SM and jet measurements at the LHC

Andy Pilkington – IPPP and Manchester

Presented at the Young Experiment and Theory Institute, Durham, January 2011

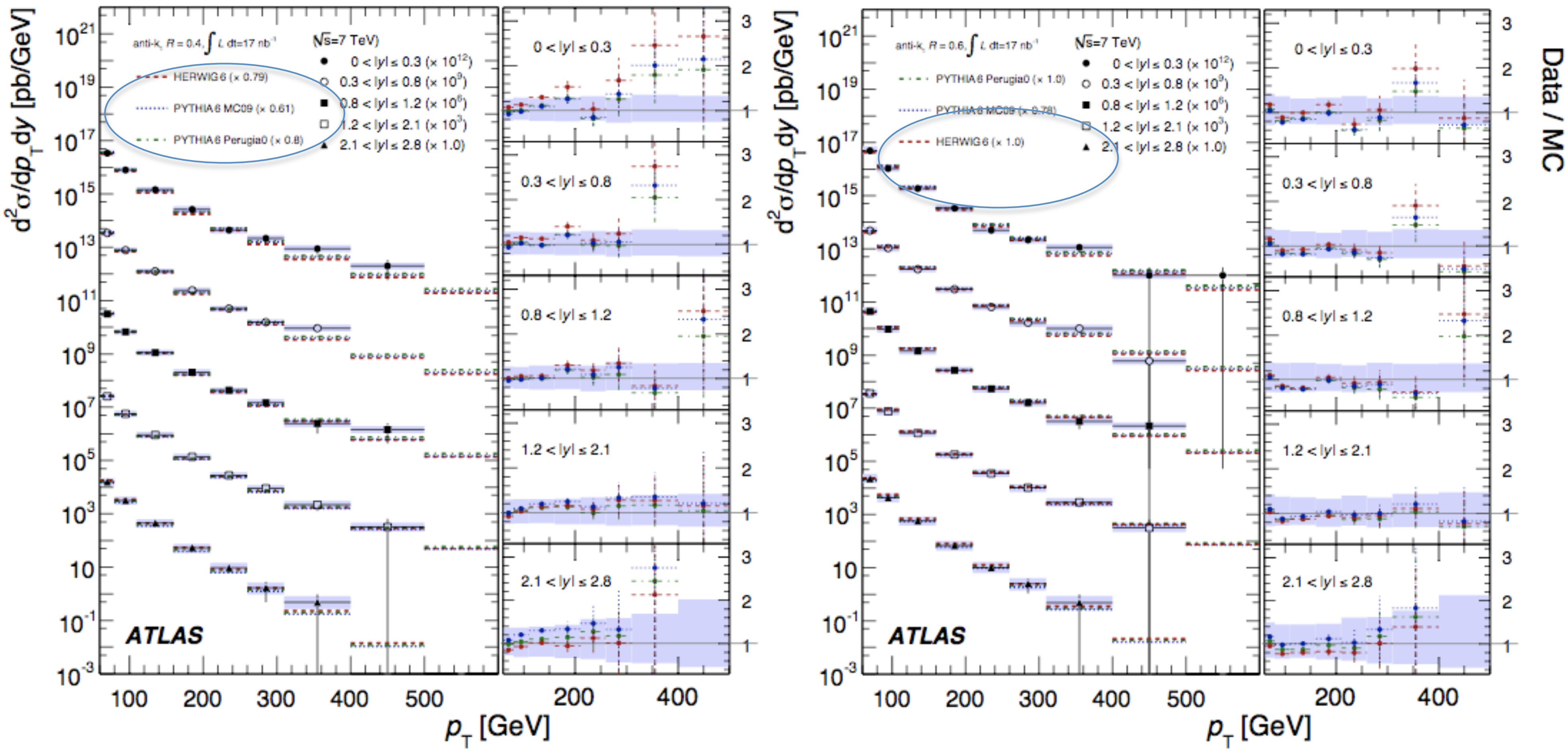
Part I – jet characteristics

1) Introduction to ATLAS, CMS and the LHC
2) Jet reconstruction and performance
3) Inclusive jet measurements

Part II – event structure

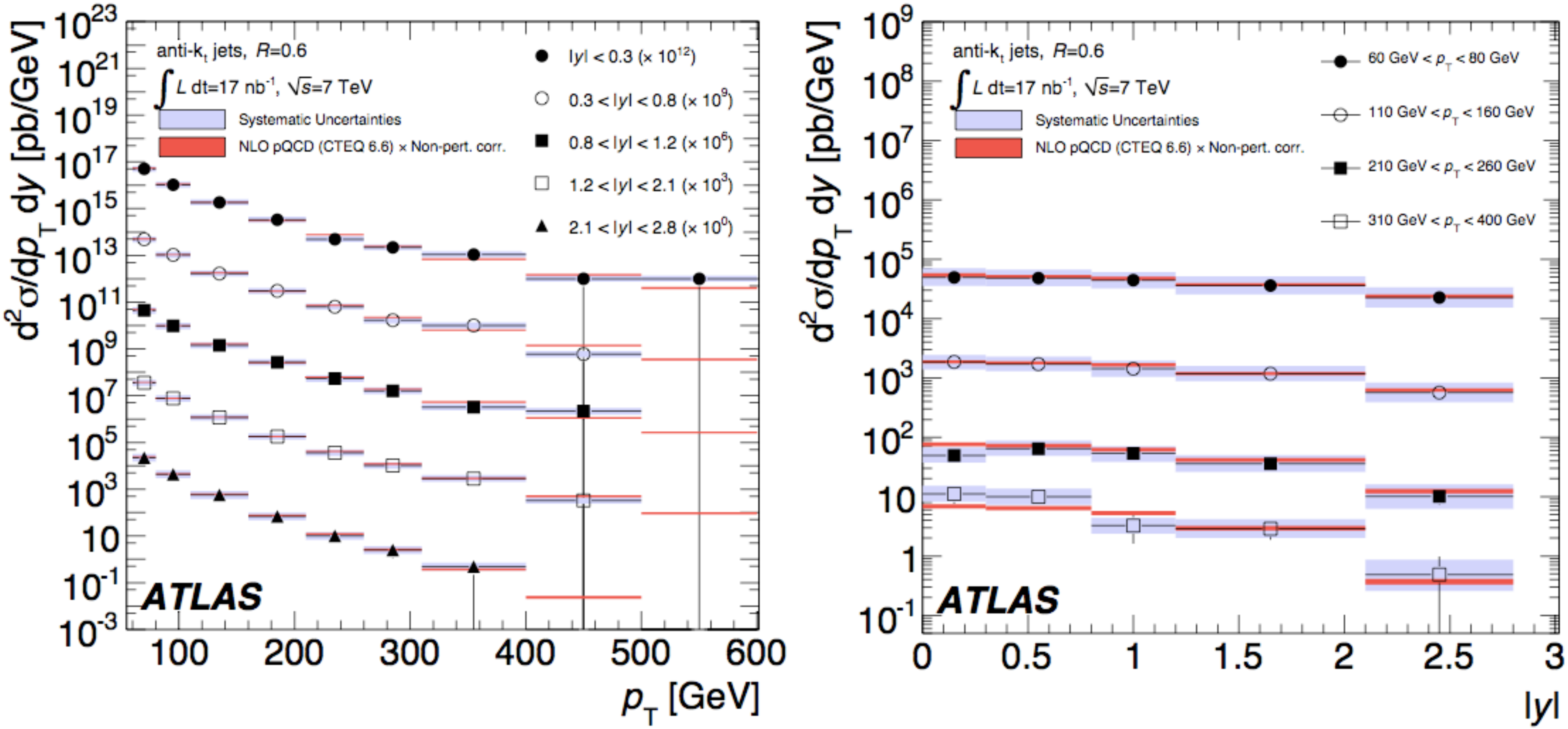
4) Inclusive jets and jet shapes revisited
5) Multi-jet final states
6) Vector boson production without jets

Remember: Inclusive jets vs LO event generators



- Shape is described by the LO 2->2 matrix element + parton shower approaches
- Normalization required to get the MC to match the data
  - Different normalization for each MC depending on jet radius (FSR,ISR,UE effects)
  - Dependency of cross-section on higher order effects and soft physics activity (UE)

Reminder (II): normalization fixed with NLO calculations



- MC event generators used in this case to provide ‘soft-physics’ corrections (hadronization, UE)
  - This correction was needed to take NLO parton-level prediction to jet-level

YETI question: An R-dependent normalization factor?

Generator	R=0.4 K-factor	R=0.6 K-factor
PYTHIA 6, MC09 tune	0.61	0.78
PYTHIA 6, PERUGIA0 tune	0.8	1.0
HERWIG 6 +JIMMY	0.79	1.0

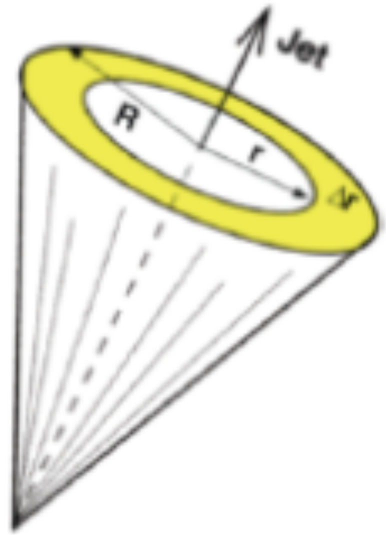
20% difference in K-factor between R=0.4 and R=0.6 (regardless of MC and tune)

From Mrinal's talk: there are R-dependent corrections to the p_T of the jet
- correction from perturbative radiation has a ln(R) dependence
- correction from UE has an R^2 dependence

If the MC correctly models the event structure, then the normalization factor should be the same at both jet radii.
- the dependence of the normalization factor with R indicates that the MC is not getting the physics right, which is expected, but the size of the dependence is surprising

A word on jet shapes…….

