W/Z production cross sections in association with jets and their ratio with the ATLAS detector

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LHC Discussion Session – 6 November 2011
Vector Boson Production in *pp* Collisions

Overview

Will present ATLAS measurements of the production cross sections of W and Z vector bosons in association with jets in various observable distributions:

- Inclusive jet multiplicity $\sigma(V + \geq \mathrm{njets})$
- Differential coss sections $d\sigma / dp_T^{jet}$, $d\sigma / d|y^{jet}|$
- Di-jet quantities ΔR_{jj}, $|\Delta y_{jj}|$, $|\Delta \varphi_{jj}|$, m_{jj}
- Complex quantities $H_T = \Sigma\, p_T^{(l,\nu,\, jets)}$

All quantities defined inclusively:
less sensitive to modeling of soft component and migration effects

Measure the cross sections

- at particle level
- in the fiducial volume of the detector
- use ratios whenever possible to cancel experimental **and** theoretic uncertainties
  - $(d\sigma/d\xi) / \sigma(V)$
  - $\sigma(V + \geq n{+}1 \text{ jets}) / \sigma(V + \geq n \text{ jets})$
  - $\sigma(W + 1 \text{ jet}) / \sigma(Z + 1 \text{ jet})$

Motivation

1. Test higher order calculations and perturbative QCD

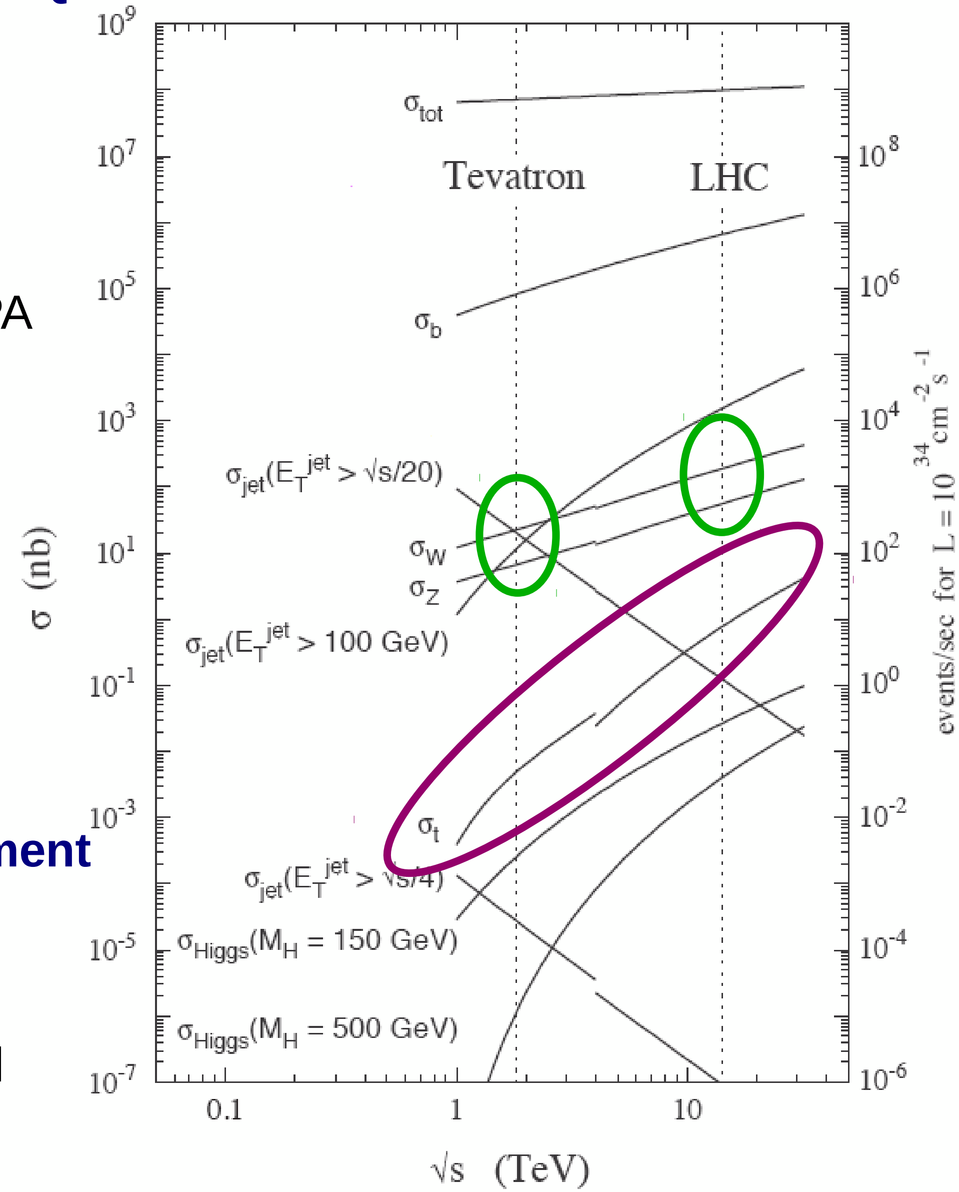
- Can use electroweak process to
  - “tag” events (W/Z decay has clear signature)
  - provide well-defined scale
    - $H^N_T = P_t^l + MET + \Sigma p_T^{jet}$
      scale used in MCFM and BLACKHAT-SHERPA
  - Different scattering amplitudes than multijet production
    (mainly gluon jets rather than quark jets)

2. Understand as irreducible background

- Top quark production
- Searches for (new) physics: Higgs, SUSY …

3. Solve experimental challenges in SM environment

- Provide lepton samples
  - In presence of jets (→ eg. study isolation)
  - in extreme regions of phase space at high recoil
  - (T&P, train identification)
- Tune simulation of V+jets samples
- Jet calibration
- Inclusive samples for di-boson production, searches



Very different interest and features compared to Tevatron measurements and future 14 TeV measurements

Presented ATLAS Publications

W + jets

- *"Measurement of the production cross section for W-bosons in association with jets in pp collisions using 33 pb-1 at sqrt(s) = 7 TeV with the ATLAS detector",*
  ATLAS-CONF-2011-060 (33 pb^{-1})
  (paper in preparation)

- *"Measurement of the production cross section for W bosons in association with jets in pp collisions at s√ = 7 TeV with the ATLAS detector",*
  Phys.Lett.B698:325-345,2011 (1.3 pb^{-1})

Z/γ + jets

- *"Measurement of the production cross section for Z/γ∗ in association with jets in pp collisions at √s = 7 TeV with the ATLAS detector",*
  Submitted to Phys.Rev.D, arXiv:1111.2690 (35 pb^{-1})

$R_{jets} = \sigma(W + 1\text{-jet}) / \sigma(Z + 1\text{-jet})$

- *"A measurement of the ratio of the W and Z cross sections with exactly one associated jet in pp collisions at (√s) = 7 TeV with ATLAS",*
  Submitted to Phys. Lett. B, arXiv:1108.4908 (35 pb^{-1})

Measurement Principle

- Theory and experiment should join at well-defined, physically meaningful level with minimal model dependencies on anything but the process of interest

Detector Level

Detector Acceptance,
Reconstruction,
Identification,
Inefficiencies,
Calibration

Particle Level / Hadron Level

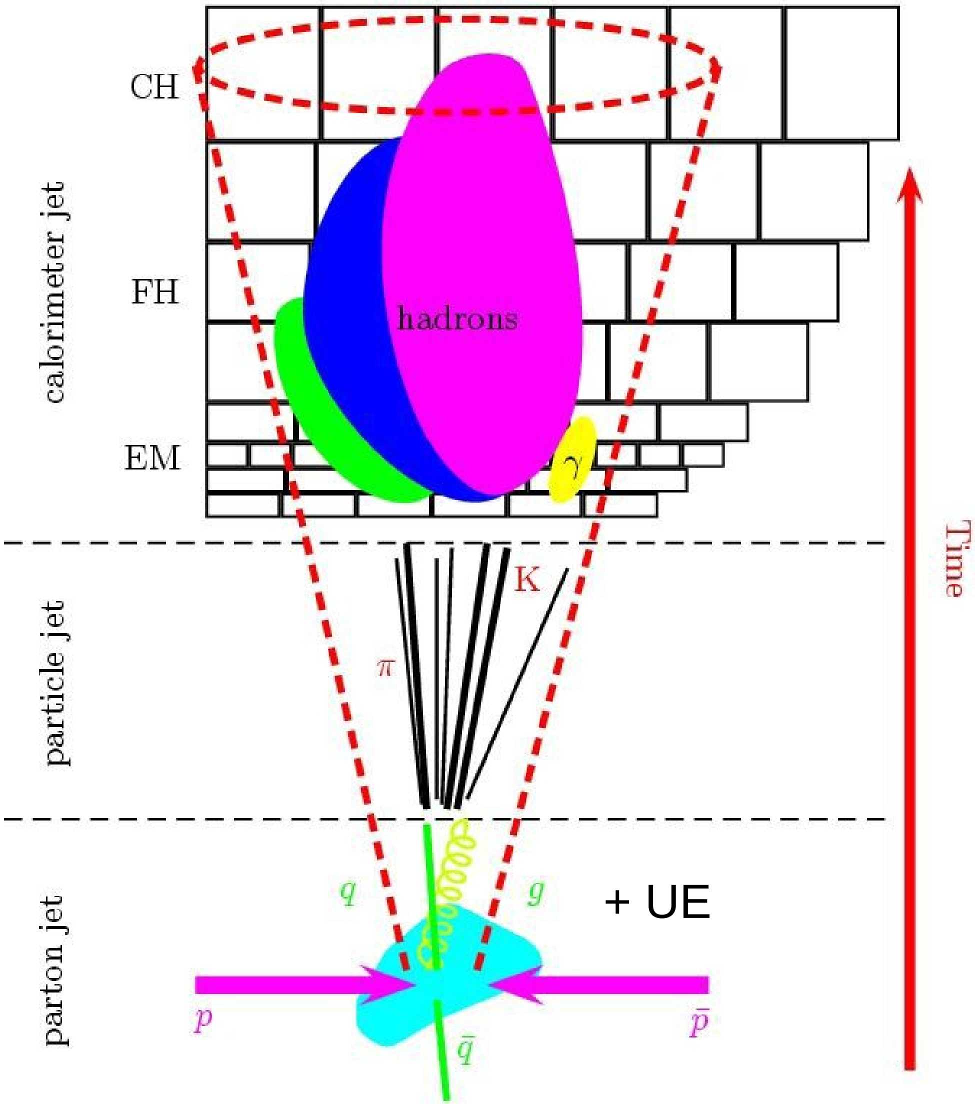
Fragmentation (nonpert.)

Parton Level

Partons (pQDC / PS)

ME (pQCD)

PDFs (nonpert.)



jet evolution – similar for leptons

Theory Status

Drell-Yan W, Z/γ*: NNLO

- FEWZ — *R. Gavin at al., arXiv:1011.3540v1*
  R. Hamberg et.al., Nucl.Phys.B 359 (1991)
  W.L.van Neerven et.al., Nucl.Phys.B 382 (1992)

W, Z/γ* + 1(2) jets: NLO

- MCFM — *K. Ellis et. al., Phys. Rev. D65:113007*
  K. Ellis et. al., Phys. Rev. D68:094021, 2003

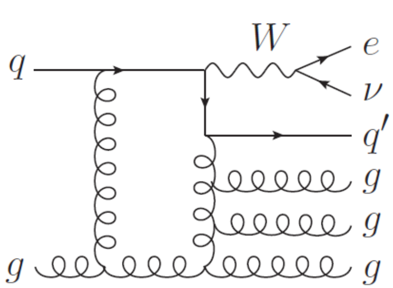
W, Z/γ* + 3 jets: NLO

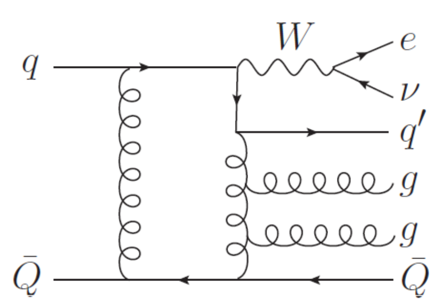
- BLACKHAT+SHERPA — *C. F. Berger et al., arXiv:1005.3728*
- W + 3 jets: — *C.F Berger et.al., Phys.Rev.D80:074036, 2009*
  R.K. Ellis et.al., Phys.Rev.D80:094002, 2009
- Z/γ*+ 3 jets: — *C.F Berger et.al., Phys.Rev.D82:074002, 2010*

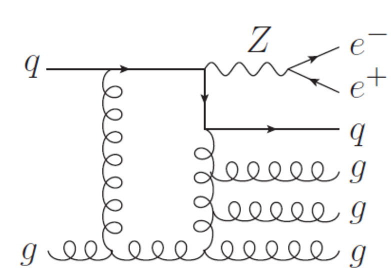
W, Z/γ* + 4 jets: NLO

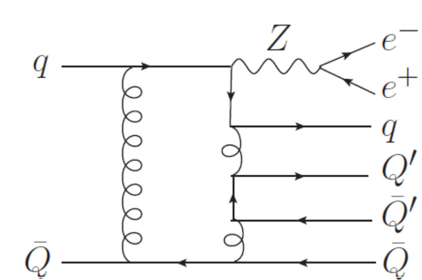
- Z/γ* + 4 jets: — *Ita et al., arXiv:1108.2229*
- W + 4 jets: — *C.F. Berger et.al., Phys.Rev.Lett. 106:092001, 2011*

