Understanding Jet Structure and Constituents: Track Jets and Jet Shapes at the ATLAS Detector

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On behalf of the ***ATLAS*** *Collaboration*

22 September 2010
XL International Symposium on Multiparticle Dynamics
Antwerp, Belgium

Overview

- ATLAS and the Large Hadron Collider
- Prologue: Jets and their properties
- Jet Reconstruction and definitions
  - Calorimeter-based: topological clustering, associated tracks
  - Inner Detector-based: apply jet algorithm to tracks
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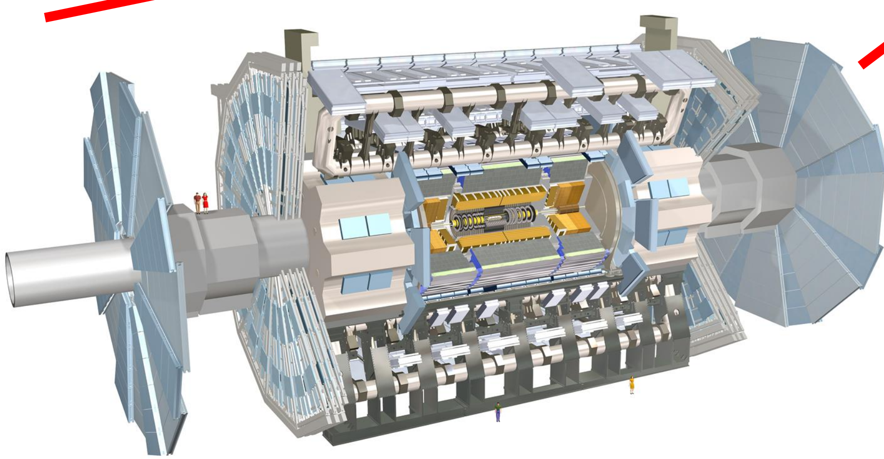
  - Inclusive cross section
  - Charged particle fragmentation w.r.t. charged particle jets

The LHC and ATLAS

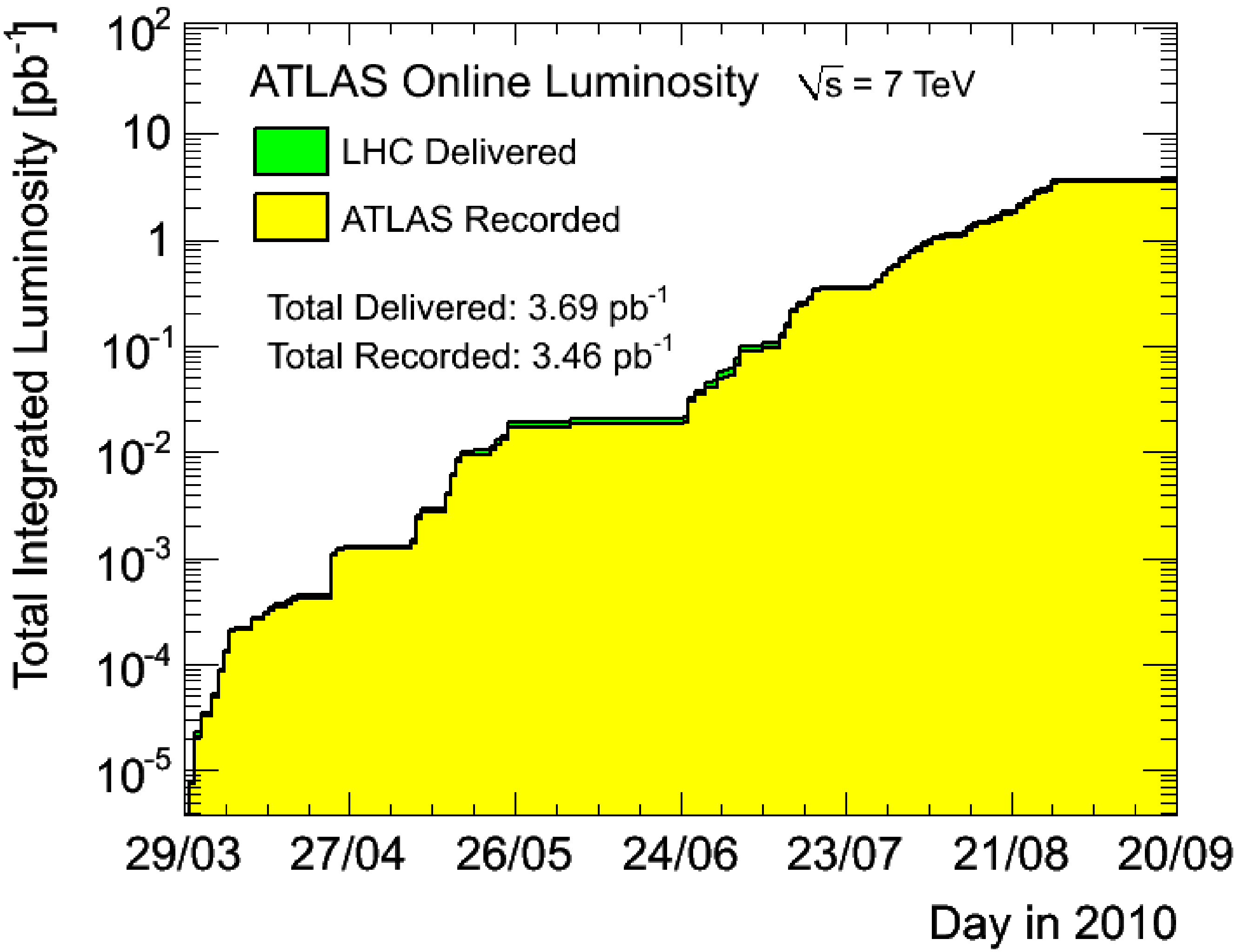
- Large Hadron Collider: **p-p**, Pb-Pb
- 2010-2011: 7 TeV CM energy, maximum luminosity: 1-2 **x** 10^{32} $cm^{-2}s^{-1}$
- Ultimately: 14 TeV CM energy, max. lumi. ~5 x 10^{34} $cm^{-2}s^{-1}$



ATLAS

- 45m long, 25m diameter, 7000 tons
- 3-level trigger: reduce design beam-crossing rate of 40 MHz to ~200 Hz recorded

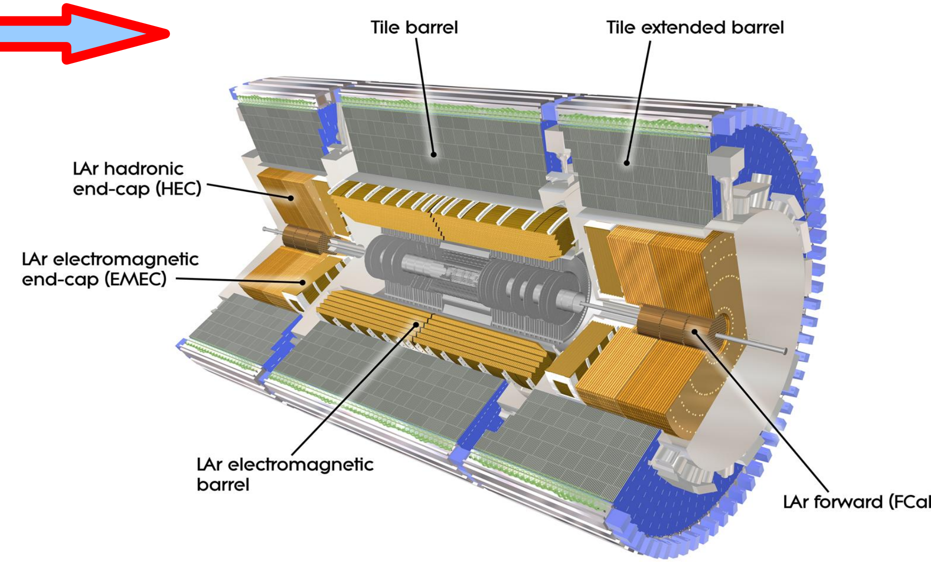
Data Collected So Far

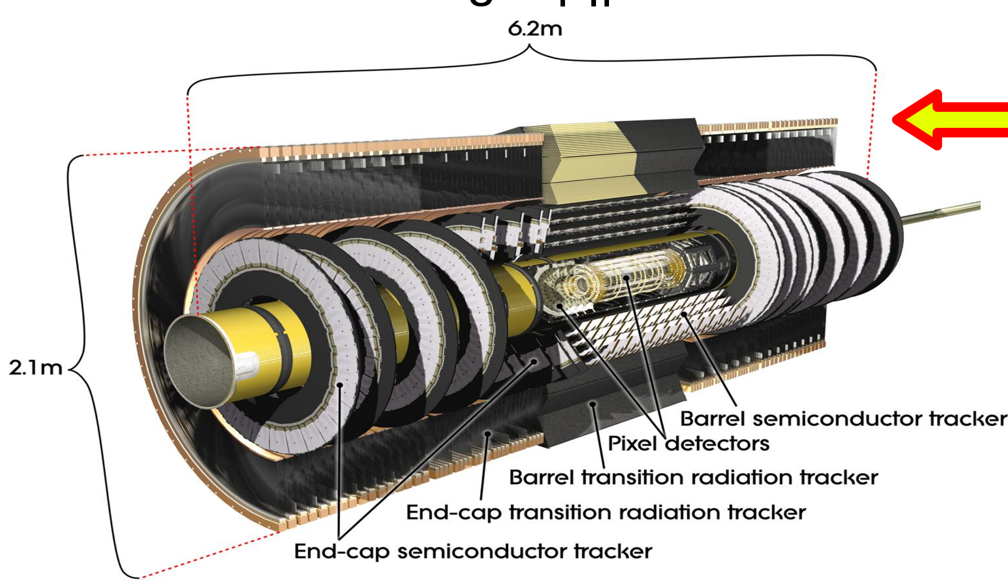


- ATLAS uptime and data quality excellent
  - >94% for all subsystems
- Luminosity increasing rapidly
  - Note log scale!
- Moving steadily to goal of 1 fb^{-1} collected through 2011

ATLAS Subdetectors

- ATLAS Calorimeters
  - Electromagnetic: Pb + Liquid Ar
    - Separate jets, e/γ
  - Hadronic
    - Central: Fe + scintillating tiles
    - Forward: Cu/W + Liquid Ar
  - Coverage: $|\eta| < 4.9$



