



## Measurements of the production of jets in association with a W or Z boson with the ATLAS detector

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and Related Subjects

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# Introduction

W/Z+jet measurements:

- Powerful test of perturbative quantum chromodynamics (pQCD) and electroweak predictions
- Backgrounds for Higgs studies and beyond SM searches  
→ Monte Carlo (MC) prediction must be tuned and validated using data

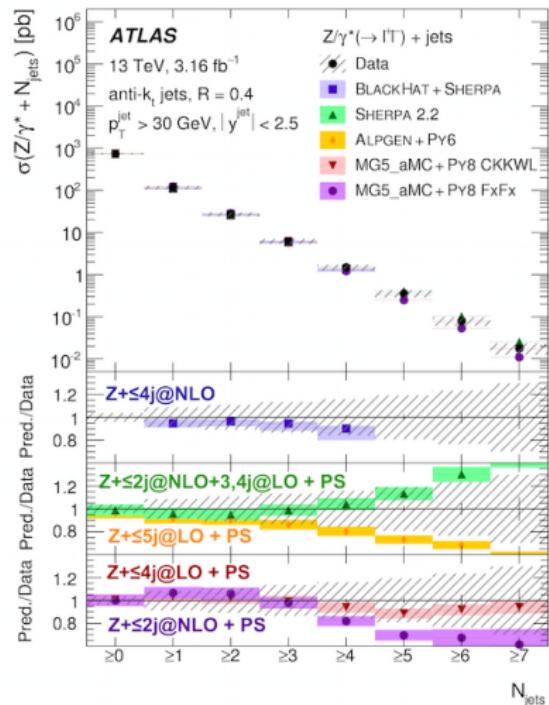
In this talk:

- Measurements of the production cross section of a Z boson in association with jets in pp collisions at  $\sqrt{s} = 13 \text{ TeV}$  with the ATLAS detector ( $3.16 \text{ fb}^{-1}$ ) [Eur. Phys. J. C77 \(2017\) 361](#)
- Measurement of differential cross sections and  $W^+/W^-$  cross section ratios for W boson production in association with jets at  $\sqrt{s} = 8 \text{ TeV}$  with the ATLAS detector ( $20.3 \text{ fb}^{-1}$ ) [arXiv:1711.03296](#)
- Measurement of W boson angular distributions in events with high transverse momentum jets at  $\sqrt{s} = 8 \text{ TeV}$  using the ATLAS detector ( $20.3 \text{ fb}^{-1}$ ) [Phys. Lett. B 765 \(2017\) 132](#)

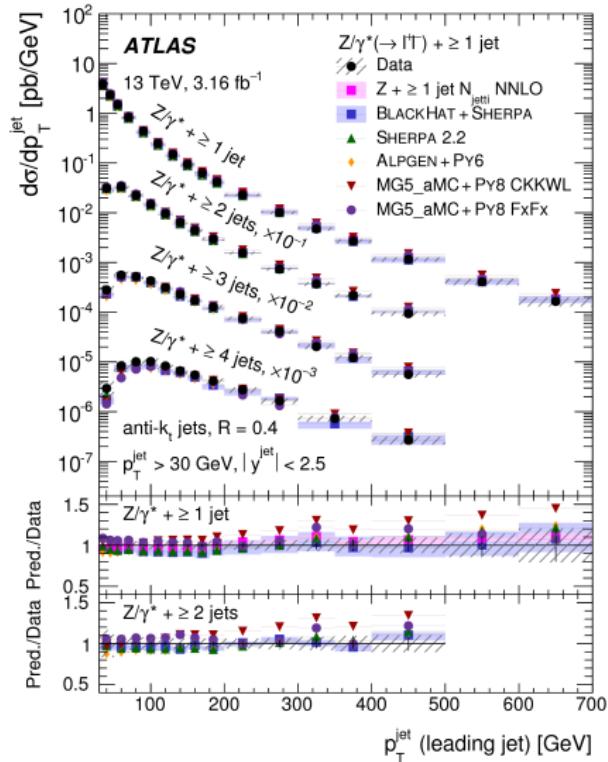
Z + jets @ 13 TeV

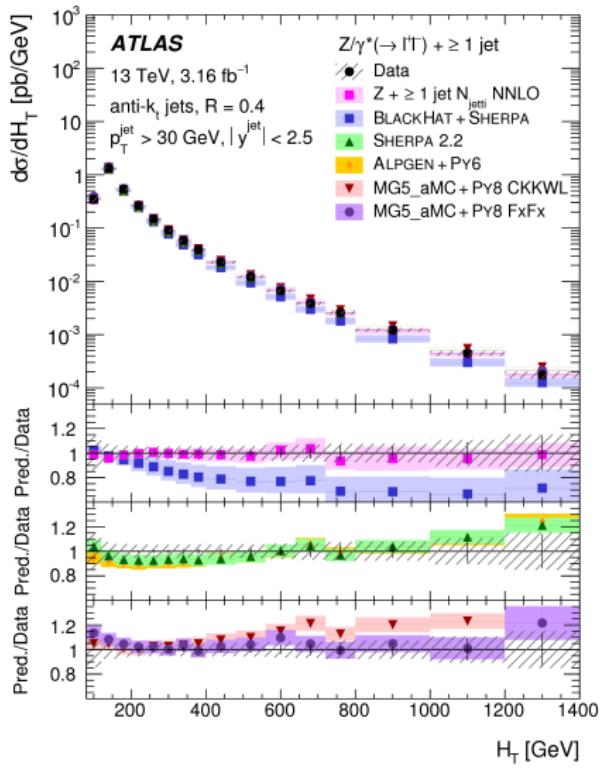
- Sensitive probe of different MC approaches
- $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$  combined for higher precision
- Differential cross sections measured for  $N_{\text{jets}}$ ,  $\frac{N_{\text{jets}}+1}{N_{\text{jets}}}$ ,  $p_T^{\text{jet}}$ ,  $|y_{\text{jet}}|$ ,  $H_T$ ,  $m_{jj}$ ,  $\Delta\phi_{jj}$
- Comparison with LO and NLO ME MC generators, NLO and  $N_{\text{jetti}}$  NNLO fixed-order calculations
- LO Alpgen + Py6 and NLO Sherpa 2.2 and MG5\_aMC + Py8 do not describe well high jet multiplicities, where large jet fraction is from parton showers (PS)

Anti- $k_T$  jets with  $R = 0.4$ ,  
 $p_T^{\text{jet}} > 30 \text{ GeV}$ ,  $|y_{\text{jet}}| < 2.5$



- LO MG5\_aMC + Py8 CKKWL models too hard  $p_T^{\text{jet}}$  spectrum for  $p_T^{\text{jet}} > 200 \text{ GeV}$   
 → dynamic  $\mu_F$  and  $\mu_R$  used in the generation not appropriate for the full  $p_T^{\text{jet}}$  range
- LO Alpgen + Py6 and NLO BlackHat + Sherpa, Sherpa 2.2 and MG5\_aMC + Py8 FxFx are in agreement with data within the systematics over the full  $p_T^{\text{jet}}$  range
- $N_{\text{jetti}}$  NNLO models well the  $p_T^{\text{jet}}$  spectrum for  $Z + \geq 1 \text{ jet}$



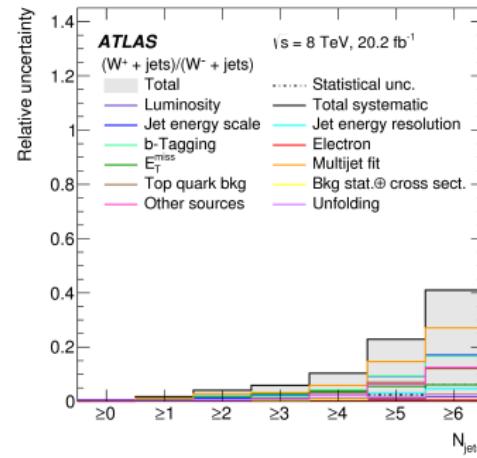
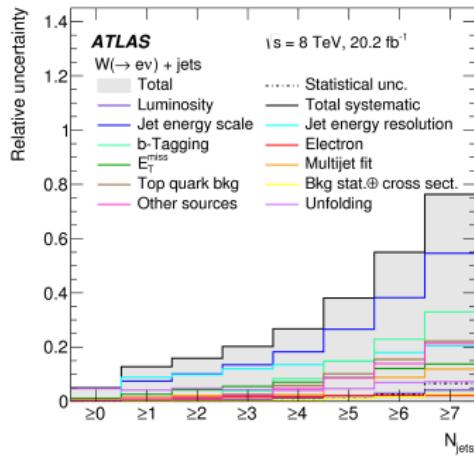


- $H_T$  - scalar sum of the  $p_T$  of all visible objects
  - ▶ common variable in beyond SM searches for heavy particles
  - ▶ often used as scale variable in pQCD calculations
- BlackHat + Sherpa underestimates data in  $H_T > 300$  GeV (missing higher orders)
- $N_{jet}^{jet}$  NNLO recovers agreement by adding higher orders in pQCD
- LO MG5\_aMC + Py8 CKKWL over-predicts large  $H_T$  (consistent with  $p_T^{jet}$  predictions)

**W and  $W^+ / W^- + \text{jets}$  @ 8 TeV**

# $W$ and $W^+/W^- + \text{jets}$ @ 8 TeV arXiv:1711.03296

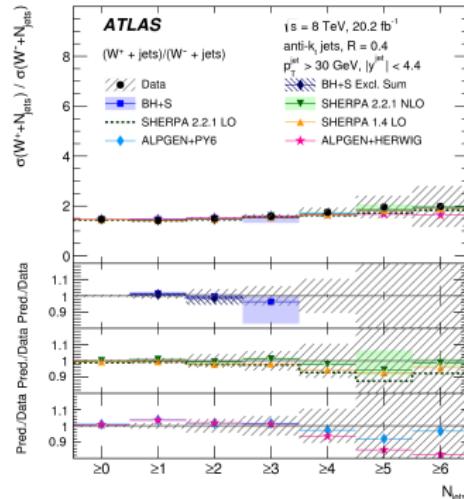
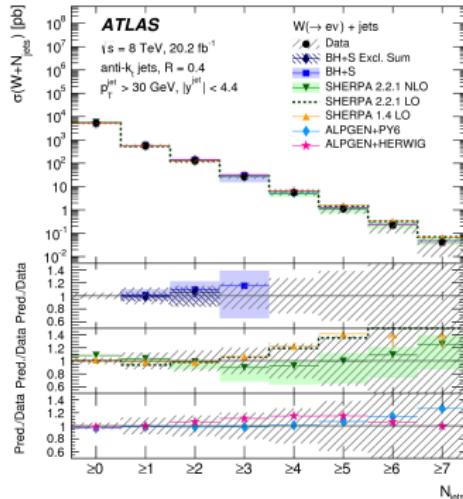
- Focus on  $W \rightarrow e\nu$  channel
- $\sim 50$   $W$ -boson and jet unfolded distributions
- Ratios of measured  $W^+/W^-$  cross sections benefit from uncertainties cancellations:



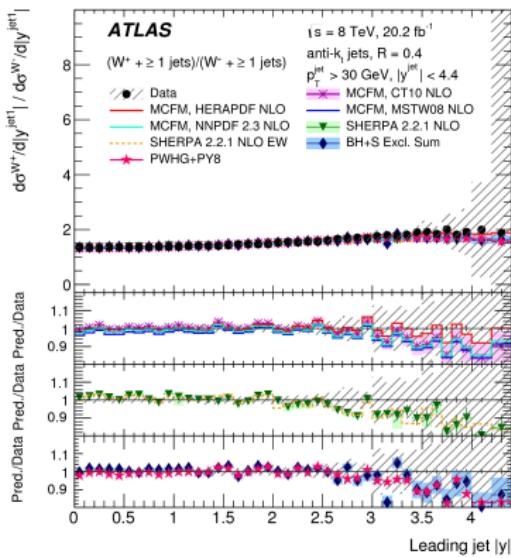
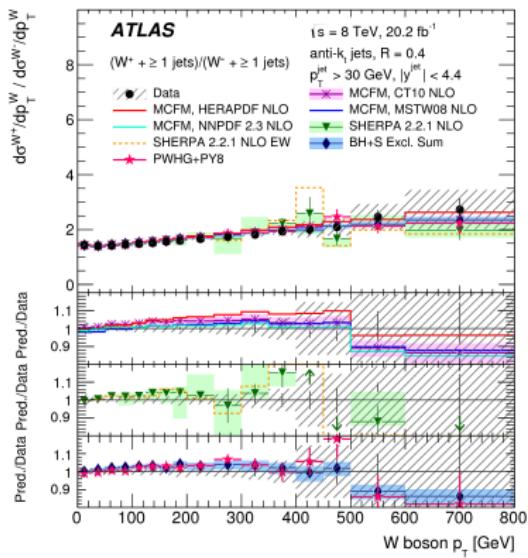
- Comparison to a variety of theoretical predictions including NNLO
- Valuable input for the valence quark and gluon PDFs at high  $x$  ( $\approx 0.1 - 0.3$ )

# $W$ and $W^+/W^- + \text{jets}$ @ 8 TeV arXiv:1711.03296

- LO Sherpa diverges from the data at high multiplicities;  
NLO Sherpa provides a good description
- Offset in Alpgen+PS for  $W^+/W^- + \geq 1 \text{ jet}$   
→ due to ME calculation and/or u/d ratio in the LO PDF
- Data/predictions agreement much improved in  $W^+/W^-$   
→ theoretical mismodelling related to jet emission cancels out in the ratio

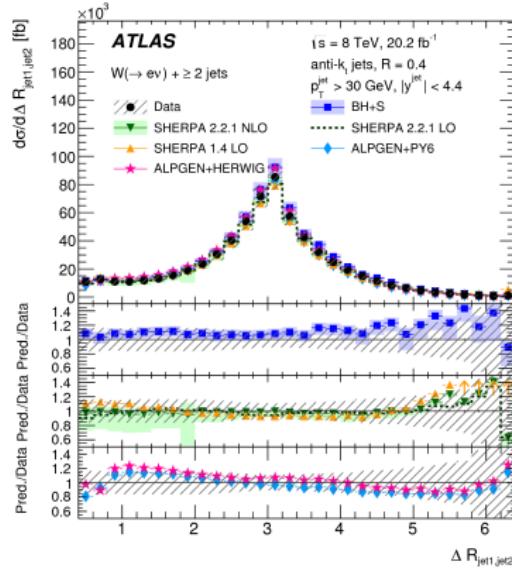
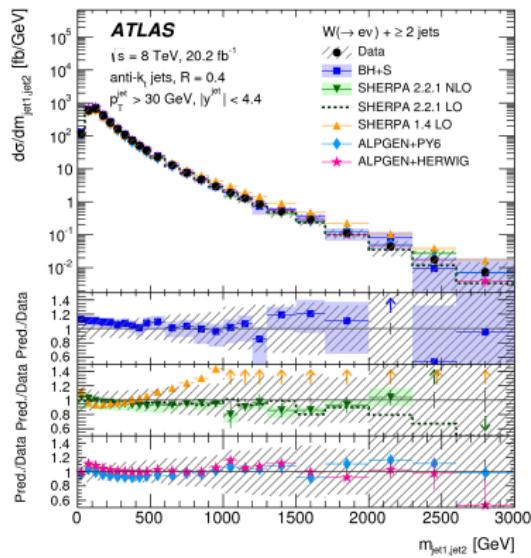


- MCFM predictions differ by  $\sim 2 - 5\%$  depending on the PDF set used
- Differences between data and MCFM predictions above experimental uncertainties for  $W$  boson  $p_T \sim 200 - 400$  GeV  
**→ results useful for PDF fits**

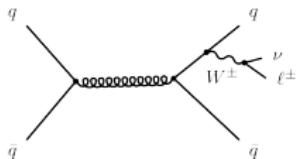


# W and $W^+/W^- + \text{jets}$ @ 8 TeV arXiv:1711.03296

- $\Delta R_{\text{jet}1,\text{jet}2}$  and  $M_{\text{jet}1,\text{jet}2}$  sensitive to hard parton radiation at large angles and different ME/PS matching schemes
- Sherpa 1.4 predicts too many events at large  $\Delta R_{\text{jet}1,\text{jet}2}$  and  $M_{\text{jet}1,\text{jet}2}$
- Both Alpgen+Herwig and Alpgen+Py6 do not describe  $\Delta R_{\text{jet}1,\text{jet}2}$  well

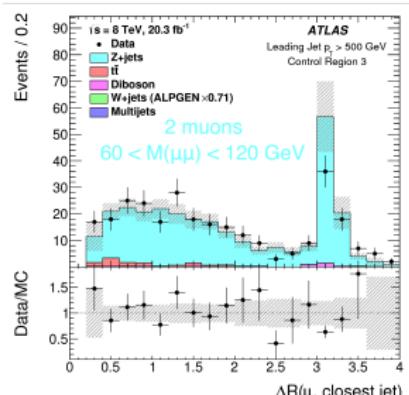
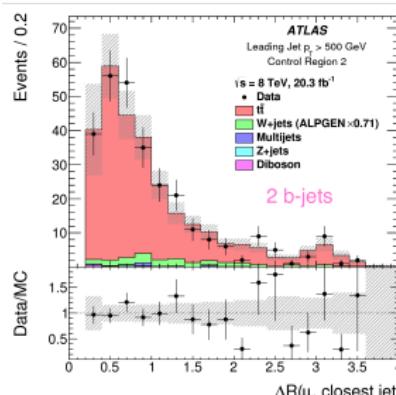
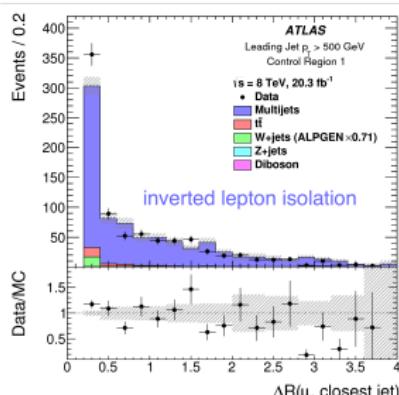


**Collinear W + jets @ 8 TeV**

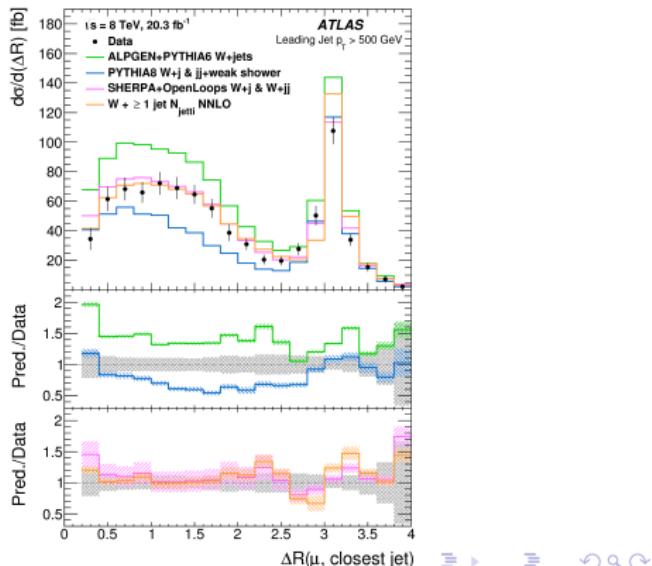
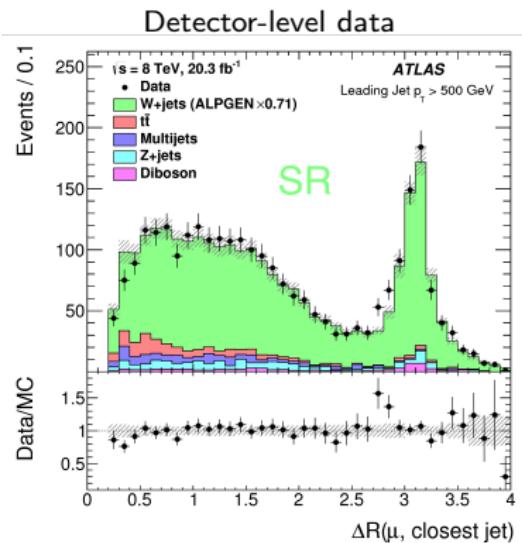


Probe real W emission by studying the region of small angular separation between W and jet

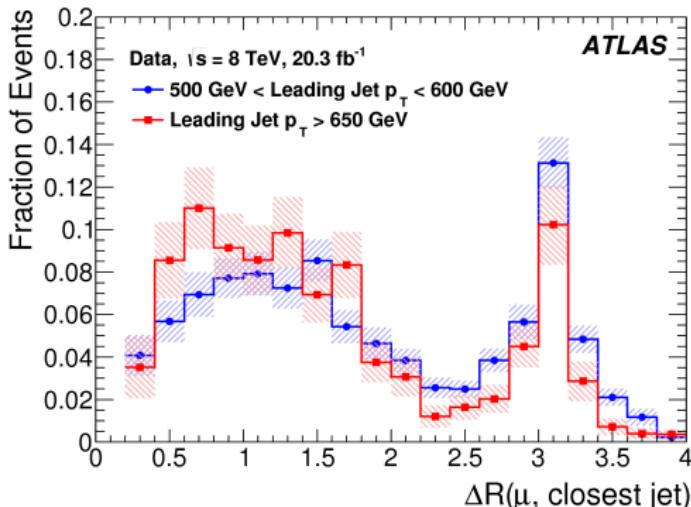
- Muon and initial W directions are highly correlated  
→ measure  $\sigma_{W(\rightarrow \mu\nu)+\text{jets}}$  as a function of  $\Delta R(\mu, \text{closest jet})$
- Leading jet  $p_T > 500$  GeV → enriches collinear production of W + jets
- Normalization correction of W + jets, multijet, tt> and Z + jets in data control regions



- LO ME **Alpgen+Pythia** describes shape well but overestimates total cross section; **Pythia8** (incl. dijet+weak shower) underestimates data at low  $\Delta R(\mu, \text{closest jet})$
- NLO QCD+EW **Sherpa+OpenLoops** and **N<sub>jetti</sub> NNLO** agree with data within uncertainties



- Fraction of collinear events increases with increasing leading jet  $p_T$   
→ also with centre of mass energy
- Real W emission important for W + jets measurements at high  $p_T$ ,  
vector boson scattering, QCD multijets at high  $m_{jj}$
- High potential to mimic highly Lorentz-boosted top quark  
→ important for new physics searches



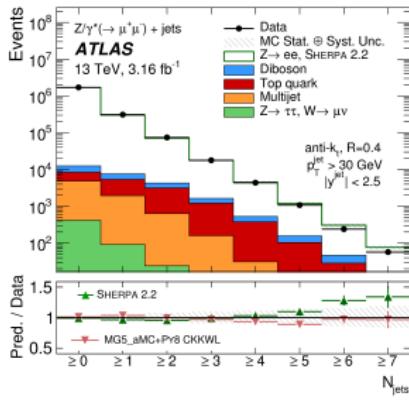
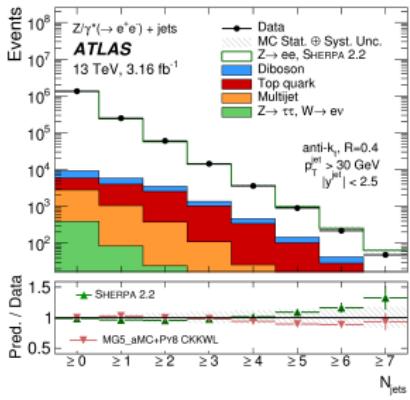
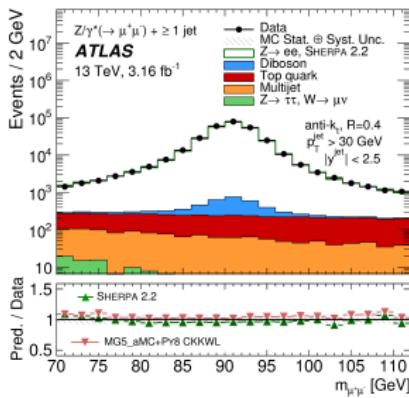
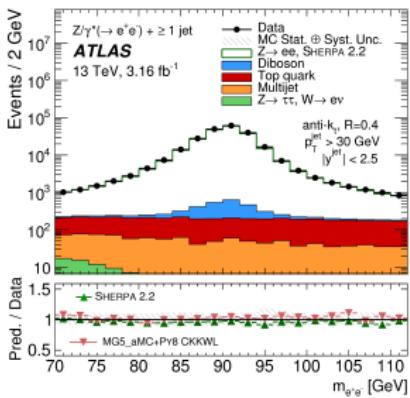
# Summary

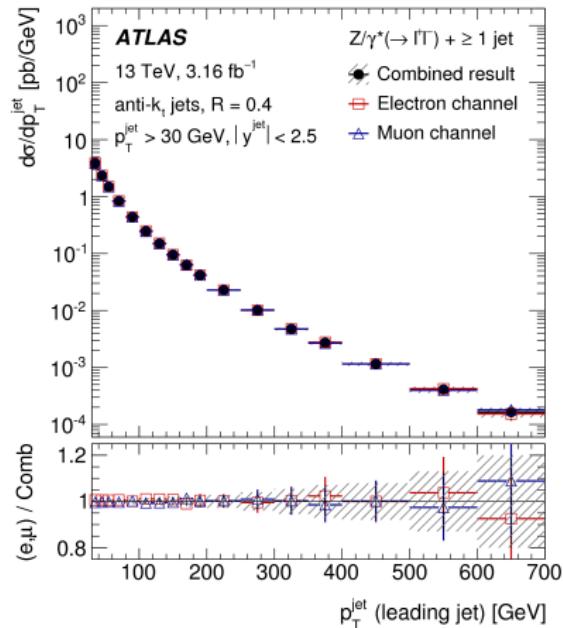
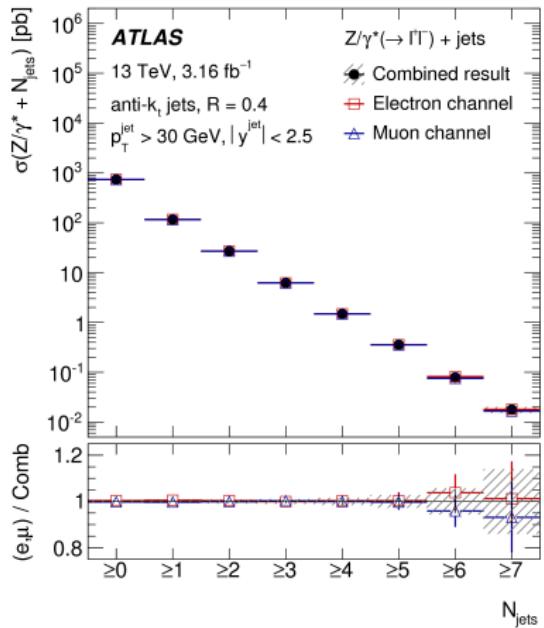
- ATLAS data provide useful inputs for Monte Carlo tuning
  - ▶ **Z + jets @ 13 TeV** - powerful test of pQCD
  - ▶ **W and  $W^+/W^-$  + jets @ 8 TeV** - precise pQCD calculations test and useful input for global PDF fits
  - ▶ **Collinear W + jets @ 8 TeV** - probe of real W emission, important for W + jets measurements at high  $p_T$ , vector boson scattering, QCD multijets at high  $m_{jj}$
- $N_{\text{jetti}}$  NNLO W/Z +  $\geq 1$  jet calculations tested, good agreement with measured data
- A lot of new exiting results are expected soon with Run 1 and Run 2 data

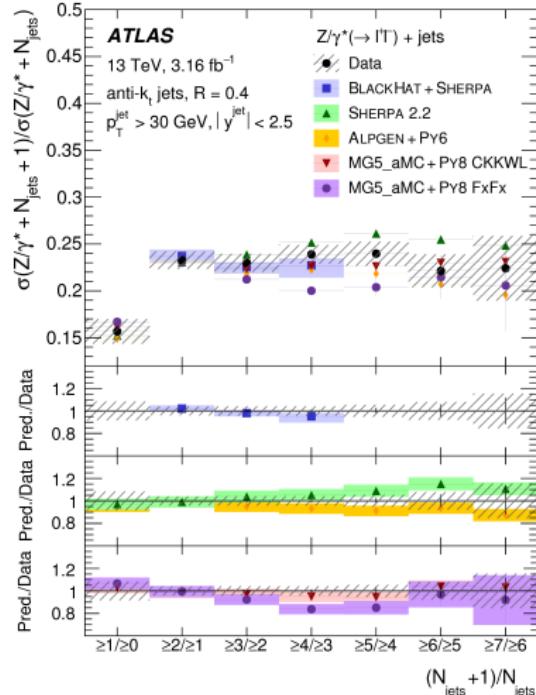
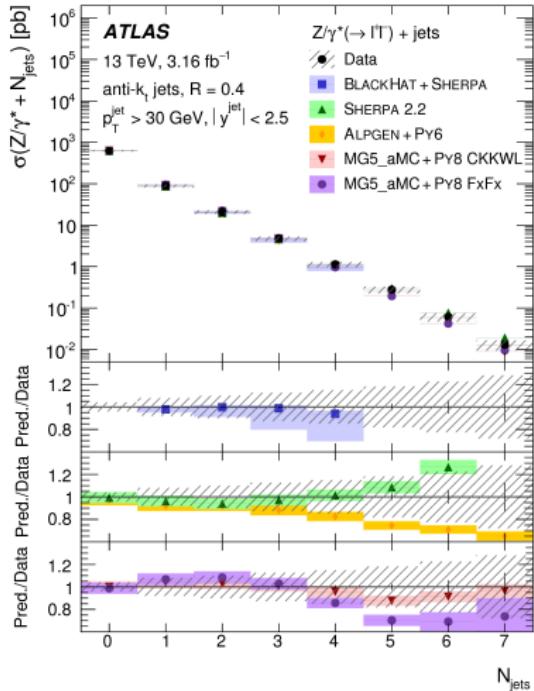
Z + jets @ 13 TeV

# Z + jets @ 13 TeV

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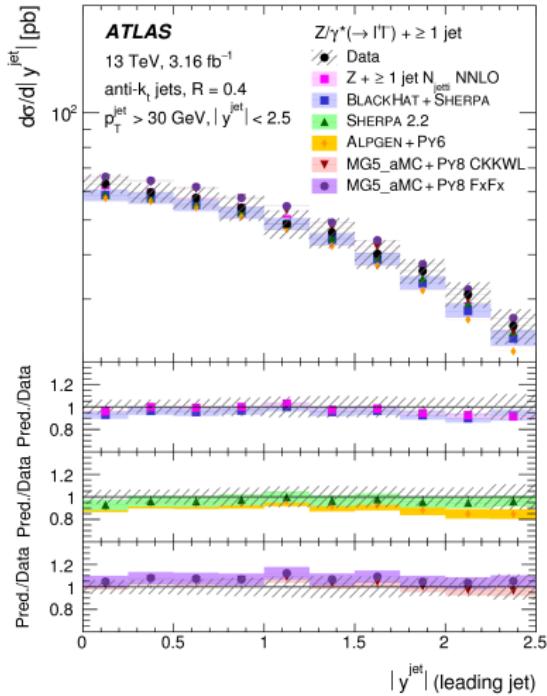
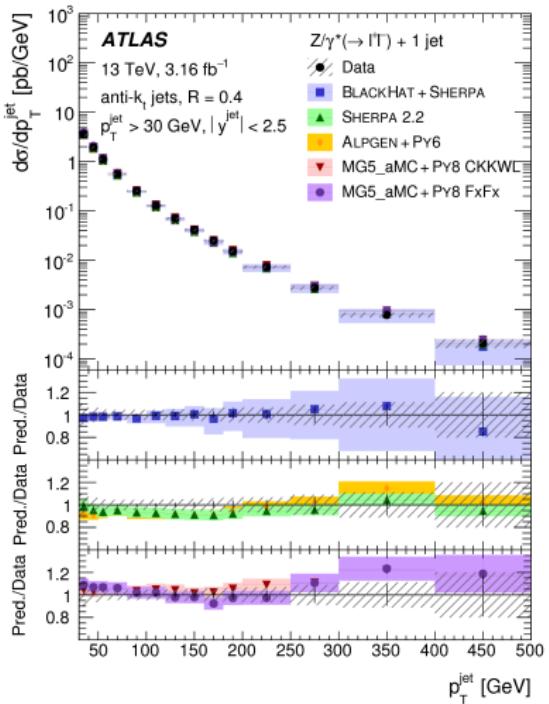


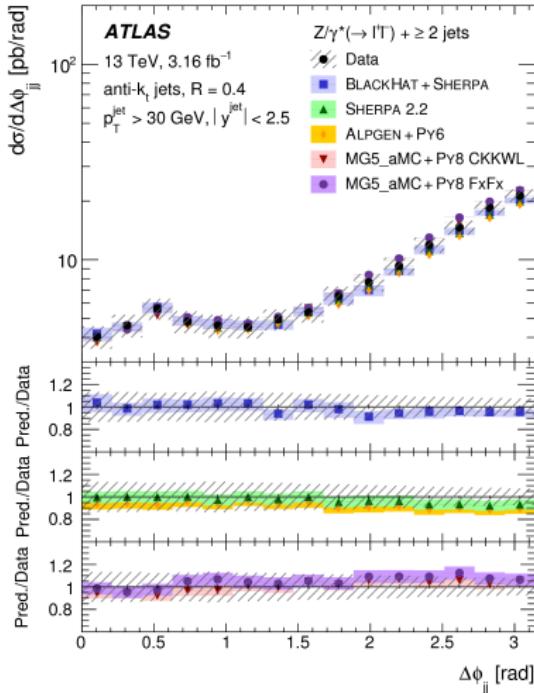
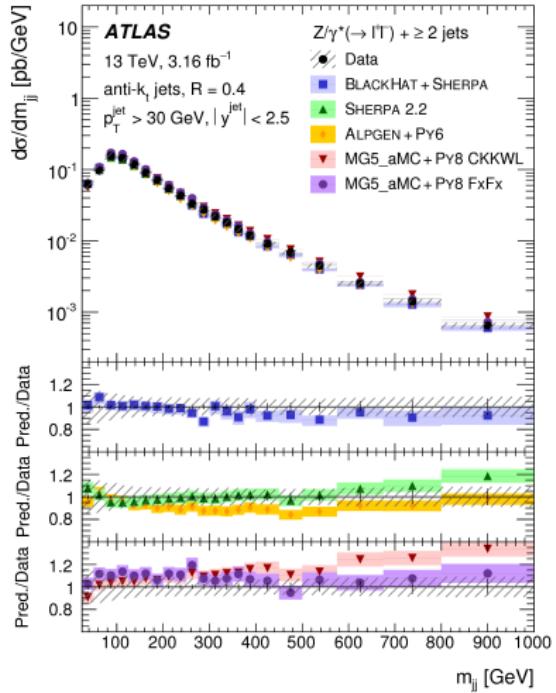


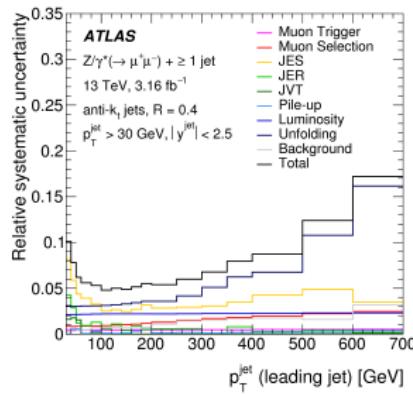
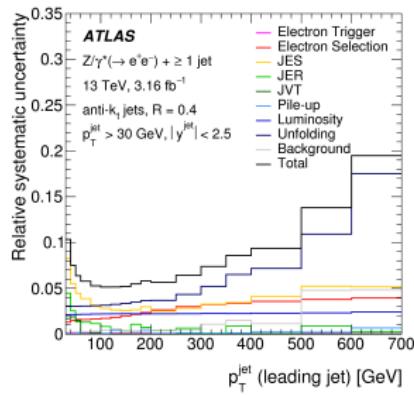
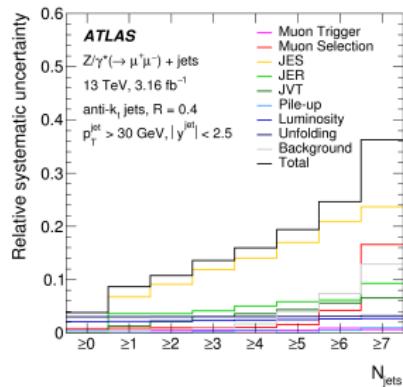
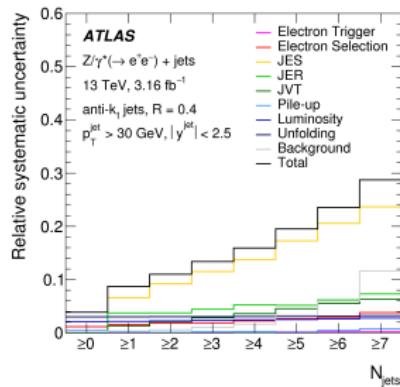


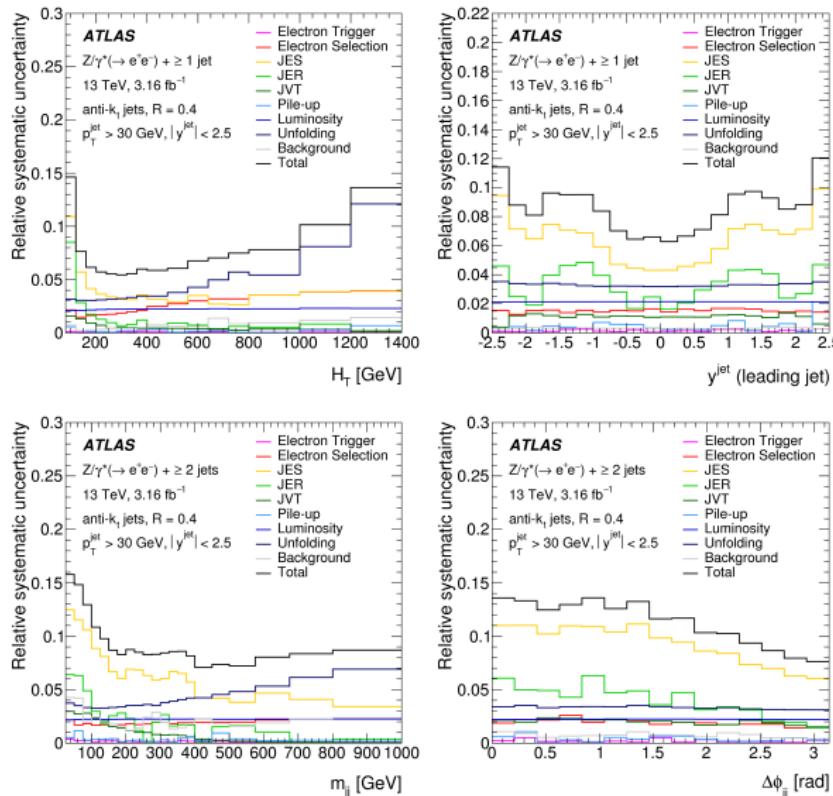
# Z + jets @ 13 TeV

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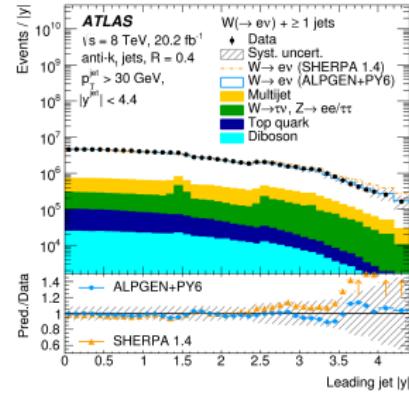
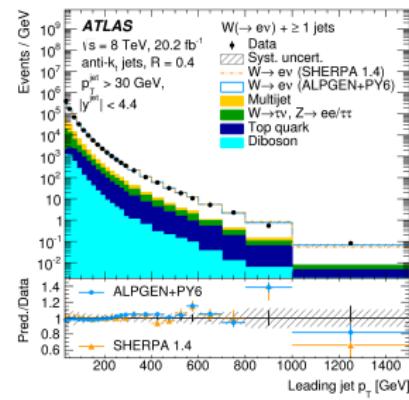
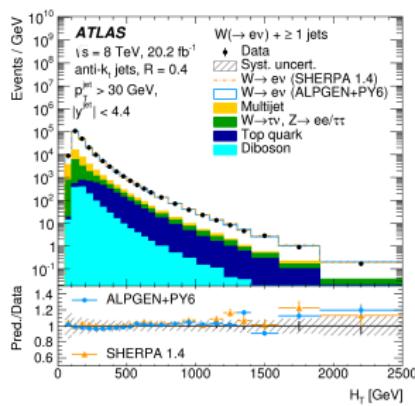
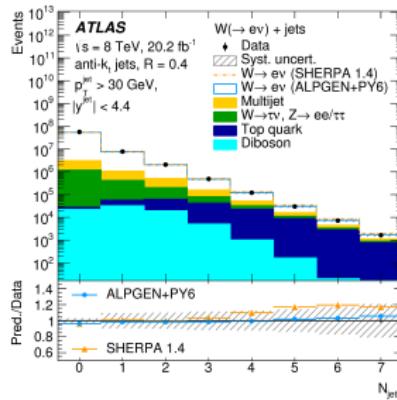
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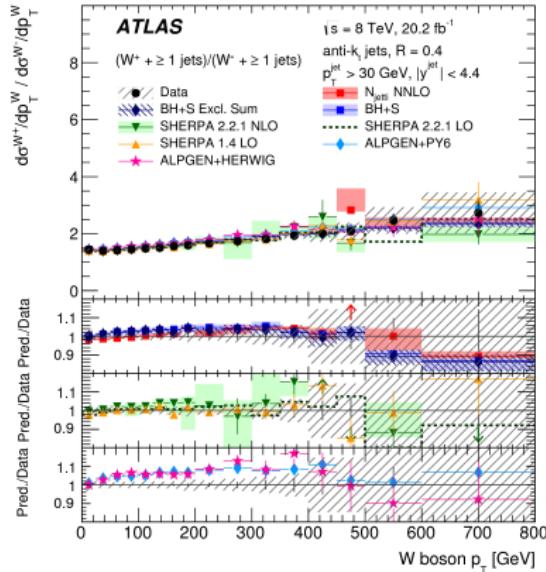
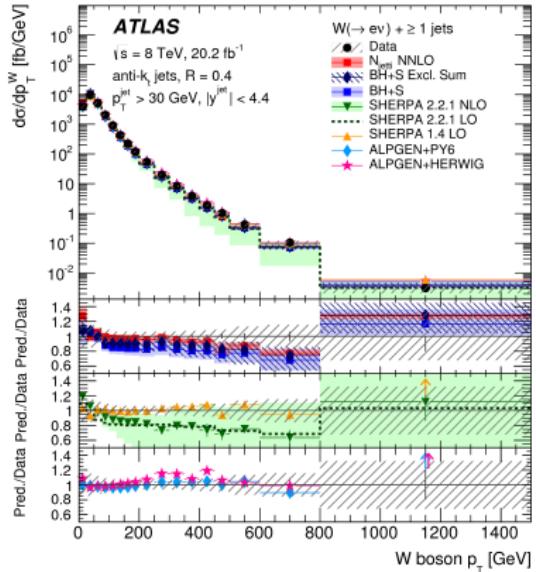
Relative uncertainty in $\sigma(Z(\rightarrow \ell^+\ell^-) + \geq N_{\text{jets}}) [\%]$								
	$Z \rightarrow e^+e^-$							
Systematic source	+ $\geq 0$ jet	+ $\geq 1$ jet	+ $\geq 2$ jets	+ $\geq 3$ jets	+ $\geq 4$ jets	+ $\geq 5$ jets	+ $\geq 6$ jets	+ $\geq 7$ jets
Electron trigger	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3
Electron selection	1.2	1.6	1.8	1.9	2.3	2.7	2.9	3.8
Jet energy scale	< 0.1	6.6	9.2	11.5	13.8	17.3	20.6	23.7
Jet energy resolution	< 0.1	3.7	3.7	4.4	5.3	5.2	6.2	7.3
Jet vertex tagger	< 0.1	1.3	2.1	2.8	3.6	4.5	5.5	6.3
Pile-up	0.4	0.2	0.1	0.2	0.2	0.1	0.4	0.8
Luminosity	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.8
Unfolding	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.2
Background	0.1	0.3	0.6	1.0	1.6	3.3	6.0	11.6
Syst. uncertainty	3.9	8.7	11.0	13.4	15.9	19.5	23.6	28.7
Stat. uncertainty	0.1	0.2	0.5	0.9	1.9	3.7	7.7	15.9
Z → $\mu^+\mu^-$								
Systematic source	+ $\geq 0$ jet	+ $\geq 1$ jet	+ $\geq 2$ jets	+ $\geq 3$ jets	+ $\geq 4$ jets	+ $\geq 5$ jets	+ $\geq 6$ jets	+ $\geq 7$ jets
Muon trigger	0.4	0.5	0.4	0.5	0.4	0.5	0.9	0.6
Muon selection	0.8	0.9	1.0	1.0	1.0	1.5	4.2	16.6
Jet energy scale	< 0.1	6.8	9.1	11.9	14.0	17.0	20.9	23.7
Jet energy resolution	< 0.1	3.6	3.6	4.1	5.0	5.9	6.2	9.3
Jet vertex tagger	< 0.1	1.3	2.1	3.1	3.6	4.4	5.6	6.6
Pile-up	0.4	0.1	0.0	0.3	0.5	0.1	0.4	0.9
Luminosity	2.1	2.1	2.2	2.3	2.4	2.5	2.6	2.7
Unfolding	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.2
Background	0.2	0.4	0.6	0.9	1.7	4.0	7.4	12.9
Syst. uncertainty	3.8	8.7	10.8	13.6	16.0	19.41	24.6	36.3
Stat. uncertainty	0.1	0.2	0.4	0.8	1.7	3.4	7.2	16.3

**W and  $W^+ / W^- + \text{jets}$  @ 8 TeV**

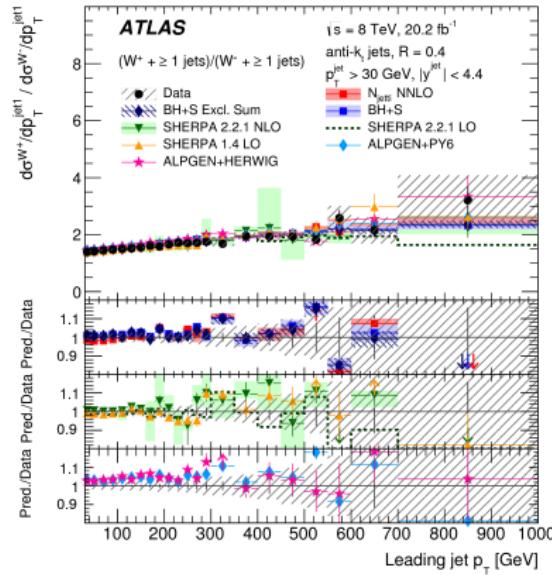
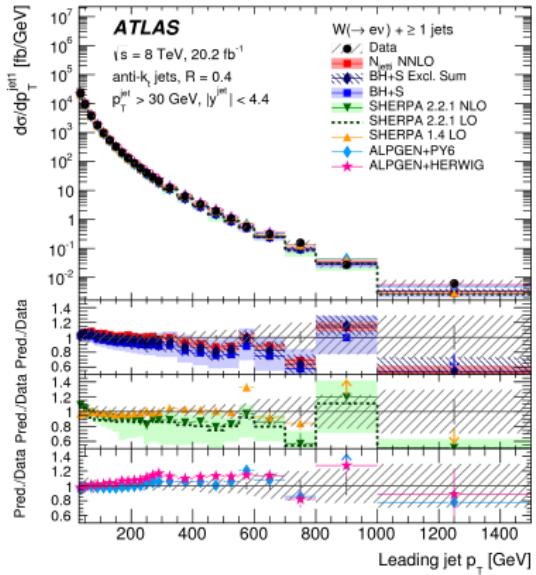
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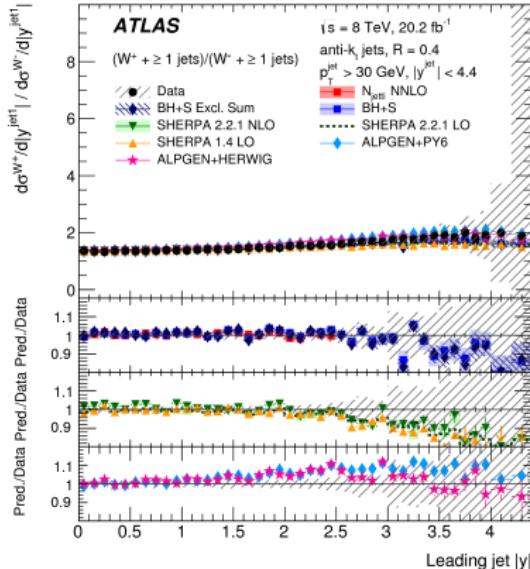
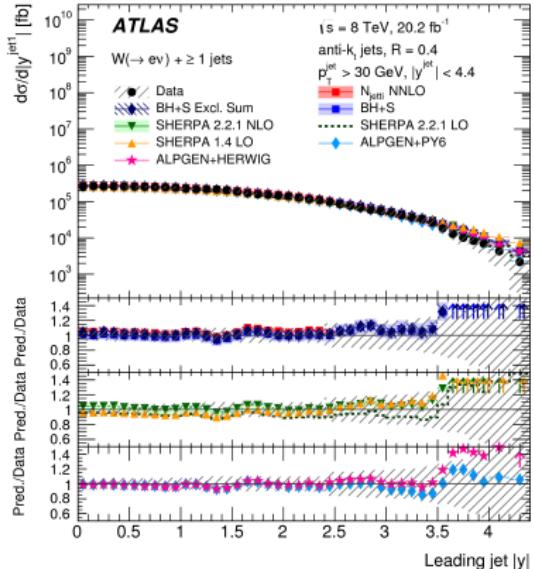
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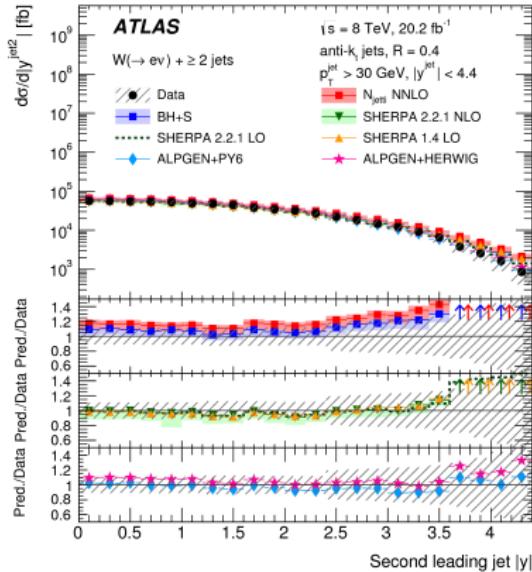
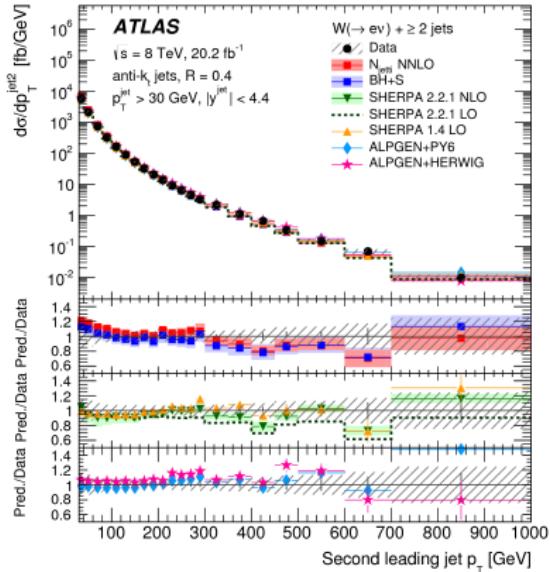
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## $W + \text{jets}$

	Inclusive	$\geq 1$ jet	$\geq 2$ jets	$\geq 3$ jets	$\geq 4$ jets	$\geq 5$ jets	$\geq 6$ jets	$\geq 7$ jets
Jet energy scale	0.1	7.5	10	14	18	27	38	55
Jet energy resolution	0.5	8.8	9.9	12	14	15	18	20
$b$ -tagging	0.1	0.5	1.5	3.8	8.3	15	23	33
Electron	1.1	1.4	1.4	1.5	1.8	2.1	2.1	2.1
$E_T^{\text{miss}}$	1.1	2.6	4.2	5.5	7.1	8.8	12	14
Multijet background	0.5	1.3	2.1	2.6	2.5	4.7	8.8	12
Top quark background	<0.1	0.2	0.8	2.5	5.7	10	16	22
Other backgrounds	<0.1	0.1	0.2	0.3	0.5	1.0	1.7	2.6
Unfolding	4.7	4.1	4.9	4.4	4.0	4.7	6.9	7.2
Other	0.3	0.8	1.0	2.1	4.6	8.7	14	21
Luminosity	0.1	0.2	0.4	0.7	1.2	2.0	2.9	4.2
Total systematic uncert.	5.0	13	16	20	27	38	55	76

