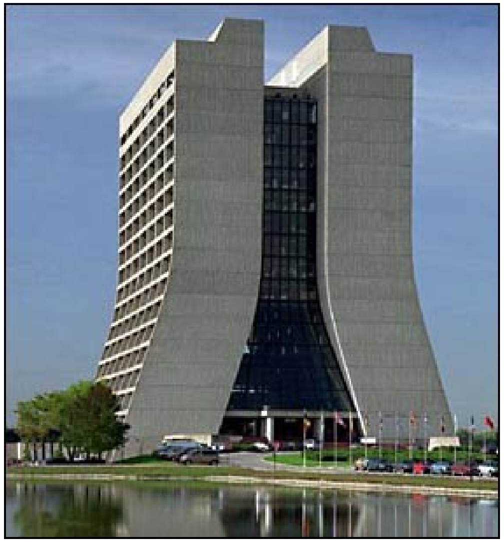


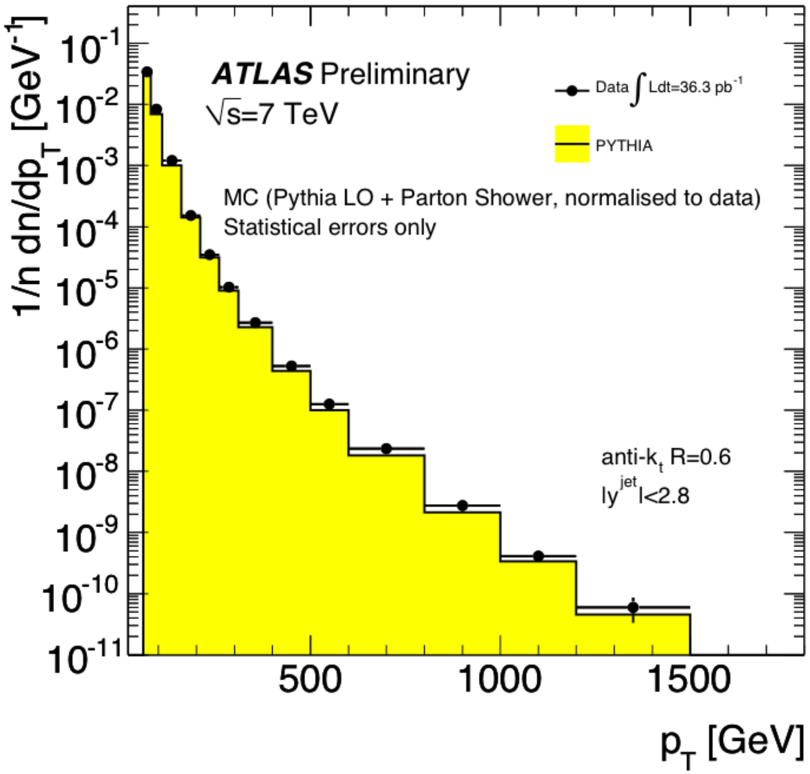
ATLAS Jets

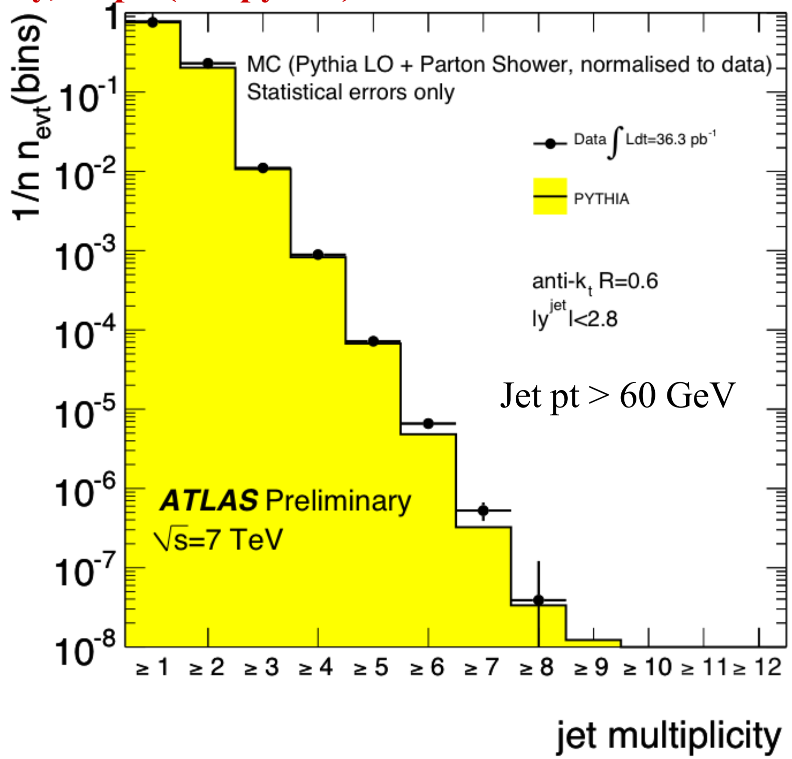
Adam Gibson
University of Toronto
On behalf of the ATLAS Collaboration

Standard Model Benchmarks at the Tevatron and LHC
Fermilab
November 19, 2010

Jet Physics at ATLAS

Illustration of the ATLAS reach in pt and multiplicity, 36/pb (LO pythia)



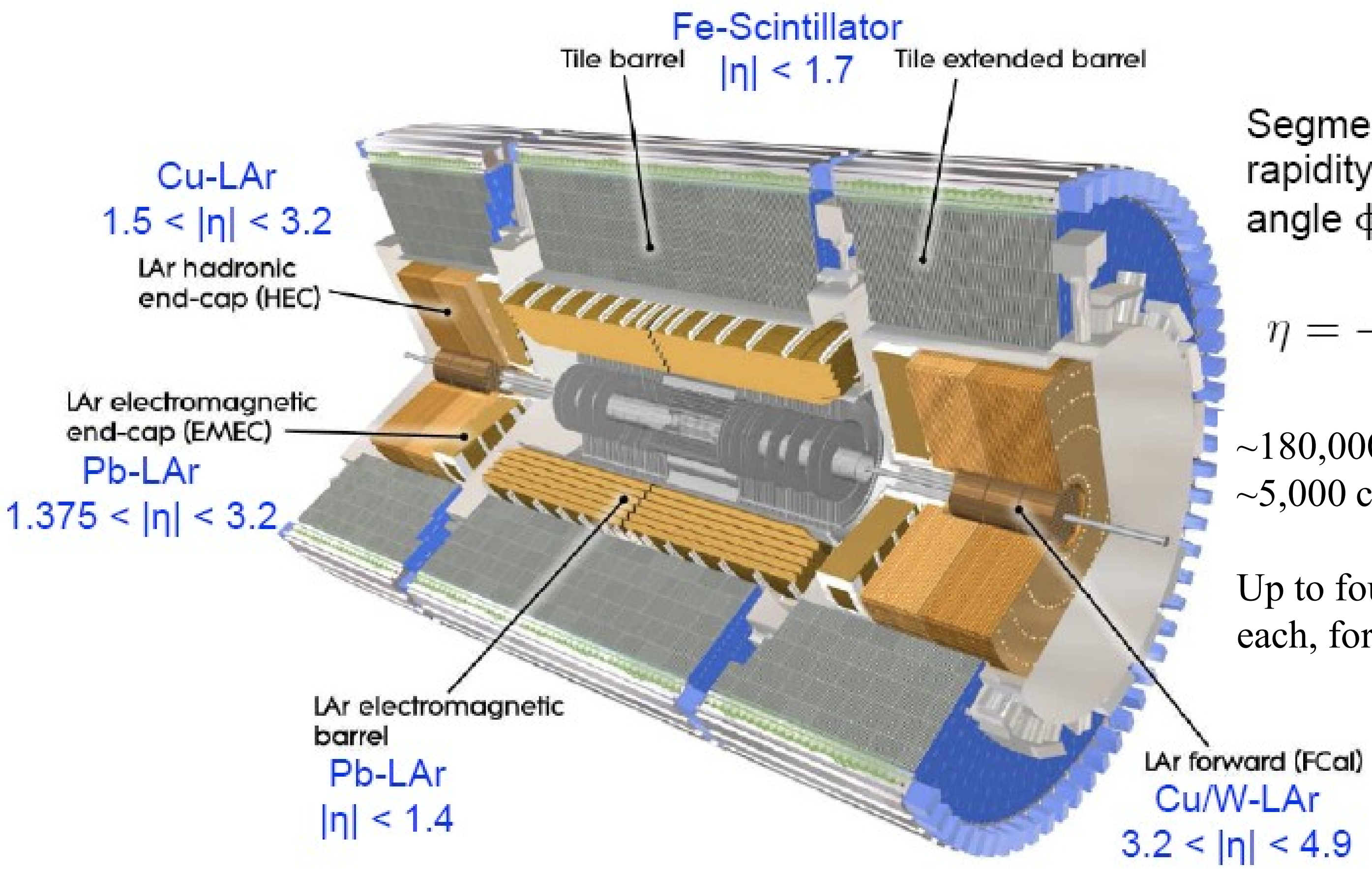


- Test QCD in a new kinematic regime, e.g. pQCD at high Q2
- Refine our understanding of soft QCD and it effects on jets and jet measurements
- Tune-up PDF's, MC’s (generators, simulation, etc.), calibrations, for ATLAS and the LHC
- Prepare for jetty measurements like top, Higgs, SUSY
- Look for discrepancies from SM QCD, and search for new physics with jets

Outline

- ATLAS and the LHC
- Jet reconstruction, properties, and calibration
- Inclusive jet and dijet cross sections
- More dijet and multi-jet studies
  - Azimuthal decorrelation
  - Multijet production
  - Dijet production with a jet veto
- Searches for new physics with jets

ATLAS Calorimeters



Segmented in pseudo-rapidity η and azimuthal angle ϕ

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

~180,000 cells in LAr calorimeter
~5,000 cells in Tile calorimeter

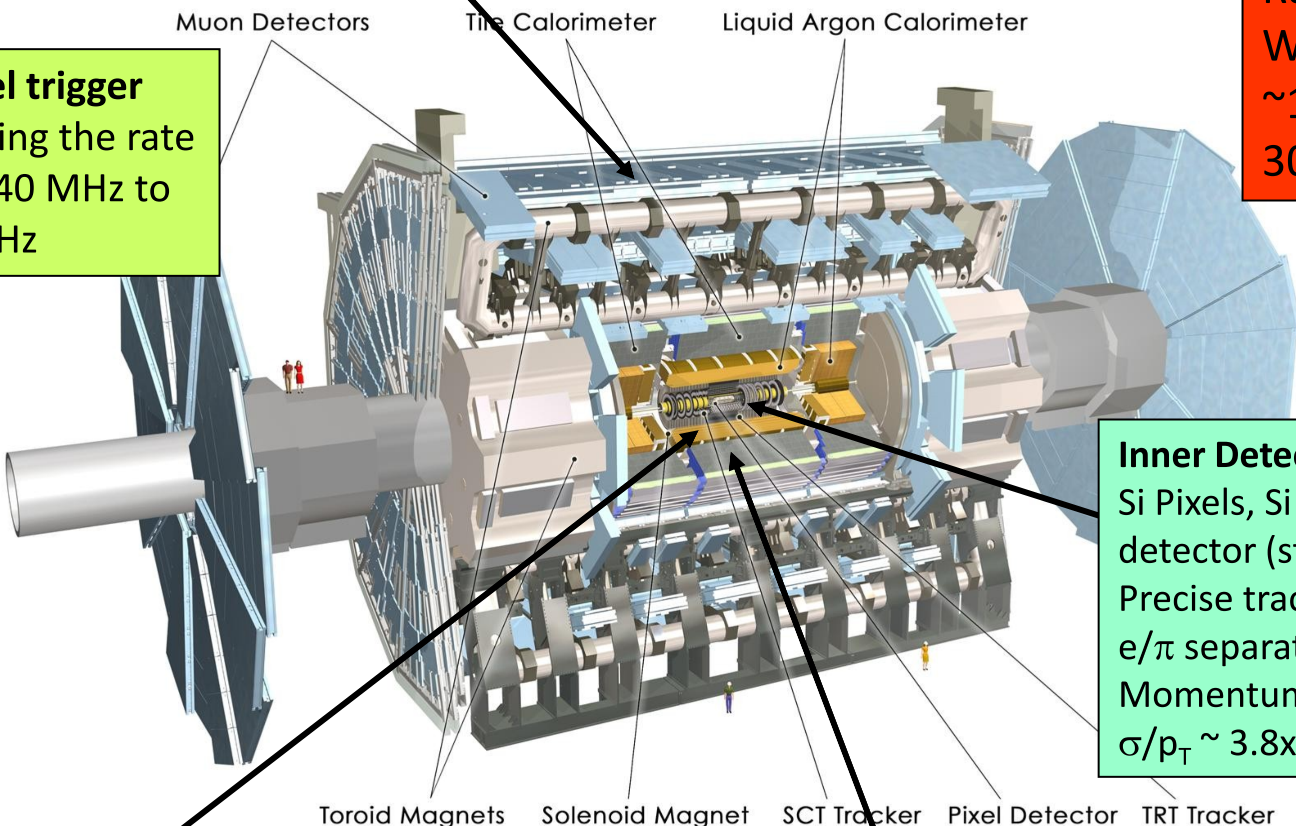
Up to four longitudinal samplings, each, for EM and hadronic.

Fine transverse and longitudinal segmentation.

Muon Spectrometer ($|\eta|<2.7$): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_{μ} ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger
reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T(\text{GeV}) \oplus 0.015$

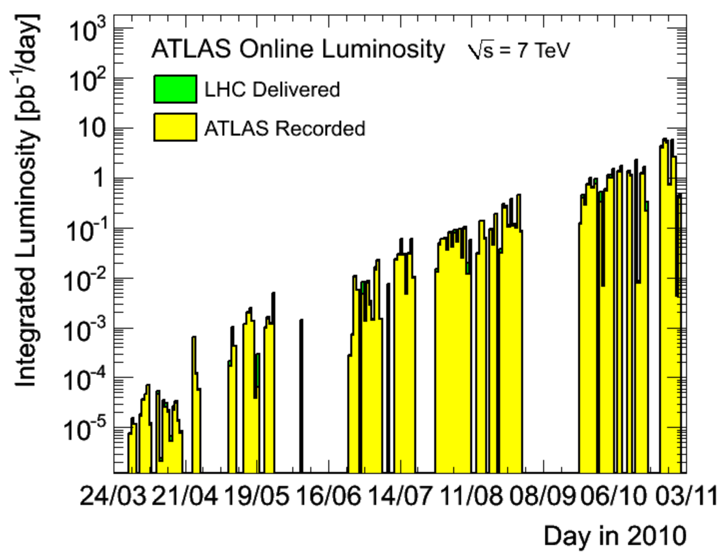
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

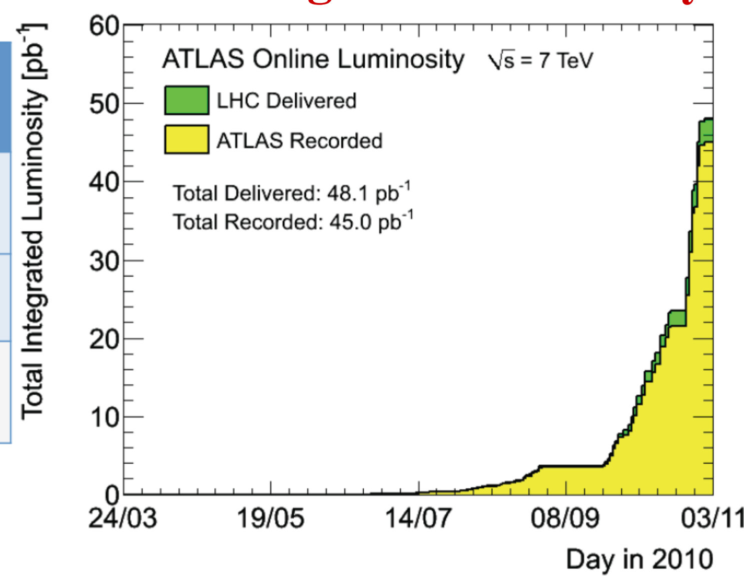
LHC and ATLAS Operations

- Exponentially increasing luminosity during 2010
  - ~2E32 /cm^2 / s by end of year
- Luminosity known to 11% from spring van der Meer scans (update forthcoming)
  - Uncertainty dominated by measurement of LHC beam currents
- Subsystems record good quality data
- An excellent start to high-energy pp operations!

Daily integrated luminosity



Total integrated luminosity



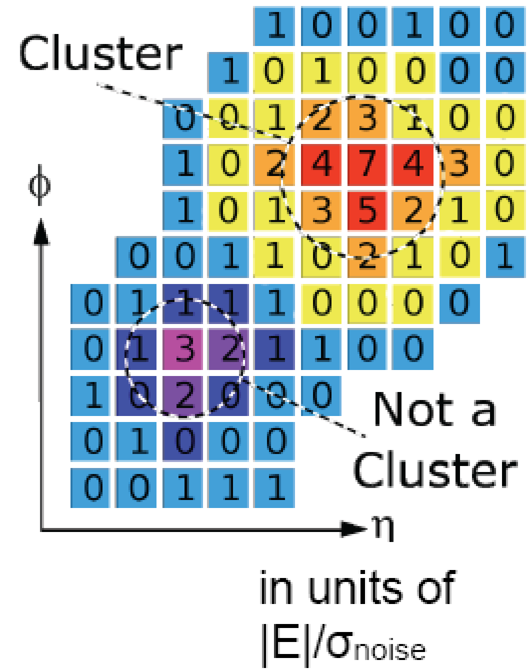
Subdetector fraction of good data for 45 pb^{-1} recorded

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.0	99.9	100	90.5	96.6	97.8	94.3	99.9	99.8	96.2	99.8

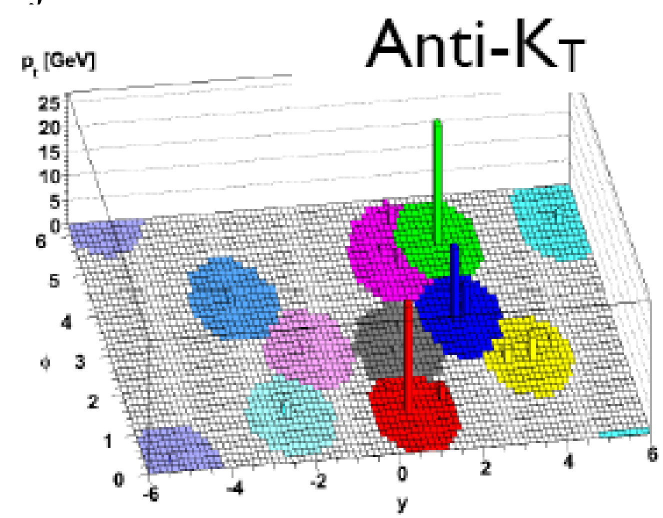
Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams at √s=7 TeV between March 30th and October 31st (in %). The inefficiencies in the calorimeters will largely be recovered in a future data reprocessing.

