APS | DIVISION OF PARTICLES & FIELDS

DPF 2017

13 TeV Jet Energy Scale at ATLAS

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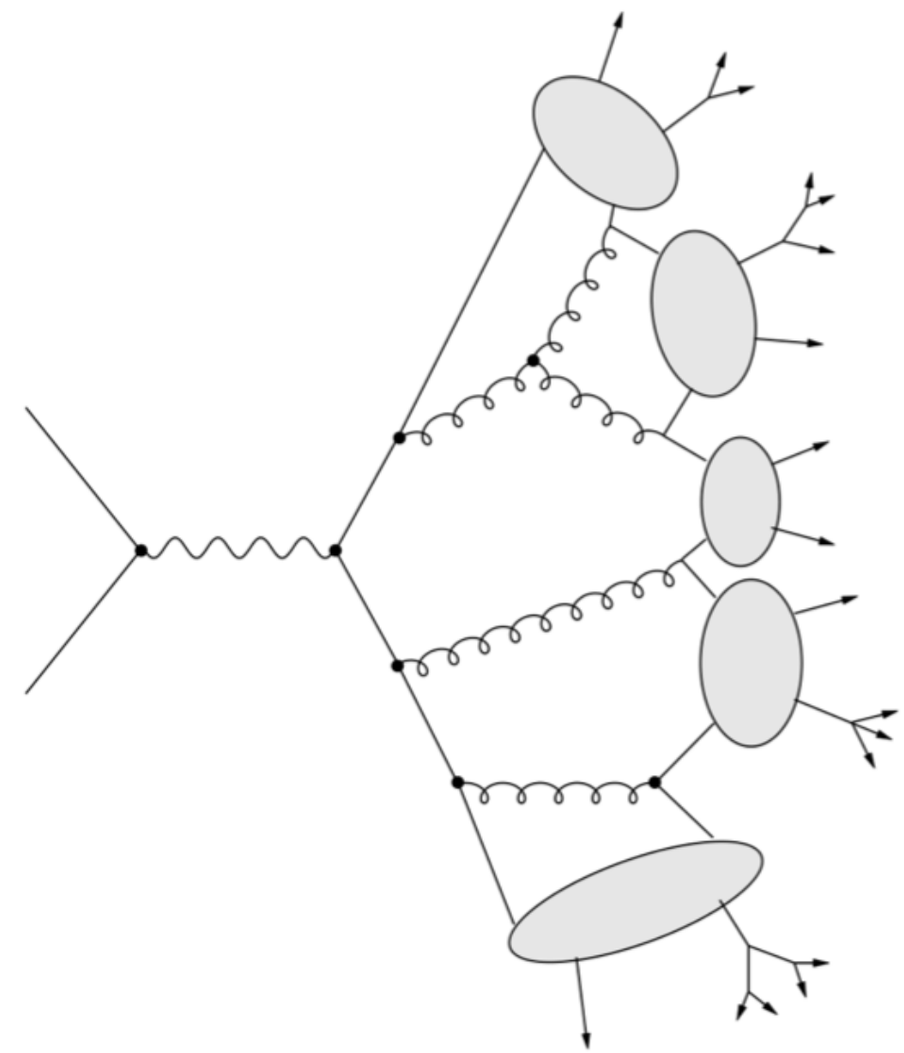
ATLAS EXPERIMENT

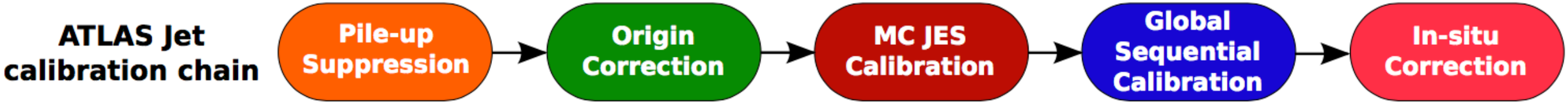
Jets at the LHC

- QCD physics is an essential part of the ATLAS physics program but is **difficult**
  - **Parton shower** and **hadronization** turn simple hard-scatter into a mess of π, *K*, p, n, γ, etc.
- Latest jet calibration techniques:
  - Quick review of jet reconstruction
  - Details of jet calibration procedure from new 2015 summary paper
  - The latest 27 fb^{-1} 2016 calibration
  - A few new techniques highlighted at jet-focused BOOST 2017



Jet Calibration

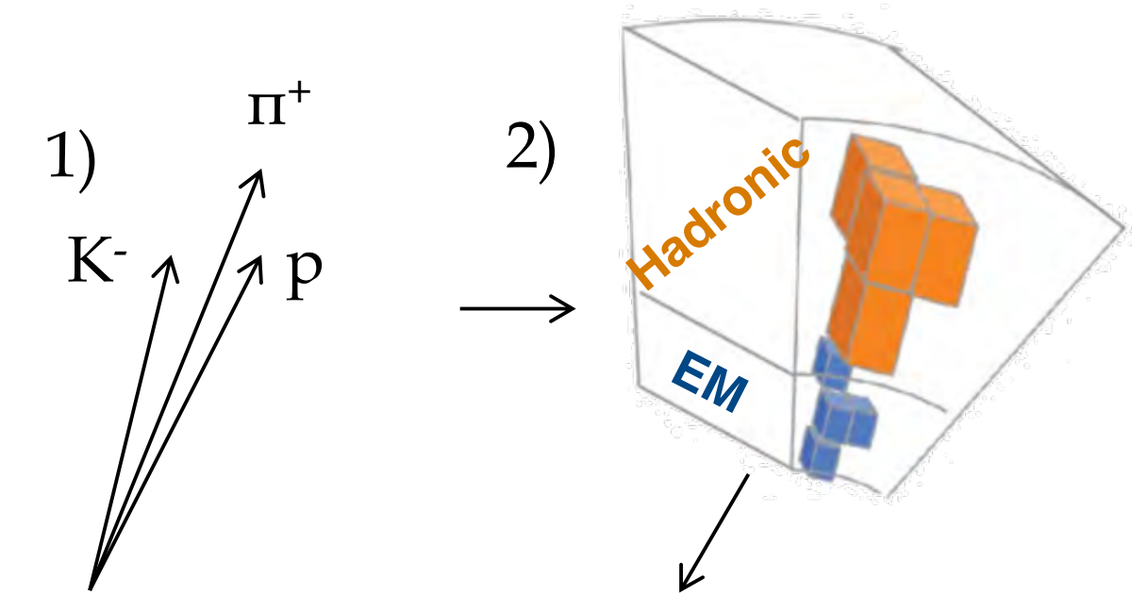
- ATLAS has fantastic EM and hadronic calorimeters, giving precise measurement of **deposited energy**
- ATLAS calorimeters are **sampling** & **non-compensating**
  - Absorber materials induce showering but cannot measure energy
  - Lower response for hadrons due to nuclear interactions
- Calibrations return jet energy to **particle scale** in MC simulation

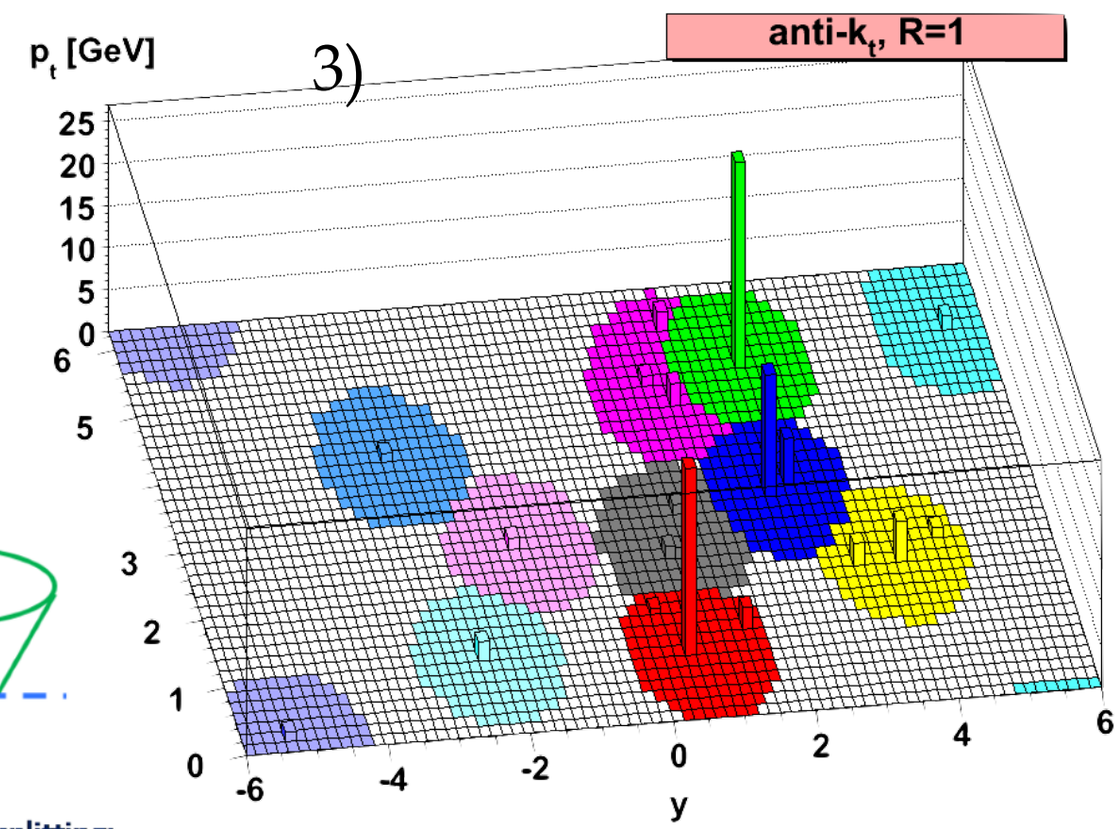


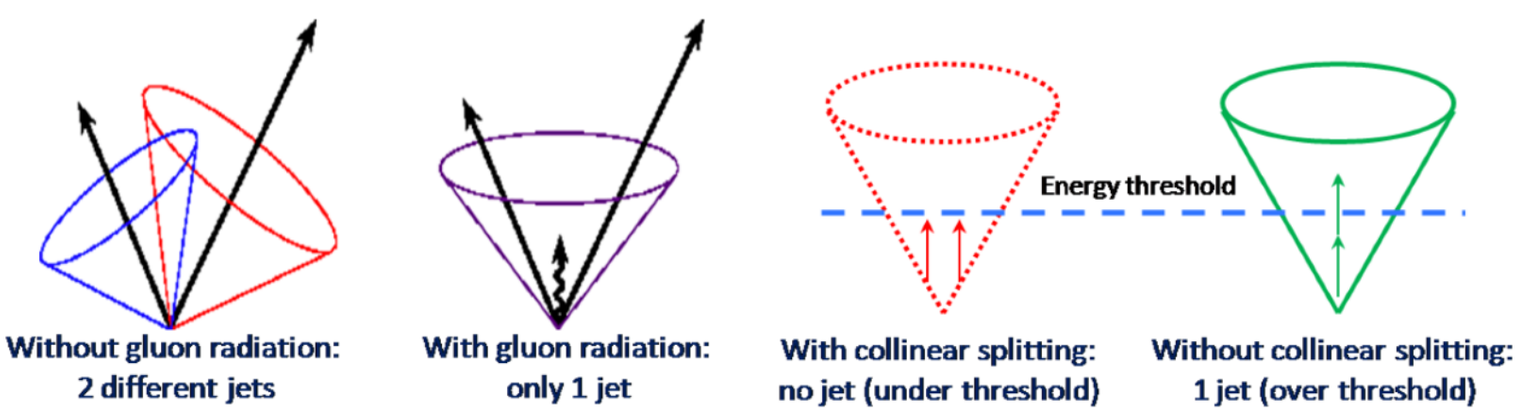
- Focus today on R=0.4 jets at **EM-scale**, but same calibrations used for
  - **Local cluster weighted** jets: correct hadronic-like topo-clusters for expected missing energy
  - **Particle-flow** jets: Use tracks to measure charged particle contribution

Jet reconstruction

- Jet finding on topo-clusters - 3D clusters of cell energies
- Anti-k_t algorithm is infrared and collinear safe, while fairly **pileup insensitive**
- **R=0.4** jets perfect for many analyses - captures bulk of parton shower while minimizing pileup contamination

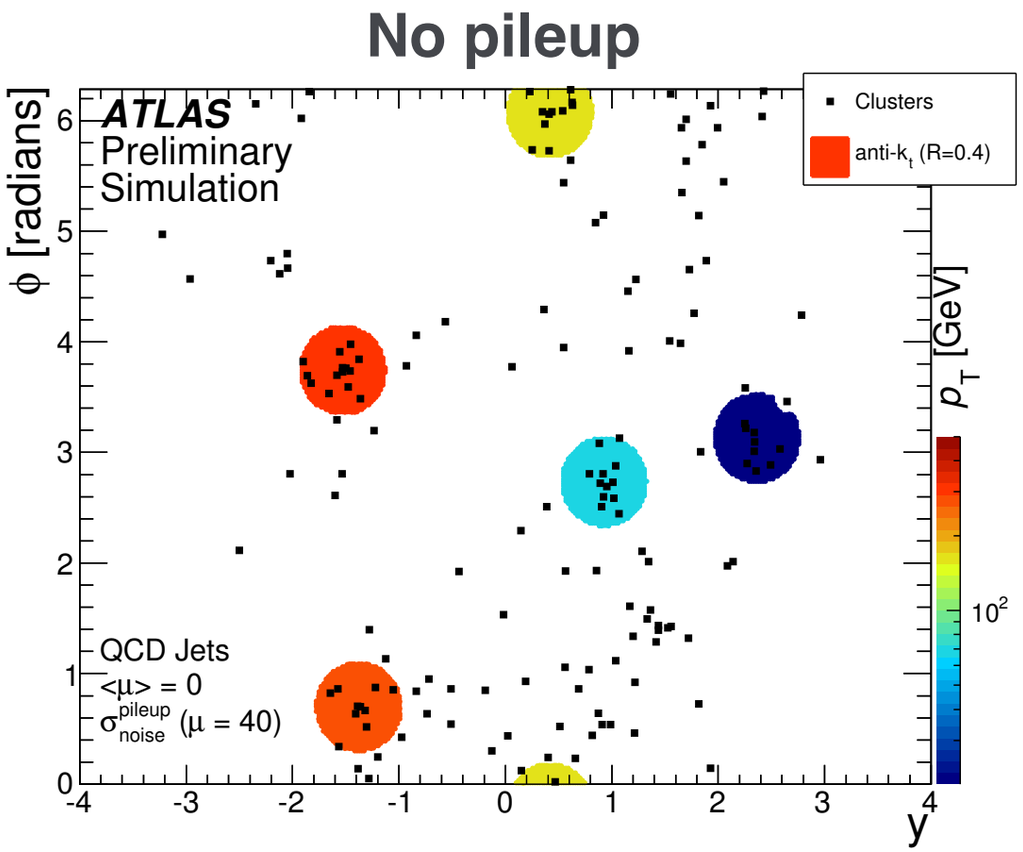


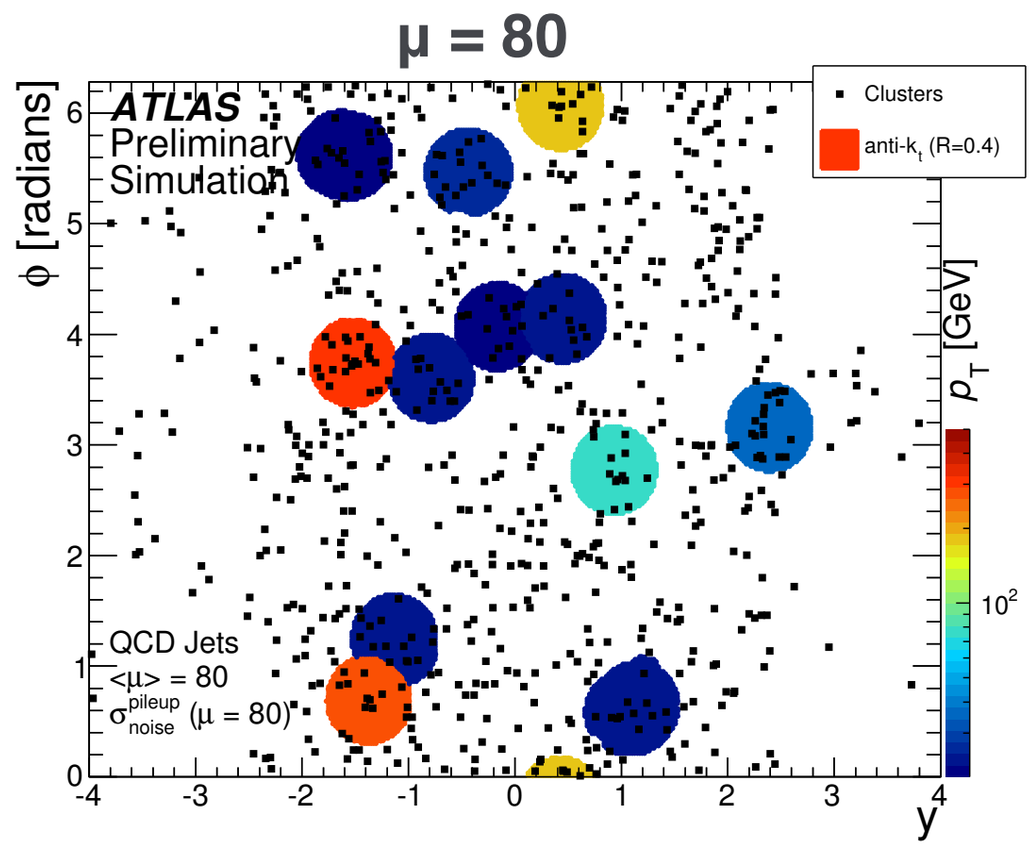




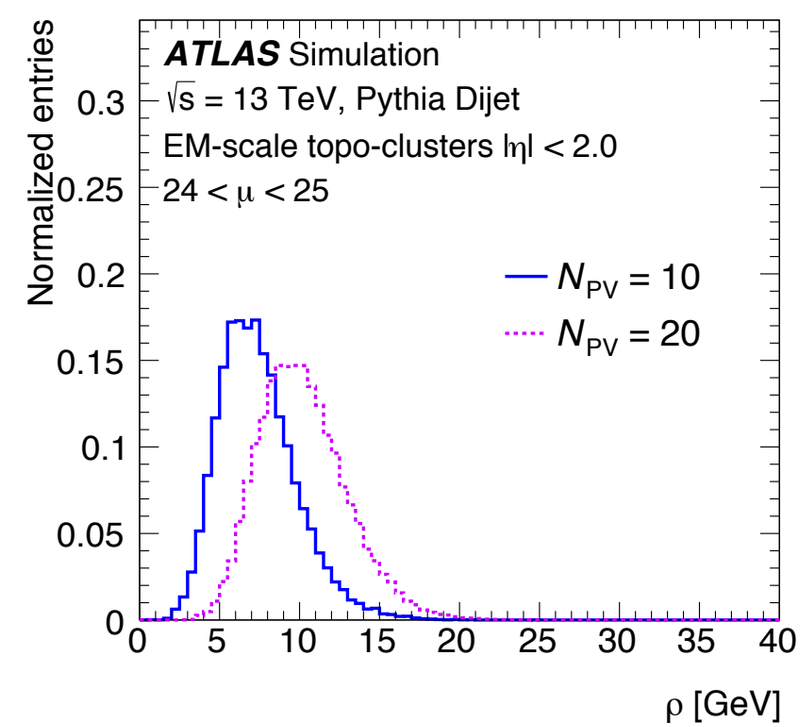
infrared safety **collinear safety**

Jet area pileup subtraction

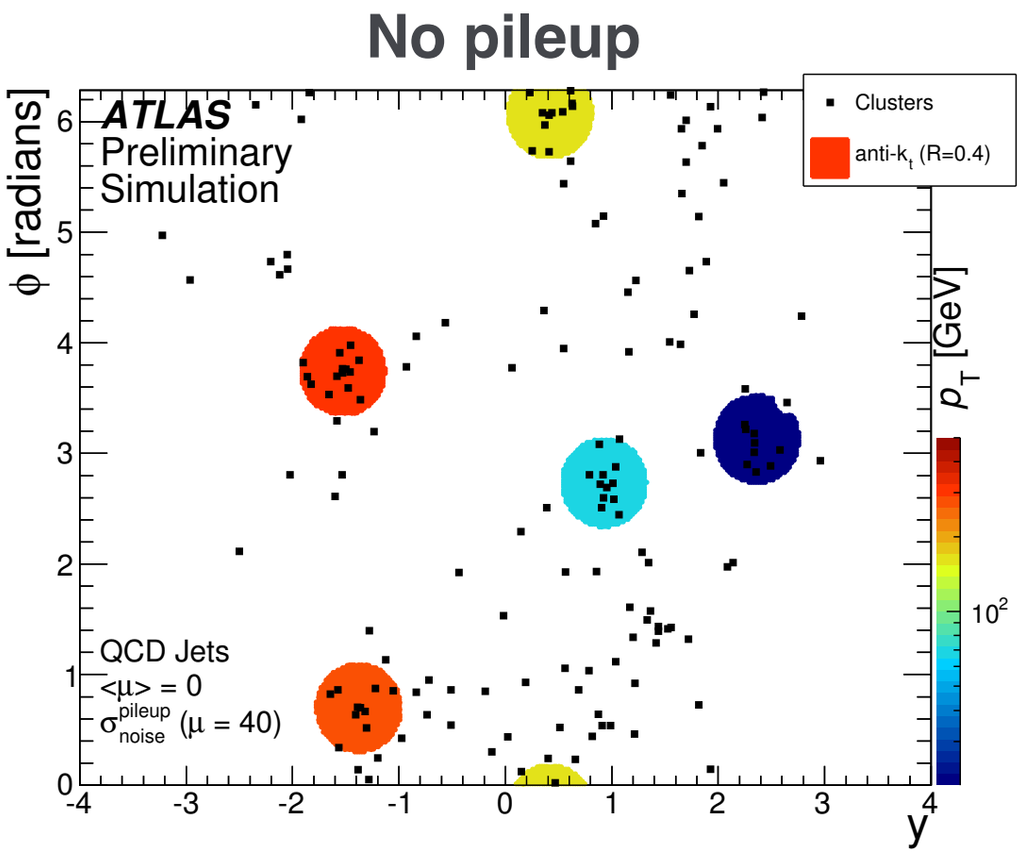


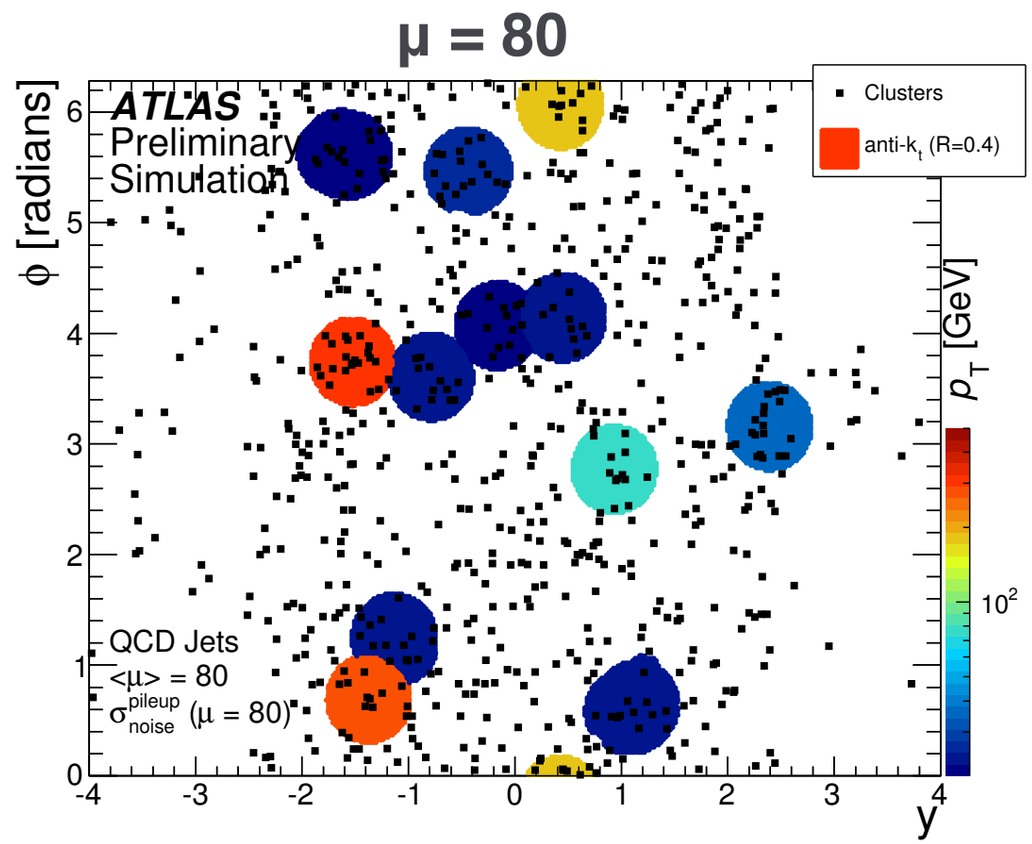


- Pileup alters the measured energy of each jet
- Subtract ambient p_T density on a per-event basis $\rho = \text{median}\left\{\frac{p_{T,i}^{jet}}{A_i^{jet}}\right\}$
- Derived using pileup-sensitive k_t jets



Jet area pileup subtraction





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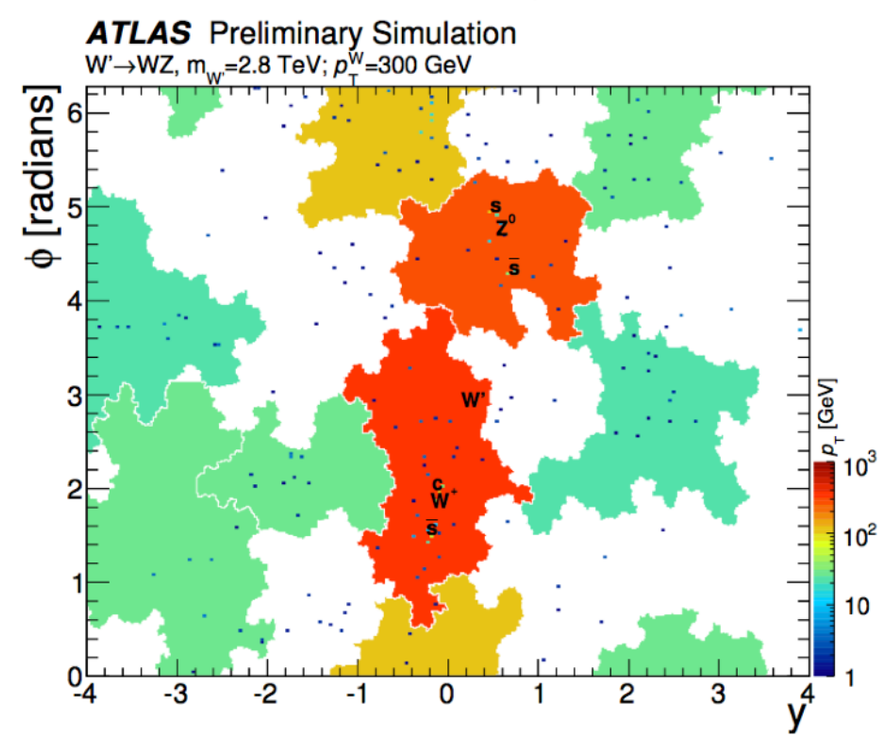
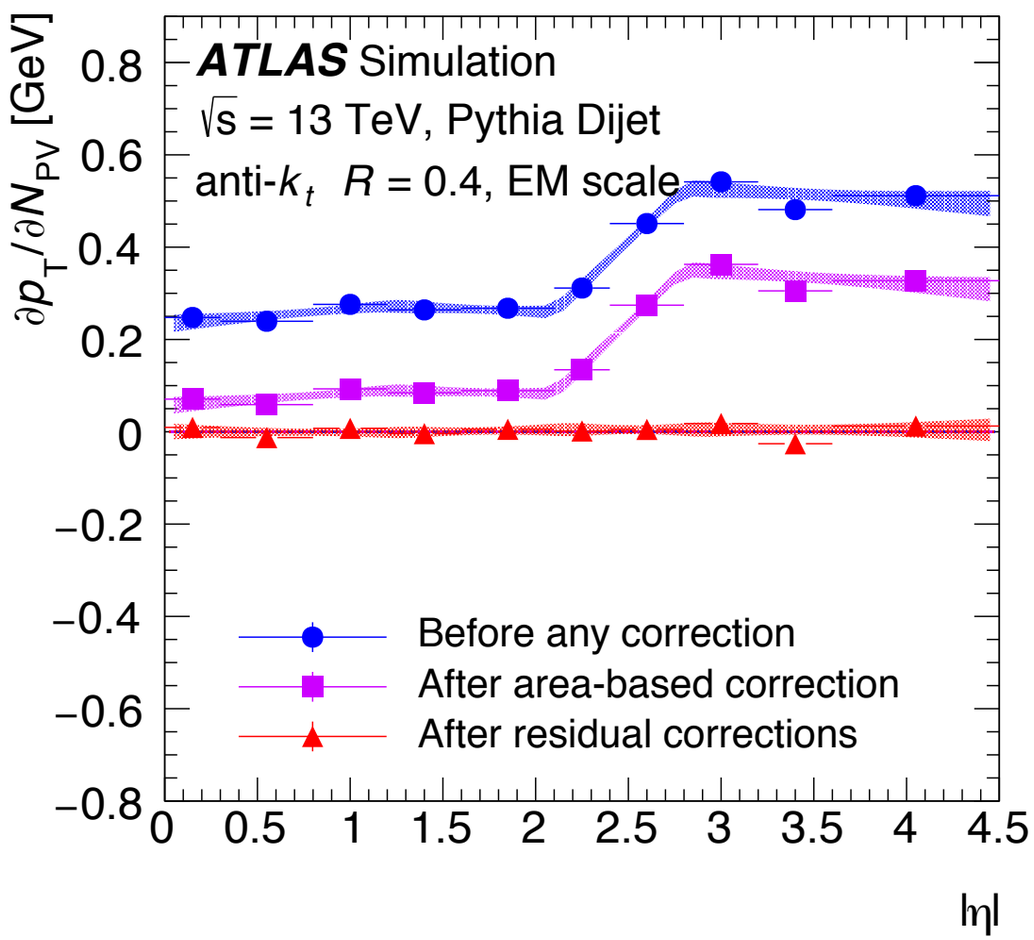
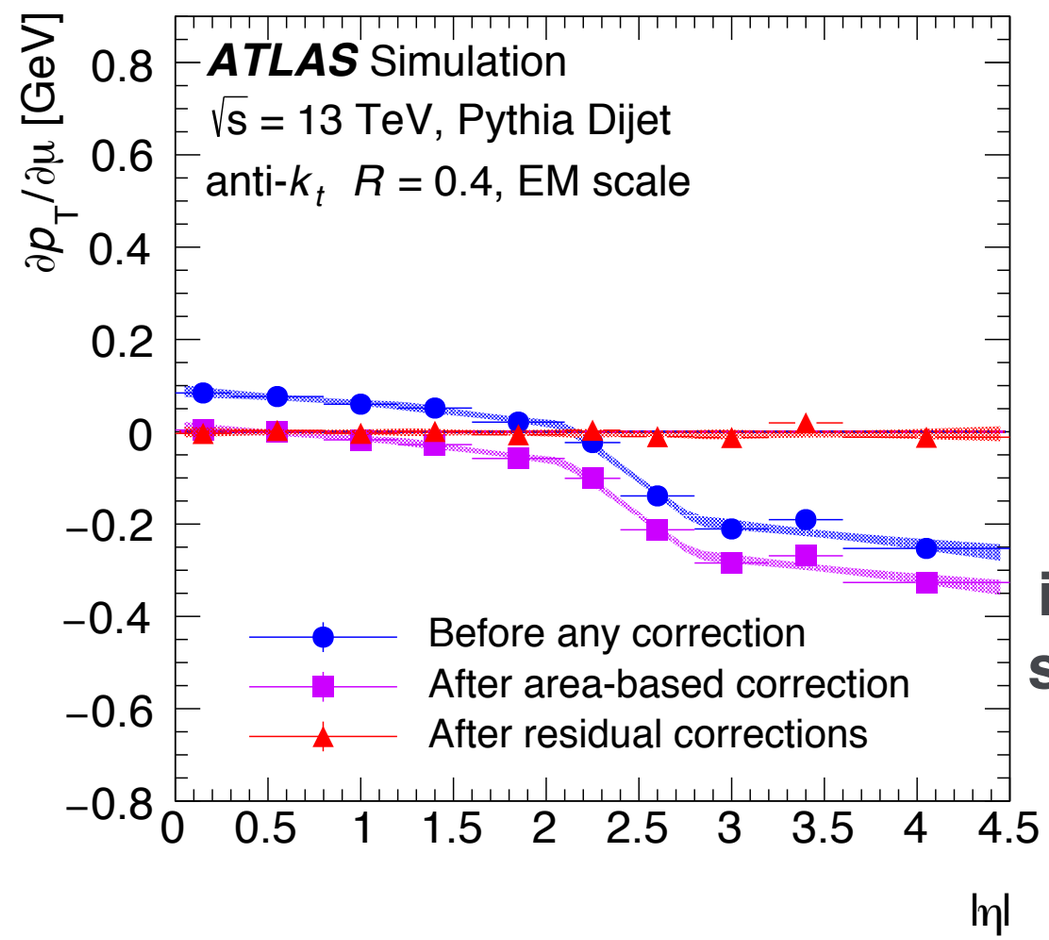


Residual pileup

- Correction leaves some dependence on **NPV** and **μ**, particularly in forward region
- Residual correction for observed dependence in MC

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



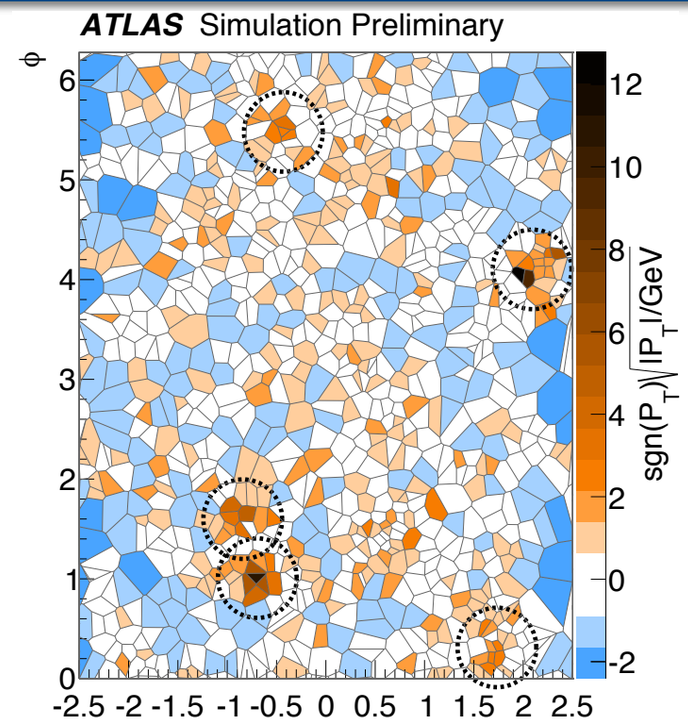


Negative! inherent PU suppression of LAr

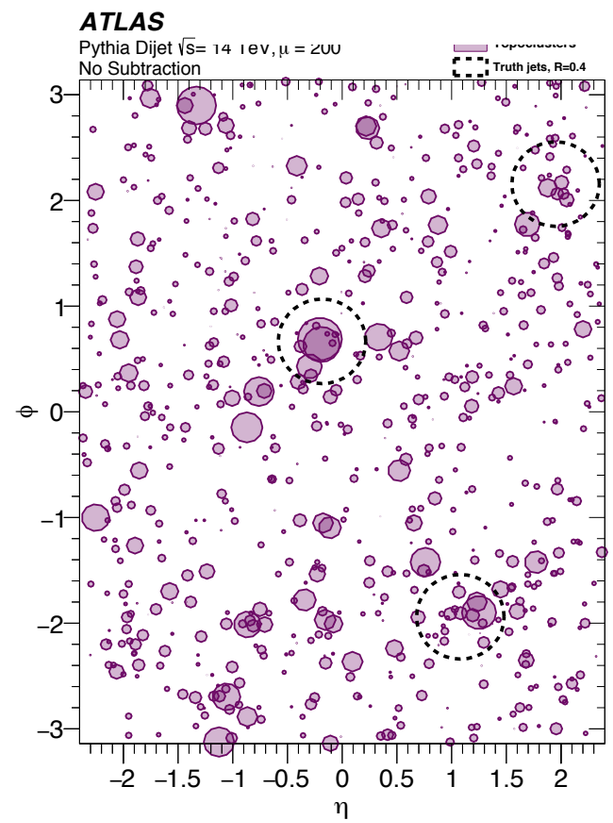
Constituent-level pileup mitigation

ATLAS-CONF-2017-065

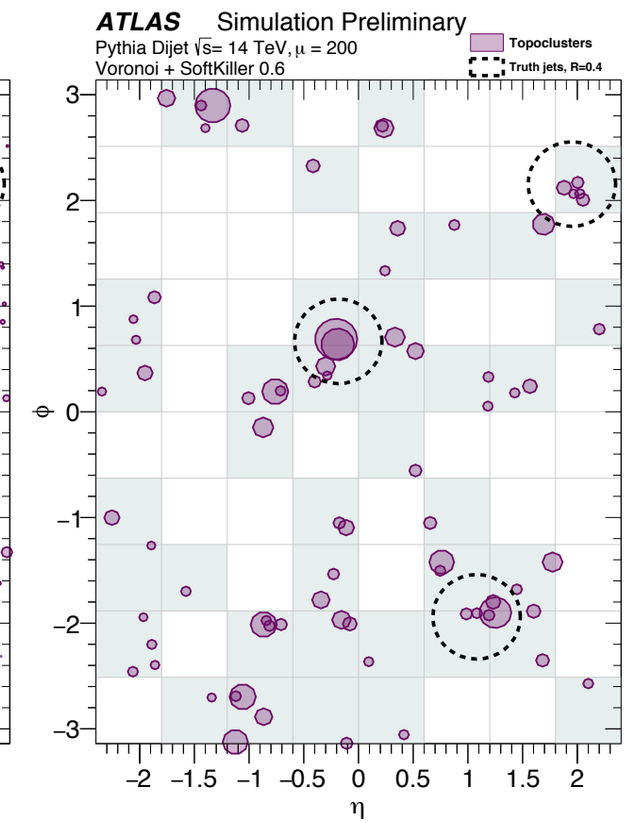
- Pileup will get worse at HLLHC
- Exploring new techniques including
  - **Cluster Vertex Fraction** associates clusters to tracks, rejecting pileup vertices
  - **Constituent Subtraction** assigns cluster area according to ghost association
  - **Voronoi Subtraction** assigns cluster area according to nearest-neighbor boundaries
  - **SoftKiller** implements a per-event p_T cut such that half the detector is empty



Voronoi area



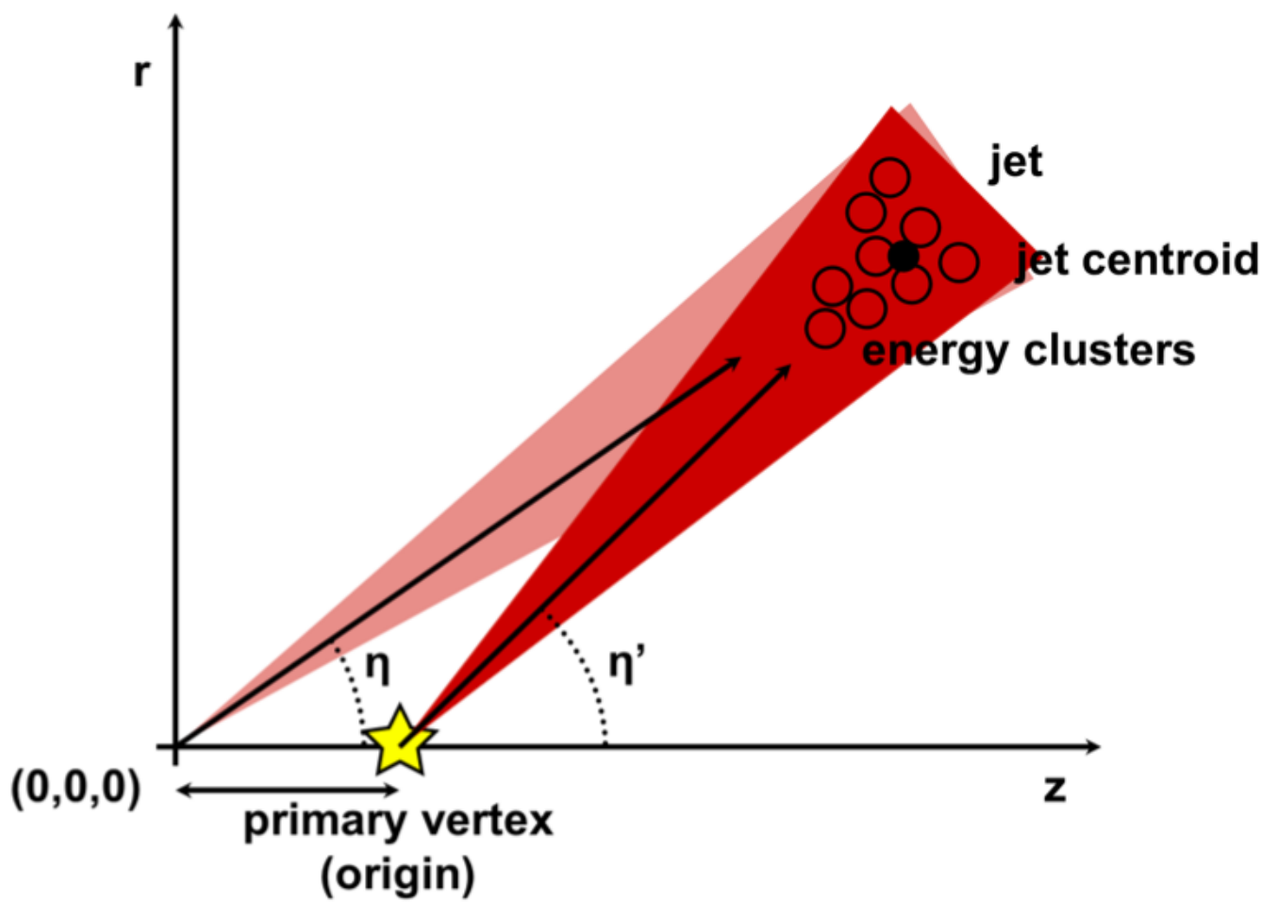
μ=200



SoftKiller+Voronoi

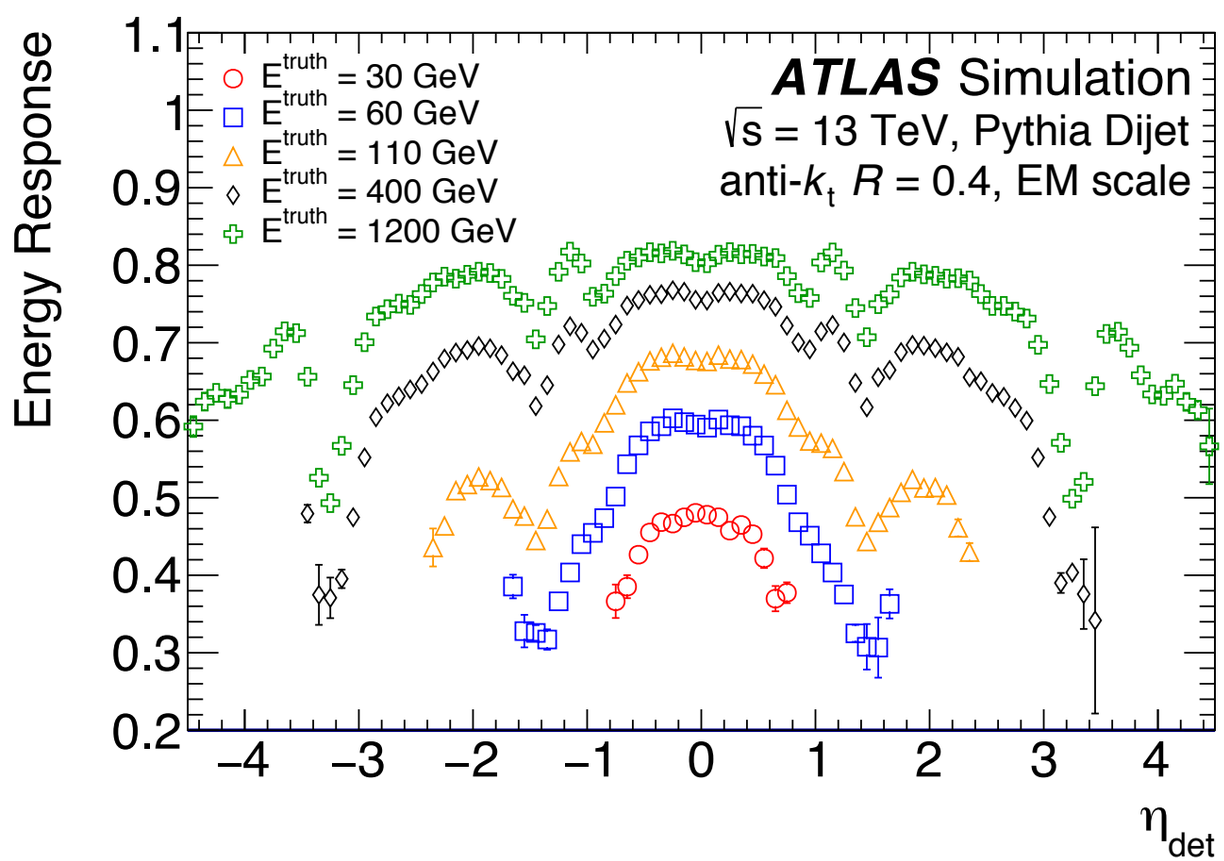
Origin correction

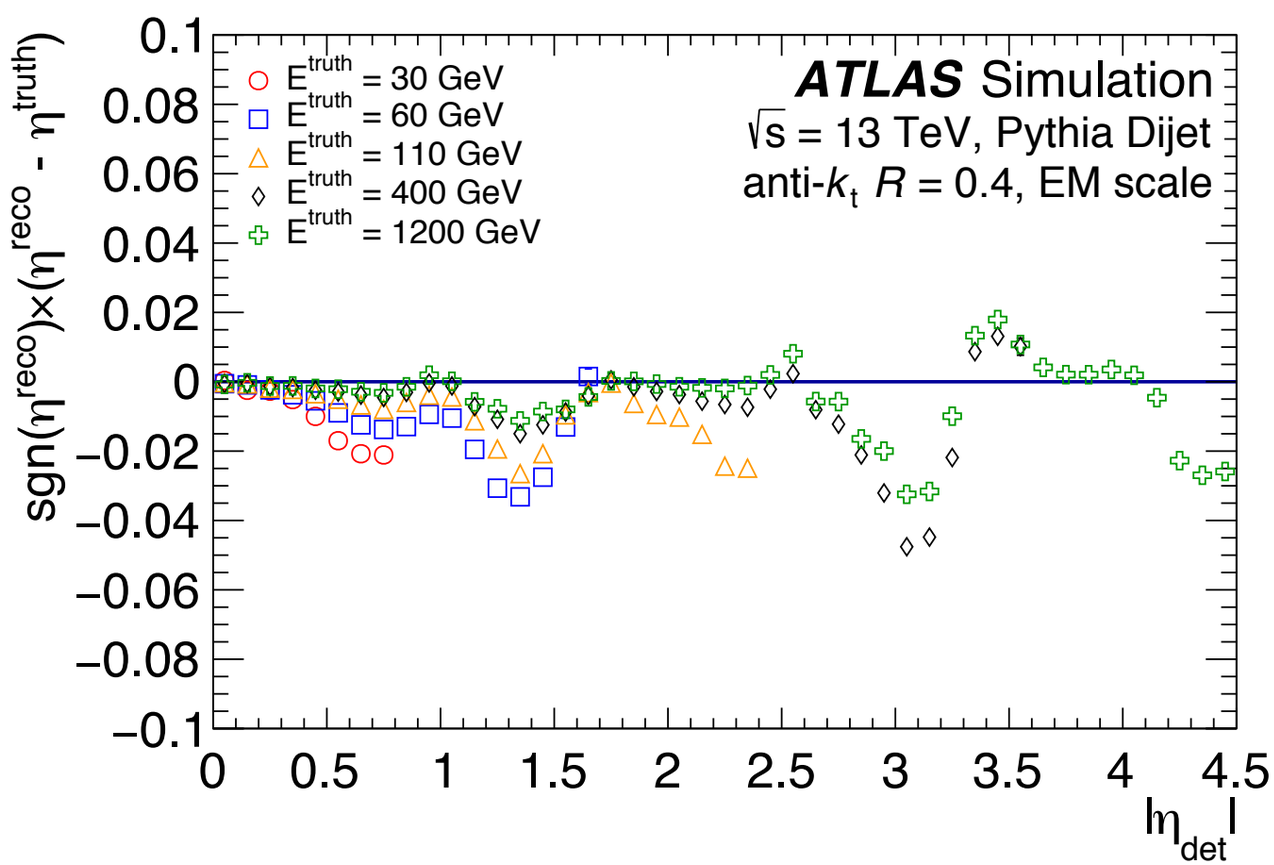
- Corrects jet axis to primary vertex, with small corrections to η and p_T resolution
- In 2017 individual topo-cluster 4-momenta are now corrected, making origin correction obsolete



MCJES correction

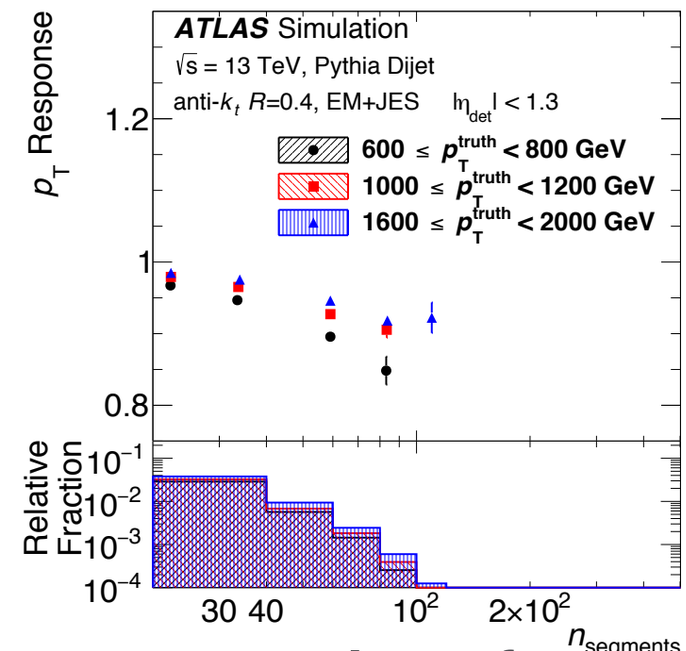
- Calibrate jet energy to **particle-scale** - sum of particles in MC minus minimally ionizing muons & neutrinos
- Residual η correction for jets in calorimeter transition regions



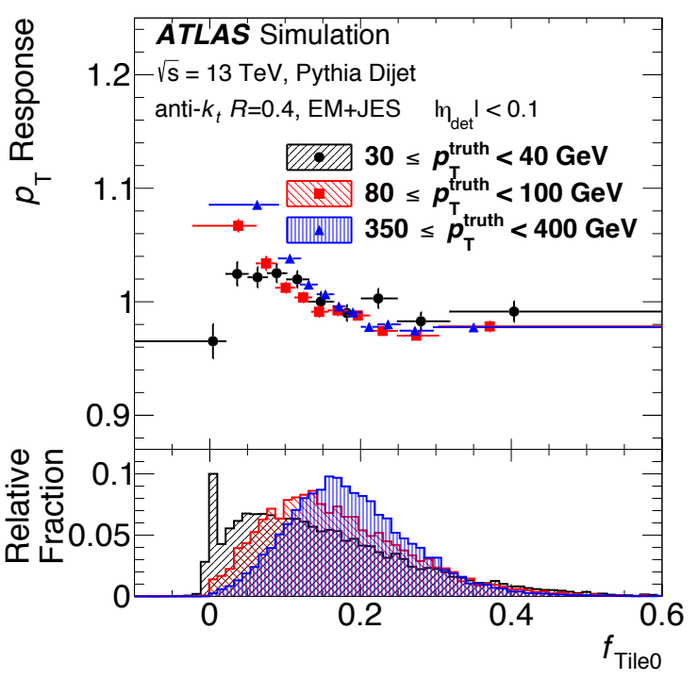


Global sequential calibration

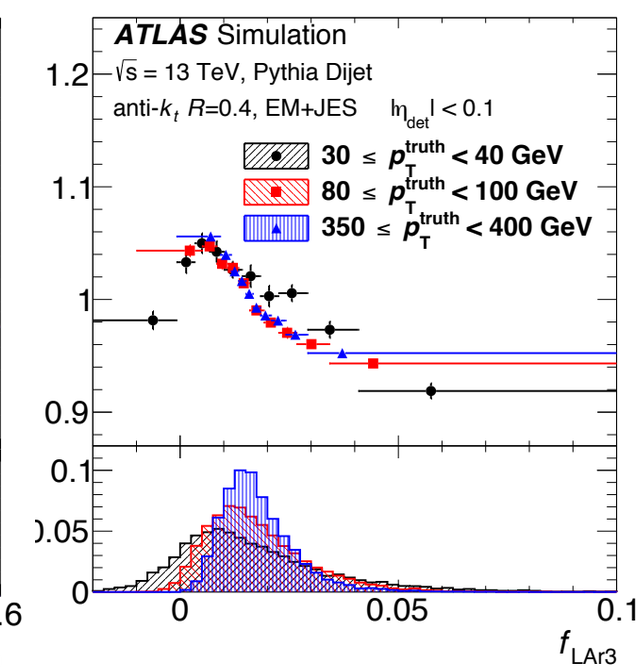
- Four p_T corrections using shower shape and track information
  - Reduces JES dependence on flavor - quark/gluon
  - No effect on absolute JES, large improvement to JER
- Fifth correction for energy escaping calorimeters into muon spectrometer



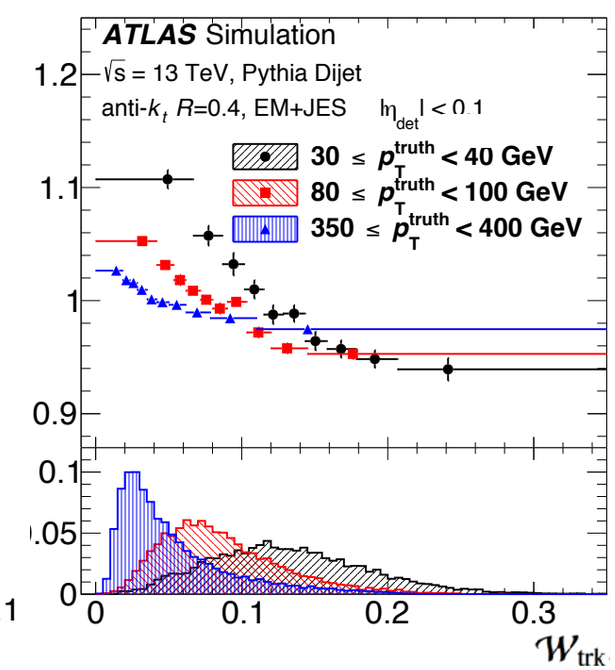
number of muon segments



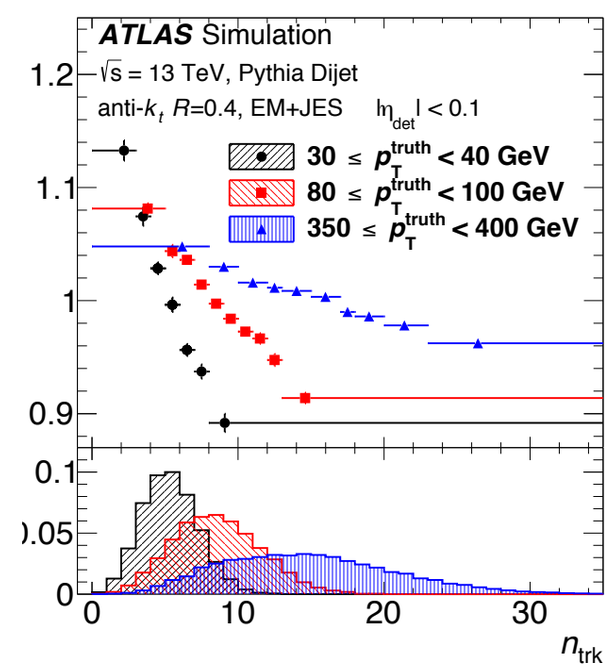
E in first Tile layer



E in last EM layer



p_T-weighted track width

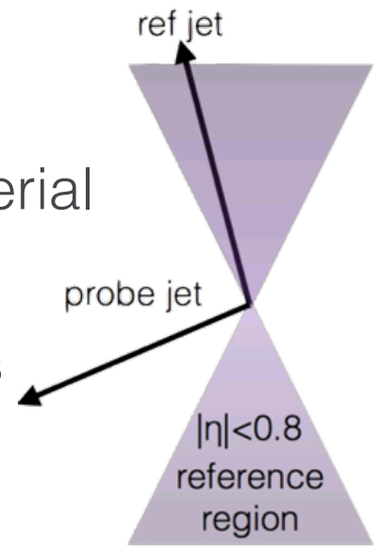


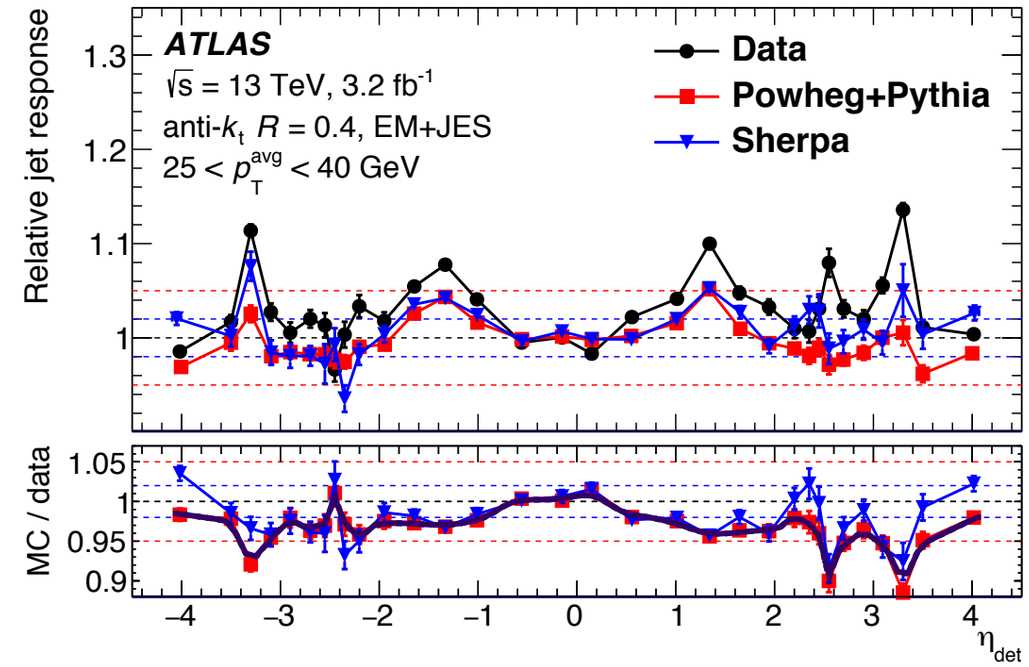
track multiplicity

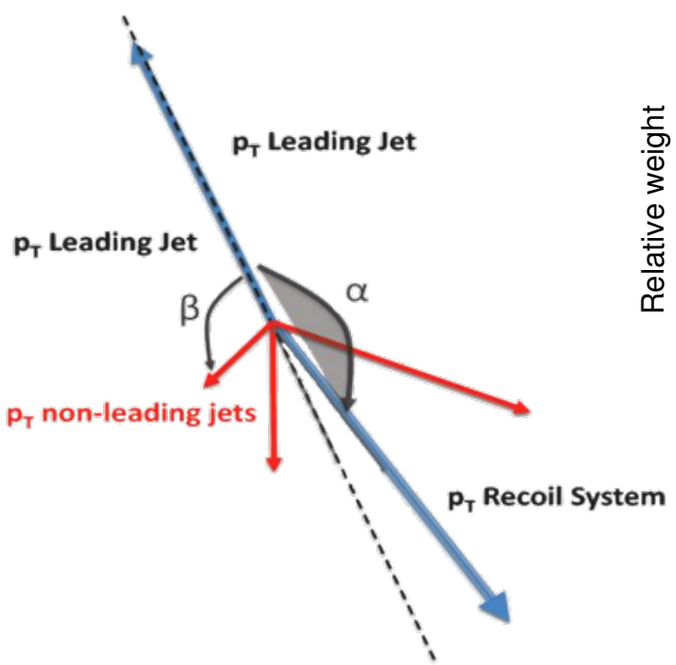
Data-driven *in situ* calibrations

Correct for **data-MC differences** in jet response ratios

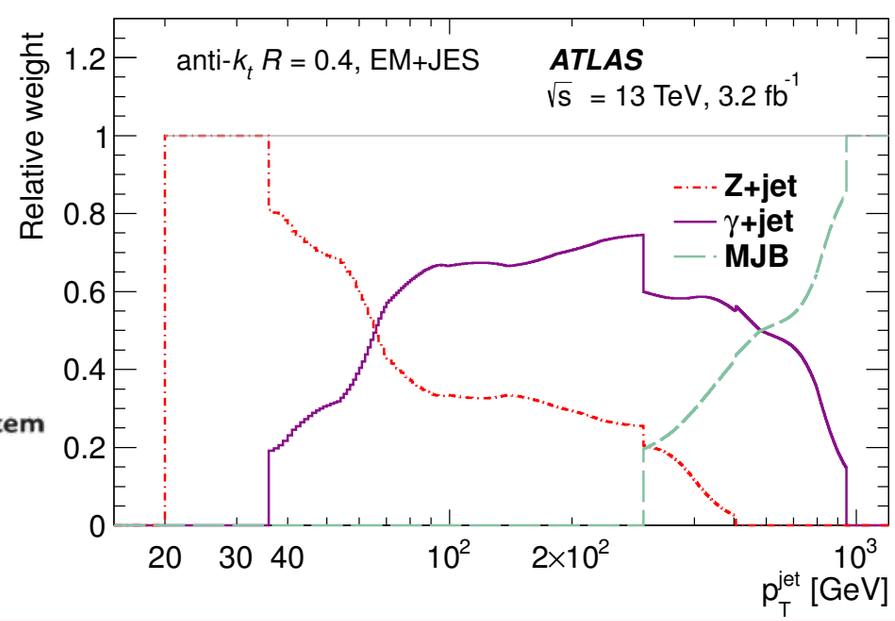
- **η-intercalibration:**
  Corrects **forward jets** in dijet system
  b/c coarser calorimeters & inactive material
- **Z/γ+jet balance:**
  Independent, well-measured references
  Missing-p_T projection fraction balances
  hadronic recoil, not the jet
- **Multijet balance:**
  High-p_T jets against recoil system



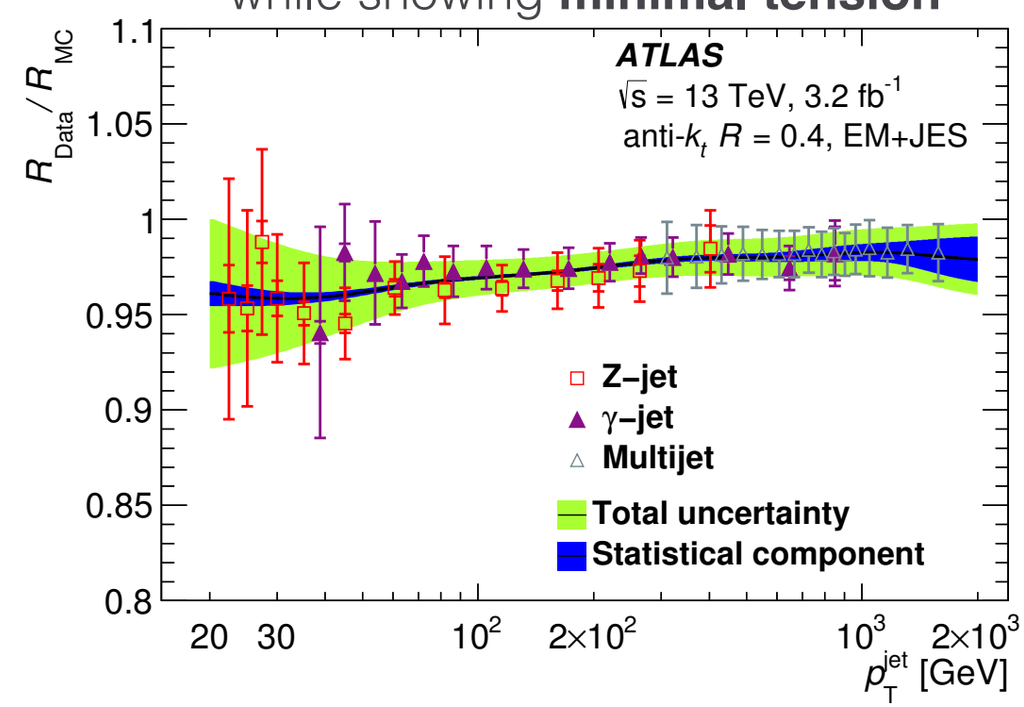




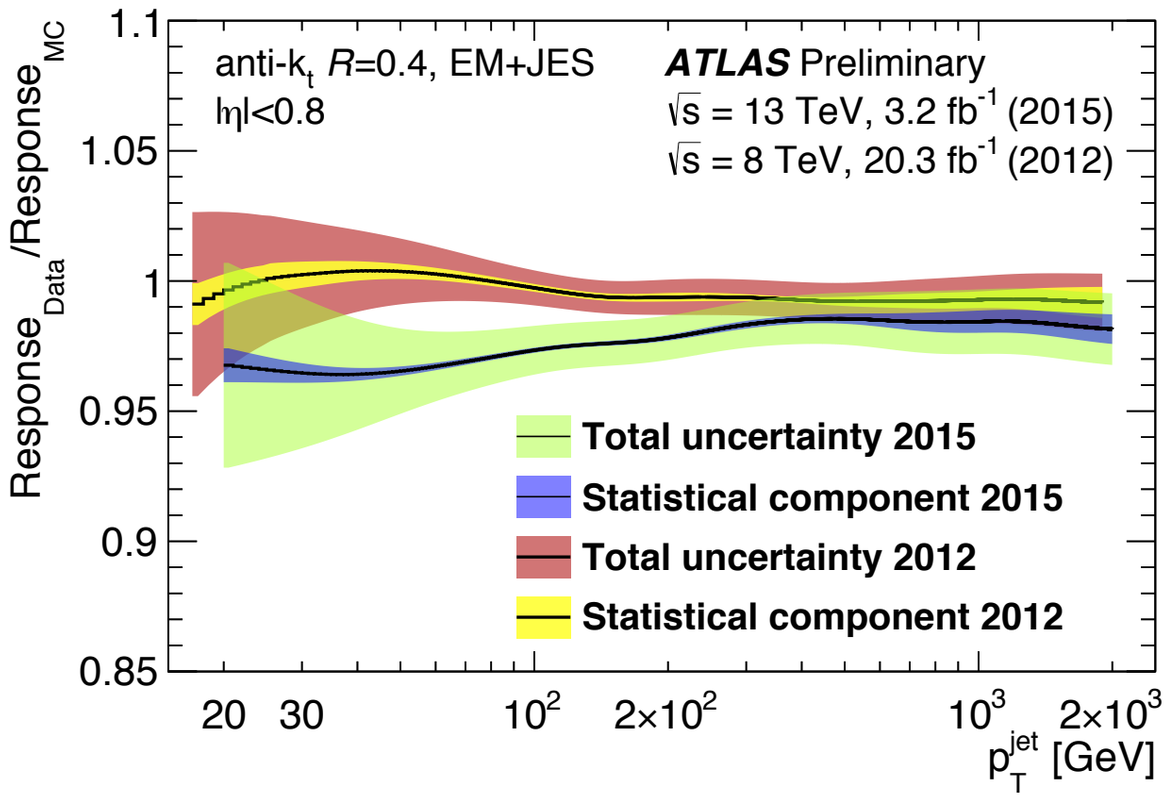
Statistically significant in low, medium, and high p_T regions

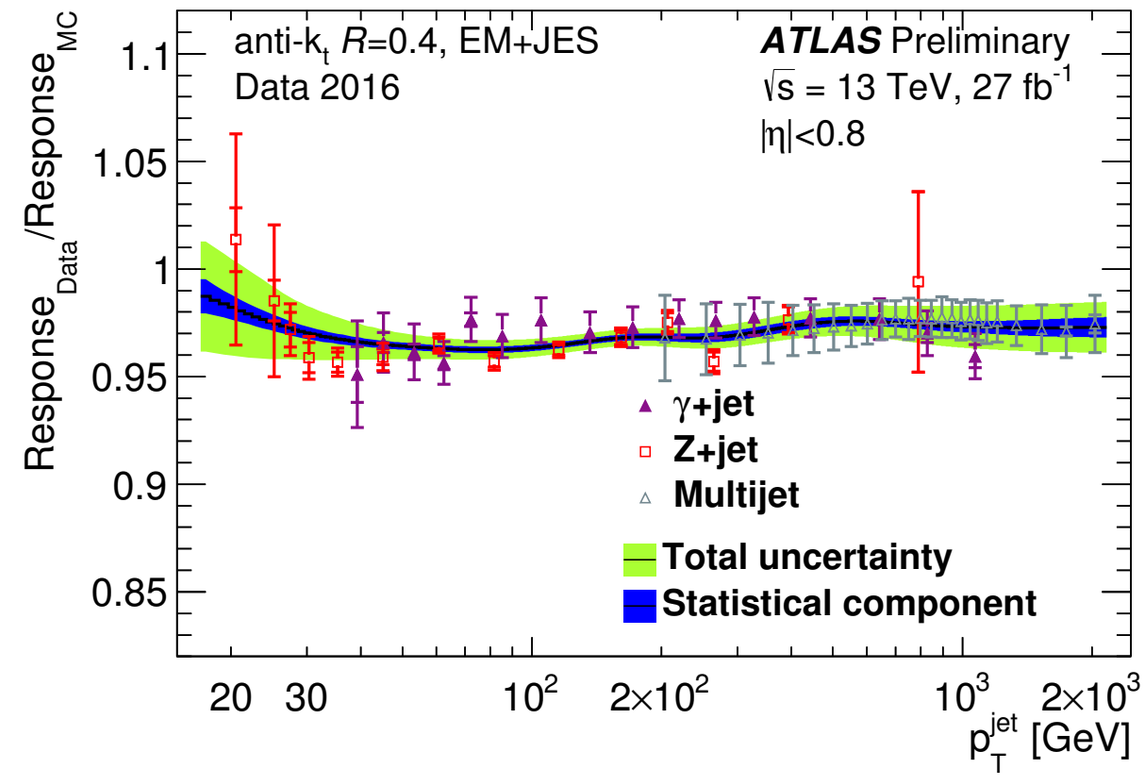


Combination **reduces uncertainty** while showing **minimal tension**

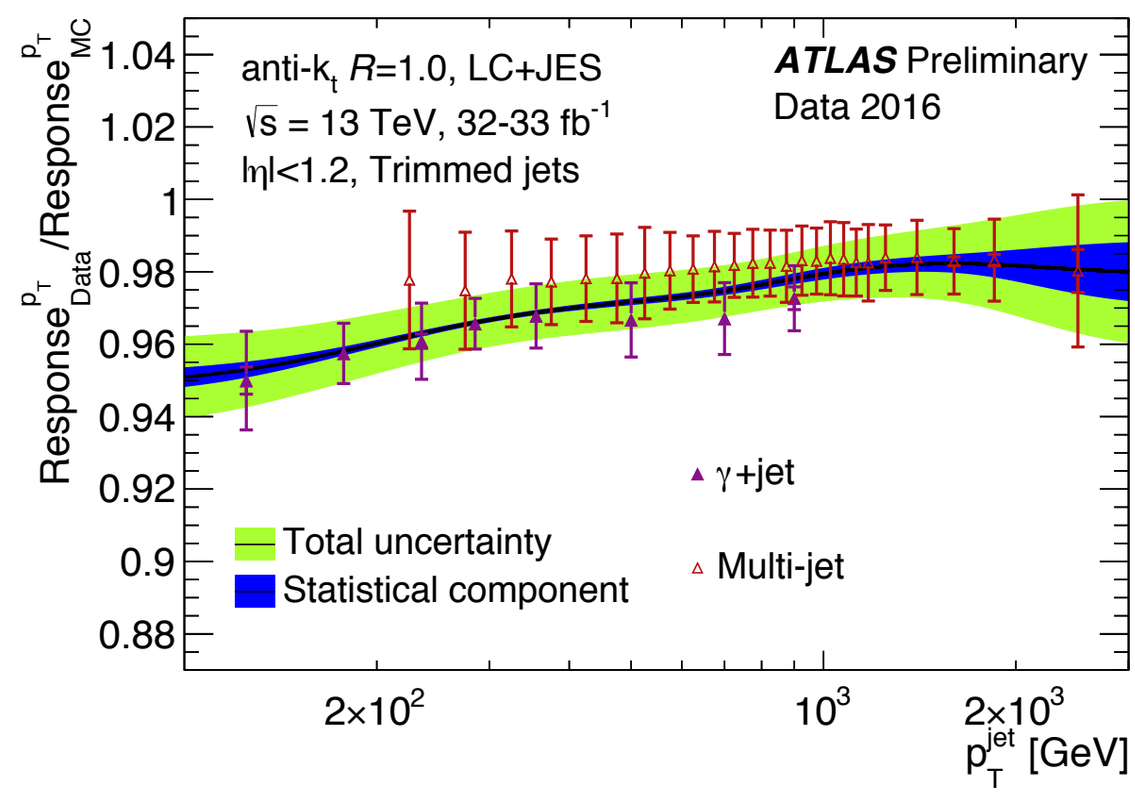


in situ combination



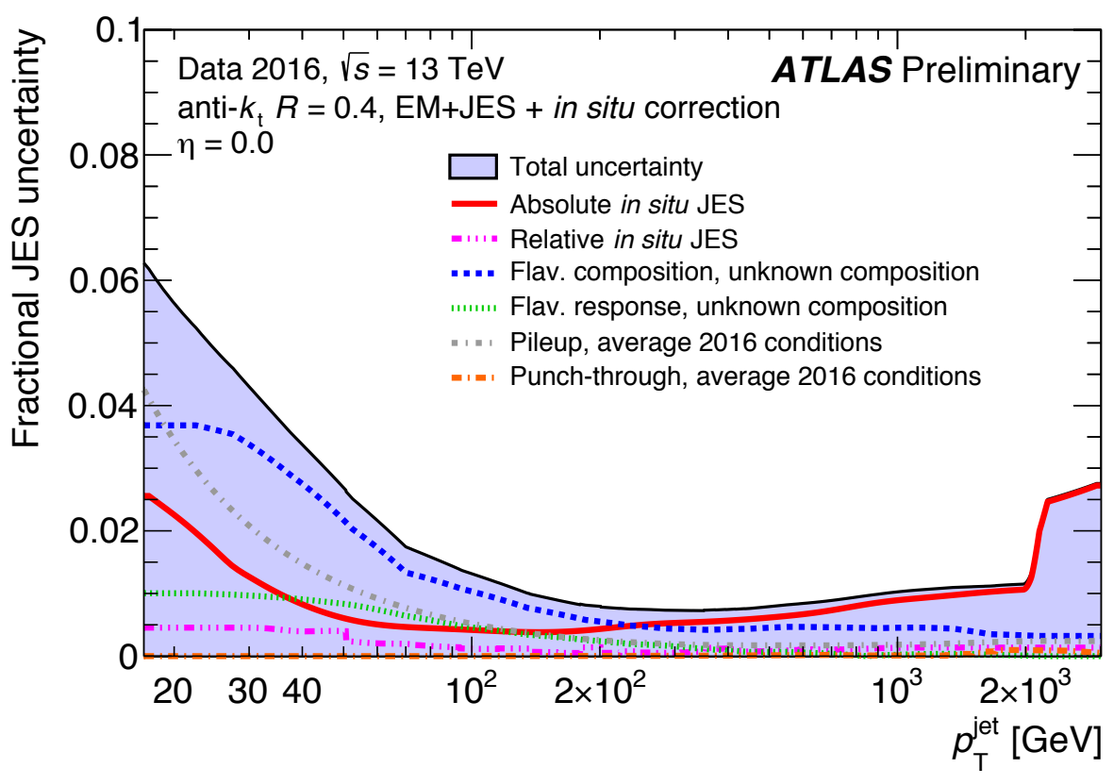


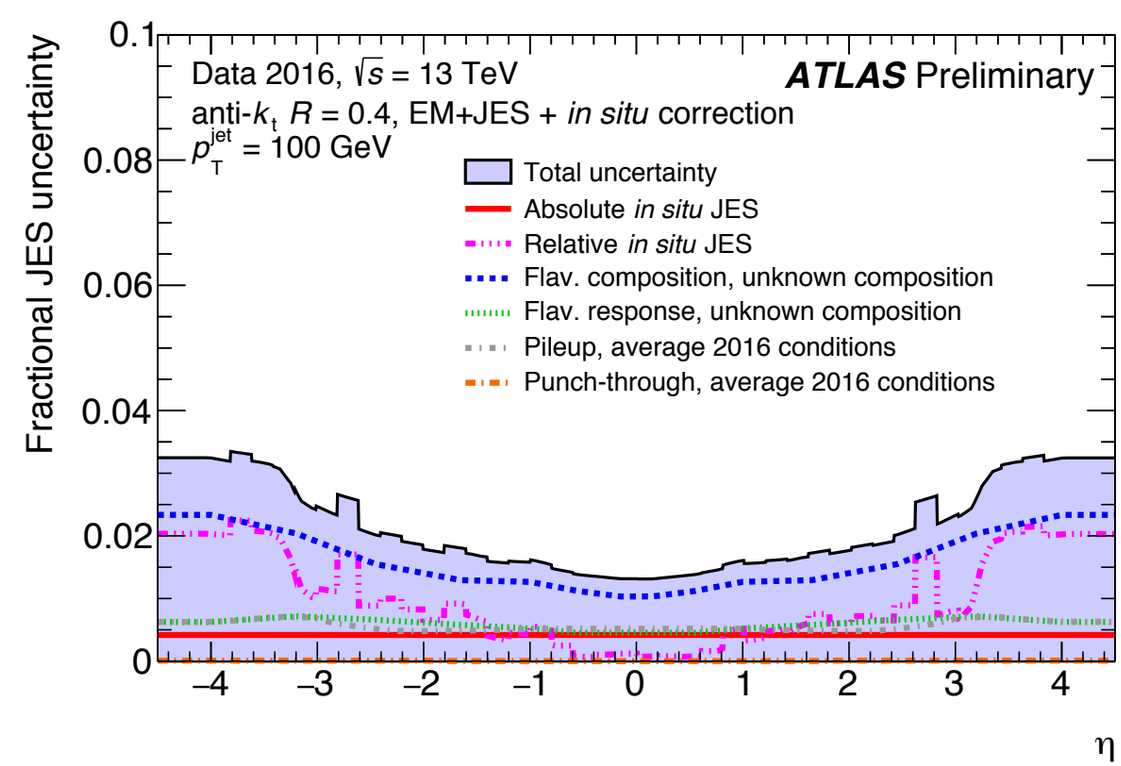
- Run 2 correction larger than Run 1 due to simulation changes
- 2016 correction agrees with 2015, with reduced uncertainties
- Same methods successfully used for R=1.0 trimmed jets
  - Working towards recommendations for various radii



Uncertainties

- **80 sources** of uncertainty, mostly *in situ (*event topology, MC simulation, statistics, etc.)
- **Flavor** generally dominant when assuming unknown composition
  - reducible on a per-analysis basis
- **Pileup** larger at low p_T - a target for reduction
- **High-p_T** from single particle studies - 13 TeV update will join the *in situ* combination





Unknown composition: 50/50 quark/gluon, 100% uncertainty

Uncertainties

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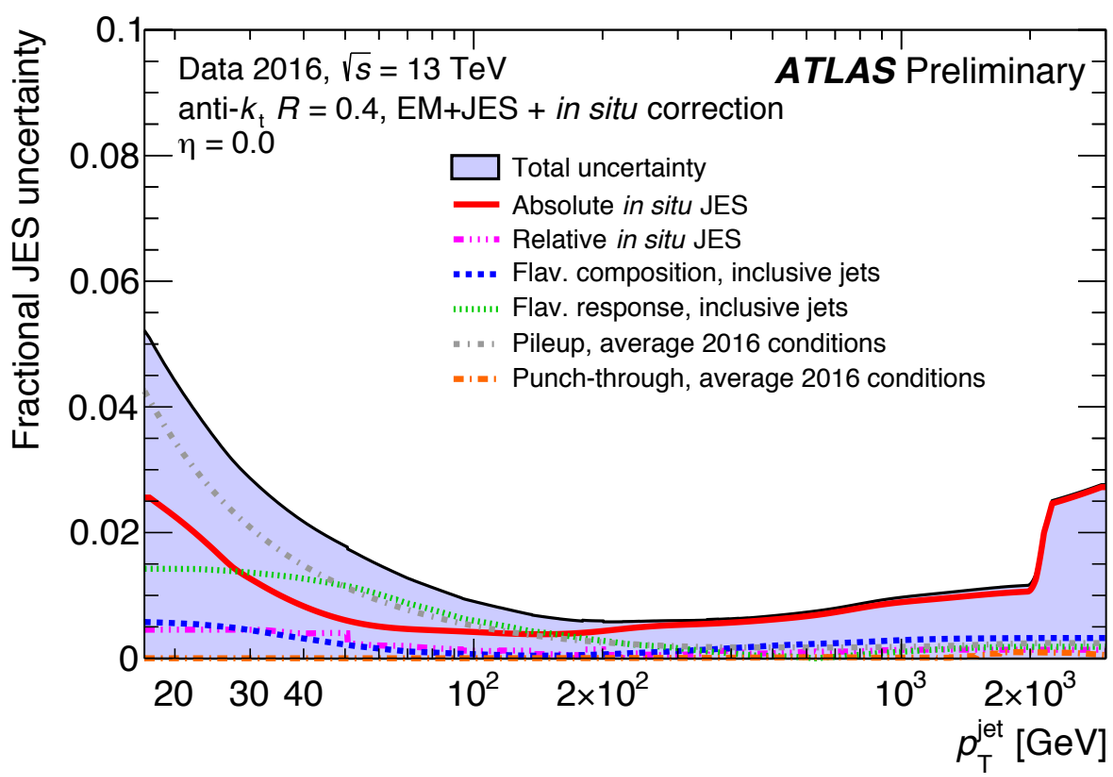
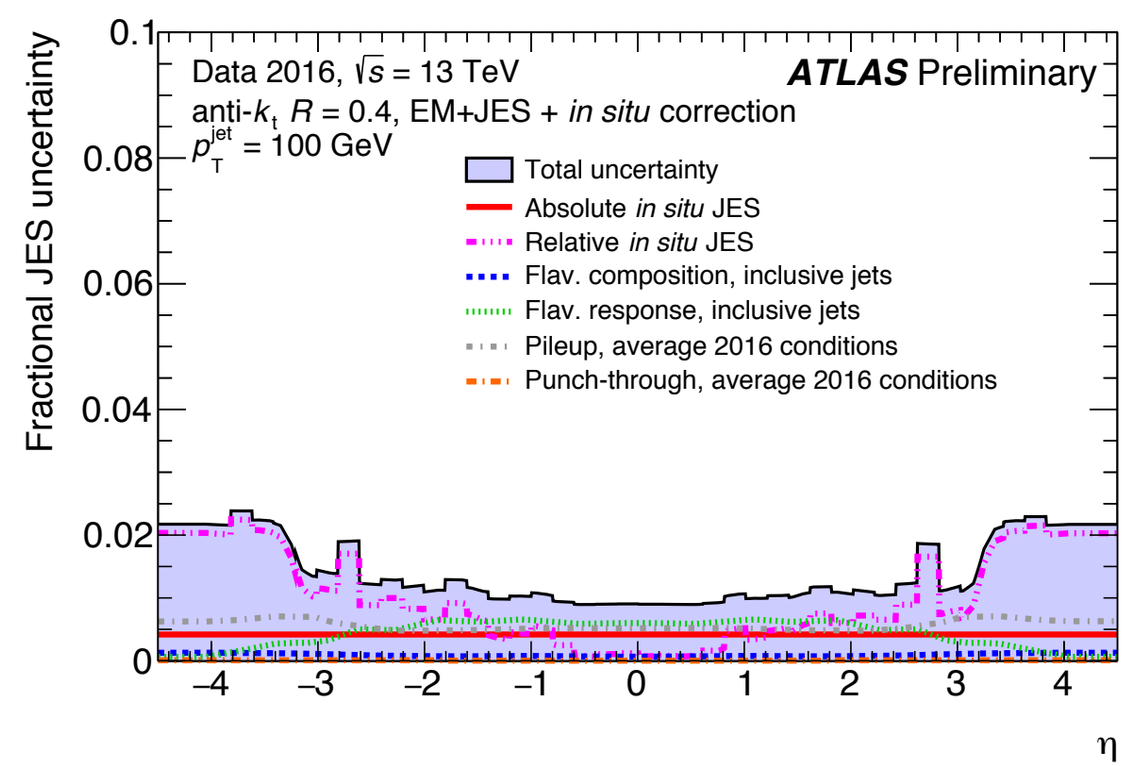
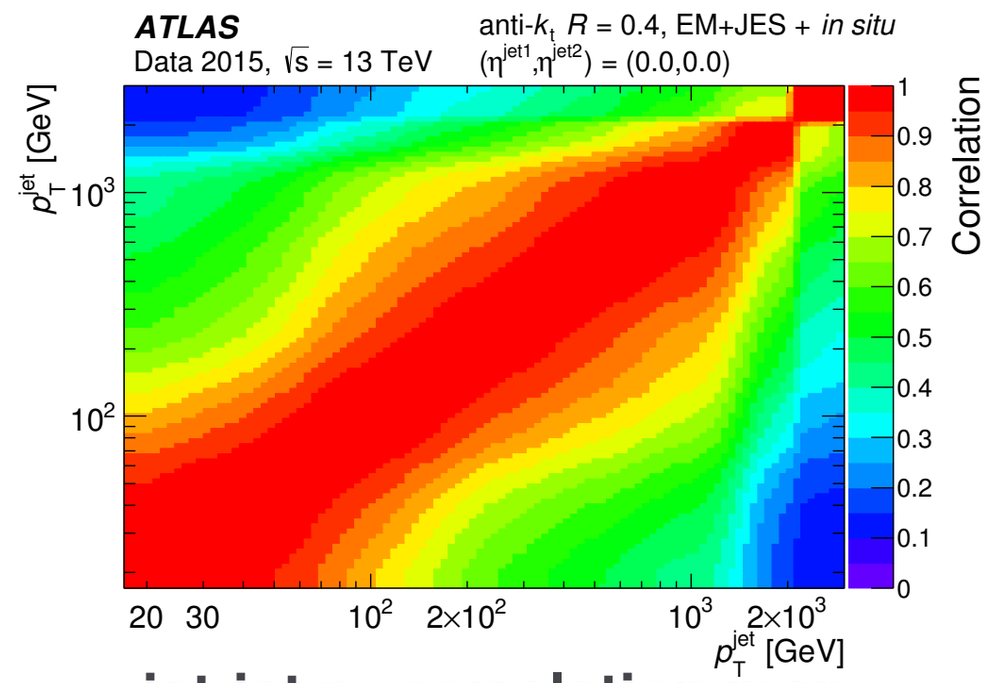




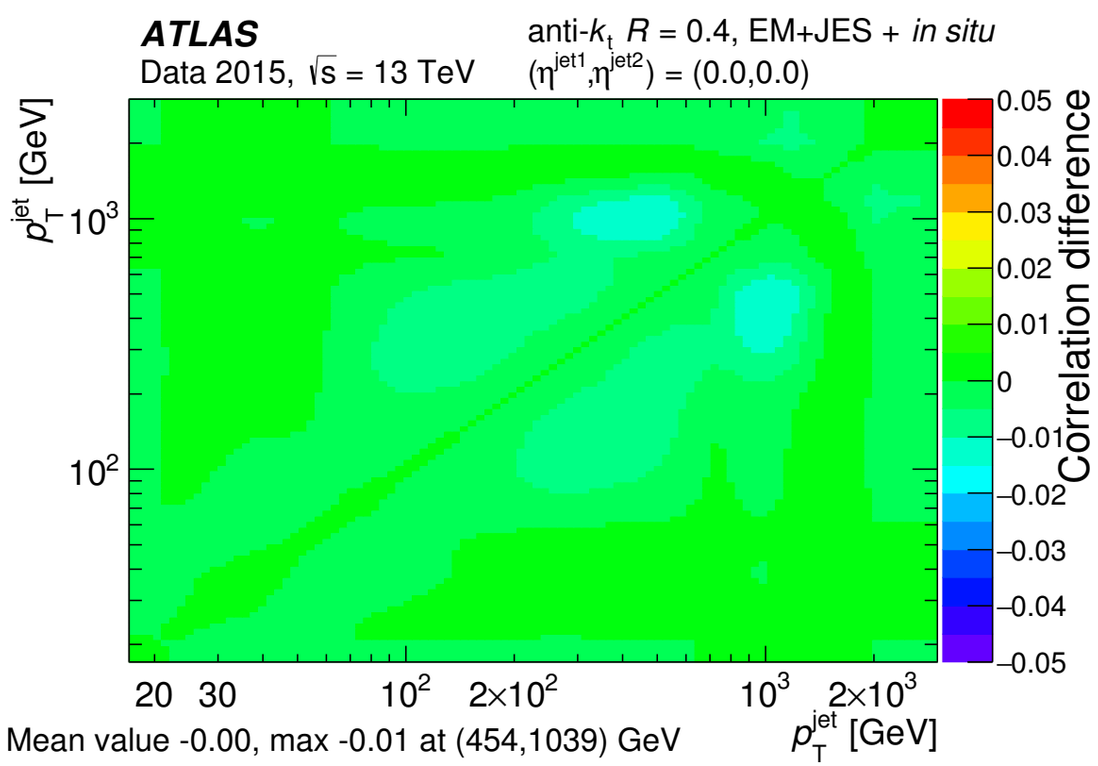
Pythia8 dijet composition

Reduction of uncertainties

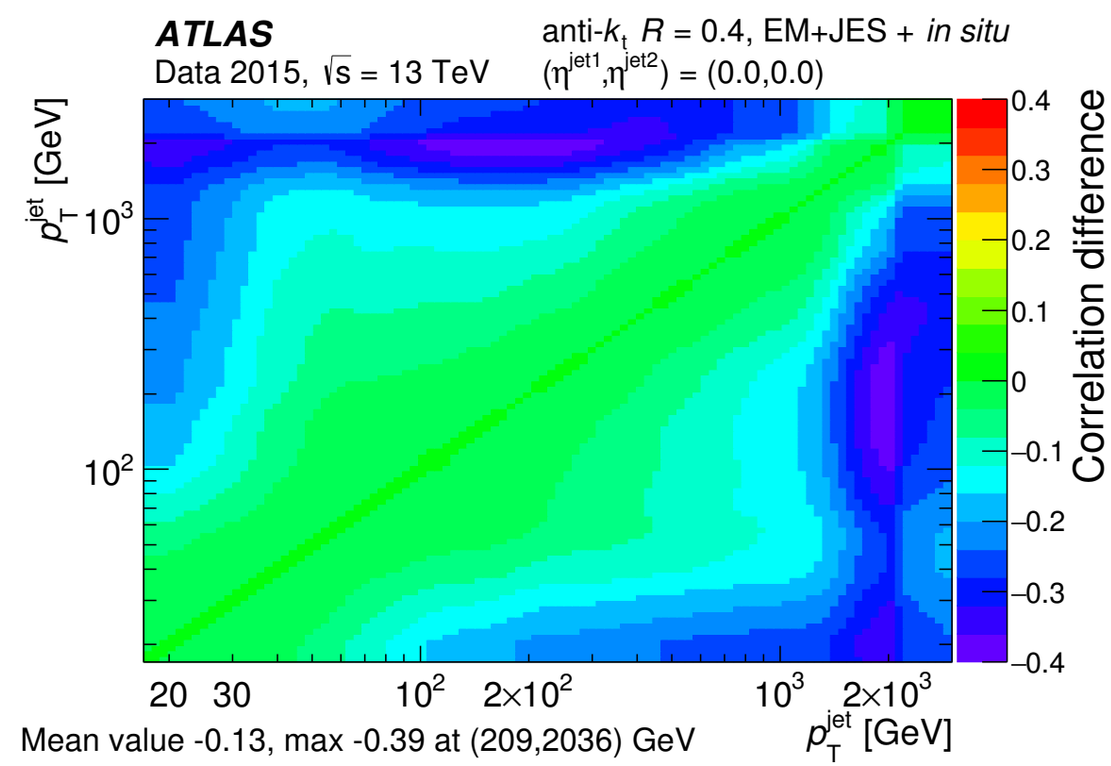
- Full set of 80 uncertainties often unnecessary → reduce number while **preserving main correlations in p_T and η**
- **Eigenvector decomposition** of *in situ* terms (67→6) w/ minimal correlation losses
- **Strong reduction** (19→4) preserves largest correlations in low, medium, and high p_T regions
  - Non-negligible correlation loss overall → 4 sets produced to bracket losses, allowing analyses to probe sensitivity



jet-jet p_T correlation map



Loss from eigenvector decomposition



Loss from strong reduction

Conclusion

- Robust jet calibration procedure for bread-and-butter R=0.4 jets
  - Techniques directly applicable to **EM**, **LC**, **pflow**, and **various radius** jets
  - Several uncertainty sets for **quick searches** or **detailed measurements**
- Continually improving JES to reduce uncertainties and prepare for pileup-heavy HLLHC
  - Quark-gluon discrimination w/ tracking & imaging - See earlier talks by Francesco Rubbo & Ben Nachman
  - Huge effort to bring substructure techniques to mainstream
- Browse the latest at the JetETMiss public website or BOOST 2017!

Conference Note	Ref Code
NEW Constituent-level pileup mitigation performance using 2015 data	ATLAS-CONF-2017-065
NEW Performance of Top Quark and W Boson Tagging in Run 2 with ATLAS	ATLAS-CONF-2017-064
NEW In-situ measurements of large-radius jet reconstruction performance	ATLAS-CONF-2017-063
NEW Jet reclustering and close-by effects in ATLAS Run 2	ATLAS-CONF-2017-062

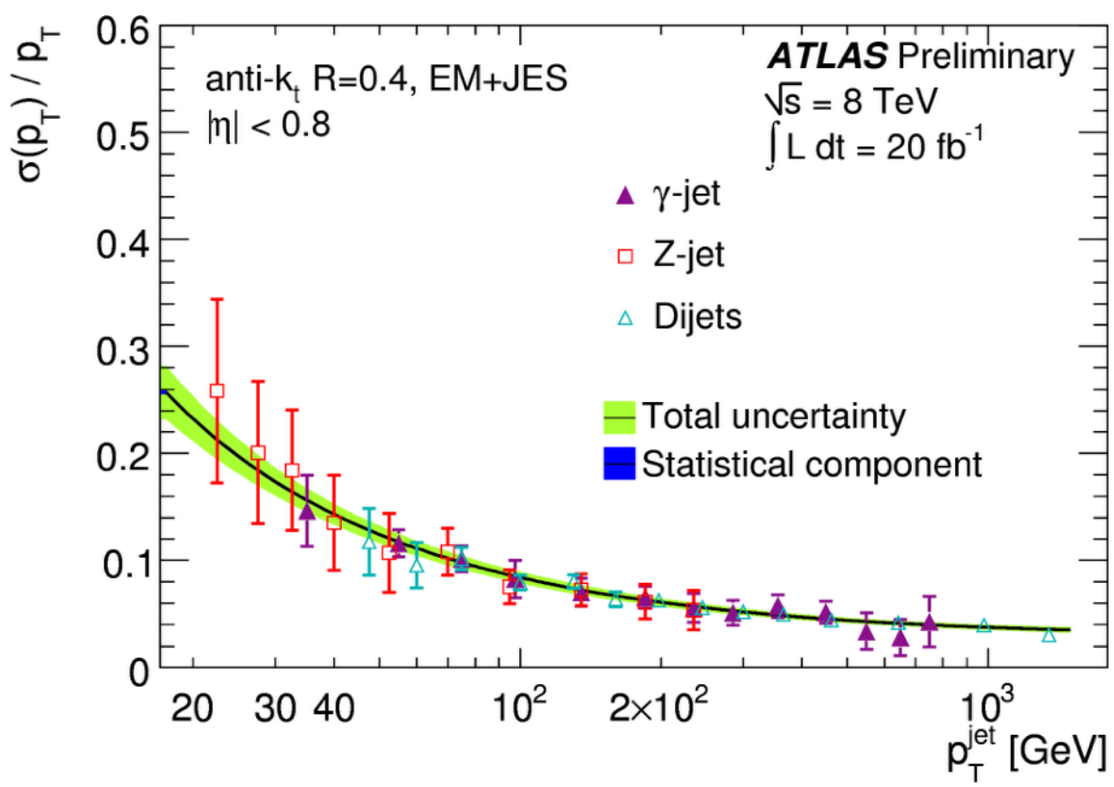
PUB Note	Ref Code
NEW Quark/gluon discrimination with jet images	ATL-PHYS-PUB-2017-017
NEW Track-calo clusters for jet substructure	ATL-PHYS-PUB-2017-015
NEW Variable Radius, Exclusive-kT, and Center-of-Mass Subjet Reconstruction for Higgs Tagging in ATLAS	ATL-PHYS-PUB-2017-010
NEW Quark versus Gluon Jet Tagging Using Charged Particle Multiplicity with the ATLAS Detector	ATL-PHYS-PUB-2017-009
NEW Top and W tagging using high-level inputs to BDT and DNN	ATL-PHYS-PUB-2017-004

Backup

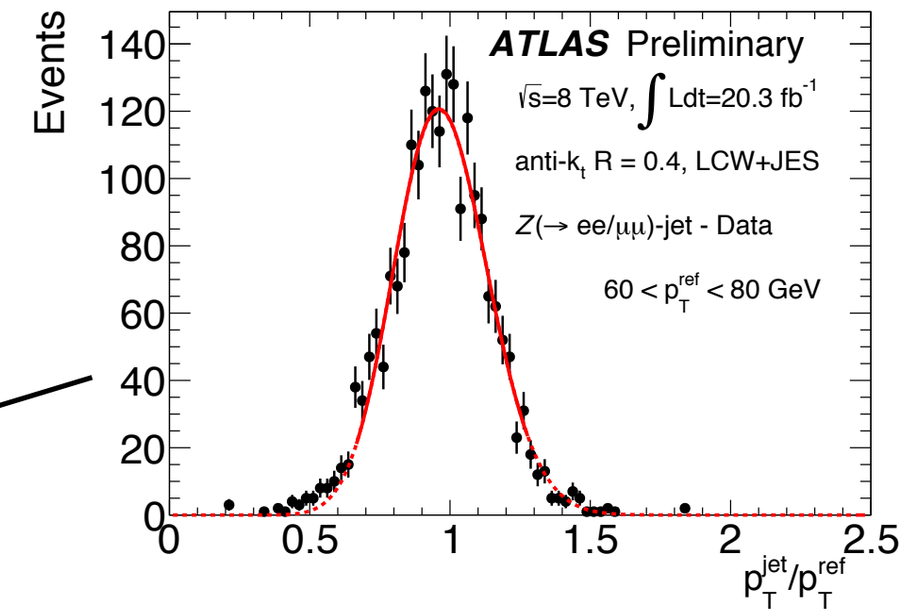
Jet energy resolution

- Resolution → accuracy of measurement for all jets
  - Noise term from zero-bias data via random noise cones & average energy density
  - Stochastic and constant terms fit to dijet & Z/γ+jet balance

$$\text{Jet Resolution: } \frac{\sigma_E}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$



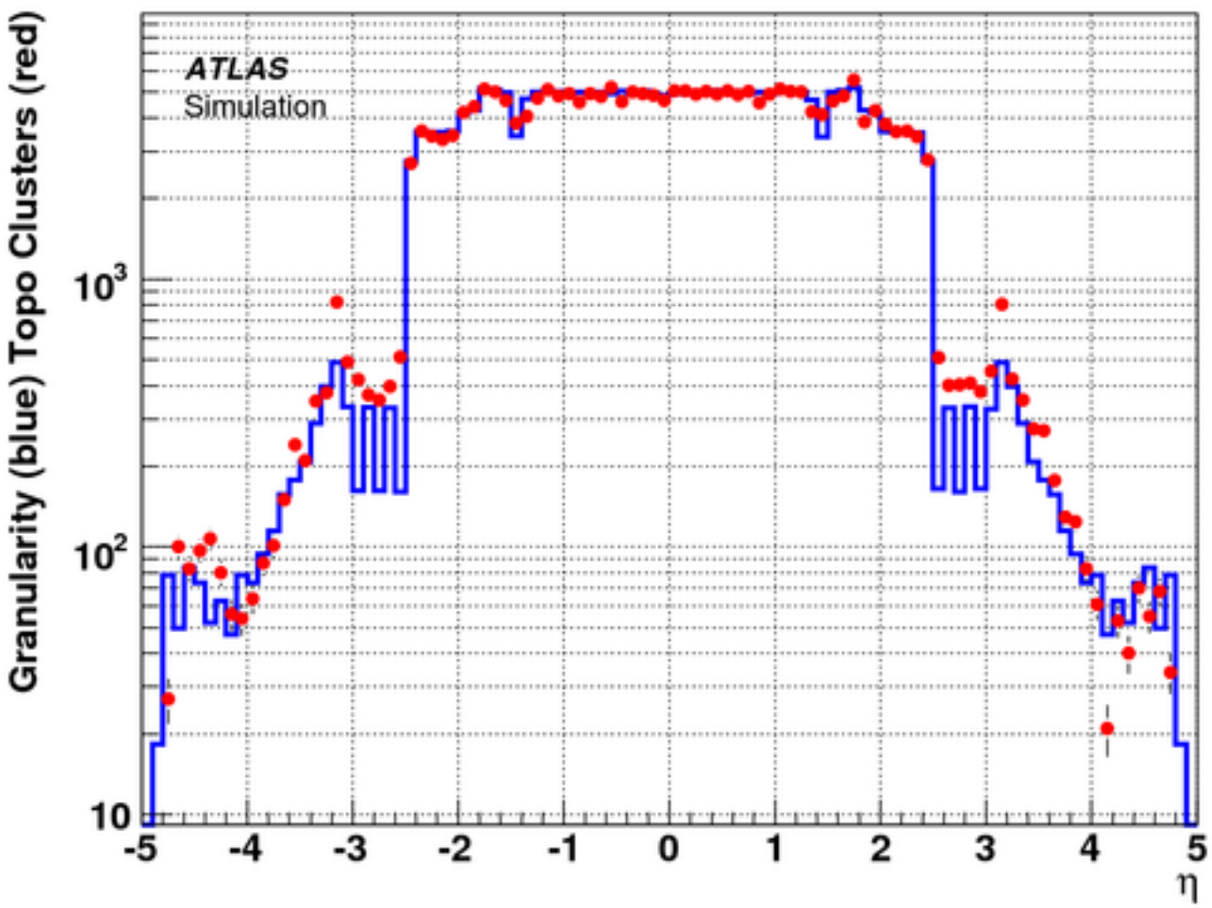
Gaussian width



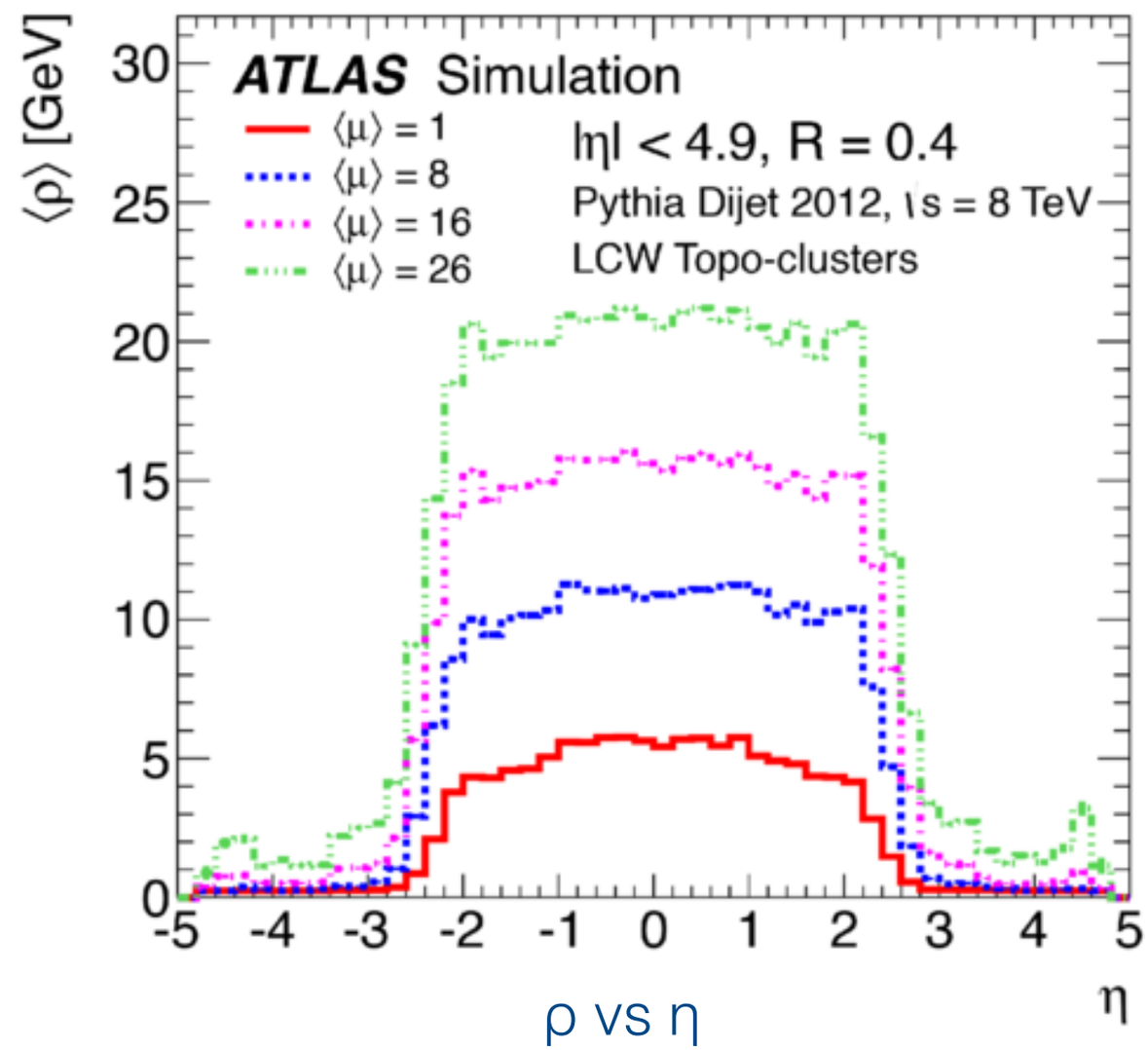
N ~ 3.33 GeV
S ~ 0.71 $\text{GeV}^{1/2}$
C ~ 3%

Pileup ρ calculation

- Coarser granularity at forward η suppresses pileup k_t reconstruction
- Use ρ from |η| < 2.0, & derive a residual pileup correction



Calorimeter granularity & topoclusters

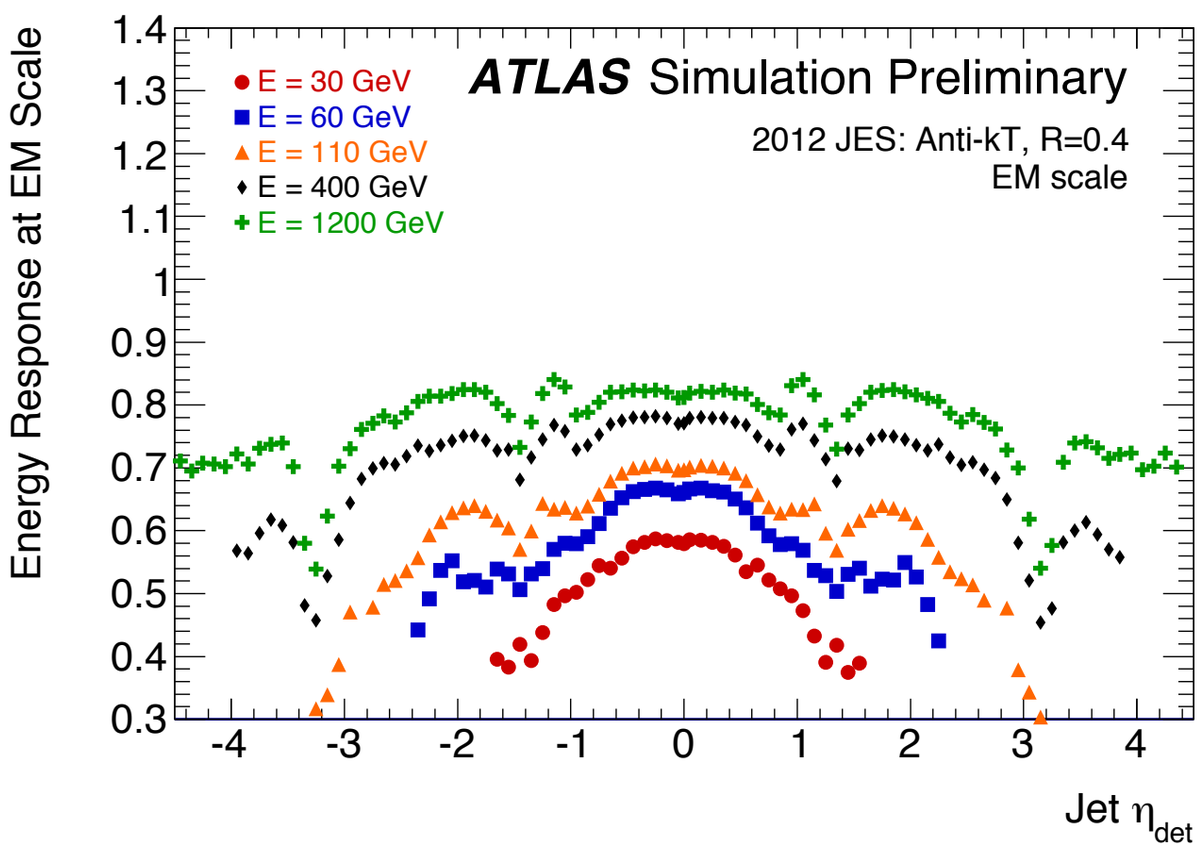


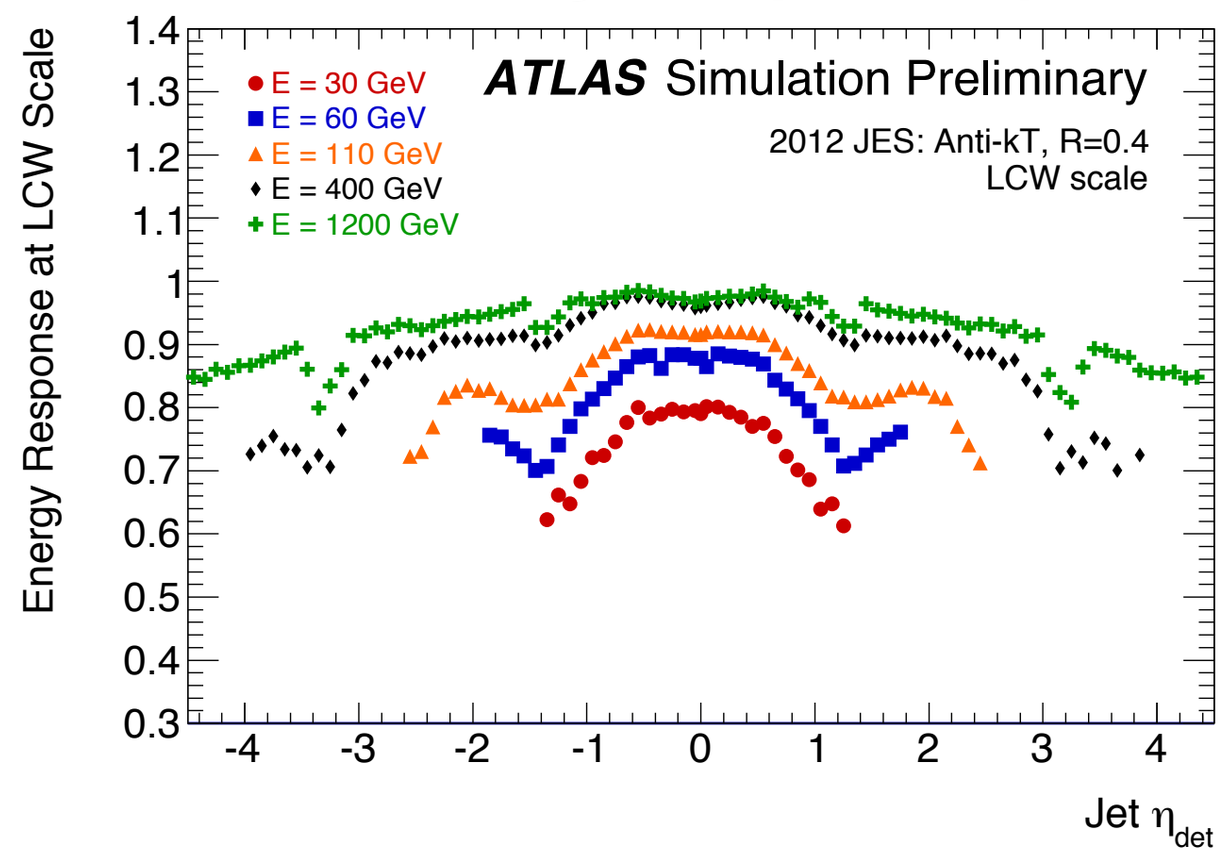
ρ vs η

MCJES correction

- Calibrate jet energy to **particle-scale** - sum of particles in MC minus minimally ionizing muons & neutrinos
- Residual η correction for jets in calorimeter transition regions

Clear difference between EM and LC jets (8 TeV)



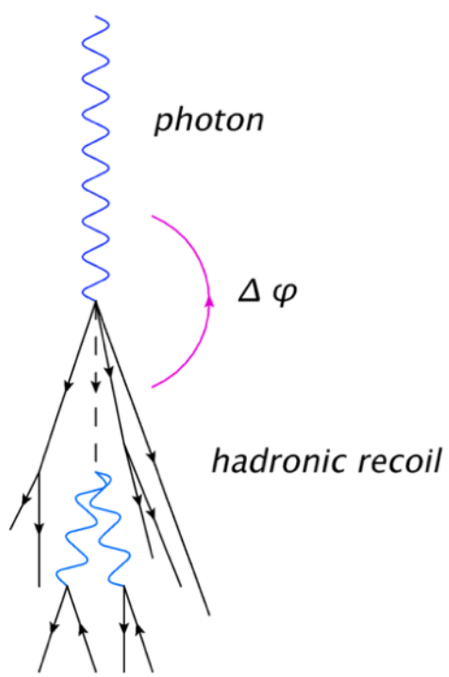


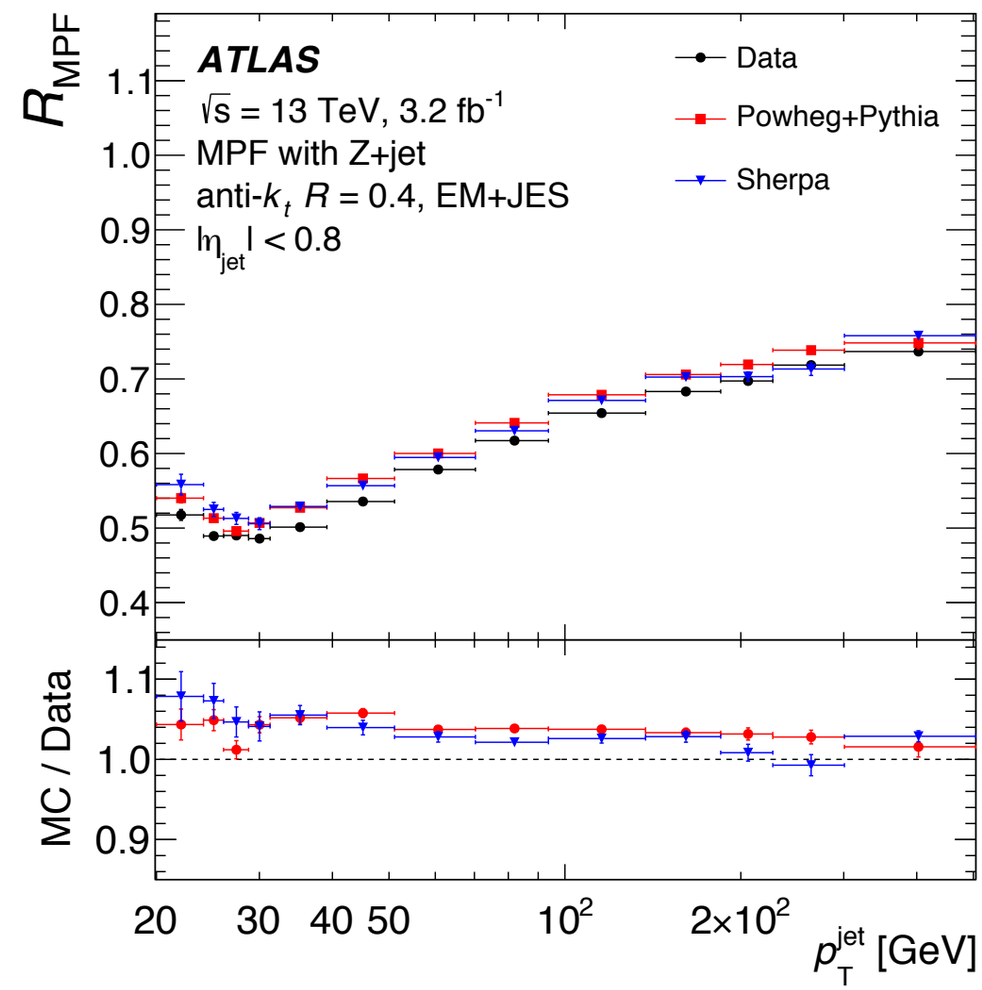
Missing-E_T projection fraction

- Balance Z/γ against entire calorimeter recoil

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

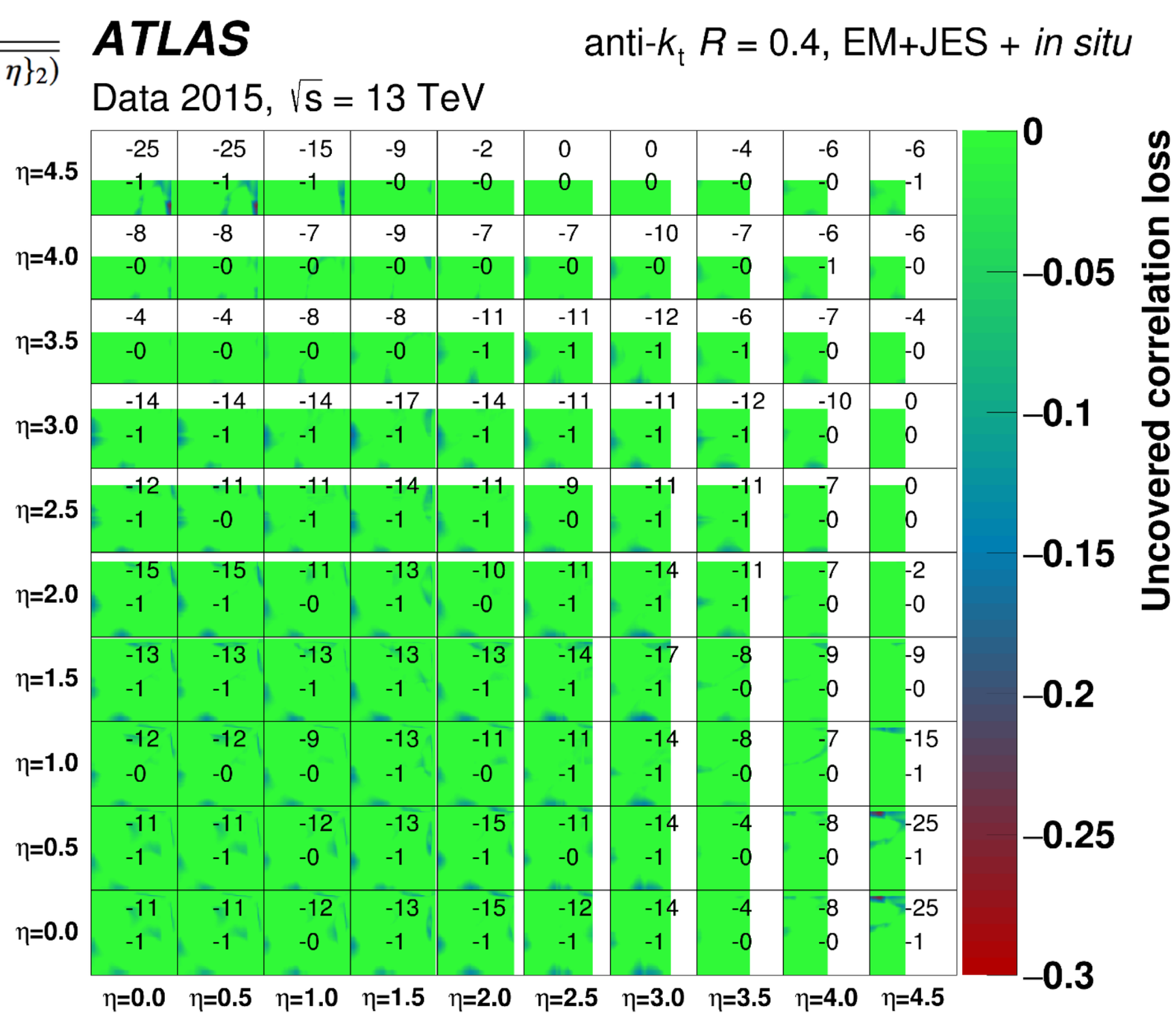
- Balance is less sensitive to jet definition, radius, out-of-cone radiation, and pileup
- Correction does not directly reflect energy within the jet (showering & topology)





Strong reduction coverage

$$\frac{\mathrm{Cov}(\{p_T,\eta\}_1,\{p_T,\eta\}_2)}{\sqrt{\mathrm{Cov}(\{p_T,\eta\}_1,\{p_T,\eta\}_1)\times\mathrm{Cov}(\{p_T,\eta\}_2,\{p_T,\eta\}_2)}}$$

- Bracket correlation loss through 4 reduced NP sets with focus on
  - low, medium, high p_T
  - low vs medium p_T & η
  - medium vs high p_T
  - very high p_T
- Measure coverage with:

$$\min_{i\in\{\mathrm{NP_{red}}\}}\left|C_{\mathrm{full}}-C^i_{\mathrm{red}}\right|-\max_{i,j\in\{\mathrm{NP_{red}}\}}^{i\neq j}\left|C^i_{\mathrm{red}}-C^j_{\mathrm{red}}\right|$$