Jet energy measurements using Run-2 ATLAS data.

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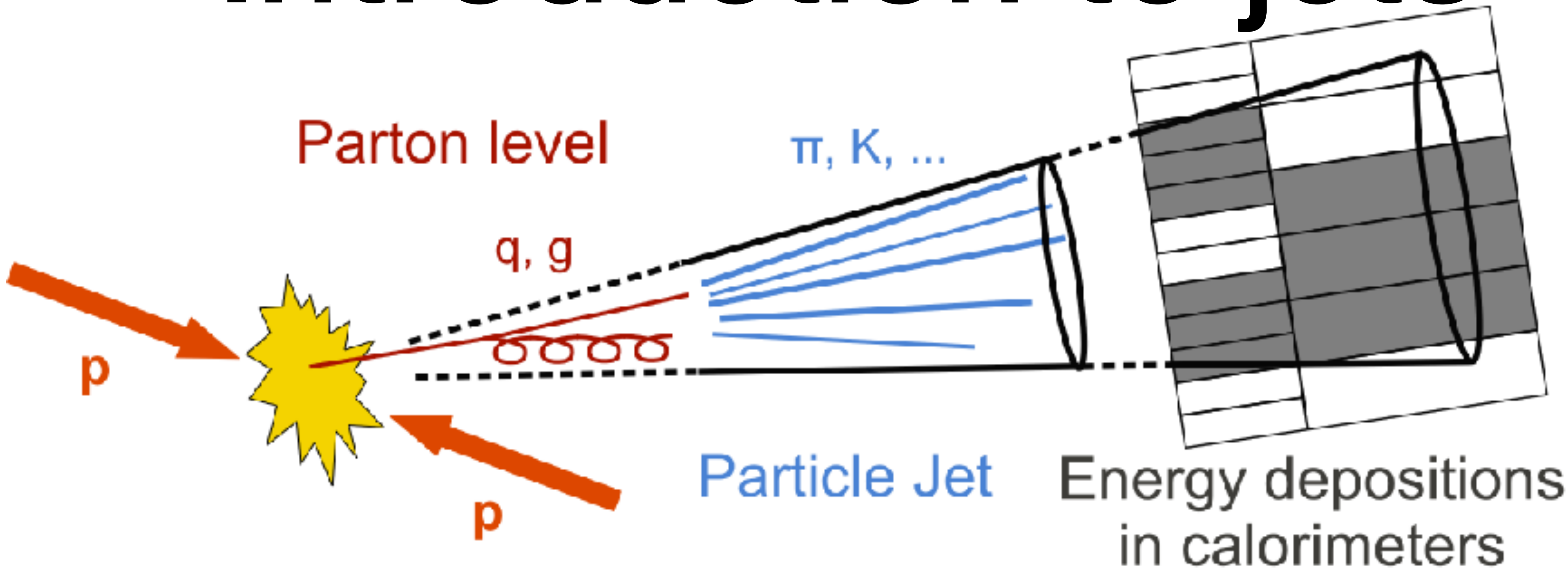
Introduction to jets

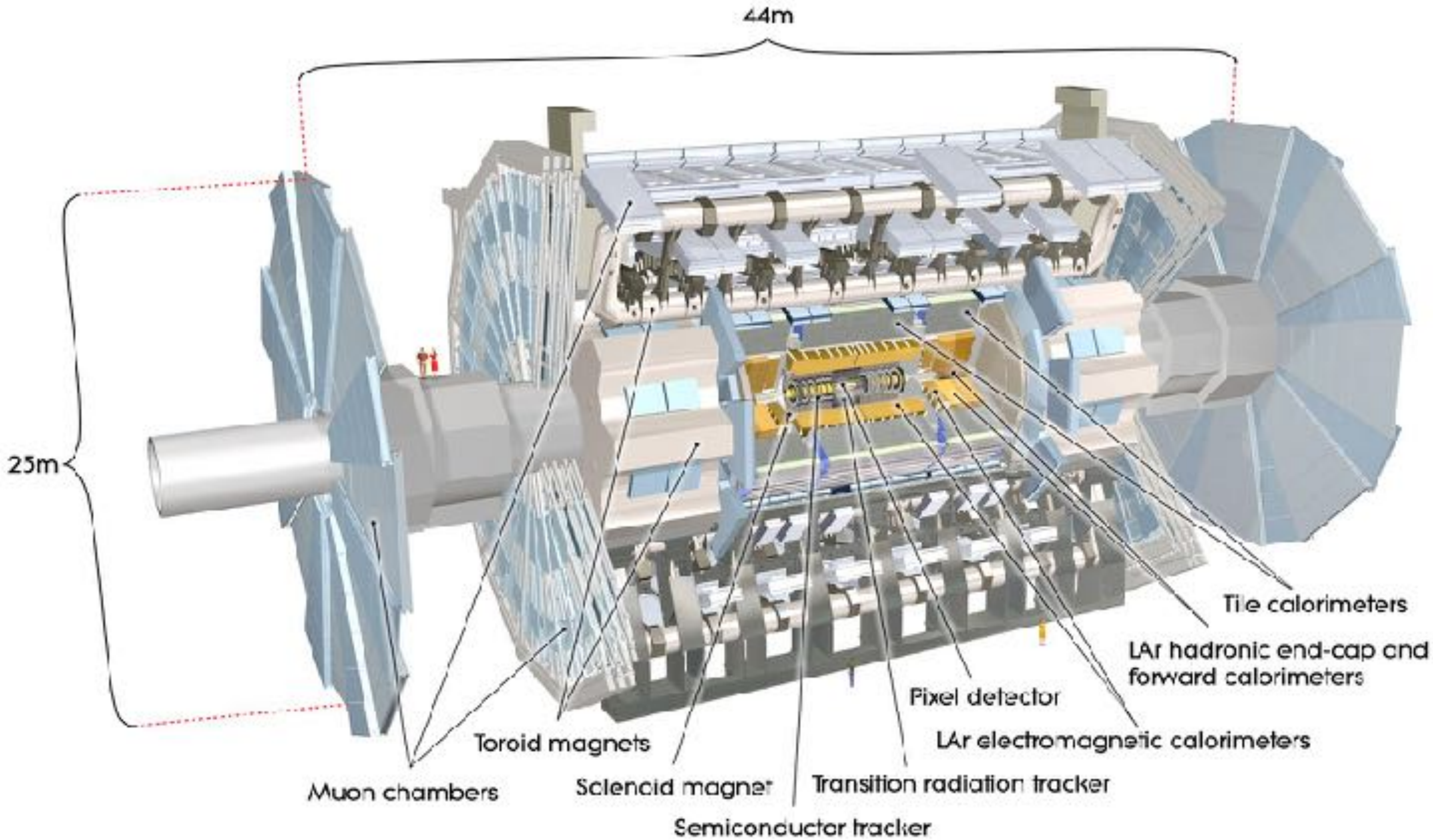


Jets are collimated sprays of hadrons arising from parton level interactions in colliding protons.
Jets are the dominant features arising in pp collisions at the LHC. Jets play a key role in many Standard Model physics analyses and searches of new phenomena. Jets are used to study the proton structure, strong coupling constants, and the non-perturbative effects of hadronisation and underlying events.

Jets are built:

- at the parton-level using partons knocked-out from protons
- at the particle-level using charged particles resulting in the parton evolution (hadronisation)
- at the reconstruction-level using calorimeter inputs (energy deposits in active cells) or tracks

ATLAS detector



- ATLAS is the multipurpose detector at the LHC
- Consists of internal tracker (inner detector), electromagnetic and hadronic calorimeters, and external muon spectrometer
- Inner detector is immersed in the solenoidal magnetic field of 2T
- Muons are bent by 1T magnetic field provided by the superconducting toroid magnets.
- ATLAS allows a wide spectrum of high energy physics studies both within the Standard Model and Beyond

