Jet Production in p+p and Pb+Pb collisions from ATLAS

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On behalf of the ATLAS collaboration

6th International Workshop on High-pT Physics at LHC

Utrecht: April 4th-7th 2011

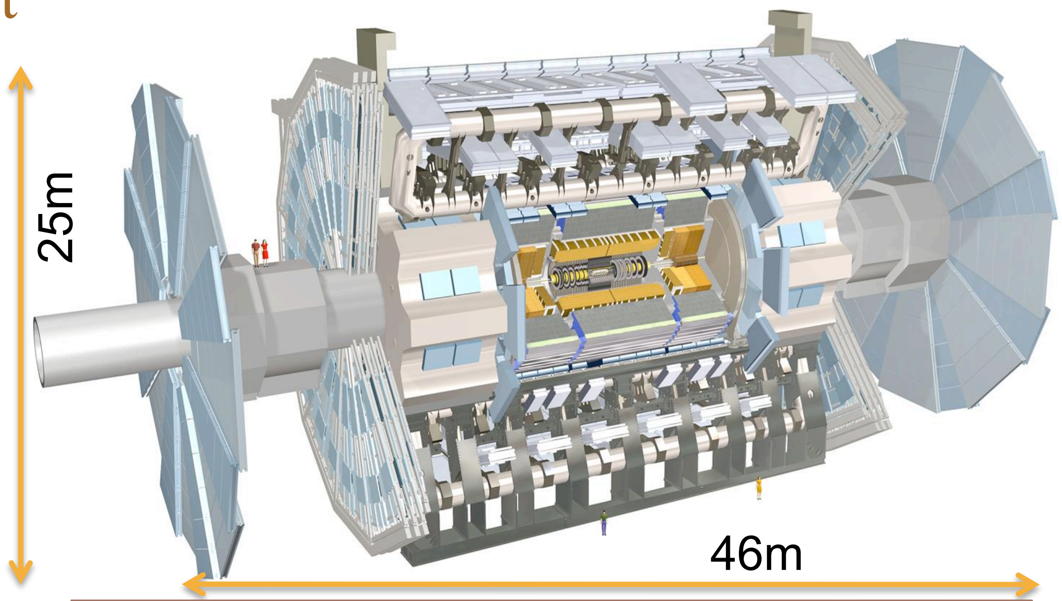
Overview

- Jet production at the LHC
  - Important test of the Standard Model in a new, unexplored energy region
  - Jets are the background to many new physics searches, it is important to understand them
- The results
  - Inclusive, di-jet and multi-jet cross sections
  - Jet shapes, Azimuthal decorrelation, di-jet production with a jet veto
  - Jet production in association with vector bosons
  - Jet quenching with pb+pb collisions

The ATLAS Detector

Design Goal: Precision measurements of the Standard Model and New Physics discovery

- Features is two large magnet systems (solenoid+toroid)
- Calorimeter has good granularity and coverage
  - EM Barrel $|\eta| < 1.475$, three sampling layers, $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
  - Hadronic barrel, interaction length of 9.7
  - Coverage out to $|\eta| < 5.0$



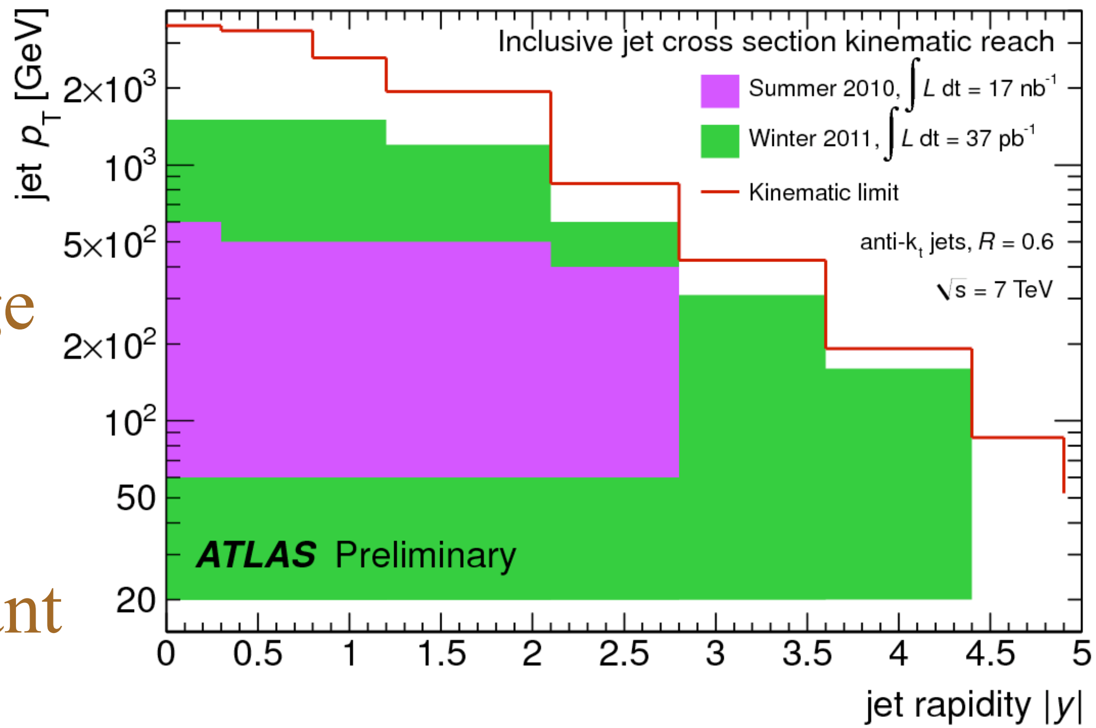
Design Goals:
Lepton energy scale ~ 0.02%
Jet energy scale ~ 1%

http://cdsweb.cern.ch/record/1338578

Inclusive Jet Cross Section

Motivation: a probe of perturbative QCD at small distances

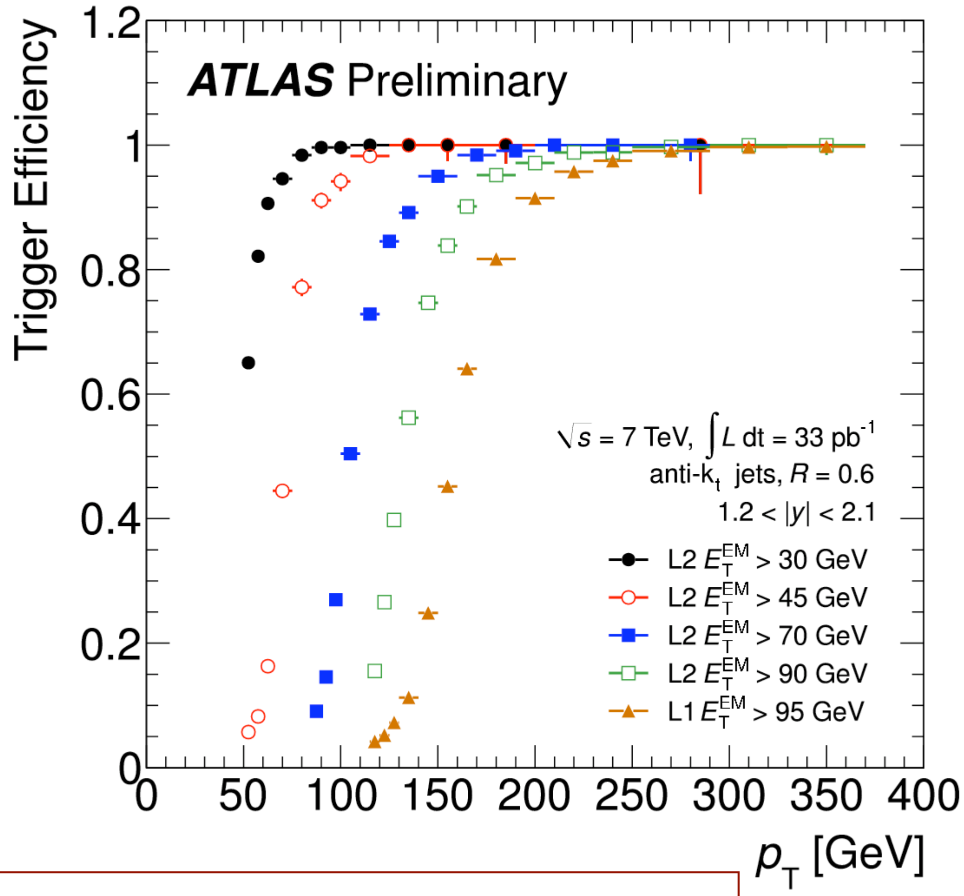
- Improvements in this analysis
  - Larger rapidity range
  - Extended p_t range (both low and high)
  - Greater dijet invariant mass (4.1 TeV)



Explores a new kinematic regime

Trigger and Selection

- Trigger – three types
  - Minimum bias scintillators (located at $2.09 < |\eta| < 3.84$)
  - Central jet trigger $|\eta| < 3.2$
  - Forward jet triggers $3.1 < |\eta| < 4.9$
- Selection
  - Jet $p_t > 20$ GeV
  - $|y| < 4.4$

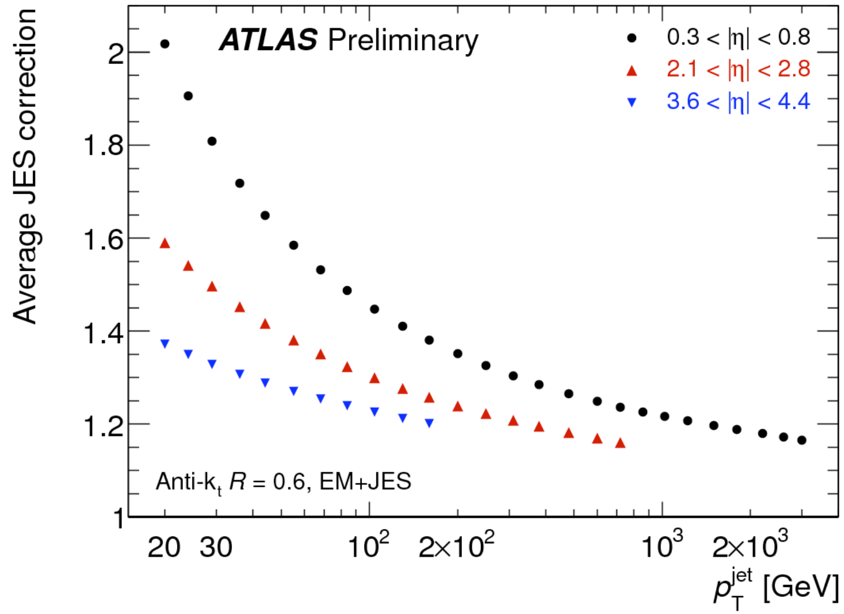


For each p_t-bin, chose the highest threshold trigger with > 99% efficiency

Jet reconstruction

- Jet inputs are clustered with an anti-k_T algorithm
  - Infrared safe, collinear safe
  - Distance parameters 0.4, 0.6 (different sensitivity to non-perturbative QCD effects)
- Jet response corrected for
  - Non-compensating calorimeter
  - Inactive material
  - Out-of-cone effects
- Data and MC-based η, p_t dependent calibration

