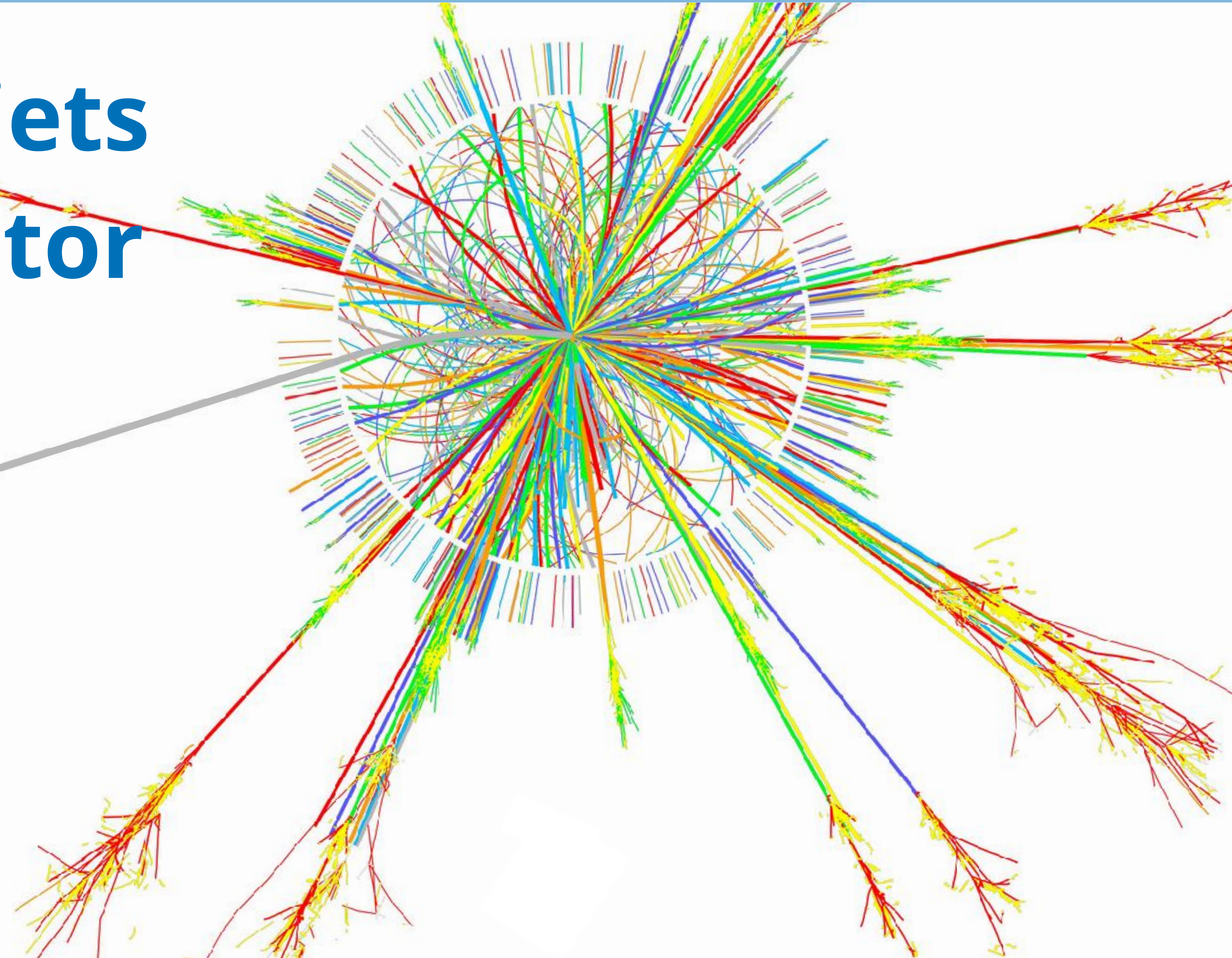
Measurements of V+jets with the ATLAS detector

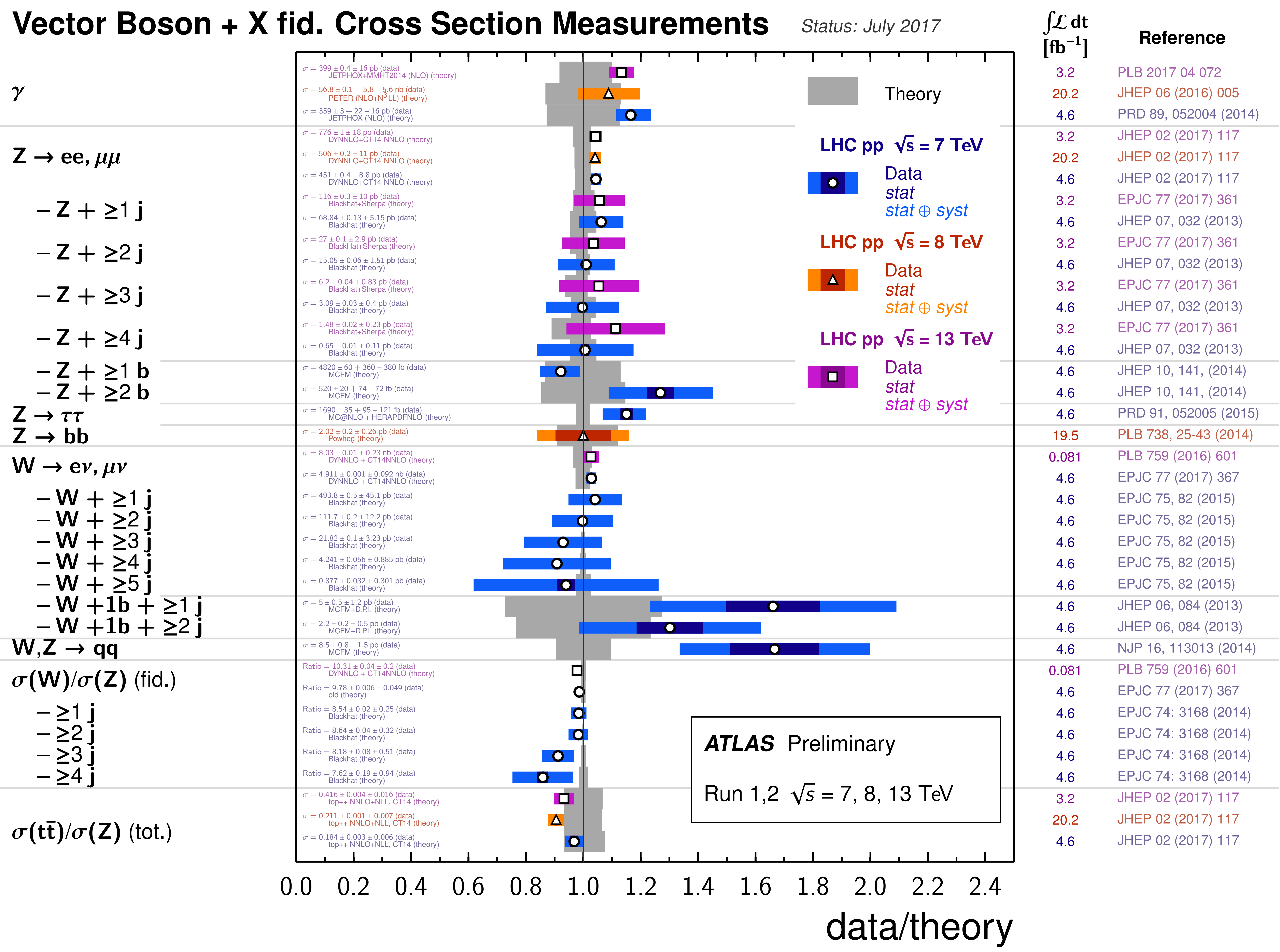


QCD@LHC 2017
Debrecen, Hungary
28/8/2017

Josh McFayden for the ATLAS Collaboration

Landscape & Motivation

- Increasingly precise measurements on V+jets production from the LHC experiments.
- Crucial for a better **understanding of QCD** and **more precise and accurate modelling** of these final states for analyses.



