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

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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
  $\rightarrow$ Monte Carlo (MC) prediction must be tuned and validated using data

In this talk:

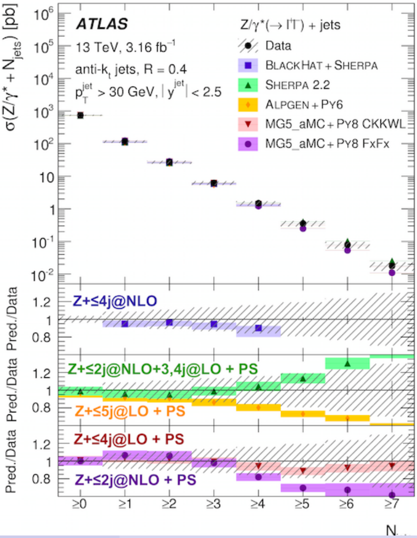
- Measurements of the production cross section of a Z boson in association with jets in pp collisions at $\sqrt{s} = \mathbf{13}$ **TeV** with the ATLAS detector ($\mathbf{3.16\ fb^{-1}}$) arXiv:1702.05725
- Measurement of W boson angular distributions in events with high transverse momentum jets at $\sqrt{s} = \mathbf{8}$ **TeV** using the ATLAS detector ($\mathbf{20.3\ fb^{-1}}$) Phys. Lett. B 765 (2017) 132
- **New!** Measurement of the k_T splitting scales in $Z \rightarrow ll$ events in pp collisions at $\sqrt{s} = \mathbf{8}$ **TeV** with the ATLAS detector ($\mathbf{20.2\ fb^{-1}}$)

Z + jets @ 13 TeV

Z + jets @ 13 TeV arXiv:1702.05725

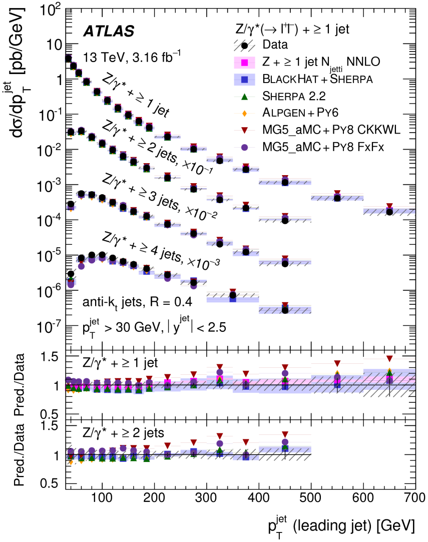
- Sensitive probe of different MC approaches
- $Z \to ee$ and $Z \to \mu\mu$ combined for higher precision
- Differential cross sections measured for N_{jets}, $\frac{N_{jets}+1}{N_{jets}}$, p_T^{jet}, $|y_{jet}|$, H_T, m_{jj}, $\Delta\phi_{jj}$
- Comparison with LO and NLO ME MC generators, NLO and N_{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 $R = 0.4$, $p_T^{jet} > 30$ GeV, $|y_{jet}| < 2.5$



Z + jets @ 13 TeV arXiv:1702.05725

- LO MG5_aMC + Py8 CKKWL models too hard p_T^{jet} spectrum for $p_T^{jet} > 200$ GeV
  $\rightarrow$ dynamic μ_F and μ_R used in the generation not appropriate for the full p_T^{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^{jet} range
- N_{jetti} NNLO models well the p_T^{jet} spectrum for Z + $\geq$ 1 jet



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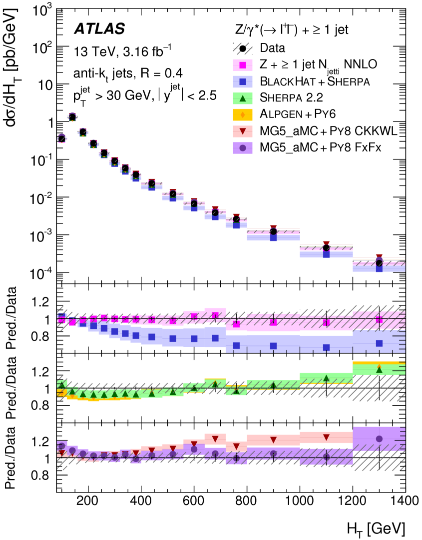
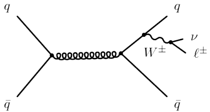


