# QCD physics at ATLAS


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*On Behalf of*
*the **ATLAS** Collaboration*

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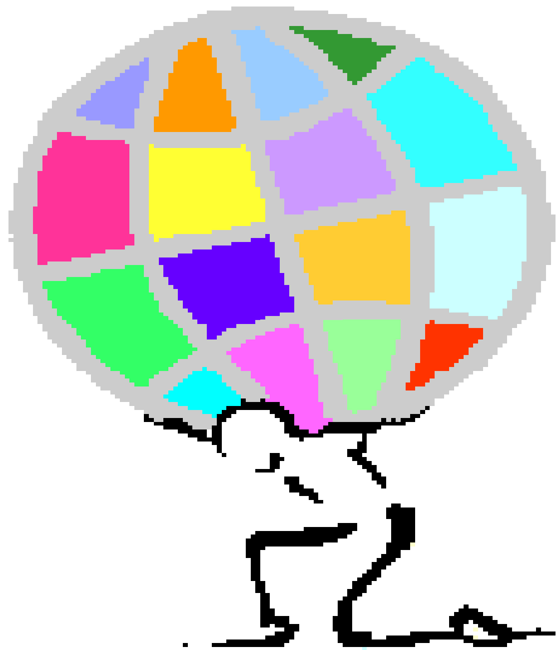


# Introduction

- QCD measurements represent an extensive part of the early physics program at ATLAS:
  - Hard QCD : the jet physics (high $p_T$)
  - Soft QCD : all the processes with low $p_T$ transfer

- Motivations:

  Measurement of the QCD processes important as precise test of the Standard Model (SM) at the unexplored LHC domain and crucial to searches for new physics:
  - Hard QCD main background for many SM and beyond SM processes
  - Deviation from high $p_T$ QCD ➔ hint to new physics
  - QCD measurements are the only way to verify and improve phenomenological models for soft physics (e.g. in Monte Carlos) at LHC energies

# Outline

- The ATLAS Detector
- The Data
- The Monte Carlo

The ingredients

- The Soft QCD measurements :
  - underlying event
- The Hard QCD measurements:
  - Jet reconstruction
  - Jet shapes
  - Inclusive jet, dijet, multijet cross sections
  - Dijet azimuthal decorrelation
  - Jets cross section in association with W/Z
  - Inclusive prompt photon cross section

The results

- Conclusions

# The ATLAS Detector

- **Inner Detector:** EPJC 70 (2010) 787

3 technologies (Pixel detectors, semiconductor tracker and transition radiation tracker) in a 2T solenoidal magnetic field up to $|\eta|<2.5$

resolution ~ 4% for $p_T$=100 GeV

- **Calorimeters:** EPJC 70 (2010) 723 EPJC 70 (2010) 755 EPJC 70 (2010) 1193

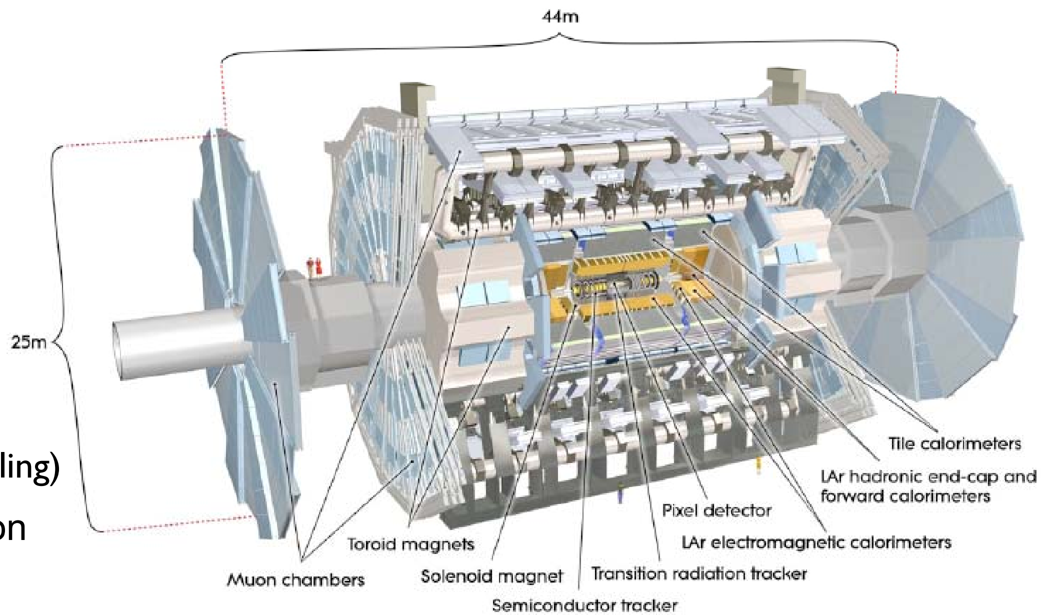
Good granularity (transverse and longitudinal sampling) and coverage ($|\eta|<4.9$) ➔ Good angular resolution

EM : Pb/Liquid Argon (both in Barrel and Endcap)

HAD: Fe/scintillation tiles (Barrel) – Cu/Liquid Argon (Endcap)

Forward (EM and HAD) : Cu/W –LAr

Non compensating calorimeter (e/h ≠1)




$$\sigma/E \approx 10-17\%/\sqrt{E} \oplus 0.7\% \text{ (EM)}$$

$$\sigma/E \approx 50\%/\sqrt{E} \oplus 0.3\% \text{ (HAD)}$$

$$\sigma/E \approx 100\%/\sqrt{E} \oplus 10\% \text{ (Forward)}$$

- **Muon Spetrometer:** EPJC 70 (2010) 875

4 technologies (MDTs and CSCs as precision chambers, RPCs and TGCs as trigger chambers) in a toroidal magnetic field in air ( 3 magnets) ➔ Resolution ~10% for muon $p_T$ = 1 TeV (standalone measurement)

# The Data

- ATLAS recorded in 2010 about 45 $pb^{-1}$ at 7 TeV

  Most measurements shown today use 17 $nb^{-1}$ to 3 $pb^{-1}$ (updates with more data are coming)

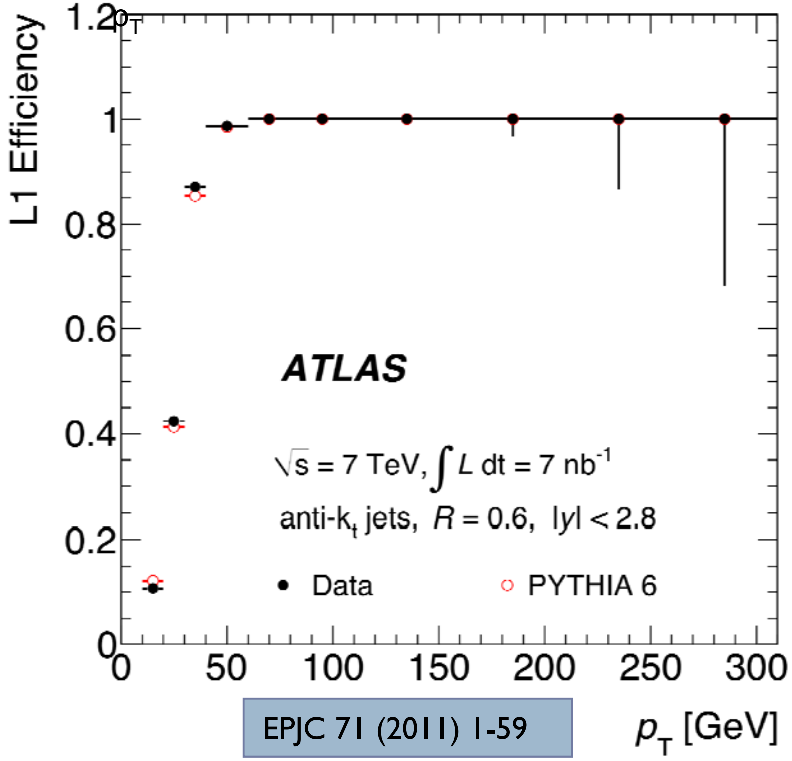
  Measurement with early data: luminosity uncertainty 11%, low pileup, unprescaled triggers

- Triggers employed in most of the measurements:

  - Minimum-bias scintillator triggers (MBTS): 2 disks located between inner detector and end-caps (2.09<|η|<4.09)

  - calorimeter jet triggers (first level employed for early measurement) used in their ~100% efficiency domain

Inclusive-jet Level 1 trigger efficiency with the lowest threshold as a function of reconstructed jet $p_T$




EPJC 71 (2011) 1-59

# The Monte Carlos

- LO Matrix elements + parton showers MCs:

  • **Pythia** 6.241 (MRST2007 LO* PDFs)

  Default Parameter tunes: ATLAS-MC09 (tuned to Tevatron 0.630-1.8 TeV underlying event and minimum bias data),

  Other tunes:

  Perugia 2010 (tuned to Tevatron and $Sp\bar{p}S$ minimum bias data) ,

  DW (tuned to CDF Run II underlying event, dijet and Drell-Yan data)

  • **Alpgen** + Herwig + Jimmy (CTEQ6L1 PDFs)

Pythia (or Alpgen) samples fully simulated employed to correct the data back to particle level (used a bin-by-bin unfolding procedure)

  • **Sherpa**

  • **Herwig6 + Jimmy / Herwig++**

Sherpa and Herwig used for x-checks and systematics estimations

- NLO calculations:

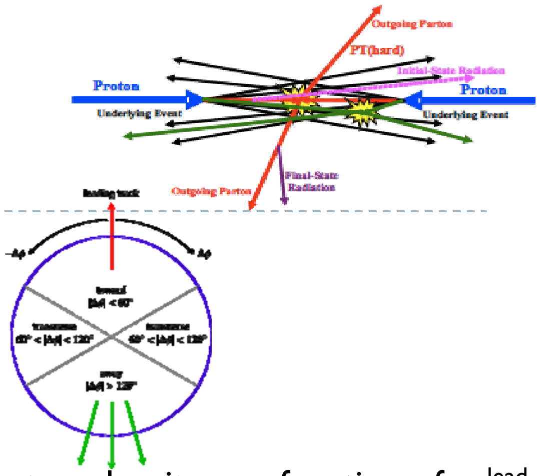
  • NLOJet++ 4.1.2 (CTEQ6.6 and MSTW2008)

  • MCFM (CTEQ6.6) for W/Z +jets studies

NLO prediction corrected for non perturbative effects for comparisons with data at particle level

# Underlying event

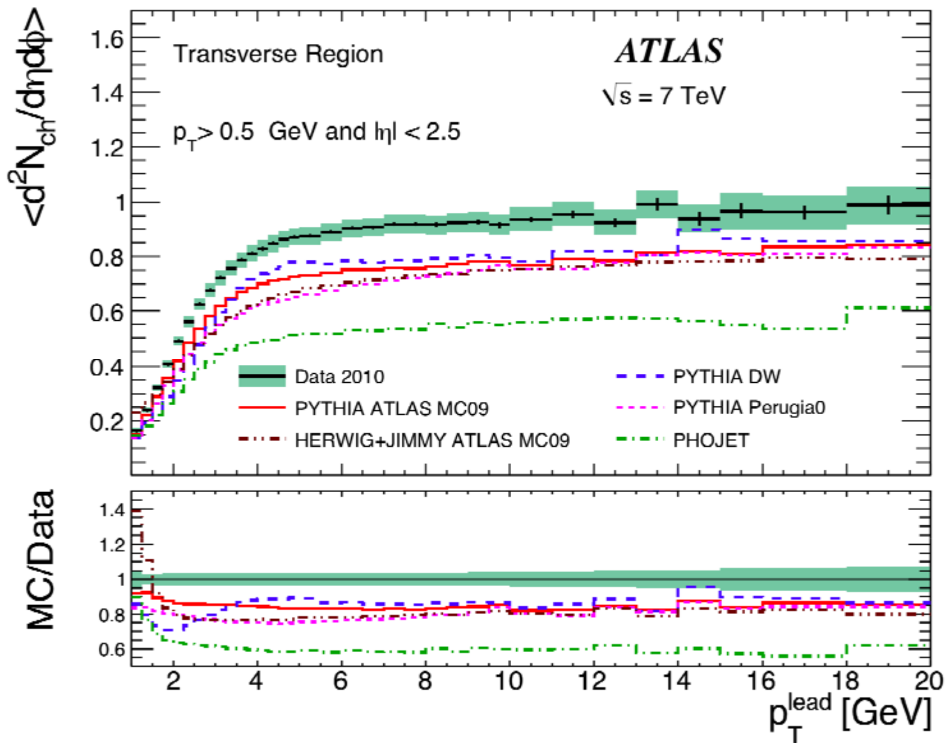
arXiv:1012.0791
Accepted by Phys Rev D



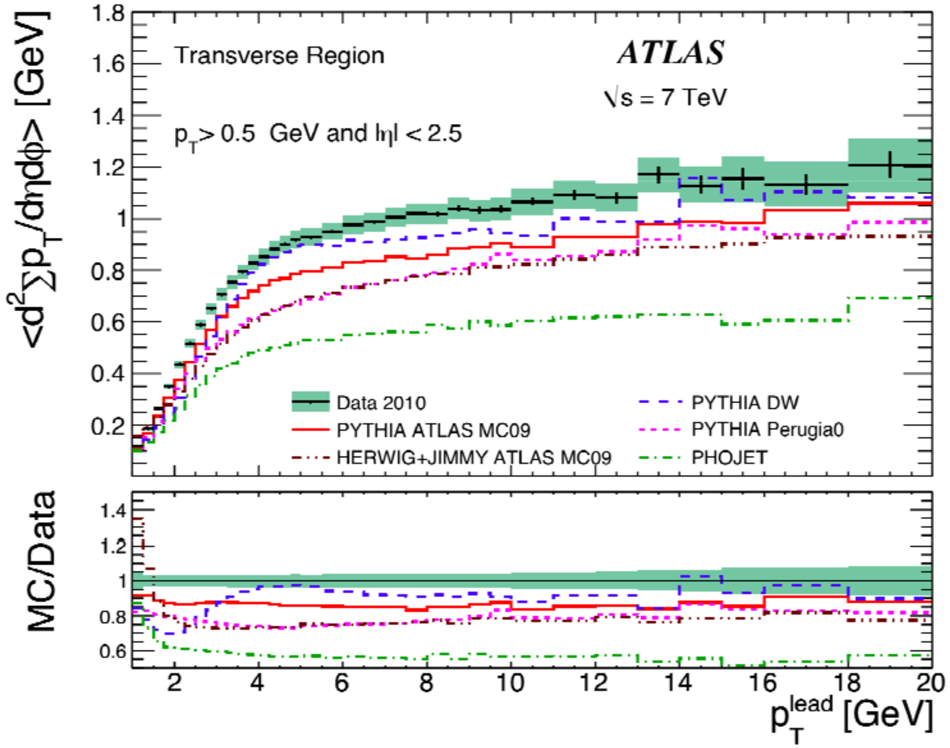
- Everything from a single pp collision except the hard process of interest
- η, φ plane divided into regions around the highest $p_T$ track ($p_T^{lead}$)

  transverse region(60°<Δϕ<120°) is the most sensitive to UE

Charged particles multiplicity density as a function of $p_T^{lead}$



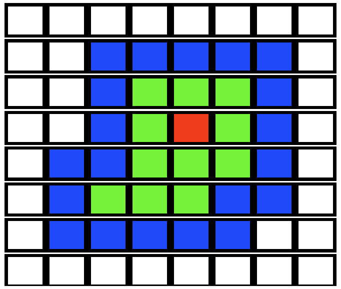

Transverse mometum density as a function of $p_T^{lead}$




Data show higher UE activity than MCs . The precise data is being used for new MC tunes

# Jet reconstruction

- JET building:
  - Input from **3D topological clusters**
  - Jet inputs clustered with **anti-$k_t$ algorithm**:
    Infra-red and collinear safe sequential algorithm,
    produces cone-like jets, distance parameters: R= 0.4, 0.6

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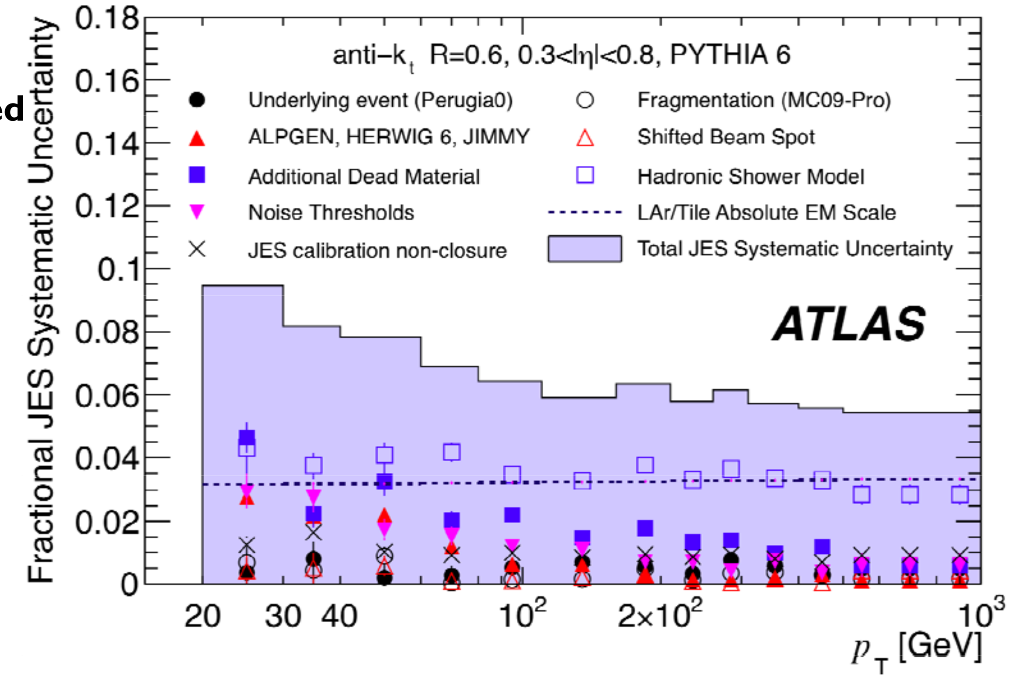
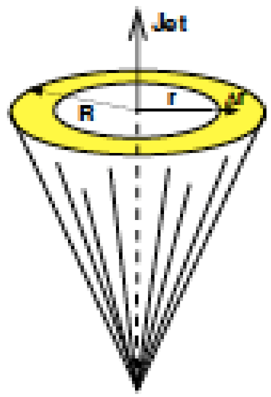
- JET Energy scale:
  jet energy scale established offline **via MC-based calibration** factors as a function of $\eta$ and $p_T$
  (MC validated with test beam data)