Jet Reconstruction at ATLAS

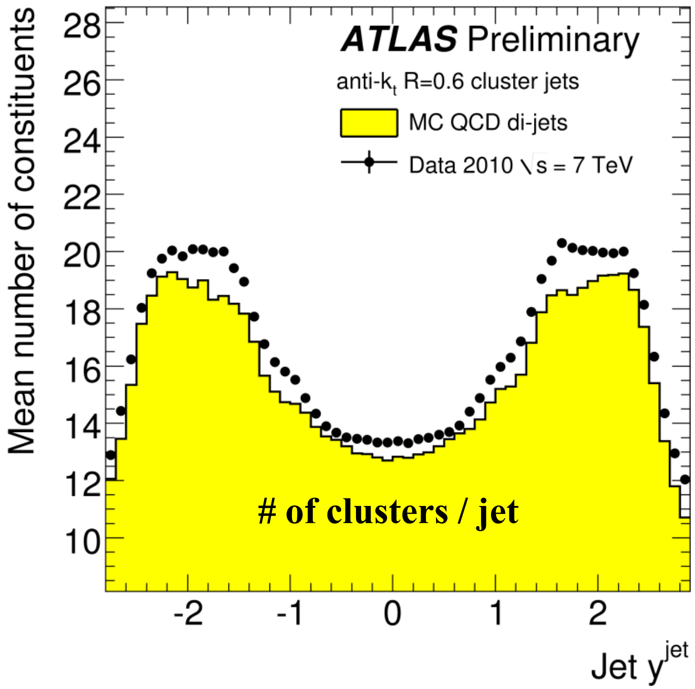
- Topological clusters (TopoClusters) of calorimeter cells
  - Reduce effect of noise, follow shower development
  - Seeded by cells with |E| > 4 x (noise level)
  - (3D) Neighboring cells with |E| > 2 x noise iteratively added
  - Then all neighbors around cluster (|E| > 0) added

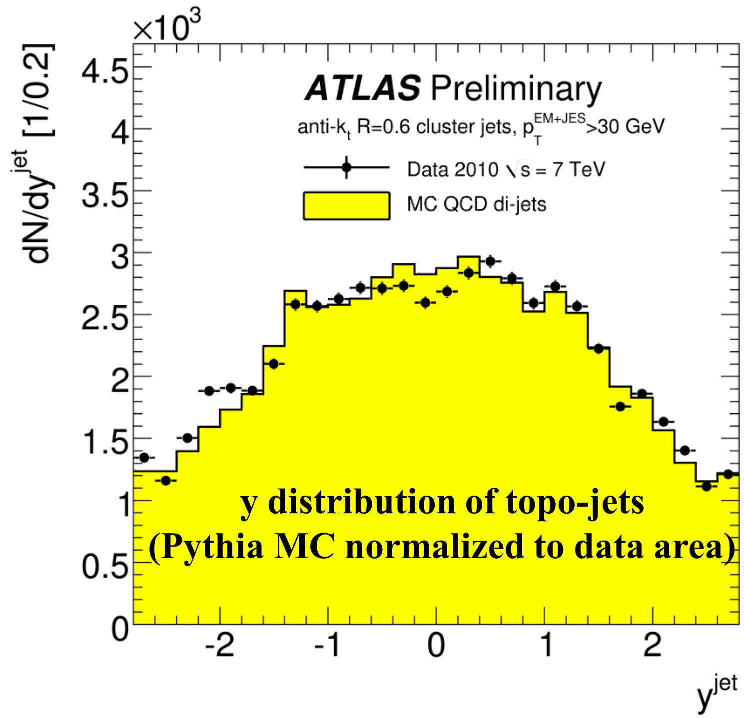


- Jets reconstructed w/ the anti-kT algorithm
  - M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)
  - Infrared and co-linear safe clustering algorithm around hard objects: produces geometrically well-defined cone-like jets
  - Size parameter, R, 0.4 or 0.6
  - In this talk we'll use TopoClusters as inputs, but ATLAS also uses tracks, noise-suppressed towers



Inputs to Jet Reconstruction





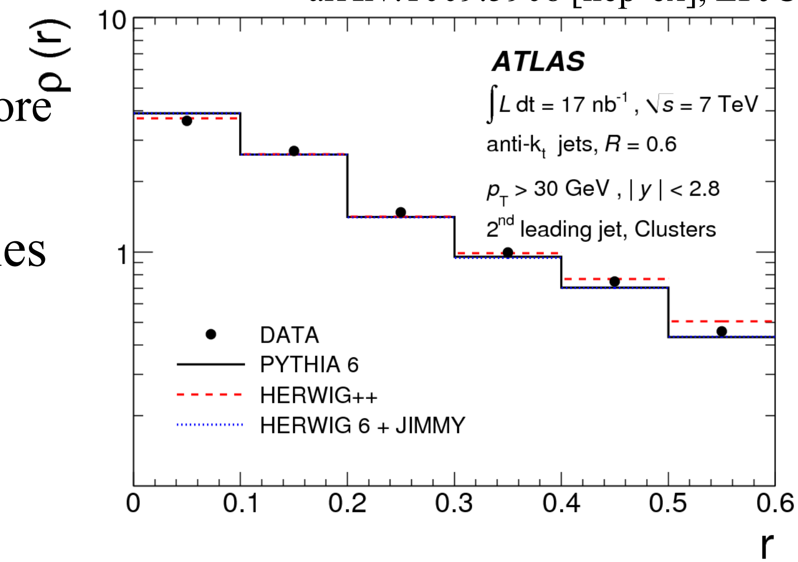
- ~4% fewer clusters seen in Pythia 6 MC
  - y distribution of jets, clusters, fairly well described

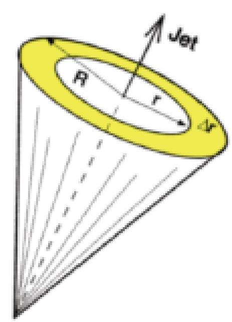
ATLAS-CONF-2010-053

Jet Shapes and Properties

- Test how well the simulation models physics and detector effects
  - Jet fragmentation, detector response to low energy particles, inputs to jet reconstruction, underlying event, pileup, etc.
- Jet shapes ρ(r) agree reasonably well with simulation
  - Considering the 2^{nd} jet, or inclusive jets
  - Pythia 6 may have somewhat too much energy in core
  - More complete analysis underway
- ATLAS-CONF-2010-053 discusses jet properties
  - Jets in data ~10% wider than in Pythia 6
  - Longitudinal profile
    - Hadronic showers in data deeper than in simulation
- Studies also conducted with track jets
  - Can be used to disentangle detector and physics effects

arXiv:1009.5908 [hep-ex], EPJC





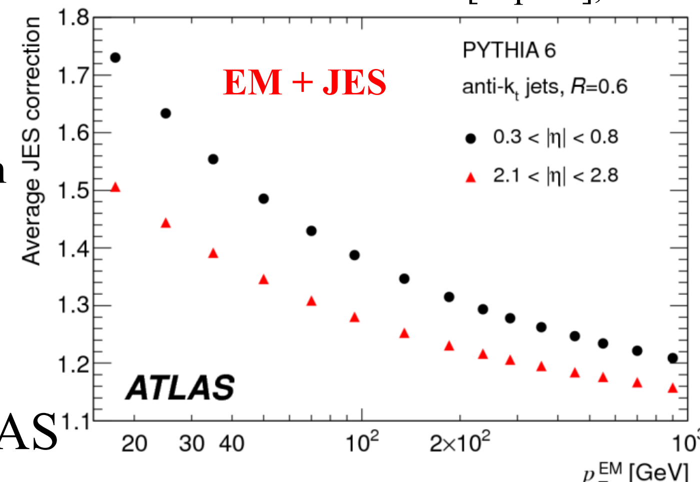
Uncorrected jet shape compared to simulation with $\rho(r) = p_T^r / p_T^R$

With p_T^R the energy within R of the jet center. p_T^r is the energy within a ring radius r, width Δr = 0.1, divided by Δr.

Jet Energy Calibration

- Dominant systematic uncertainty in many measurements involving jets or missing energy
- Current calibration scheme
  - Electromagnetic (EM) scale from test beam (electrons, muons)
  - MC-based correction referencing particle-level “truth jets” for
    - Difference in calorimeter response to EM and hadronic particles
    - Energy losses in front of calorimeter, “dead material”
    - Shower leakage
    - Inefficiencies in calorimeter clustering and jet reconstruction
  - Cross-checks with *in situ* data
    - Single particle response, E/p
    - Dijet and photon-jet balancing

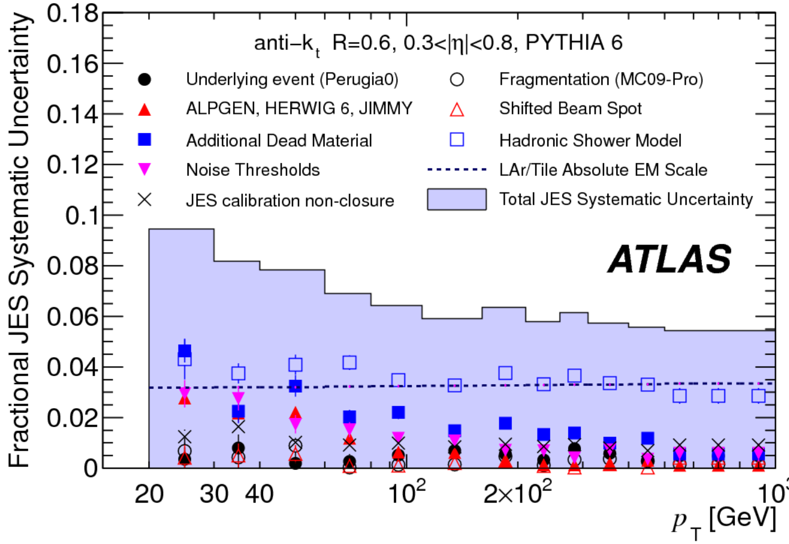
arXiv:1009.5908 [hep-ex], EPJC

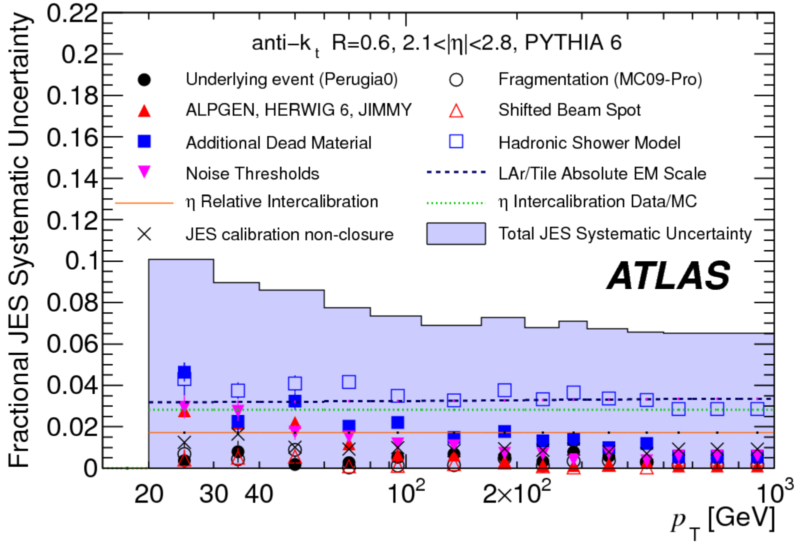


- Three MC-based corrections being explored by ATLAS
  - **EM+JES (current default):** simple pT and η dependent correction applied to EM scale jets
  - **Global Cell Weighting**: cell weights based on cell energy density: low density hadronic deposits, high density EM deposits; weights derived from fit to pt-reco / pt-true
  - **Local Cluster Weighting**: use properties of TopoCluster (e.g. energy density and position) to classify (EM, hadronic) and calibrate clusters; weights depend on shower topology, and are extracted from full simulation of single pions

Jet Energy Scale Uncertainty

- Dominant systematic uncertainty in ~all measurements involving jets or missing energy
- Uncertainty evaluated by comparing MC using various detector configurations, hadronic shower models, physics models
- Chief uncertainties
  - □ Hadronic shower model (GEANT) (~4%)
  - -- LAr/Tile EM Scale (3%)
  - ■ Detector material knowledge/simulation (~2%)
  - ▲ Generators, soft QCD modeling (<4%)
  - ▼ Noise description (<3%)
  - × "Closure Test" (<2%)
  - η intercalibration, for non-central jets, from *in situ* dijet balance (<3% for |η| < 2.8)
  - For e.g. dijet measurements, uncertainty decorrelated in η (<3% for |η| < 2.8)
  - Pile-up (variable)
- Overall uncertainty 6-10% for |η| < 2.8
  - Depending on pt, η
  - ~40% uncertainty on jet cross section

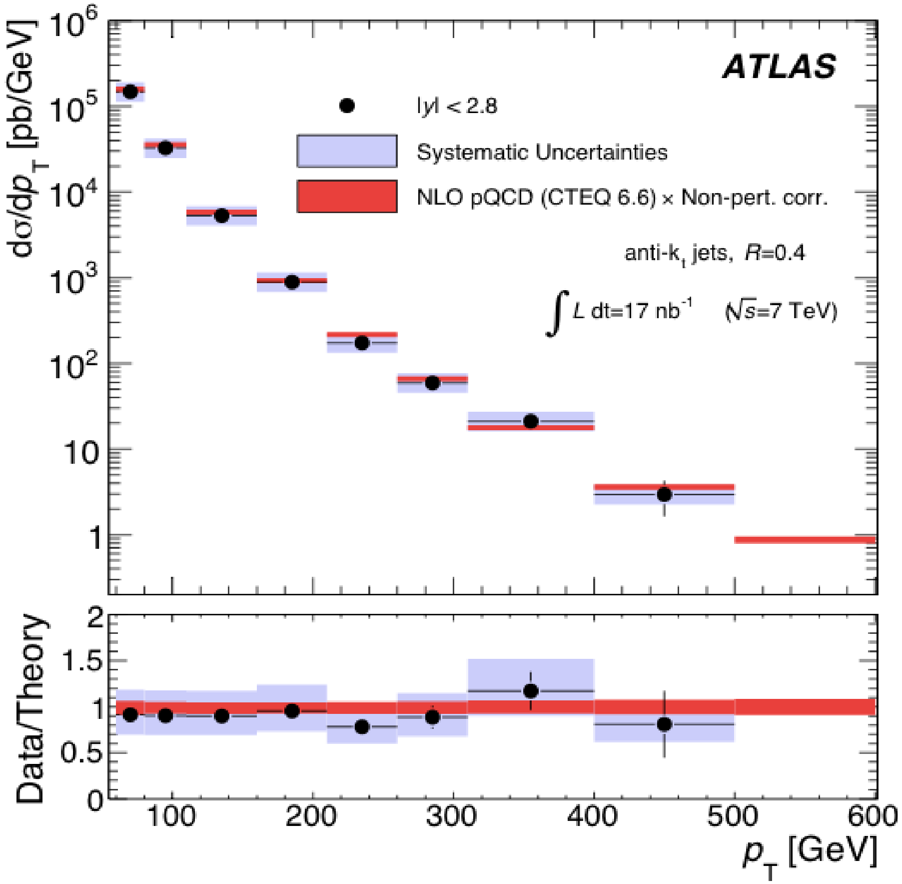


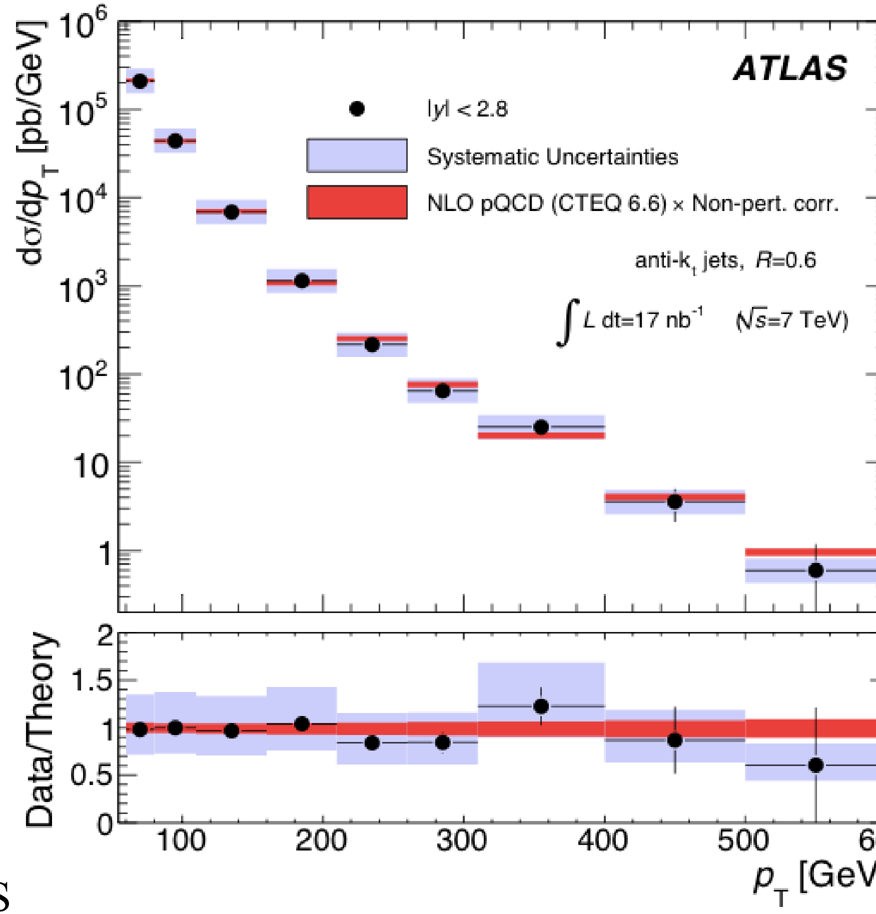


Inclusive Jet and Dijet Production

- Classic arena for studying hard scattering
  - Believed to be well described by pQCD + proton PDF's
  - Test of these tools in a new *Q*2 regime
- Accepted by EPJC with 17/nb. Now >35/pb available for analysis.
- Require at least one jet with pt > 60 GeV, |y| < 2.8
  - 60 GeV cut simplifies triggering
  - Dijet measurements require a second jet with pt > 30 GeV, |y| < 2.8
- Apply a bin-by-bin correction factor (<20%) to unfold data to particle-jet level
  - Compare to NLOJET++ corrected (for non-perturbative effects) to particle-jet level
- Also compare shapes of distributions to LO MC w/parton showers
- Comparisons dominated by jet energy scale uncertainty
  - Except at pt >~300 GeV where we're limited by statistics
  - Just 17/nb in this publication, e.g. low pile-up dataset
- NLO pQCD agrees well with data, over 5 orders of magnitude

