W/Z + Jets in ATLAS

Standard Model @ LHC Workshop

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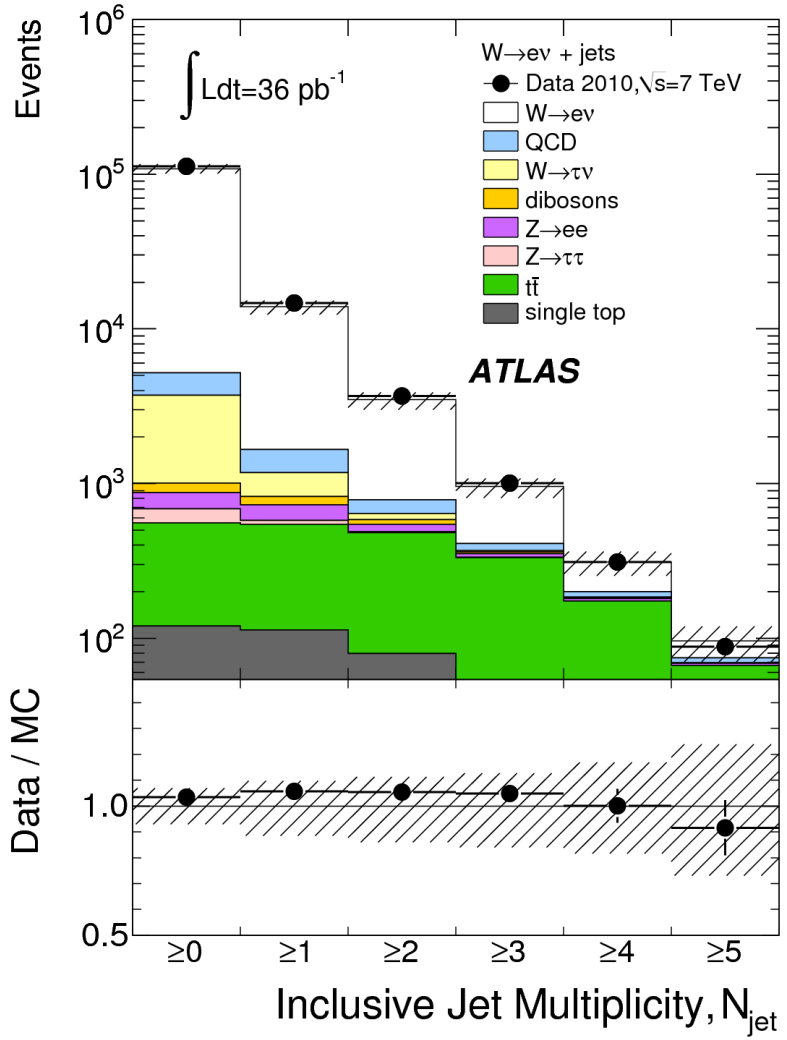
on behalf of the ATLAS Collaboration

QCD Studies with W and Z Bosons

- **Studies of jet production in association with a W or Z boson are key for understanding Standard Model (SM) and beyond SM physics**
- Important testing ground for perturbative QCD predictions
- Background to other interesting processes: top, Higgs, SUSY
- Constrain parton distribution functions (PDFs) of the proton
- Distinctive leptonic decays and abundant production at LHC

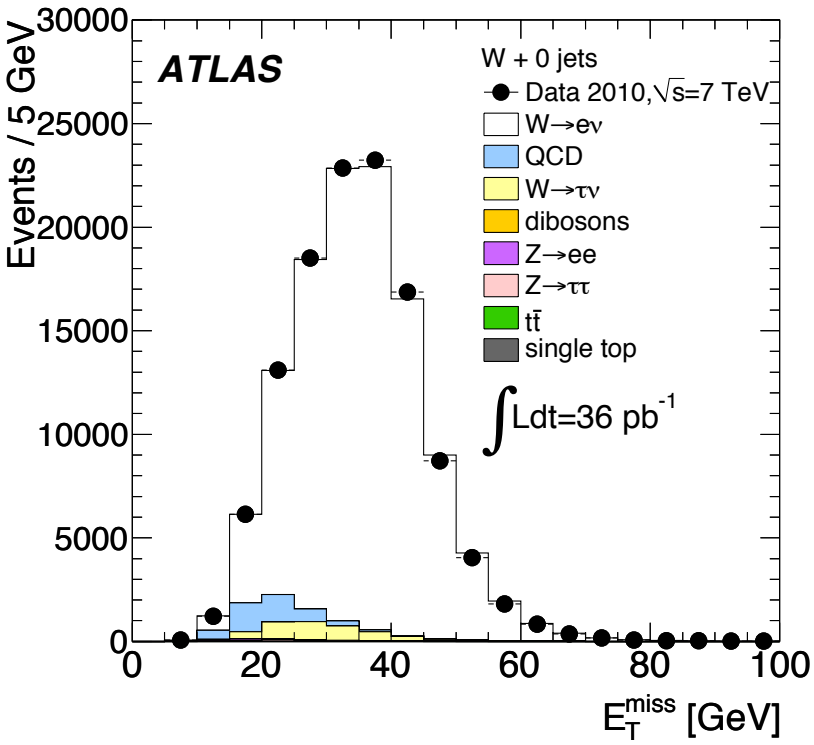


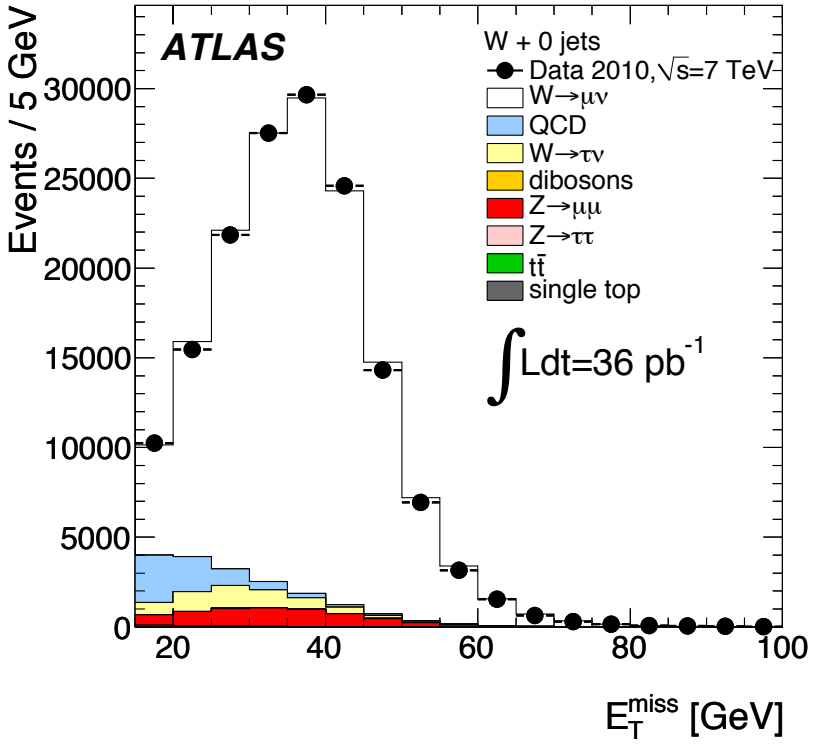
Cross Section Measurement

- Measure inclusive cross sections $\sigma(V + \geq N_{jet}) \cdot Br(W \rightarrow l\nu \text{ or } Z \rightarrow ll)$, cross section ratios $\sigma(V + \geq N_{jet})/\sigma(V + \geq N_{jet}\text{-}1)$, and differential cross sections with respect to jet p_T and other observables
- **Use lepton and jet phase space within the detector acceptance**
- Electron $p_T > 20$ GeV, $|\eta| < 2.47$ excluding $1.37 < |\eta| < 1.52$
- Muon $p_T > 20$ GeV, $|\eta| < 2.4$
- **W selection** requires exactly one electron or muon, neutrino p_T (missing E_T) > 25 GeV and transverse mass > 40 GeV
- **Z selection** requires exactly two oppositely charged electrons or muons, with invariant mass 66 GeV < m_{ll} < 116 GeV
- **Reconstruct jets using the anti-k_T algorithm with distance parameter R=0.4**
- Jet rapidity < 4.4, jet $p_T > 30$ GeV (also 20 GeV)

Backgrounds: W + Jets

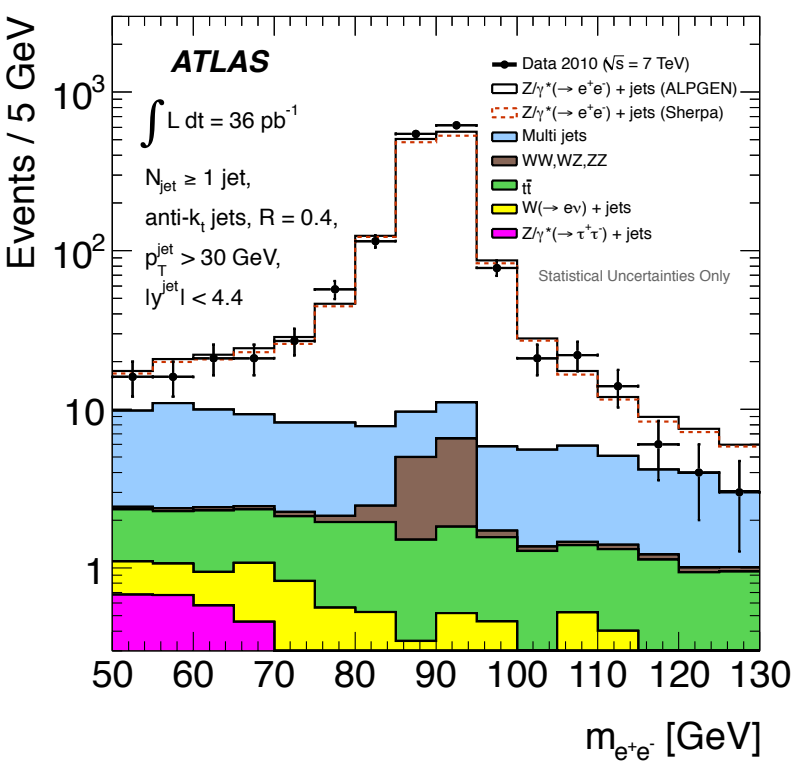
- QCD multijet background estimated from data using control sample with reversed lepton selection criteria, normalized by fitting missing E_T before final selection (missing E_T > 25 GeV and transverse mass > 40 GeV)
- All other processes estimated from simulation and normalized to (N)NLO cross section predictions