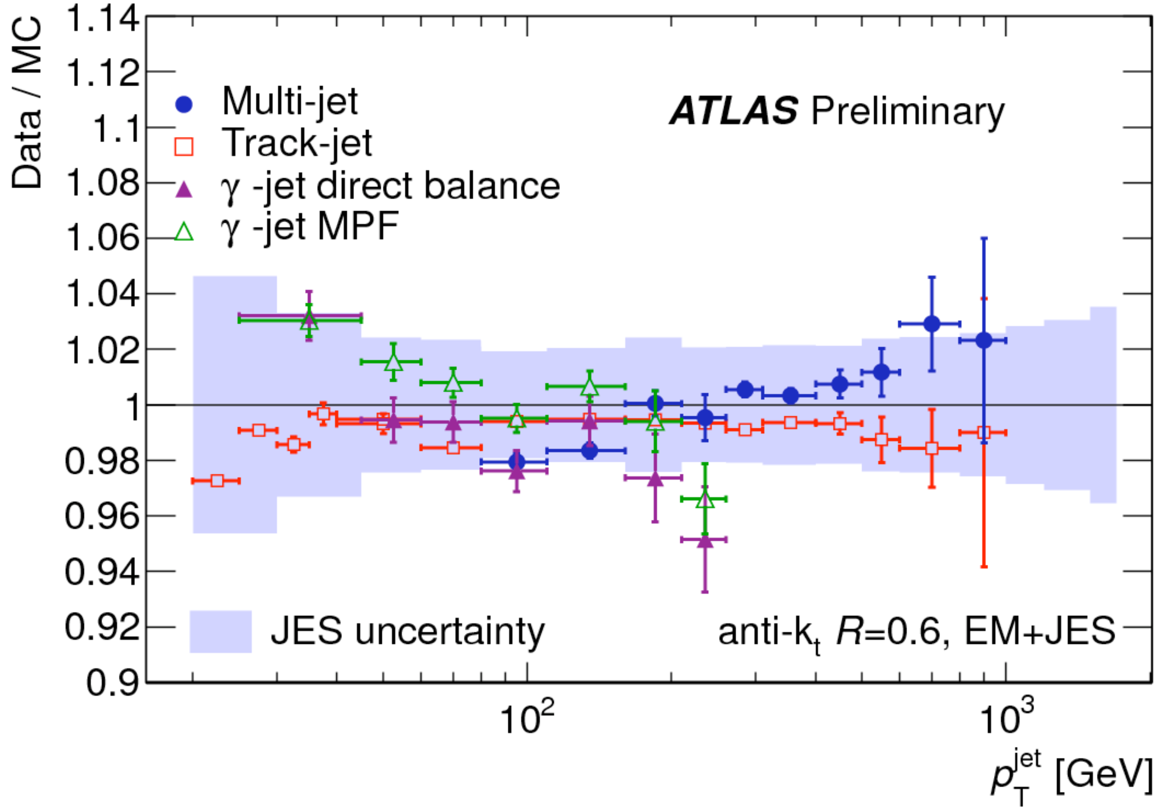
http://cdsweb.cern.ch/record/1337782



Jet energy scale uncertainties

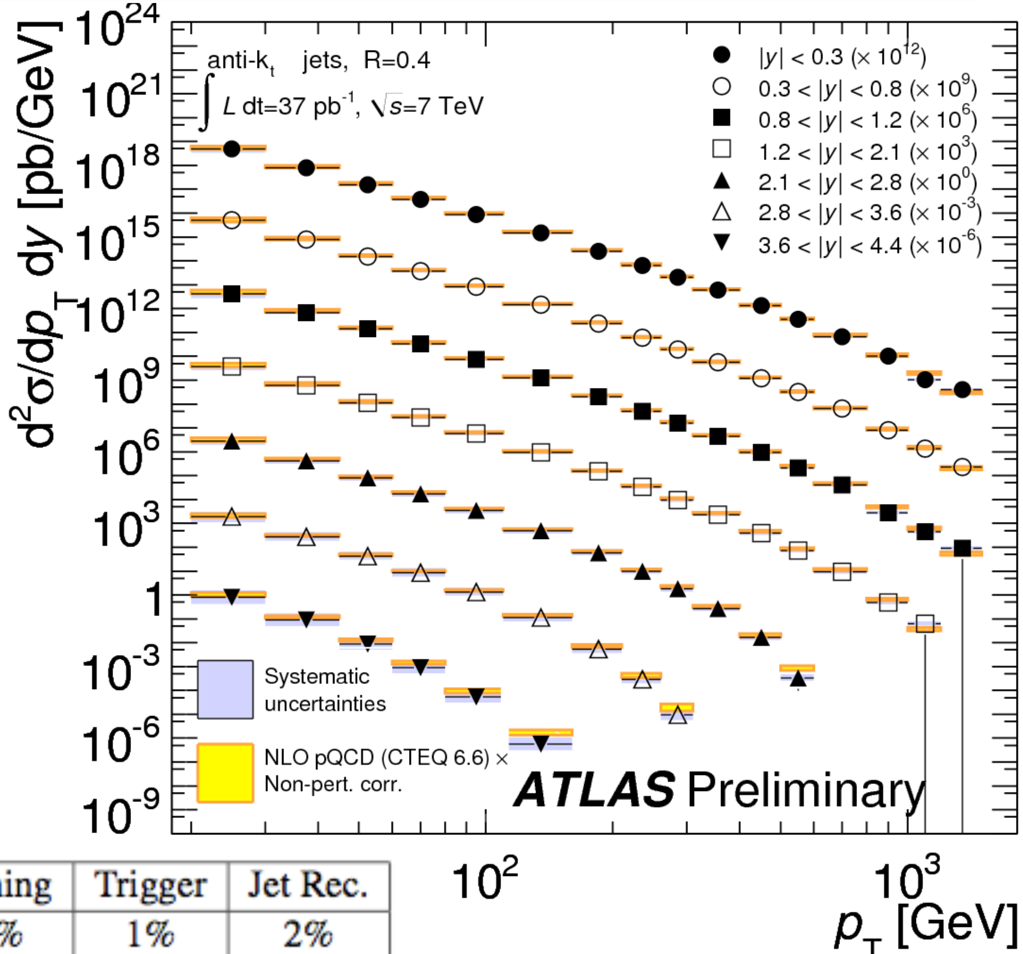
- Jet energy scale is the dominant uncertainty
  - Improved from 7% to 2.5% for central jets p_t>60 GeV

Use several *in-situ* methods to confirm the jet energy scale uncertainties



Inclusive Jet Cross Section

- Comparing to NLO predictions (NLOJet++)
- Some disagreement at high jet p_t and |y| but in general good agreement

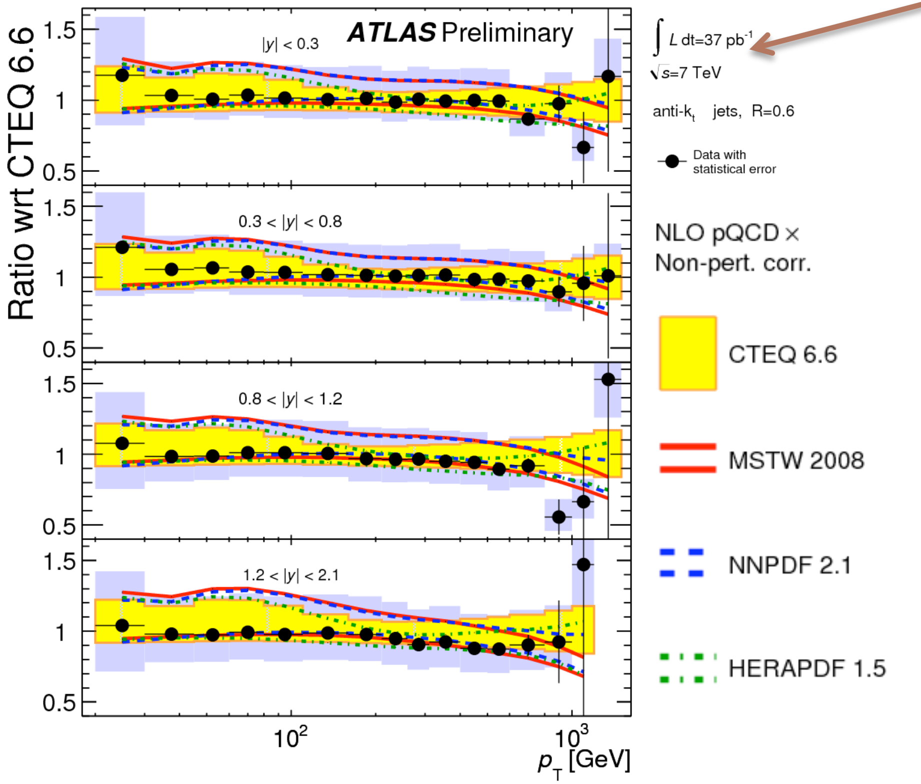


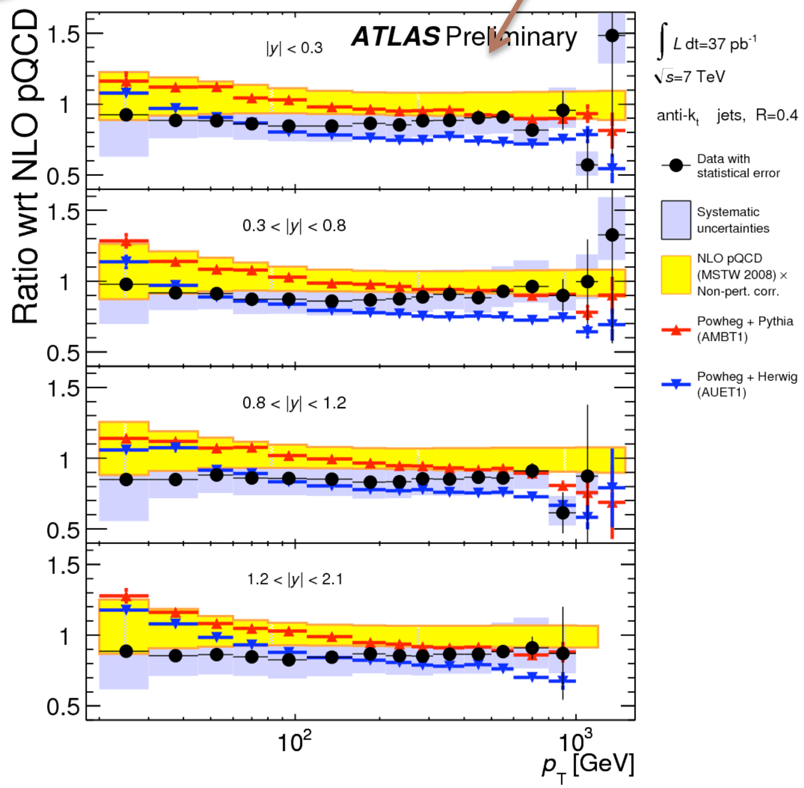
p_T [GeV]	|y|	Abs. JES	Unfolding	Cleaning	Trigger	Jet Rec.
20	2.1-2.8	$^{+40\%}_{-30\%}$	20%	0.5%	1%	2%
20	3.6-4.4	$^{+80\%}_{-50\%}$	20%	0.5%	1%	2%
100	< 0.3	10%	2%	0.5%	1%	1%