Inclusive Jet Cross Sections





- Inclusive single jet cross section measured to *pt* of 550 GeV

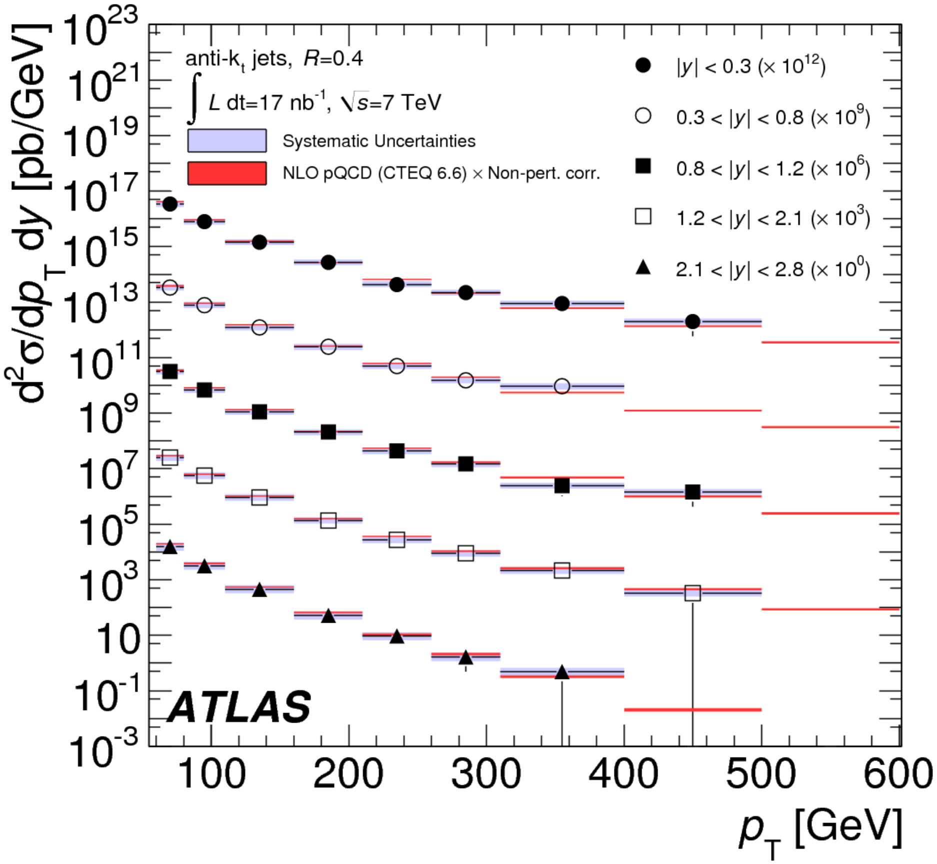
-Excellent agreement with NLO prediction over 5 orders of magnitude for different R parameters (different sensitivity to soft QCD corrections)

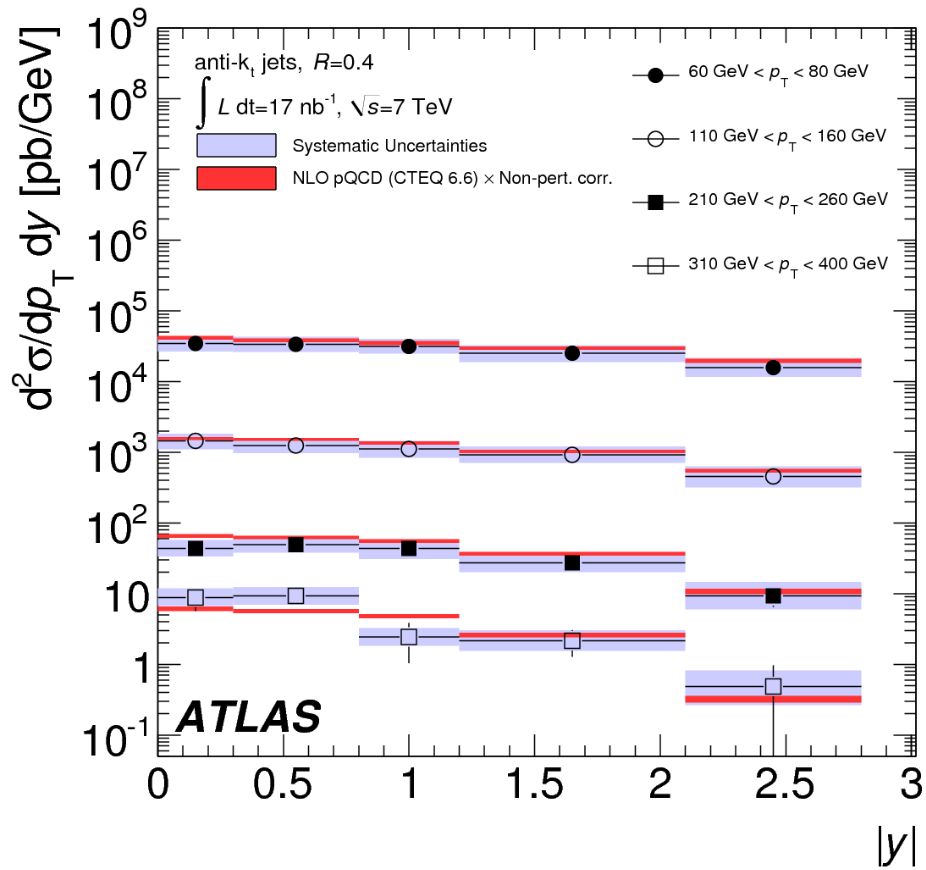
- Dominant systematic uncertainty for the data is the JES

- 11% Luminosity uncertainty not shown (true for many plots in this talk)

CERN-PH-EP-2010-034
arXiv:1009.5908 [hep-ex]
Accepted by EPJC

Inclusive jet double-differential cross sections



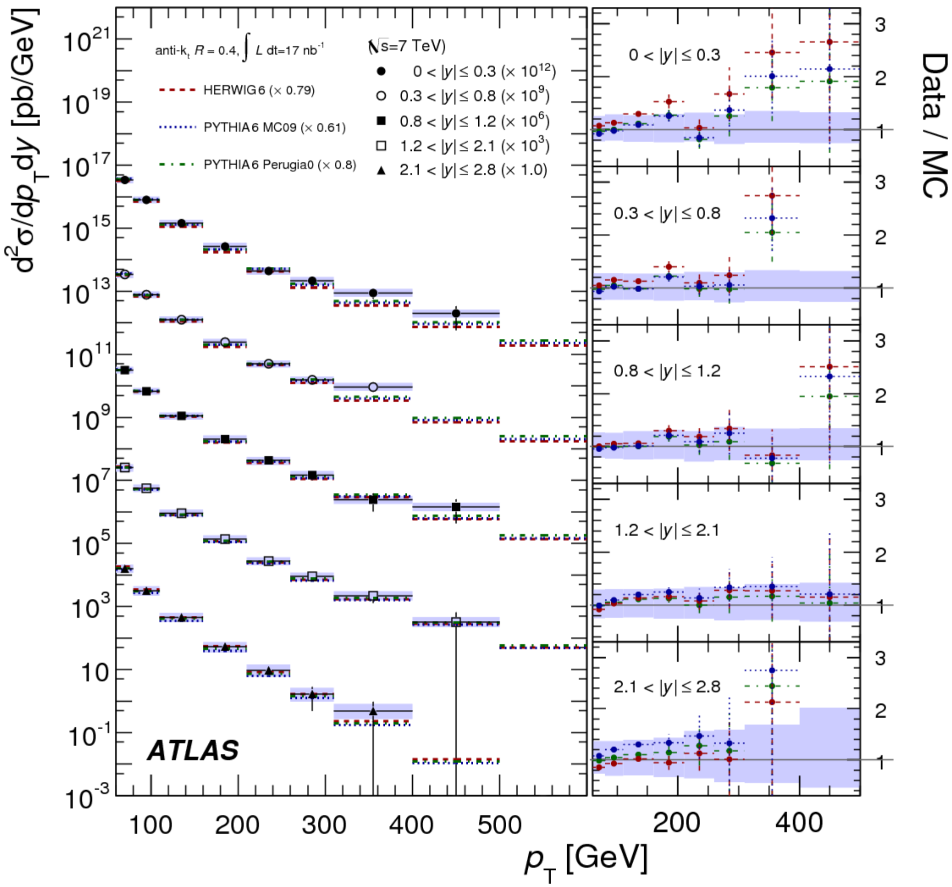


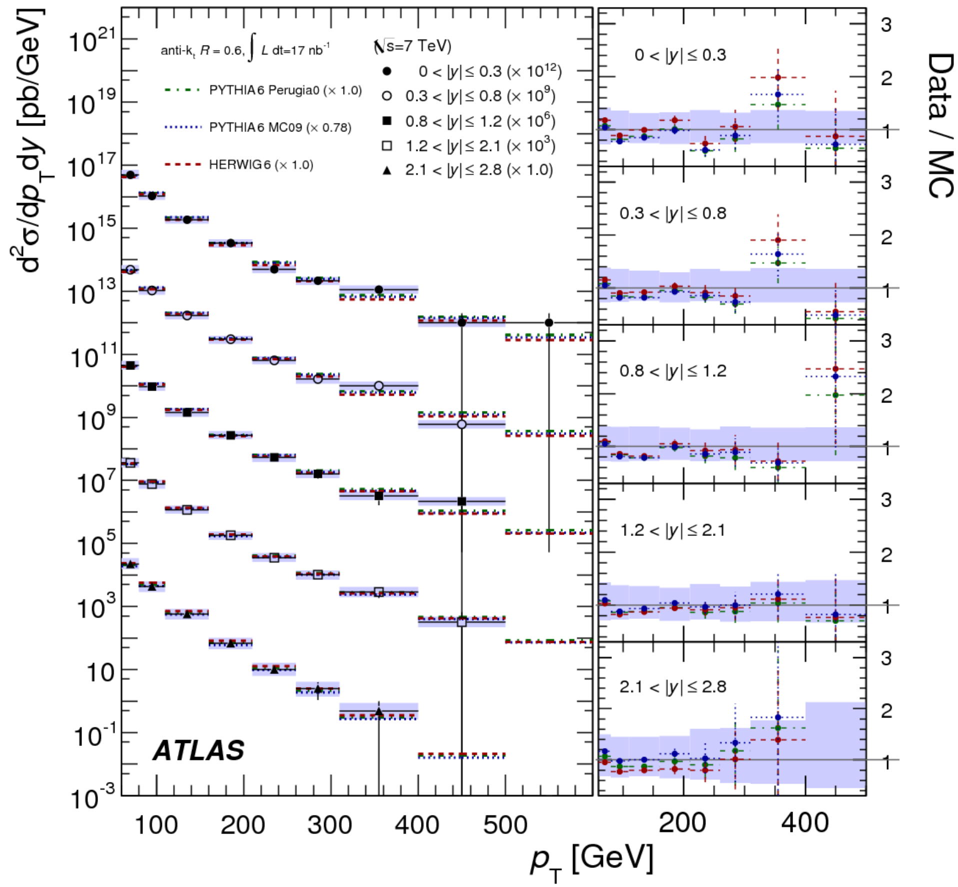
-Excellent agreement with NLO predictions for different slices in rapidity

CERN-PH-EP-2010-034
arXiv:1009.5908 [hep-ex]
Accepted by EPJC

Inclusive Jet Cross Section Compared LO MC

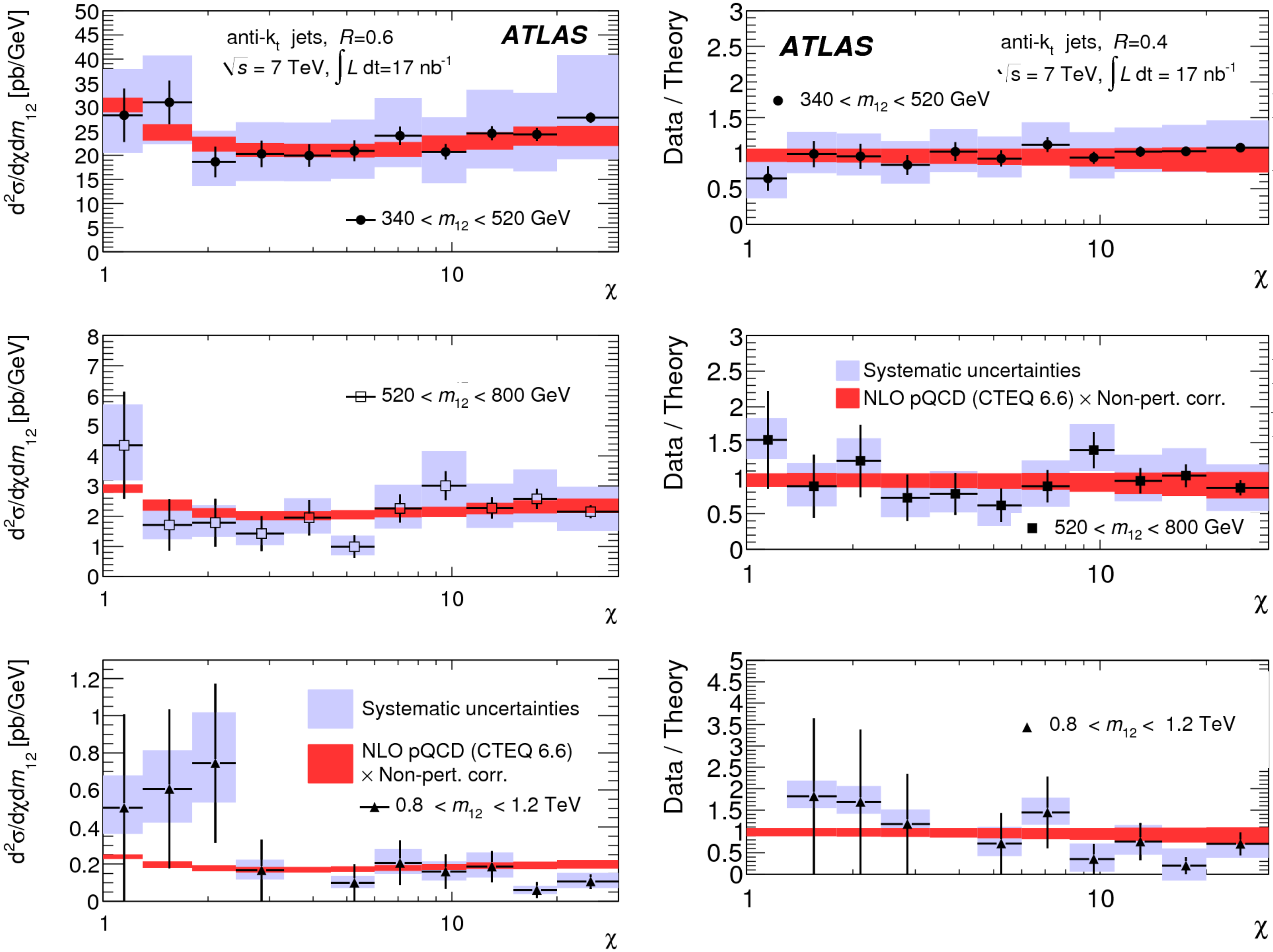
- Compare shape to HERWIG 6 + Jimmy, Pythia 6 with different underlying event and fragmentation tunes





CERN-PH-EP-2010-034
arXiv:1009.5908 [hep-ex]
Accepted by EPJC

Dijet double-differential cross sections as a function of χ = exp (|y1-y2|)