- Internal structure of the jet can be used to test event generator machinery:
  - Parton shower algorithms
  - Underlying event contribution



- Fraction of jet p_T contained within an annulus of size Δr:

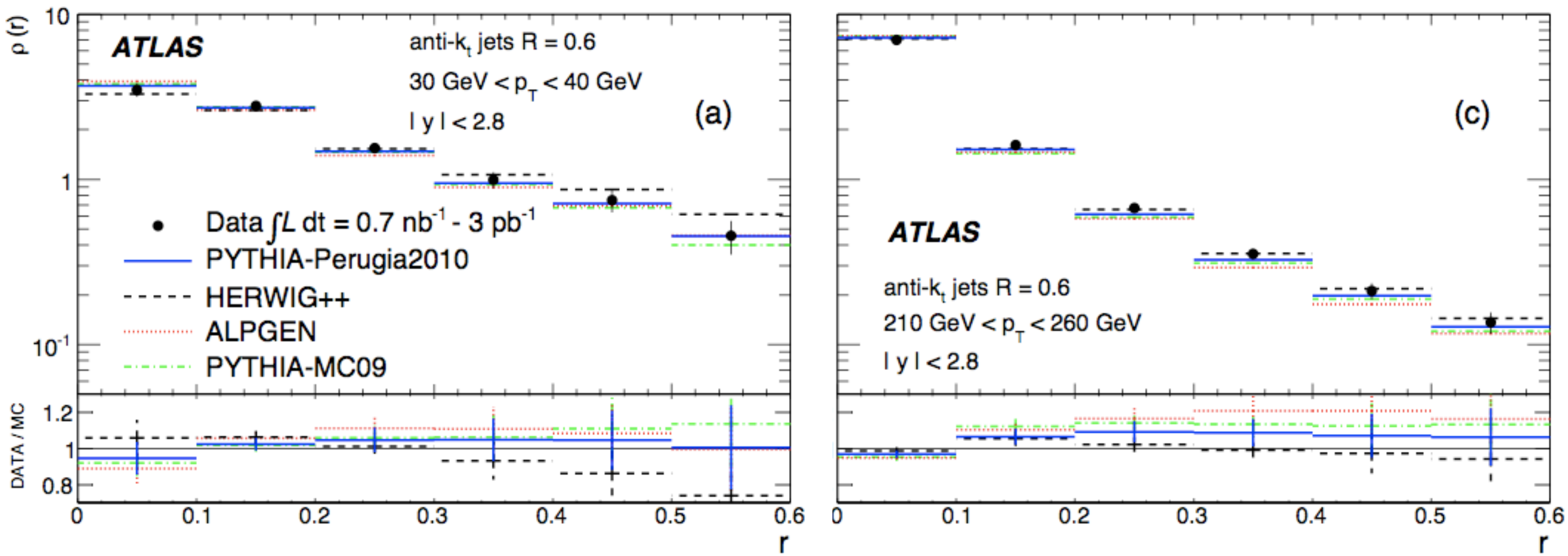
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\text{jet}}}\sum_{\text{jets}}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)}$$

- Fraction of jet p_T that lies within a cone of size r:

$$\Psi(r) = \frac{1}{N^{\text{jet}}}\sum_{\text{jets}}\frac{p_T(0,r)}{p_T(0,R)}$$

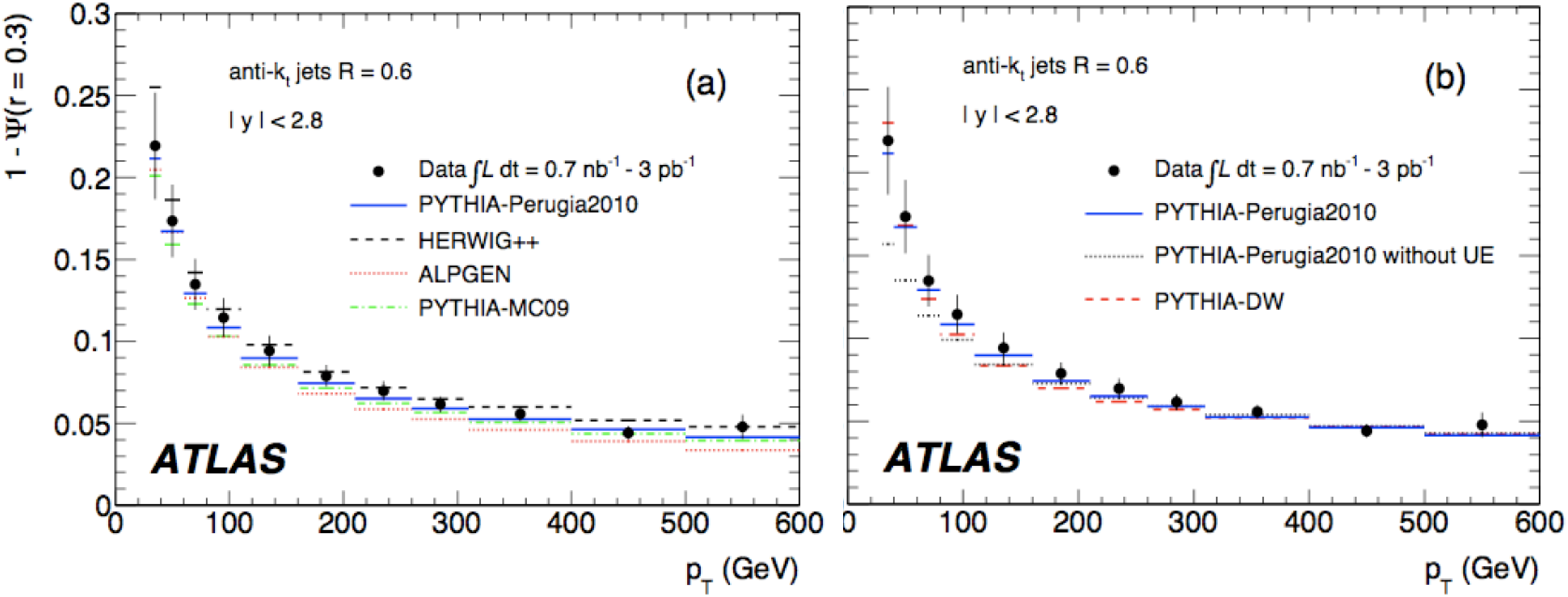
- ATLAS measurement performed with ~$3pb^{-1}$ of data (see arXiv: 1101.0070), internal structure studied as a function of p_T and |y| for anti-k_T jet algorithm with R=0.6 (Δr=0.1)

Jet shapes (I)



- As usual, one tune/MC does not fit all
- At low p_T expect a larger (relative) contribution from UE activity.
- Jet shape is an interplay between UE and the shower – a particular event generator tune could describe the data but get both contributions very wrong

Jet shapes (II)



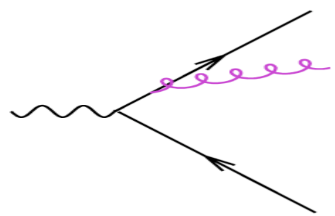
- Integrated jet shape shows the same results
  - HERWIG++ broadest jets,
  - ALPGEN+HERWIG+JIMMY has narrowest jets.
  - Huge effect of UE at low p_T

Multi-jet final states

Multi-jet measurements

- The shape of the inclusive and di-jet measurements were reasonably well described by the LO 2->2 scattering plus parton shower in PYTHIA & HERWIG
  – Not surprising as these distributions only depend weakly on the third, fourth jets.

- The internal jet structure was also described fairly well by the parton shower approximation plus underlying event:
  – Dominant contribution to 3 jet matrix element occurs when the third jet is soft or collinear
  – PS resums leading logarithmic contributions to give a reasonable description of **soft** and **collinea**r radiation



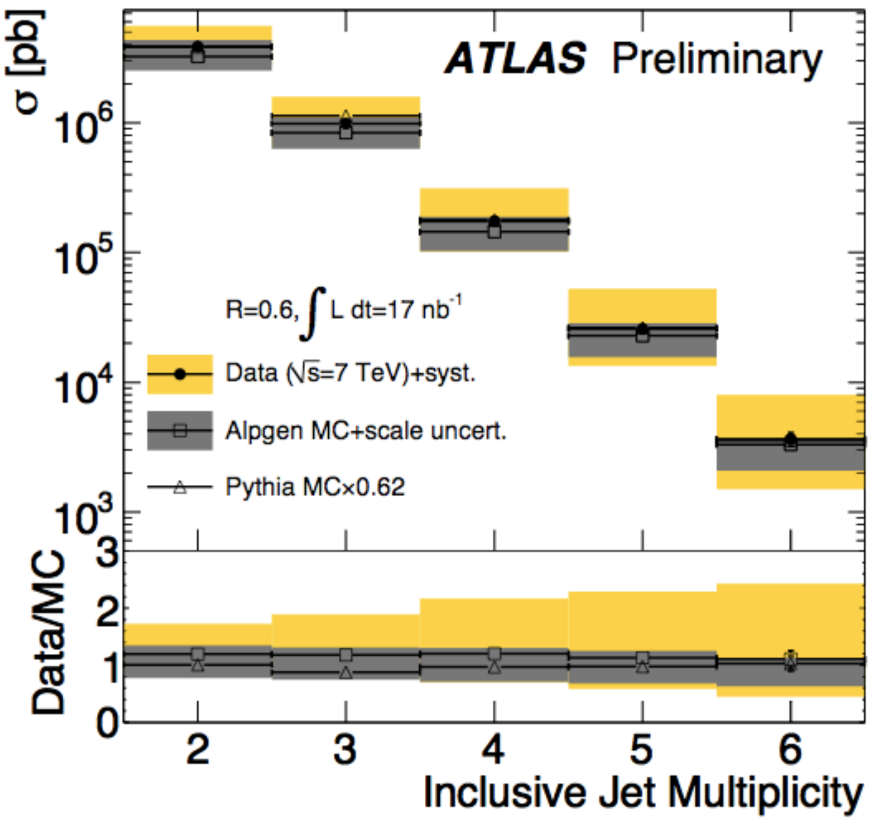
- For observables sensitive hard wide angle emission - expect that PYTHIA and HERWIG will not describe the data very well.
  – Should use generators with implementation of 2->3, 2->4 matrix elements (and then apply a parton shower) – i.e. Sherpa, Alpgen