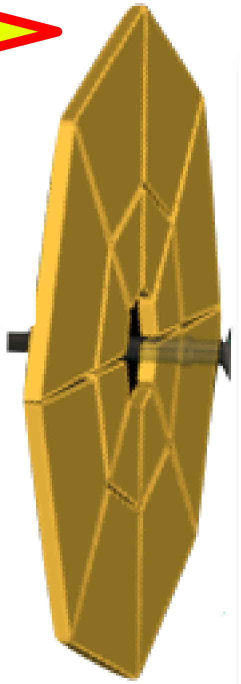


- ATLAS Inner Detector
  - 3 silicon pixel layers
  - 4 double-sided silicon strip layers
  - Transition Radiation Tracker
  - 2.0 T solenoid magnet
  - Coverage: $|\eta| < 2.5$
  - $\sigma/pT \sim 3.8\text{x}10^{-4}$ pT (GeV) $\oplus$ 0.015

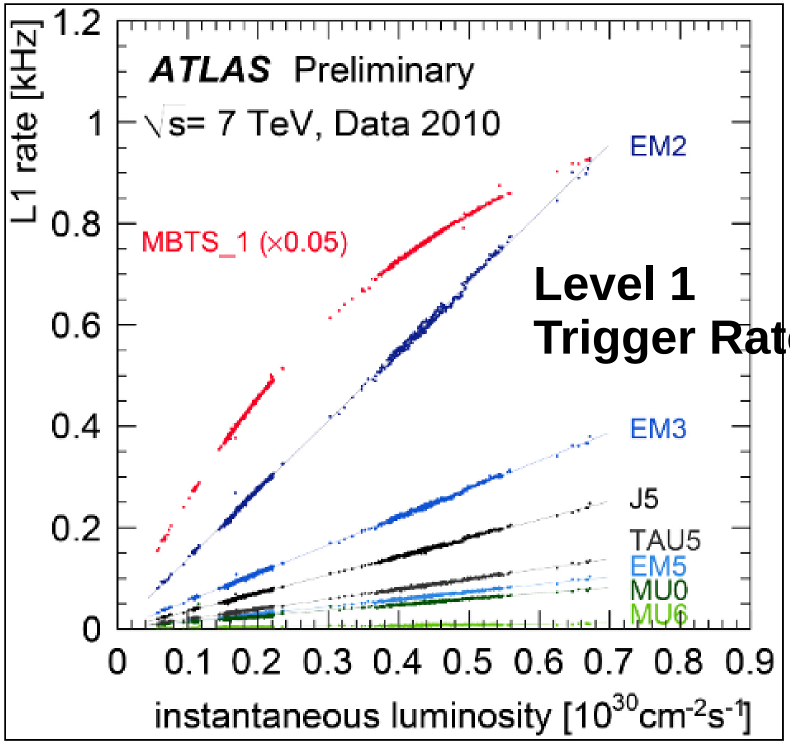
And, of course, ATLAS got its name from the large toroidal magnetic field for the muon system...
Not used for this talk!

Triggers (in this talk)

- Minimum Bias Trigger Scintillator (MBTS)
  - Polystyrene structures mounted on endcap calorimeter cryostat
  - 2 cm thick, Z = 3.6m
  - Acceptance: 2.09 < |η| < 3.48



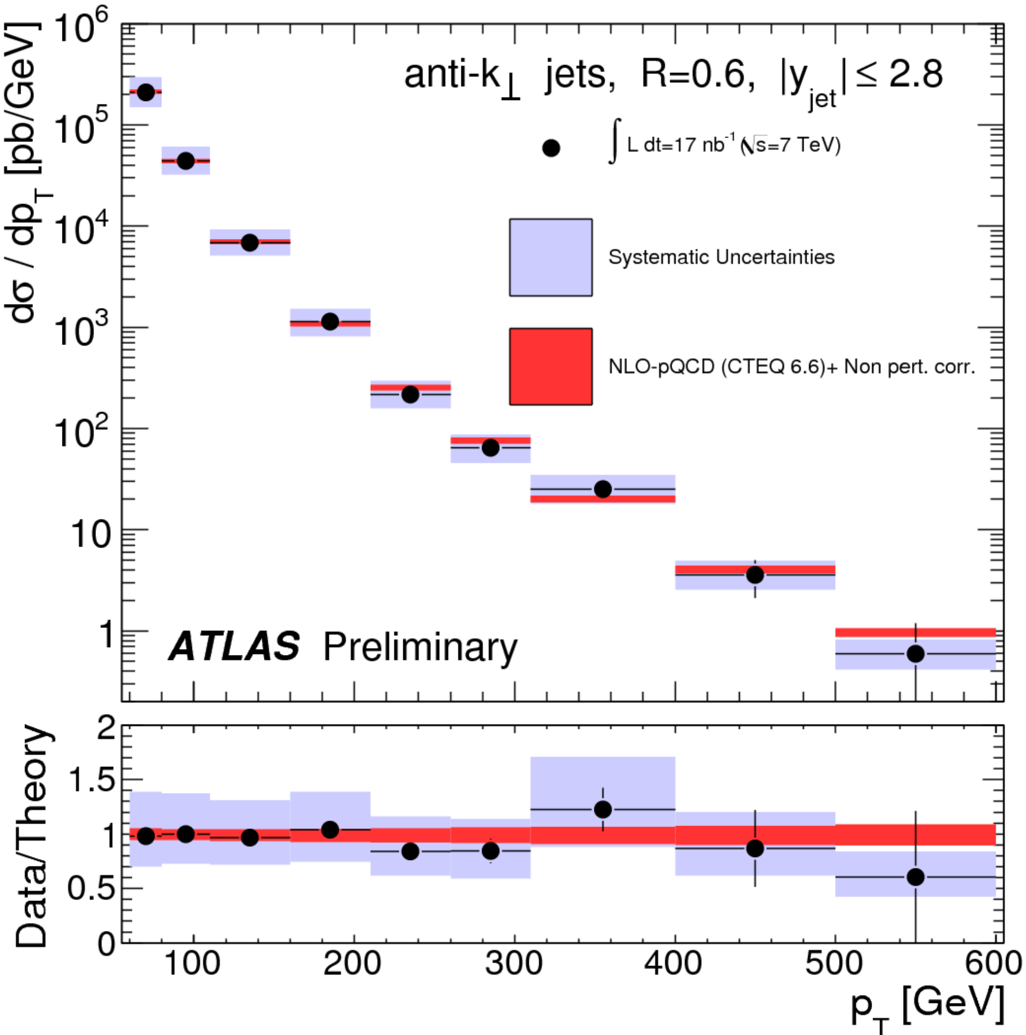
- Most plots in this talk triggered with 1 MBTS hit
  - ~100% efficiency for events with jets
- Jet and EM triggers based on sliding tower jet-finding in calorimeter
  - Jet shape plots use lowest-threshold jet trigger, which is 100% efficient for applicable jet momenta (p_T > 60 GeV)



Level 1 Trigger Rates

Prologue: Jets and their Properties

- ATLAS jet measurements
  - Inclusive jet cross-section
    (see talk – A. Alonso)
  - New di-jet resonance limit
    (see talk – H. Peng)
- Major uncertainty: jet energy scale
- Pileup will impact *every* ATLAS measurement
  - Continuum from very soft interactions to dijets
- Need to verify modeling of QCD and soft physics that produces jet structure
- This talk: our knowledge so far, measurements to improve it...



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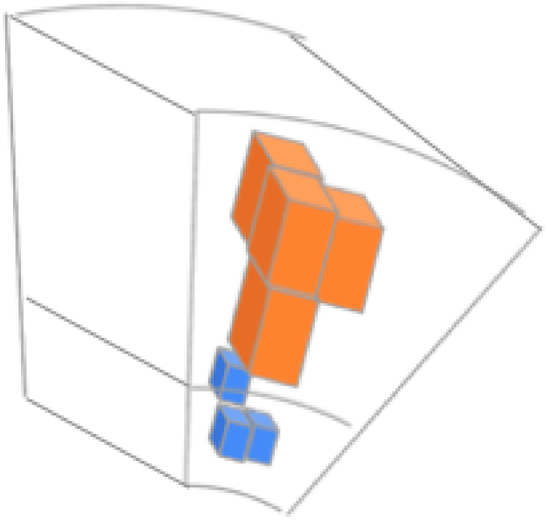
Jet Reconstruction: Calorimeter



- Main constituent algorithm: topological clusters
  - Seed with cells with signal 4σ above noise
  - Extend with adjacent (3D) cells 2σ above noise
  - Add one final "layer" of cells above noise
- Apply anti-k_T jet algorithm (R=0.6, 0.4)
  - **Cone-like**
  - **Infrared safe** – JHEP 04 (2008) 063
- Association of tracks with jet:
  - Select good-quality tracks (next slide)
  - Associate track with jet if: $\Delta R(\text{Track, Jet}) < R_{Jet}$

Jet Reconstruction: Tracks

- Select good-quality tracks:
  - $p_T > 500$ MeV, $|\eta| < 2.5$
  - Impact parameter requirements w.r.t primary vertex
    - $|d_0| < 1.5$ mm, $|z_0 \sin\theta| < 1.5$ mm
  - Silicon hit requirements
    - Analysis: 6 SCT hits, innermost pixel hit + outer pixel or inner SCT hit
    - Calorimeter matching: 6 SCT hits, any pixel hit
- *Anti-k_T* jet algorithm (R=0.6, 0.4) applied to selected tracks
  - Track jet analysis requirements: jet $p_T > 4$ GeV, $|\eta| < 0.57$
- Complement to calorimeter jet measurements
  - Independent systematic errors
  - Very low momentum – emergence of jets from soft collisions

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N.B. Not corrected for detector effects

