Dijet cross-section measurement using the ATLAS experiment

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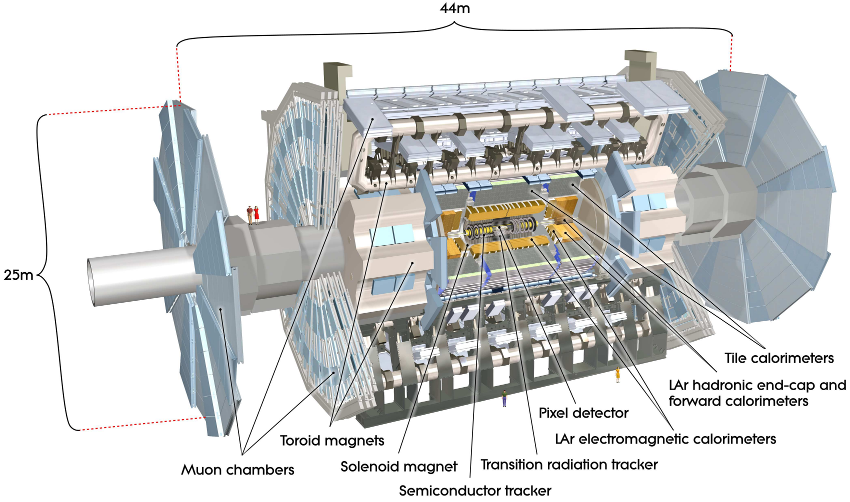
Introduction

- Two topics connected with ATLAS experiment at CERN
  - Detector operation
    - Time calibration of ATLAS Tile Calorimeter
  - Physics analysis
    - Dijet cross-section measurement using ATLAS

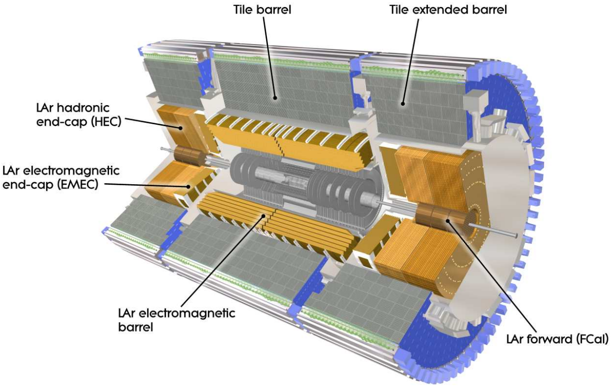
ATLAS

- Multi-purpose detector at LHC with broad scientific program
- Multiple sub-detectors: Inner Detector, calorimeters, Muon Spectrometer, ...



ATLAS—calorimeters

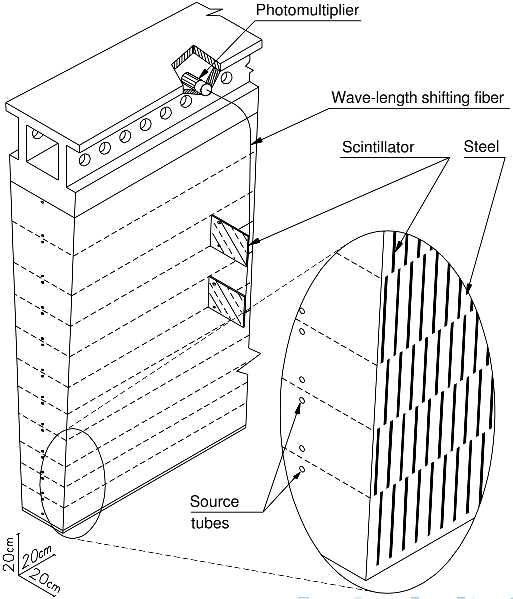
- Measurement of energy and direction of particles
  - Electromagnetic calorimeters—electrons and photons
  - Hadronic calorimeters—jets and single hadrons
- Two types
  - Liquid Argon (LAr) calorimeter
  - Tile calorimeter (Tilecal)