## $W^+/W^- + \text{jets}$

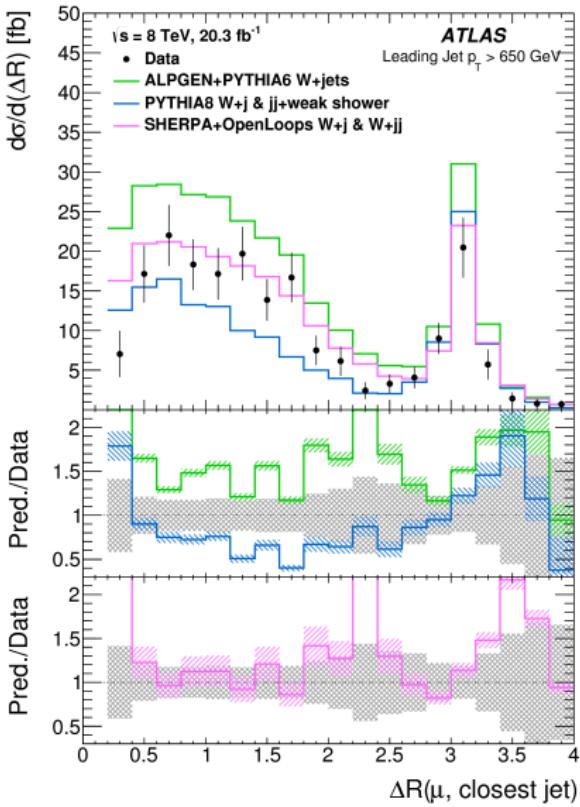
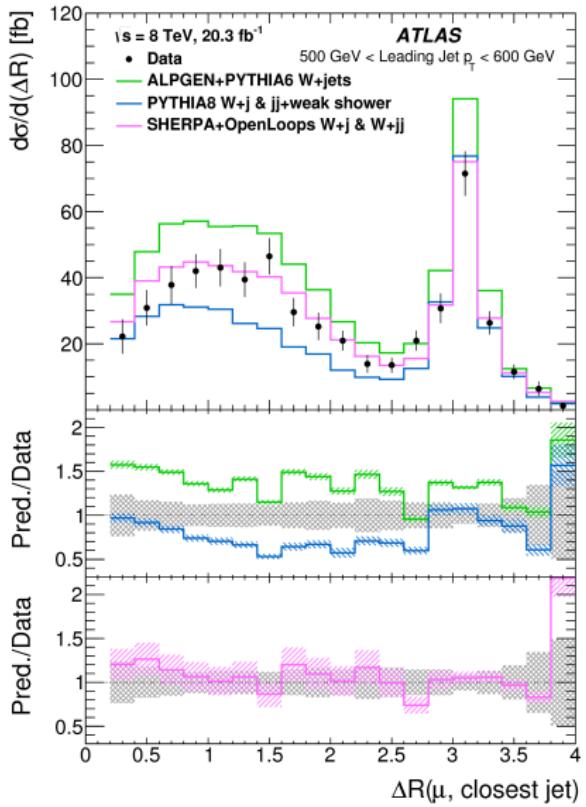
	Inclusive	$\geq 1$ jet	$\geq 2$ jets	$\geq 3$ jets	$\geq 4$ jets	$\geq 5$ jets	$\geq 6$ jets
Jet energy scale	<0.1	0.3	1.2	2.3	3.9	9.2	17
Jet energy resolution	0.1	0.7	1.6	2.5	2.6	3.0	4.6
$b$ -tagging	<0.1	0.2	0.5	1.5	4.2	9.4	17
Electron	0.1	0.1	0.1	0.1	0.5	0.5	0.5
$E_T^{\text{miss}}$	0.1	0.8	1.9	2.8	3.8	5.5	6.1
Multijet background	0.3	1.2	2.9	3.2	5.9	15	27
Top quark background	<0.1	0.1	0.3	1.2	3.3	7.0	12
Other backgrounds	<0.1	0.1	0.2	0.3	0.7	1.7	2.8
Unfolding	0.6	0.5	0.6	0.7	1.3	1.8	2.7
Other	<0.1	0.1	0.3	0.9	2.4	6.4	13
Luminosity	<0.1	<0.1	0.1	0.2	0.5	1.1	1.8
Total systematic uncert.	0.7	1.8	4.1	5.9	10	23	41

# $W$ and $W^+/W^- + \text{jets}$ @ 8 TeV [arXiv:1711.03296](https://arxiv.org/abs/1711.03296)

Program	Order in $\alpha_S$	$N_{\text{partons}}^{\max}$ at highest order	PDF set	NPC	PS	Comments
$N_{\text{jetti}}$	NNLO	1	CT14	✓		Not shown for $N_{\text{jets}}$ , $\Delta R_{\text{jet1,jet2}}$ and $m_{\text{jet1,jet2}}$
<b>BLACKHAT+SHERPA</b>	NLO	1, 2 or 3	CT10	✓		
<b>MCFM 6.8</b>	NLO	1 + 3 more	CT10	✓		Figure 7 only
<b>POWHEG+PYTHIA 8</b>	NLO	1	CT14	✓		Figure 7 only
<b>SHERPA 2.2.1</b>	NLO	2	CT10	✓		Including NLO EW corrections in Figure 7
<b>SHERPA 2.2.1</b>	LO	2 (3)	NNPDF 3.0	✓		
<b>ALPGEN+PYTHIA 6</b>	LO	5	CTEQ6L1 (LO)	✓		
<b>ALPGEN+HERWIG</b>	LO	5	CTEQ6L1 (LO)	✓		
<b>SHERPA 1.4.1</b>	LO	4	CT10	✓		

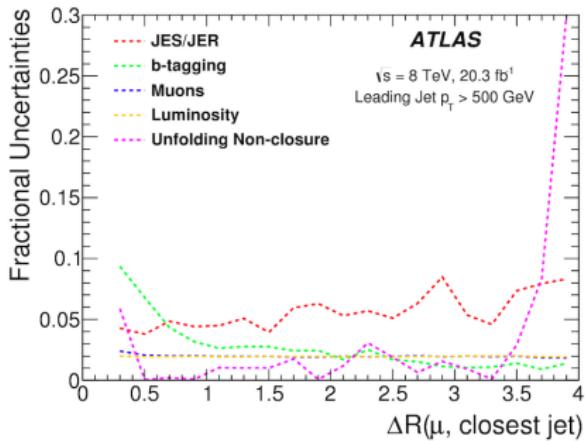
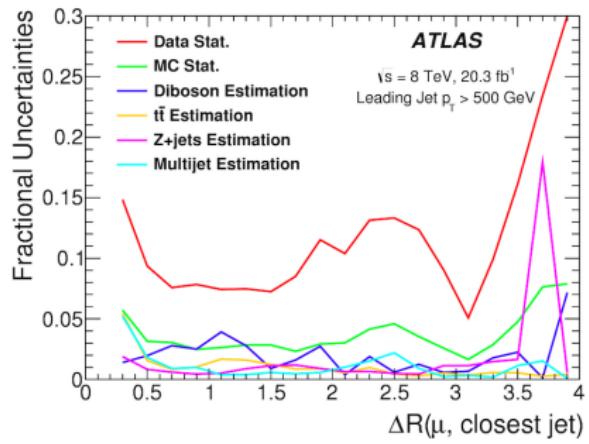
**Collinear W + jets @ 8 TeV**

# Collinear W + jets @ 8 TeV Phys. Lett. B 765 (2017) 132



# Collinear W + jets @ 8 TeV

Phys. Lett. B 765 (2017) 132



Systematic Source	$0.2 < \Delta R < 2.4$	$\Delta R > 2.4$	Inclusive
Scaling of dijets to data	0.4%	0.1%	0.3%
Scaling of $t\bar{t}$ to data	0.6%	0.2%	0.5%
Scaling of $Z + \text{jets}$ to data	0.6%	0.3%	0.5%
Jet energy scale	4.6%	5.8%	5.0%
$b$ -tagging efficiency	3.7%	1.2%	2.9%
Data/MC disagreement for dijets	0.9%	0.6%	0.8%
Data/MC disagreement for $t\bar{t}$	1.2%	0.4%	1.0%
Data/MC disagreement for $Z + \text{jets}$	0.6%	1.5%	0.9%
Diboson background estimate	2.2%	0.1%	1.5%
Unfolding dependence on prior	1.1%	1.8%	1.3%
Muon momentum scale and resolution	0.0%	0.1%	0.1%
Muon reconstruction efficiency	0.4%	0.4%	0.4%
Muon trigger efficiency	2.0%	1.9%	1.9%
Jet energy resolution	0.6%	0.8%	0.6%
MC background statistical	2.4%	1.8%	2.3%
MC response statistical	1.7%	2.2%	1.9%
Total systematic (excluding luminosity)	7.6%	7.4%	7.3%
Luminosity	1.9%	2.0%	2.0%
Data statistical	2.7%	3.6%	2.2%