Analyses covered

- New or recent V+jets measurements to be presented:
  - 8 TeV kT-splittings
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-14/ (submitted to JHEP)
  - 7&8 TeV Electroweak W production
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-11/ (EPJC)
  - 8 TeV W boson angular distributions
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-16/ (PLB)
  - 13 TeV Z+jets
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-01/ (EPJC)

8 TeV k_T-splittings

[arXiv:1704.01530]

8TeV k_T-splittings | Overview

- Splitting scales are sensitive to the hard perturbative modelling at high scale values as well as soft hadronic activity at lower values.
  - Provide a valuable input complementary to standard jet measurements, in particular in the transition region.

- Splitting scales are measured for
  - $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ channels
  - jet-radius parameters of R = 0.4 and R = 1.0.
  - **Charged-particle tracks** are used for the analysis.

- Results are compared to state-of-the-art theoretical predictions with
  - NNLO accuracy matrix elements
  - Multi-leg NLO merging

[arXiv:1704.01530]

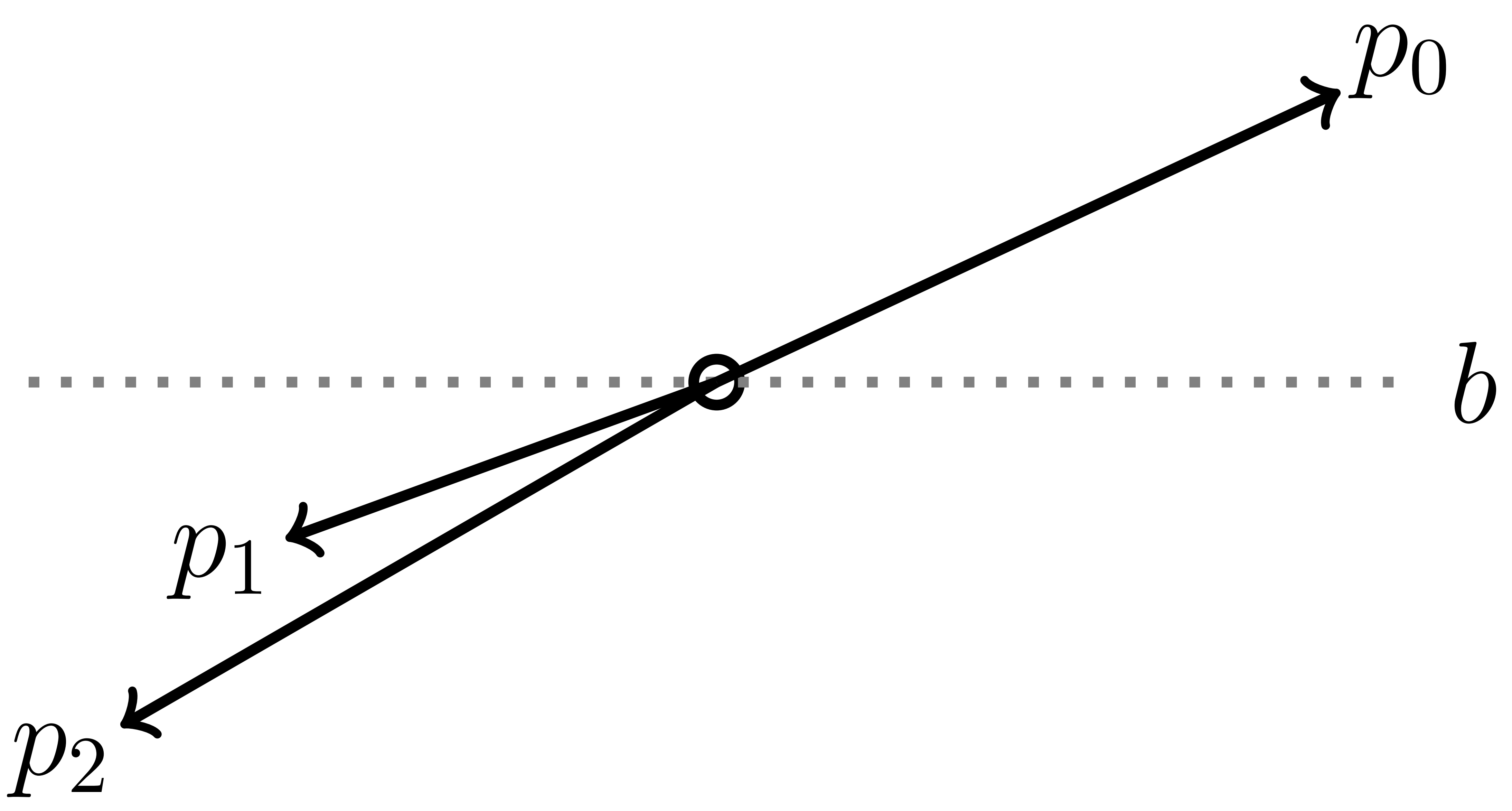
8TeV k_T-splittings | Definition

$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$
$$d_{ib} = p_{\mathrm{T},i}^2,$$

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

$\sqrt{d_0} = p_T$ of the leading ***k_t*-jet**,
$\sqrt{d_N}$ = distance measure where **N**-jet event is resolved as **N+1**-jet event.

