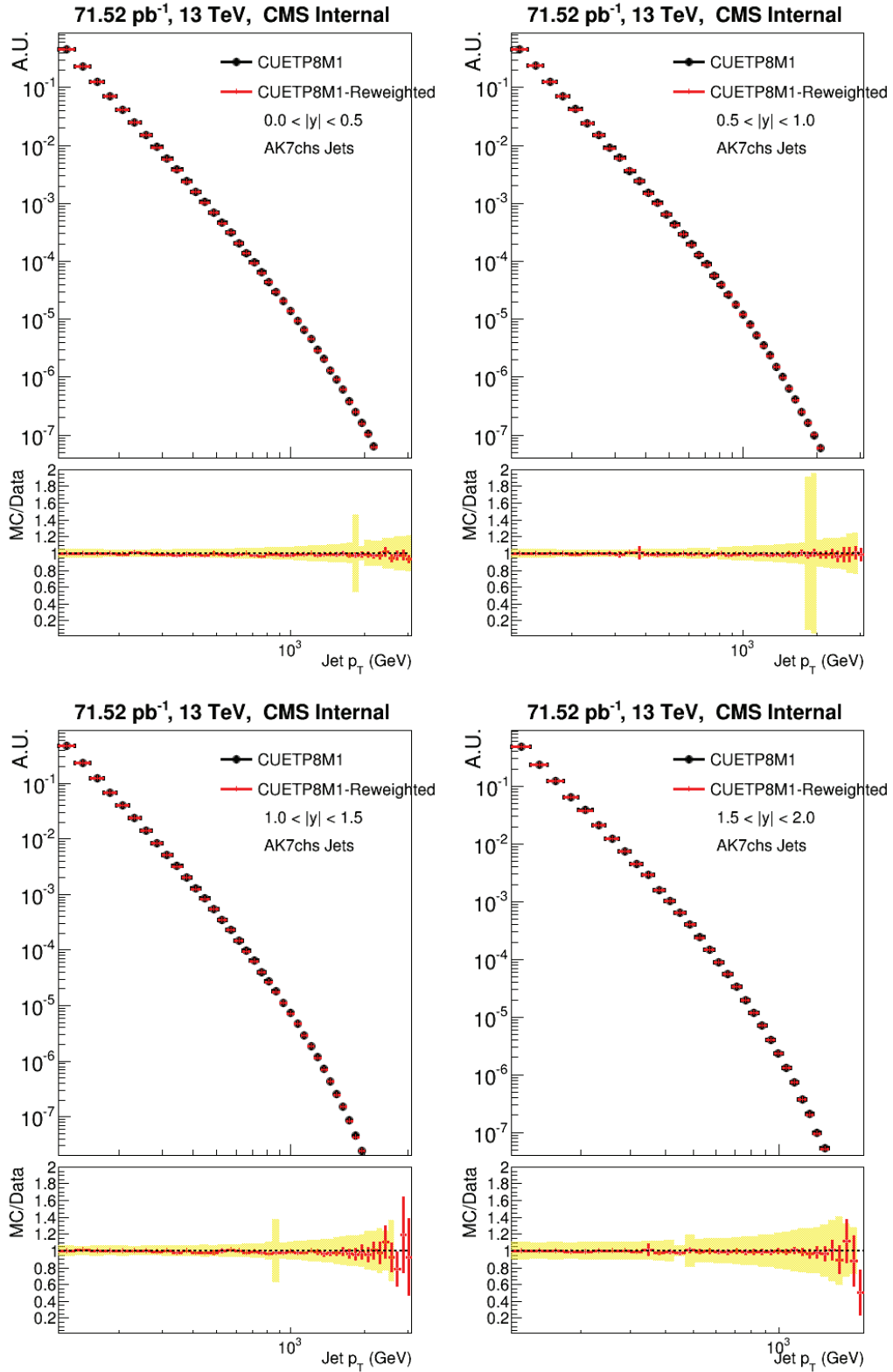


FIGURE 6.17: Control distributions at detector level as a function of jet p_T from predictions of PYTHIA 8 Tune CUETP8M1 without any requirement in the number of primary vertices and with number of primary vertices less than 10 (“Low Pile-up”) in different rapidity bins: $0.0 < |y| < 0.5$ (top left), $0.5 < |y| < 1.0$ (top right), $1.0 < |y| < 1.5$ (bottom left), $1.5 < |y| < 2.0$ (bottom right).

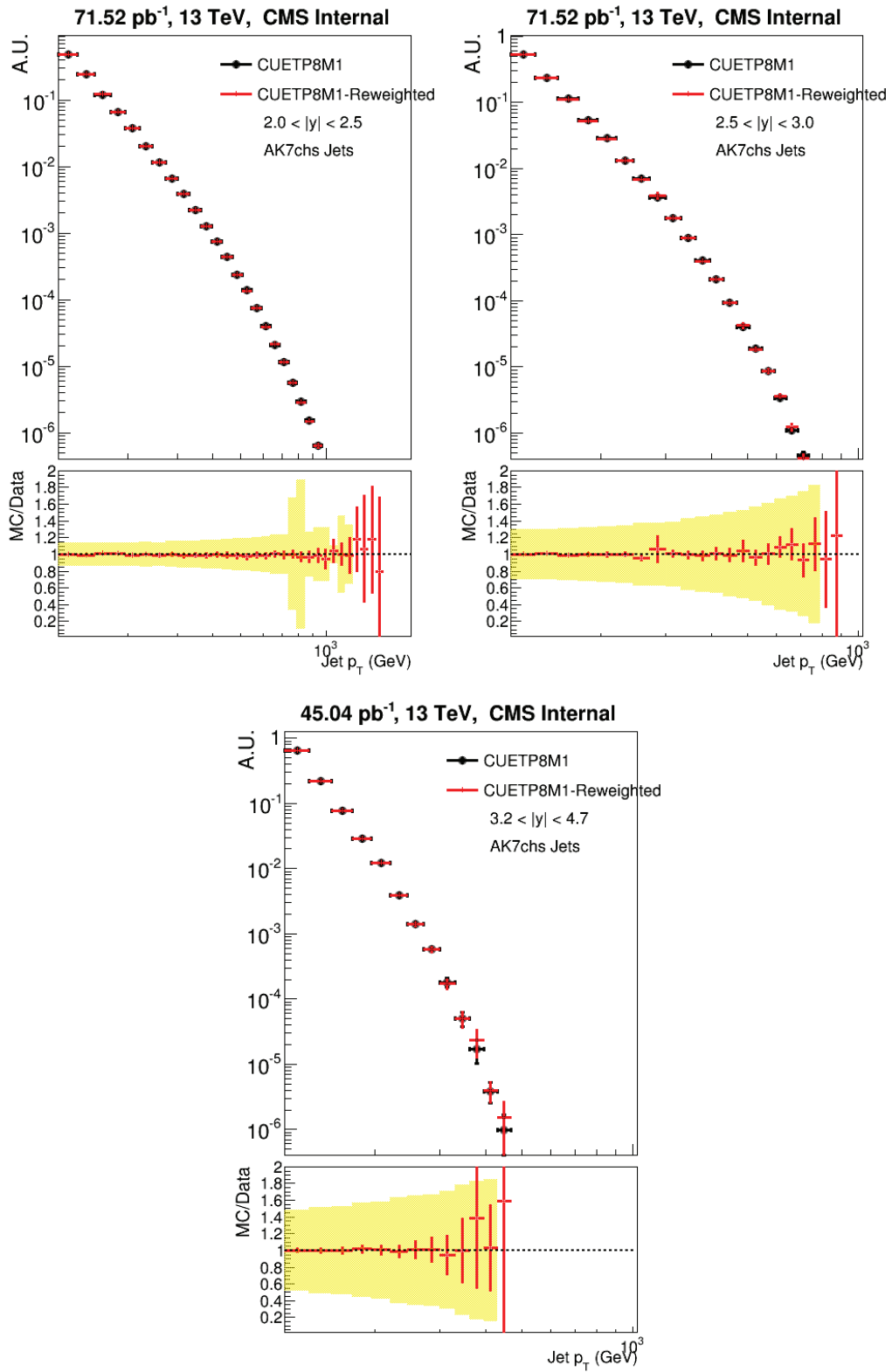


FIGURE 6.18: Control distributions at detector level as a function of jet p_T from predictions of PYTHIA 8 Tune CUETP8M1 without any requirement in the number of primary vertices and with number of primary vertices less than 10 (“Low Pile-up”) in different rapidity bins: $2.0 < |y| < 2.5$ (top left), $2.5 < |y| < 3.0$ (top right), $3.2 < |y| < 4.7$ (bottom).

Chapter 7

Resolution studies

In this Chapter, various experimental effects are discussed in detail. The investigation of the detector effects is performed in different steps:

- study of the detector resolution from simulated events: this helps to choose an appropriate binning for the measured distribution of the observables(Section 7.0.1);
- investigation of purity, stability, background and acceptance to understand the migration effects (Section 7.0.2);
- estimation of the jet resolution in bins of transverse momentum and rapidity(through fits) (Section 7.0.3);
- construction of the response matrices, which connect detector and generator level quantities through studies of the detector resolution (Section 7.0.4);

The first two studies, which are not directly related to the unfolding but only provides a cross check of the results from the resolution fits, are shown only for AK7chs jets. Resolution studies from fits to the MC response are instead shown for both AK4chs and AK7chs jets.

7.0.1 Effects due to migration

Measurement of detector resolution for the observables under study is crucial for the determination of the histogram binning. Detector resolution represents how much the measured value differs from the true one. In binned histograms, one must be careful about the fact that the measured quantities may migrate from one bin to another with respect to their true value. This effect complicates the correction procedure of data and one should try to avoid these migrations. The solution is to choose histogram bin widths which are at least two to three times larger than the detector resolution in that particular bin.

Detector resolution is studied for all the rapidity ranges. The sample generated with PYTHIA8 is used where events at detector and generator level are selected. The jets are matched at the two levels by applying a cut in the $\eta - \phi$ plane according to $R = \sqrt{(\eta_j^{\text{gen}} - \eta_j^{\text{det}})^2 + (\phi_j^{\text{gen}} - \phi_j^{\text{det}})^2}$. If ΔR is equal to or less than 0.3, the jets are considered to be matched. Figure 7.1 and Figure 7.2 show the scatter plots of reconstructed p_T versus generated p_T for the rapidity ranges considered. In each of them, a diagonal structure is observed with relatively symmetric migration effects in the off-diagonal terms. The amount of these migration is estimated by evaluating the purity and the stability of the measured quantities (see Section 7.0.2).

The resolution is measured from the distributions of the relative difference of the quantities measured at generator and detector levels for the matched jets. These distributions are observed to have a Gaussian core with a non-Gaussian tail at values far from

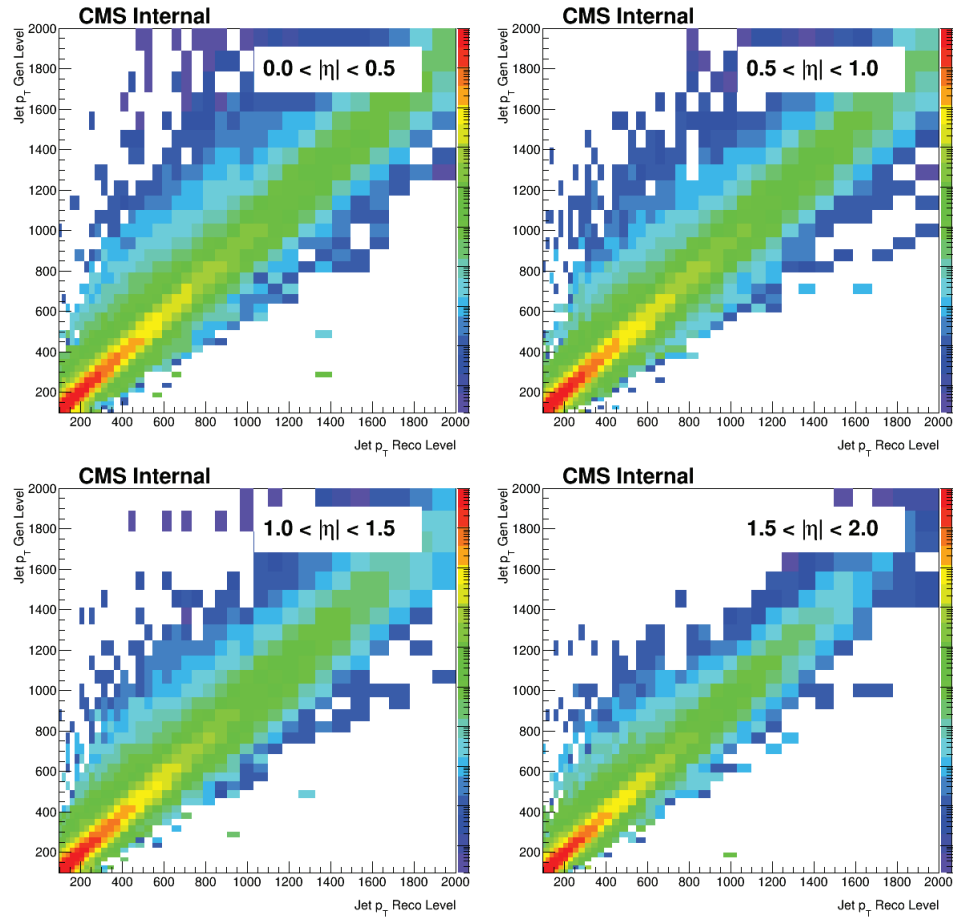


FIGURE 7.1: Migration matrix as a function of jet transverse momentum for different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$

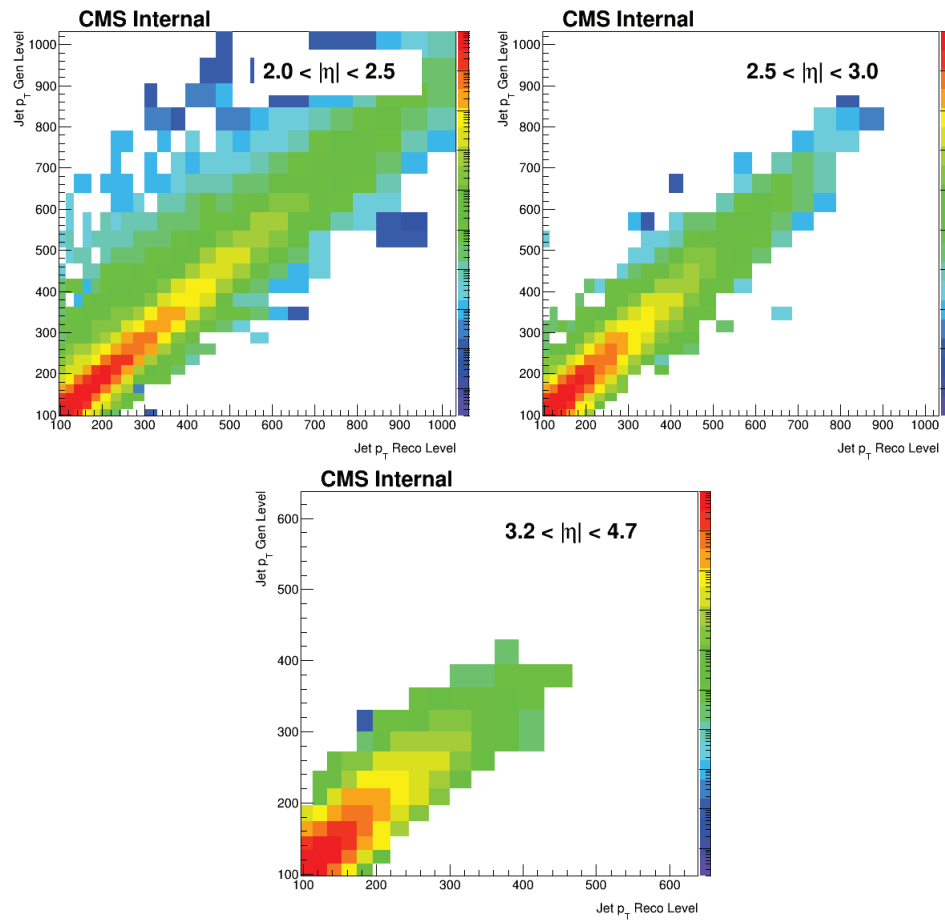


FIGURE 7.2: Migration matrix as a function of jet transverse momentum for different rapidity bins: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$.

0. The resolution, plotted in Figure 7.3 (left), is then obtained by taking the width of the Gaussian distributions in each rapidity bin (without dividing them in bins of p_T).

In Figure 7.3 (right), migration effects affecting adjacent rapidity bins are evaluated by matching jets at generator and detector levels in the p_T - ϕ plane and by counting the number of jets which are in a different rapidity bin at the two levels. The so-built response matrix shows that only a small fraction ($< 3\%$) of the reconstructed jets comes from a different rapidity bin. Migration effects due to resolution in the rapidity can be therefore considered negligible with respect to the ones due to resolution in p_T . This is the reason why in this analysis a one-dimensional unfolding is performed for the final results.

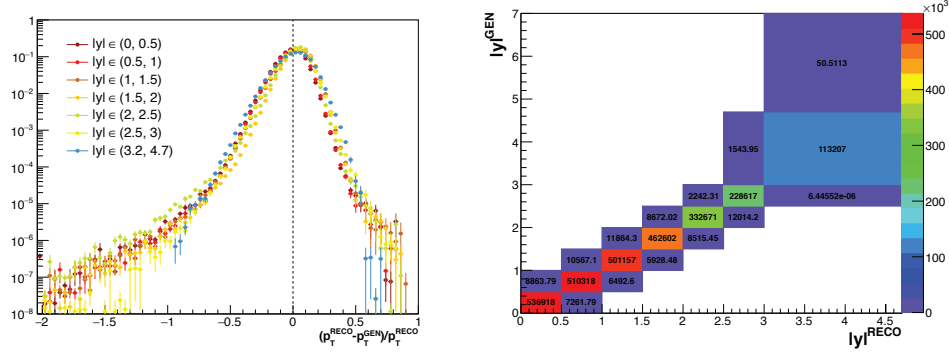


FIGURE 7.3: (left) Relative transverse momentum resolution obtained by using the Summer15_50nsV5 correction set for the different jet rapidity bins. (right) Migration matrix as a function of jet rapidity for the different considered bins.

7.0.2 Evaluation of purity, stability, acceptance and background

After determining the bin widths, the responses are studied at generator and detector levels. Several cases may arise for a measured observable: the measurements at detector and generator level stay in the same bin or the measurements correspond to different bins at the two levels. It may also happen that an event is selected only in one of two levels. “Migration effect” alludes to the situation when the measurements at generator and detector levels do not remain in the same bin. There are two types of migration effects: the migrations “within the phase space” are the ones where the events are selected in both levels but they fill different bins in the histograms at detector and generator levels while the migrations “into or out of the phase space” are the ones where the events are selected in only one of the two levels. Studies on migration effects are performed by measuring purity, stability, background and acceptance. The first two measure the behaviour of the migration within the phase space, while with the other two are related to the migration into or out of the phase space. These quantities are defined as follows:

- Purity represents the percentage of events in a certain bin i at the detector level det , which are also selected at the generator level gen and belong to the same bin. In a compact formula, it can be written as:

$$P_i^{\text{MC}} = \frac{N_{\text{both select}}^{\text{MC}}(E_{\text{det}}^{\text{MC}} \in \text{bin } i \wedge E_{\text{gen}}^{\text{MC}} \in \text{bin } i)}{N_{\text{both select}}^{\text{MC}}(E_{\text{det}}^{\text{MC}} \in \text{bin } i)}; \quad (7.1)$$

- Stability quantifies the percentage of events in a certain bin i at the generator level gen , which are also selected at the detector level det and belong to the same bin. In

the same way, it can be written as:

$$S_i^{\text{MC}} = \frac{N_{\text{both select}}^{\text{MC}}(E_{\text{det}}^{\text{MC}} \in \text{bin } i \wedge E_{\text{gen}}^{\text{MC}} \in \text{bin } i)}{N_{\text{both select}}^{\text{MC}}(E_{\text{gen}}^{\text{MC}} \in \text{bin } i)}; \quad (7.2)$$

- Background measures the percentage of events in a certain bin i at the detector level det , which are also selected also at the generator level gen . This translates into the following definition:

$$B_i^{\text{MC}} = 1 - \frac{N_{\text{both select}}^{\text{MC}}(E_{\text{det}}^{\text{MC}} \in \text{bin } i)}{N_{\text{select}}^{\text{MC}}(E_{\text{det}}^{\text{MC}} \in \text{bin } i)}; \quad (7.3)$$

- Acceptance measures the percentage of events in a certain bin i at the generator level gen , which are also selected also at the detector level det . It can be written as:

$$A_i^{\text{MC}} = \frac{N_{\text{both select}}^{\text{MC}}(E_{\text{gen}}^{\text{MC}} \in \text{bin } i)}{N_{\text{select}}^{\text{MC}}(E_{\text{gen}}^{\text{MC}} \in \text{bin } i)} \quad (7.4)$$

where N represents generic number of events, subscripts *both select* and *select* indicate events selected at both levels and at only one of them respectively. These quantities are determined with PYTHIA 8. Figures 7.4-7.10 show the results of the migration effects for the different rapidity ranges as a function of p_T . It can be seen that acceptance and background are rather flat around the whole range and they are never below 99% or above 1% respectively. In other words, this means that a percentage of 99% of jets at the generator level is efficiently selected at the detector level, and that only less than 1% of the jets selected at the detector level do not correspond to a jet at generator level. In addition, the purity and stability for observables related to the additional jets are between 30% and 50%. Thanks to the high purity and stability observed in these studies, one can conclude that the binning set for the measurement as a function of jet p_T is a good choice given the available detector reconstruction performance.

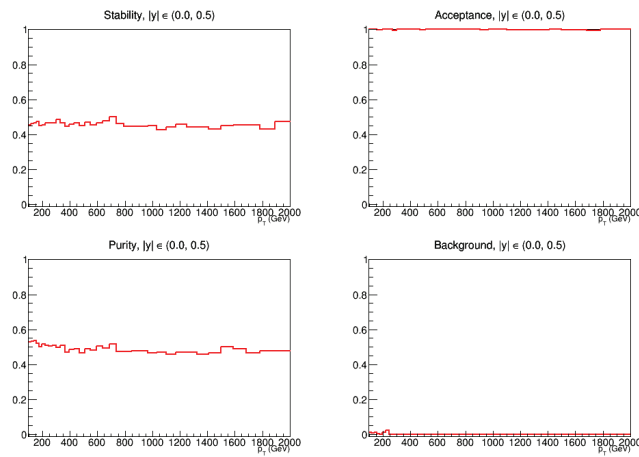


FIGURE 7.4: Purity, stability, acceptance and background as a function of jet p_T selected in the first rapidity bin ($0.0 < |y| < 0.5$)

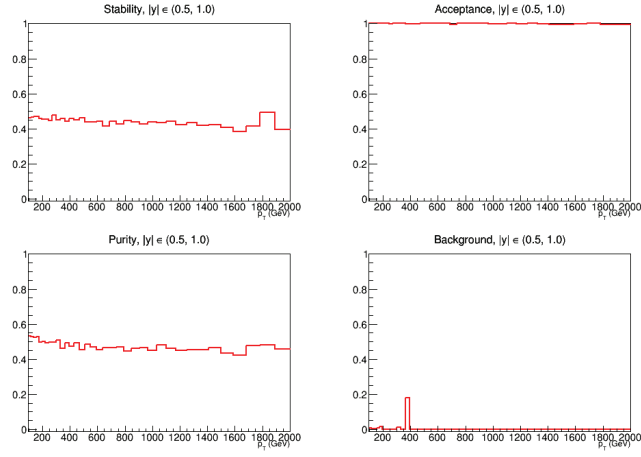


FIGURE 7.5: Purity, stability, acceptance and background as a function of jet p_T selected in the second rapidity bin ($0.5 < |y| < 1.0$)

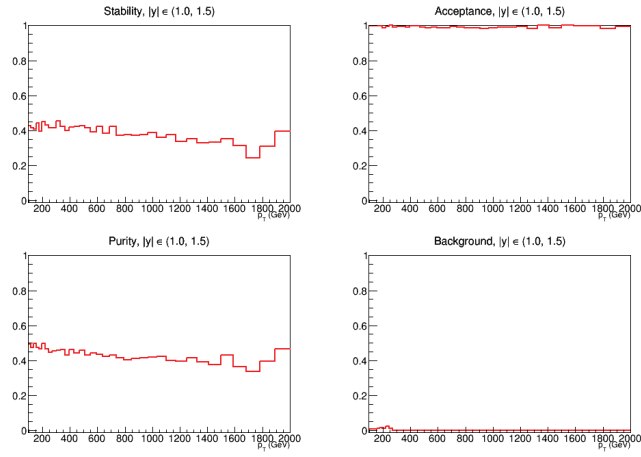


FIGURE 7.6: Purity, stability, acceptance and background as a function of jet p_T selected in the third rapidity bin ($1.0 < |y| < 1.5$)

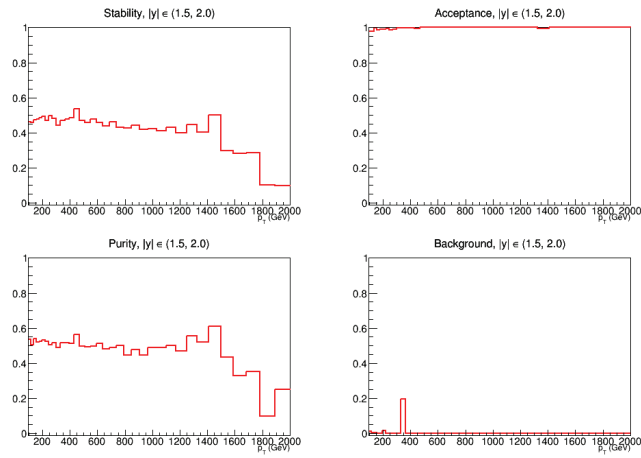


FIGURE 7.7: Purity, stability, acceptance and background as a function of jet p_T selected in the fourth rapidity bin ($1.5 < |y| < 2.0$)

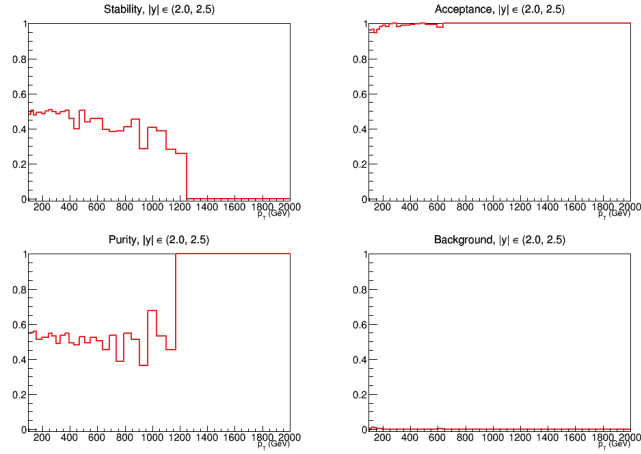


FIGURE 7.8: Purity, stability, acceptance and background as a function of jet p_T selected in the fifth rapidity bin ($2.0 < |y| < 2.5$)

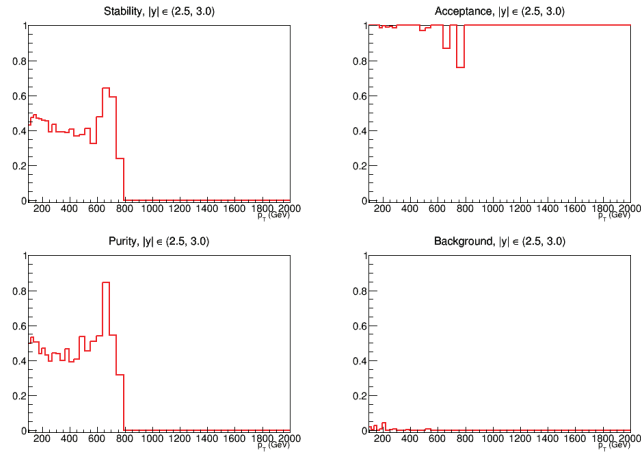


FIGURE 7.9: Purity, stability, acceptance and background as a function of jet p_T selected in the sixth rapidity bin ($2.5 < |y| < 3.0$)

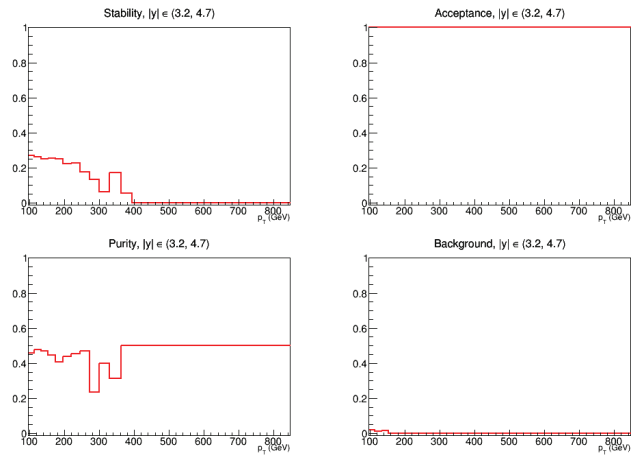


FIGURE 7.10: Purity, stability, acceptance and background as a function of jet p_T selected in the seventh rapidity bin ($3.2 < |y| < 4.7$)

7.0.3 Resolution studies for AK7

The jet p_T resolution is responsible for migration of events between the various bins in the spectra, and is studied using the PYTHIA8 tune CUETM1 slice Monte Carlo. Transverse momentum resolution studies are very important to perform the unfolding of the measured inclusive spectra. The jet p_T resolution is reasonably Gaussian, although some non-Gaussian low response tails are present due to rare detector effects, such as ECAL holes and high p_T particles punching through the HCAL. Such effects are typically well-modeled by a double-sided Crystal Ball. In figures 7.11 and 7.12 the jet p_T resolution for AK7chs is shown, fitted with a double-sided Crystal Ball function for various p_T ranges and for all rapidity bins. The core of the jet p_T resolution is Gaussian and it is shown in figure 7.13 for all the rapidity bins. Figure 7.14 summarizes the jet p_T resolution for AK7. It is to be noted that, in this section, although AK7chs and AK7 are written interchangeably, it is always AK7chs that has been used.

7.0.4 Resolution studies for AK4

Figures 7.15 and 7.16 show the jet p_T resolution for a smaller cone size AK4. The distributions are fitted with a double-sided Crystal Ball function for various p_T ranges and for all rapidity bins. The Gaussian core of the jet p_T resolution is shown in figures 7.17 for AK4 for all rapidity bins. It is to be noted that for the outer rapidity bin $3.2 < |y| < 4.7$ a higher statistics MC is needed for a more accurate study. Finally Fig. 7.18 summarizes the jet p_T resolution for AK4. It is to be noted that, in this section, although AK4chs and AK4 are written interchangeably, it is always AK4chs that has been used.