Jet energy scale dominates uncertainties

Inclusive Jet Cross Section

- Comparison between different PDF sets and Powheg

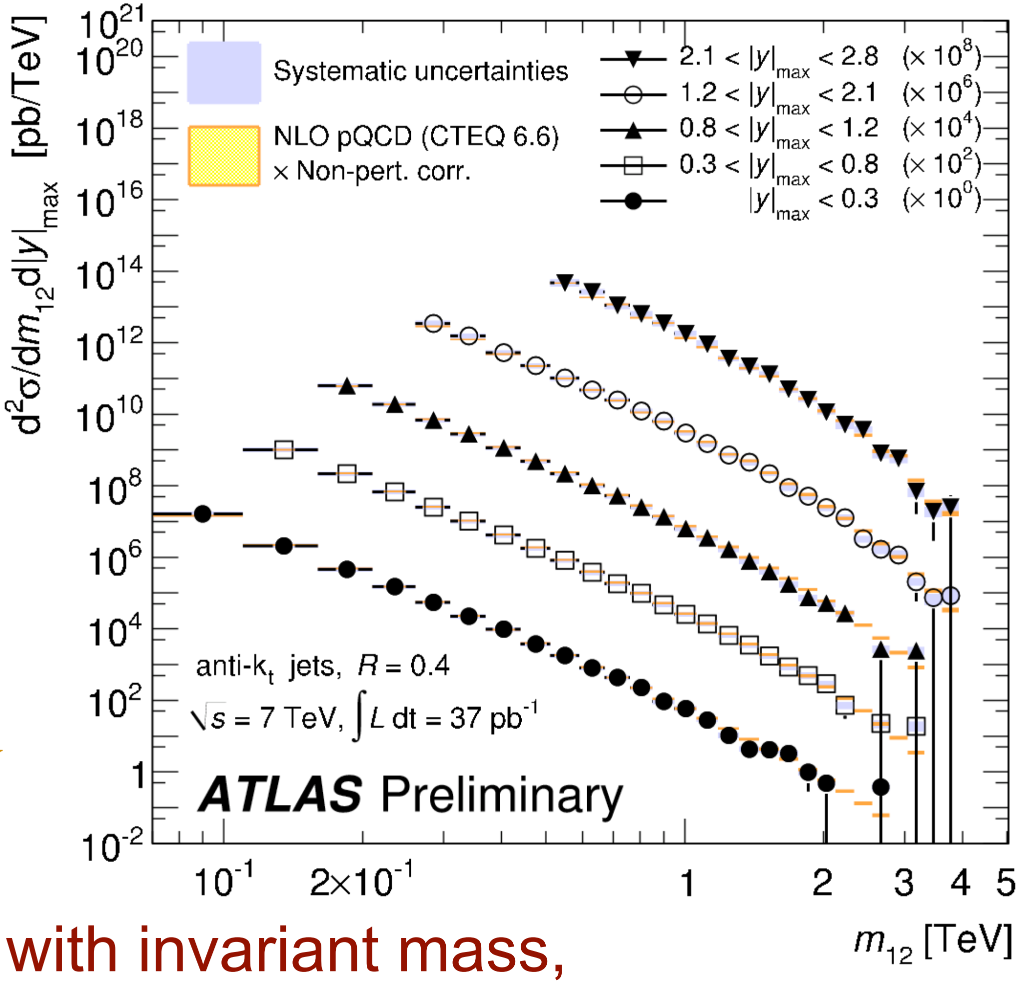




Powheg, larger at low p_t, smaller at high p_t compared to NLOJet++
These are regions with large scale uncertainties for NLOJet++

Di-Jet Cross Section

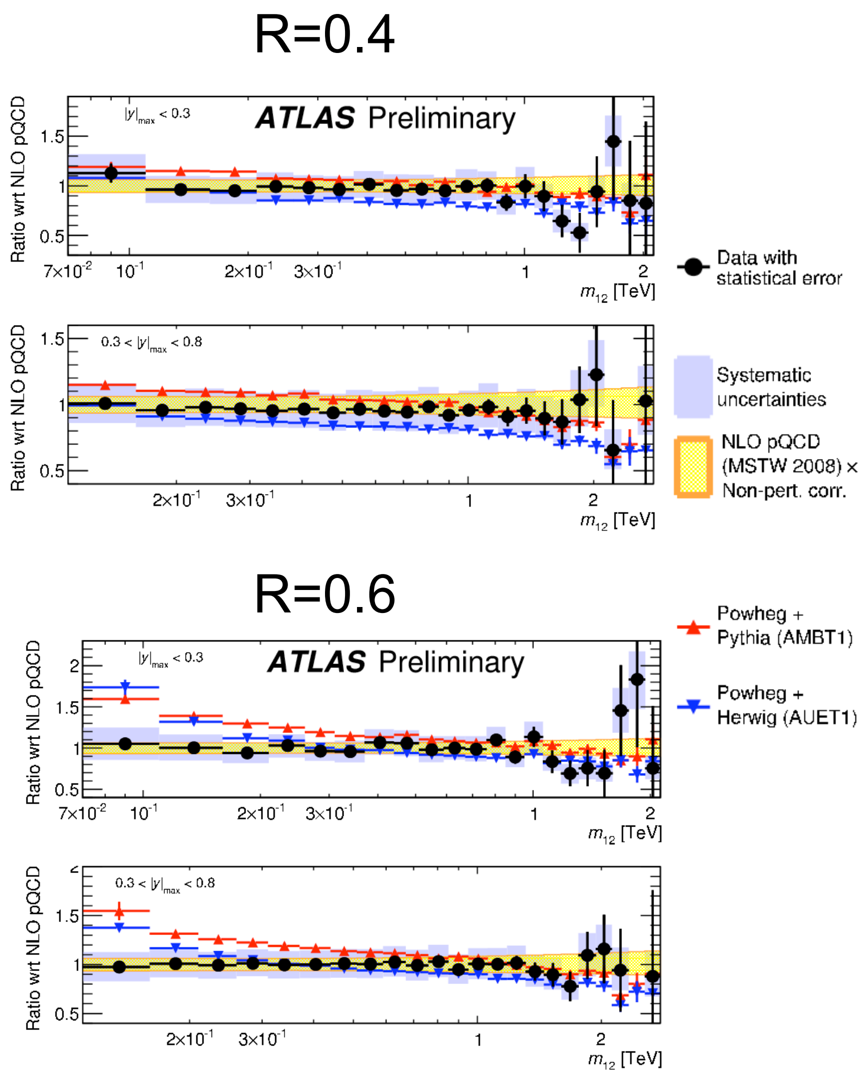
- Trigger
  - Use an OR of central and forward jet triggers to be fully efficient over all η
- Selection
  - Lead jet $p_t > 30$ GeV
  - Subleading jet $p_t > 20$ GeV
  - $|y| < 4.4$
  - $|y_{max}|$ is maximum rapidity of the two leading jets



Cross section falls rapidly with invariant mass, measured up to 4 TeV

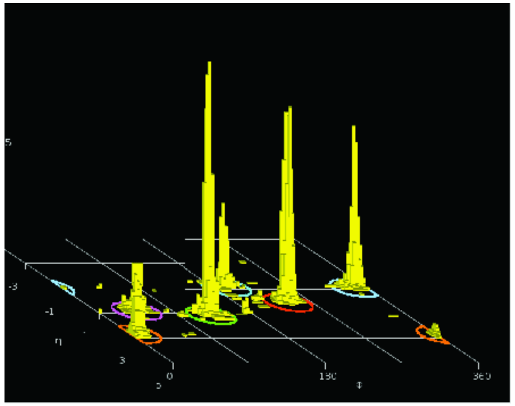
Di-Jet Cross Section

- Comparing NLOJet++ to Powheg with different tunes
  - R=0.4, Powheg models the data
  - R=0.6, Powheg predicts larger cross sections
  - Low di-jet mass → non-perturbative corrections have significant influence



http://cdsweb.cern.ch/record/1338572

Multi-jet Cross Section



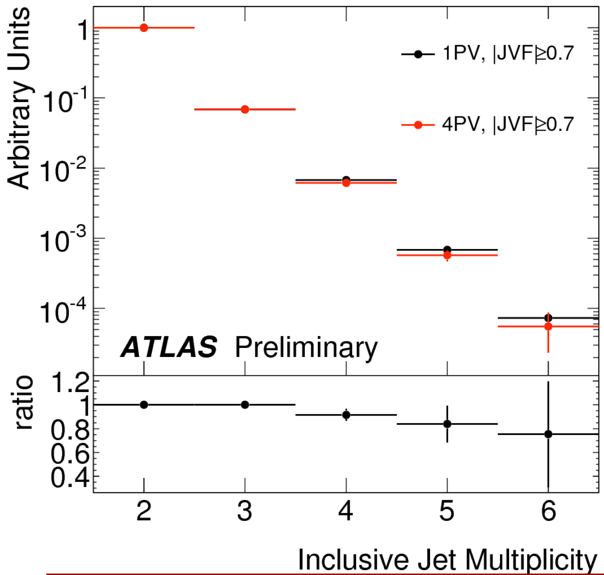
eta vs. phi

- Motivation
  - Test of higher order pQCD
  - Multi-jet final states important for searches
- Trigger
  - Use two or three-jet triggers with symmetric threshold
  - 10 GeV trigger threshold → Fully efficient at p_t>60 GeV
- Selection
  - One jet p_t > 80 GeV, other jets p_t > 60 GeV
  - $|y| < 2.8$
  - 70% of charged particles in jet come from primary vertex (JVF)