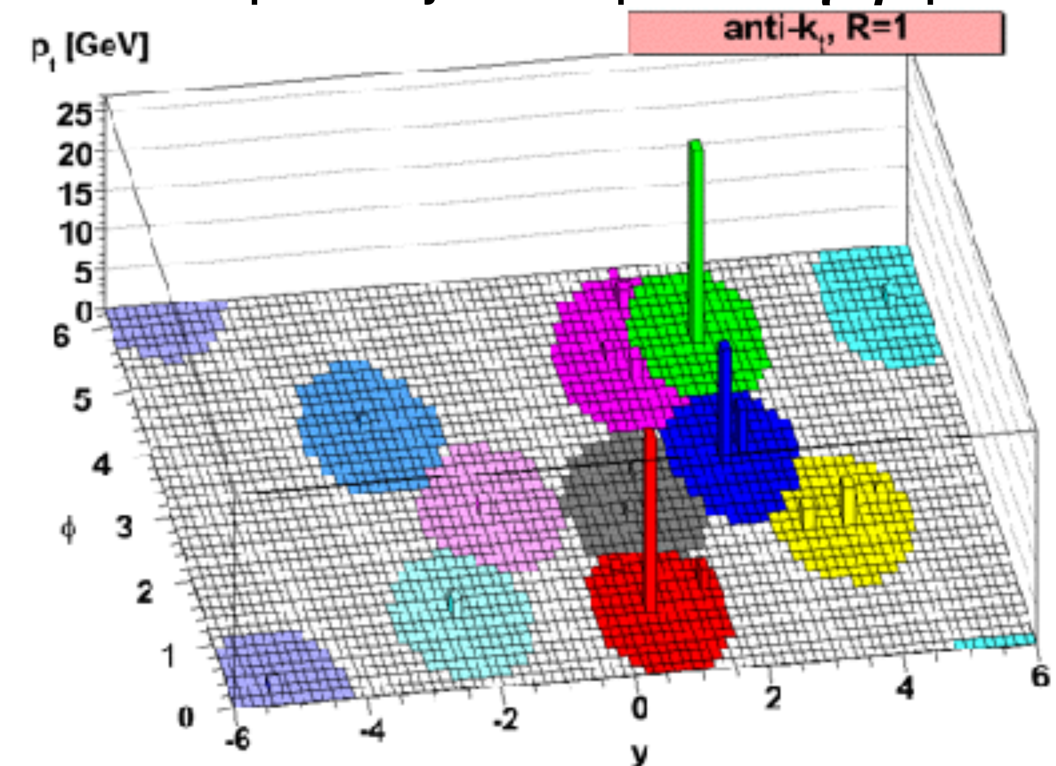
Jets reconstruction in ATLAS

Jets are reconstructed in atlas using the Anti-k_t jet algorithm:

- Recombines all the entities (particles or calorimeter inputs), within a fixed cone of size ΔR (mostly with ΔR=0.4 in ATLAS), starting from the most energetic input.
- The algorithm is infrared and collinear safe.

The inputs for jets reconstruction in ATLAS are the topologically connected calorimeter cells, that contain a significant signal above noise (topoclusters).

The example of jet shapes in η-ϕ plane



arXiv:0802.1189

There are three main types of jets, based on the inputs:

- **EMTopo jets**. Cells in topoclusters are calibrated at the EM scale.
- **LCTopo jets**. Clusters are classified as EM or hadronic. Additional calibration applies to hadronic clusters to account for different calorimeter response to hadrons.
- **EMPFlow jets**. Momenta of charged hadrons are taken from tracks, while calorimeter is used to reconstruct neutral-particles.

Jet energy scale (JES) calibration sequence

- The jet energy scale (JES) calibration restores the energy scale of reconstructed jets to that of simulated truth jets.
- JES calibration consists of several consecutive stages derived from a combination of MC-based methods and in situ techniques.

EM-scale jets → **Origin correction** → **Jet area-based pile-up correction** → **Residual pile-up correction** → **Absolute MC-based calibration** → **Global sequential calibration** → **Residual *in situ* calibration**

EM-scale jets: *Jet finding applied to topological clusters at the EM scale.*

Origin correction: *Changes the jet direction to point to the hard-scatter vertex. Does not affect E.*

Jet area-based pile-up correction: *Applied as a function of event pile-up p_T density and jet area.*

Residual pile-up correction: *Removes residual pile-up dependence, as a function of μ and N_{PV}.*

Absolute MC-based calibration: *Corrects jet 4-momentum to the particle-level energy scale. Both the energy and direction are calibrated.*

Global sequential calibration: *Reduces flavor dependence and energy leakage effects using calorimeter, track, and muon-segment variables.*

Residual *in situ* calibration: *A residual calibration is derived using in situ measurements and is applied* ***only to data****.*

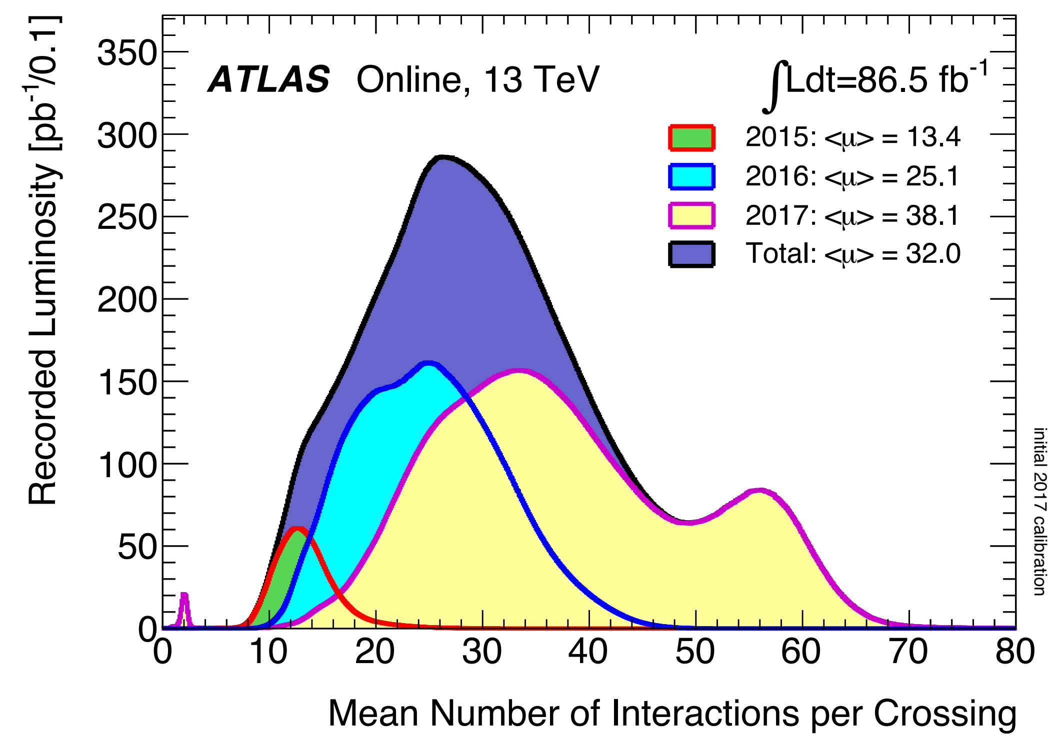
- The jet energy scale calibration sequence is similar for all types of reconstructed jets.
- Only EMTopo jets are covered in this talk.

Pile-up correction

Proton-proton collisions in ATLAS undergo high **pile-up, additional soft pp interactions in the actual and neighbouring bunch crossings.**

- Up to 70 additional soft pp interactions within the same bunch crossing in 2017

Mean number of interactions per crossing

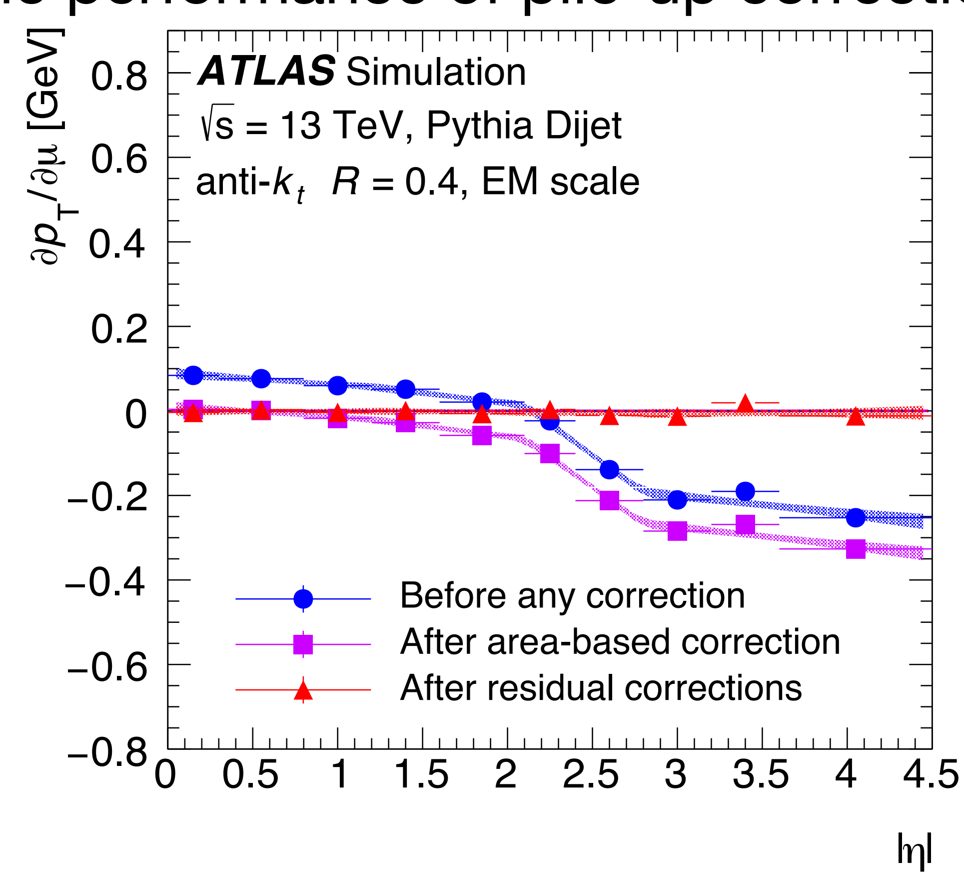


Jets, originating from pile-up vertices, are usually removed by the jet selection in physics analyses.

