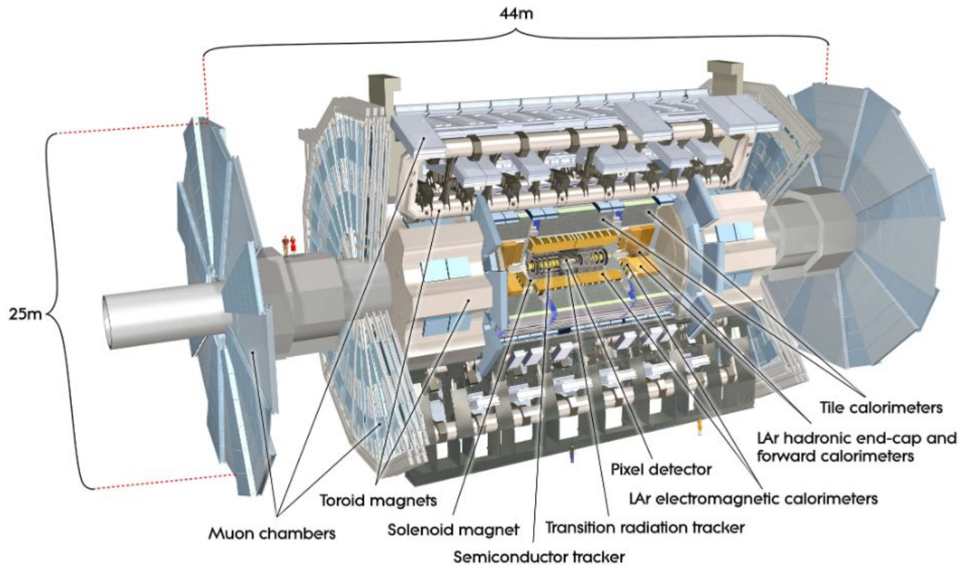
Jets and missing transverse energy reconstruction and calibration in ATLAS

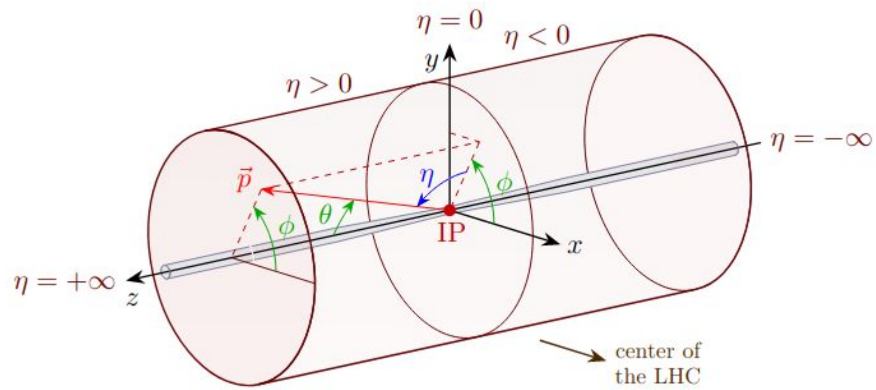
ICNFP 2022,
Crete, Greece

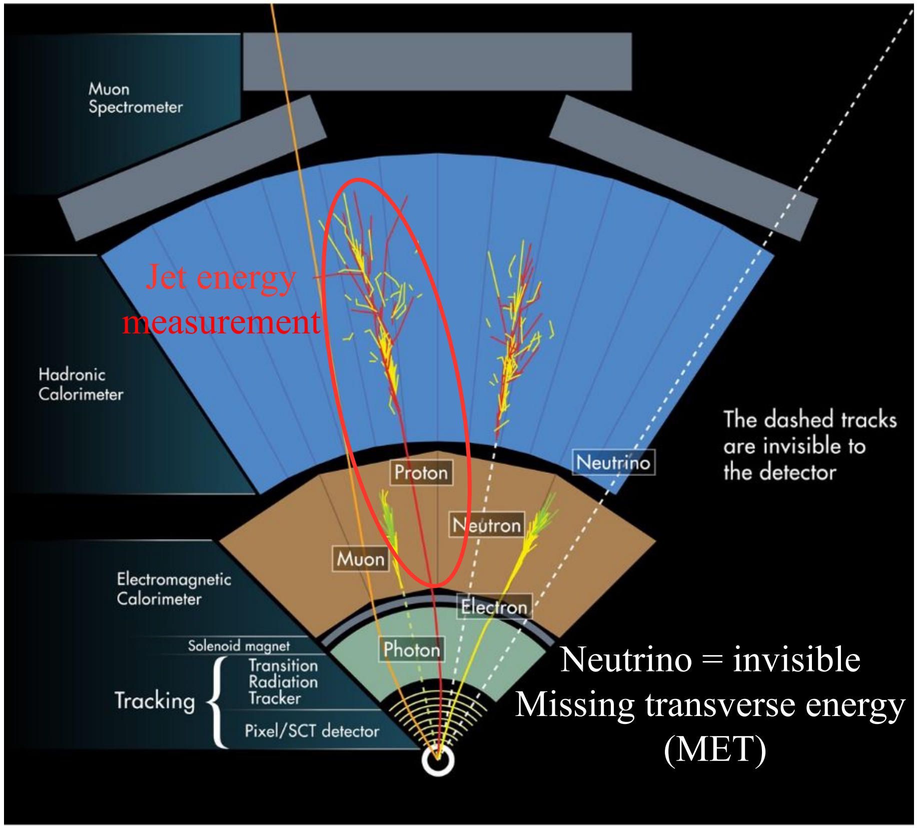
Romain Bouquet,
On behalf of the ATLAS Collaboration



Cylindrical system of coordinates:

$$(r, \theta, \phi) \Leftrightarrow (r, \eta, \phi) \text{ with } \eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



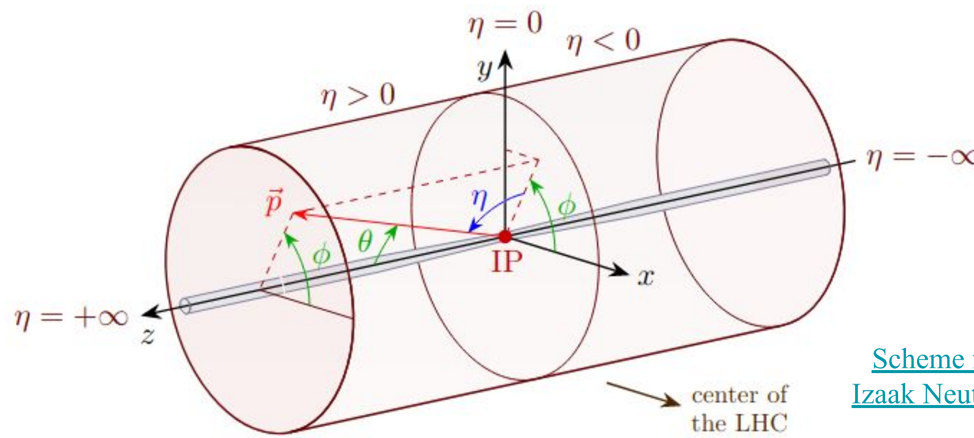


ATLAS = multilayer detector

- **Tracker:** charged particle tracks and momenta measurements
- **Electromagnetic calorimeter**: electron and photon energy measurement
- **Hadronic calorimeter:** hadron energy measurement
- **Muon spectrometer:** muon energy and momentum measurement