ATLAS Tile Calorimeter

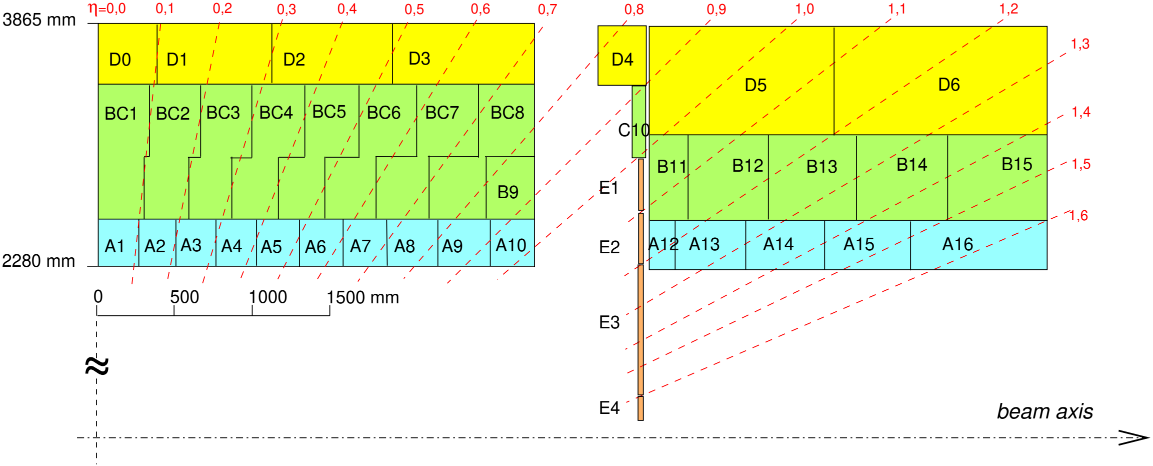
Tile Calorimeter—Introduction

- Hadronic calorimeter of ATLAS
- Sampling calorimeter
  - Passive medium: steel
  - Active medium: scintillator tiles
- Scintillation light transported by optical fibers to photomultipliers (PMTs)

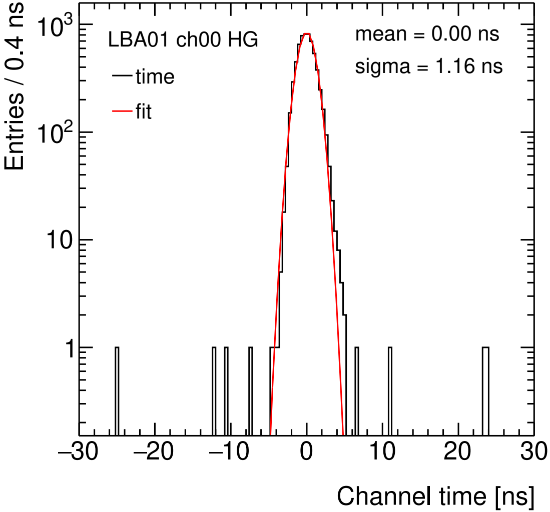


Tile Calorimeter—Introduction

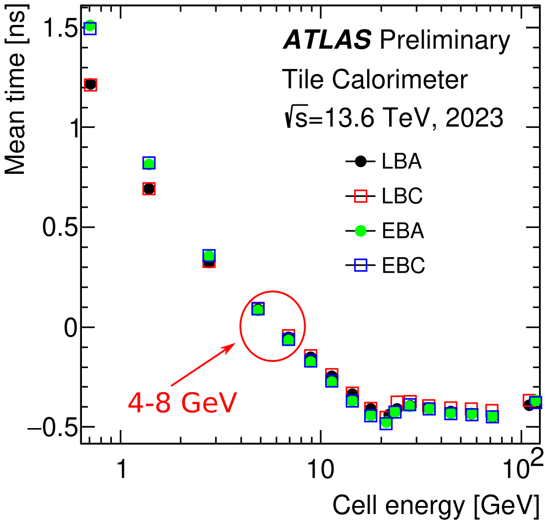
- Readout cells defined by groupings of optical fibers to the same PMTs
- Typical cell—two PMTs (= two channels)



- Importance of time calibration
  - Energy reconstruction depends on correct timing
  - Non-collision background removal
  - Time of flight measurements
- Time calibration = time constants set in each channel



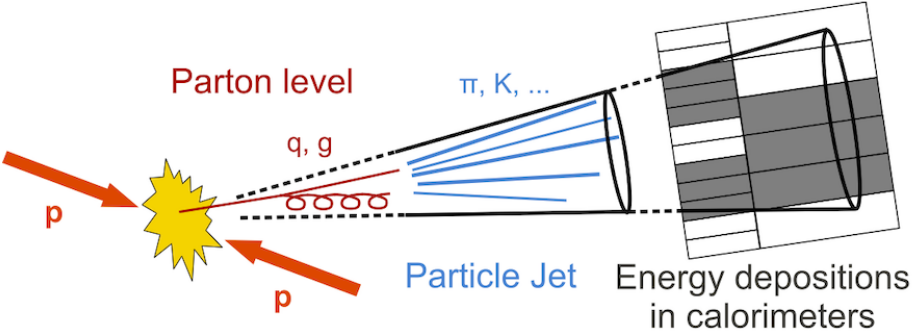
- Multiple time calibration methods, final method uses jets in *pp* collision data
  - Slight energy dependence of reconstructed time on energy deposited in cell for jets
  - Calibration using specific energy range