- Important to have NLO calculations available
- Uncertainties decrease from 50% at LO to ~15-20% at NLO
- In particular PYTHIA not expected to be precise for $N_{jet}>1$
- Not all NLO calculations technically available in all cases at time of analysis



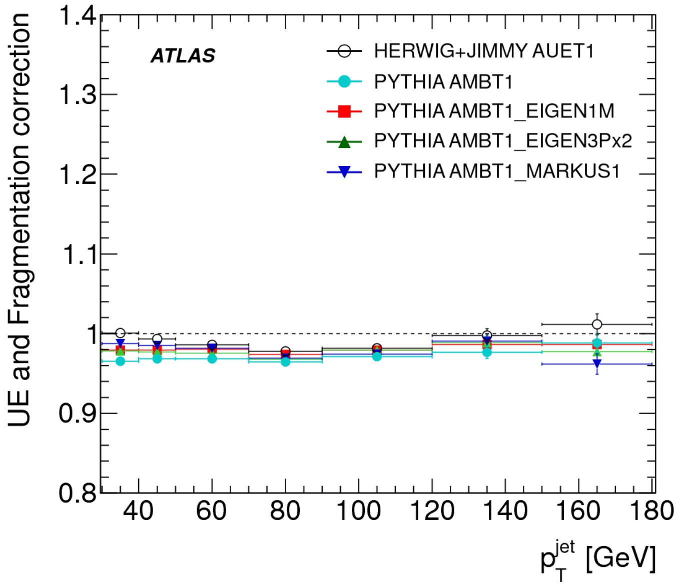






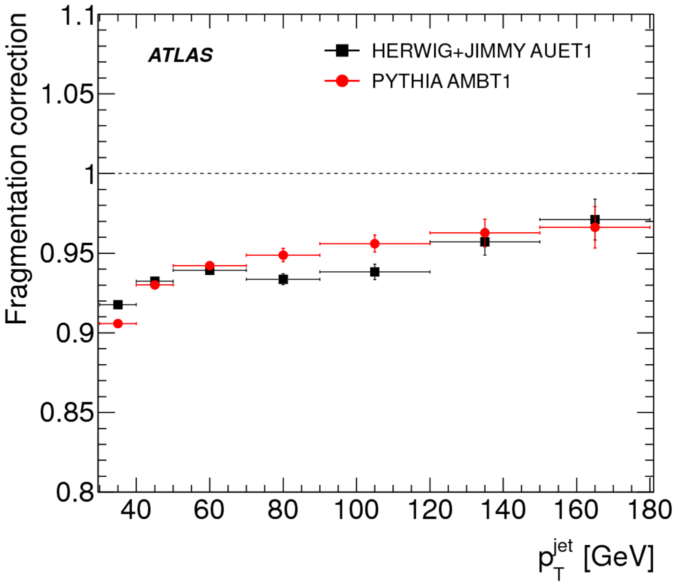
Parton-to-Particle Correction

- MCFM and BlackHat-SHERPA are not full NLO Shower-MCs, but “just” parton level predictions
- Have to evaluate non-perturbative effects on parton level predictions
- Calculated using MC variation samples (tune variations: UE on/off...)

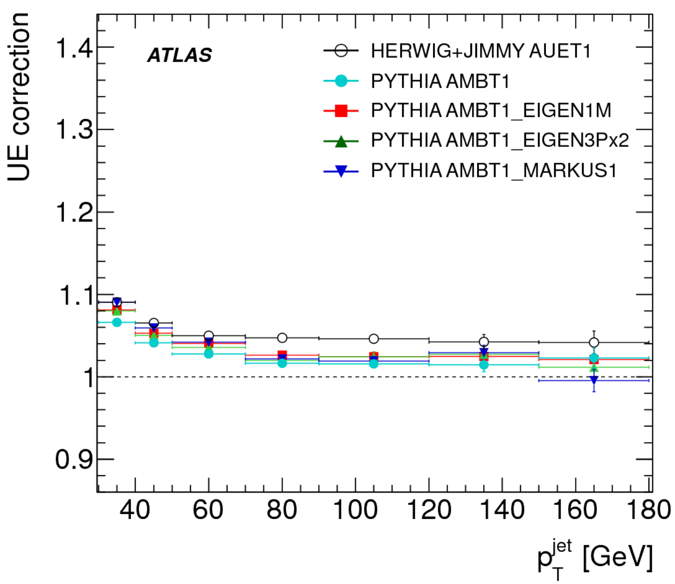


Fragmentation
- Losses:
  lower p_T jets, less jets

Underlying event
- Adds energy:
- higher pT jets, more jets



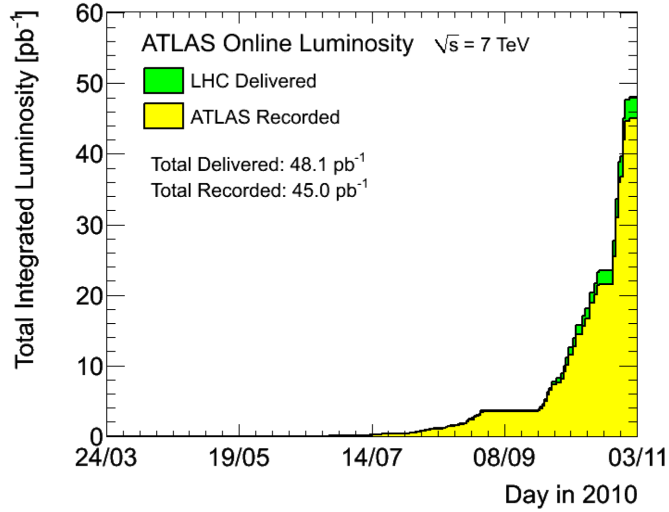
- Partial cancellation in total correction (~1-2%)
- About 10% correction at p_T = 30 GeV (2-5% syst. unc.)

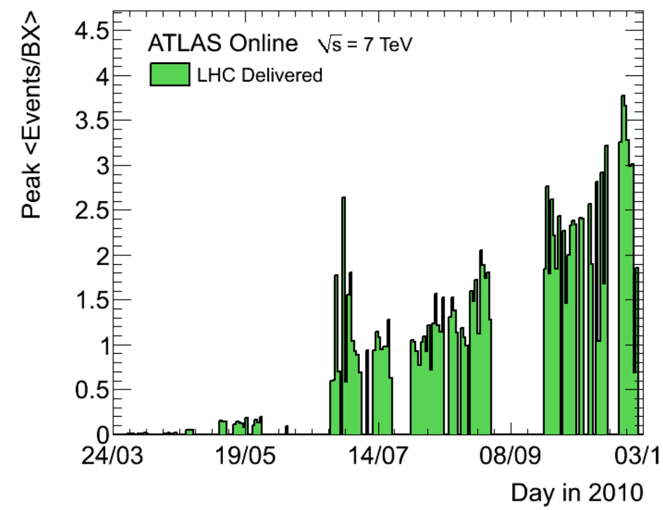


LHC Data

Presented results: 2010 data

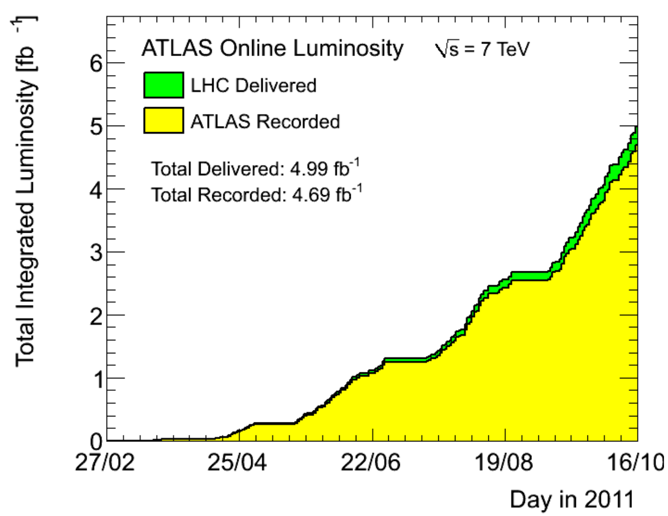
- Int. lumi 33 – 36 pb^{-1}
- Well understood electron, muon and jet performance
- Relatively low collision rates
- **Low pile-up rates**
- Allow cross section measurement at low jet transverse momentum
- Statistics for higher jet multiplicities / large recoil low

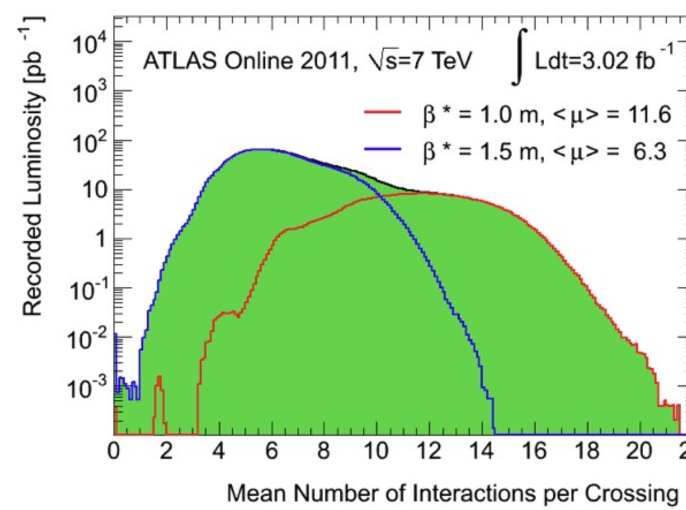




Next: 2011 data

- 4.69 fb^{-1}
- Up to 20 interactions/bx ($<\mu>$ up to >20)
- Precision analyses in progress...





Lepton Selection and Phase Space

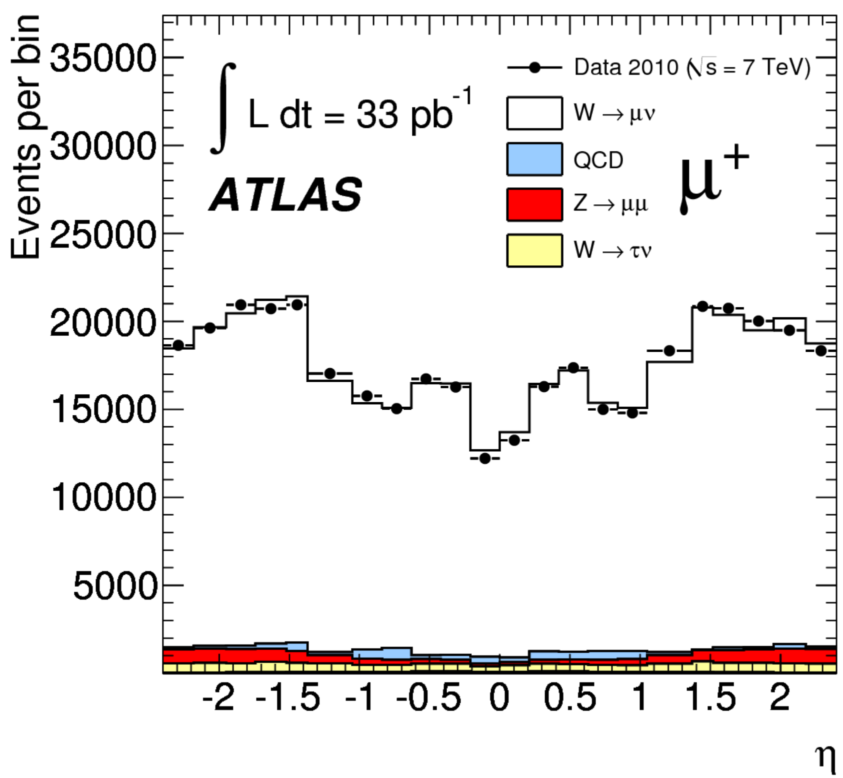
Muons

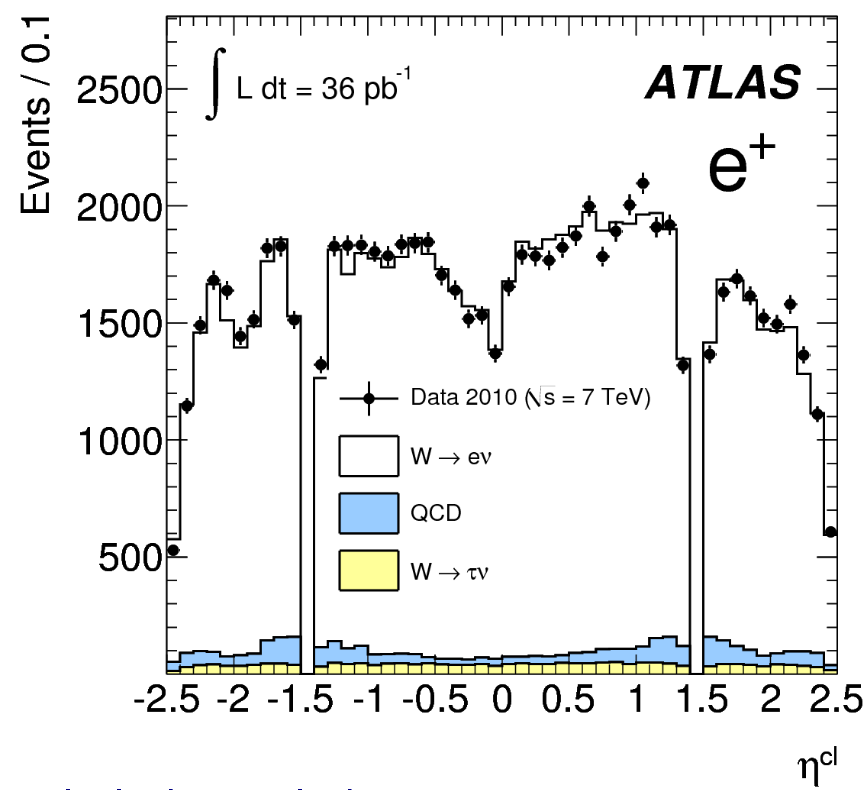
- $p_T > 20$ GeV
- $|\eta| < 2.4$
- Inner Detector + Muon System
- Various quality requirements
- Track isolation