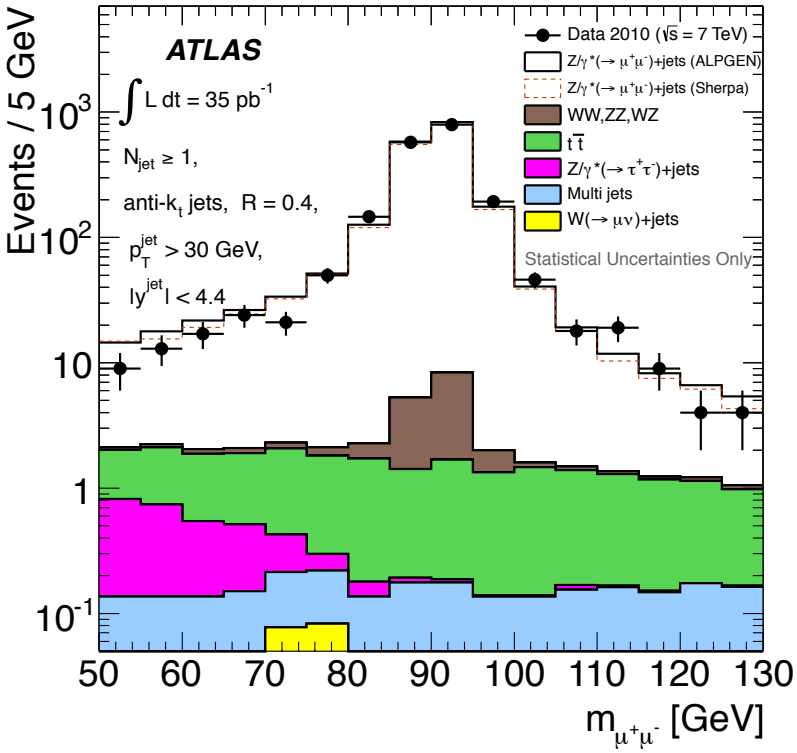




Backgrounds: Z + Jets

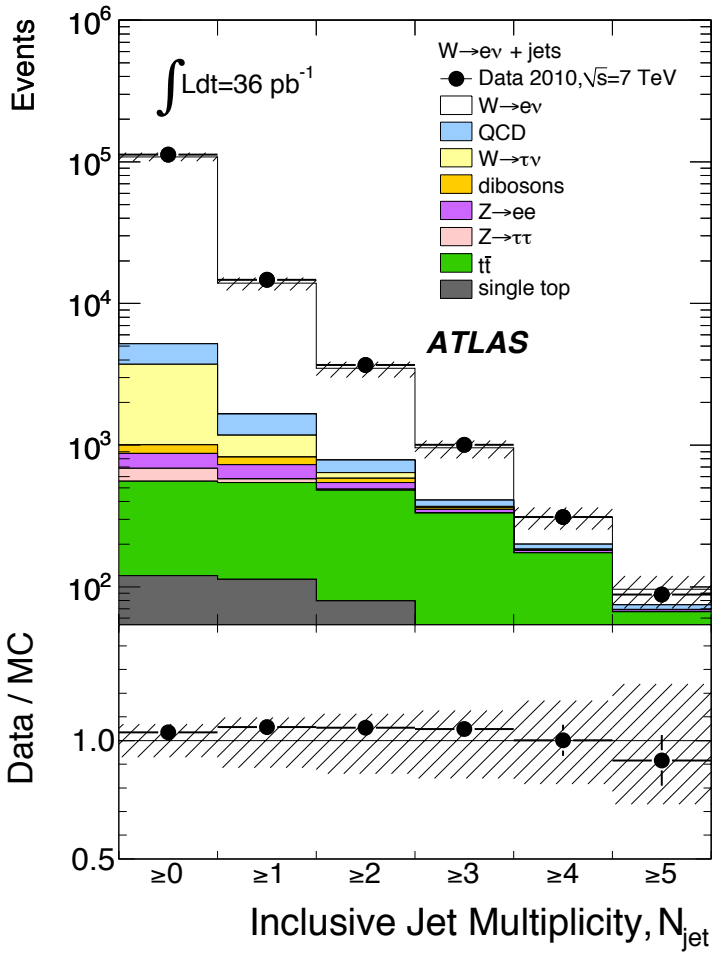
- QCD multijet background estimated from data using control sample with reversed lepton selection criteria, normalized by fitting dilepton invariant mass before final selection (66 GeV < m_{ll} < 116 GeV)
- QCD background less significant in the muon channel

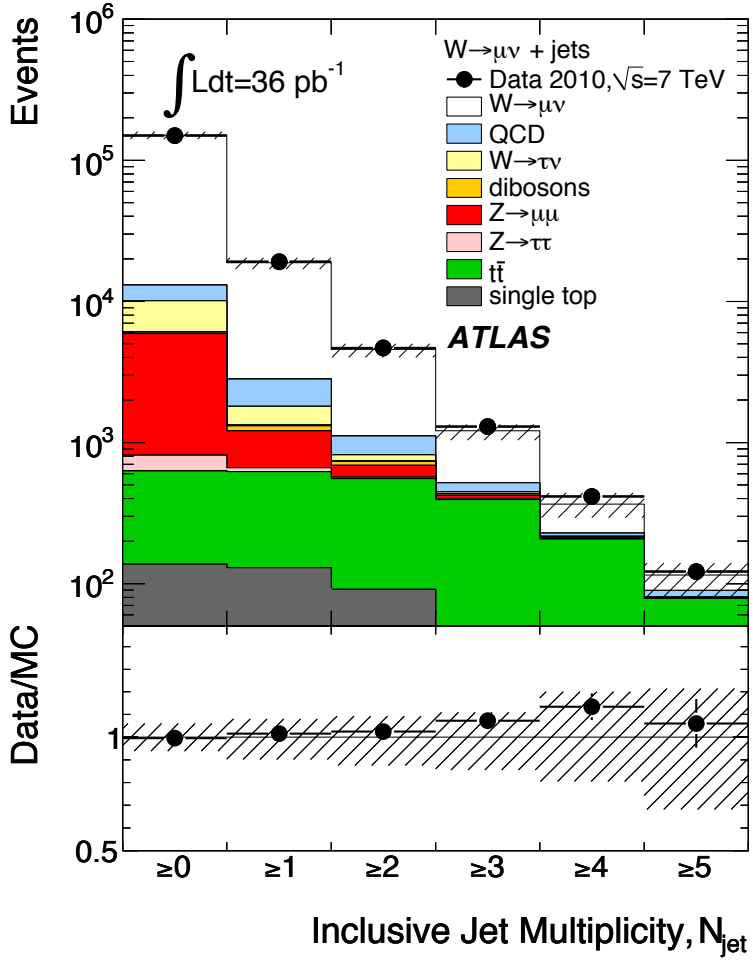




Uncorrected Jet Multiplicity: W + Jets

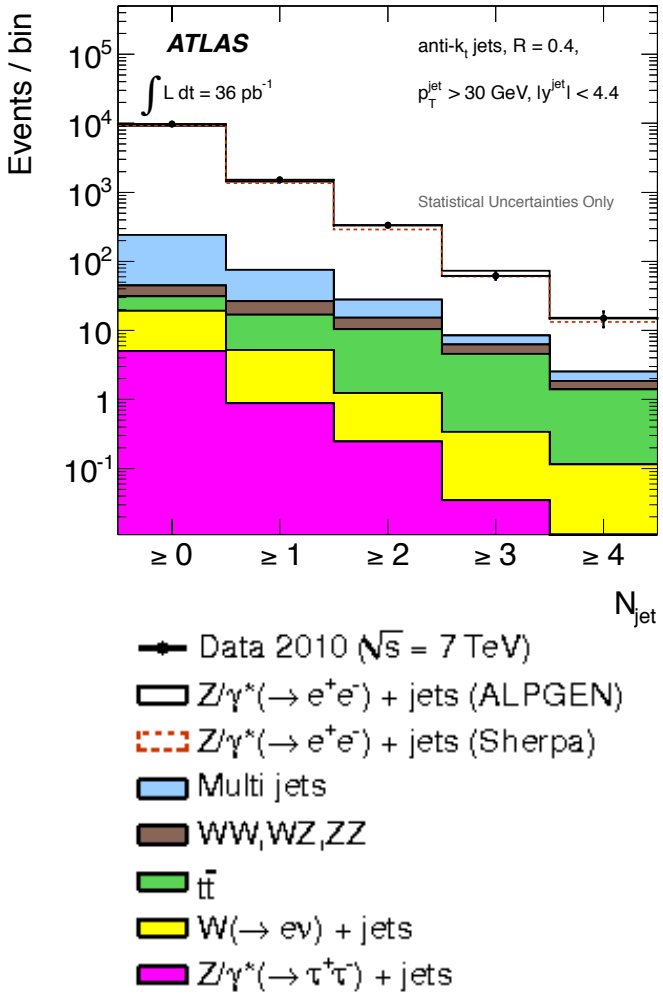
- Observed jet multiplicities shown before background subtraction and correction for detector effects
- Good agreement between data and predictions