- H_T - scalar sum of the p_T of all visible objects
  - common variable in beyond SM searches for heavy particles
  - often used as scale variable in pQCD
- BlackHat + Sherpa underestimates data in $H_T > 300$ GeV (missing higher orders)
- N_{jetti} NNLO recovers agreement by adding higher orders in pQCD

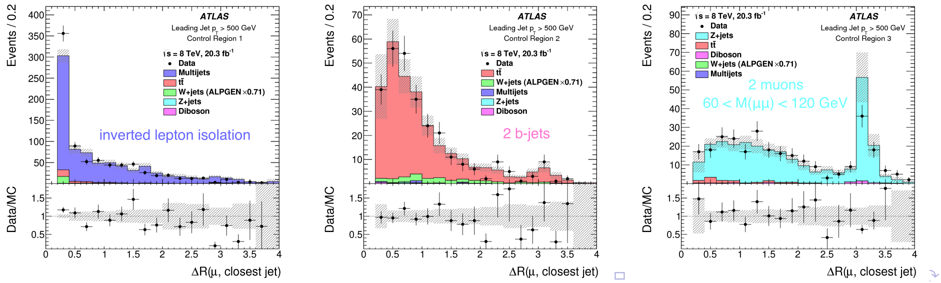
Collinear W + jets @ 8 TeV

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



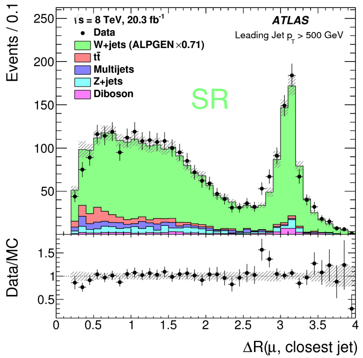
Probe real W emission by studying the region of small angular separation between W and jet

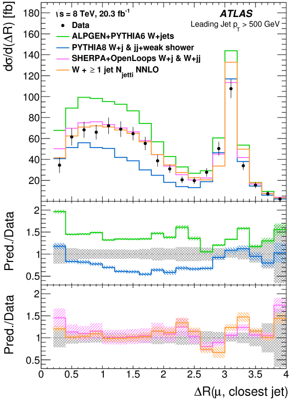
- Muon and initial W directions are highly correlated
  $\Rightarrow$ measure $\sigma_{\mathtt{W}(\rightarrow\mu\nu)+\mathtt{jets}}$ as a function of $\Delta\mathtt{R}(\mu, \mathtt{closest\ jet})$
- Leading jet $p_T > 500$ GeV $\rightarrow$ enriches collinear production of $\mathtt{W} + \mathtt{jets}$
- Normalization correction of $\mathtt{W} + \mathtt{jets}$, multijet, $\mathtt{t\bar{t}}$ and $\mathtt{Z} + \mathtt{jets}$ 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 $\Delta R(\mu, \texttt{closest jet})$
- NLO QCD+EW Sherpa+OpenLoops and $\texttt{N}_{\texttt{jetti}}$ NNLO agree with data within uncertainties

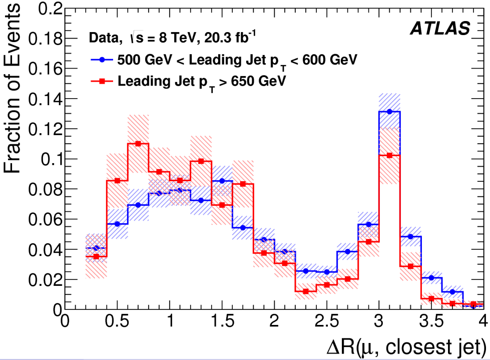
Detector-level data





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

- Fraction of collinear events increases with increasing leading jet p_T
  $\rightarrow$ 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
  $\rightarrow$ important for new physics searches



k_T splittings in Z + jets @ 8 TeV

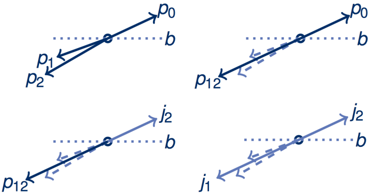
k_T splittings in Z + jets @ 8 TeV

k_T algorithm:

$d_{ij} = \min(p_{T,i}^2, p_{T,j}^2) \times \frac{\Delta R_{ij}^2}{R^2}$, $d_{iB} = p_{T,i}^2$,
$\Delta R^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$

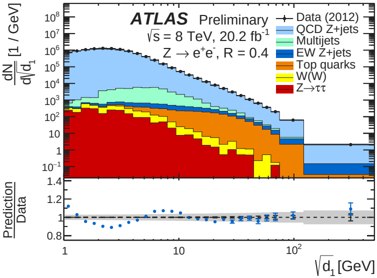
- $d_{ij} < d_{iB}$: combine i and j
- $d_{ij} > d_{iB}$: remove i, call it jet

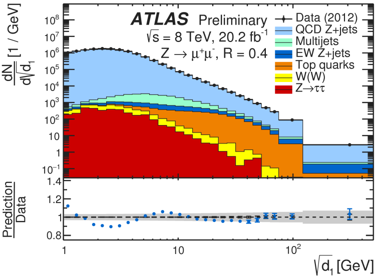
Iterate until input collection is empty



- k_T recombination approximates QCD evolution
- **Splitting scale $\mathbf{d_k = \min(d_{ij}, d_{ib})}$:**
  number of input momenta drops from $k + 1$ to k
  - d_0 is a leading jet p_T
  - higher orders probe QCD evolution

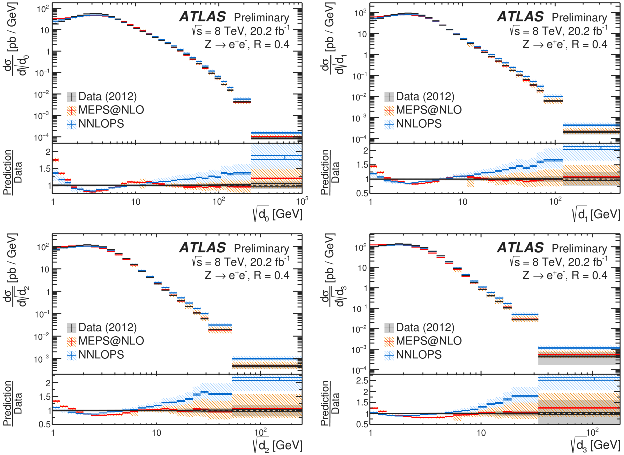
- Measured differential cross sections of $Z \to ll$, $l = e, \mu$, as a function of splitting scales $\sqrt{d_k}$, $k = 0...7$
  - sensitive to hard perturbative modelling at high scales, to soft hadronic activity at low scales
- $71 < m_{ll} < 111$ GeV, $p_T^{lep} > 25$ GeV, $|\eta_{lep}| < 2.5$
- Splitting scales $\sqrt{d_k}$ constructed from ID tracks with $p_T > 400$ MeV ("*charged-only*")
- Jet-radius parameters $R = 0.4$ and $R = 1.0$ are used





