ATL-COM-PHYS-2024-624

QCD Measurements With ATLAS

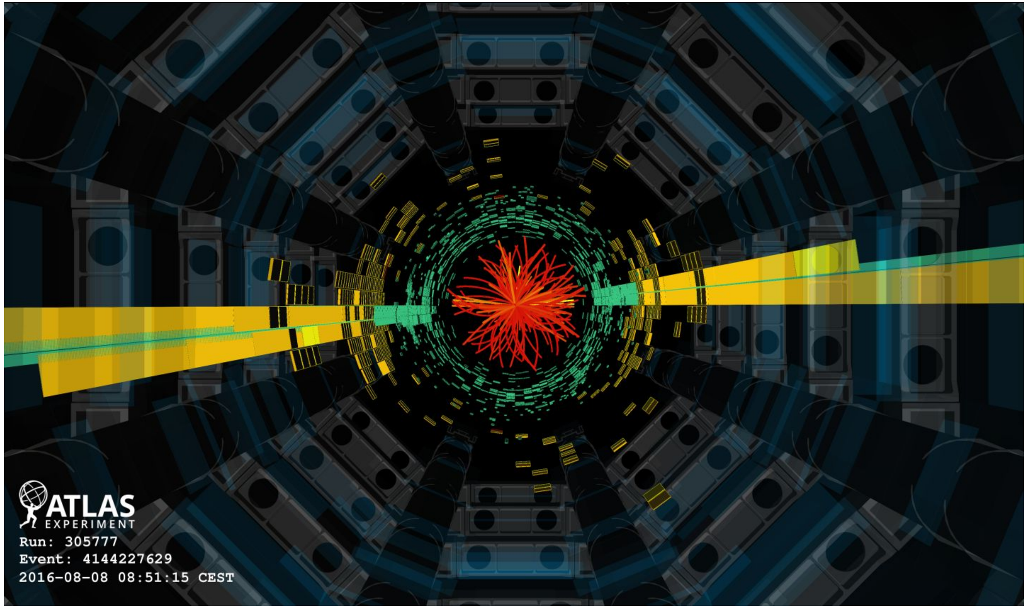
Dionysios Fakoudis
Johannes Gutenberg University Mainz
CEA Saclay

on behalf of the **ATLAS** Collaboration

XIII International Conference on New Frontiers in Physics

Introduction

- **Why QCD?**
  - Still persistent questions:
    - Hadronization
    - Colour confinement
    - Quark Gluon Plasma
    - Parton Distribution Functions
    - Non-Perturbative QCD
    - And Many More…



https://cds.cern.ch/record/2669151

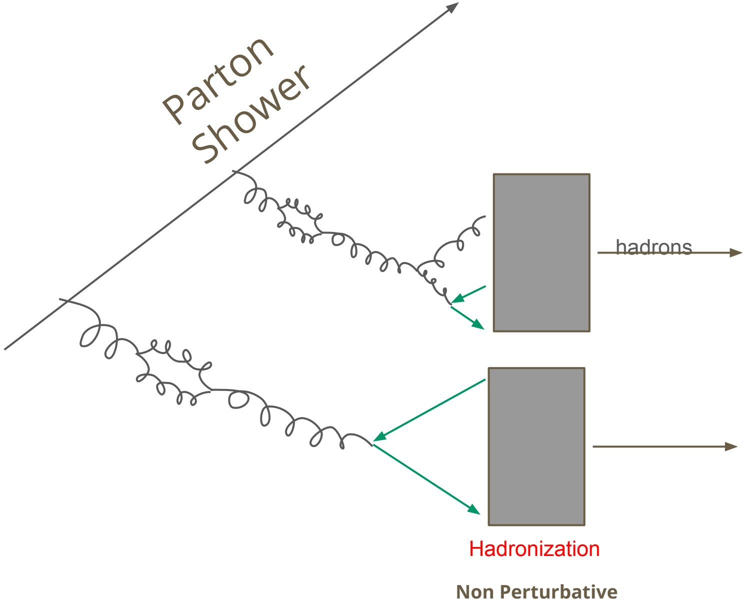
Perturbative QCD:
Short distance - big energies→ α_s small

- Expansion of α_s
- Simulate QCD in orders of α_s

Non Perturbative QCD:
Large distance - Small energies → α_s large, hadronization, colour confinement

- Expansion of α_s Not Possible
- Tuning parameters from data
- Using Lund string model, Lattice QCD e.t.c.

To test existing methods → dive in the jet structure and kinematics



- **New ATLAS results include**:
  - Increased precision on Jet calibration
  - Testing of simulation generators
    - Jet structure studies
    - Kinematics of heavy jets

Introduction

Various Interesting new QCD measurements in ATLAS:

- *'New techniques for jet calibration with the ATLAS detector'*, ***CERN-EP-2023-028 30th March 2023***
- *'Measurements of jet cross-section ratios in 13 TeV proton–proton collisions with ATLAS'*, ***arXiv:2405.20206v1 [hep-ex] 30 May 2024***
- *'Measurement of the Lund jet plane in hadronic decays of top quarks and W bosons with the ATLAS detector'*, ***arXiv:2407.10879v1 [hep-ex] 15 Jul 2024***
- *'Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector'*, ***arXiv:2402.13052v1 [hep-ex] 20 Feb 2024***
- *'Measurement of Jet Track Functions in ATLAS Run 2 Data'*, ***ATLAS-CONF-2024-012 30 July 2024***
- *'Underlying-event studies with strange hadrons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, ***arXiv:2405.05048v1 [hep-ex] 8 May 2024***

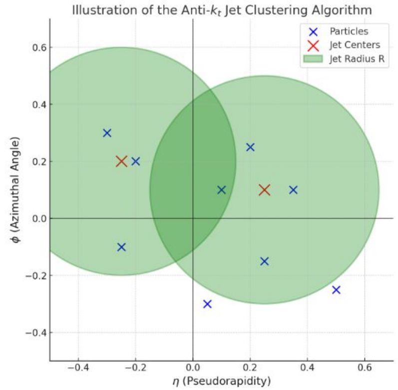
Jets in ATLAS

- Introduction
    - ATLAS Detector
    - **Jets in ATLAS**
- Jet Calibration
- Measurements of jet cross-section ratios
- Measurements of Lund jet Plane with top and W jets
- Sub-jet multiplicities in dijet events
- Measurement of jet track functions
- Underlying events studies with Strange Hadrons

Jets in ATLAS

- Reconstructed by **energy deposits** in the electromagnetic and hadronic calorimeters.
  - Associated with tracks in the Inner Detector
- Produced by **hadronization of gluons/quarks** in inelastic hadron collisions
- Key features:
  - Anti-kT algorithm
    - Grouping of particles and energy deposits into jets
  - Jet Energy Scale Calibration (JES)
  - Jet Multiplicity
    - number of jets reconstructed in event. Events with high jet multiplicity -> complex processes, ex: top quarks or Higgs bosons.
  - Lund jet Plane:
    - Representation of jet structure and evolution

- Anti-kT algorithm:
  - Jet reconstruction method
  - Main parameter is the **angular distance R**, which drives the jet radius



Small R Jets:

- quark/gluon initiated mostly
- Reconstructed with anti-kT R=0.4

Large R Jets:

- Boosted Higgs,W,Z e.t.c. hadronic decays
- Reconstructed with anti-kT R=1

Jet Calibration

- Introduction
    - ATLAS Detector
    - Jets in ATLAS
- **Jet Calibration**
- Measurements of jet cross-section ratios
- Measurements of Lund jet Plane with top and W jets
- Sub-jet multiplicities in dijet events
- Measurement of jet track functions
- Underlying events studies with Strange Hadrons

Jet Calibration

2021 publication:' ***Jet energy scale and resolution measured in proton–proton collisions at √s = 13 TeV with the ATLAS detector'***

2023 publication:***'New techniques for jet calibration with the ATLAS detector'***

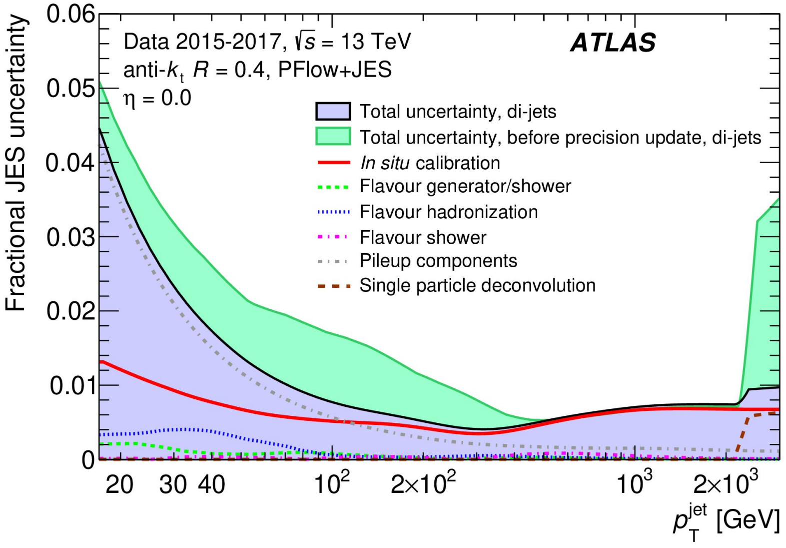
Motivation:

- Calibration essential for **physics precision**
- Jets are complex, sensitive to **miss-simulations**:
    - Detector
    - Magnetic field
    - Flavour Physics

- Two stages:
    - MC based:
        - Correct MC scale to truth Scale
    - In Situ (Data Based)
        - Correct for remaining differences between data and MC

Jet Calibration (Final JES uncertainty result)

- Decreased uncertainty:
    - MC based calibration:
        - Jet Flavour Response
            - Impact of flavour - jet initiation
            - Update: Impact factorised → better understood
            - Flavour uncertainties reduction → large reduction at low/medium pT
    - Data based:
        - MC modeling
        - Single particle deconvolution uncertainties large reduction at high pT



arXiv:2405.20206v1 [hep-ex] 30 May 2024

Figure 1: The jet energy scale uncertainty for a dijet flavor composition is shown. A comparison is done for the updated and the precious uncertainty estimation.