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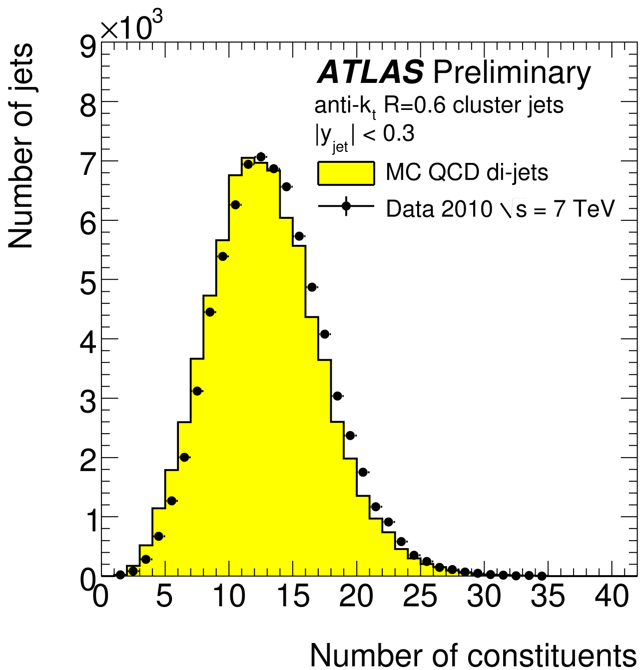
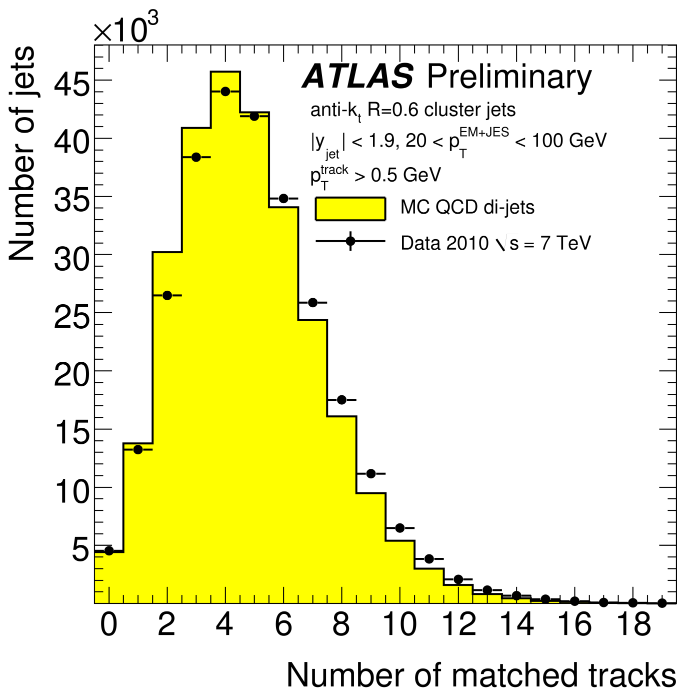
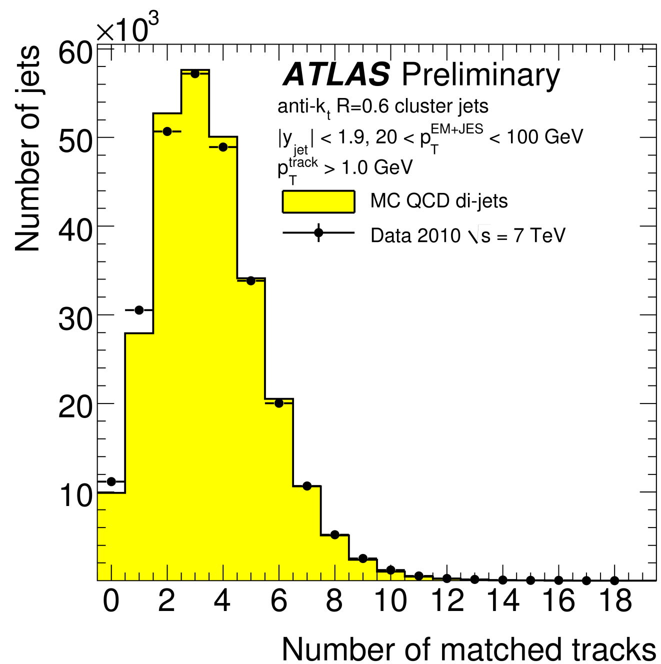
Constituent Multiplicity



Clusters

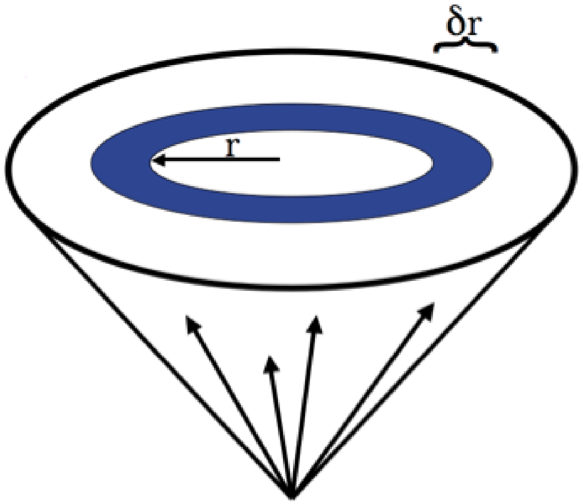


Tracks - p_T > 0.5 GeV



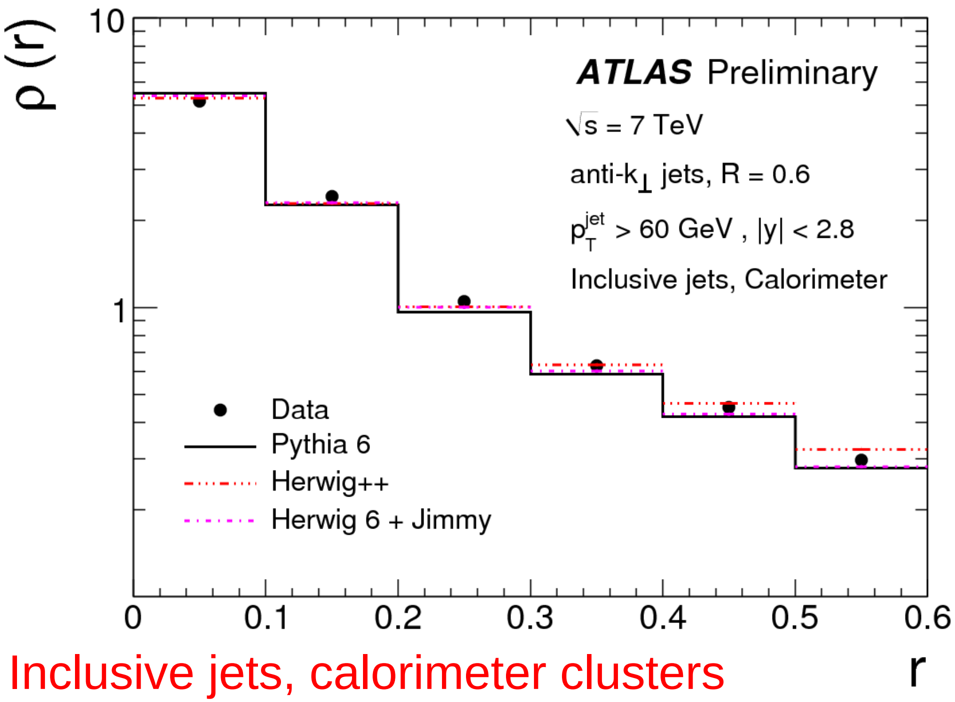
Tracks - p_T > 1.0 GeV

- Sensitive to soft particle modeling

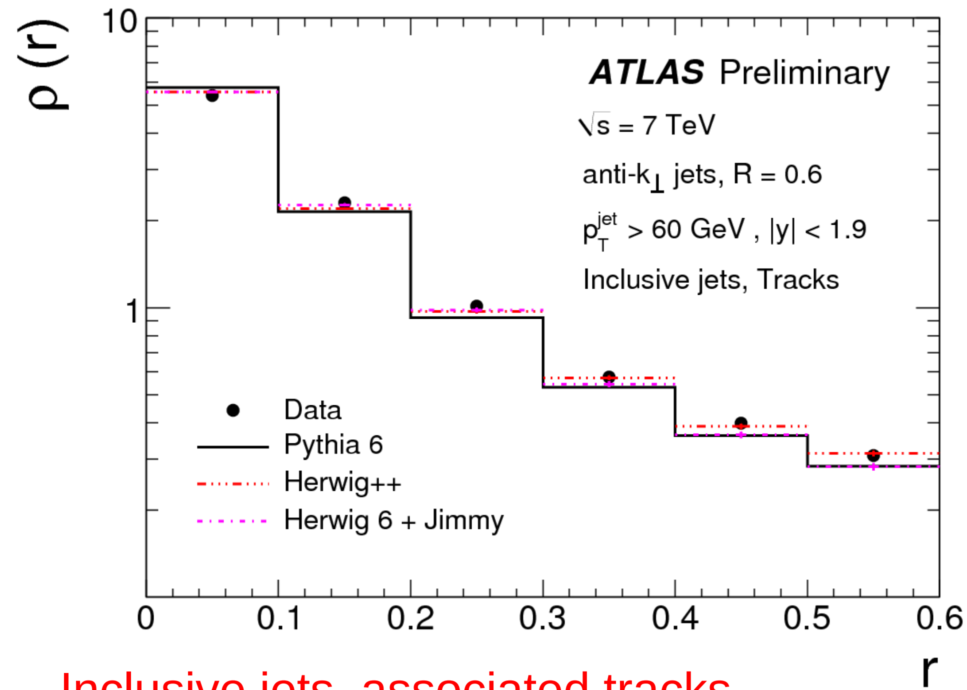


Jet Shapes

- $\rho(r) = \left\langle \frac{1}{r}\frac{dp_T}{dr} \right\rangle_{jets} = \frac{1}{A}\frac{1}{N_{\text{jet}}}\sum_{jets} p_{\text{T}}(r-\Delta r/2, r+\Delta r/2)$
- Shape depends on event generator, but generally good agreement