$\chi = (1+\cos\theta^*)/(1-\cos\theta^*)$

Leading jet pt > 60 GeV

2^{nd} jet p2 > 30 GeV

|y| < 2.8

Excellent agreement with NLO pQCD

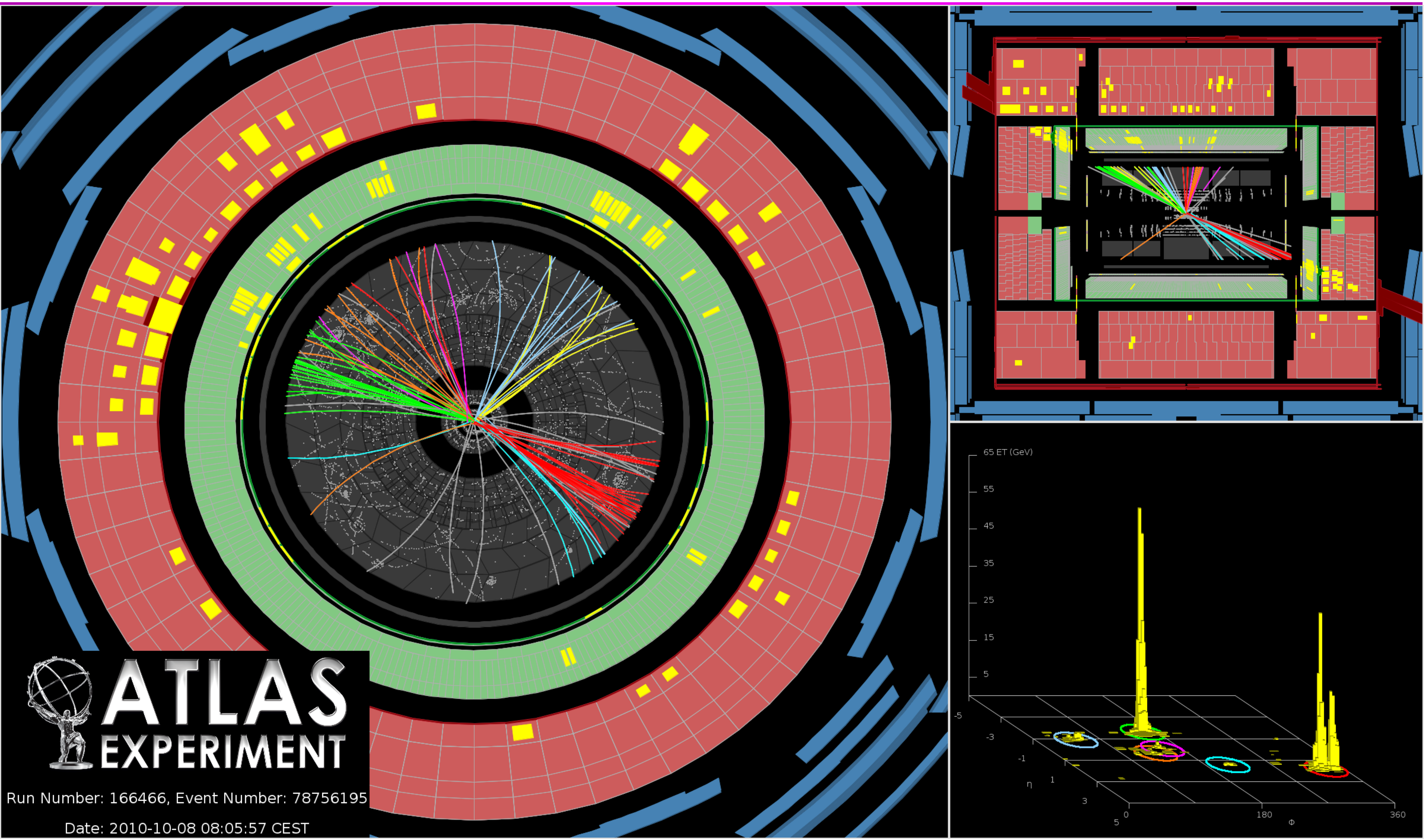
CERN-PH-EP-2010-034

arXiv:1009.5908 [hep-ex]

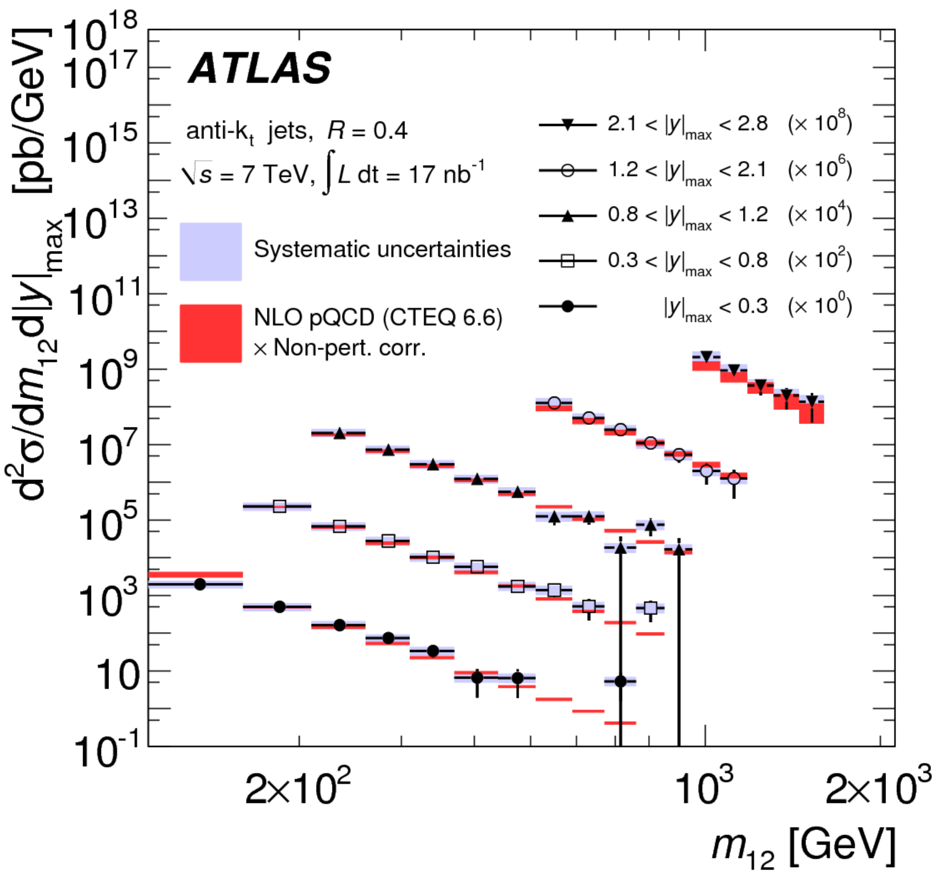
Accepted by EPJC

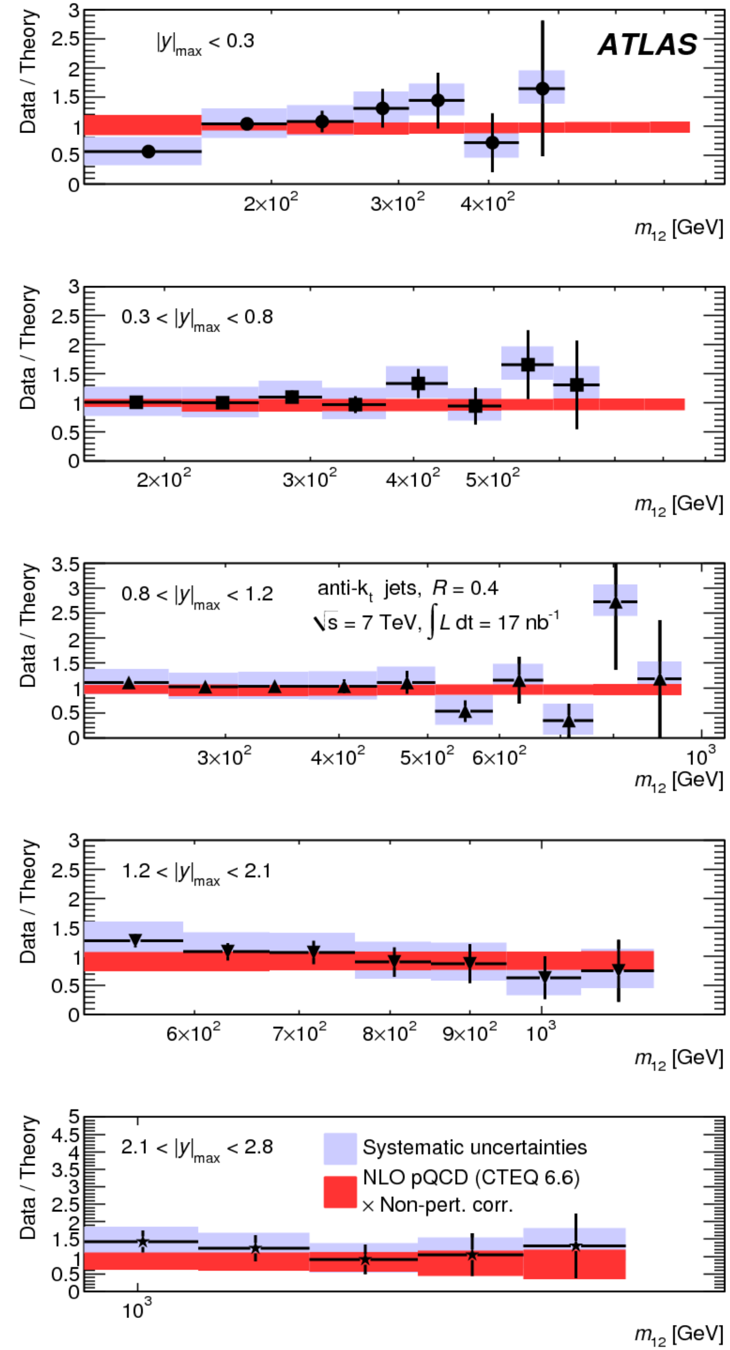
Highest mass dijet event

p_T jet1=670 GeV,
p_T jet2=610 GeV, m_{jj}=3.7 TeV



Dijet double-differential cross section as a function of m12

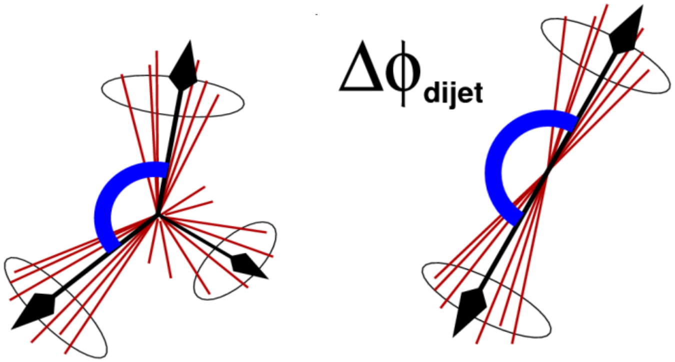


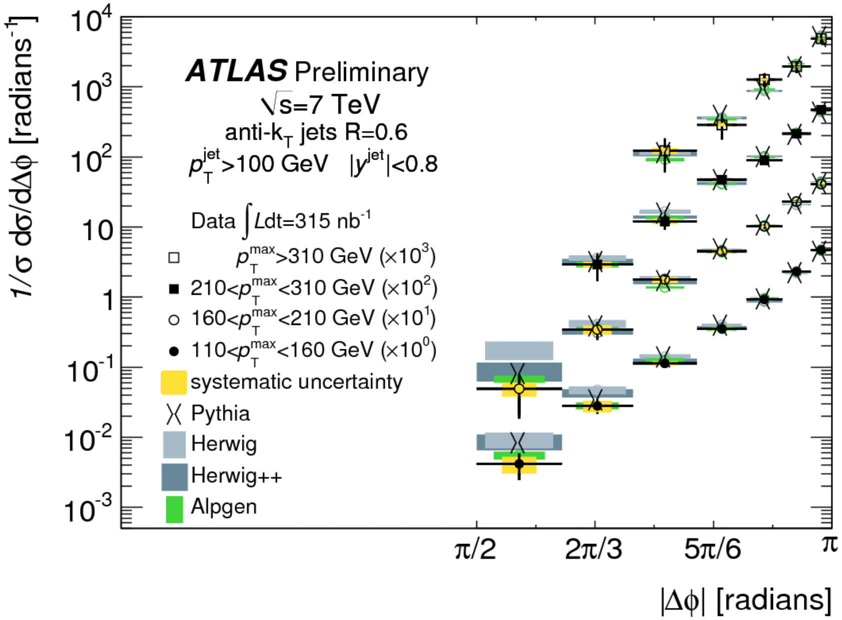


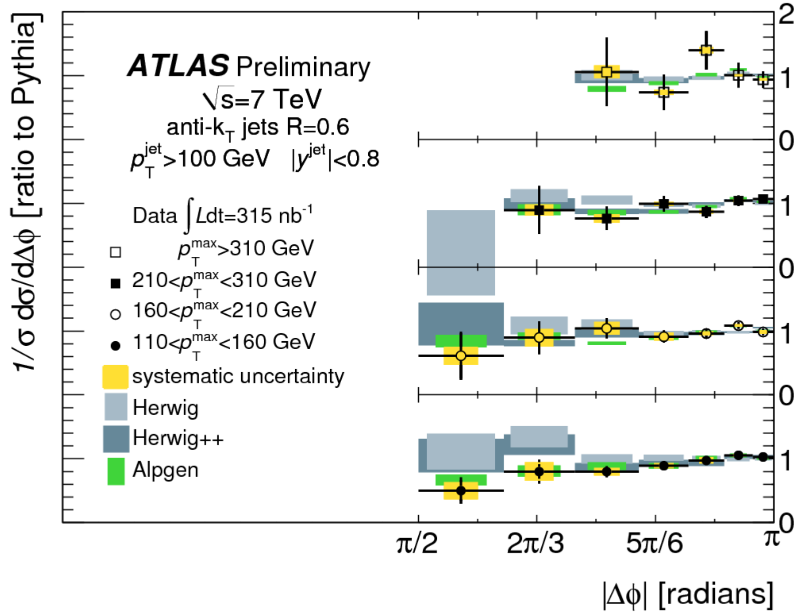
- Dijet cross section measured to **M ~ 2 TeV**
- **Excellent agreement with NLO predictions**

Azimuthal Decorrelations in Dijet Events

- Inclusive dijet events are not back-to-back in ϕ
- Soft and hard QCD effects
- Does MC describe it properly?
  - Can be used to tune ISR







Alpgen works well over 3 orders of magnitude

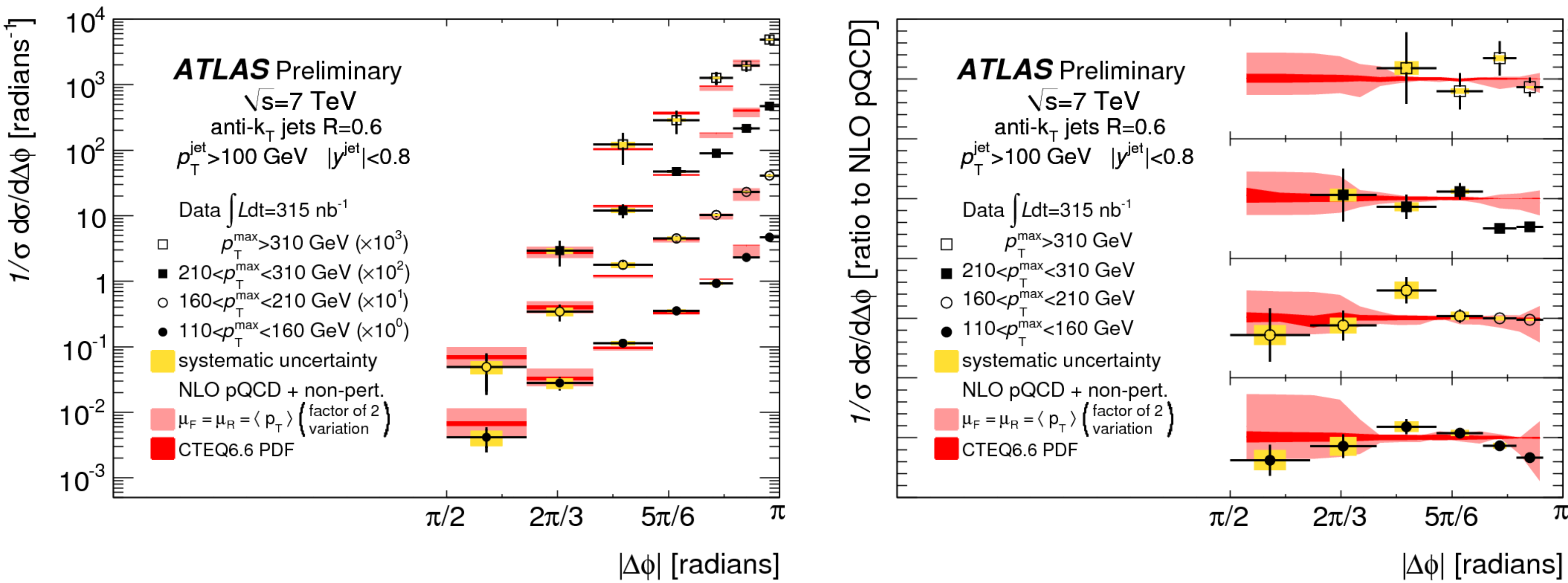
ATLAS-CONF-2010-083

Azimuthal Decorrelations in Dijet Events, cont.

- As for the inclusive jet cross section, we correct data to particle-jet level
  - Bin-by-bin unfolding correction for data, to particle-jet level
  - Compare to particle-jet level MC (previous page)
  - Or, correct NLOJet++ for non-perturbative effects, to particle-jet level
- Differential cross section and ratio
  - Agrees with NLO pQCD predictions

ATLAS-CONF-2010-083

- Statistics limited, except for pt < 160 GeV (then JES, etc.)