Dijet cross-section measurement

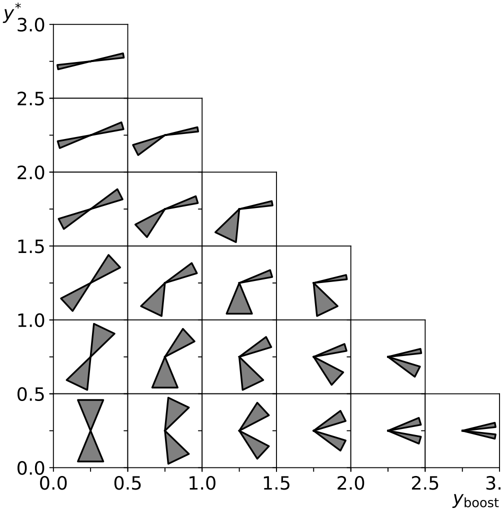
Dijet measurement—Jets

- Jet: *pp* collision $\rightarrow$ partons $\rightarrow$ hadronization $\rightarrow$ collimated hadron shower
- Jet reconstruction
  - Topological jets: energy deposited in calorimeters
  - Particle flow (PFlow) jets: calo. energy + tracks of charged hadrons from Inner Detector



Dijet measurement—Cross-section and observables

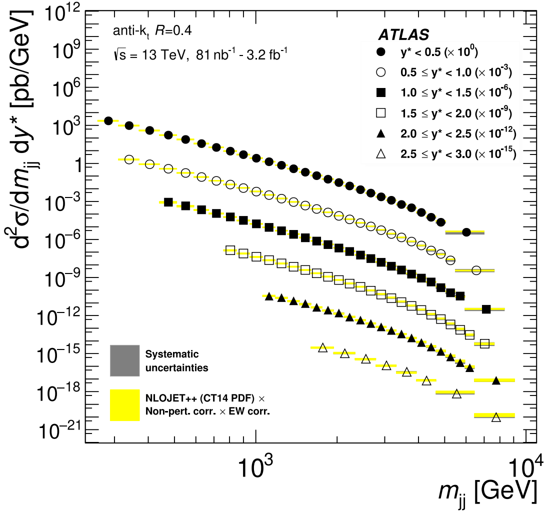
- Measurement of production of two jets (PFlow) in 13 TeV pp collisions
- Full LHC Run 2 dataset (140 fb^{-1})
- Motivation: high-x gluon PDF extraction
- Two double-differential cross-sections using
  - $m_{\text{jj}} = \sqrt{(P_1 + P_2)^2}$
  - $y^* = |y_1 - y_2|/2$
  - $y_{\text{boost}} = |y_1 + y_2|/2$
- Jet selection
  - $p_{\text{T}} > 75$ GeV, $|y| < 3$
  - $p_{\text{T},1} + p_{\text{T},2} > 200$ GeV



Dijet event topology

Dijet measurement—Past ATLAS measurements

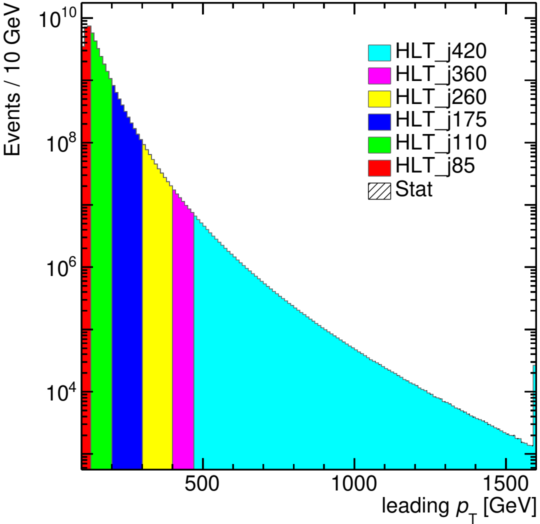
- *JHEP* **05** (2018) 195
  - 2015 data (3.2 fb^{-1})
  - 13 TeV *pp* collisions
  - $d^2\sigma/dm_{jj}dy^*$
  - m_{jj} up to 9 TeV
- *JHEP* **05** (2014) 059
  - 2011 data (4.5 fb^{-1})
  - 7 TeV *pp* collisions
  - $d^2\sigma/dm_{jj}dy^*$, m_{jj} up to 5 TeV