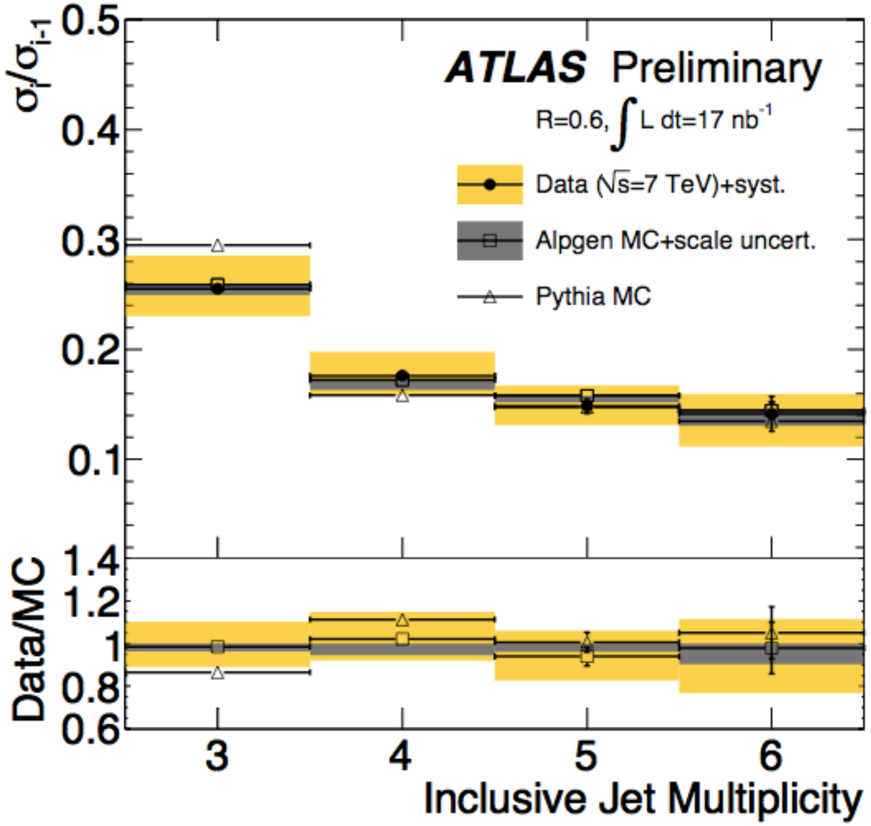
Jet multiplicity measurements (I)

- ATLAS measurement presented at HCP in August 2010 using $17nb^{-1}$ of data.
- Simplest extension of the inclusive jet measurement.
- Event selection:
  - All jets have $|\eta|<2.8$
  - Leading jet must have $p_T>60GeV$ (to be in plateau region of lowest threshold trigger)
  - Other jets must have $p_T>30GeV$ (to be in well described JES region)
  - Same vertex requirement and jet cleaning cuts as inclusive jet measurement

- Observables:
  - Cross-section for n-jet production
  - Ratio of the n+1 jet cross-section to n-jet cross-section (σ_{i+1}/ σ_i)
  - Both of these as a function of (i) the number of jets, (ii) the p_T of the n'th jet and (iii) as a function of $H_T = \Sigma p_T^{jets}$

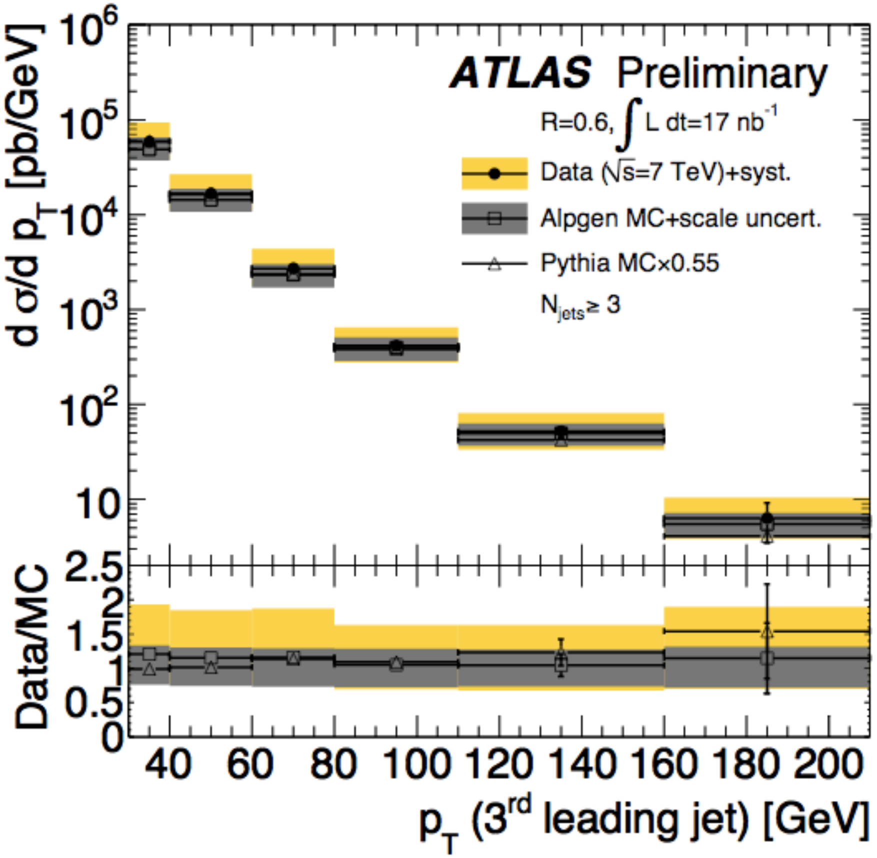
Jet multiplicity measurements (II)

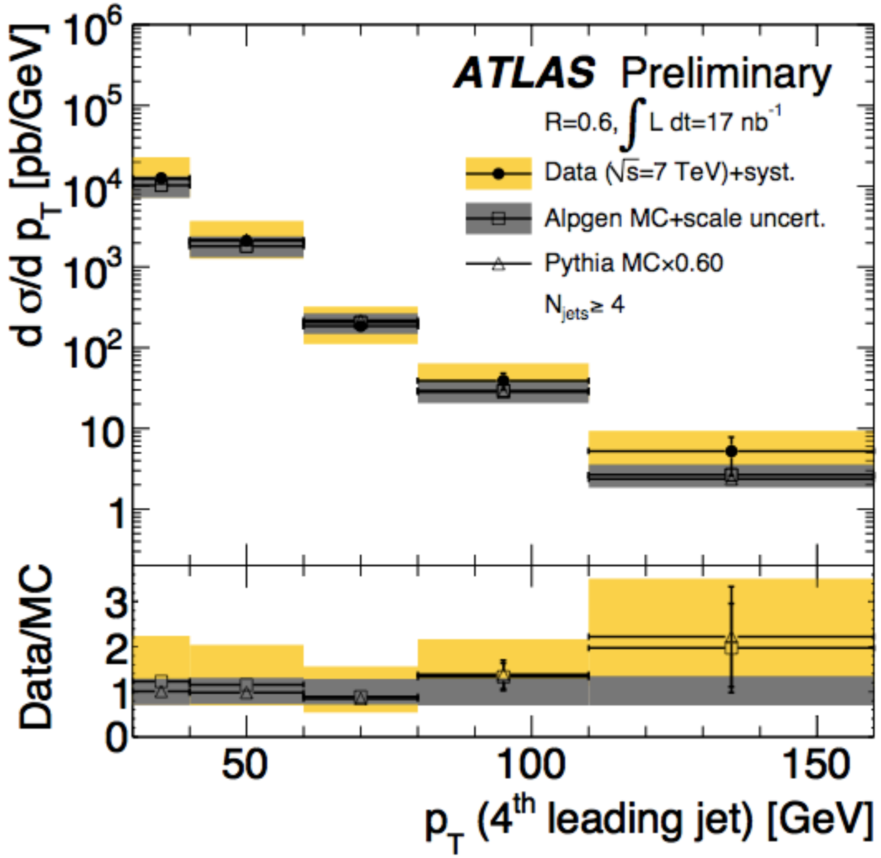




- Normalization required to get absolute PYTHIA prediction to match the data
  - ALPGEN needs no normalization, despite being a LO calculation!
- Ratio shows that PYTHIA is overproducing the third jet in the parton shower.
  - PYTHIA tuning overcompensating for the natural hard emission deficiency in shower?

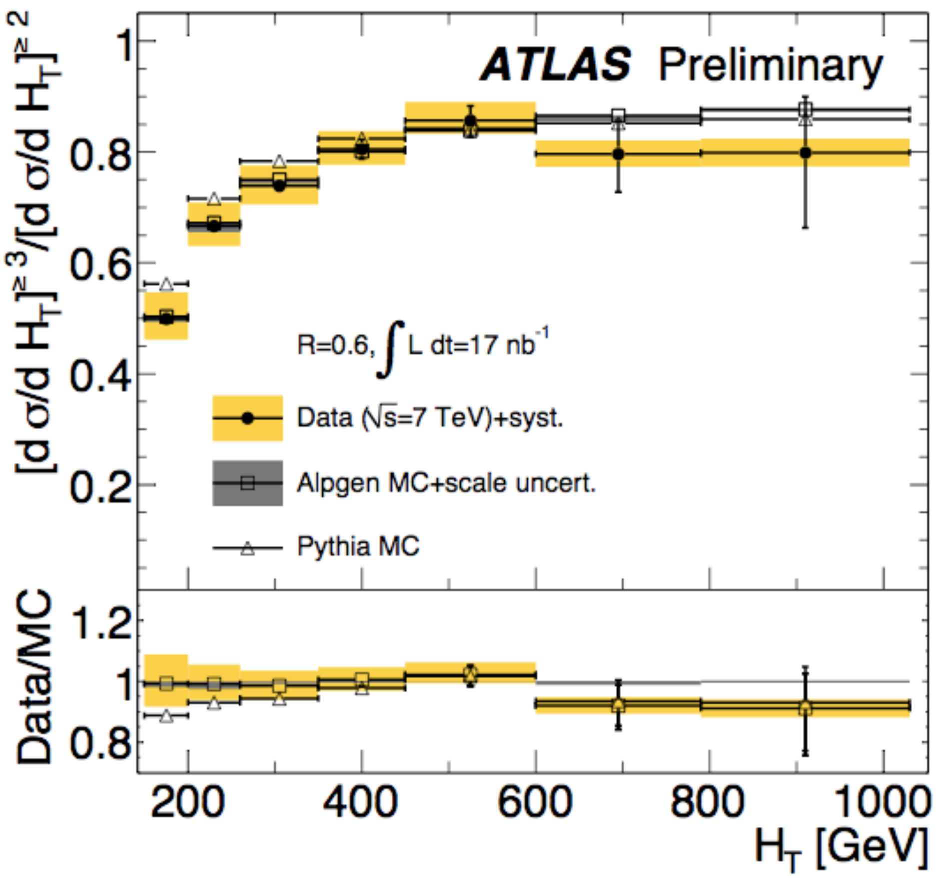
Jet multiplicity measurements (III)