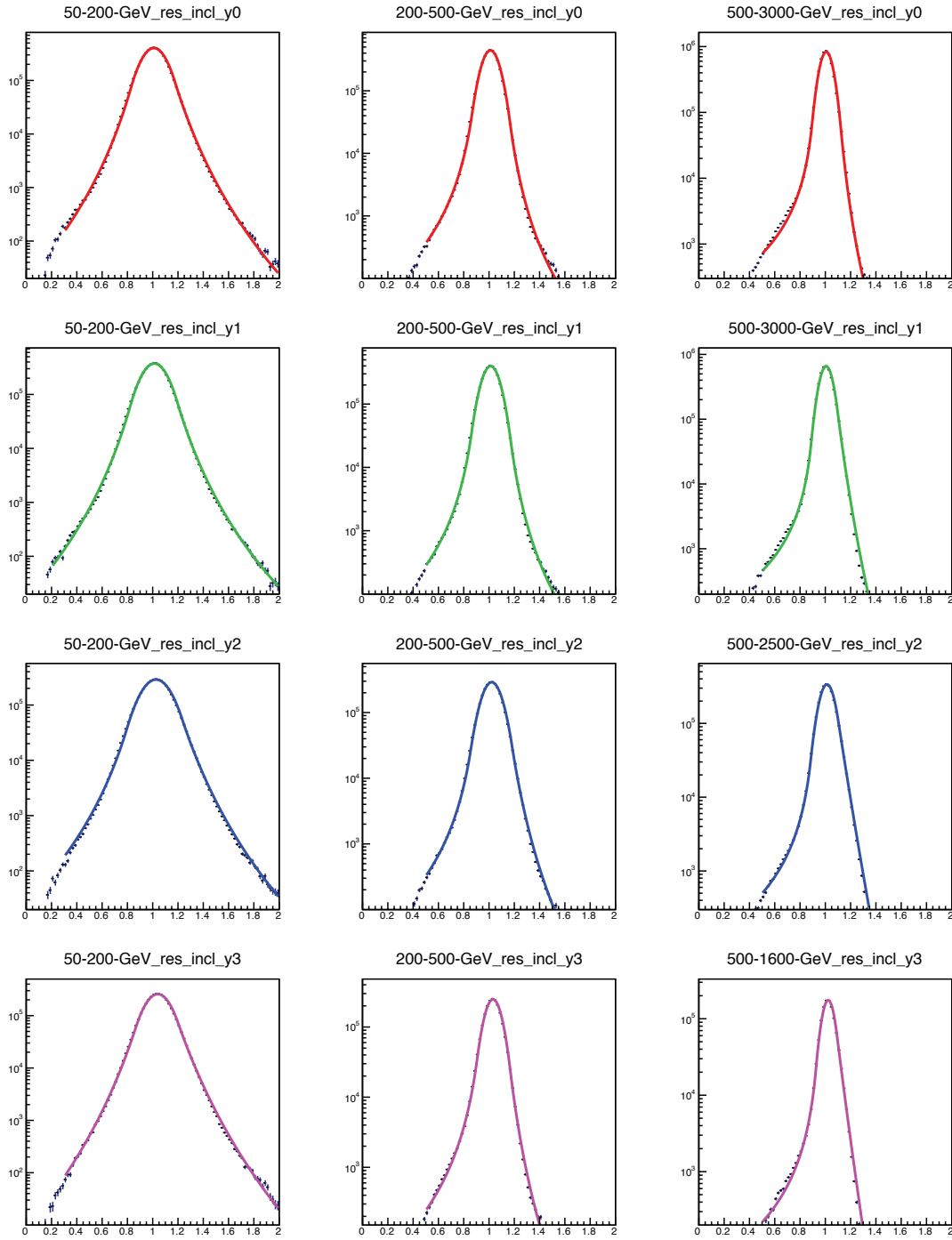


FIGURE 7.11: Jet p_T resolution for AK7 extracted using PYTHIA8 tune CUETM1 slice Monte Carlo and fitted with a double-sided Crystal Ball function. Results are shown for rapidity bins (top to bottom) ($0.0 < |y| < 0.5$), ($0.5 < |y| < 1.0$), ($1.0 < |y| < 1.5$) and ($1.5 < |y| < 2.0$). In each row, the three columns are for three different p_T regions (50-200 GeV, 200-500 GeV, 500-3000 GeV)

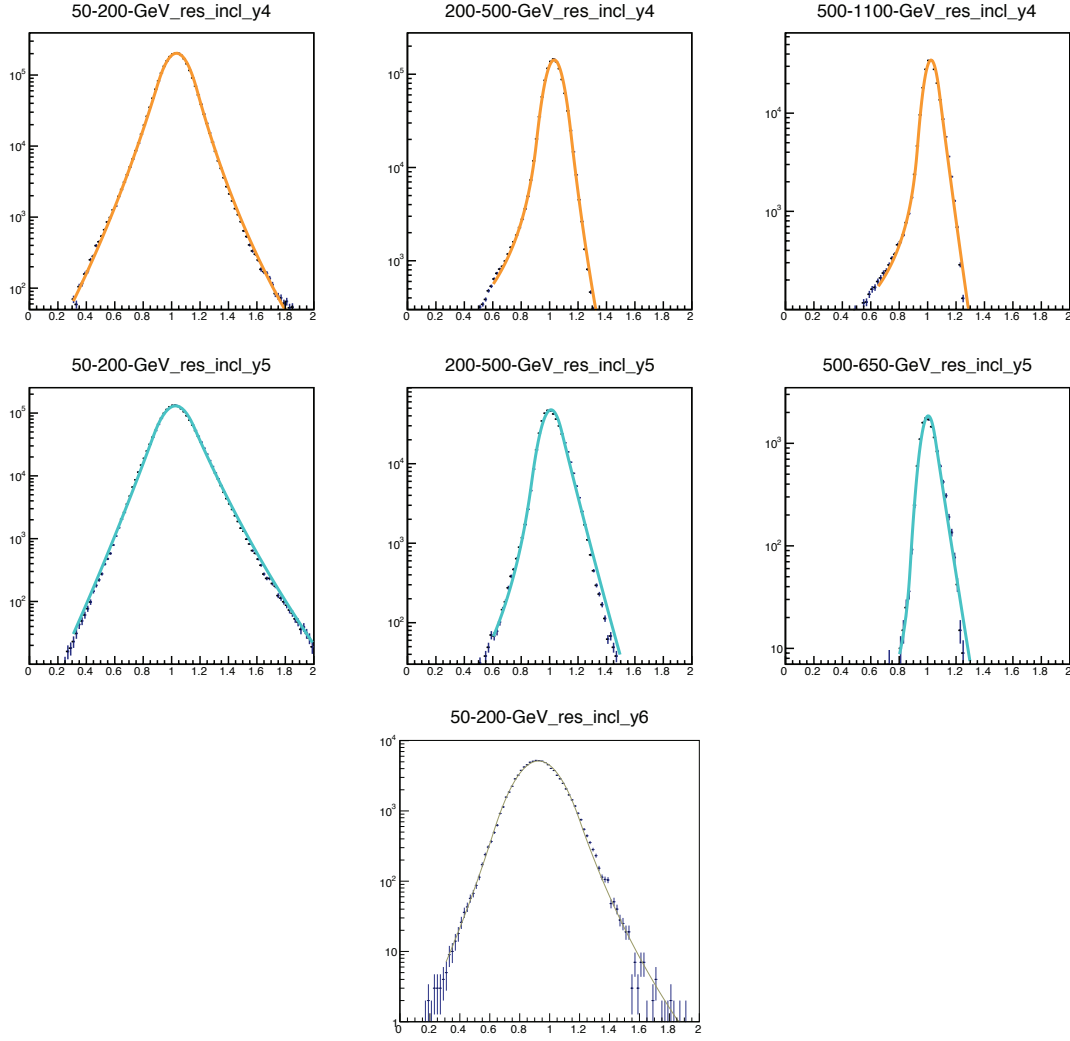


FIGURE 7.12: Jet p_T resolution for AK7 extracted using PYTHIA8 tune CUETM1 slice official CMS MC and fitted with a double-sided Crystal Ball function. Results are shown for rapidity bins (top to bottom) ($2.0 < |y| < 2.5$), ($2.5 < |y| < 3.0$) and ($3.2 < |y| < 4.7$). In each row, the three columns are for three different p_T regions (50-200 GeV, 200-500 GeV, 500-3000 GeV).

Last plot is for 50-200 GeV only

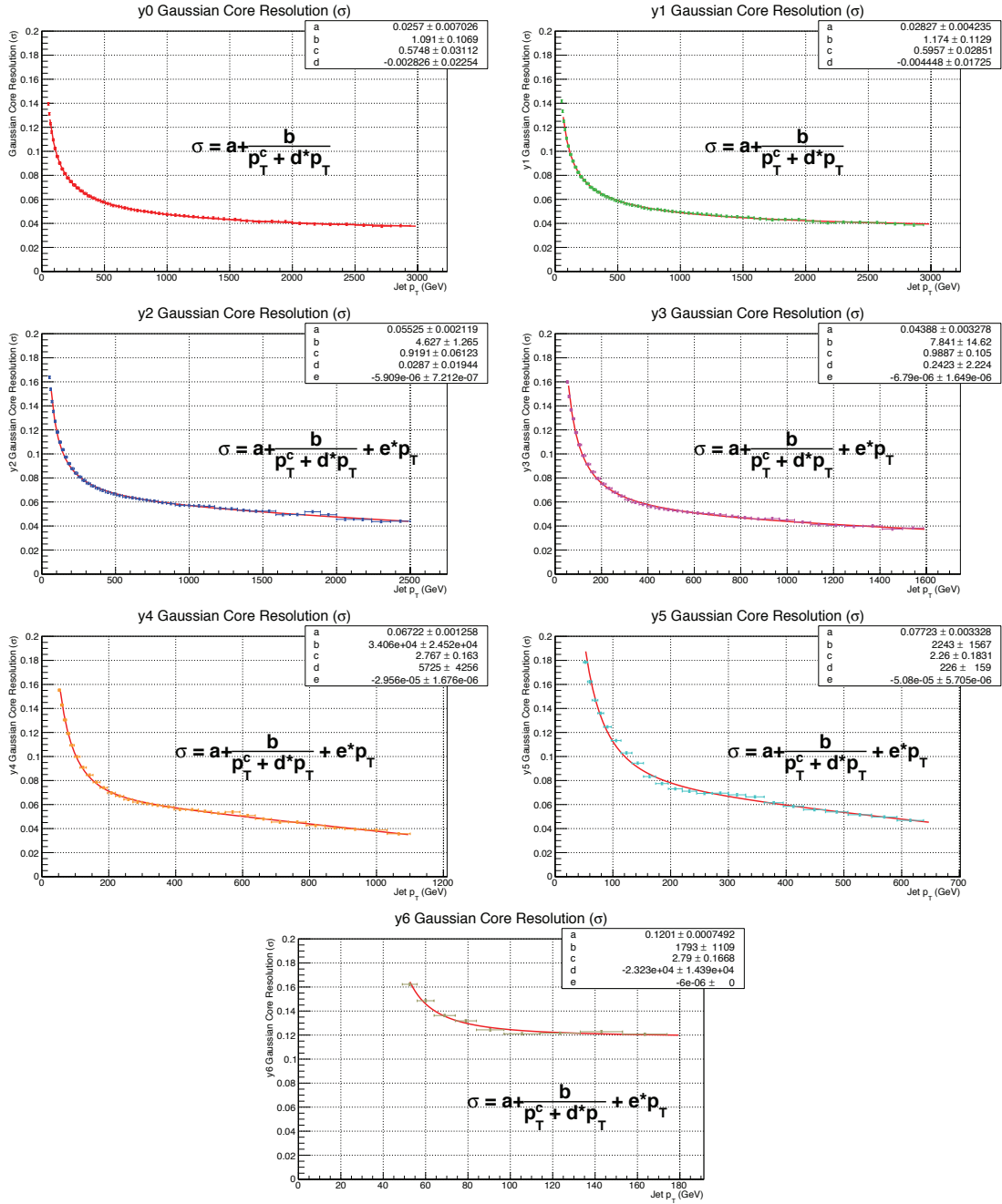


FIGURE 7.13: The p_T resolution for AK7 extracted using PYTHIA8 tune CUETM1 slice Monte Carlo for rapidity bins (top to bottom) $(0.0 < |y| < 0.5)$, $(0.5 < |y| < 1.0)$, $(1.0 < |y| < 1.5)$ and $(1.5 < |y| < 2.0)$, $(2.0 < |y| < 2.5)$, $(2.5 < |y| < 3.0)$ and $(3.2 < |y| < 4.7)$.

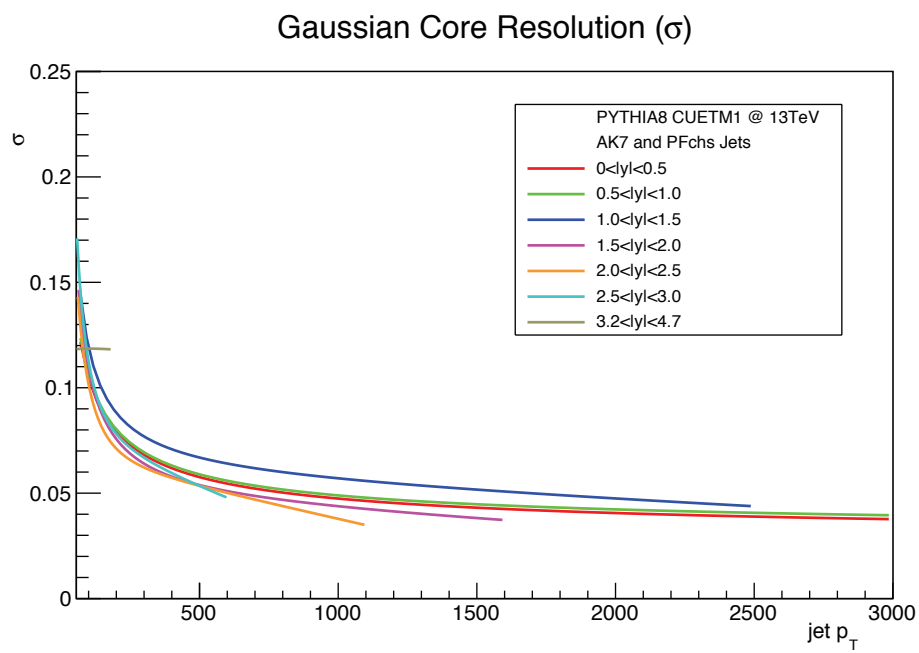


FIGURE 7.14: The p_T resolution for AK7 extracted using PYTHIA8 tune CUETM1 slice Monte Carlo for all rapidity bins.

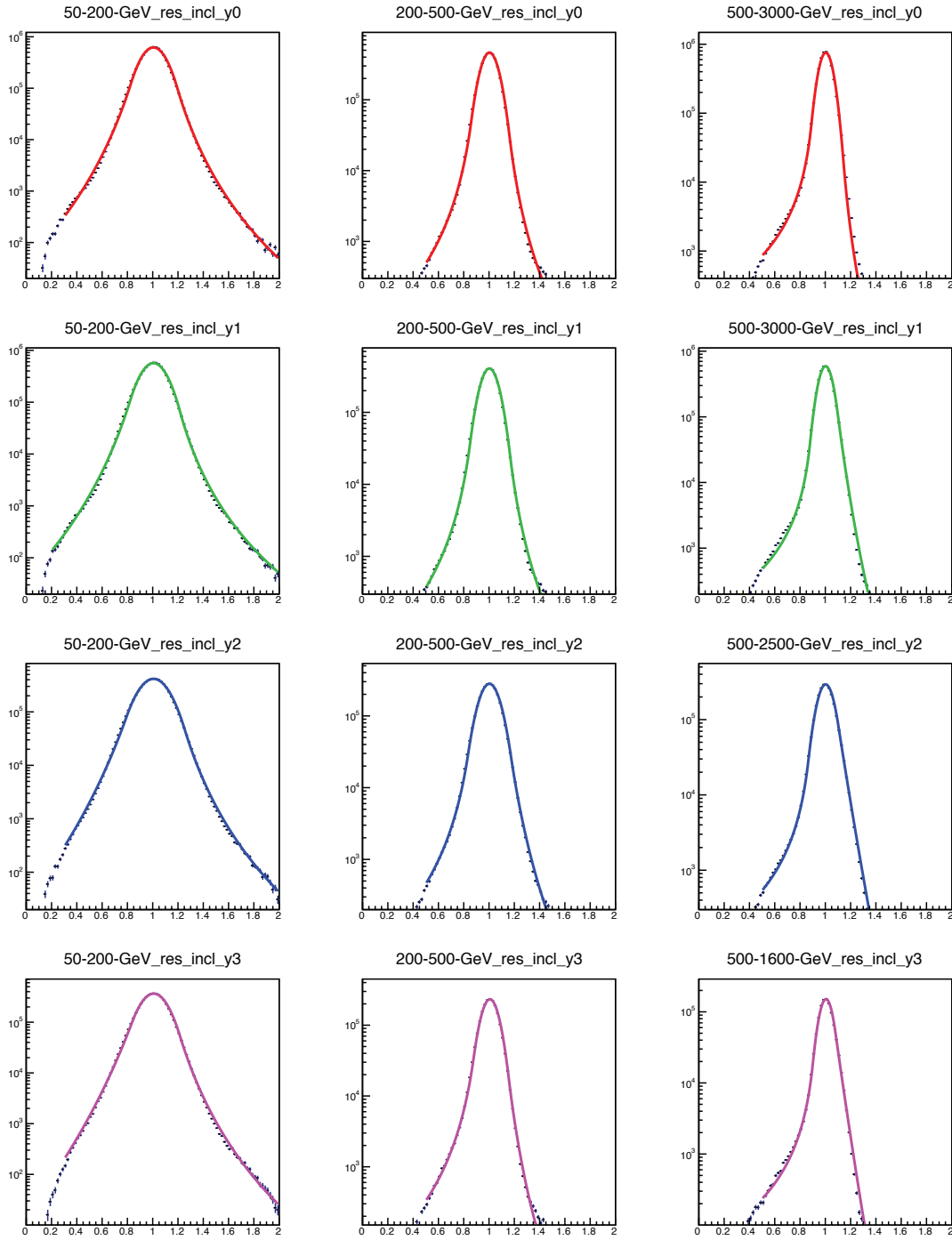


FIGURE 7.15: Jet p_T resolution for AK4 extracted using PYTHIA8 tune CUETM1 slice official CMS MC and fitted with a double-sided Crystal Ball function. Results are shown for rapidity bins (top to bottom) ($0.0 < |y| < 0.5$), ($0.5 < |y| < 1.0$), ($1.0 < |y| < 1.5$) and ($1.5 < |y| < 2.0$). In each row, the three columns are for three different p_T regions (50-200 GeV, 200-500 GeV, 500-3000 GeV)

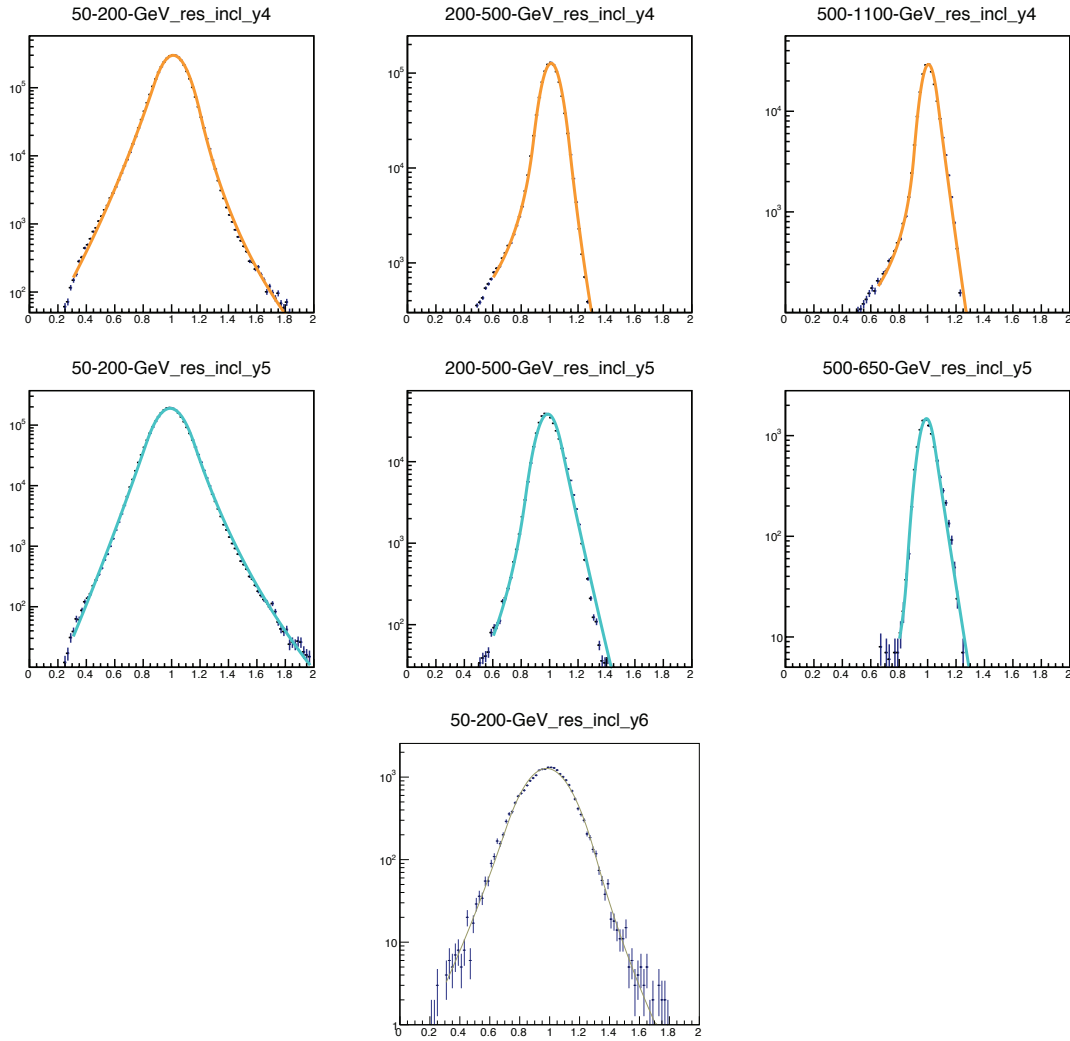


FIGURE 7.16: Jet p_T resolution for AK4 extracted using PYTHIA8 tune CUETM1 slice official CMS MC and fitted with a double-sided Crystal Ball function. Results are shown for rapidity bins (top to bottom) ($2.0 < |y| < 2.5$), ($2.5 < |y| < 3.0$) and ($3.2 < |y| < 4.7$). In each row, the three columns are for three different p_T regions (50-200 GeV, 200-500 GeV, 500-3000 GeV).

Last plot is for 50-200 GeV only

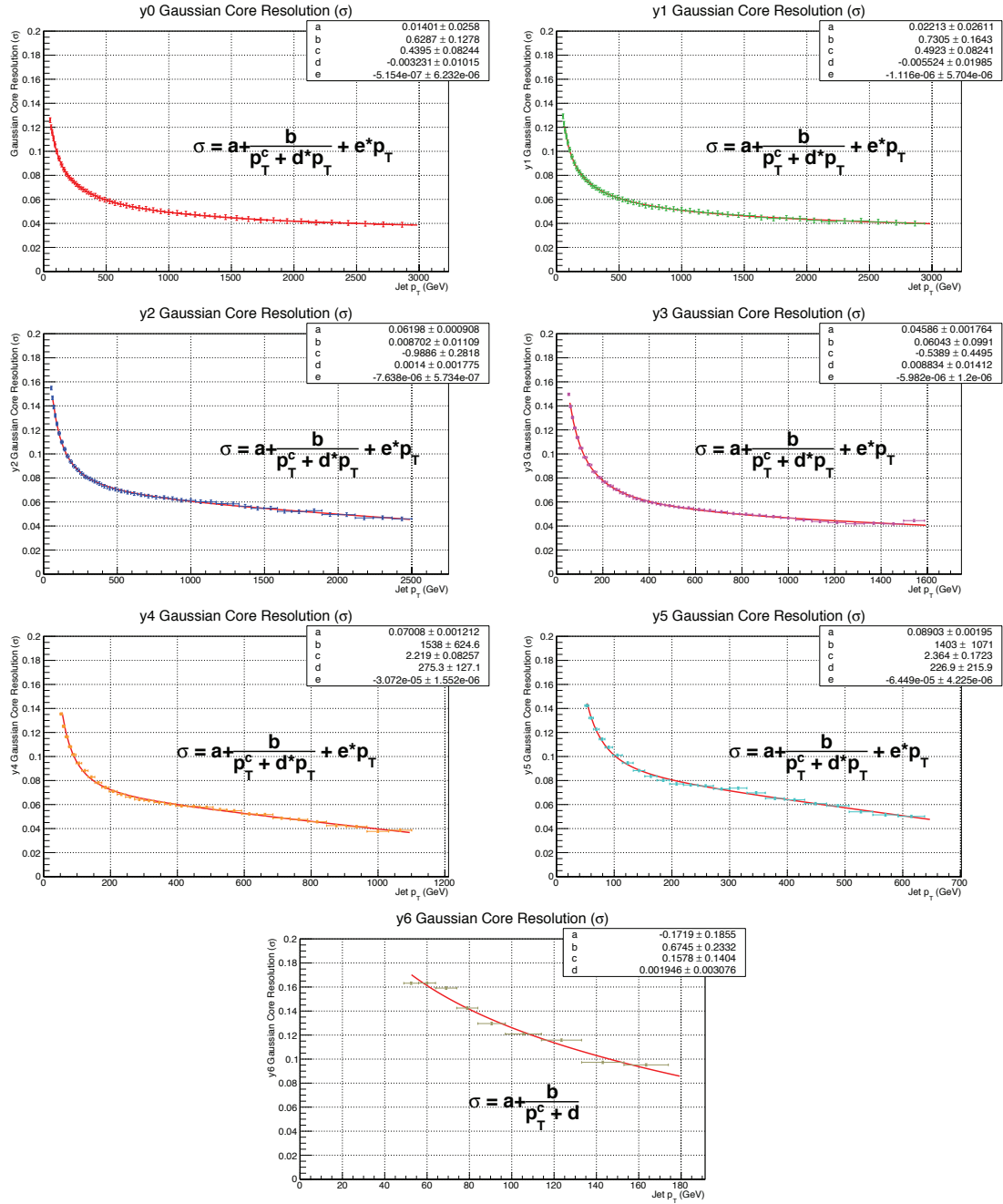


FIGURE 7.17: The p_T resolution for AK4 extracted using PYTHIA8 tune CUETM1 slice Monte Carlo for rapidity bins (top to bottom) $(0.0 < |y| < 0.5)$, $(0.5 < |y| < 1.0)$, $(1.0 < |y| < 1.5)$ and $(1.5 < |y| < 2.0)$, $(2.0 < |y| < 2.5)$, $(2.5 < |y| < 3.0)$ and $(3.2 < |y| < 4.7)$.

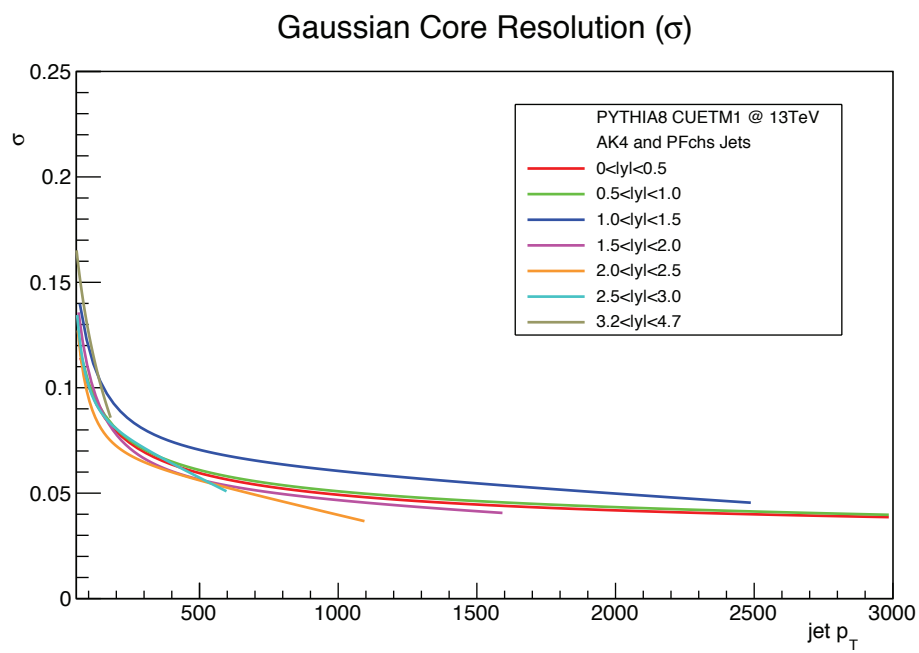


FIGURE 7.18: The p_T resolution for AK4 extracted using PYTHIA8 tune CUETM1 slice Monte Carlo for all rapidity bins.

Chapter 8

Unfolding

The finite detector resolution in jet p_T affects the jet p_T distribution and hence distorts the measured cross-section. To compare results from different experiments and between experiments and theoretical predictions, experimental results need to be corrected for the detector effects. The method which eliminates detector effects and guesses the best possible “true” results is technically unfolding.

The measured cross-sections are corrected for detector smearing effects and unfolded to stable-particle level. The unfolding method used here is the iterative D’Agostini Bayesian method [29] with four iterations, implemented in the RooUnfold software package [4].

Unfolding parametrizes the measurement effects using a response matrix that maps the true distribution onto the measured one. There is an indirect way of constructing the response matrix which uses a custom Toy Monte Carlo by utilizing MC simulation. The method is based on the Forward Smearing. Generation of events using the Toy MC utilizes the following steps:

- Events are generated with flat jet p_T spectrum.
- These events are then weighed by the theoretical cross-section obtained from fastNLO using the CT14 PDF set and are corrected for non-perturbative effects. In this way Toy MC constructs the true jet p_T spectrum.
- The measured cross-sections are generated by smearing the true p_T with it’s resolution presented in Chapter 7 scaled by the values of Table 8.1.
- Using the Toy MC a total of 100M events are generated for each rapidity region. The Toy MC statistics is at least one order of magnitude larger than that in the data, throughout the entire phase space.

Table 8.1 shows the scale factors used to scale JER obtained from PYTHIA 8 CMS MC in Chapter 7. The scale factors of Table 8.1 represent the best knowledge as of October 2015 for the 13 TeV data. This goes in accordance with the recommendations by the Jet-MET group of the CMS Experiment.

8.0.1 Unfolding for cone size $R=0.7$

Figure 8.1 shows the true theoretical cross-section spectra, obtained from fastNLO using the CT14 PDF set, and fitted by a cubic Spline function. The Spline function is used to weight the Toy MC flat p_T spectrum.

The response matrices derived using the Toy MC are shown in figures 8.2 and 8.3. All matrices are exactly diagonal, as expected.

On each plot, the jet cross-section for data at reconstruction level (open circles) and at stable-particle level (solid circles) are shown in Figure 8.4 and Figure 8.5. the ratio between stable-particle level and reconstruction level is shown at the bottom of each plot.

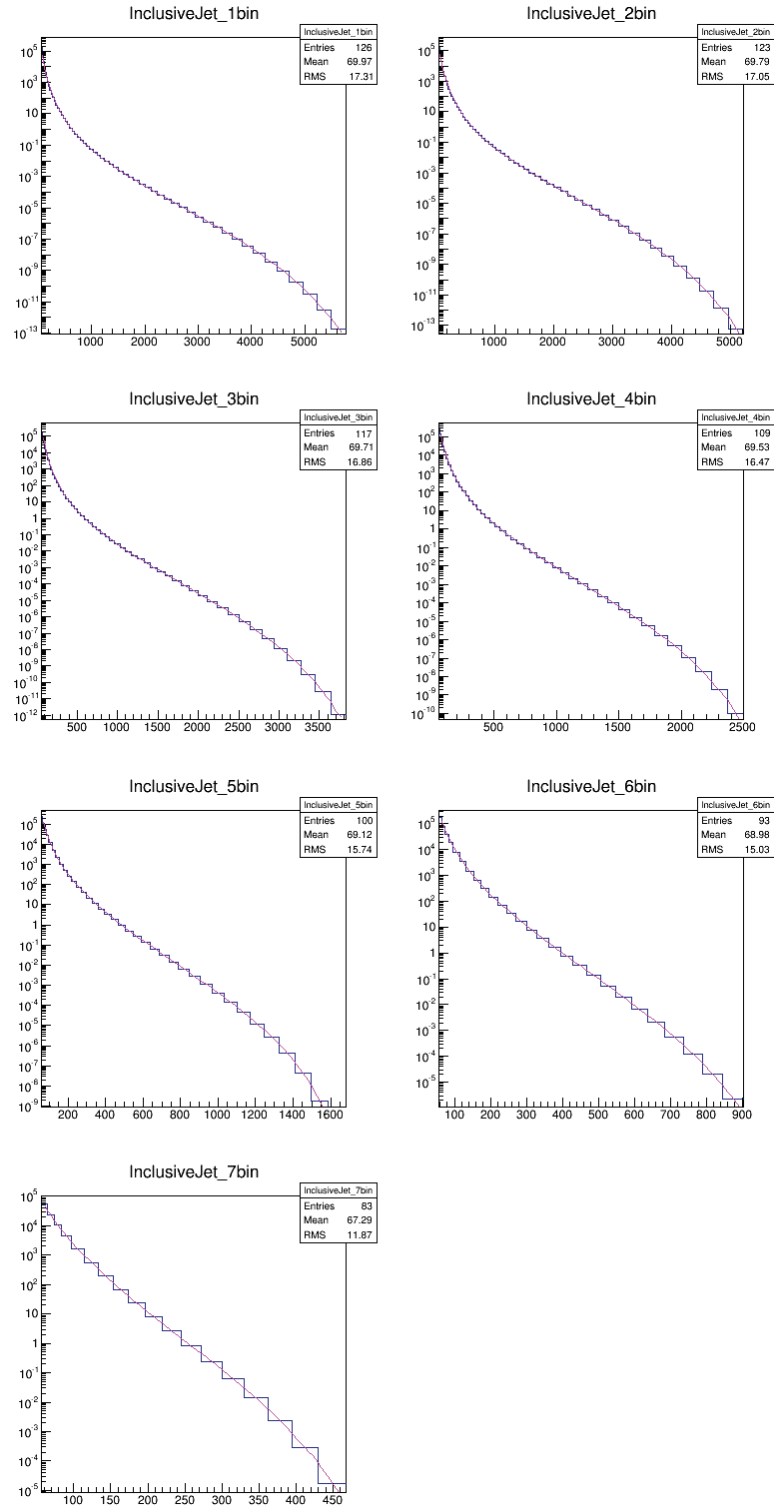


FIGURE 8.1: The true theoretical cross-section spectra for AK7 jets for rapidity bins $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$, obtained from fastNLO using the CT14 PDF set, and fitted with a cubic Spline function.