Total list of uncertainties in Backup

Measurements of jet cross-section ratios

- Introduction
    - ATLAS Detector
    - Jets in ATLAS
- Jet Calibration
- **Measurements of jet cross-section ratios**
- Measurements of Lund jet Plane with top and W jets
- Sub-jet multiplicities in dijet events
- Measurement of jet track functions
- Underlying events studies with Strange Hadrons

arXiv:2405.20206v1 [hep-ex] 30 May 2024

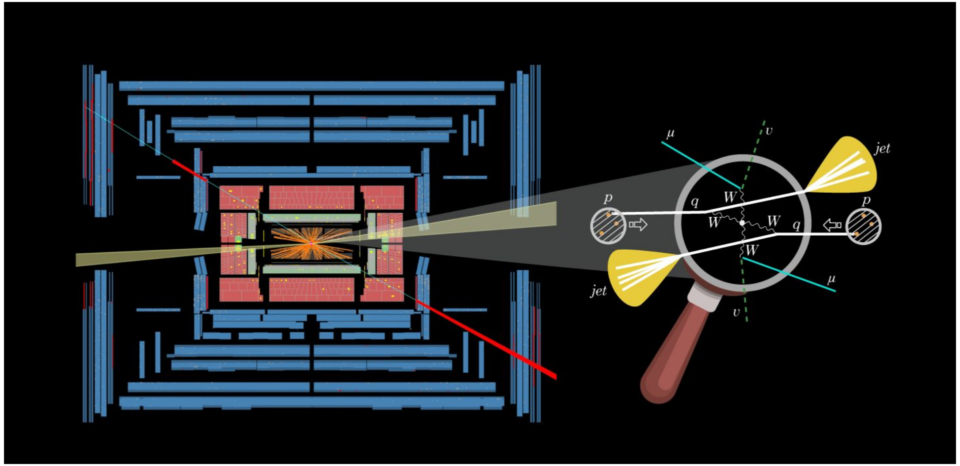
Measurements of jet cross-section ratios

- ***'Measurements of jet cross-section ratios in 13 TeV proton–proton collisions with ATLAS'***

Motivation:

- ❖ Study MC generators (NLO & NNLO) vs Data, through cross section measurements, for variables
  - ➢ Sensitive to jet energy scale
  - ➢ Angular distribution of radiation
    - ■ **Measurements sensitive to QCD**
    - ■ **Perturbative - Non perturbative regimes**

- Measured observables:
  - ○ H_{T2}
    - ■ $\mathbf{H_{T2}=p_{T,1}+p_{T,2}}$
    - ■ proxy for energy scale of hard-scattering interaction
  - ○ Δy_{jj}
    - ■ **Δy** between leading jets
    - ■ Sensitive vector-boson scattering/fusion (VBS/VBF)



https://cds.cern.ch/images/ATLAS-PHOTO-2020-037-4

Measurements of jet cross-section ratios (Results)

$H_{T2}=p_{T,1}+p_{T,2}$

- MC generators:
    - Pythia: LO + PS (string had. model)
    - Herwig7: LO + PS (cluster had. model)
    - PH+Pythia: NLO + PS (string had. model)
    - PH+Herwig: NLO + PS (cluster had. model)
    - Sherpa (Lund string had. model)
    - Sherpa (2.2.5)
- Significant difference seen in large **Δy_{jj}** and m_{jj} (not shown here)

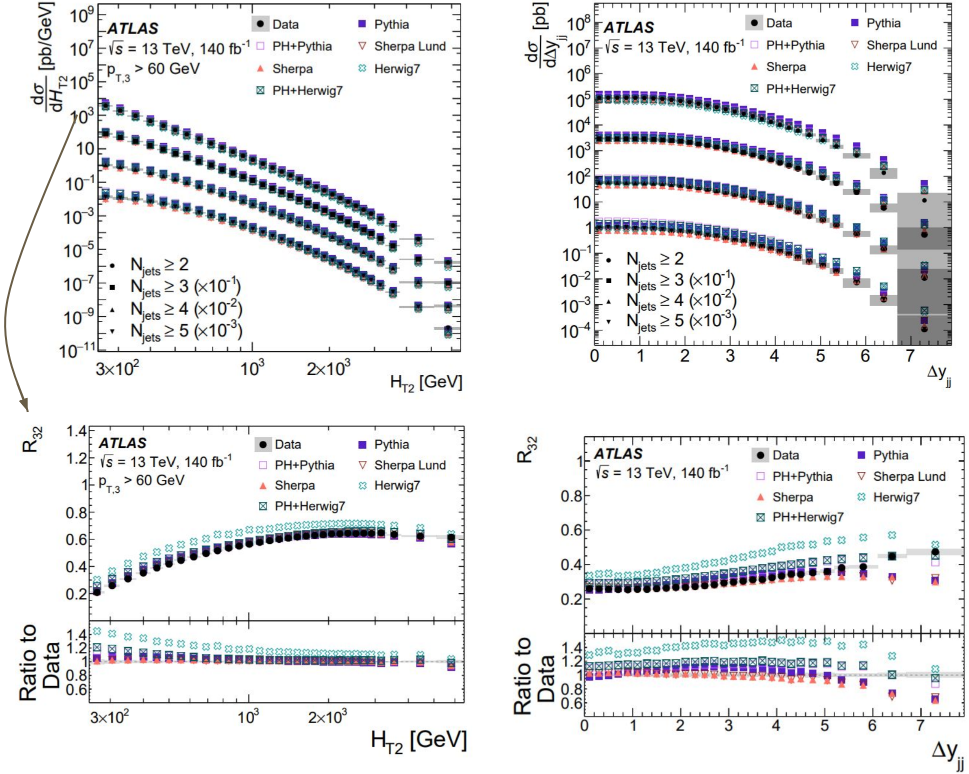


Figure 2: Differential cross section to H_{T2} and Δy_{jj} for different jet multiplicity (top) and cross section ratios N_{jets}>3 /N_{jets}>2: R_{32} (bottom)

arXiv:2405.20206v1 [hep-ex] 30 May 2024

Measurements of jet cross-section ratios (Results)

$H_{T2}=p_{T,1}+p_{T,2}$

- **NNLO H_{T2}** well modeled in all $p_{T,3}$ bins
  (only 1rst one shown here)

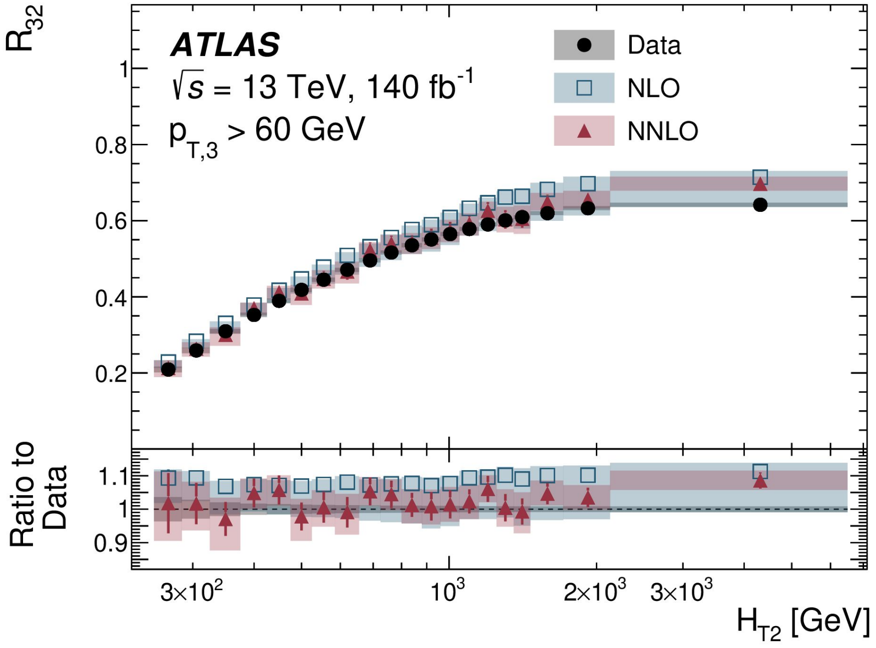


Figure 3: NLO and NNLO comparison for R_{32}

arXiv:2405.20206v1 [hep-ex] 30 May 2024

Measurements of Lund Plane with top and W jets

- Introduction
  - ATLAS Detector
  - Jets in ATLAS
- Jet Calibration
- Measurements of jet cross-section ratios
- **Measurements of Lund jet Plane with top and W jets**
- Sub-jet multiplicities in dijet events
- Measurement of jet track functions
- Underlying events studies with Strange Hadrons

arXiv:2407.10879v1 [hep-ex] 15 Jul 2024

Lund jet Plane,
Jet substructure representation

- **Lund diagrams** are a theoretical representation of phase space within jets
- x axis → **R of parent jet/emission angle** → represents the relative angle between the emitted parton and the parent parton. It's related to the scale of the emission.
- y axis → **Relative transverse momentum**: pт of the emitted parton relative to the parent parton + emitted parton pт
- Different regions correspond to different processes during a jet evolution:
  - **Soft and collinear Emissions:** upper-right region
  - **Hard and wide-angle emissions:** lower-left region

C/A algorithm representation

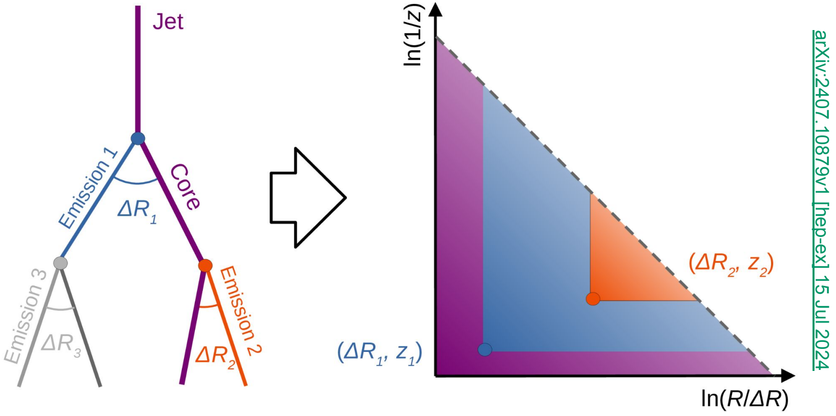


Figure 4: Jet evolution (right) and Lund plane (left) with x axis:**R of parent jet/emission angle** and y axis: **Relative Ttransverse momentum (1/z)**

$$z = \frac{p_{\mathrm{T}}^{j}}{p_{\mathrm{T}}^{i} + p_{\mathrm{T}}^{j}}$$

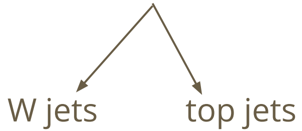
$$\Delta R^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