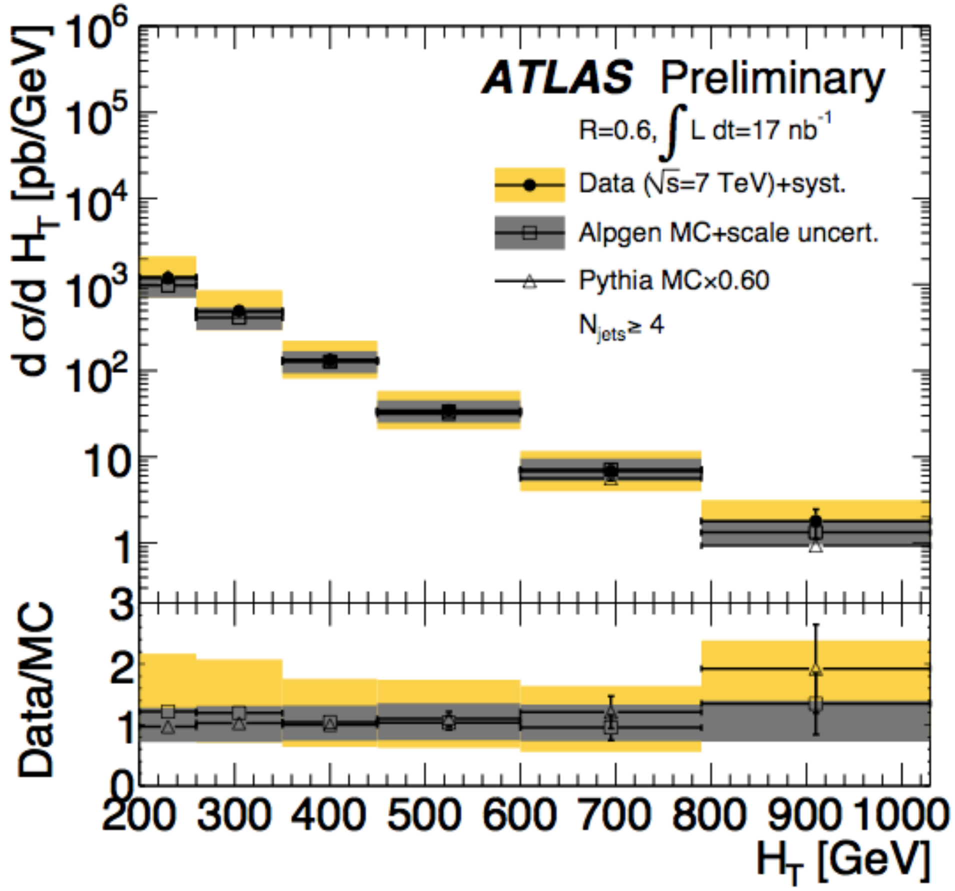




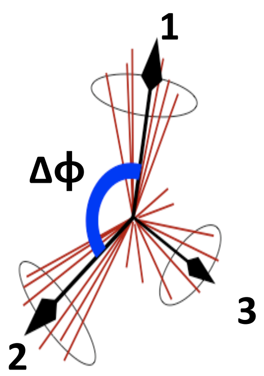
- Cross-section differential in jet p_T shows that PYTHIA and ALPGEN are in reasonable agreement (after normalization of each bin)
  - this agreement would be somewhat reduced of course if a global normalization was used.

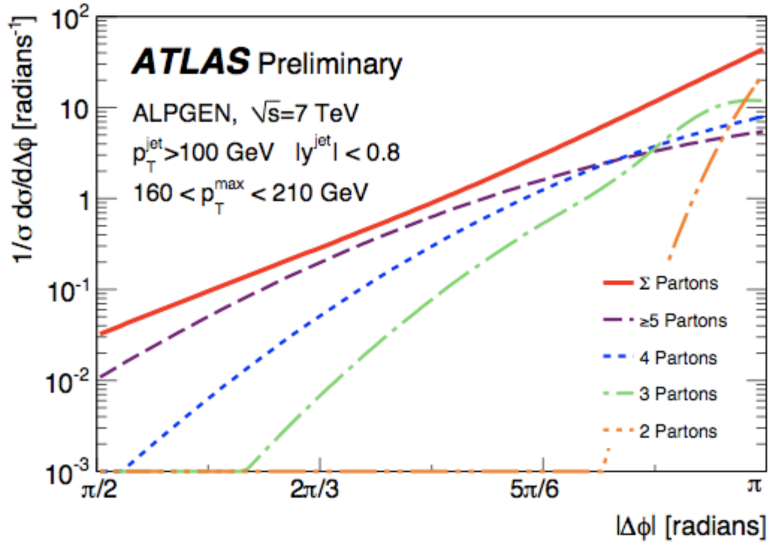
Jet multiplicity measurements (IV)





Azimuthal decorrelations (I)

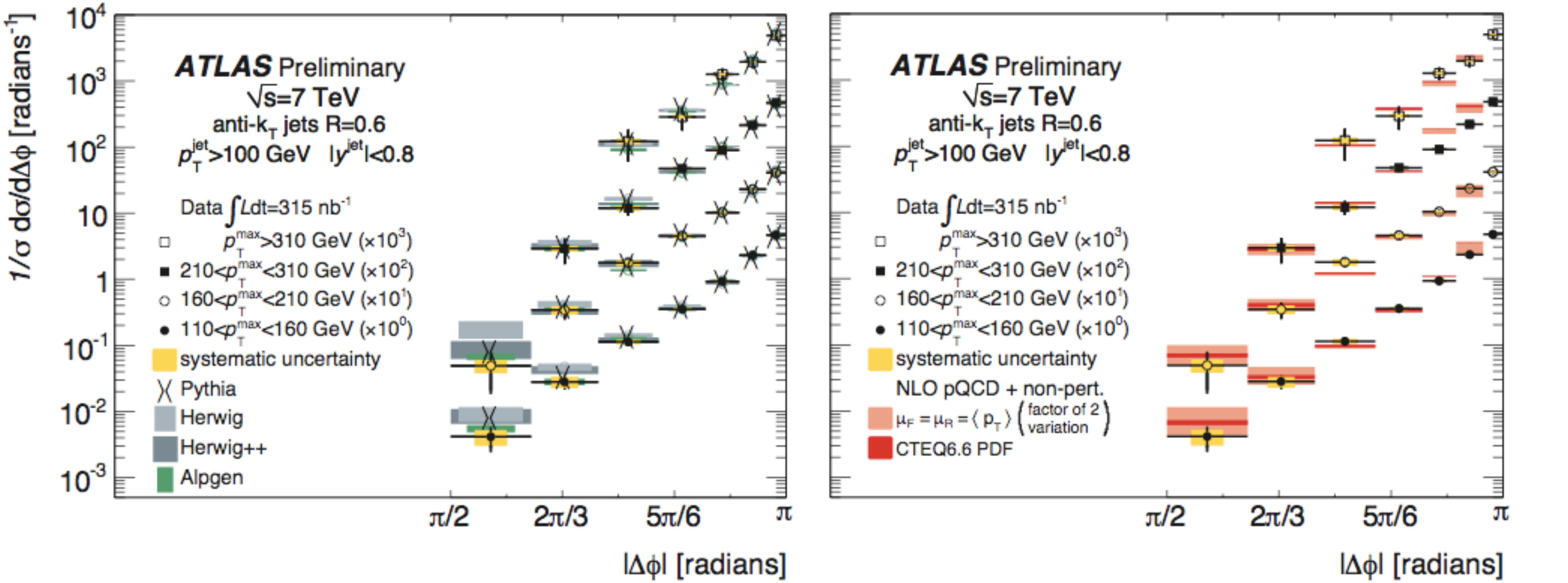




- The azimuthal decorrelation between the two leading jets also probes higher-order QCD effects
  - LO dijet production produces back-to-back partons , i.e. $\Delta\phi = \pi$
  - Soft radiation causes small decorrelations, i.e. . $\Delta\phi \sim \pi$
  - Hard emission causes large decorrelations such that $\Delta\phi << \pi$

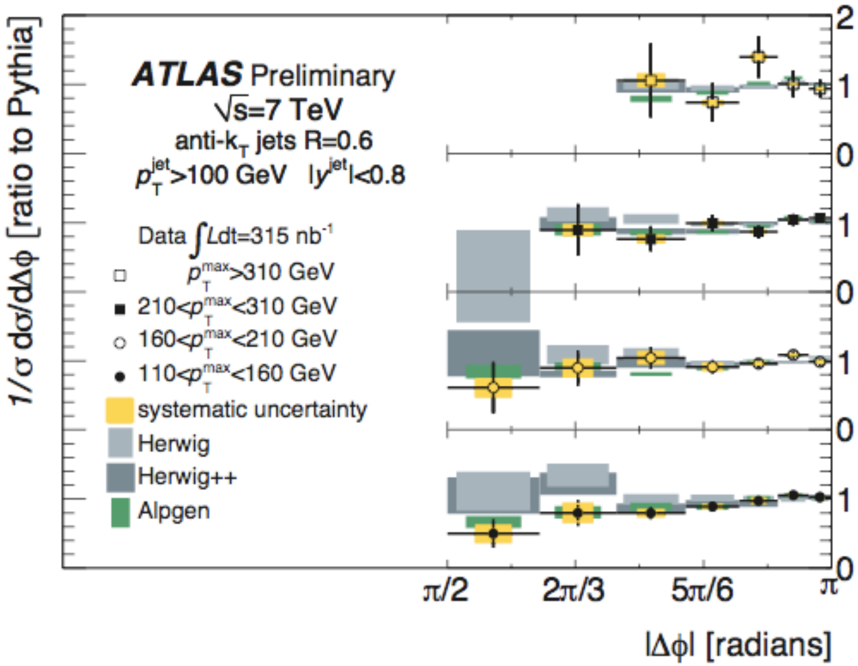
- Experimentally, nice observable because it does not require the additional jets to be reconstructed (sensitive to low p_T emission) - important for jets with p_T<15GeV
- Event selection:
  - All jets with $|y|<0.8$.
  - Leading jet with p_T>100GeV (trigger requirement), second jet with p_T>30GeV