Electrons

- $|\eta| < 2.47$ excluding $1.37 < \eta < 1.52$
- em. shower shape in calorimeter
- Various quality definitions to optimise signal efficiency / background rejection ("medium", "tight")

Different acceptance requires inter/extrapolation of fiducial region for combination





Pseudorapidity distributions from inclusive analysis
Similar for negative leptons

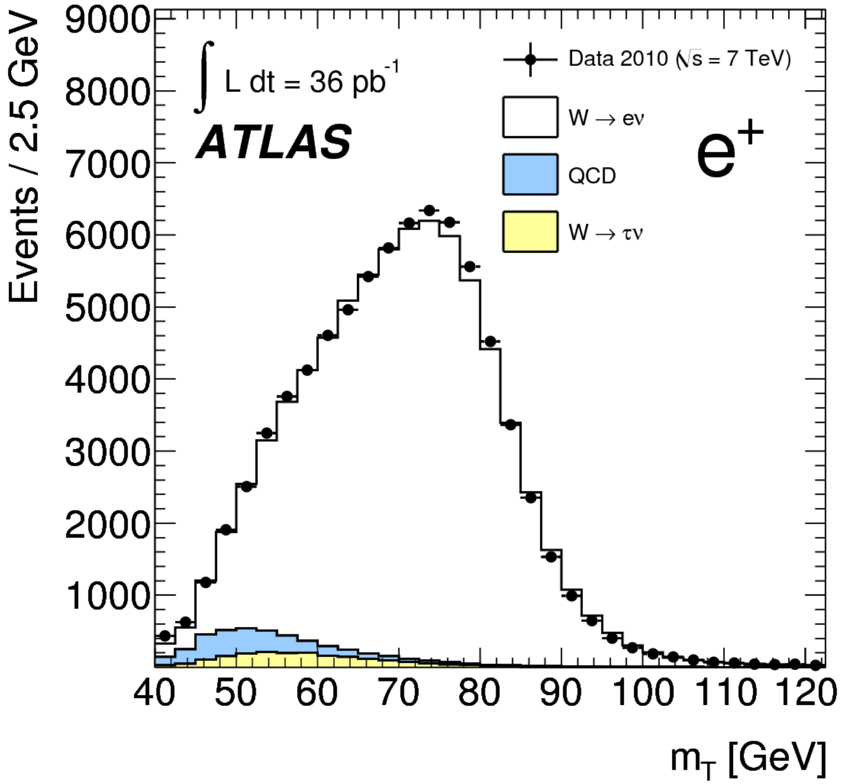
Vector Boson Selection and Phase Space

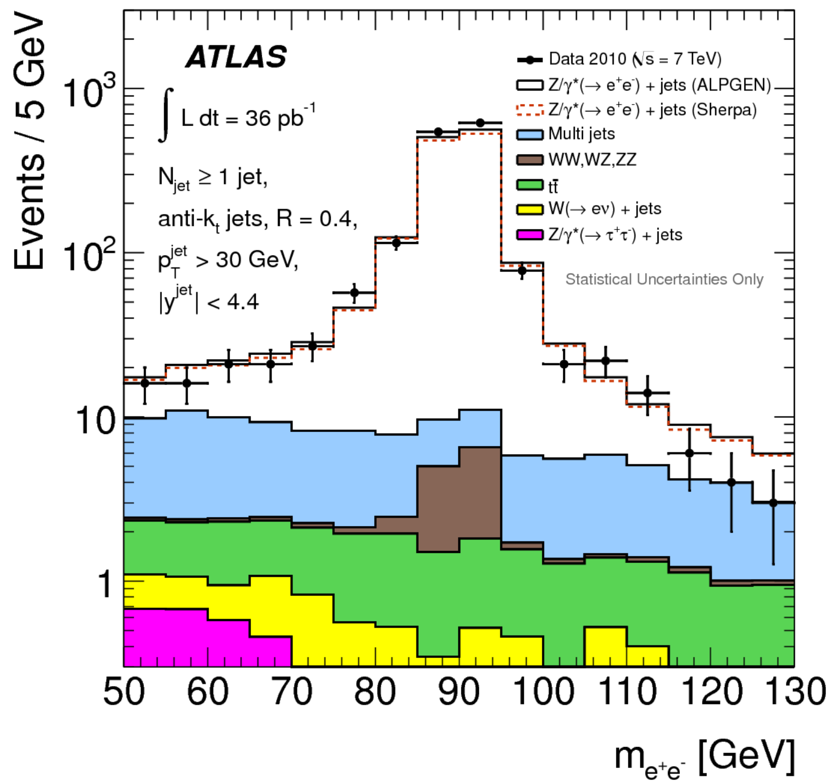
W

- Exactly one lepton (veto 2nd)
- ETmiss > 25 GeV
- M_T > 40 GeV

Z

- Exactly two leptons
- Opposite charges
- 66 < M_{ll} < 116 GeV





Taken from inclusive W,Z measurement

- Acceptance ~45%
- Inclusive backgrounds: ~10% (*W*), ~2% (*Z*)

Jet Selection and Phase Space

Jets

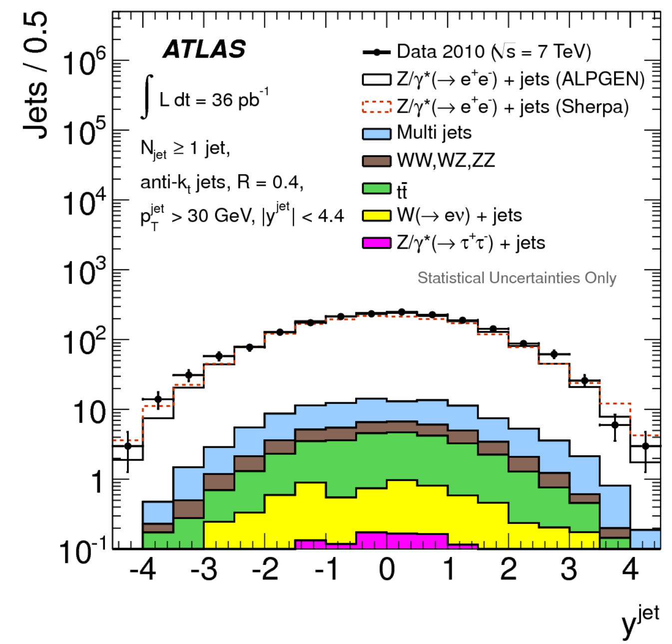
- Anti-k_T algorithm R = 0.4
- p_T > 20 GeV (W+jets)
- p_T > 30 GeV (Z+jets and R_{jets})
- $|\eta| < 4.4$ ($|\eta| < 2.8$ for R_{jets})
- lepton-jet separation $\Delta R_{lj} > 0.5$ (0.6 for Rjets) (prevent distortion of jet by em. showers)

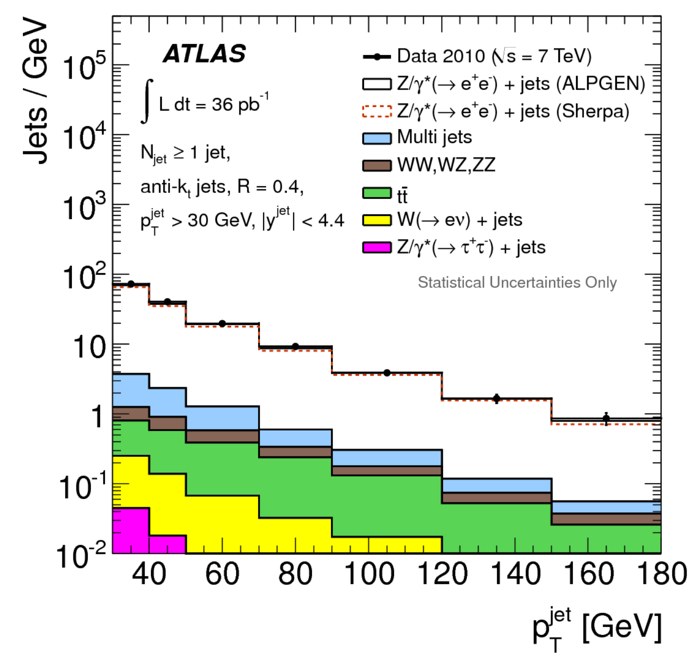
- Pileup removal using “Jet Vertex Fraction” JVF > 0.75
- Source of large systematic uncertainty in V+jets – small for R_{jets} : pile-up almost cancels
- JVF only usable in 2010 data with low pileup

- JES calibration largely MC based

Particle level definition of jets
- Use all final-state particle
  - including HF decay products
  - excluding W/Z decay products

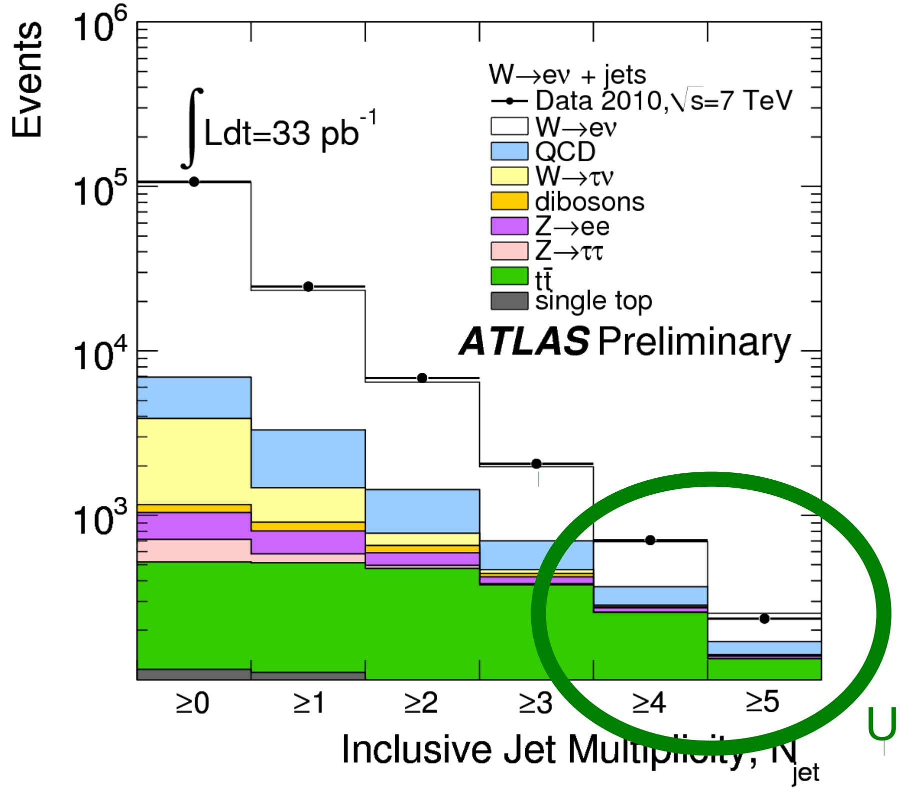
Inclusive y and p_T jet (Z+jets)