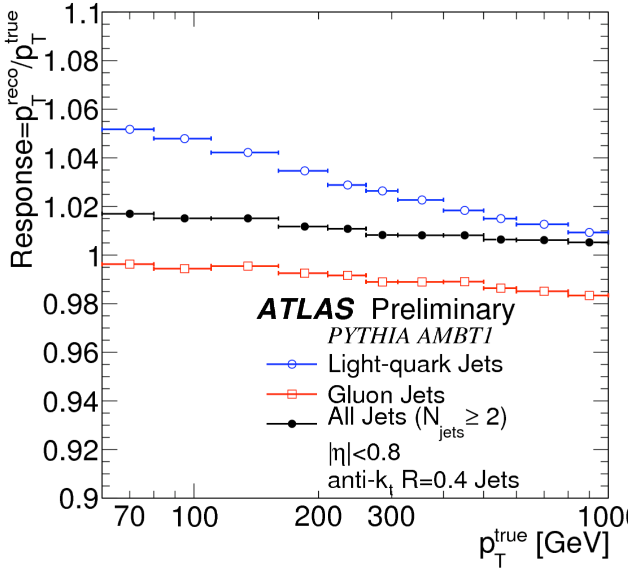
Additional Jet Uncertainties

- Multi-jet environment is more 'crowded' therefore additional jet energy scale uncertainties are required

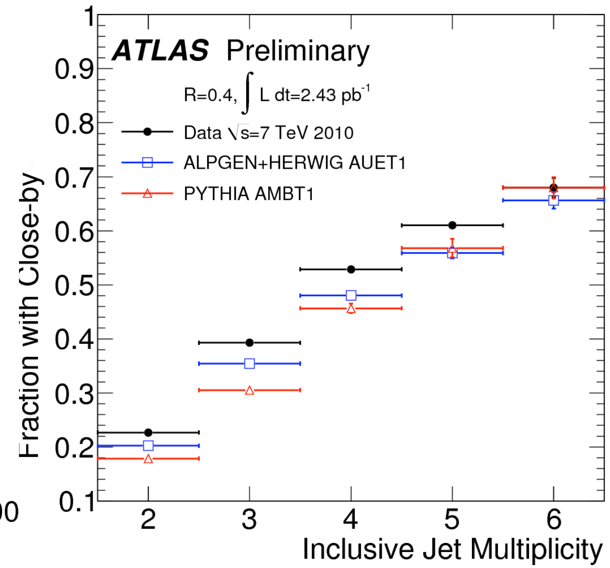
Pile-up Jets



Quark/gluon content



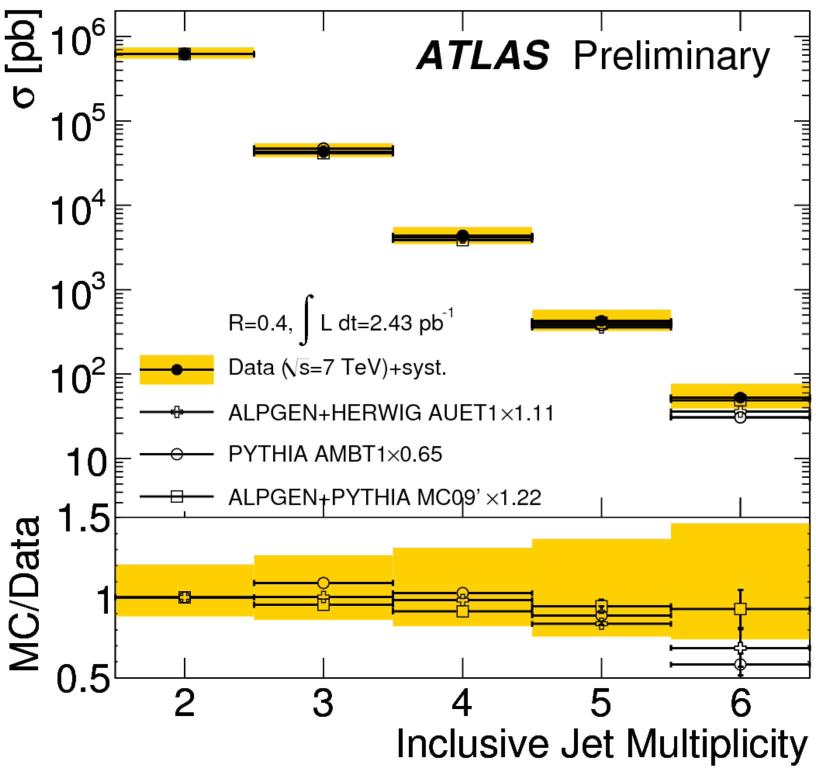
Close-by Jets

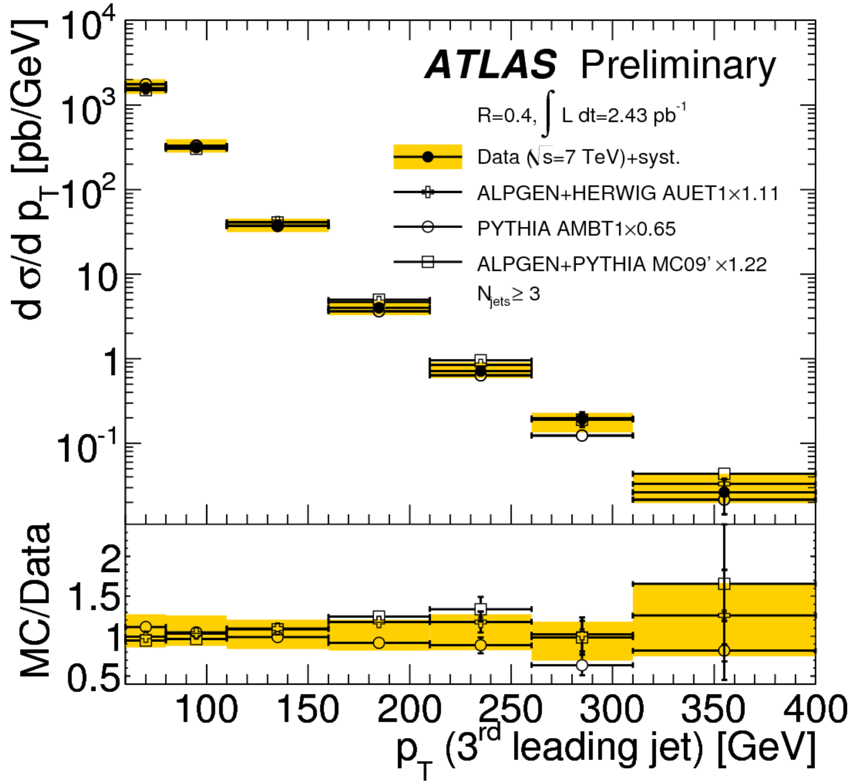


→Jets from pile-up reaches 3.4% for six-jet cross section if not removed
→Uncertainties in quark/gluon fraction up to 3% additional uncertainty
→Uncertainty due to close-by jets up to 1.5%

Multi-jet Cross Section

- MC are normalized to inclusive two-jet cross section
- Different models all tend to model the data within uncertainties

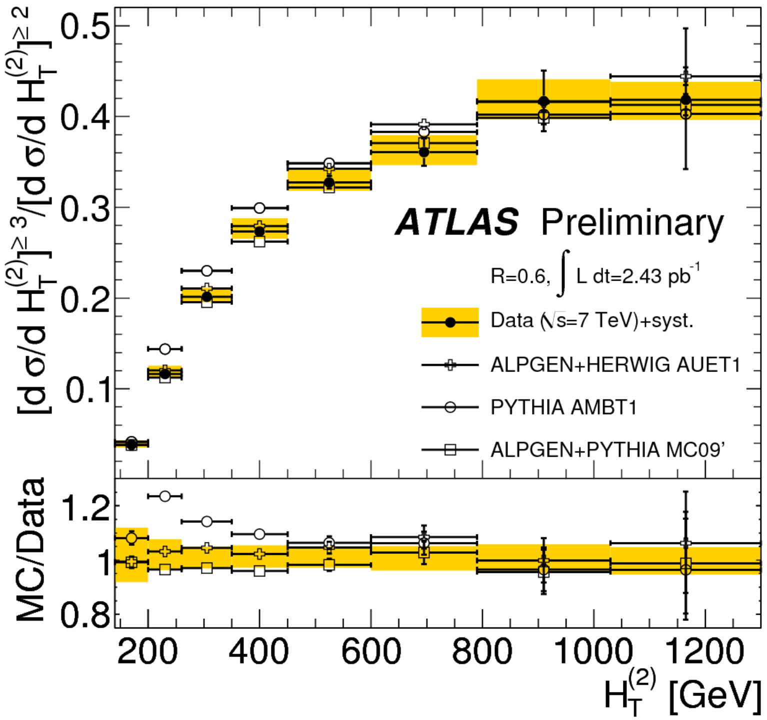


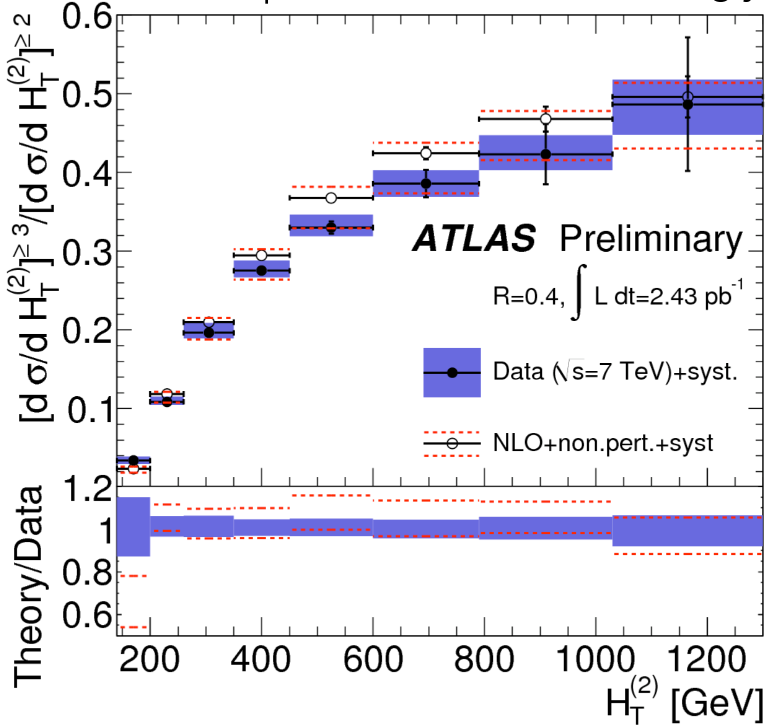


Multi-jet Cross Section

- Measurement of three-jet to two-jet ratio: Reduces uncertainties, sensitive to discrepancies in LO (left) and NLO (right) calculations