Start with three input momenta p_0, p_1 and p_2



8TeV k_T-splittings | Definition

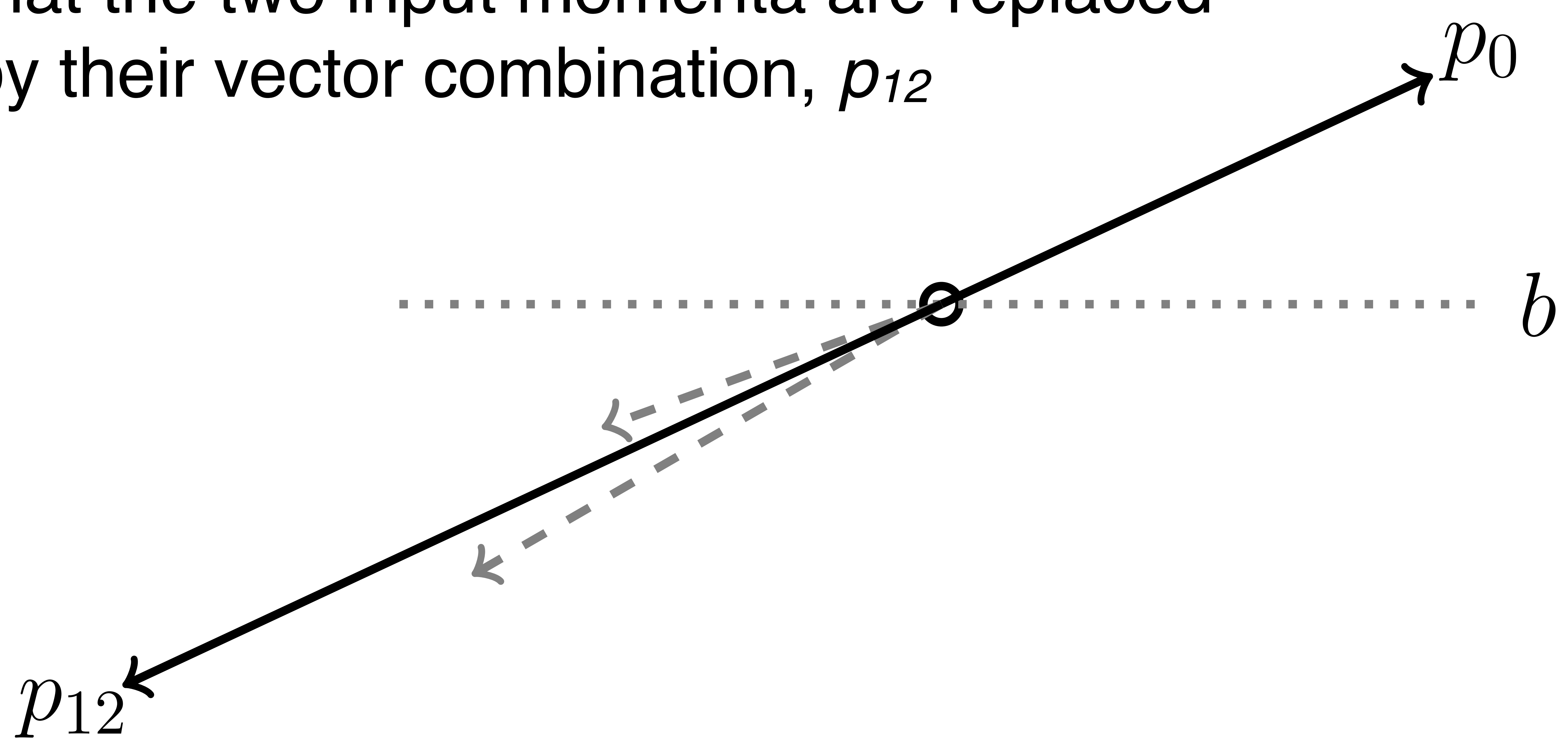
$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{ib} = p_{\mathrm{T},i}^2,$$

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

$\sqrt{d_0}$ = p_T of the leading ***k_t*-jet**,
$\sqrt{d_N}$ = distance measure where **N**-jet event is resolved as **N+1**-jet event.

Minimum distance measure is the one between two input momenta p_1 and p_2, so that the two input momenta are replaced by their vector combination, p_{12}



[arXiv:1704.01530]

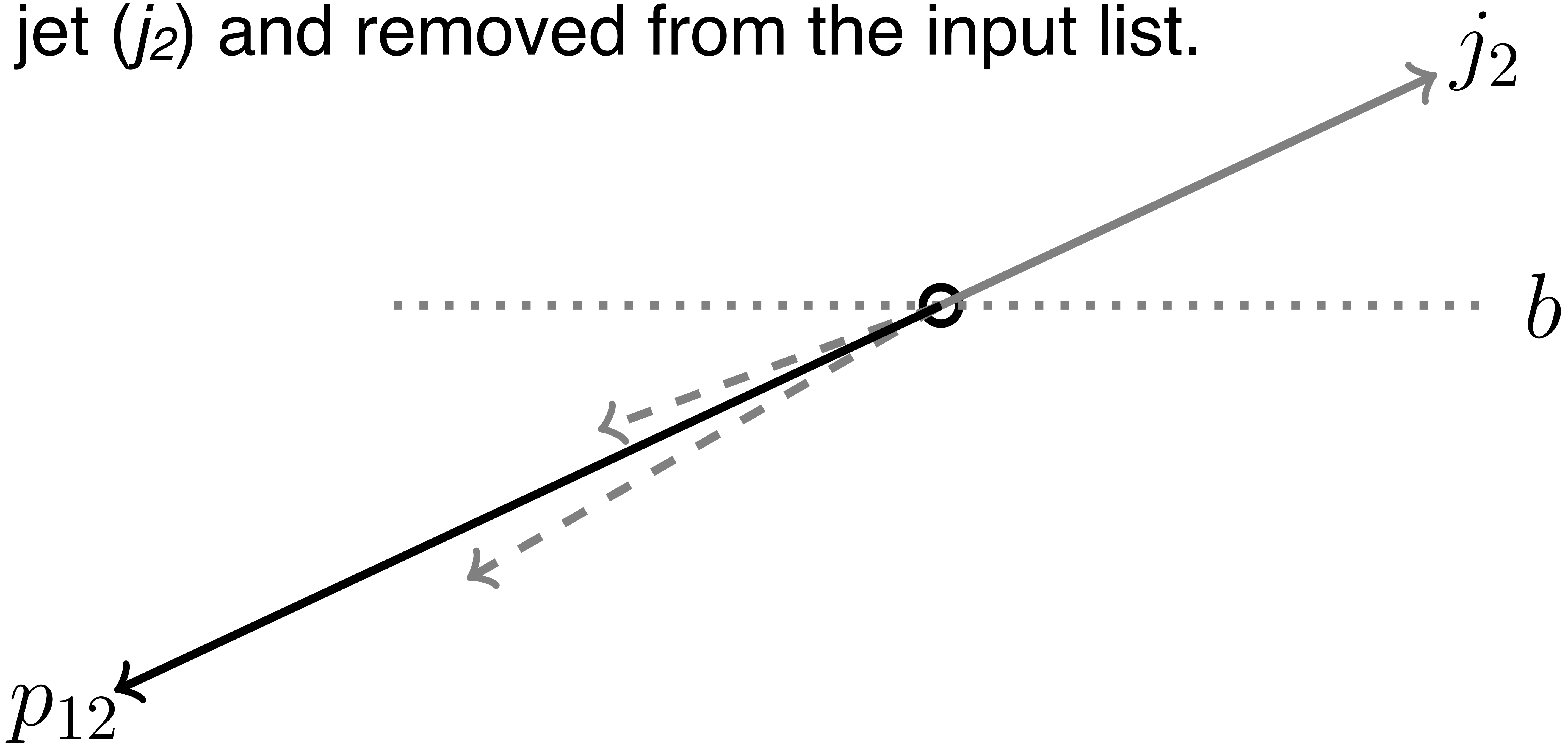
8TeV k_T-splittings | Definition

$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$
$$d_{ib} = p_{\mathrm{T},i}^2,$$

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

$\sqrt{d_0}$ = p_T of the leading ***k_t*-jet**,
$\sqrt{d_N}$ = distance measure where **N**-jet event is resolved as **N+1**-jet event.

Minimum distance measure is between the p_0 and the beam line, so that p_0 is declared a jet (j_2) and removed from the input list.