Dijet cross-section, *JHEP* **05** (2018) 195

Dijet measurement—Data

- Events after selection: $\sim$ 240M
- For lowest-energy jets, only fraction of evts. saved
  - To reduce event rate to manageable level
  - As low as 1 in $\sim$15,000 jets (using our selection)
- Effective number of events: $\sim 10^{11}$



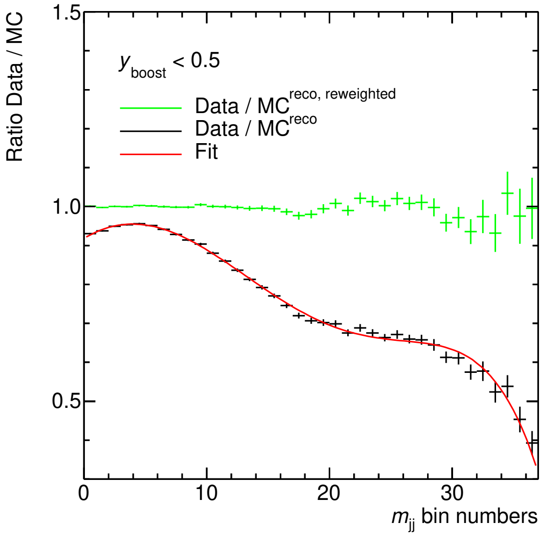
Leading jet p_T using single-jet triggers in 2018 data

Dijet measurement—Unfolding

- Data corrected for detector resolution and efficiency effects using unfolding procedure (IDS method)
- Monte Carlo events
  1. Generation of events (Pythia8) $\rightarrow$ Particle (truth) level
  2. Propagation of particles through detector and simulated detector response (Geant4)
  3. Reconstruction of events $\rightarrow$ Reco. level
- Response matrix (RM)
  - Created using events with corresponding truth and reco. dijets
  - Describes detector response
- Three steps of unfolding: $N_i^{\text{truth}} = \sum_j N_j^{\text{reco}} \cdot \mathcal{P}_j \cdot \mathcal{U}_{ij} / \mathcal{E}_i$
  1. Purity correction $\mathcal{P}_j$
  2. Event migrations between bins (unfolding matrix $\mathcal{U}_{ij}$ = normalized RM)
  3. Efficiency correction $\mathcal{E}_i$

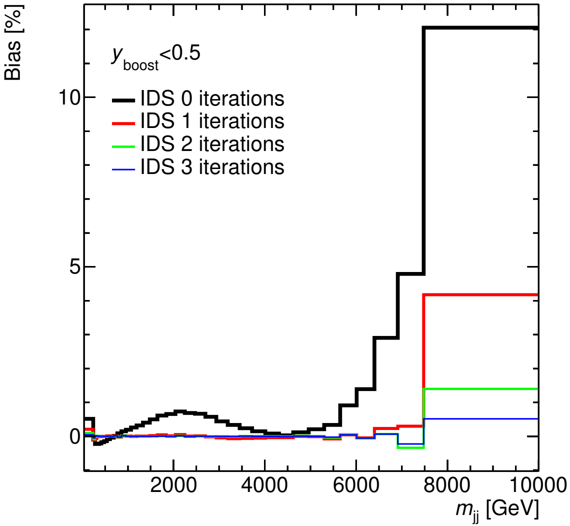
Dijet measurement—Unfolding bias

- Estimated using data-driven closure test
- Asumption: Data–MC difference on reco. level caused by improper MC modeling on truth level
- Procedure:
  1. Purity correction of data
  2. Data/MC on reco. level
  3. Smooth function fit (5th order polynomial)
  4. Fit function used to re-weight MC on the truth level
  5. Closure: corresponding reco. MC agrees with Data well



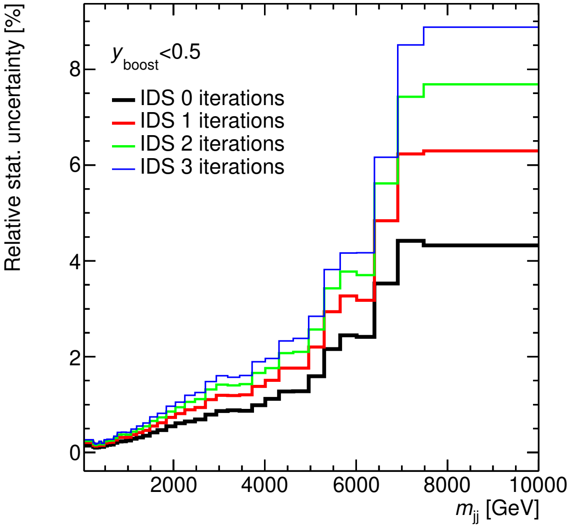
Dijet measurement—Unfolding bias

6 Comparison:
  - Re-weighted reco. MC unfolded using nominal RM
  - Re-weighted truth. MC
- This difference interpreted as unfolding bias
- Bias decreases with increasing number of IDS iterations



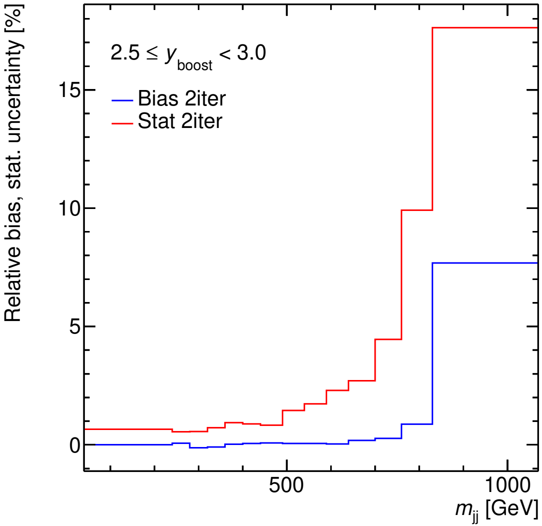
Dijet measurement—Statistical uncertainty

- Statistical uncertainty estimated using bootstrap method
  - To account for events contributing with different weights (MC weights, Data prescales) and migration of events during unfolding
- Data contribution
  1. Events re-weighted 100 times according to Poisson distribution with mean = 1, creating 100 replicas of the spectrum
  2. Unfolding of replicas → 100 unfolded spectra
  3. Stat. unc. estimate = RMS error
- MC contribution
  - Same, just replicas of response matrix
- Stat. unc. increases with increasing number of IDS iterations



Dijet measurement—Unfolding iterations

- Number of iterations chosen so that stat. unc. larger than bias
  - Stat. unc.—well-understood method of estimation using bootstrap replicas, clear interpretation
  - With increasing number of iterations bias decreases faster than stat. unc. increases
- Choice:
  - 1 iteration for y^*
  - 2 iterations for y_{boost}



Dijet measurement—Systematic uncertainties and jet calibration

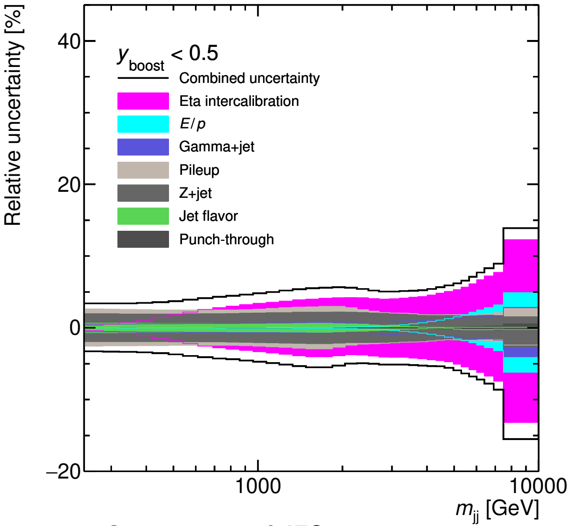
- Many different sources of systematic uncertainty
  - Jet energy scale (JES)
  - Jet energy resolution (JER)
  - Other sources

Jet calibration—multiple steps and methods (connected with JES uncertainty)

- Pileup correction
- Absolute calibration
  - MC-based correction of p_{T} and η
- Global sequential calibration
  - MC-based correction of residual dependence on e.g. jet flavor
- Residual *in situ* calibration
  - Correction of MC–Data difference
  - Various methods of comparing jets to well-calibrated objects
    - Forward to central jets
    - Jet to gamma or Z
    - E/p measurement (π from W decay, ...)