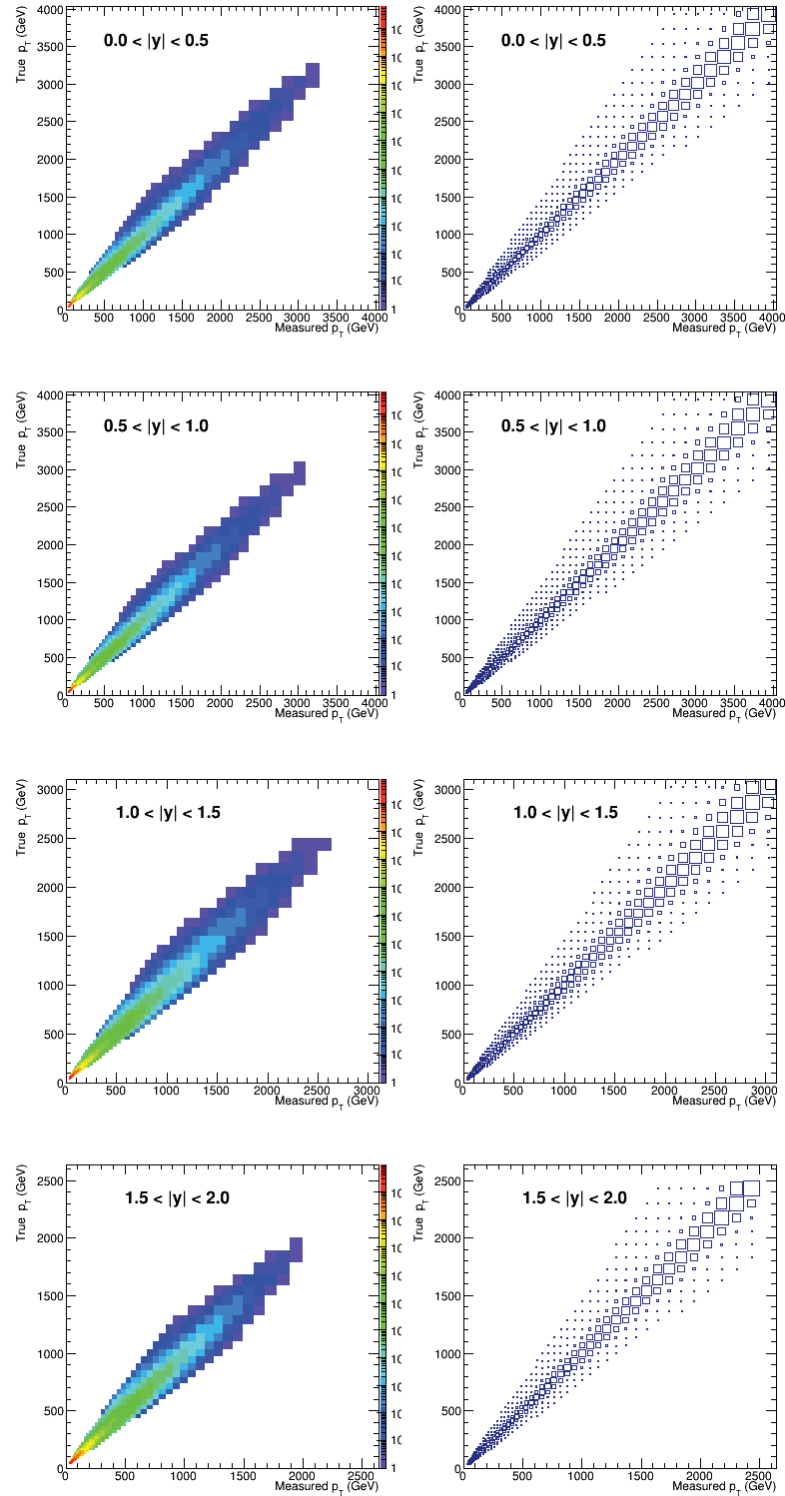


FIGURE 8.2: The response matrices derived using a Toy MC for AK7 jets for $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, and $1.5 < |y| < 2.0$. The two columns show the same plot with different representations

TABLE 8.1: The scale factors for the jet p_T resolution as recommended by the CMS Jet-MET group for 13 TeV data (October 2015).

$ y $	c	c-up	c-down
0.0-0.5	1.086	1.195	0.977
0.5-1.1	1.128	1.241	1.015
1.1-1.7	1.143	1.257	1.029
1.7-2.3	1.109	1.220	0.998
2.3-2.8	1.254	1.379	1.128
2.8-3.2	1.395	1.535	1.256
3.2-5.0	1.056	1.247	0.865

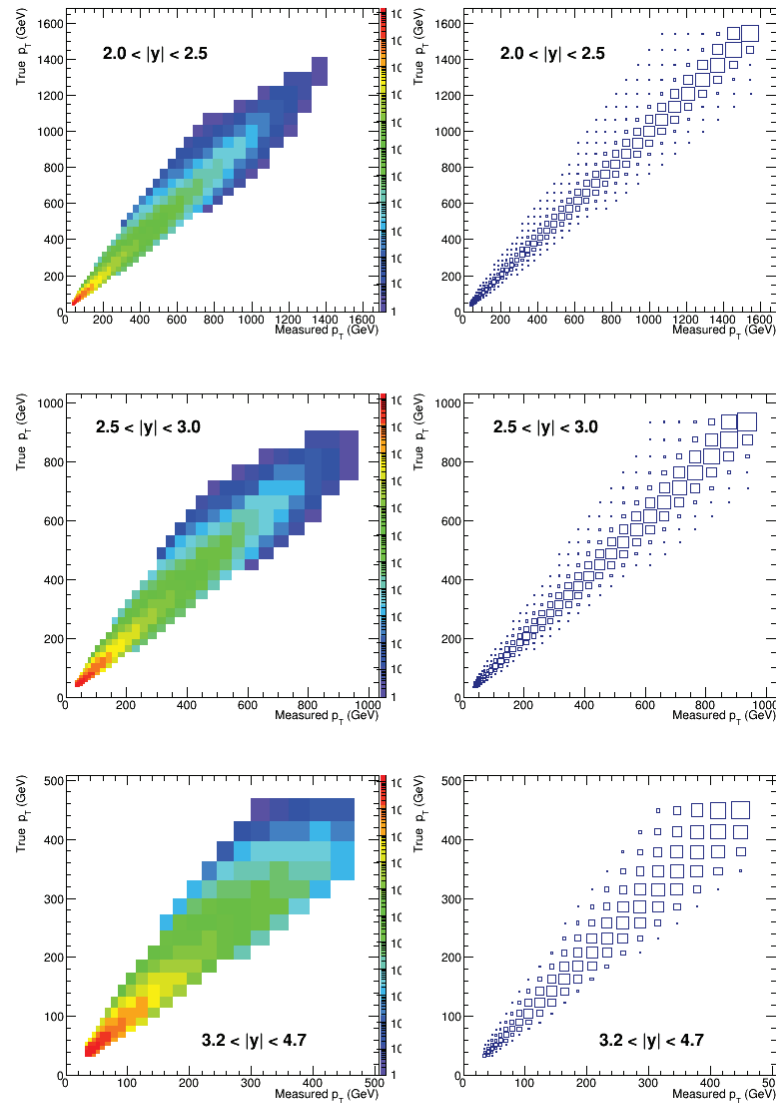


FIGURE 8.3: The response matrices derived using a Toy MC for AK7 jets for $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$. The two columns show the same plot with different representations

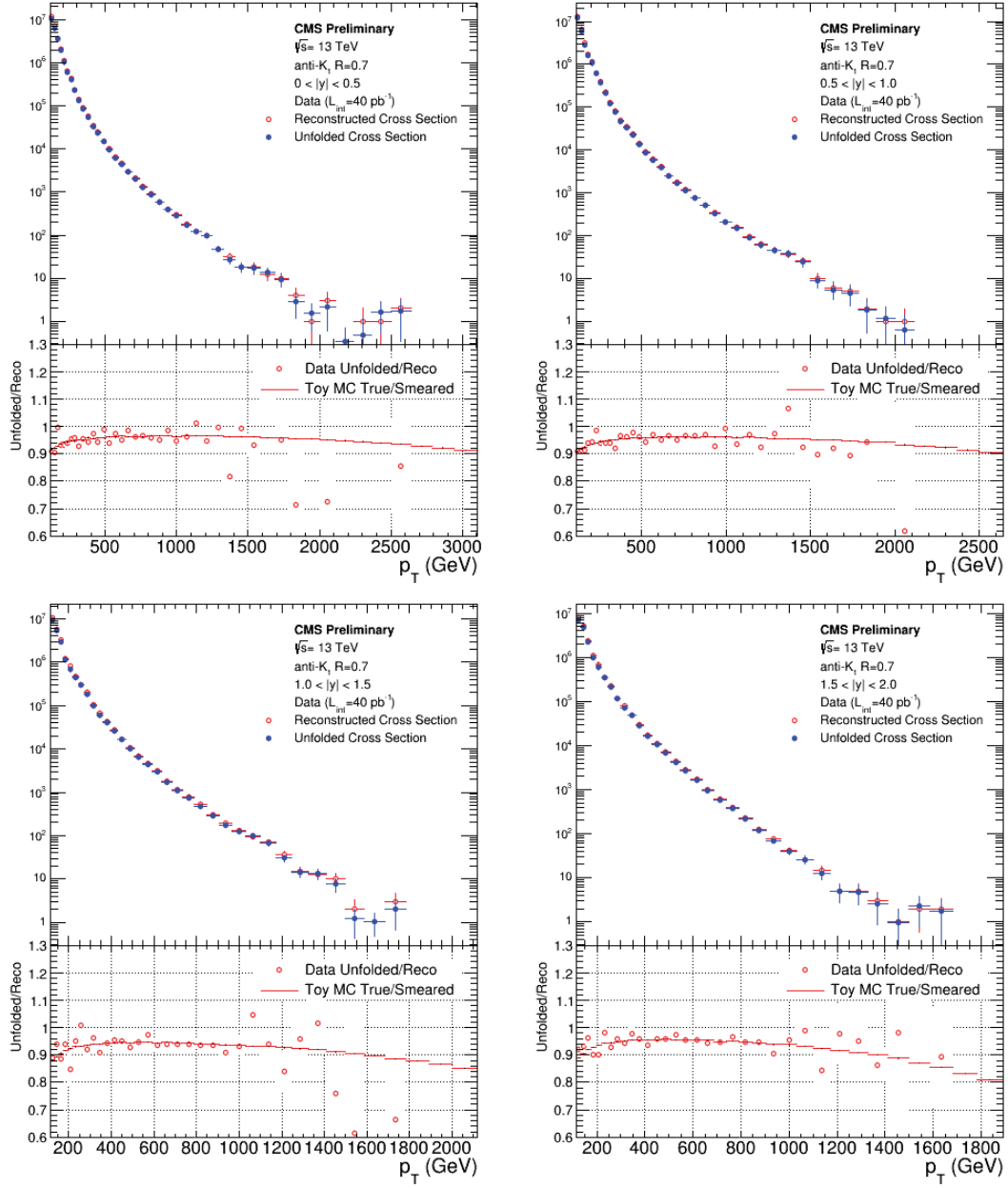


FIGURE 8.4: The jet cross-sections for AK7 jets for data at reconstruction (detector) level (open circles) and at stable-particle level (solid circles) and for rapidity bins $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$ and $1.5 < |y| < 2.0$. Ratios between stable-particle level and reconstruction level are shown at the bottom part of each plot.

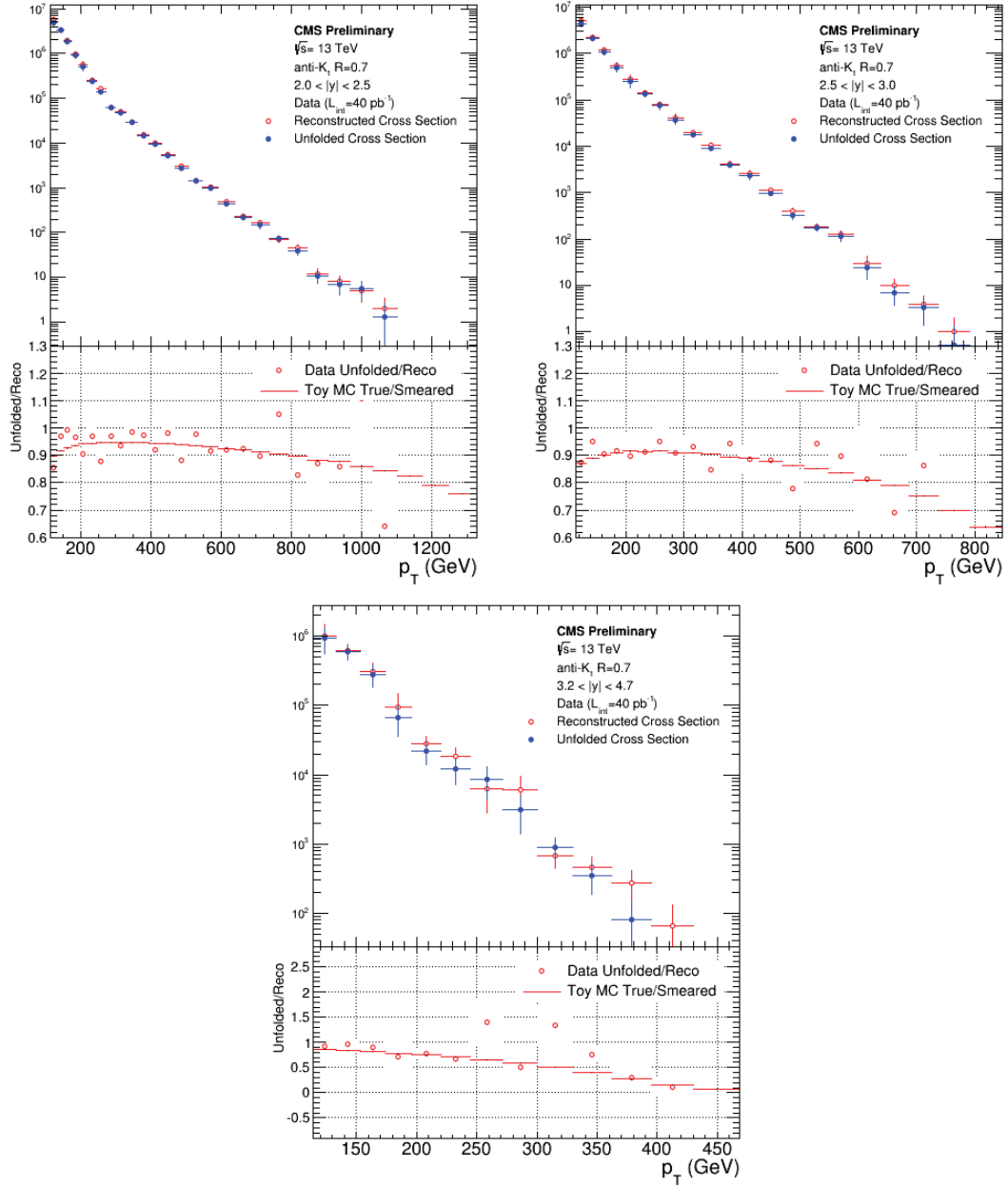


FIGURE 8.5: The jet cross-sections for AK7 jets for data at reconstruction (detector) level (open circles) and at stable-particle level (solid circles) and for rapidity bins $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$. Ratios between stable-particle level and reconstruction level are shown at the bottom part of each plot.

Figure 8.6 shows the fractional statistical errors for the unfolded and the measured inclusive jet cross-section. Errors after unfolding are slightly larger as expected.

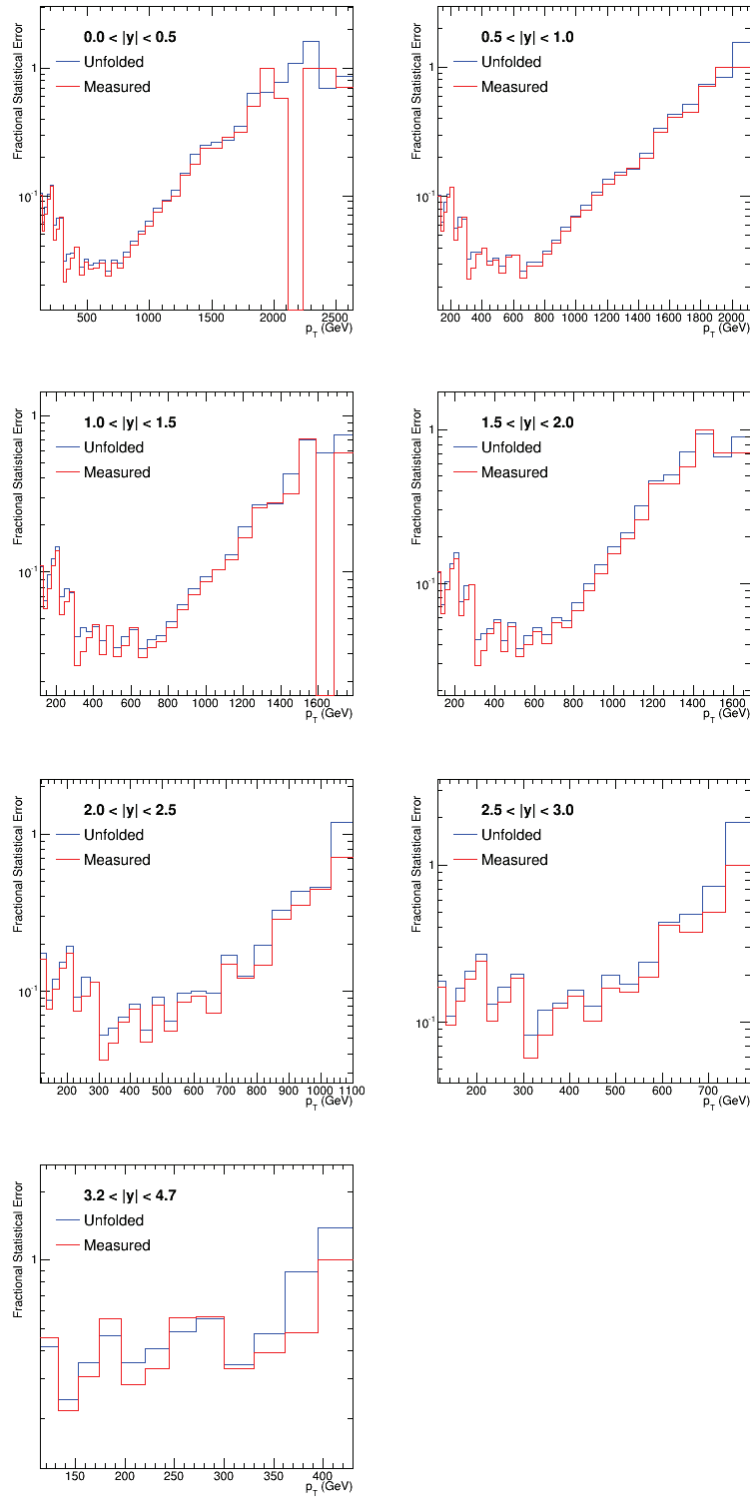


FIGURE 8.6: The fractional statistical errors for AK7 jets for the unfolded and the measured inclusive jet cross-section. The total rapidity range is divided in different bins, namely $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$.

8.0.2 Unfolding for cone size $R=0.4$

We have also studied unfolding for AK4 jets. Figure 8.7 shows the true theoretical cross-section spectra for AK4 jets, obtained from fastNLO using the CT14 PDF set, and fitted by a cubic Spline function as before. The Spline function is used to weight the Toy MC flat p_T spectrum.

Response matrices derived using the Toy MC are shown in figures 8.8 and 8.9 for AK4 jets. All the matrices are exactly diagonal, as expected.

Figure 8.10 and Figure 8.11 shows, on the top of each plot, the jet cross-section for data at reconstruction (detector) level (open circles) and at stable-particle level (solid circles). In each plot at the bottom it is shown the ratio between stable-particle level and reconstruction level.

Figure 8.12 shows, the fractional statistical errors for the unfolded and the measured inclusive jet cross-section. As expected errors after unfolding are slightly larger than those for AK7 jets.

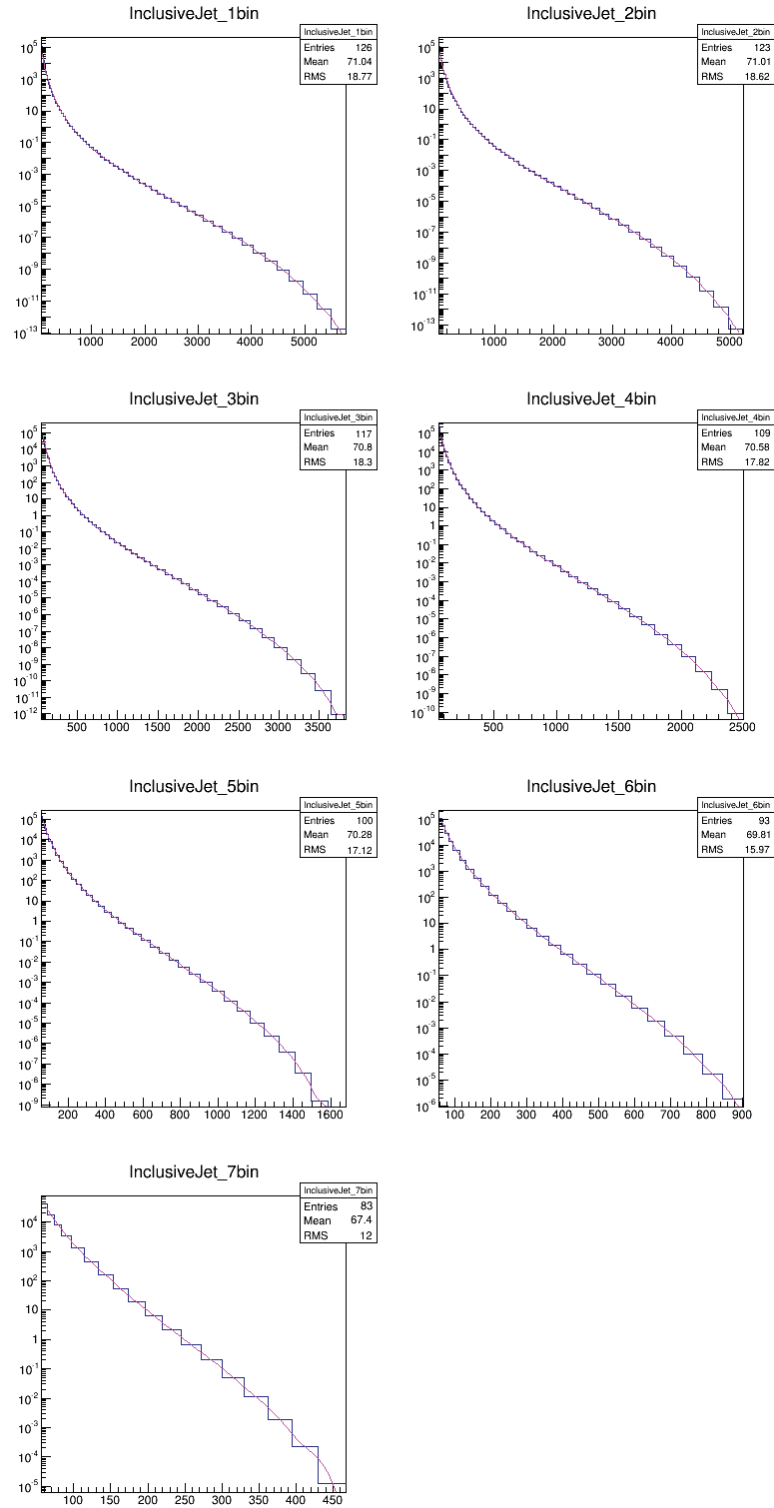


FIGURE 8.7: The true theoretical cross-section spectra for AK4 jets for rapidity bins $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$, obtained from fastNLO using the CT14 PDF set, and fitted by a cubic Spline function.

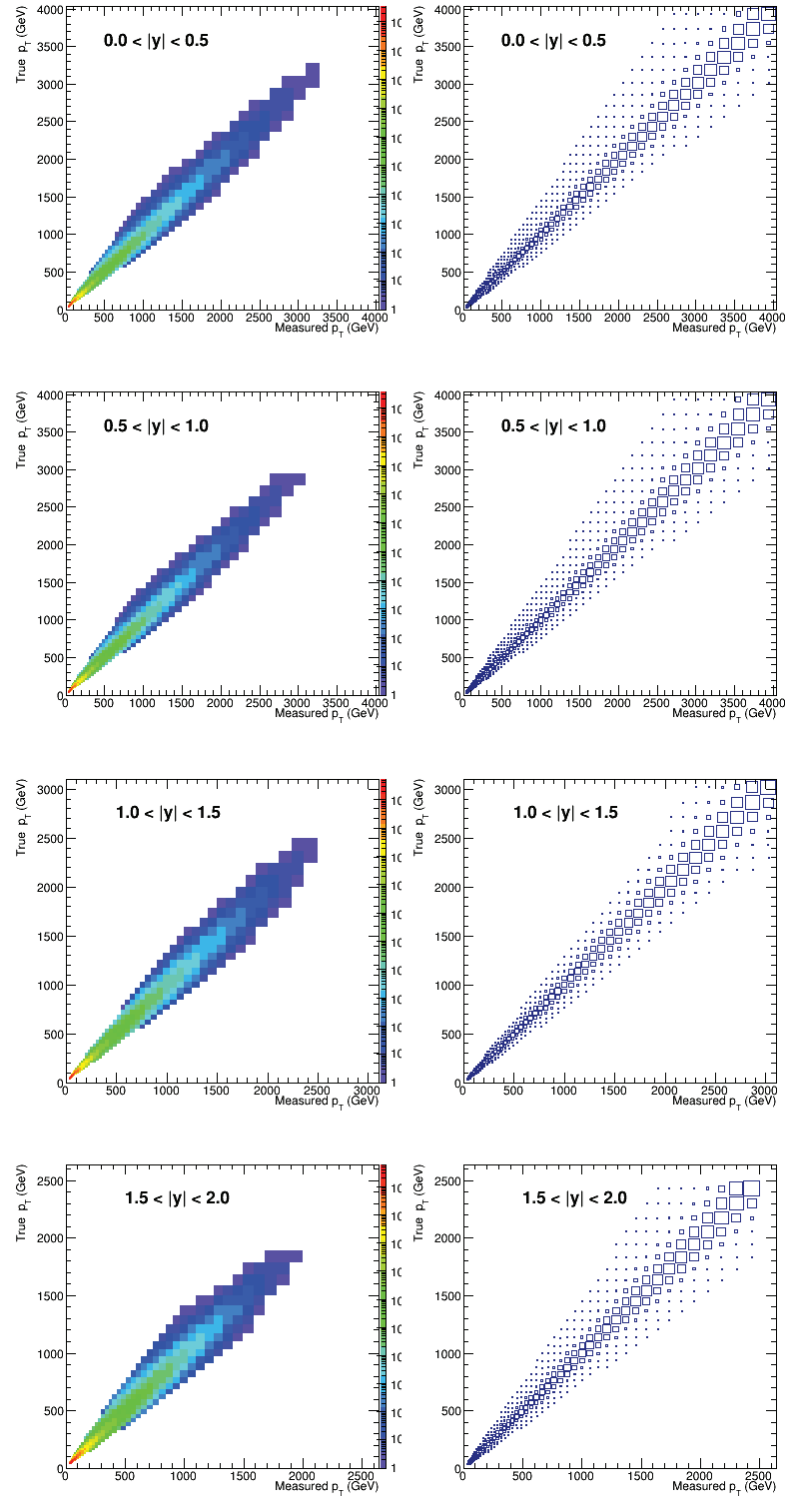


FIGURE 8.8: The response matrices derived using a Toy MC for AK4 jets for $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, and $1.5 < |y| < 2.0$. The two columns show the same plot with different representations

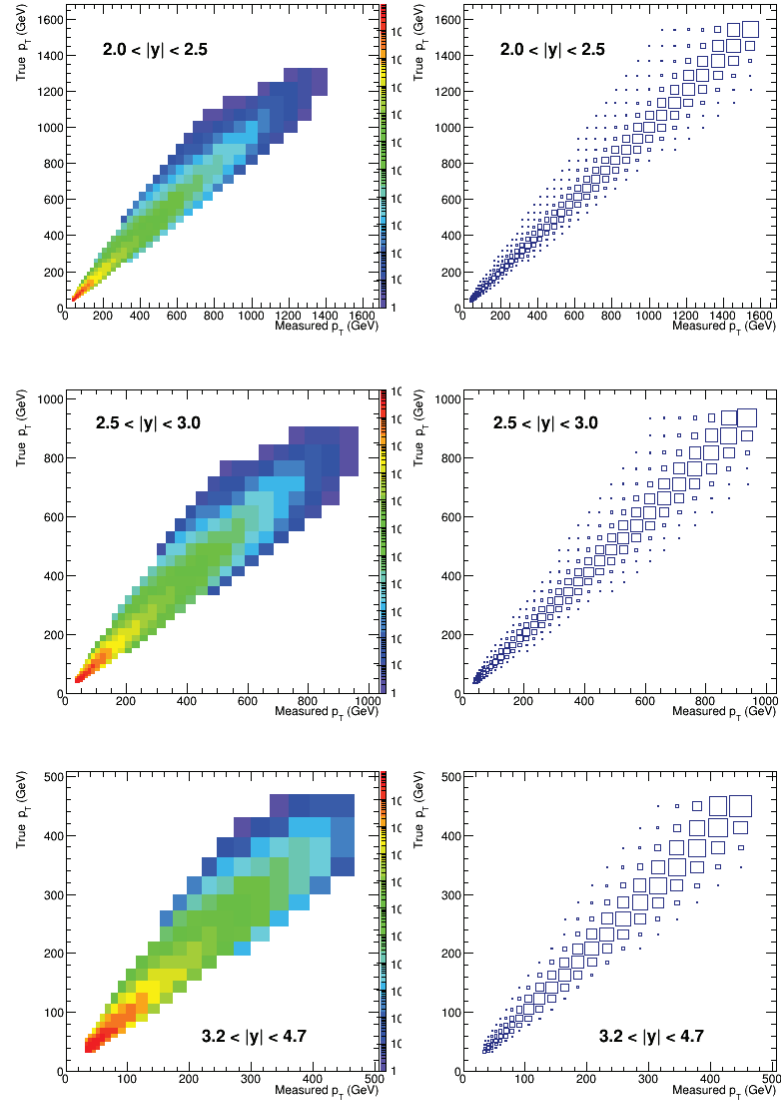


FIGURE 8.9: The response matrices derived using a Toy MC for AK4 jets for $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$. The two columns show the same plot with different representations

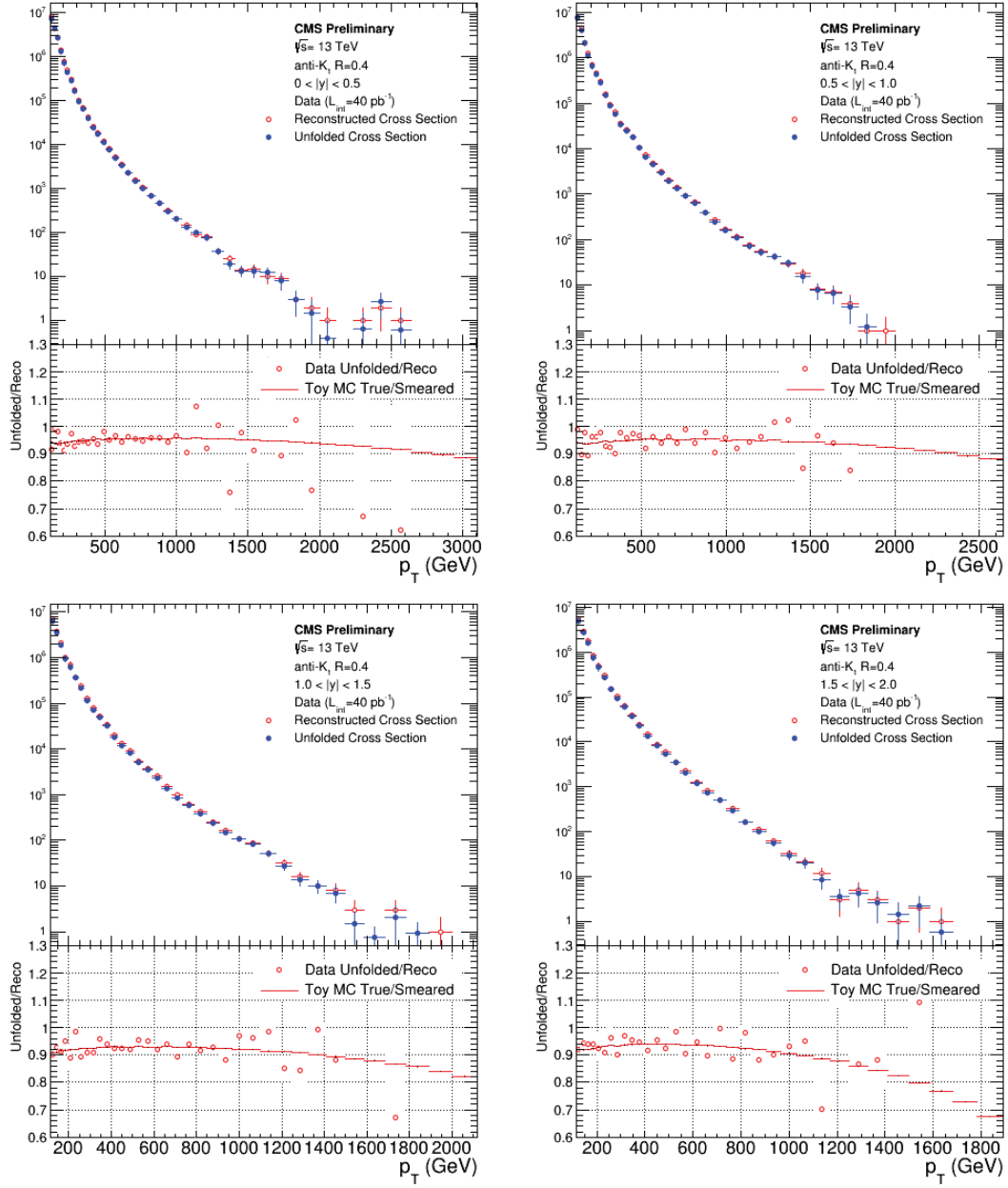


FIGURE 8.10: The jet cross-sections for AK4 jets for data at reconstruction (detector) level (open circles) and at stable-particle level (solid circles) and for rapidity bins $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$ and $1.5 < |y| < 2.0$. Ratios between stable-particle level and reconstruction level are shown at the bottom part of each plot.