- JES uncertainty (dominant systematic uncertainty in all the analyses)
  Estimation derived combining information from test-beam data, early collisions data and MC simulations **below 7% for central jets with $p_T$>60 GeV**



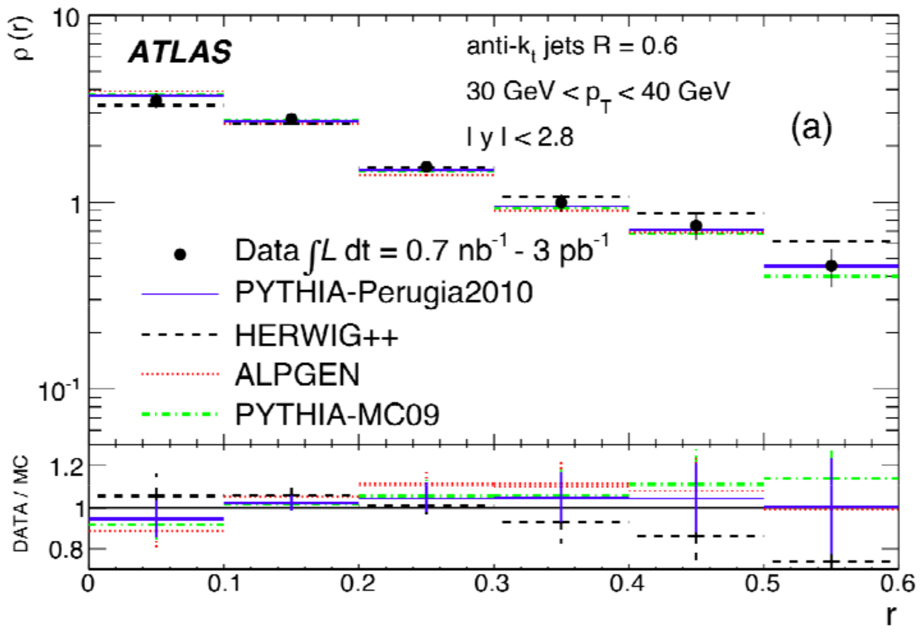
# Jet shapes (1/2)

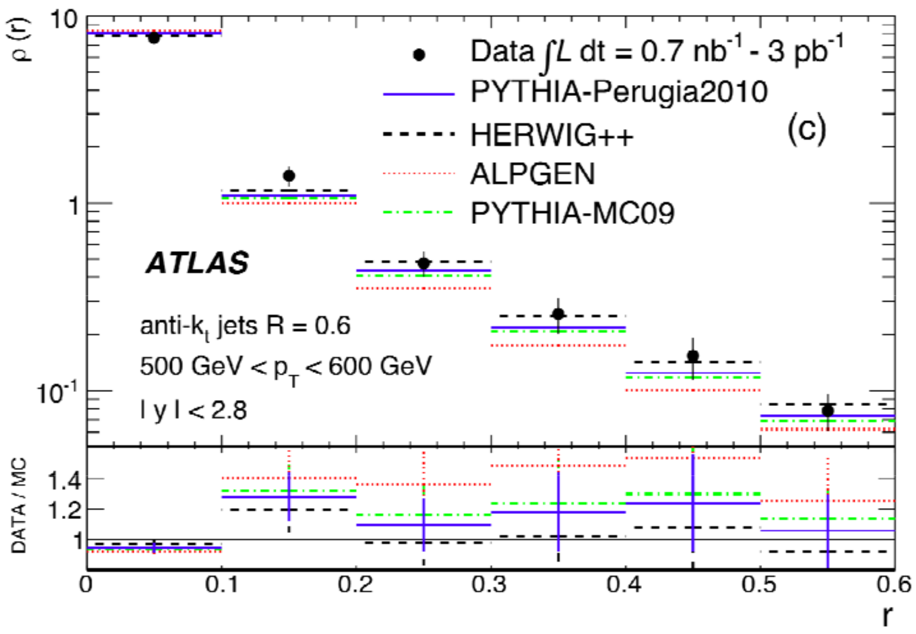
arXiv:1101.0070
Accepted by Phys Rev. D




- Probe the jet internal structure using its constituents (the clusters)
- Jet shape is sensitive to non perturbative fragmentation effects, underlying event
  - ➔ Good test of Parton Shower models

The Differential jet shape $\rho(r)$ is the fraction of jet $p_T$ within $r - \Delta r/2$ and $r + \Delta r/2$

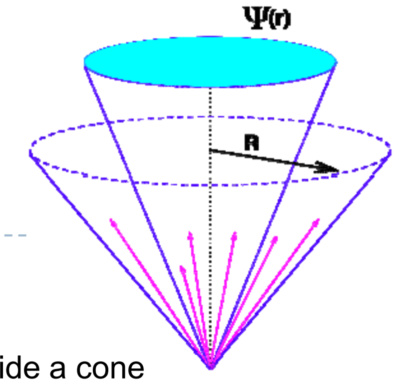



- Jets become narrower as $p_T$ increases, as expect

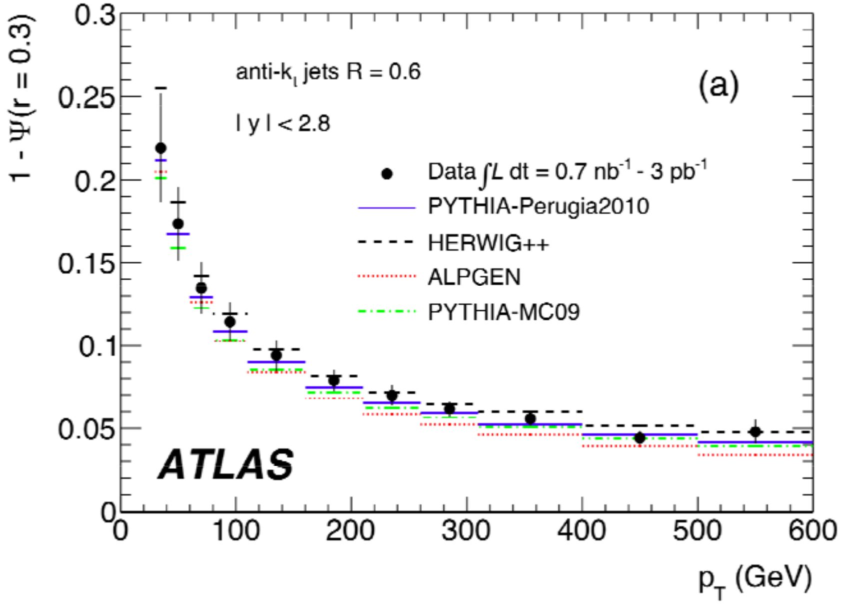
# Jet shapes (2/2)

arXiv:1101.0070
Accepted by Phys Rev. D

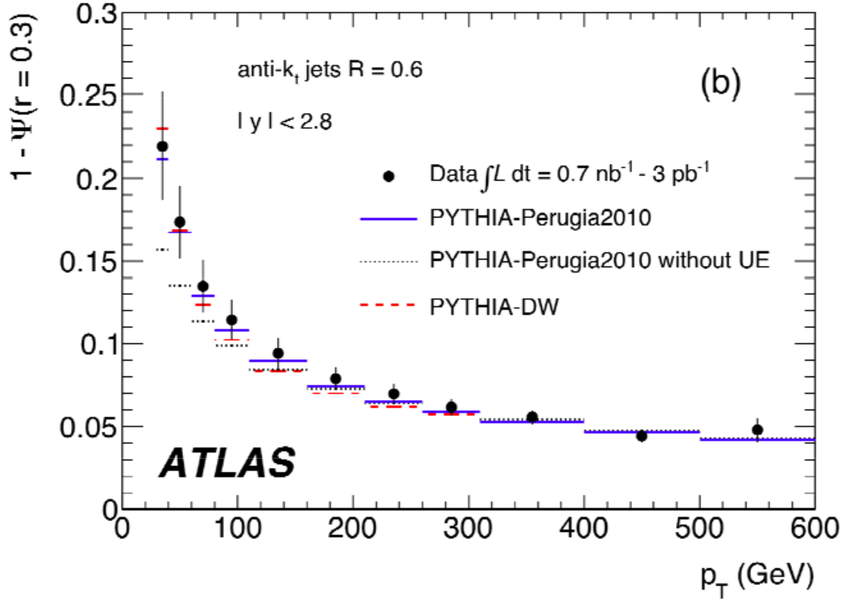



Integral Jet Shape $\Psi(r)$ is the fraction of jet $p_T$ inside a cone of radius r

Fraction of the jet $p_T$ outside a cone of 0.3 as a function of the jet $p_T$




Fraction of the jet $p_T$ outside a cone of 0.3 as a function of the jet $p_T$




- Perugia2010 gives reasonable description of data
- HERWIG++ broader than data
- ALPGEN, MC09, DW tend to be narrower.
- Turning off UE gives much narrower jets at low $p_T$.

# Inclusive jet cross section (1/2)

- **Importance :**
  - Probe pQCD
  - Sensitive in the tails to New Physics
  - Understand dominant background for many analyses
  - Early testing ground for jet performance

- **The measurement:**
  - Jets with $p_T$ >60 GeV, |y| <2.8
  - Pythia-derived bin-by-bin unfolding
  - Dominant systematic uncertainty: jet energy scale (impact at ~ 40%)

- **Comparison with the shapes of LO ME+PS MCs** : in general, agreement with data.