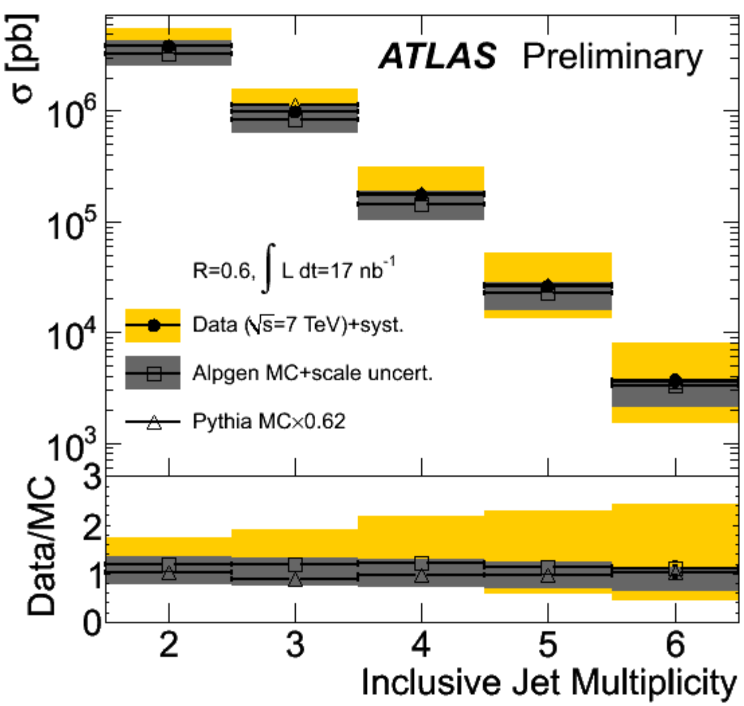


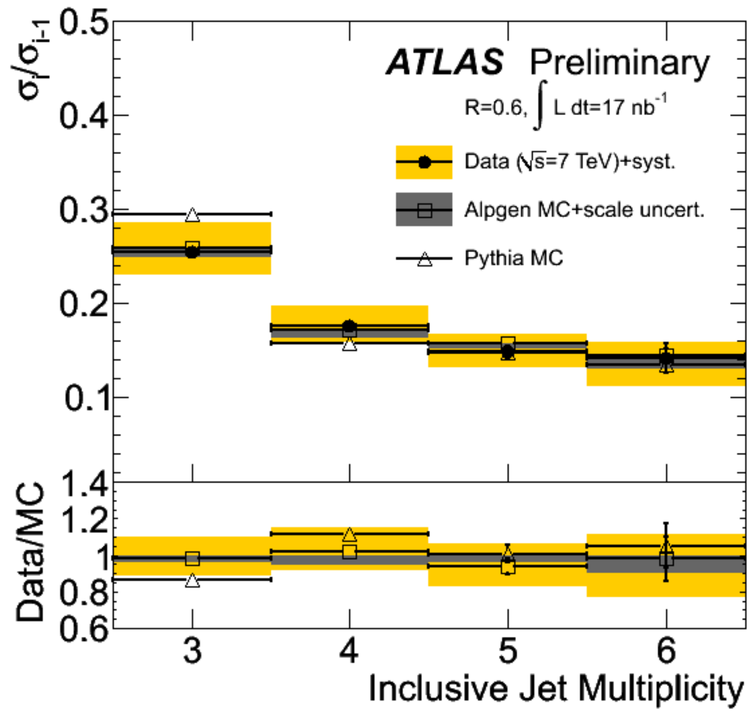
Multijet production

- Can we count and characterize the additional jets?
  - Essential to understand for new-particle searches

ATLAS-CONF-2010-084

- Count jets with pt > 30 GeV, |y| < 2.8
  - Require at least one jet with pt > 60 GeV
  - Bin-by-bin unfolding factor derived from fully simulated MC
  - Jet energy scale depends on distance to nearest jet, overlap
  - An additional systematic uncertainty is applied (e.g. default corrections often derived from isolated jets)
- Plot ratio of cross sections for successive multiplicities
  - Many systematic uncertainties cancel; Alpgen seems to do better than Pythia

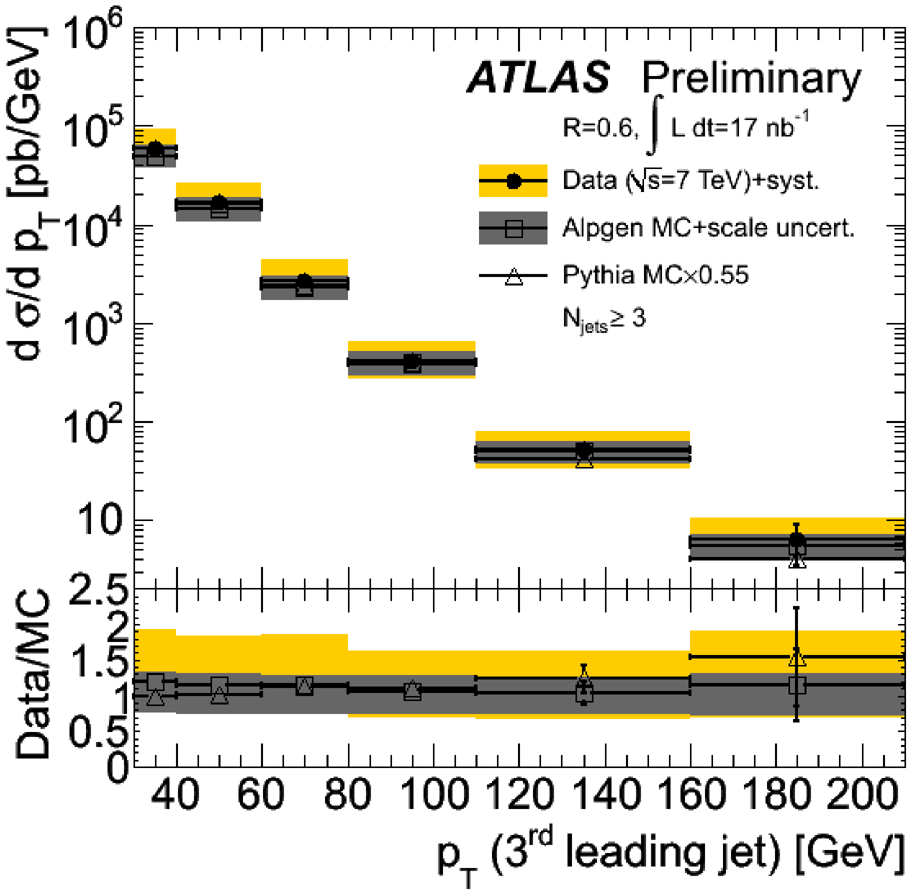


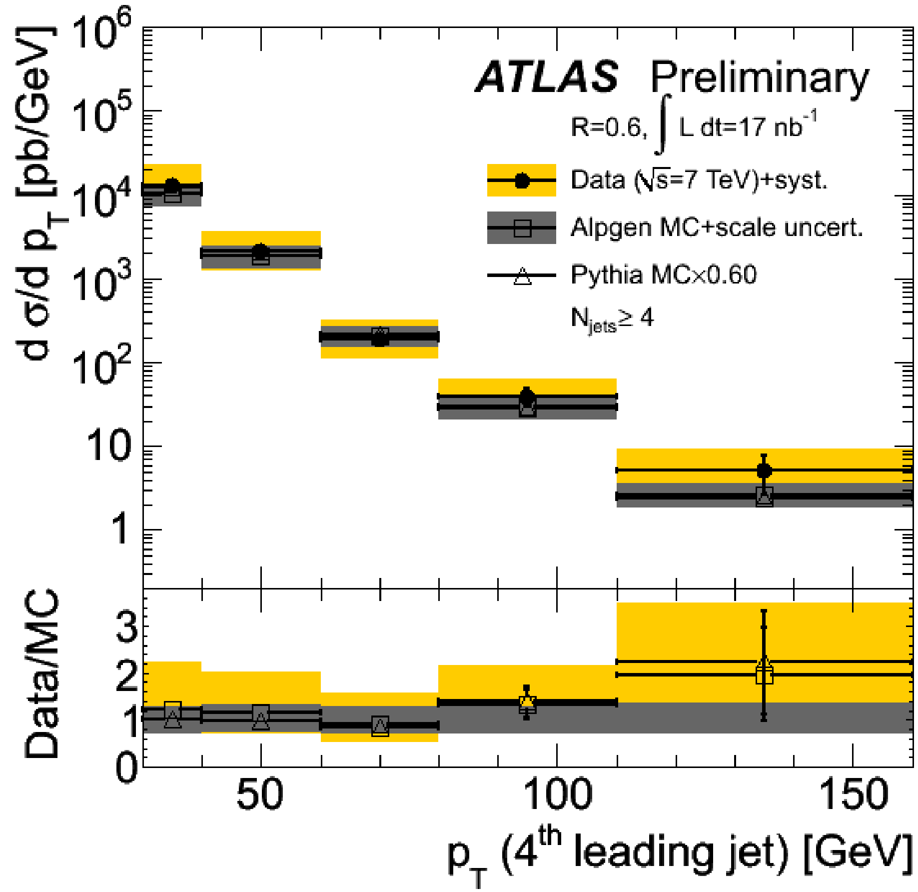


Multijet production, cont.

- Do we understand the *pt* spectrum of the extra jets?
  - Pythia spectrum renormalized to data for each jet multiplicity
  - Results in good agreement with Alpgen

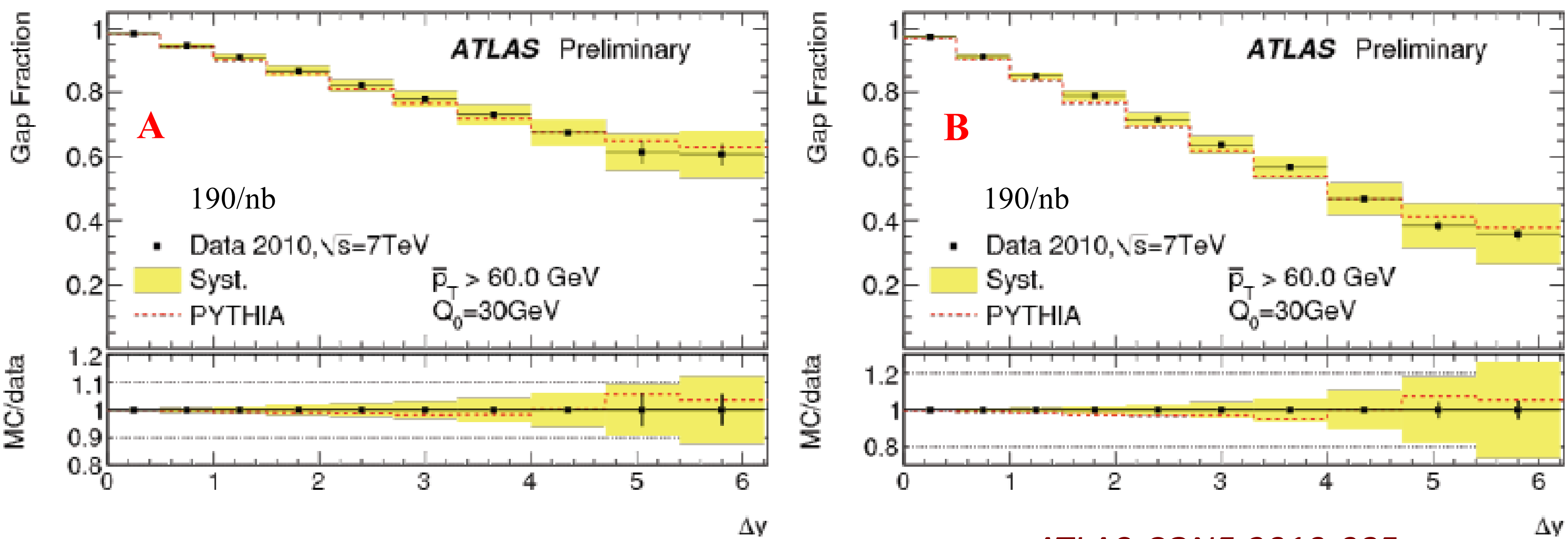
ATLAS-CONF-2010-084





Measurement of dijet production with a jet veto

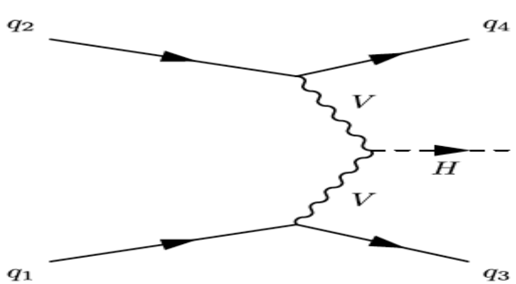
- Define "boundary jets" as either:
  - **A: Boundary jets are the two highest pT jets**
  - **B: Boundary jets are the two most forward/backward jets with pT > 30 GeV**
- Select dijet events w/ boundary jets pt1, pt2 > 30 GeV, (pt1 + pt2) / 2 > 60 GeV.
  - Use jets with $|\eta| < 4.5$, additional uncertainty of up to 10%
- Plot "Gap Fraction": fraction of dijet events with no jet, pT > 30 GeV, in the gap between the boundary jets

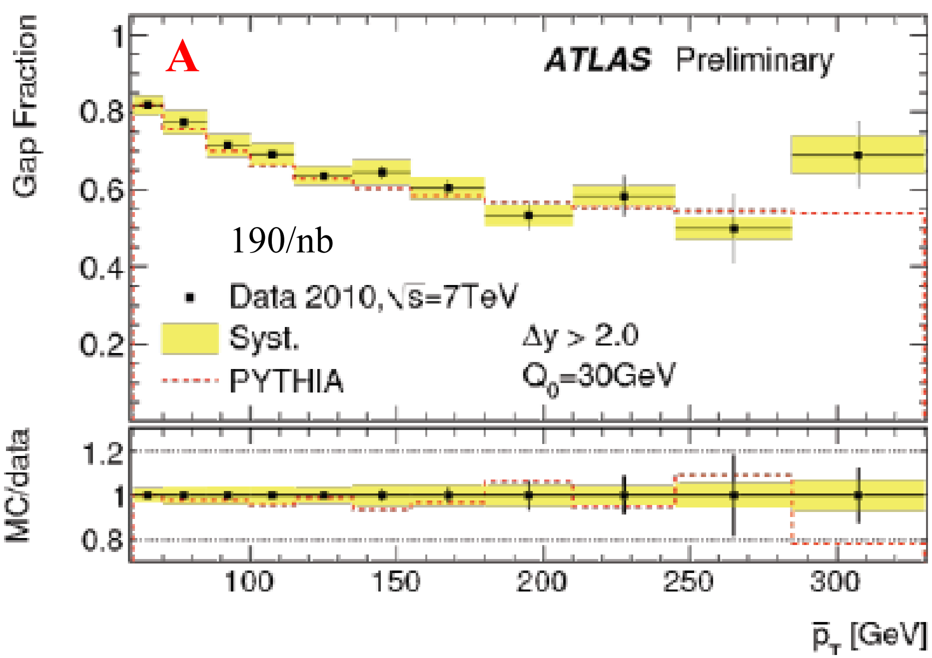


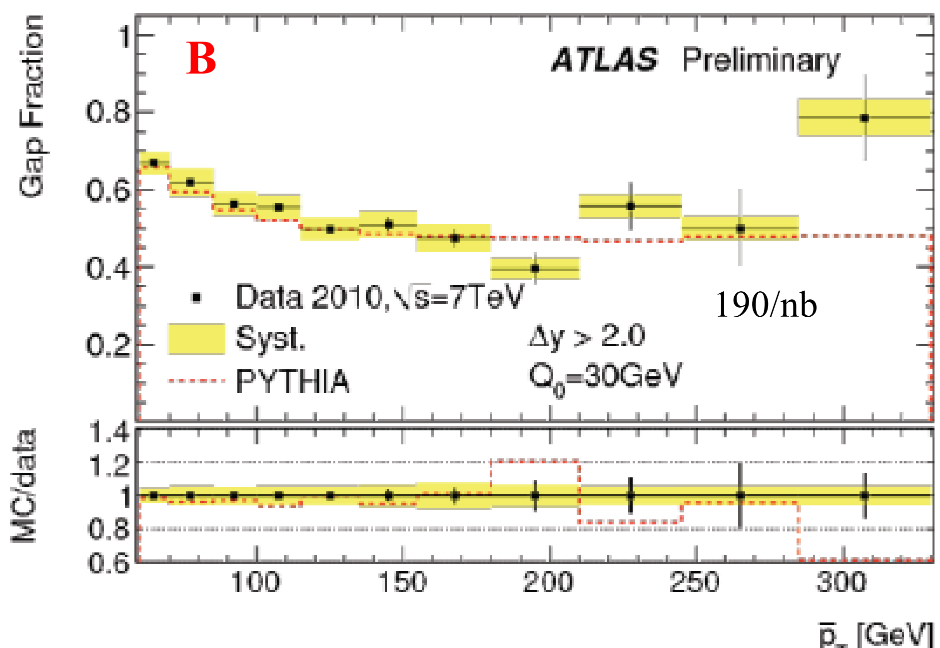
ATLAS-CONF-2010-085

Measurement of dijet production with a jet veto, cont.