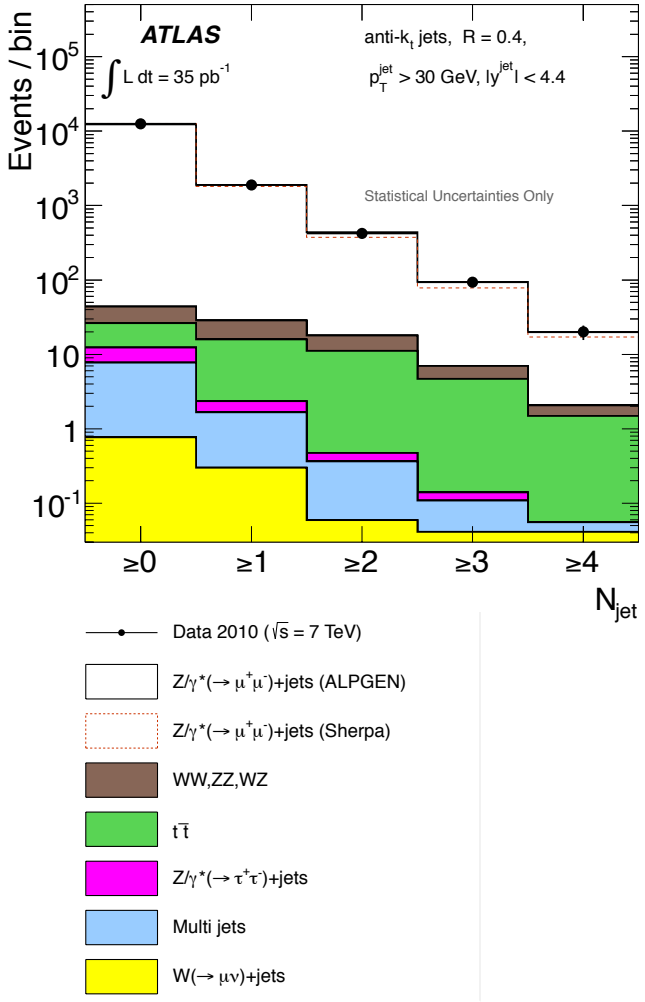




Uncorrected Jet Multiplicity: Z + Jets

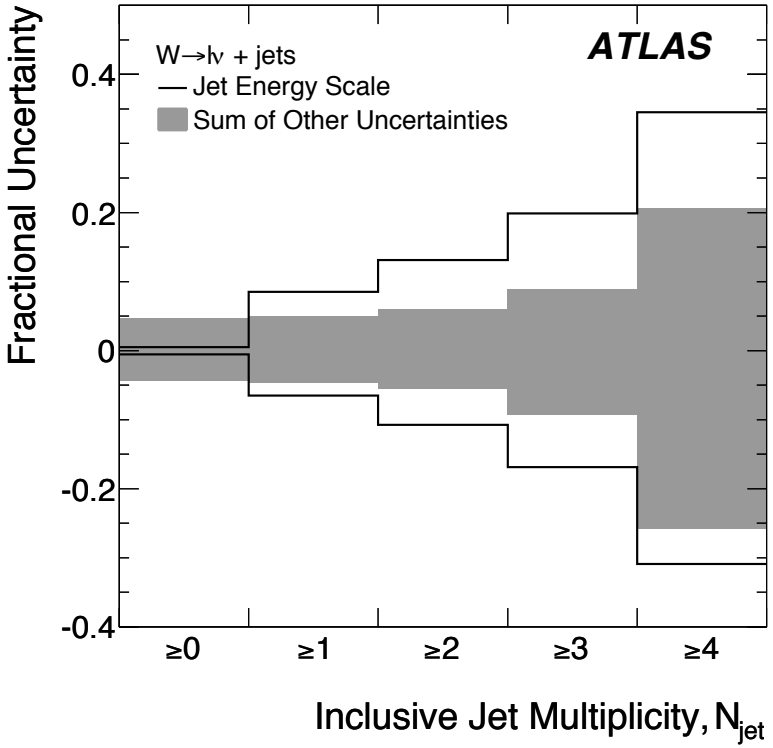
- Detector level expectations for Z + jets also agree with data