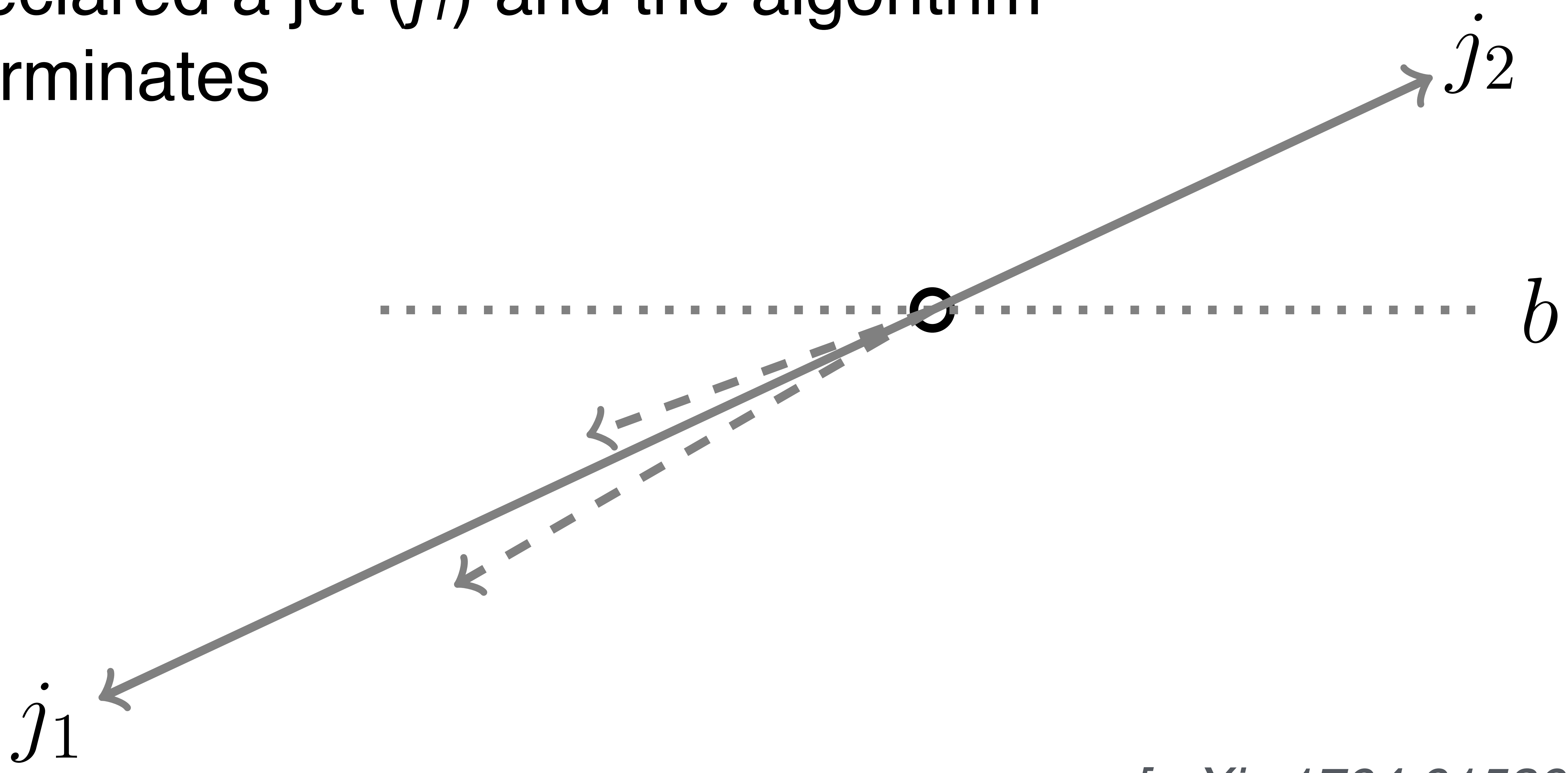
$$d_{ij} = \min\left(p_{\mathrm{T},i}^2, p_{\mathrm{T},j}^2\right) \times \frac{\Delta R_{ij}^2}{R^2}$$

$$d_{ib} = p_{\mathrm{T},i}^2,$$

$$d_k = \min_{i,j}(d_{ij}, d_{ib})$$

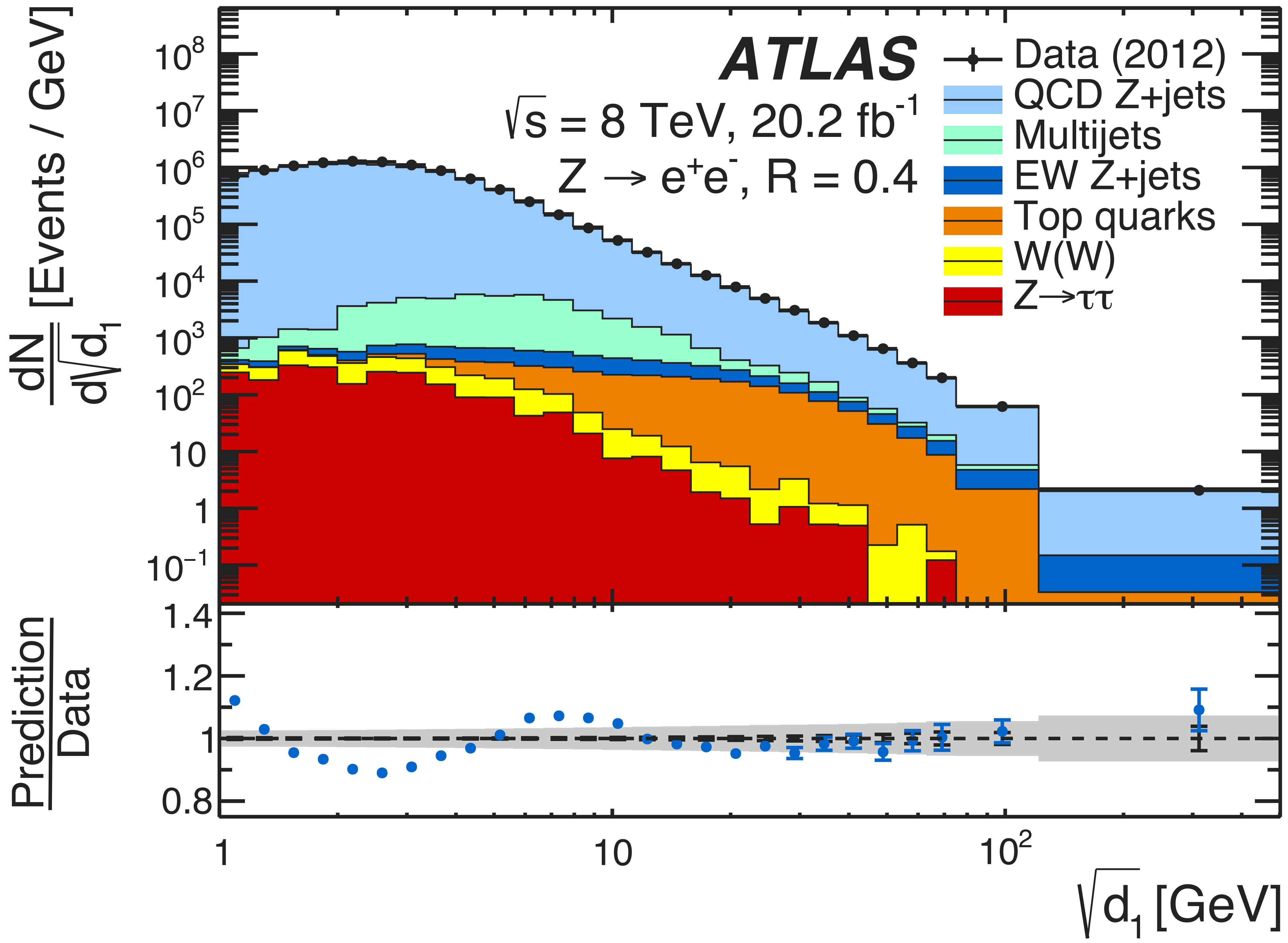
$\sqrt{d_0}$ = p_T of the leading ***k_t*-jet**,
$\sqrt{d_N}$ = distance measure where **N**-jet event is resolved as **N+1**-jet event.