- Probes a variety of QCD phenomena
  - BFKL-like dynamics
  - Wide-angle, soft-gluon radiation
  - Color singlet exchange
  - Move to lower veto pT, higher y and Δy
- Important for Vector Boson Fusion (VBF) Higgs
  - Central jet veto to reduce backgrounds







ATLAS-CONF-2010-085

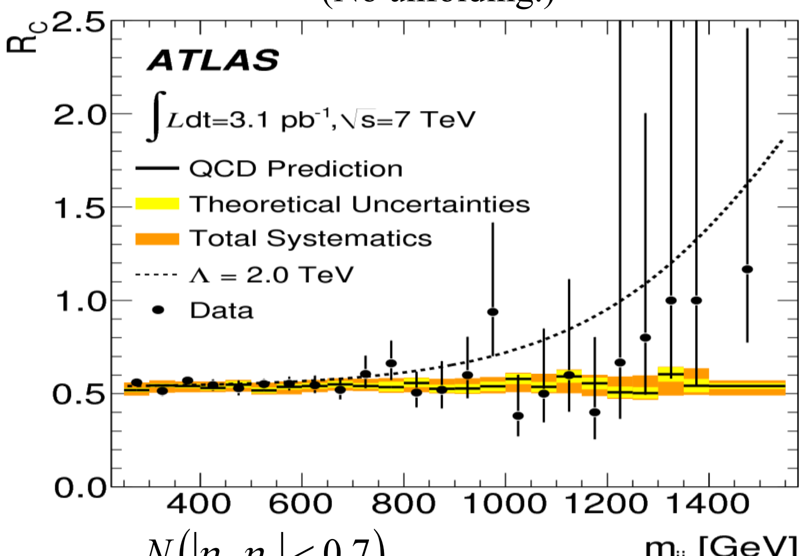
Search for Quark Contact Interactions in Dijet Angular Distributions

Accepted by Phys. Lett. B
DOI:10.1016/j.physletb.2010.10.021

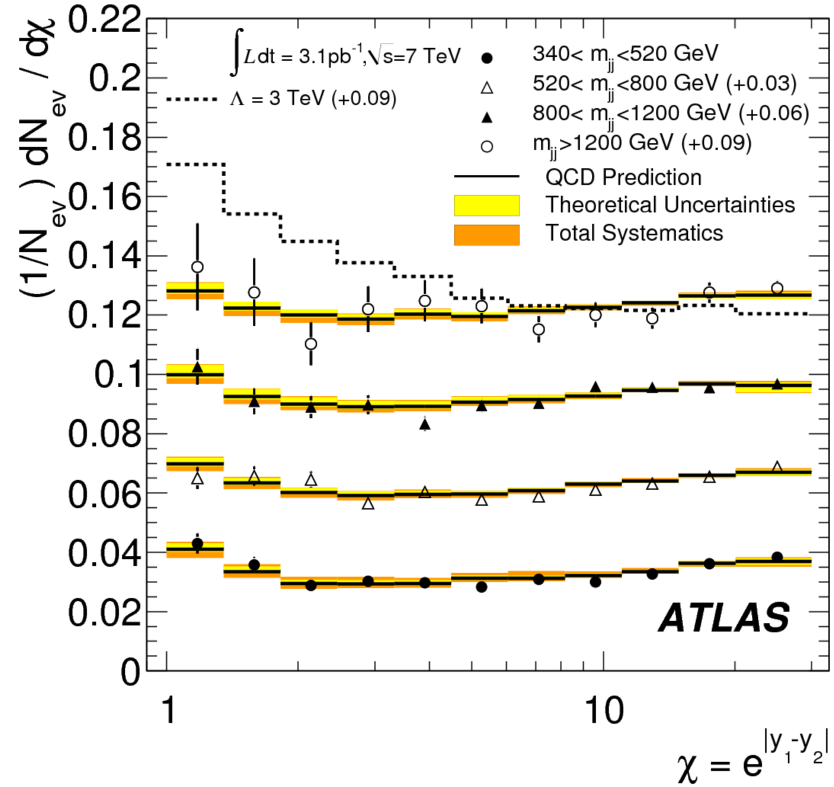
From χ: Λ_q>3.4 TeV (95% CL)

Compare D0, Λ_q > 2.8-3.1 TeV
Phys. Rev. Lett. 103, 191803 (2009)

Fully simulated MC compared to detector-level jets.
(No unfolding.)



$$R_C = \frac{N\left(|\eta_1,\eta_2|<0.7\right)}{N\left(0.7<|\eta_1,\eta_2|<1.3\right)}$$



With no deviation from QCD prediction seen in the highest mass bin, use Fχ, the fraction of events in the first four χ bins, to limit Λ.

See also arXiv:1010.4439v1 [hep-ex] from CMS.

Search for New Particles in Two-Jet Final States

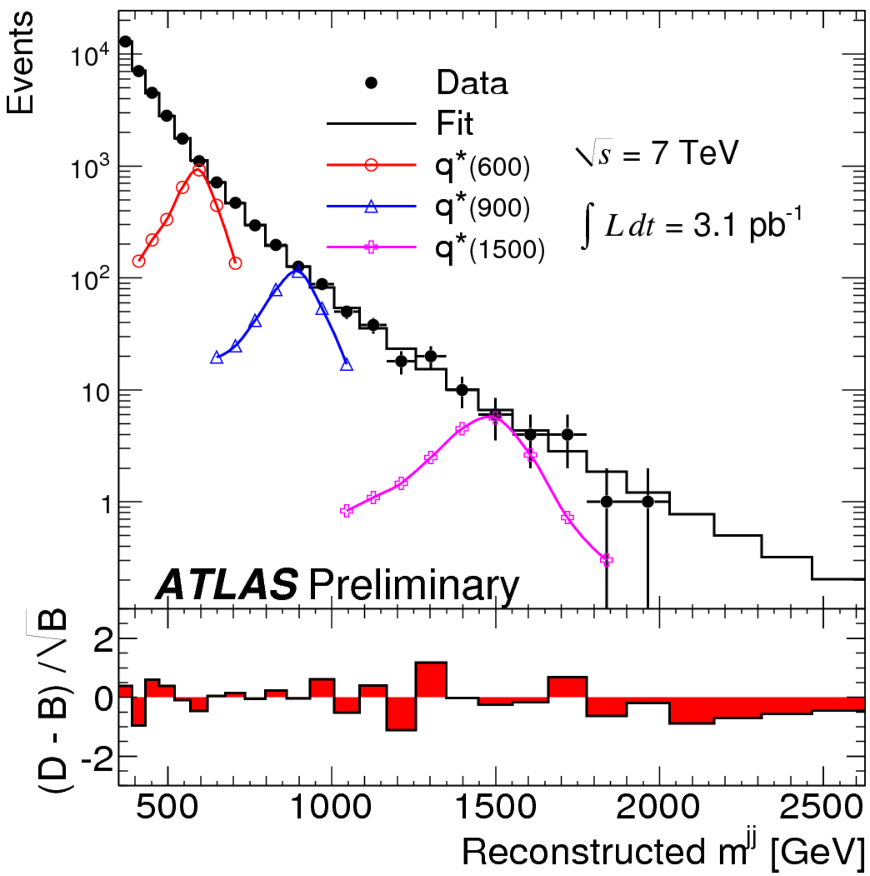
315/nb published in
Phys. Rev. Lett. 105, 161801 (2010)

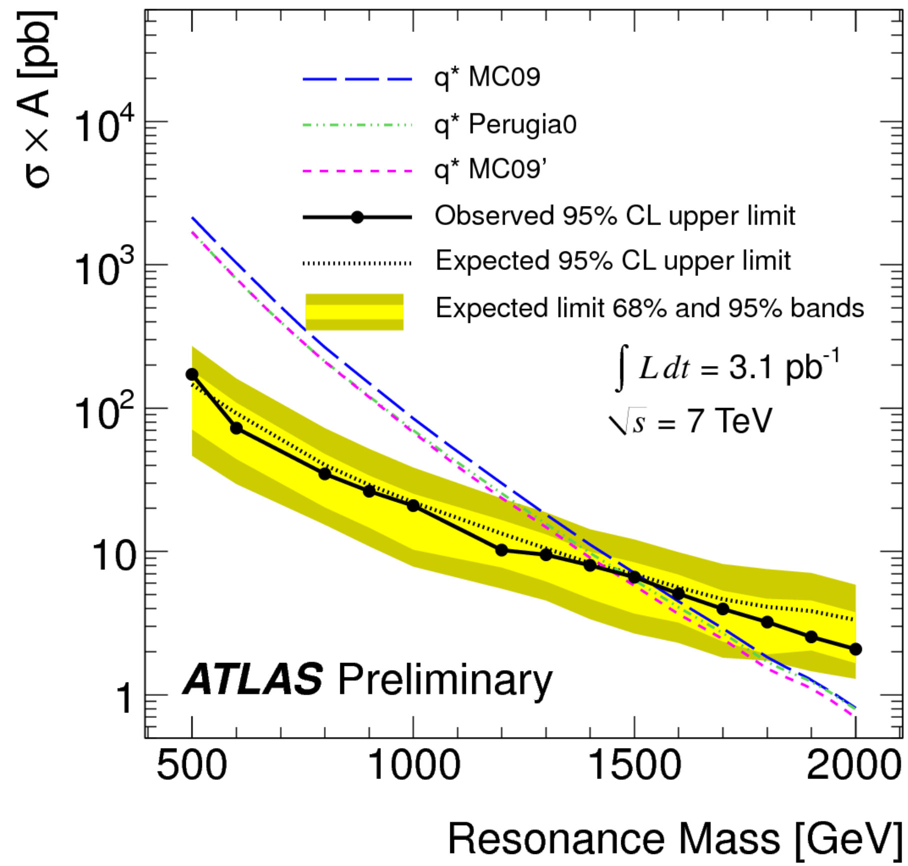
Detector-level jets (no unfolding), which are compared to fully simulated MC for limit setting.

m(q*)>1.53 TeV (95% CL)

3.1/pb: ATLAS-CONF-2010-093

Compare CDF, m(q*) > 870 GeV
Phys. Rev. D 79, 112002 (2009)





See also Phys. Rev. Lett. 105, 211801 (2010) from CMS.

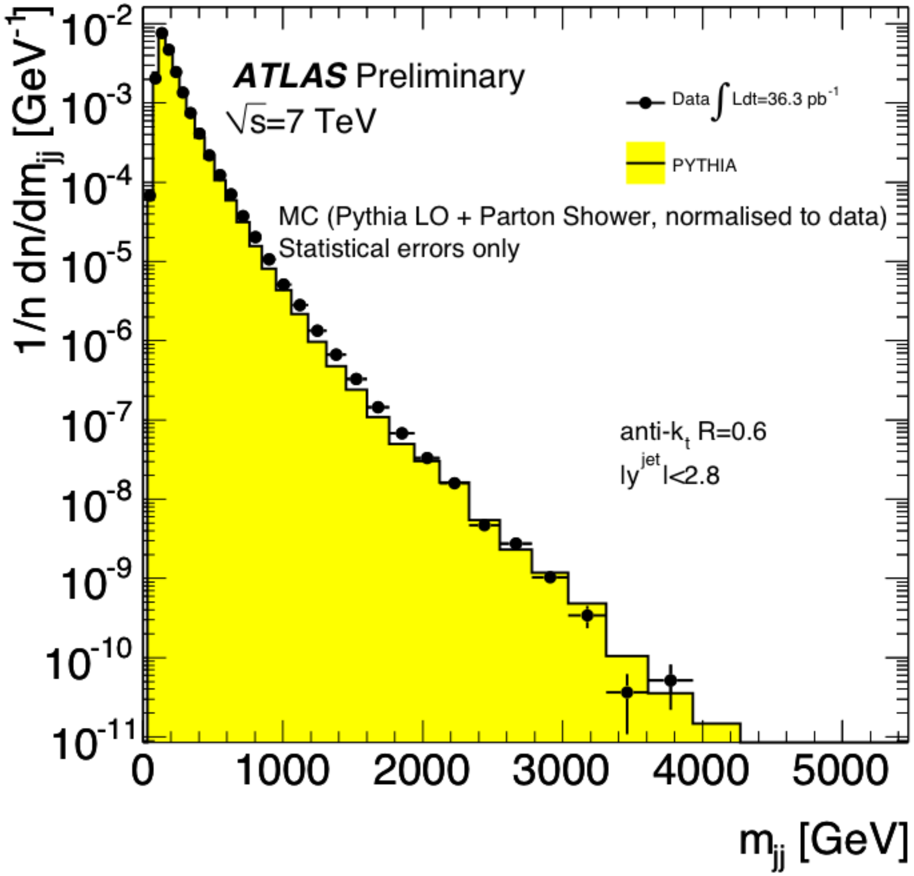
Additional Studies

- Jets at sqrt(s) = 900 GeV
  - Jet kinematic distributions in proton-proton collisions at sqrt(s) = 900 GeV with the ATLAS detector: ATLAS-CONF-2010-001
  - Properties and internal structure of jets produced in proton-proton collisions at sqrt(s) = 900 GeV ATLAS-CONF-2010-018
- Track jets
  - To understand fragmentation, jet properties, jet reconstruction, etc.
  - ATLAS-CONF-2010-049 , 370/ub
  - Measurement of differential cross section and fragmentation of jets from tracks in proton-proton collisions at centre-of-mass energy sqrt(s) = 7 TeV with the ATLAS detector
- Boosted jets
  - ATL-PHYS-PUB-2010-008, MC
  - Prospects for top anti-top resonance searches using early ATLAS data
  - Interesting for ttbar resonances and other new physics, but also considered from a SM QCD perspective
- Search for new physics in multi-body final states
  - Search for three objects with invariant mass > 800 GeV and Sum(pt) > 700 GeV
  - Background dominated by multi-jet QCD, 300/nb
  - ATLAS-CONF-2010-088

Conclusions

- The LHC and ATLAS are performing very well
  - Reach in jet pt and mjj now well beyond the Tevatron
- Initial calibration of the jet energy scale in place
  - ~6% uncertainty for central high pt jets
  - Continue to investigate additional calibration schemes
  - In-depth exploration of in situ methods
  - Reevaluating systematic uncertainties, based on what we've learned in situ
- First jet cross section at sqrt(s) = 7 TeV
  - arXiv:1009.5908 [hep-ex], accepted for publication EPJC
  - Good agreement with NLO QCD
- Many preliminary results with SM jets and jet properties
  - Exploring agreement with theory, MC, simulation
  - Shower profiles somewhat deeper, wider than in our Pythia6 simulation
  - Generally theory and MC codes work well in their applicable domains
- Searches for new physics with dijets, limits well beyond the Tevatron
- An exciting new era for jet physics!