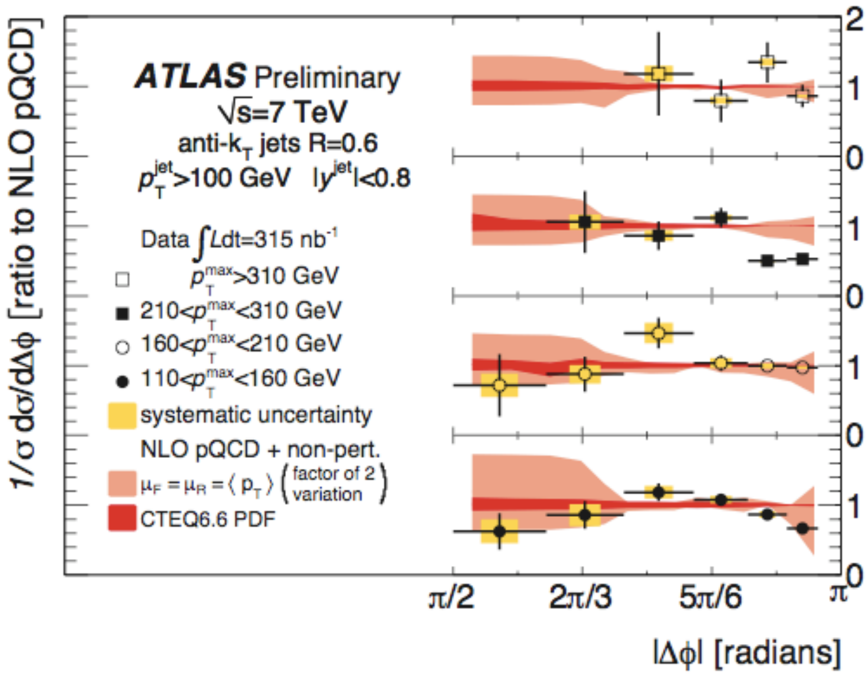
Azimuthal decorrelations (II)



- Normalised differential cross-section compared to
  - MC generators (left) and
  - NLO calculation plus non-perturbative corrections (right)

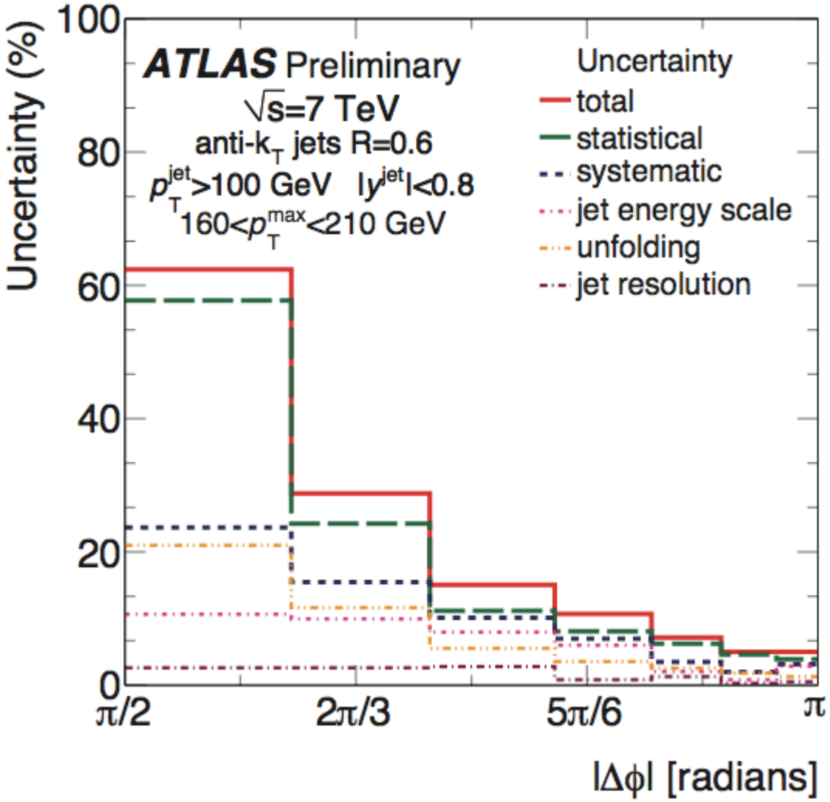
Azimuthal decorrelations (III)

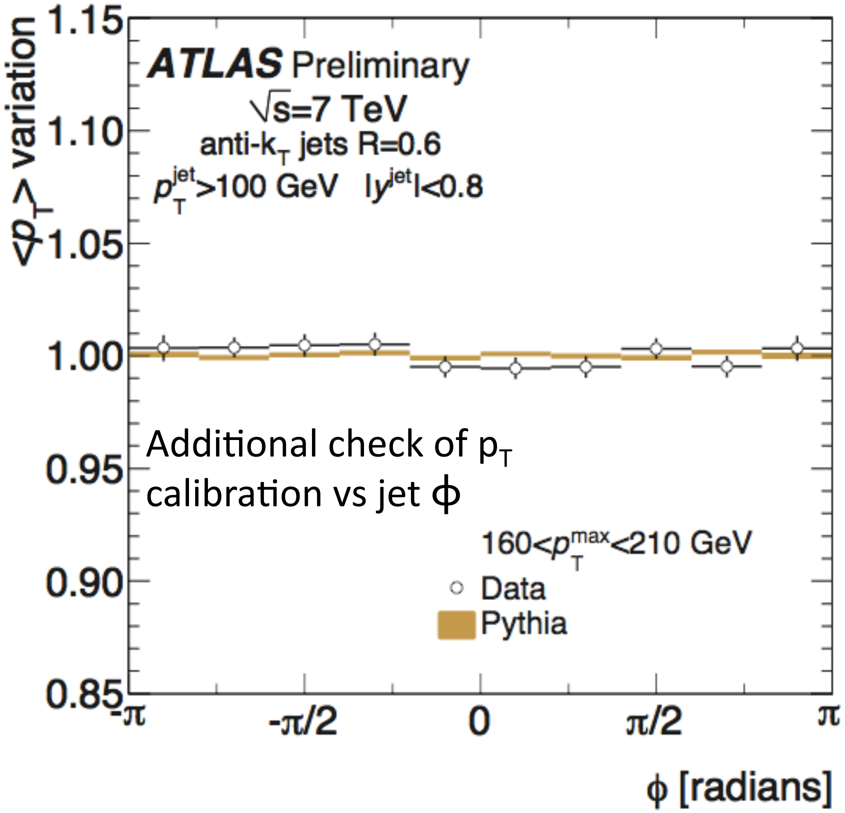




- PYTHIA overestimates the de-correlation consistent with the overestimation of the three-jet cross-section in the jet multiplicity measurement

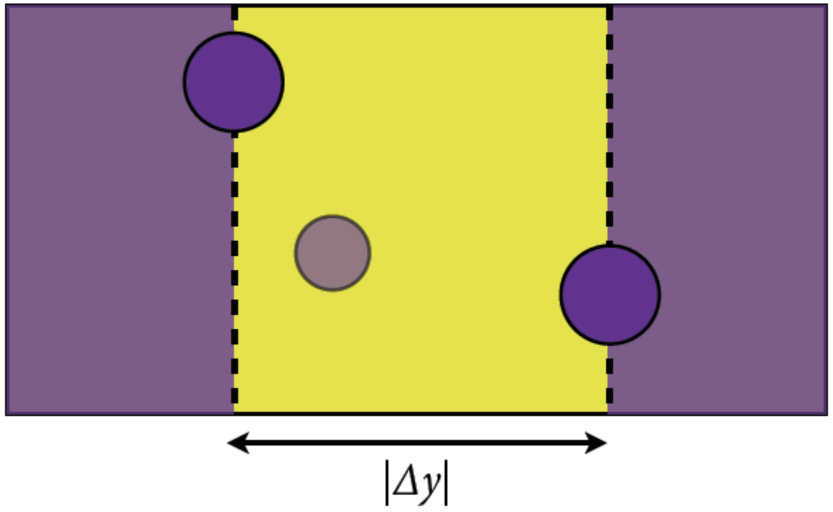
Azimuthal decorrelations (IV)

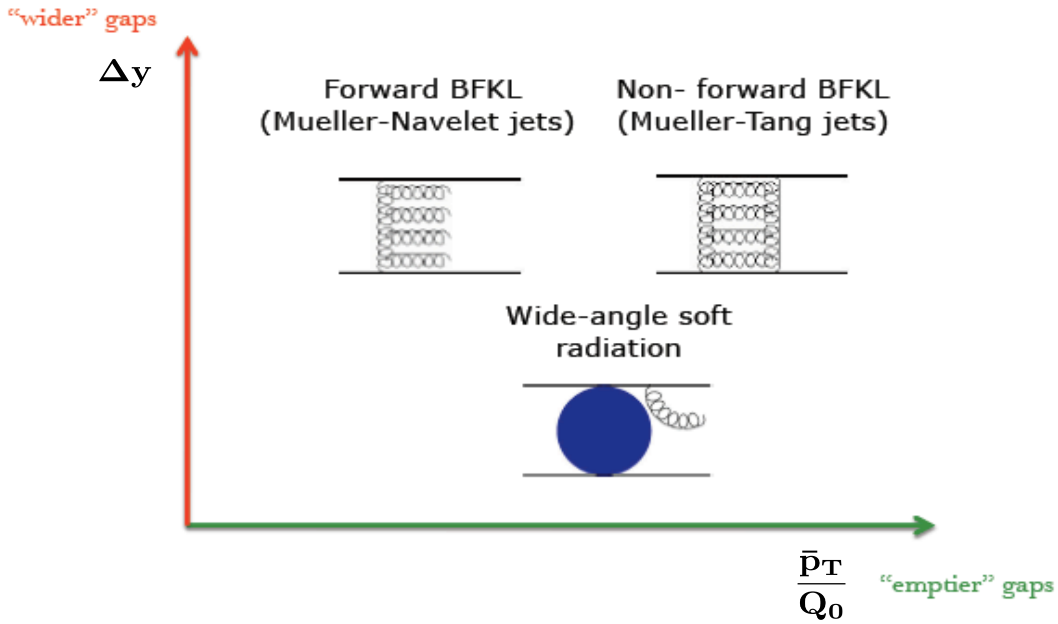




- Dominant uncertainty in measurement was statistical (315nb^{-1})
- Unfolding detector effects also very large – actually sue to the statistics in the MC samples – updated analysis will have to rectify this.