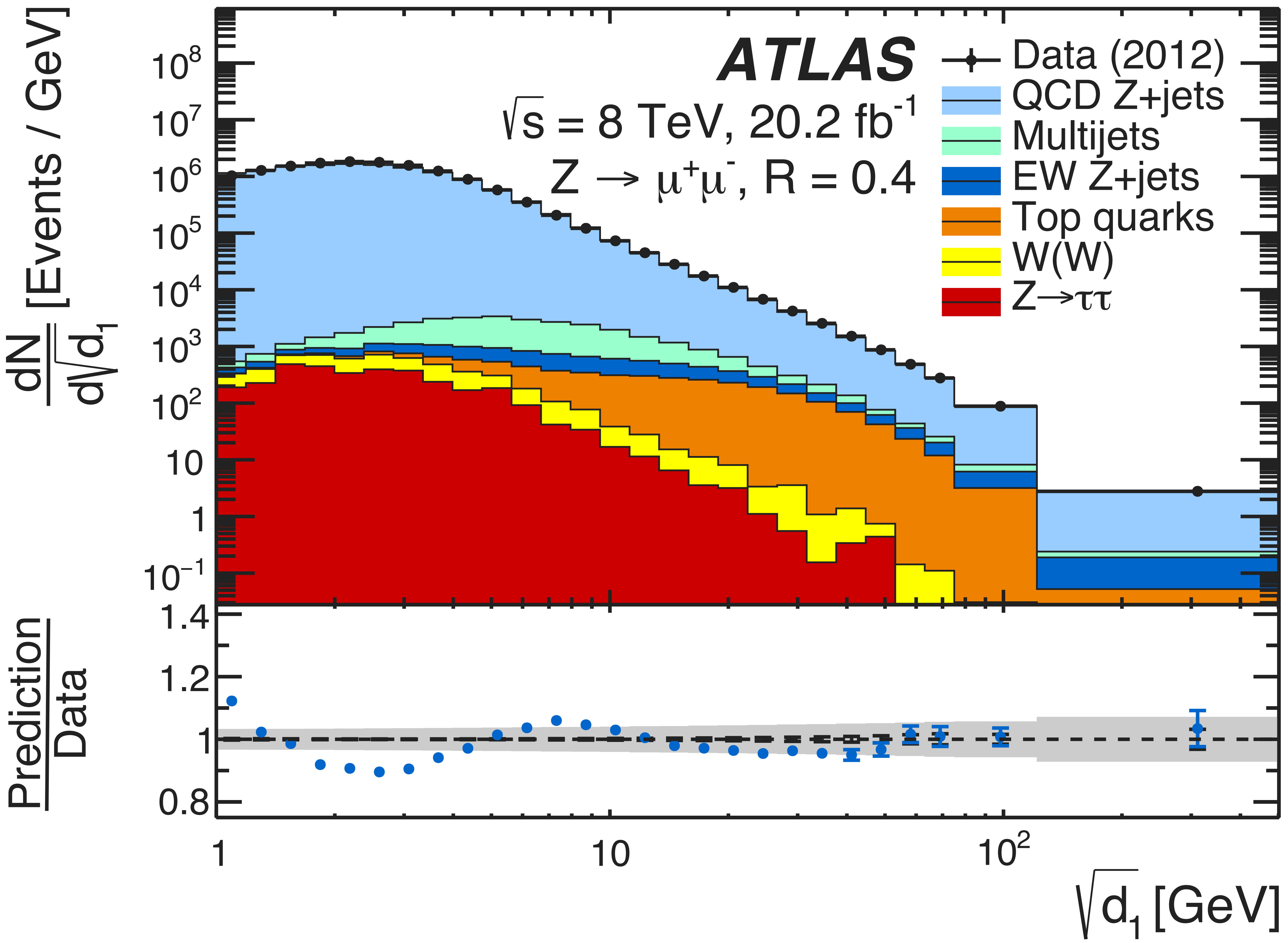
There is only the combined input momentum p_{12} left and so it will be declared a jet (j_1) and the algorithm terminates



8TeV k_T-splittings | Background estimation

- Most backgrounds taken from MC
- **Multijet** background is estimated from data
  - Reverse some lepton identification criteria to get a multijet sample from data. Use in template fit.
- Purity of the signal is ~99 %

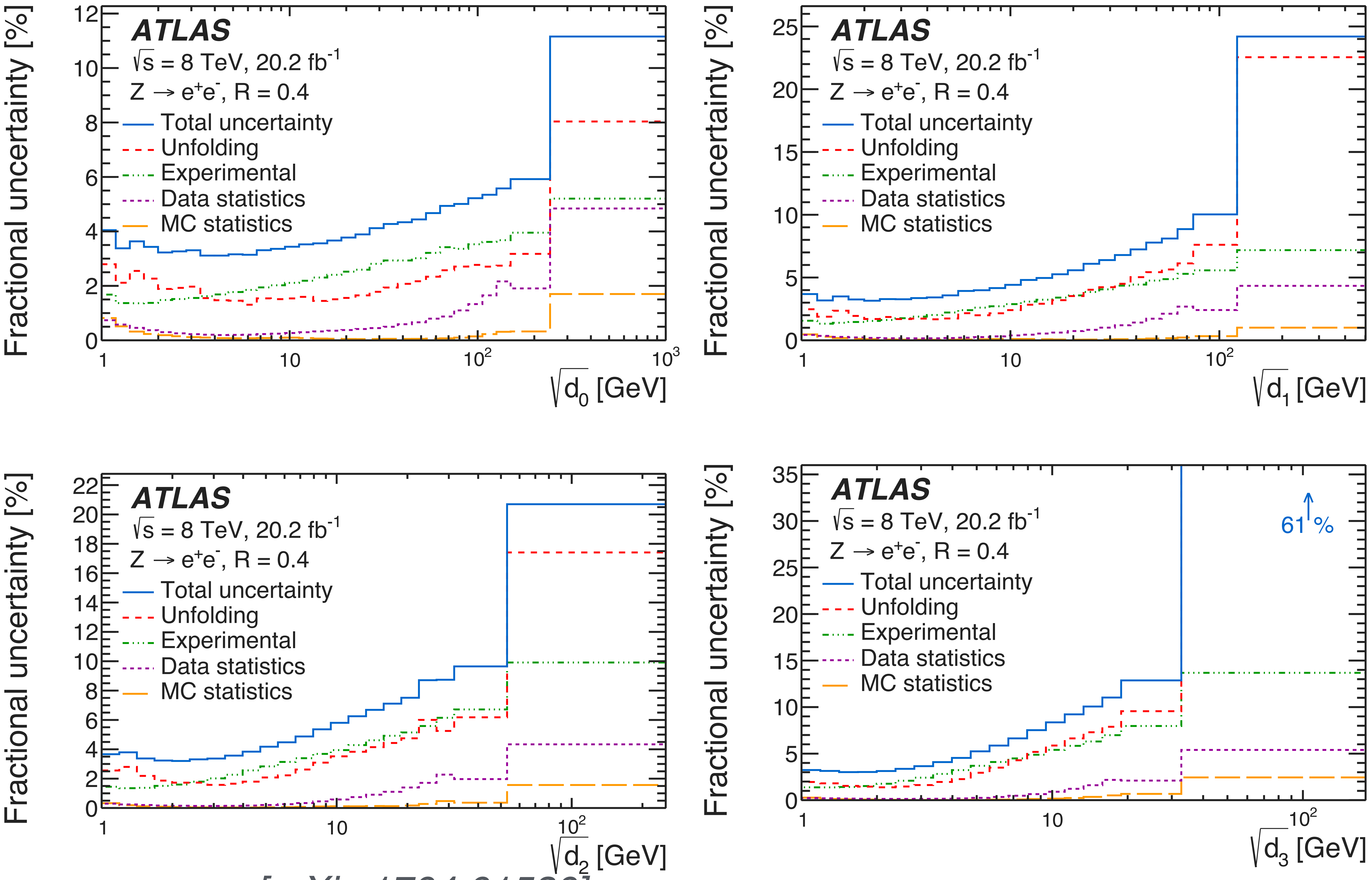




[arXiv:1704.01530]