With i core and j emission

Measurements of Lund jet Plane with top and W

- Paper: ***'Measurement of the Lund jet plane in hadronic decays of top quarks and W bosons with the ATLAS detector'***
- First measurement of the Lund Jet Plane (LJP) in ATLAS for:
    - Hadronic decays of boosted heavy particles
    - R=1.0 → anti-k_T algorithm
- Motivation:
    - **Jet complex structure and evolution**
    - Jet emissions sensitive to
        - **soft, hard QCD**
        - Hadronization
    - Kinematics of top pairs sensitive to **α_s.**
    - Test MC generators kinematics:
        - Perturbative and Non Perturbative QCD regime
    - Test of Jet reconstruction algorithms used in ATLAS

- Jet clustering with **C/A algorithm**
- Observable: **Lund Plane**
- Jets:
    - anti-k_T R=1.0
    - $p_T > 350$ GeV
    - Events:
    - tt → W + b


W jets

top jets

Measurements of Lund jet Plane(Results)

- Good separation of W and top jets in: **$\ln(1/z) < 1.5$, $\ln(R/\Delta R) < 1.5$**
- Low ΔR , z, high density regions:
    - Transition between perturbative and non-perturbative regimes
    - $k_T \sim \Lambda_{QCD}$
    - α_s ↑ emission density ↑
- Upper right corner:
    - $k_T < \Lambda_{QCD}$
    - Non perturbative regime

top jets

W jets

arXiv:2407.10879v1 [hep-ex] 15 Jul 2024

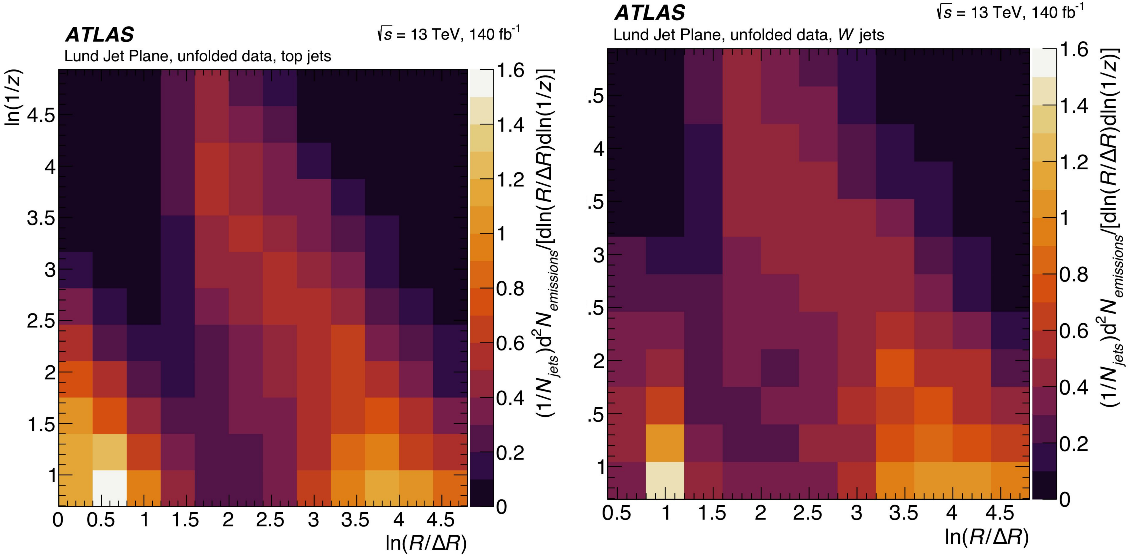


Figure 5: Emission density in Lund Plane for top jets (left) and w jets(right) per jet

Measurements of Lund jet Plane(Results)

- Comparison of Lund Plane **Simulation** and **Data** derived.
- Simulation prediction derived with multiple generators (more MC generators in paper)
  - Powheg+Pythia 8
  - Powheg+Pythia 8 (MEC Off): Matrix Element Corrections off
  - Powheg+Pythia 8 (RTT)
  - MadGraph5_aMC@NLO+Pythia 8
  - Sherpa 2.2.10
- Agreement in most regions
- Tensions in central region
  - Mostly for W jets
    - In 2.5 to 3.5 in ln(R/ΔR) large tensions between all prediction models and Data

top jets

W jets

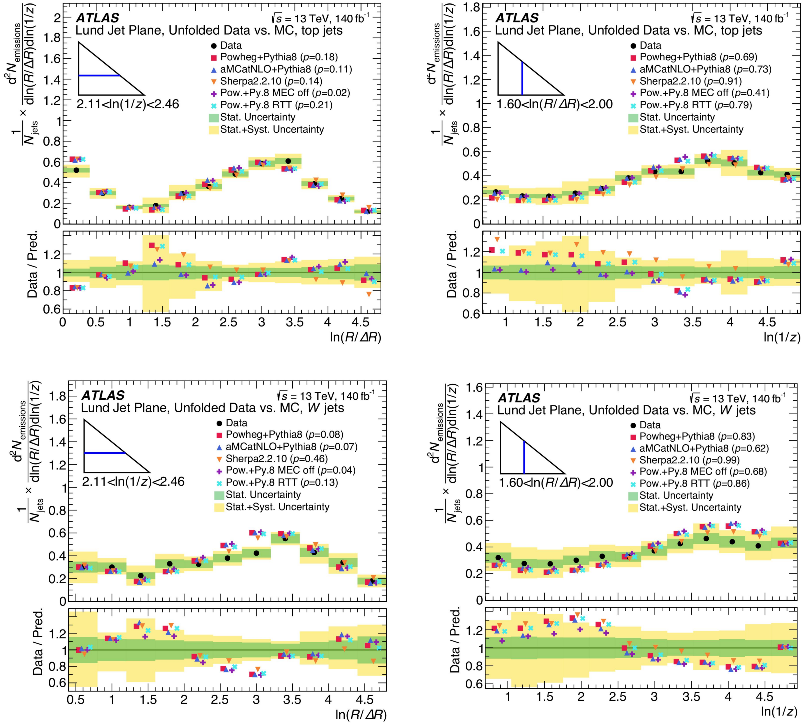


Figure 6: Lund Plane Profiles for top jets (top row) and W jets (bottom row) for horizontal (left column) and perpendicular (right column) slices, comparing nominal (red square) MC prediction and other MC generator with data with the corresponding statistical and systematic uncertainty. Local p-values for the bins in the slice are shown for each prediction

arXiv:2407.10879v1 [hep-ex] 15 Jul 2024

Sub Jet Multiplicities in di-jet Events

- Introduction
  - ATLAS Detector
  - Jets in ATLAS
- Jet Calibration
- Measurements of jet cross-section ratios
- Measurements of Lund jet Plane with top and W jets
- **Sub-jet multiplicities in dijet events**
- Measurement of jet track functions
- Underlying events studies with Strange Hadrons

Sub Jet Multiplicities in di-jet Events

- ***'Measurements of Lund subjet multiplicities in 13 TeV proton-proton collisions with the ATLAS detector'***
- Motivation:
  - Studies of multiplicities using Lund Formalism:
    - Test of MC generators
      - Soft, hard QCD regimes
      - Final State multiplicities
      - Possibility of tuning them in the future
- Jet clustering with **C/A algorithm**

- Observables:
  - **N_{Lund}:** Number of Emissions
  - **$N_{\text{Lund,Primary}}$:** Number of splittings of core of jet

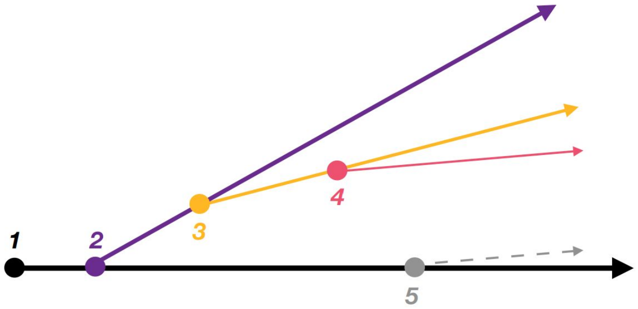


Figure 7: Example of Jet evolution with **$N_{\text{Lund}} = 4$, $N_{\text{Lund,Primary}} = 2$**

arXiv:2402.13052v1 [hep-ex] 20 Feb 2024

- k_t: momentum of emission relative to the core

$$k_t = p_{\mathrm{T}}^{\text{emission}} \cdot \Delta R(p^{\text{emission}}, p^{\text{core}})$$

Sub Jet Multiplicities in di-jet Events (Results)

- MC generators:
  - Pythia
  - Powheg + Pythia
  - Sherpa (Lund string model)
  - Sherpa 2.2.5
  - Sherpa 2.2.11
  - Sherpa (DIRE)
  - Sherpa (Alaric)
  - Herwig (Angular Ordering)
- **Herwig** (Angular Ordering) best description of Data
  - Fails in Non Perturbative regime (high multiplicity and k_T > 1.0 GeV)
- **Sherpa** recent version
  - Better agreement in Non Perturbative regime
- **Pythia**
  - Discrepancy for high multiplicities

Emission
k_T > 1.0 GeV

N of emissions

Number of splittings of Primary jet

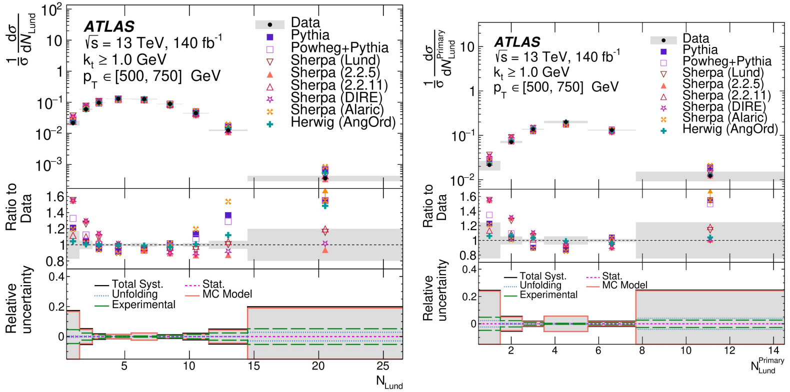


Figure 8: Differential cross section of N_{Lund} and $N_{Lund,Primary}$

arXiv:2402.13052v1 [hep-ex] 20 Feb 2024

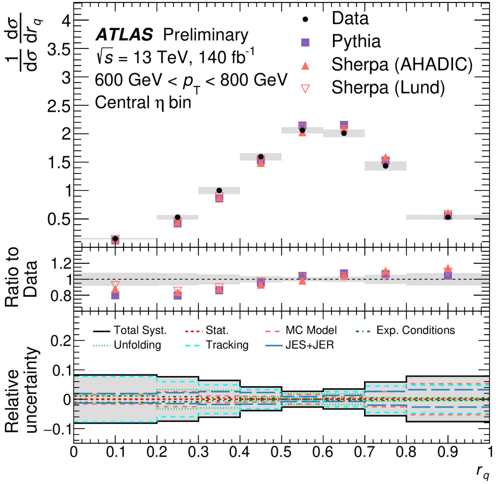
Measurement of Jet Track Functions

- Introduction
  - ATLAS Detector
  - Jets in ATLAS
- Jet Calibration
- Measurements of jet cross-section ratios
- Measurements of Lund Plane with top and W jets
- Sub-jet multiplicities in dijet events
- **Measurement of Jet Track Functions**
- Underlying events studies with Strange Hadrons