Pile-up correction subtracts an excess of energy in jet due overlay of signals. Performed in two steps:

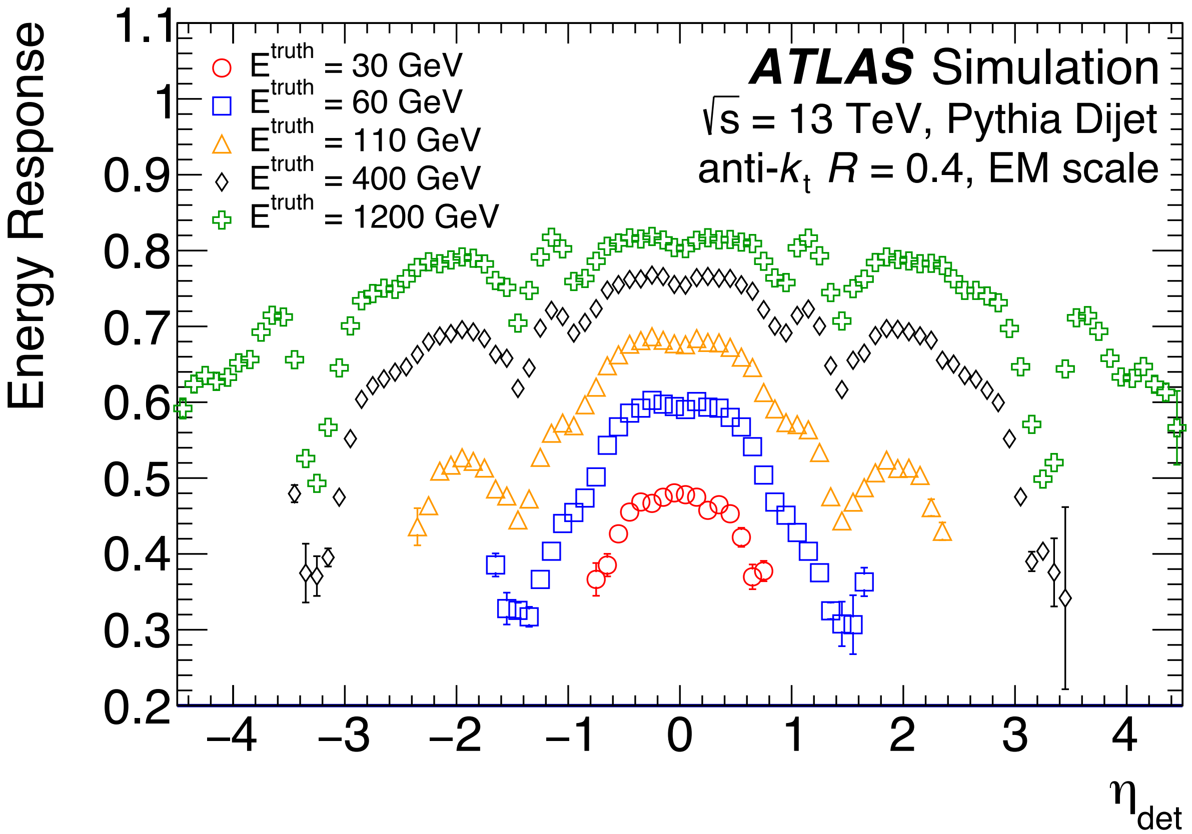
1. The pile-up contribution is subtracted from jets using the median p_T density of k_t jets and the area of a jet in each event.
2. The residual correction, derived from MC simulation, subtracts the dependence on the number of reconstructed primary vertices (N_{PV}) and average number of interactions per bunch crossing $<\mu>$

The performance of pile-up corrections

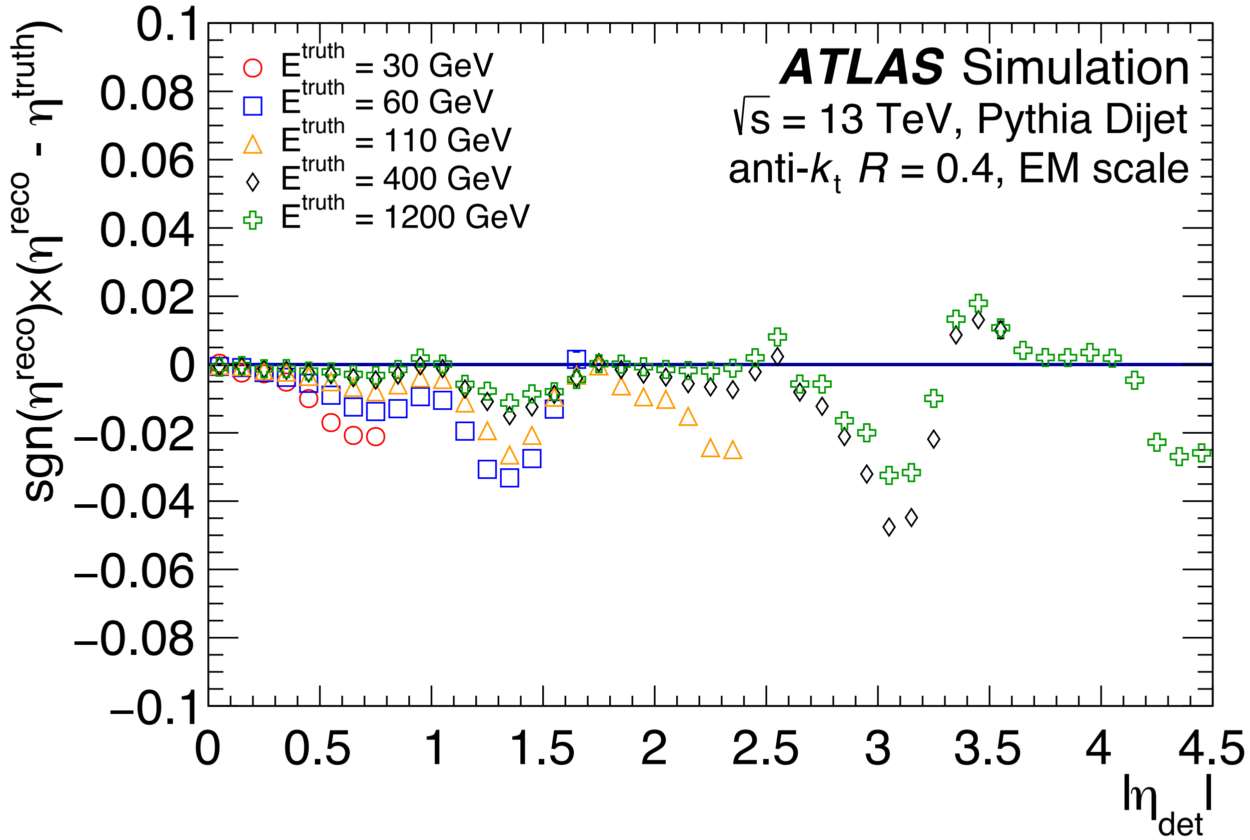


Absolute MC-based jet 4-momentum calibration

Jet energy correction



Jet pseudorapidity correction



The absolute jet energy calibration corrects the reconstructed jet energy to the particle-level energy scale, using E_{reco}/E_{truth} defined for geometrically matched jets.

The pseudorapidity calibration corrects for the biases caused by the transition between different calorimeter regions, using $\eta_{reco}-\eta_{truth}$ parametrised as the function of truth jet energy.