Inclusive jet double differential cross-section as a function of $p_T$ in different rapidity regions

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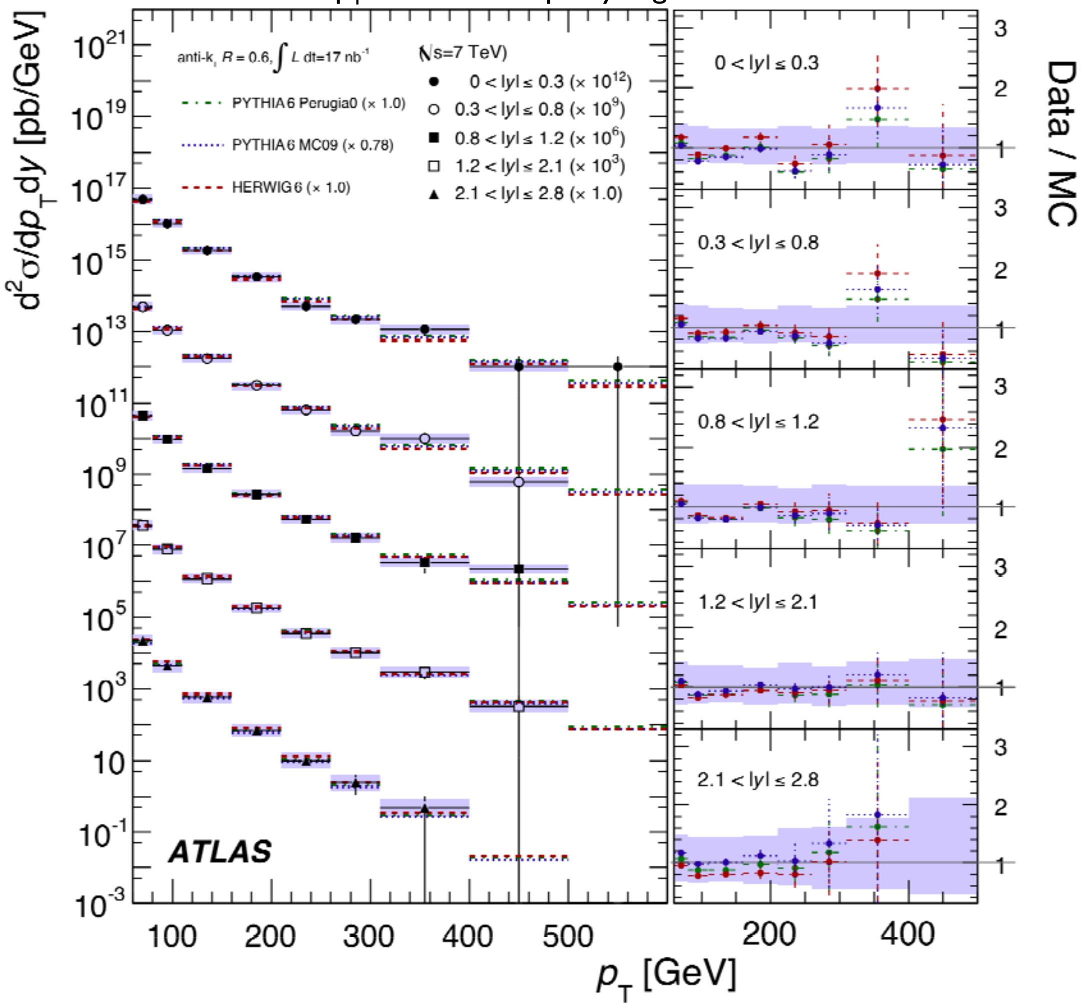
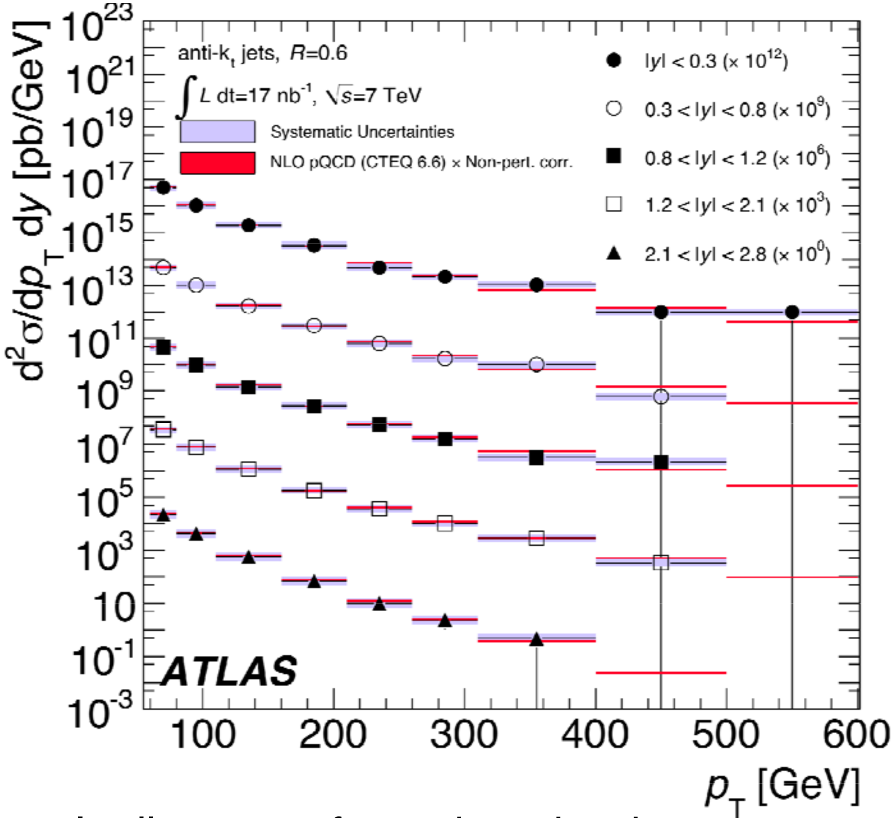


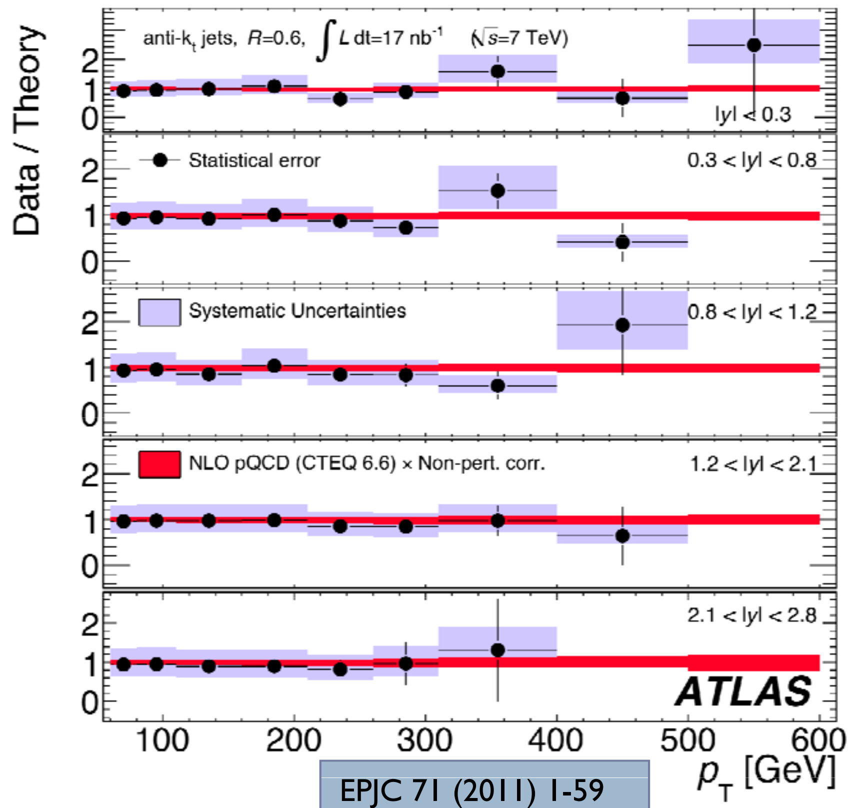
# Inclusive jet cross section (2/2)

- Comparison to NLO pQCD+ non perturbative corrections (at level of 5% over most the kinematical region, increase with decreasing $p_T$)

Inclusive jet double-differential cross-section as a function of $p_T$ in different rapidity regions




Ratio Data/NLO of the Inclusive jet double-differential cross section as a function of $p_T$ in different rapidity regions

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In all regions of $p_T$ and rapidity theory consistent with the data