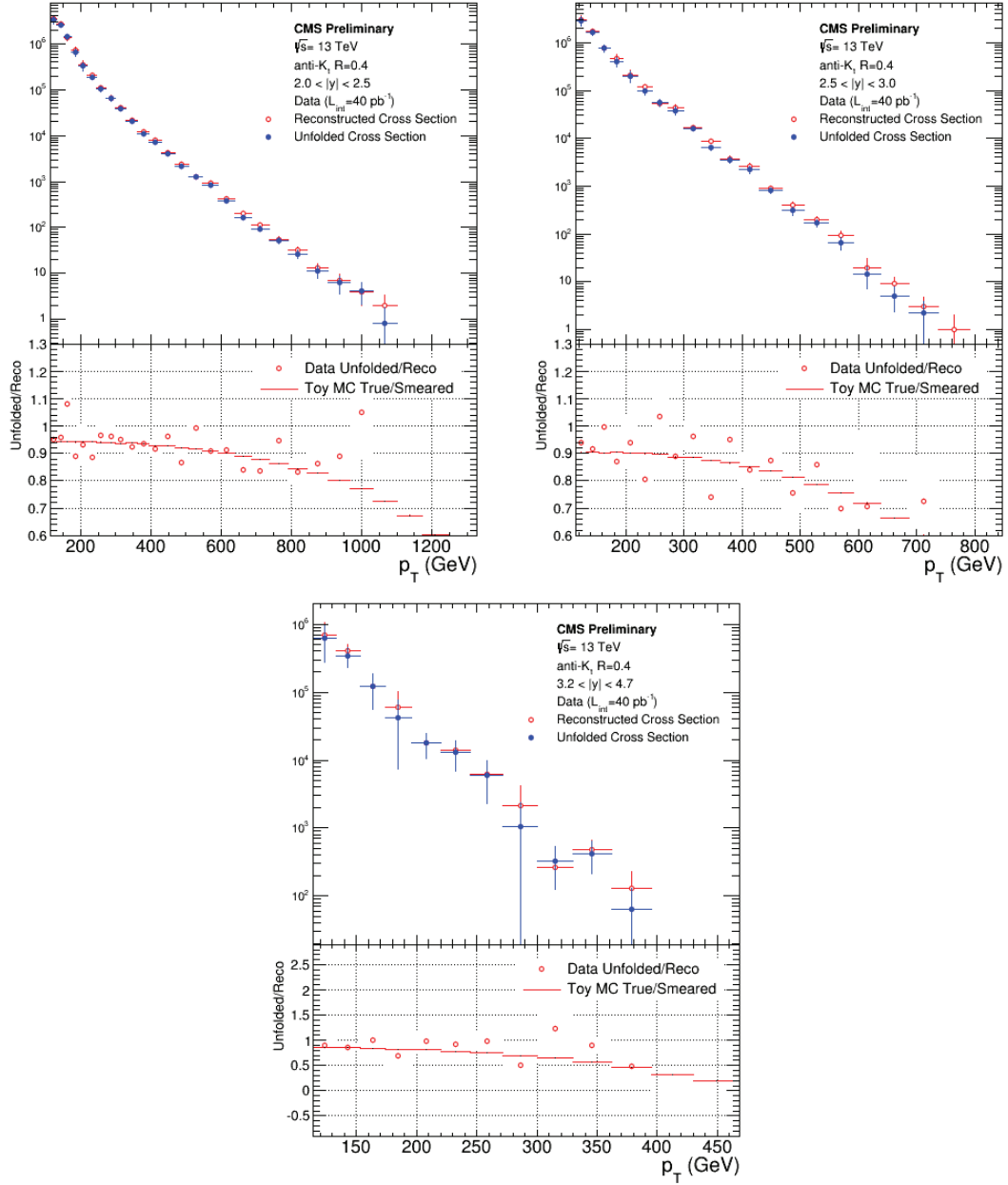


FIGURE 8.11: The jet cross-sections for AK4 jets for data at reconstruction (detector) level (open circles) and at stable-particle level (solid circles) and for rapidity bins $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$. Ratios between stable-particle level and reconstruction level are shown at the bottom part of each plot.

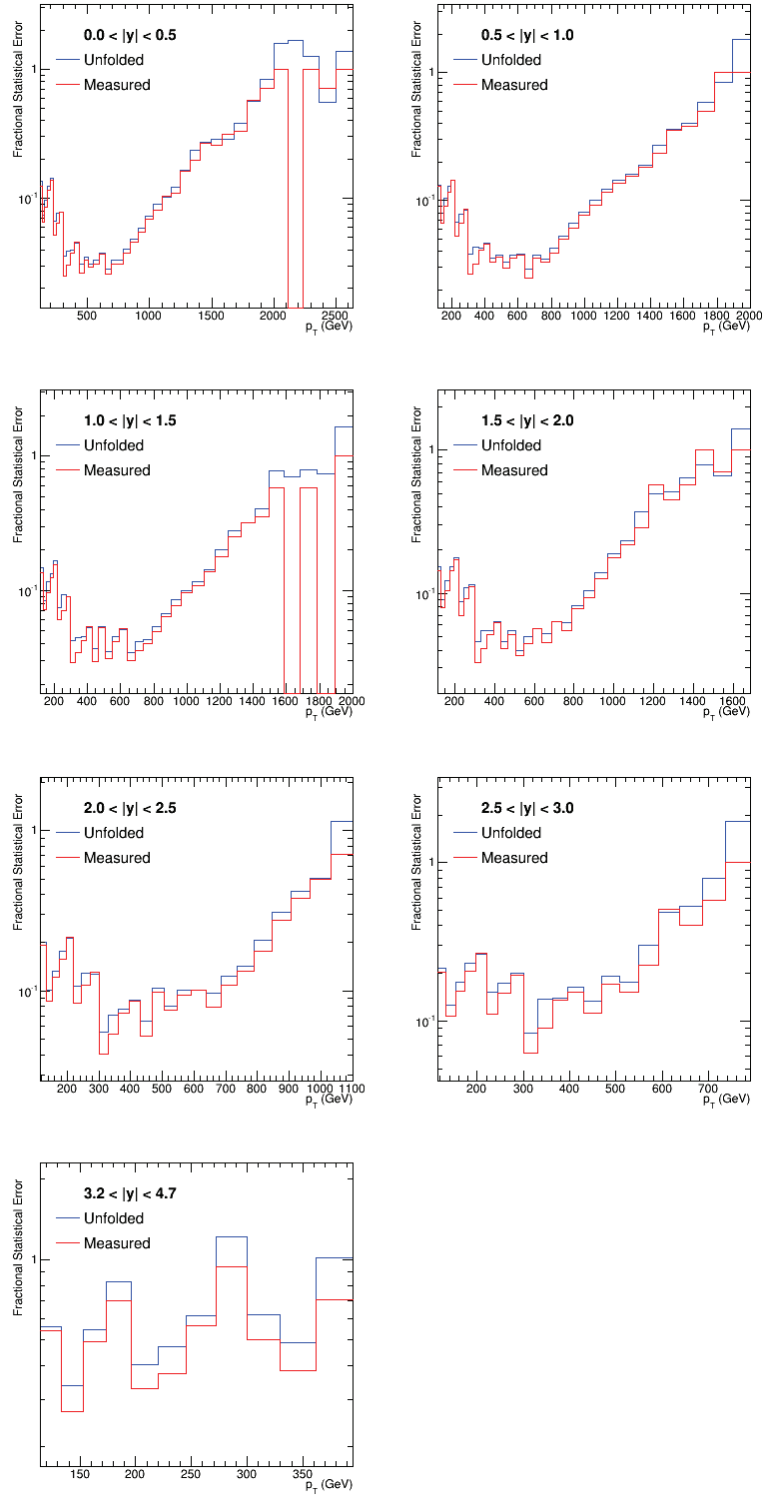


FIGURE 8.12: The fractional statistical errors for AK4 jets for the unfolded and the measured inclusive jet cross-section. The total rapidity range is divided in different bins, namely $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$.

8.0.3 A closure test

A closure test is performed in order to check the tools used. The test is done using as input to the unfolding the smeared Toy MC jet cross-section distributions. The output “true” distributions are then compared to the Toy MC true jet cross-section distributions.

Figure 8.13 shows, at the top of each plot, the jet cross-section for the various rapidity bins, both for the Toy MC unsmeared original spectra (open circles) and for the unfolded spectra (solid circles). At the bottom of each plot the ratio between unsmeared original spectra and unfolded spectra is shown. This distribution is perfectly flat with the mean value at one. This demonstrates the validity of the tools used.

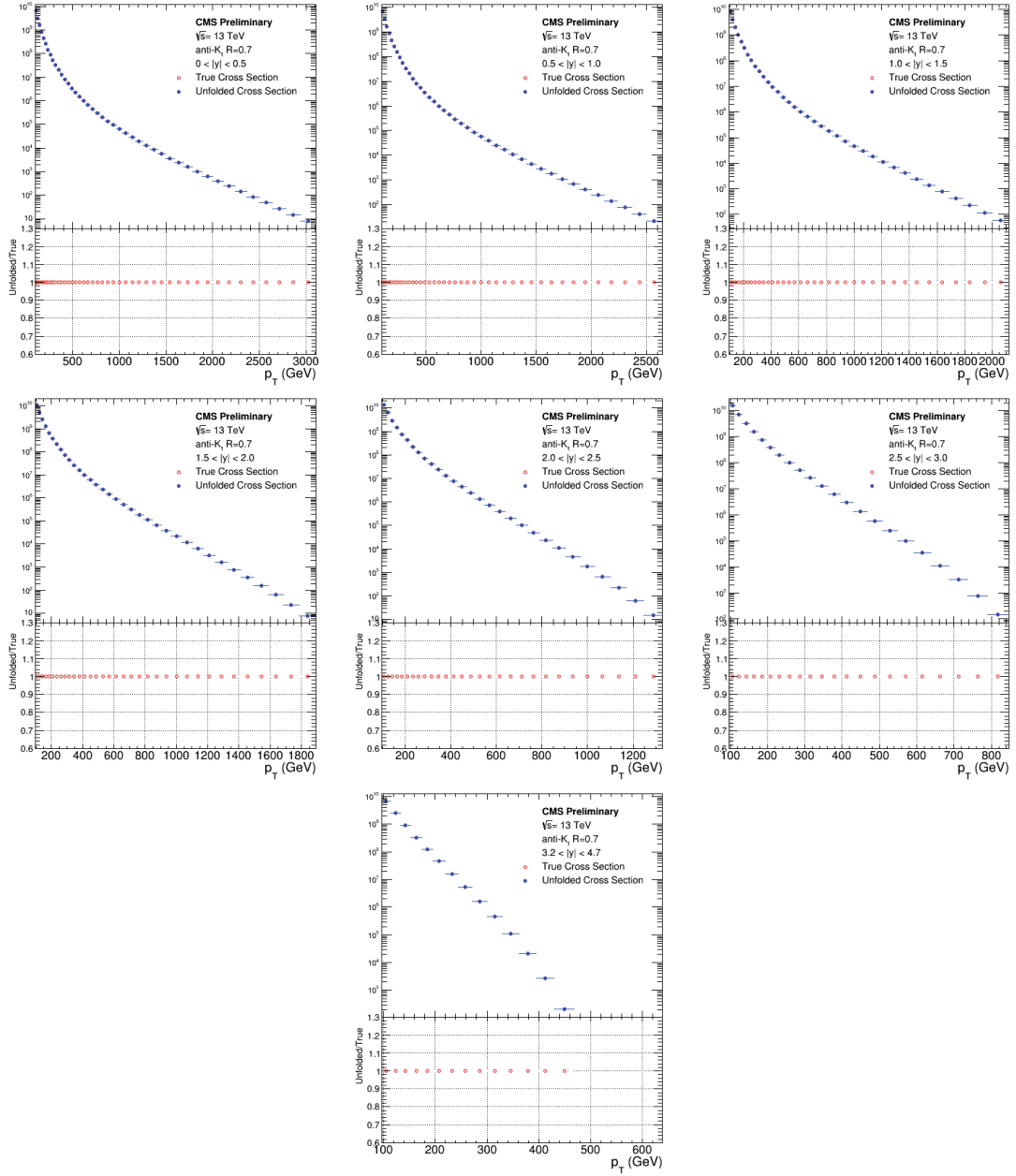


FIGURE 8.13: The AK7 jet cross-section (top of each plot) for rapidity bins $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$, for the Toy MC unsmeared original spectra (open circles) and for the unfolded spectra (solid circles). Ratios between unsmeared original spectra and unfolded spectra are shown at the bottom part of each plot.

TABLE 8.2: The cross-section systematic uncertainty introduced by JER uncertainty through the unfolding procedure.

$ y $	AK7 Jets	AK4 jets
0.0-0.5	1%	1%
0.5-1.1	1%	1%
1.1-1.7	1%	1%
1.7-2.3	1%	1%
2.3-2.8	1%	1.5%
2.8-3.2	1.5%	2%
3.2-5.0	2%	2%

8.0.4 Systematics due to Jet Energy Resolution(JER)

The jet energy resolution (JER) uncertainty affects the unfolding process and introduces an uncertainty on the cross-section measurement. Table 8.1 shows the scale factors (second column) which are used to scale JER obtained from PYTHIA 8 official CMS MC in Chapter 7. The scale factors of Table 8.1 do have an up and a down value (third and fourth columns) which correspond to JER uncertainty. The unfolding procedure is repeated by using the c-up and the c-down values of Table 8.1. The new spectra are then compared to the spectra with the nominal value of JER.

Figure 8.14 and Figure 8.15 show the jet unfolded spectra (top of each plot) for AK7 jets using the nominal, the c-up and the c-down values for JER from Table 8.1. At the bottom of each plot, two ratios are shown. One is the ratio between $|\text{JER-up}|$ and $|\text{JER Nominal}|$, while the other one is between $|\text{JER-down}|$ and $|\text{JER Nominal}|$. They show the effect of JER uncertainty in the measurement of the cross-section. Figure 8.16 and Figure 8.17 show the same for AK4.

Table 8.2 presents systematic uncertainty on cross-section introduced by JER uncertainty through the unfolding procedure for AK7 and AK4.

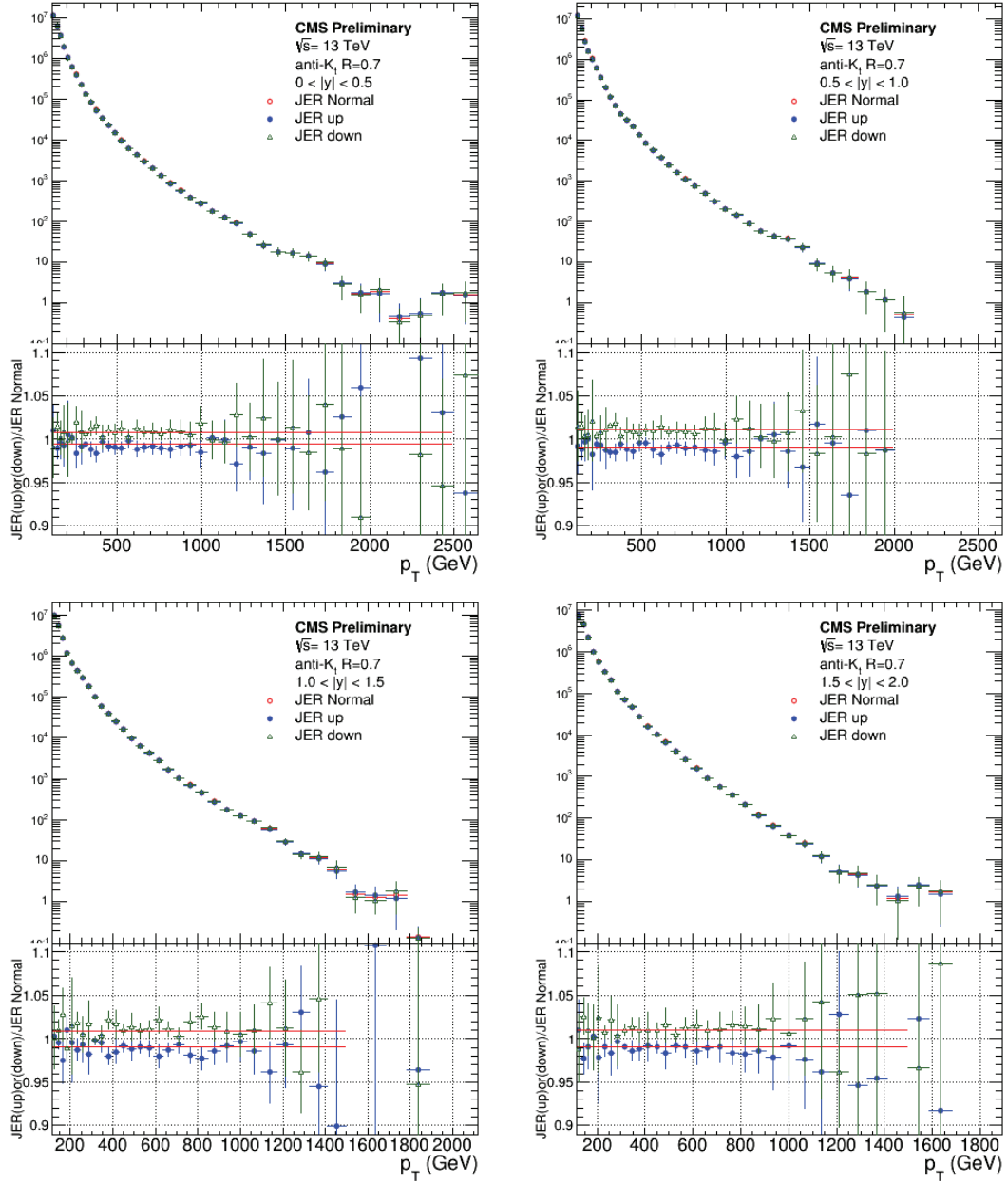


FIGURE 8.14: The jet unfolded spectra for AK7 jets (top of each plot) using the nominal, the c-up and the c-down values for JER. The ratio between $|JER-up|$ and $|JER Normal|$ and ratio between $|JER-down|/|JER Normal|$ are at the bottom of each plot. The rapidity regions are $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, and $1.5 < |y| < 2.0$

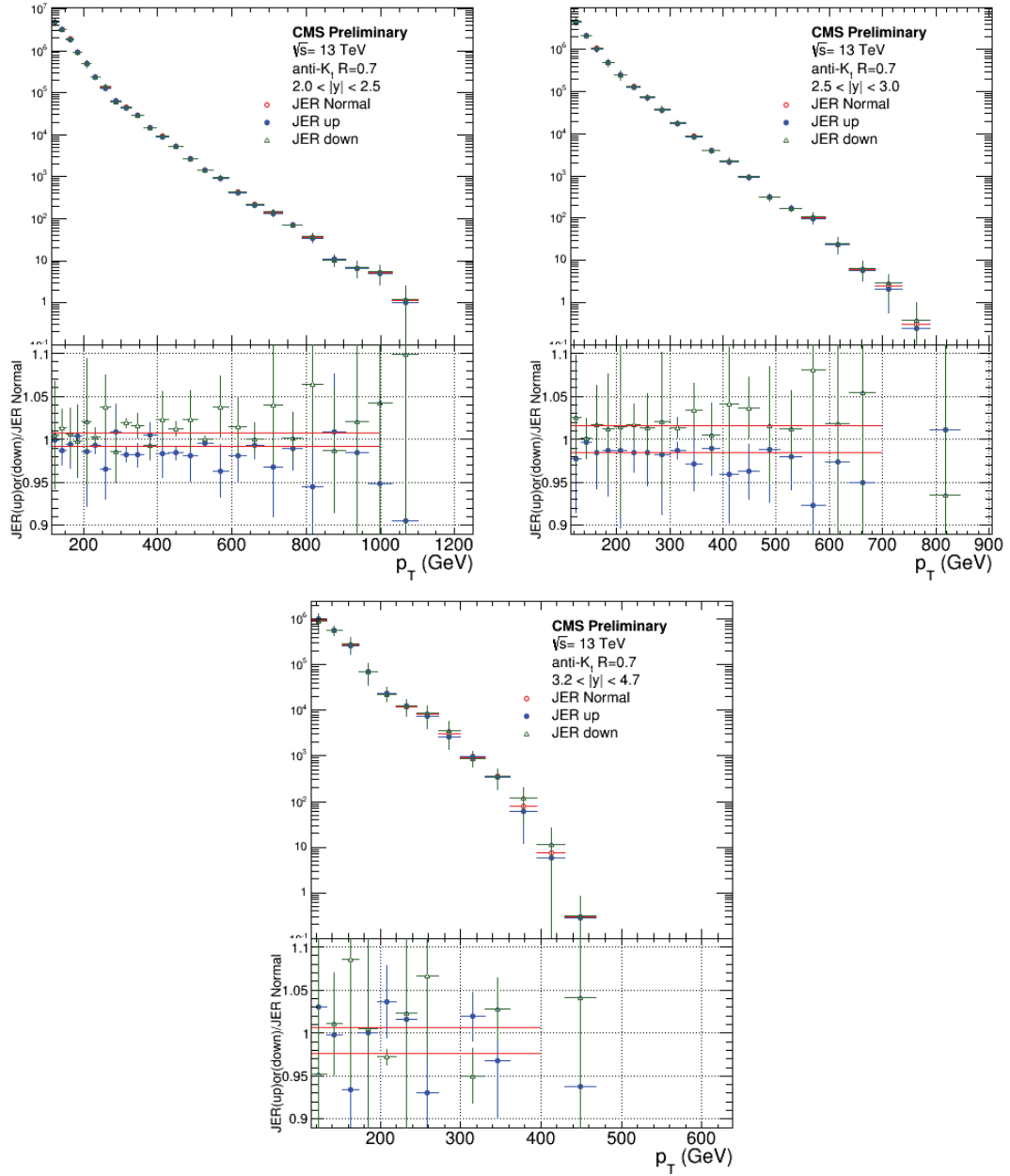


FIGURE 8.15: The jet unfolded spectra for AK7 jets (top of each plot) using the nominal, the c-up and the c-down values for JER. The ratio between $|JER-up|$ and $|JER Normal|$ and ratio between $|JER-down|/|JER Normal|$ are at the bottom of each plot. The rapidity regions are $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$

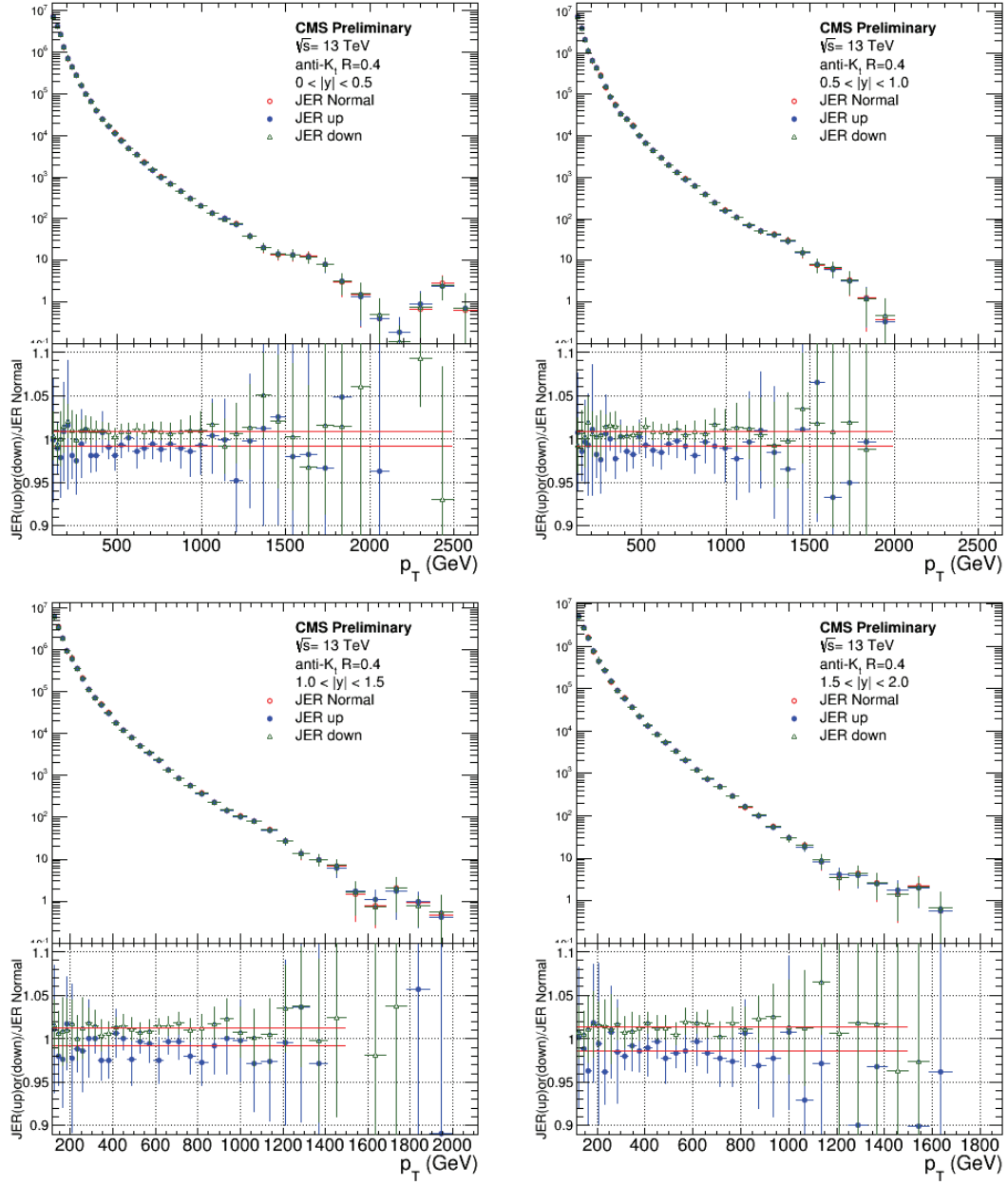


FIGURE 8.16: The jet unfolded spectra for AK4 jets (top of each plot) using the nominal, the c-up and the c-down values for JER. The ratios between $|JER-up|$ and $|JER Normal|$ and ratio between $|JER-down|$ and $|JER Normal|$ are at the bottom of each plot. The rapidity regions are $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, and $1.5 < |y| < 2.0$

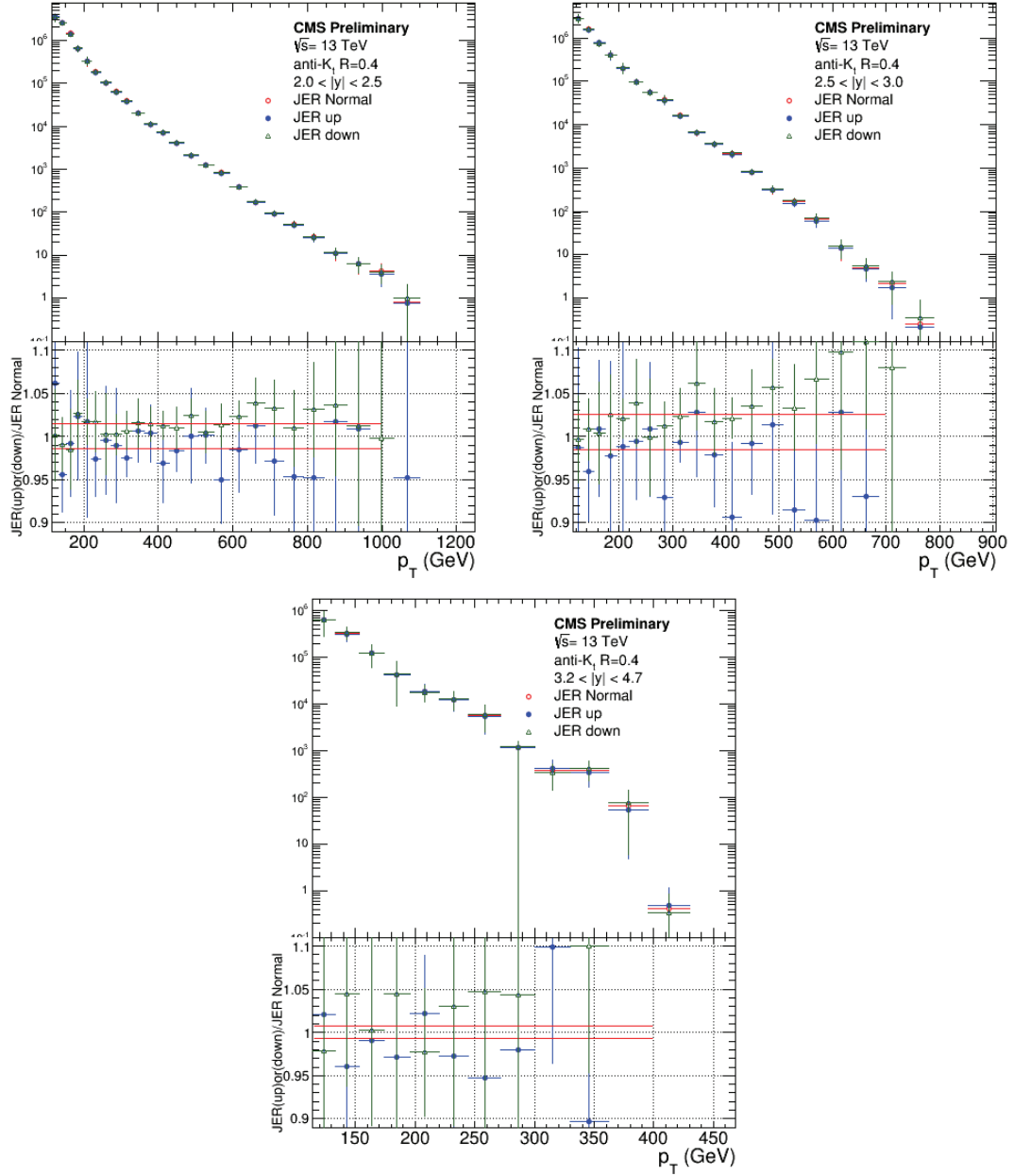


FIGURE 8.17: The jet unfolded spectra for AK4 jets (top of each plot) using the nominal, the c-up and the c-down values for JER. The ratios between $|JER\text{-}up|$ and $|JER\ Normal|$ and ratio between $|JER\text{-}down|/|JER\ Normal|$ are at the bottom of each plot. The rapidity regions are $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$

8.0.5 Systematics due to theory spectra

The theoretical spectra used to construct the response matrices with the Toy MC are taken from CT14 PDF sets. To estimate the model dependence of the unfolding results from the theoretical p_T spectrum used to calculate the response matrix, the unfolding procedure is repeated using the theoretical spectra from MMHT2014, NNPDF, and HERAPDF PDF sets. The resulting effects observed on the cross-section are negligible for both AK7 and AK4 jets.

For example, figure 8.18 and figure 8.19 show for AK7 jets the comparison of the unfolded spectra using Toy MC theory spectra from CT14 and HERAPDF.