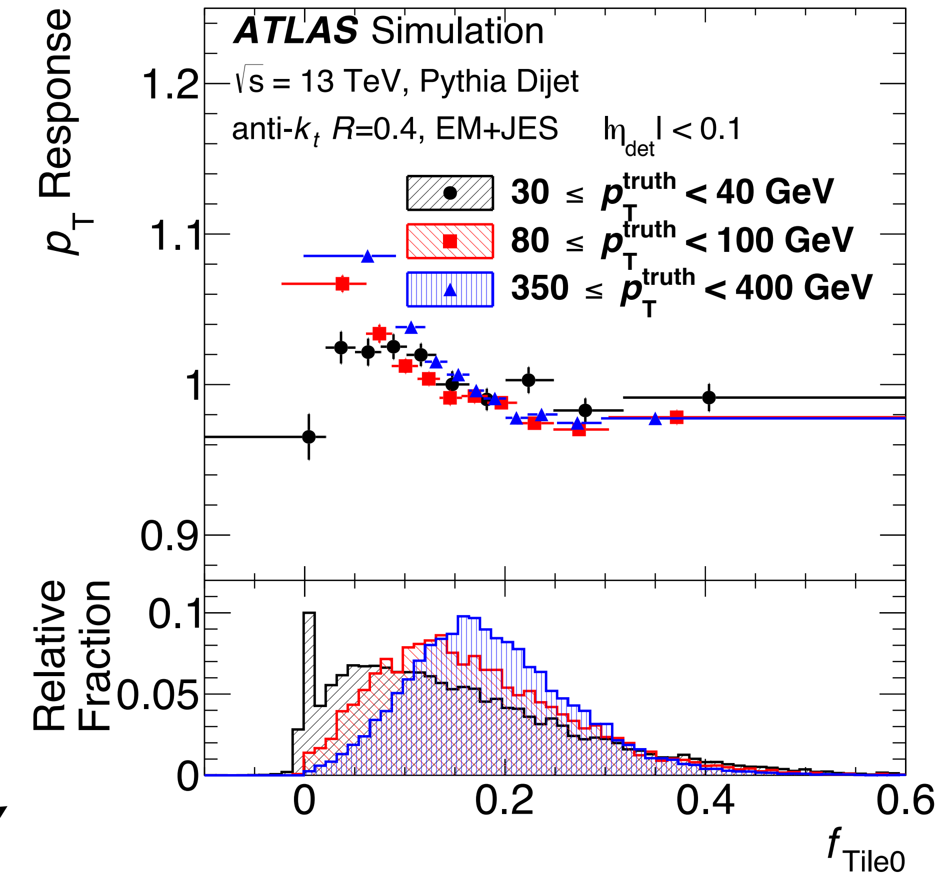
Global sequential calibration (GSC)

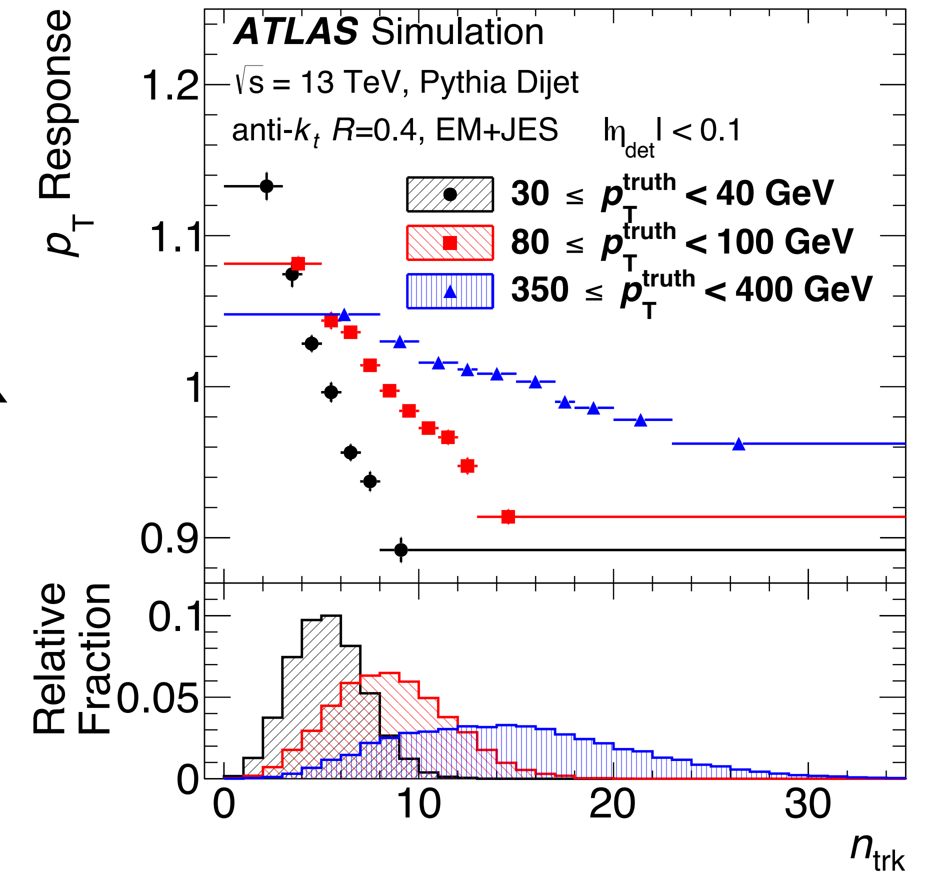
The GSC reduces the jet response dependence on the flavour of the jet-initiated parton (quark or gluon):

- quark jets penetrate deeper to the calorimeter
- gluon jets have wider jet transverse profile

The correction, extracted from the MC simulation, flattens the jet p_T response dependence on the:

1. Energy fraction in the last electromagnetic calorimeter layer.
2. Energy fraction in the first hadronic calorimeter layer (f_{Tile0}).
3. Number of tracks (n_{trk}).
4. The average p_T-weighted transverse distance in the η-ϕ plane between the jet axis and all tracks, track width.
5. Number of muon segments behind jet.





In-situ calibration

Corrects the jet p_T in data by the data-MC difference between a jet and a well calibrated reference object.

As a function of η:

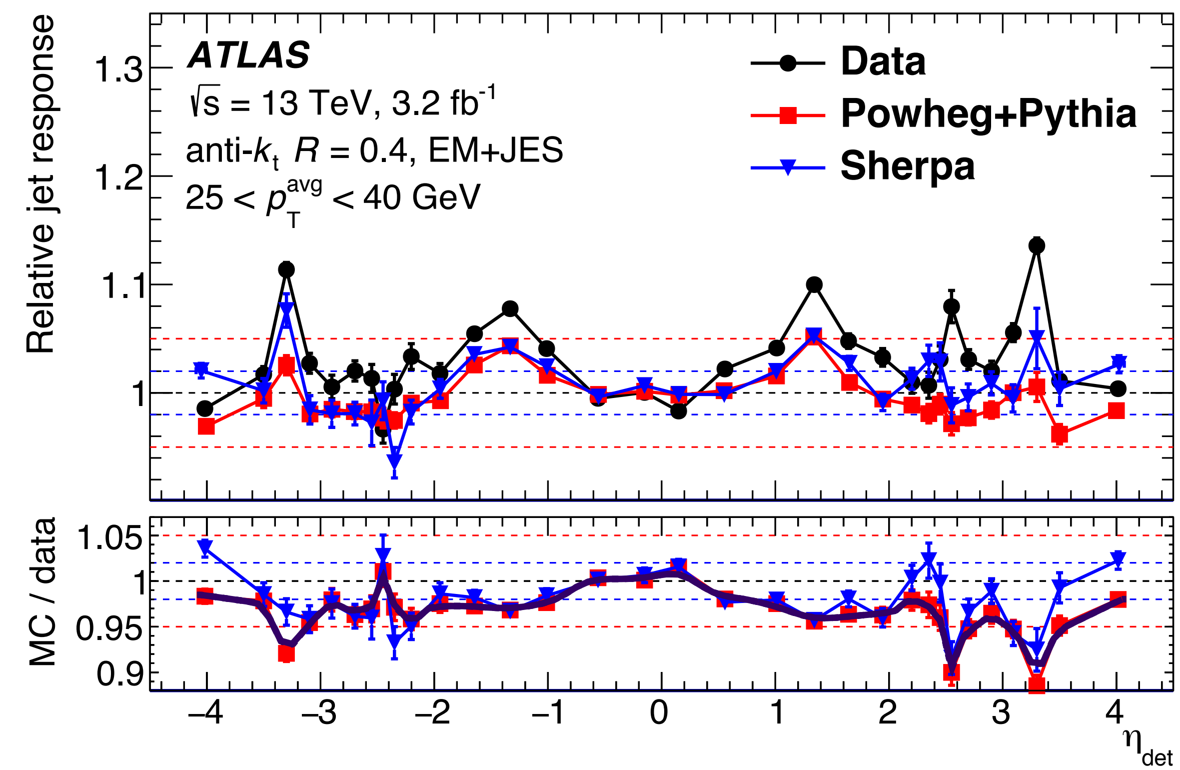
- η-intercalibration exploits central jets to calibrate forward jets using dijet events.