ATLAS-CONF-2024-012

Measurements of Jet Track Functions

- ***'Measurement of Jet Track Functions in ATLAS Run 2 Data'***
- Motivation:
  - Test of Jet Track Functions
    - Jet Substructure
    - Non Perturbative regime
    - Insights in Hadronization



ATLAS-CONF-2024-012

- Observables:
  - Track Functions:
    - describe energy distribution of charged hadrons from quarks/gluons fragmentation

$$\mathbf{r_q = p_{T,charged} / p_{T,all}}$$

Where, $p_{T,charged}$ → p_T sum of charged particles

$p_{T,all}$ → p_T of overall jet

  - Cumulants & Moments of **rq**:
    - Fragmentation functions
    - Non-linear renormalization group evolution of correlations in the hadronization process

Measurements of Jet Track Functions (Results)

- Cumulants of **r_q** as a function of Jet p_T
  - Data
  - Pythia + Next Leading Order Logarithm of RG flow
- Compare → direction of flow
- Divergence between MC and Data at high energies
- Higher Jet p_T is needed to investigate further

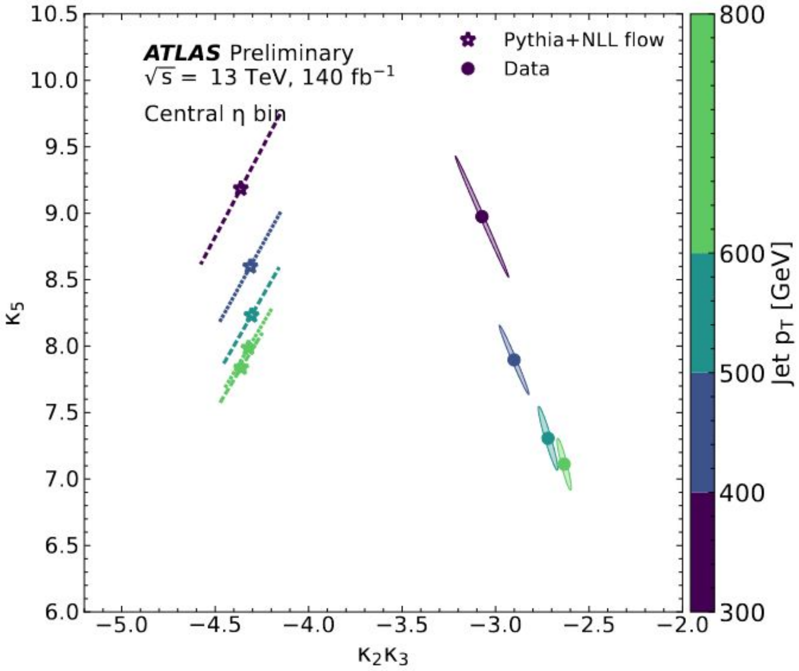


Figure 9: r_q cumulatives as a function Jet p_T (z - axis)

ATLAS-CONF-2024-012

Underlying-event studies with strange hadrons

- Introduction
    - ATLAS Detector
    - Jets in ATLAS
- Jet Calibration
- Measurements of jet cross-section ratios
- Measurements of Lund Plane with top and W jets
- Sub-jet multiplicities in dijet events
- Measurement of jet track functions
- **Underlying events studies with Strange Hadrons**

UE With Strange Hadrons

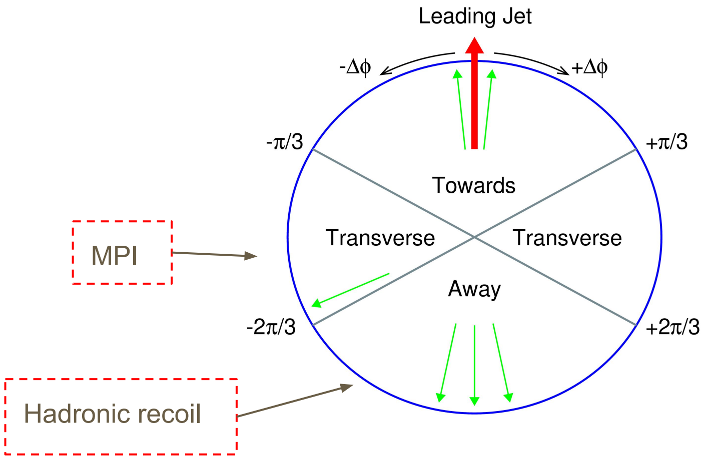
- Paper:***'Underlying-event studies with strange hadrons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector'***
- Motivation:
  - **Underlying events** → reveal in-jet kinematics and structure
  - Give insight to "tune" parameters of hadronisation process
    - Sensitive to Multi Parton Interaction (MPI) –> soft processes
  - $\mathrm{Mass}_{\text{s-quark}} \sim \Lambda_{\mathrm{QCD}}$ interplay between kinematic effects and soft QCD

- Observables:
  - Production rate of K_S, Λ
    - Relative to primary Jet p_T
- MC generators:
  - EPOS-LHC:
    - Used for heavy ion collisions
    - Simulation of collective effects in core of jet
    - Lacks hard scattering
  - Pythia 8
    - A2: Standard Pythia, ATLAS tuned
    - MONASH + CR: Tunes Soft QCD + FInal State Hadronization

UE With Strange Hadrons (Analysis Strategy)

- Analysis repeated
    - For azimuthal regions relative to the primary jet
    - as a function of:
        - Leading jet pT
        - multiplicity of prompt charged-particles in the transverse regions (not shown here)

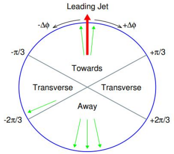
- Analysis is performed to coordinates relative to the leading jet in the transverse plane:



arXiv:2405.05048v1 [hep-ex] 8 May 2024

Figure 10: Illustration of the underlying-event regions relative to the leading jet

UE With Strange Hadrons (Results)



- Underestimation in low p_T (0-4 GeV)
- EPOS-LHC
  - Good performance for soft regime
- Python8 A2
  - Worse performance in all regions
- Python MONASH + CR
  - Better performance in low p_T , Towards region

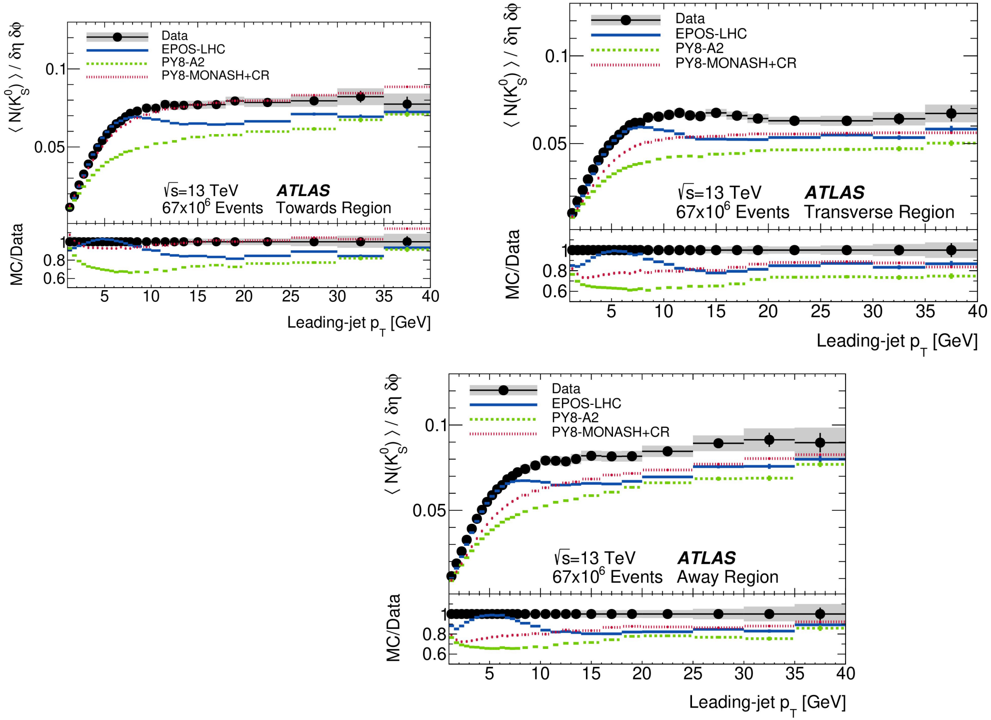


Figure 11: Production rate of Ks, normalised to η,φ

arXiv:2405.05048v1 [hep-ex] 8 May 2024

Summary

Jet Calibration:

- Improvements in precision and uncertainty in respect to Run2 previous publication (2021)
- Uncertainty:
    - **1%** relative uncertainty in **medium and high p_T**

Compared MC generators:

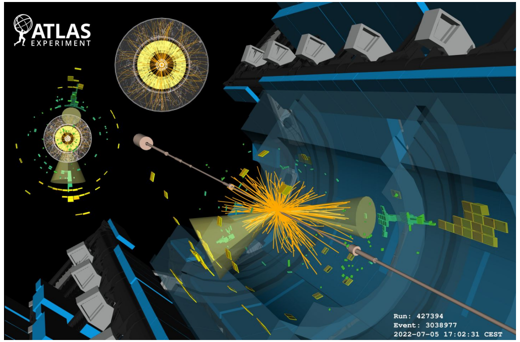
- Cross section ratios
- Lund Plane observables - multiplicities
- Underlying events

Conclusions:

- Generators different response in Soft and Hard QCD regimes
- Larger disagreements between Data and MC in non perturbative regimes
- **Obtained useful results for generators tuning**

Questions?