# Dijet cross section

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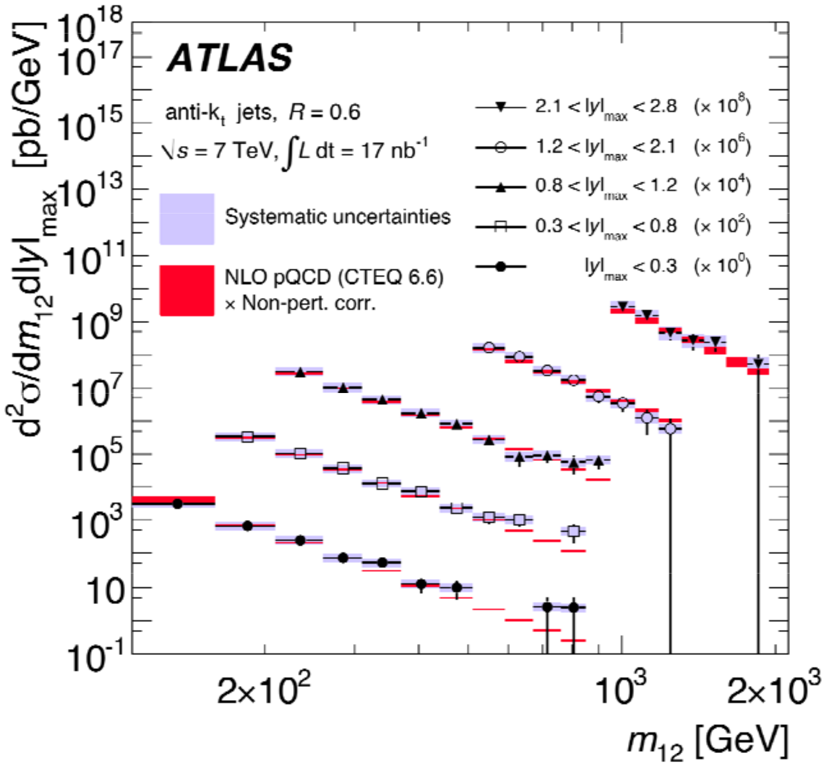
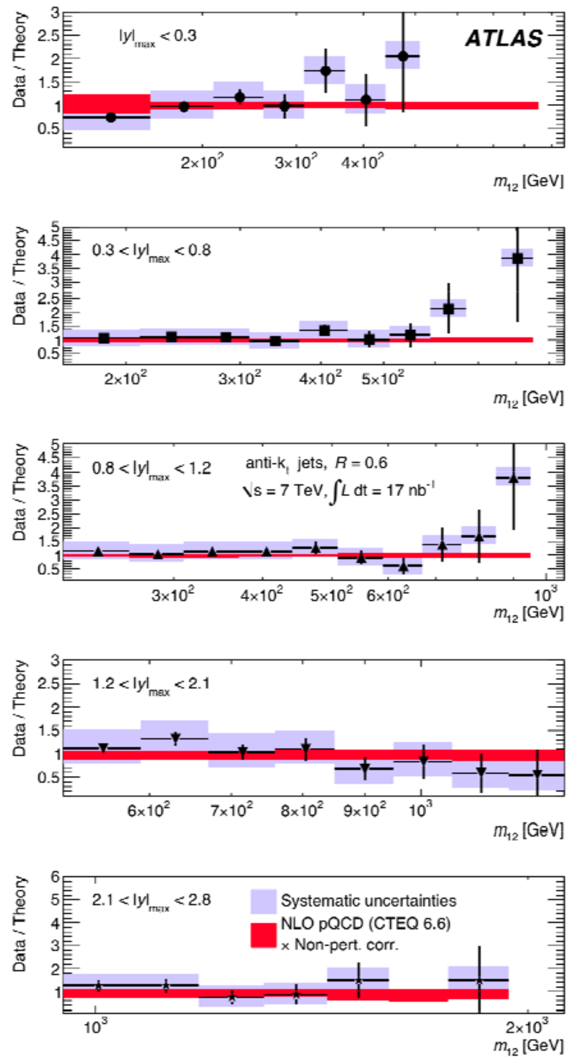
- **The measurement:**

  first jet $p_T$ > 60 GeV second jet $p_T$ > 30 GeV, both |y|<2.8

Dijet double-differential cross section as a function of the dijet mass binned in $|y_{max}|$




Again good agreement between data and theory

# Multijet cross section

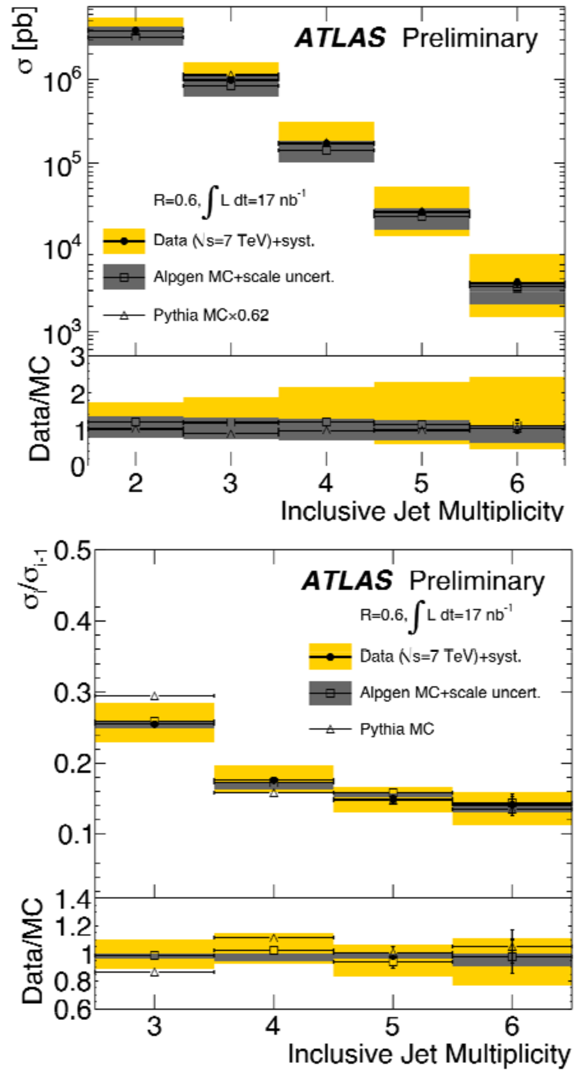
ATLAS-CONF-2010-084

- **Importance:**
  - test the higher order pQCD
  - multijet final state relevant in searches

- **The measurement :**
  - at least 2 jets: first $p_T$>60GeV, others $p_T$>30 GeV (|y|<2.8)
  - Unfolding done with Alpgen (+Herwig+Jimmy)
  - Main systematics: Jet Energy scale (including 'close-by jets' effects)

- **Data compared to ME+PS** : Alpgen (+ Jimmy + Herwig) and Pythia (shapes only): agreement within the uncertainties

- **Ratio measurement:** the systematics from jet energy scale considerably reduced, good agreement data MC confirmed



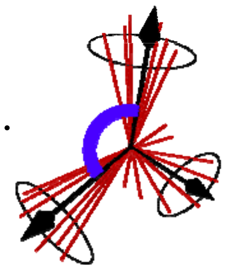
# Dijet Azimuthal decorrelation

arXiv:1102.2696v2.
Submitted to PRL
**Measurement with the overall 2010 statistics**

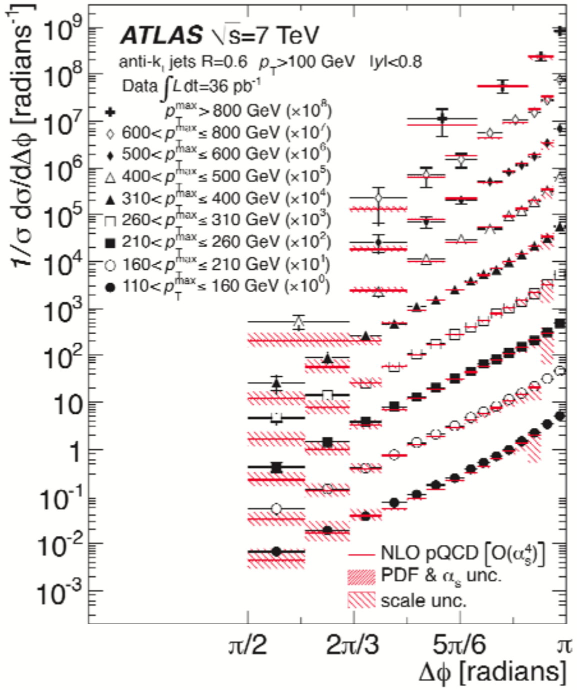

Complementary to multijet cross section measurement

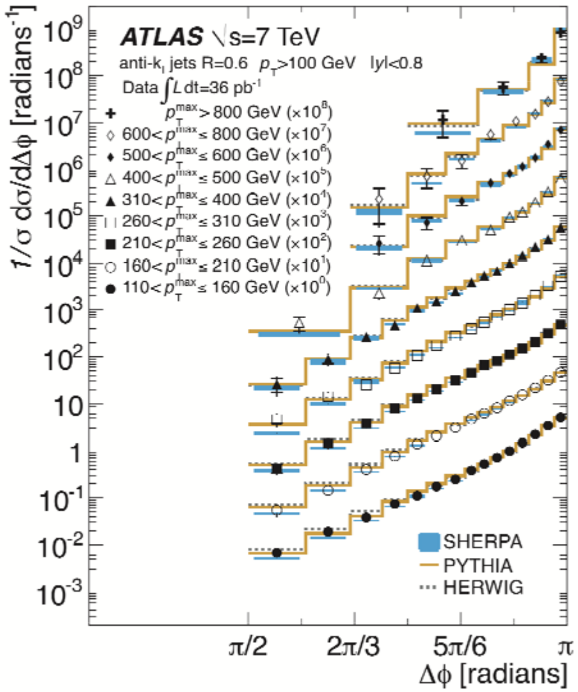
Measure $\Delta\phi$ between 2 leading jets:

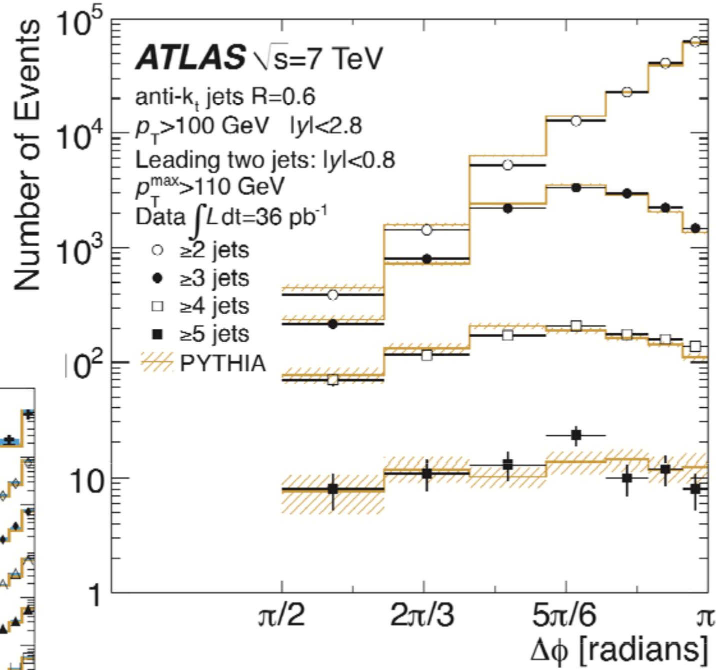
$\Delta\phi = \pi$ (pure dijet), $\Delta\phi$ smaller (with extra jets).