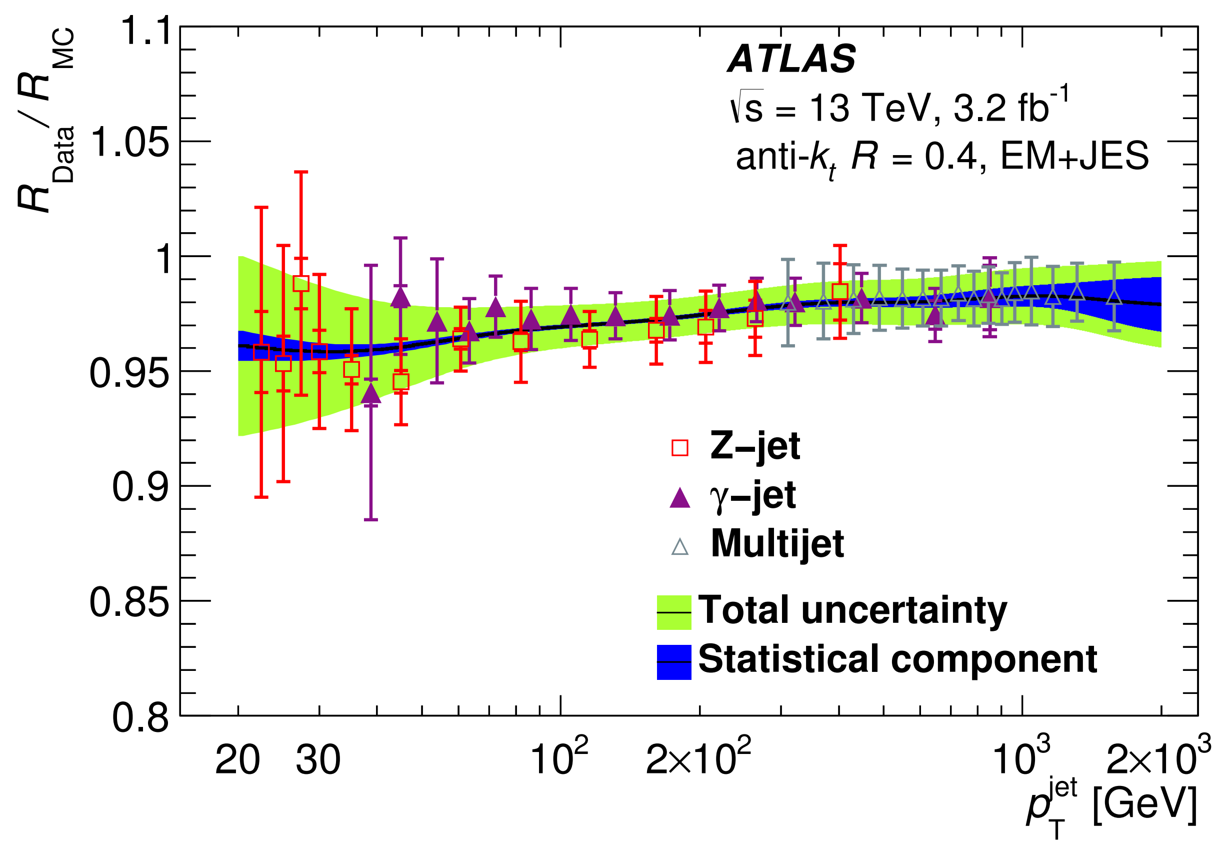
As a function of jet p_T:

- Jet p_T is balanced by the p_T of the Z-boson (covers $20<p_T<500$ GeV).
- Jet p_T is balanced by the p_T of the photon (covers $36<p_T<950$ GeV).
- High-p_T jet is balanced by the calibrated low-p_T jet (up to 2 TeV).

A good overlap of resulting corrections, obtained with different methods is observed.

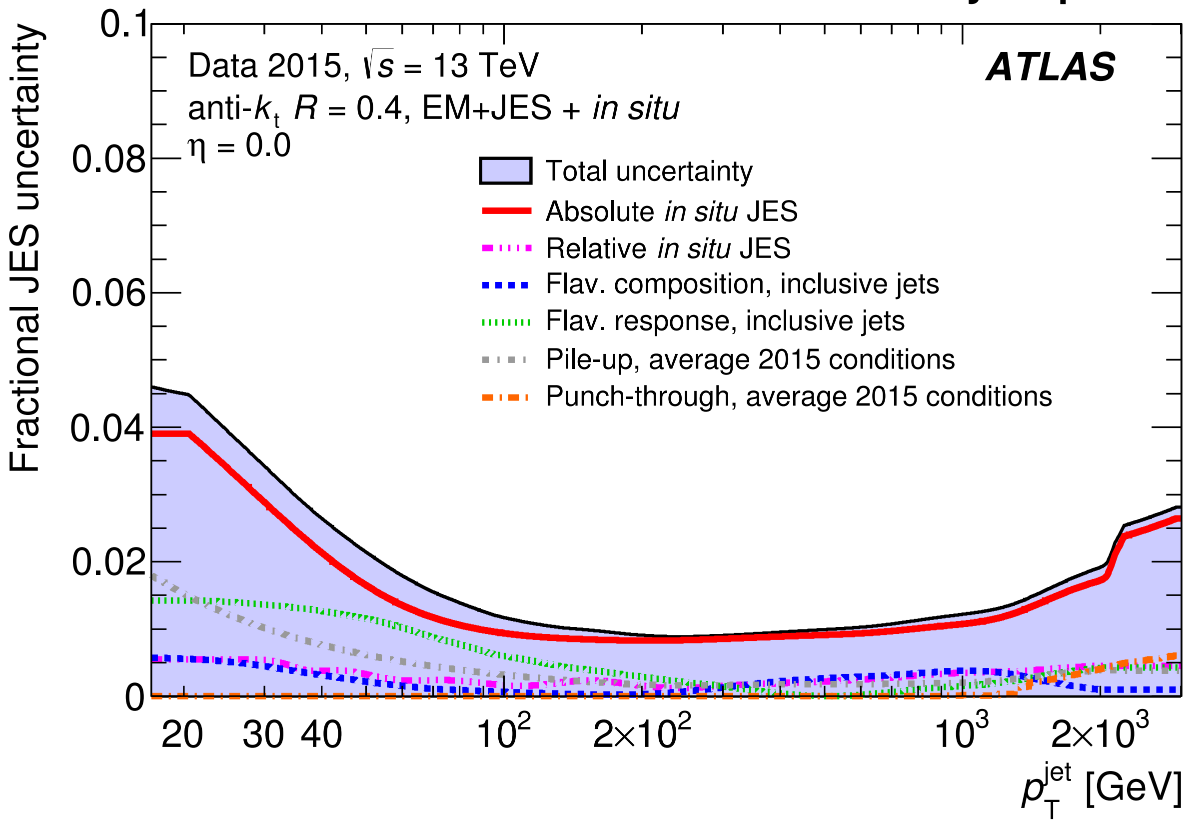
The results are then combined using a weighted average of contributions from different methods, where weights are obtained by χ^2 minimisation.