Paving the way for a precise and productive ongoing Run 3



Run 3 Event

BackUp

ATLAS detector

- Multi purpose detector
- Operating in the ring of **Large Hadron Collider**
- Three major systems
  - Inner detector (tracker) [|η|<2.5]
  - **Calorimeters** [|η|<4.9]
  - Muon spectrometer [|η|<2.7]

- ATLAS calorimeter system:
  - Sampling Calorimeter
  - Electromagnetic calorimeter
    - Liquid Argon
  - Hadronic Calorimeter
    - Crystal scintillator (Barrel)
    - LAr (EndCaps)

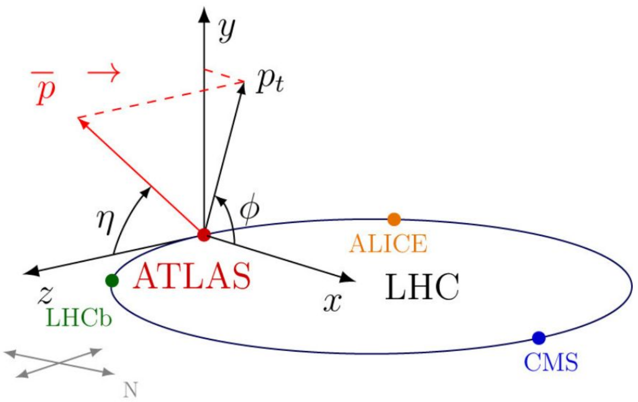
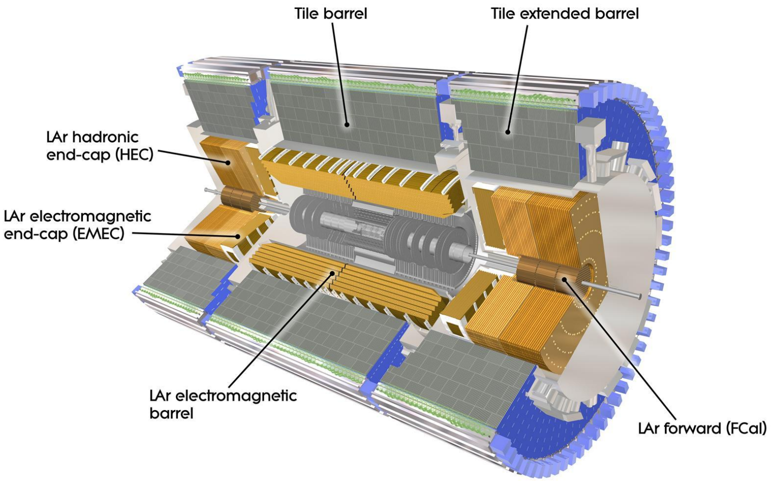


Illustration of the coordinate system



https://cds.cern.ch/images/CERN-GE-0803015-01

Jet Calibration (MC based)

- Calibrate Reconstruction level to truth level
    - Using Energy and p_T response
- Accounts for pile up, flavour physics - initiation of jet, fractions of the jet energy in the different calorimeter layers e.t.c
- Three stages of MC based calibration:
    - Correct for Pileup
    - Jet Energy Scale and η corrections
    - Global sequential Calibration
        - Flavour dependent

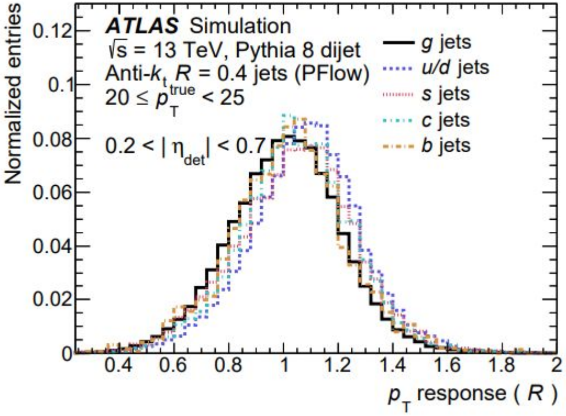
Quark initiated:

- Hard pT Hadrons
- Hard pT jet

Gluon initiated:

- More particles
- Softer jet pT

- Studying response for different flavour physics → **reduced uncertainty (to be shown later)**



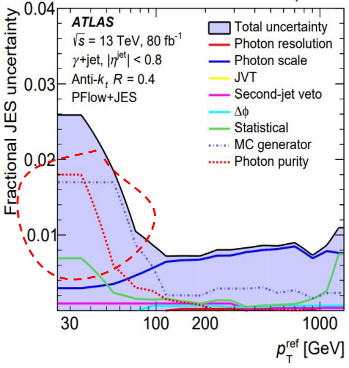
CERN-EP-2023-028

Jet Calibration (In Situ-Data Based)

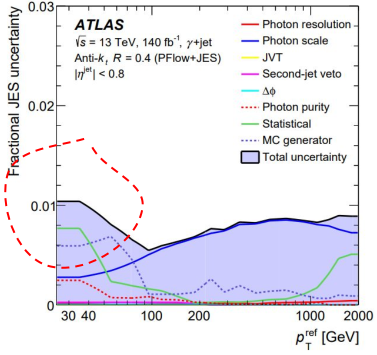
Uncertainty reduction due to:

- Photon purity uncertainty updates

arXiv:2007.02645v2 [hep-ex]



CERN-EP-2023-028



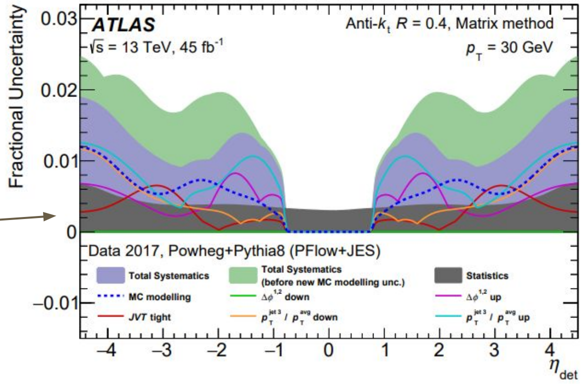
- Calibrate data to
  - Reconstructed MC
  - Reference regions in η, where energy response is known and well behaved
  - Reference decays → well calibrated objects
- Two stages of In Situ calibration:
  - η intercalibration
  - Calibration to reference object Z/γ + jets

- Uncertainty reduction in
  - η intercalibration
  - γ calibration updates

Uncertainty reduction due to:

- MC modeling derived in truth level
  - Reco level→ detector effects uncertainties → already included in MC based calibration

CERN-EP-2023-028

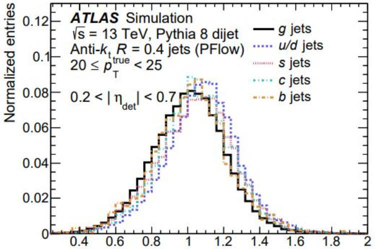


Global Sequential Calibration

- **pT Scale Correction**
- Additional factors to correct:
  - Energy distributions in jet
  - Energy distribution deposits in different calorimeter layers
  - Types of hadrons produced in jet
- Is sensitive to more variables (**reference variables**):
  - Fractions of the jet energy in the different calorimeter layers
  - Transverse extension of the jet
  - etc(full list in backup)
- Dependent on :
  - jet pT
  - quark or gluon initiated jets

Quark initiated:
- Hadron included
- Hard jet pT

Gluon initiated:
- More particles
- Softer jet pT



Corrections:
- Measurement of the pT response independently in reference variable, pT, η bins
- Correction = inverse of pT response

Limitations:
- Independent variables, as for every variable correction is independent

In contrast using a Deep Neural Network(DNN)-> **adding correlated parameters**(full list in backup)

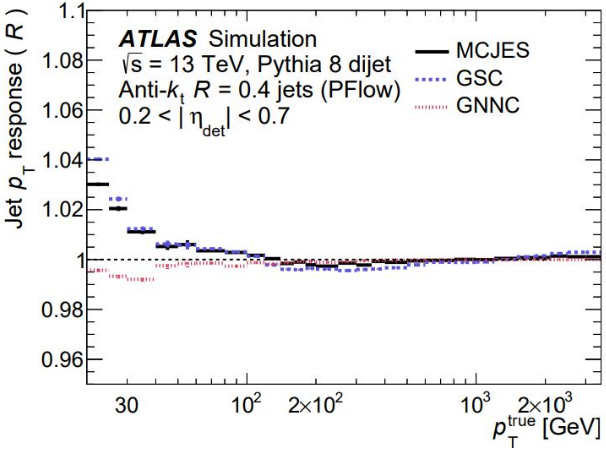


Figure XXX: Jet pT response as a function $$p_{T}^{true}$$ for three different methods: MCJES(jet energy scale correction), GSC(Global Sequential Calibration) and GNNC (GSC with DNN)

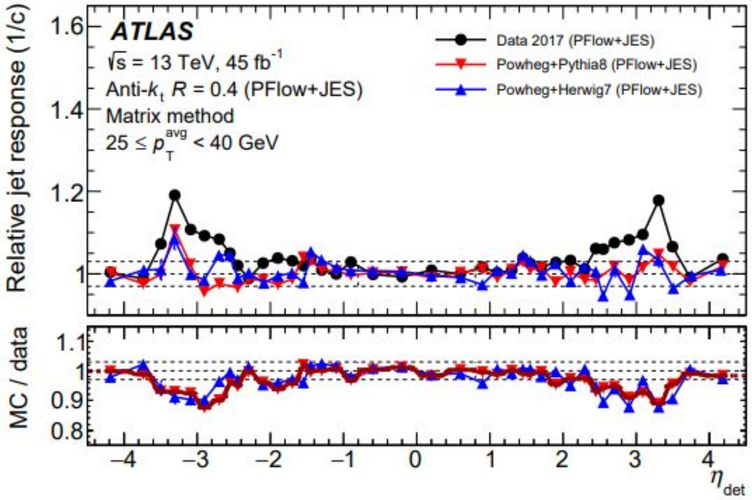
η-intercalibration

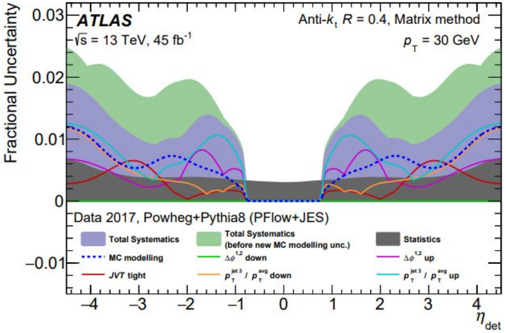
- Jet response is less understood in Forward region(0.8<|η|)
    - **Matching energy scale: Central - Forward jets**
- Matrix Fitting Method
    - All detector is fitted simultaneously
    - Dijets events
- Relative response:

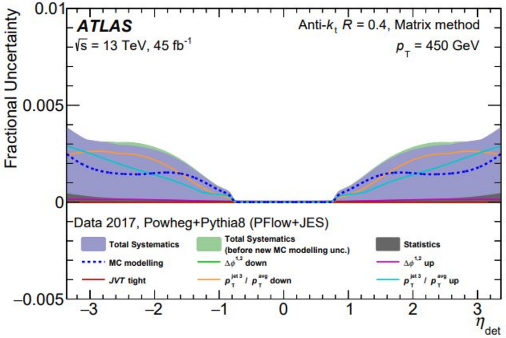
$$\mathcal{R} = \frac{c^{\text{right}}}{c^{\text{left}}} = \frac{2+\langle\mathcal{A}\rangle}{2-\langle\mathcal{A}\rangle} \approx \frac{\langle p_{\text{T}}^{\text{left}}\rangle}{\langle p_{\text{T}}^{\text{right}}\rangle}$$

With:

$$\mathcal{A} = \frac{p_{\text{T}}^{\text{left}} - p_{\text{T}}^{\text{right}}}{p_{\text{T}}^{\text{avg}}}$$

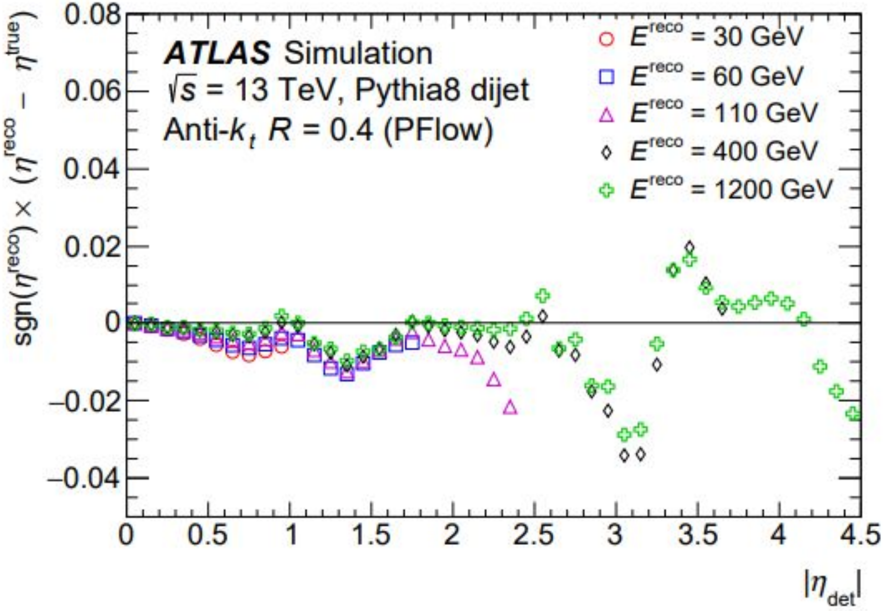




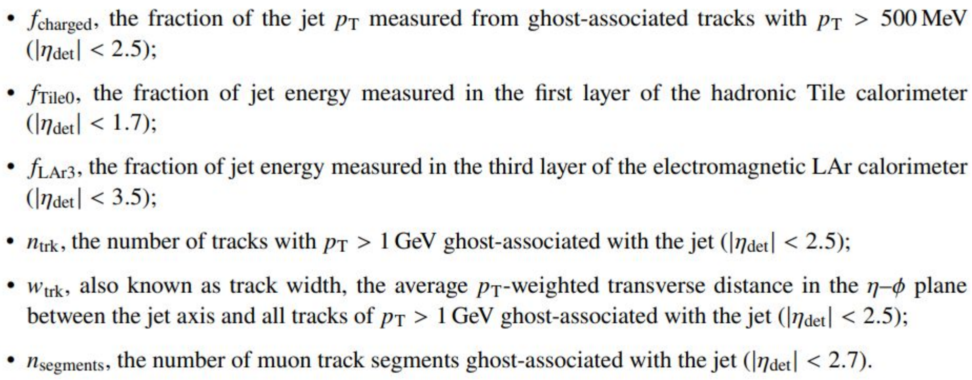


Jet η difference in particle and reco level

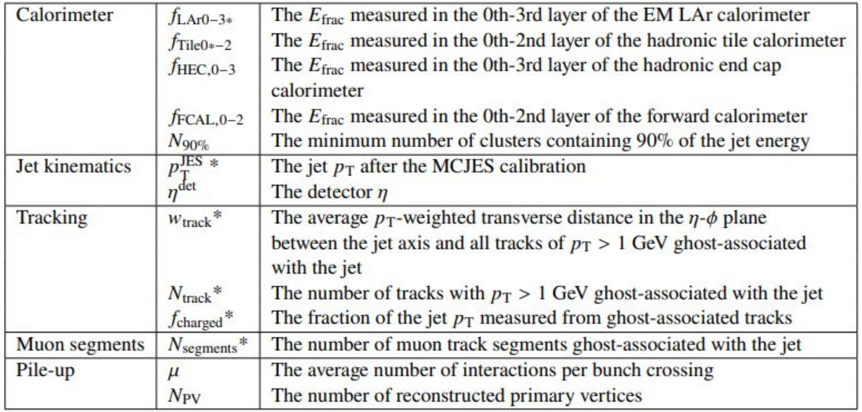
- During Jet Energy Scale calibration in MC based calibration also an η calibration takes place
- Reconstruction level MC η is matched to truth level MC η



List of variable for GCC



- f_{charged}, the fraction of the jet p_{T} measured from ghost-associated tracks with $p_{\mathrm{T}} > 500$ MeV ($|\eta_{\mathrm{det}}| < 2.5$);
- f_{Tile0}, the fraction of jet energy measured in the first layer of the hadronic Tile calorimeter ($|\eta_{\mathrm{det}}| < 1.7$);
- f_{LAr3}, the fraction of jet energy measured in the third layer of the electromagnetic LAr calorimeter ($|\eta_{\mathrm{det}}| < 3.5$);
- n_{trk}, the number of tracks with $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet ($|\eta_{\mathrm{det}}| < 2.5$);
- w_{trk}, also known as track width, the average p_{T}-weighted transverse distance in the η–ϕ plane between the jet axis and all tracks of $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet ($|\eta_{\mathrm{det}}| < 2.5$);
- n_{segments}, the number of muon track segments ghost-associated with the jet ($|\eta_{\mathrm{det}}| < 2.7$).



Calorimeter	$f_{\mathrm{LAr0-3*}}$	The E_{frac} measured in the 0th-3rd layer of the EM LAr calorimeter
	$f_{\mathrm{Tile0*-2}}$	The E_{frac} measured in the 0th-2nd layer of the hadronic tile calorimeter
	$f_{\mathrm{HEC,0-3}}$	The E_{frac} measured in the 0th-3rd layer of the hadronic end cap calorimeter
	$f_{\mathrm{FCAL,0-2}}$	The E_{frac} measured in the 0th-2nd layer of the forward calorimeter
	$N_{90\%}$	The minimum number of clusters containing 90% of the jet energy
Jet kinematics	$p_{\mathrm{T}}^{\mathrm{JES}}$ *	The jet p_{T} after the MCJES calibration
	η^{det}	The detector η
Tracking	w_{track}*	The average p_{T}-weighted transverse distance in the η-ϕ plane between the jet axis and all tracks of $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet
	N_{track}*	The number of tracks with $p_{\mathrm{T}} > 1$ GeV ghost-associated with the jet
	f_{charged}*	The fraction of the jet p_{T} measured from ghost-associated tracks
Muon segments	N_{segments}*	The number of muon track segments ghost-associated with the jet
Pile-up	μ	The average number of interactions per bunch crossing
	N_{PV}	The number of reconstructed primary vertices

List of reference variables for GCC

List of reference variables for DNN GCC

Flavour Uncertainty

Two Flavour Uncertainties Studied:

Flavour response Uncertainty:

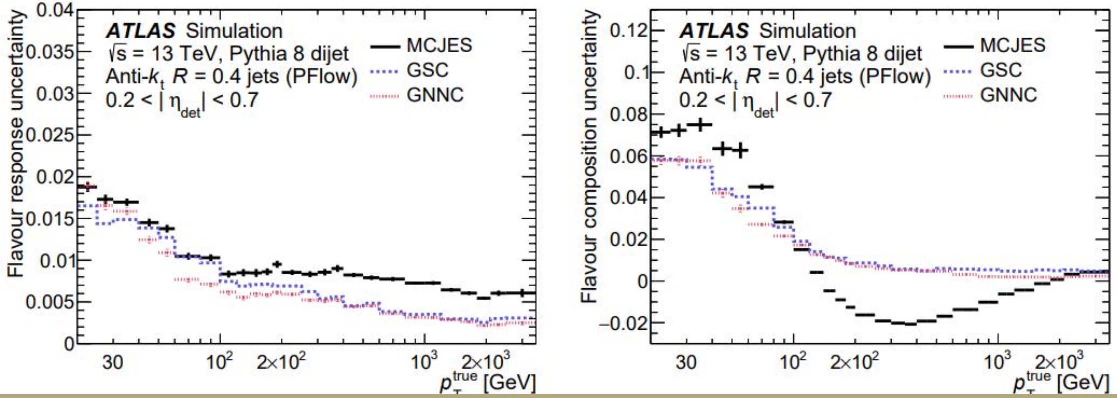
- pT Response for quark initiated jets->**Independent** from generators
- pT Response for gluon initiated jets->**Dependent** from generators

$$\sigma_{\text{response}} = f_g\left(\mathcal{R}_{g,\textsc{Pythia8}} - \mathcal{R}_{g,\textsc{Herwig}}\right)$$

Flavour composition uncertainty:

- pT Response difference for:
  - gluon
  - quark

$$\sigma_{\text{composition}} = \sigma_g^f \frac{\mathcal{R}_q - \mathcal{R}_g}{f_g\mathcal{R}_g + (1 - f_g)\mathcal{R}_q}$$



η-intercalibration

- Jet response less understood in Forward region(0.8>|η|)
    - **Matching energy scale: Central - Forward jets**
- Relative response between $$\eta$$ regions
    - Matrix Fitting Method
        - All detector is fitted simultaneously
        - Dijets events
- Reduced uncertainty due to further understanding of flavour uncertainty in MC