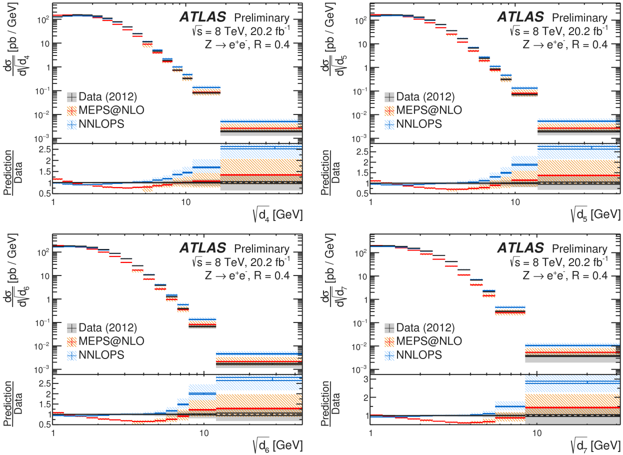
k_T splittings in Z + jets @ 8 TeV

- Compared to Sherpa (MEPS@NLO) and DY@NNLO+Powheg+Pythia8 (NNLOPS)
- Both predictions underestimate data in the peak region of the lower-order splitting scales
- In hard perturbative region NNLOPS overestimates cross section, MEPS@NLO provides good description



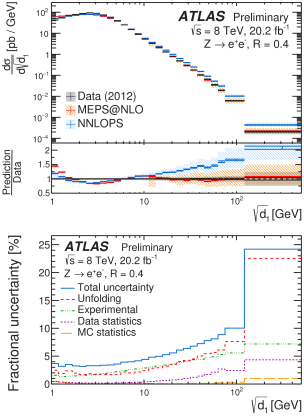
k_T splittings in Z + jets @ 8 TeV

- NNLOPS description improved significantly in the soft region for the higher-order splitting scales
- **Data can provide new input for non-perturbative parameters tuning**

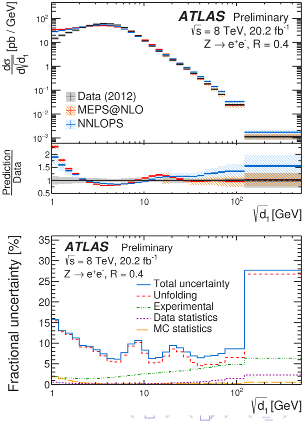


- Results extrapolated to "*charged+neutral*" for the benefit of theoretical calculations
- Uncertainty increase for the extrapolated results

"*charged-only*"



"*charged+neutral*"

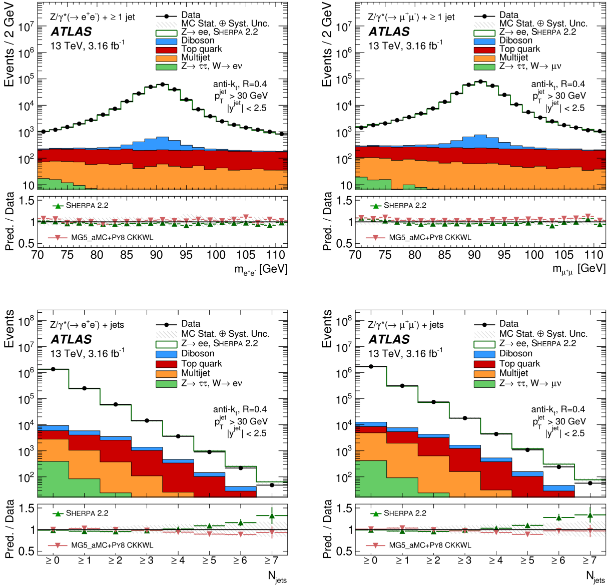


Summary

- ATLAS data provide useful inputs for Monte Carlo tuning
  - **$\mathbf{Z+jets}$ @ 13 TeV** - powerful test of pQCD
  - **Collinear $\mathbf{W+jets}$ @ 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}
  - **$\mathbf{k_T}$ splittings in $\mathbf{Z+jets}$ @ 8 TeV** - sensitive to the hard perturbative modelling as well as soft hadronic activity, complementary to standard jet measurements
- A lot of interesting Run 1 and Run 2 results are expected soon