$H_T^{(2)}$ = Sum of two leading jet



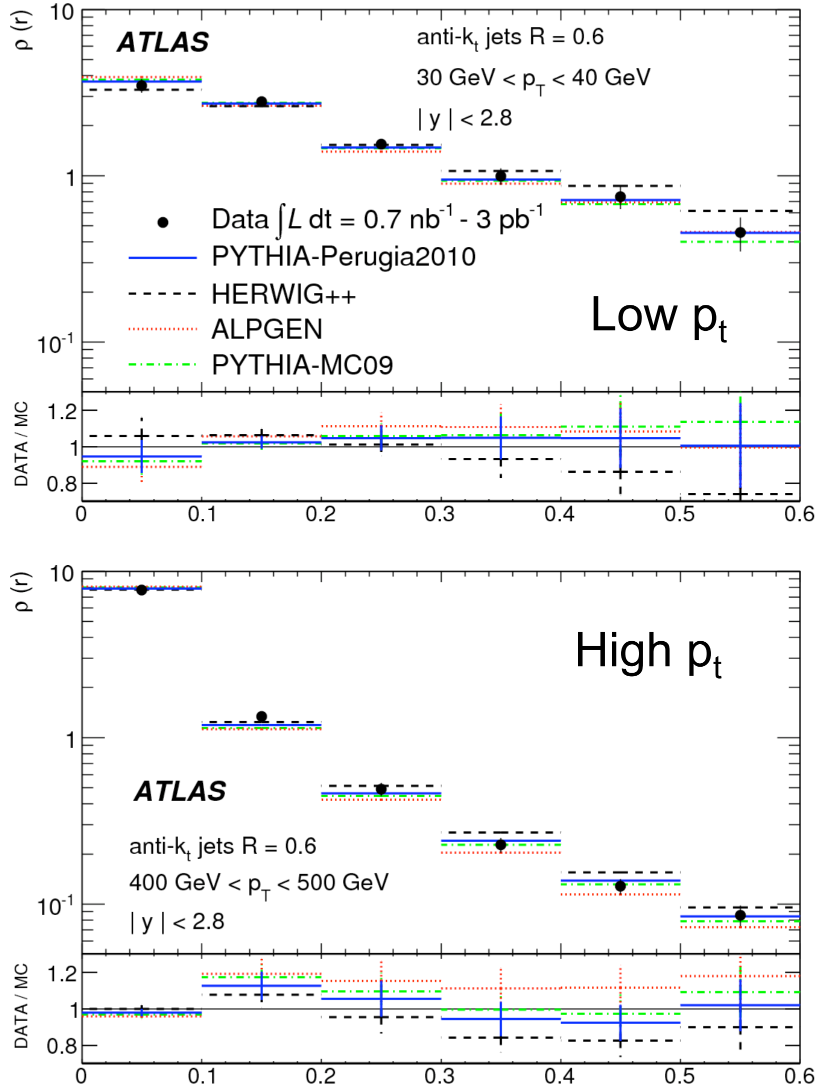


H_t is interesting since it is stable under renormalization scale variations

http://arxiv.org/pdf/1101.0070.pdf
Phy Rev D, 83, 052003

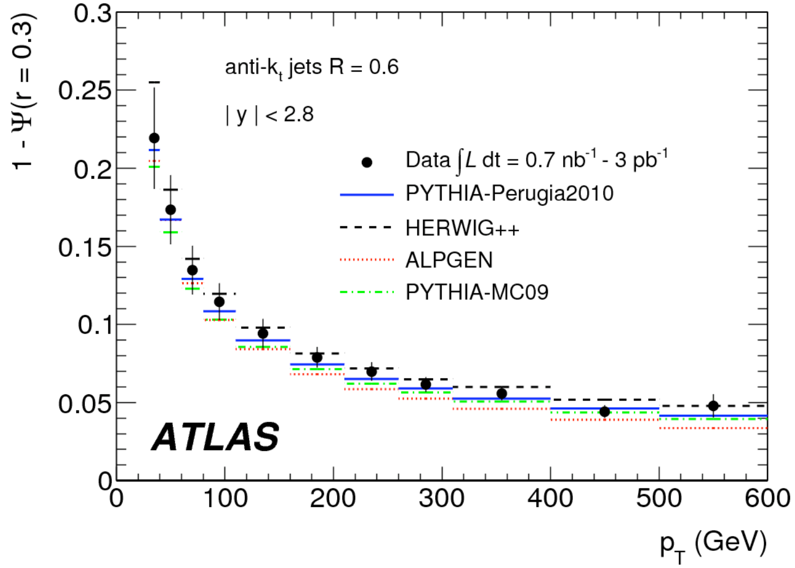
Jet Shapes

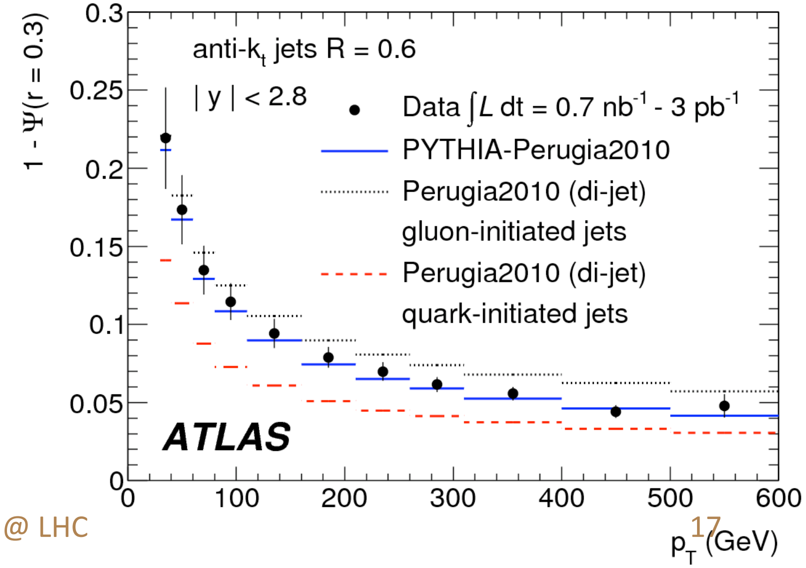
- Sensitive to details of parton shower fragmentation and underlying event
- Selection
  - Only one primary vertex
  - At least one jet $p_t > 30$ GeV and $|y| < 2.8$
- Observable
  - Average fraction of jet p_t inside an annulus: $\rho(r)$
  - Average fraction of jet p_t inside a cone: $\Psi(r)$



Jet Shapes

- Majority of energy is concentrated near to axis
- Jets - Narrower with increasing p_t, moderate rapidity dependence
  - Pythia in reasonable agreement
  - Herwig++ predicts broader jets
  - Alpgen narrower at high p_t
- At low p_t, shape gluon-like; at higher p_t shape is a quark/gluon admixture