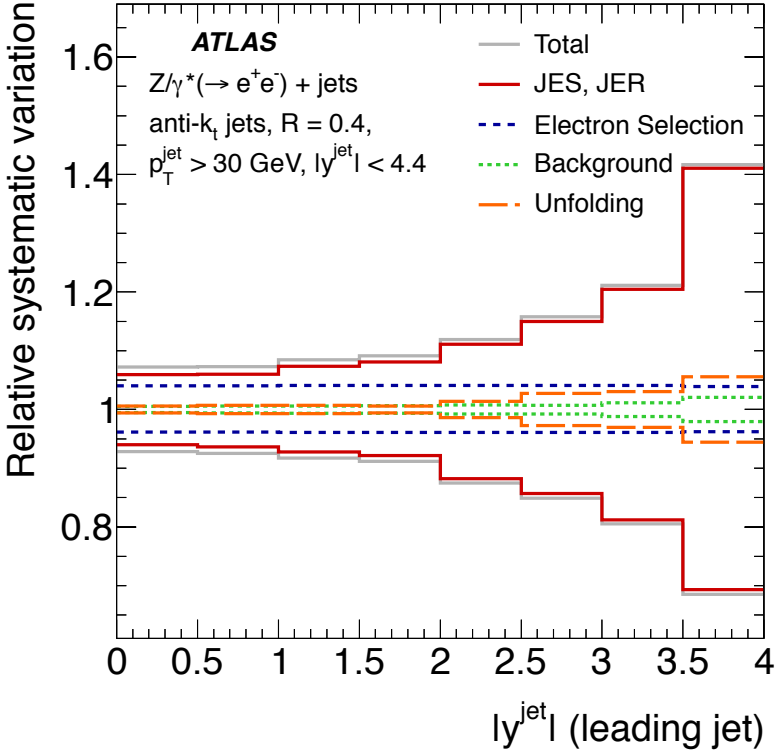




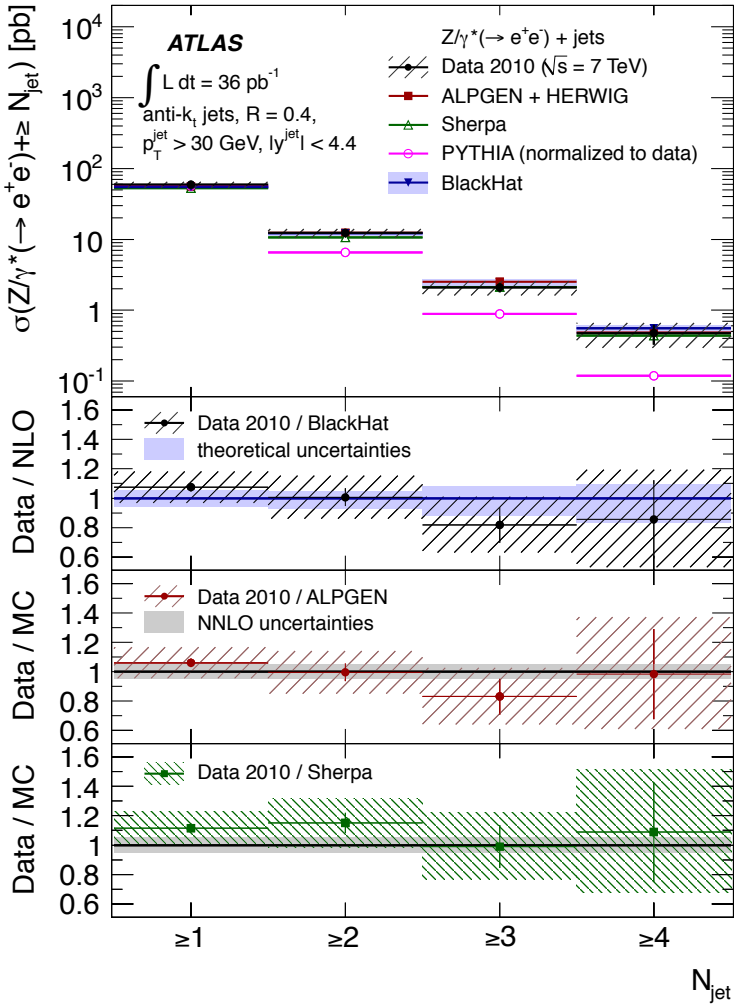
Systematic Uncertainties

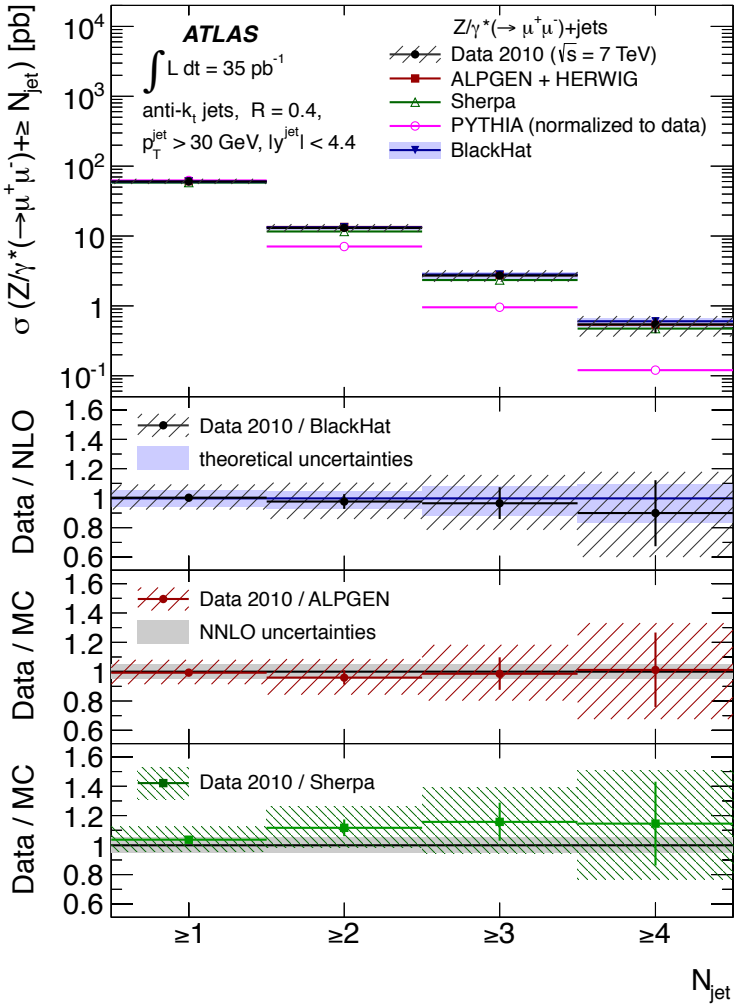
- Dominated by uncertainty on the jet energy scale (JES)
- JES uncertainty 2.5% to 14%, depending on jet p_T and rapidity





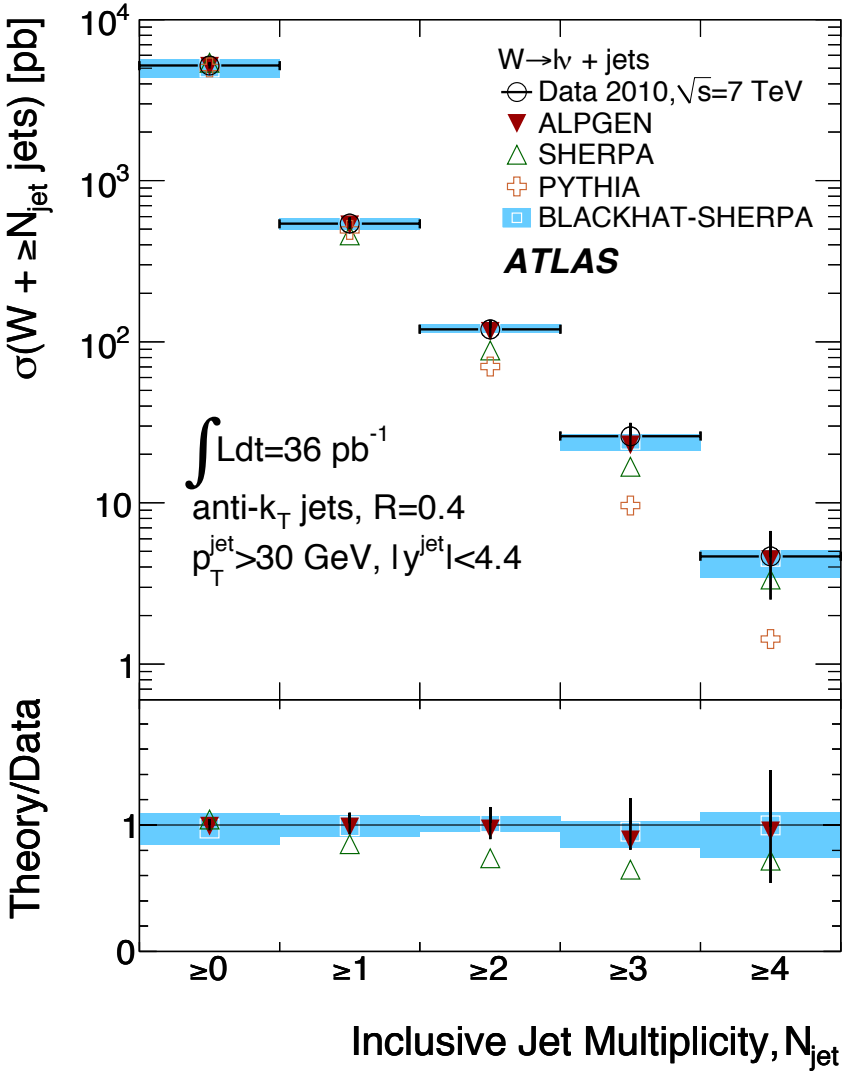
Cross Section Results





- Results from electron and muon decay channels combined using Best Linear Unbiased Estimate (BLUE) method

Cross Section Results: W + Jets

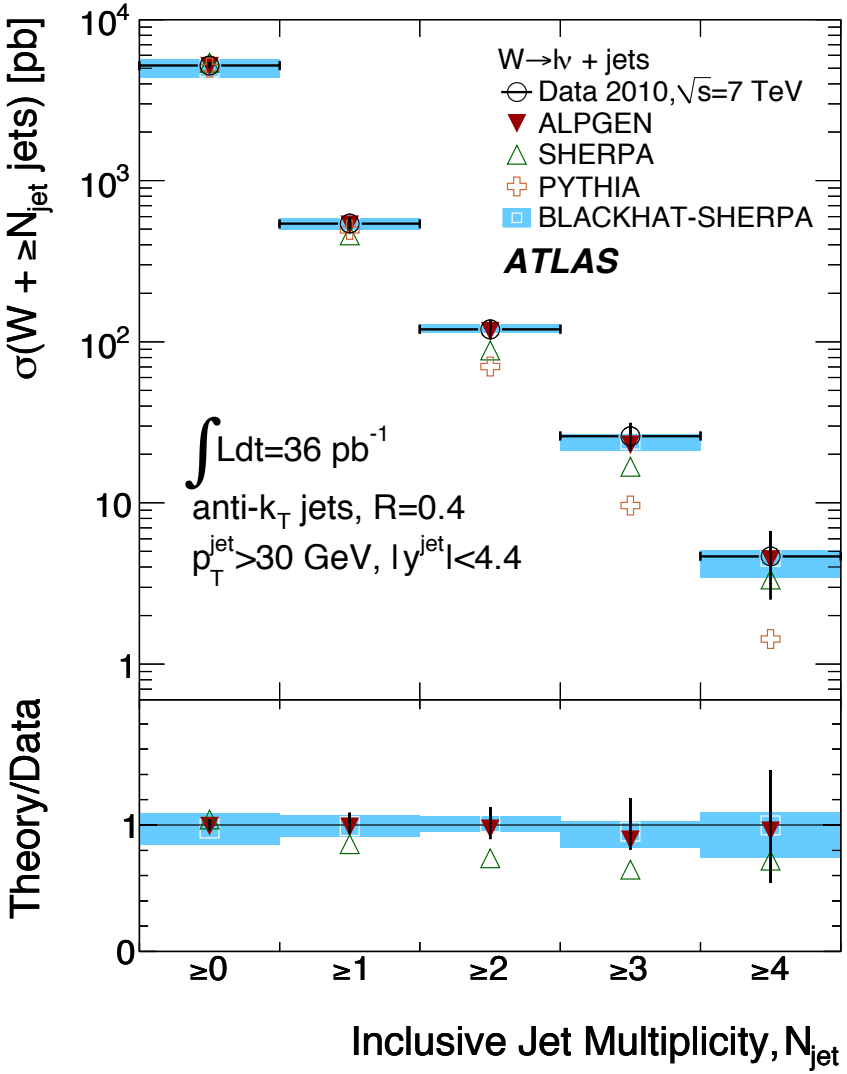


- Compare measured cross sections

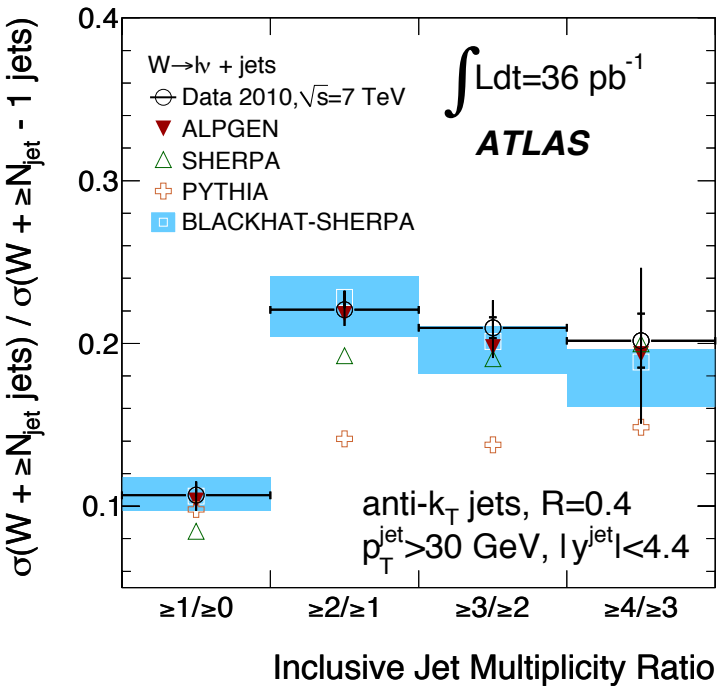
  $$\sigma(W + \geq N_{jet}) \cdot Br(W \rightarrow l\nu)$$

  with LO ME+PS simulations, all normalized to NNLO inclusive cross section calculated with FEWZ:
- **ALPGEN** version 2.13 with CTEQ6L1 PDFs and AUET1 tune
- **SHERPA** version 1.3.1 with CTEQ6.6M PDFs and default tune
- **PYTHIA** (2 → 2) version 6.4.21 with MRST 2007 LO* PDFs, AMBT1 tune
- Also compare with NLO pQCD calculations for up to 4 jets from **BLACKHAT-SHERPA** using CTEQ6.6M PDFs, renormalization and factorization scales H_T / 2, with non-perturbative corrections applied