Z + jets @ 13 TeV

Z + jets @ 13 TeV arXiv:1702.05725



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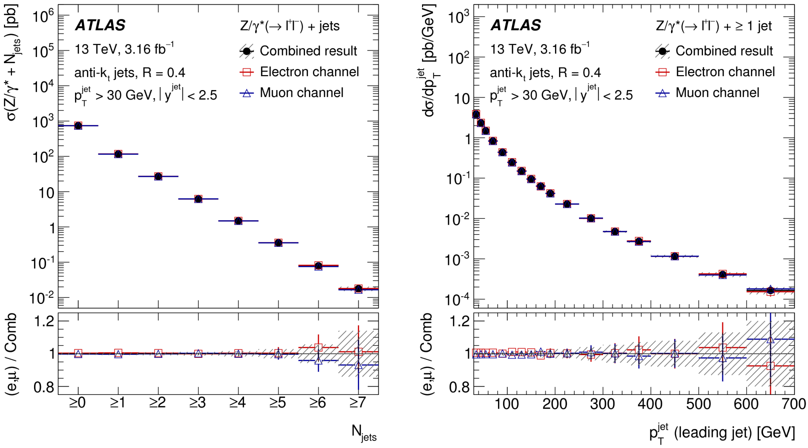

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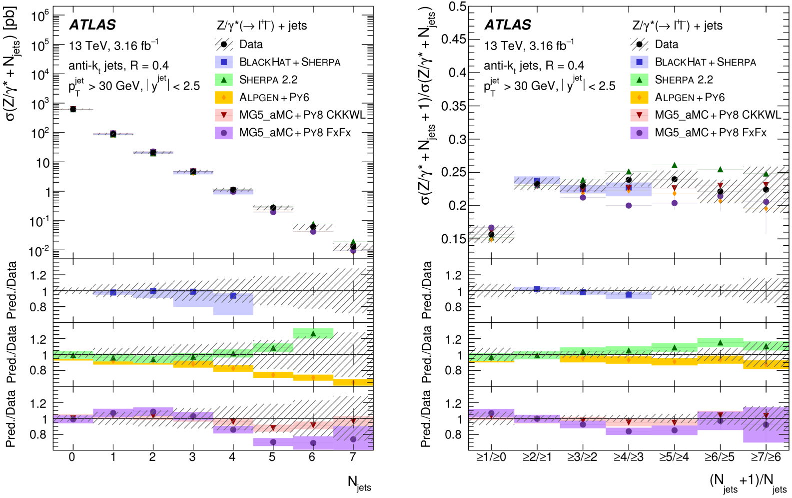

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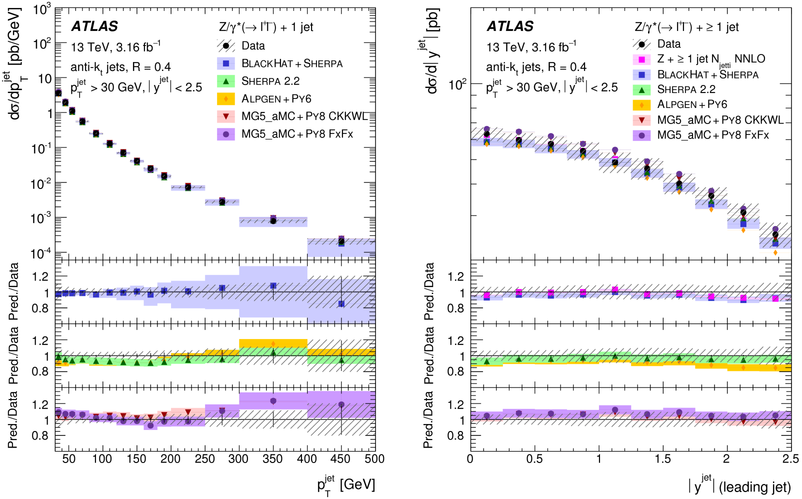

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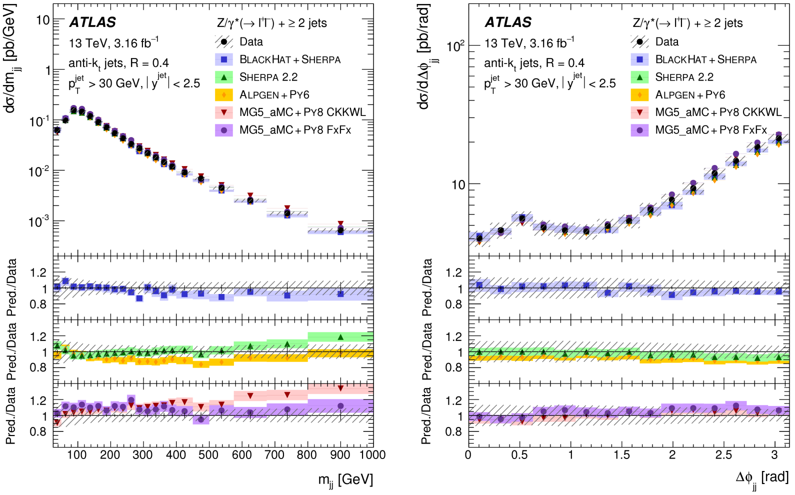

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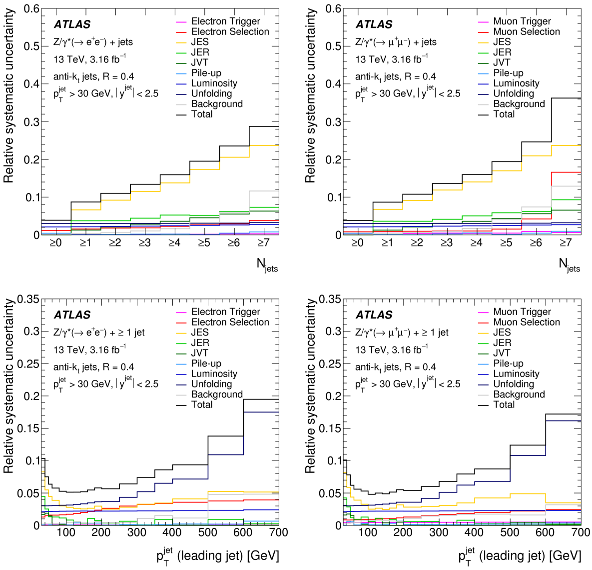

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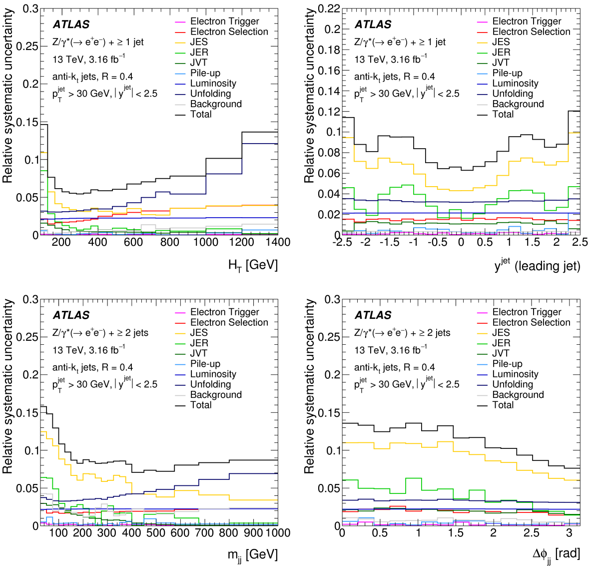
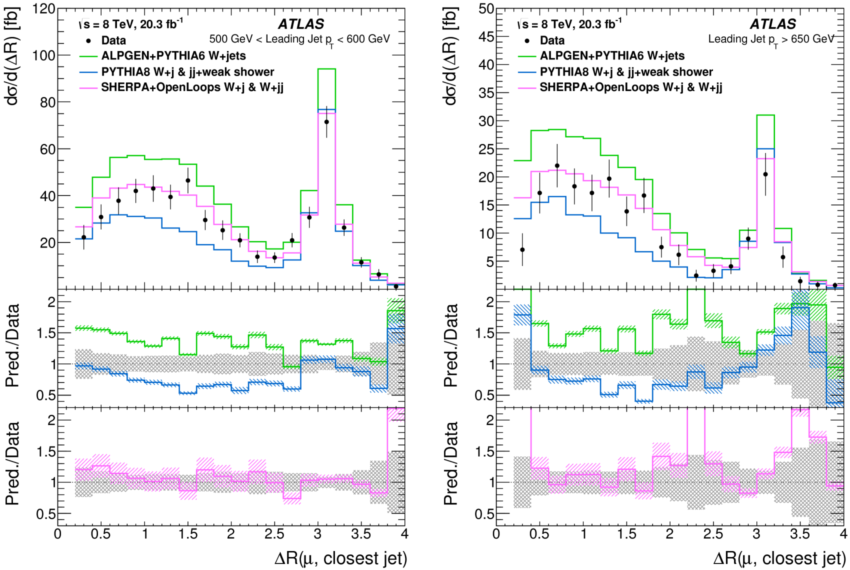


Z + jets @ 13 TeV arXiv:1702.05725

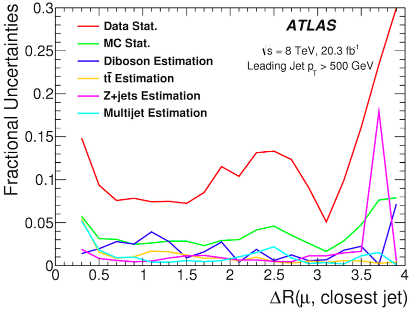
Relative uncertainty in $\sigma(Z(\rightarrow \ell^+\ell^-)+ \geq \mathrm{N_{jets}})$ [%]								
	$Z \rightarrow e^+e^-$							
Systematic source	+ $\geq$ 0 jet	+ $\geq$ 1 jet	+ $\geq$ 2 jets	+ $\geq$ 3 jets	+ $\geq$ 4 jets	+ $\geq$ 5 jets	+ $\geq$ 6 jets	+ $\geq$ 7 jets
Electron trigger	0.1	0.1	0.1	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
	$Z \rightarrow \mu^+\mu^-$							
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

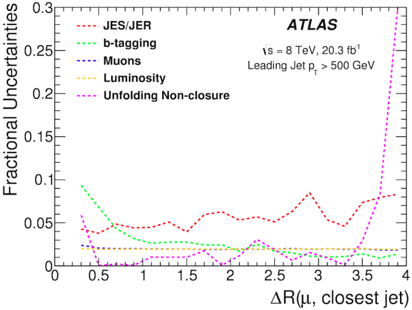
Collinear W + jets @ 8 TeV

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



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





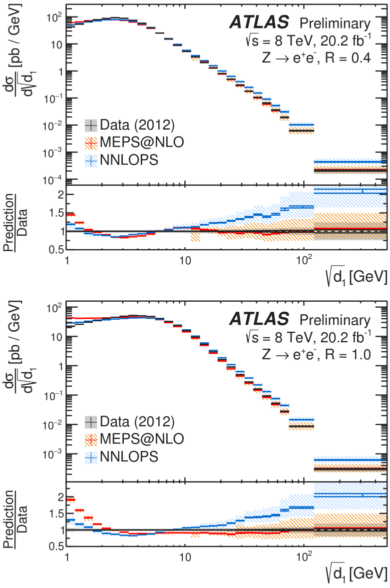
Collinear W + jets @ 8 TeV Phys. Lett. B 765 (2017) 132

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 + 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 + 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%

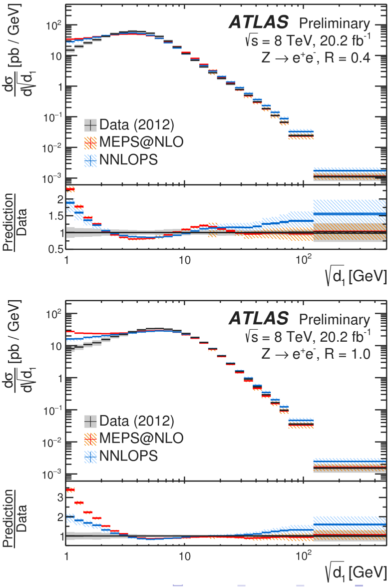
k_T splittings in Z + jets @ 8 TeV

k_T splittings in Z + jets @ 8 TeV

"*charged-only*"



"*charged+neutral*"



"*charged-only*" "*charged+neutral*"