Observation of Energetic Jets in *pp* Collisions at $\sqrt{s}$ =7 TeV using the ATLAS Experiment at the LHC

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on behalf of the ATLAS Collaboration

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Outline

- Introduction
- Data sample & event selection
- Dijet and multi-jet event displays
- Inclusive jet and dijet kinematic distributions
- Jet internal structure and particle flow
- Conclusions

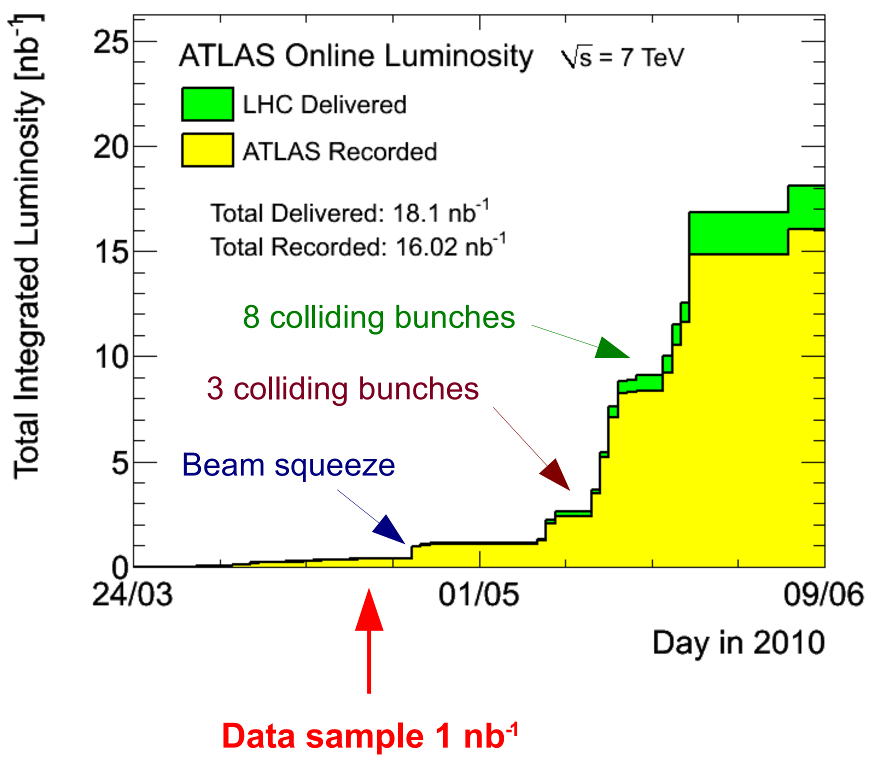
Introduction

- We report here the observation of energetic jet production in *pp* collisions at a center-of-mass energy of 7 TeV using 1 nb^{-1} of data taken with the ATLAS detector
  - Documented in conference note ATLAS-CONF-2010-043: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-043
- Calorimeter response of single isolated hadrons described earlier (P.O. DeViveiros)
- Jet reconstruction and calibration also detailed earlier (R. Seuster)
- This talk focuses on the kinematics and internal structure of the jets produced
- Early searches using these jets will be discussed afterwards (V. Lendermann)

Data sample and event selection

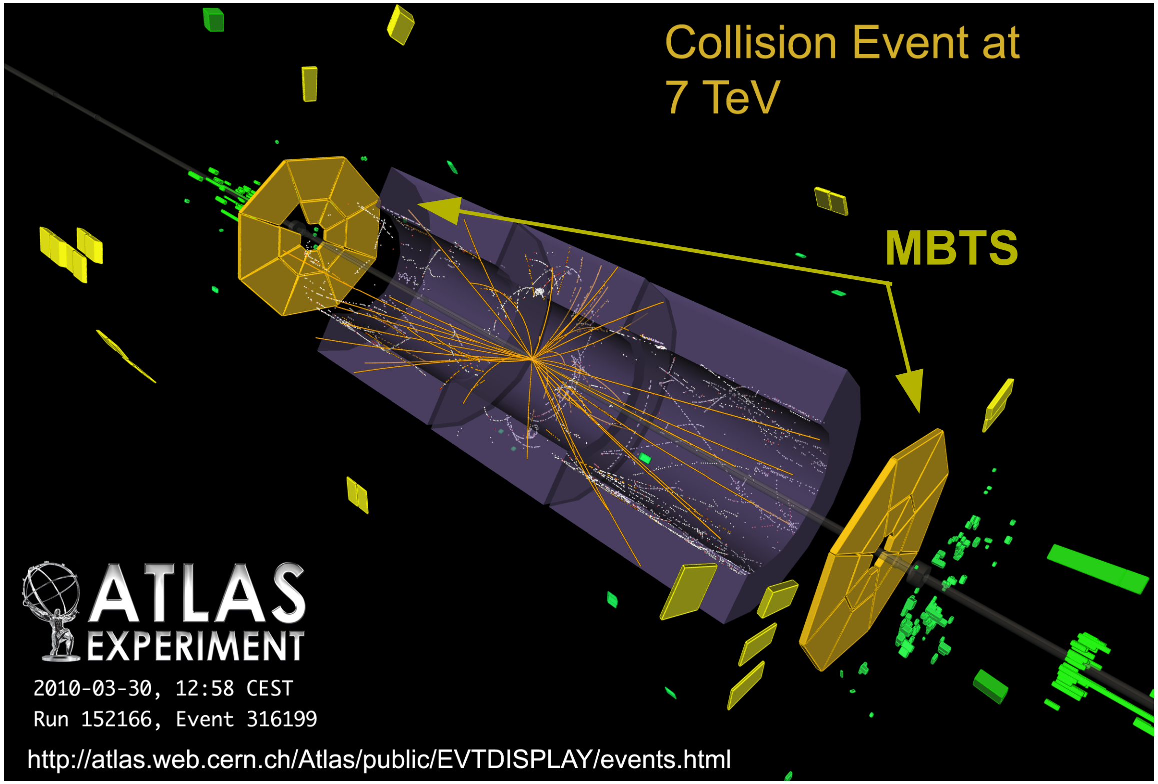
Data sample

- Data sample studied encompasses approximately 1 nb^{-1} of data collected through April 22
  - 18.1 nb^{-1} delivered by LHC to date
  - Peak instantaneous luminosity ~ 2.1 x 10^{29} cm^{-2} s^{-1}



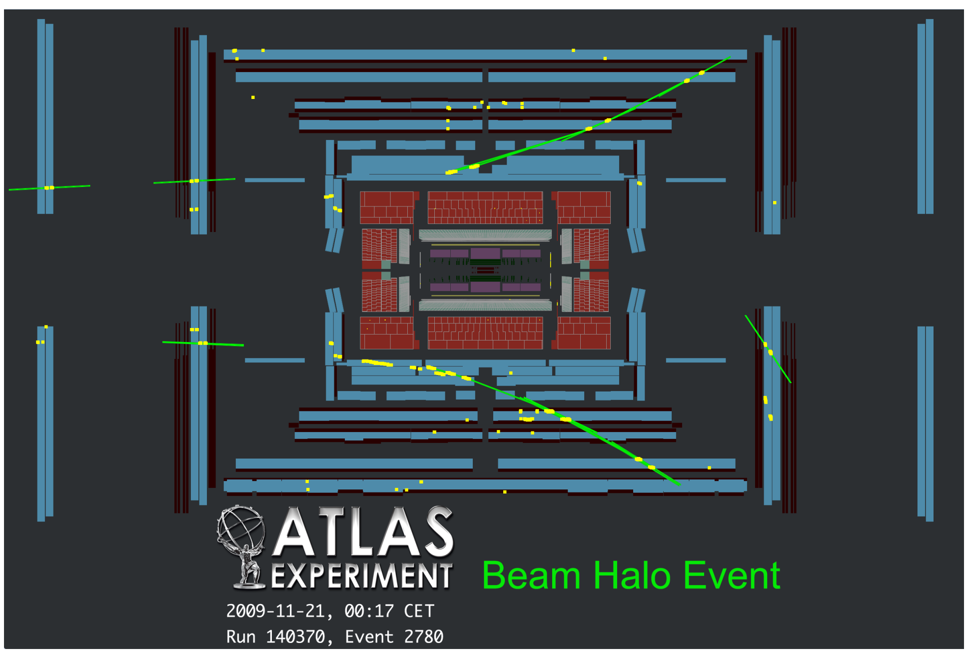
Trigger

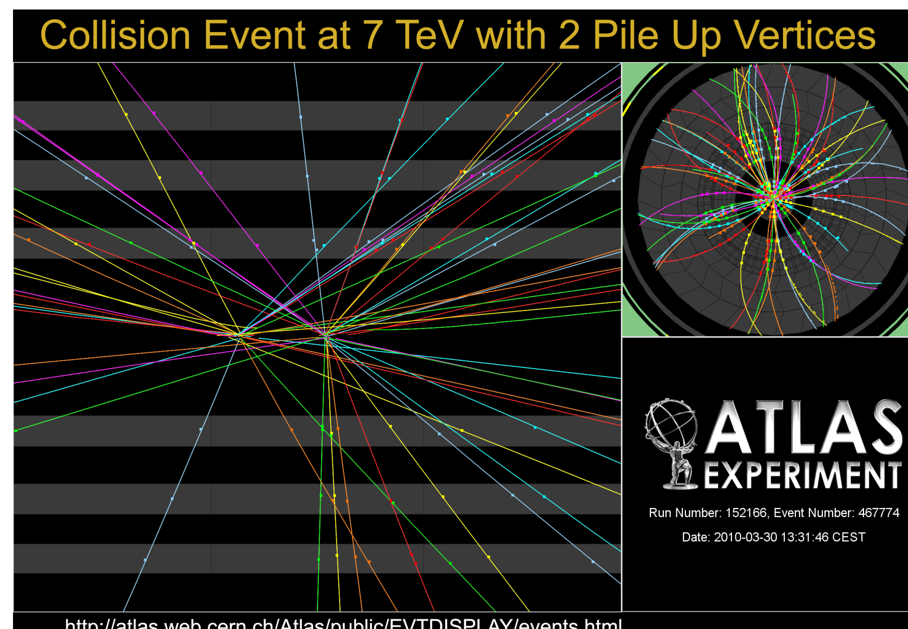
- MBTS (Minimum Bias Trigger Scintillator) inclusive trigger
  - Require at least one scintillator fired from either η hemisphere: $2.09 < |\eta| < 3.84$
  - No significant bias introduced to the inclusive jet sample



Vertex requirement

- Require at least one vertex reconstructed with $|z|<10$cm (luminous region is ~5cm)
  - Suppresses contamination from non-collision backgrounds such as beam halo and beam gas
- Negligible impact from pileup in data sample studied
  - Fraction of events with more than one reconstructed vertex is ~0.2 %



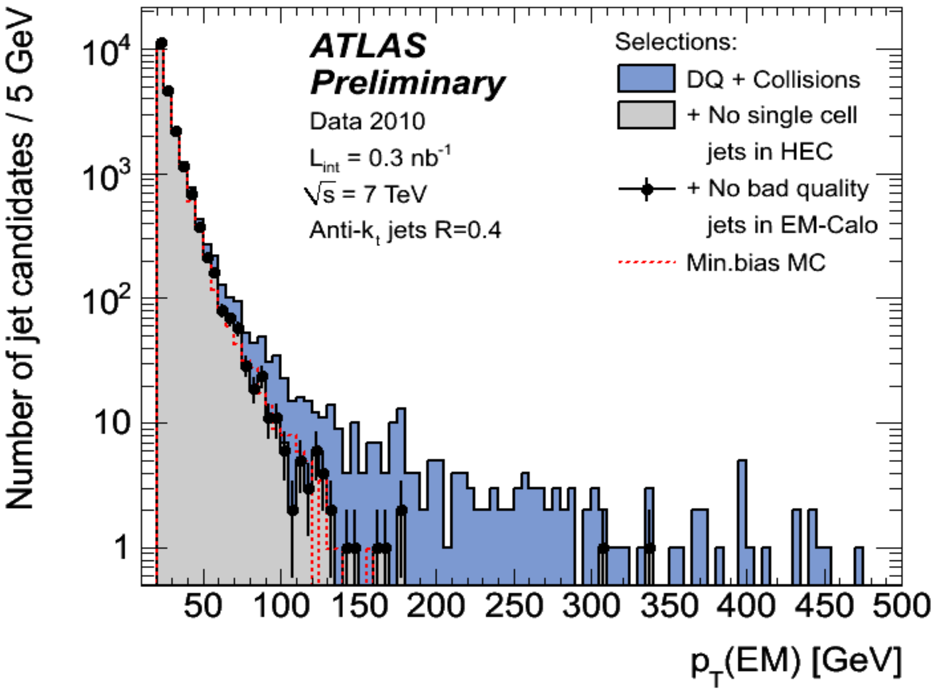


Jet reconstruction & calibration

- Jets reconstructed from calorimeter clusters using Anti-k_T jet algorithm with clustering parameter R=0.6
  - Jet transverse momentum corrected on average from the "electromagnetic scale" back to the hadron level using an MC-based calibration as a function of jet p_T and y
    - Electromagnetic scale is the calibrated scale for energy deposited by electrons & photons in the calorimeter
    - Non-compensation for hadrons due to nuclear interactions
  - Further details on reconstruction and calibration of clusters and jets in earlier talks by P.O. DeViveiros and R. Seuster
- Jets selected with calibrated p_T > 30 GeV within rapidity acceptance $|y|<2.8$

Jet cleaning

- Events with at least one "bad" jet with p_T >10 GeV at electromagnetic scale anywhere in detector are removed
- "Bad" jet definition is based on cuts designed to remove:



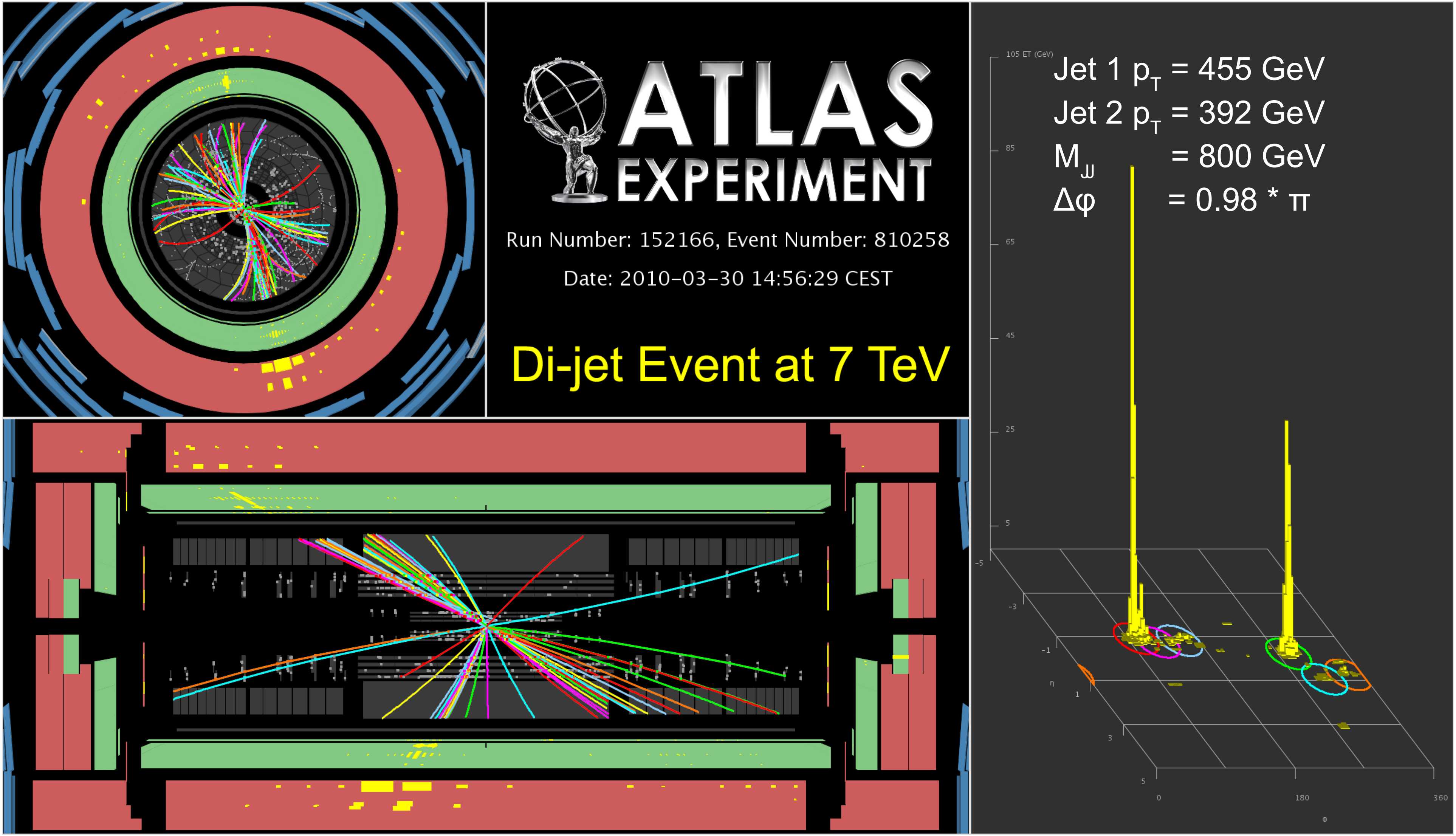
- Noisy cells in the hadronic endcap calorimeter
- Coherent noise in the electromagnetic calorimeter
- Large out-of-time energy depositions, e.g. from cosmic ray muons

- Already discussed in earlier talk on missing E_T performance (A. Yurkewicz)

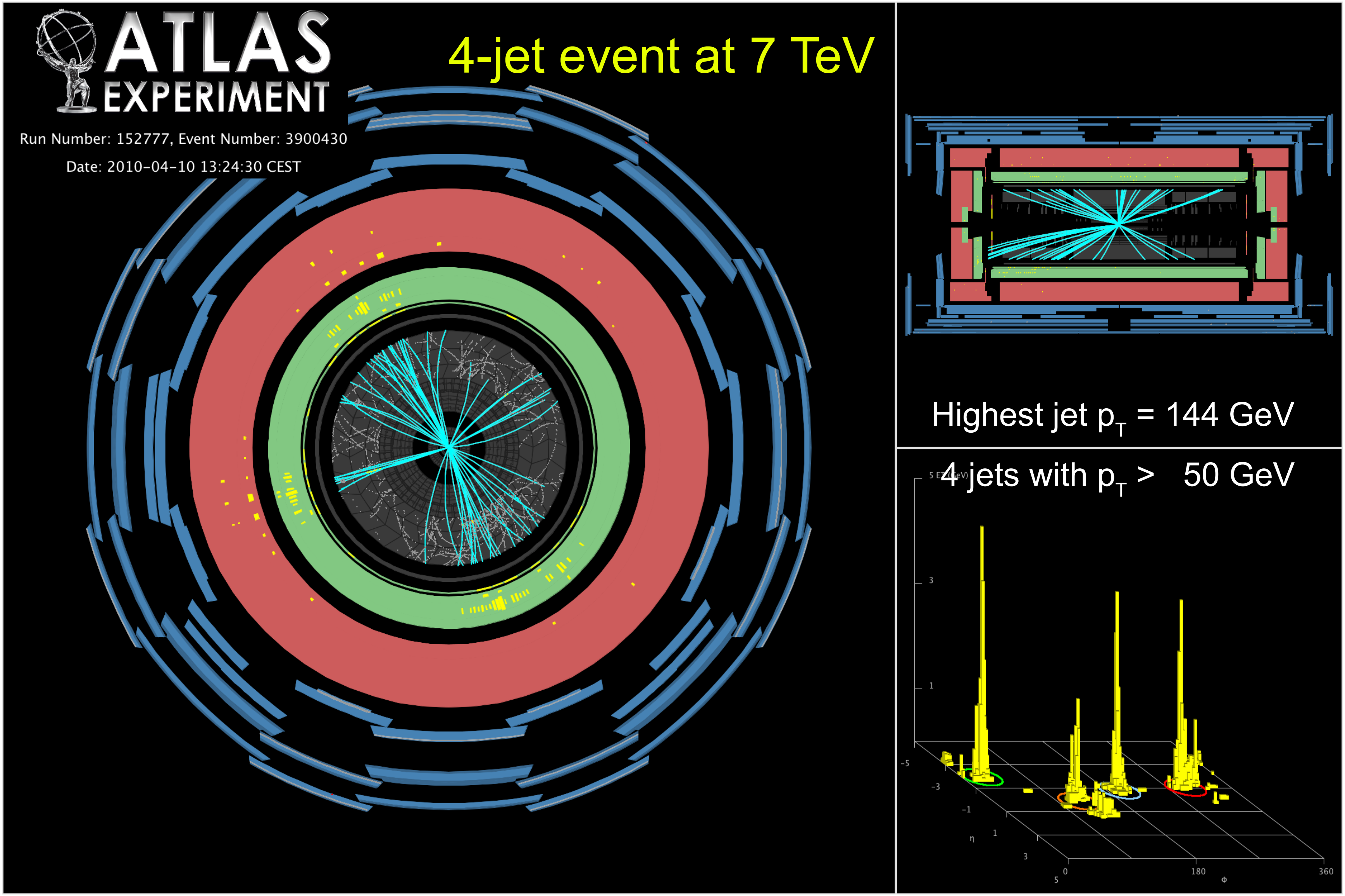
- Further details in backup slides and in conference note ATLAS-CONF-2010-038: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-038

Dijet and multi-jet event displays

Highest p_T dijet event



Example of 4-jet event



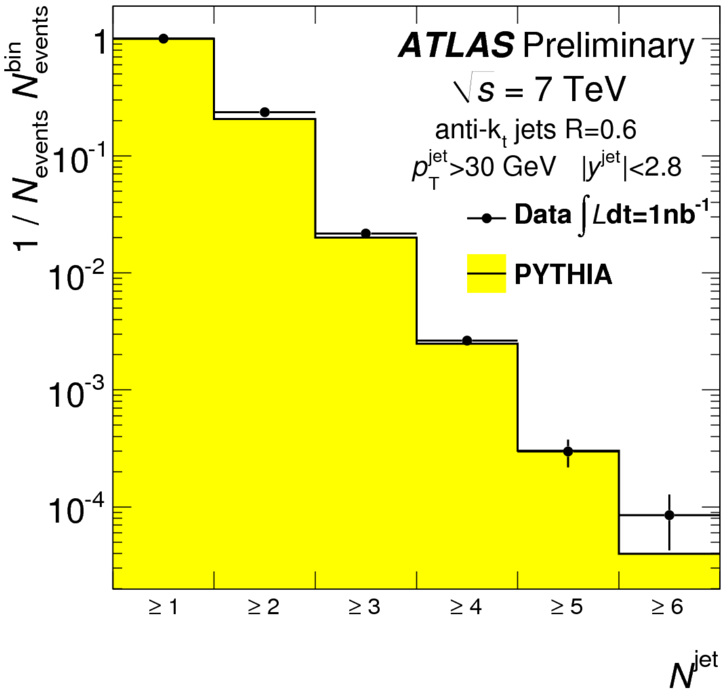
Inclusive jet and dijet kinematic distributions

Comparison of data vs. Monte Carlo

- Pythia dijet Monte Carlo (LO matrix element + parton shower) used for theoretical model prediction
- All jet kinematic distributions normalized to unity
  - Normalization contains no information – comparisons only sensitive to shape differences
  - Jet cross-sections will be reported later this summer
- Data distributions compared to Monte Carlo at reconstruction level (not unfolded to particle level)
- Only statistical uncertainties shown
  - No attempt to show systematic uncertainties from jet energy scale or other sources
  - Absolute JES uncertainty is O(10%) for $|y|<2.8$, which would introduce a large error band on the plots

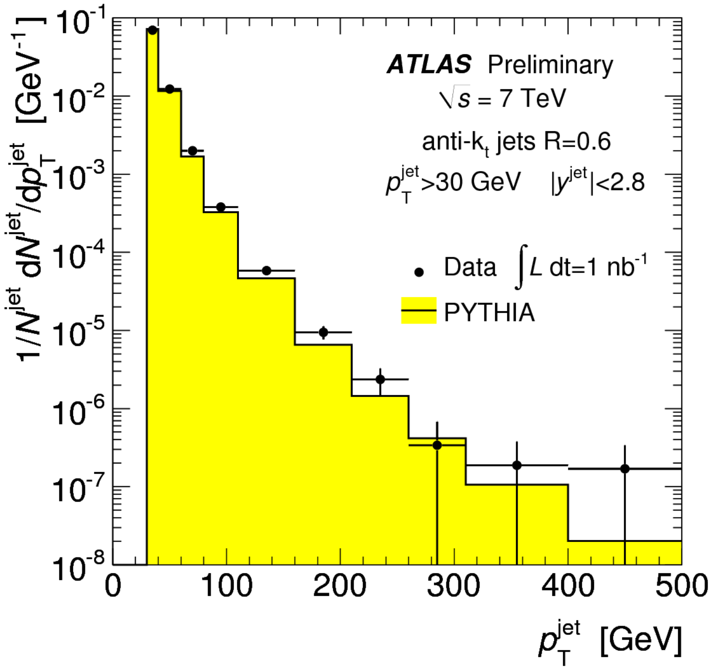
Inclusive jet multiplicity

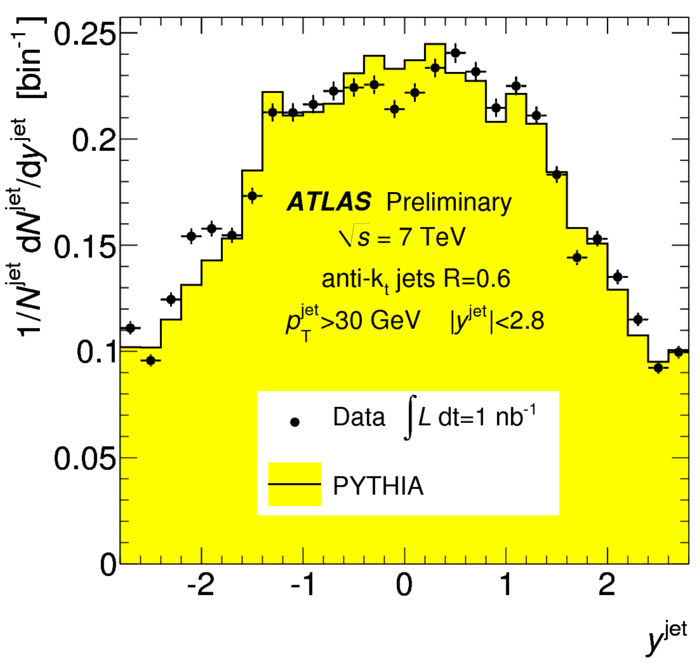
- Integral distribution of number of jets
  - Data decreases with increasing jet multiplicity
  - Events with up to 6 jets in the final state are observed
- Data and Monte Carlo agree well
  - Good performance by LO parton shower Monte Carlo



Inclusive jet p_T spectrum and rapidity

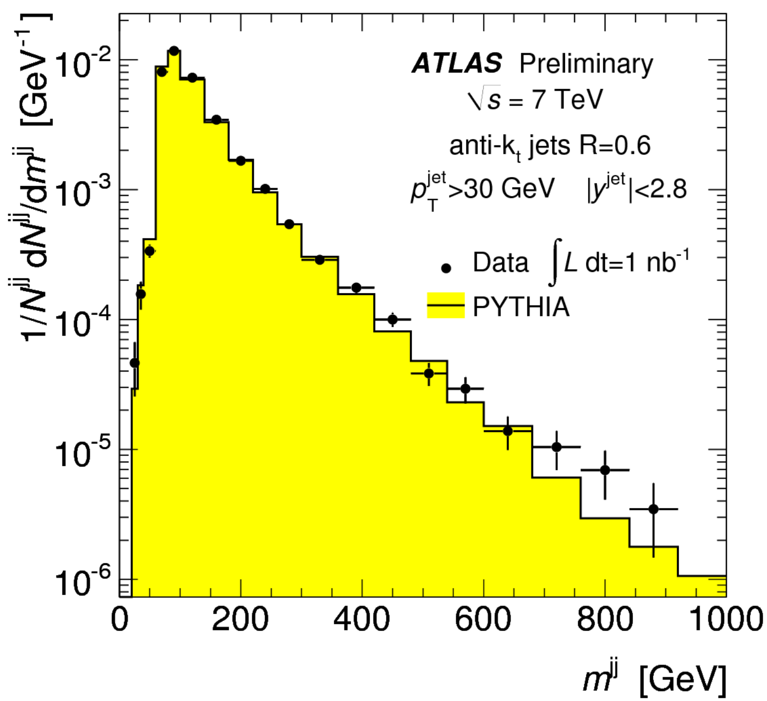
- Observed p_T spectrum falls steeply with increasing jet p_T
  - Jets with transverse momentum up to 500 GeV are observed
  - Monte Carlo follows the shape reasonably well
- Rapidity distribution is also described by the Monte Carlo
  - Some small deficiencies near y=0 and y=-2.1 (under investigation)

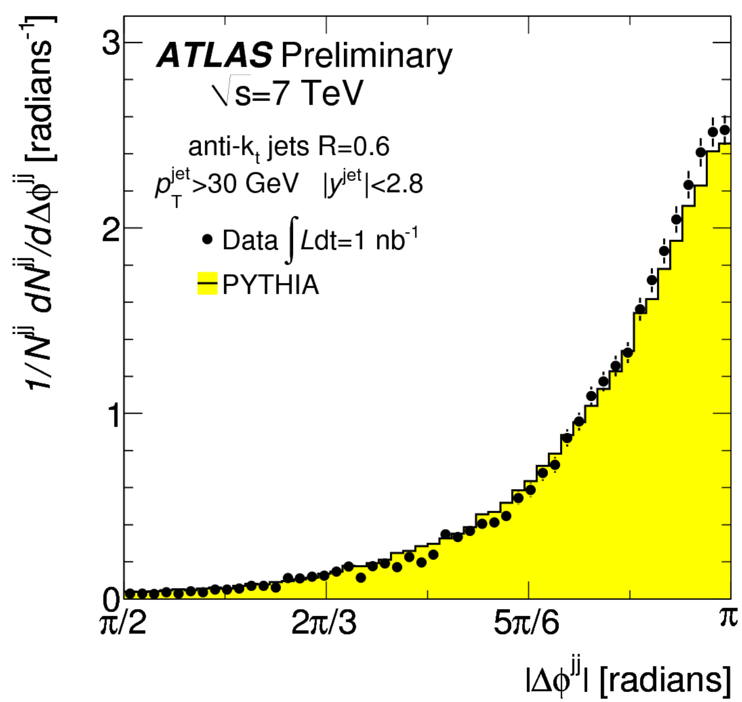




Dijet mass and angular separation

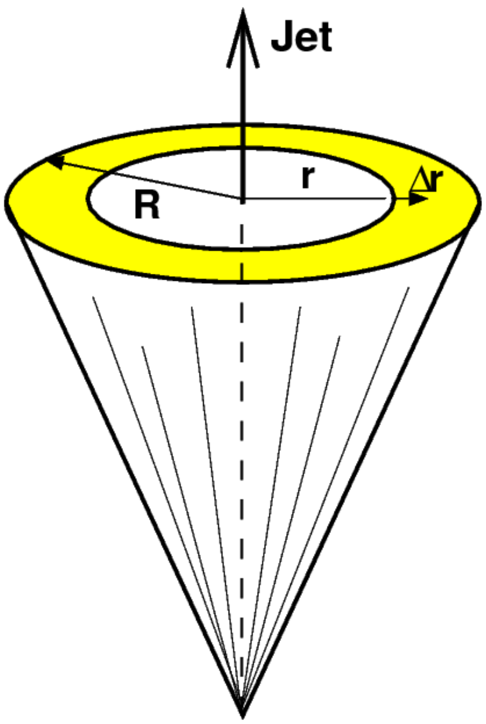
- Invariant mass of two leading jets is observed up to 900 GeV
  - Limited phase space at low dijet mass from jet p_T and y thresholds
- Azimuthal separation Δφ indicates predominant back-to-back dijet final state
- Monte Carlo describes reasonably the shape of both distributions
  - Underestimates data at large Δφ





Jet internal structure and particle flow

Jet shapes: Method



- Jet shapes in inclusive jet production:

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{jet}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},\ 0 \le r \le R$$

is the average *fraction* of jet transverse momentum within annulus of inner radius (r – Δr/2) and outer radius (r + Δr/2)

  – Proportional to transverse momentum density inside the jet

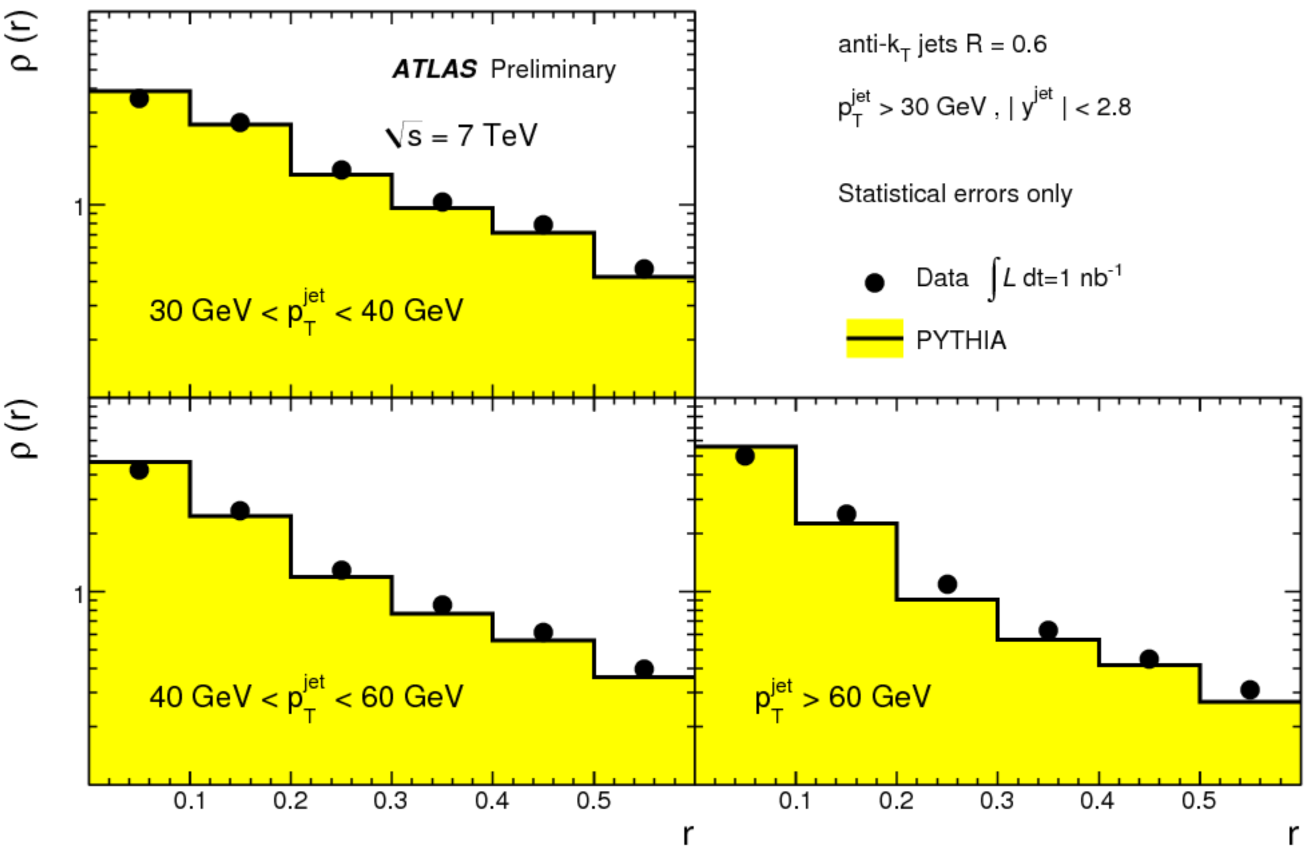
  – Relatively insensitive to the jet energy scale because jet p_T normalized away

- Here p_T is computed as the scalar sum of transverse momenta of a jet's constituent clusters that lie within the annulus

  – Uses calorimeter clusters

Jet shapes: Data distributions

- Density of transverse momentum peaks at low r with most of jet p_T within r<0.3, indicating collimated flows of particles around jet axis
- Shifts to lower r for higher p_T jets, indicating they are more collimated
- Monte Carlo describes data reasonably well, producing slightly narrower jets than data



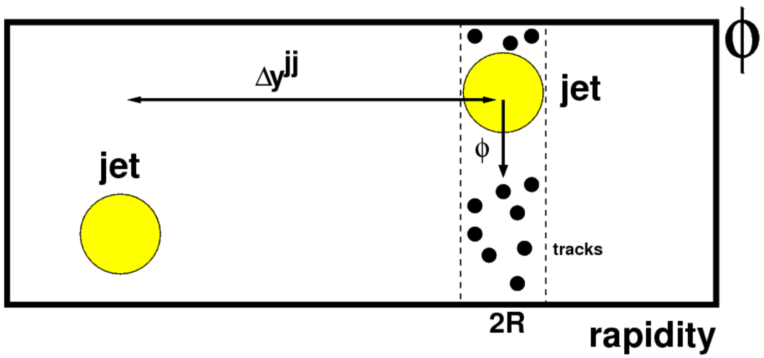
Charged particle flow: Method

- Charged particle flow in inclusive dijet events:

$$< \frac{d^2 p_T}{|d\phi| dy} >_{jets} = \frac{1}{2R|\Delta\phi|} \frac{1}{N^{jet}} \sum_{jets} p_T(|\phi - \Delta\phi/2|, |\phi + \Delta\phi/2|), \text{with } 0 \leq |\phi| \leq \pi$$

  is the average transverse momentum as a function of the azimuthal distance from the jet axis and rapidity separation between the two leading jets

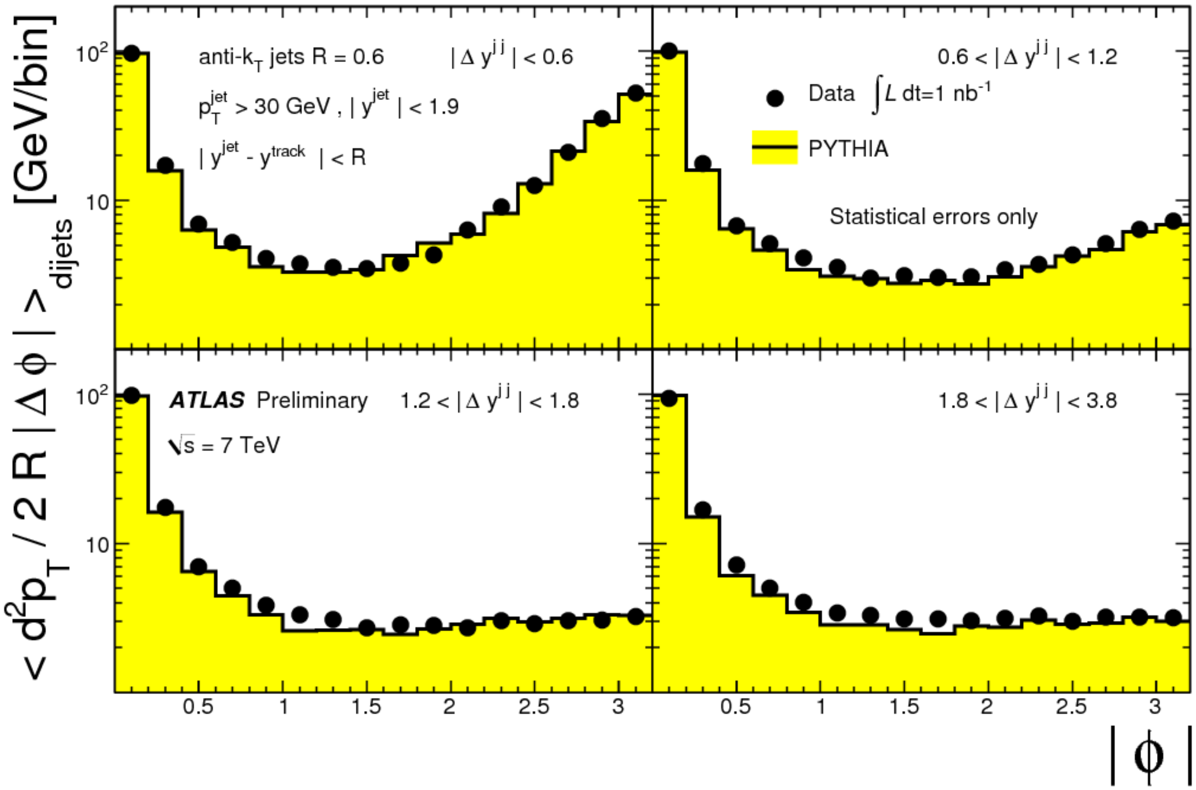
- Here p_T is computed as the scalar sum of the transverse momenta of tracks at a given angle φ with respect to jet axis



- Only tracks within rapidity range occupied by jet are used
- Jet required to be within |y|<1.9 to ensure that jet is fully within tracker acceptance |y|<2.5
- Track-based method is useful to confirm results from calorimeter-based jet shapes

Charged particle flow: Data distributions

- For $|\Delta y^{jj}| < 0.6$, two collimated flows of charged particles (dijets) observed at $|\varphi|=0$ and $|\varphi|=\pi$
- For $|\Delta y^{jj}|>1.2$, jet structure observed at low $|\varphi|$ followed by plateau of remaining hadronic activity as $|\varphi|$ increases
- Monte Carlo provides reasonable description of data, but slightly underestimates hadronic activity away from the jet direction (see backup)

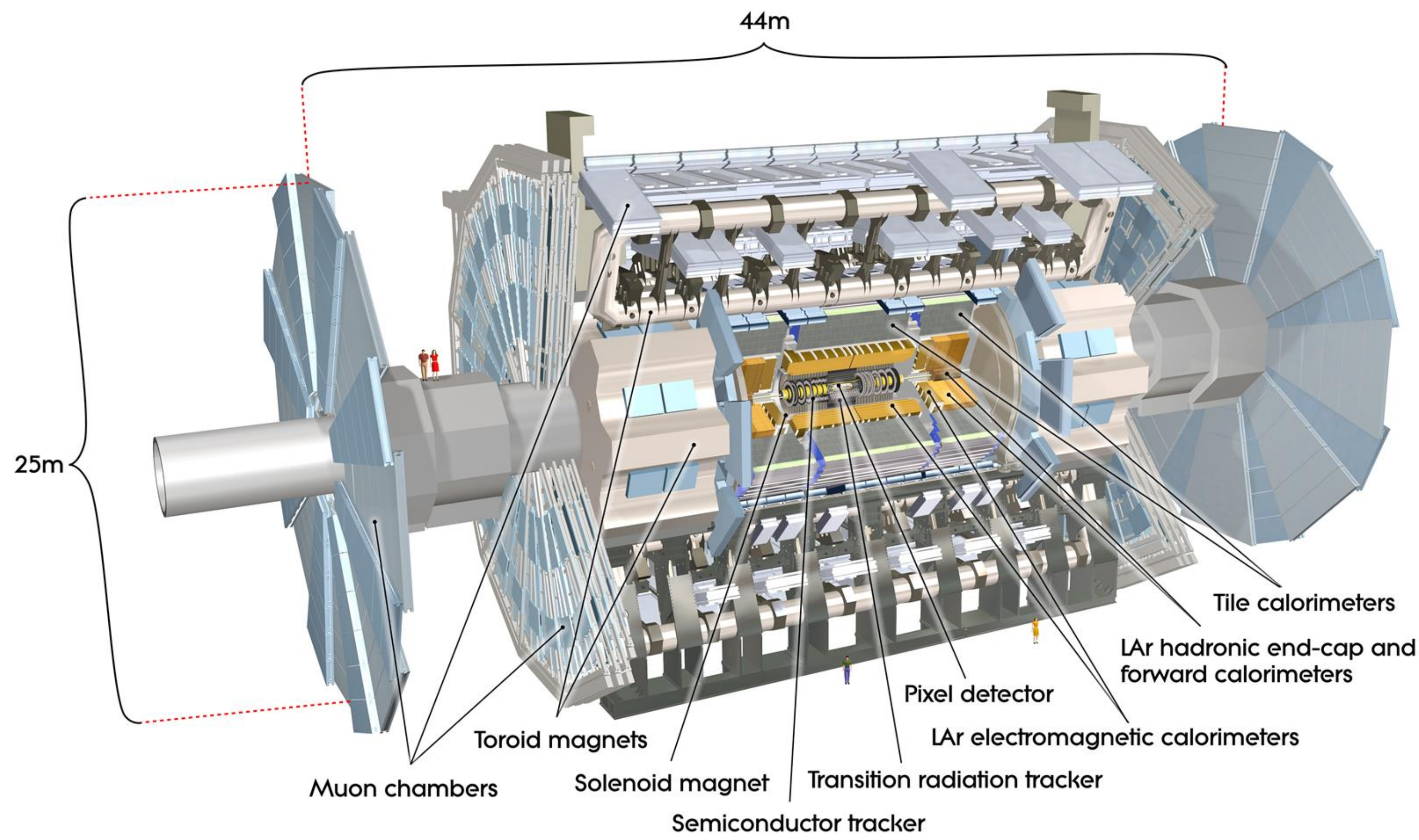


Conclusions

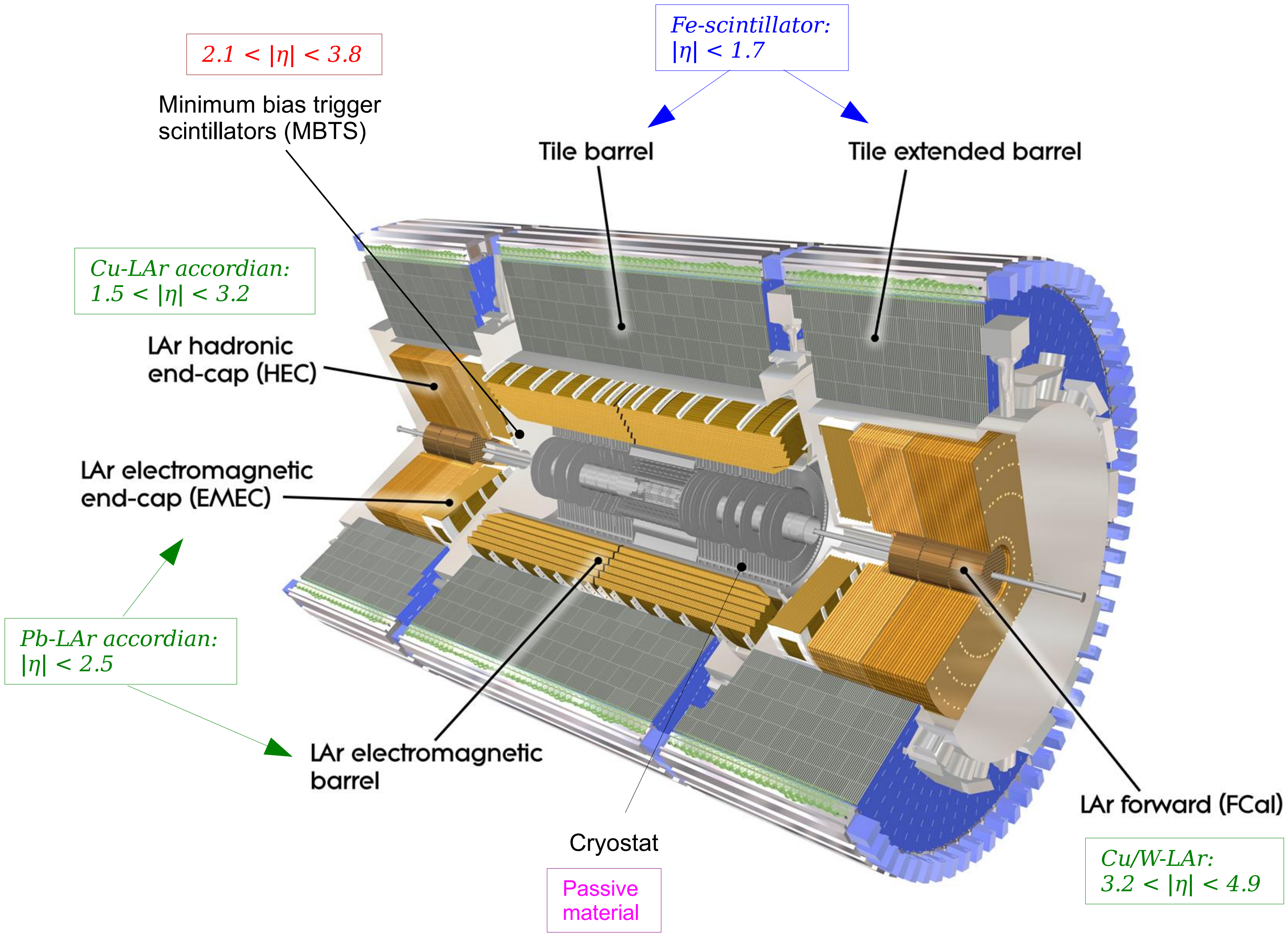
- We have reported the observation of jet production in *pp* collisions at 7 TeV using 1 nb^{-1} data collected by the ATLAS detector
- Jets with p_T up to 500 GeV and dijet invariant mass up to 900 GeV have been observed using this data sample
- Shapes of inclusive jet and dijet kinematic distributions are reasonably described by Pythia dijet Monte Carlo
- Jet internal structure studied through jet shapes and charged particle flow
  - Confirms the presence of collimated flows of particles in the final state
- Measurement of jet cross-sections will be reported later this summer using more integrated luminosity from the LHC

ADDITIONAL MATERIAL

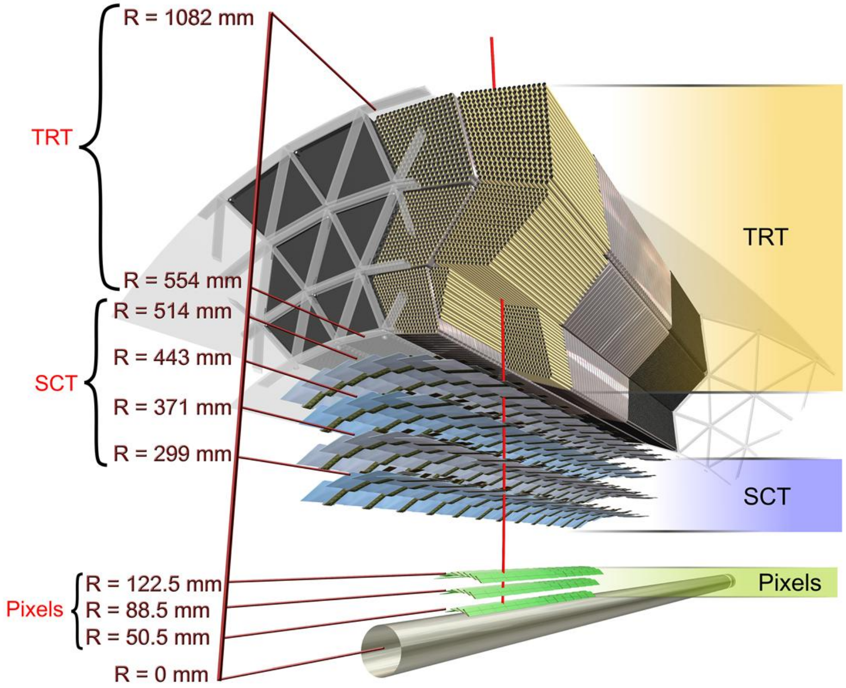
ATLAS Detector

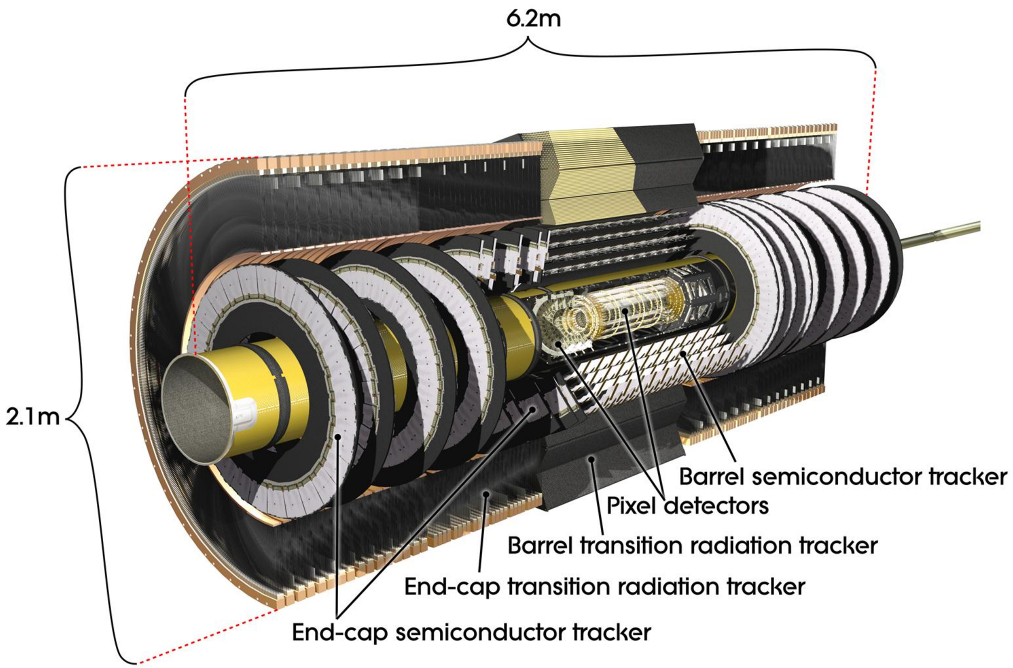


ATLAS Calorimeter



ATLAS Tracker



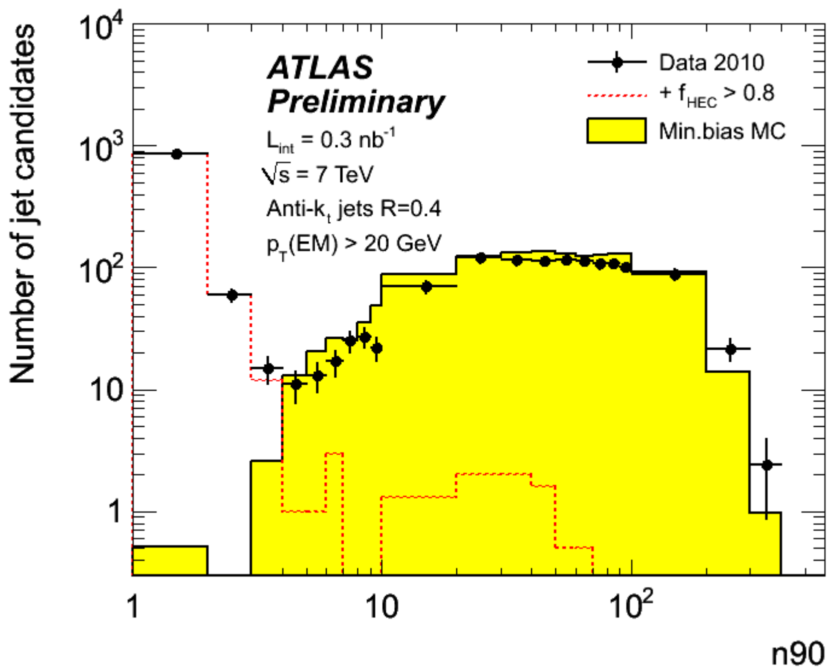


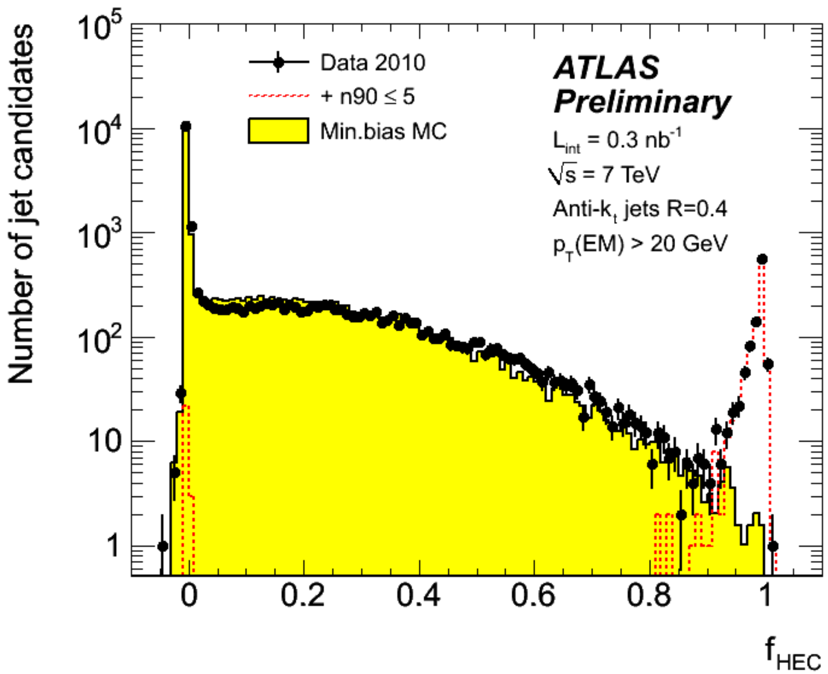
Jet cleaning cuts

- Detailed description in conference note ATLAS-CONF-2010-038: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-038
- Identify "bad" jets as follows:
  - Noisy cells in the hadronic endcap calorimeter:
    $n_{90} <= 5$ and $f_{HEC} > 0.8$
  - Coherent noise in the electromagnetic calorimeter:
    $|f_{quality}| > 0.8$ and $f_{EM} > 0.95$
  - Large out-of-time energy depositions, e.g. from cosmic ray muons:
    $|t_{jet}| > 50$ ns
- Definitions of n_{90}, f_{HEC}, $f_{quality}$, f_{EM}, and t_{jet} are on following slides

Cleaning cuts: n_{90} and HEC fraction

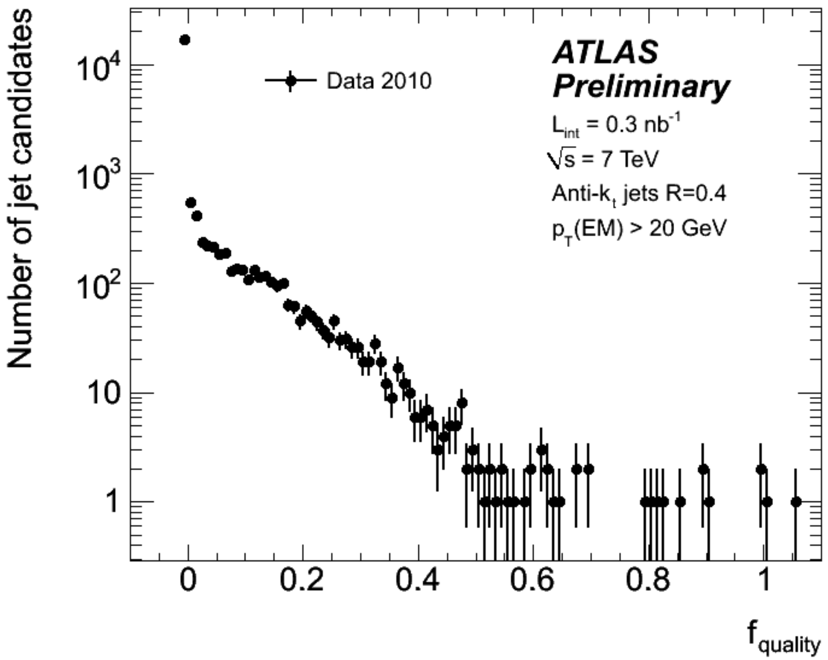
- n_{90} (left) = Number of energy-ordered cells accounting for at least 90% of jet energy
- f_{HEC} (right) = Fraction of jet energy in the Hadronic Endcap Calorimeter
  - Both shown after application of the jet timing and electromagnetic coherent noise cuts

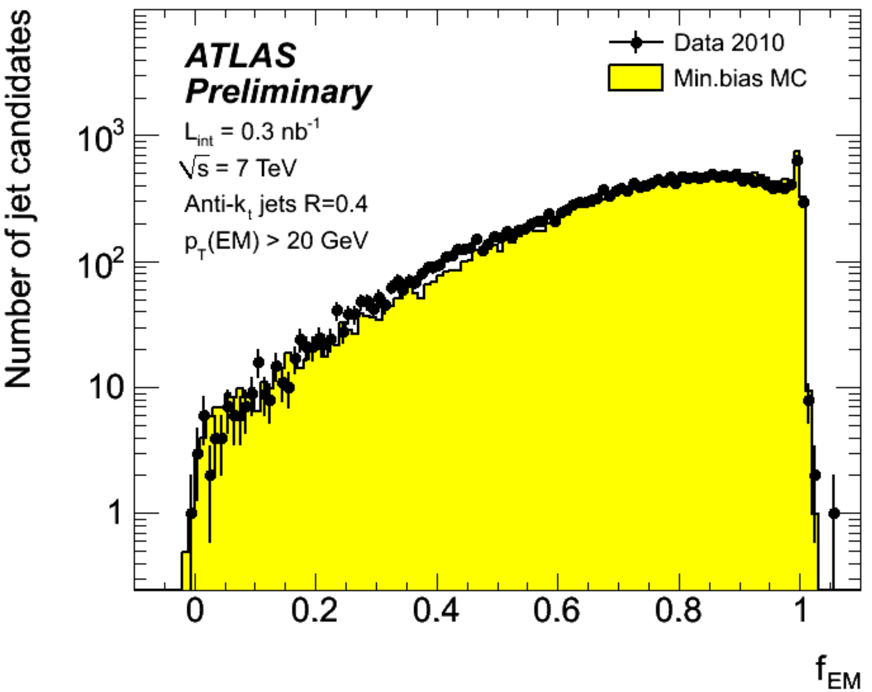




Cleaning cuts: Jet quality and EM fraction

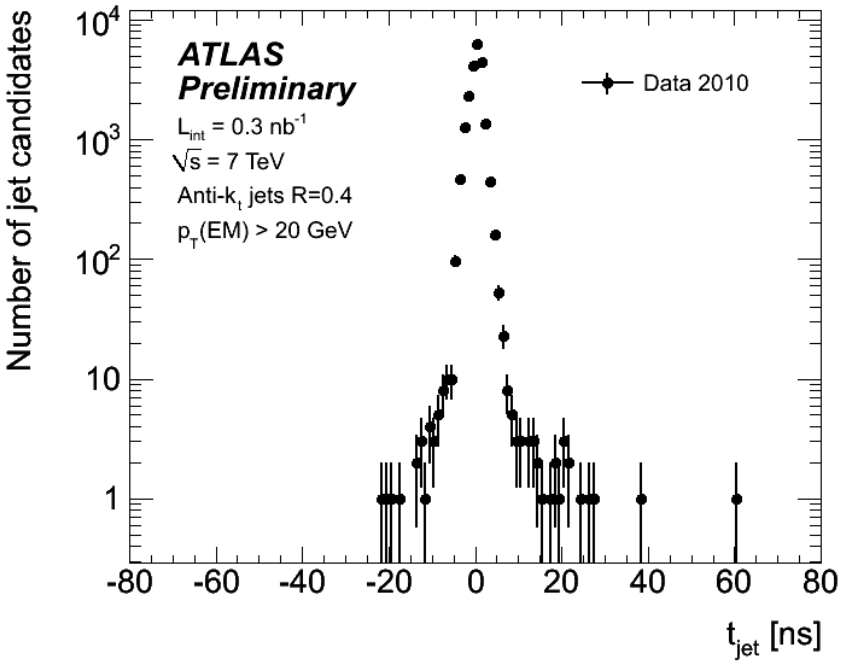
- $f_{quality}$ (left) = Jet quality fraction
- f_{EM} (right) = fraction of jet energy in the electromagnetic calorimeter
  - Both shown after application of the single cell and jet timing cuts
- Monte Carlo distribution for $f_{quality}$ is zero by construction so not shown





Cleaning cuts: Jet timing

- t_{jet} = Jet timing as energy weighed times of cells
  - After application of single cell and electromagnetic coherent noise cuts
- Corresponding Monte Carlo distribution is peaked at zero with no discernible width so not shown



Pythia tune & underlying event

- Charged particle flow indicates that hadronic activity away from the jet axis is slightly underestimated by Monte Carlo
- Studies of the sum p_T of tracks transverse to the leading track shows that the Monte Carlo tunes underestimate the underlying event:
    - Conference note: ATLAS-CONF-2010-029 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-029/