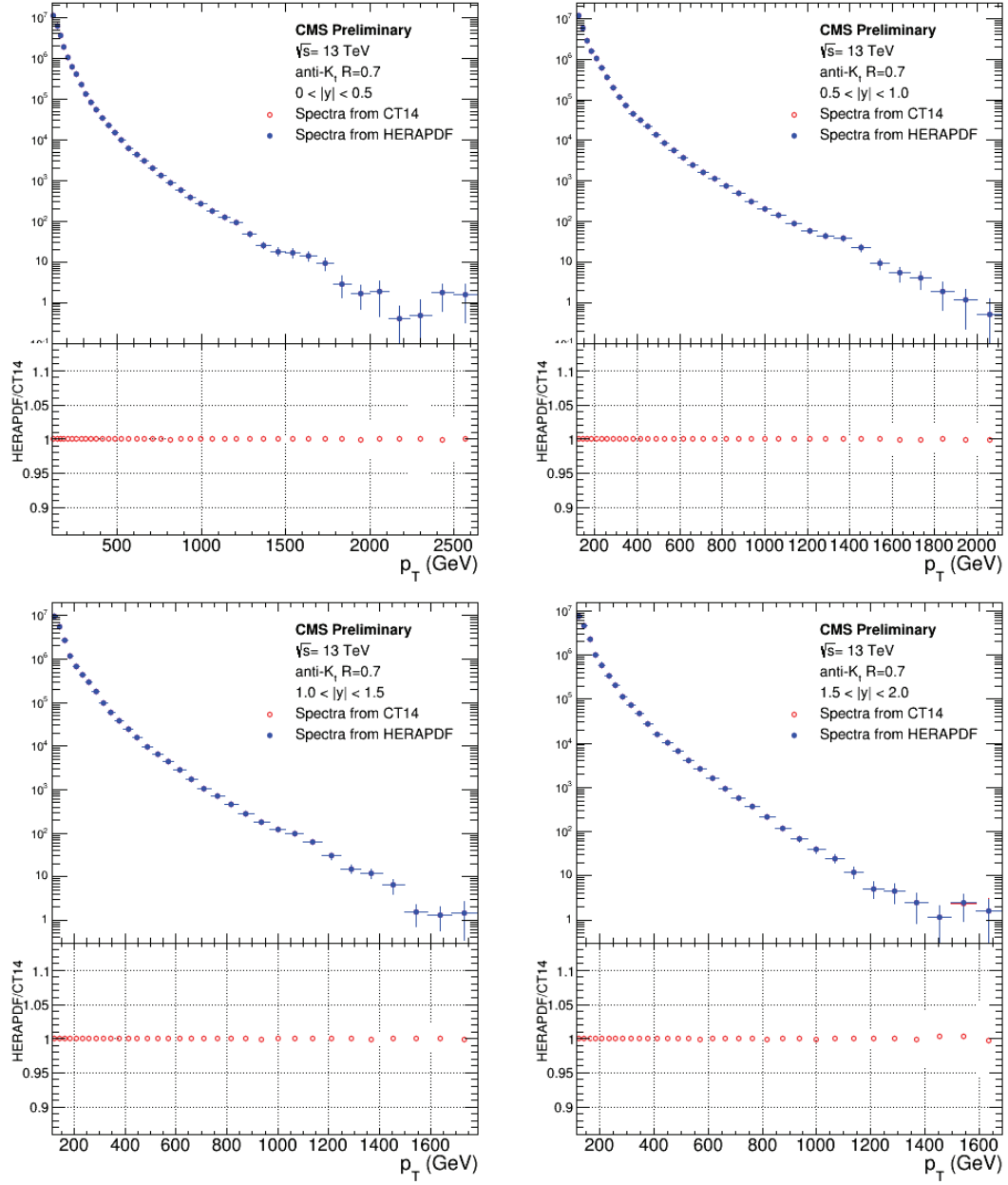


FIGURE 8.18: Comparison of the unfolded spectra for AK7 jets using in Toy MC theory spectra from CT14 and HERAPDF. The ratios between the unfolded spectra are shown at the bottom of each plot. The rapidity regions are $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, and $1.5 < |y| < 2.0$.

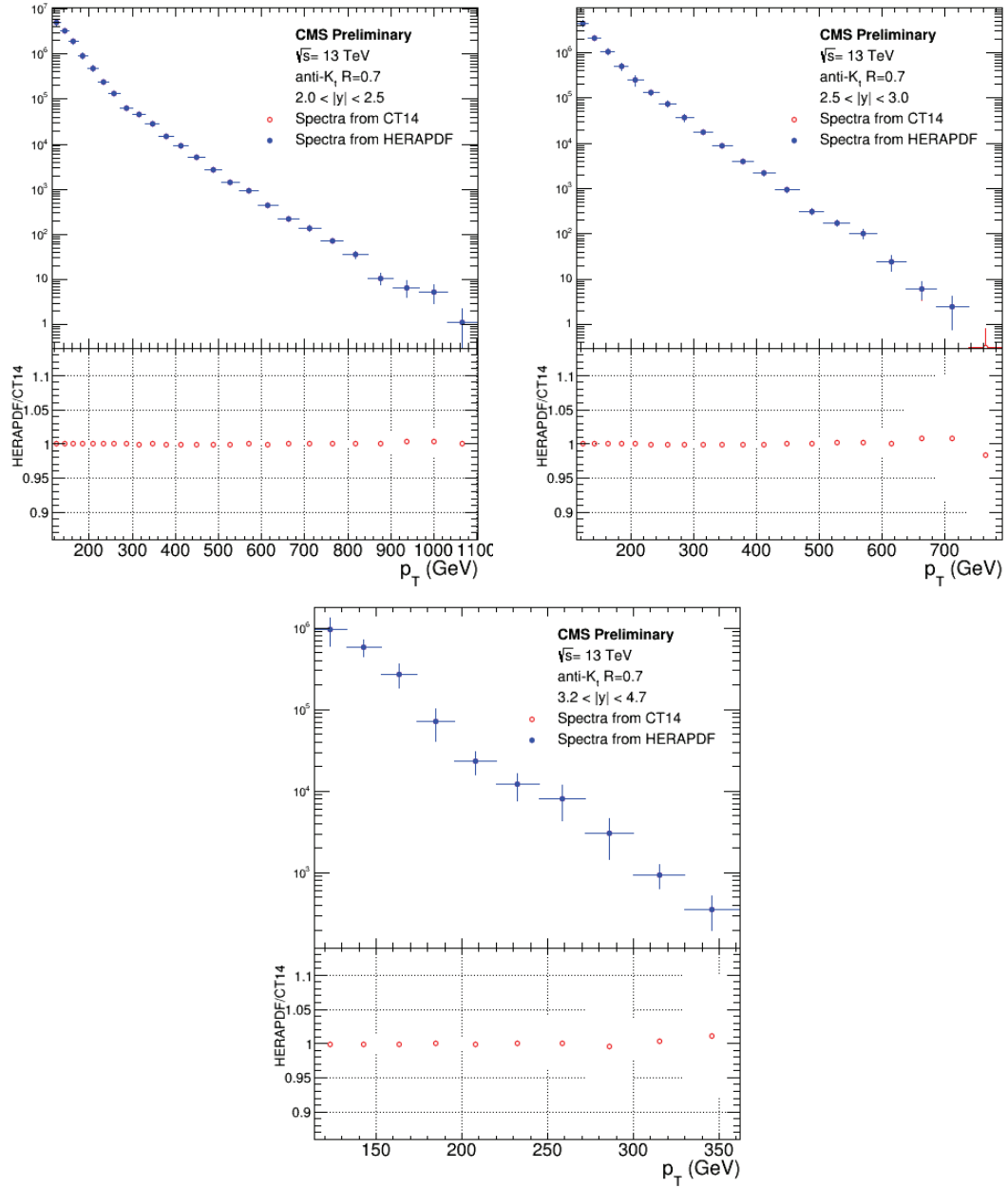


FIGURE 8.19: Comparison of the unfolded spectra for AK7 jets using in Toy MC theory spectra from CT14 and HERAPDF. The ratios between the unfolded spectra are shown at the bottom of each plot. The rapidity regions are $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, and $3.2 < |y| < 4.7$

Chapter 9

Systematic Effects

In this Chapter, the systematic effects which affect the inclusive jet cross-section measurements are discussed in detail and their impact is estimated. A summary of the assigned uncertainties is provided at end of the chapter.

9.0.1 Systematic uncertainties from jet energy scale

One of the major uncertainties in jet measurements comes from jet energy scale. The energy deposited in the detector, which is reconstructed as a jet, needs to be corrected to obtain a reliable measurement in order to match, as precisely as possible, with the kinematical quantities of the object which originated it. The corrections, organized in three sequential levels, introduce a measurement uncertainty. The uncertainty on the jet energy scale for the data recorded in 2015 is about 1–3% in the central region ($|y| < 2$) and increases up to 7–8% in the forward region ($|\eta| \sim 4$). The uncertainty is slightly higher for lower p_T , of the order of 2% at 100 GeV, and decreases at larger p_T , to the order of 1% at 200 GeV [23].

The effect of the jet energy scale is evaluated by varying the energy of all the jets by the uncertainty up and downward. The observables obtained with these changes are then compared to the nominal distributions measured with the nominal values of the jet energy scale. The differences between the nominal distributions and the ones obtained with the modified jet scale reflect the effect of the jet energy scale. The values of these differences, taken bin-by-bin, are referred to as the jet energy scale uncertainties. When applying the jet energy scale uncertainties, symmetric differences are obtained in the up and downward directions, with respect to the nominal distributions. They vary between 8% and 65% on the absolute cross-sections, depending on the rapidity region and increase with increasing y . Uncertainties related to the JEC are stable with respect to the considered jet cone size.

9.0.2 Systematic uncertainties from jet energy resolution

Together with jet energy scale, another important detector effect is jet energy resolution. The detector response in any measured quantity does not exactly correspond to the true value of the measured physical quantity but results in a Gaussian distribution around it. The wider the distribution, the less accurate is the measurement. The width of the distribution is called resolution. While the accurate angular resolutions in η and ϕ in CMS have a negligible effect on the measurement described in the thesis, the resolution in transverse momentum is more relevant and needs to be taken into account. In particular, it is important that the resolution measured in data matches the one observed in the simulation. It has been observed that this can be achieved by applying a correction to the jet p_T in the simulation at the detector level. This correction depends on the jet η and p_T . These correction factors are officially provided by the CMS Collaboration

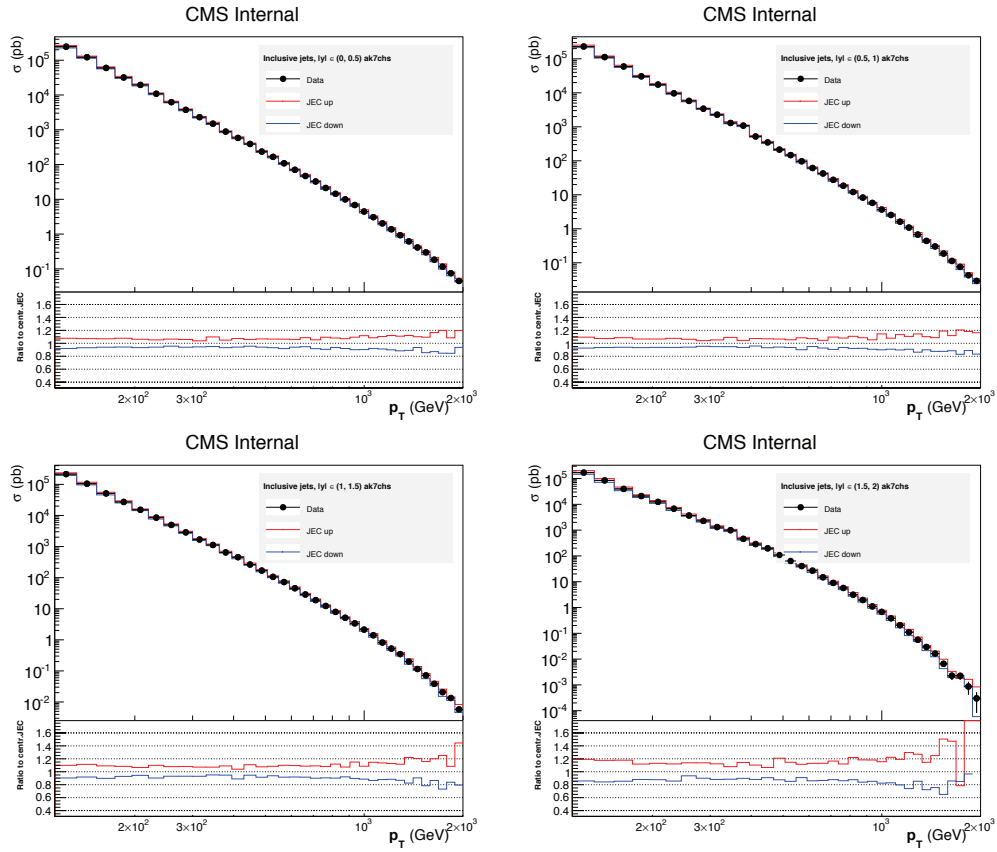


FIGURE 9.1: Cross-section measurement at detector level for AK7chs jets as a function of jet p_T for central, up and down values of the jet energy correction values in different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$. The distributions and the JEC uncertainties used for the analysis have been estimated by using the simulation provided by the PYTHIA 8 CUETP8M1 sample.

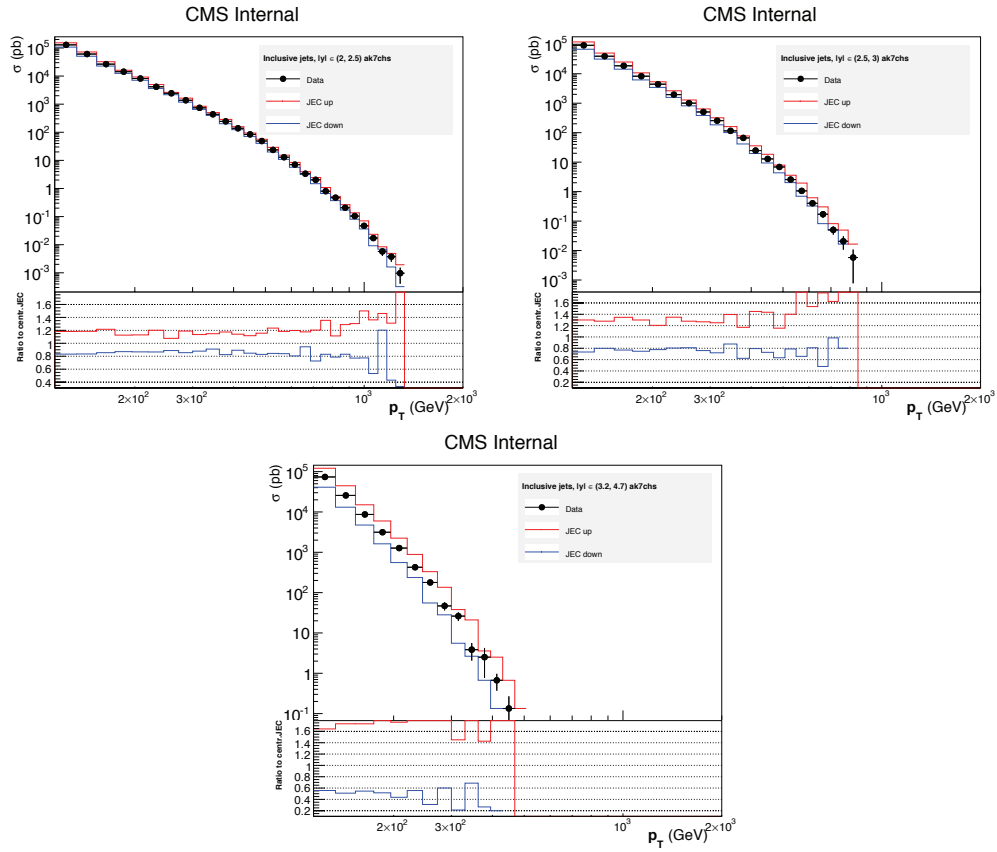


FIGURE 9.2: Cross-section measurement at detector level for AK7chs jets as a function of jet p_T for central, up and down values of the jet energy correction values in different rapidity bins: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$. The distributions and the JEC uncertainties used for the analysis have been estimated by using the simulation provided by the PYTHIA 8 CUETP8M1 sample.

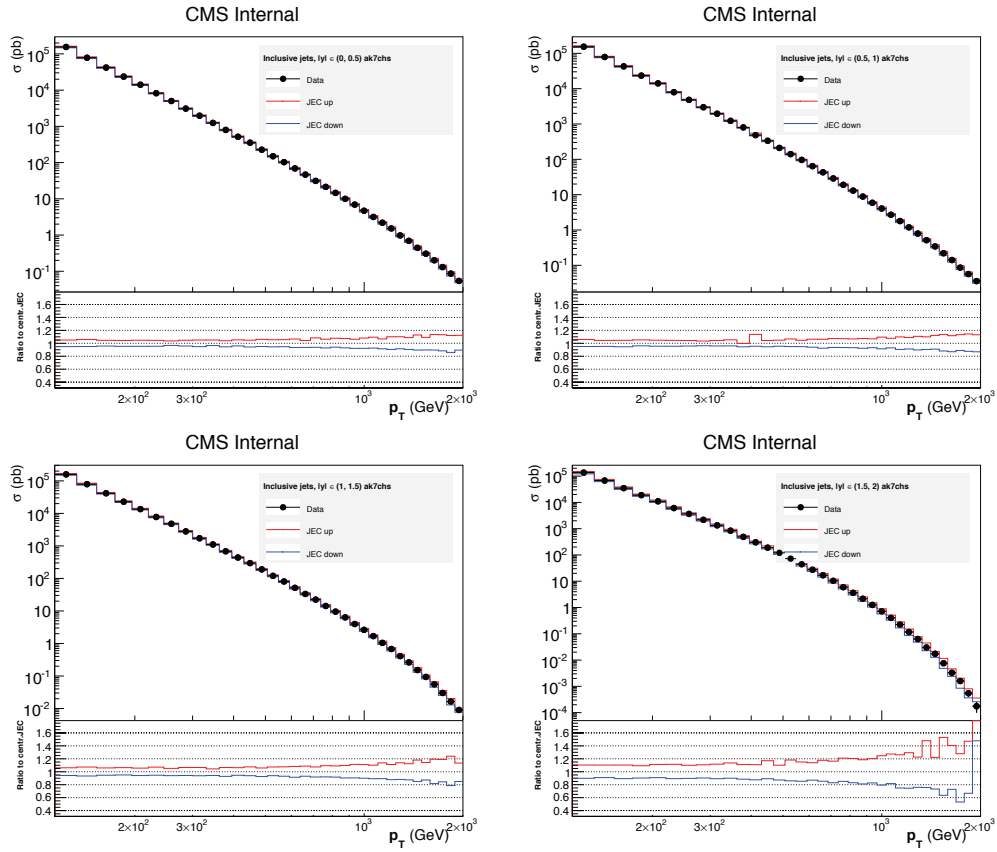


FIGURE 9.3: Cross-section measurement at detector level for AK4chs jets as a function of jet p_T for central, up and down values of the jet energy correction values in different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$. The distributions and the JEC uncertainties used for the analysis have been estimated by using the simulation provided by the PYTHIA 8 CUETP8M1 sample.

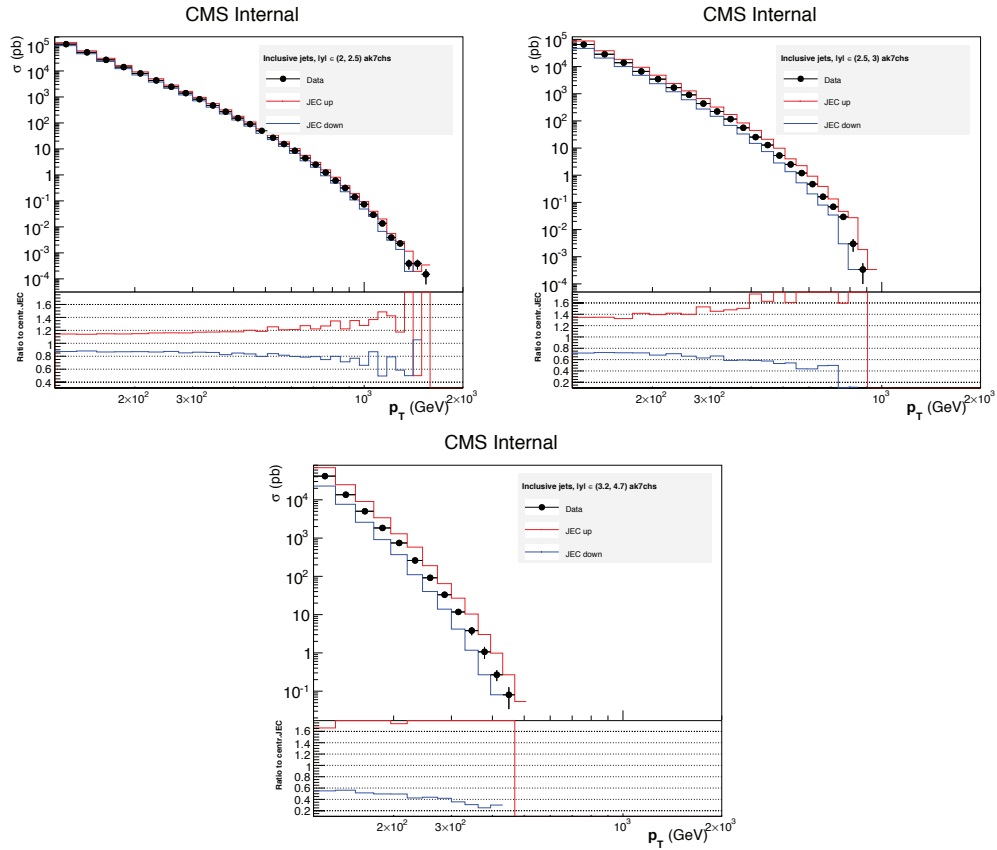


FIGURE 9.4: Cross-section measurement at detector level for AK4chs jets as a function of jet p_T for central, up and down values of the jet energy correction values in different rapidity bins: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$. The distributions and the JEC uncertainties used for the analysis have been estimated by using the simulation provided by the PYTHIA 8 CUETP8M1 sample.

for all the angles. They range between 1.06 and 1.17 with higher values when going to larger rapidities, as shown in the previous Chapter. In order to correct for the resolution mismatch, the jet p_T resolution estimated from the simulation has been corrected by applying the given correction factors. The correction factors a have been measured in Z-boson and dijet events [16]. The uncertainty on cross-section due to this effect depends on the uncertainty of the correction factors themselves. The value for each bin is taken as uncertainty. The results show a contribution which ranges between 1 and 2% for the measured cross-sections.

9.0.3 Other systematic effects

Other systematic effects which affect the measurement are related to trigger efficiency correction, pile-up reweighting, luminosity determination etc.

Trigger efficiency uncertainty

The trigger efficiency correction introduces a systematic uncertainty of 1% to take into account the fact that the turn-on point is evaluated at 99% of efficiency for each single trigger used in the analysis.

Uncertainty from Pile-Up reweighting

The pile-up reweighting procedure also introduces a systematic effect for the measurements depending on how well the primary vertex distribution in data matches the one in simulation. Since an iterative procedure has been applied, the uncertainty is estimated by the difference between the results at detector level obtained without any reweighting procedure and the one obtained with three iterations on the primary vertex distribution. This effect contributes with a negligible uncertainty ($< 0.1\%$) on the measured cross-sections.

Luminosity Uncertainty

For 2015 data at 50 ns, an additional uncertainty of 4.8% due to the luminosity is added for the inclusive jet cross-section measurement.

Statistical uncertainty

In addition to the systematic sources, an uncertainty coming from the limited number of selected events also contributes to the measurement and needs to be assigned to the distributions: this is the statistical uncertainty. This has been calculated by considering the contents of each bin as quantities following a Poisson distribution. The statistical uncertainty adds a 1% contribution to the measurements.

9.0.4 Theory uncertainty

This could be subdivided into PDF Uncertainty, Scale Uncertainty and Uncertainty from Non-Perturbative correction factor.

PDF Uncertainty

The PDF variation introduces uncertainties on the theoretical prediction up to 30%, while the variation of α_S (M_Z) by 0.001 introduces an additional uncertainty of 1-2%.

Scale Uncertainty

The renormalization and factorization scale uncertainty is estimated as the maximum deviation at the six points $(\mu_F/\mu, \mu_R/\mu) = (0.5, 0.5), (2, 2), (1, 0.5), (1, 2), (0.5, 1), (2, 1)$, where $\mu = p_T$ (inclusive).

NP Uncertainty

This is discussed in detail in Chapter 10. Contribution from this correction is 1% for AK7 jets and 2% for AK4 jets.

9.0.5 Total uncertainty

The uncertainties discussed above are combined to get the total systematic uncertainty. The combination of the uncertainties is evaluated by summing in quadrature the individual contributions, assuming absence of correlation among the different sources.

TABLE 9.1: Systematic uncertainties affecting the inclusive jet cross-section distributions. For all the sources of systematic uncertainty the interval values reflect the range over all bins of the observable and all rapidity regions. Generally, systematic uncertainties increase with increasing jet rapidity.

Systematic effect	AK7 jet measurement	AK4 jet measurement
JES	8-65%	8-65%
JER	1-2%	1-2%
Luminosity	4.8%	4.8%
Trigger efficiency	1%	1%
Pile-up	-	-
PDF	1-8%	2-10%
Scale	1-12%	1-10%
NP Corrections	1%	2%
Total	10-65%	10-65%

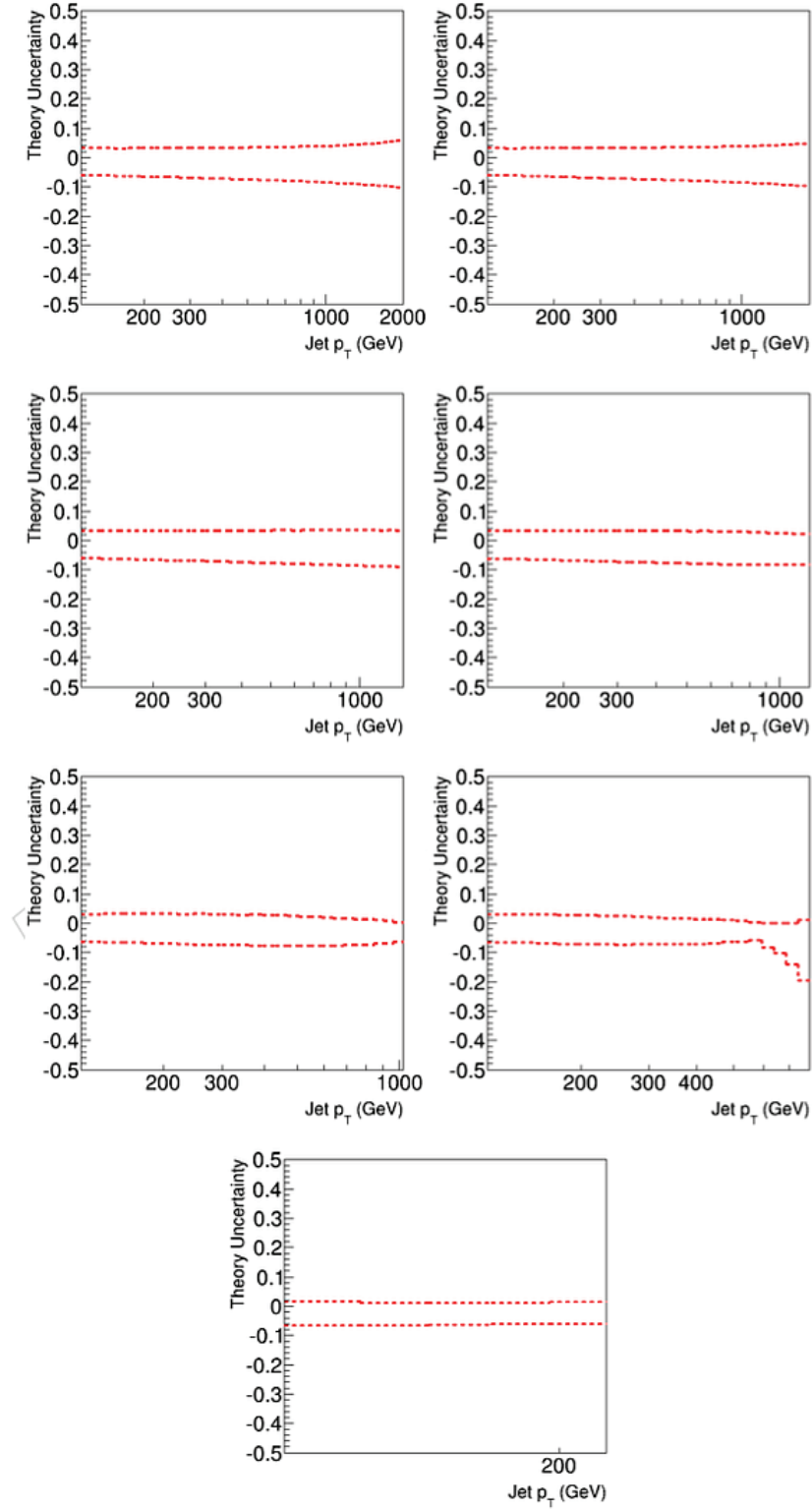


FIGURE 9.5: Scale uncertainties evaluated as a function of jet p_T for different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$ for AK7 jets.

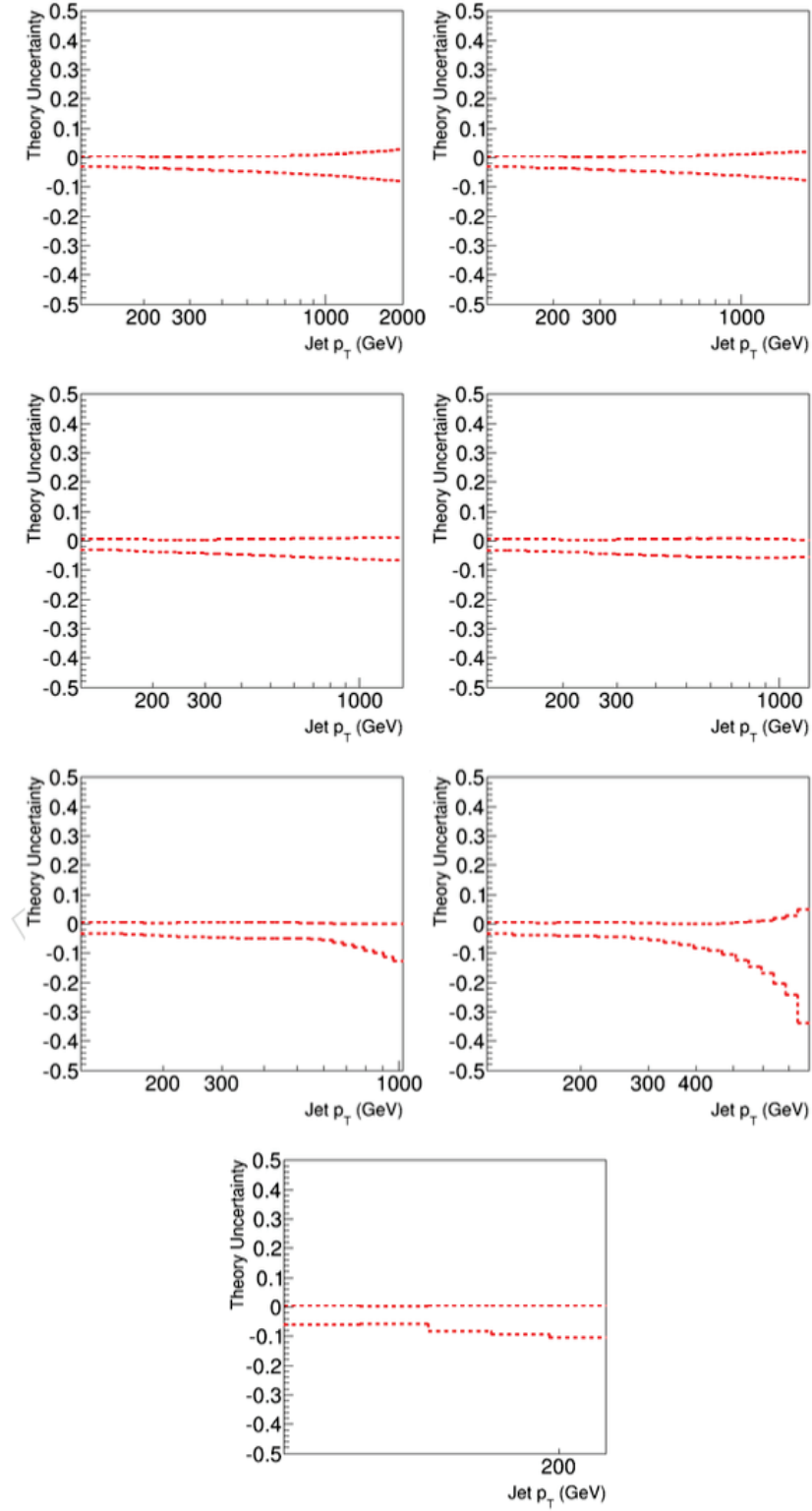


FIGURE 9.6: Scale uncertainties evaluated as a function of jet p_T for different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$ for AK4 jets.