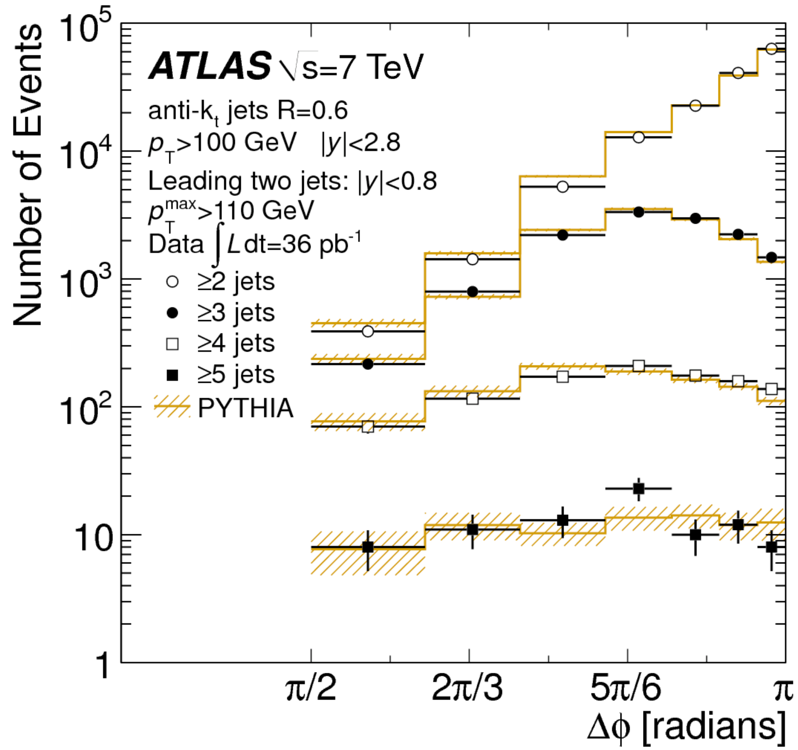


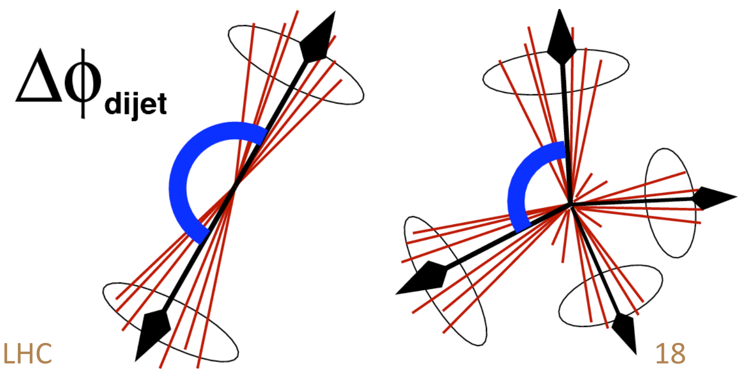


http://arxiv.org/pdf/1102.2696.pdf
Accepted by PRL

Azimuthal Decorrelation

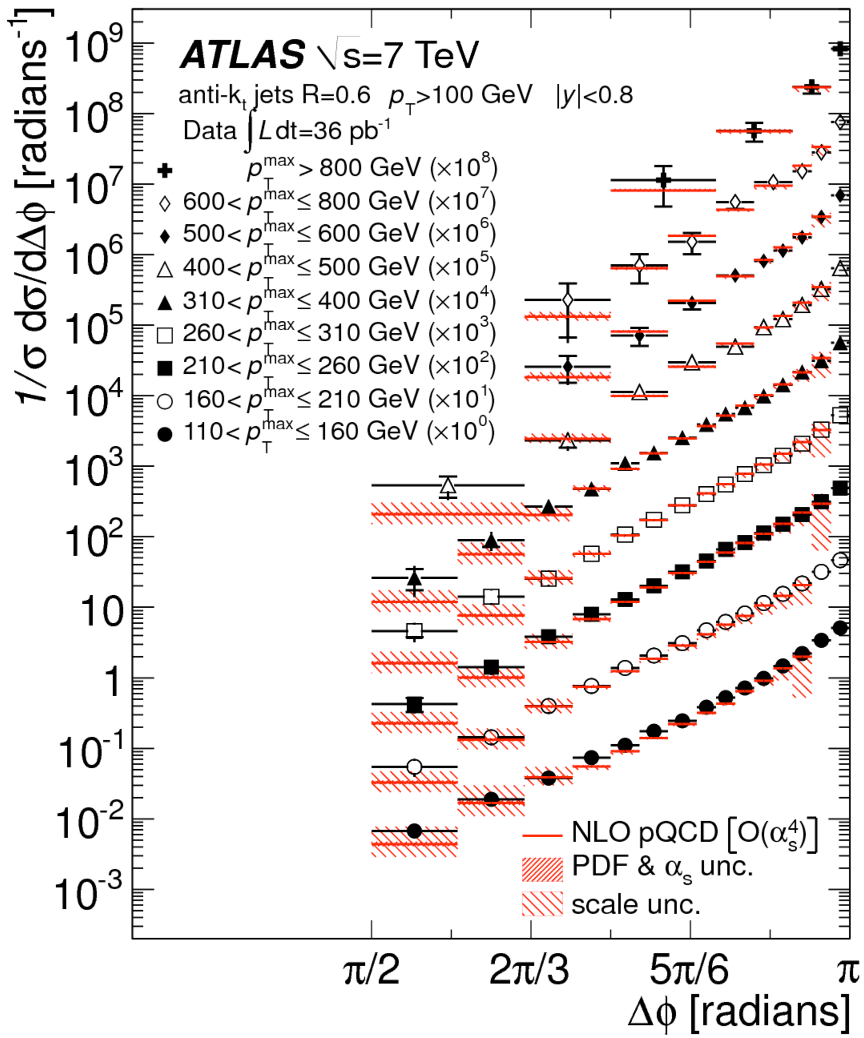
- Tests QCD modeling of Δφ distribution
  - A multi-jet environment without needing to measure the additional jets
- Selection
  - Jet p_t > 100 GeV, |y| < 2.8
  - Two leading jets, |y| < 0.8
  - Δφ: angle between 2 leading jets
- Events with additional high p_t jets widen the distribution





Azimuthal Decorrelation

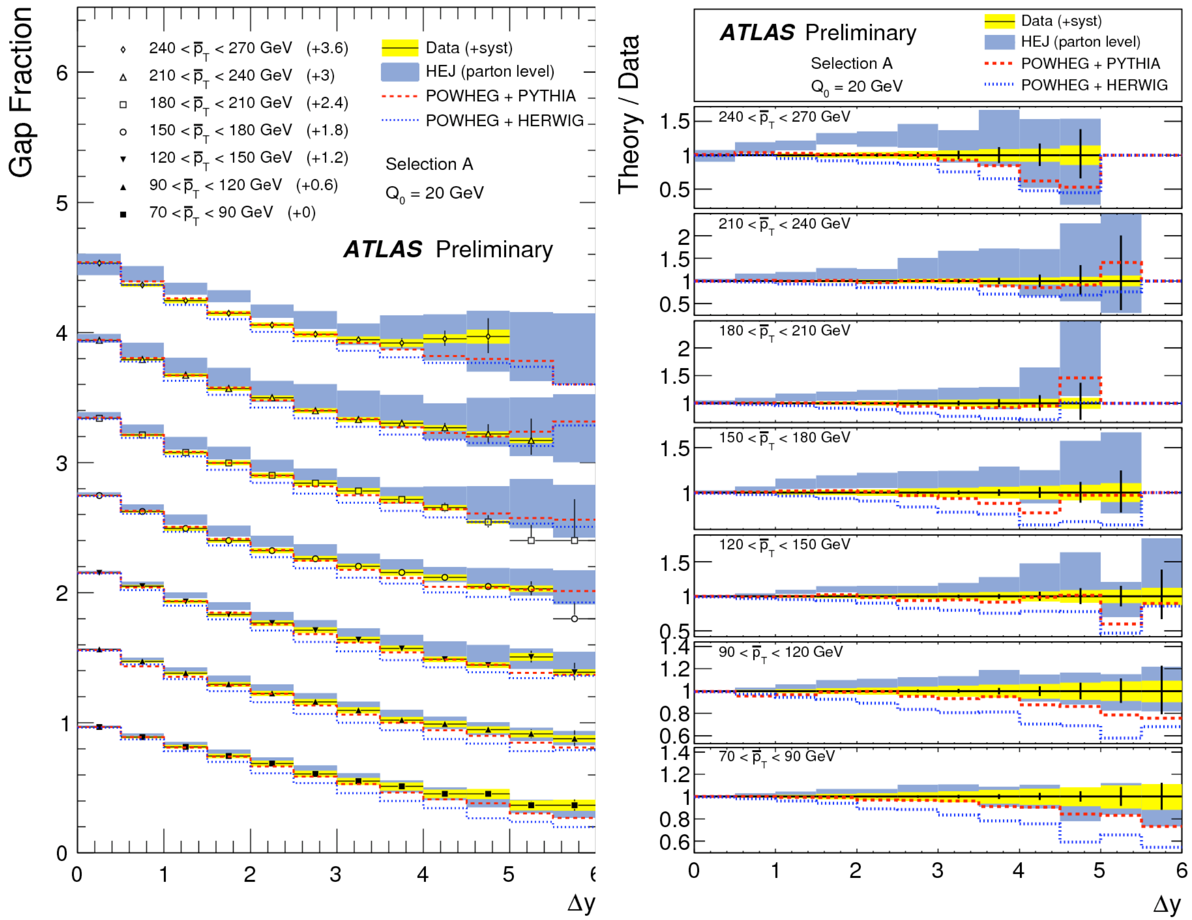
- Results compared to NLOJet++
- Systematics dominated by jet energy scale (2-17%) and unfolding (1-19%)
- Good agreement overall, prediction relative low in range $110<p_t< 160$ GeV



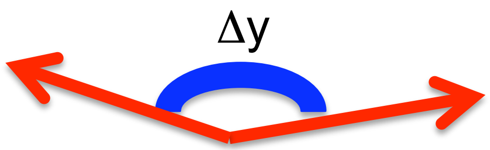
http://cdsweb.cern.ch/record/1337788

Di-jet production with Jet Veto

- Test QCD with large jet rapidity separation, high p_t
- Selection
  - Only one primary vertex
  - p_t >20 GeV, |y|<4.5
  - Average di-jet p_t>50 GeV
- Compared to NLO



Shown: Fraction of jets with no jets inside Δy

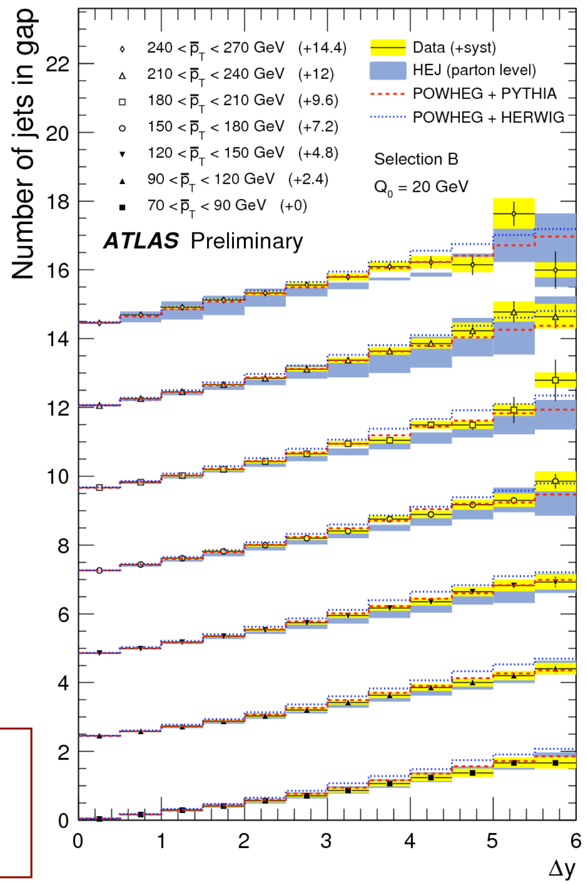


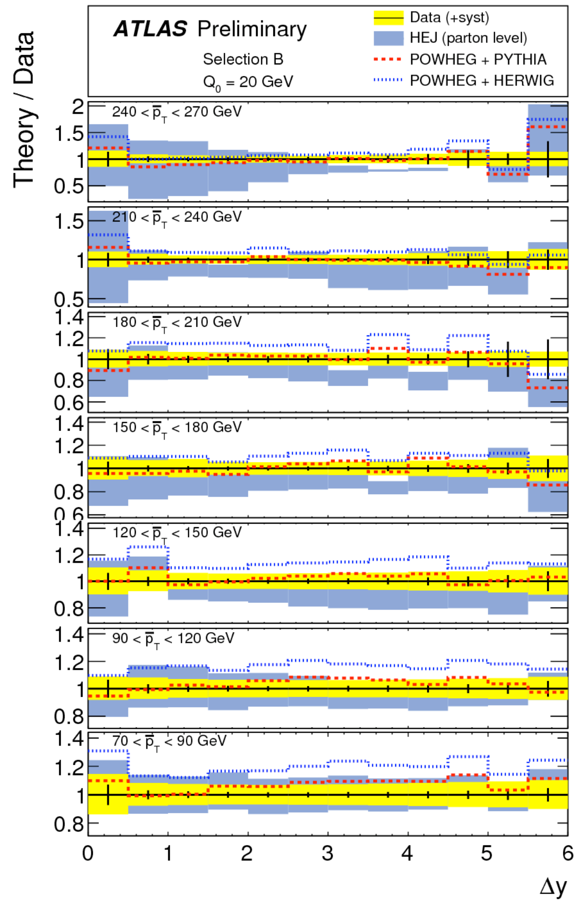
Boundary jets
A: Highest P_t
B: Highest y

Di-jet production with Jet Veto

- Compared to NLO predictions: HEJ and POWHEG

- POWHEG has good agreement, only disagreements at large Δy
- HEJ does not well describe the data in some cases





