# Vector boson + jet production with ATLAS

XXI. International Workshop on Deep-Inelastic Scattering and Related Subjects

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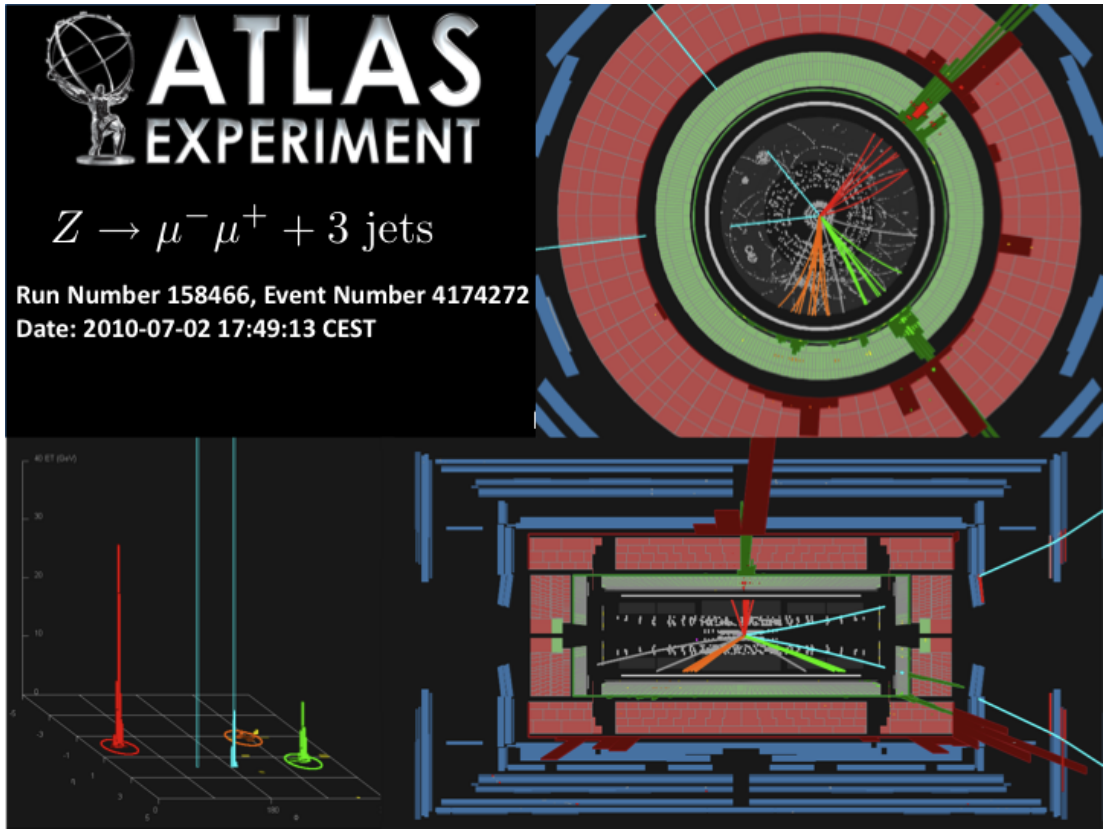
On behalf of the ATLAS Collaboration

# Outline



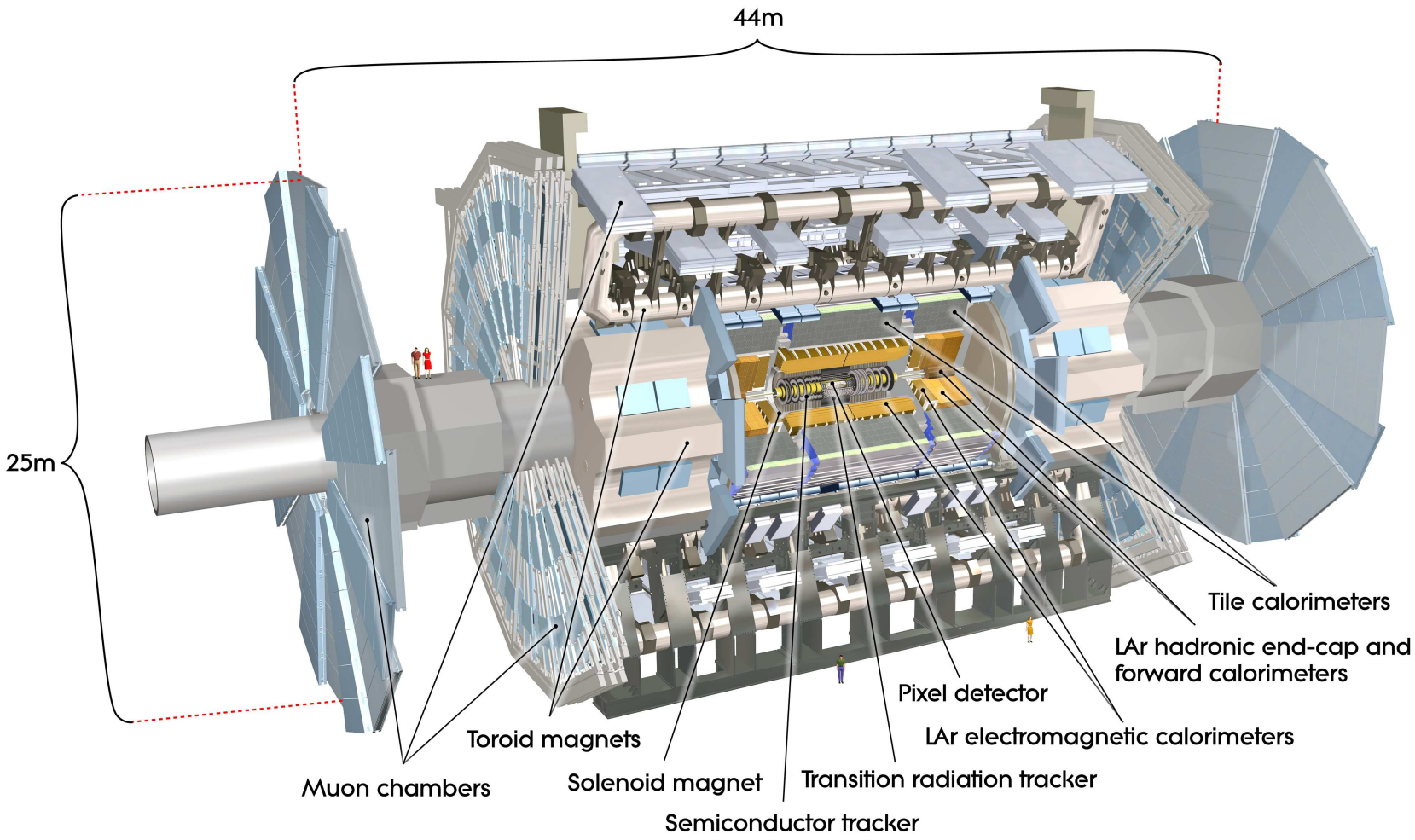


# Introduction

- Study of vector boson production in association with jets is an important test of perturbative QCD
- Final states with $W/Z$ + jets are backgrounds to many Standard Model, Higgs and beyond the Standard Model analyses
- Ratio of jet multiplicities and of $W$ + jets and $Z$ + jets exploits the cancellation of theoretical and experimental uncertainties and provides a high precision test of the Standard Model
- Results shown use 33–36 $\text{pb}^{-1}$ of data recorded in 2010 ($W$ + jets, $W/Z$ ratio) and 4.6 $\text{fb}^{-1}$ of data recorded in 2011 ($Z$ + jets) at $\sqrt{s} = 7$ TeV

| | |
|---|---|
| SHERPA | Multi-parton LO matrix element (ME) and parton shower (PS) |
| ALPGEN | Multi-parton LO ME, using HERWIG PS |
| MC@NLO | NLO ME, using HERWIG PS |
| BLACKHAT | NLO ME for $W/Z$ + $n$ jets, interfaced to SHERPA |
| MCFM | NLO ME, corrected to particle level using PYTHIA |

# The ATLAS detector




Geometrical acceptance: inner tracker: $|\eta| < 2.5$, muon system: $|\eta| < 2.7$, calorimeter: $|\eta| < 4.9$

# $W$ + jets

Lepton selection:

- $p_{\mathrm{T}}^{\ell} > 20\,\mathrm{GeV}$
- $|\eta^{e}| < 1.37$ or $1.52 < |\eta^{e}| < 2.47$
- $|\eta^{\mu}| < 2.4$
- $E_{\mathrm{T}}^{\mathrm{miss}} > 25\,\mathrm{GeV}$
- $m_{\mathrm{T}}(W) > 40\,\mathrm{GeV}$

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} \left(1 - \cos(\Delta\phi^{\ell\nu})\right)}$$

Jet selection:

- Anti-$k_t$ jets with $R = 0.4$
- $p_{\mathrm{T}} > 30\,\mathrm{GeV}$
- $|y| < 4.4$ and $\Delta R^{\ell j} > 0.5$

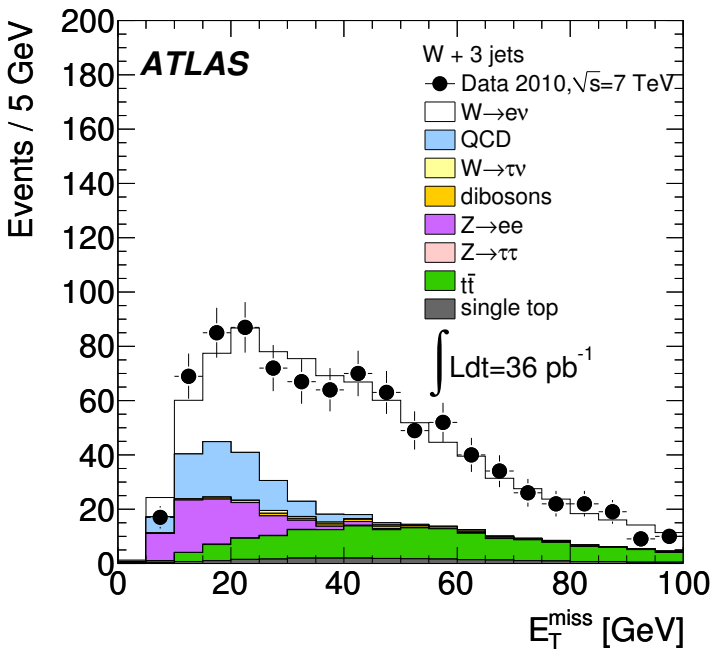
Leptonic backgrounds:

- $t\bar{t}$ and single top
- Diboson ($WW$, $WZ$, $ZZ$)

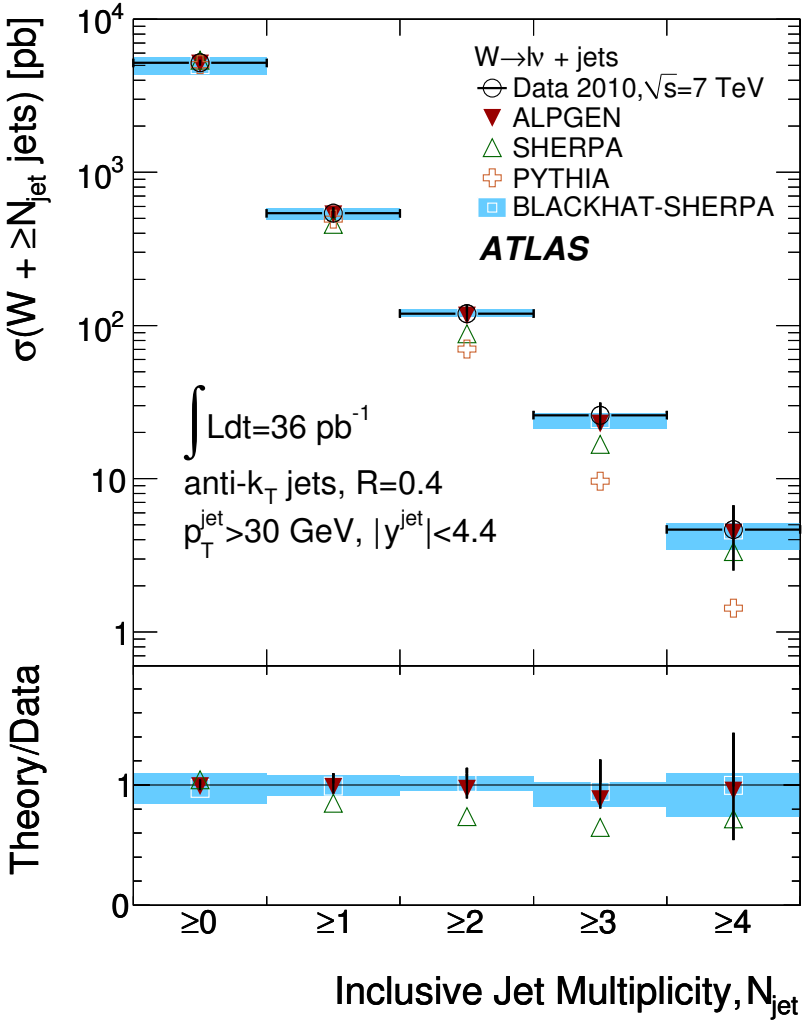
Estimated from Monte Carlo

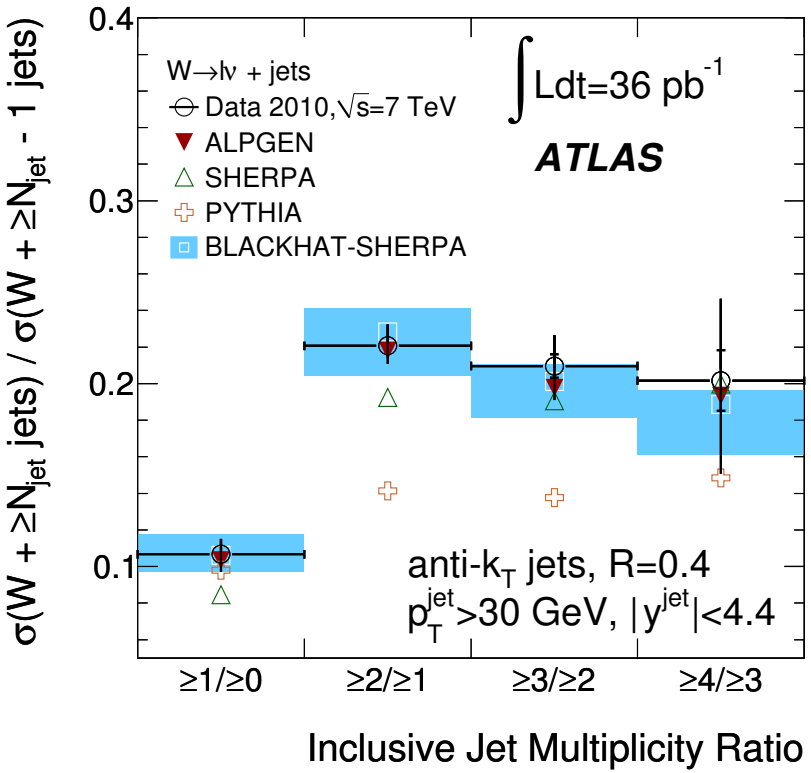
Multijet background:

- Light flavour jets passing the electron selection together with fake $E_{\mathrm{T}}^{\mathrm{miss}}$
- Leptonic bottom or charm hadron decays
- Estimated using a template fit
- Templates extracted from control region



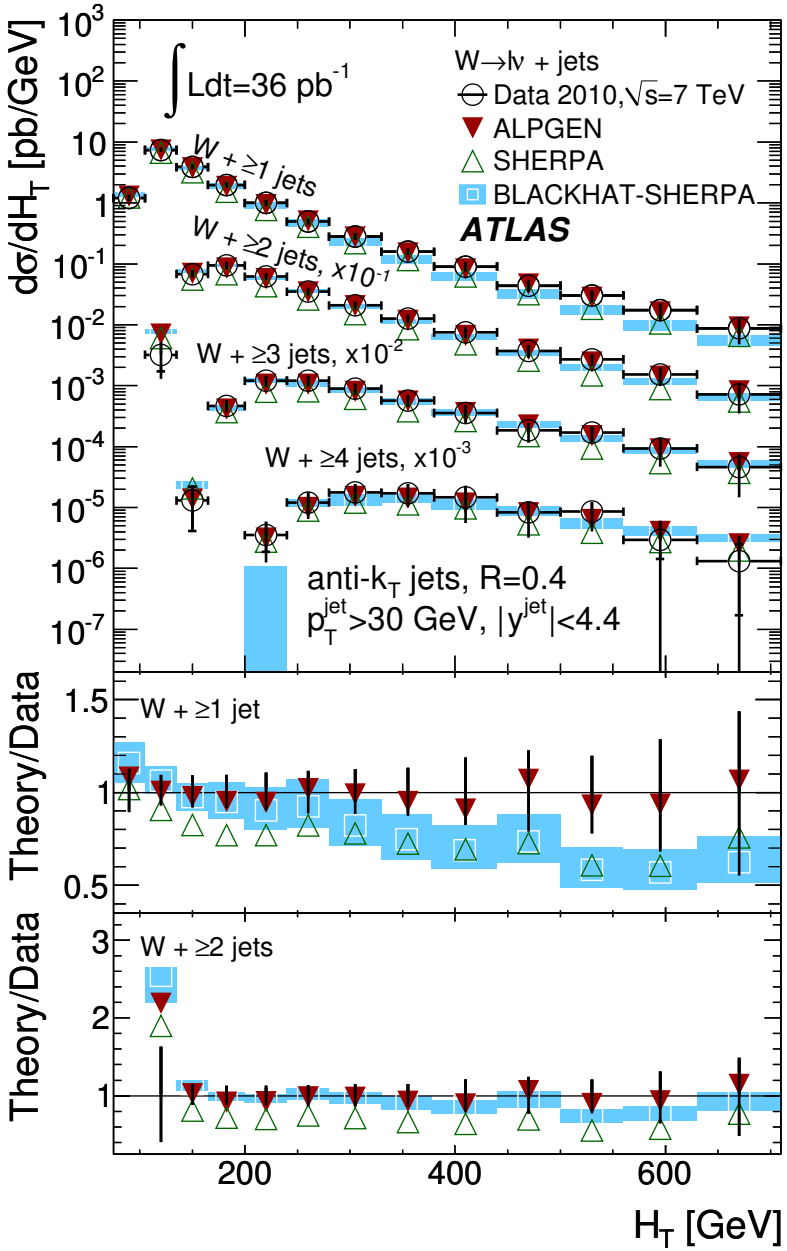

Phys. Rev. D85 (2012) 092002



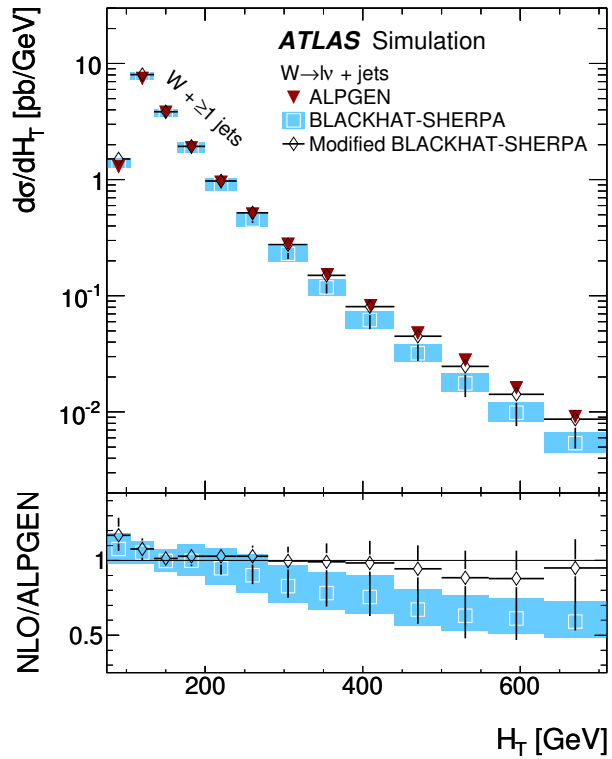

ALPGEN interfaced to HERWIG PS, SHERPA v1.3.1
BLACKHAT+SHERPA using CTEQ6.6M, scale $\mu_F = \mu_R = H_T/2$

- Systematic uncertainty dominated by multijet background uncertainty
- Multiplicity shows good agreement with ALPGEN and BLACKHAT+SHERPA
- Reasonable agreement with SHERPA




$$H_{\mathrm{T}} = E_{\mathrm{T}}^{\mathrm{miss}} + \sum_{\ell,\mathrm{jet}} |p_{\mathrm{T}}|$$

- Commonly used for renormalisation and factorisation scales ($H_{\mathrm{T}}/2$)
- Using exclusive sums (arXiv:1203.6803) improves BLACKHAT+SHERPA prediction:



# $Z$ + jets

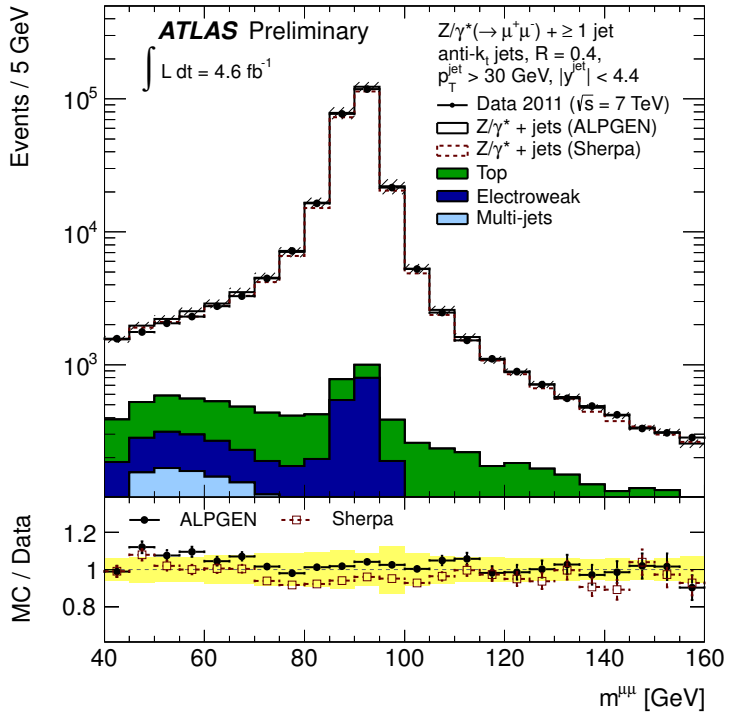
- Updated result using 4.6 fb$^{-1}$ of data at $\sqrt{s} = 7$ TeV recorded in 2011
- Extending previous measurement to larger multiplicities and higher jet $p_T$
- Comparing to BLACKHAT+SHERPA $Z$+3/4 jet predictions:
  - Phys.Rev. D82 (2010) 074002
  - Phys.Rev. D85 (2012) 031501

Lepton selection:

- $p_{T,\ell} > 20$ GeV
- $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$
- $|\eta_\mu| < 2.4$
- $\Delta R^{\ell\ell} > 0.2$ and $66 < m^{\ell\ell} < 116$ GeV

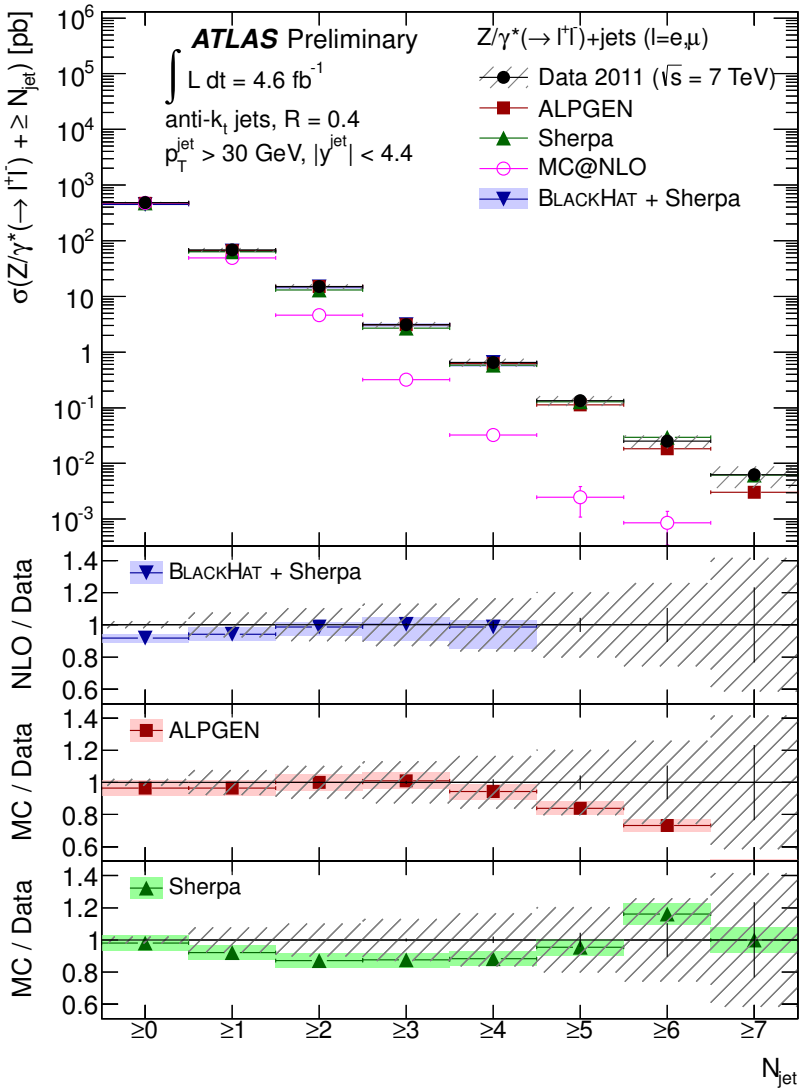
Jet selection:

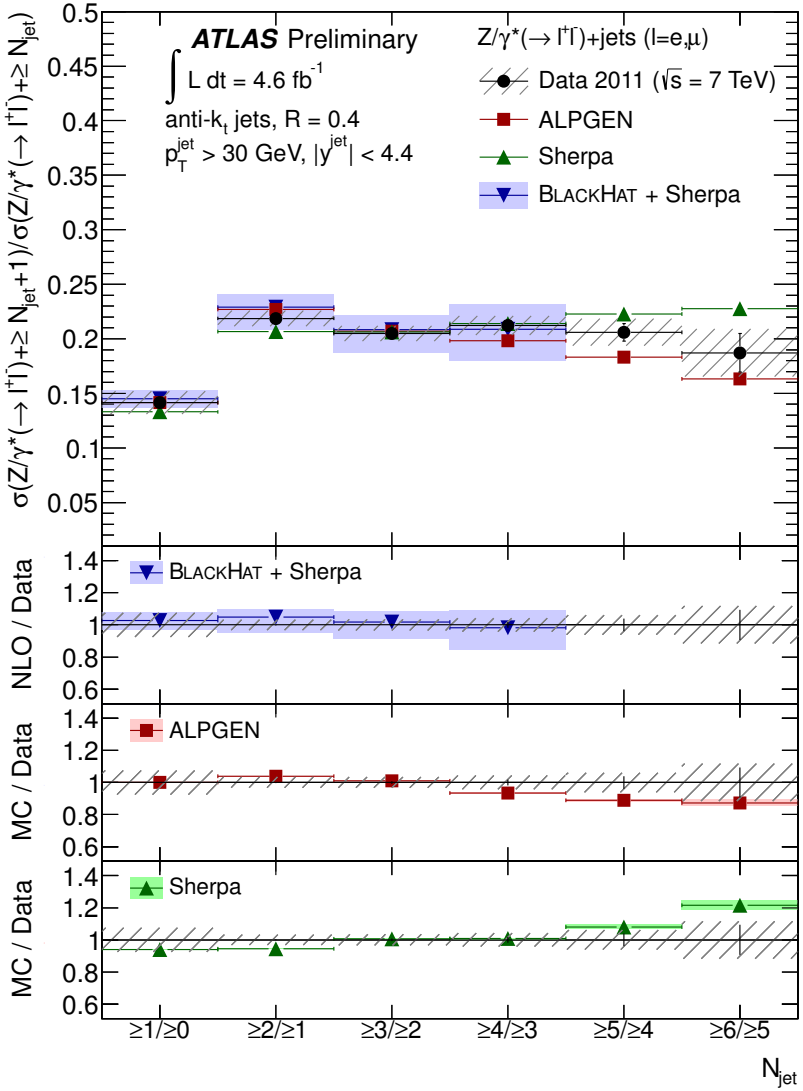
- $p_T > 30$ GeV
- $|y| < 4.4$ and $\Delta R^{\ell j} > 0.5$




MC@NLO using HERWIG PS, SHERPA v1.4.1
PDFs CT10, $\mu_F = \mu_R = H_T/2$

To be submitted to JHEP



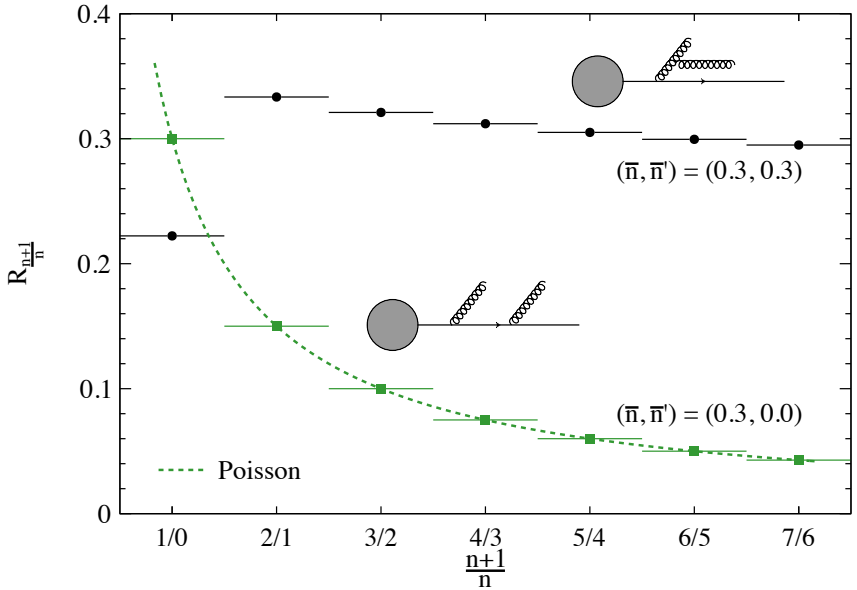




- Dominant systematic uncertainty for $Z$ + jets is the jet energy scale and resolution
- MC@NLO parton shower underestimates additional jet emission by a factor of two

# Jet ratio scaling patterns

Gerwick et al., JHEP 1210 (2012) 162

- Jet multiplicity ratio's are expected to follow one of two benchmark patterns
- Scaling can be used to extrapolate the jet rate to higher multiplicities



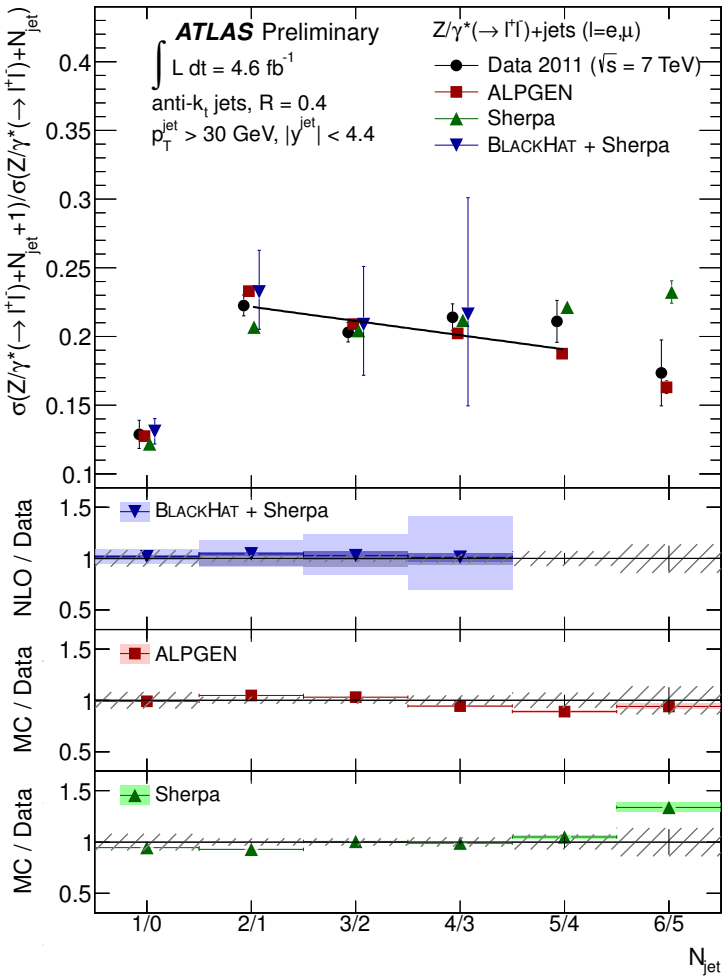

## Staircase scaling

- Ratio $R_{(n+1)/n} = R = \text{const.}$
- Jet rate $\sigma_n \sim \sigma_0 R^n$
- Inclusive and exclusive ratio scale in the same way
- Expected in the absence of major kinematic cuts

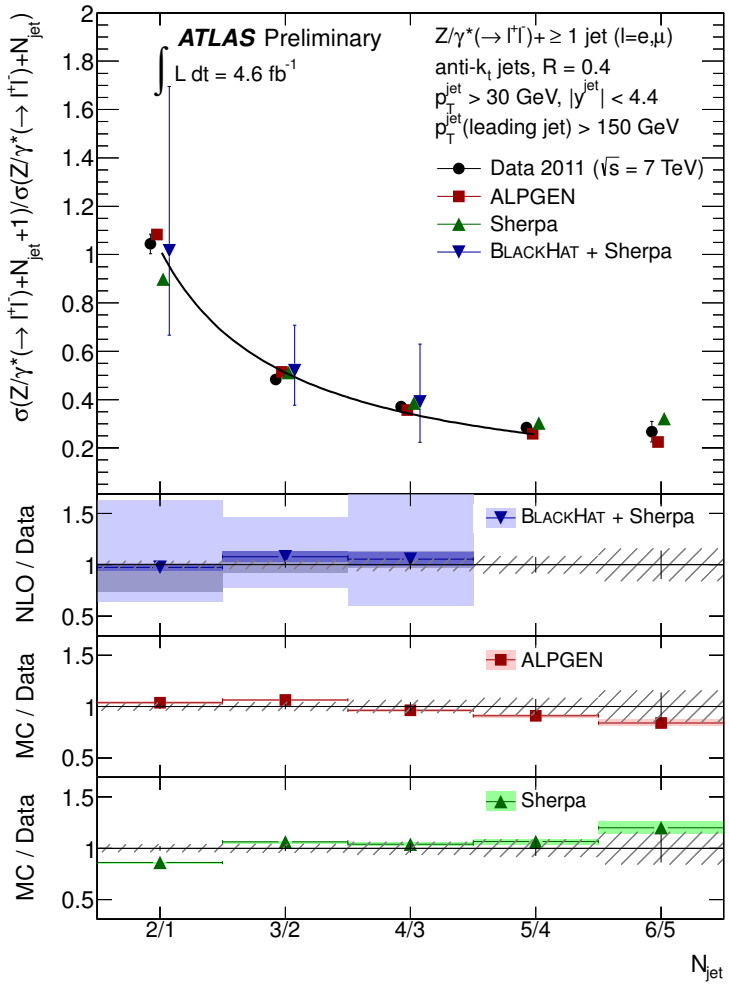
## Poisson scaling

- Ratio $R_{(n+1)/n} = \frac{\bar{n}}{n+1}$
- Jet rate $\sigma_n \sim \frac{\bar{n}^n e^{-\bar{n}}}{n!}$
- Expected when jet acceptance cut much larger than hard process scale

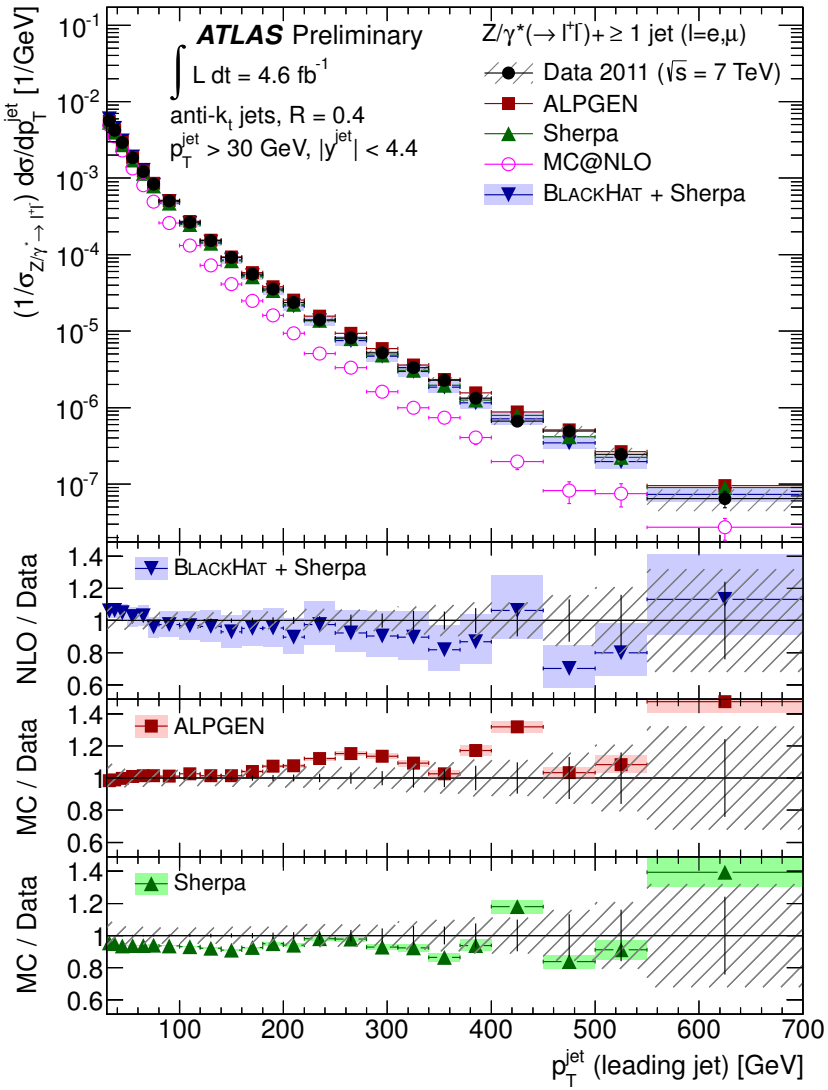
$p_T > 30$ GeV

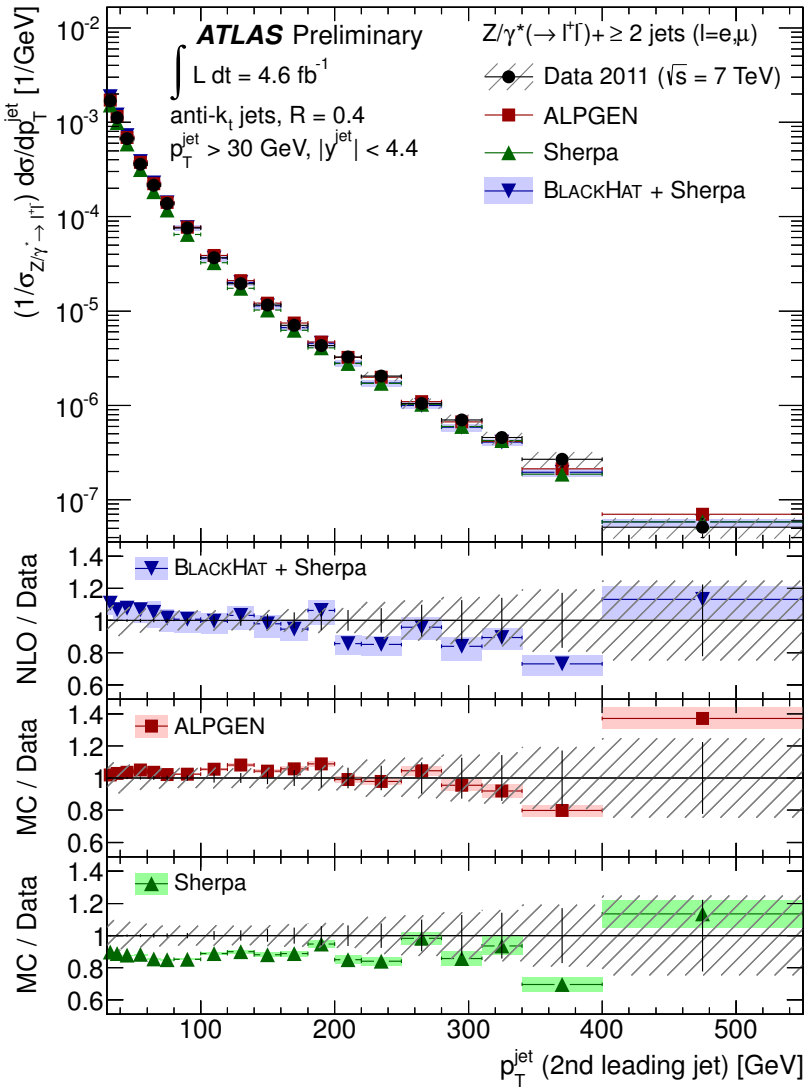



$p_{T,\text{leading}} > 150$ GeV

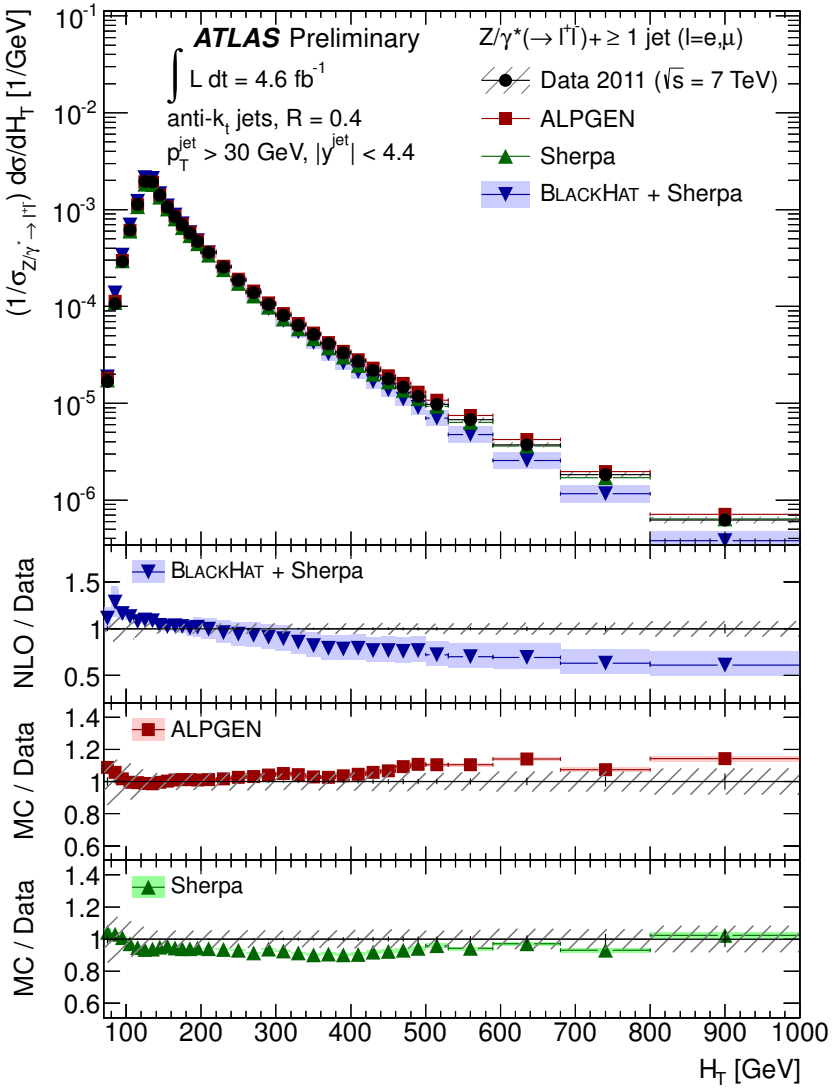


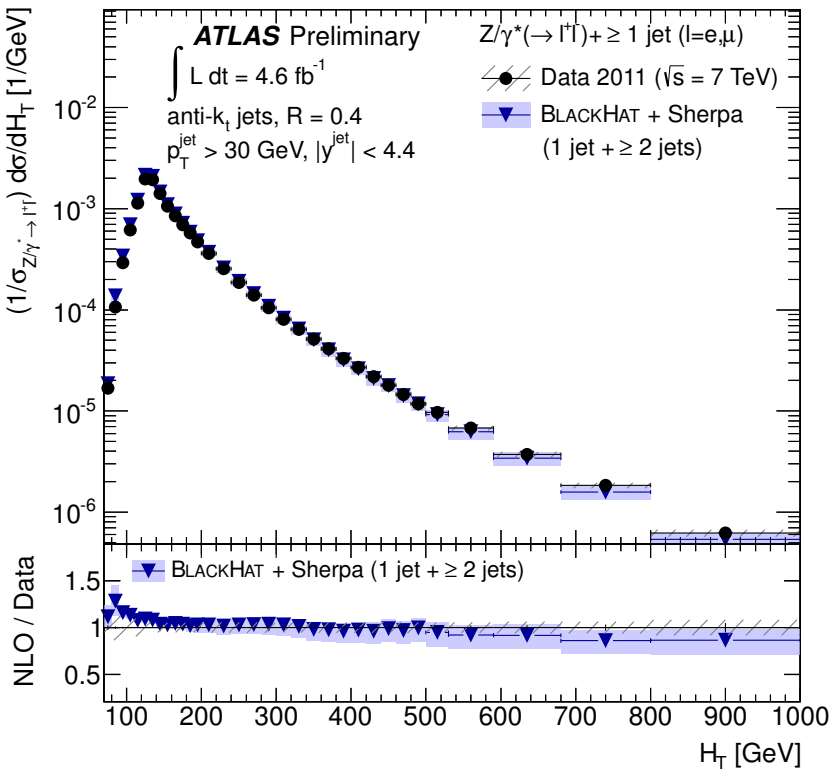

- Scale uncertainty shown:
  - No scale uncertainty applied (dark shaded)
  - Correlated between multiplicity bins (medium shaded)
  - Uncorrelated (light), following the prescription of Phys.Rev. D85 (2012) 034011



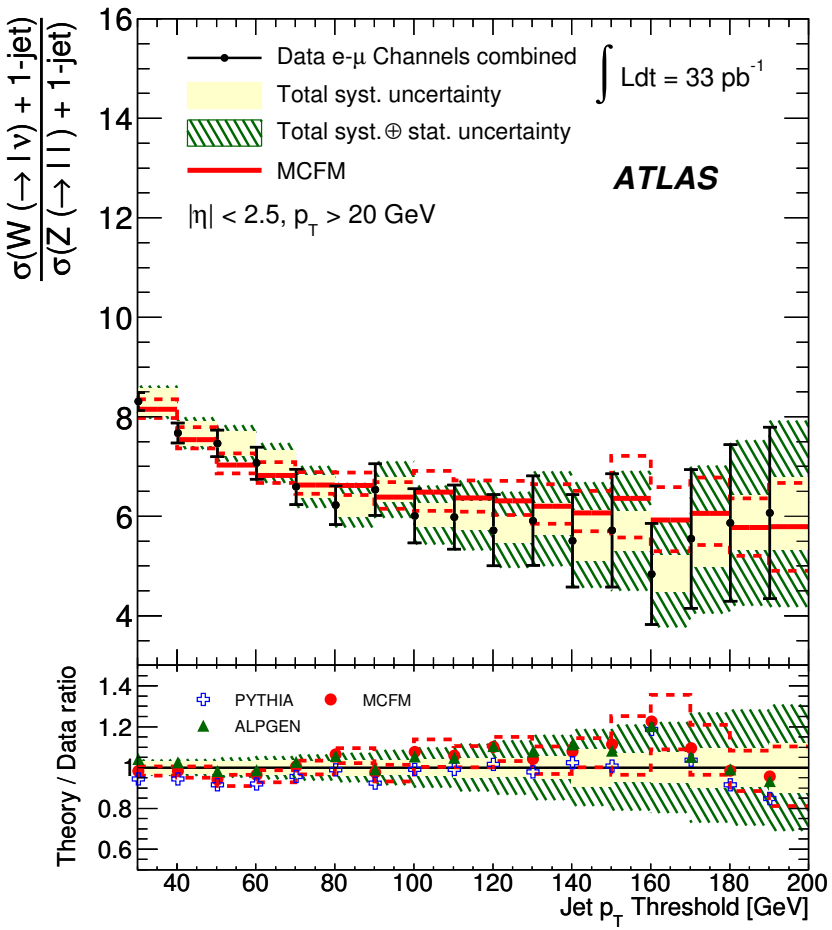

- For the leading jet, data precision is now better than the theory uncertainty
- ALPGEN predicts a too hard leading jet $p_T$ spectrum, $2^{nd}$–$4^{th}$ jet consistent with data
- SHERPA shows an offset of 5–15% compared to data




- BLACKHAT+SHERPA deviates increasingly for large values of $H_T$
- The exclusive sum of $Z$ + 1 jet and $Z$ + $\geq$2 jets is consistent with data

# Ratio of $W$ + 1 jet and $Z$ + 1 jet




(MCFM with CTEQ6.6M PDFs, $\mu_{F/R} = H_T/2$)

- Ratio $\frac{\sigma(W+1j)}{\sigma(Z+1j)}$ measured as a function of the jet $p_T$ threshold
- $71 < m_{\ell\ell} < 111$ GeV and $|\eta_{\text{jet}}| < 2.8$
- Combination of the $e$ and $\mu$ channels in the fiducial volume of the detector

- Ratio results in cancellation of many systematic uncertainties
- Remaining systematic uncertainty dominated by the boson reconstruction
- For jet $p_T$ thresholds $> 50$ GeV the statistical uncertainty dominates

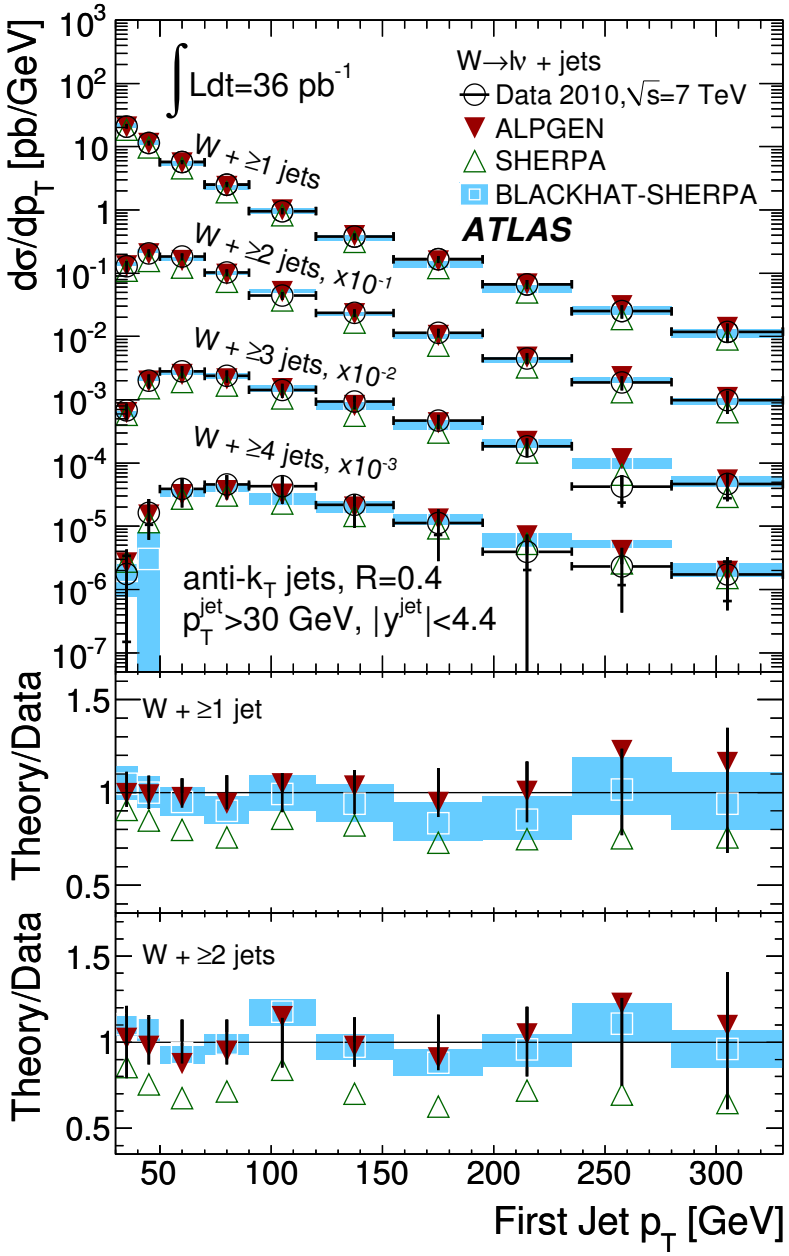
$$R_{\text{jet}}(e) = 8.73 \pm 0.30\,(\text{stat}) \pm 0.40\,(\text{syst})$$
$$R_{\text{jet}}(\mu) = 8.49 \pm 0.23\,(\text{stat}) \pm 0.33\,(\text{syst})$$

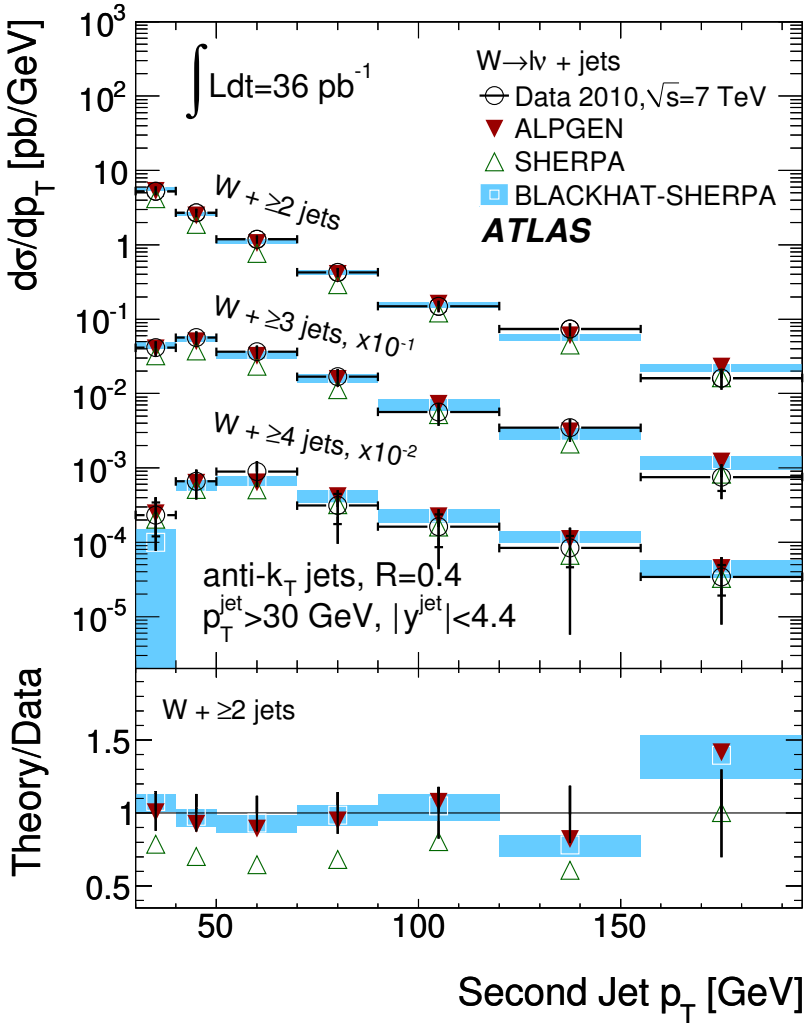
Phys. Lett. B708 (2012) 221-240

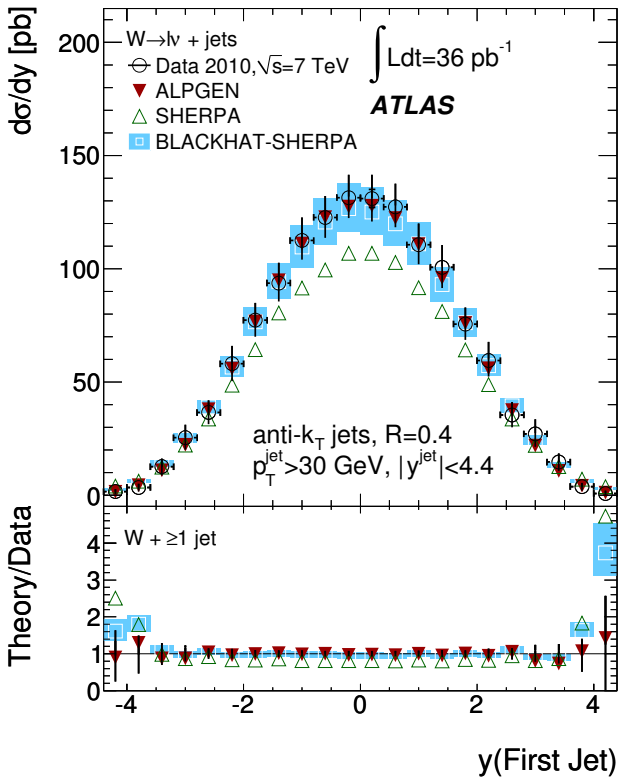
# Conclusions

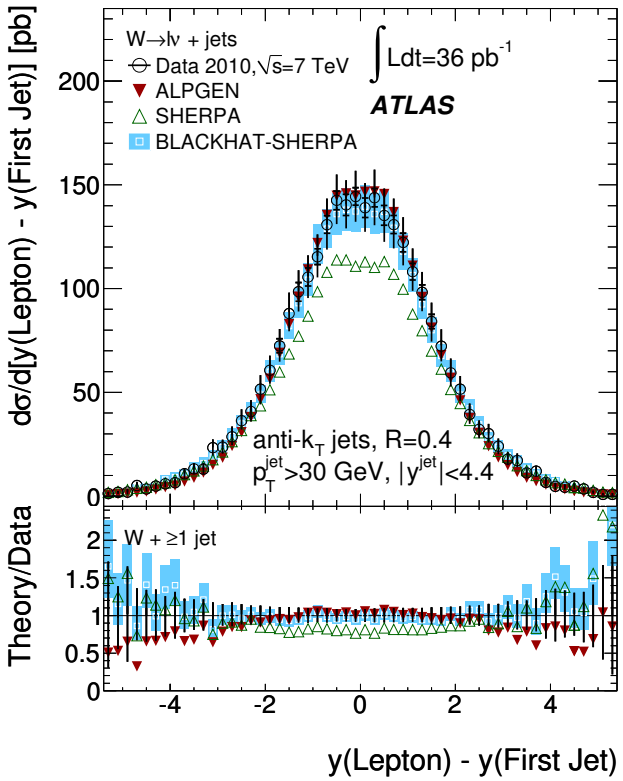
- ATLAS has performed a wide range of $W/Z$ + jets cross section measurements at $\sqrt{s} = 7$ TeV
- The 2011 data will allow these measurements to be extended to higher jet momenta and multiplicities, as was shown today for the $Z$ + jets cross section
- Calculations based on NLO matrix elements are generally in good agreement, but deviations are observed for large values of $H_T$ and in some of the jet kinematic variables
- MC@NLO fails to model higher jet multiplicities and leading jet momentum well
- For exclusive jet multiplicities the transition from staircase to Poisson scaling is observed in data
- The ratio of $W$ + 1 jet to $Z$ + 1 jet is modelled well by all generators

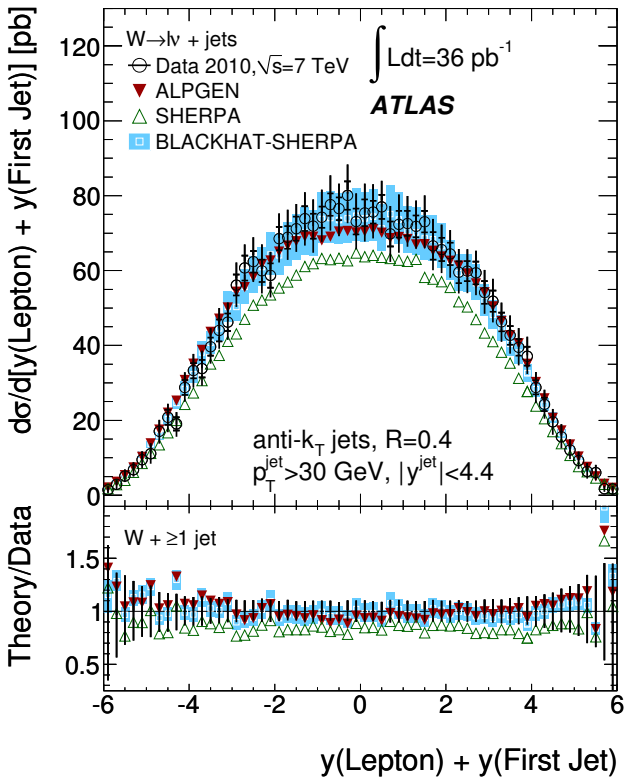
# Backup slides


∫Ldt=36 pb-1
W→lν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
W + ≥1 jets
W + ≥2 jets, x10-1
W + ≥3 jets, x10-2
W + ≥4 jets, x10-3
anti-kT jets, R=0.4
pTjet>30 GeV, |yjet|<4.4
dσ/dpT [pb/GeV]
Theory/Data
W + ≥1 jet
W + ≥2 jets
First Jet pT [GeV]


∫Ldt=36 pb-1
W→lν + jets
Data 2010,√s=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
ATLAS
W + ≥2 jets
W + ≥3 jets, x10-1
W + ≥4 jets, x10-2
anti-kT jets, R=0.4
pTjet>30 GeV, |yjet|<4.4
dσ/dpT [pb/GeV]
Theory/Data
W + ≥2 jets
Second Jet pT [GeV]

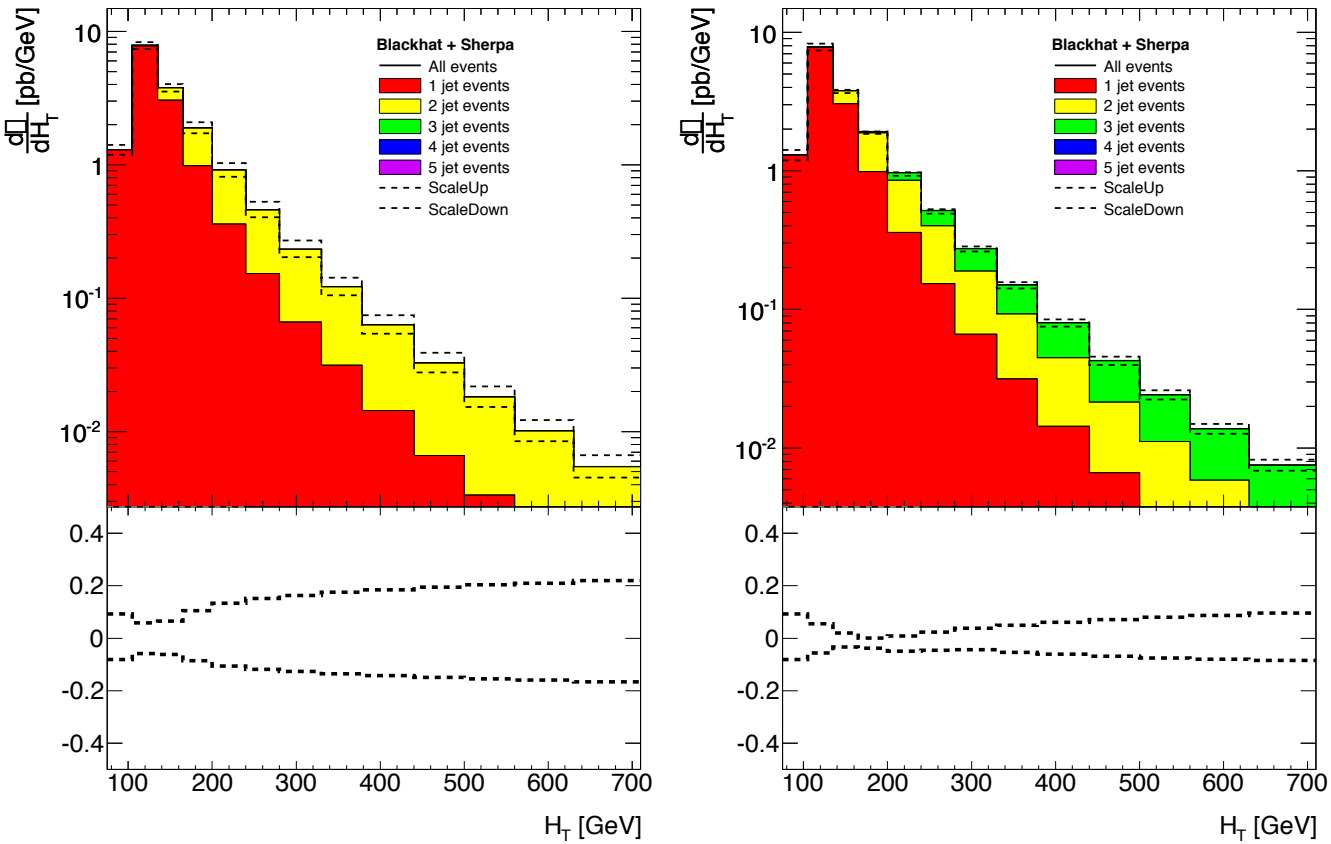


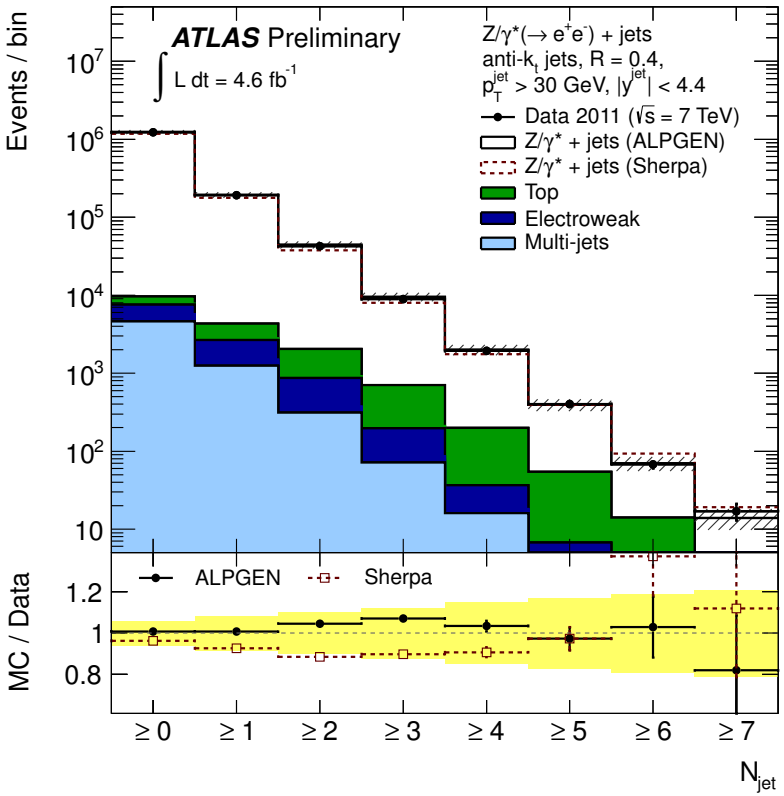

- Rapidity distributions sensitive to the PDF
- BLACKHAT+SHERPA and SHERPA using CTEQ6.6M
- ALPGEN using CTEQ6L1

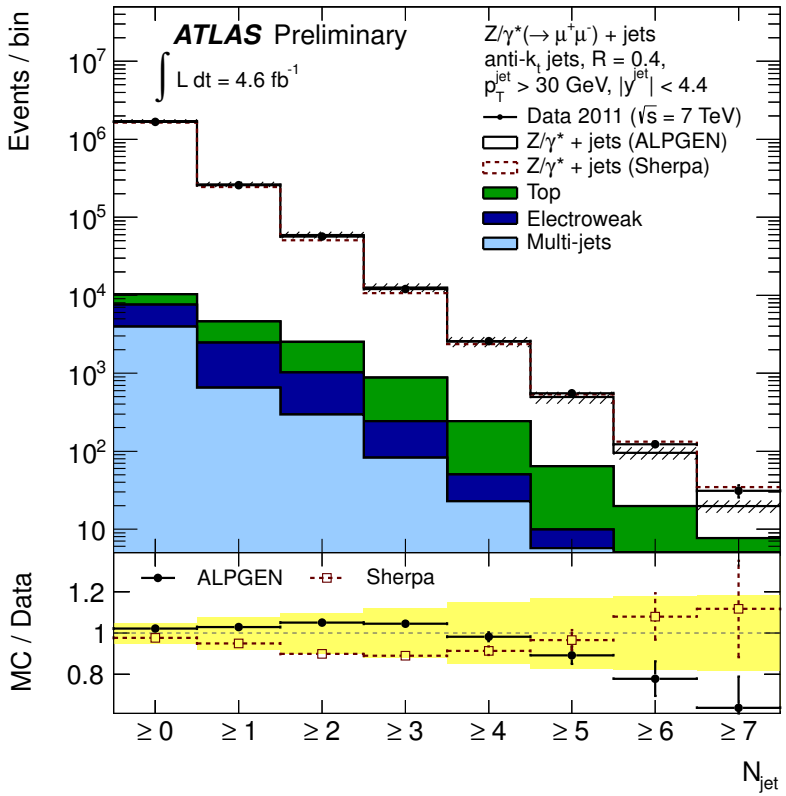
# Exclusive sums




- $W + \geq n$ jets prediction includes events with $n$ and $n + 1$ partons
- Exclusive sums technique combines multiple predictions, counting the number of jets to remove overlap

arXiv:1203.6803


ATLAS Preliminary
∫ L dt = 4.6 fb-1
Z/γ*(→ e+e-) + jets
anti-kt jets, R = 0.4,
pTjet > 30 GeV, |yjet| < 4.4
Data 2011 (√s = 7 TeV)
Z/γ* + jets (ALPGEN)
Z/γ* + jets (Sherpa)
Top
Electroweak
Multi-jets
Events / bin
ALPGEN
Sherpa
MC / Data
≥ 0
≥ 1
≥ 2
≥ 3
≥ 4
≥ 5
≥ 6
≥ 7
Njet


ATLAS Preliminary
∫ L dt = 4.6 fb-1
Z/γ*(→ μ+μ-) + jets
anti-kt jets, R = 0.4,
pTjet > 30 GeV, |yjet| < 4.4
Data 2011 (√s = 7 TeV)
Z/γ* + jets (ALPGEN)
Z/γ* + jets (Sherpa)
Top
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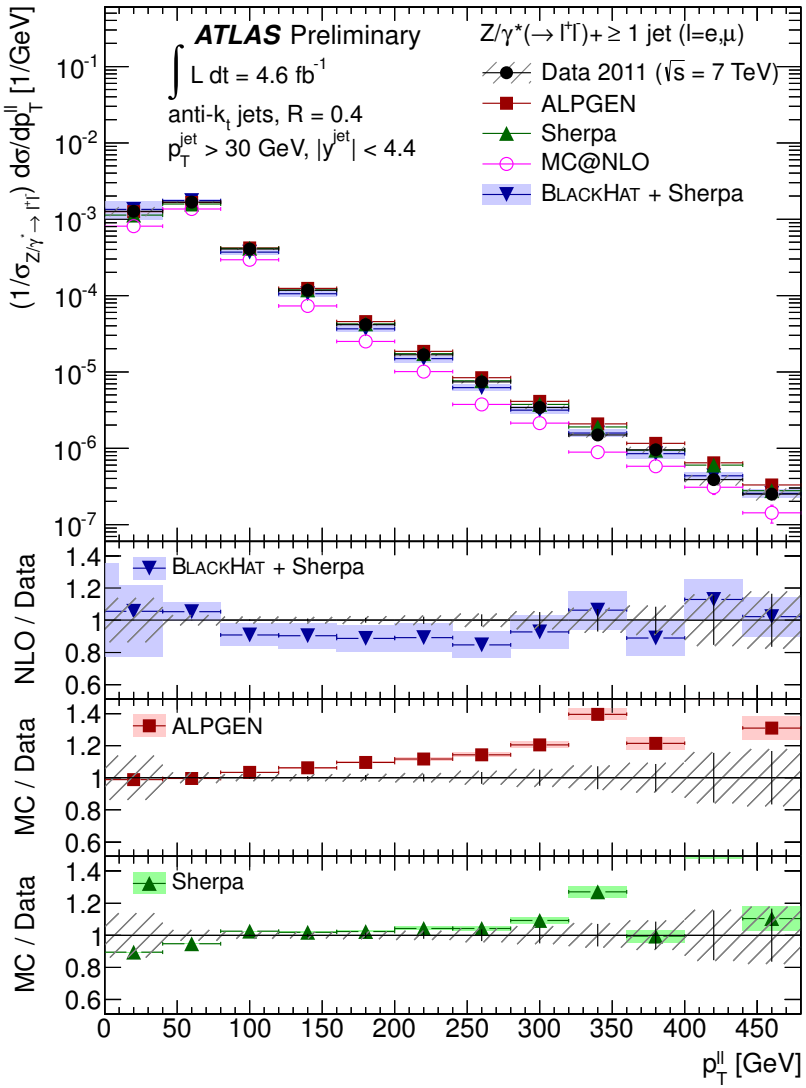
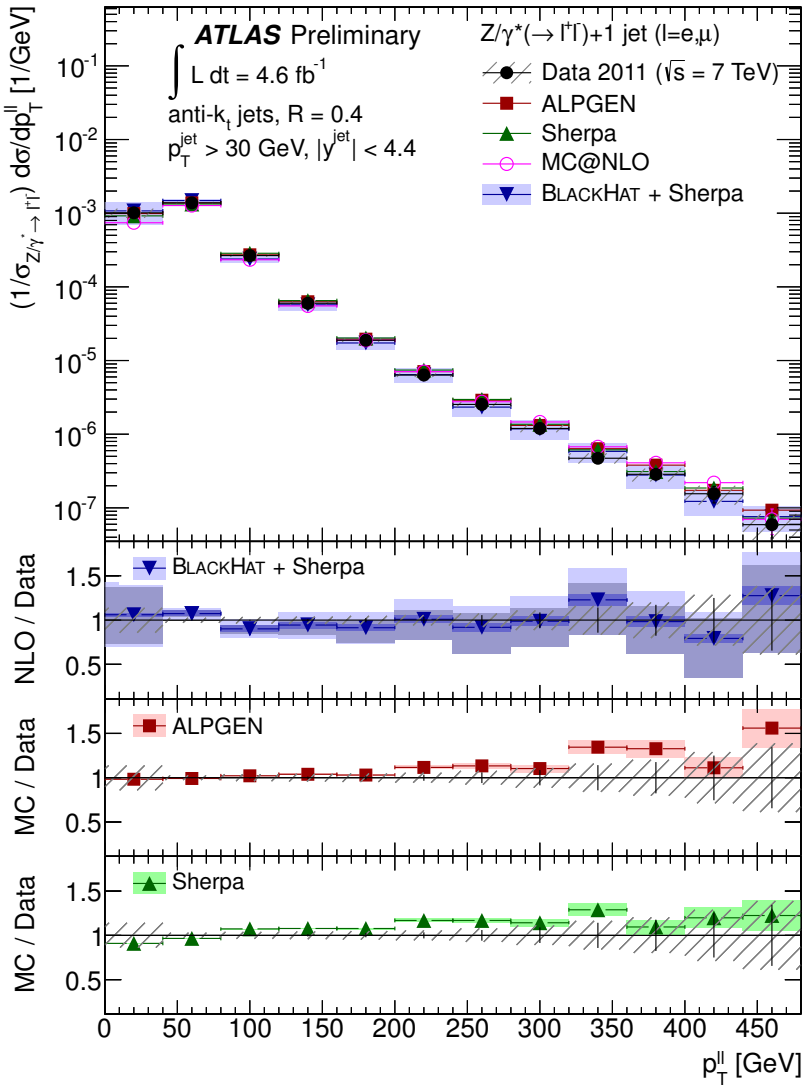
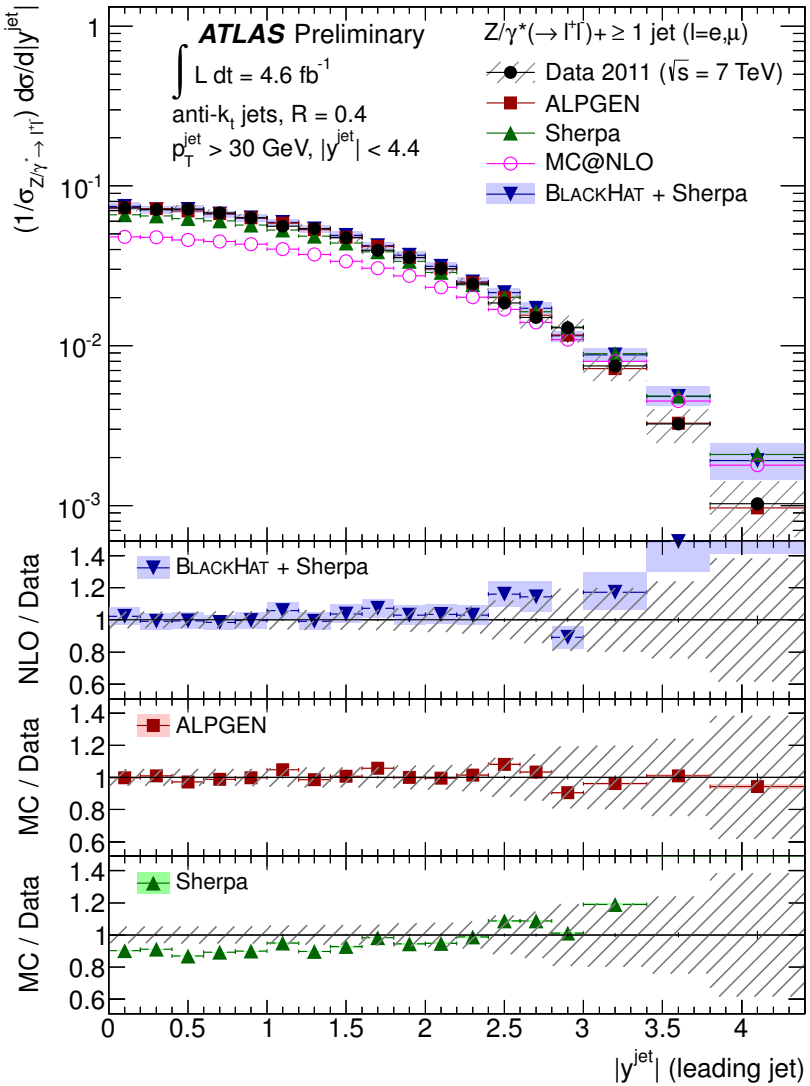
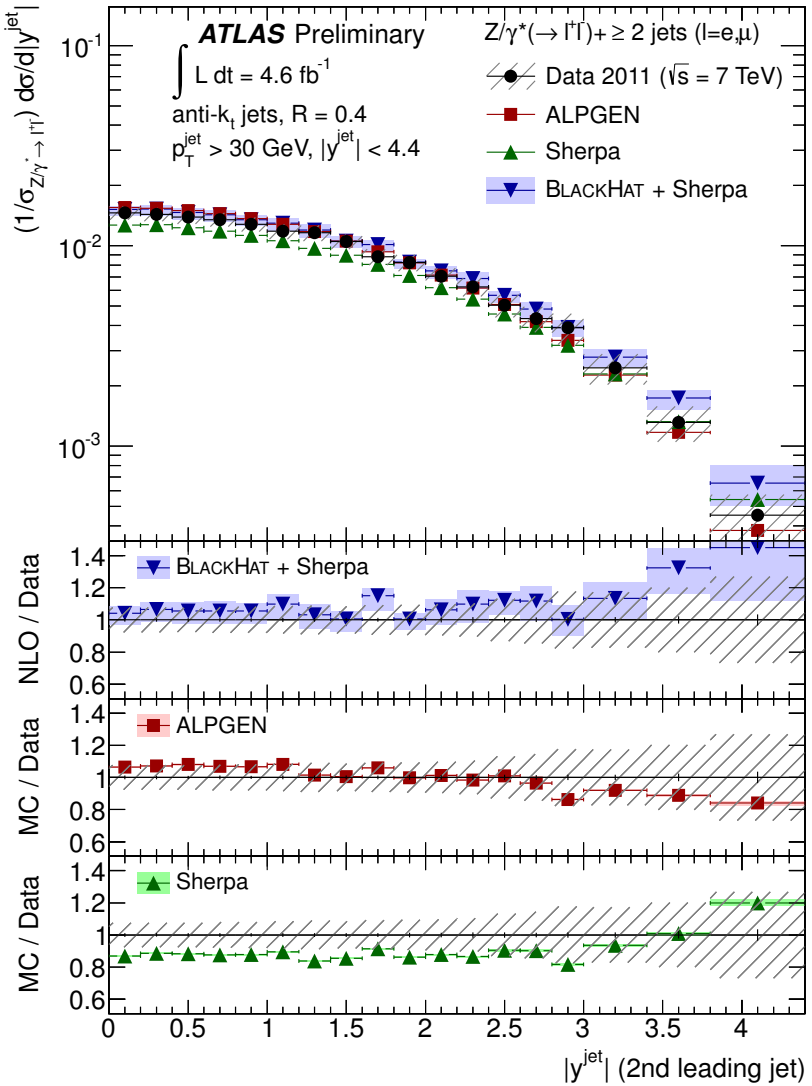
Events / bin
ALPGEN
Sherpa
MC / Data
≥ 0
≥ 1
≥ 2
≥ 3
≥ 4
≥ 5
≥ 6
≥ 7
Njet

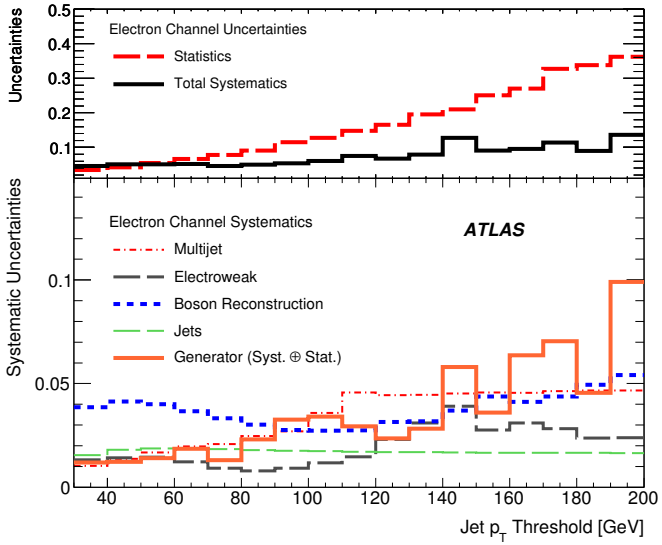


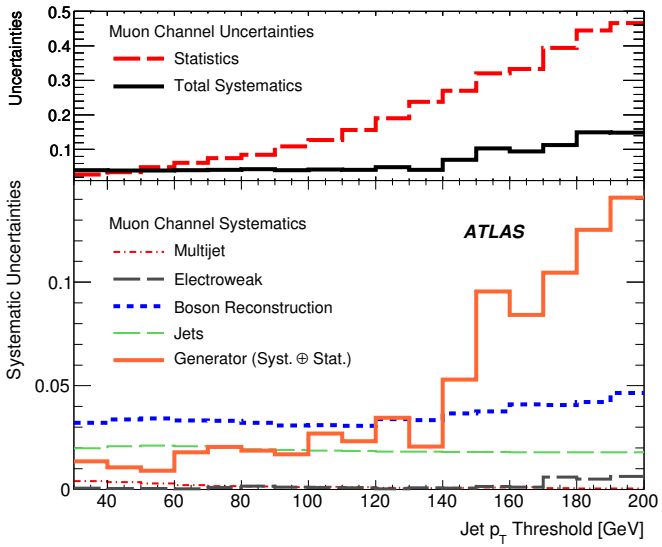



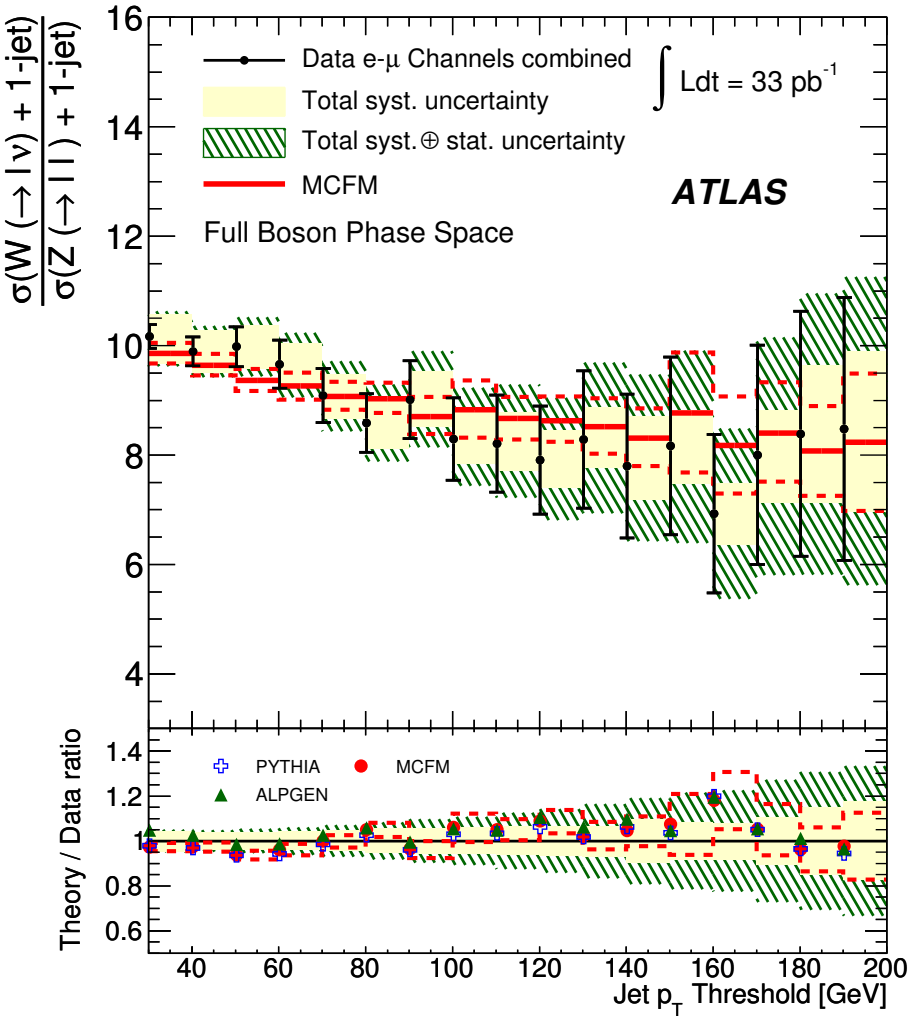

- Both ALPGEN and SHERPA predict a too hard $p_{\mathrm{T}}^{Z}$ spectrum
- BLACKHAT+SHERPA inclusive prediction is too soft due to missing higher jet multiplicities


ATLAS Preliminary
∫ L dt = 4.6 fb-1
anti-kt jets, R = 0.4
pTjet > 30 GeV, |yjet| < 4.4
Z/γ*(→ l+l-)+ ≥ 1 jet (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
Sherpa
MC@NLO
BLACKHAT + Sherpa
(1/σZ/γ*→l+l-) dσ/d|yjet|
NLO / Data
MC / Data
|yjet| (leading jet)


ATLAS Preliminary
∫ L dt = 4.6 fb-1
anti-kt jets, R = 0.4
pTjet > 30 GeV, |yjet| < 4.4
Z/γ*(→ l+l-)+ ≥ 2 jets (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
Sherpa
BLACKHAT + Sherpa
(1/σZ/γ*→l+l-) dσ/d|yjet|
NLO / Data
MC / Data
|yjet| (2nd leading jet)


Uncertainties
Electron Channel Uncertainties
Statistics
Total Systematics
Systematic Uncertainties
Electron Channel Systematics
ATLAS
Multijet
Electroweak
Boson Reconstruction
Jets
Generator (Syst. ⊕ Stat.)
Jet p_T Threshold [GeV]


Uncertainties
Muon Channel Uncertainties
Statistics
Total Systematics
Systematic Uncertainties
Muon Channel Systematics
ATLAS
Multijet
Electroweak
Boson Reconstruction
Jets
Generator (Syst. ⊕ Stat.)
Jet p_T Threshold [GeV]


σ(W (→ lν) + 1-jet) / σ(Z (→ ll) + 1-jet)
Data e-μ Channels combined
Total syst. uncertainty
Total syst. ⊕ stat. uncertainty
MCFM
Full Boson Phase Space
∫ Ldt = 33 pb^-1
ATLAS
Theory / Data ratio
PYTHIA
MCFM
ALPGEN
Jet p_T Threshold [GeV]