8TeV k_T-splittings | Systematics

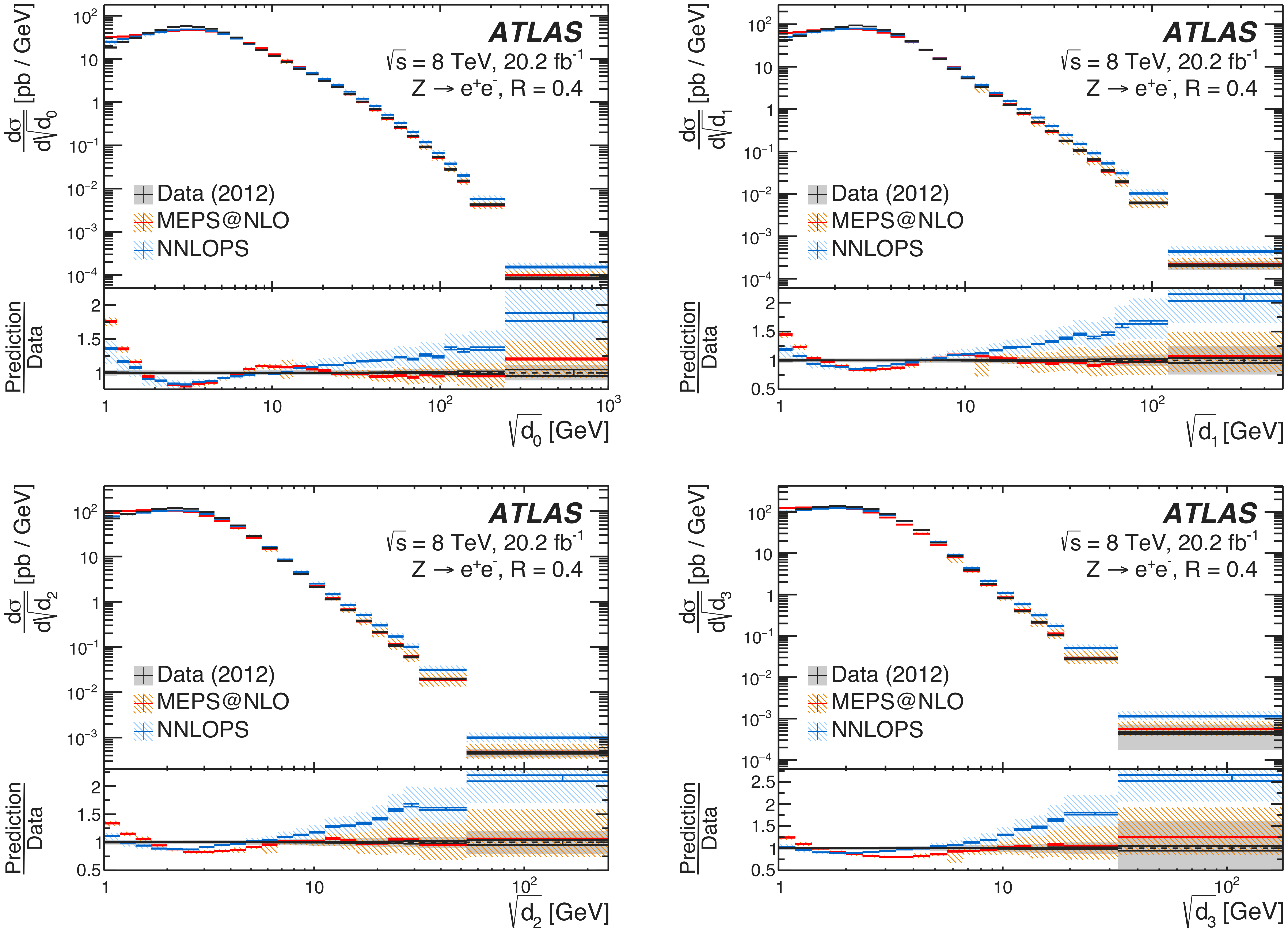
- Using **only tracking information** significantly reduces the uncertainty wrt previous result (STDM-2012-12).
- Dominant uncertainties:
  - Experimental
    - ID track reconstruction
  - Unfolding
    - Data/MC differences
    - Choice of generator



[arXiv:1704.01530]

8TeV k_T-splittings | Results

- Neither prediction provides a fully satisfactory description of the data.
- In lower-order splitting scales
  - both predictions underestimate the peak region by 10–20%
- At higher values of $\sqrt{d_i}$
  - MEPS@NLO agrees well
  - NNLOPS systematically overestimates the cross section.
- In the soft region:
  - Both overshoot data in lower-order splitting scales
  - NNLOPS improves significantly for higher-order splitting scales.