Differential cross-section (normalized to the inclusive dijet cross-section)



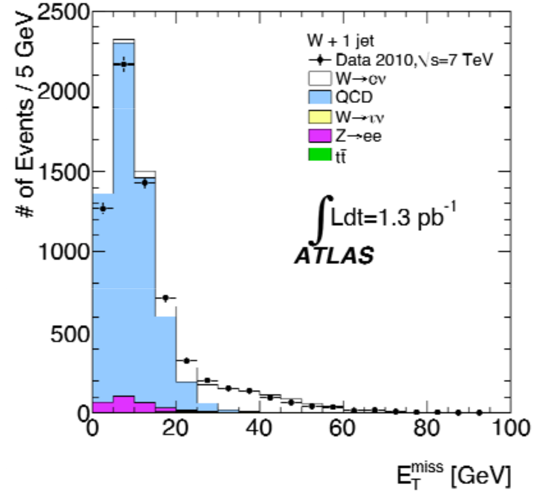




Prediction consistent with data in most bins

# W+Jets cross section

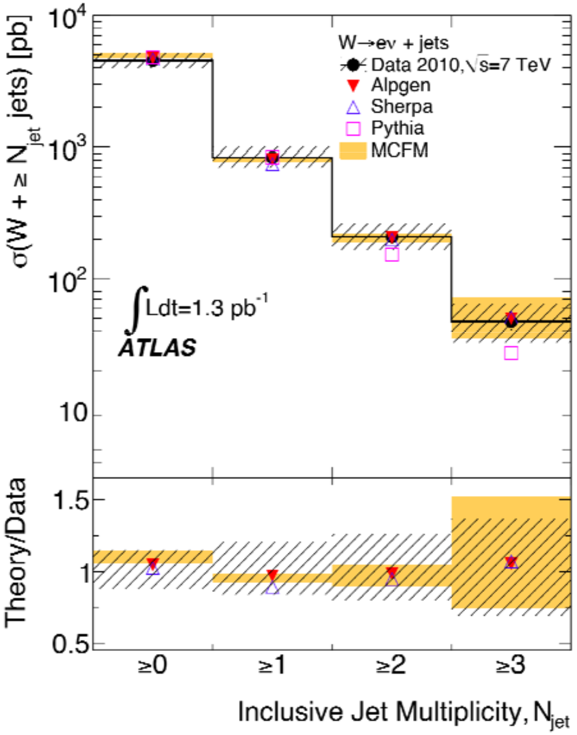
arXiv:1012.5382
Submitted to Physics Letter B

**Importance:** Vector Boson+jets cross section stringent test of pQCD and background for SM and beyond SM processes




**The measurement:**

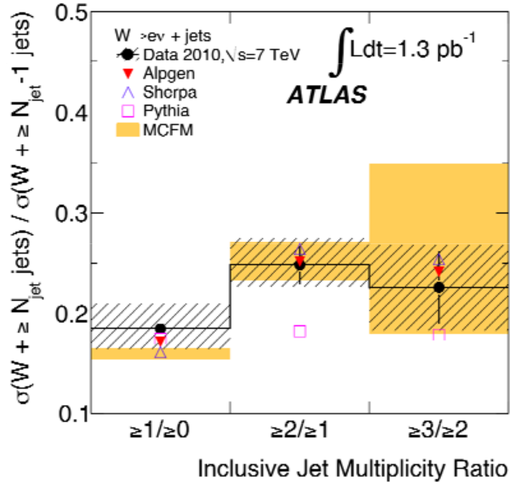
- Lepton trigger (e or $\mu$), 1 electron with $E_T$>20 GeV $|\eta|$<1.37 or 1.52<$|\eta|$<2.47 or 1 muon with $p_T$>20 GeV and $|\eta|$<2.4, Missing $E_T$>25 GeV , $M_T$> 40 GeV
  Jet (anti-$k_t$ R=0.4) with $p_T$>20 GeV $|\eta|$<2
  $\Delta R_{jet,lepton}$>0.5




- QCD background estimated by data driven method :
  fitting signal+background templates to the $E_T^{miss}$ distribution in data

- Alpgen samples for unfolding

Cross-section ratio (reduction of the systematics)




**The comparisons:**

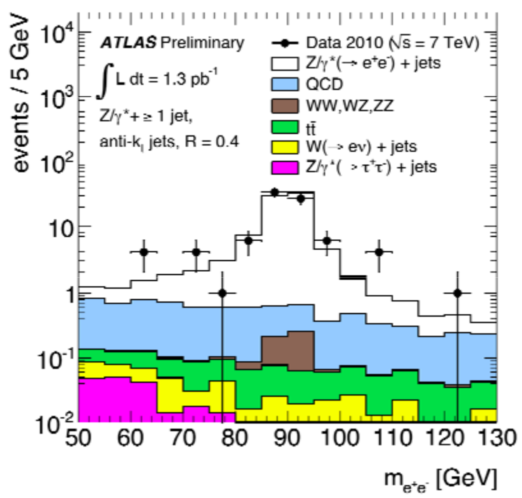
Pythia+PS (2→1 ME + 2→2 ME) doesn't provide a good description of data for $N_{jet}$
Alpgen and Sherpa show good agreemen
MCFM NLO (LO for $N_{jet}$=3) predictions also in agreement

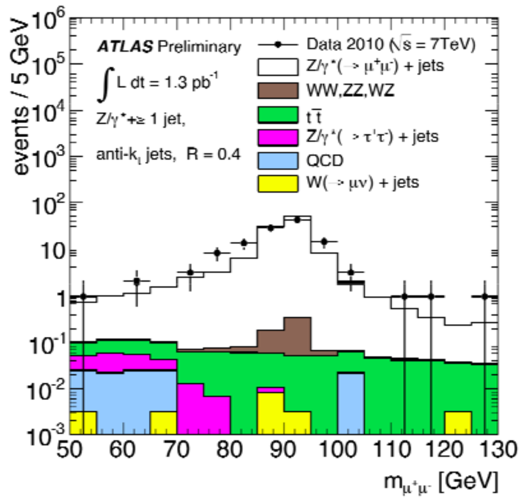
# Z+Jets cross section

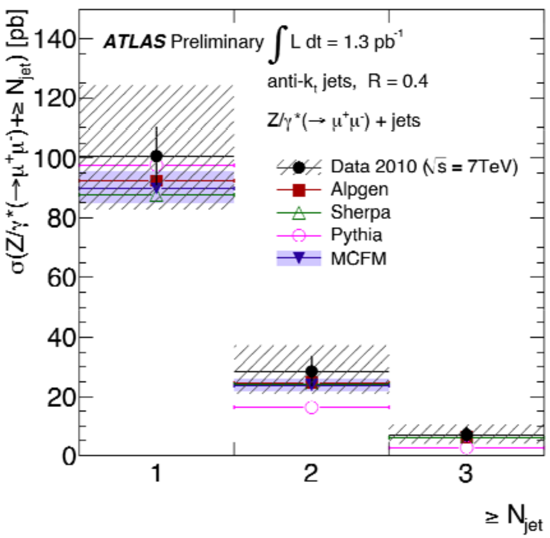
ATLAS-CONF-2011-001

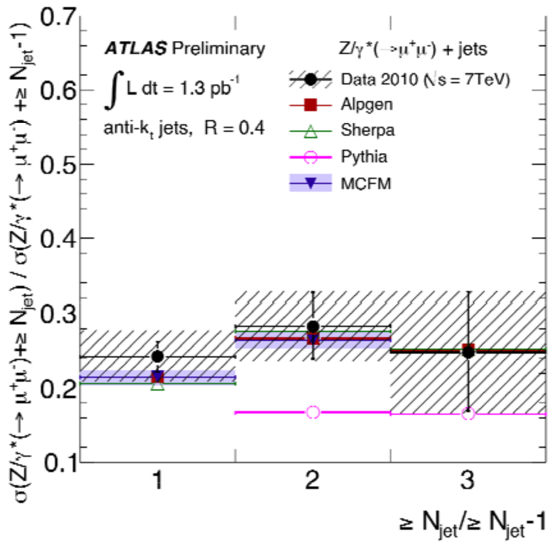
Cross section 10 times smaller that
W+jets (first measurement affected by
large statistical uncertainty)

Measurement done in the same
kinematical region of the W+jets
analysis for Leptons and Jets
$71 GeV < M_Z < 111 GeV$