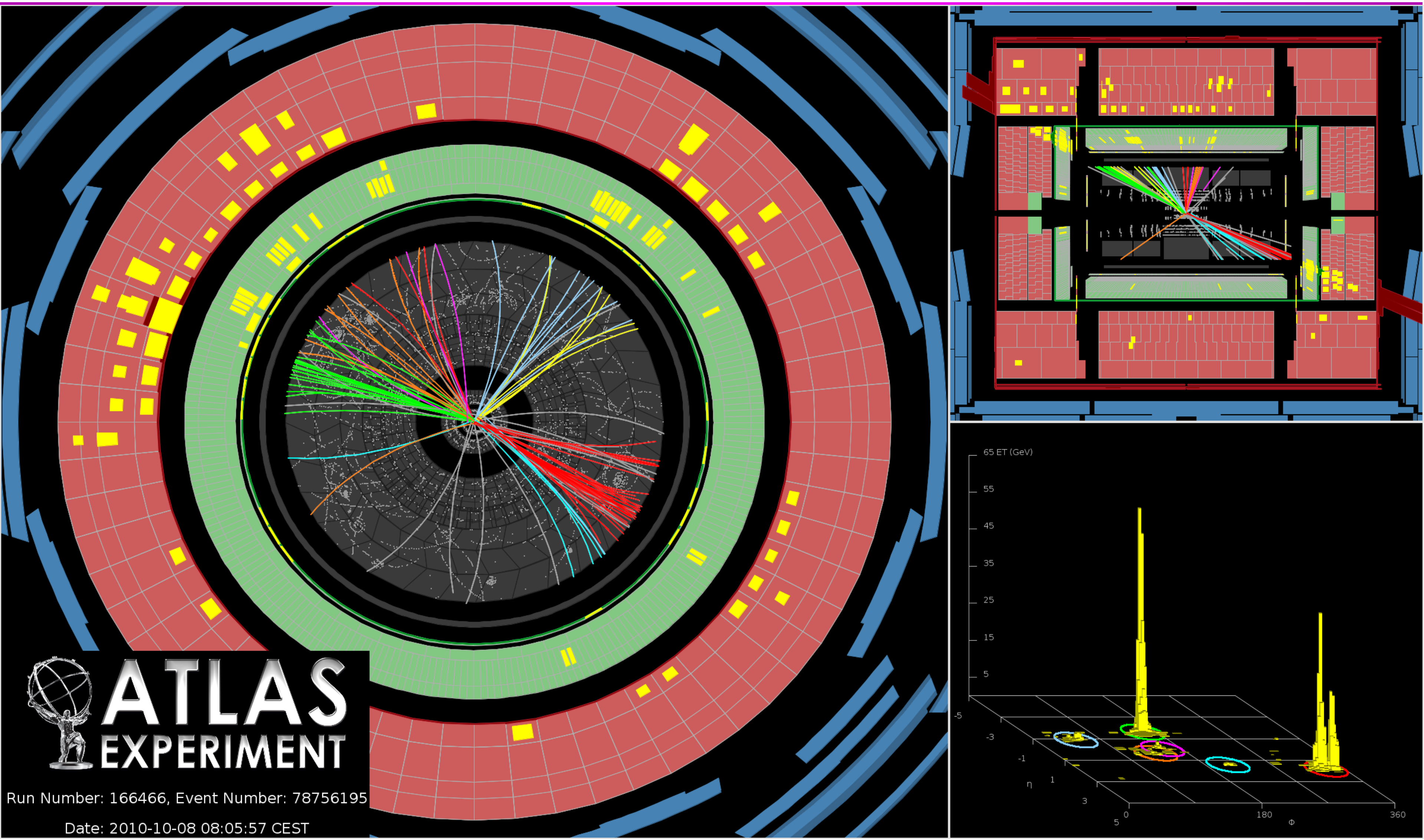
Additional Plots, Slides

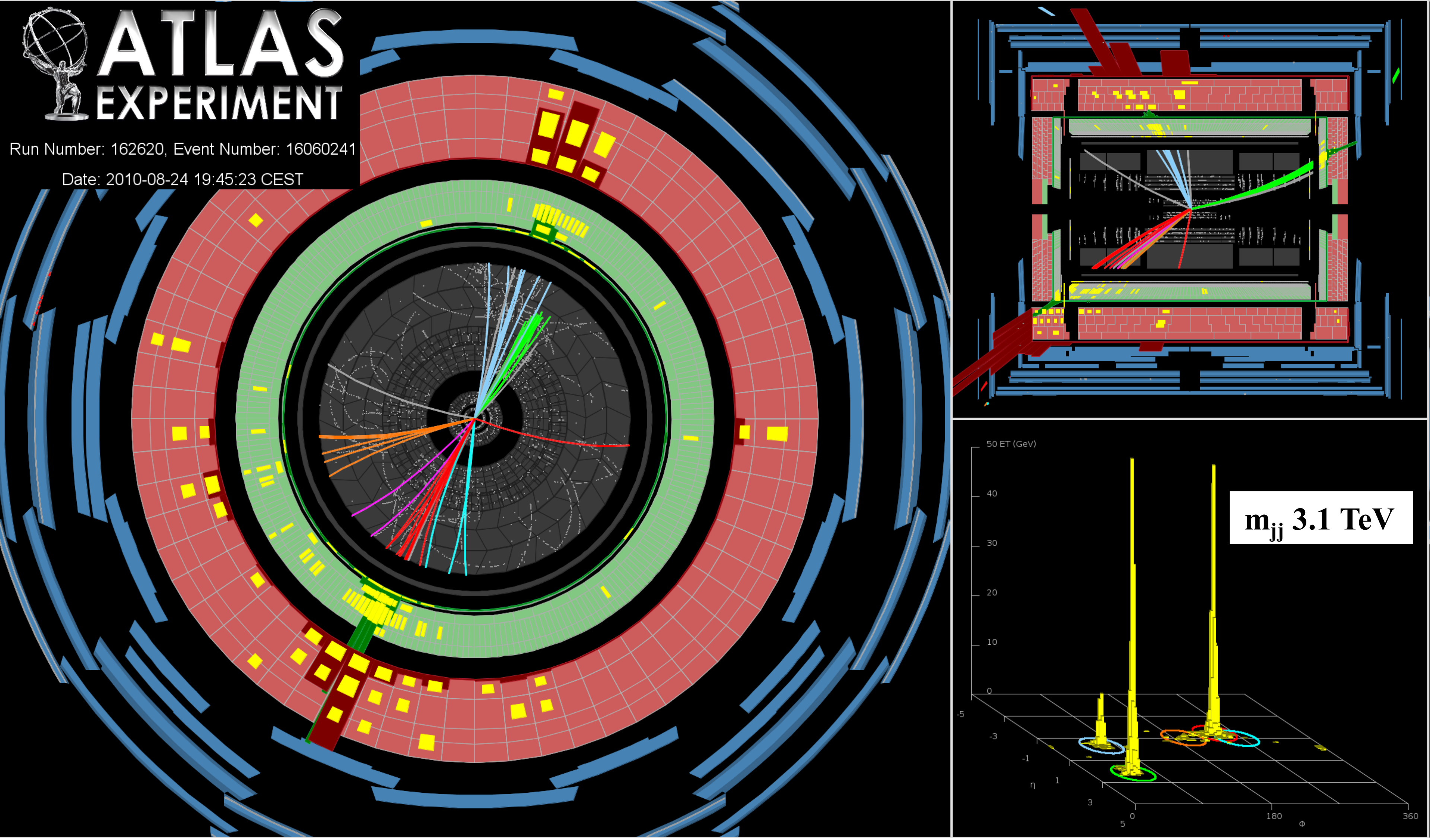


- Pt j1 > 60 GeV, Pt j2 > 30 GeV

Highest mass dijet event

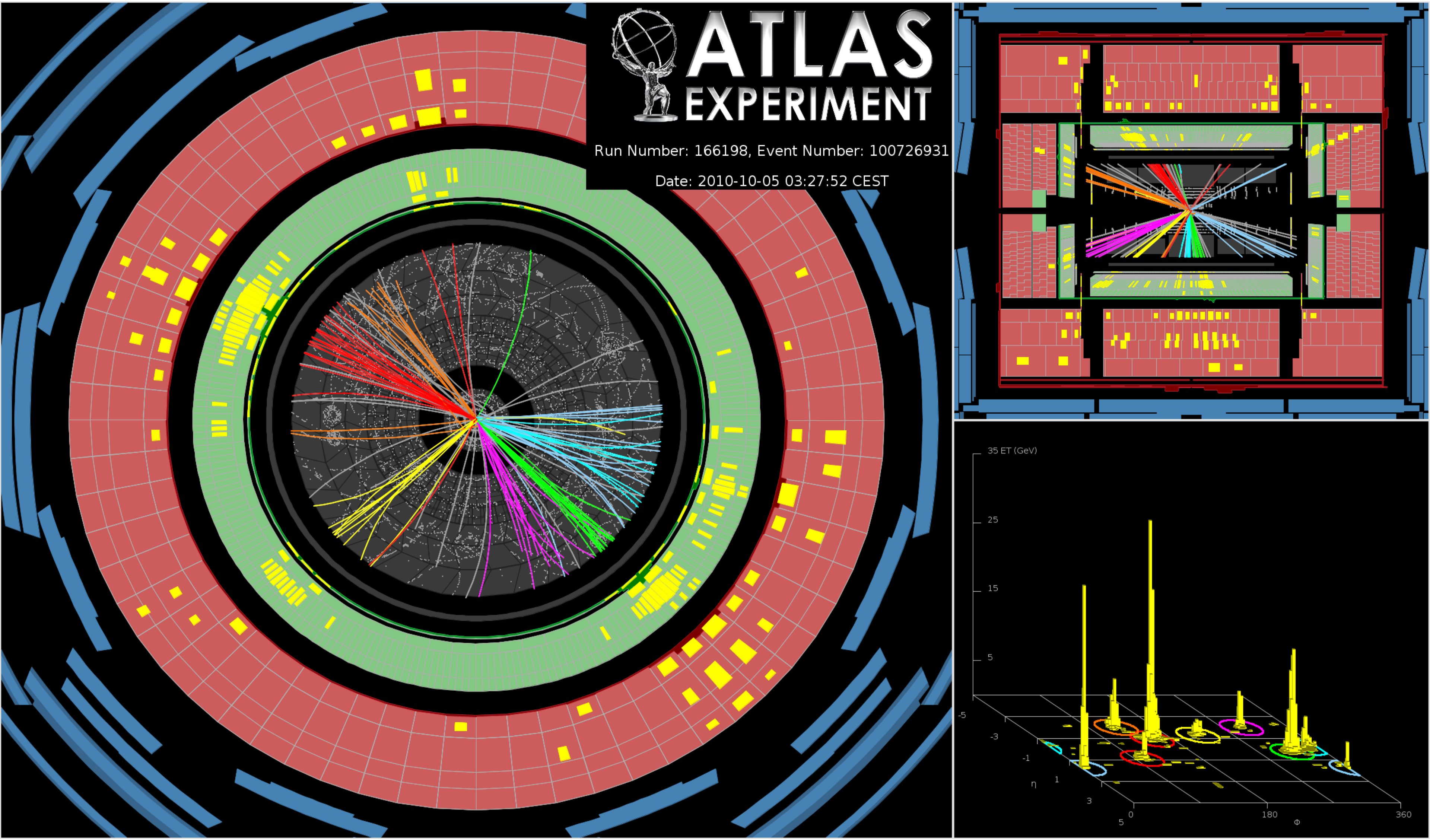
p_T jet1=670 GeV,
p_T jet2=610 GeV, m_{jj}=3.7 TeV




ATLAS EXPERIMENT
Run Number: 162620, Event Number: 16060241
Date: 2010-08-24 19:45:23 CEST
50 ET (GeV)
40
30
20
10
0
-5
-3
-1
1
3
5
η
0
180
360
Φ
m_{jj} 3.1 TeV

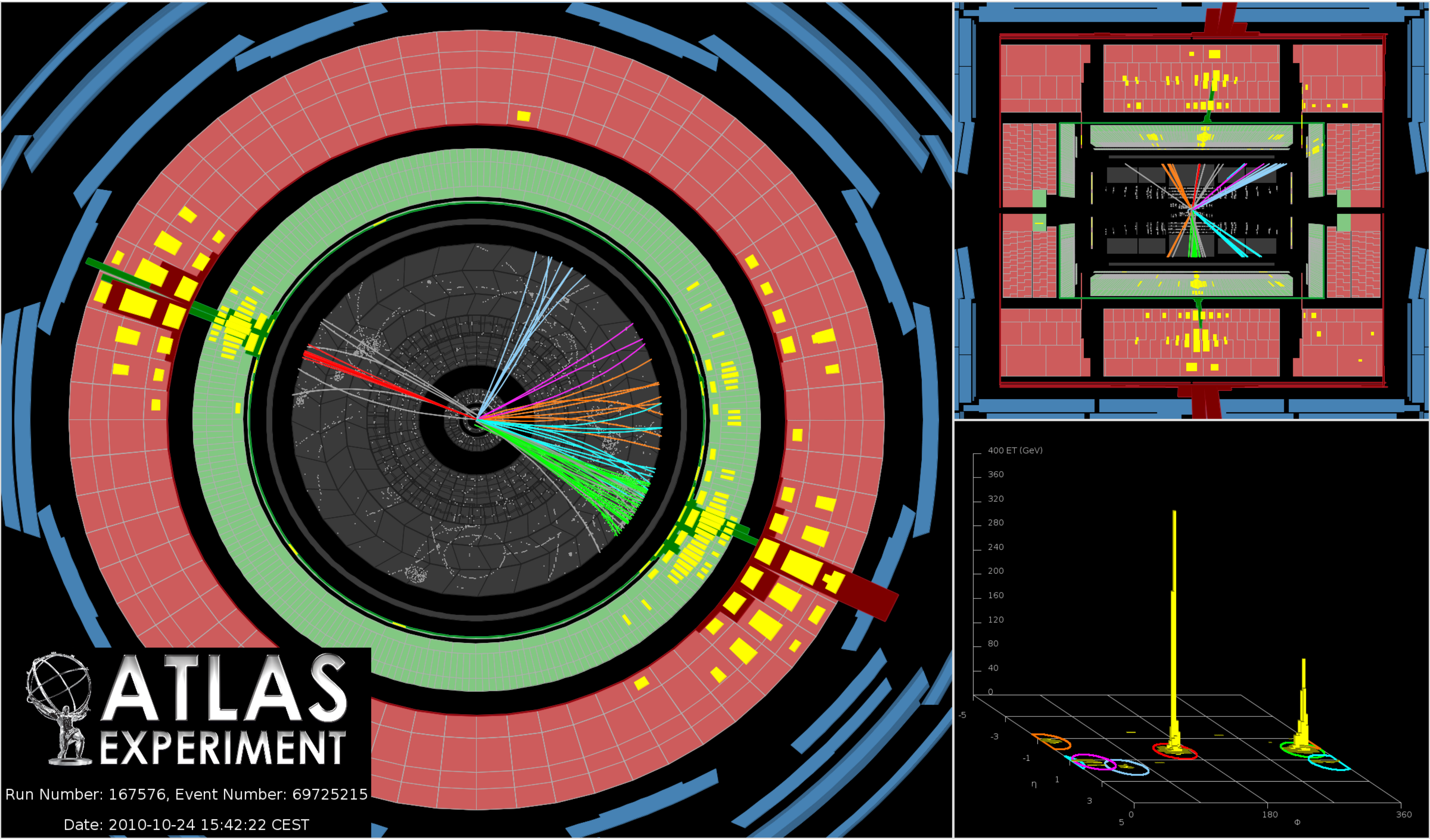
8-jet event

8 jets with p_T>60 GeV



Highest pT jet event

p_T jet1=1.3 TeV (also p_T jet2=1.2 TeV, m_{jj}=2.6 TeV)

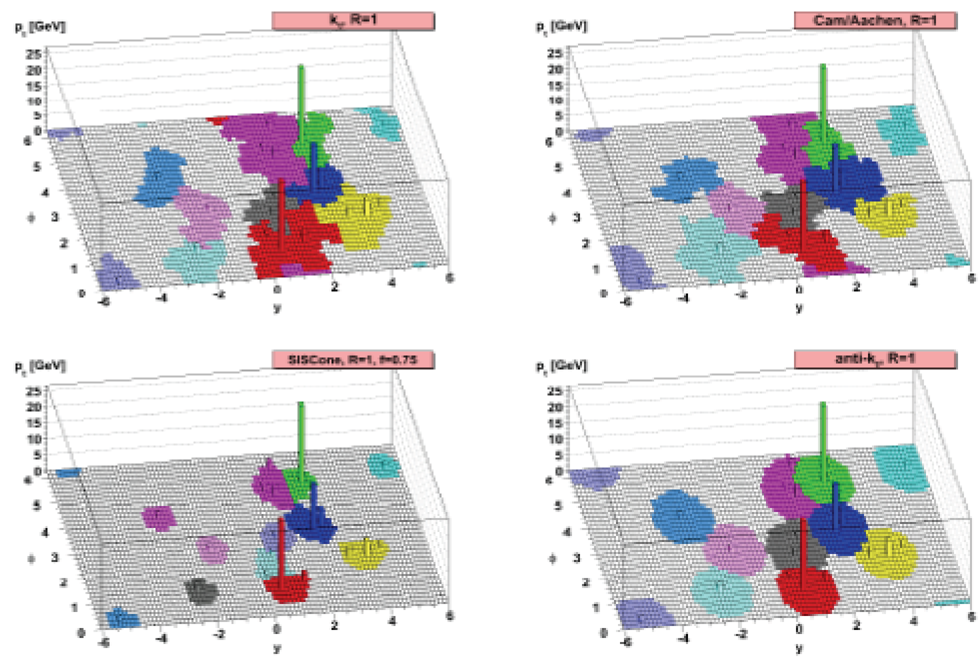


Anti-k_t Algorithm

- Infra-red and collinear safe
  - Resultant jets stable under these effects
- Two general classes
  - Cone algorithms around seeds
    - Require split-merge if overlapping cones
  - Clustering algorithms
    - May give irregular shapes with complicated background corrections
- Anti-k_t is a clustering algorithm
  - p=1 for k_t clustering, p=0 for Cambridge/Aachen, p=-1 for anti-k_t
  - Cluster smallest distance and recompute

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2} \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$d_{iB} = k_{ti}^{2p}$$

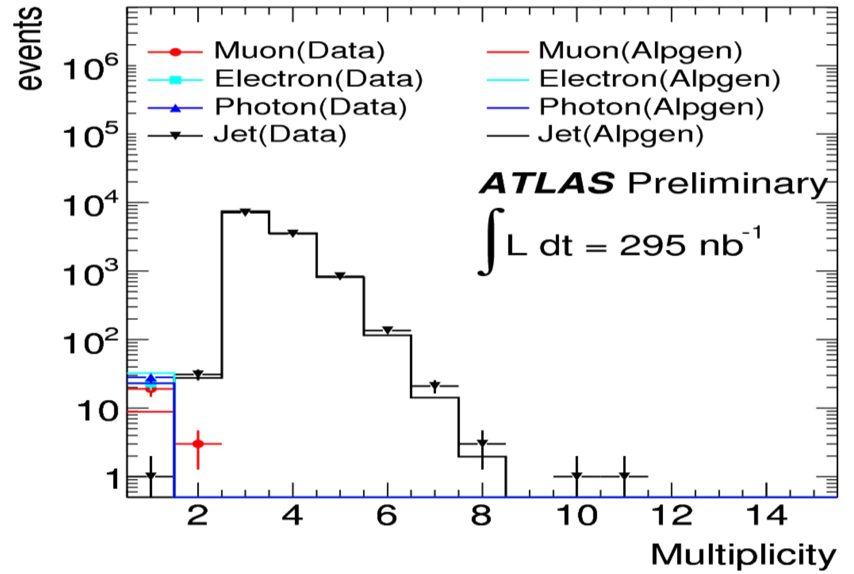


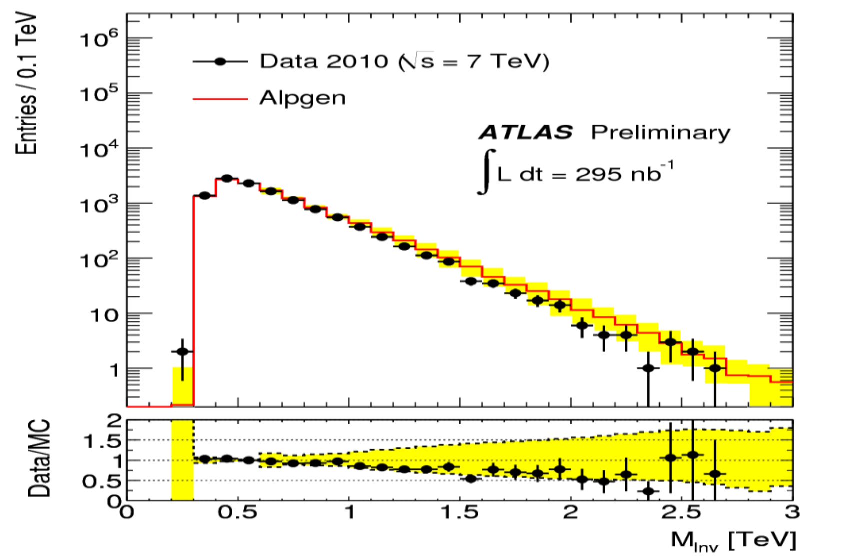
arXiv:0802.1189v2

Search for new physics in multi-body final states

- One may attempt to look for new particles in multijet final state

- An upper limit of 0.34 nb, at the 95% confidence level, is determined for the production cross section times acceptance of new physics models that result in final states with at least three particles and an invariant mass above 800 GeV and with pt > 700GeV