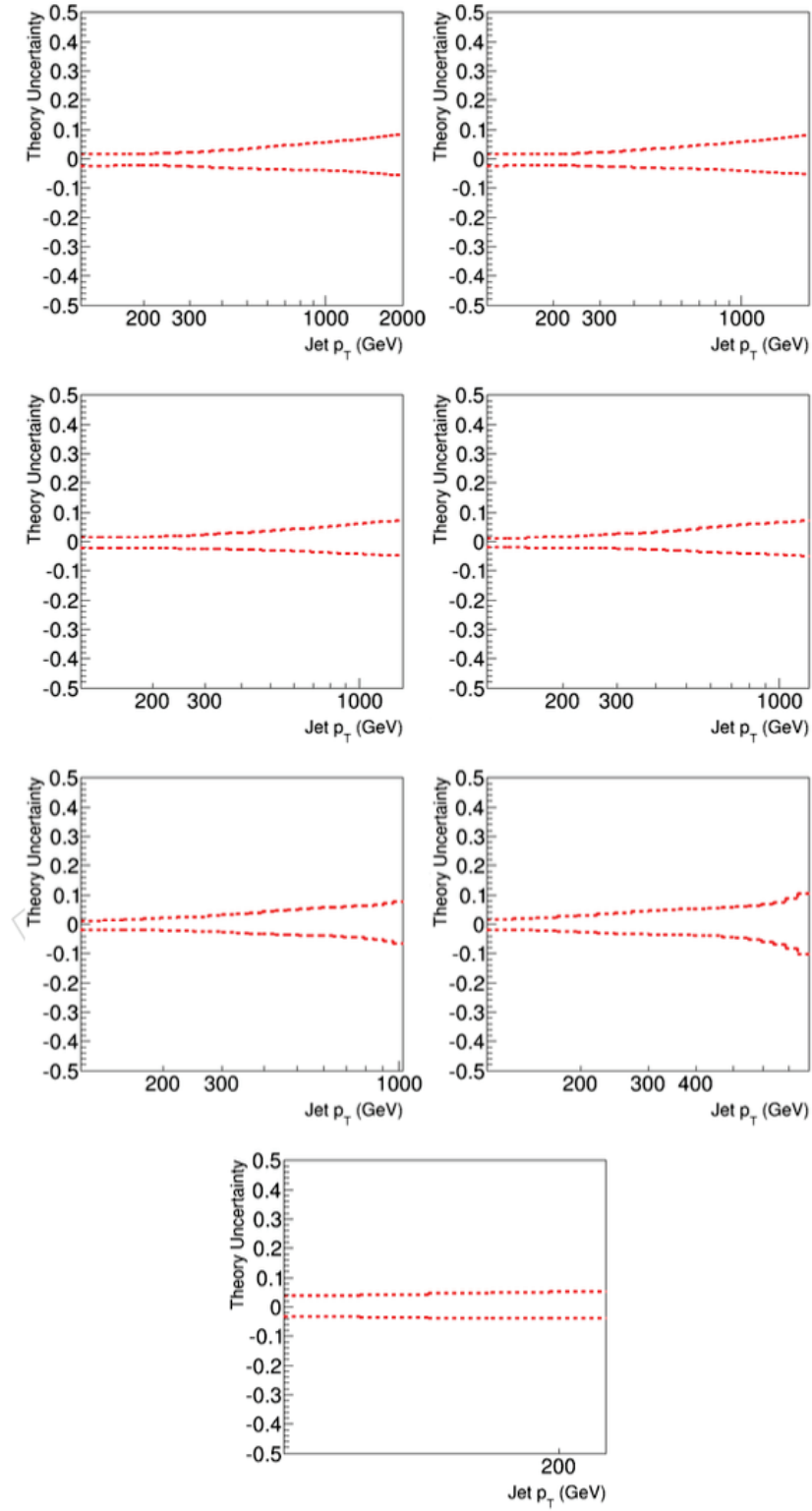


FIGURE 9.7: PDF uncertainties evaluated as a function of jet p_T for different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$ for AK7 jets.

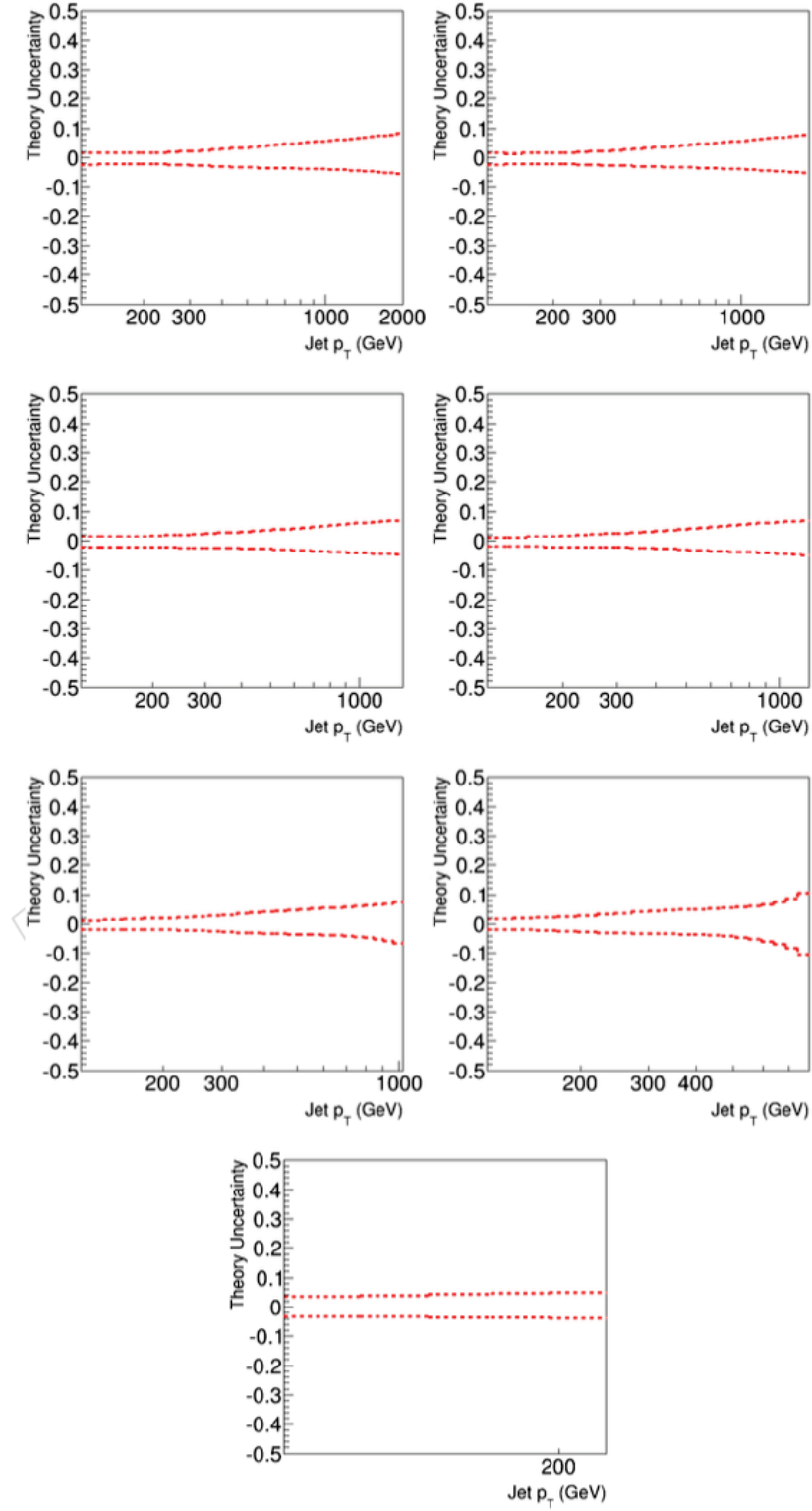


FIGURE 9.8: PDF uncertainties evaluated as a function of jet p_T for different rapidity bins: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$, $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$ for AK4 jets.

Chapter 10

Non-Perturbative Effects

10.0.1 Sources of Non-perturbative Effects

In perturbative QCD (pQCD) calculations, the scattering amplitude of hard scattered partons is computed for a fixed order of perturbation theory. In reality, the incoming and outgoing hard partons radiate soft partons. This phenomena are known as initial state radiation (ISR) and final state radiation (FSR), respectively. Alongside these, the scattering between partons, not taking part in hard scattering process, take place which is termed as multi parton interaction (MPI). The other non-perturbative process that needs to be taken care of is hadronization. The MPI and hadronization cannot be dealt within the pQCD framework. Hence to compare the Next to Leading Order(NLO) theory predictions with data, it has to be corrected for these non-perturbative (NP) effects and it is collectively called NP corrections.

Multiple Parton Interaction

The basis for understanding hadronic collisions at high energy is provided by the QCD improved parton model. In this framework each hadron is described as a collection of essentially free elementary constituents. The interactions between constituents belonging to different colliding hadrons are the seeds of the complicated process which eventually leads to the particles observed in the detector. Due to the composite nature of hadrons, it is possible to have multiple parton hard-scatterings, *i.e.* events in which two or more distinct hard parton interactions occur simultaneously in a single hadron-hadron collision. At fixed final state invariant masses, such cross-sections tend to increase with collision energy because partons with successively lower momentum fraction, hence rapidly increasing fluxes, are being probed. As a result, events with relatively low invariant masses could receive enhanced contributions from multiple hard scatterings. This class of events is known as Multiple Parton Interactions (MPI), while those in which only a single pair of partons produce a hard scattering are referred as Single Parton Scattering (SPS).

Hadronization

The pQCD is valid at short distances but at long distances, *i.e.* at very low energy scales (below 0.2 GeV) pQCD breaks down. In this case, the colored quarks transform into colorless objects, and this process is called “hadronization”. Partons from hard scattering cannot be observed at the detector level but the hadrons, which are formed due to hadronization process, are observed. After the parton collision (quarks, anti-quarks or gluons) in the hard scattering process, the outgoing partons carry color charges and these create strong color fields between themselves and with the rest of the proton. The strong color fields between two color charges increase linearly with the separation of charges until getting enough energy to create additional quark-anti quark pairs. Due to this reason, the original parton loses some of its own energy and momentum every time until they

do not have sufficient energy to create a new pair of quark and anti-quark and the color charge becomes neutral. At the end of the hadronization process, the original partons transform into hadrons which appear as “particle jets”. Thus the energy of collimated hadrons forms calorimeter cluster leading to formation of “calorimeter jets” and these are observed by the detector.

10.0.2 Corrections of Non-perturbative Effects

Currently, the standard non-perturbative effects are evaluated by using Monte Carlo event generators (*e.g.* Pythia[46]). The ratio between a nominal event generation using a well performing tune and a sample with hadronization and MPI effects switched off is estimated as the effect and considered as correction. The perturbative effects are instead currently ignored. This approach has been used in several jet measurements [17, 2]. It is to be noted that the NP corrections, so defined, are used to correct any available NLO calculation at parton level to bring it to the jet level for direct comparison. In a compact formulation, the NP correction factors can be defined as:

$$C_0^{\text{NP}} = \frac{N_{\text{LO}}^{\text{PS+HAD+MPI}}}{N_{\text{LO}}^{\text{PS}}} \quad (10.1)$$

where in the superscript, the components of the simulated Underlying Events (UE) are listed and in the subscript the order of the Matrix Element (ME) is specified. In [17], these factors are evaluated with different tunes, generators and PDF sets, and the envelope resulting from them is considered as theoretical uncertainty of the correction factors. LO stands for Leading Order.

As it is now possible to match NLO calculations, like *e.g.* Powheg[42, 34], with Parton Shower (PS), it is important that these corrections are also evaluated with a NLO ME. This removes possible inconsistencies in the corrections, due to different treatment of hard emissions in LO and NLO ME. The new correction factors are defined in a compact way as:

$$C^{\text{NP}} = \frac{N_{\text{NLO}}^{\text{PS+HAD+MPI}}}{N_{\text{NLO}}^{\text{PS}}} \quad (10.2)$$

Corrections obtained with NLO and LO event generators are considered in the following and shown separately for AK7 and AK4 jets. The following settings are investigated and taken into account for the NP corrections:

- POWHEG (CT10nlo) + PYTHIA 8 CUETP8M1
- POWHEG (CT10nlo) + PYTHIA 8 CUETP8S1-CTEQ6L1
- POWHEG (HERAPDF1.5NLO) + PYTHIA 8 CUETP8S1-HERAPDF
- PYTHIA 8 CUETP8M1
- HERWIG++ UE-EE-5C
- HERWIG++ CUETHppS1

where for POWHEG, the PDF set used for the simulation of the matrix element is also indicated. The combinations of PDF, matrix element and tunes used for the evaluation of the NP corrections have been validated on UE, ME and jet variables and they are able to reproduce a wide set of observables [24]. The interface between POWHEG and HERWIG++[12] is not yet included, since at this stage good agreement between its predictions and some of the considered observables has not been obtained.

10.0.3 Non-perturbative corrections for AK7 jets

In this Section, NP corrections obtained from the different MC event generators are shown. Figure 10.1 shows NP corrections resulting from LO event generators (PYTHIA 8 and HERWIG++ standalone), while Figure 10.2 considers the NLO event generators for the different rapidity ranges. All curves tend to flatten at 1 starting from $p_T > 300$ -400 GeV, while in the lower part of the spectrum (smaller p_T values), they increase up to 1.2-1.3. Curves obtained for PYTHIA 8 standalone and POWHEG+PYTHIA 8 are very similar to each other. Bigger differences in values and trend are observed when considering NP corrections obtained for HERWIG++. This is mainly due to the different models of MPI and hadronization which are implemented in HERWIG++ with respect to PYTHIA 8. No relevant difference is observed for the curves obtained with two tunes in HERWIG++.

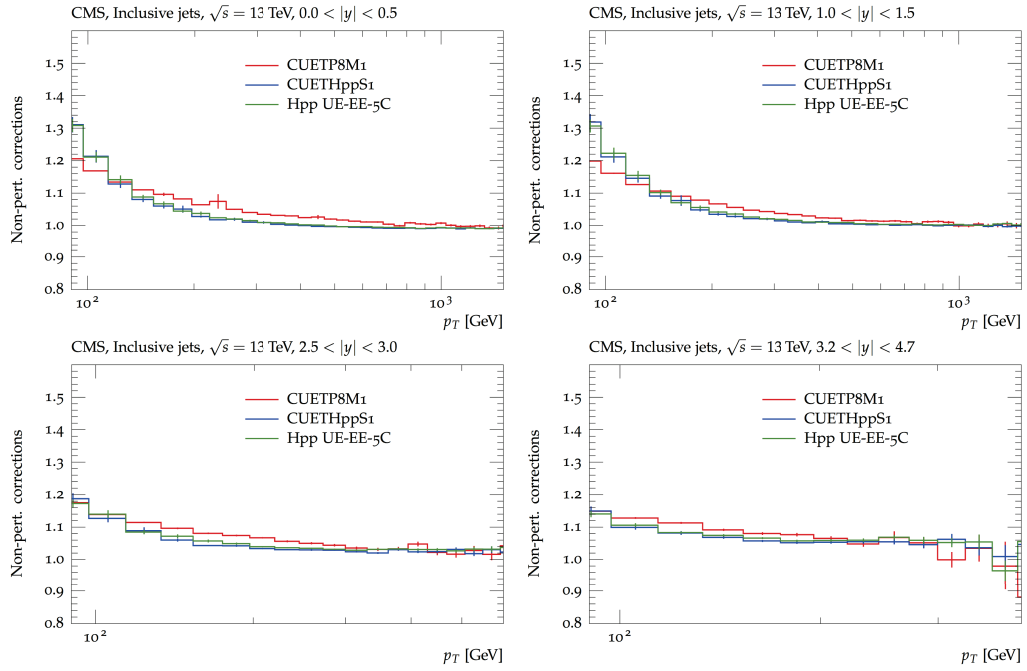


FIGURE 10.1: Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right) for Leading Order.

In Figure 10.3, the envelopes of the curves obtained with LO and NLO event generators are shown for the different rapidity regions. These are important to give an idea of the size of the final uncertainty which affects the NP corrections.

The NP corrections shown in Figure 10.1 are averaged out for the final correction. Fits to the averaged curve are performed by using a power law function, like:

$$y = a + b \cdot x^c \quad (10.3)$$

Three free parameters are used in the fit. In order to evaluate the theoretical uncertainties from the NP corrections, fits are also performed by considering the upper and lower points of the envelopes. The resulting functions are shown for each rapidity bin in Figure 10.4. These functions are applied to the NLOJet++[41] predictions and are used to estimate their theoretical uncertainties.

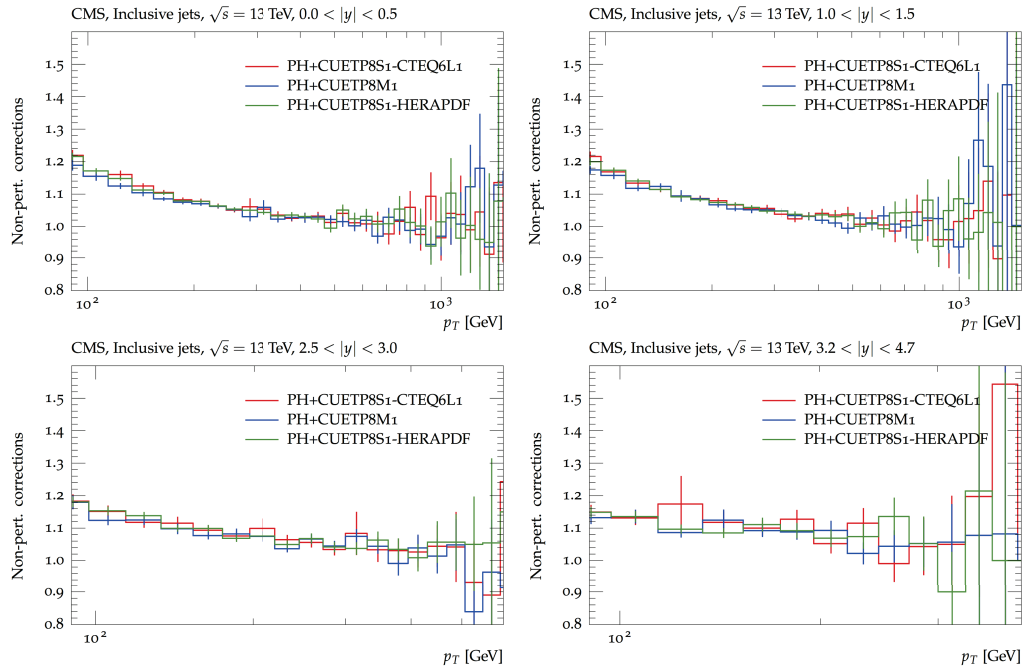


FIGURE 10.2: Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right) for Next to Leading Order.

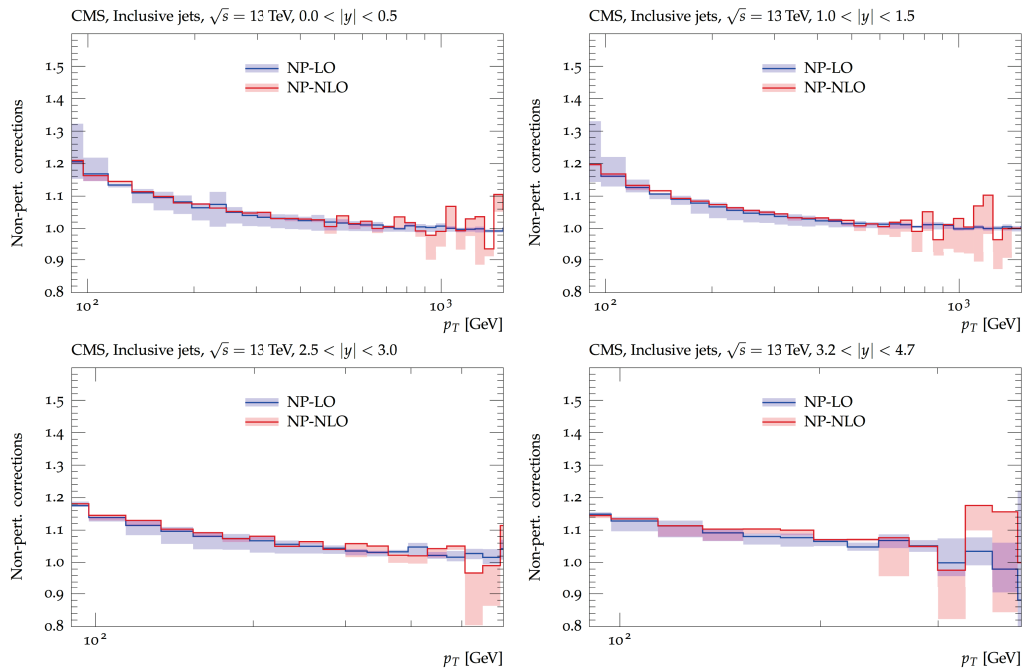


FIGURE 10.3: Envelopes of Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right)

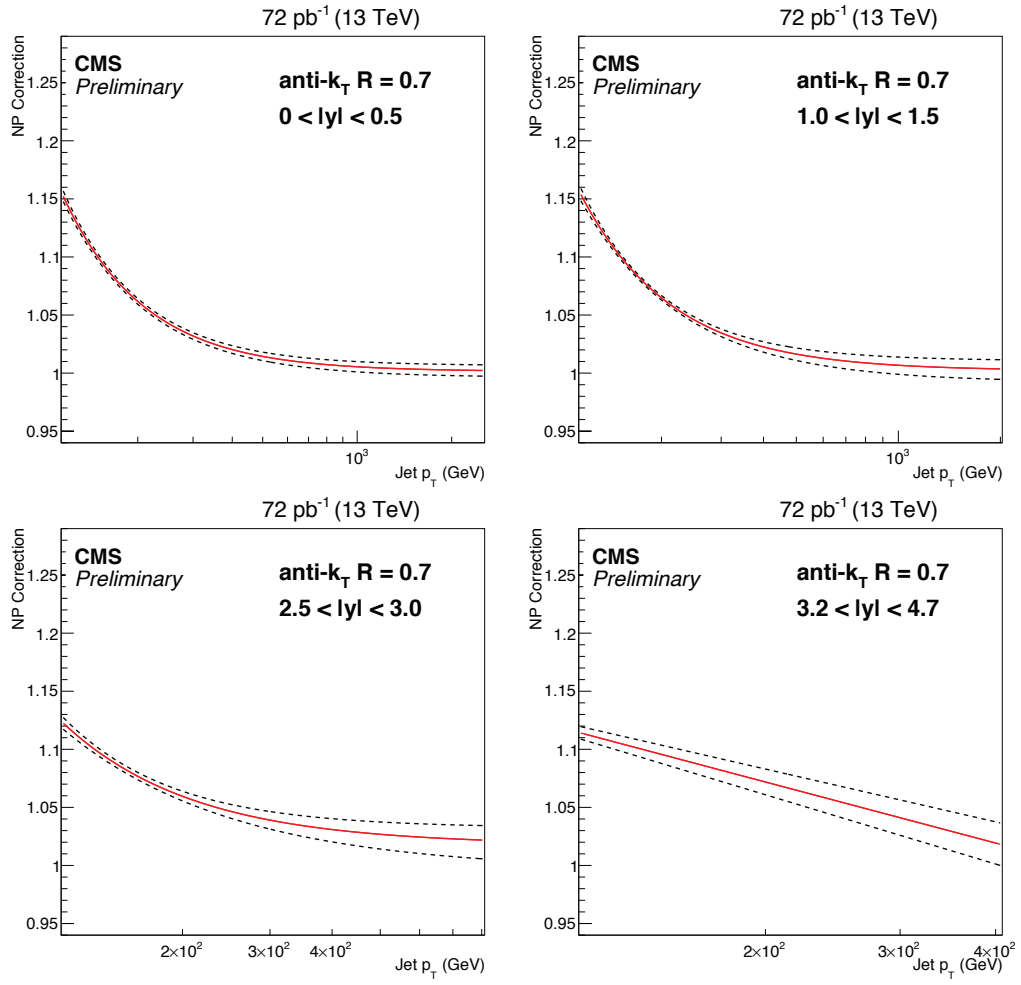


FIGURE 10.4: Fits of Non-perturbative corrections as a function of jet p_T obtained from upper and lower points of the envelopes for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right)

10.0.4 Non-perturbative corrections for AK4 jets

Same treatment is applied to AK4 jets for NP effects. Results are shown in Figure 10.5 for LO event generators and in Figure 10.6 for NLO event generators. For smaller cone radius, NP corrections are much flatter and they are closer to 1. In the whole phase space in p_T considered, they range between 1.05 and 1 for PYTHIA 8 and POWHEG+PYTHIA 8, while for HERWIG++ they are always slightly below 1. This is mainly due to out-of-cone hadronization effects, namely to partons which after hadronization escape from the jet cone. This does not happen for larger jet cone sizes.

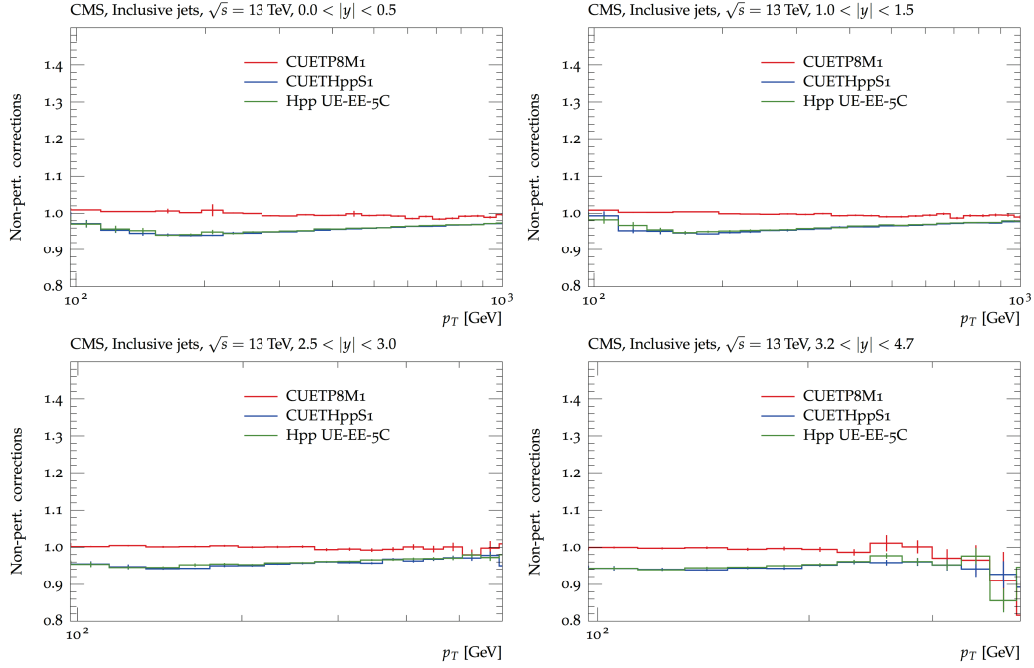


FIGURE 10.5: Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right) for Leading Order.

In Figure 10.7, separate envelopes of NP corrections obtained for LO and NLO event generators are shown for the different rapidity ranges. As observed for AK7 jets, the source of uncertainty is the difference between HERWIG and PYTHIA 8 NP corrections. Fits are performed to the average of all curves according to the function:

$$y = a + b \cdot x^c \quad (10.4)$$

Three free parameters are used in the fit. In order to evaluate the theoretical uncertainties from the NP corrections, fits are also performed by considering the upper and lower points of the envelopes. The resulting functions are shown for each rapidity bin in Figure 10.8. These functions are applied to the NLOJet++ predictions and are used to estimate their theoretical uncertainties.

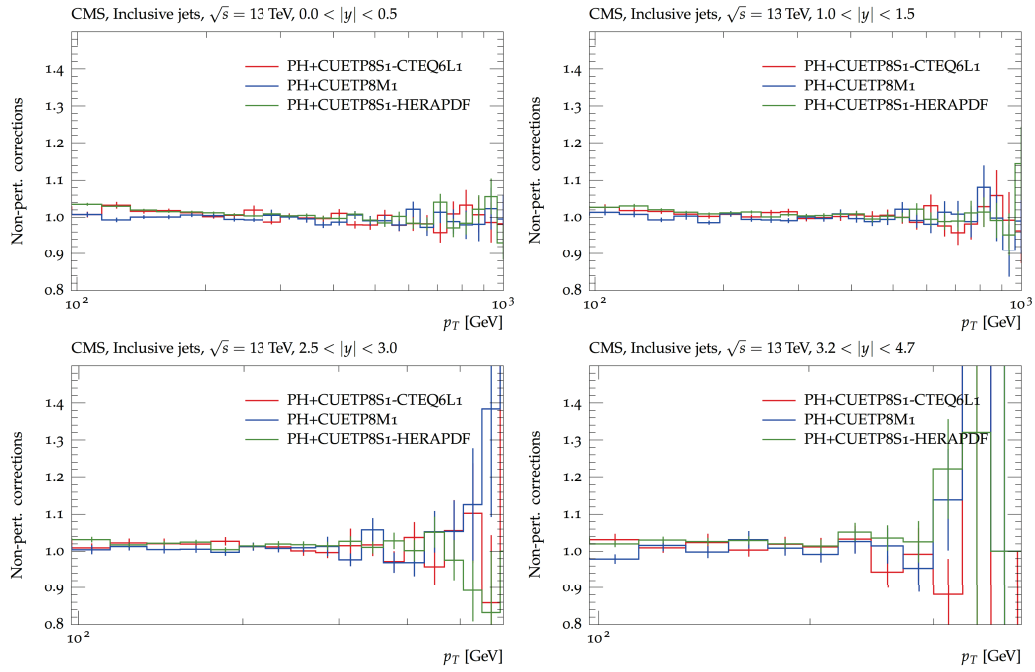


FIGURE 10.6: Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right) for Next to Leading Order.