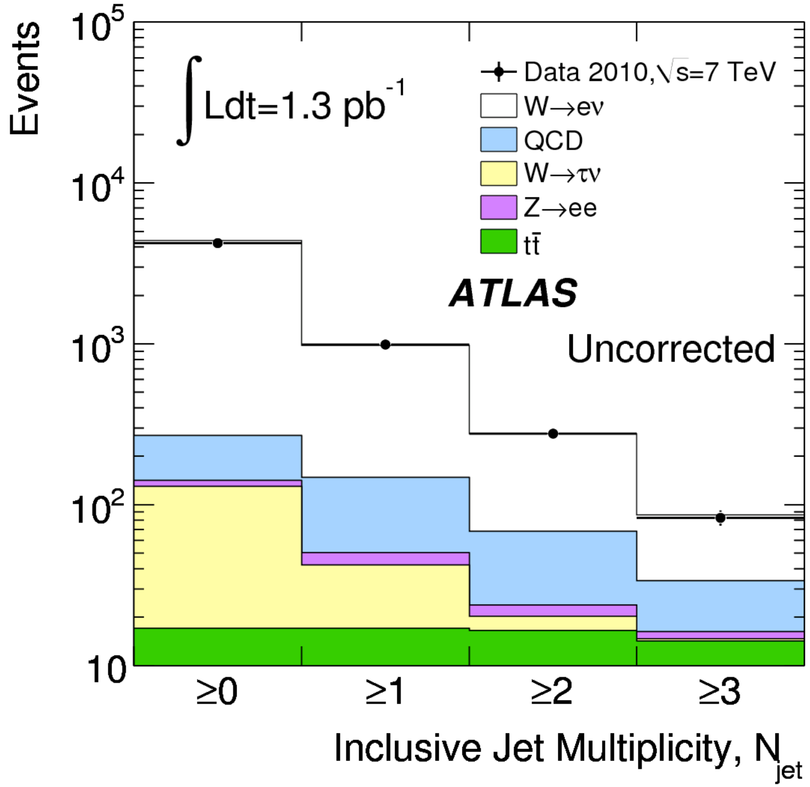
Shown: Mean number of jets inside Δy

http://arxiv.org/pdf/1012.5382.pdf
Accepted by PLB

Jets with a W Boson

An important test of QCD in addition to an important background to many new physics searches

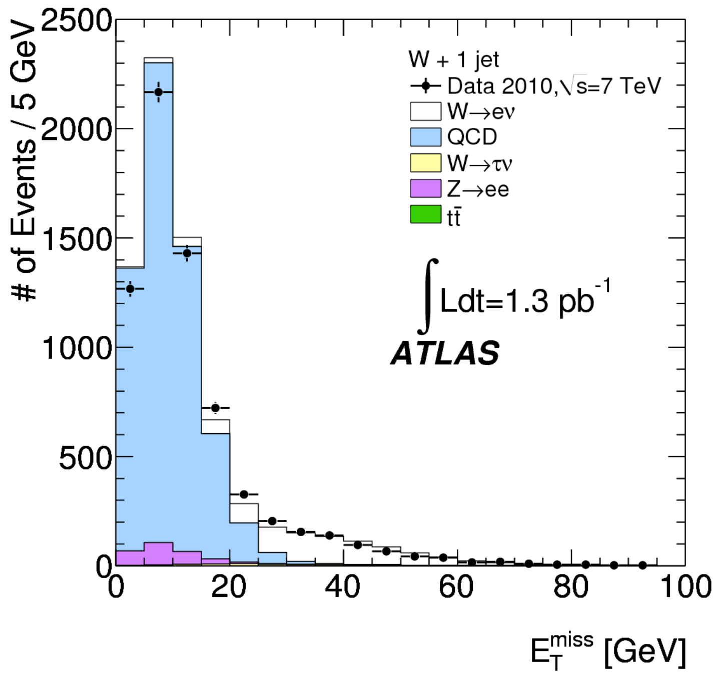
- Selection
  - Jet p_t > 20 GeV, |y| < 2.8, no jet with ΔR <0.5 of lepton
  - 75% of charge particles in jet come from primary vertex
  - Lepton p_t > 25 GeV, |η| < 2.4 (2.47 for electron)
  - Missing E_t > 25 GeV, W_{mT} > 40 GeV

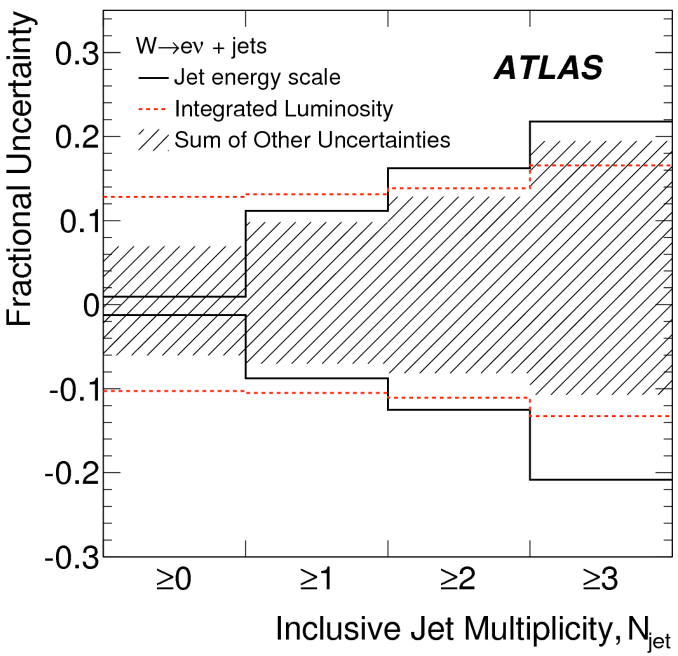


For Z+jets see M. Beckingham's talk

W+jets: Backgrounds and Systematics

QCD multi-jet events can 'fake' an electron
→Must use a data-driven control sample to subtract the QCD multi-jets from W+jets signal
→ In muon channel, heavy flavor events dominate the QCD background





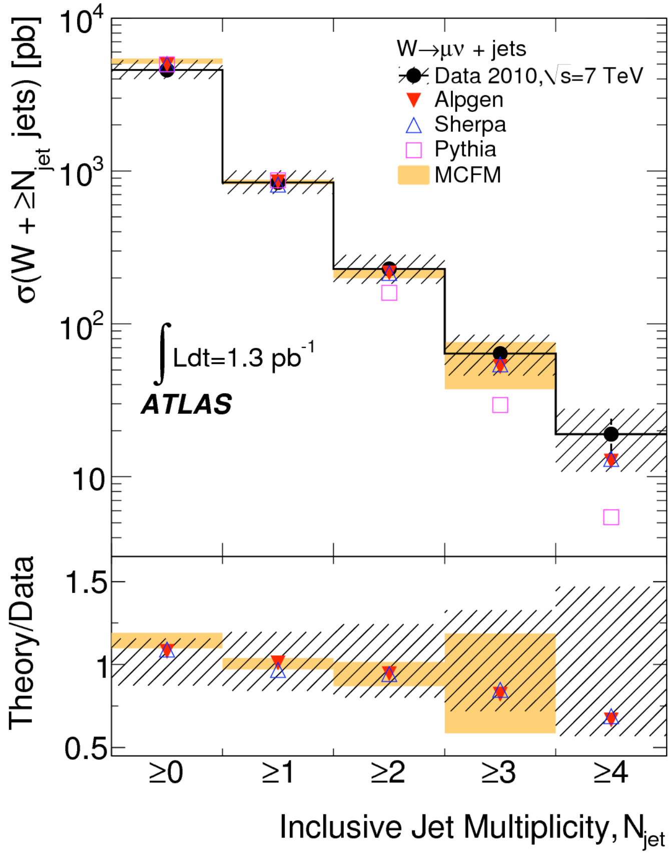
Jet energy scale dominates the uncertainties
→More than 20% in the high jet multiplicities
→Other major uncertainties include uncertainties from QCD backgrounds and lepton reconstruction

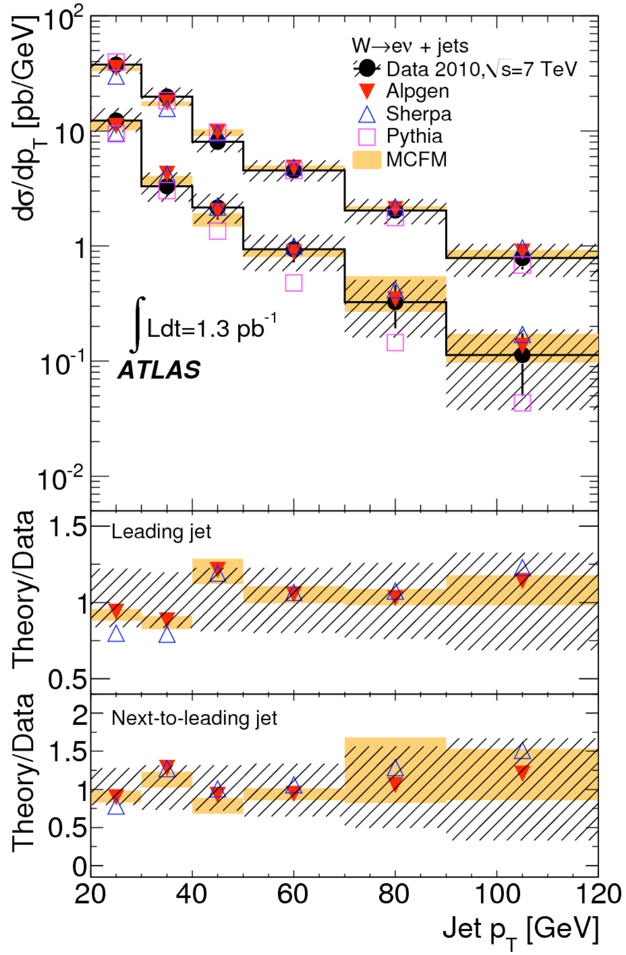
W+jets: Results

- Excellent agreement to NLO calculations

Compare to Alpgen, Sherpa and NLO MCFM

→Pythia is a LO calculations and does not model the multiplicity spectrum well





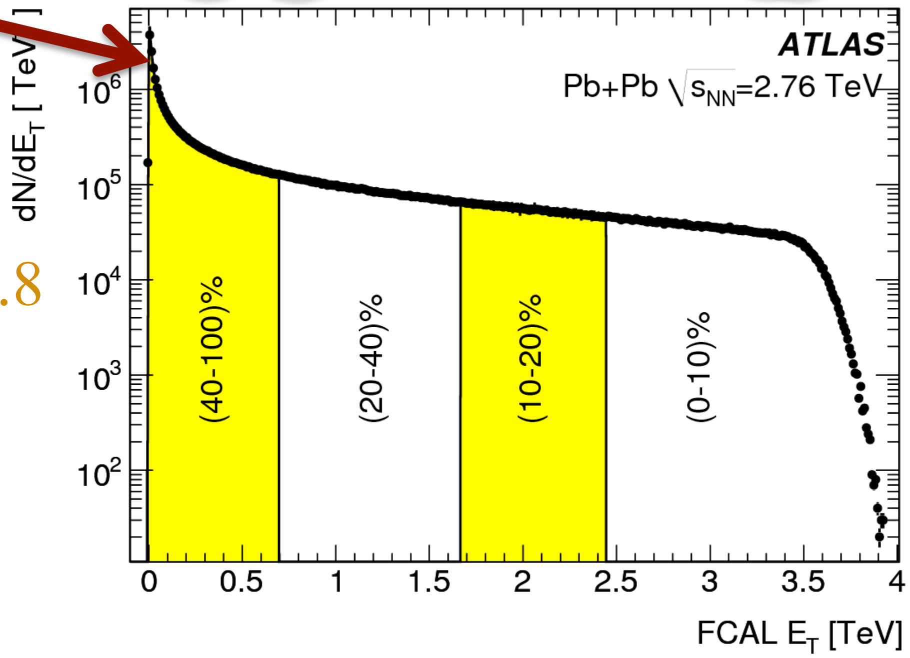
Alpgen, Sherpa and Pythia normalized to NNLO inclusive W cross section

http://arxiv.org/abs/1011.6182
PRL 105, 252303

Jet Quenching in Pb+Pb

→ "Centrality" quantified as total energy in forward calorimeter
→ Binned in fractions of total Pb+Pb cross section