Cross Section Results: W + Jets

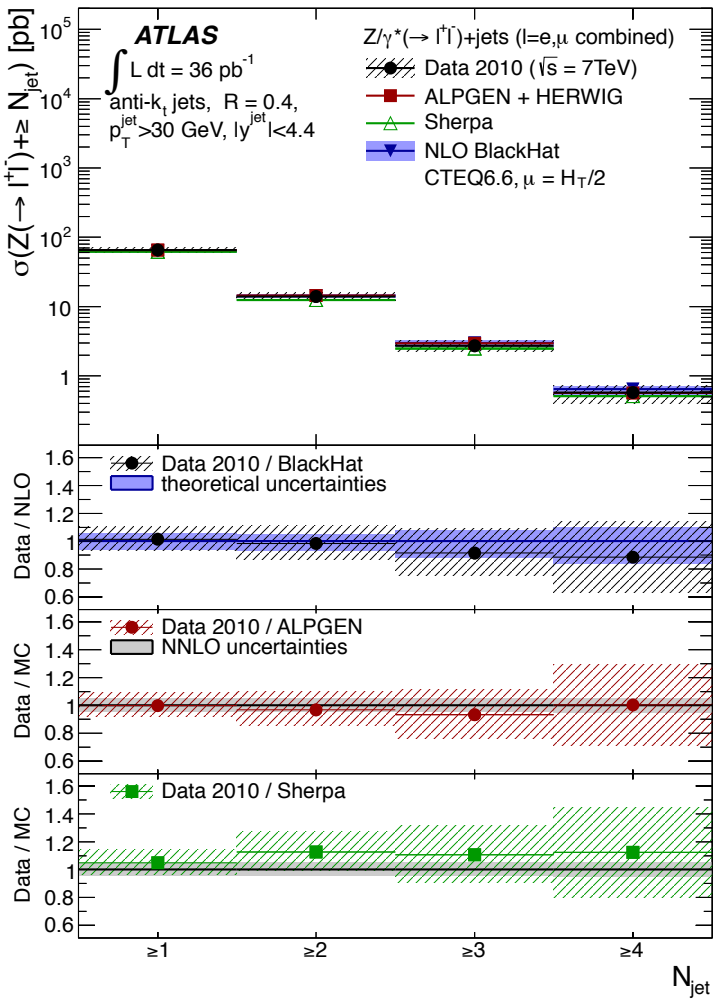


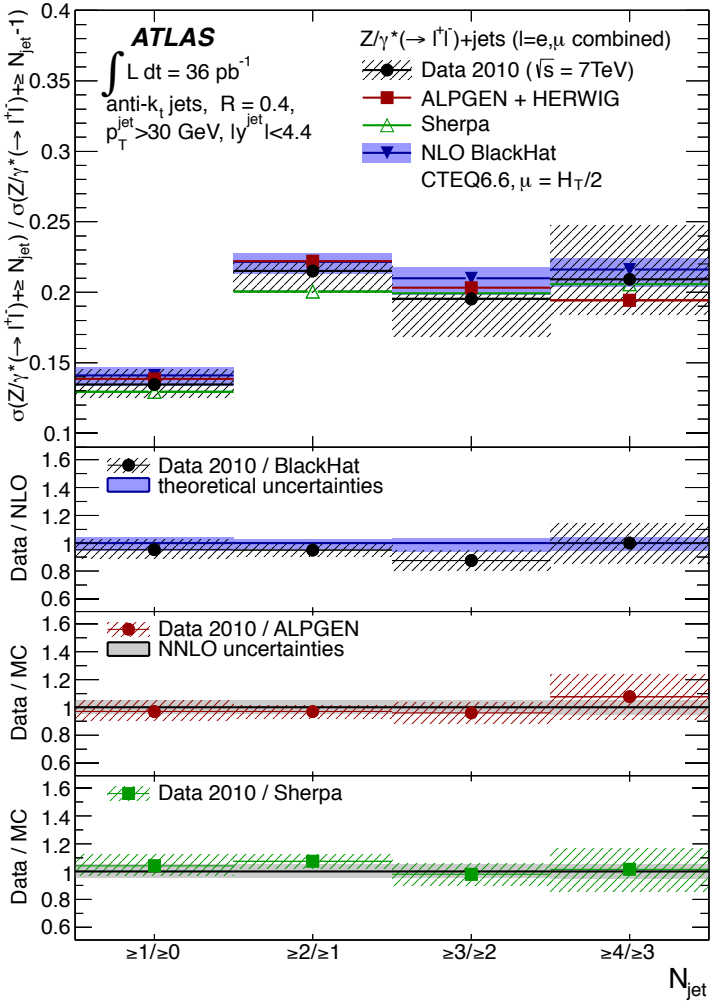
- Good agreement between data and predictions, except Pythia
- Many systematic uncertainties cancel in ratios of cross sections:
  $\sigma(W + \geq N_{jet})/\sigma(W + \geq N_{jet}\text{-}1)$



Cross Section Results: Z + Jets

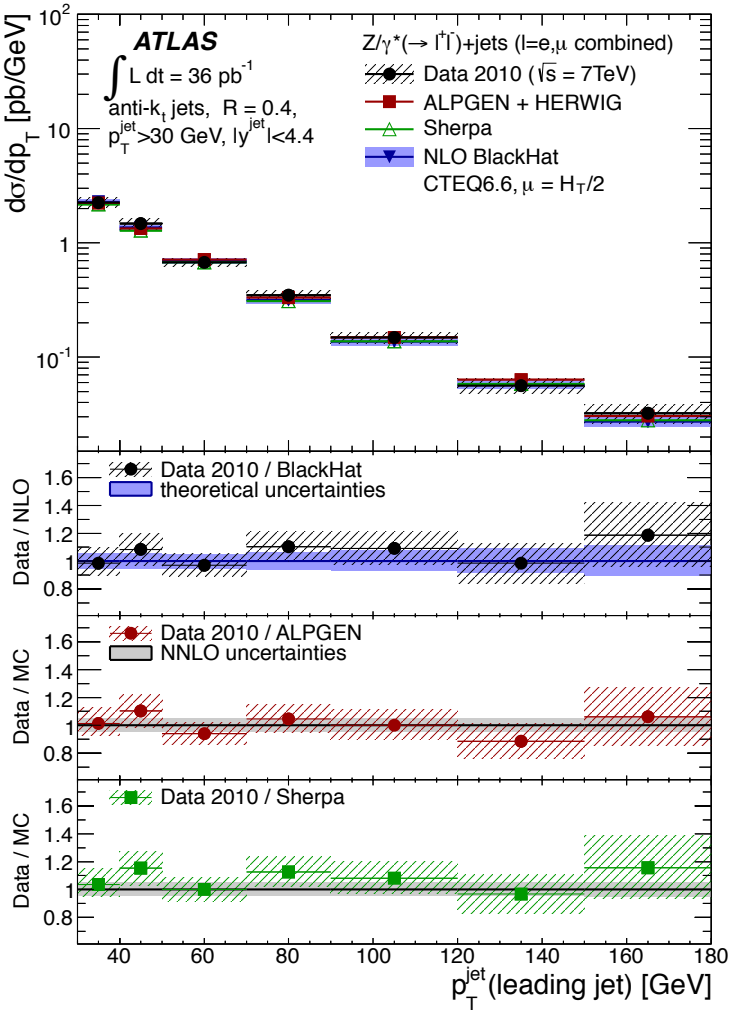
- Data and predictions also agree for Z + jets cross sections and ratios
  - **ALPGEN** and **BLACKHAT-SHERPA** configured as for W + jets; **SHERPA** version 1.2.3