Inclusive jets, calorimeter clusters



Inclusive jets, associated tracks

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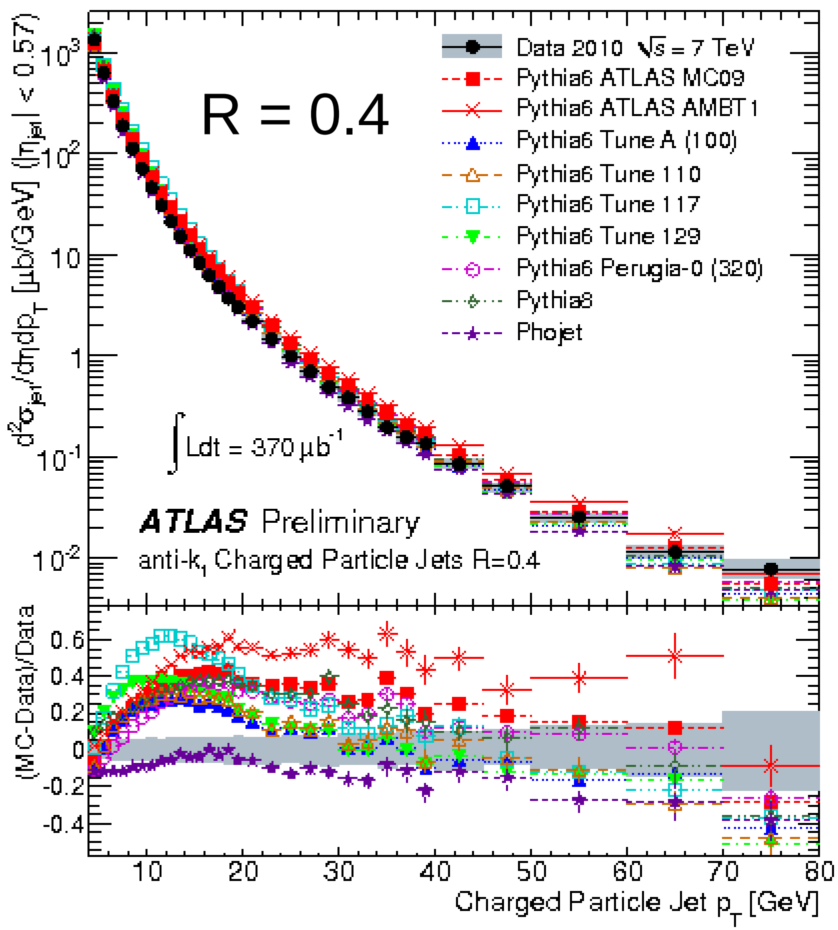
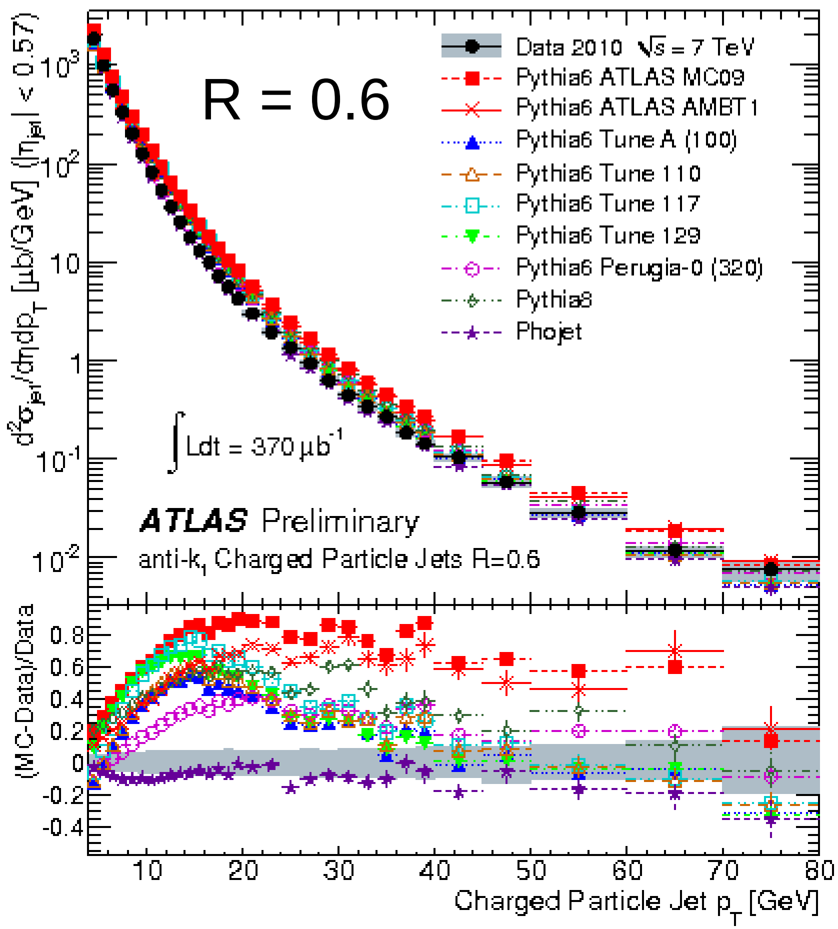
Charged Particle Jet Measurements

- Charged particle jets: apply anti-k_T algorithm to all charged primary particles with p_T > 500 MeV
  - No direct comparison to pQCD
  - Can compare to Monte Carlo generators
- Inclusive cross section measurement
  - Correction method: bayesian iterative unfolding
  - Systematic uncertainties, R = 0.6:

Uncertainty	4 - 6 GeV	14 - 15 GeV	28 - 30 GeV	40 - 45 GeV	70 - 80 GeV
Tracking efficiency	$^{+4\%}_{-4\%}$	$^{+7\%}_{-7\%}$	$^{+8\%}_{-7\%}$	$^{+8\%}_{-8\%}$	$^{+9\%}_{-8\%}$
Fragmentation/ U.E.	$^{+2\%}_{-1\%}$	$^{+0.4\%}_{-3\%}$	$^{+2\%}_{-0.0\%}$	$^{+2\%}_{-1\%}$	$^{+5\%}_{-11\%}$
High p_T tracks	negligible	negligible	$^{+0.1\%}_{-0.7\%}$	$^{+1\%}_{-4\%}$	$^{+6\%}_{-10\%}$
Unmatched reconstructed jets	$\pm 1.0\%$				
Mismodelling in φ	$\pm 1.6\%$				
Luminosity	$\pm 11\%$				

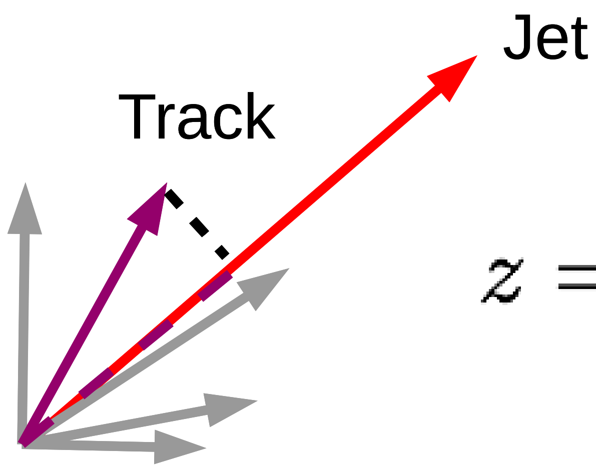
Inclusive cross section





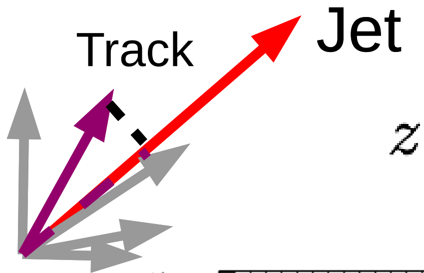
- Cross-section best modeled by Phojet
- Disagrees with Pythia

Fragmentation measurement



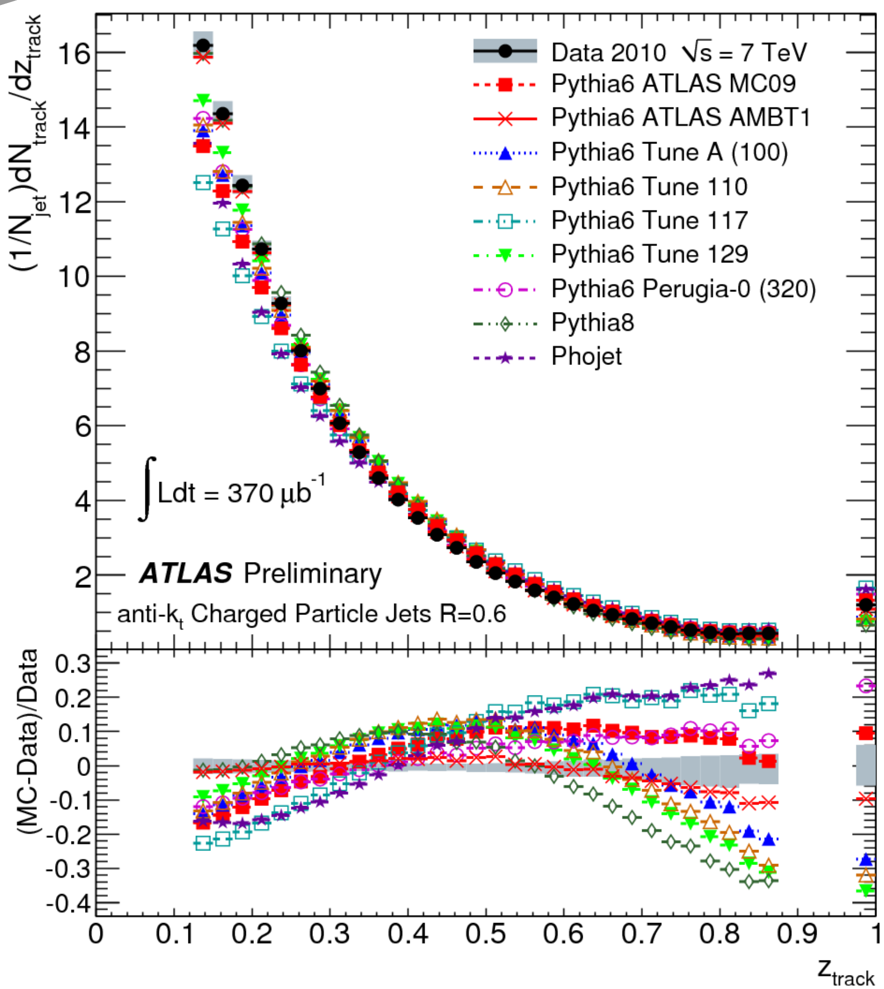
$$z = \frac{\vec{p}_{track} \cdot \hat{p}_{jet}}{|\vec{p}_{jet}|}$$

- z correction uses simple bin-by-bin factors from simulation
- Systematic uncertainties
  - Track-finding efficiency
  - Event generator tuning