Recover p+p behavior in peripheral collisions (small nuclear overlap)



- Selection
  - First jet: $p_t > 100$ GeV, $|\eta| < 2.8$
  - $\Delta\varphi > \pi/2$
  - Second jet: highest p_t jet with $p_t > 25$ GeV in opposite hemisphere

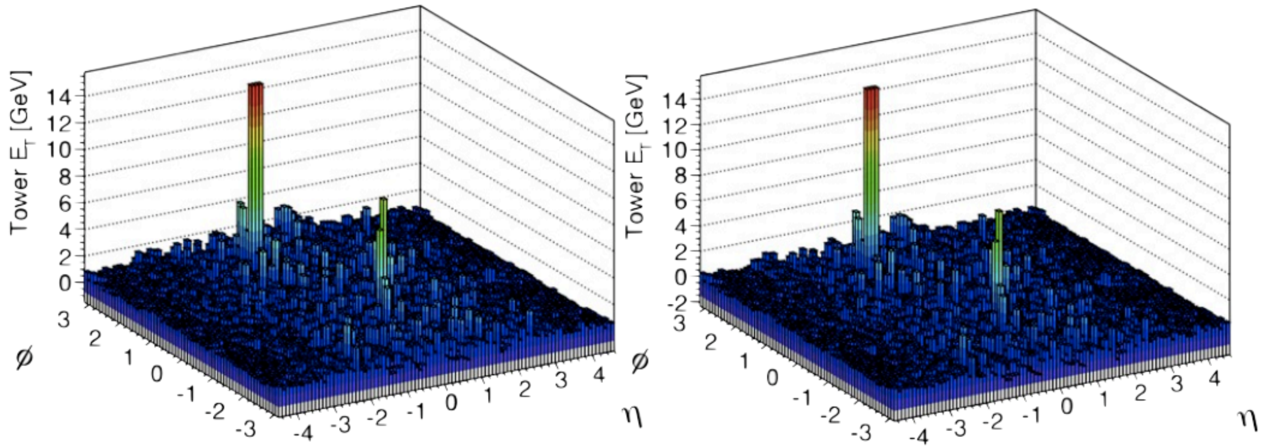
Jet Reconstruction in Pb+Pb

- Use anti-k_T algorithm ($R = 0.4$), with calorimeter towers
- Event-by-event background subtraction needed
  - Underlying event estimated for each longitudinal layer and η slice separately
  - Exclude jets from averaging

$$D = \frac{E_T^{TowerMax}}{\left\langle E_T^{Tower} \right\rangle} > 5$$

Excludes jets with large "core" region

Before

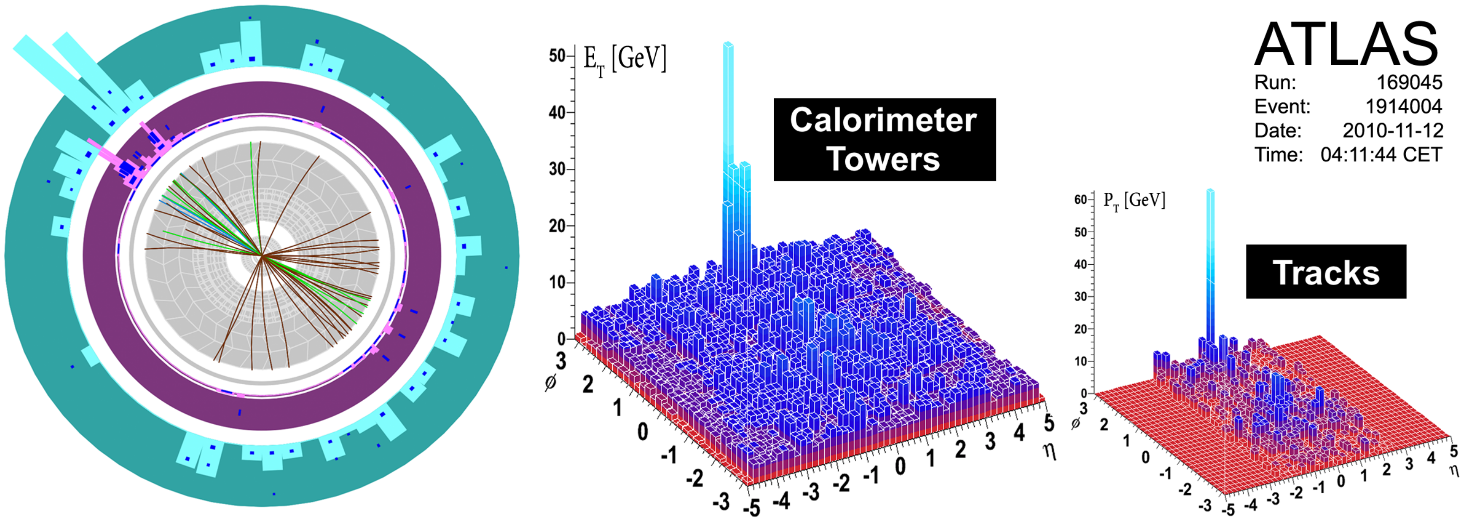


After

No change in topological features of the events
No jets are removed by or in the subtraction procedure

Jet Quenching in Pb+Pb

- Observe that di-jets in opposite hemispheres become more unbalanced with increasing centrality
- Points to strong jet energy loss in a hot, dense medium



Many cross-checks done → Compared calorimeter vs. track jets, varied the jet η range, varied the jet radius, verified events are not in one region of detector, no large anomalously missing E_t, no high p_t muons

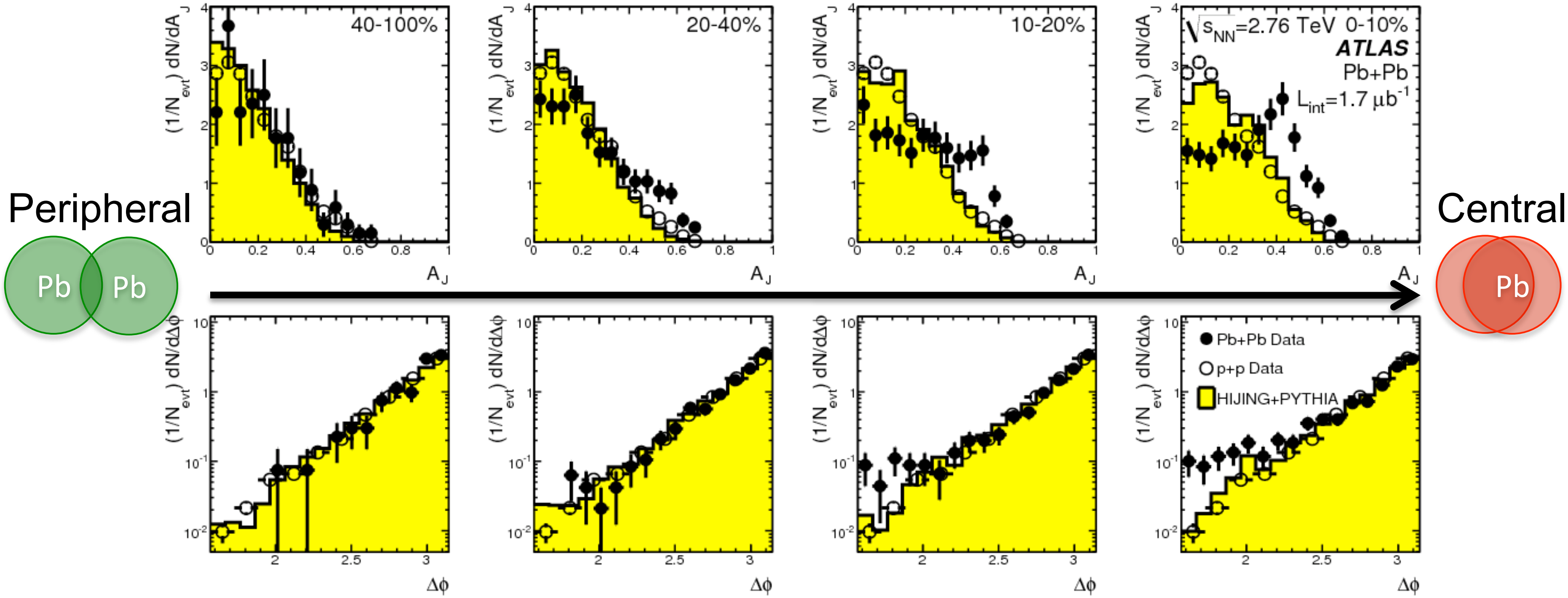
Jet Quenching in Pb+Pb

Peripheral events agree well with p+p data and MC

Asymmetry definition

$$A_j = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Pb+Pb large asymmetry, no longer peaks at zero



Δφ primarily back-to-back for all centralities, at high centrality second jet is at large angles with respect to recoil direction

Conclusions

- Many new tests of perturbative QCD ongoing at ATLAS
- With 2010 LHC data, have extended the reach to large rapidities, high transverse momentums and large invariant masses
- In Pb+Pb collisions, observe di-jet unbalance, suggesting strong jet energy loss in a hot, dense medium

With 2011 LHC operations already starting, we are looking forward to even more data and new results!