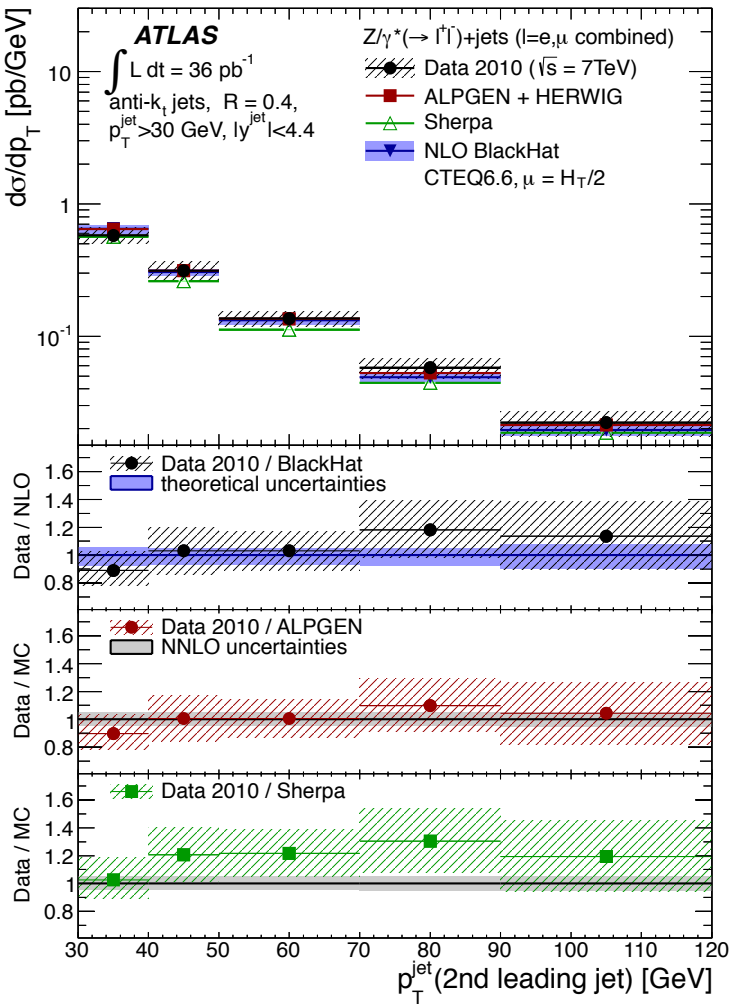




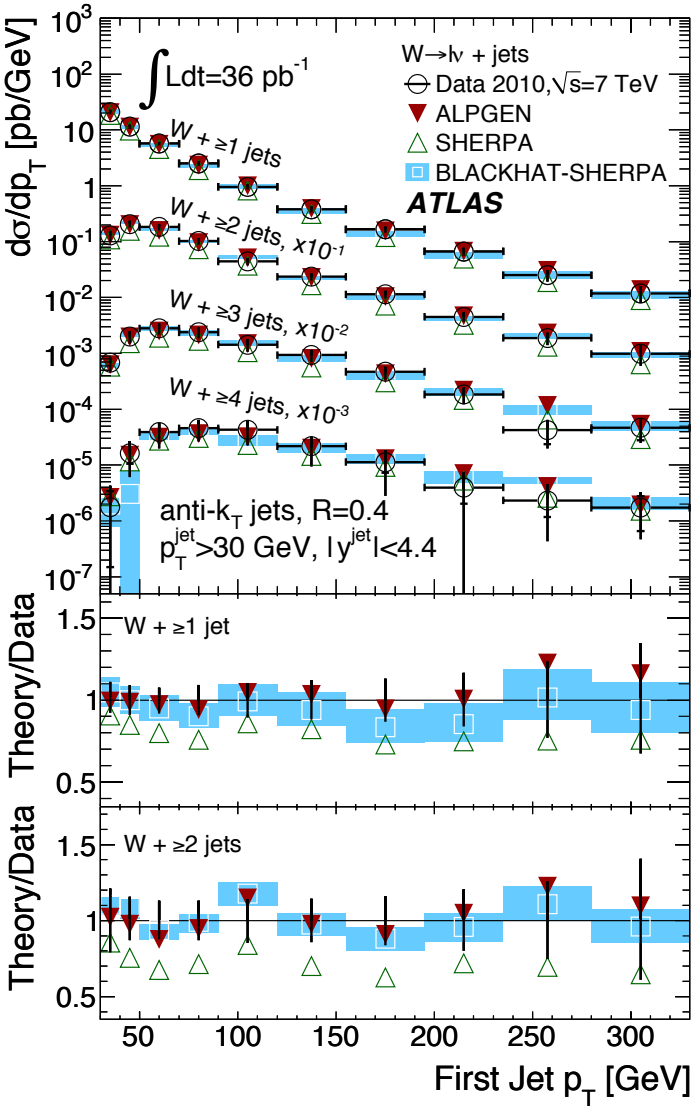
Differential Cross Sections: Jet p_T

- Data are well-described by theory predictions as a function of leading jet p_T in Z + ≥1 jet events and second jet p_T in Z + ≥2 jet events

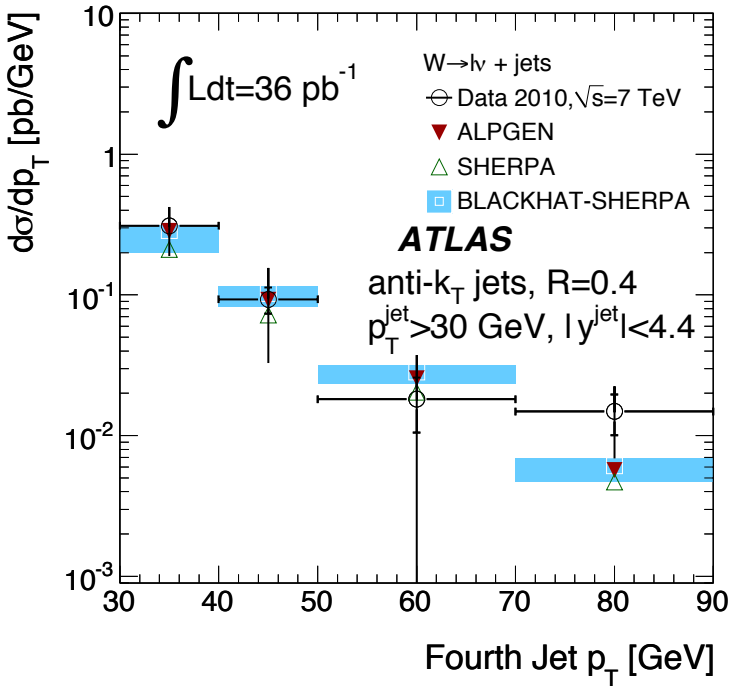




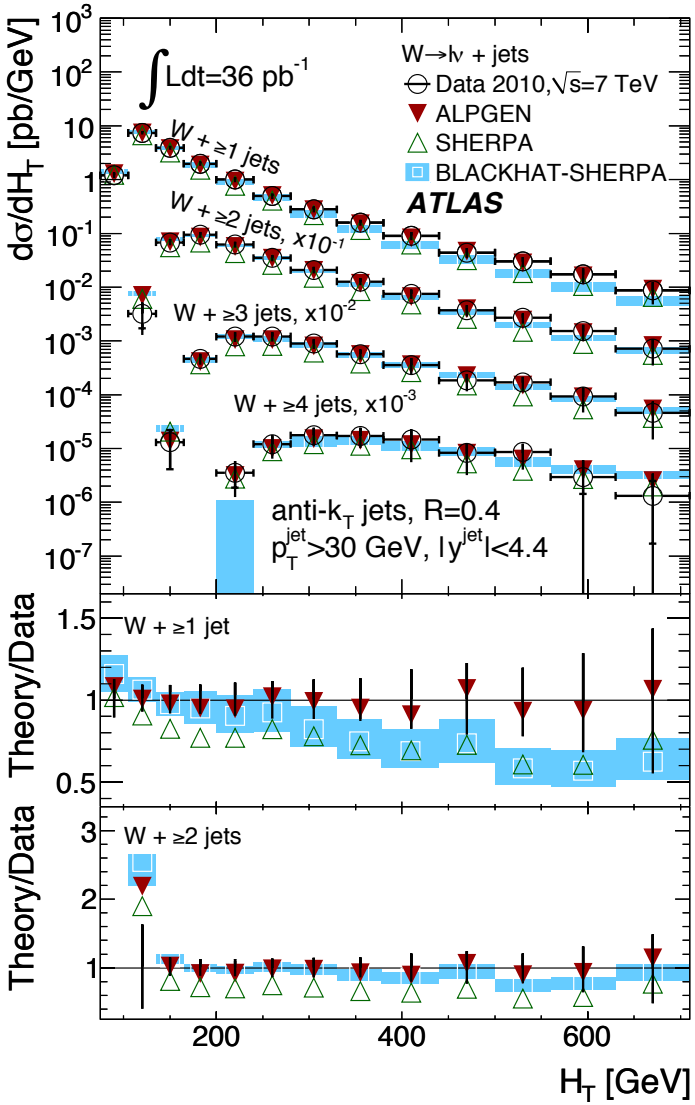
Differential Cross Sections: Jet p_T



- Compare cross sections with predictions for W + ≥1 jet through W + ≥4 jets
- Predictions describe data well, even p_T of fourth sub-leading jet