Alpgen and Sherpa (NNLO normalization) agree with data

Pythia (2→2 process normalized at the inclusive 1 jet bin of data) underestimates cross-section and ratio

MCFM at NLO describes the data

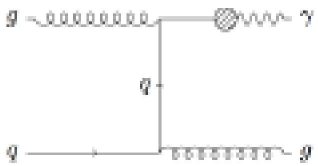
# Inclusive Isolated Prompt photon cross section

arXiv:1012.4389, Accepted by PRD

- Signal :

  Prompt photons

  Fragmentation photons



  Main background:

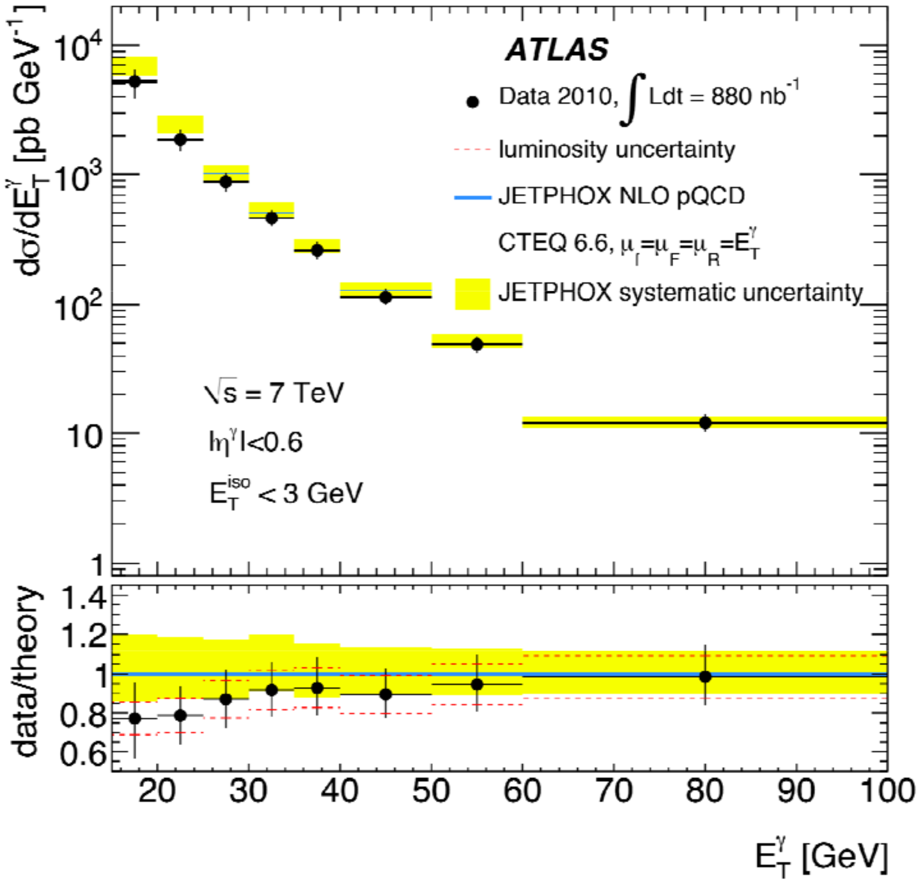
  Fake photons (jets and electrons)

  Non prompt photons from mesons decay

  Rejected by: Photon ID (shower properties)

  Isolation

- NLO pQCD predictions agree with data for $E_T$>25 GeV



# Conclusions

- Presented first QCD results at ATLAS with early data:

  Soft QCD: - Understanding of soft QCD crucial in hadronic environment

  - Tuning to LHC data in progress

  Hard QCD: - Results compared to LO+PS MCs and to NLO pQCD predictions corrected for non perturbative effects

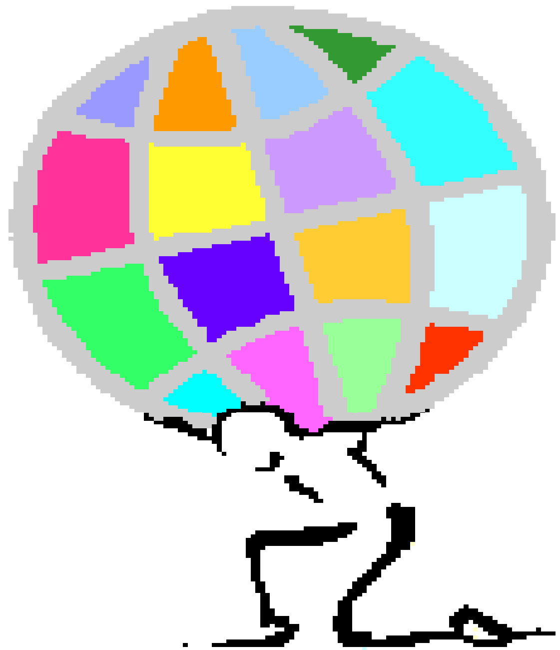
  - Good agreement between Data and Theory

  - First steps for SM backgrounds estimations to search of New Physics

- Detector working well and understanding of it improving continuously

- Expect significant updates of analyses soon with the full 2010 dataset

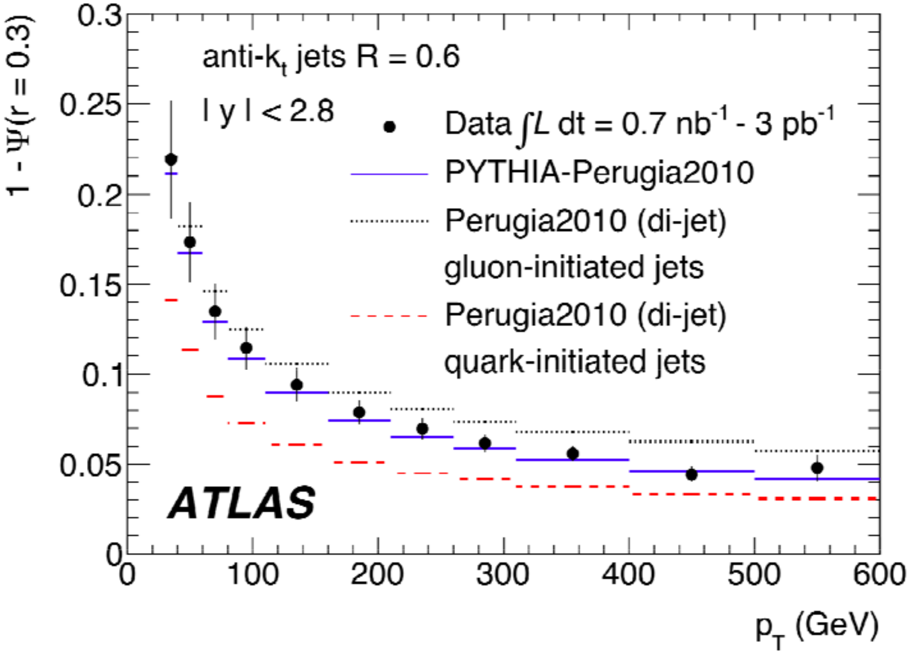
# BACKUP



# Jet Shape

arXiv:1101.0070
Accepted by Phys Rev. D

- Jet Shape is sensitive to the type of partons (quark or gluon) that give rise to jet




For illustration, separate contribution from quark- and gluon-initiated jets.

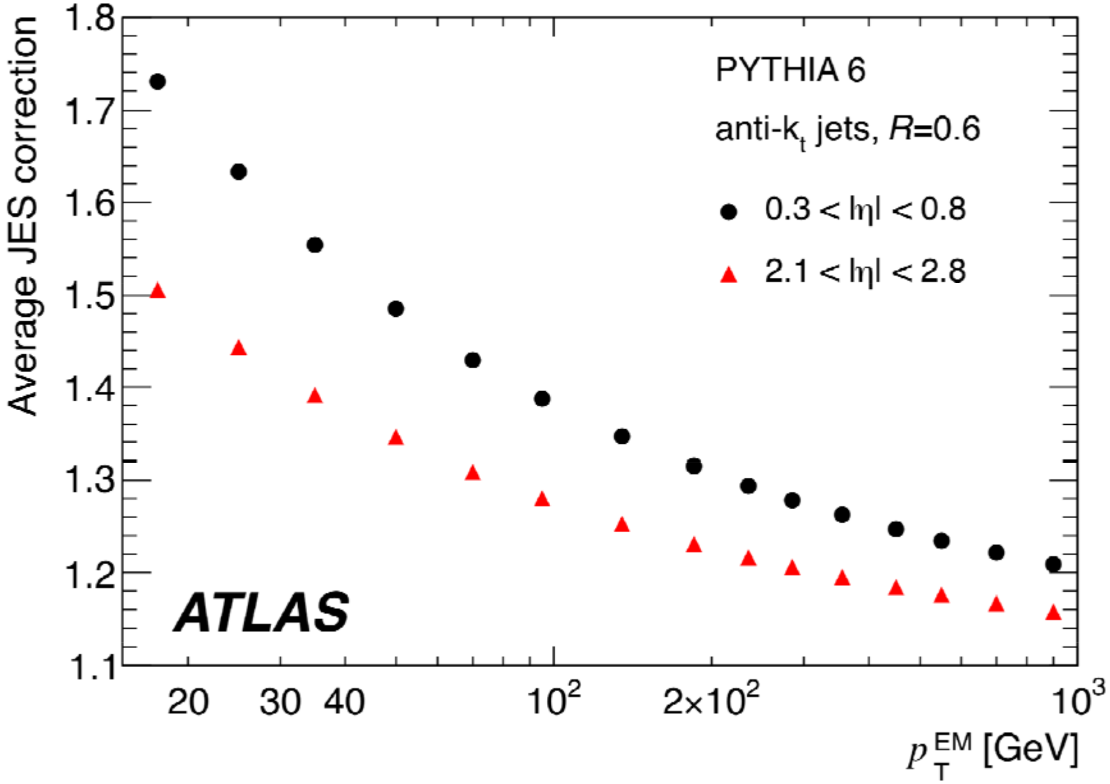
At low $p_T$, data similar to gluon-initialized jets (dominance of hard process with gluons)