Dijet production with a jet veto (I)

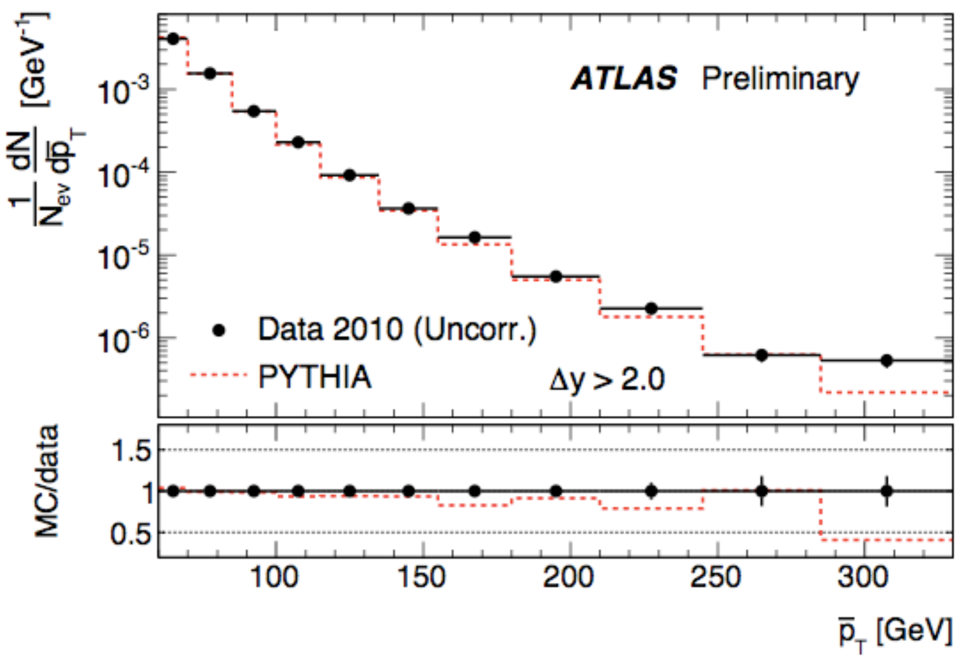


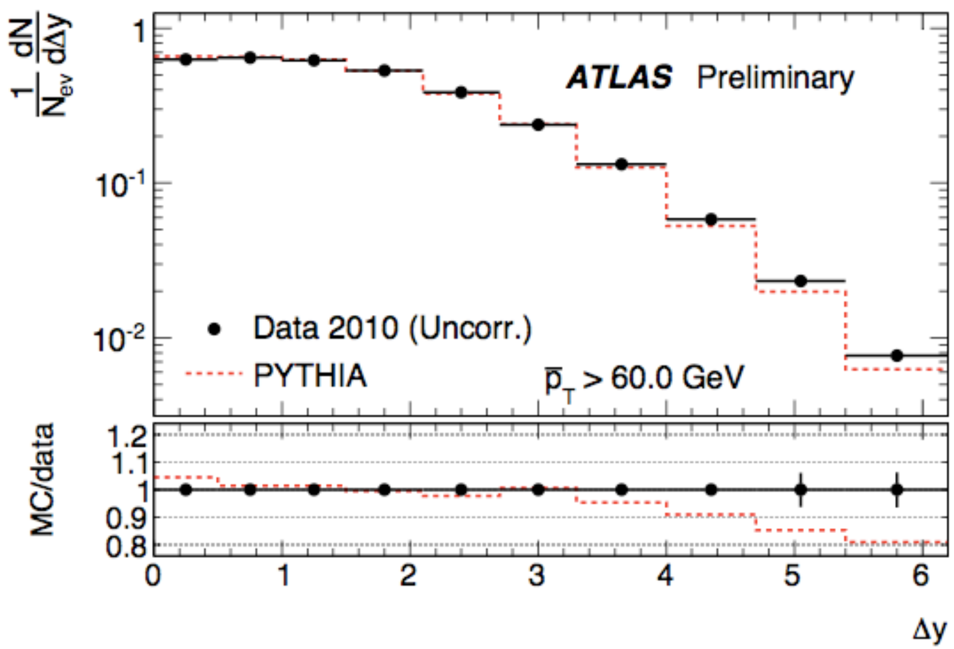


- At least two good/clean anti-k_T jets (R=0.6) with p_T>30GeV and rapidity |y|< 4.5.
  - This was the first ATLAS measurement that used forward jets!
- Boundary jets identified as the two highest p_T jets in the event.
- Gap events defined as the subset of events that do not contain an additional jet with p_T above the veto scale (Q_0=30GeV).

- Gap fraction studied as a function of the average transverse momentum of the boundary jets, pt(avg), and the rapidity separation, Δy, of the boundary jets.

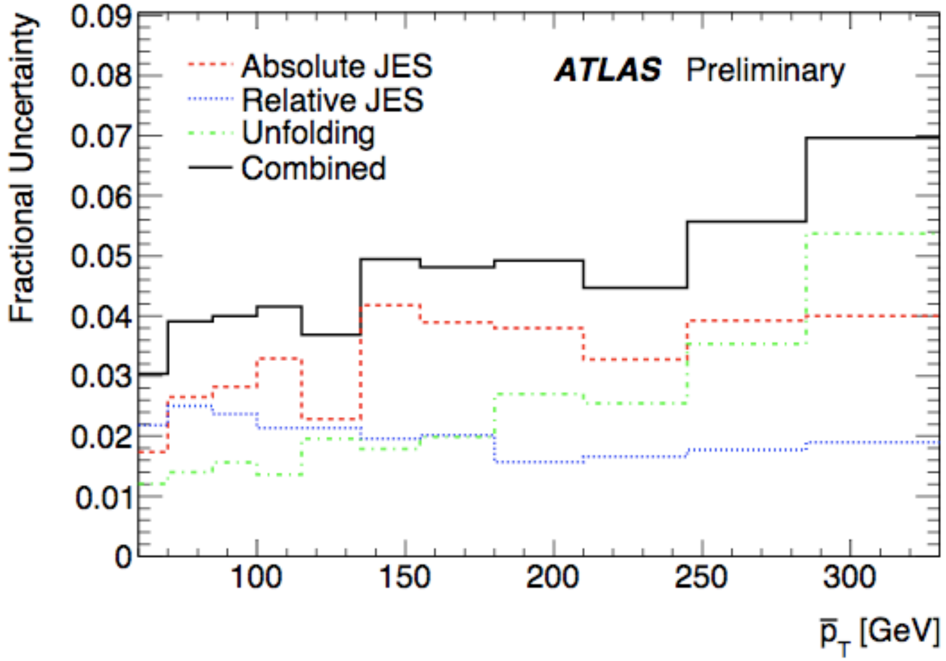
Dijet production with a jet veto (III)

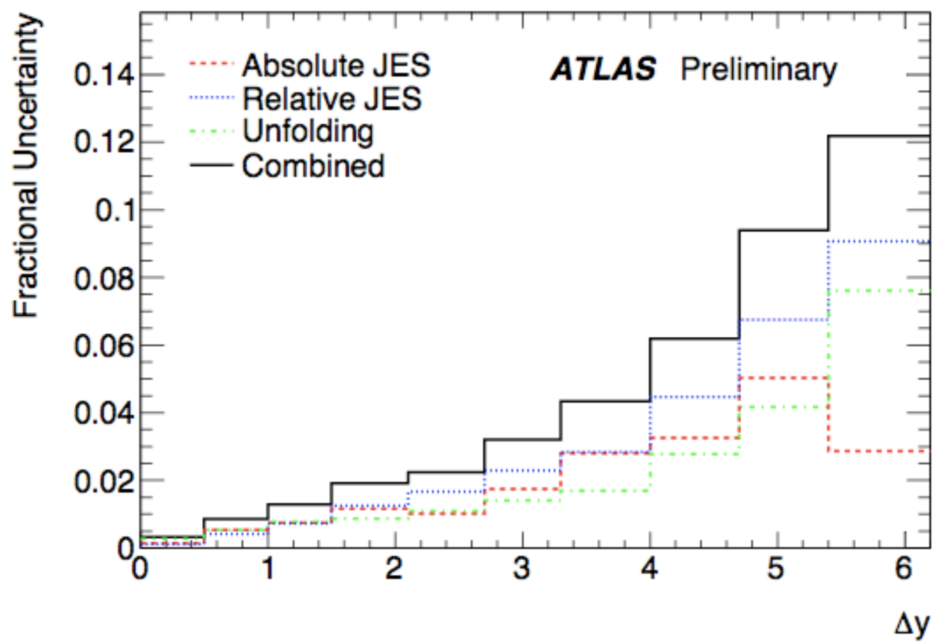




- Boundary jet distributions consistent with PYTHIA MC09 tune
  - JES systematics (very large) are not shown on this plot – data is in fact well within the JES band.

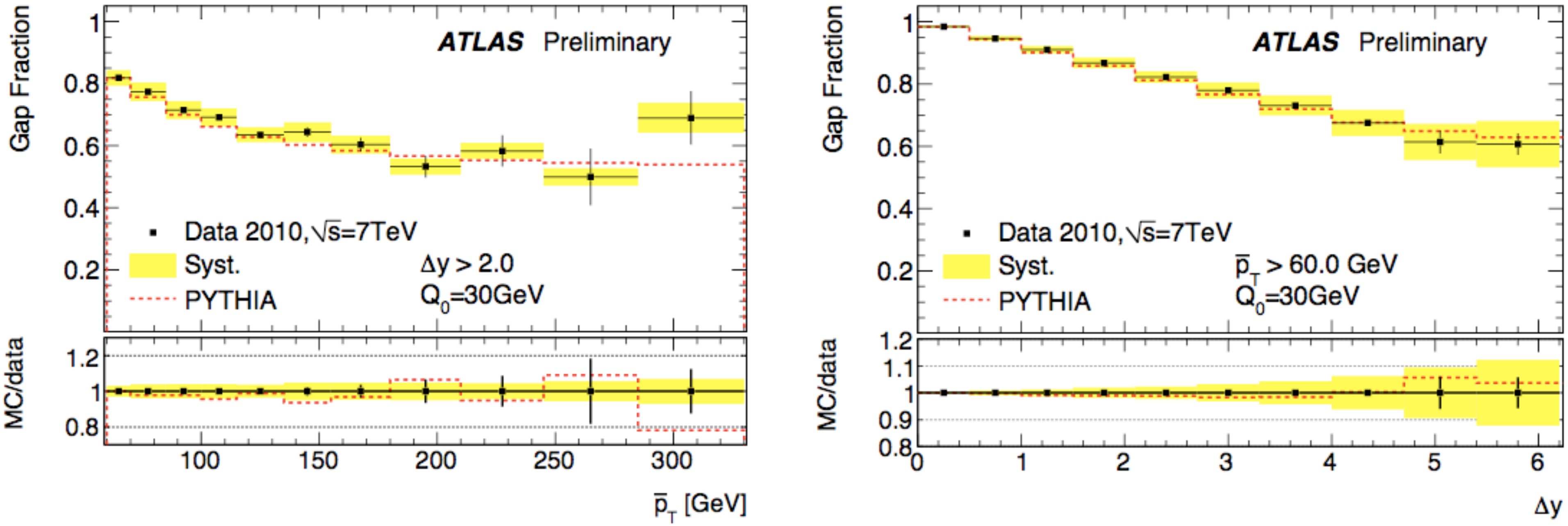
Dijet production with a jet veto (IV)