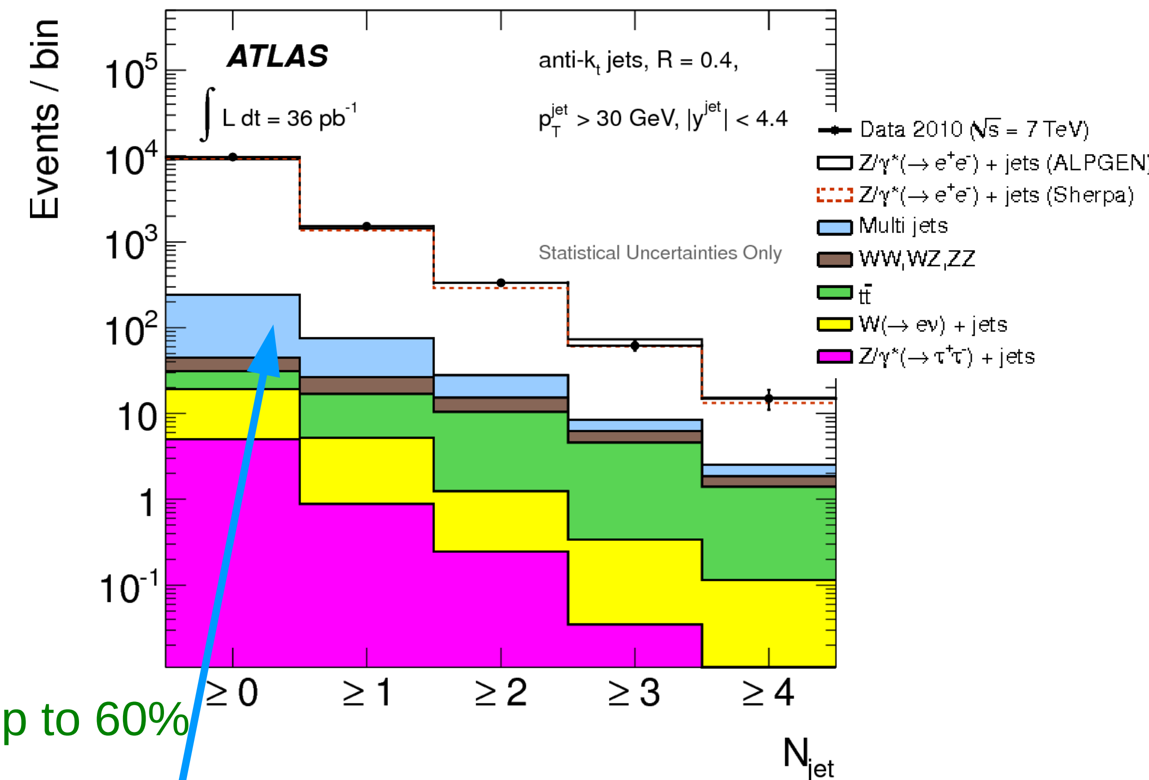


Inclusive Jet Multiplicity (Detector Level)

W + jets



Z + jets



Up to 60%

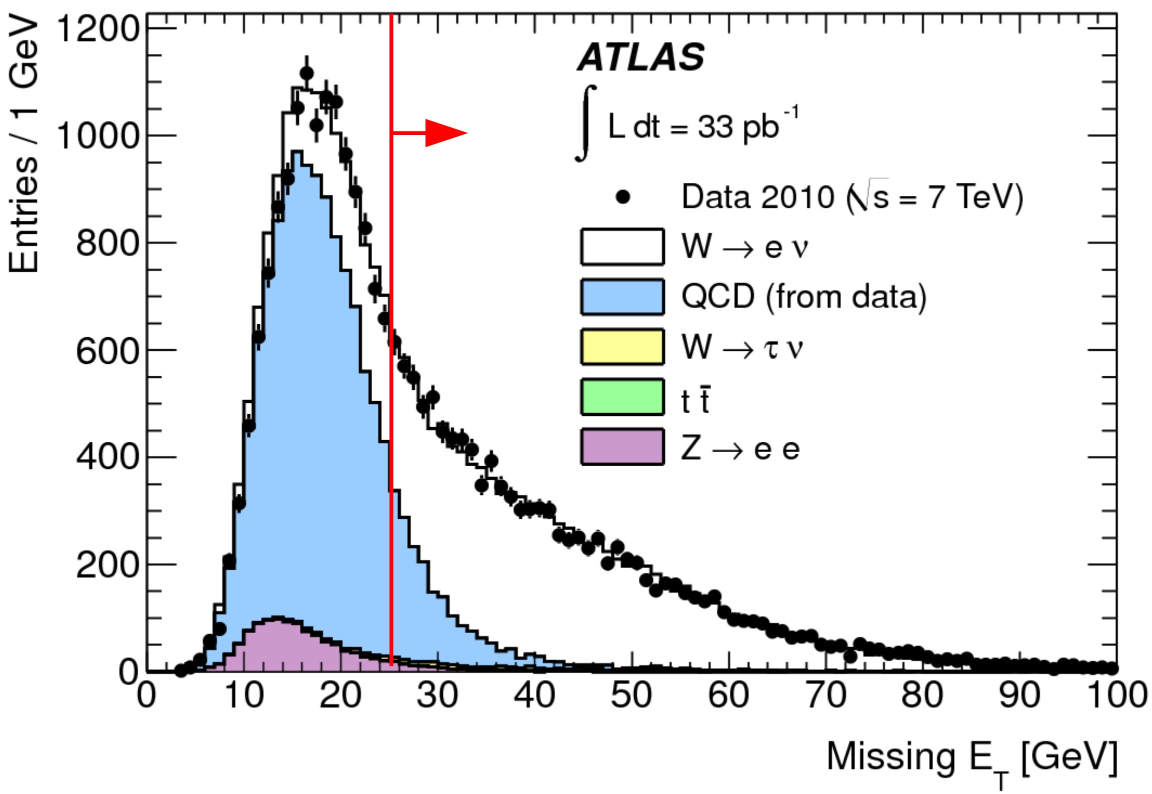
- Backgrounds increasing towards higher N_{jet}
- EW and top taken from simulation – **QCD important at low multiplicities (*next slide*)**
- **Top becomes important at higher jet multiplicities (N_{jet} > 3,4) in *W* channel**
- Overall good agreement data / prediction
- Very similar plots for R_{jets} in respective phase space

  (Statistics not enough to cover more than 1 jet: limited by *Z* channel)
- Inclusive bin: Can already estimate σ(*W*) / σ(*Z*) ~10

QCD Background Modeling

Depending on final state use data driven method or MC estimates

- *W→ee* Fit data to MET distribution using QCD template
  - electron ID reversal or
  - electron selection replaced with photon
- *W→μμ* Fit MET distribution, QCD template from MC
- *Z→ee* Loosen electron ID, normalize with dilepton-mass
- *Z→μμ* directly from MC (HF dominated)



QCD template and Normalisation from data in W+1-jet

(from R_{jets} analysis)

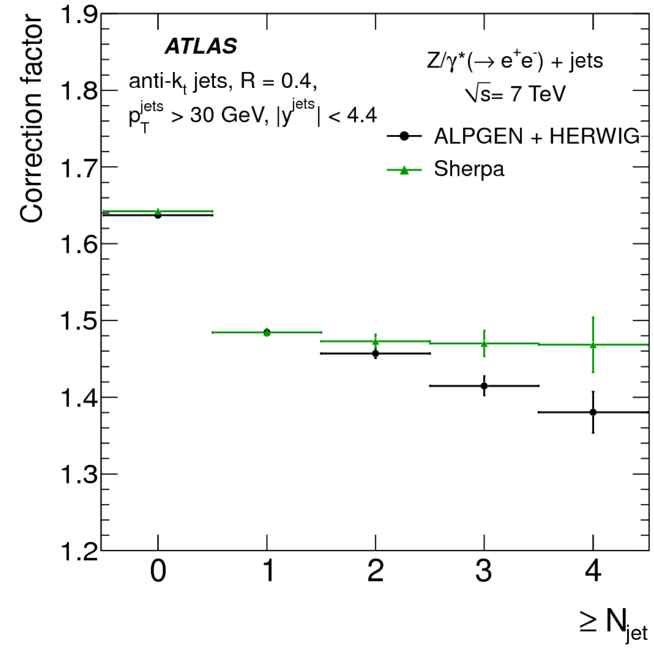
V+jets Unfolding for Detector Effects

Bin-by-bin correction factors U(ξ)

$$\frac{d\sigma}{d\xi} = \frac{1}{\mathcal{L}} \frac{1}{\Delta\xi}(N_{\text{data}} - N_{\text{backg}}) \times U(\xi)$$

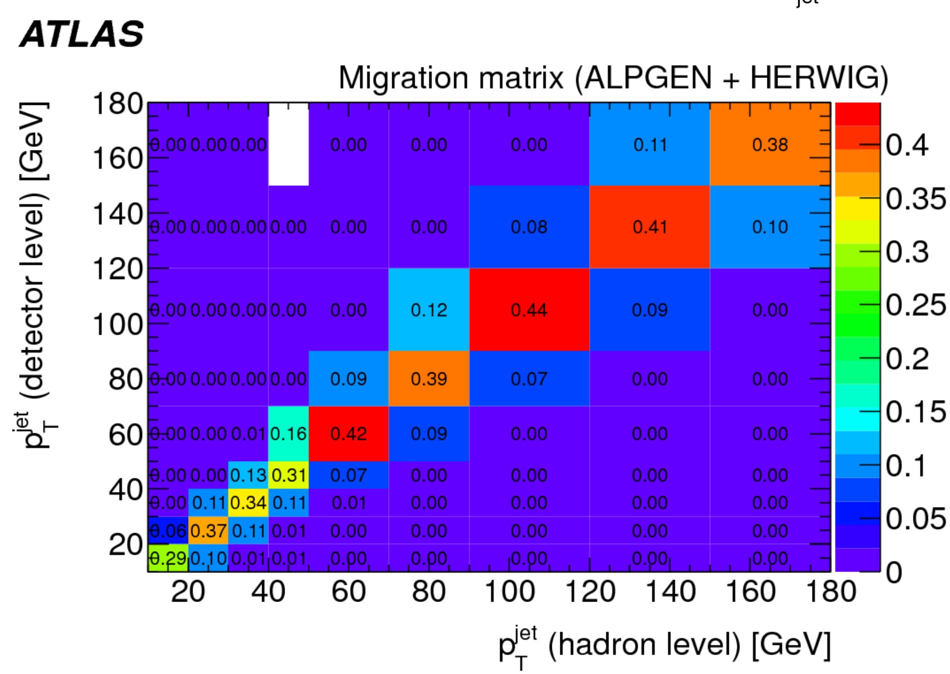
- U(ξ) contains all trigger and reconstruction (leptons and jets) inefficiencies / resolutions
- Determined using ALPGEN simulation
  Electron channel: U(ξ) = 1.65 to 1.35
  Muon channel: U(ξ) = 1.16 to 1.1
- Systematic uncertainty : difference between ALPGEN and SHERPA derived corrections

Electron Channel $U(N_{jet})$



Bayesian Method “d'Agostini”

- Cross check + future use
- Lower MC dependence, better statistical treatment
- More complex, need to pay attention to regularization
- This round confident in bin-by-bin results:
  - Good agreement data-MC at Detector level
  - W/Z + jets measurements are systematically limited
  - Little migration: off-diagonal elements small



W/Z Ratio Correction Procedure

- R_{jets} calculated from ratio of individually corrected event yields in W, Z channels
- Allows correct evaluation of statistical correlations in numerator/denominator

$$N^{\ell,V}_{\text{part}} = \frac{N^{\ell,V}_{\text{sig}}}{\epsilon^{\ell}_{\text{trig}} \times \epsilon^{\ell} \times C^{\ell}_{V}}$$

Signal events (backgrounds subtracted)

Trigger efficiency

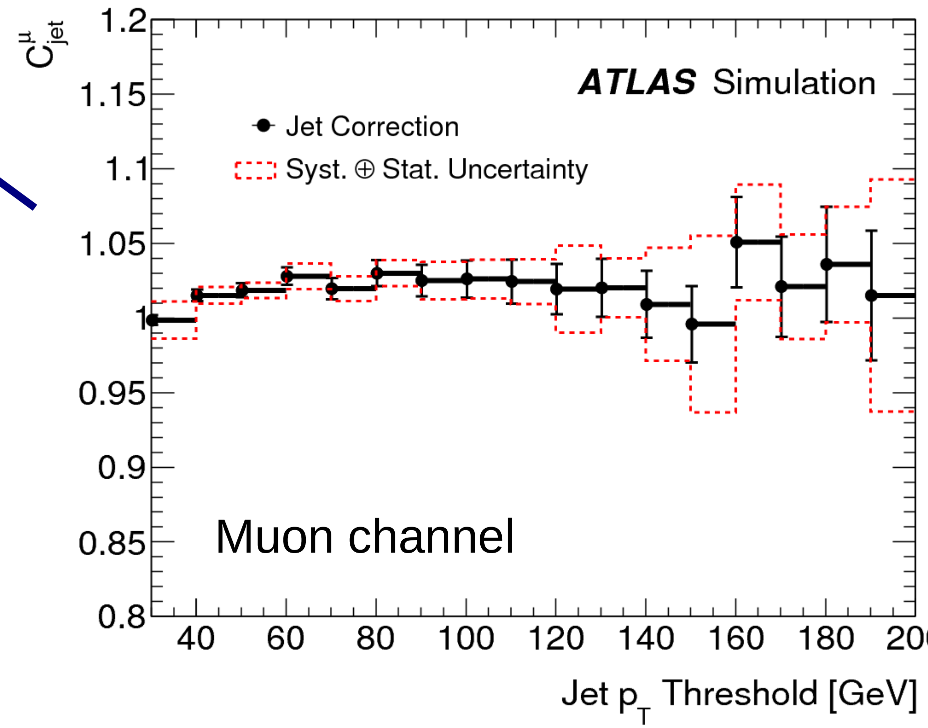
Lepton identification

Boson reconstruction

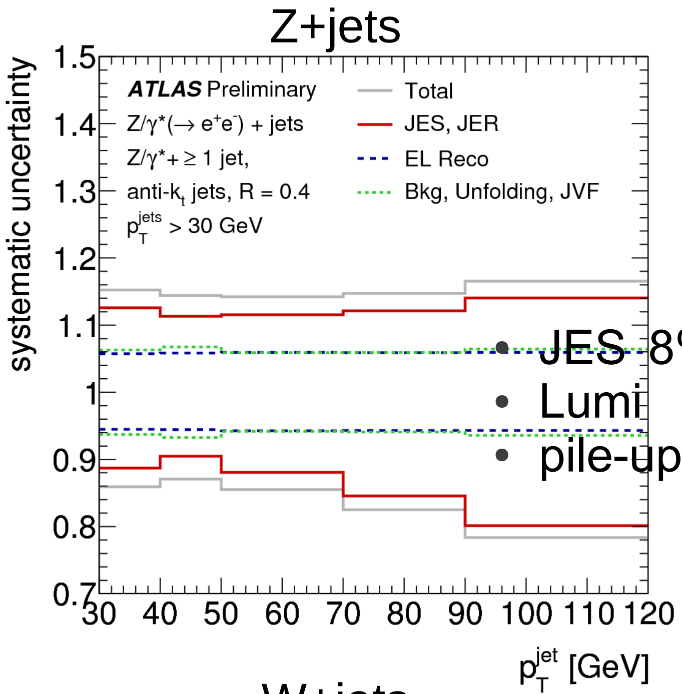
$$R_{\text{jet}} = \frac{N^{\ell,W}_{\text{part}}}{N^{\ell,Z}_{\text{part}}} \times C^{\ell}_{\text{jet}}$$

Jet spectrum correction directly on ratio

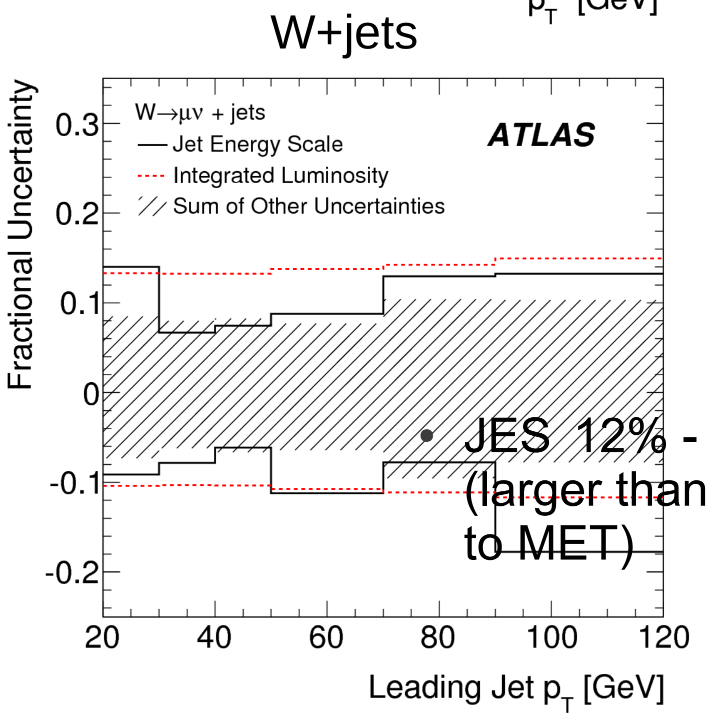
- Almost complete cancellation of jet resolution effects
- Remaining effects from W/Z phase space differences below ~5%
- Determined on ratio by smearing particle level jets according to JES
- Syst. Uncertainty from difference between ALPGEN and PYTHIA



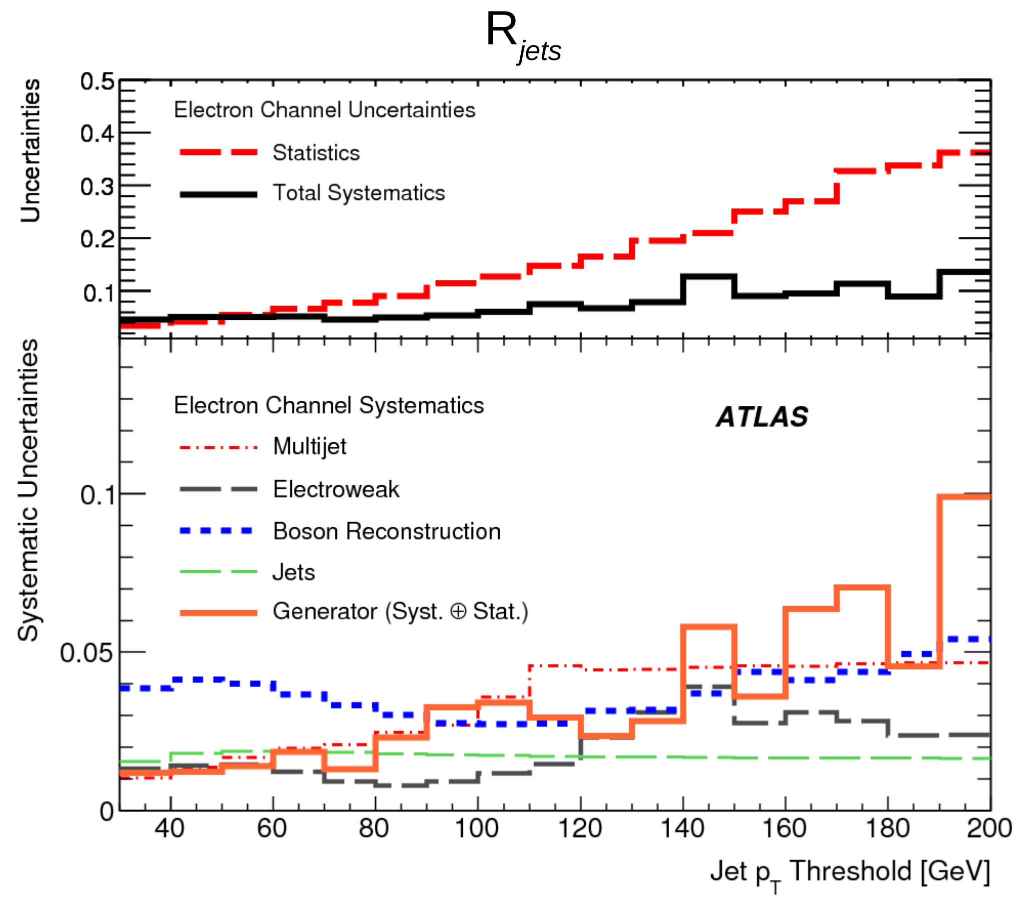
Systematic Uncertainties in lead. p_T^{jet}



- JES 8% - 20%
- Lumi 3.4%
- pile-up ≈5%

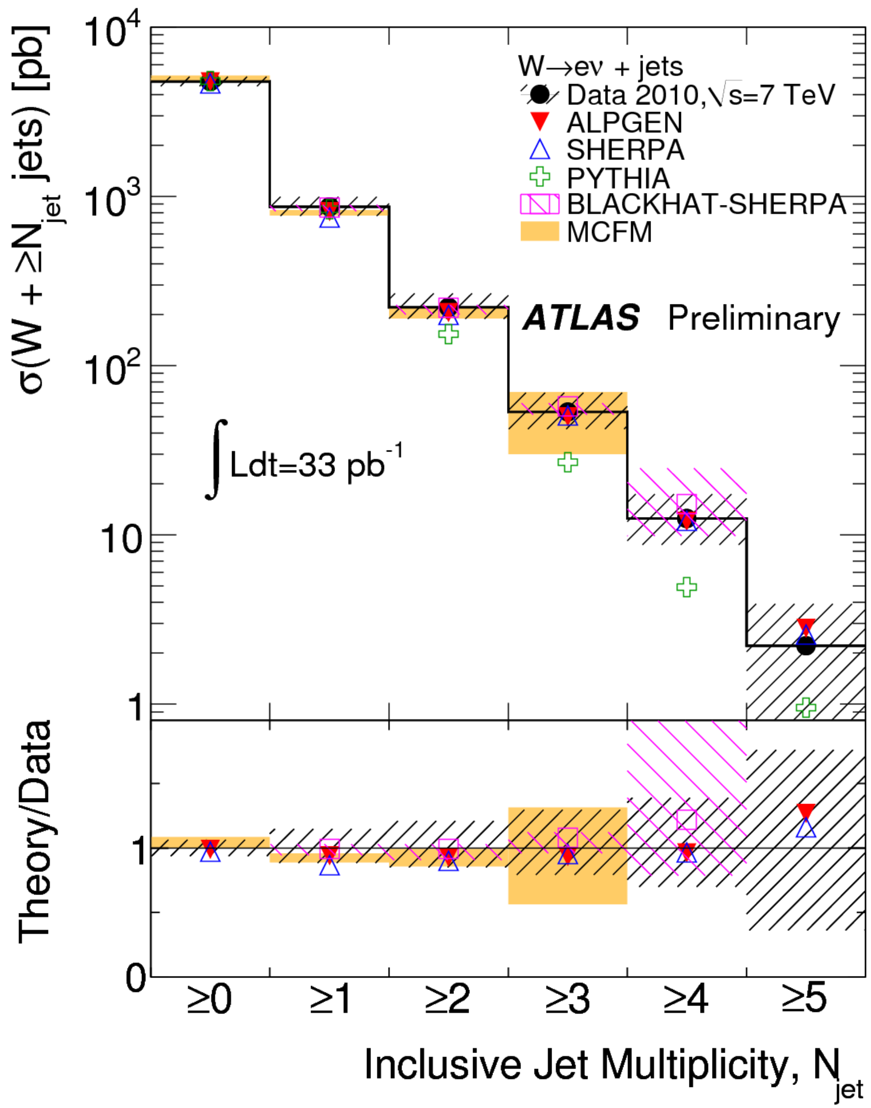


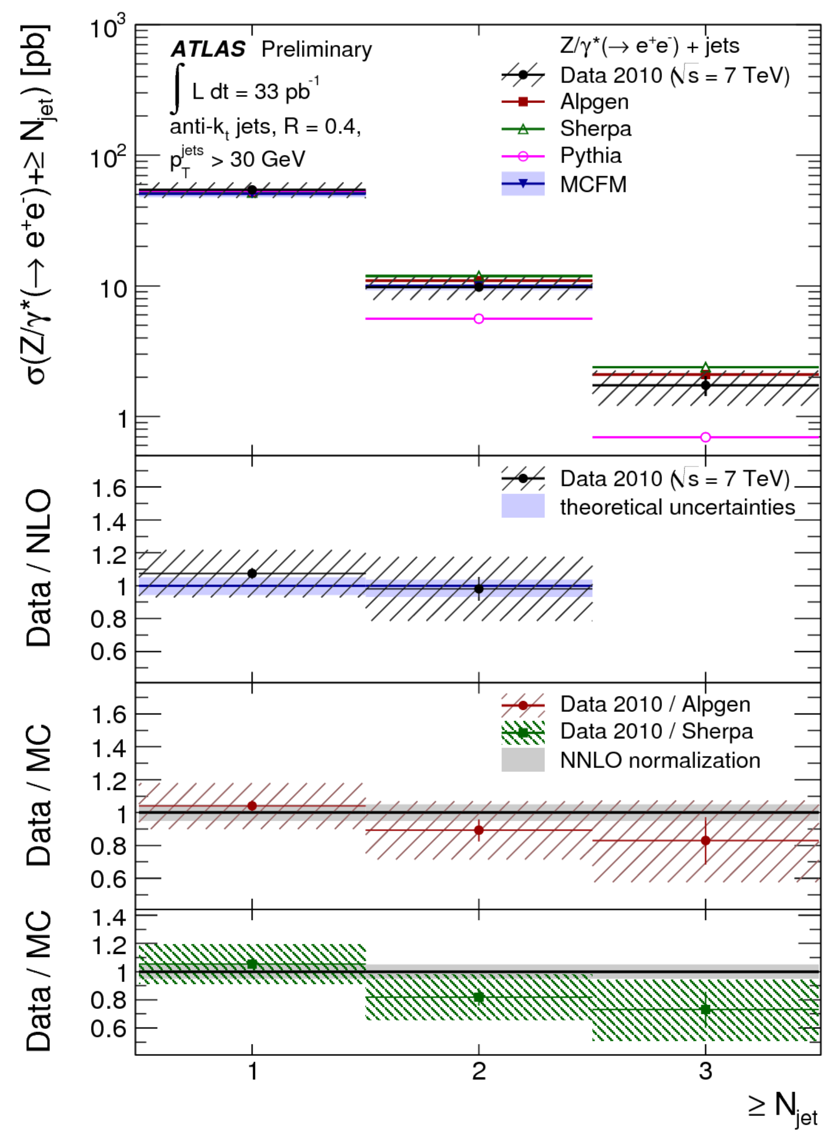
- JES 12% - 22% (larger than Z due to MET)



- Rjets: Systematic uncertainties substantially smaller than in V+jets individually
- In particular reduction on the jet systematic uncertainties
- Systematic uncertainties of the order of less than 5%
- Precision still statistically limited.

Inclusive Results V+jets Cross Sections

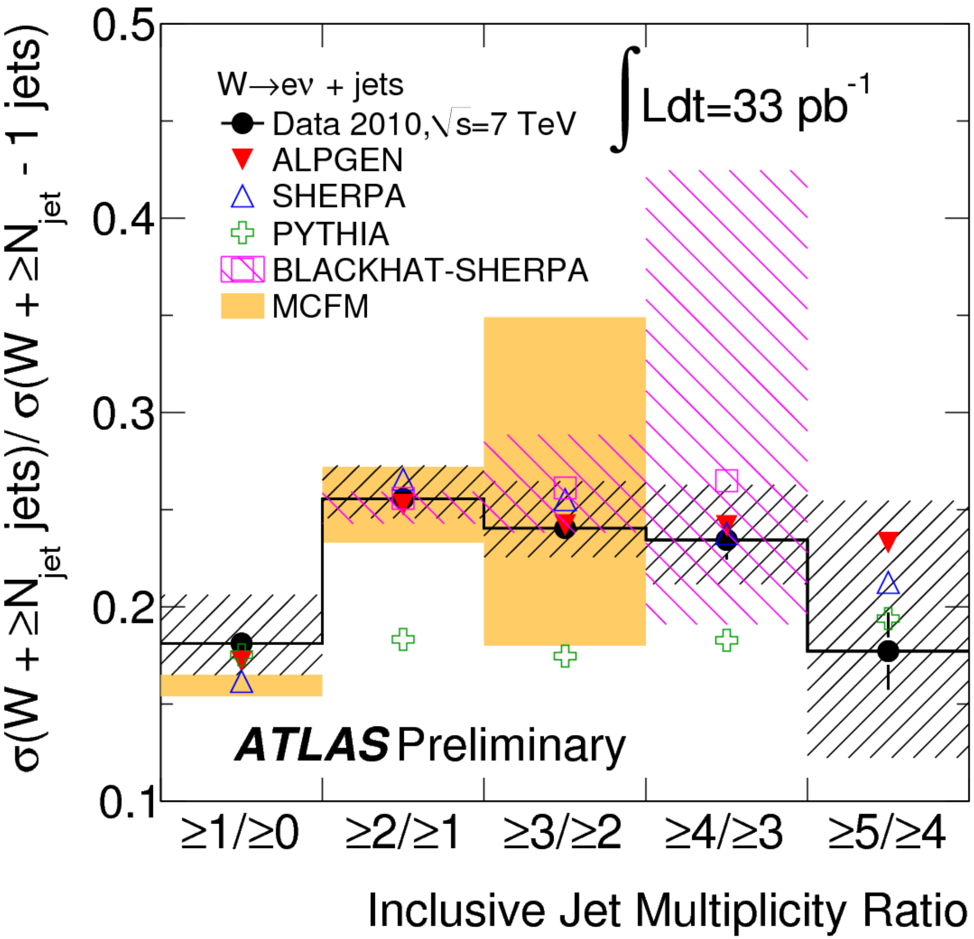


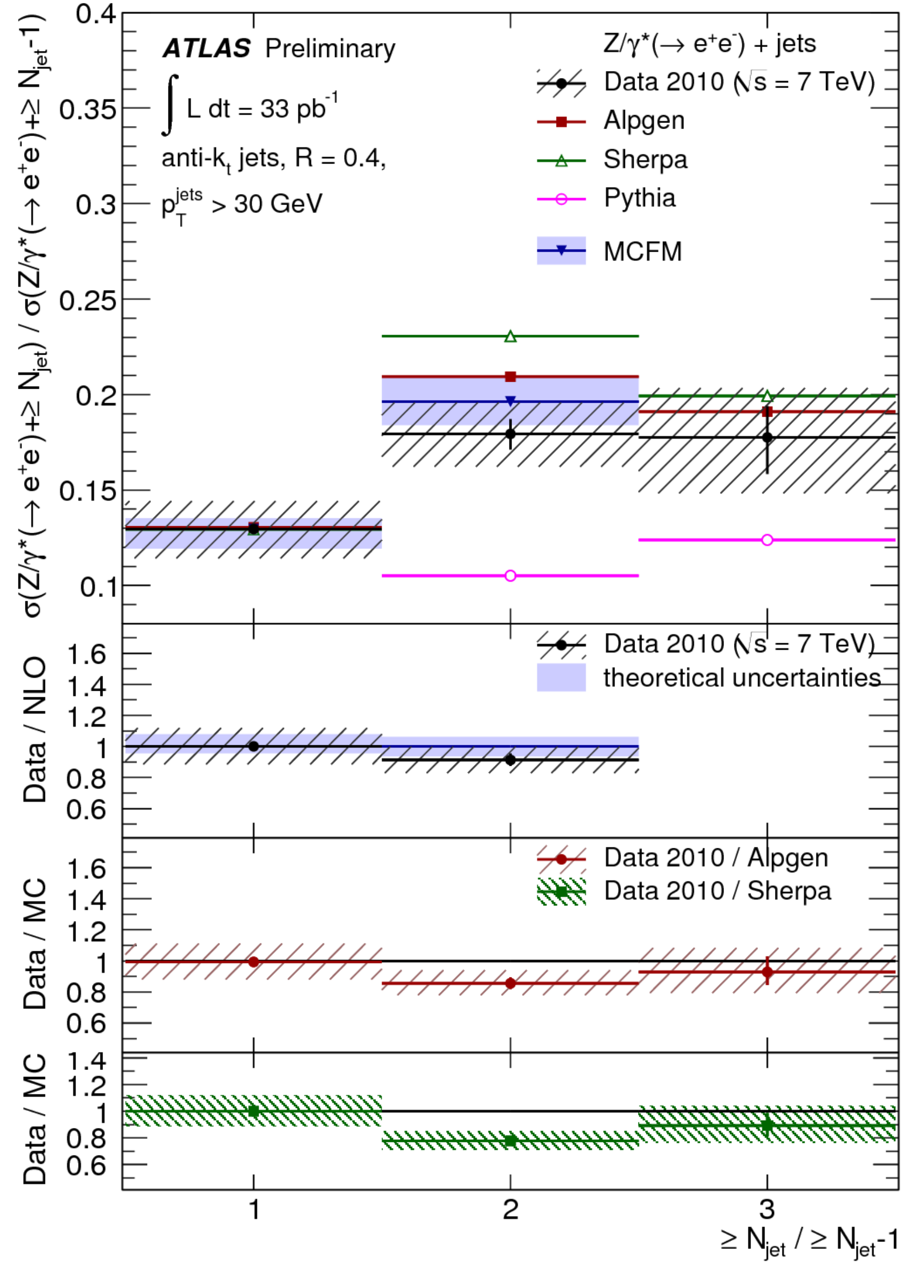


- Blackhat-Sherpa: NLO for N jets ≤ 3, LO for N jets = 4
- MCFM: NLO for N jets ≤ 3
- As expected PYTHIA underestimates rates of high multiplicites

pQCD works well

Jet Multiplicity Ratios



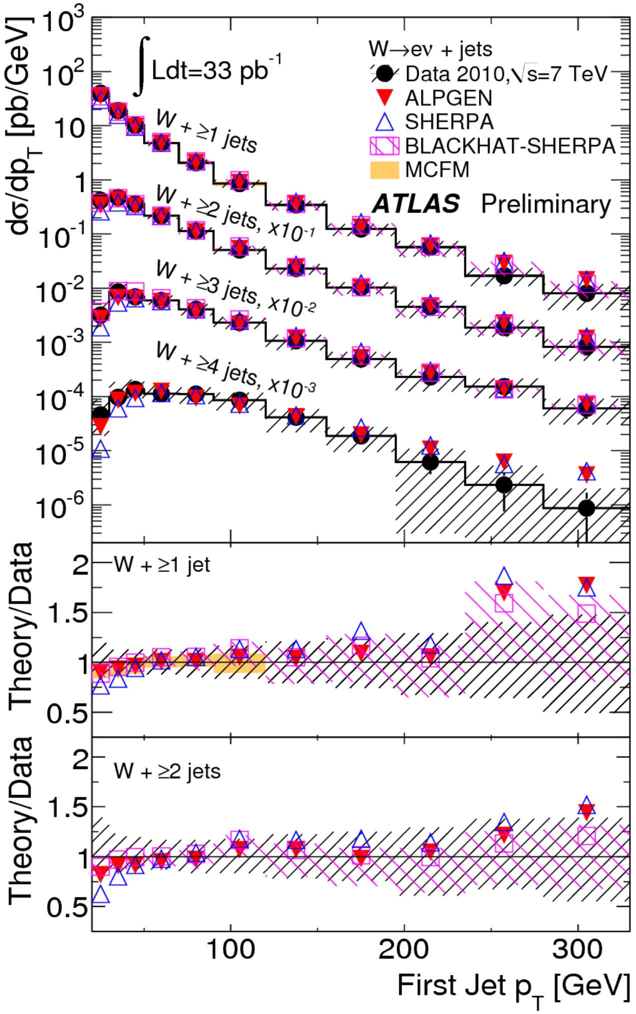


- Some systematic uncertainties cancel (Lumi, lepton ID, boson acceptance)
- Increased uncertainty on MCFM and Blackhat-Sherpa (in bin 3 and 4 respectively) due to LO prediction

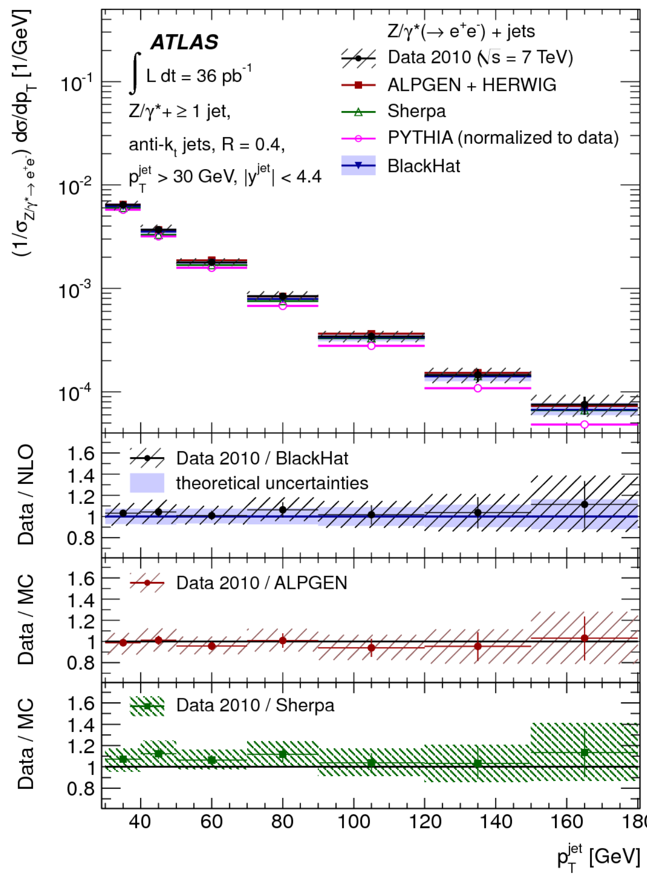
- Ratio roughly ~25% (W), ~20% (Z) per jet except first bin ~15%

Cross section in leading jet p_T

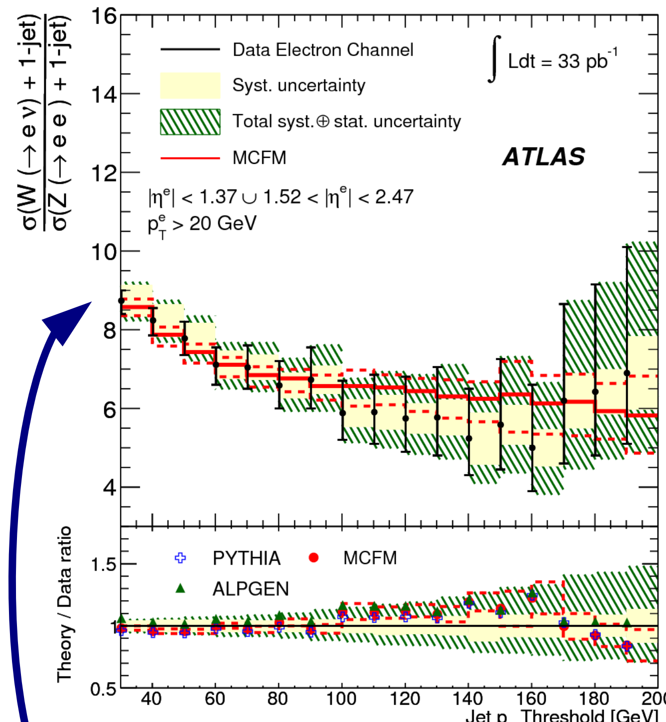
W+jets (N_{jet} >= 1,2,3,4)



Z+jets (N_{jet} >= 1)



R_{jets} (N_{jet} = 1)



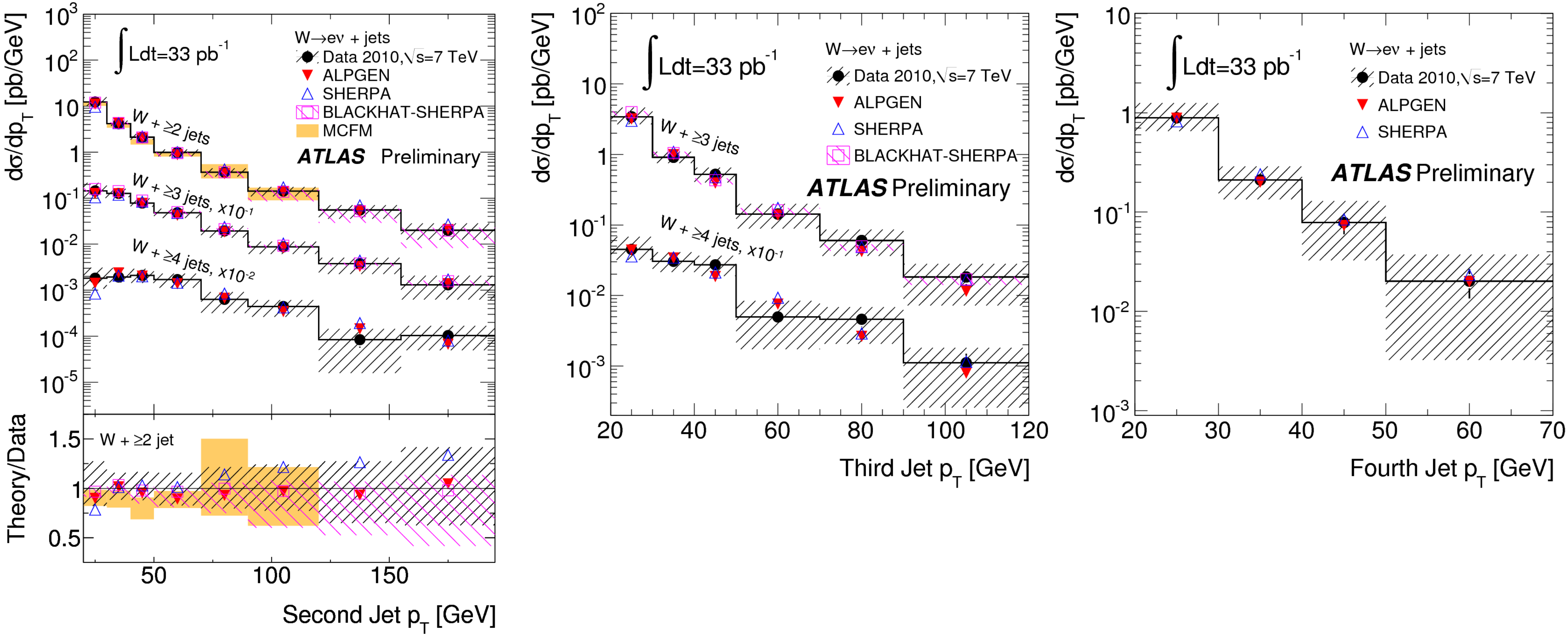
$$8.73 \pm 0.30\,(\mathrm{stat}) \pm 0.40\,(\mathrm{syst})$$

Rjets
- Syst. cancellation:
  - lumi
  - Partially lepton id
  - Mostly JES/JER, detector effects,
  - parton-to-hadron corr.

- Cross section normalised to inclusive cross section
- canellation of lumi, partially lepton id and boson acceptance systematics

Transverse momenta of 2nd, 3rd, 4th jet

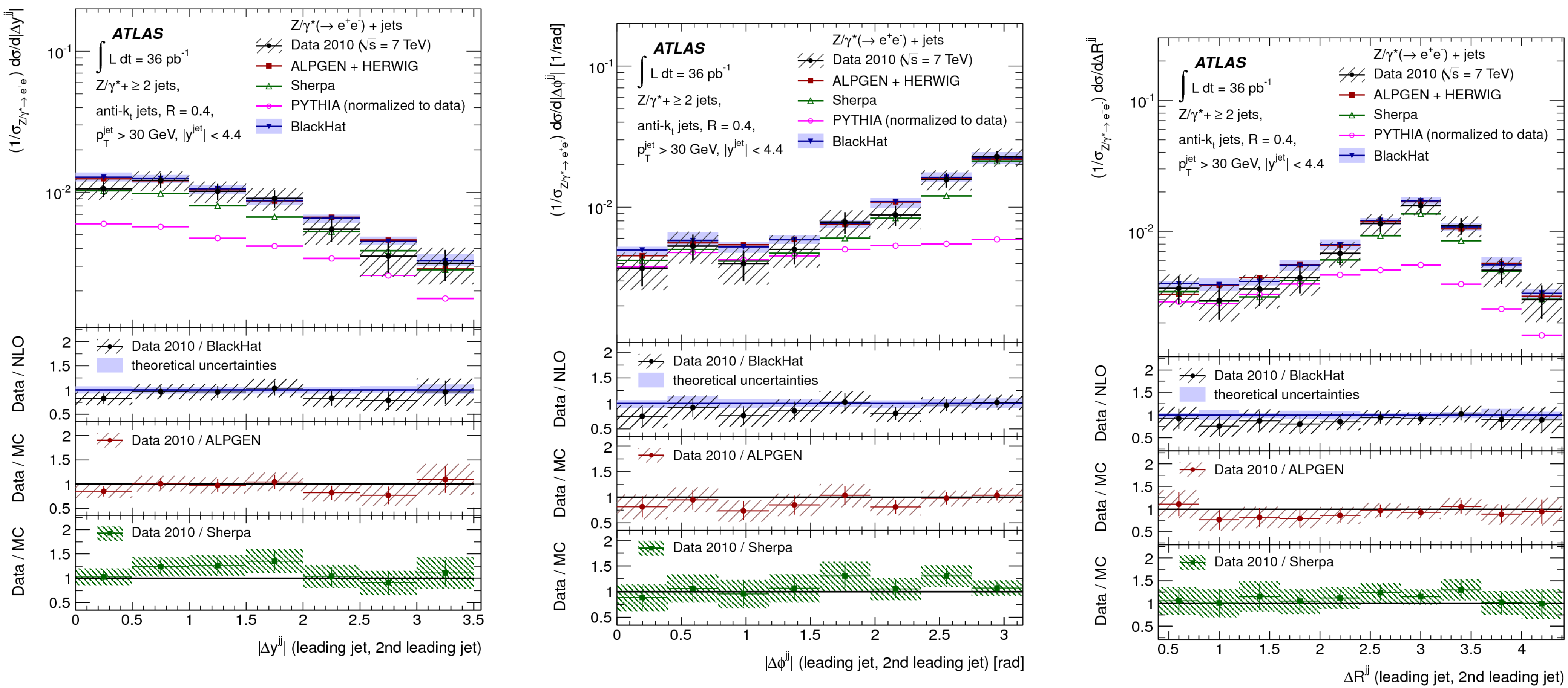
W+jets



- Various energy scales and high multiplicities already available in 2010 data
- Data consistent with NLO pQCD prediction and with ME generators SHERPA and ALPGEN
- Not consistent with PYTHIA parton shower

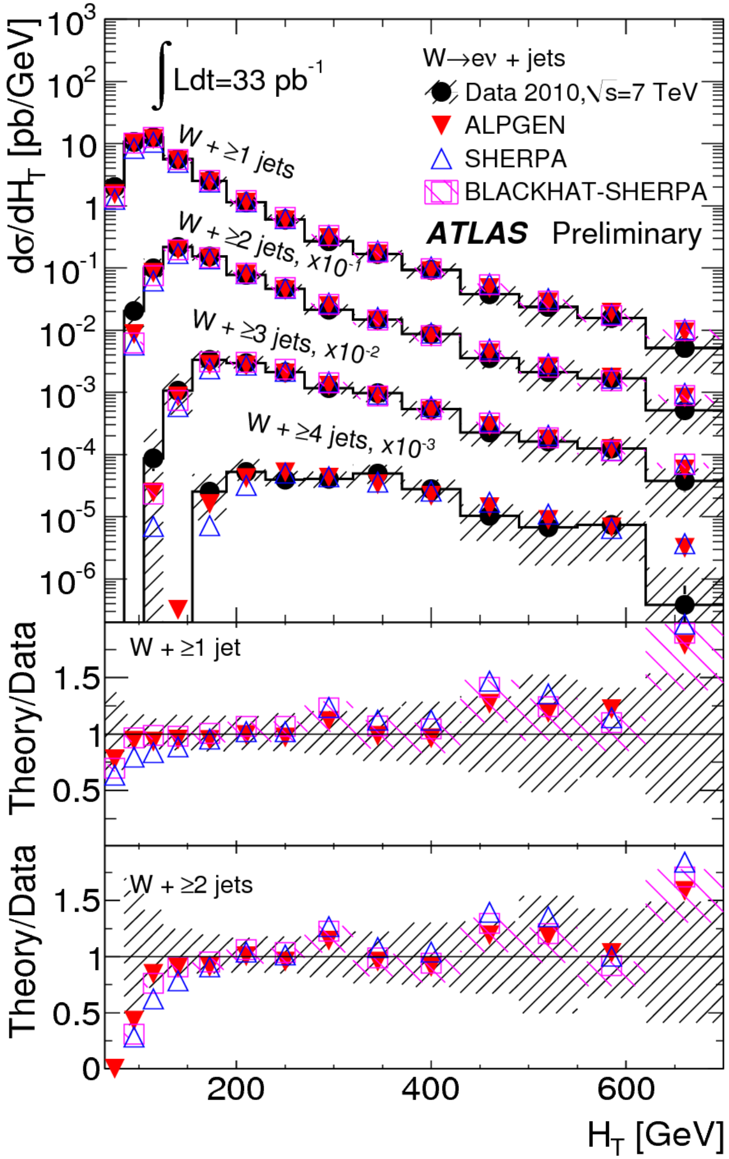
Dijet Angular Distributions

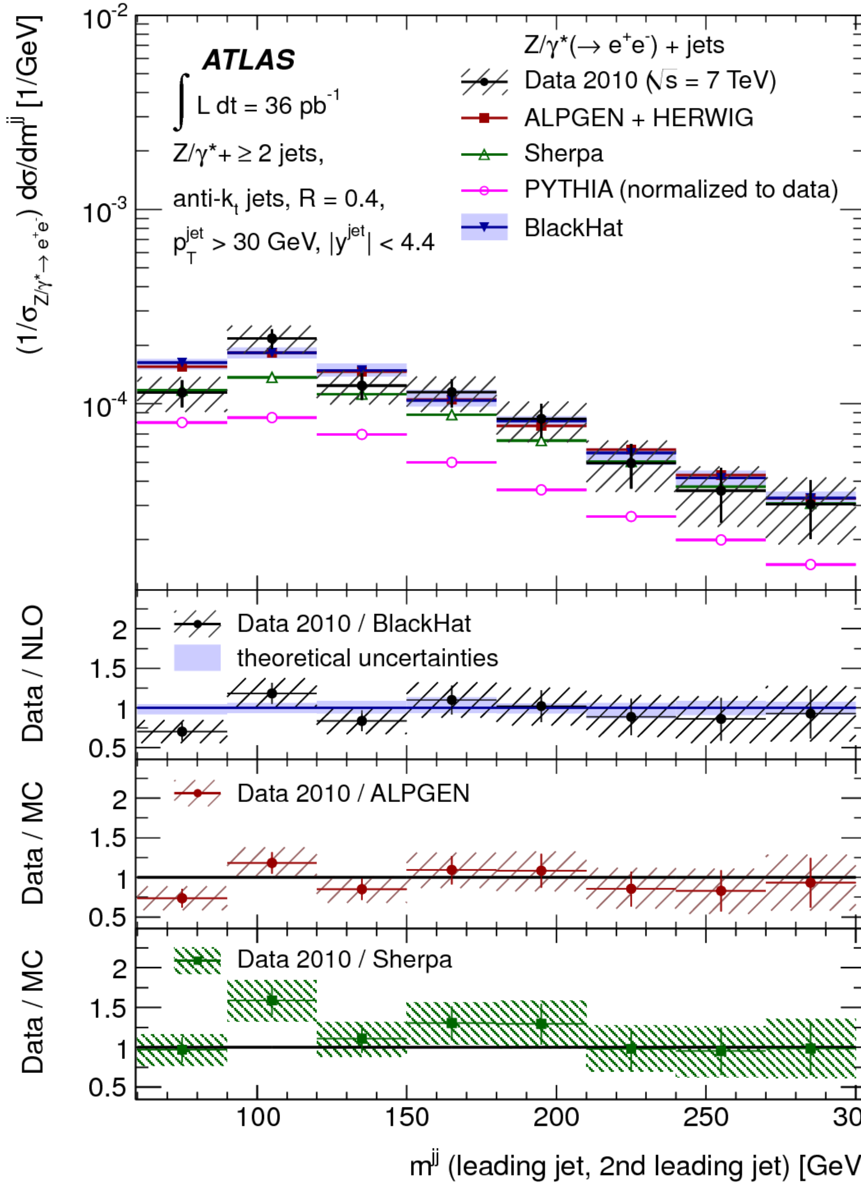
Z+jets



- Probe hard parton emission at large angles
- Of interest for example for VBF topologies (Higgs searches)
- Well described by NLO pQCD predictions and SHERPA+ALGPEN ME generators

Results in More Complex Variables



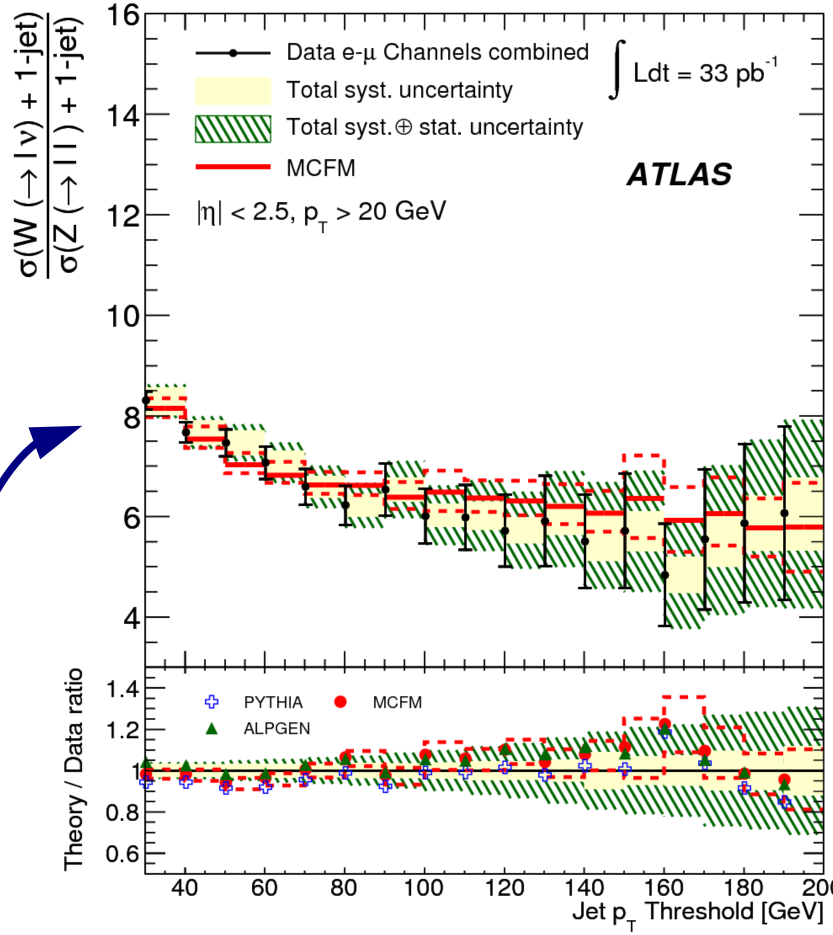


- H_T often scale choice – $m_{W/Z}$ not good scale any more at large jet p_T
- Interesting for searches, also: invariant mass m_{12}
- Variables well described by pQCD predictions and ME generators

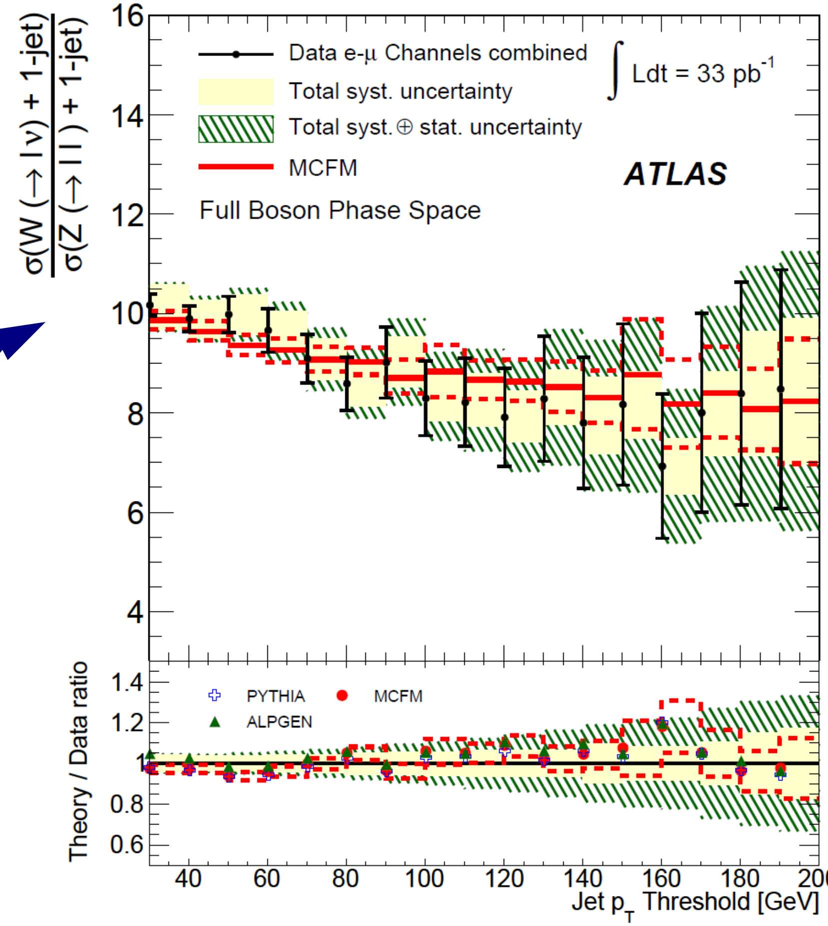
Extrapolation to Combined and Full Phase Space

For combined e/μ cross section

- Minimal extrapolation to common e/μ phase space to minimize model dependent corrections
- V+jets: use the BLUE (BestLinearUnbiasedEstimate) method
- Rjets: use BAT (Bayesian Analysis Toolkit)



$$8.29 \pm 0.18\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})$$



Also provide results in full boson phase space extrapolated using simulation

$$10.13 \pm 0.22\,(\mathrm{stat}) \pm 0.45\,(\mathrm{syst})$$

Conclusions

- Presented measurements of the production cross-section for W and Z bosons in association with jets, performed with data collected in 2010
  - Inclusive cross-section as a function of jet multiplicity and its ratio
  - Differential cross-sections with respect to jet and di-jet kinematics
- Cross-sections corrected for all detector effects and quoted in the kinematic region of the detector acceptance
- Precision is mainly limited by systematic uncertainties
- Data compared to predictions at LO and NLO in QCD
  - Good agreement between data and predictions from ALPGEN, SHERPA, MCFM and Blackhat-Sherpa in region probed by measurements
  - PYTHIA disagrees with data when $N_{jet}>1$ (expected)

Outlook

Many possibilities... have already 100x the statistics available

- V+jets: Measure at higher multiplicites (7/8), go to higher p_T (TeV regime) possibly probe forward regions
- R_{jets}: probe more distributions (already explored by V+jets)
- Add novel distributions interesting for backgrounds. Examples:
  - V + 2-jets specific distributions → VBF-like signature
  - Jet vetoes / rapidity gaps
  - Event shapes, jet shapes
- Searches: Exploit precision of ratio measurements to look for deviation from SM predictions in model-independent way
- PDFs: W+/W- and Z probe different pdfs – input for pdf-fits?
- Theory: Compare to shower MCs in the future

… there is still a lot of work to do in the Standard Model

B A C K U P

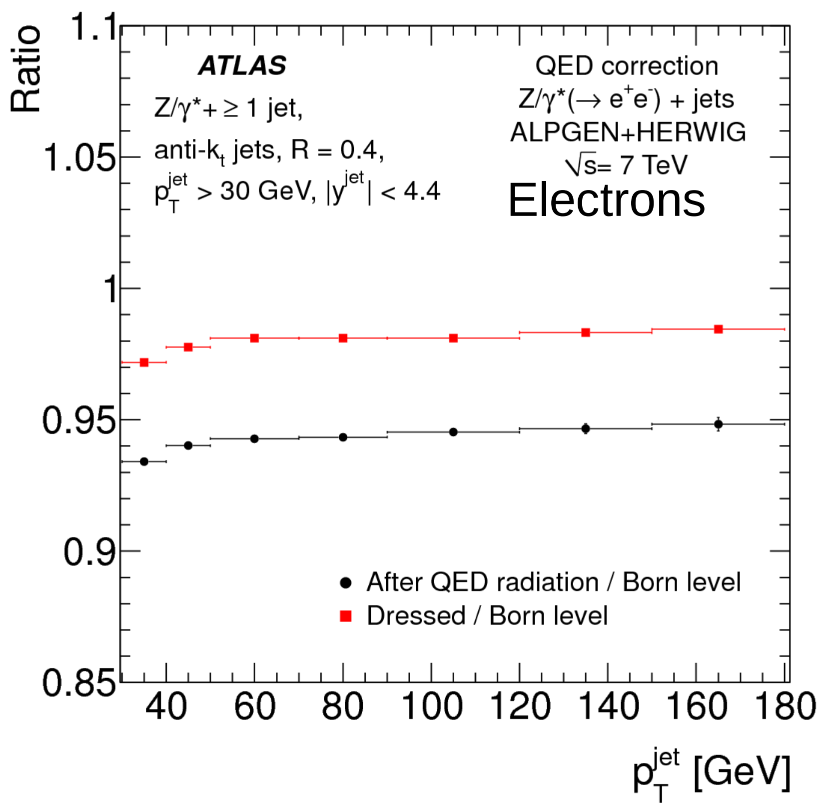
Generators

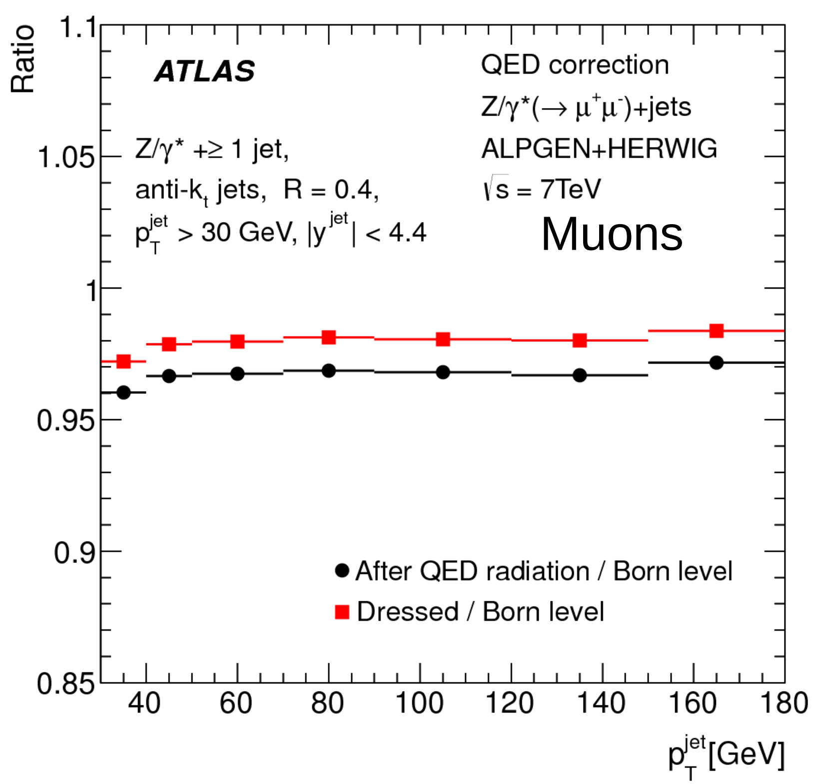
- Used for background simulation and estimation and unfolding of detector effects

Generator	Comments
ALPGEN 2.13 + HERWIG + JIMMY	PHOTOS, CTEQ6L1, ATLAS MC09 tune MLM matching, pQCD normalized to NNLO
SHERPA 1.13	CTEQ6L1, Default UE tune CKKW matching, pQCD normalized
PYTHIA 6.4.21	PHOTOS, MRST 2007 LO LO MatrixElement + ISR, PS corrections PQCD normalized
MCFM 5.8	CTEQ6.6/CTEQ6L1 PYTHIAUE, fragmentation
SHERPA+BLACKHAT	CTEQ6.6M
FEWZ NNLO	MRST2007LO* PDF Used for pQCD normalization K-factors: 1.20 (W), 1.24 (Z) @ 5% unc.

Lepton Dressing

- Bare leptons at propagator are also not physically meaningful
- "Dress" leptons:
  Add photon 4-vectors in $\Delta R < 0.1$ around lepton to lepton 4-vector
- Mainly from FSR
- Compromise to avoid worst shortcomings of born and bare definition of leptons
- Provide clear definition where experiment and theory can meet
- Results in ~1.5% acceptance correction per lepton
- Effect on cross section 2%-2.5% (*Z* channel)





Extrapolation to full vector boson phase space