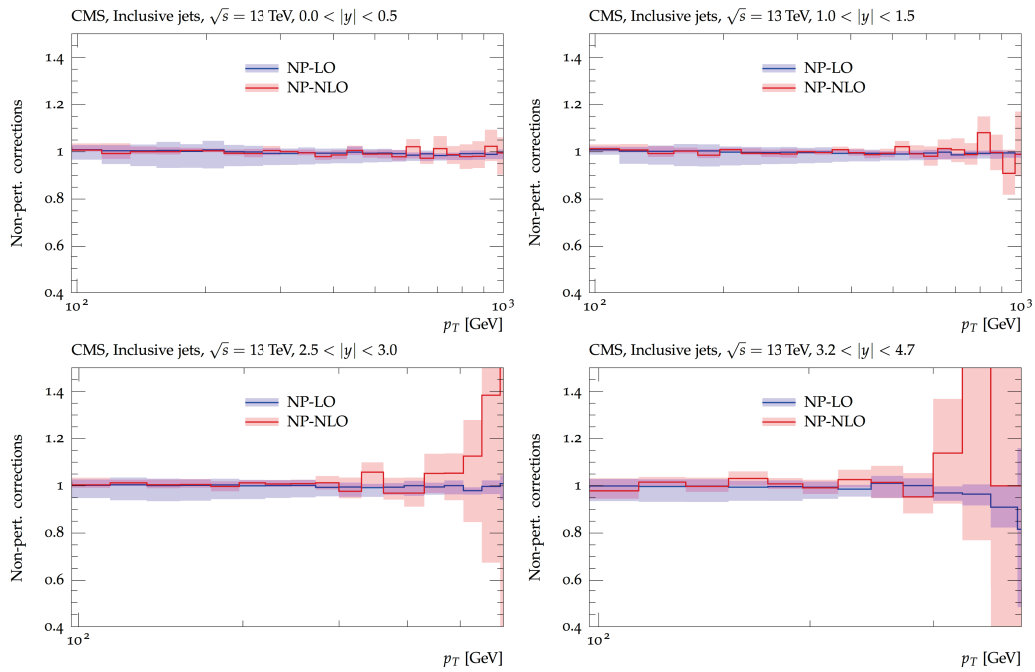


FIGURE 10.7: Envelopes of Non-perturbative corrections as a function of jet p_T obtained with different Monte Carlo event generators for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right)

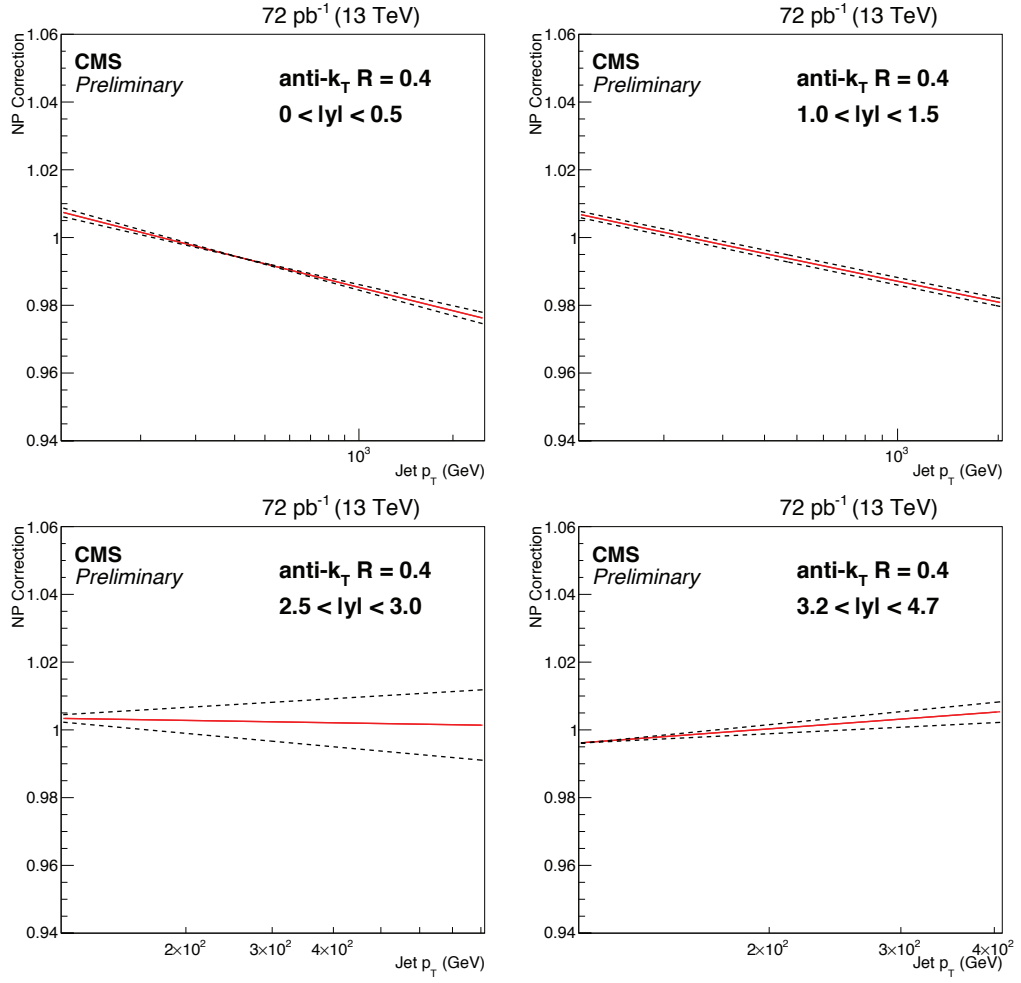


FIGURE 10.8: Fits of Non-perturbative corrections as a function of jet p_T obtained from upper and lower points of the envelopes for different rapidity bins: $0.0 < |y| < 0.5$ (top left), $1.0 < |y| < 1.5$ (top right), $2.5 < |y| < 3.0$ (bottom left), $3.2 < |y| < 4.7$ (bottom right)

Chapter 11

Results

Unfolding of the data distributions corrects the measurements from detector effects and provide absolute and normalized differential cross-sections at the stable particle level. For each bin i in the p_T - y space, the cross-section can be written as:

$$\frac{d\sigma^i}{dp_T dy} = \frac{N^i}{\mathcal{L} \cdot \Delta p_T^i \Delta y^i \cdot C_{unfold}^i} \quad (11.1)$$

where $\mathcal{L}$ is the integrated luminosity, C^i is the correction factor determined from the unfolding procedure and N^i is the number of events measured in the bin i at the detector level. The variables Δy^i and Δp_T^i indicate the bin widths used for transverse momentum and rapidity, respectively.

The absolute double differential cross-sections are measured as a function of the jet p_T and y . Results are compared to predictions from different event generators at the stable particle level. The theoretical predictions for the inclusive jet cross-section comprise a next-to-leading order (NLO) perturbative QCD (pQCD) calculation. They are complemented by a non-perturbative (NP) factor that corrects for multiparton interactions (MPI) and hadronization (HAD) effects. These predictions are obtained through the calculations based on the parton-level program NLOJET++ [41] and are performed within the FASTNLO framework [14]. Predictions from POWHEG [34], which simulate the NLO dijet matrix element, are interfaced with the parton shower effects as provided by PYTHIA8 [46] using the tune CUETP8M1.

In Figures 11.1 and 11.2, p_T spectra for AK7 and AK4 jets are shown for all rapidity ranges, scaled for presentation purpose. For both cone sizes, all measured distributions fall over several orders of magnitude with increasing p_T . For each rapidity range, the upper limit in the p_T spectra is chosen to be the last bin filled at the detector level. This criterion gives an acceptable statistical accuracy for all measured data points.

The measured inclusive jet cross-sections are presented using 71.52 pb^{-1} of data from proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ collected with the CMS detector. The results are presented as a function of both jet transverse momentum p_T and rapidity y . A large range in jet p_T from 114 GeV up to 2.0 TeV is covered in seven rapidity bins up to $|y| = 4.7$. For the first time inclusive jet cross-section is measured over the full rapidity coverage.

Detailed studies of experimental and theoretical sources of uncertainty are carried out. The dominant sources of experimental systematic uncertainty are due to the jet energy scale, unfolding and luminosity measurement uncertainties. These lead to about 15-55% uncertainty in the differential cross-section measurement, depending on the considered rapidity range. In comparison, the theory predictions are most affected by PDF uncertainties, and their range is strongly dependent on the p_T and rapidity interval: at low p_T they are about 7%, which increases up to 40% in the most central intervals, and exceeds 200% in the outermost regions.

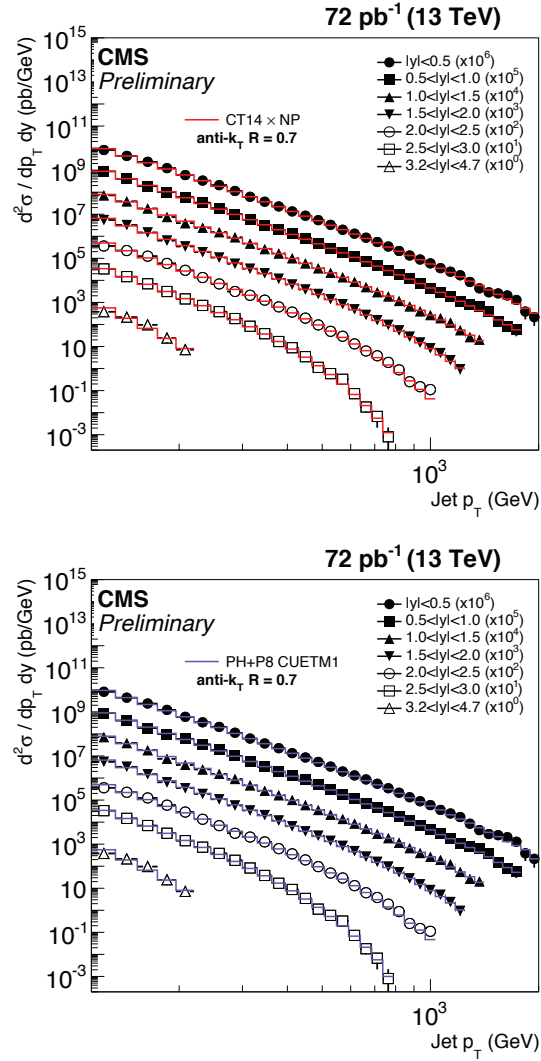


FIGURE 11.1: Inclusive jet cross-section as a function of jet p_T at the stable particle level compared to predictions obtained with NLOJet++ and POWHEG + PYTHIA8 Tune CUETP8M1 in the various rapidity bins. Jets are clustered with the anti- k_T $R = 0.7$ algorithm.

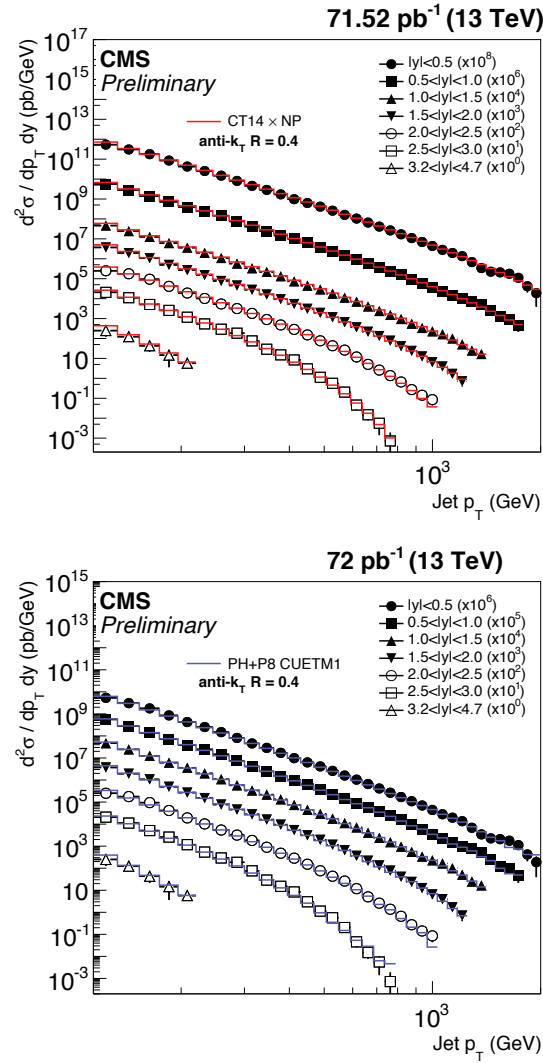


FIGURE 11.2: Inclusive jet cross-section as a function of jet p_T at the stable particle level compared to predictions obtained with NLOJet++ and POWHEG + PYTHIA8 Tune CUETP8M1 in the various rapidity bins. Jets are clustered with the anti- k_T R = 0.4 algorithm.

It is demonstrated that perturbative QCD, supplemented by a small non-perturbative correction, is able to describe the data well over a wide range of jet transverse momentum and rapidity and over many orders of magnitude in cross-section. Predictions from MC event generators simulating dijet matrix element at next-to-leading order accuracy is interfaced with simulation of parton-shower effects and underlying-event contributions to demonstrate this. This measurement of inclusive jet cross-section probes a wide range in x and momentum scale Q and hence can be used in the future to constrain PDFs in a new kinematic regime.

11.1 Comparison to theoretical predictions

The same NLO prediction as in [41] is used, i.e. the calculations are based on the parton-level program NLOJET++ version 4.1.3 [40, 31] and are performed within the FASTNLO framework version 2.1 [14]. The renormalization and factorization scales, μ_R and μ_F , are set to the individual jet p_T and the number of active (massless) flavours N_f in NLOJET++ is chosen to be five. Four recent sets of PDFs are available for a series of values of the strong coupling constant $\alpha_S(M_Z)$. PDF uncertainties are provided at 68.3% confidence level (CL).

The second set of presented plots shows comparison of data to predictions obtained with MC event generators interfaced to parton-shower and underlying-event (UE) simulation. The UE simulation is provided by using the most recent tunes which provide the best description of hadronic event shapes at different energies [24]. The considered predictions are listed in the following along with the PDF used in the matrix element and the tune for the UE simulation:

- POWHEG (CT10nlo) + PYTHIA 8 CUETP8M1
- POWHEG (CT10nlo) + PYTHIA 8 CUETP8S1-CTEQ6L1
- POWHEG (HERAPDF1.5NLO) + PYTHIA 8 CUETP8S1-HERAPDF
- PYTHIA 8 (CTEQ6L1) CUETP8M1
- HERWIG++ (CTEQ6L1) CUETHppS1

Event samples are generated using two different Monte Carlo (MC) event generators: HERWIG ++ (version 2.7.0) [12] and PYTHIA 8.185 [46]. Both of them use a Leading Order (LO) $2 \rightarrow 2$ matrix element. The PYTHIA 8 event generators simulates parton showers ordered in transverse momentum and use the Lund string model [7] for hadronization, while HERWIG ++ generates parton showers in an angular-ordered region of phase space and uses a cluster fragmentation model [53] for hadronization. The contribution of MPI is simulated in PYTHIA and HERWIG. The free parameters of MPI are obtained from tunes to measurements in pp collision at the LHC. The parameters used for hadronization are determined from tunes to LEP data for both PYTHIA [28] and HERWIG [35].

The PYTHIA8 event generator with tune CUETP8M1 [24] applies a model [28] where MPI are interleaved with parton showering. They use the NNPDF2.3LO PDF set [9, 10] and improve the description of Underlying Event (UE) data [22] at different collision energies. The HERWIG++ event generator with the tune to LHC and CDF data, CUETHppS1 [24] using the CTEQ6L1 PDF set [44], is also used for comparison.

The data are also compared to NLO perturbative QCD predictions obtained with the POWHEG package [42, 34] matched with PYTHIA parton showers including a simulation of MPI. This is provided by a tune obtained with the PYTHIA matrix element. A

retuning of the UE simulation interfaced to the matrix element generated with POWHEG has not been carried out. The POWHEG sample uses the CT10nlo PDF set [38] and the UE provided by PYTHIA 8 is simulated with the CUETP8M1 tune [24] which uses the NNPDF2.3LO PDF set [9, 10] and reproduces with very high precision UE and jet observables at various collision energies [24].

11.1.1 Predictions from fixed-order calculations and shower MC event generators

In this section, results unfolded at the stable-particle level are compared to predictions obtained with the afore mentioned generators. In Figure 11.3 and 11.4, ratios of predictions from NLOJet++ and the data are shown for AK7 jets in the various rapidity regions. Results are presented normalized to the predictions obtained with the NNPDF3.0 PDF set. The data are very well reproduced in each considered rapidity range by all predictions using different PDF sets. In each bin in transverse momentum, the predictions fall within the theoretical and experimental uncertainties which affect the measurement. In Figures 11.5 and 11.6, ratios of predictions from MC event generators, interfaced to parton shower and UE simulation, and the data are shown for AK7 jets in the various rapidity regions. Results are in this case presented as ratios to predictions obtained with POWHEG + PYTHIA8 CUETP8M1 tune. It is shown that predictions obtained with POWHEG independently on the tune used for the UE simulation agree very well with the data. Predictions from LO MC event generators, i.e. PYTHIA and HERWIG, show bigger discrepancies. In particular, PYTHIA tends to overestimate the measurement over the whole range with differences of about 20%, while the data are above the predictions obtained with HERWIG by about 40-50%. This behaviour was already observed in measurements at 7 TeV and confirms the need for higher orders included in the ME calculation for the description of inclusive jet cross-sections.

Figures 11.7, 11.8 and 11.9, 11.10 show similar comparisons for AK4 jets in each rapidity region. Predictions from NLOJet++ tend to be slightly higher than the measurement, by about 10%, independent of the PDF used in the calculation. This is an effect which was already observed for measurement of jet cross-sections with small cone size at 7 TeV. Predictions from POWHEG seem to agree better with the measurement. The ratios have a stable behaviour around 1 in each rapidity region, while predictions from PYTHIA and HERWIG have a similar behaviour as in the comparisons with AK7 jets.

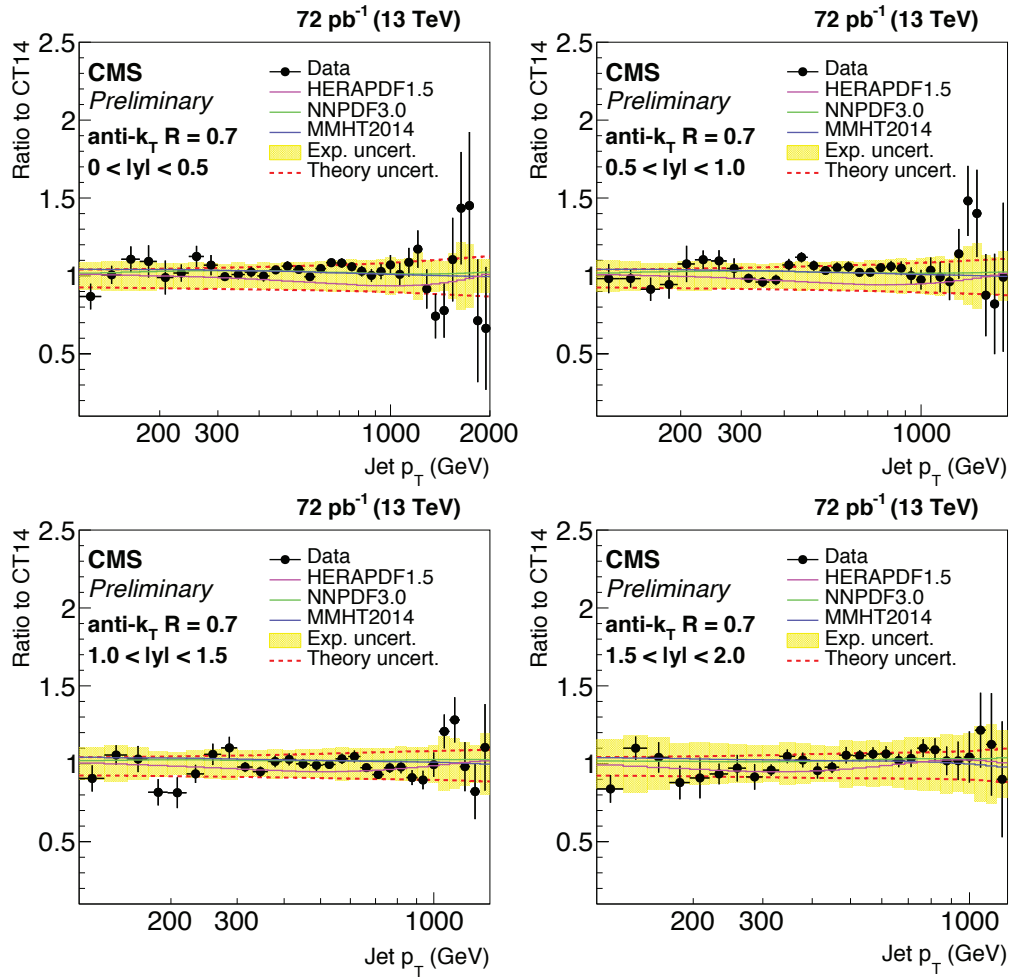


FIGURE 11.3: Ratio of measured values to theoretical prediction from NLOJet++ using the CT14 PDF set and corrected for the NP and electroweak effects. Predictions employing three other PDF sets are also shown for comparison. Jets are clustered with the anti- k_T algorithm with a distance parameter of 0.7. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$

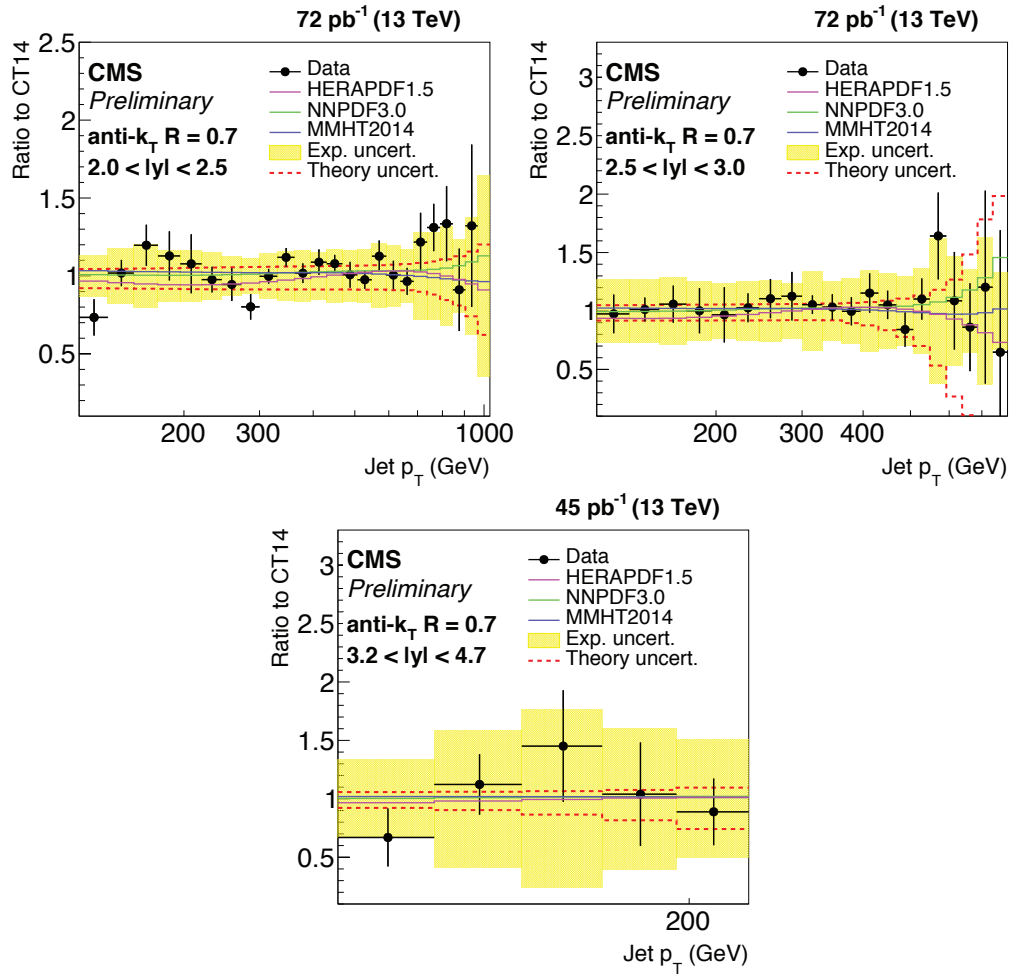


FIGURE 11.4: Ratio of measured values to theoretical prediction from NLOJet++ using the CT14 PDF set and corrected for the NP and electroweak effects. Predictions employing three other PDF sets are also shown for comparison. Jets are clustered with the anti-kt algorithm with a distance parameter of 0.7. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$

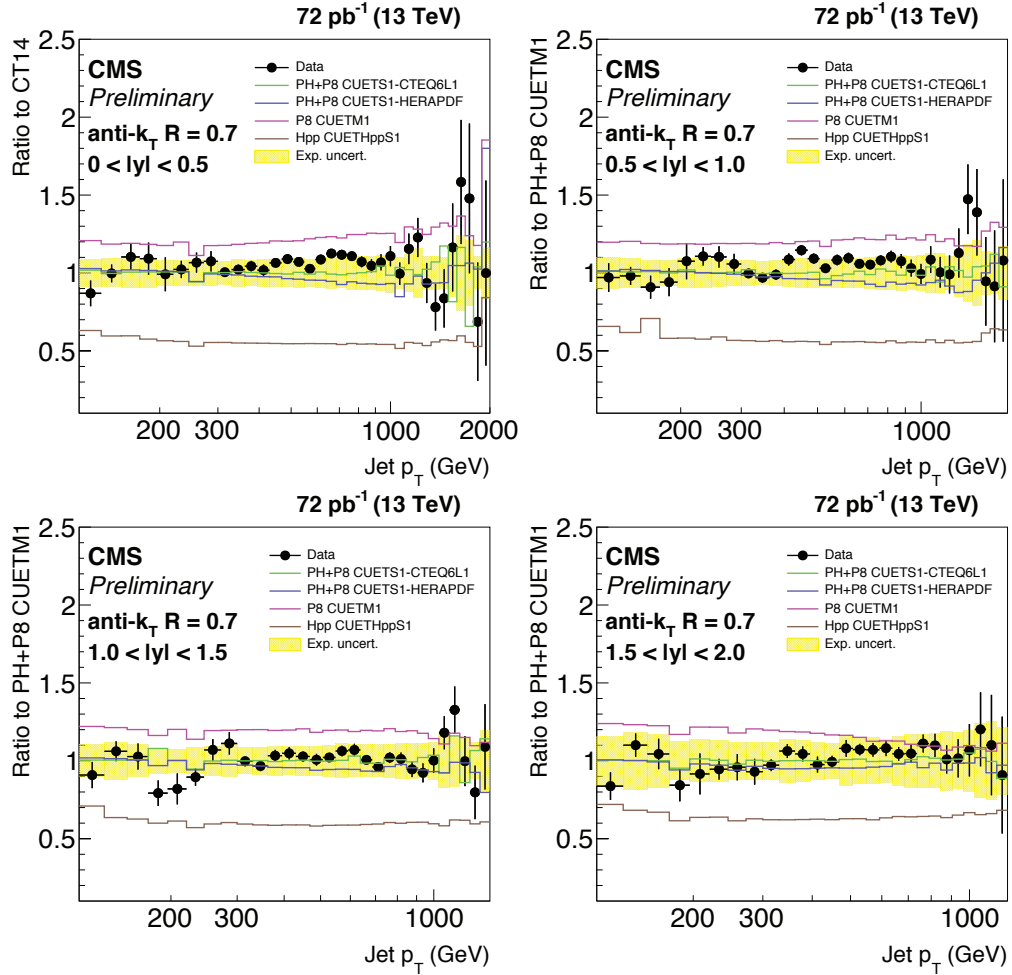


FIGURE 11.5: Ratio of measured values to predictions from POWHEG (PH) + PYTHIA8 (P8) with tune CUETM1. Predictions employing four other MC generators are also shown for comparison, where PH, P8, and Hpp stands for POWHEG, PYTHIA8, and HERWIG++ (HPP), respectively. Jets are clustered with the anti-kt algorithm with a distance parameter of 0.7. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$

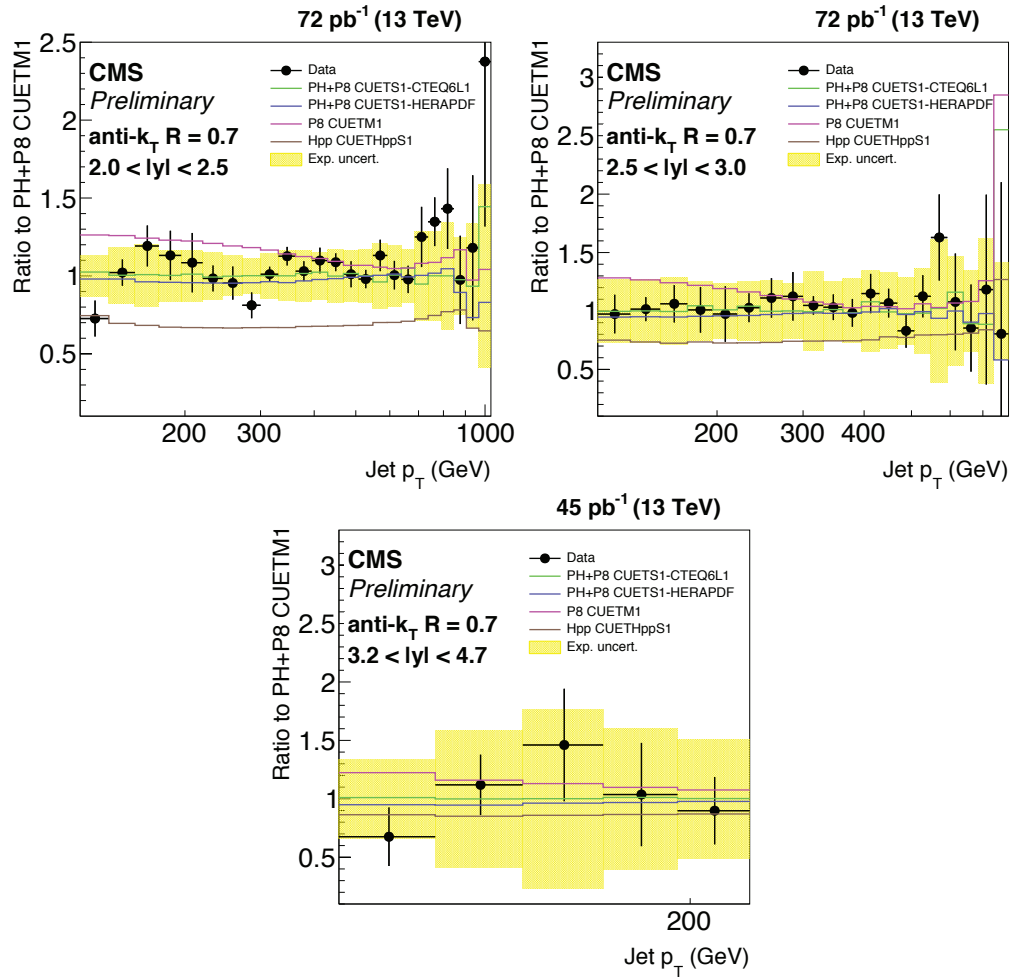


FIGURE 11.6: Ratio of measured values to predictions from POWHEG (PH) + PYTHIA8 (P8) with tune CUETM1. Predictions employing four other MC generators are also shown for comparison, where PH, P8, and Hpp stands for POWHEG, PYTHIA8, and HERWIG++ (HPP), respectively. Jets are clustered with the anti- k_T algorithm with a distance parameter of 0.7. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties.

Different rapidity bins are: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$

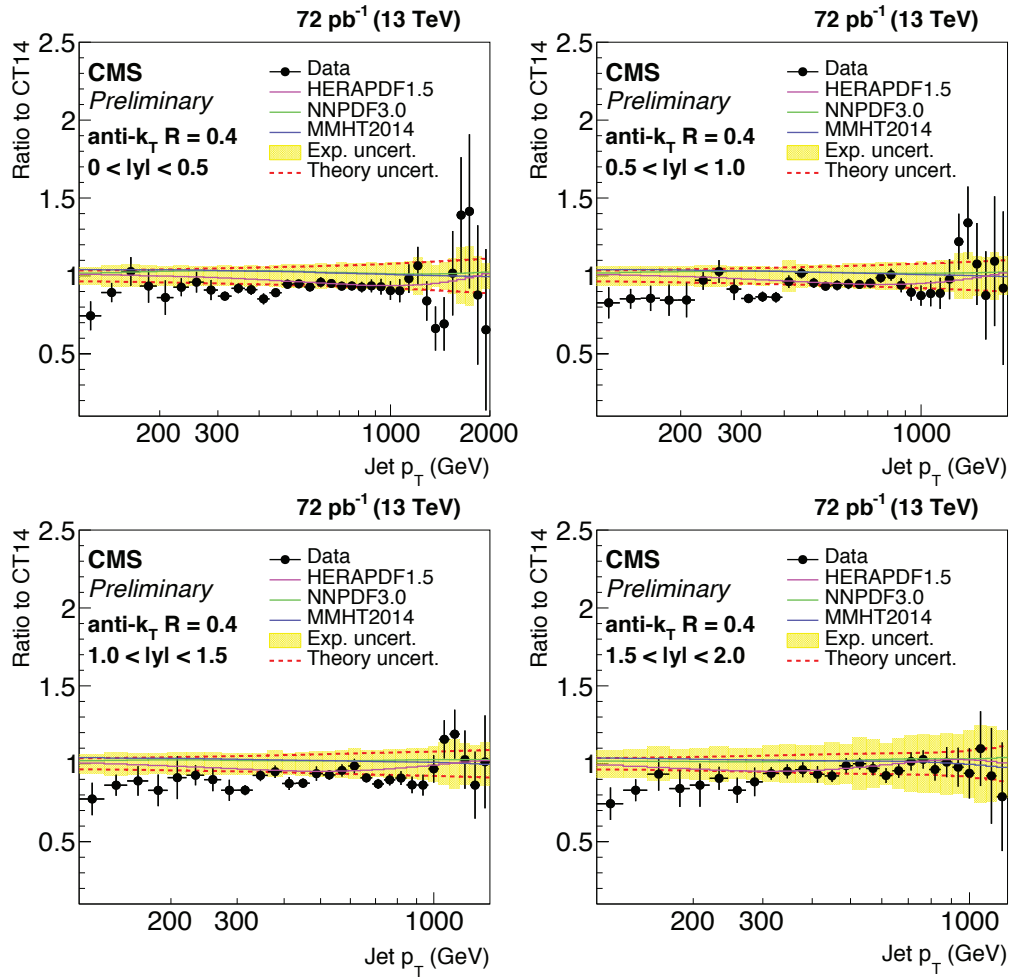


FIGURE 11.7: Ratio of measured values to theoretical prediction from NLOJet++ using the CT14 PDF set and corrected for the NP and electroweak effects. Predictions employing three other PDF sets are also shown for comparison. Jets are clustered with the anti- k_T algorithm with a distance parameter of 0.4. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$

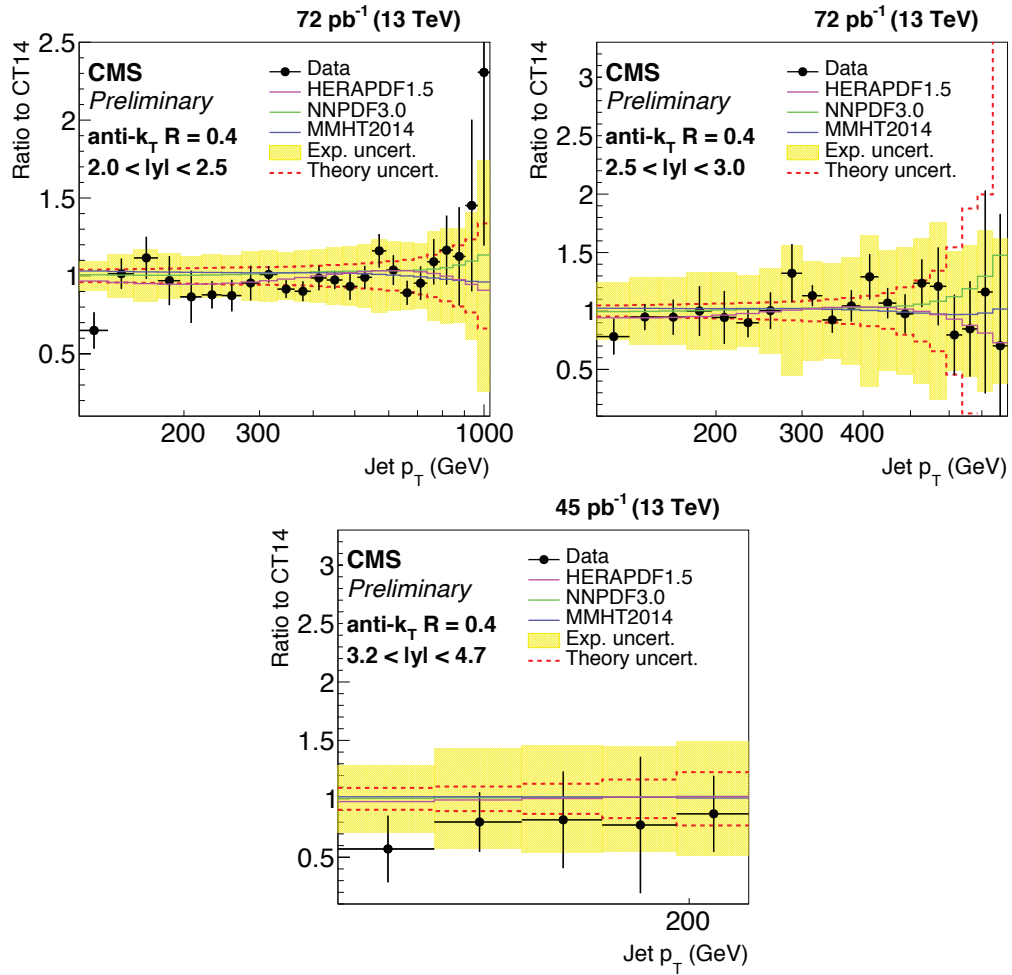


FIGURE 11.8: Ratio of measured values to theoretical prediction from NLOJet++ using the CT14 PDF set and corrected for the NP and electroweak effects. Predictions employing three other PDF sets are also shown for comparison. Jets are clustered with the anti-kt algorithm with a distance parameter of 0.4. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$.