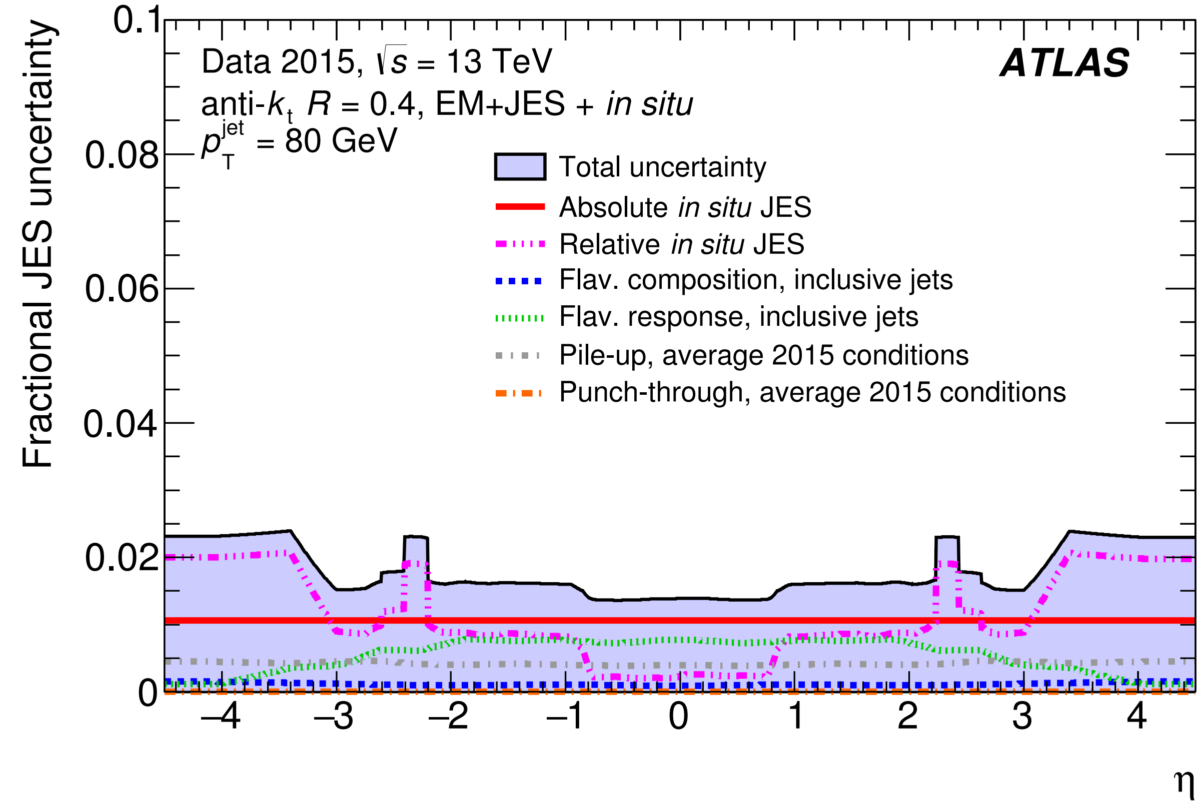


JES uncertainties

Uncertainties as a function of jet p_T



Uncertainties as a function of jet η

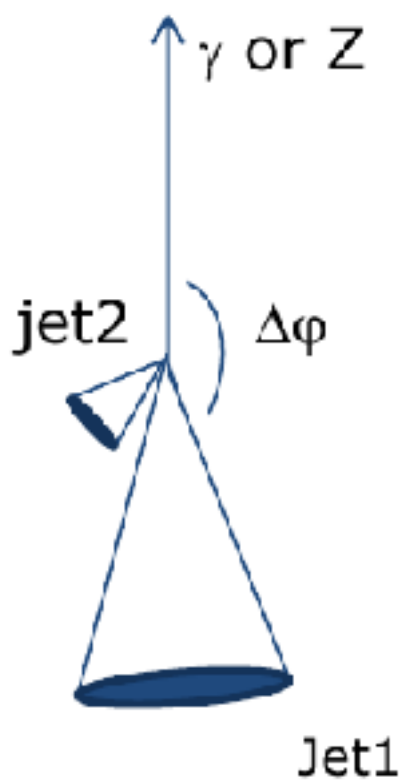


The jet energy scale calibration is established with an uncertainty of 1% in the $100<p_T<1000$ GeV range.

The calibration is supplied with the set of 80 independent sources of systematics uncertainties to correctly account for all correlations in jet calibration.

A reduced set of systematics uncertainties is produced to simplify physics analyses while keeping the loss of correlation information to a minimum.

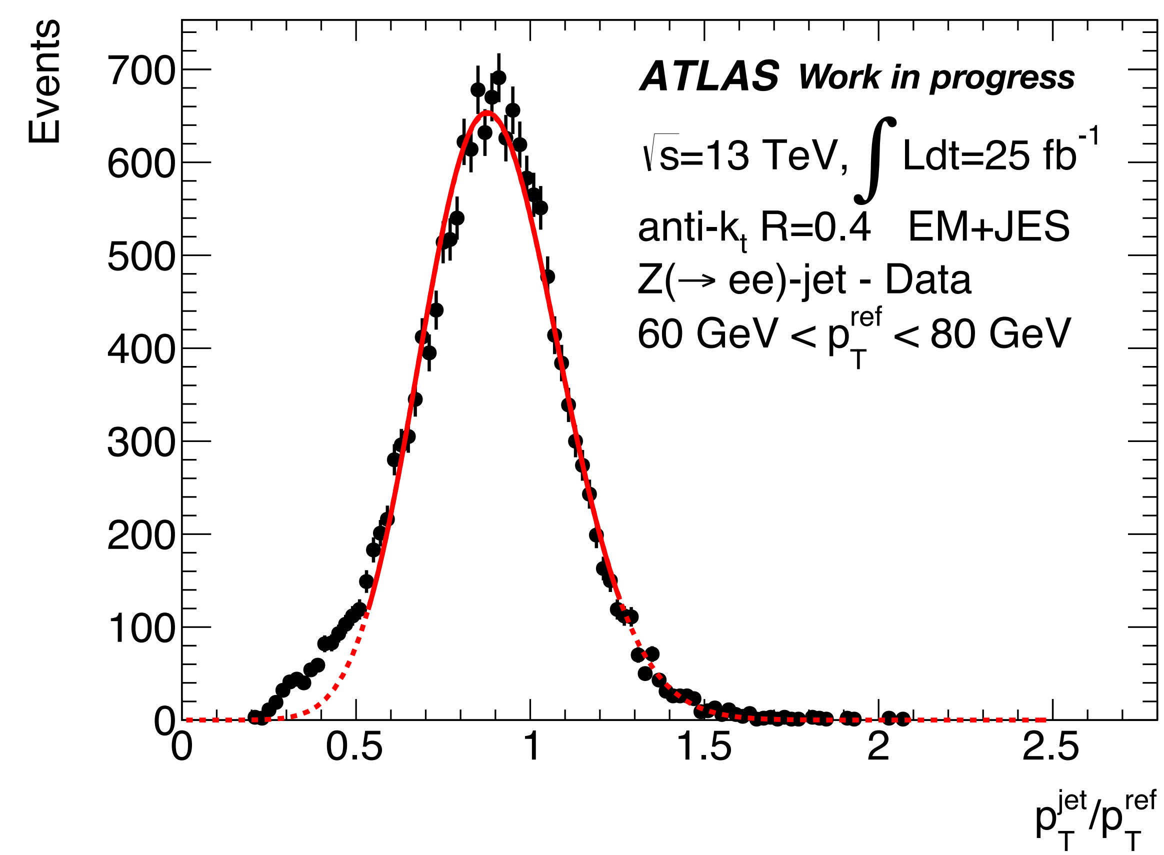
Direct balance (DB) method using Z+jet events



- For a 2→2 Z+jet event at LO, the p_T of the jet ideally balances the p_T of the Z-boson.
- In practice, the measurement is affected by:
  - uncertainty of the lepton energy measurements
  - additional parton radiation (sub-leading jets)
  - energy leakage outside of the jet cone
  - pile-up