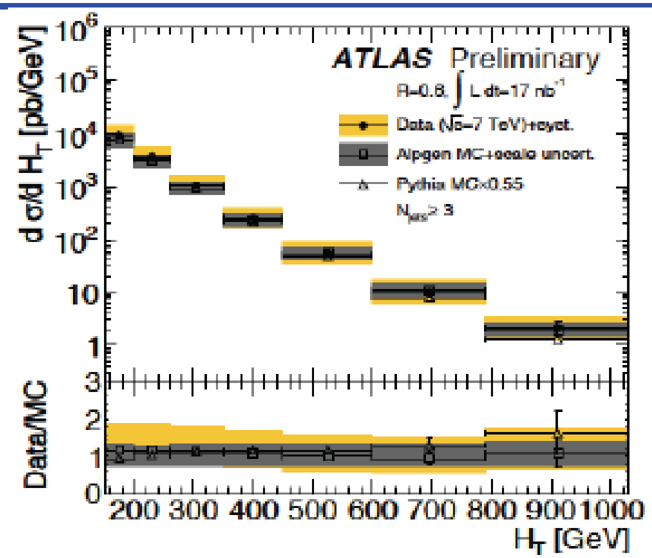
ATLAS-CONF-2010-088

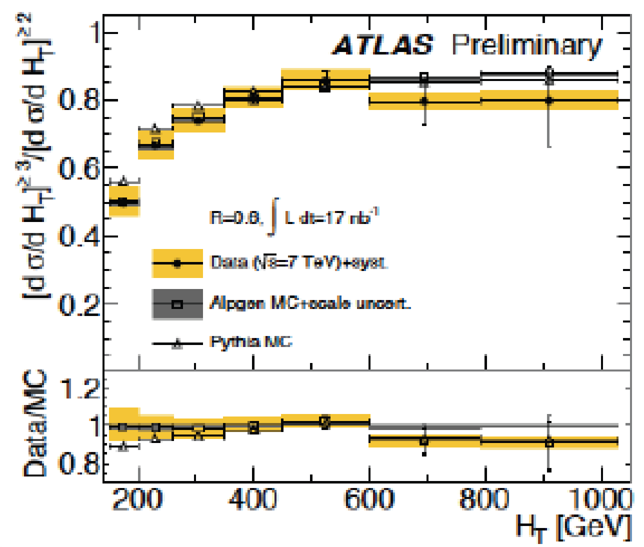
Multijet Production and Ht

- Many new-particle searches use the H_t variable to characterize the level of high-p_t activity in an event
  - Scalar sum of jet p_t values

$$H_t = \sum_{\text{jets}} p_t$$

  - Overall spectrum well described (top)
    - Ratio for successive multiplicities reduces uncertainties to ~10% level
- Quantitative aspects of multijet final states very well described by Alpgen MC model
  - Comparisons with higher statistics in the future
  - Many checks already at 10% level

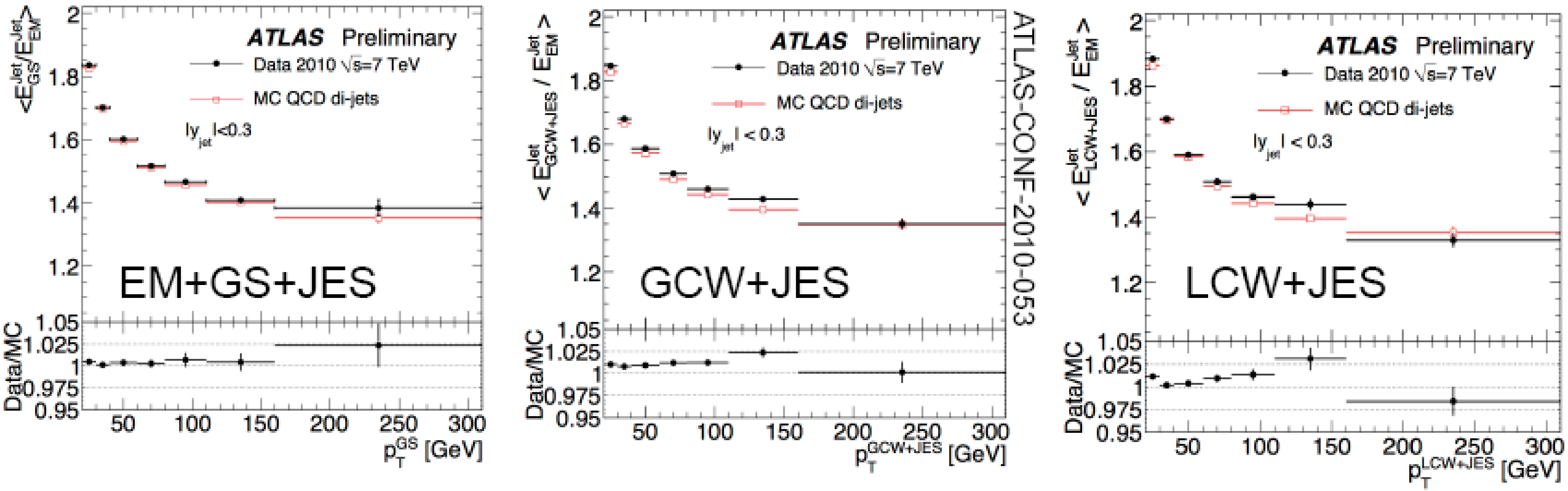




Jet Energy Calibration

- The energy of jets needs to be corrected for calorimeter non-compensation, energy losses in dead material, shower leakage, "out of cone" energy, and pileup
- Jets are calibrated using Monte Carlo particle-level truth jets as reference
- Three calibration schemes are being explored by ATLAS
  - EM+JES
    - simple p_T and η-dependent correction to jet energy scale (JES) applied to jets measured at EM scale
  - Global cell weighting: GCW+JES
    - use cell weights based on cell energy density to compensate for the different calorimeter response to hadronic (low E-density) and electromagnetic depositions.
  - Local cluster weighting: LCW+JES
    - use properties of topological clusters (including energy density and position) to classify them and calibrate them individually
    - cluster calibration derived from Monte Carlo simulations of single charged and neutral pions
- For all three schemes, global sequential calibration can be used to improve jet-by-jet fluctuations by correcting for the dependence on jet shapes and other properties. Correction done such that the mean energy does not change

Jet Calibration Schemes



- Mean ratio of calibrated over un-calibrated jet energies as a function of calibrated jet p_T (here shown for central region)
  - same average correction for all three calibration schemes
  - the agreement between the correction factors applied to data and Monte Carlo is better than 2%
  - similar agreement in the whole rapidity range

Inclusive Jet and Dijet Production

- Model comparisions
  - Pythia 6.4
    - Leading order matrix elements for $2 \to 2$ processes
    - p_t-ordered parton showers in leading-log approximation
    - Lund string model for hadronization
    - Underlying event modeled by multiple parton interactions
  - Herwig 6
    - Leading order matrix elements for $2 \to 2$ processes
    - angle-ordered parton showers
    - Cluster hadronization model
    - Underlying event using the Jimmy package
  - PDFs from MRST2007LO*
  - Also NLO cross sections from NLOJET++

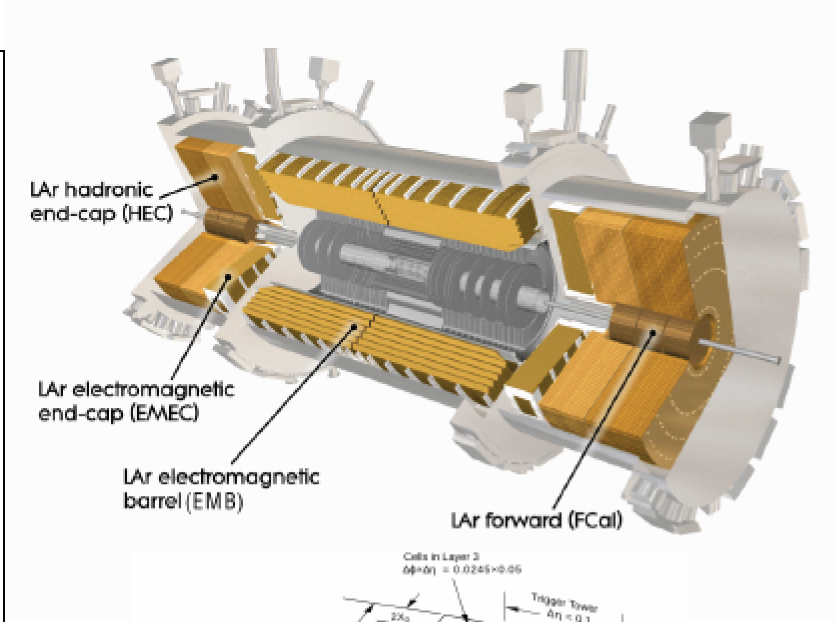
LAr Calorimetry

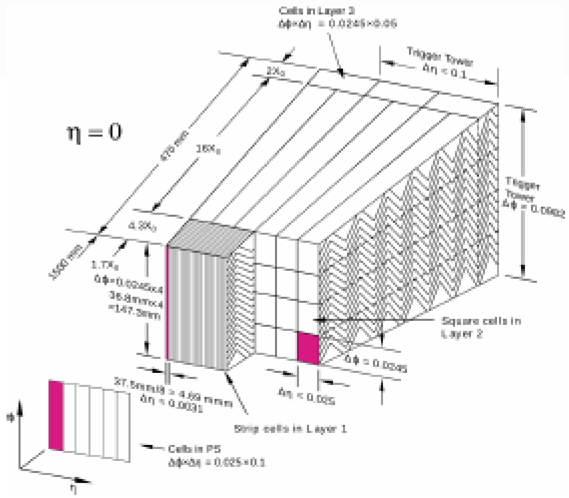
<u>Electromagnetic Calorimeter (EM)</u>

- Absorbers : Pb
- Active Medium : LAr
- Accordion geometry : full ϕ coverage
- Coverage : $|\eta| < 3.2$
- Segmentation in η and in depth
- 3 layers up to $|\eta| = 2.5$; 2 up to $|\eta| = 3.2$
  - Layer 1 : $\Delta\eta \times \Delta\phi = 0.0031 \times 0.1$
  - Layer 2 : $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
- Presampler up to $|\eta| = 1.8$
- 173312 readout channels(98 % operational)

- Design resolution : (from test beam) $\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E(GeV)}} \oplus 0.7\%$

- Photon angular resolution : $\approx \frac{50\mu rad}{\sqrt{E(GeV)}}$





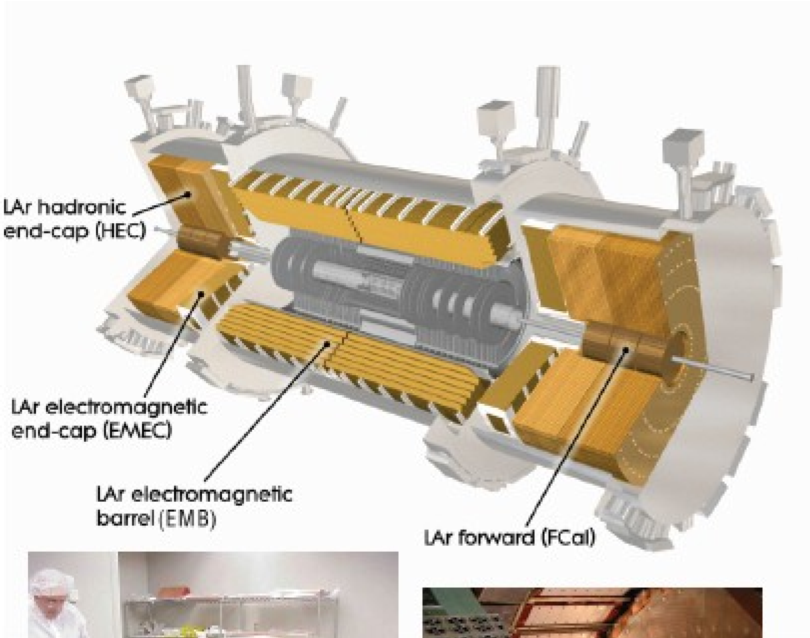
LAr Calorimetry, cont.

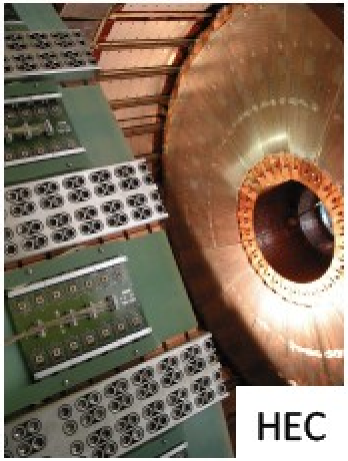
Hadronic Endcap (HEC)

- Absorbers : Cu
- Active medium : LAr
- Coverage : $1.5 < |\eta| < 3.2$
- 4 layers ($\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ or 0.2×0.2)
- 5632 readout channels (99.9% operational)
- Design resolution : $\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 3\%$

Forward Calorimeter (FCal)

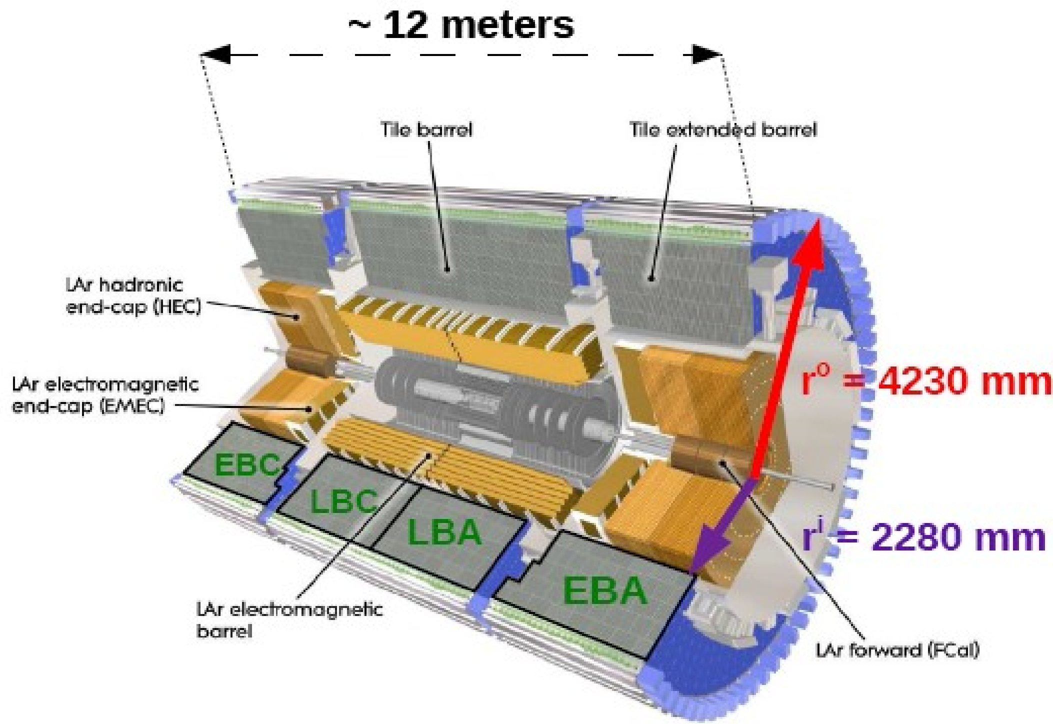
- Absorbers : Cu/W
- Active medium : LAr
- Coverage : $3.1 < |\eta| < 4.9$
- 1 EM + 2 Hadronic layers
- 3524 readout channels (100% operational)
- Design resolution : $\frac{\Delta E}{E} = \frac{100\%}{\sqrt{E(GeV)}} \oplus 10\%$

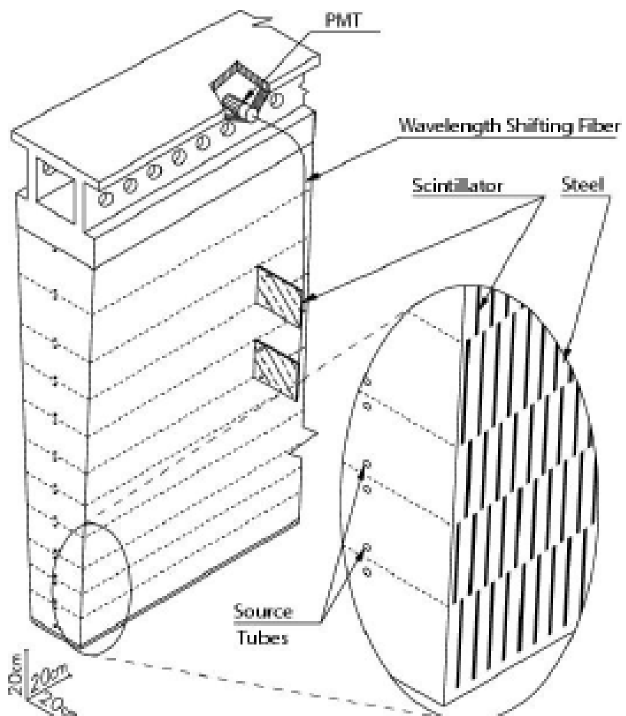




Tile Hadronic Calorimeter

- Scintillating tiles in an steel matrix
- Light transported by wavelength shifting fibers
- Coverage | η | < 1.7
- 3 layers (Δη x Δφ = 0.1 x 0.1 or 0.2 x 0.2)





$$\frac{\Delta E}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 6\%$$

- ~10,000 channels
- ~97% operational
- Each collecting signal from a group of tiles, a cell
- Double-sided readout of each cell (~5,000 cells)