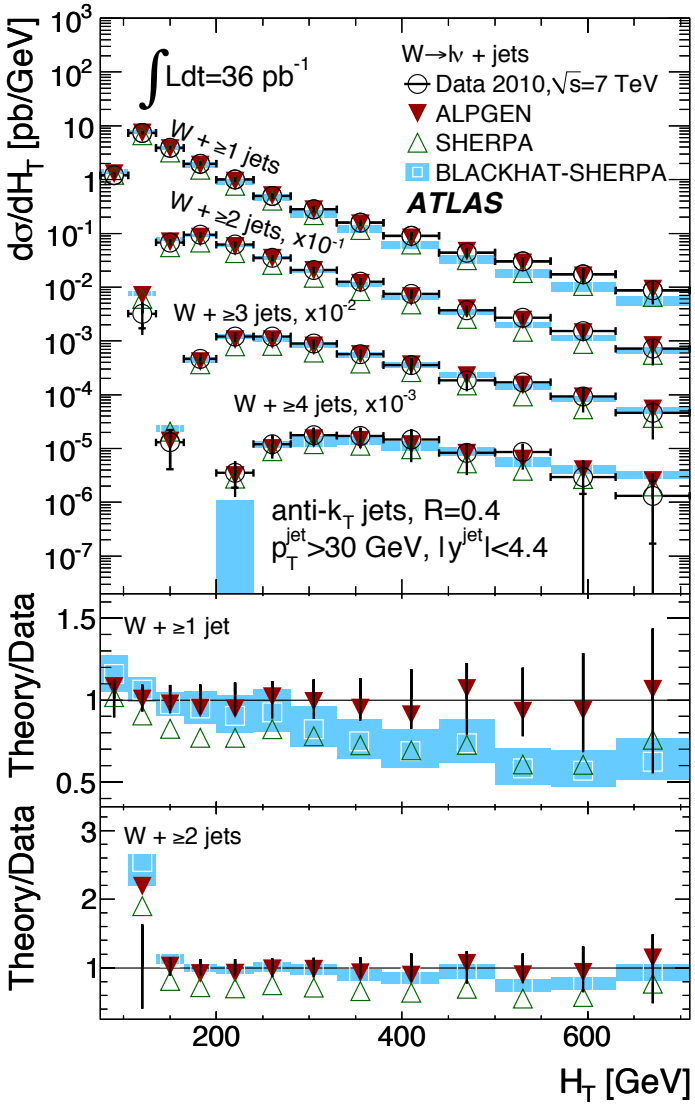


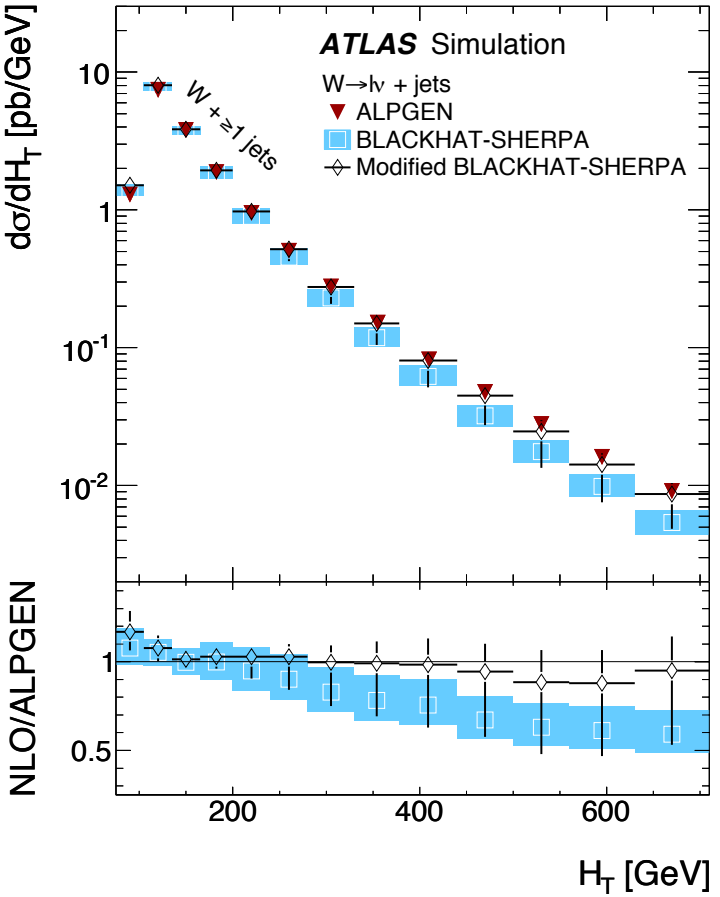
Differential Cross Sections: H_T



- H_T, the scalar sum of lepton, neutrino, and jet p_T, is a common choice for renormalization and factorization scales
- Measure differential cross sections as a function of H_T for W + ≥1 jet through W + ≥4 jets
- BLACKHAT-SHERPA NLO predictions include matrix elements for one additional real emission in each sample
- ALPGEN predictions with LO matrix elements for up to 5 partons better describe large H_T, where the contribution from events with many jets is important

Differential Cross Sections: H_T

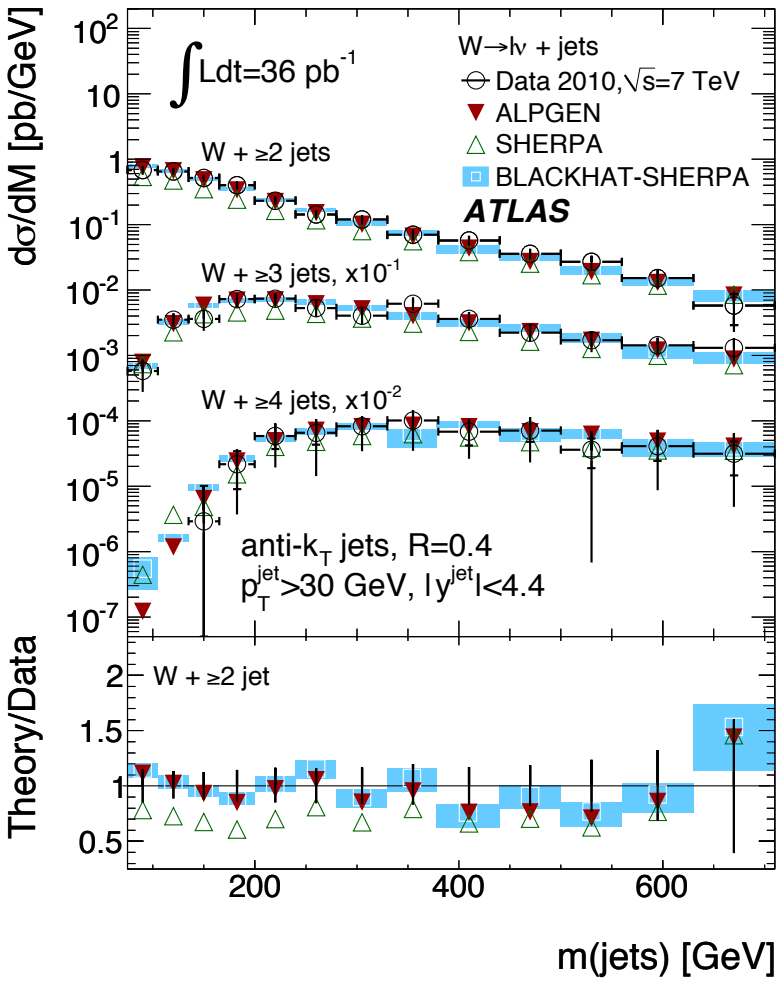


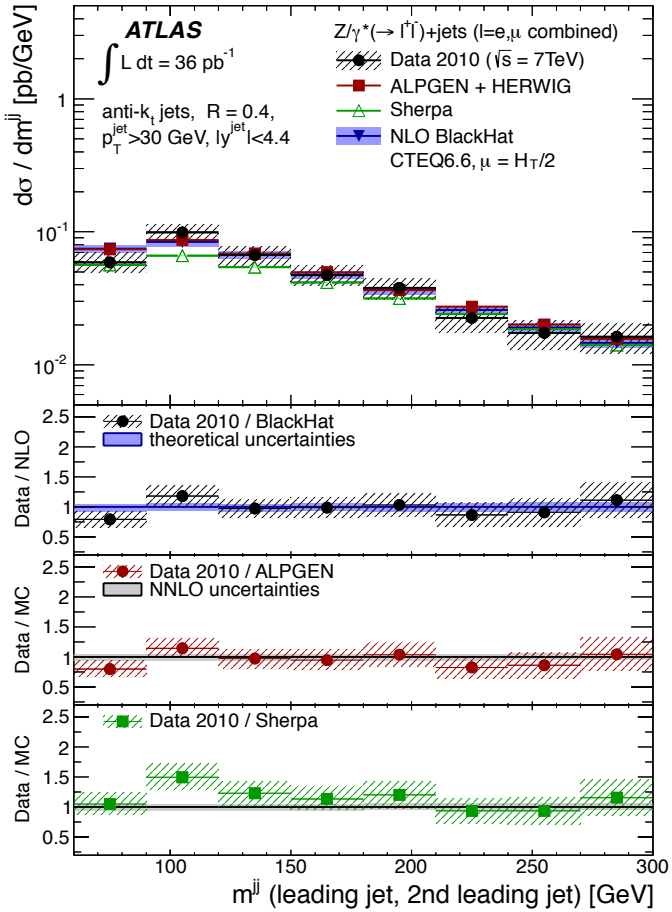


- Modified BLACKHAT-SHERPA predictions including matrix elements for additional real emissions better describe large H_T