Dijet measurement—JES systematic uncertainty

- Jet energy scale (JES) uncertainty—1172 components
  - Dominant systematic uncertainty source
- Uncertainty propagated through unfolding
  - Each component—shifted p_T and/or η of jets in MC simulation
  - Shifted reconstructed MC spectrum unfolded using nominal RM
  - Compared to the nominal truth spectrum = uncertainty estimate

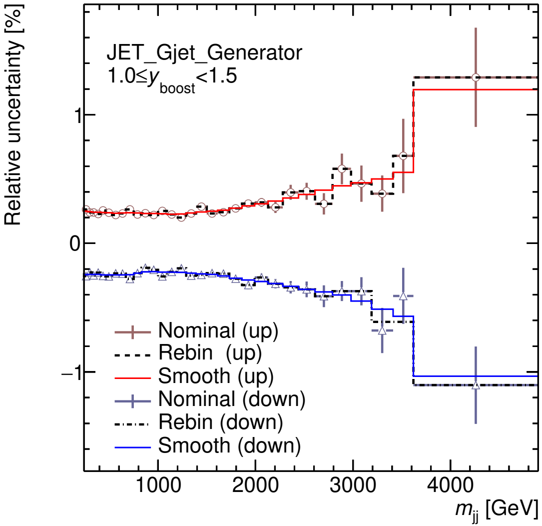


Components of JES uncertainty

Dijet measurement—Smoothing of systematic uncertainties

- Three-step smoothing procedure to minimize effects of statistical fluctuations:

1. Statistical uncertainty estimation (bootstrap method)
2. Rebinning until significant (2 σ)
3. Gaussian kernel smoothing in original fine binning
    - Each bin recalculated as weighted average of all bins
    - Weights according to Gaussian distribution → closest bins most important

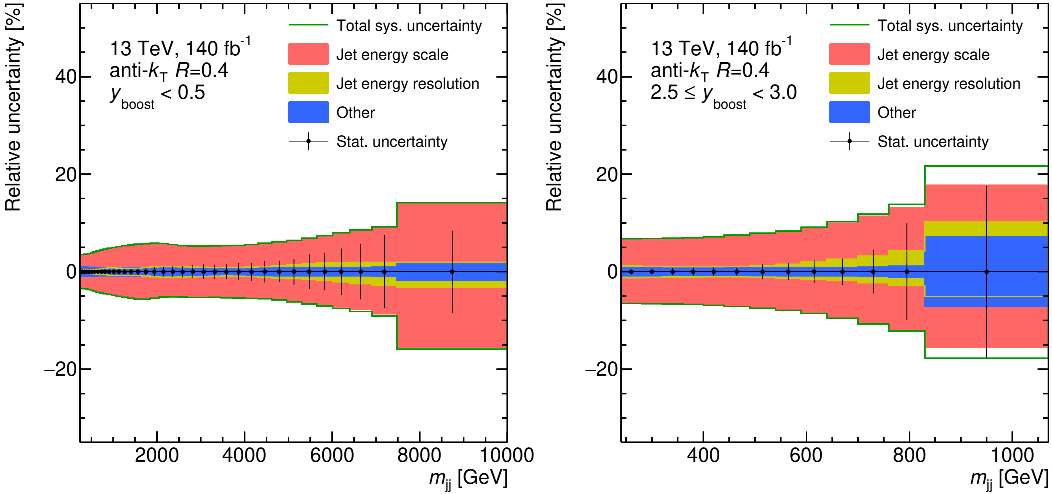


Dijet measurement—JER and other systematic uncertainties

- Jet energy resolution (JER)—34 components
  - $\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C$
  - N—noise term (electronics and pileup noise)
  - S—stochastic term (stat. fluct. due to energy sampling)
  - C—constant term (response non-uniformity, signal loss in passive material)
  - JER measured using various methods, uncertainties propagated through unfolding
- Other sources
  - Luminosity uncertainty (140.07 ± 1.17 fb^{-1}), flat 0.83% uncertainty in each bin
  - Unfolding bias (after smoothing)
  - More ...

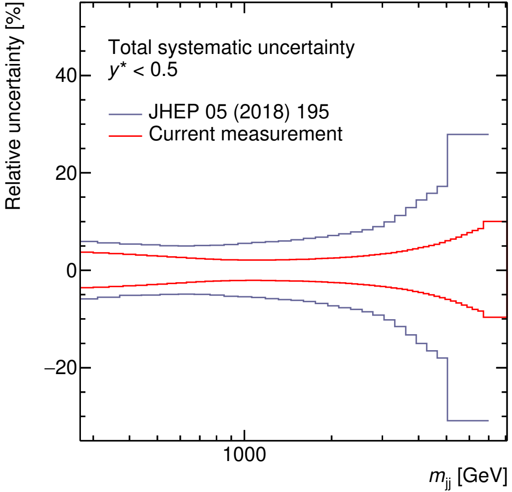
Dijet measurement—Total systematic uncertainty

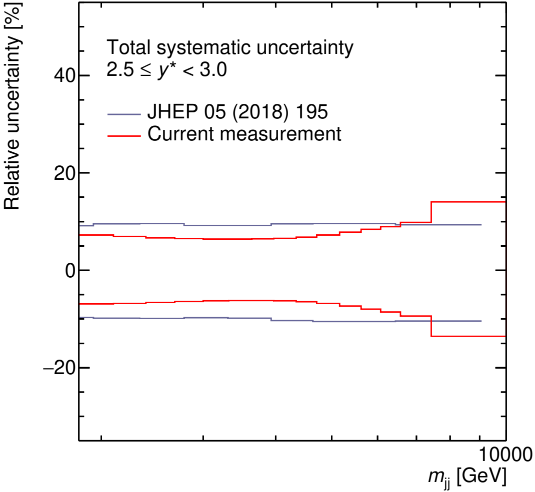
- Total systematic and statistical uncertainties of the dijet cross-sections
  - Mostly at level of 5–10%
  - Up to ∼15–20% in last m_{jj} bins



Dijet measurement—Uncertainty comparison

- Total systematic uncertainty compared to the previous measurement (*JHEP* **05** (2018) 195)
- Improvement by factor up to ∼3

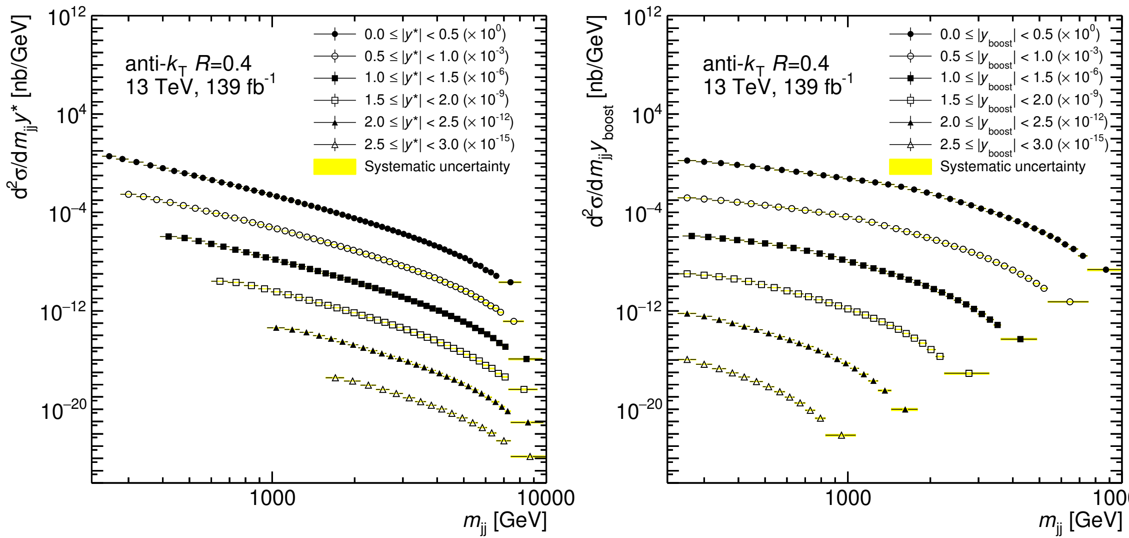




Dijet measurement—Cross-sections

- Two double-differential dijet cross-sections

$d^2\sigma/dm_{jj}dy^*$ $\qquad$ $d^2\sigma/dm_{jj}dy_{boost}$



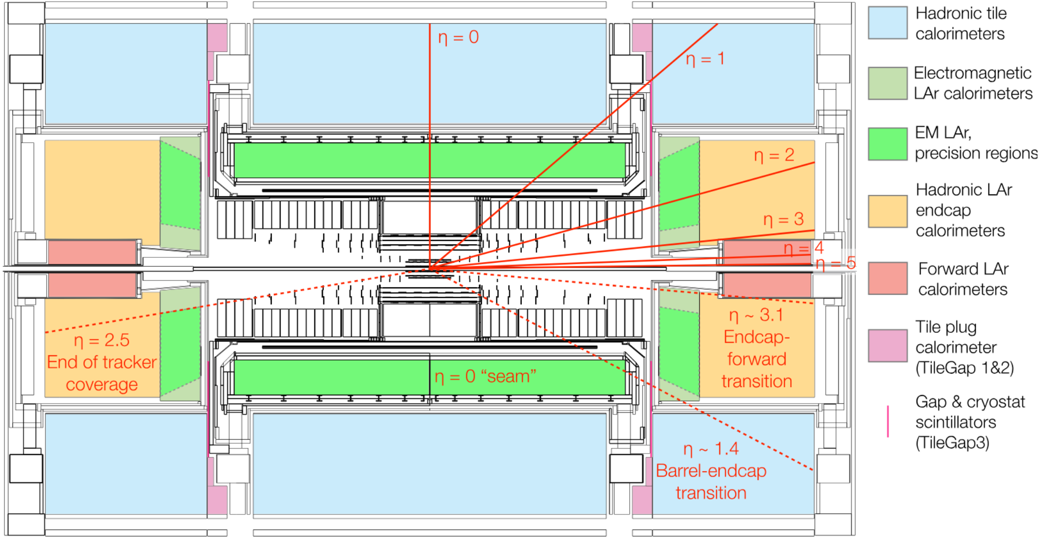
Summary

- Current dijet cross-section measurement improves the results obtained in the previous ATLAS measurements
  - Better statistics (140 fb^{-1} vs 3.2 fb^{-1})
    - $\sim 2\times$ finer binning, better energy reach
  - Improved treatment of systematic uncertainties
    - Uncertainty reduced by factor ~ 3 in some bins
  - Additional rapidity variable y_{boost}
    - Better sensitivity to PDFs
  - NNLO theory will be compared with the measurement
    - Previously NLO
- My contribution
  - Evaluation of systematic and statistical uncertainties
  - Study and optimization of unfolding procedure
  - Other dedicated studies
- Analysis currently in internal review process of ATLAS

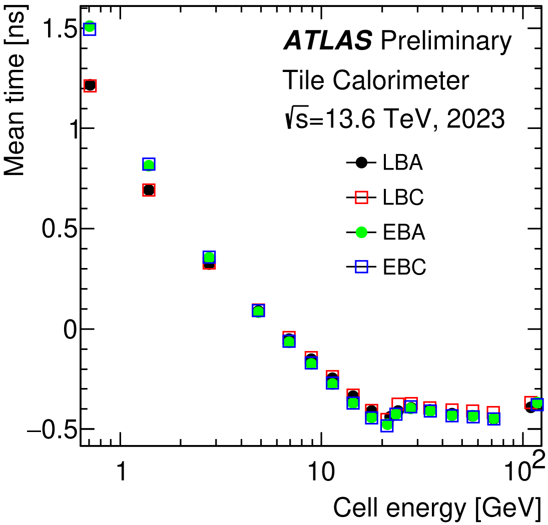
Backup

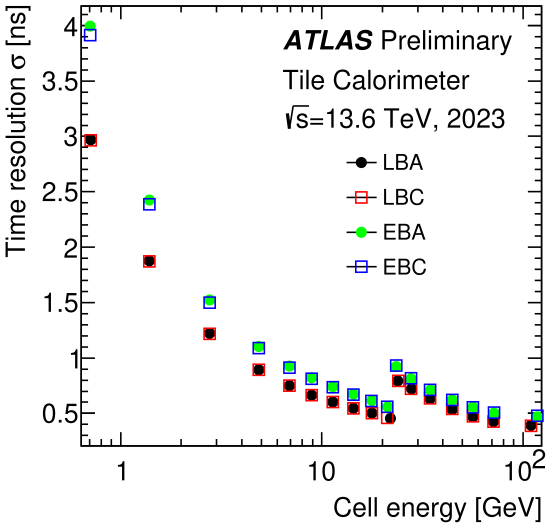
Tile Calorimeter—Calorimeters

- $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, $\eta = -\ln \tan(\theta/2)$, $\sim 10\lambda_{\text{int}}$ (interaction lengths) at $\eta = 0$



Tile Calorimeter—Mean time and resolution





Dijet measurement—Uncertainty comparison

- Total statistical uncertainty compared to the previous measurement (*JHEP* **05** (2018) 195)