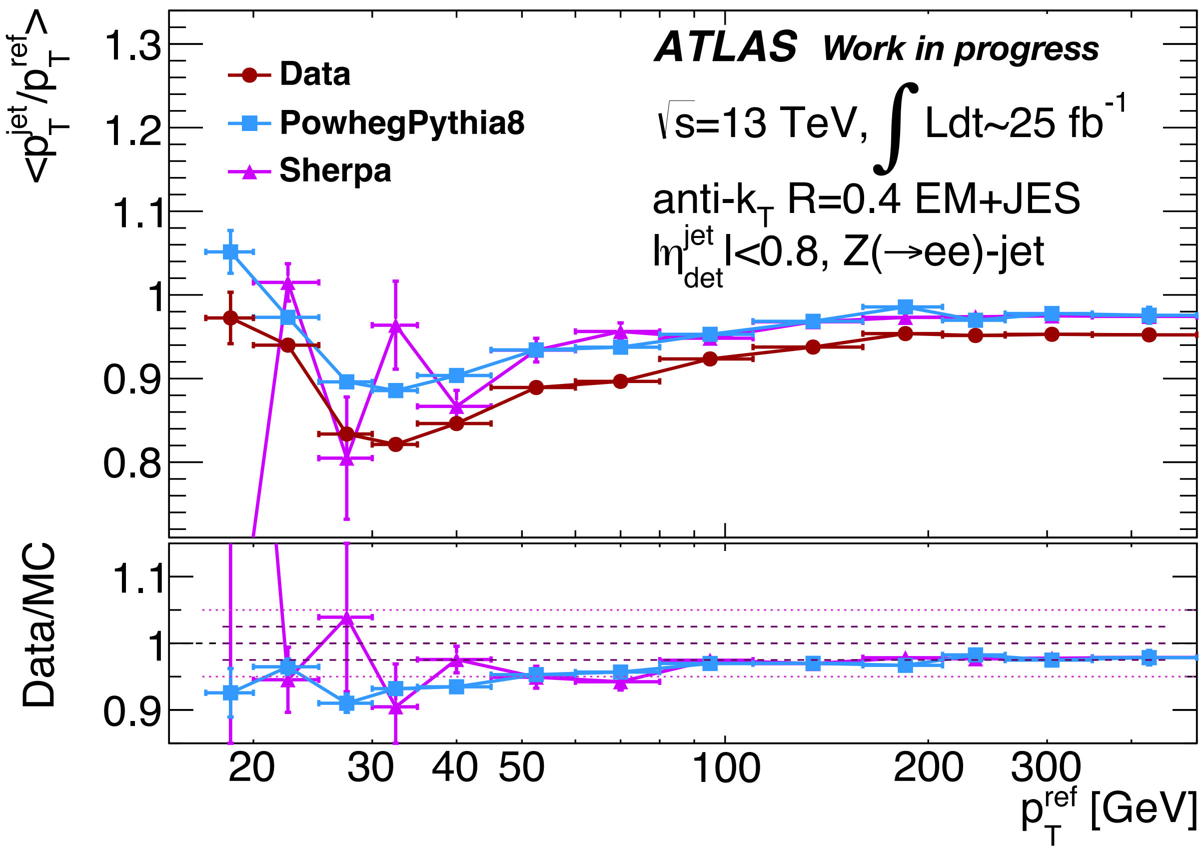
- Event selection vetoes high-p_T sub-leading jets and requires Z-boson and jet to be back-to-back.
- To reduce the contribution of low-p_T sub-leading jet, the leading jet is balanced by a p_T of reference object (p_T^{jet}/p_T^{ref}), where $p_T^{ref} = p_T^Z \cos\Delta\phi(Z, jet)$
- The p_T^{jet}/p_T^{ref} distributions are built in bins of p_T^{ref}.
- The poisson fit, extended to non-integer values, is performed to find mean balance