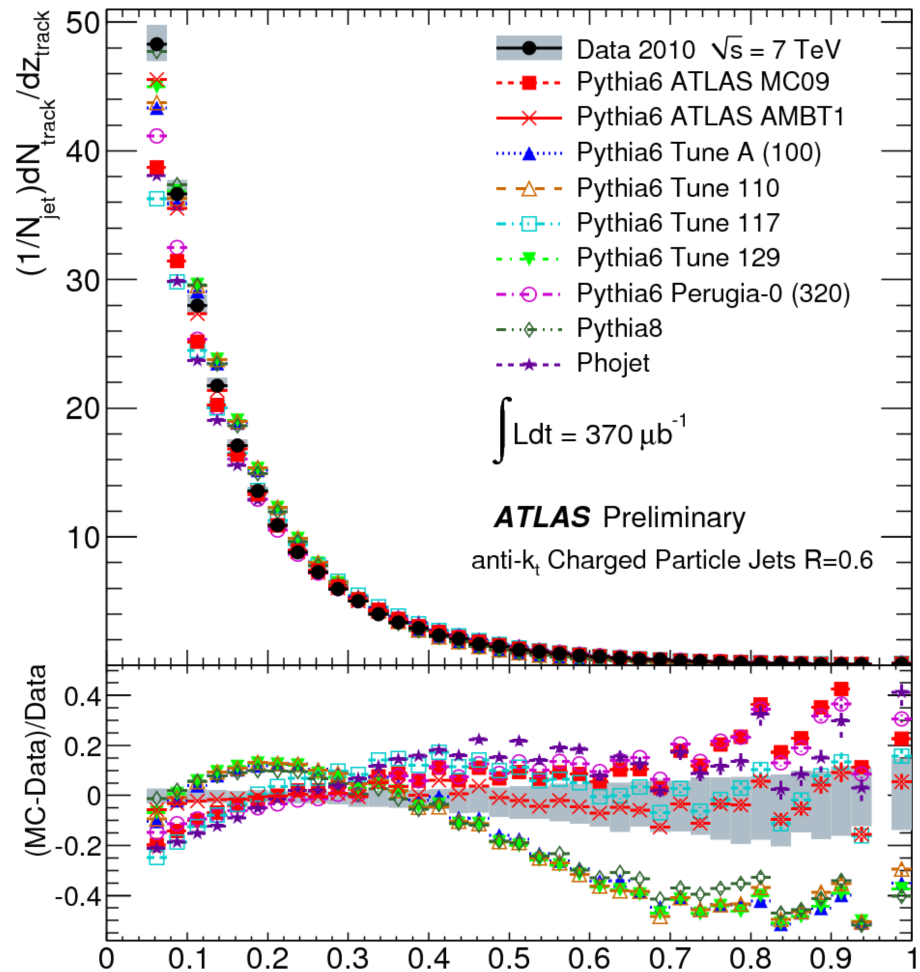


$$z = \frac{\vec{p}_{track} \cdot \hat{p}_{jet}}{|\vec{p}_{jet}|}$$

z Distributions



$4 \text{ GeV} < p_{T,Jet} < 6 \text{ GeV}$



$10 \text{ GeV} < p_{T,Jet} < 15 \text{ GeV}$

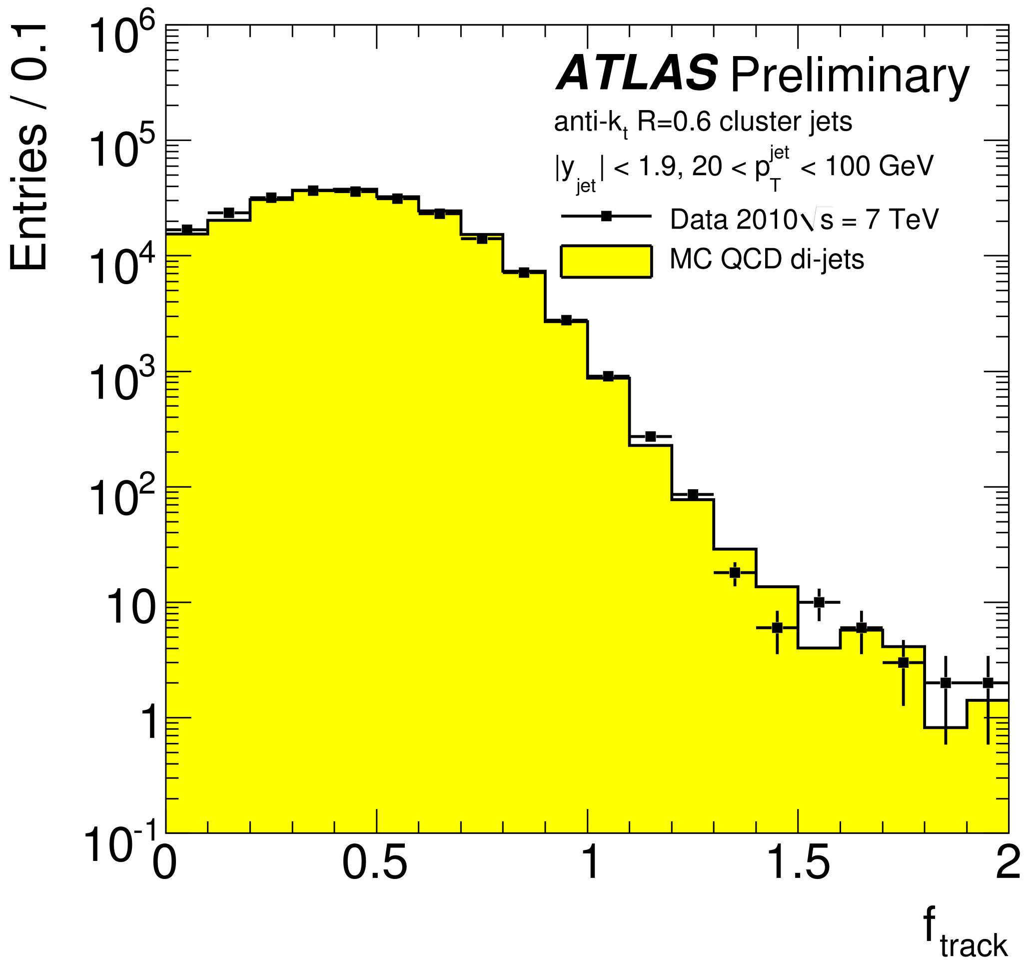
- Impacted by jet fragmentation, underlying event
- Best described by AMBT1 Tune of Pythia

Conclusions

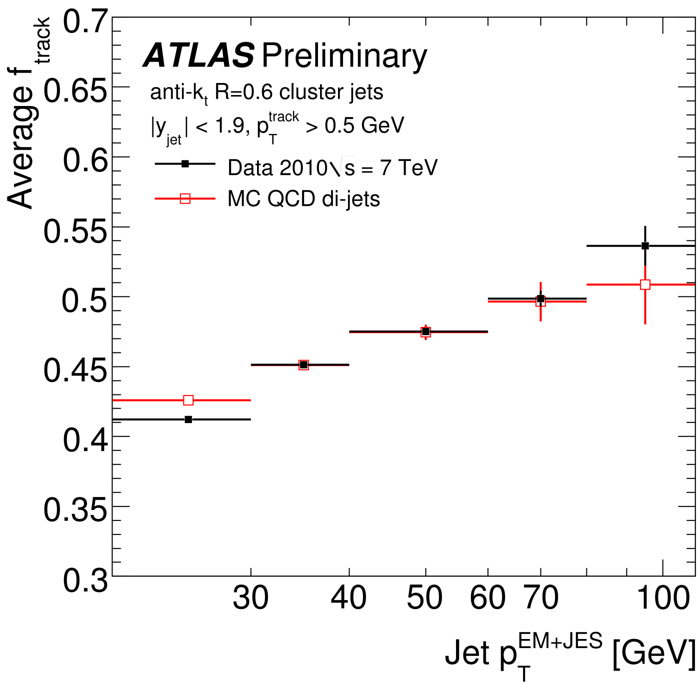
- First ATLAS measurements and studies of jet constituents done
  - Number of constituents in fair agreement, improves with p_T > 1 GeV
  - Jet shapes – good agreement
  - Charged particle jet momentum – Pythia prediction too high at low end
  - Charged particle jet ***z* –** AMBT1 tune good, suggests further tuning
- Studies so far give confidence in jet measurements, further measurements and refinements planned...
- Foundations being laid for years of exciting discoveries ahead!

Extras

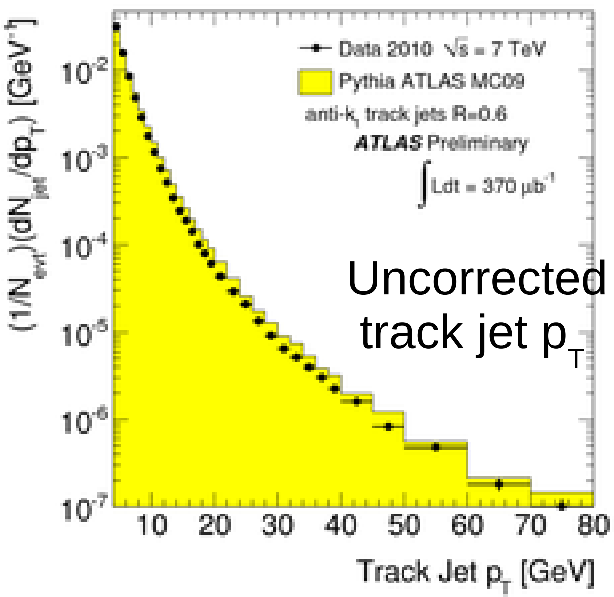
Charged Fraction

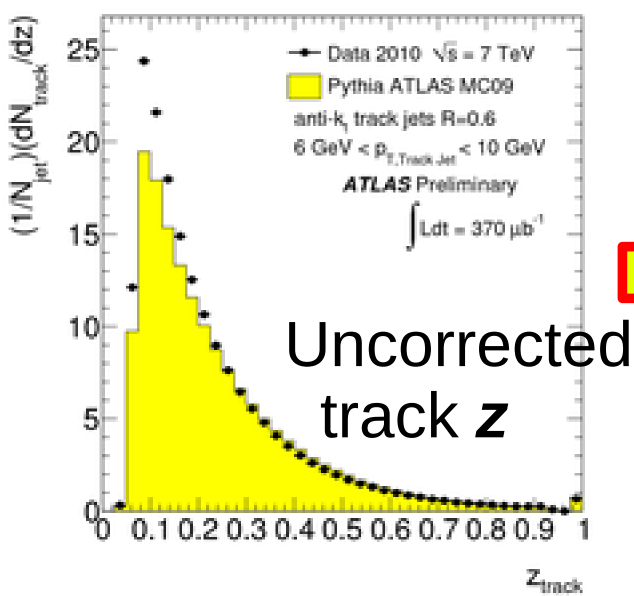


- $f_{track} = \Sigma p_{T,track} / p_{T,jet}$
- Good between simulated events and data!
- $f_{track} > 1$ mostly due to calorimeter fluctuating low



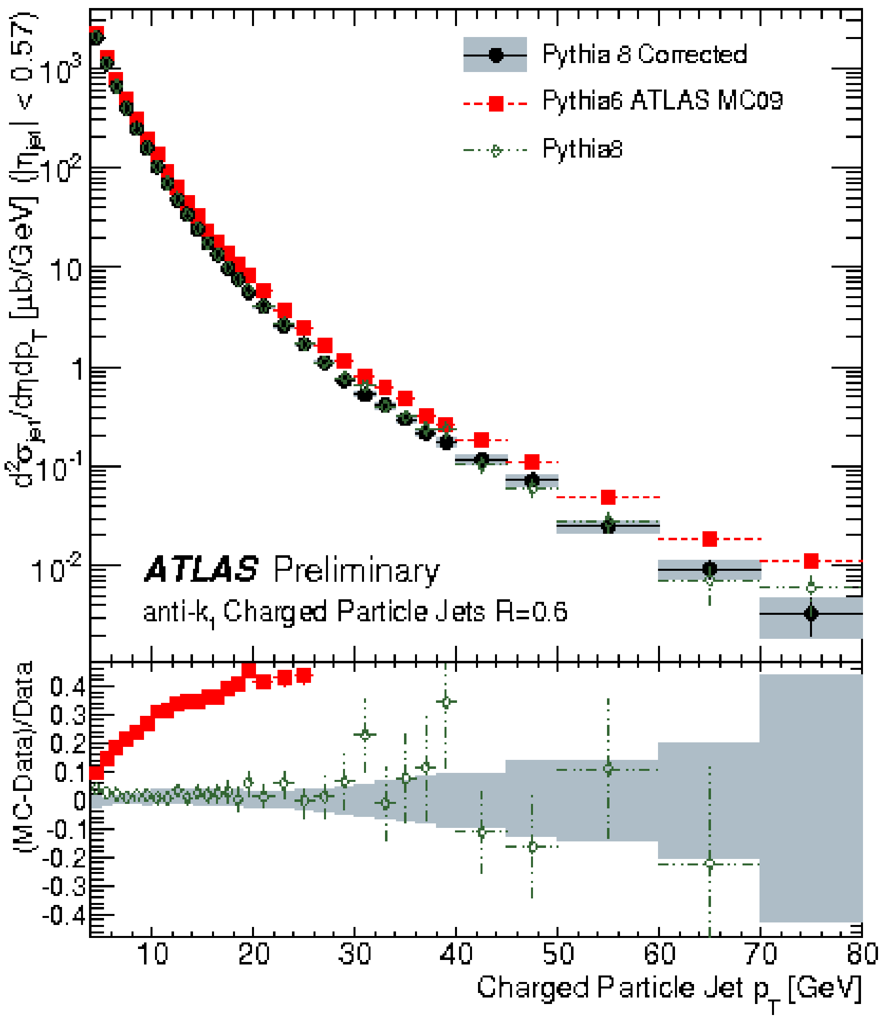
More on Unfolding





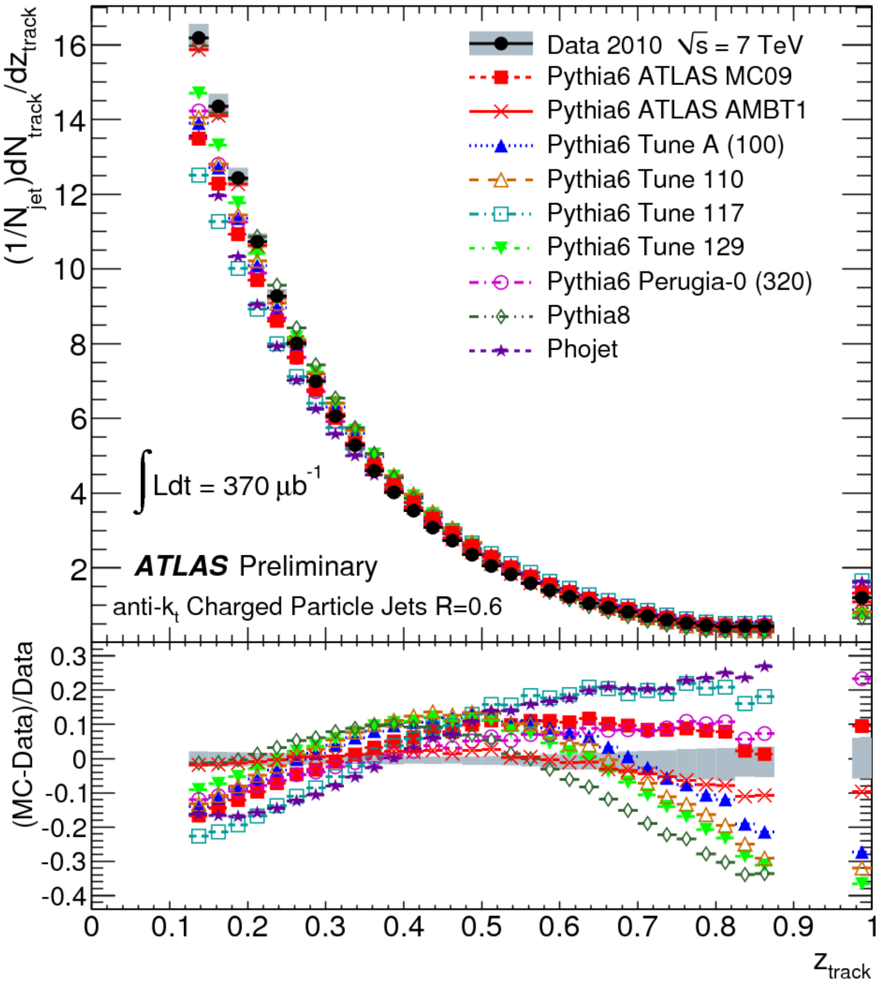
- Inclusive charged particle jet cross section determined from track jet distributions using Bayesian Iterative unfolding
- Corrects for:
  - Jet-finding efficiency
  - Reconstructed track jets not matched to charged particle jets
  - Bin-to-bin migration of reconstructed jets due to tracking efficiency and resolution smearing
  - Corrections determined from migrations in simulated sample
- Correction of ***z*** done with simple correction factors in bins of jet p_T – correction factors vary slowly with p_T

Tests of Unfolding

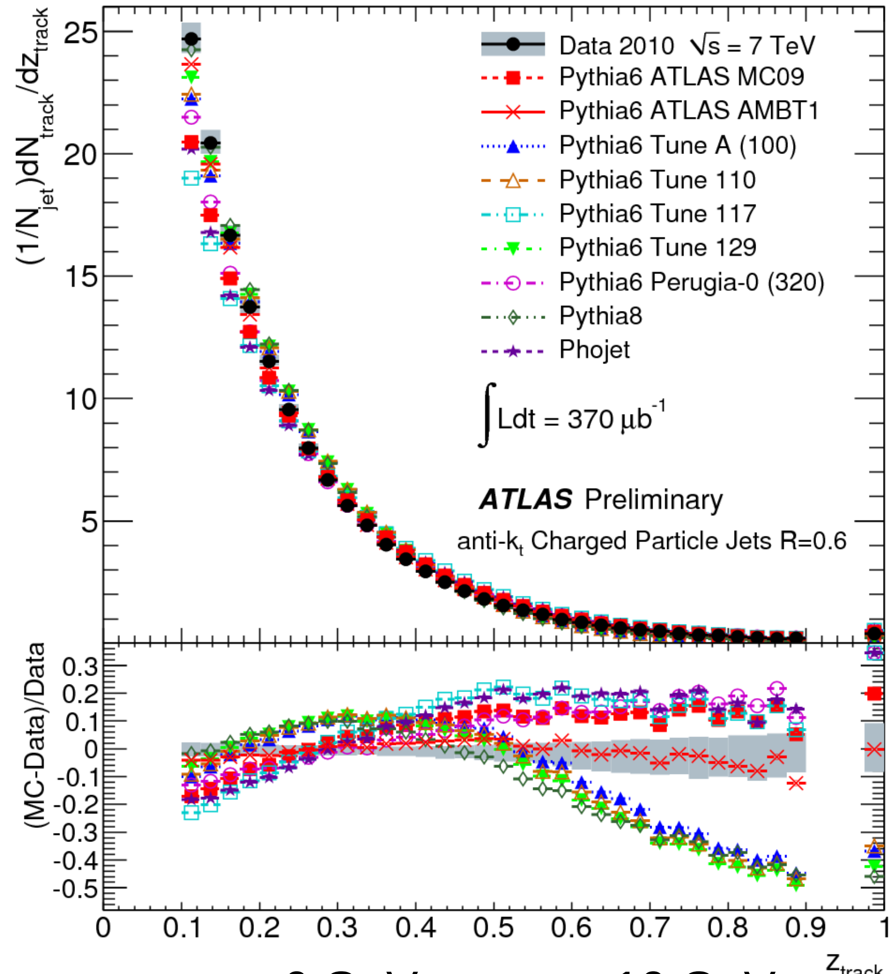


- Unfolding validated with toy samples
  - Simulated MC tracks smeared
- Also tested with fully-simulated MC pseudodata
  - Produce response matrix with Pythia 6 main sample
  - Apply to reconstructed track jets in fully-simulated Pythia 8 sample – quite different truth distribution from Pythia 6
  - Compare unfolded result to original Pythia 8 truth
  - Agrees within uncertainties that are correlated between samples

R = 0.6 *z* distributions (1)