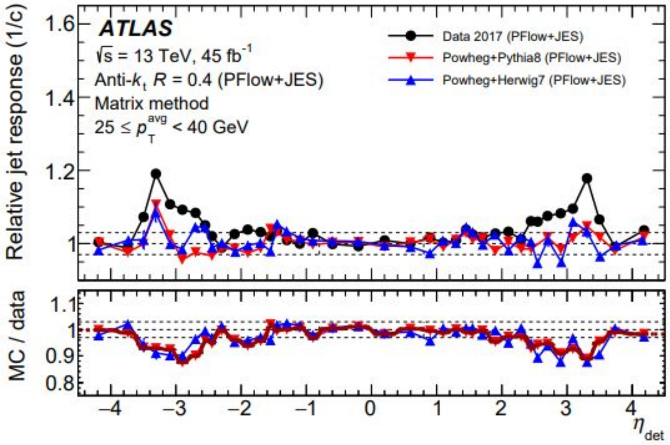
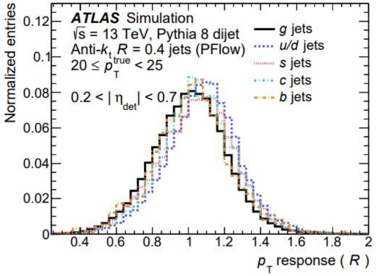
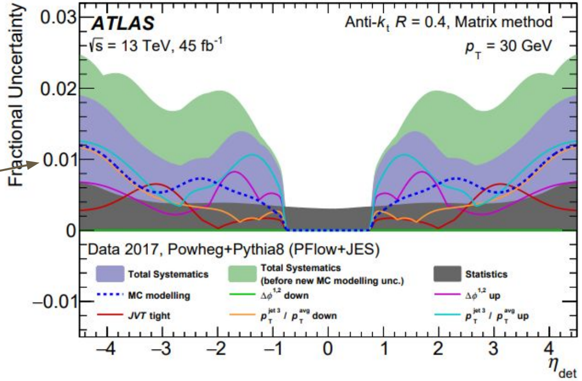
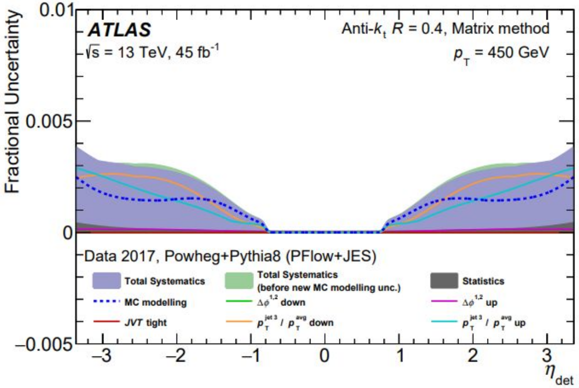


Figure XXX: Relative jet response in *η* intercalibration, for data and two MC generations







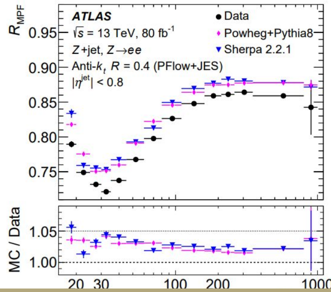
Z/γ+jets energy scale calibration

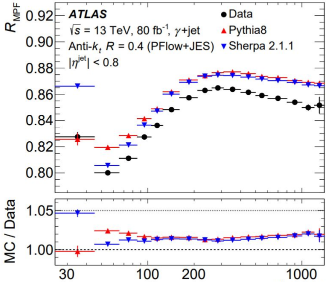
- Match **energy scale** in data to MC
    - pT balance between hadronic recoil - well-calibrated **Z/γ**
    - Using events:
        - Z+jets
        - γ+jets
- Reconstruction of events with hadronic recoil and reference object (Z or γ):

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{ref}} + r_{\mathrm{MPF}}\;\vec{p}_{\mathrm{T}}^{\,\mathrm{recoil}} = -\vec{E}_{\mathrm{T}}^{\,\mathrm{miss}}$$

- Relative response as a function of $$p_{T}_{ref}:

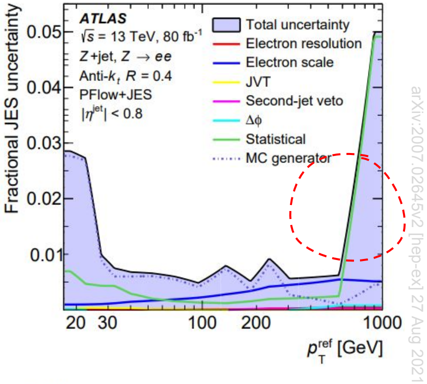
$$\mathcal{R}_{\mathrm{MPF}} = \left\langle 1 + \frac{\hat{n}_{\mathrm{ref}} \cdot \vec{E}_{\mathrm{T}}^{\,\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ref}}} \right\rangle$$

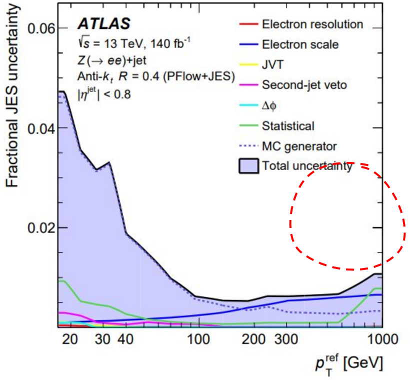


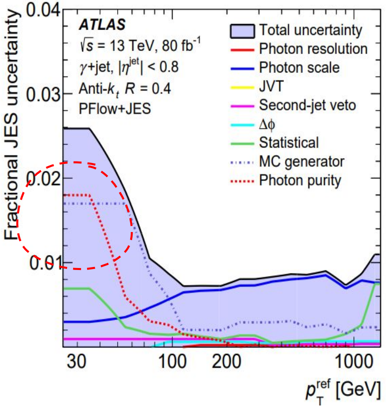


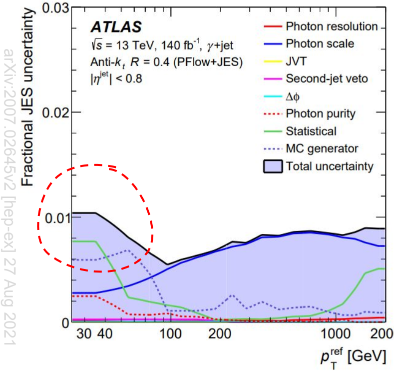
Large improvement in Z+jets and γ+jets Fraction Uncertainty:

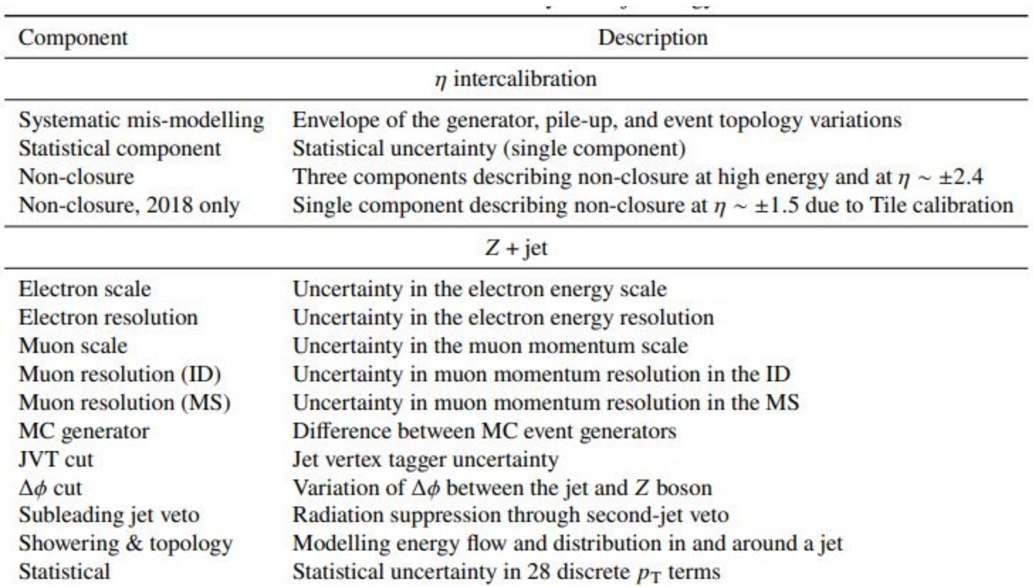
- Production of Z boson decay simulation events for high pT -> Smaller statistical uncertainty in high pT
- Smaller photon resolution



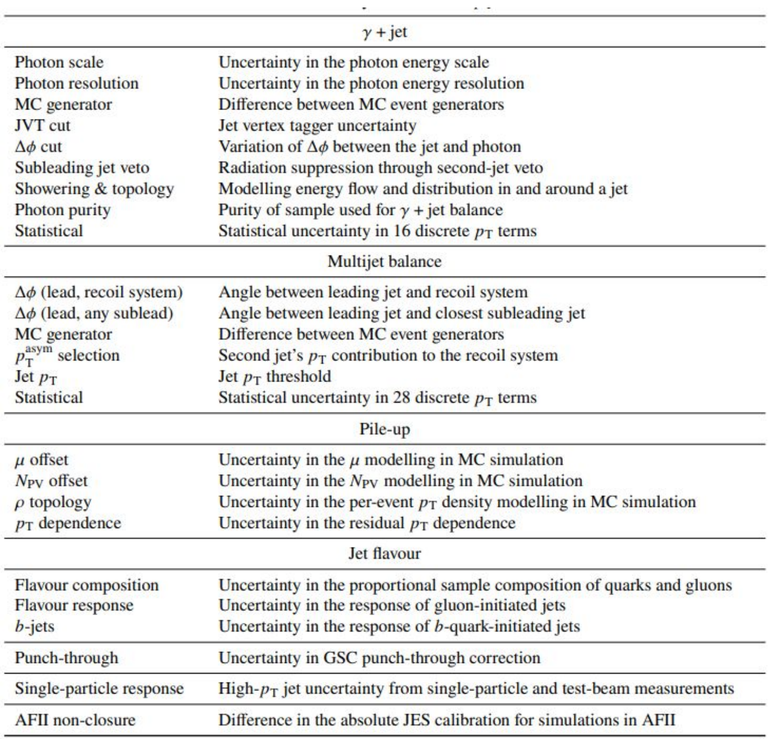








Component	Description
η intercalibration	
Systematic mis-modelling	Envelope of the generator, pile-up, and event topology variations
Statistical component	Statistical uncertainty (single component)
Non-closure	Three components describing non-closure at high energy and at $\eta \sim \pm 2.4$
Non-closure, 2018 only	Single component describing non-closure at $\eta \sim \pm 1.5$ due to Tile calibration
$Z + \text{jet}$	
Electron scale	Uncertainty in the electron energy scale
Electron resolution	Uncertainty in the electron energy resolution
Muon scale	Uncertainty in the muon momentum scale
Muon resolution (ID)	Uncertainty in muon momentum resolution in the ID
Muon resolution (MS)	Uncertainty in muon momentum resolution in the MS
MC generator	Difference between MC event generators
JVT cut	Jet vertex tagger uncertainty
$\Delta\phi$ cut	Variation of $\Delta\phi$ between the jet and Z boson
Subleading jet veto	Radiation suppression through second-jet veto
Showering & topology	Modelling energy flow and distribution in and around a jet
Statistical	Statistical uncertainty in 28 discrete p_T terms