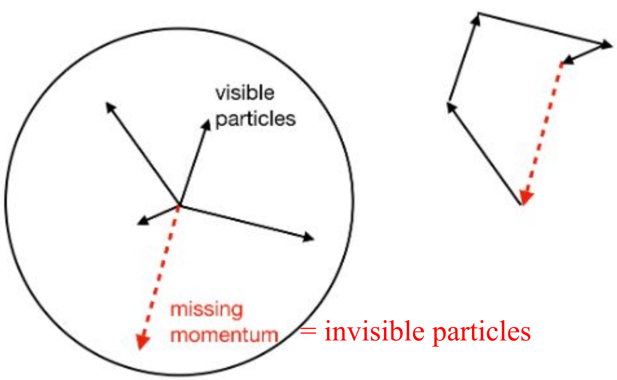
p_T = transverse momentum of a particle
= projection of its momentum on the x-y plane

$$p_{\mathrm{T}} = \sqrt{p_x^2 + p_y^2} = |\boldsymbol{p}| \sin(\theta)$$



Scheme from Izaak Neutelings

Transverse momentum conservation:
Before the collision, $p_T = 0$
for partons inside the protons
→ After the collision $\sum \vec{p}_T = \vec{0}$



arXiv:1712.01391

u = x or y direction

$$E_u^{\mathrm{miss}} = -\left(\sum_{i \in \{\text{hard objects}\}} p_{u,i} + \sum_{i \in \{\text{soft signal}\}} p_{u,i} \right)$$

$$E_u^{\mathrm{miss}} = E_u^{\mathrm{miss},e} + E_u^{\mathrm{miss},\mu} + E_u^{\mathrm{miss},\tau_{\mathrm{had}}} + E_u^{\mathrm{miss},\gamma} + E_u^{\mathrm{miss,jets}} + E_u^{\mathrm{miss,soft}}$$

Missing transverse energy

$$E_{\mathrm{T}}^{\mathrm{miss}} = \left| \boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}} \right| = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

Why jets are so important?
H→b$\overline{\text{b}}$ decay example

Jet = hadronization of a parton (quark or gluon)
leading to a spray of collimated hadrons in the detector

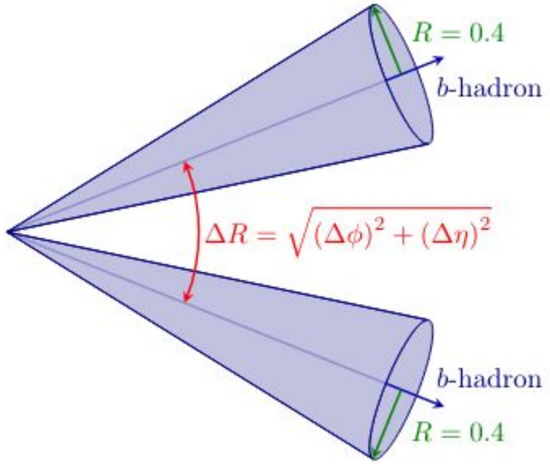
Angular distance between 2 particles i & j

$$\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

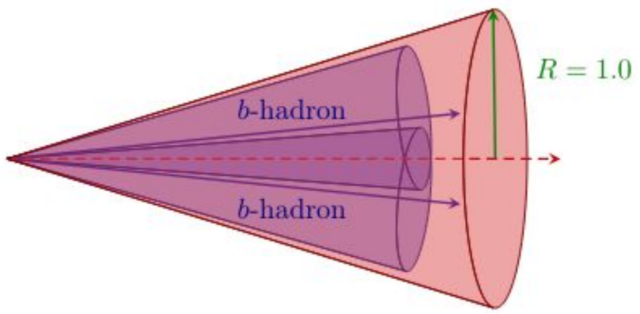
Higgs main decay (58%): H→b$\overline{\text{b}}$

$$\Delta R(b,\bar{b}) \approx \frac{2m_H}{p_T^H}$$

Low energy Higgs decay
→ Resolved topology



High energy Higgs decay
→ Boosted topology



→ Reconstruct the Higgs with small radius or large radius jets depending on the regime

→ Jets are one of the most basic objects used by many SM & BSM analyses

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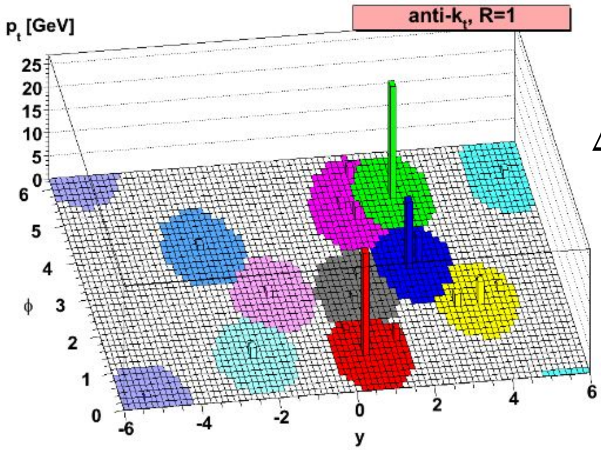


→ Reconstruction by clusterization of hits in the detector approximately into cones of a certain angular distance (ΔR)

$$\Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$ → Jet ≈ "circles" in the η-ϕ plane

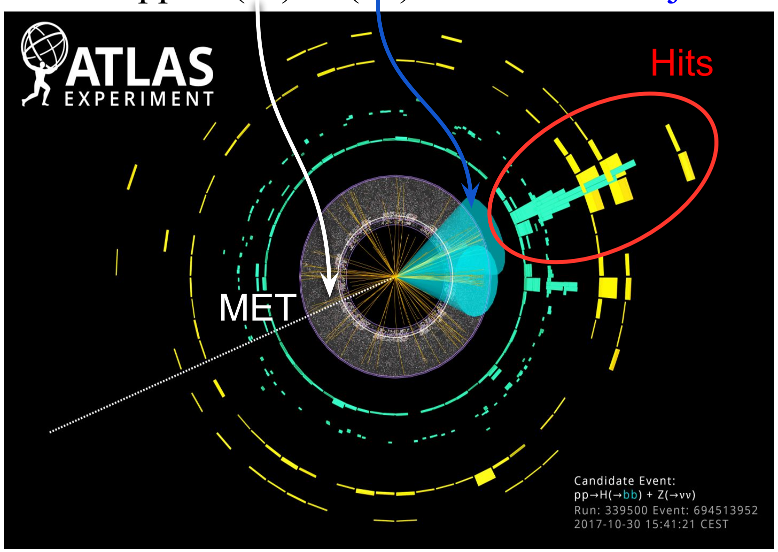
Calorimeter-based jets:

- Small R-jets: R = 0.4
- Large R-jets: R = 1.0

Track-based jets:

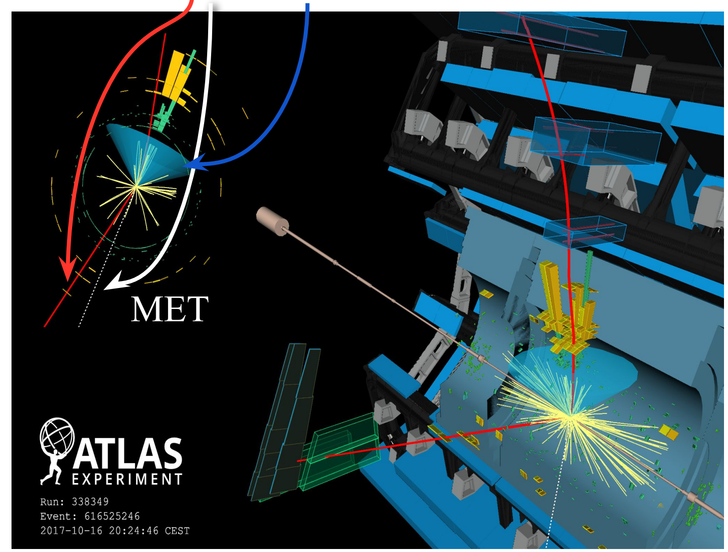
- Variable radius (VR) track jets: 0.02 < R < 0.4

qq→Z(νν)+H(bb) with 2 small R-jets



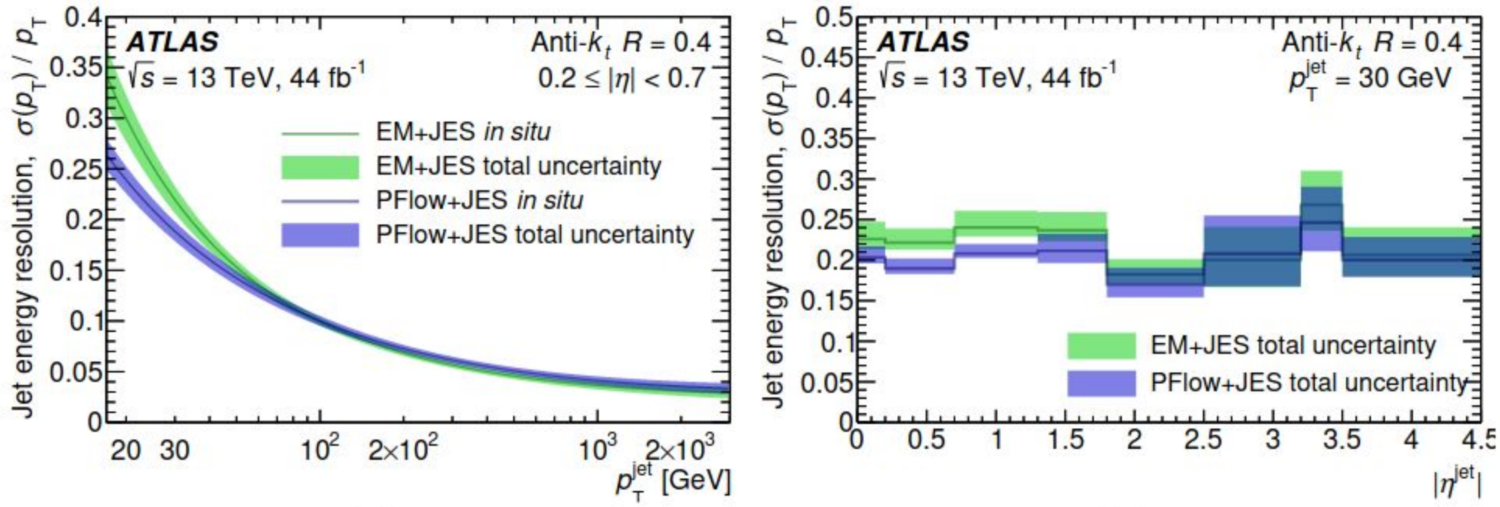
https://cds.cern.ch/record/2636049

qq→W(lν)+H(bb) with 1 large R-jet



https://atlas.cern/updates/briefing/measuring-beauty-higgs-boson

Particle Flow vs EM Topological reconstruction algorithms for small R-jets



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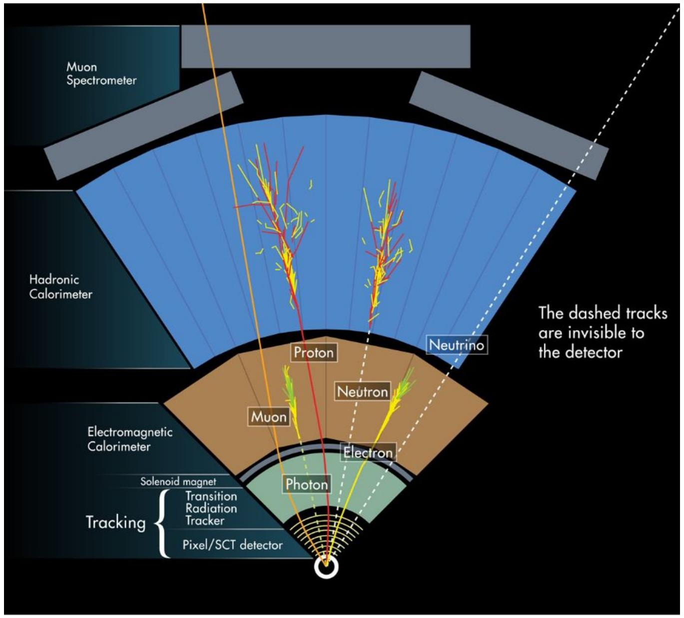
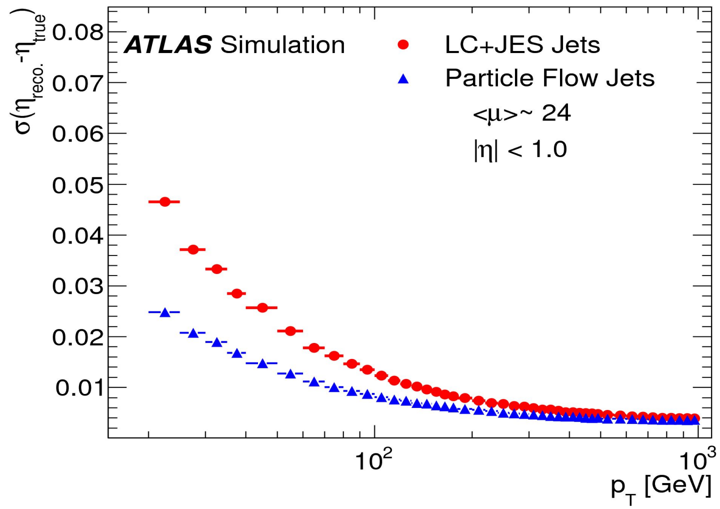
EMTopo (old algorithm): jets reconstructed using only calorimeter info
PFlow (new algorithm): using calorimeter+tracker info

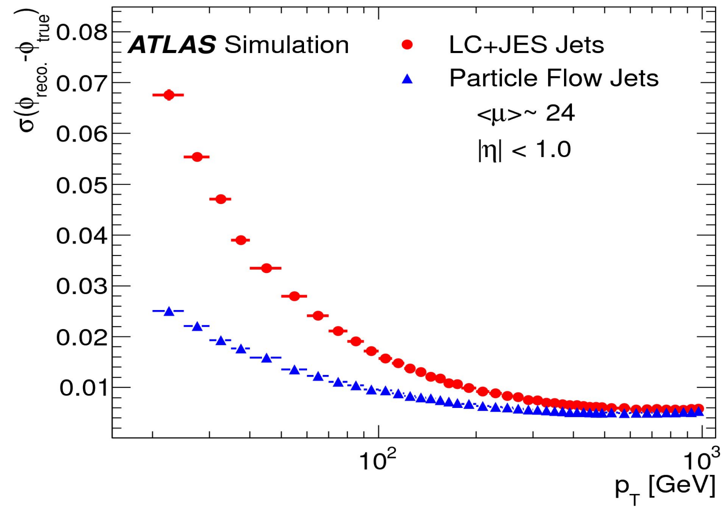
PFlow is better than EMTopo in terms of:

- Reconstruction efficiency
- Angular resolution
- Energy resolution
- Pile-up stability (thanks to the high granularity of the tracker)



Angular resolution & jet reconstruction efficiency for EMTopo vs PFlow jets





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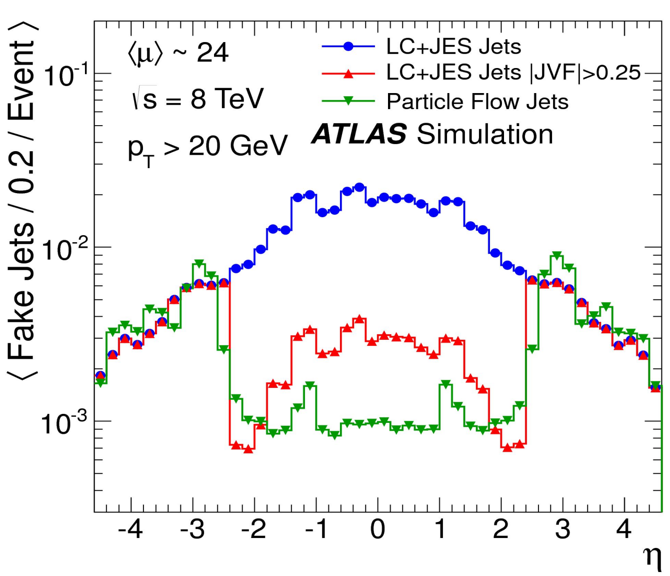

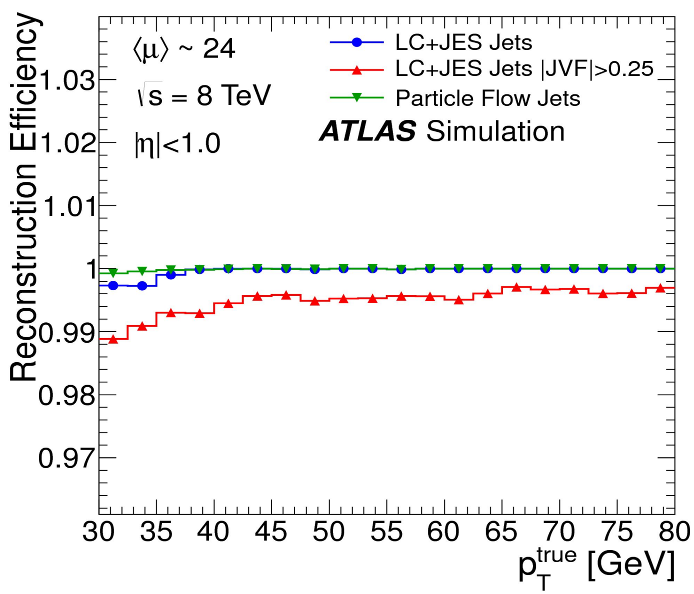

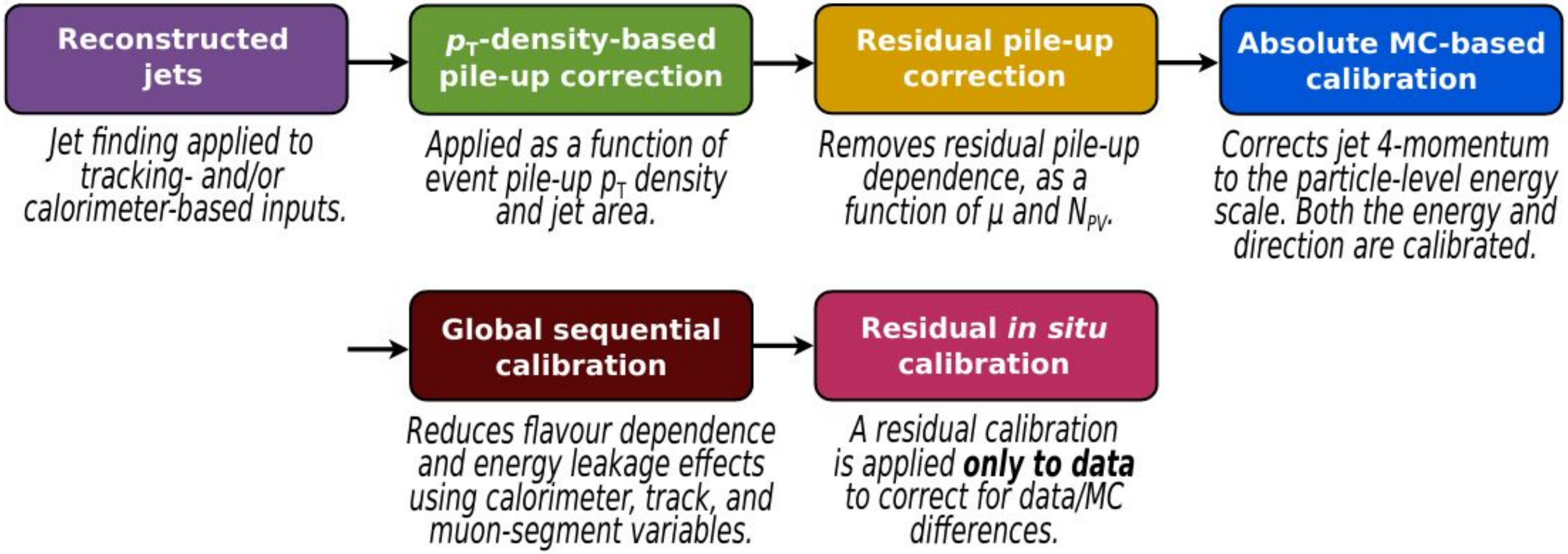

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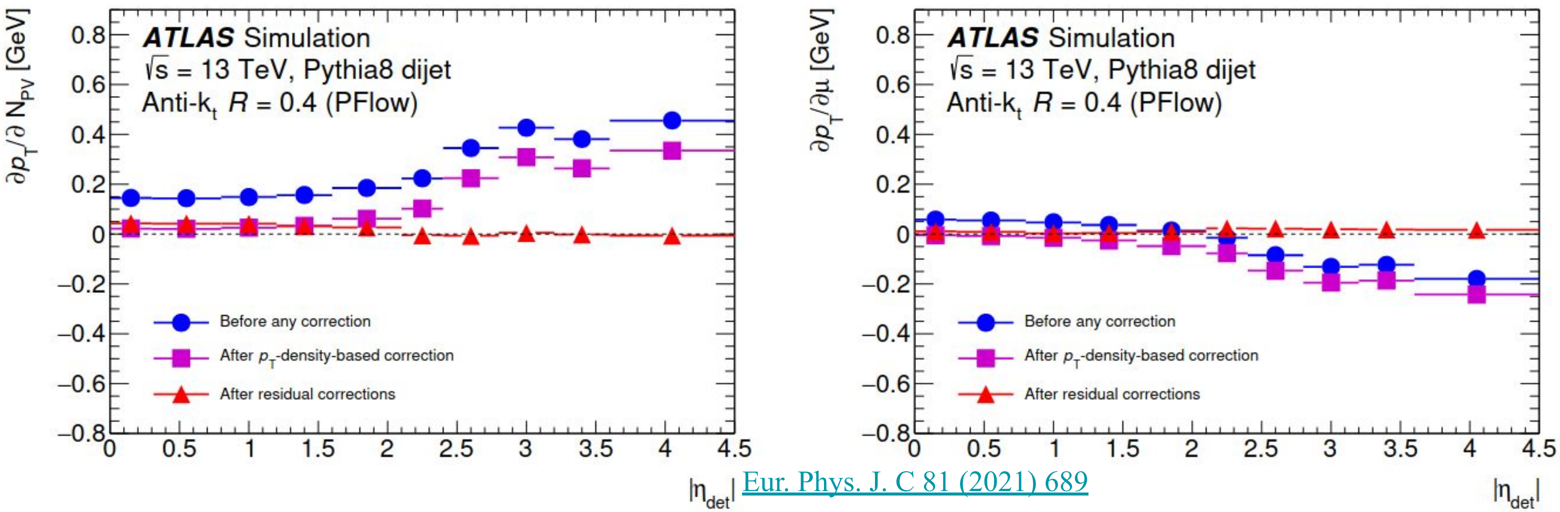
Once reconstructed, jets go through a serie of corrections & calibrations:

- Pile-up corrections
- Particle level corrections derived from simulation
- Reduce jet flavor + energy leakage dependance
- In-situ correction applied to data only to correct discrepancies with simulation

Jet pile-up corrections



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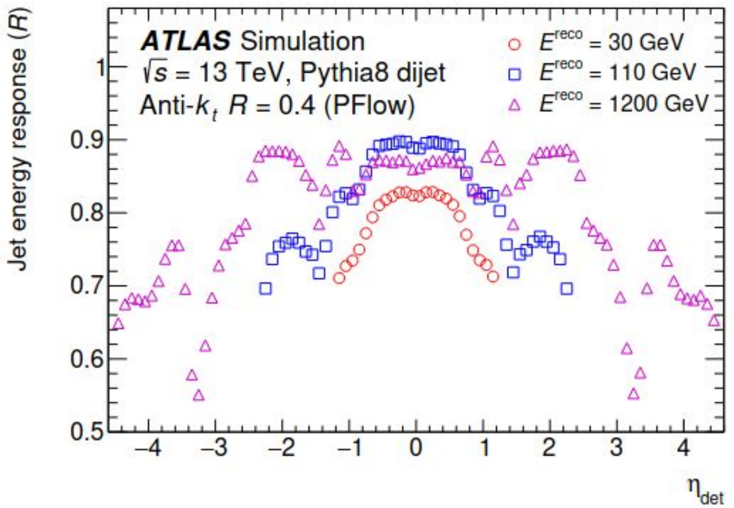
$$p_T^{corr} = p_T^{reco} - \rho \times A - \alpha \times (N_{PV} - 1) - \beta \times \mu$$

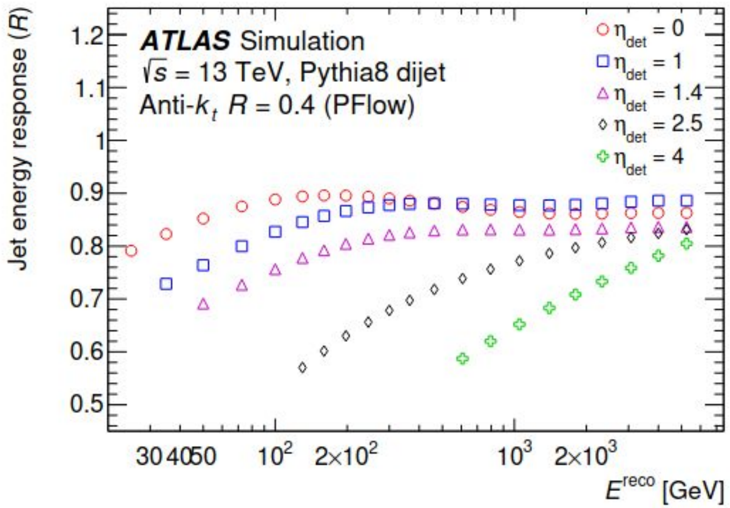
- corrected p_T (p_T^{corr})
- reconstructed p_T (before correction) (p_T^{reco})
- p_T-density correction ($\rho \times A$)
- Residual corrections ($\alpha \times (N_{PV} - 1) - \beta \times \mu$)
- N_{PV}: # of primary vertices
- μ: # of inelastic collision per bunch crossing

p_T-density correction = subtraction of the average contribution to jet energy due to pileup (estimated in the η-ϕ plane)

Residual correction = remove residual pile-up p_T dependence w.r.t N_{PV} and μ after p_T-density correction

→ **Significant reduction of pile-up dependence**





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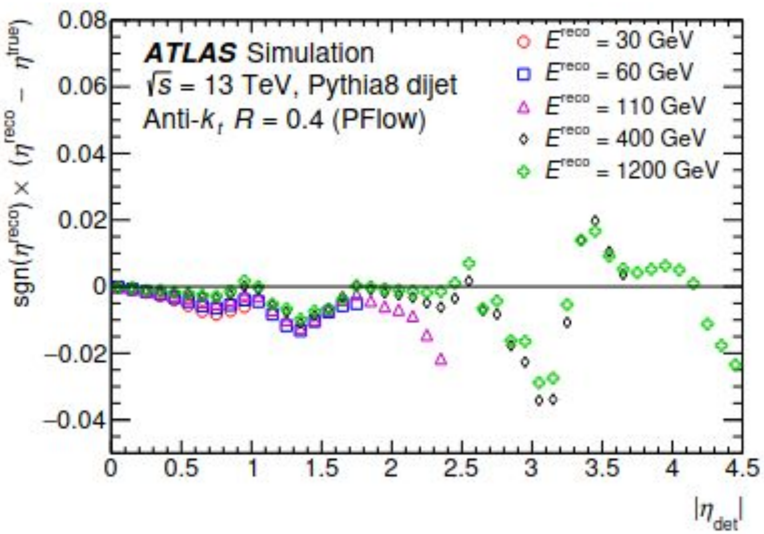


Reconstructed jet energy ≠ true energy + depends on pseudorapidity

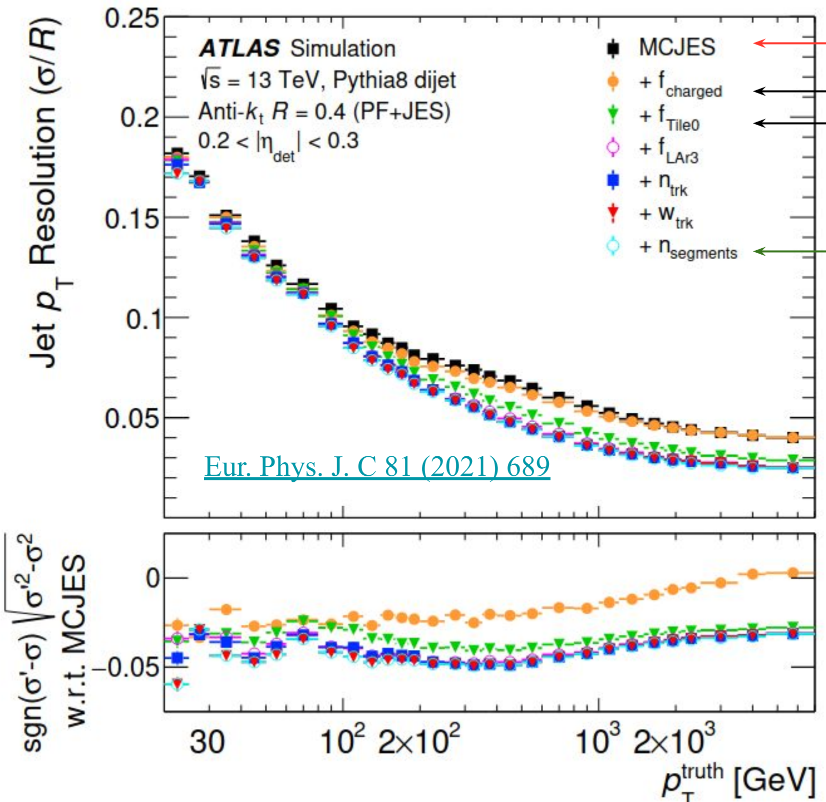
→ Correction needed to mitigate detector effects

→ Jet energy response correction factor : $R = \dfrac{E_{\text{reco}}}{E_{\text{truth}}}$

Reconstructed jet pseudorapidity also needs to be corrected

→ **Correction are derived using MC simulations**

Jet global sequential calibration (GSC)



GSC → 6 corrections for flavour dependence + energy leakage dependence:

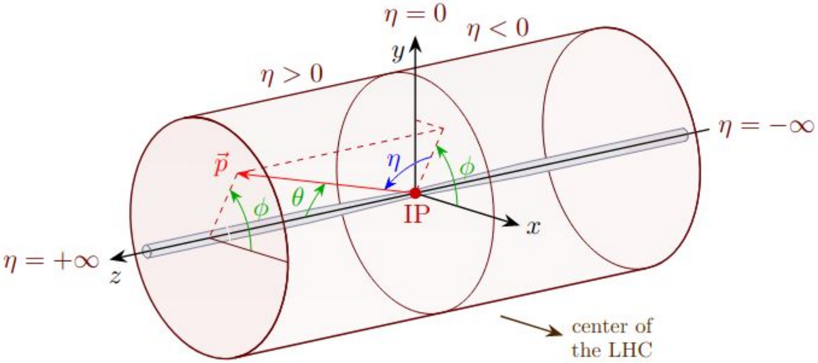
- Jet response depend on the flavour and energy distribution of particles constituting the jet
  → quark initiated jets have hadrons with high p_T fraction
  → gluon initiated jets: higher multiplicity, low fraction of jet p_T, larger transverse dimension
  → lower calorimeter response for gluon jets
- Energy leakage = energy not deposited in the calorimeter by high energy jets

→ Improvement of the resolution after GSC is applied
(correction based on fraction of energy in a calo layer, number of tracks, charged fraction etc)

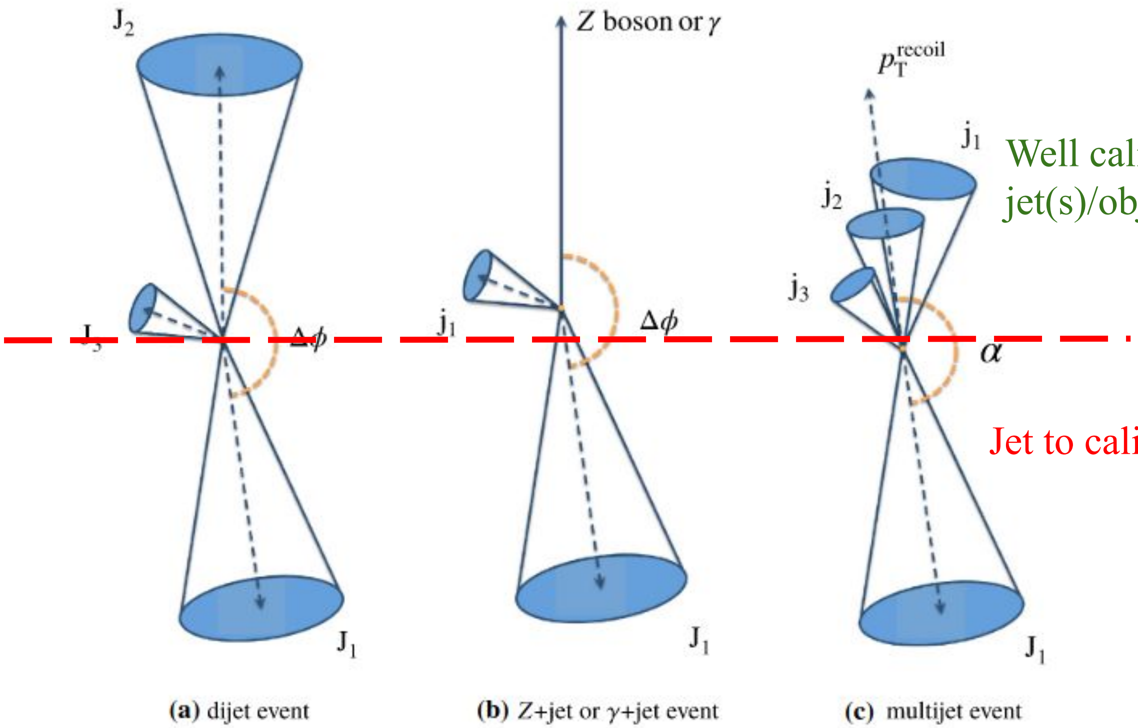
Transverse momentum conservation:

Before the collision, $p_T = 0$ for partons inside protons

→ After the collision $\sum \vec{p}_T = \vec{0}$



In situ correction = correction **only applied to data** to correct for discrepancies between data and simulations



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Well calibrated reference jet(s)/objects

Jet to calibrate

$$\vec{p}_{T,\rm ref} + \vec{p}_{T,\rm jet} = \vec{0}$$

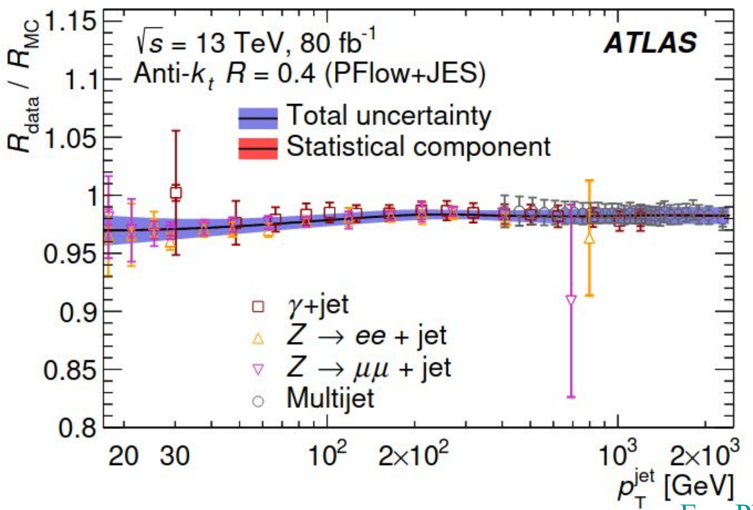
→ Define jet p_T-response ratio

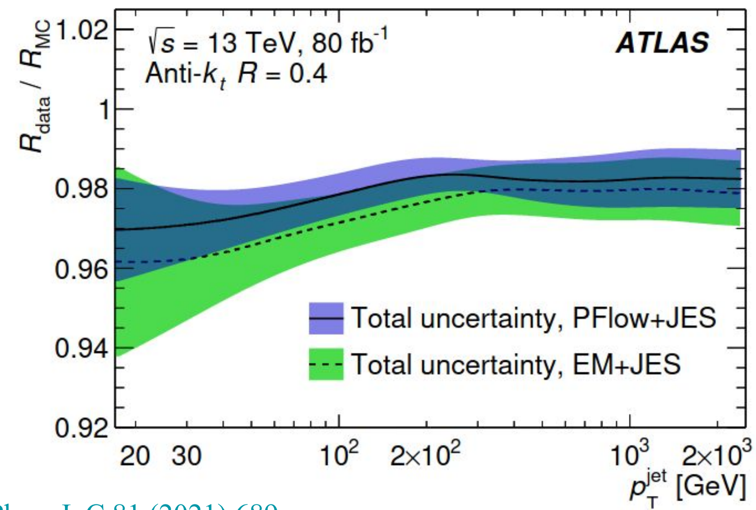
$$R = \frac{p_{T,\rm jet}}{p_{T,\rm ref}}$$

→ Derive correction for data (in p_T bins)

$$c = \frac{R_{\rm data}}{R_{\rm MC}}$$

→ Derive also p_T-correction for forward jets $0.8 \leq |\eta| \leq 4.5$ using dijet events





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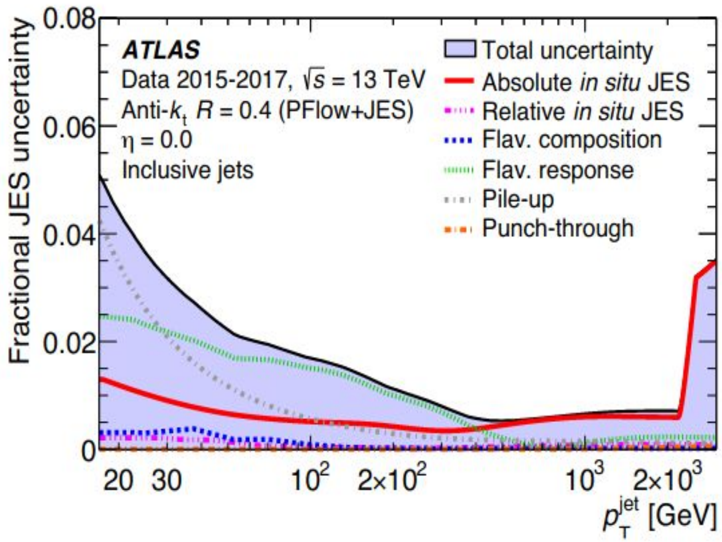
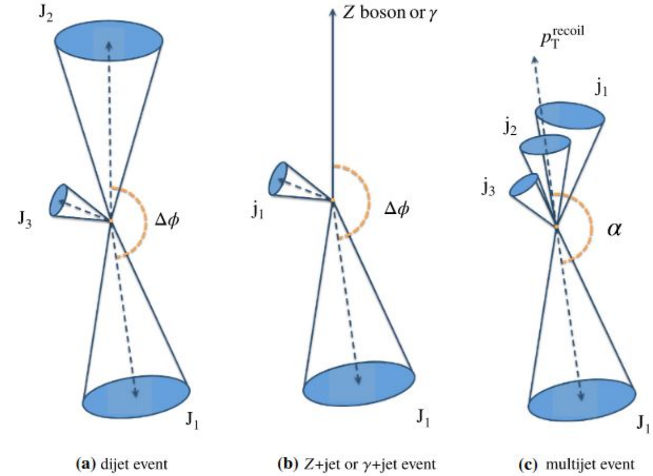


At low p_T : calibration with Z+jet & gamma+jet events

At high p_T: mainly multijet events

→ combine results from Z+jet, gamma+jet & mulitjet



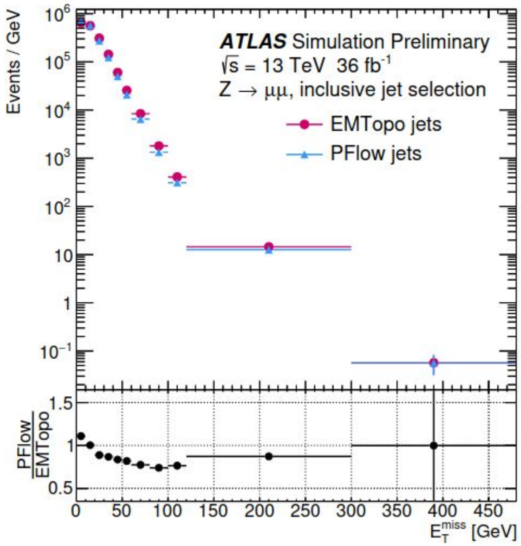
Missing transverse energy reconstruction
EMTopo vs PFlow

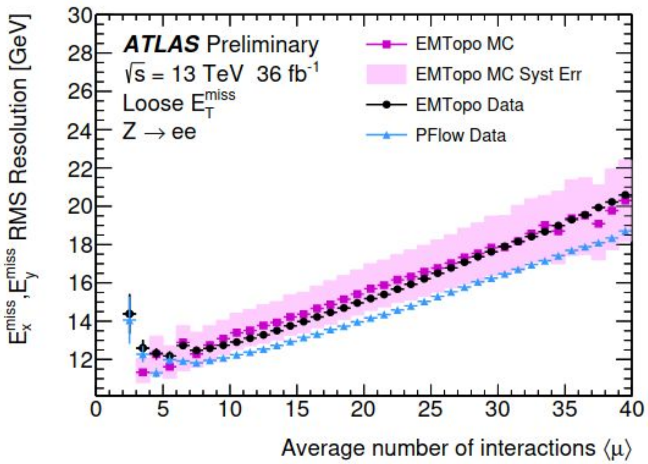
u = x or y direction

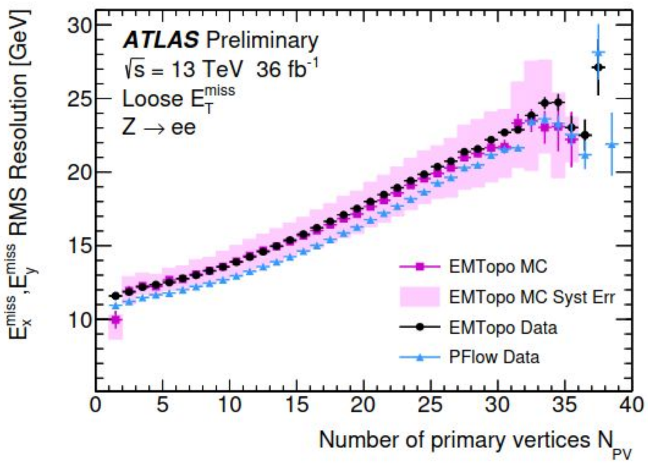
$$E_u^{\text{miss}} = E_u^{\text{miss},e} + E_u^{\text{miss},\mu} + E_u^{\text{miss},\tau_{\text{had}}} + E_u^{\text{miss},\gamma} + E_u^{\text{miss,jets}} + E_u^{\text{miss,soft}}$$ → MET depends on jet algorithm used

Reconstruction of MET in $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$ events

→ Expect MET = 0 for those events





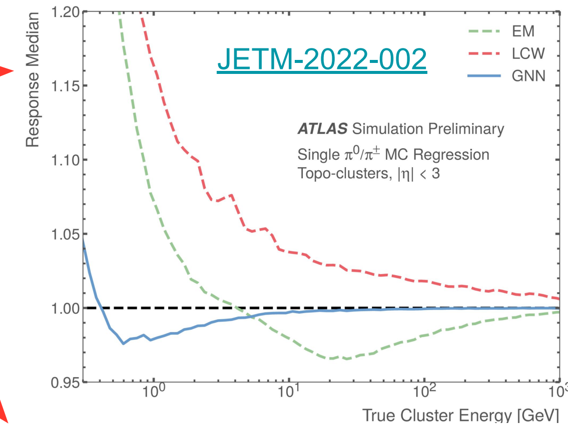


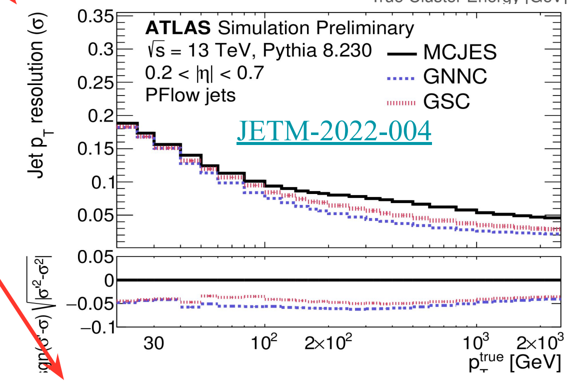
https://cds.cern.ch/record/2625233

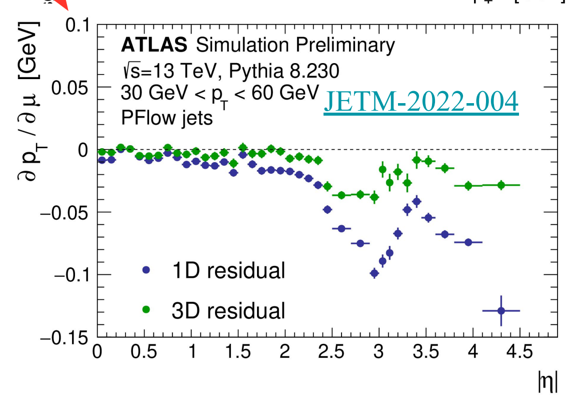
MET is closer to expected value with PFlow jets

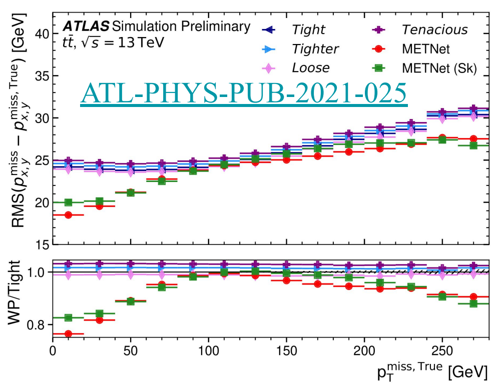
+ a better resolution is achieved

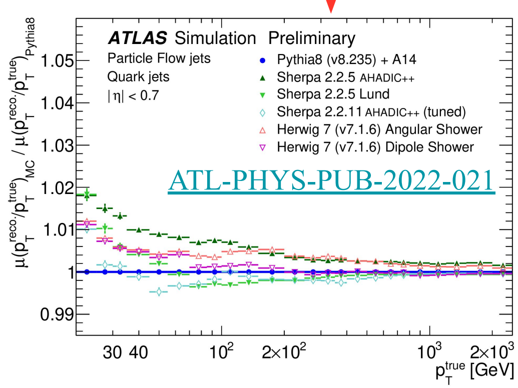
- **Machine learning for classifying and calibrating clusters** (= group of hits in the detector, clusters are constituent of jets) π^0 and $\pi^{\pm}$ different response → key step for jet reconstruction
- **Machine Learning for the GSC corrections** → exploit correlations instead of 6 independent corrections → better jet resolution obtained
- **Improved pile-up correction taking into account p_T dependence (currently only derived as a function of η) + correlation between N_{PV} and μ**
  1D = correction not taking into account correlation
  3D = correction taking into account correlation
- **Flavour uncertainties: difference between generators is related to how the relative amount of baryons and kaons produced within a jet is modelled in that MC.**
  → Careful tuning of fraction of gluon jets especially in baryon and kaon production in the generator can lead to reduction of uncertainties (*Sherpa Ahadic++*)
- **Machine learning for MET reconstruction (METNet)**
  → Better resolution and pileup resilience









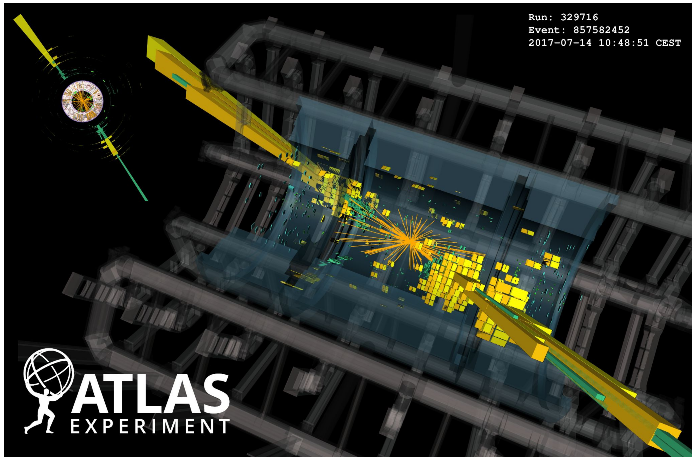


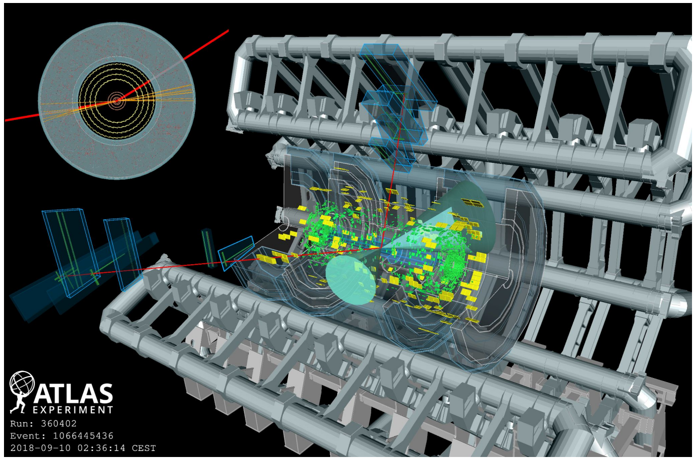
Conclusion

- **Jet reconstruction is crucial for many SM & BSM analyses**
  → Needed for searches & precision measurement in many final states (Higgs, top quark, W/Z decays…)
  → Huge efforts on theory/simulations and experimental sides to reduce uncertainties
  → New algorithms are developed to reach better resolution and stability w.r.t pile-up for instance

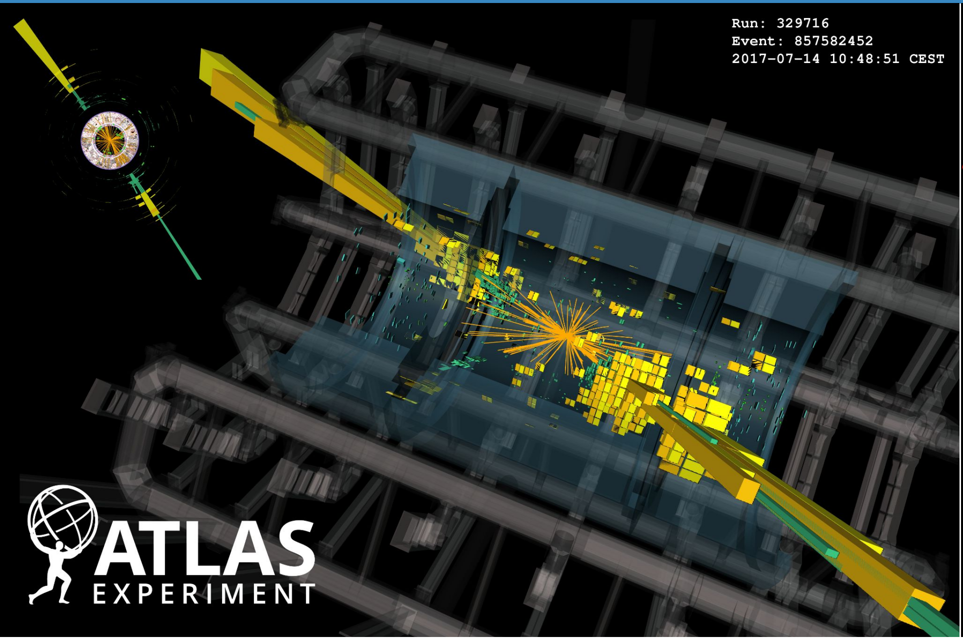
- **Multistep corrections**
  → Pile-up corrections
  → MC absolute calibration
  → Global sequential calibration
  → In situ corrections to account for data versus MC discrepancies

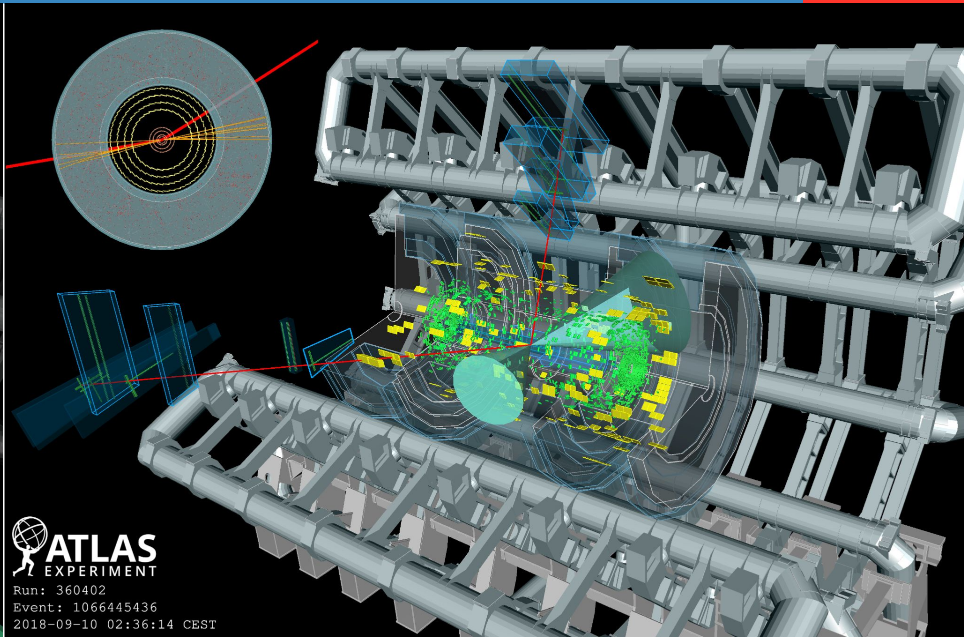
- **Many improvements to come thanks to machine learning and new algorithms developed!**





Can you guess
to which processes
correspond those
2 events?
(answers in next slide)





dijet event

qq→Z(→μμ)+H(→bb) event

Events display from
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Physics
https://atlaspo.cern.ch/public/event_display/

Backup