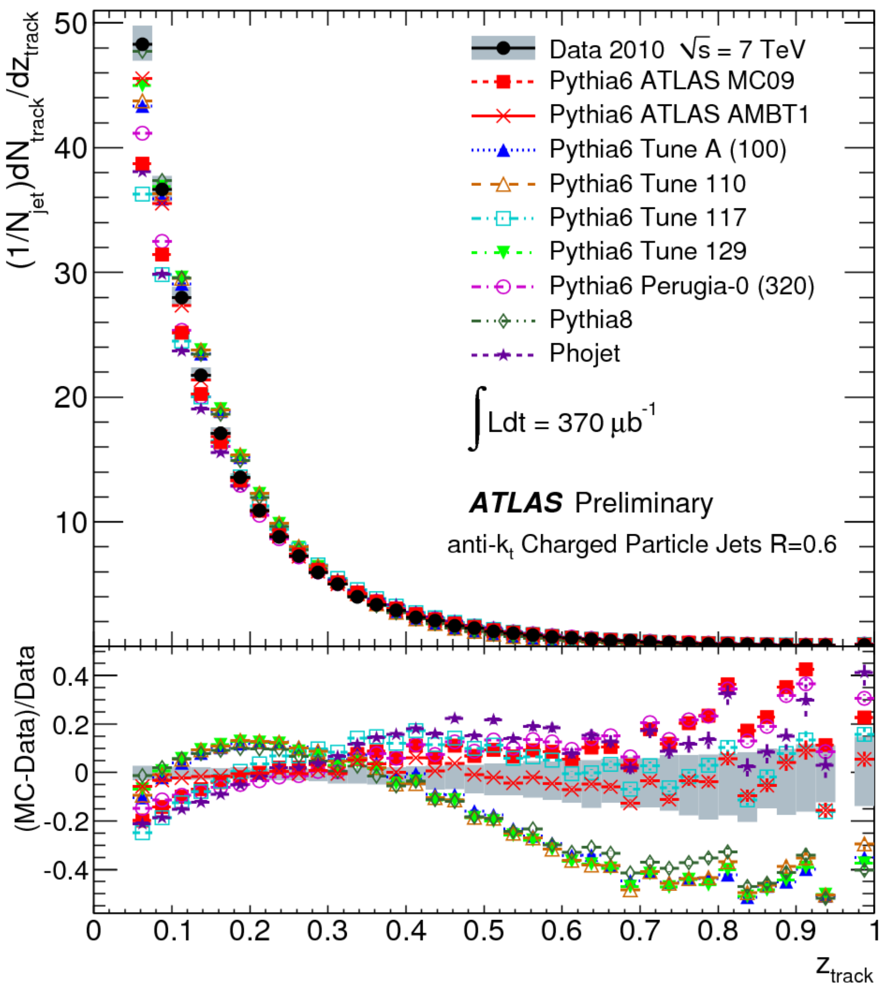


4 GeV < $p_{T,Jet}$ < 6 GeV

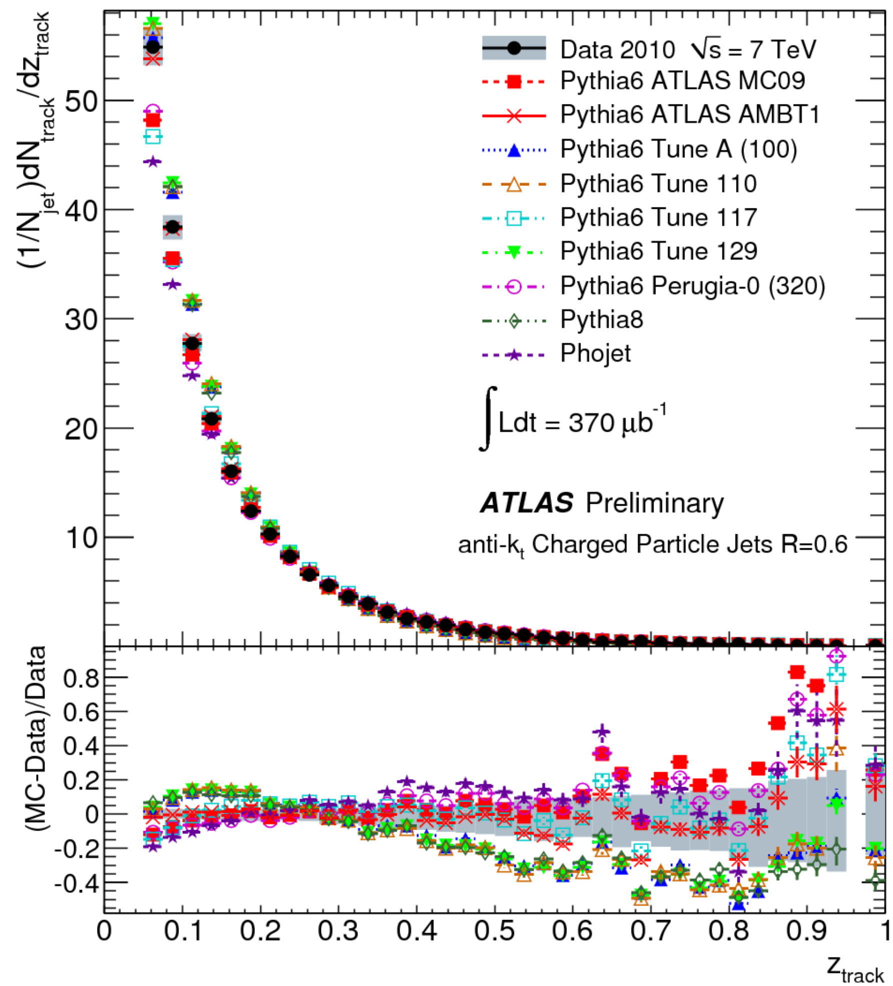


6 GeV < $p_{T,Jet}$ < 10 GeV

R = 0.6 *z* distributions (2)

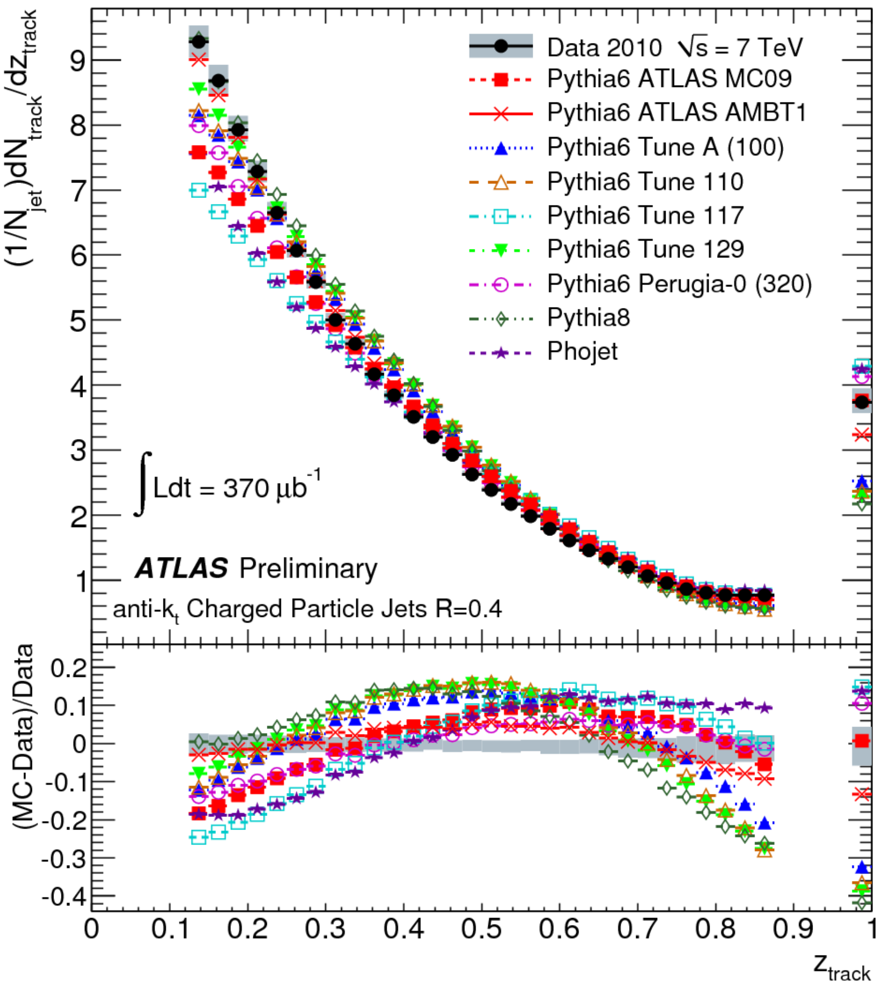


10 GeV < $p_{T,Jet}$ < 15 GeV

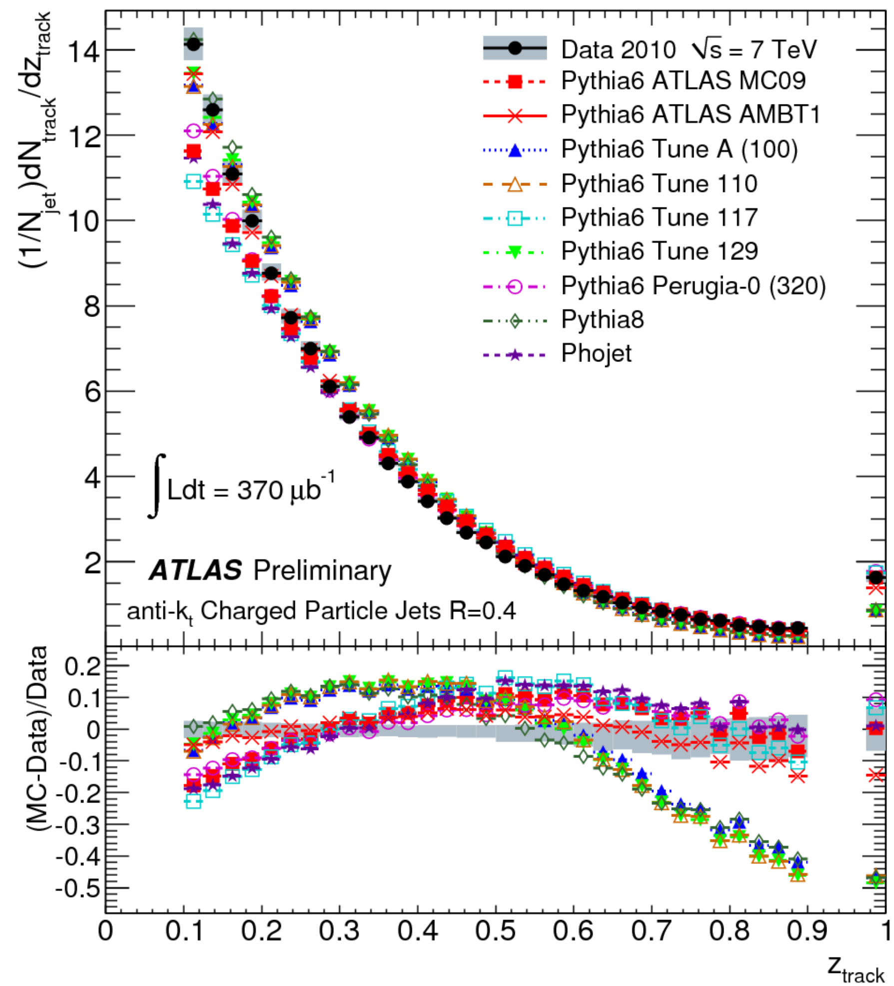


15 GeV < $p_{T,Jet}$ < 24 GeV

R = 0.4 *z* distributions (1)