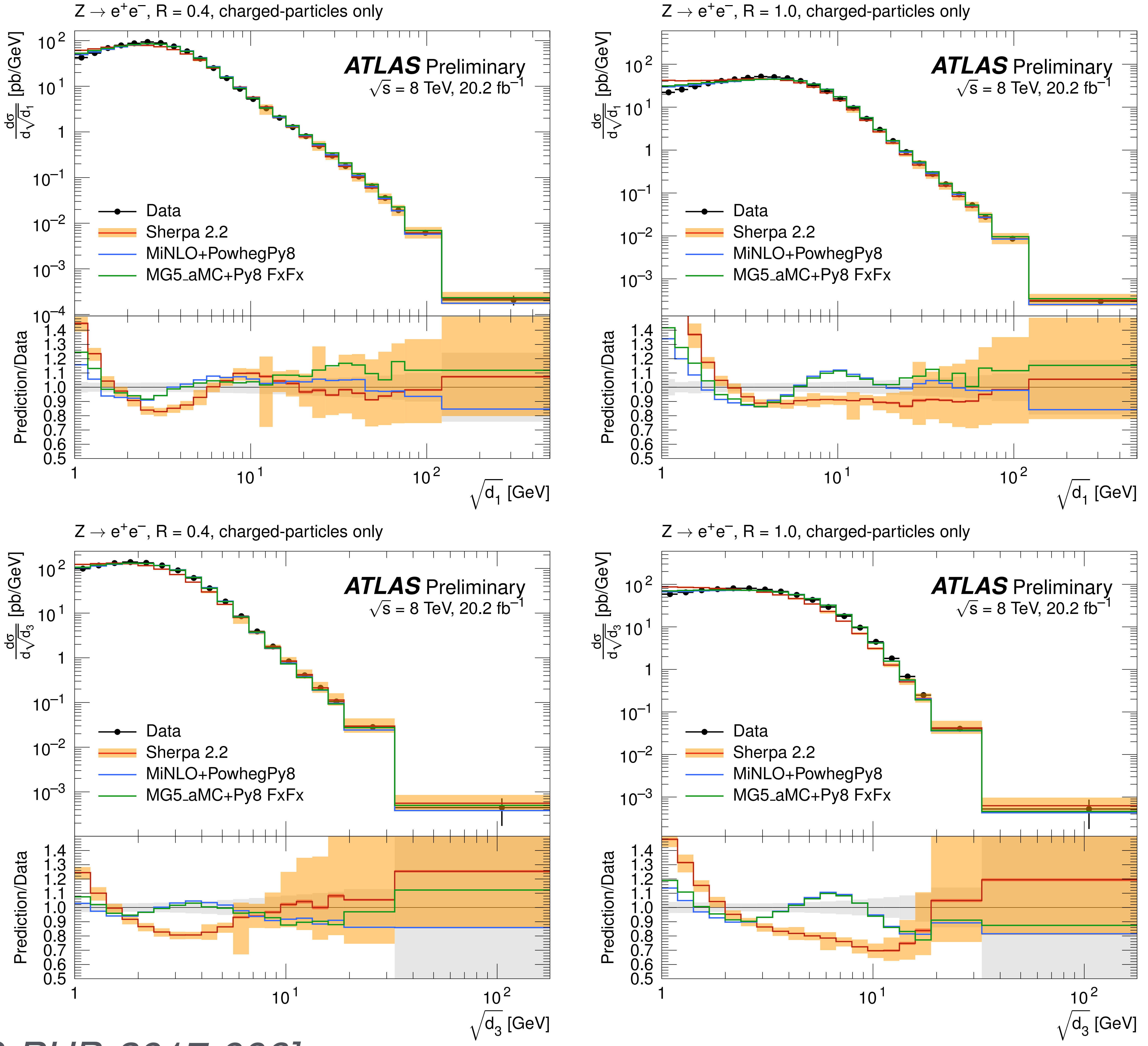


NLO@2j LO@4j NNLO@0j

[arXiv:1704.01530]

8TeV k_T-splittings | MC studies

- Now used for validation of new ATLAS MC configurations.
  - Sherpa MEPS@NLO *(NLO@2j LO@4j)*
  - Powheg MiNLO+Pythia8 *(NLO@1j)*
  - MG5_aMC+Pythia8 FxFx *(NLO@2j)*
- All MCs struggle with transition between perturbative & non-perturbative regions.
- Sherpa slightly better than MG5_aMC+Py8 FxFx for high-energy part.
- The parton shower-dominated region is better described by Pythia8 than Sherpa.
- Small uncertainty gives constraints for better modelling in future.



[ATL-PHYS-PUB-2017-006]

7&8 TeV Electroweak W production

[Eur. Phys. J. C 77 (2017) 474
arXiv:1703.04362]

7&8 TeV EW Wjj | Introduction

- Most precise measurement of VBF boson production
- Sensitive to triple-gauge couplings
- Validate uncertainties common to VBF Higgs measurements
- Only measurement of VBF boson production at 7 TeV
- Differential measurements of VBF boson production

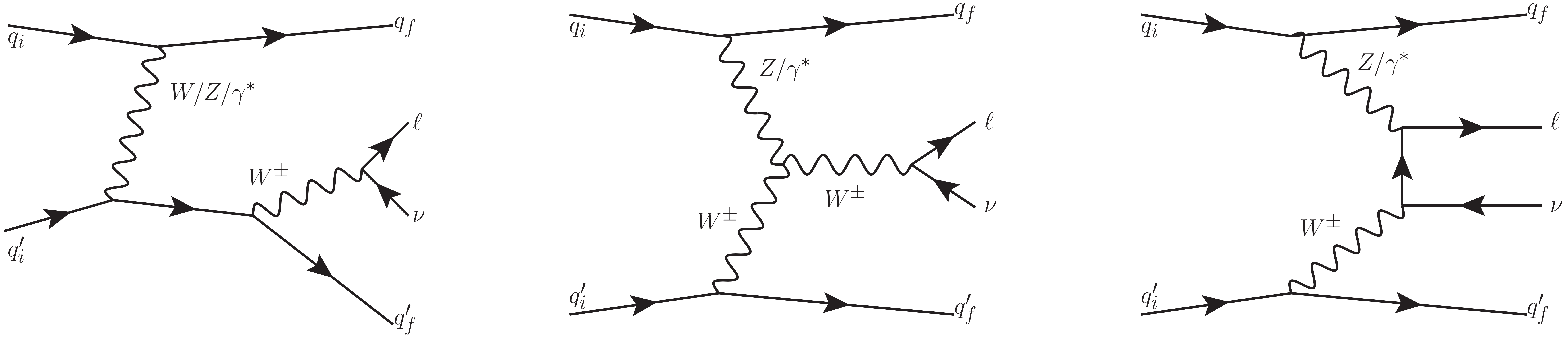
[arXiv:1703.04362]

7&8 TeV EW Wjj | Introduction

- Most precise measurement of VBF boson production
- Sensitive to triple-gauge couplings
- Validate uncertainties common to VBF Higgs measurements
- Only measurement of VBF boson production at 7 TeV
- Differential measurements of VBF boson production

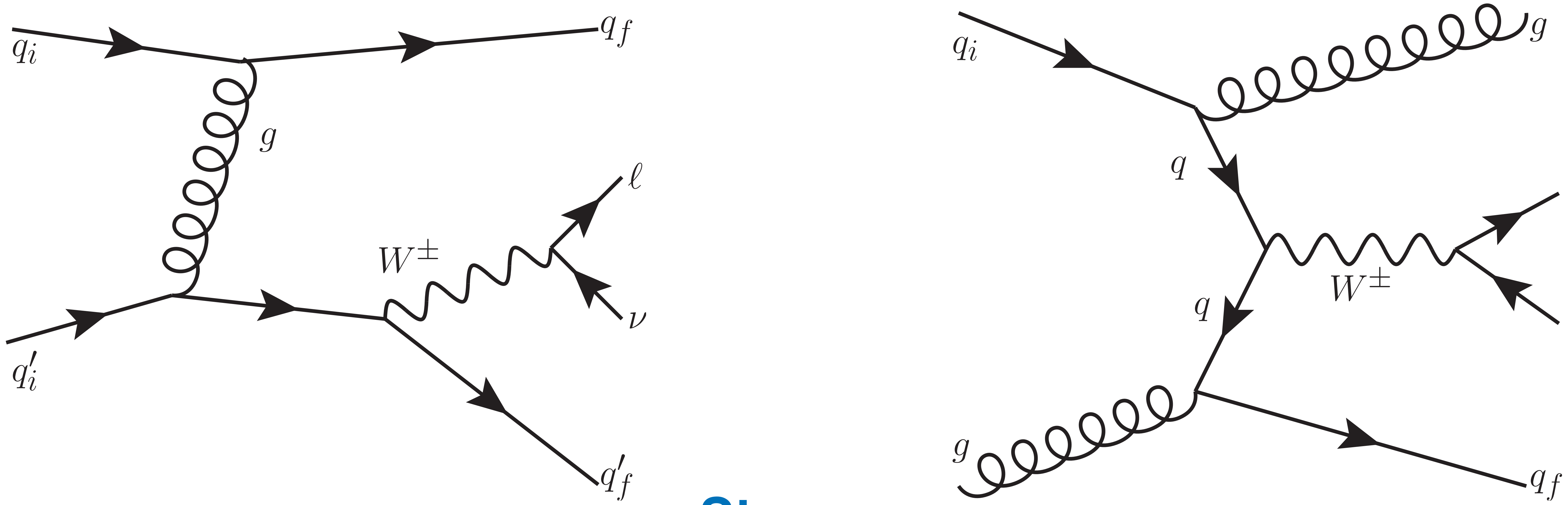
This talk will focus on the strong Wjj results
→ the EWK Wjj results were covered in Ismet's talk.