At high $p_T$, data mixture of quark and gluon jets convoluted with perturbative QCD effects related to the running of the strong coupling

# JET Energy Scale

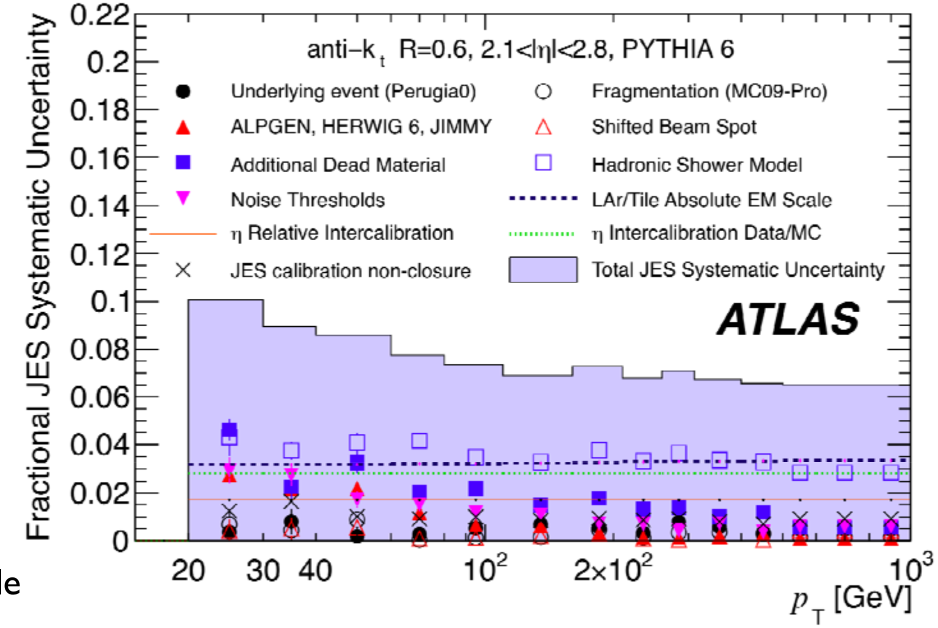
EPJC 71 (2011) 1-59

- Average jet energy scale correction as a function of the jet $p_T$ at the EM scale



# JES Uncertainty

EPJC 71 (2011) 1-59




- **Experimental Conditions and Calibrations:**

  Dead Material: used dedicated geometry model in simulation (additional material amount estimated with test beam data and comparison 900 GeV data-MC)

  Noise Threshold: possible discrepancy data-MC evaluated in MC, varying the level of noise (used a conservative estimation taken from special monitor runs)

  Beam Spot : Varied the beam spot position in MC to account for possible shifts data-MC

  EM scale : EM scale uncertainty is 3% in LArs and 4% in Tile

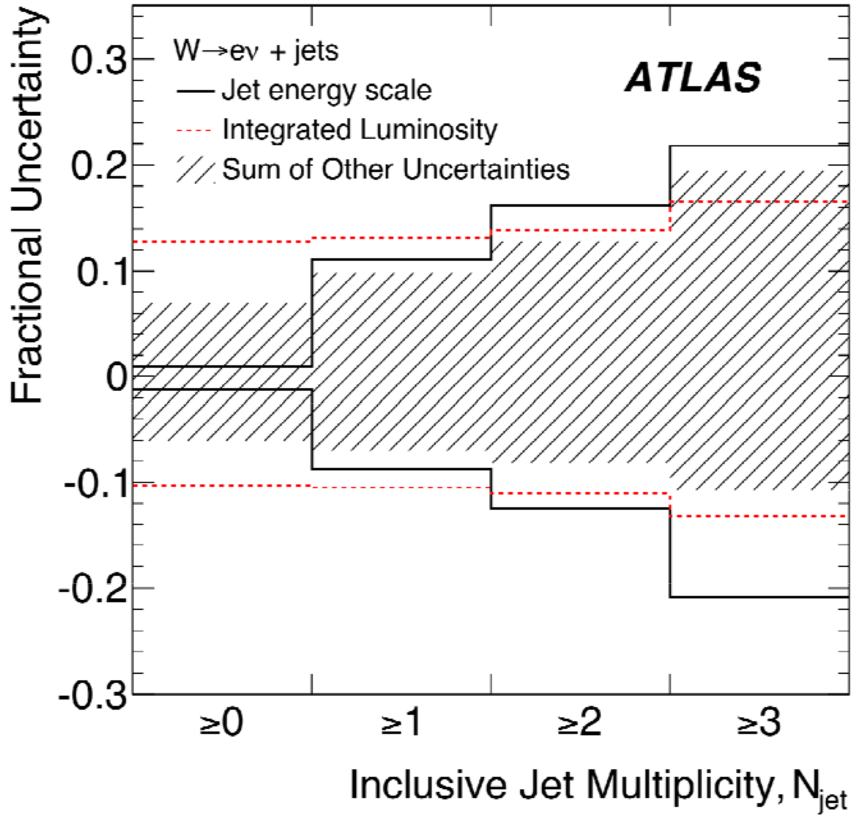
  JES calibration non-closure: deviation from unity of the final jet energy response , used the largest deviation observed

- **Hadronic Shower Model**: used 2 different MCs and compared with test beam data on single pions, test beam data lie between the 2 descriptions and the variations are within ±4%
- **Generators:** account for different fragmentation, UE and other parameters in different MC
- **Pileup** : look in the data at the average energy deposit in calorimeter as a function of the number of vertices
- **Eta intercalibration**: in forward region the uncertainty derived from the one in the central region adding an additional contribution using $p_T$ balance of forward jets in dijet events

# W+jets

arXiv:1012.5382
Submitted to Physics Letter B

Systematical uncertainties on the cross section

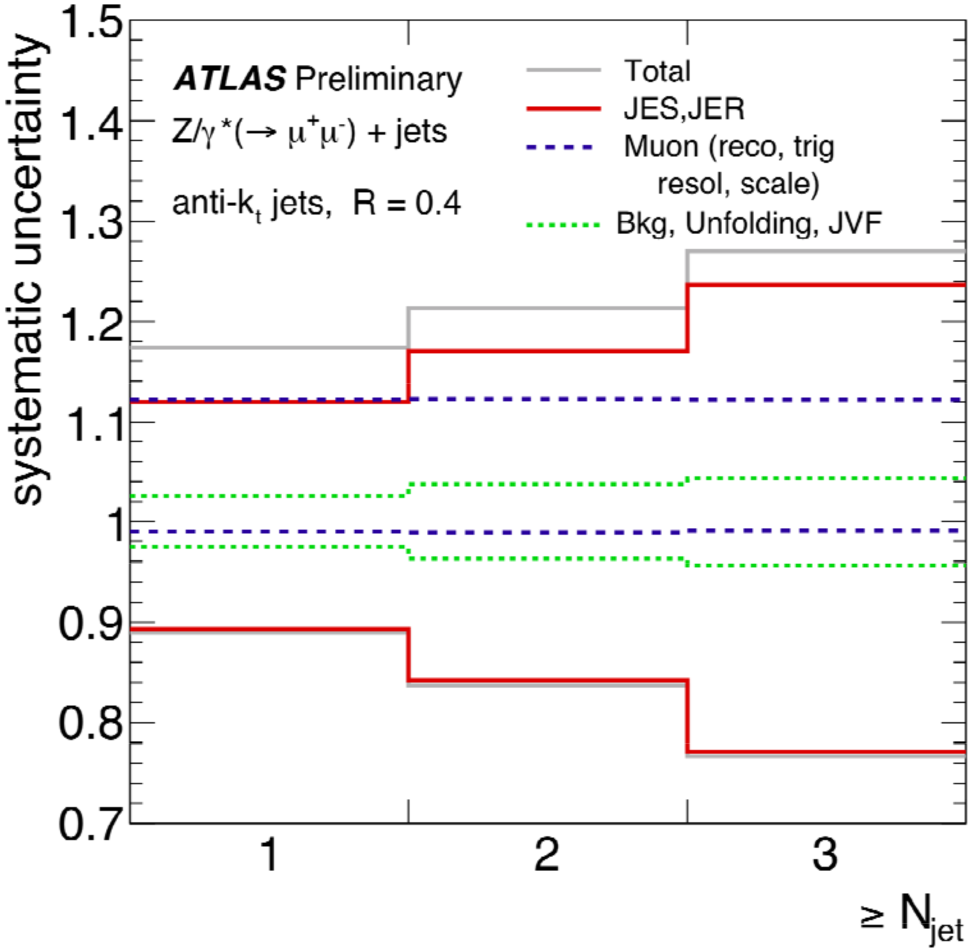



The jet energy scale uncertainty includes the uncertainty on missing $E_T$. The main contribution to the ``sum of other uncertainties'' was from the QCD background

# Z+jets

ATLAS-CONF-2011-001

Systematical uncertainties on the cross section



# Z+jets

Uncorrected distributions with the full 2010 datasets