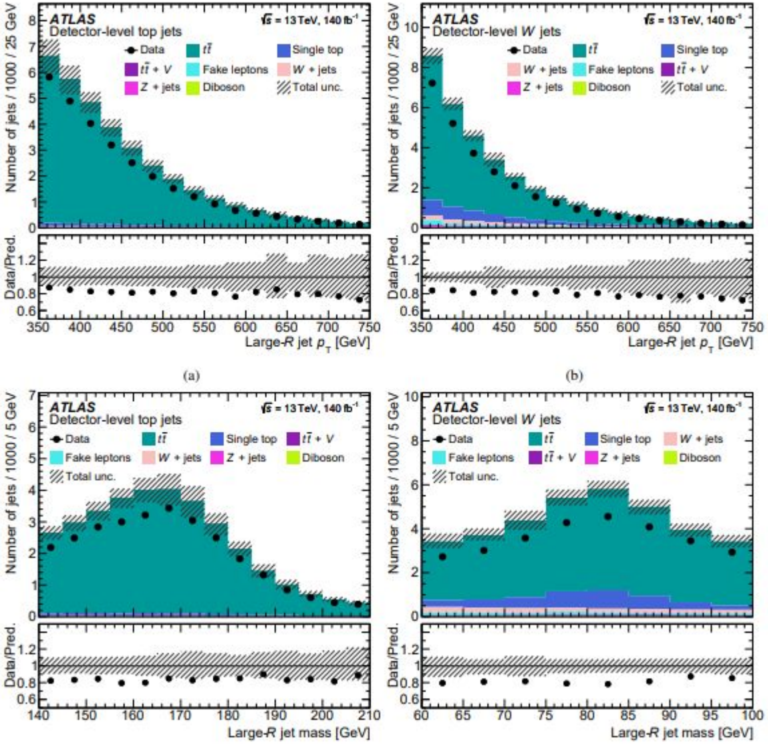


$\gamma + \text{jet}$	
Photon scale	Uncertainty in the photon energy scale
Photon resolution	Uncertainty in the photon energy resolution
MC generator	Difference between MC event generators
JVT cut	Jet vertex tagger uncertainty
$\Delta\phi$ cut	Variation of $\Delta\phi$ between the jet and photon
Subleading jet veto	Radiation suppression through second-jet veto
Showering & topology	Modelling energy flow and distribution in and around a jet
Photon purity	Purity of sample used for $\gamma + \text{jet}$ balance
Statistical	Statistical uncertainty in 16 discrete p_T terms
Multijet balance	
$\Delta\phi$ (lead, recoil system)	Angle between leading jet and recoil system
$\Delta\phi$ (lead, any sublead)	Angle between leading jet and closest subleading jet
MC generator	Difference between MC event generators
p_T^{asym} selection	Second jet's p_T contribution to the recoil system
Jet p_T	Jet p_T threshold
Statistical	Statistical uncertainty in 28 discrete p_T terms
Pile-up	
μ offset	Uncertainty in the μ modelling in MC simulation
N_{PV} offset	Uncertainty in the N_{PV} modelling in MC simulation
ρ topology	Uncertainty in the per-event p_T density modelling in MC simulation
p_T dependence	Uncertainty in the residual p_T dependence
Jet flavour	
Flavour composition	Uncertainty in the proportional sample composition of quarks and gluons
Flavour response	Uncertainty in the response of gluon-initiated jets
b-jets	Uncertainty in the response of b-quark-initiated jets
Punch-through	Uncertainty in GSC punch-through correction
Single-particle response	High-p_T jet uncertainty from single-particle and test-beam measurements
AFII non-closure	Difference in the absolute JES calibration for simulations in AFII

Uncertainties to Jet Energy Scale

Measurements of Lund Plane(Signal and Background)

- *Signal*
  - *$t\bar{t}$ pairs: one decays hadronically , other produces W → lepton + neutrino and b-tagged jet*
  - *W boson: hadronic decays*
- *Background*
  - *Estimated from simulation:*
    - *Z +jets*
    - *W+jets*
    - *Diboson*
    - *Single top*
  - *Estimated from data-driven method:*
    - *Fake Leptons*
- Miss-modeling increases with large-R jet pT:
  - Observed in CMS and ATLAS
  - Origin: missing higher order predictions than NLO



Measurements of Lund Plane(Unfolding)

- Correction applied to data for **detector-level effects** with **Bayesian Unfolding**
- Derived with comparison **particle**, **reconstruction** level **simulation**
- **Unfolding equation:**

$$\frac{d^2 N_{\text{emissions}}}{d\ln(1/z)\, d\ln(R/\Delta R)} = \frac{1}{\Delta X \Delta Y \epsilon^{I}_{\text{eff}}} \sum_{J} {M^{-1}}^{I}_{J} \cdot \epsilon^{J}_{\text{acc}} \cdot (N^{J}_{\text{obs}} - N^{J}_{\text{bkg}})$$

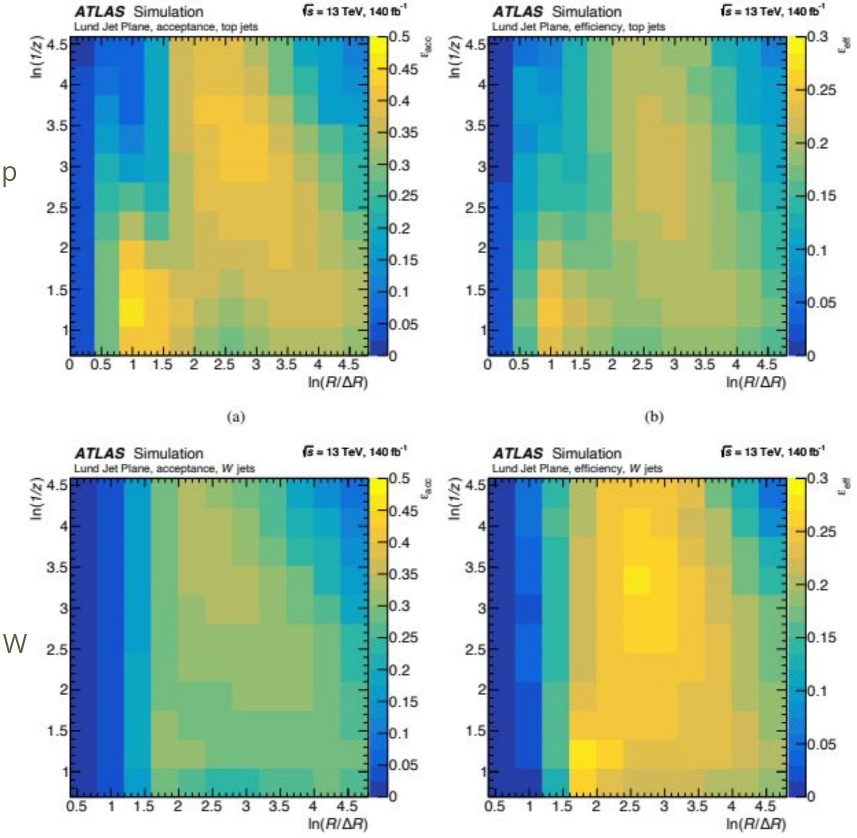
Where:

- I is the index of the bin in the particle-level LJP
- J bin index at detector level
- ΔX,ΔY widths of the bins corresponding to I across the two axes
- M response matrix
- Nobs->number of observed events
- Nbkg->number of background events predicted
- $$\epsilon_{eff}$$ corrects for emissions passing the particle-level selection but not the detector-level requirements
- $$\epsilon_{acc}$$ removes the emissions passing the detector-level requirements and not matched to the particle-level ones

$$\espilon_{acc}$$$$\espilon_{eff}$$

top

W



Measurements of Lund Plane(Unfolding)

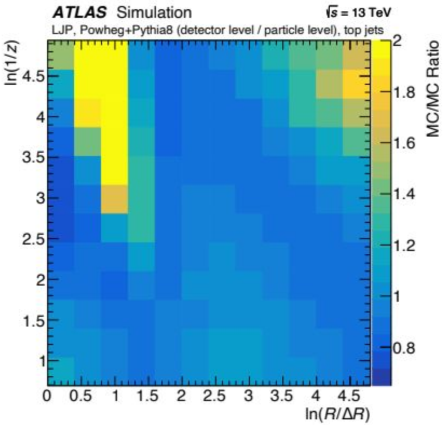
- Correction applied to data for **detector-level effects** with **Bayesian Unfolding**
- Derived with comparison **particle**, **reconstruction** level **simulation**
- **Unfolding equation:**

$$\frac{d^2 N_{\text{emissions}}}{d\ln(1/z)\, d\ln(R/\Delta R)} = \frac{1}{\Delta X \Delta Y \epsilon^I_{\text{eff}}} \sum_J {M^{-1}}^I_J \cdot \epsilon^J_{\text{acc}} \cdot (N^J_{\text{obs}} - N^J_{\text{bkg}})$$

Where:

- I is the index of the bin in the particle-level LJP
- J bin index at detector level
- ΔX,ΔY widths of the bins corresponding to I across the two axes
- M response matrix
- Nobs->number of observed events
- Nbkg->number of background events predicted
- $$\epsilon_{eff}$$ corrects for emissions passing the particle-level selection but not the detector-level requirements
- $$\epsilon_{acc}$$ removes the emissions passing the detector-level requirements and not matched to the particle-level ones

top



W