Differential Cross Sections: Mass

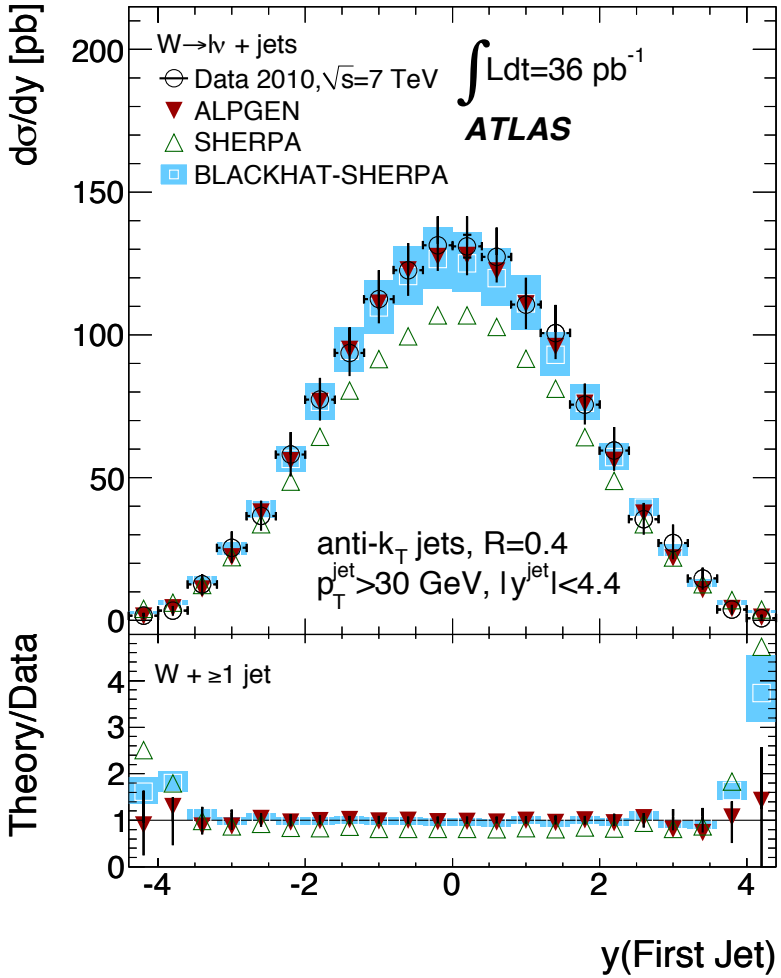
- Invariant mass of jets of interest for new physics searches
- Predictions in good agreement with measured cross sections

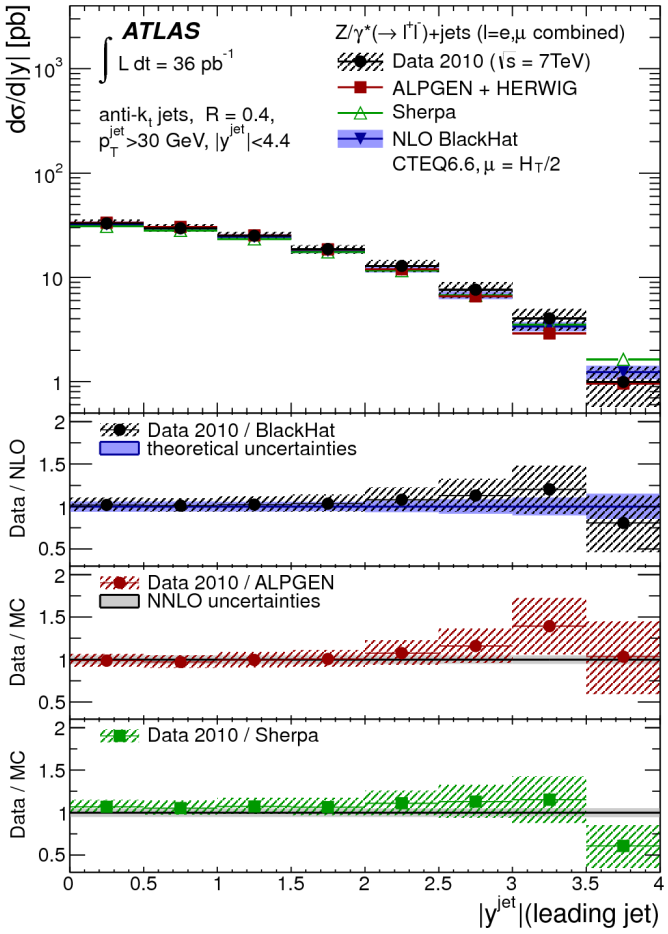




Differential Cross Section: Jet Rapidity

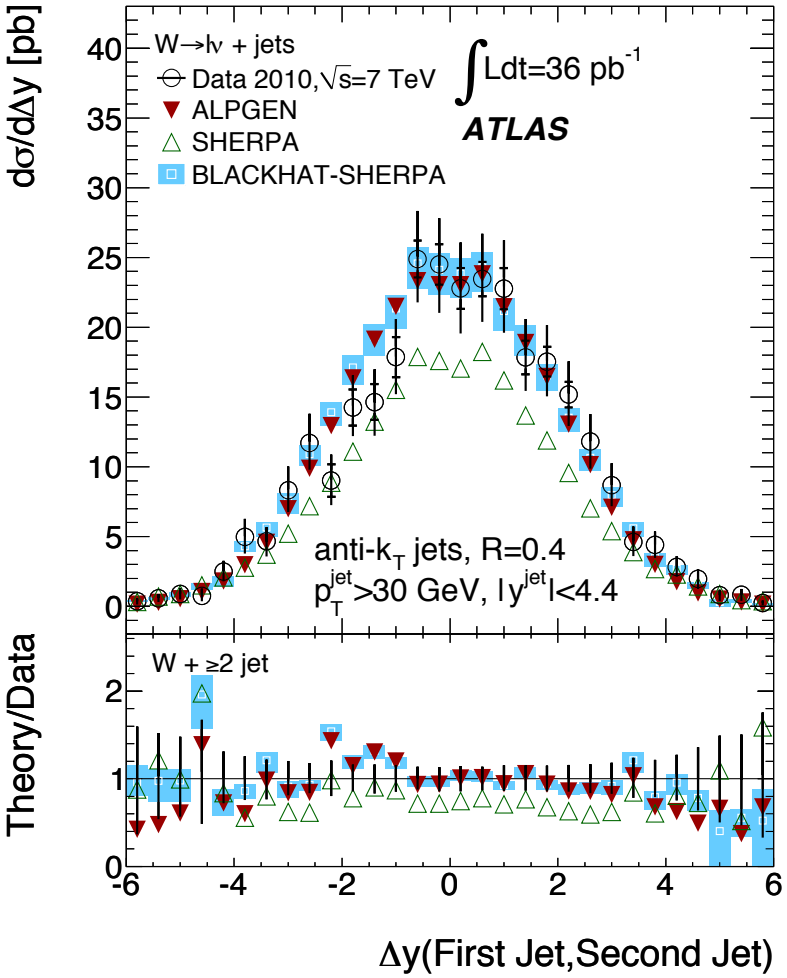
- Measured cross sections and NLO pQCD predictions differ at large jet rapidity, where PDF sensitivity increases

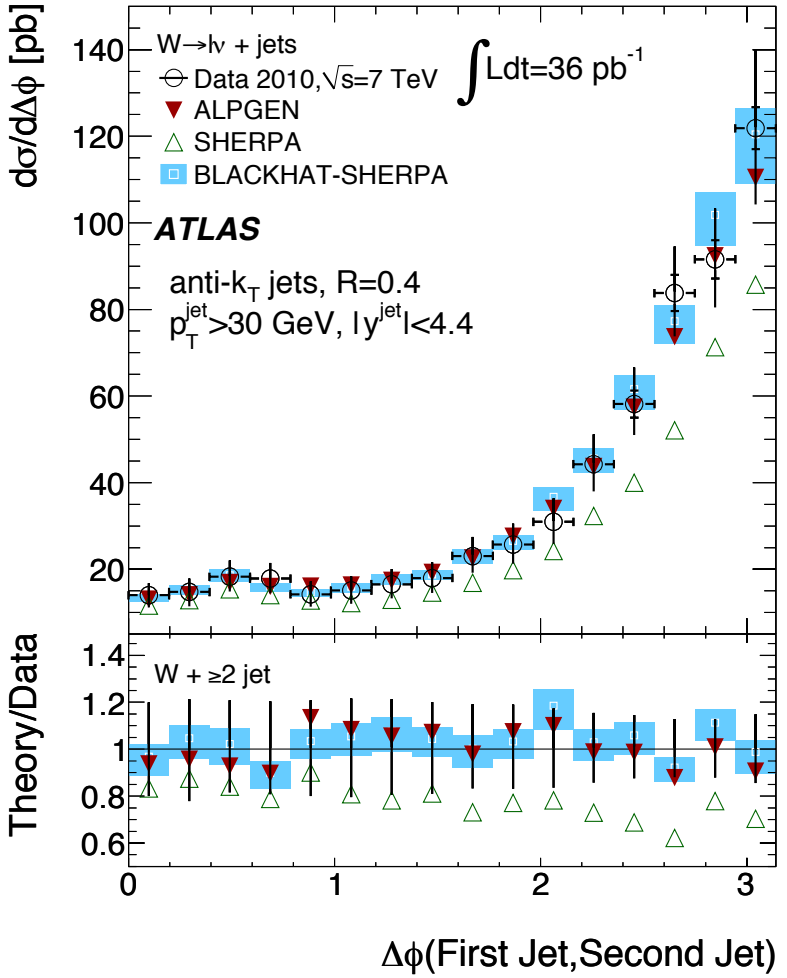




Differential Cross Sections: Jet Separation

- Jet angular differences sensitive to QCD radiation
- Particularly useful distributions for testing ME+PS simulations





Conclusions

- W/Z + jets inclusive and differential cross section measurements generally well-described by predictions
  - Agreement between data and LO ME+PS simulations with high multiplicity ME
  - **First comparison with NLO pQCD calculations up to W/Z + 4 jets**
- Differential measurements, especially jet separation, provide information for further development of ME+PS simulations
  - SHERPA comparison in W+jets deviates slightly due to different scales and PDFs
  - **Cross sections in HEPDATA and already in use**, see *e.g.*, arXiv:1201.5882 [hep-ph]
- Further details and results for jet p_T > 20 GeV available
  - Measurement of the production cross section for Z/γ* in association with jets in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, Phys. Rev. D85 (2012) 032009
  - Study of jets produced in association with a W boson in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, arXiv:1201.127
  - More results including W + b and Z + b at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults