GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Vector-boson production plus N-jets

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PHYSICS AT THE TERA SCALE Helmholtz Alliance

FSP 101 ATLAS

Bundesministerium für Bildung und Forschung

V+jets in ATLAS

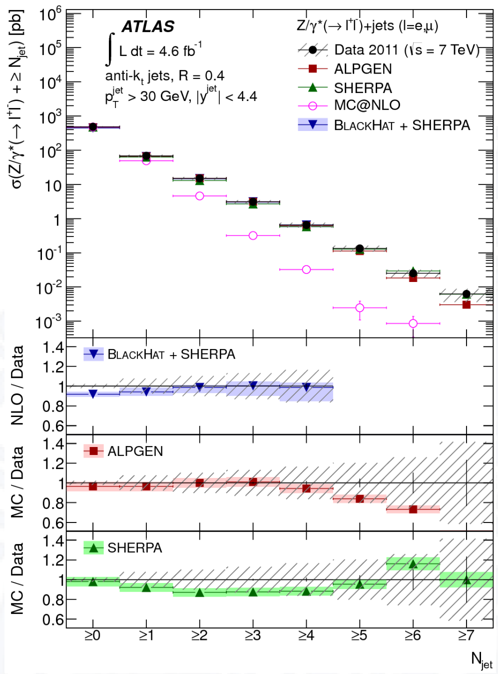
V+jets

Proton structure (sea quark (s,b,c)), gluon

Sensitive to α_s

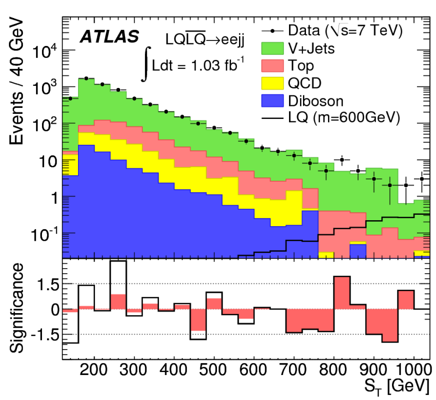
Validation of MC generators (ALPGEN, SHERPA, ...)

Precision test of fixed-order NLO pQCD predictions

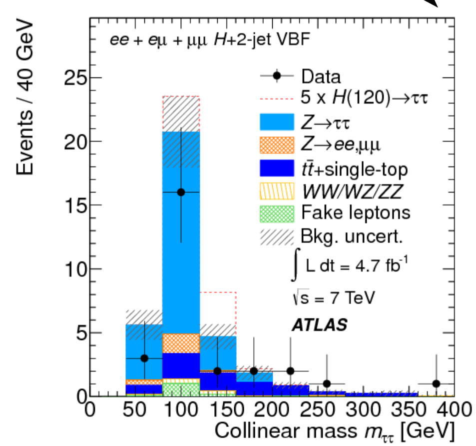


JHEP 07 (2013) 032

Searches for new physics (SUSY, excited quarks, leptoquarks, ...



Phys. Lett. B709 (2012) 158-176



JHEP 1209 (2012) 070

Background for studies of the Higgs boson

V+jets in ATLAS

		ATLAS public results, $\sqrt{s}$=7 TeV
Z + jets	4.6 fb^{-1}	JHEP 07 (2013) 032
W + jets	36 pb^{-1}	Phys. Rev. D85 (2012) 092002
R jets	36 pb^{-1}	Phys. Lett. B708 (2012) 221-224
Z + b jets	36 pb^{-1}	Phys. Lett. B706 (2012) 295-313
W + b jets	4.6 fb^{-1}	JHEP 06 (2013) 084
W + c jets	4.6 fb^{-1}	ATLAS-CONF-2013-0045
W + 2 jets DPI	36 pb^{-1}	New J. Phys. 15 (2013) 033038

Z + light jets

Analysis Strategy

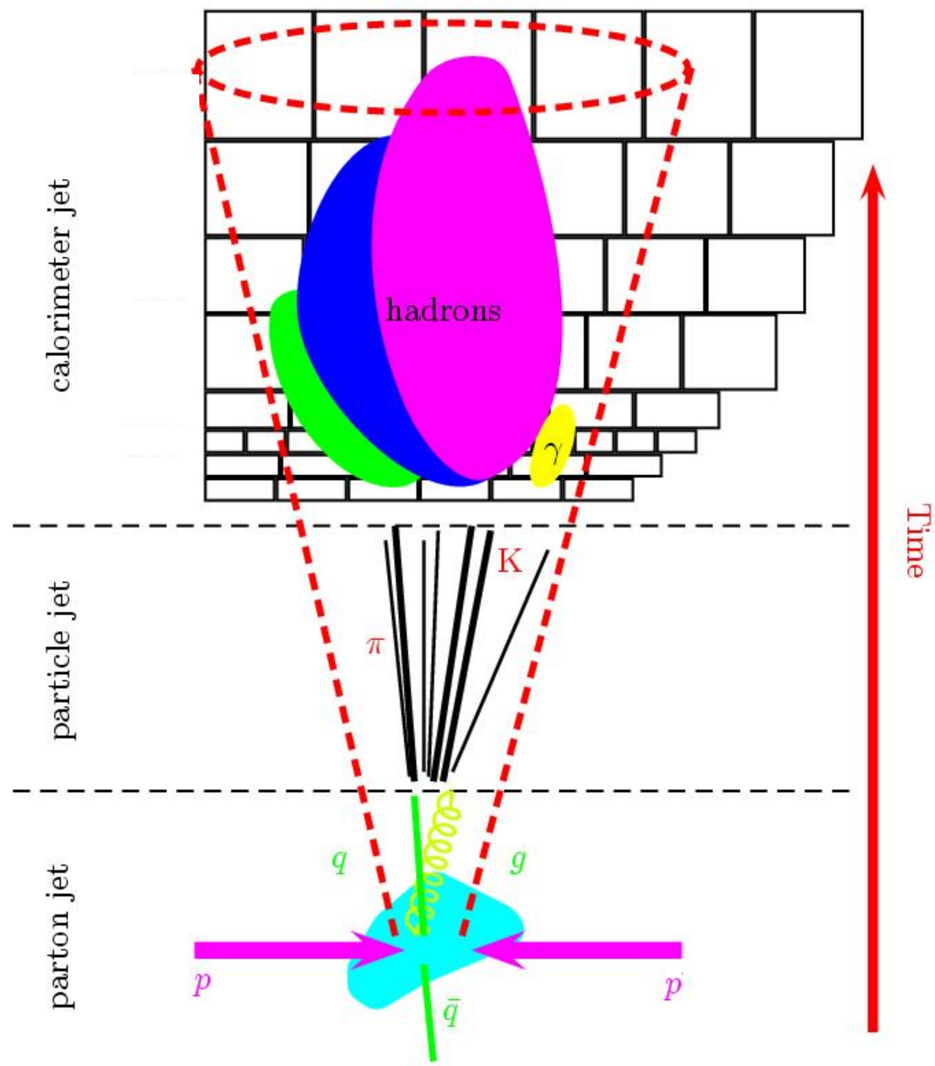
Detector level (data)

Unfolding for detector effects

Particle level

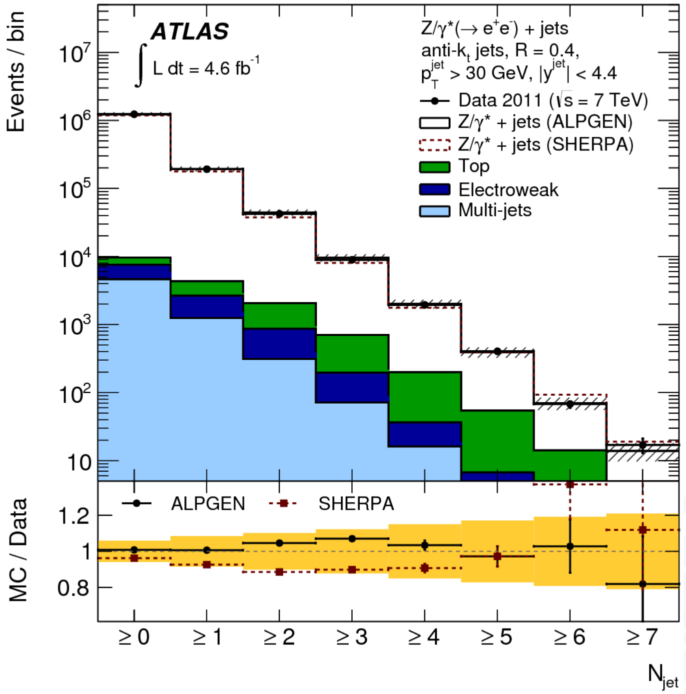
Correction for non-perturbative and QED radiation effects

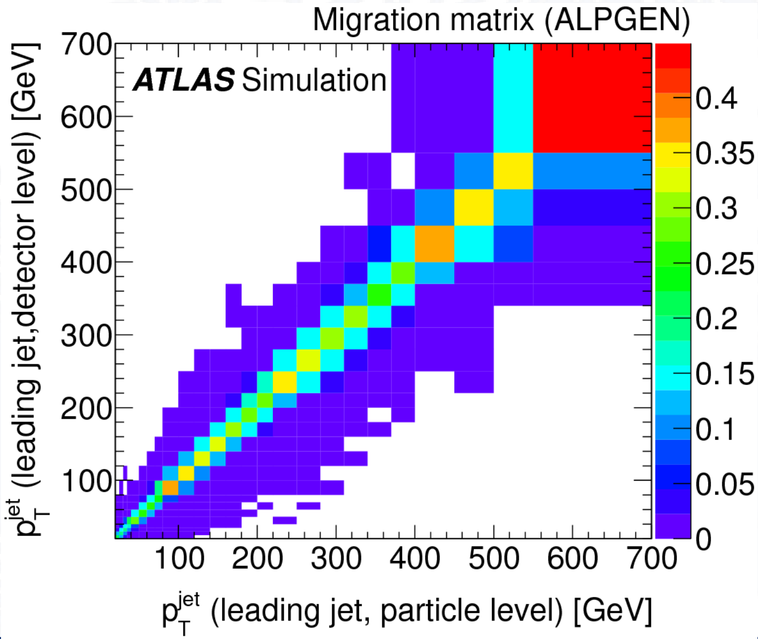
Parton level (BH+SHERPA)



Extraction of cross section

- Event selection
- Subtraction of backgrounds
  - Main backgrounds:
    - Multi-jets from data (0.4%-1.5%)
    - Ttbar from data (0.2%-26%)
    - Diboson (0.2%-1.2%)
- Unfolding method: iterative (Bayes) method (Nucl. Instrum. Meth. A 362 (1995) 487
  - Trainings sample: ALPGEN+HERWIG
- Differential measurements on dressed level separately for electron and muon channel
- For combination individual results extrapolated to common phase space region





Leptons:	pT> 20 GeV, |eta| < 2.5, add photons in ΔR<0.1
Z -Boson :	Opposite sign leptons, 66 < m(ll) < 116 GeV
Jets:	antikt, R=0.4, pT > 30 GeV, |y| < 4.4, ΔR(j,l) < 0.5

Systematic uncertainties

$Z(\to ee)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_T^{jet} (30 – 500 GeV)
Electron reconstruction	2.8%	2.8%	2.8%	2.8%	2.6-2.9%
Jet energy scale, resolution	7.4%	10.1%	13%	17%	4.3-9.0%
Backgrounds	0.26%	0.34%	0.44%	0.50%	0.21-3.2%
Unfolding	0.22%	0.94%	1.2%	1.9%	1.4-6.8%
Total	7.9%	10.5%	13%	17%	5.5-12.0%

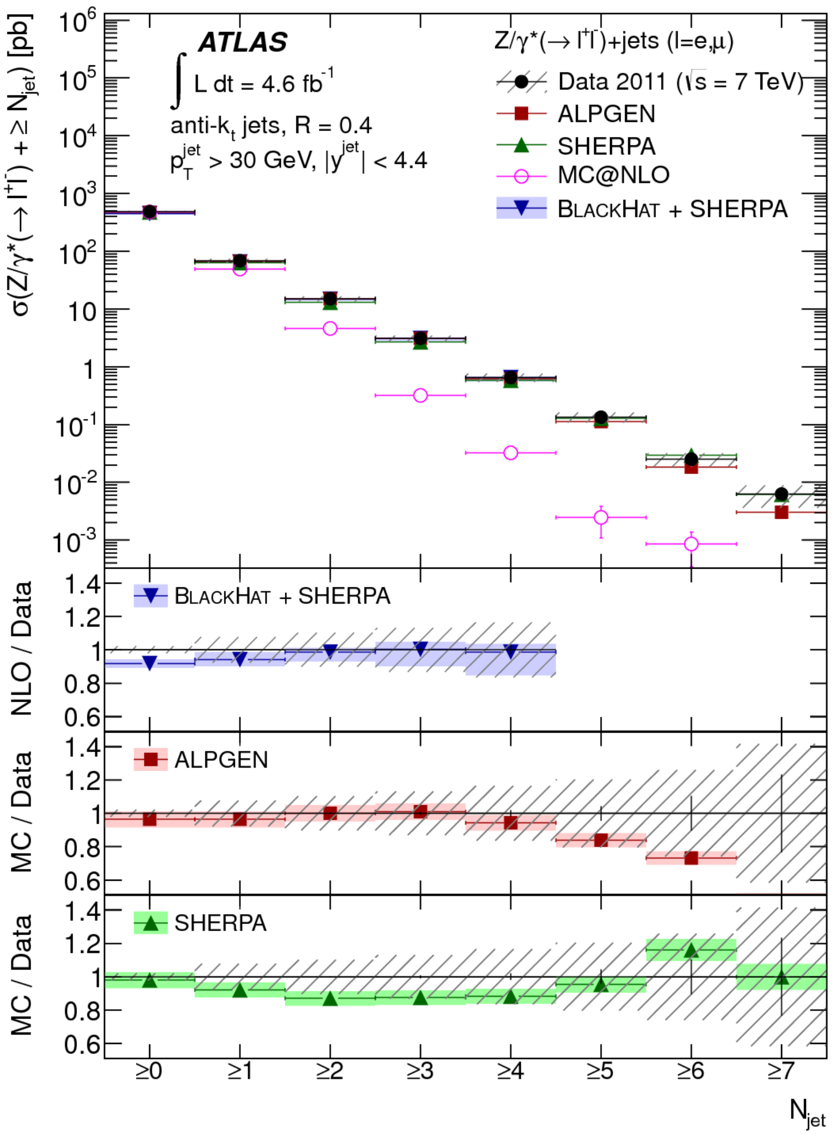
$Z(\to \mu\mu)$	≥ 1 jet	≥ 2 jets	≥ 3 jets	≥ 4 jets	p_T^{jet} (30 – 500 GeV)
Muon reconstruction	0.86 %	0.87 %	0.87 %	0.88 %	0.8 – 1.0%
Jet energy scale, resolution	7.5 %	9.9 %	13%	16%	3.2 – 8.7%
Backgrounds	0.093 %	0.20 %	0.41 %	0.66 %	0.1 – 1.9%
Unfolding	0.30 %	0.68 %	0.52 %	1.3 %	0.5 – 6.2%
Total	7.6 %	10.0 %	13 %	16 %	4.4-10.2%

JES dominant component to total uncertainty

in particular in forward region: JES uncertainty 20%-30%

JES uncertainty reduced in cross section ratios for successive multiplicities: 3-4%

Results on Particle Level



- Cross sections quoted for dressed electrons and particle level jets in fiducial acceptance region
- Unfolded data compared to:
  - BlackHat+SHERPA fixed-order NLO pQCD
  - ALPGEN+HERWIG+JIMMY (Z+0-5p), AUET2 tune, CTEQ6L PDF
  - SHERPA 1.4 MENloPS (Z+0-5p), CT10 PDF
  - MC@NLO (DY) + HERWIG AUET2 tune, CT10 PDF

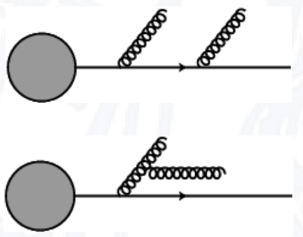
Differential cross sections normalised to inclusive cross section:
→ Cancel uncertainties on electron reconstruction and integrated luminosity

Results – Jet Multiplicity

- Motivation:
  - Test of perturbative QCD (IS/FS QCD radiation, potentially sensitive to α_s)
  - Background for studies of the Higgs boson and BSM physics (jet-binned results, jet vetos)
- Observables:
  - Inclusive jet multiplicity (less problematic from theoretical point of view)
  - Exclusive jet multiplicity (expected to follow two benchmark patterns)
  - Jet multiplicity ratios (allows more precise tests of SM)

Benchmark patterns:

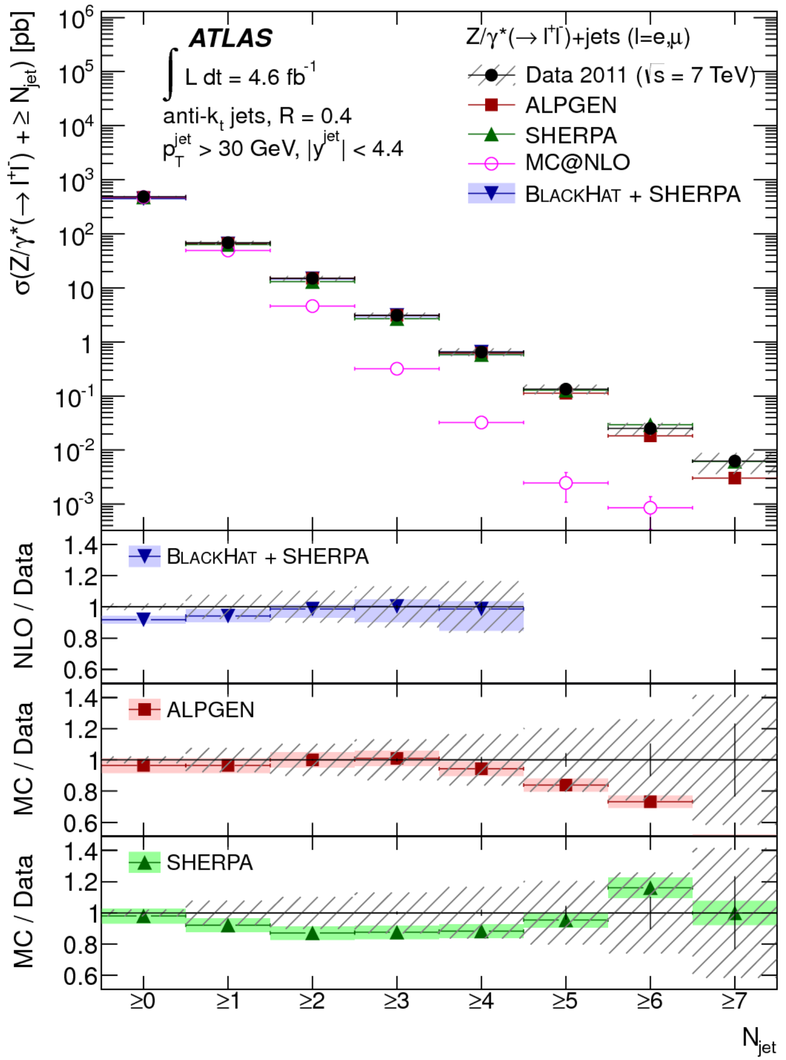
- QED: Abelian-type splittings $\rightarrow R_{(n+1)/n} \sim \frac{1}{n}$ (Poisson scaling)
- QCD: Non-Abelian splittings $\rightarrow R_{(n+1)/n} \sim const$ (staircase scaling)



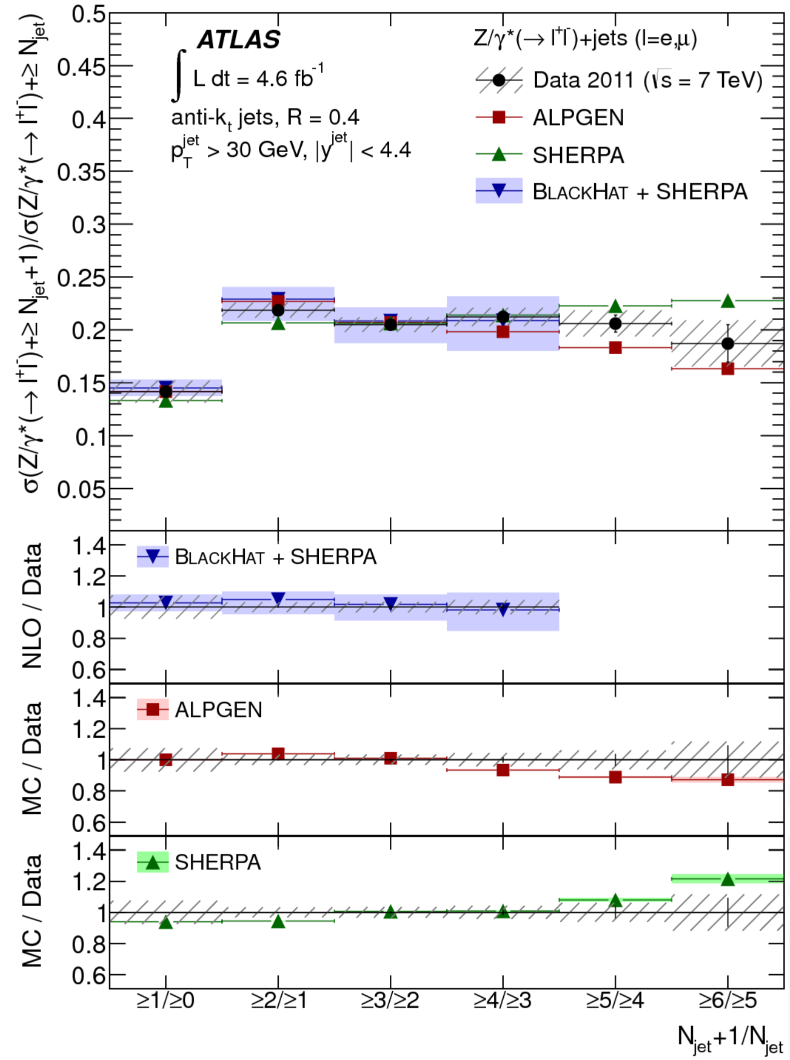
  - For large scale differences in QCD staircase scaling is expected to revert to Poisson scaling (E. Gerwick et al, JHEP 1210 (2012) 162)

Results – Inclusive Jet Multiplicity

inclusive jet multiplicity

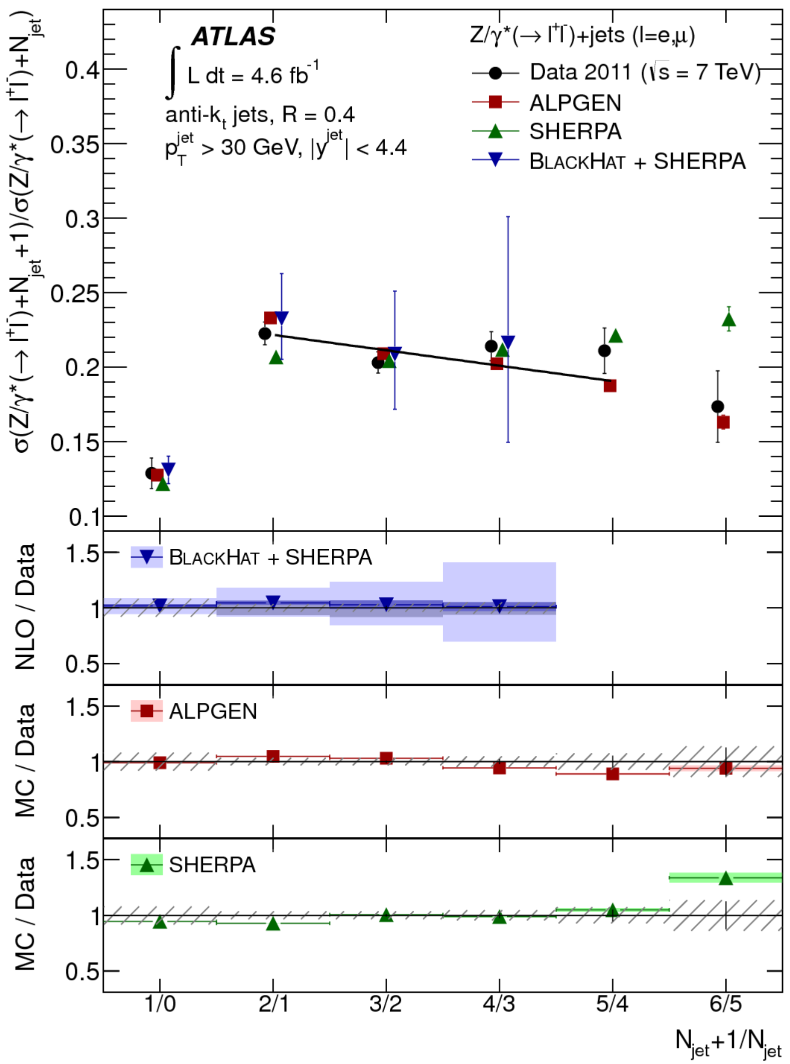


inclusive jet multiplicity ratio



- NLO pQCD, ME+PS: consistent with data
- MC@NLO: HERWIG PS fails to model jet multiplicities

Results – Exclusive Multiplicity Ratios



Inclusive scale variations, uncertainties uncorrelated wrt multiplicity

I.W.Stewart, F.J. Tackmann
Phys. Rev. D 85 (2012) 034011

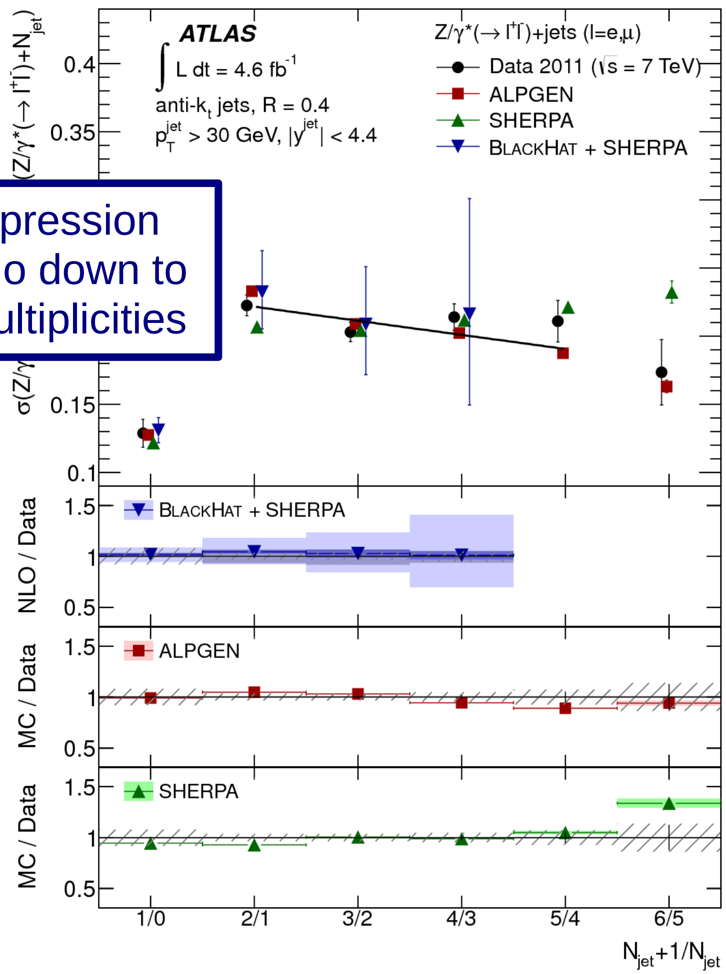
Naive scale variation, correlated uncertainties

no scale variation

- Cross section for exclusive Z+1-4 jets well modelled by fixed-order NLO pQCD

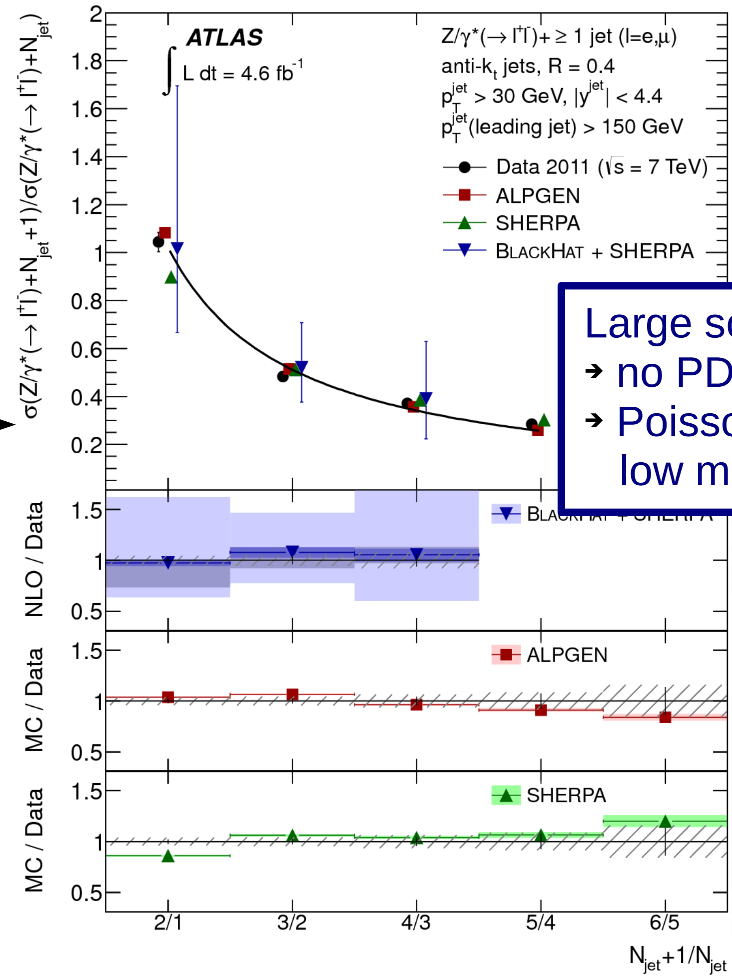
Results – Exclusive Multiplicity Ratio

p_T (leading jet) > 30 GeV



PDF suppression
→ flat ratio down to low multiplicities

p_T (leading jet) > 150 GeV



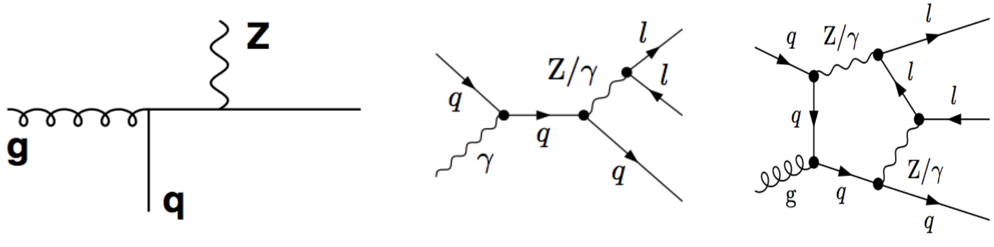
Large scale difference
→ no PDF suppression
→ Poisson scaling for low multiplicities

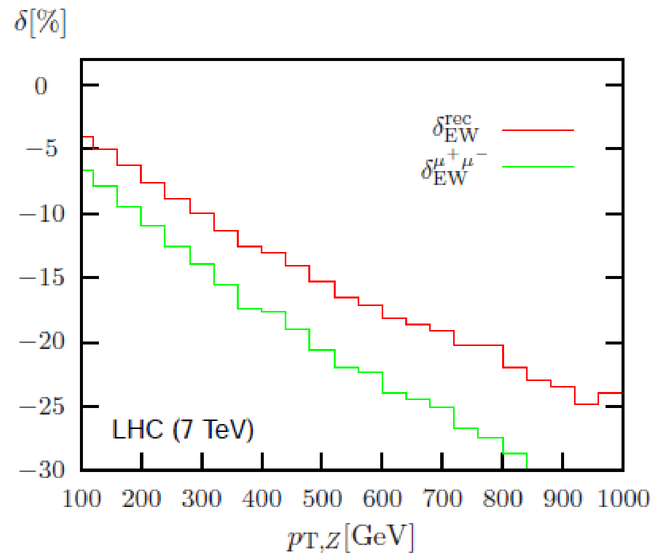
- Change of scaling pattern in general well modeled by nominal pQCD and ME+PS

Results – Transverse Momenta

- Motivation:
  - Test of limitations of ME+PS generators and fixed order pQCD in regions where large logarithmic corrections and EW NLO corrections are expected to become important

QCD higher orders EW NLO effects





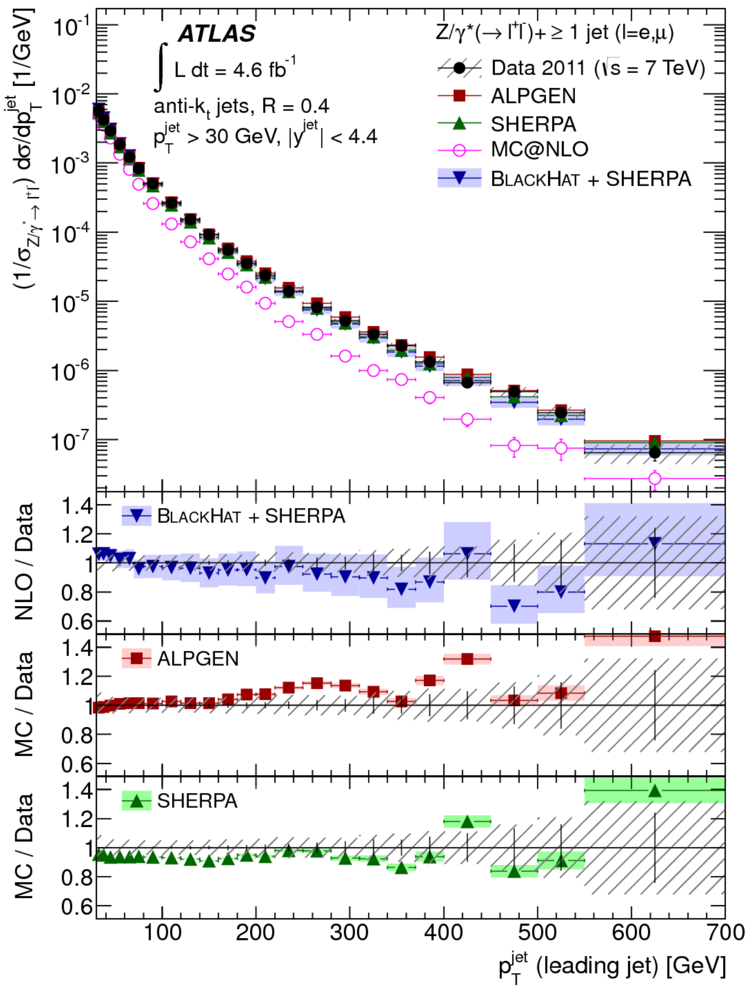
A. Denner et al, JHEP06 (2011) 069, 7TeV: A. Mueck

factorize for pT(Z), exclusive pT(jet)

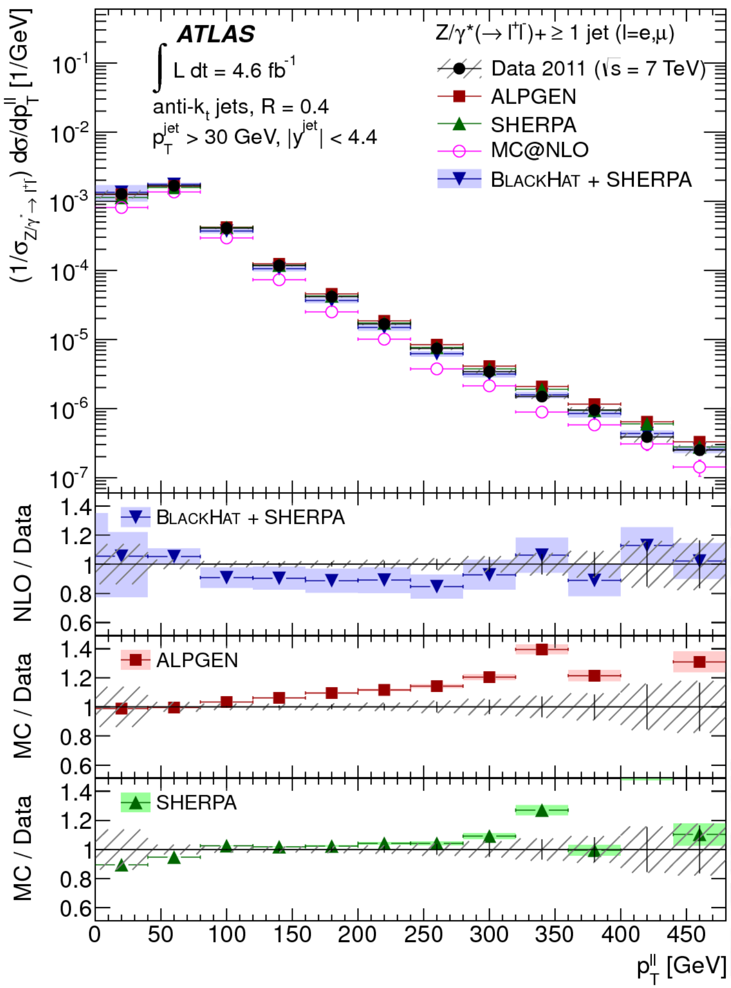
- Observables:
  - Jet transverse momenta (1st, 2nd, 3rd and 4th jet)
  - Jet p_T ratio
  - Transverse momentum of the Z boson

Results – Transverse Momenta

Leading jet p_T, $N_{jet} \geq 1$



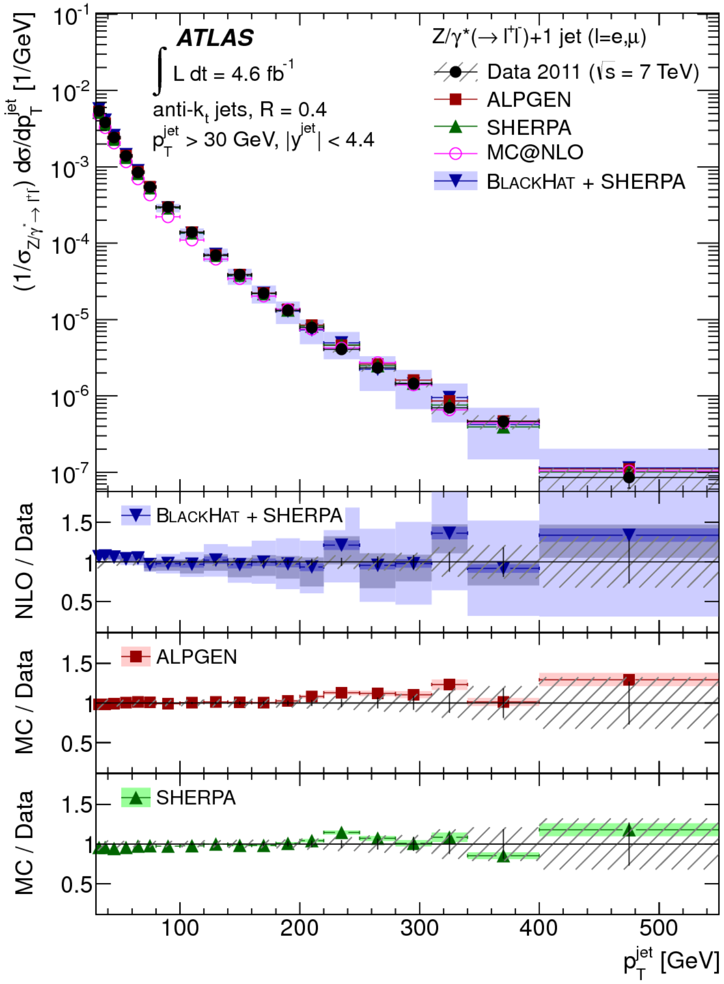
Z p_T, $N_{jet} \geq 1$



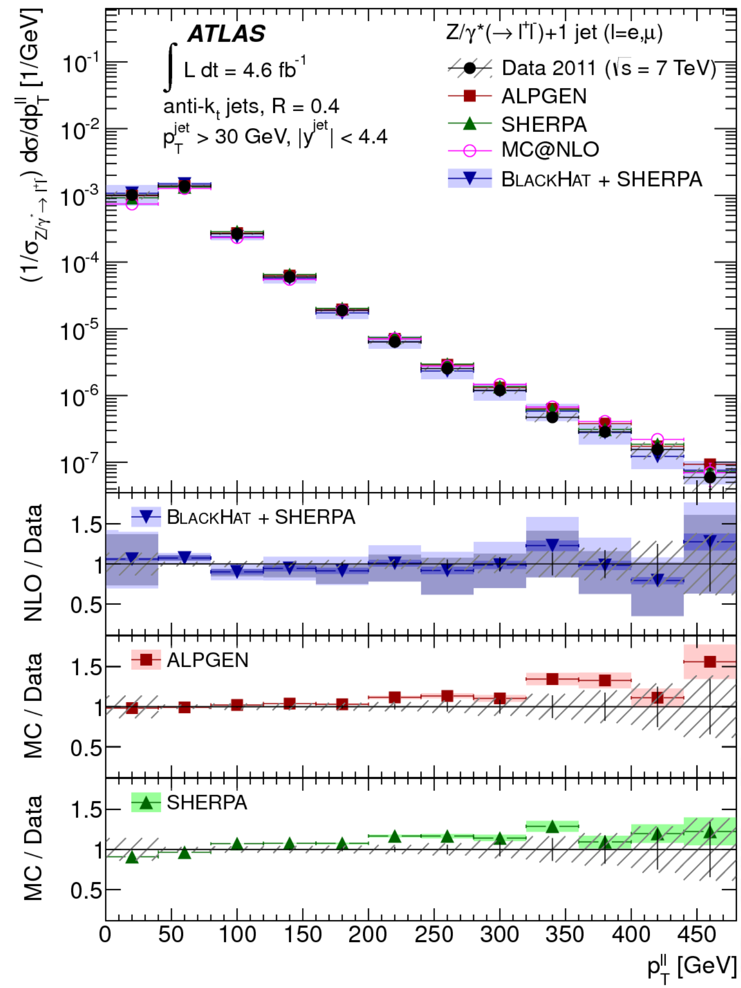
- ALPGEN: overestimates cross section for large p_T
- → missing NLO EW and NLO QCD corrections
- MC@NLO: underestimates cross section

Results – Transverse Momenta

Leading jet p_T, $N_{jet} = 1$



Z p_T, $N_{jet} = 1$



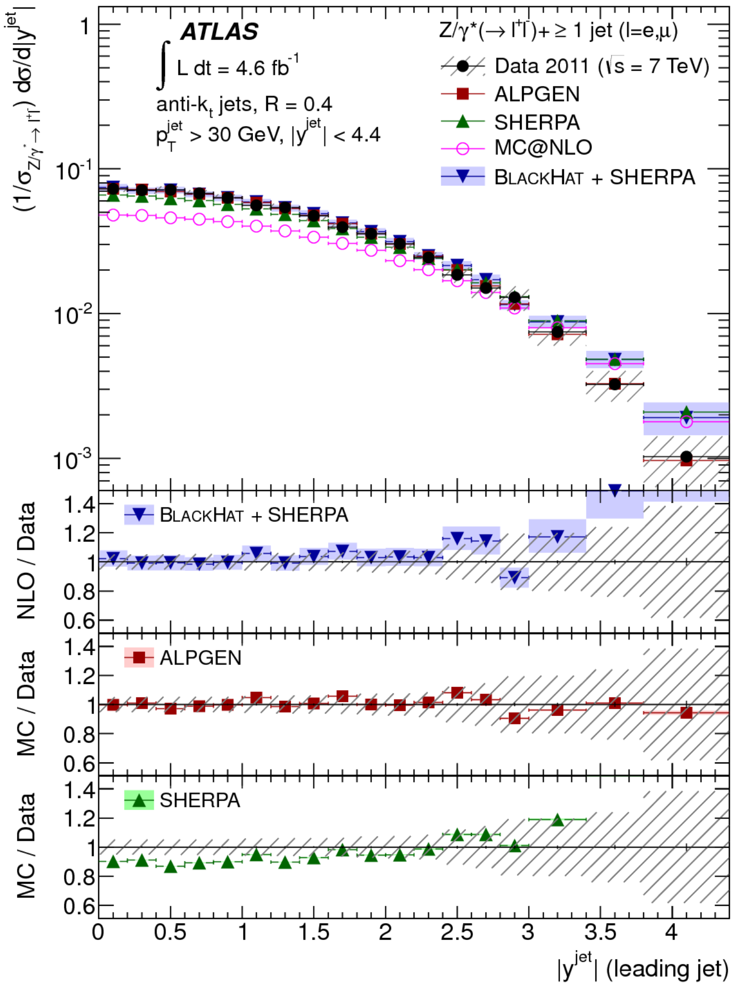
- ALPGEN: overestimates cross section for large p_T
  - ➔ missing NLO EW and NLO QCD corrections
  - ➔ Deviation mainly due to higher order QCD effects

Results – Angular Distributions

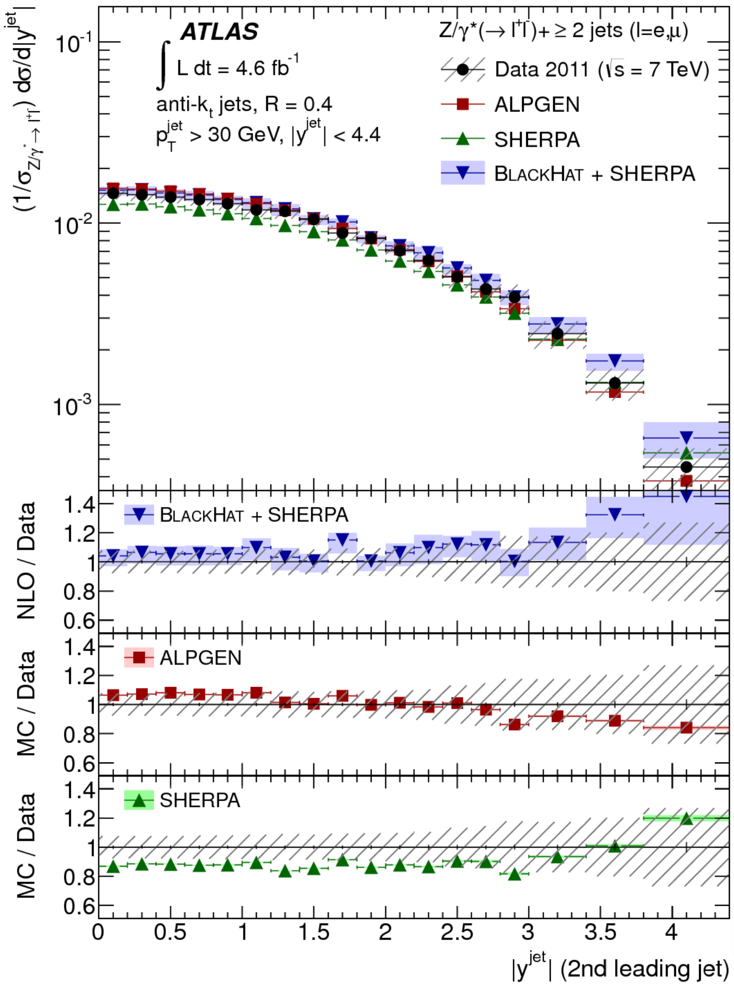
- Motivation:
  - Typical signatures of Higgs boson production and BSM physics are characterised by high energetic well separated forward jets
  - → Excellent knowlegde of angular distributions can be used to distinguish signal from background
- Observables:
  - Absolute jet rapidity (1st, 2nd, 3rd and 4th jet)
  - Invariant dijet mass
  - Angular separations between the leading jets ($|\Delta y|$, $|\Delta\phi|$, ΔR)
- Challenges:
  - Jet energy scale (JES), especially in the forward region

Results – Angular Distributions

Leading jet rapidity



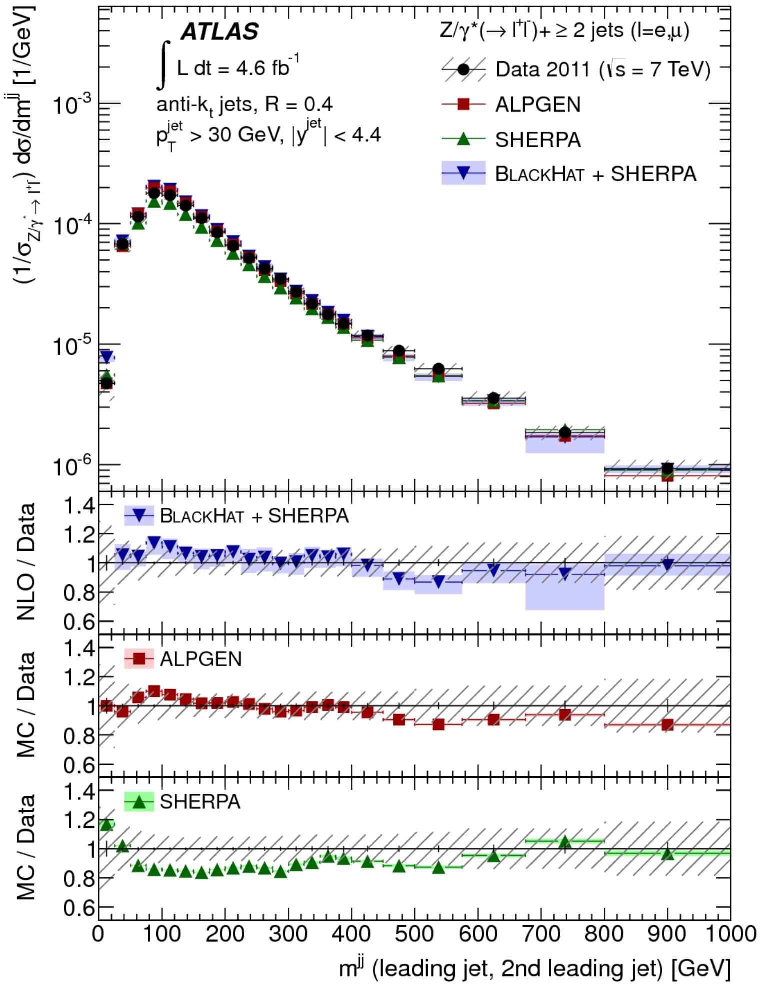
2nd leading jet rapidity



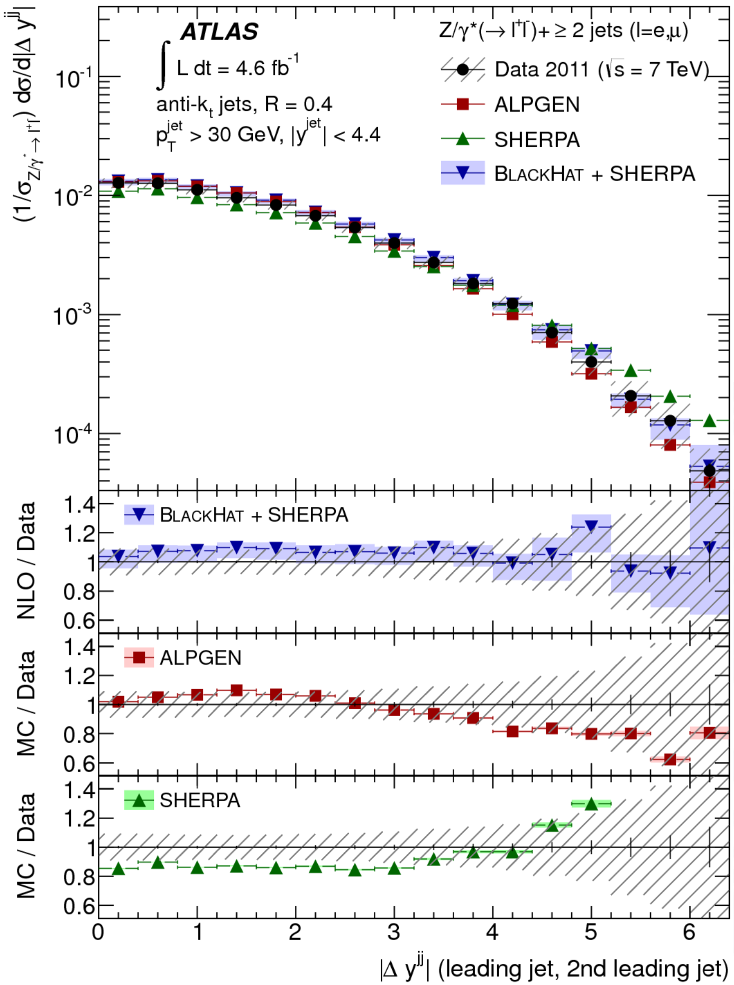
- SHERPA and NLO fixed-order pQCD overestimate cross section in forward region
- MC@NLO predicts too broad rapidity distribution

Results – Dijet Quantities

Invariant dijet mass



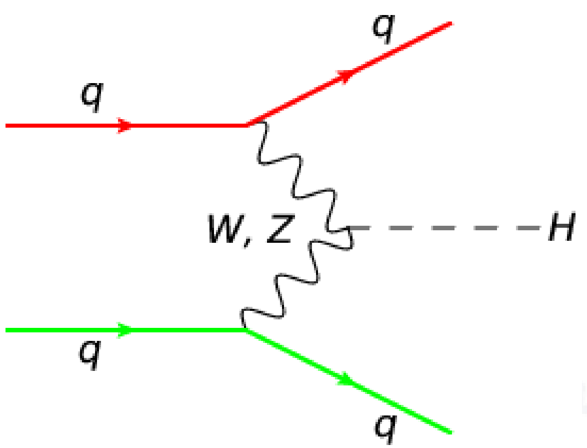
Absolute rapidity difference



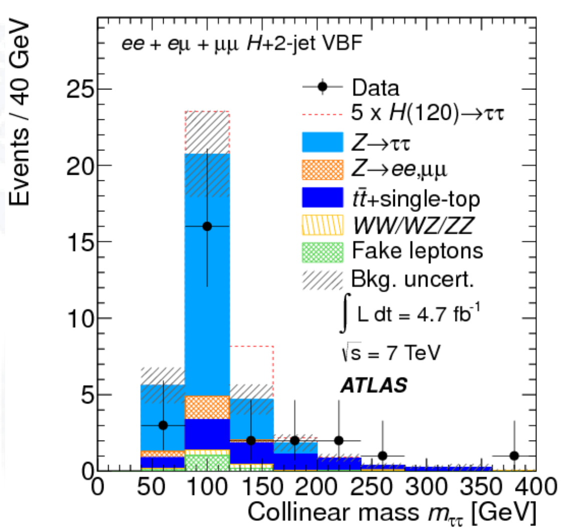
- Tendencies observed in y distributions are reflected in dijet distributions
- BH+SHERPA/data: good agreement

Results – Distributions after VBF Cuts

- Motivation:
  - Higgs boson production via vector boson fusion (VBF) is characterised by high energetic well separated forward jets and reduced central activity
  - → Excellent knowlegde of distributions after VBF preselection can be used to distinguish signal from background



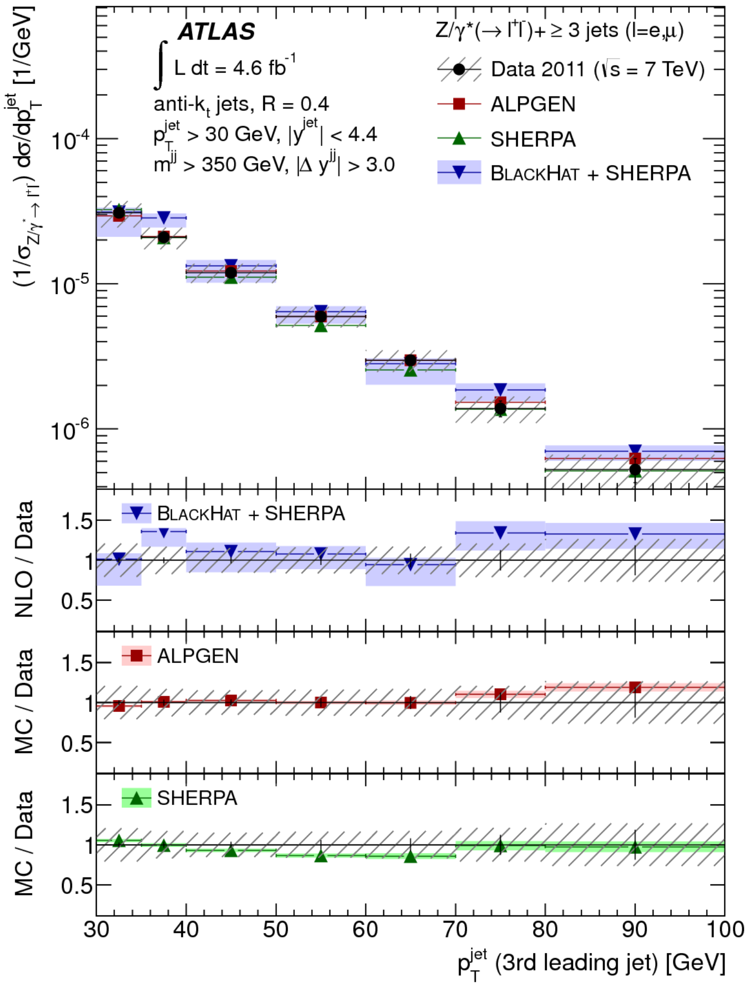
- VBF preselection:
  - m_{jj} > 350 GeV
  - $|\Delta y^{jj}|$ >3.0
- Observables
  - Exclusive jet multiplicity
  - 3rd jet transverse momentum
  - 3rd jet absolute rapidity
  - Survival efficiency of a 3rd jet



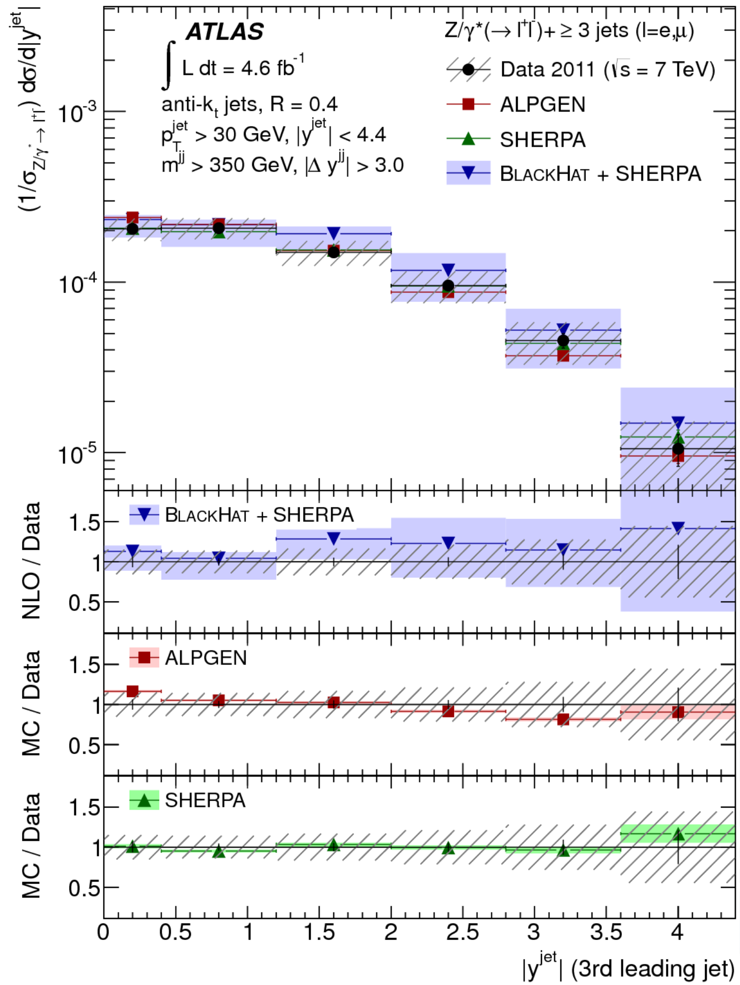
JHEP 1209 (2012) 070

Results – Distributions after VBF Cuts

3rd leading jet p_T



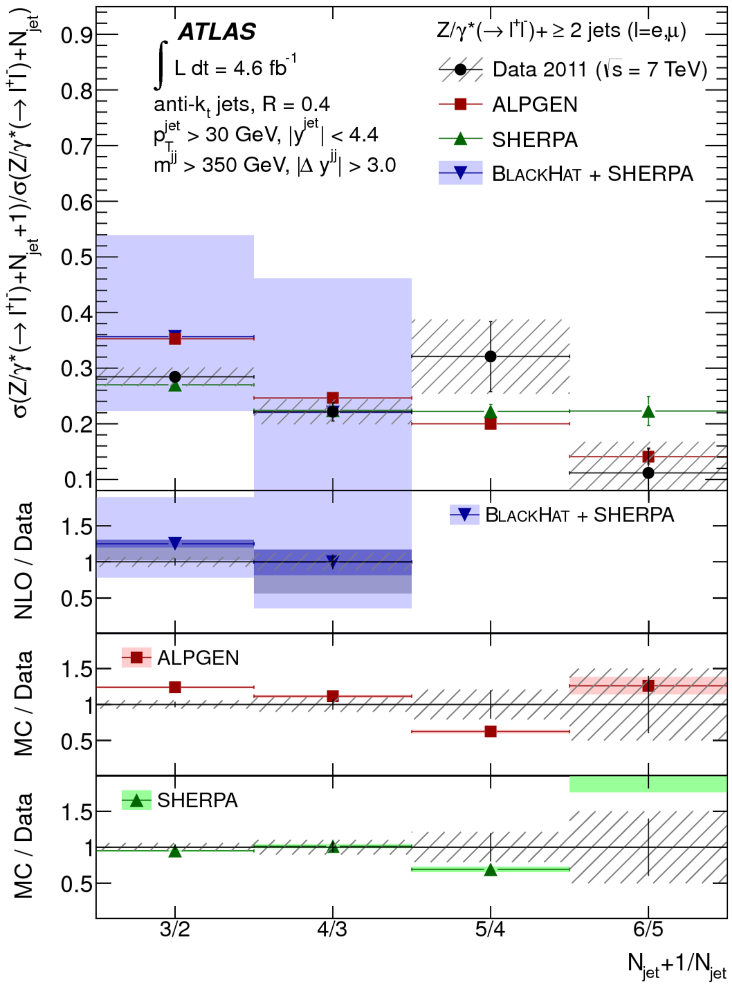
3rd leading jet rapidity



- Good agreement between predictions and data up to 70 GeV
- For larger values a lack of data is observed

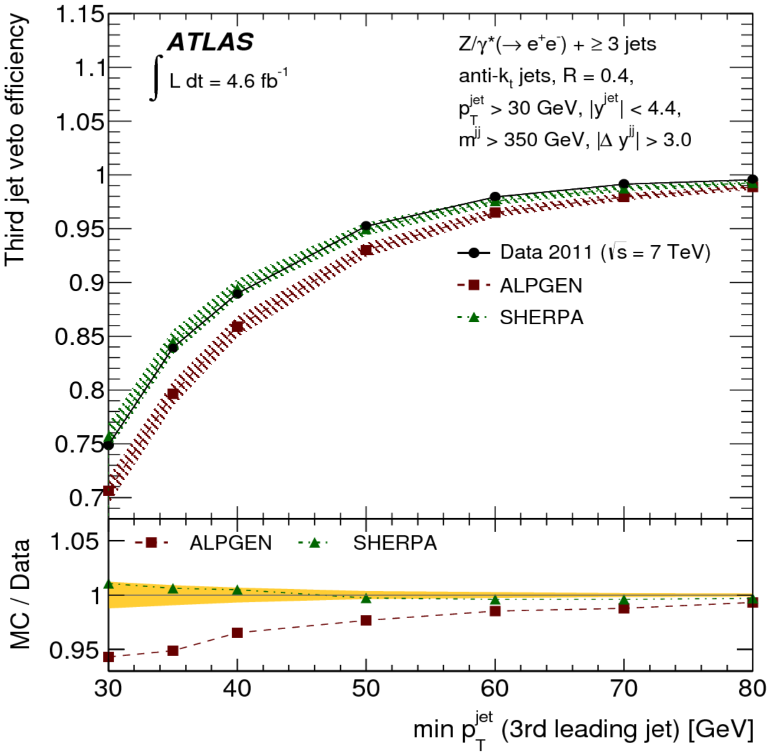
Results – Distributions after VBF Cuts

Exclusive jet multiplicity ratio



- ALPGEN overestimates 3/2

Survival efficiency of a 3rd jet



- SHERPA/data: good agreement
- ALPGEN predicts too small efficiency

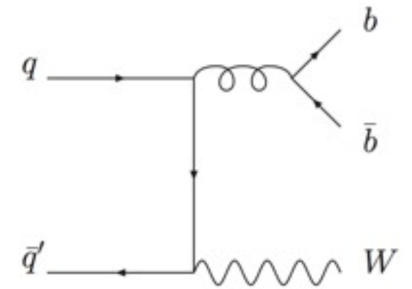
W + heavy flavour

W + b jets

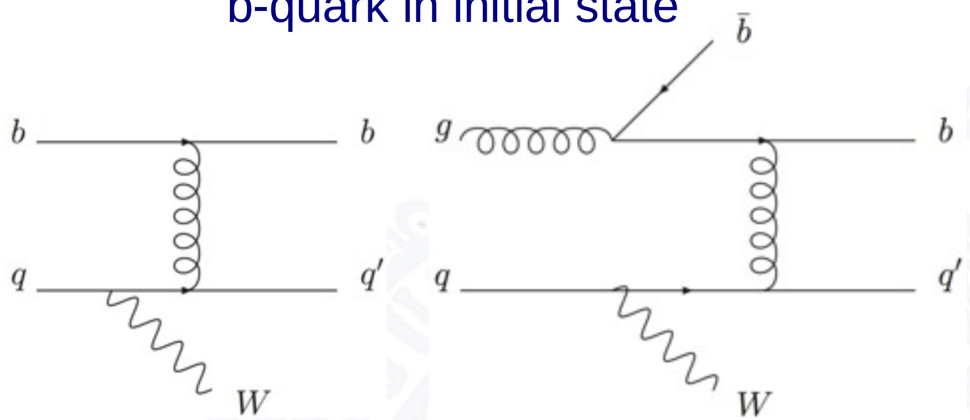
- Motivation:
  - Test of pQCD predictions:
    - LO 2→2 process CKM supressed
    - Competing flavour shemes: 4FNS vs 5FNS
    - Massive vs massless quarks
  - Irreducible background to Higgs boson associated production (VH) with H→bb decays, single top production and BSM physics

- Observables:
  - Jet multiplicity
  - Transverse momentum of the leading b-jet

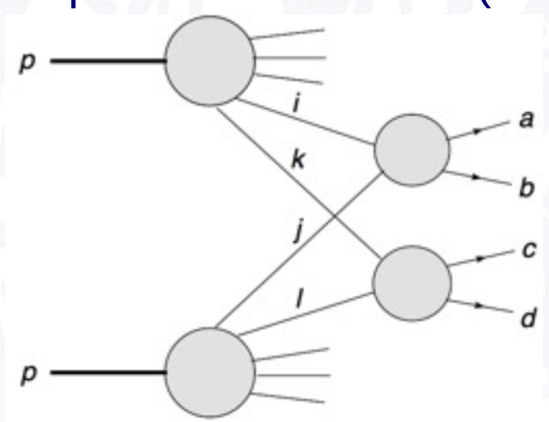
no b-quark in initial state



b-quark in initial state



Double parton interactions (DPI)

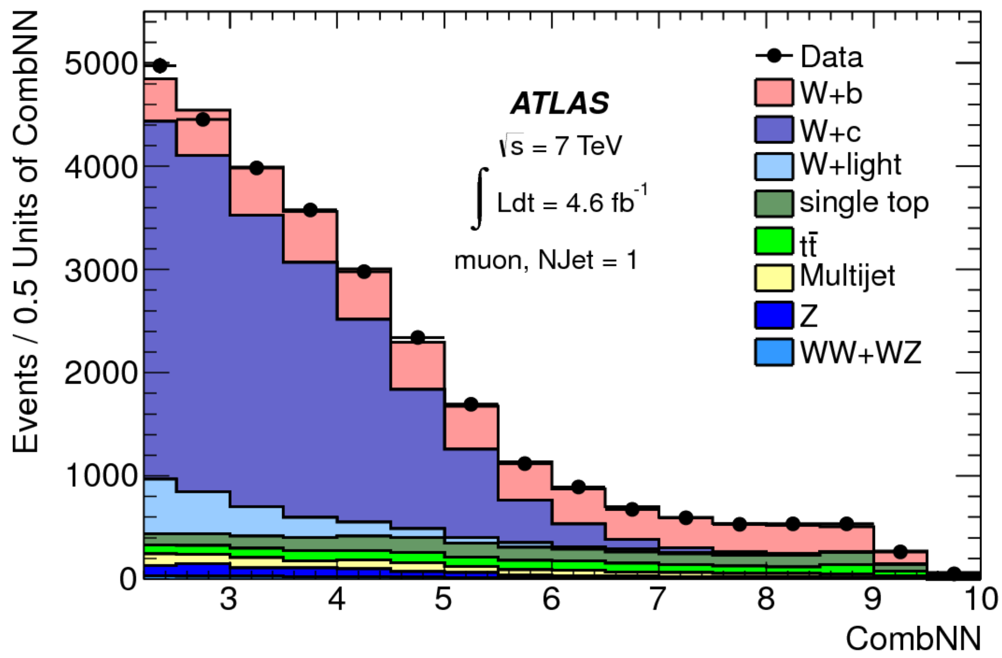


W + b jets – Signal Extraction

- W+b cross section with exactly one or two b-jets (particle level)

Requirement	Cut
Lepton transverse momentum	$p_T^\ell > 25$ GeV
Lepton pseudorapidity	$\|\eta^\ell\| < 2.5$
Neutrino transverse momentum	$p_T^\nu > 25$ GeV
W transverse mass	$m_T(W) > 60$ GeV
Jet transverse momentum	$p_T^j > 25$ GeV
Jet rapidity	$\|y^j\| < 2.1$
Jet multiplicity	$n \leq 2$
b-jet multiplicity	$n_b = 1$ or $n_b = 2$
Jet-lepton separation	$\Delta R(\ell, \text{jet}) > 0.5$

  - b jets: jet-b-hadron matching $\Delta R<0.3$, $p_T(b)>5$ GeV
- Main Backgrounds: W+c, W+light, ttbar, single top
- Signal extraction:
  - Maximum likelihood fit to b-tagger distribution (CombNN)
  - → Separate b-jets from c-jets and light jets
  - Unfold to particle level



Signal fraction ~ 20%

Experimental uncertainties:

- Statistical: 7-20%
- Systematics: 20-25%

  (JES, JER, MC modelling)

W + b jets - Results

Unfolded data compared to theoretical predictions from:

Monte Carlo	Process	Proton model	Precision	Parton shower, underlying event	Double parton interactions (DPI)
Alpgen/Herwig/Jimmy	W+b/c/light-jets	4 flavors	LO with NNLO k-factor = 1.2	Yes	Yes
Powheg/Pythia	W+bb	4 flavors	NLO	Yes	No
MCFM	W+b+X	4 and 5 f.	NLO	No	No

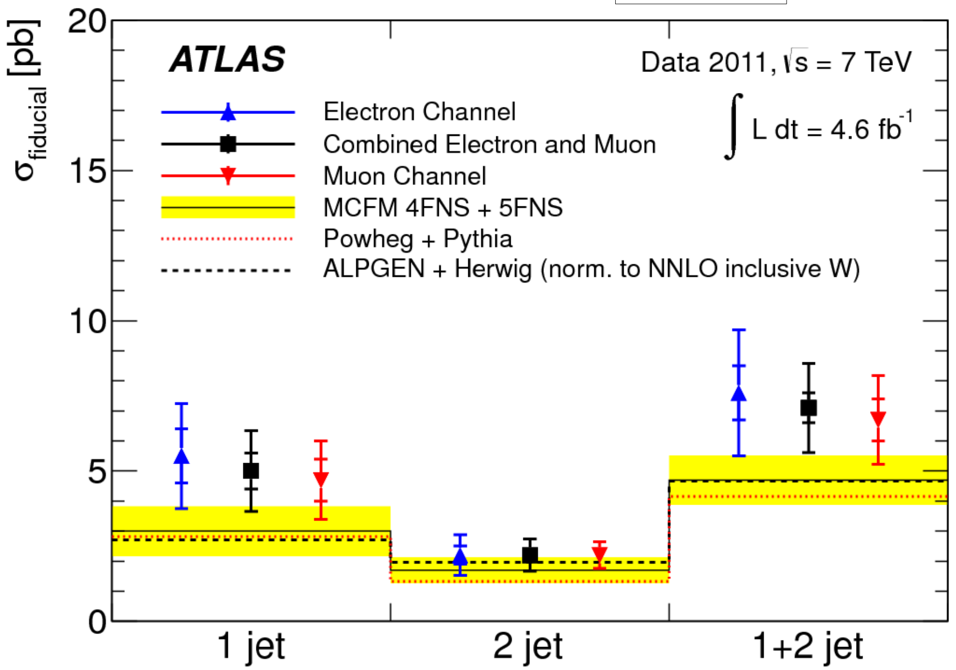
Correction	1 jet	2 jets
Non-perturbative	0.92 ± 0.02 (had.) ± 0.03 (UE)	0.96 ± 0.05 (had.) ± 0.03 (UE)
DPI [pb]	1.02 ± 0.05 (stat) $^{+0.40}_{-0.29}$ (syst)	0.32 ± 0.02 (stat) $^{+0.12}_{-0.09}$ (syst)

Multiplicative

Additive

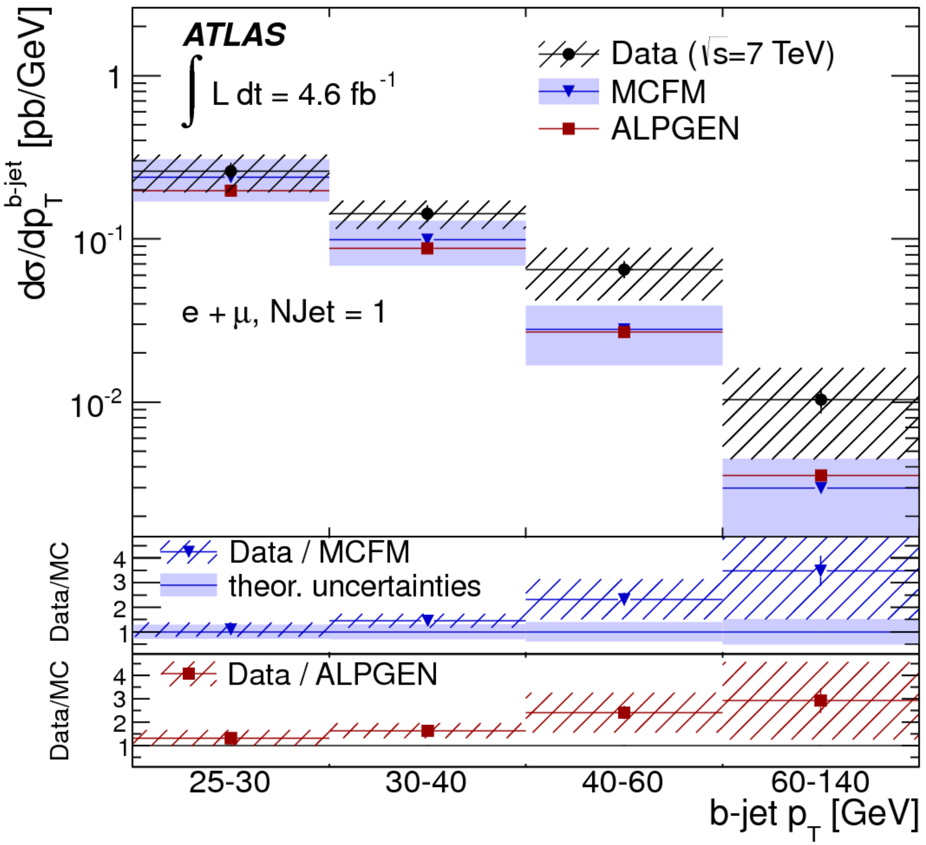
Results:

- 1 jet: consistent within 1.5σ
- 2 jets: good agreement

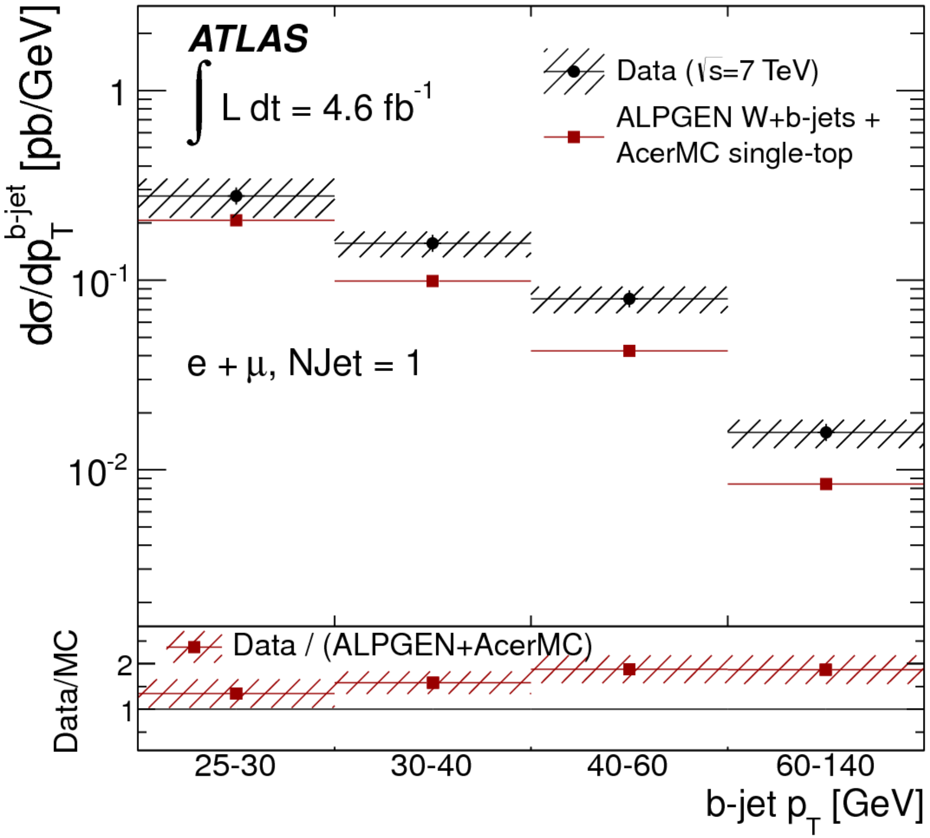


W + b jets - Results

W+b jets



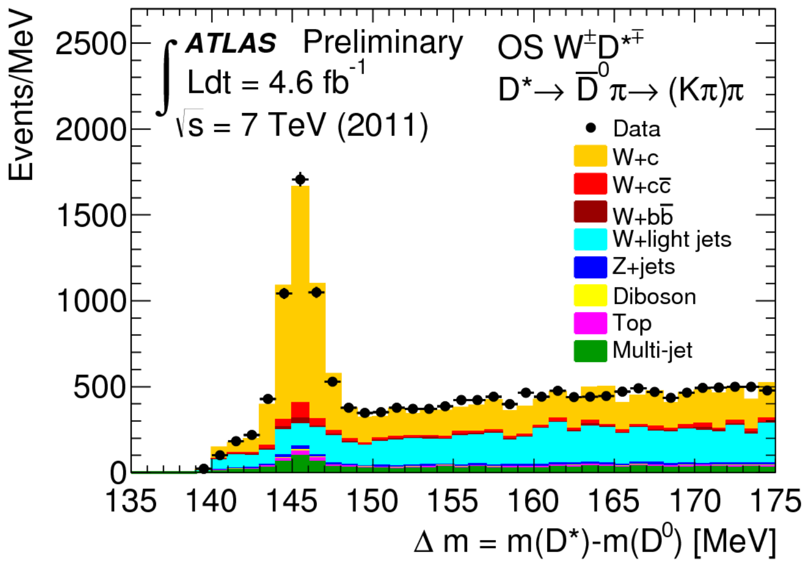
W+b jets + single top

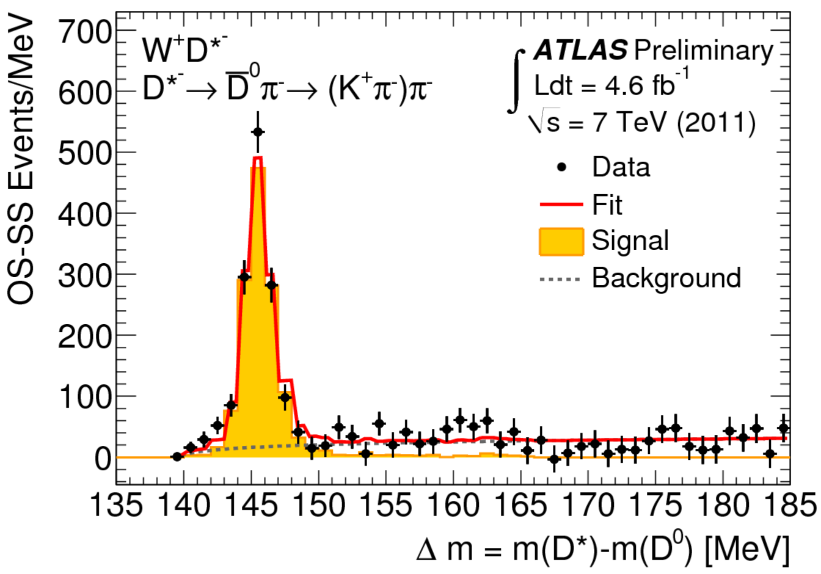


- ALPGEN and MCFM tend to underestimate cross section for large b-jet p_T
- Combined W+b-jets + single top cross section measurement has larger precision

W + D – Signal Extraction

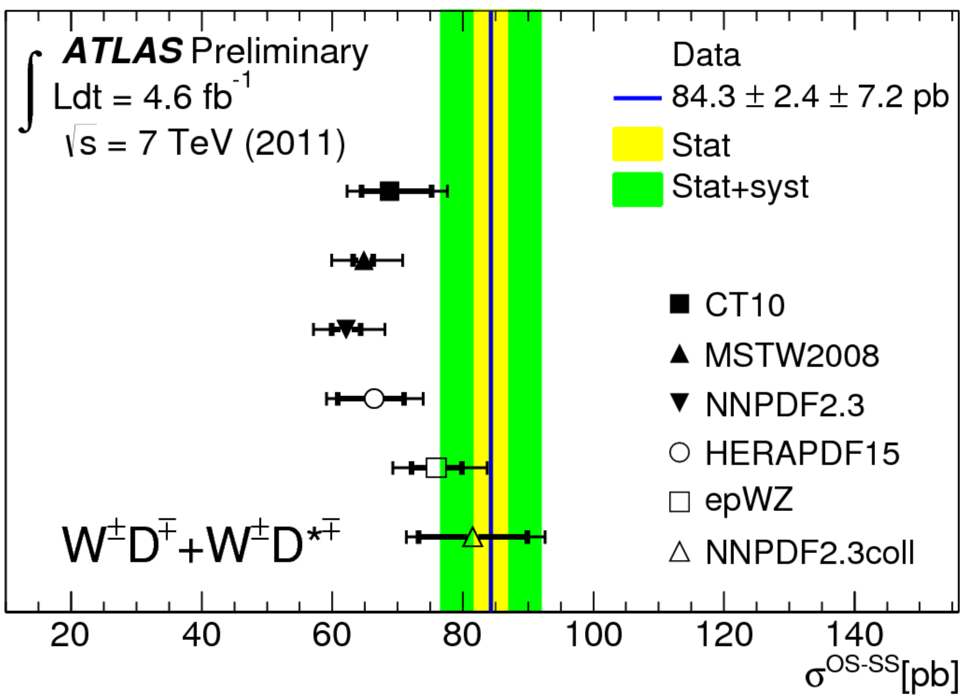
- Motivation: Sensitive to strange quark PDF at x~0.01
- W+c cross section (particle level)
  - $p_T^\ell > 20$ GeV and $|\eta^\ell| < 2.5$
  - $p_T^\nu > 25$ GeV
  - $m_T^W > 40$ GeV
  - $p_T^D > 8$ GeV and $|\eta^D| < 2.2$,
  - OS-SS: $W^\pm D^{(*)\mp} - W^\pm D^{(*)\pm}$
- Signal extraction:
  - Charm hadrons reconstructed of four D(*) + hadron decay channels
  - Charge correlation lepton from W and D(*)+: OS-SS subtraction (reduce W+cc)
  - Shape of signal and combinatorial background determined from data
  - Fit of signal and background templates
  - Correction for detector effects
- Dominant experimental uncertainty: tracking efficiency ~7%





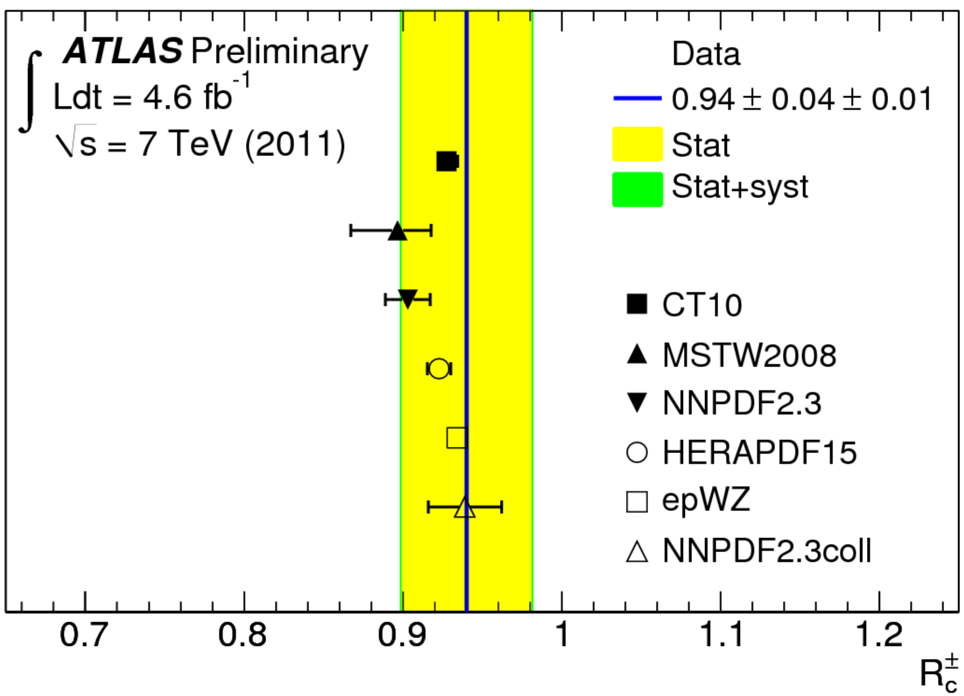
W + D – Results

OS-SS cross section



- Prefers PDFs with enhanced strange content (epWZ, NNPDF2.3coll, CT10)

Charge asymmetry ratio $\sigma(W^+D^{(*)-}/\sigma(W^-D^{(*)+})$



- Data consistent with all PDFs studied

Summary

- V + jets constitutes important test of pQCD predictions with light and heavy quarks
- Important background for studies of the Higgs boson and searches for new physics
- Dataset of 2011 allows to measure V+jets cross section with higher precision and in new phase space regions
  - In general, good agreement between predictions and data
  - Discrepancies between predictions and data in several regions
    - Fixed-order NLO / data: missing higher order effects
    - ME+PS / data: provides input for generator tuning
    - No satisfying description of W + b process
  - W+c measurement supports symmetric light-quark sea

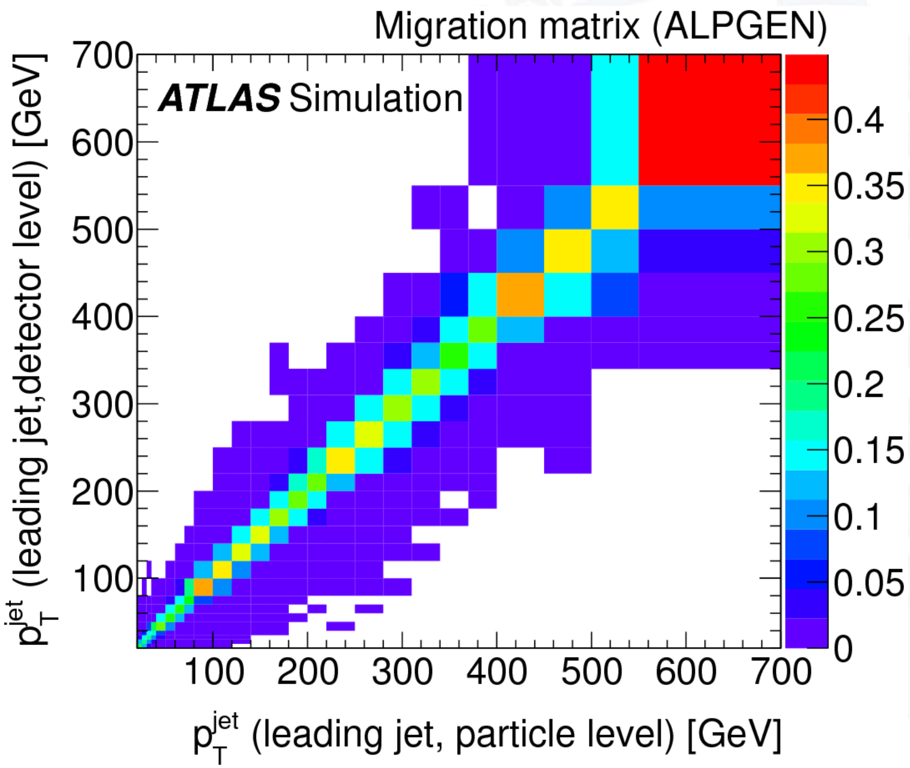
Back-Up

Unfolding for detector effects

- Differential cross sections: fiducial region for dressed leptons and particle level jets
  Dressed leptons: photons within cone of 0.1 around lepton direction
- Unfolding method: iterative (Bayes) method (Nucl. Instrum. Meth. A 362 (1995) 487)
  - Trainings sample: ALPGEN+HERWIG+JIMMY
  - Correction for mis-matched jets and different hierarchy at reco and truth level
  - Number of iterations optimized for each distribution by minimizing χ^2 between unfolded and truth Sherpa and MC@NLO pseudodata

$$\chi^2 = \sum_i \frac{(U_i - T_i)^2}{(\delta T_i)^2}$$

- Dominant systematic uncertainties:
  - Comparison of unfolded cross sections using Alpgen and Sherpa as training sample
  - Limited MC statistics in migration matrix



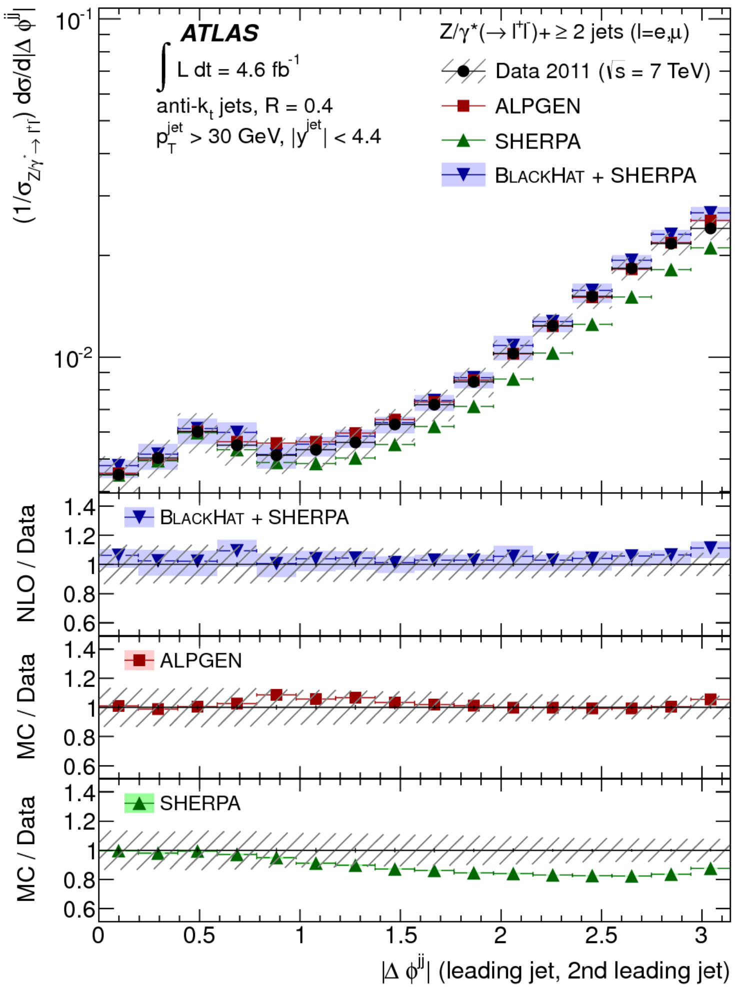
NLO pQCD Predictions

- BlackHat+Sherpa fixed order NLO. Five complete sets: Z+0,1,2,3,4 jets
  (C.F. Berger et al, Phys.Rev. D82 (2010) 074002, H. Ita et al, Phys. Rev. D 85 (2012) 031501)

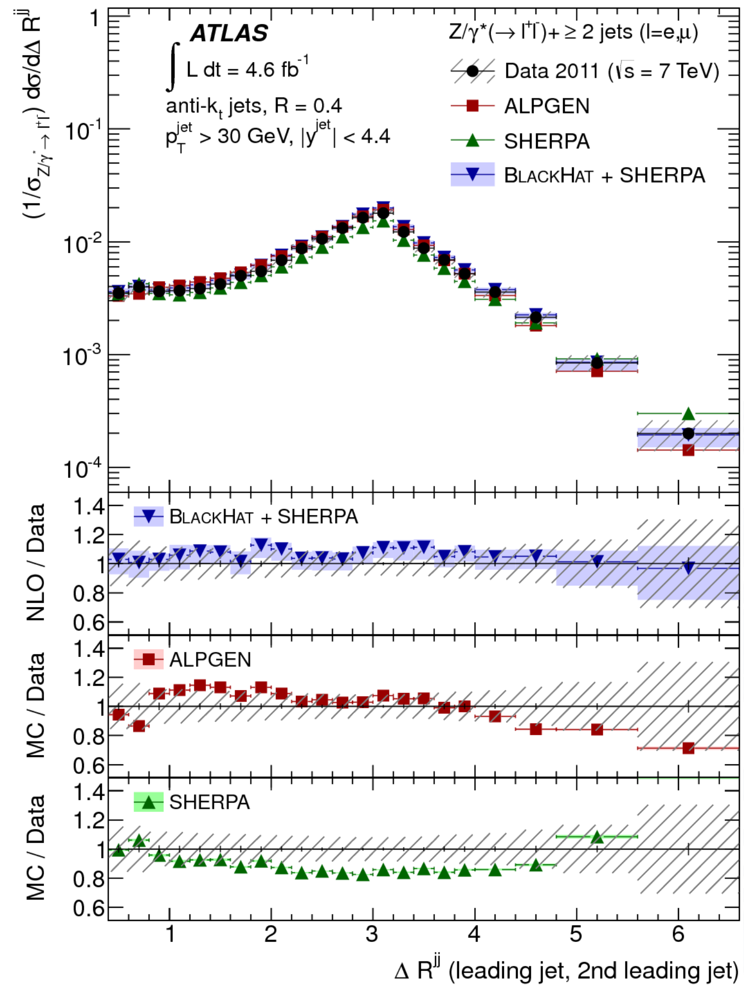
- Scale:
  - Nominal hadronization and factorization scale: $H_T/2$
  - Systematics: varying both scales simultaniously by factor of 2
    → 4% - 13% for $N_{jet} \geq$ 1-4, dominant uncertainty
  - Exclusive distributions: I.W.Stewart, F.J. Tackmann, Phys.Rev. D 85 (2012) 034011
- PDF:
  - CT10
  - Systematics: complete PDF CTEQ10 error set, 68%CL (1% - 3% for $N_{jet} \geq$ 1-4)
- α_s uncertainty:
  - varying the input α_s at the Z scale by +/- 0.0012 (1% - 3% for $N_{jet} \geq$ 1-4)
- Theoretical prediction are corrected for
  - QED radiation effects:
    - Nominal correction: ALPGEN+HERWIG+PHOTOS (~2%)
    - Systematics: Sherpa 1.4 +YFS
  - non-perturbative contributions (UE, fragmentation) and DPI:
    - Nominal correction: ALPGEN+HERWIG AUET2 tune (~3%-4%)
    - Systematics: ALPGEN+Pythia6 Perugia2011 tune

Results – Dijet Quantities

Absolute azimuthal separation



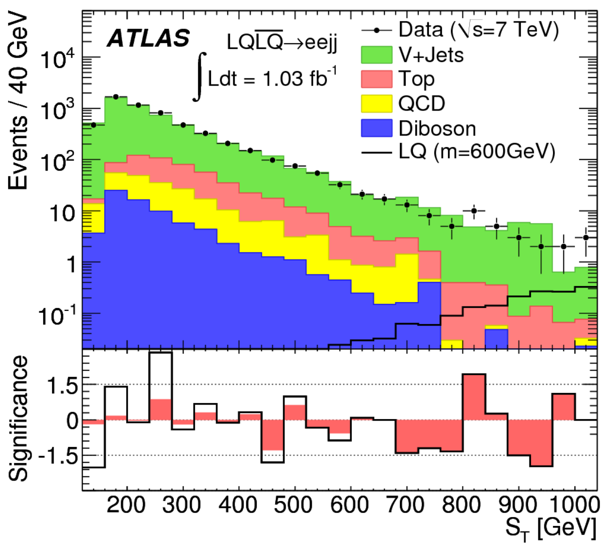
Angular separation in y-ϕ space



- Sherpa/data: distributions too flat
- ALPGEN/data: discrepancies for large ΔR^{jj}
- BH+Sherpa/data: good agreement

Results – Inclusive Quantities

- Motivation:
  - Inclusive quantities are of particular interest for BSM physics (final states with large jet activity)
  - QCD renormalisation and factorisation scale is often set to $H_T/2$
  - Test recent NLO fixed-order pQCD predictions
- Observables:
  - H_T: scalar p_T sum of all final state objects
  - S_T: scalar pT sum of all hadronic jets in final state



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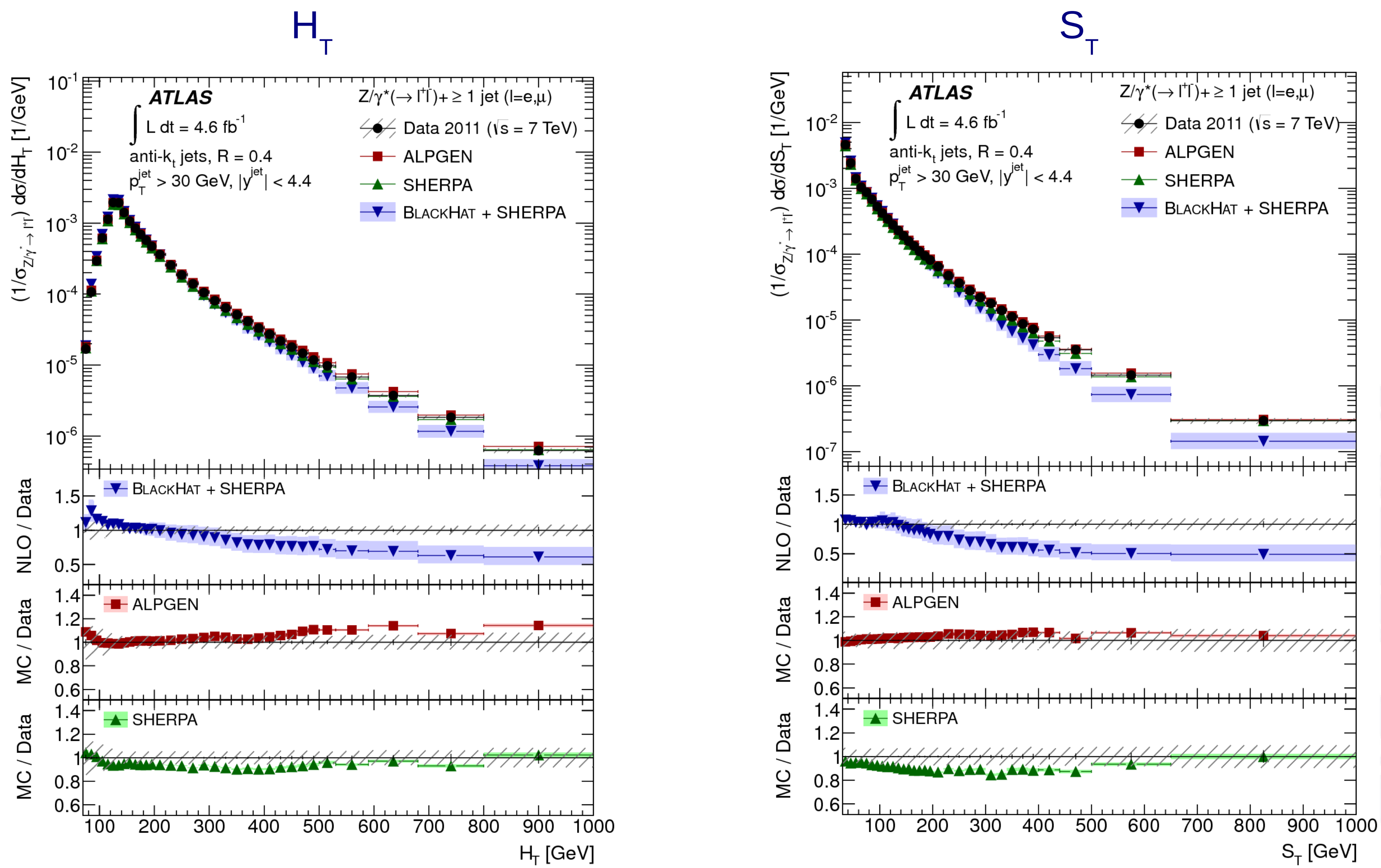
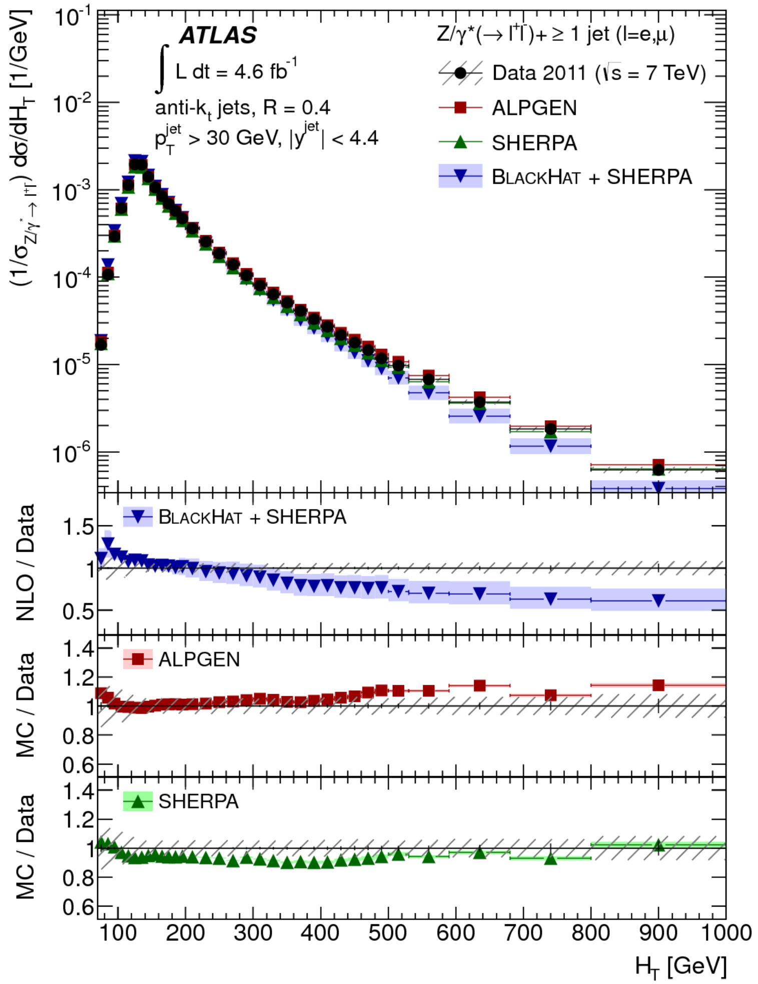
Results – Inclusive Quantities



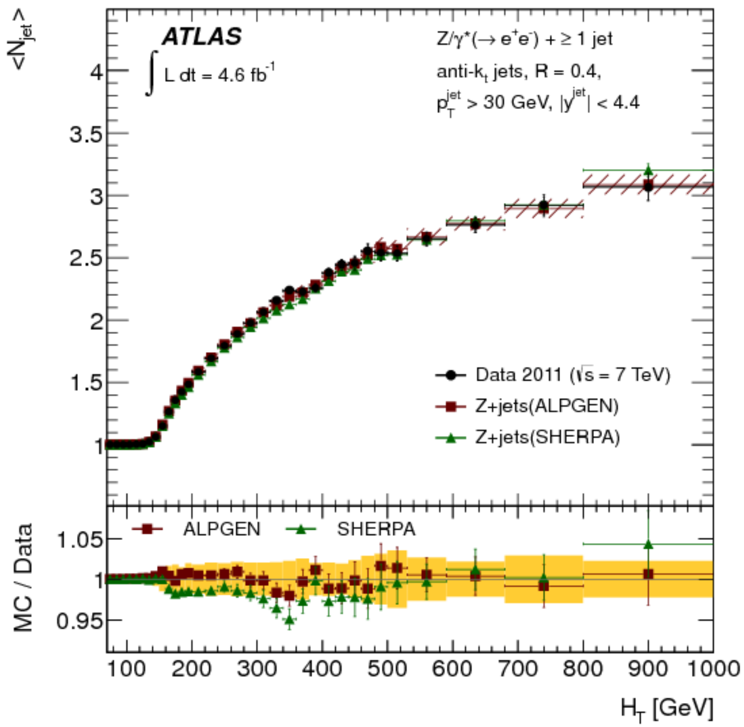
- ALPGEN, SHERPA consistent with data
- NLO fixed order Z+≥1 jet underestimates large H_T, S_T
- Possible explanation: missing higher orders in QCD

Results – Inclusive Quantities

H_T



Average N_{jet} vs H_T

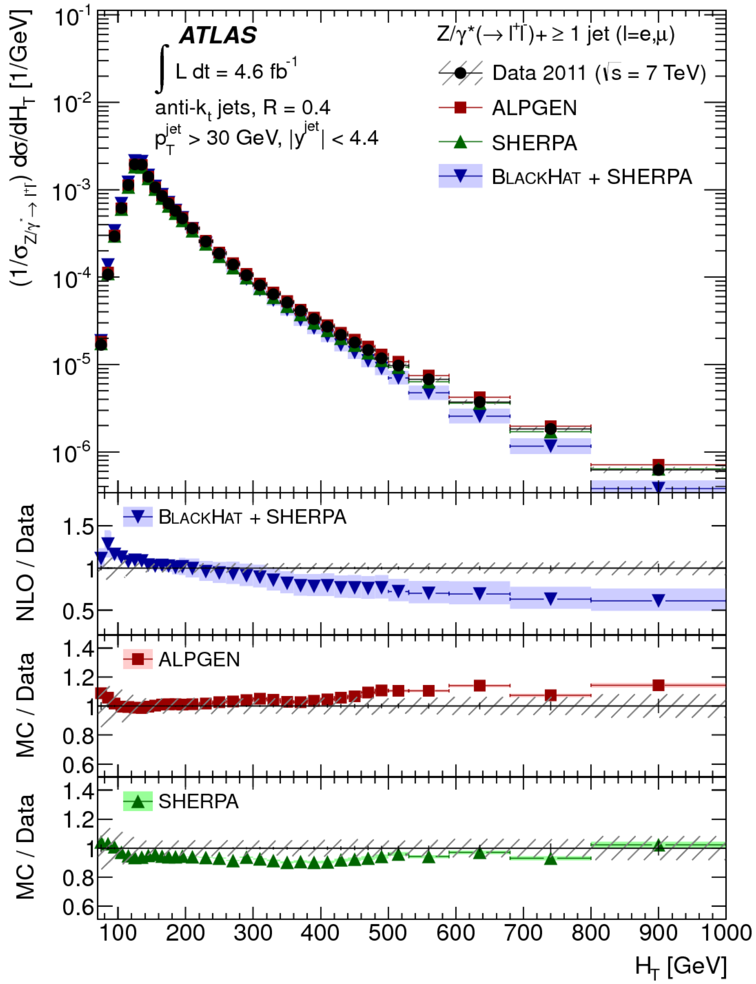


- <Njets> 2 for H_T > 300 GeV
- test exclusive sum

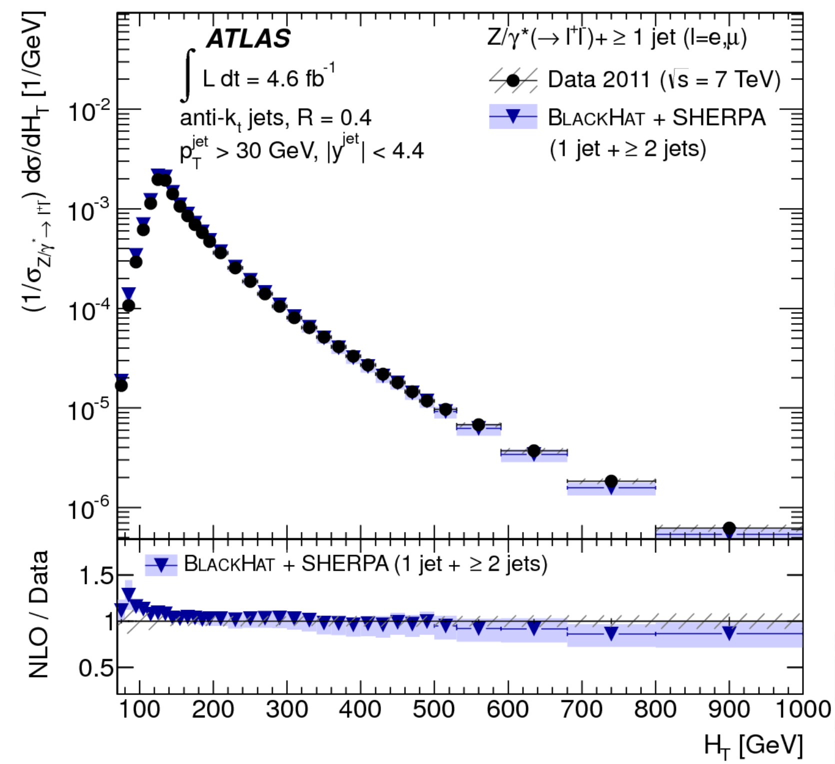
- ALPGEN, SHERPA consistent with data
- NLO fixed order Z+≥1 jet underestimates large H_T
- Possible explanation: missing higher orders in QCD

Results – Inclusive Quantities

H_T



BH+SHERPA 1 Jet + ≥ 2 Jets



- Exclusive sums perform better

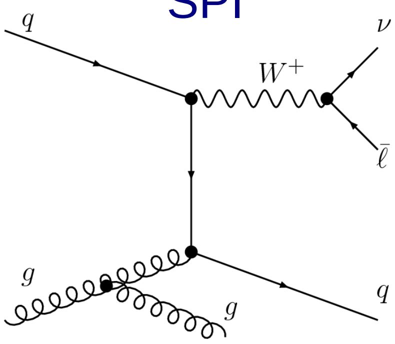
- ALPGEN, SHERPA consistent with data
- NLO fixed order Z+≥1 jet underestimates large H_T
- Possible explanation: missing higher orders in QCD

DPI in W + 2 jets

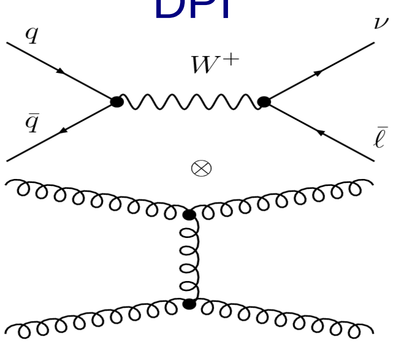
Introduction

W+2jets production via

SPI



DPI



DPI cross section: $\hat{\sigma}^{(\mathrm{DPI})}_{Y+Z} = \frac{\hat{\sigma}_Y \cdot \hat{\sigma}_Z}{\sigma_{\mathrm{eff}}}$

σ_{eff}: parameter related to the proton size :
- Naive estimate: 50-70mb
- Tevatron: 5-15mb

$$\hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s) + \hat{\sigma}^{(\mathrm{DPI})}_{Y+Z}(s) = \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s) + \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{\sigma_{\mathrm{eff}}(s)}$$

$$\rightarrow \quad \sigma_{\mathrm{eff}}(s) = \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{\hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s) - \hat{\sigma}^{(\mathrm{SPI})}_{Y+Z}(s)} = \frac{\hat{\sigma}_Y(s) \cdot \hat{\sigma}_Z(s)}{f^{(\mathrm{D})}_{\mathrm{DP}} \cdot \hat{\sigma}^{(\mathrm{tot})}_{Y+Z}(s)}$$

$$\sigma = \frac{N}{\mathcal{A}\, C\, \varepsilon\, \mathscr{L}}$$

In W+jets: $\sigma_{\mathrm{eff}} = \frac{\sigma_{W_{0j}} \cdot \sigma_{2j}}{\sigma_{W_{0j}+2j\,\mathrm{DPI}}} = \frac{\sigma_{W_{0j}} \cdot \sigma_{2j}}{f^{(\mathrm{D})}_{\mathrm{DP}}\ \sigma_{W+2j}} = \frac{1}{f^{(\mathrm{D})}_{\mathrm{DP}}} \cdot \frac{N_{W_{0j}}}{N_{W+2j}} \cdot \frac{N_{2j}}{\mathcal{L}_{2j}}$

- Acceptance A: cancel
- Unfolding corrections C: cancel
- Trigger: $\varepsilon_W = \varepsilon_{W+2j}$, $\varepsilon_{2J} \approx 1$

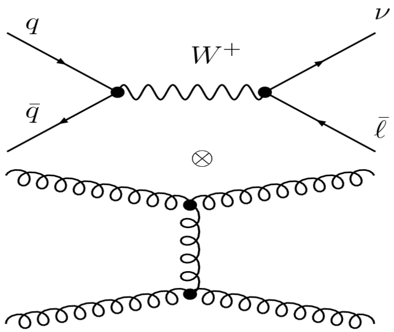
$f^{(\mathrm{D})}_{\mathrm{DP}}$: Fraction of DPI-produced W+2j events at detector level

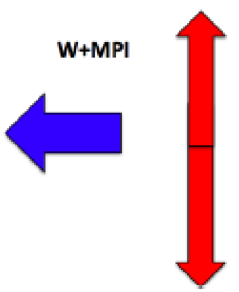
Measurement strategy

Normalized transverse momentum balance: $\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{J_1} + \vec{p}_{\mathrm{T}}^{J_2}|}{|\vec{p}_{\mathrm{T}}^{J_1}| + |\vec{p}_{\mathrm{T}}^{J_2}|}$

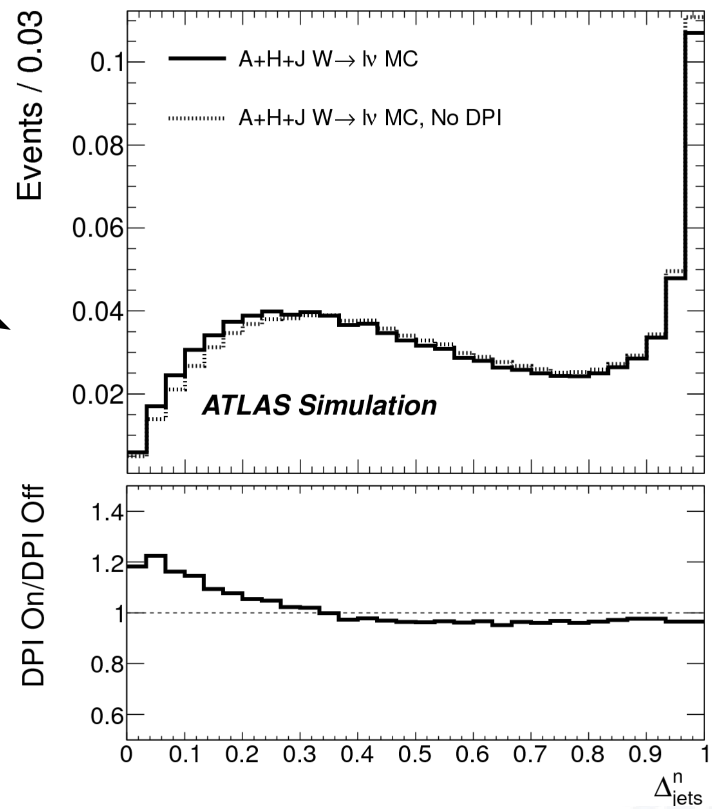
➔ extract fraction of DPI-produced events f_{DP}
using a fit with two templates: $(1 - f_{\mathrm{DP}}^{(\mathrm{D})}) \cdot A + f_{\mathrm{DP}}^{(\mathrm{D})}$

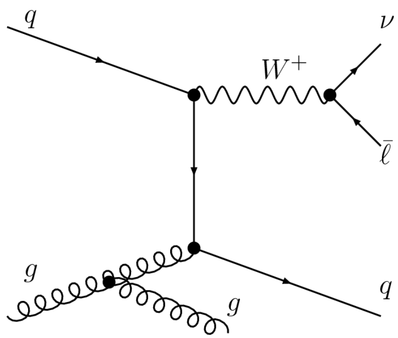
- A: DPI off: Alpgen+Herwig+Jimmy W+2jets
  hard MPI removed: p_T^{max} = 15GeV
- B: DPI: Dijets from data (2010, 184μb^{-1})

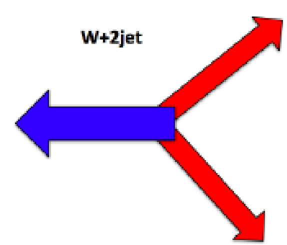




$\Delta^{\mathrm{n}}_{\mathrm{jets}}$ small

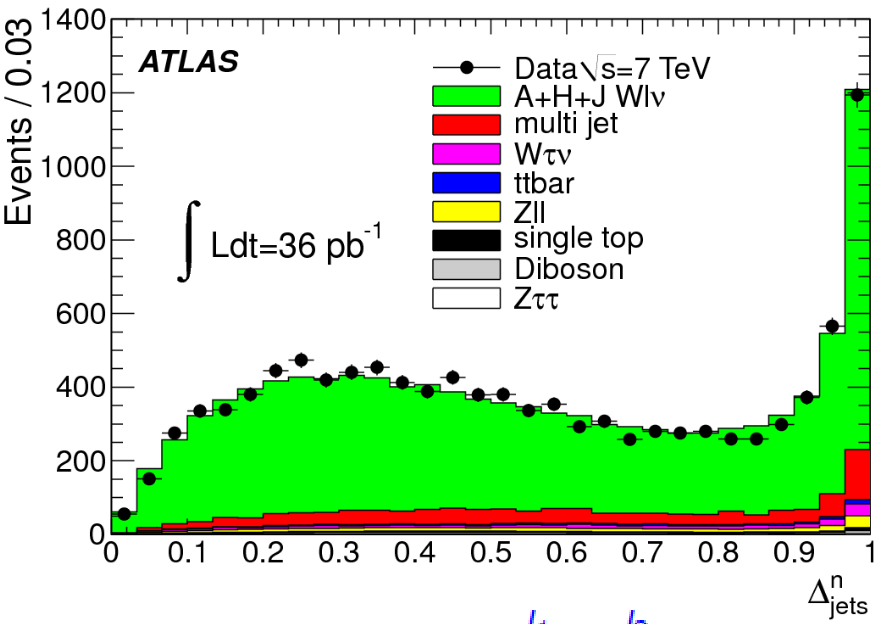




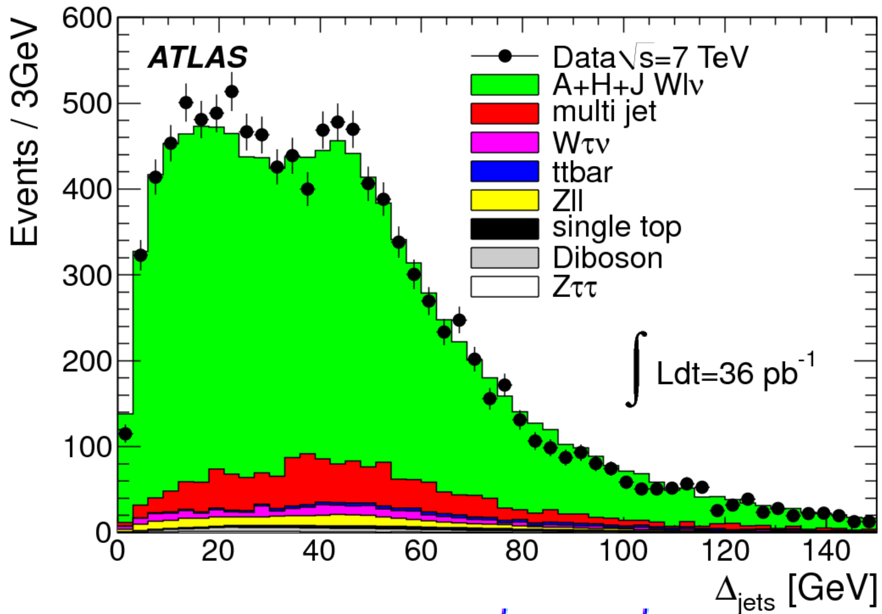


$\Delta^{\mathrm{n}}_{\mathrm{jets}}$ large

Distribution of observables



$$\Delta^{\rm n}_{\rm jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$$



$$\Delta_{\rm jets} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$$

W, W+2jets: using 2010 data (36 pb^{-1})

Selection:

Leptons: $p_T^\ell > 20\,\text{GeV}$ and $|\eta| < 2.4$ $(|\eta| < 2.47)$

Etmiss, mT: $E_T^{\rm miss} > 25\,\text{GeV}$ and $m_T > 40\,\text{GeV}$

Jets: $p_T > 20\,\text{GeV}$ and $|y| < 2.8$, $\Delta R(jl) > 0.5$

Backgrounds:
- multi-jet: 6-14%, data driven
- EW, top: 5-8%, MonteCarlo

Signal MC:
- Alpgen+Herwig+Jimmy, AUET tune
- Sherpa 1.31

Extraction of results: Uncertainties

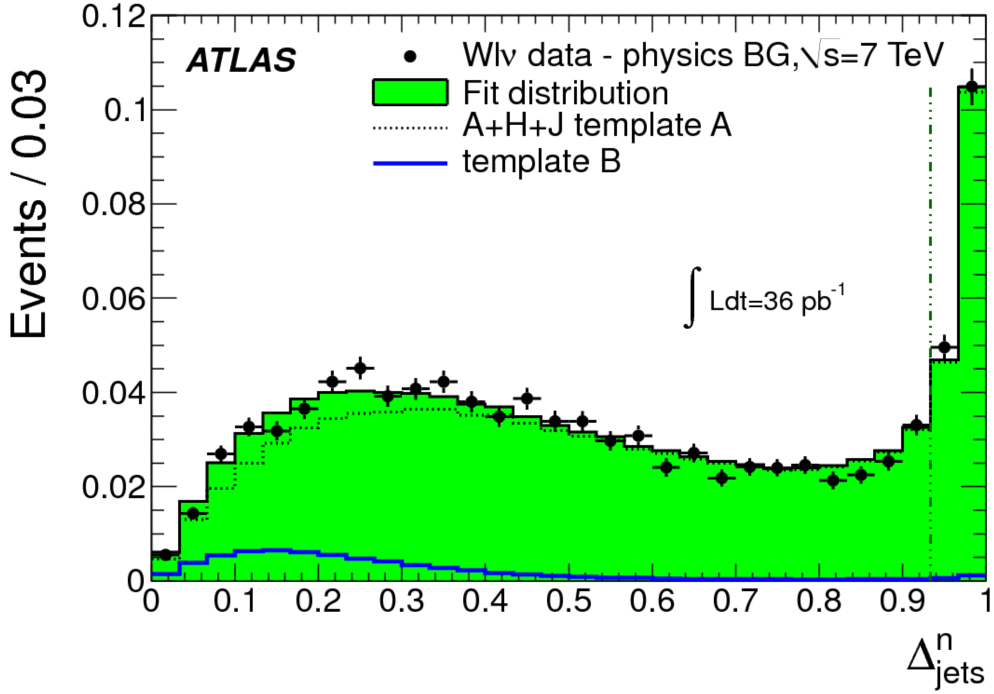


Table 1. Summary of the fractional uncertainties on $f_{\mathrm{DP}}^{(\mathrm{D})}$

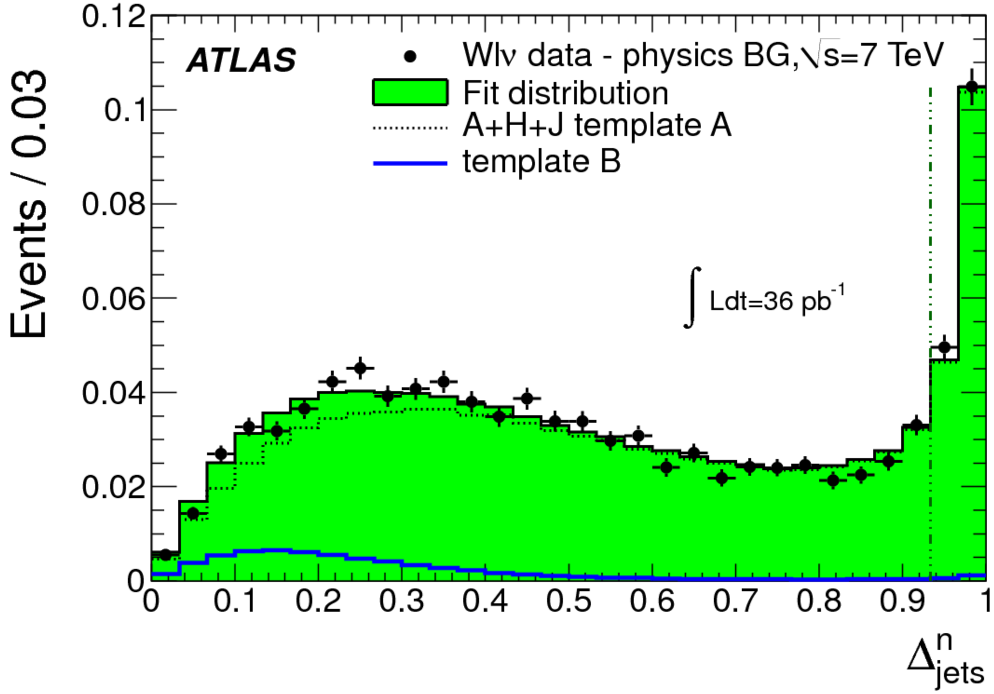
Systematic source	Uncertainty (%)
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background modelling and lepton response	11
Total systematic	24
Total statistical	17

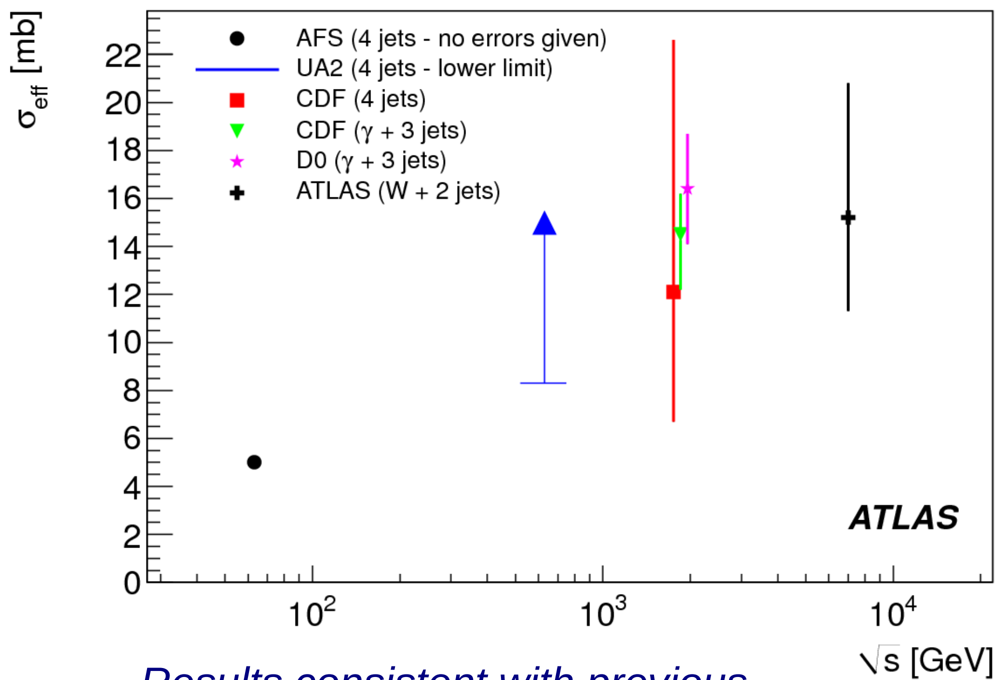
Fractional uncertainties on

$\sigma_{\mathrm{eff}} = 1/f_{\mathrm{DP}}^{(\mathrm{D})} \cdot N_{W_{0j}}/N_{W+2j} \cdot N_{2j}/\mathcal{L}_{2j}$

Systematic source	Uncertainty (%)
$f_{\mathrm{DP}}^{(\mathrm{D})}$	24
Background and lepton response	5
Luminosity	3
Total systematic	$^{+33}_{-20}$
Total statistical	17

Extraction of results





Results consistent with previous measurements at lower energies

$$f_{\mathrm{DP}}^{(\mathrm{D})} = 0.08 \pm 0.01\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{sys.})$$

$$\longrightarrow \sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\ (\mathrm{stat.})\ ^{+5}_{-3}\ (\mathrm{sys.})\ \mathrm{mb}$$

Direct comparison with theory: $f_{\mathrm{DP}}^{(\mathrm{P})}$

→ unfold distributions to the hadron level:

$$p_{\mathrm{T}}^{\mathrm{P}} \geqslant 20\,\mathrm{GeV}, \quad |y^{\mathrm{P}}| \leqslant 2.8 \quad \mathrm{and} \quad \Delta R_{\mathrm{P}\ell} > 0.5,$$

→ fit unfolded distributions

→ results within 10% of detector level results, as expected