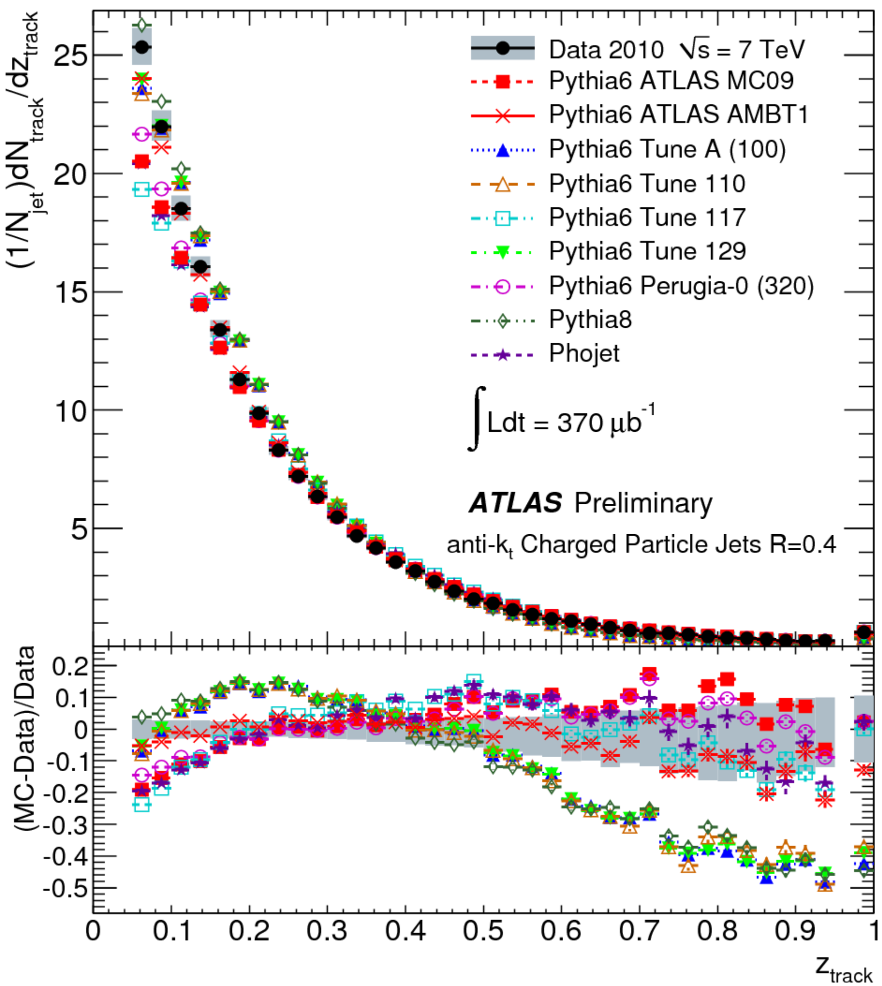


4 GeV < $p_{T,Jet}$ < 6 GeV



6 GeV < $p_{T,Jet}$ < 10 GeV

R = 0.4 *z* distributions (2)



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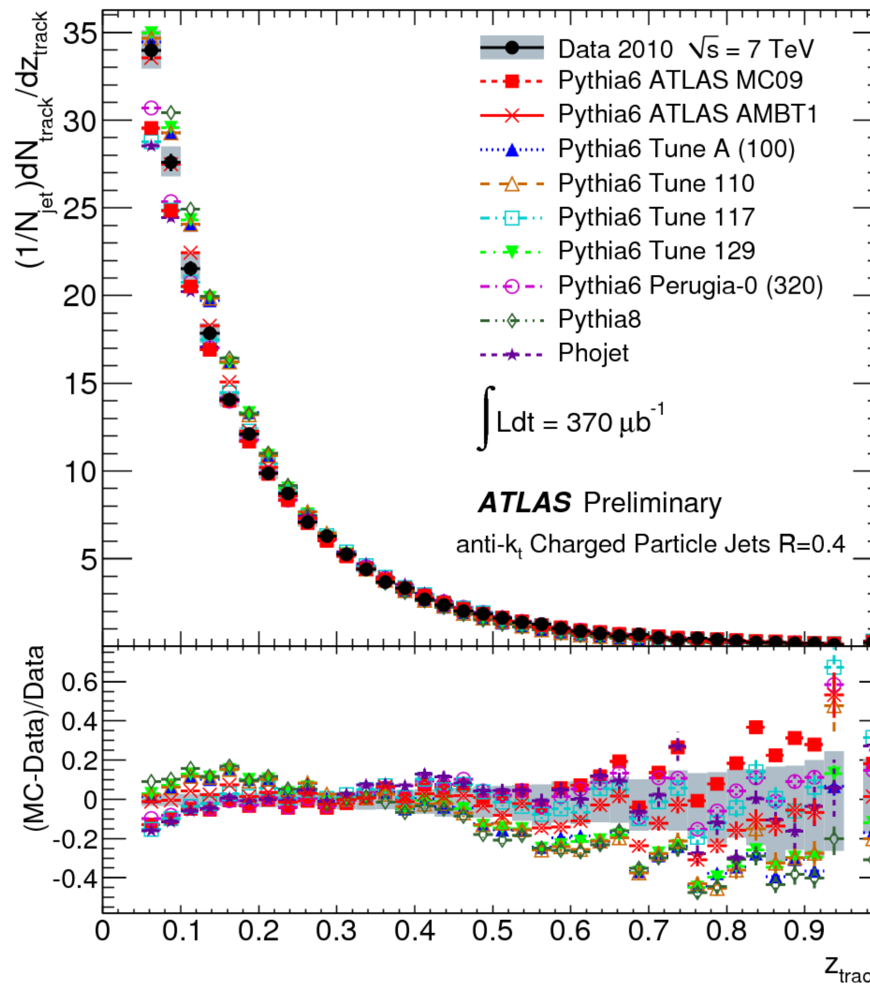
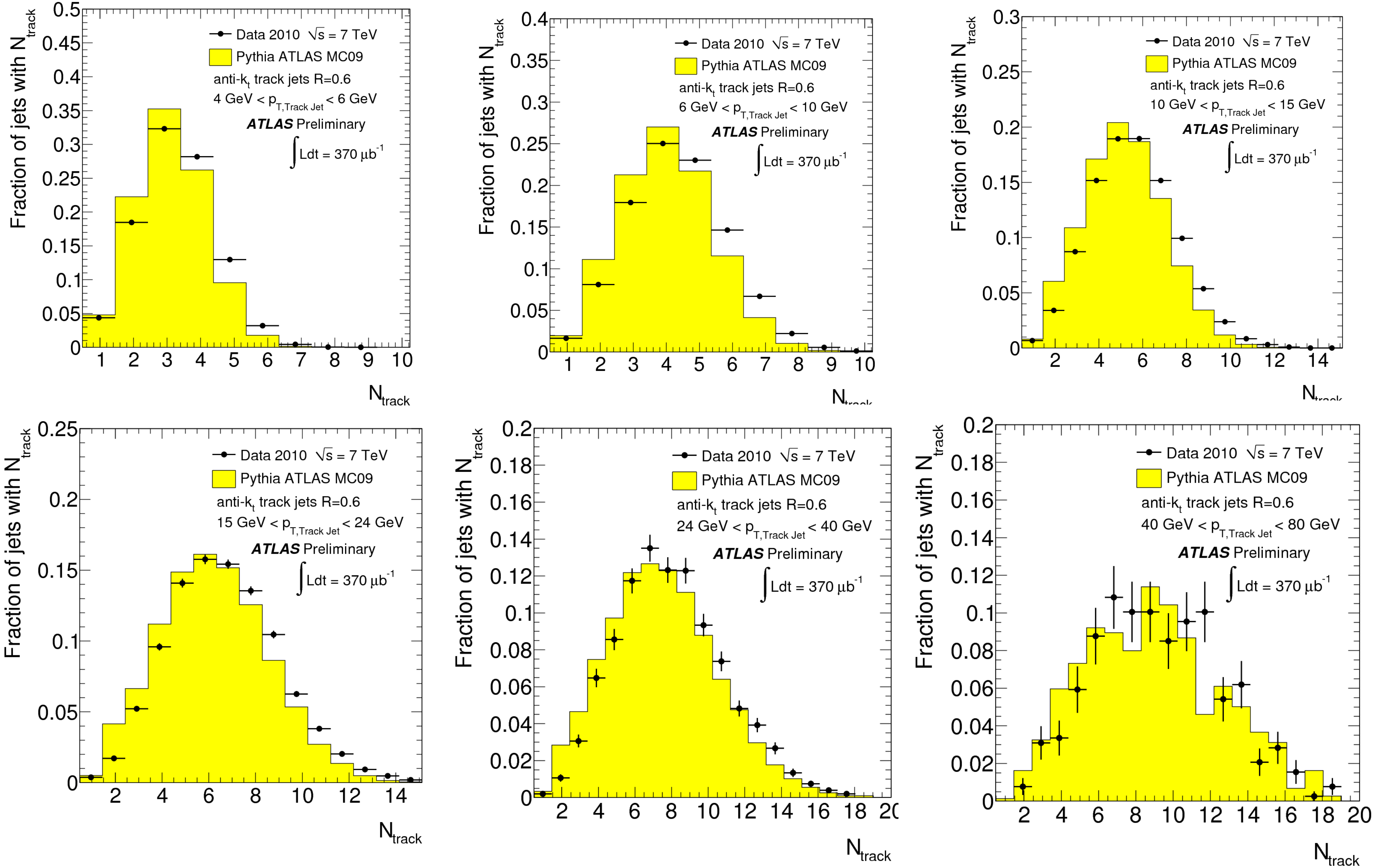


$15\ \text{GeV} < p_{T,Jet} < 24\ \text{GeV}$

Raw track multiplicity in track jets



Anti-k_T Jet Algorithm

- Anti-k_T algorithm is related to k_T – operates by iteratively combining constituent pairs with smallest "distance" d
  - Difference with k_T is in the exponent in the definition of "distance"
  - Shown recently to be **infrared safe** – JHEP 04 (2008) 063
  - Results are **cone-like**: well-contained inside radius D in (y,φ) space and thus approximately contained inside radius D in (η,φ) space
- Algorithm: make a list of distances between constituents d_{ij} and distances to beam axis d_{iB} (defined below), proceed iteratively:
  - If smallest value is a d_{ij}, replace them on the list with their sum
  - If smallest value is a d_{iB}, call it a jet and remove it from the list
  - Continue until the list is empty

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{[\Delta R_y(i,j)]^2}{D^2} \qquad d_{iB} = p_{T,i}^{-2}$$