- Systematic uncertainty on gap-fraction is small
  - Many uncertainties cancel in ratio (JES, lumi, etc)
  - Main uncertainty is still the JES, but increasing contribution from unfolding (mainly MC stats at large p_T and Δy

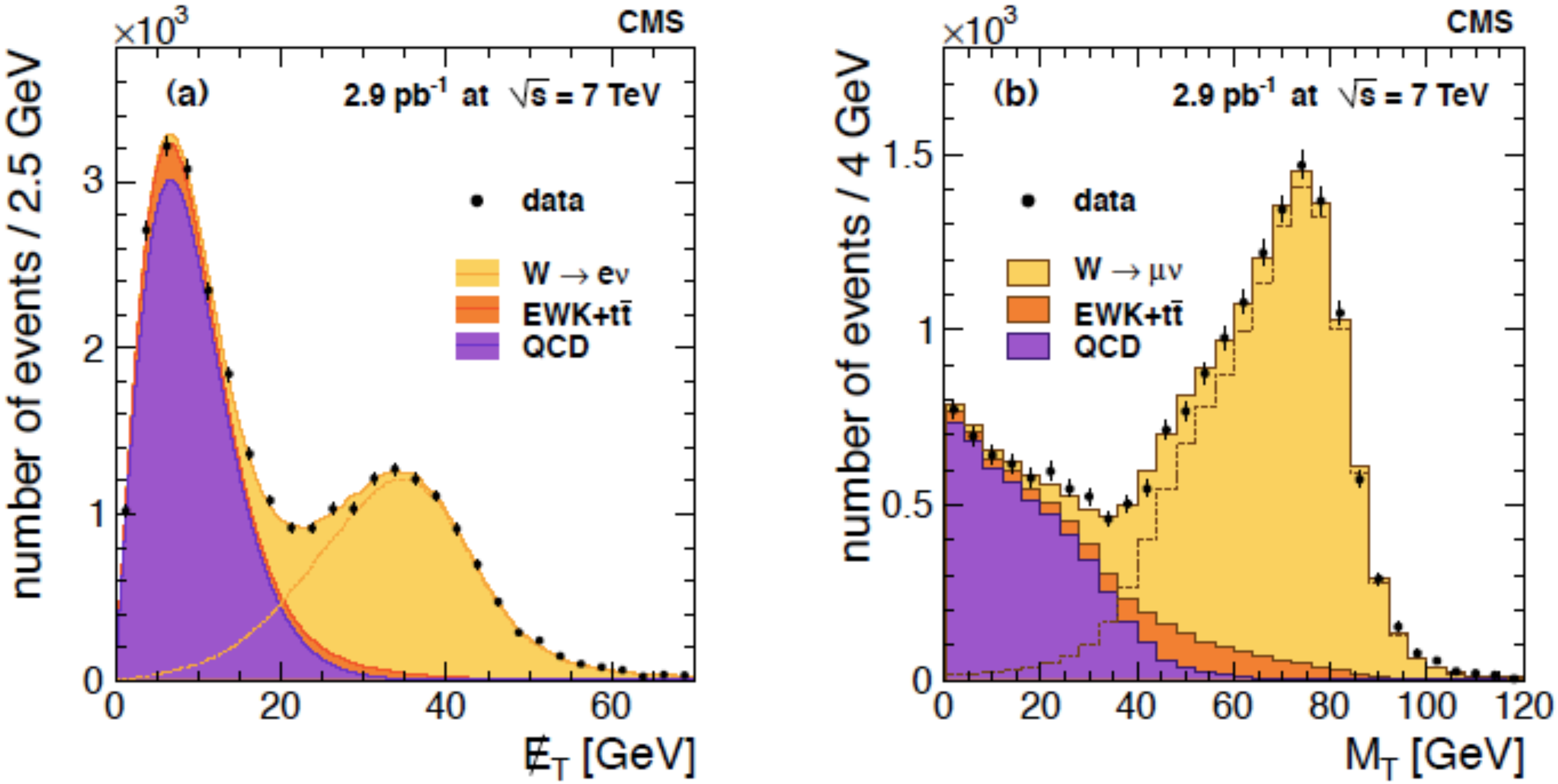
Dijet production with a jet veto (V)



- Final results with $190 nb^{-1}$ of data.
- Remarkable agreement between this PYTHIA tune and data for this preliminary analysis
  - Somewhat inconsistent with other multi-jet results (over production of additional jets in those analyses).
  - Updated analysis soon with more data, reduced JES/unfolding systematic, smaller Q_0 and more event generators (HERWIG++, Sherpa, POWHEG, HEJ)

Inclusive W/Z production – a quick look

Inclusive W/Z production at CMS (I)



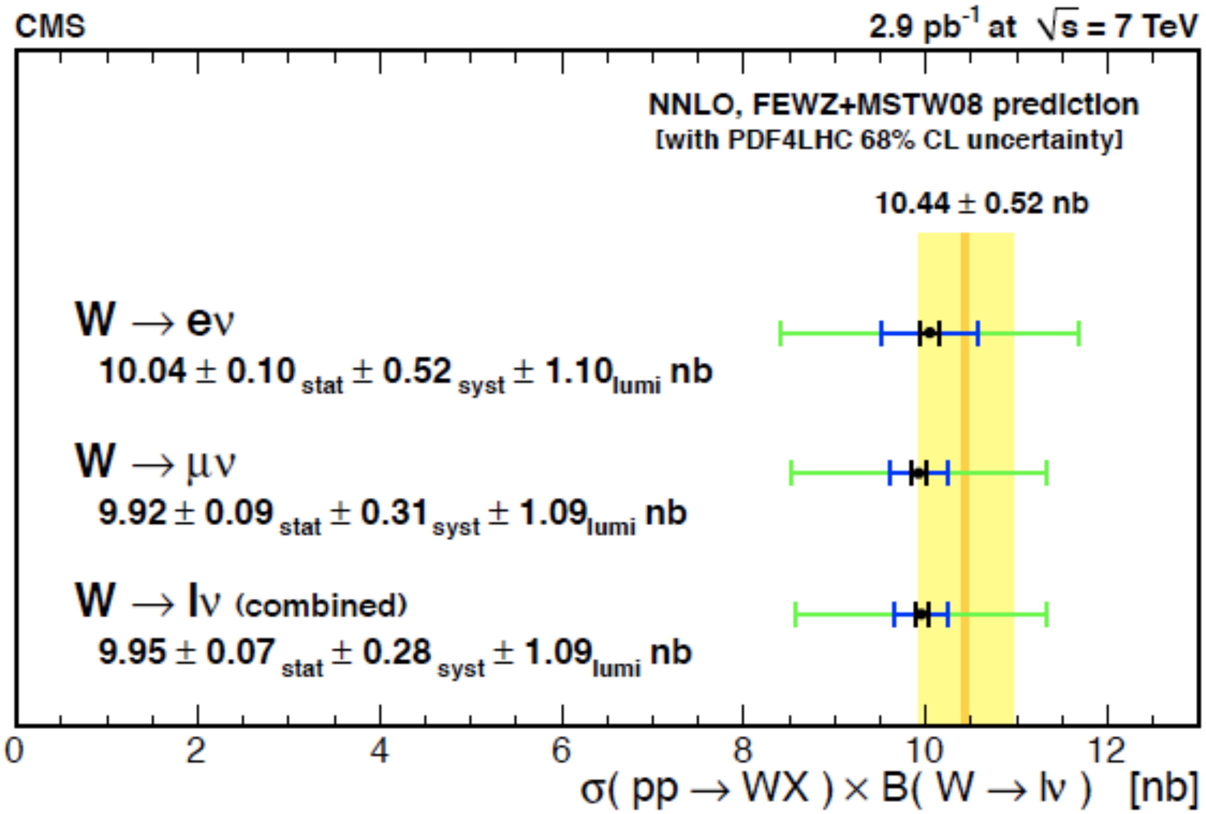
Electron channel: one electron with:

- p_T>20GeV and|η|<1.44, 1.57<|η|<2.5
- fit missing E_T distribution with templates to remove backgrounds

Muon channel: one muon with:

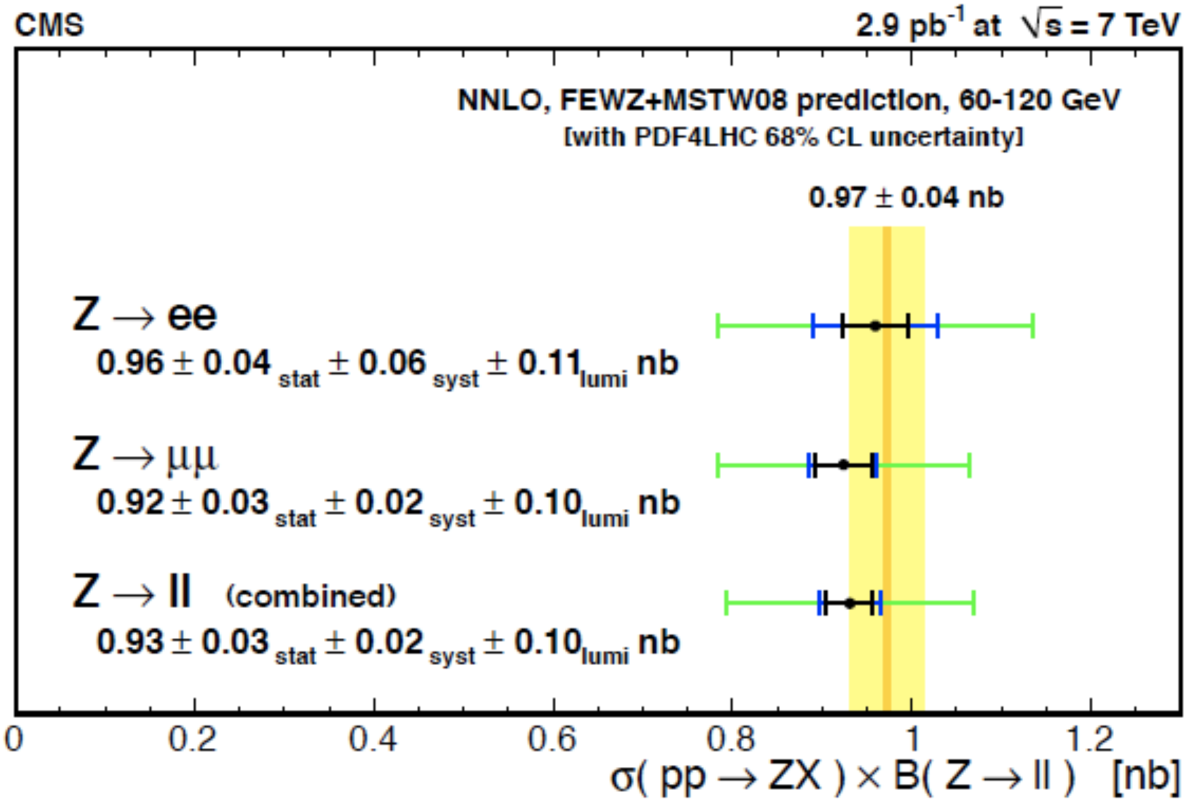
- p_T>20GeV and|η|<2.1
- fit W transverse mass distribution with templates to remove backgrounds

Inclusive W production (II)



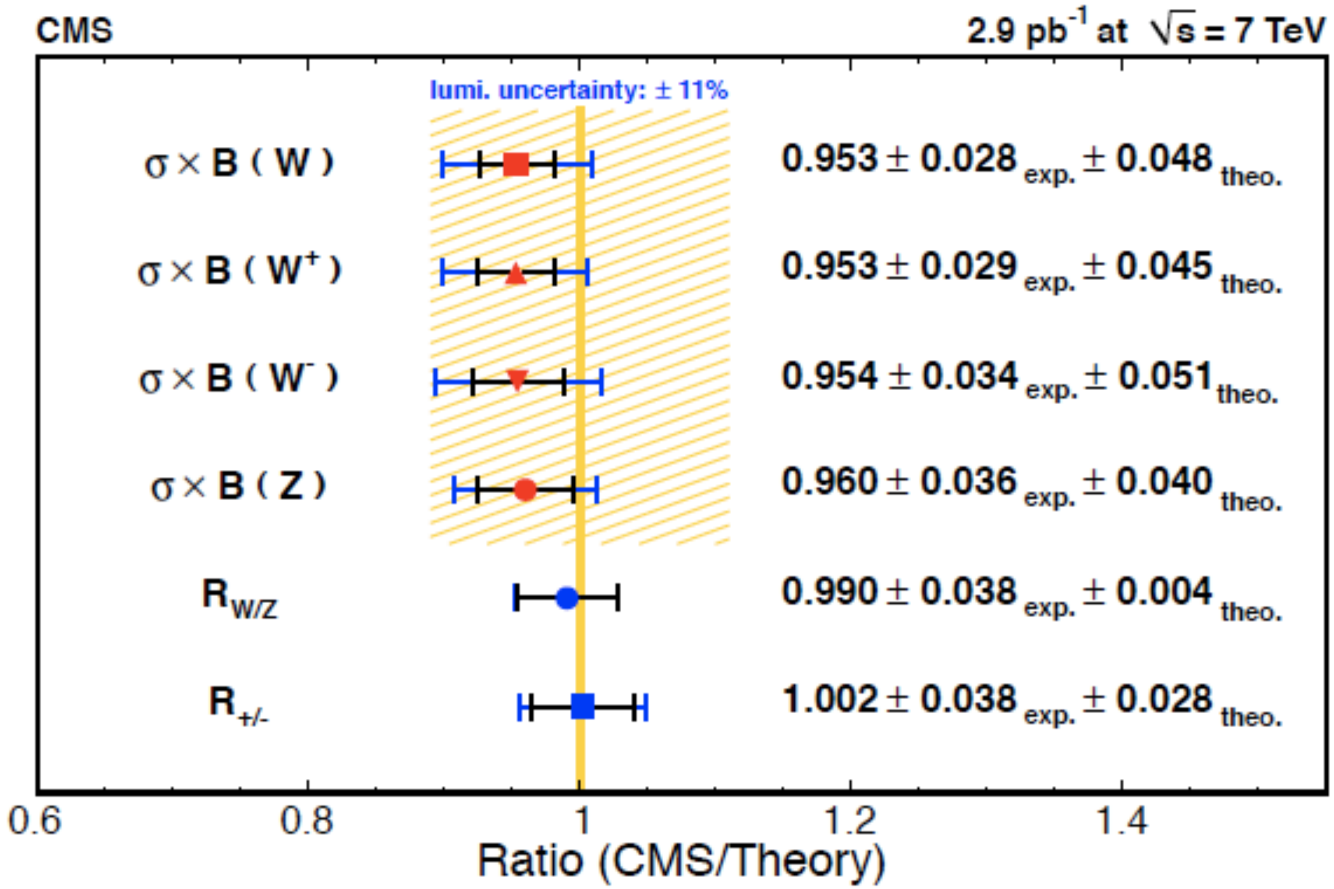
- Comparison to NNLO QCD prediction
  - Experimental systematics (except luminosity) are smaller than the theoretical uncertianties

Inclusive Z production (III)



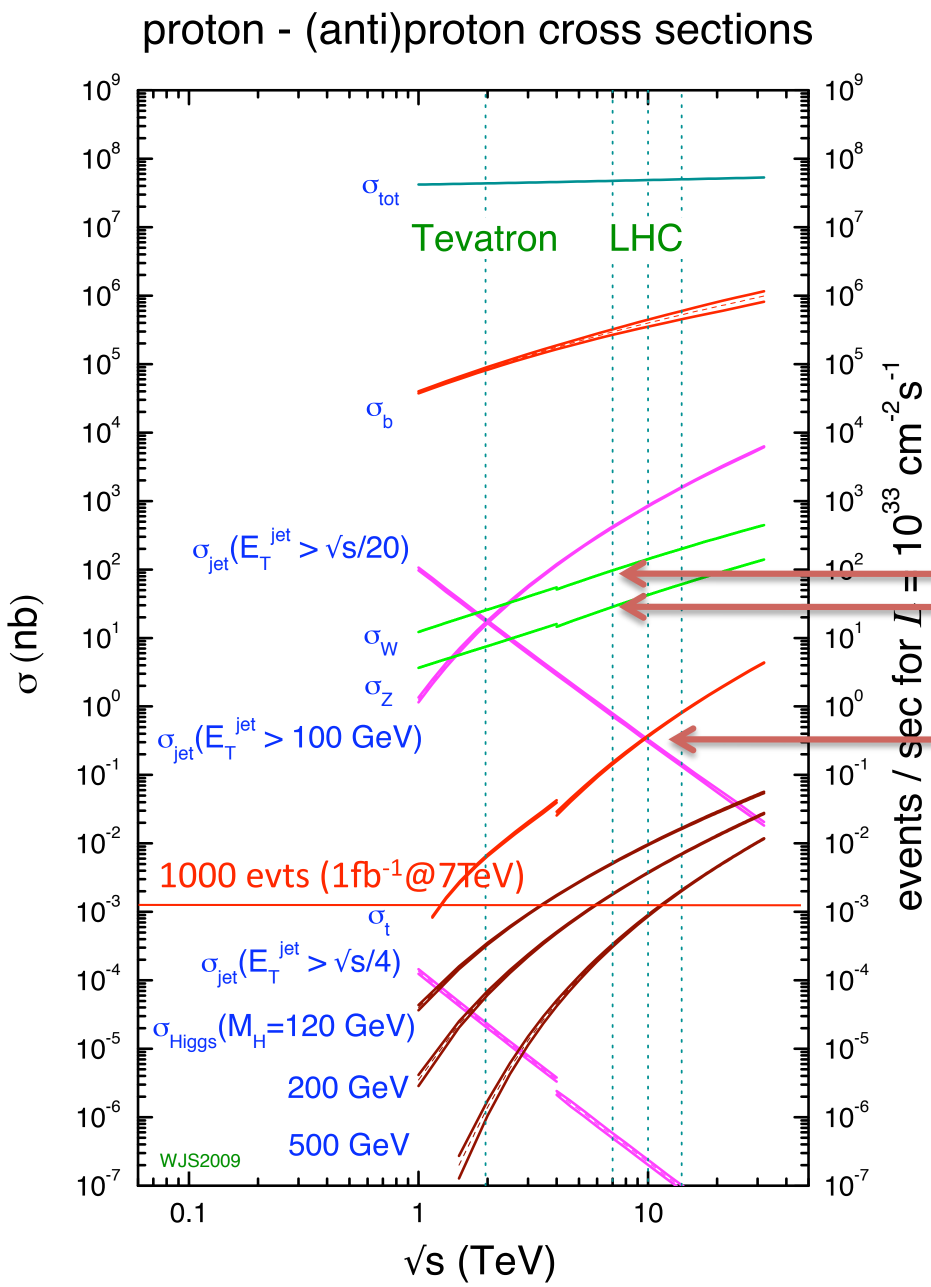
- Event selection:
  - 2 good electrons (or muons) with same p_T and η cuts as the W analysis
  - Di-lepton mass required to be in the range $60 < M_{ll} < 120$ GeV.

Inclusive W/Z production - summary



- For all results: current experimental systematic uncertainty is much smaller than the theoretical uncertainty, which is much smaller than the luminosity uncertainty……..

SM physics reach in 2011



1 fb^{-1} at 7 TeV

100 million W's

20 million Z's

500k ttbar

ATLAS or CMS with 1fb^{-1}
~ 0.5 million Z →ee

cf CDF or D0 with 10fb^{-1}
~ 0.5 million Z →ee