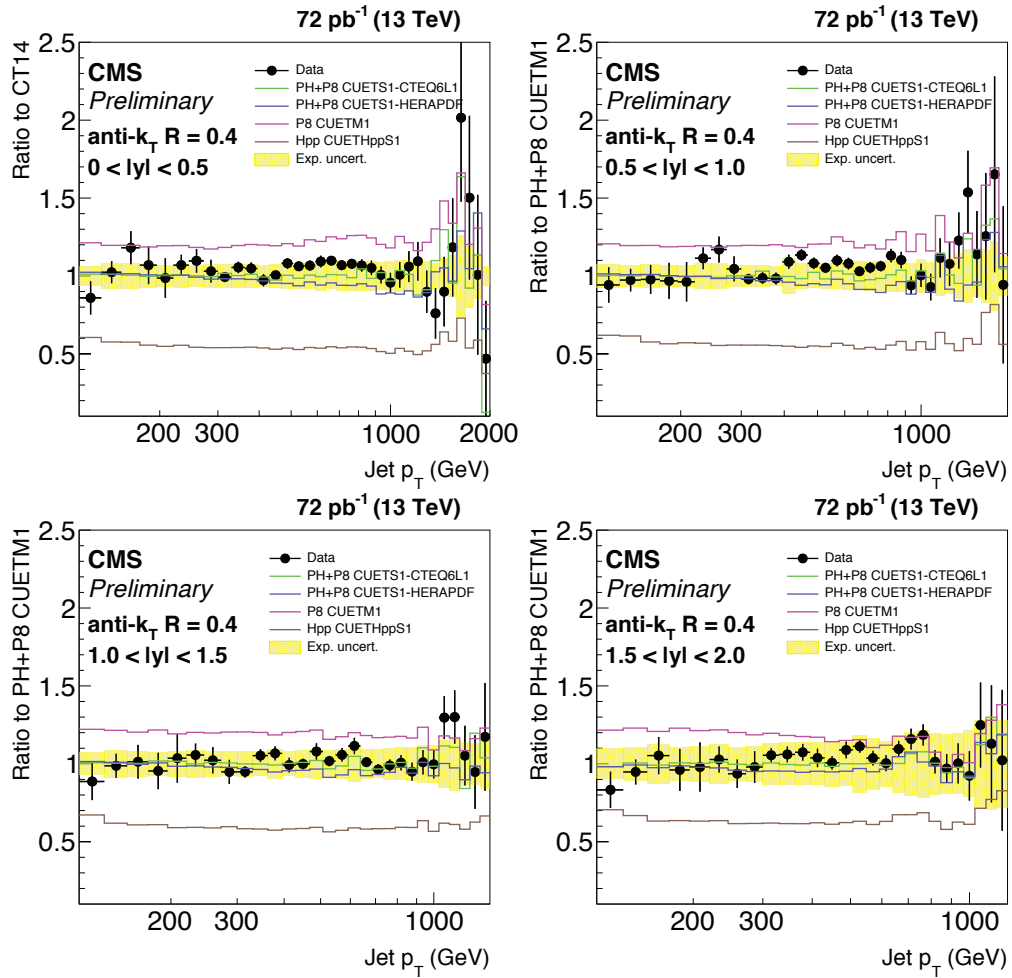


FIGURE 11.9: Ratio of measured values to predictions from POWHEG (PH) + PYTHIA8 (P8) with tune CUETM1. Predictions employing four other MC generators are also shown for comparison, where PH, P8, and Hpp stands for POWHEG, PYTHIA8, and HERWIG++ (HPP), respectively. Jets are clustered with the anti-kt algorithm with a distance parameter of 0.4. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties. Different rapidity bins are: $0.0 < |y| < 0.5$, $0.5 < |y| < 1.0$, $1.0 < |y| < 1.5$, $1.5 < |y| < 2.0$

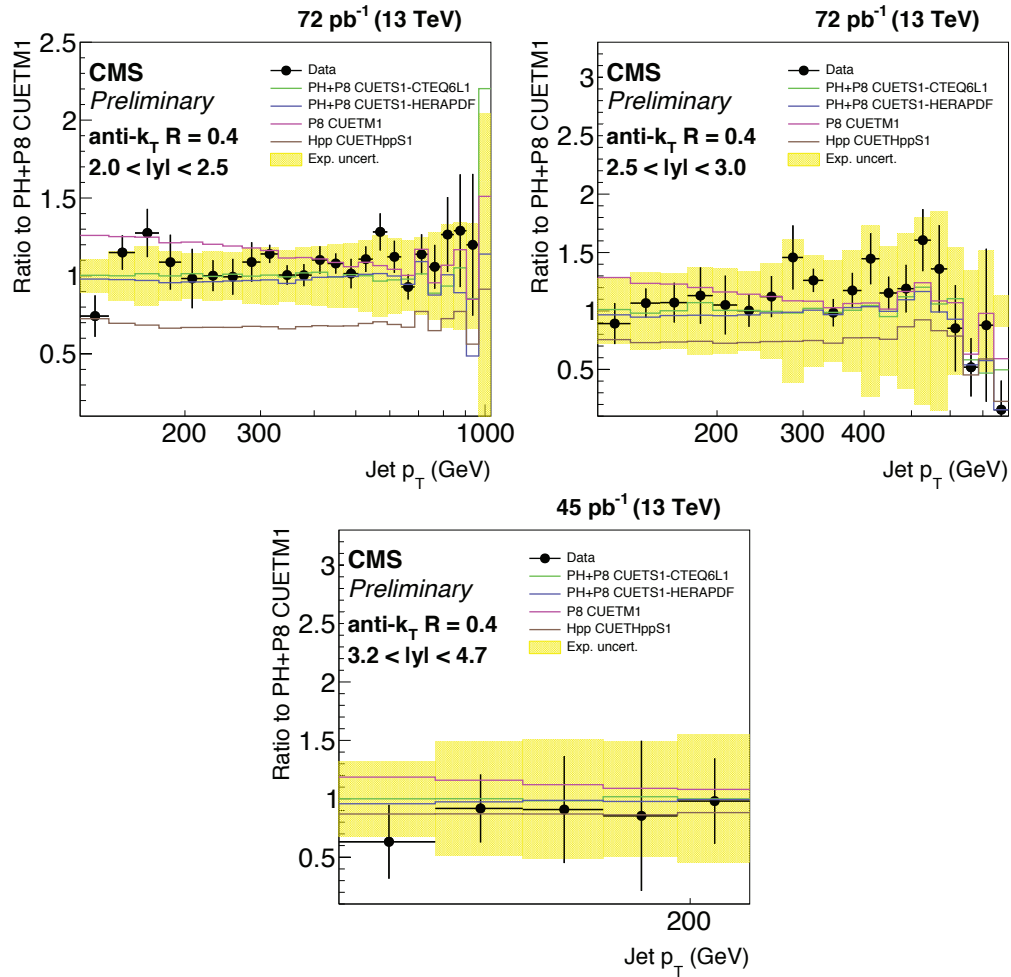


FIGURE 11.10: Ratio of measured values to predictions from POWHEG (PH) + PYTHIA8 (P8) with tune CUETM1. Predictions employing four other MC generators are also shown for comparison, where PH, P8, and Hpp stands for POWHEG, PYTHIA8, and HERWIG++ (HPP), respectively. Jets are clustered with the anti- k_T algorithm with a distance parameter of 0.4. The error bars correspond to the statistical uncertainties of the data and the shaded bands to the total experimental systematic uncertainties.

Different rapidity bins are: $2.0 < |y| < 2.5$, $2.5 < |y| < 3.0$, $3.2 < |y| < 4.7$

Appendix A

Contribution to the Experiment : Bad Component Calibration of the CMS Silicon Tracker

The silicon tracker is the most central part of the CMS Detector. It consists of highly granular silicon microstrip detectors and three layers of silicon pixel detectors. A brief description of the tracker along with other part of the detectors can be found on [3](#). For a more detailed description, one should look into [\[51\]](#).

A.1 Bad Component Calibration

In proton-proton collision, a huge number of charged particles are produced inside the CMS Detector and they travel through the tracker volume producing tracks. These tracks are reconstructed using the information from the tracker which consists of ~ 15000 detector modules with ~ 10 million channels. These channels can go Bad in two ways. Some channels are noisy or hyperactive, they always produce signals irrespective of the presence of any track. We denote them as Hot. On the other hand, sometimes the channels simply do not produce any signal at all, thus we name it Dead. For efficient reconstruction of tracks, a prior knowledge of these Bad channels is necessary. Identification of Bad channels are done during the calibration and the information is stored in the condition database so that it can be accessed during track reconstruction.

A.2 Calibration Procedure

Bad Component Calibration is performed retrieving detector occupancy information during data taking in the Prompt Calibration Loop (PCL). A subset of data sample is used at the PCL and it consists of physics events as well as events selected by calibration triggers, known as “Express Stream”. The PCL runs within a couple of hours of data taking at the central computer facility (Tier0) at CERN. A number of calibration procedures are performed at the PCL and Bad Component Calibration is one of them. A thorough description of the PCL can be found in [\[43\]](#).

In [A.1](#), a schematic diagram of the PCL is shown and different steps of the PCL are described below.

Express Processing: Parallel jobs are run on the “Express Stream” of data and events are reconstructed. The basic input for the calibrations are stored in AlCaReco data sets. All the various AlCaReco products are merged in a temporary data set. In case of Bad Component calibration the AlCaReco products are a set of occupancy histograms for each detector module and are filled up accessing information from the reconstructed events.

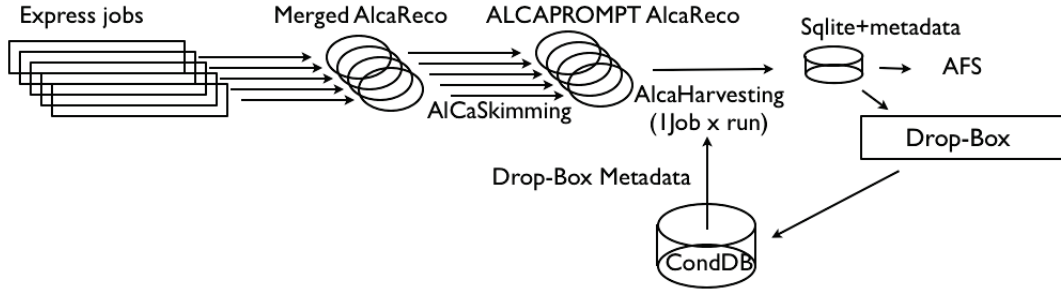


FIGURE A.1: Workflow of Prompt Calibration Loop of the CMS.

ALCaReco splitting: Parallel jobs run on the temporary “merged ALCaReco” data set from above step and write out different data sets for different types of calibrations. In this stage the PCL also runs CPU intensive computations on the ALCaReco products and stores the “aggregated” products in a separate dedicated data set with the special data-tier ALCAPROMPT. This is still parallel processing. All the Lumi Sections (LS) are considered “atomic” meaning that each parallel job still sees 1 or more complete LSs.

ALCaHarvesting: Single job is executed per run on all the ALCAPROMPT files. This is the step where Bad component calibration algorithm is run on the aforementioned histograms. At the end, an sqlite file is produced with the calibration information and is stored on a common accessible storage area.

ConditionsUpload: The sqlite files are uploaded(1 per PCL workflow) to the condition database for calibration while reconstruction of events.

The detector modules or individual channels are found Bad during this process are masked in the condition database. This information is accessed during the reconstruction and the masked modules and channels are ignored during the reconstruction.

A.3 Calibration Algorithm

The charge on each microstrip is read out and amplified by an Analogue Pipeline Voltage (APV25) chip and a chip has 128 channels. Depending on the size of a detector module, a module can have four or six APV chips. Depending on the number of Bad strips an APV, even a whole module can be marked as Bad. The algorithm has following steps to identify Bad channels and the basis is the occupancy histogram for each module :

- Mean and rms (of the median values) are calculated for all the APVs in a specific Layer/Disc in a given position. This is calculated in an iterative way where number of iterations is fixed by a configurable parameter.
- For each APV the median occupancy is calculated first.
- Once the mean and the rms of a group of APVs (same layer/ disc and same position) are found, individual APVs are checked one by one too. An APV is considered Bad if it does not satisfy certain conditions on its mean and median.

- In the next step stray Bad strips are identified through an iterative procedure. There could be single or limited groups of these Bad strips distributed along the detector module.

A.4 Monitoring the Results from the Workflow

There is a monitoring tool which accesses Bad components (APVs, Modules, Strips) from condition data base and creates histograms, Trend Plots where fraction of Bad components are plotted as a function of Interval of Validity (IOV), Log file with the summary list of Bad components (simple text file) and TrackerMaps. TrackerMaps are two dimensional pictorial representation of the strip tracker where each cell represents a detector module. In figure A.2 such a map is shown. The color scale represent the fraction of Bad channels in a given detector. A detector in white implies that there is no Bad strip, while dark blue to red indicates increase in the percentage of Bad strips.

All of these can be accessed through a web interface.

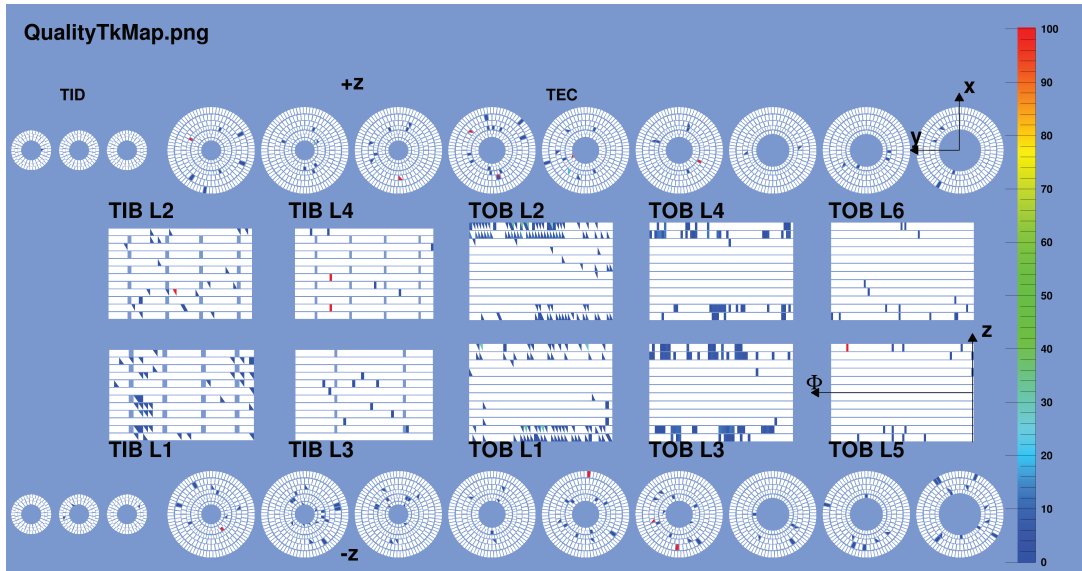


FIGURE A.2: A sample TrackerMap with a few Bad strips.

Appendix B

Contribution to the Experiment : Pulse shape and timing studies in CMS Hadron Calorimeter with Isolated Bunches

The CMS Hadron Calorimeter(HCAL) measures the energy of “hadrons”, particles made of quarks and gluons (for example protons, neutrons, pions and kaons). Additionally it provides indirect measurement of the presence of non-interacting, uncharged particles such as neutrinos. It is a sampling calorimeter meaning it finds a particle’s position, energy and arrival time using alternating layers of “absorber” and fluorescent “scintillator” materials which produce a rapid light pulse when the particle passes through. Special optic fibres collect up this light and feed it into readout boxes where photo-detectors amplify the signal. When the amount of light in a given region is summed up over many layers of tiles in depth, called a “tower”, this total amount of light is a measure of a particle’s energy. A brief description of the tracker along with other part of the detectors can be found on 3. For a more detailed description, one should look into [48].

B.1 Timing and Pulse Shape in HCAL

Timing study is important for the CMS experiment to reject backgrounds from Cosmic Rays, which pass closely to the interaction point and can create fake missing energy objects. These Cosmic Rays arrive randomly and they do not correlate with the LHC bunch crossing time for obvious reason. The tracker does not carry timing information within 25 ns, and hence cannot be used for any meaningful study. But both ECAL and HCAL measure the scintillation light pulses, enabling a timing measurement better than 25ns.

B.2 Isolated Bunch

Proton bunches from LHC has certain spacing. Sometimes, for calibration purpose, LHC delivers data with proton bunches which are far apart from each other. End to end overlap of bunches or out of time pileup is almost negligible in this case. These bunches of protons are called “Isolated Bunches”. They are useful for studying pulse shape and timing studies in HCAL. As these bunches are delivered not so frequently by the LHC, it is important to select data from those bunches efficiently as one needs high energy deposits in the hadron calorimeter to make meaningful studies.

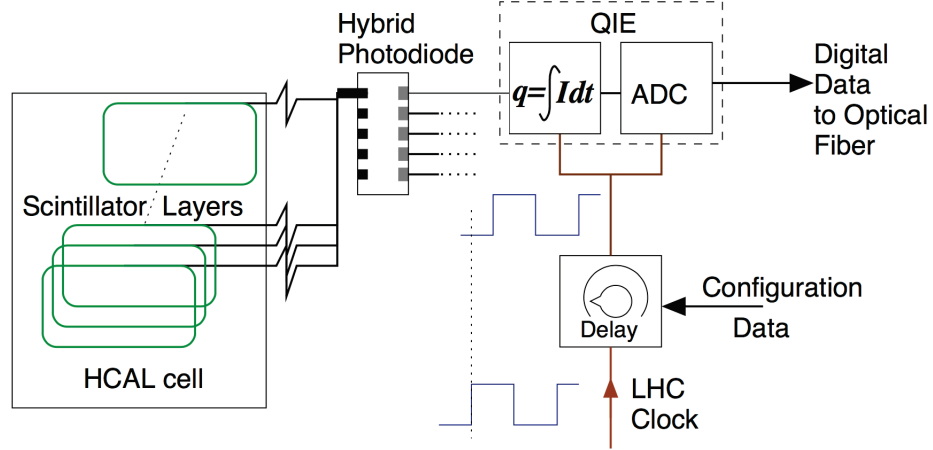


FIGURE B.1: A schematic view of the HCAL front-end readout electronics. The readout for one HCAL cell/channel is shown. Key features are the optical summing of layers, charge integration followed by sampling and digitization, and per-channel programmable delay settings. The “QIE” is a custom chip that contains the charge-integrating electronics with an analog-to-digital converter (ADC). The Configuration Data input defines the sampling delay settings.

B.3 Selection of Isolated Bunch Events

Events with Isolated Bunches are selected from primary data sets with best possible rate. Two different techniques were applied to see if one can obtain a better rate.

B.3.1 Using Offline Filter

An offline filter (AlCaIsolatedBunchFilter) is written to select isolated bunch events from the JetHT primary data set. It is now a part of the CMS software since CMSSW_8_1_0_pre7. At first it has been tested using JetHT primary data set (integrated luminosity of 2.1 fb^{-1}) But the rate of such events is rather low (the fraction of passed events in the data set is 2×10^{-6})

B.3.2 Using a dedicated HLT path

To get a better rate it is useful to produce a special HLT path which can select such events. The HLT path uses two filters:

- the first one selects isolated bunch.
- the second one is a logical OR of several L1 Jet triggers

These two filters are combined in an HLT path and is tested using the ZeroBias primary data set. This rate is found to be 0.9% of the overall rate of isolated bunch crossings. So with a reasonable bandwidth ($\sim 200 \text{ Hz}$) at the Level 1 trigger one can get a few Hz of useful events from this trigger.

The trigger is now a part of the deployed HLT menu. A specific AlCaReco data set path is defined for this.

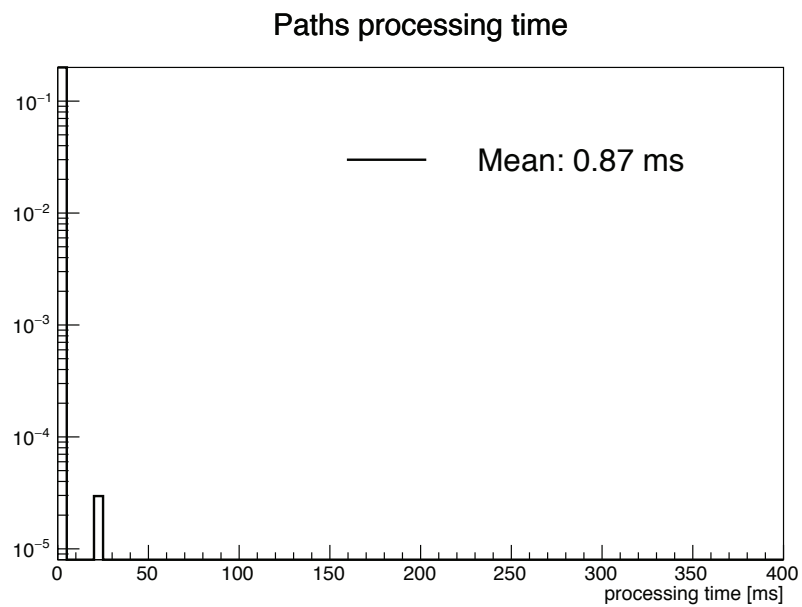


FIGURE B.2: Sample timing plot for the Isolated Bunch HLT

Appendix C

Display of various events

In this Section, interesting event displays from 2015 data are shown. They display clean dijet and multijet events with high p_T objects.

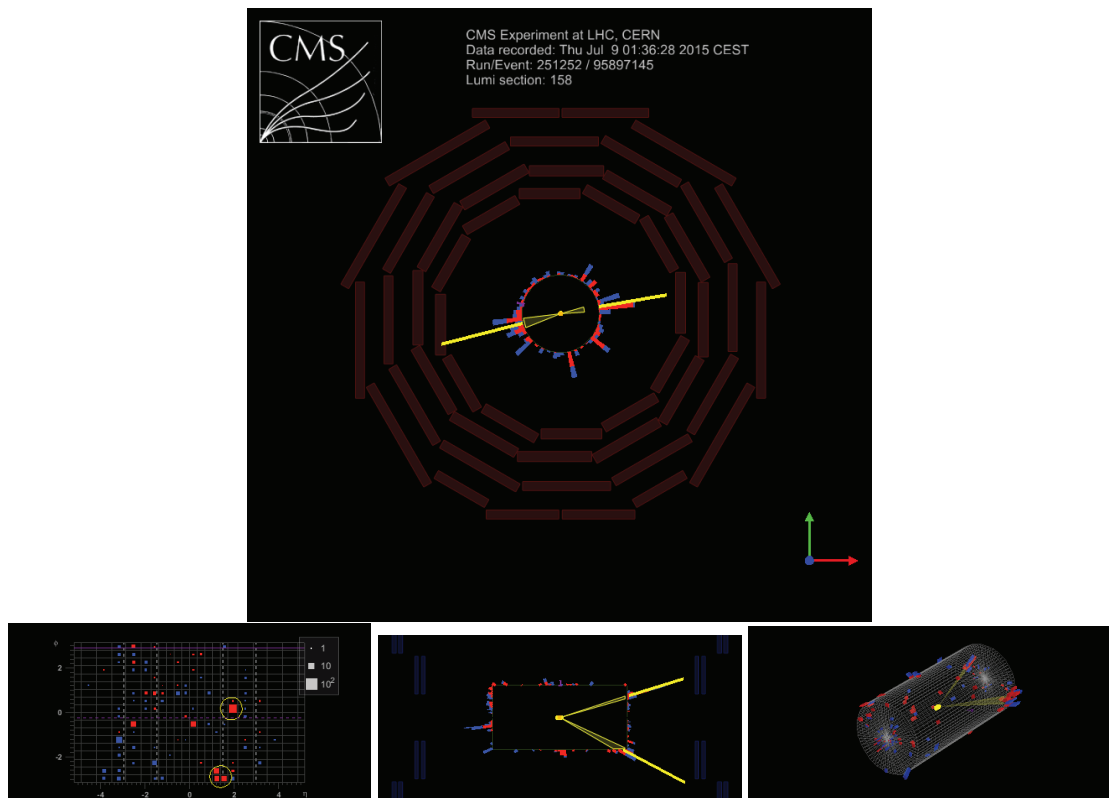


FIGURE C.1: Event display of a two-jet event at 13 TeV in the considered sample.

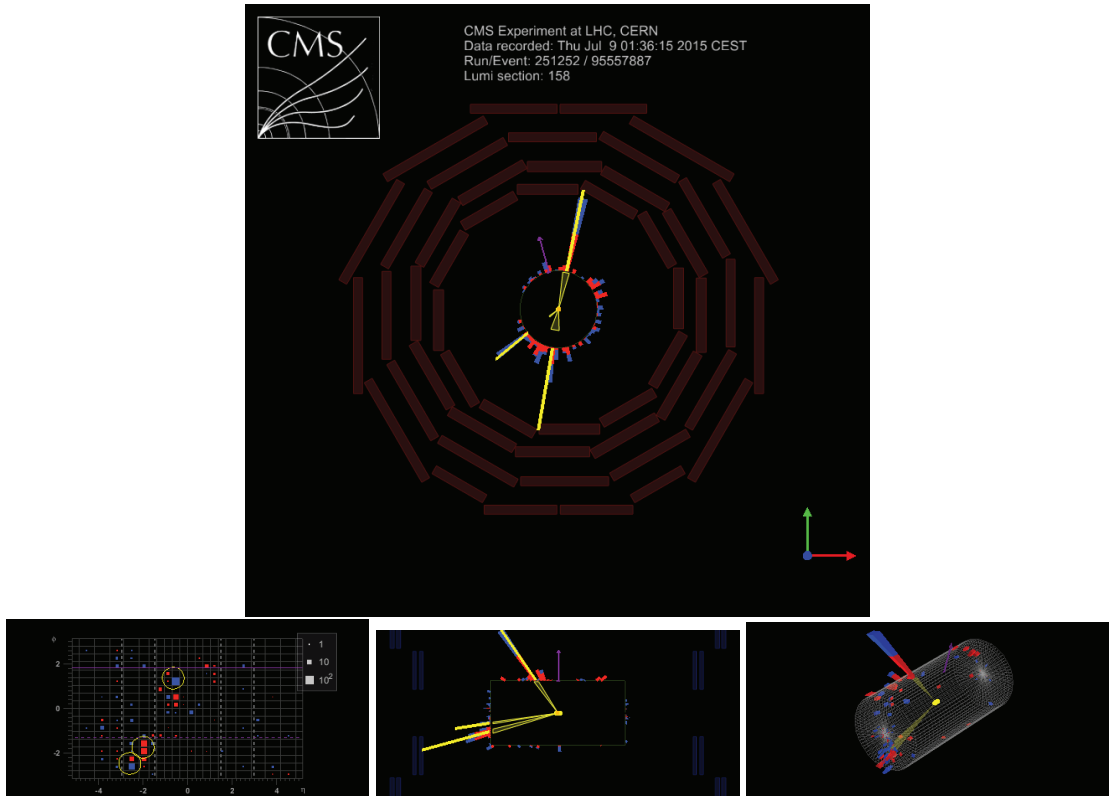


FIGURE C.2: Event display of a three-jet event at 13 TeV in the considered sample.

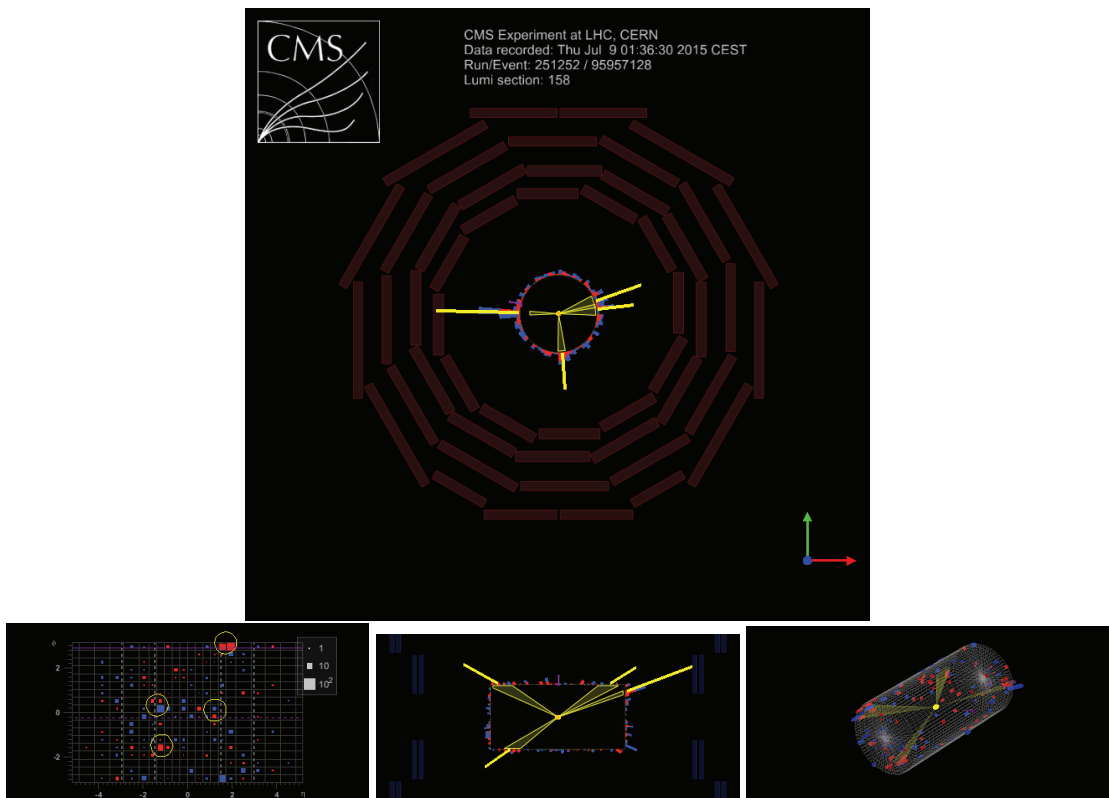


FIGURE C.3: Event display of a four-jet event at 13 TeV in the considered sample.

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