p_T^{jet}/p_T^{ref} distribution

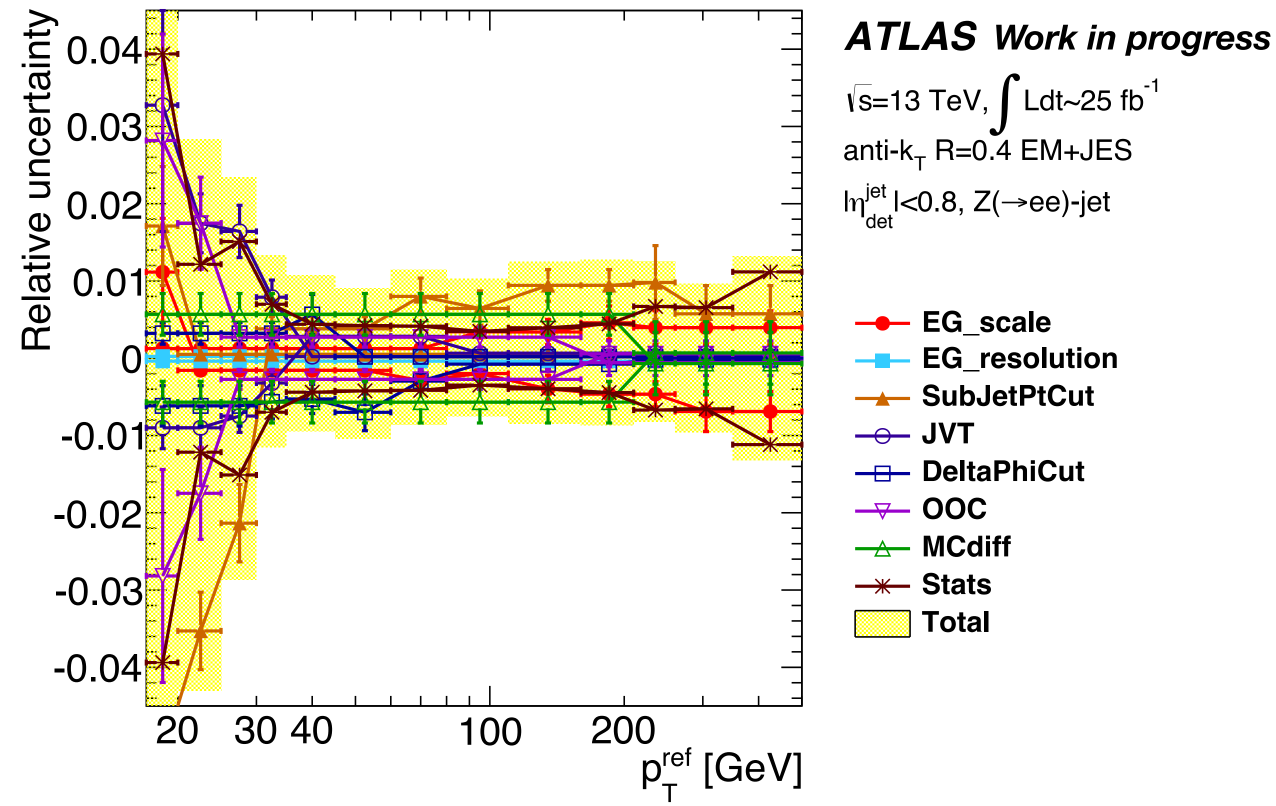


Z+jet DB results

Mean p_T^{jet}/p_T^{ref} as a function of p_T^{ref}



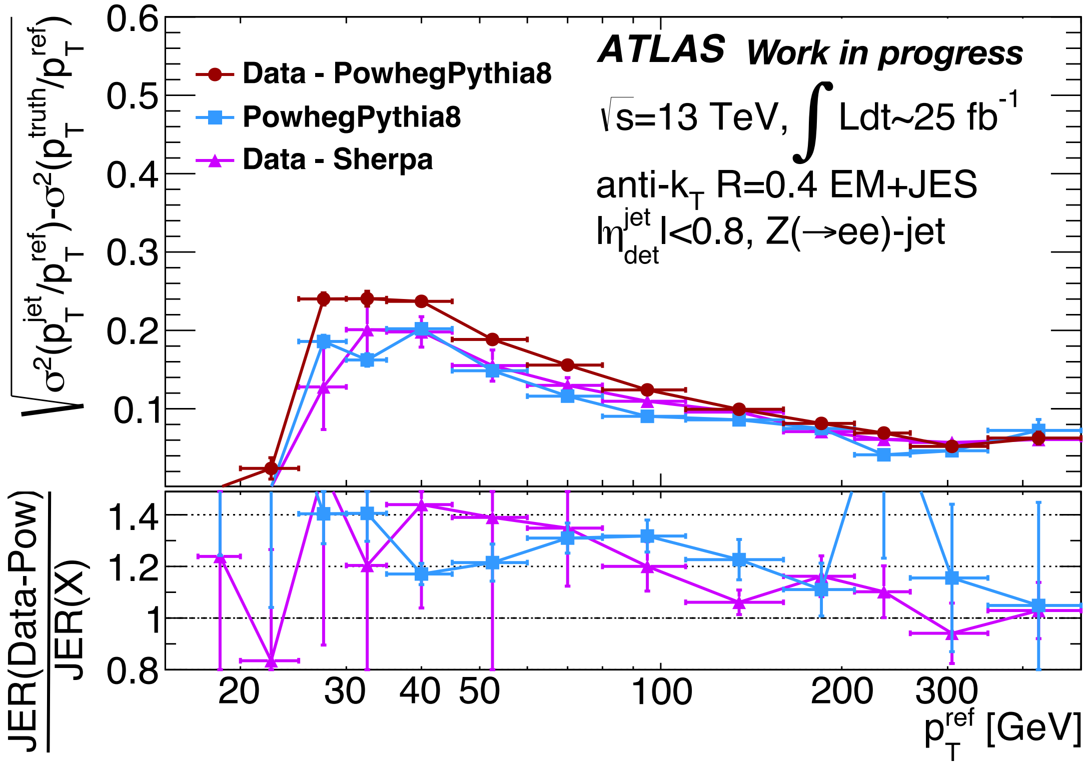
Uncertainties of the method



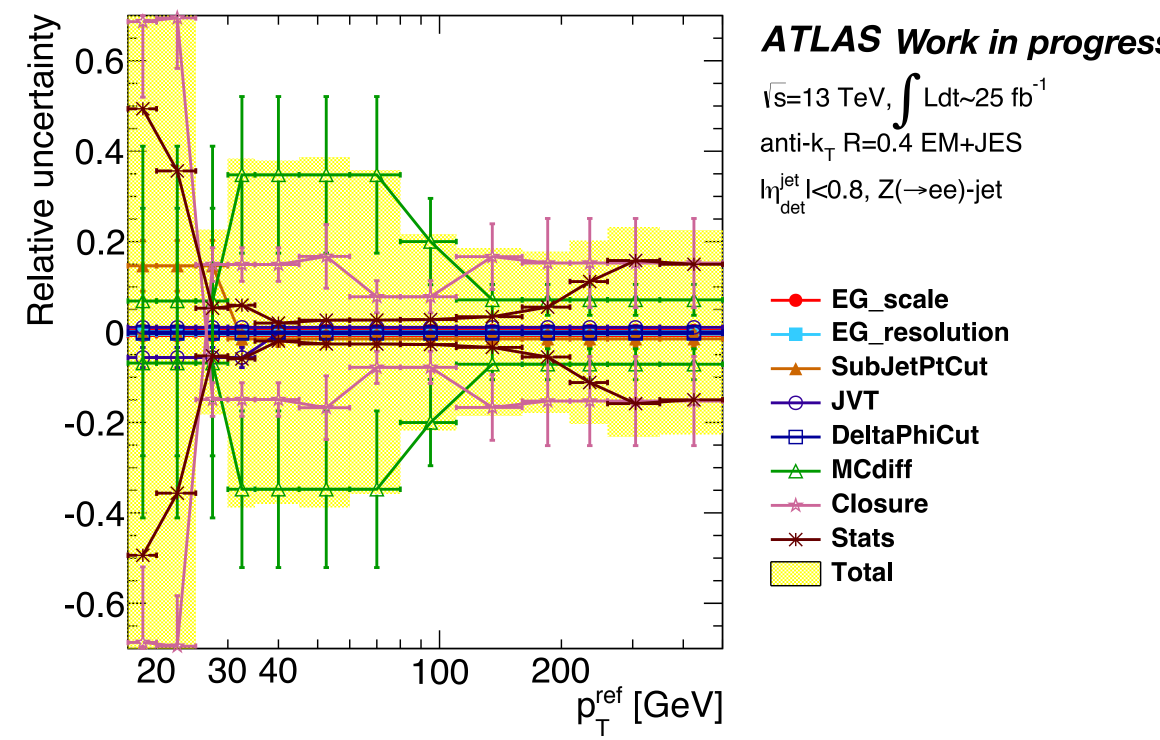
- The difference between mean p_T^{jet}/p_T^{ref} in data and in simulation is used to correct data.
- The correction is of 2-5% depending on p_T^{ref}.
- The method systematics uncertainties include
  - lepton energy scale and resolution
  - variation in sub-leading jet, pile-up suppression, ΔΦ(Z,jet) selections.
  - data-MC difference in the contribution outside of jet cone
  - difference between models in MC generator
- The total uncertainty is below 1% for p_T^{ref}>35 GeV, but it is up to 4% in lower p_T^{ref}.

Probing jet energy resolution using Z+jet DB

Jet energy resolution as a function of p_T^{ref}



Jet energy resolution uncertainties



The DB method allows to probe the jet energy resolution (JER) in data.

- The width of p_T^{jet}/p_T^{ref} distributions is measured in data.
- The contribution to the width from physics effects is subtracted in quadrature using the stable particles from MC simulation.

The measured JER in Z+jet DB is limited in $p_T^{ref}>35$ GeV in 2015-2016 data due to low p_T jet cut during the reconstruction.

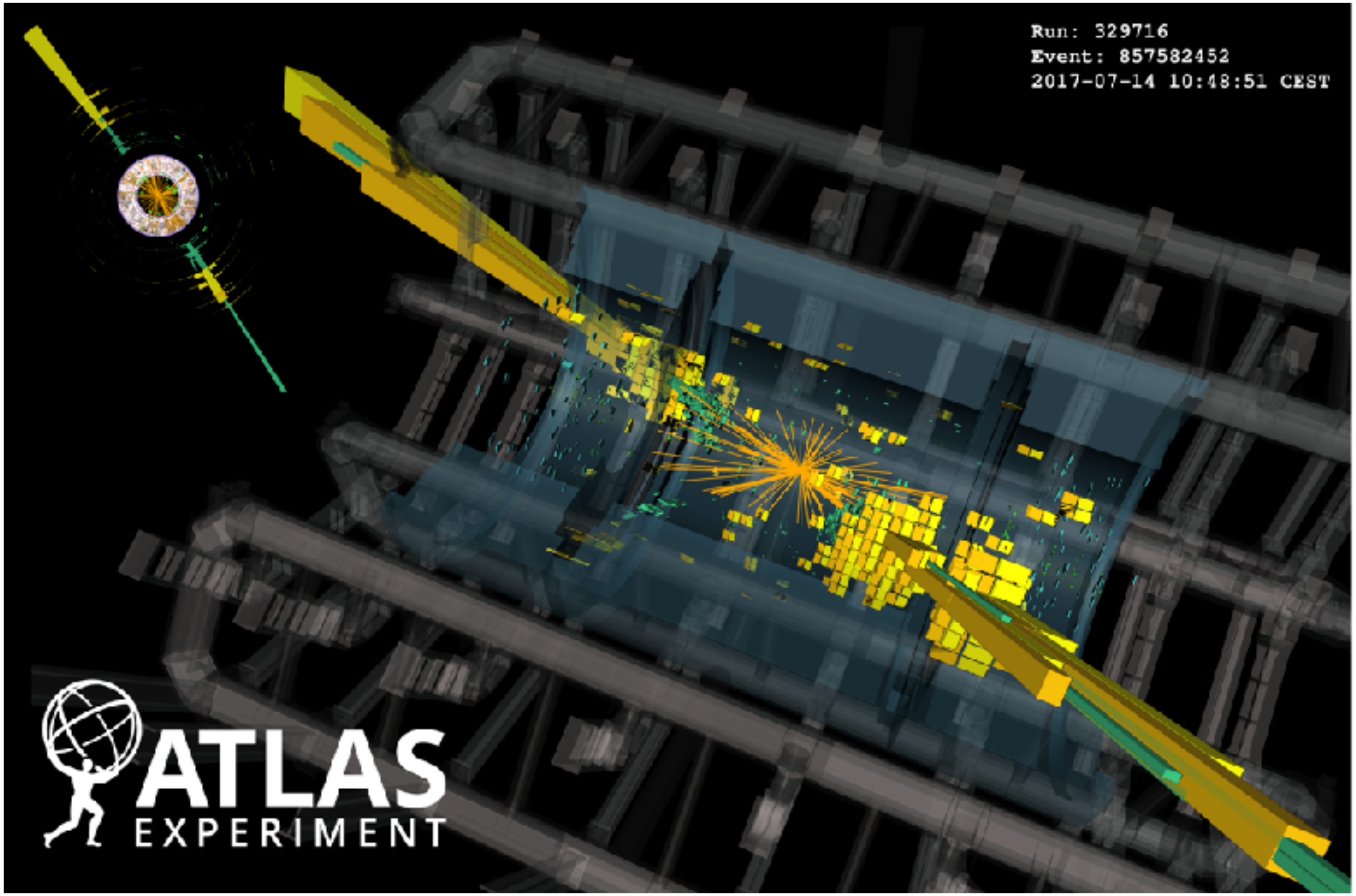
The JER changes from 0.25 in $p_T^{ref}=40$ GeV, to 0.05 in $p_T^{ref}=300$ GeV.

The JER uncertainties are of 10-40%, mostly driven by the difference between MC generators. The data-MC difference in JER is covered by the uncertainties.

Conclusions

- The jet energy scale calibration is established yearly during the data taking for a wide spectrum of jet transverse momenta, and provides the best precision for the physics analysis in ATLAS.
- The precision of the jet energy measurement is constantly improved with the advanced methods and high statistics of pp collisions data. The uncertainty of the jet energy scale goes down to 1% for jet within $100<pT<1000$ GeV range.
- However, even with 1% precision, the jet energy scale uncertainty is one of the dominant uncertainty in the physics measurements of the processes with jets in the final-state, so further improvements are essential.
- These results are recently published in Phys. Rev. D.

High-pT jet event



Display of a di-jet event (Run=329716, Event=8575822452) with mjj=9.3 TeV, produced in pp collisions at $\sqrt{s}$ = 13 TeV data in 2017. The two high-pT jets both have pT=2.9 TeV, one is at η=-1.2 and the other at η=0.9. The two yellow cone represent the reconstructed jets.