[arXiv:1703.04362]



Vector boson fusion | W bremsstrahlung | Non-resonant

Electroweak

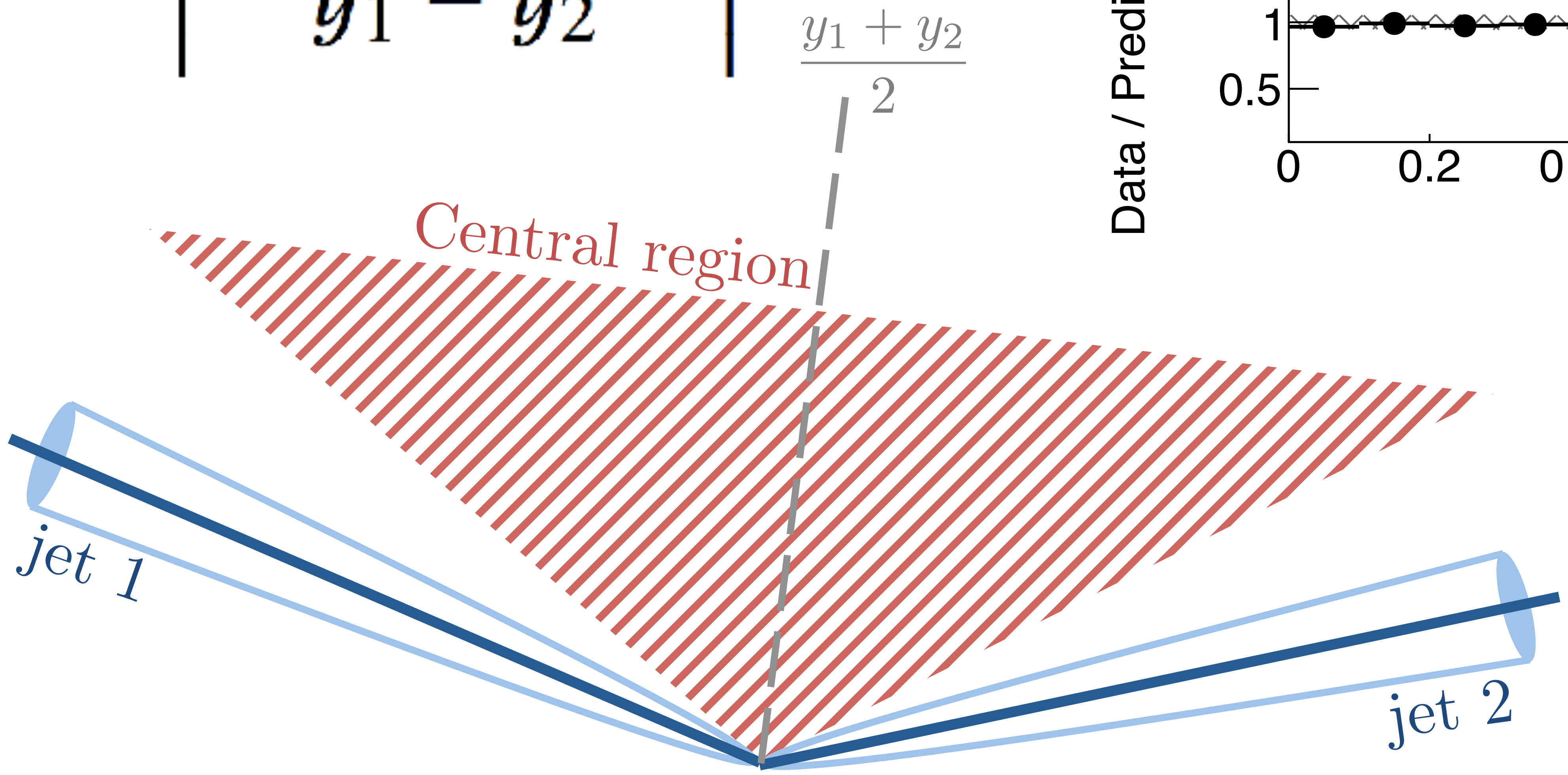


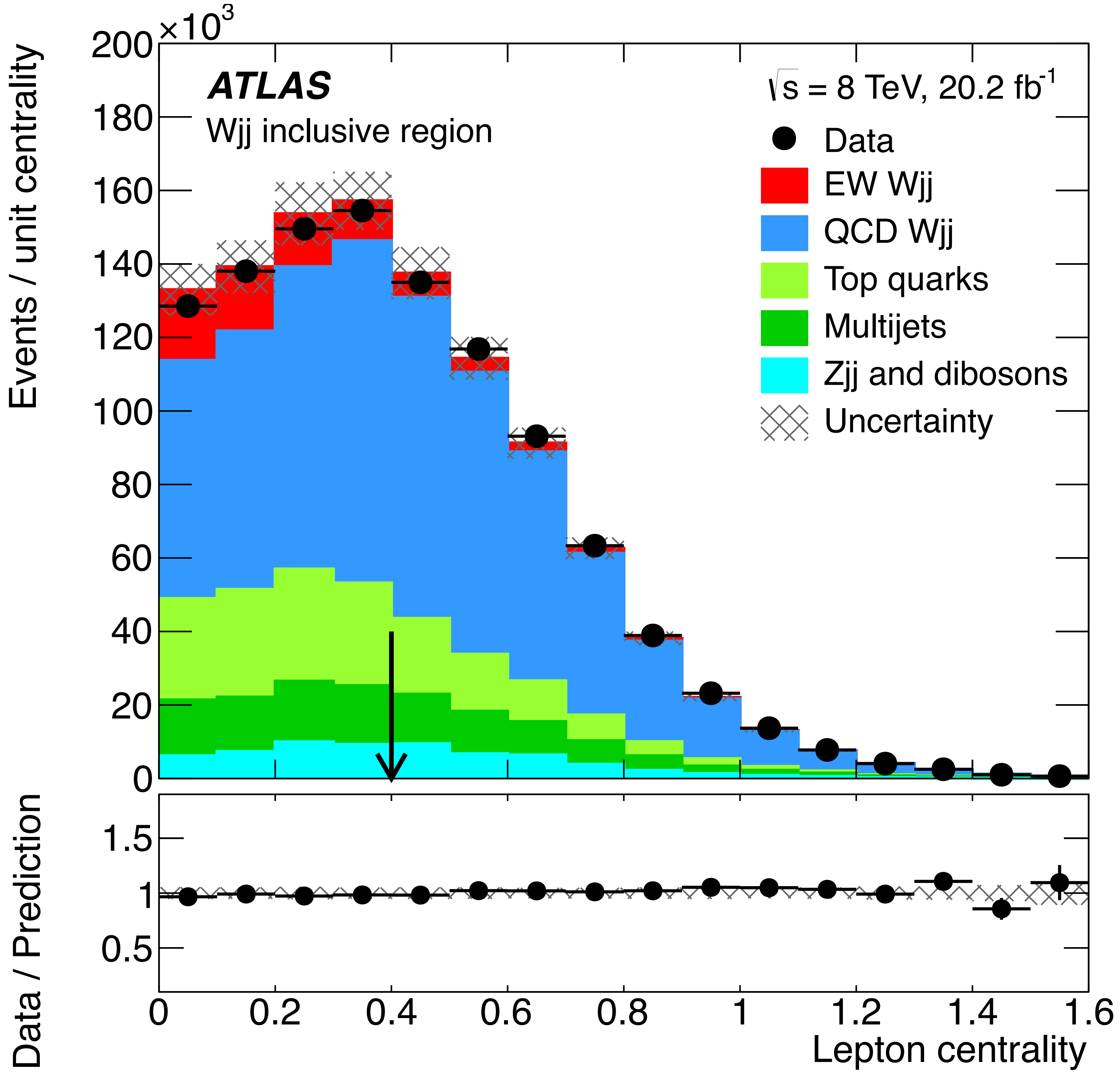
Strong

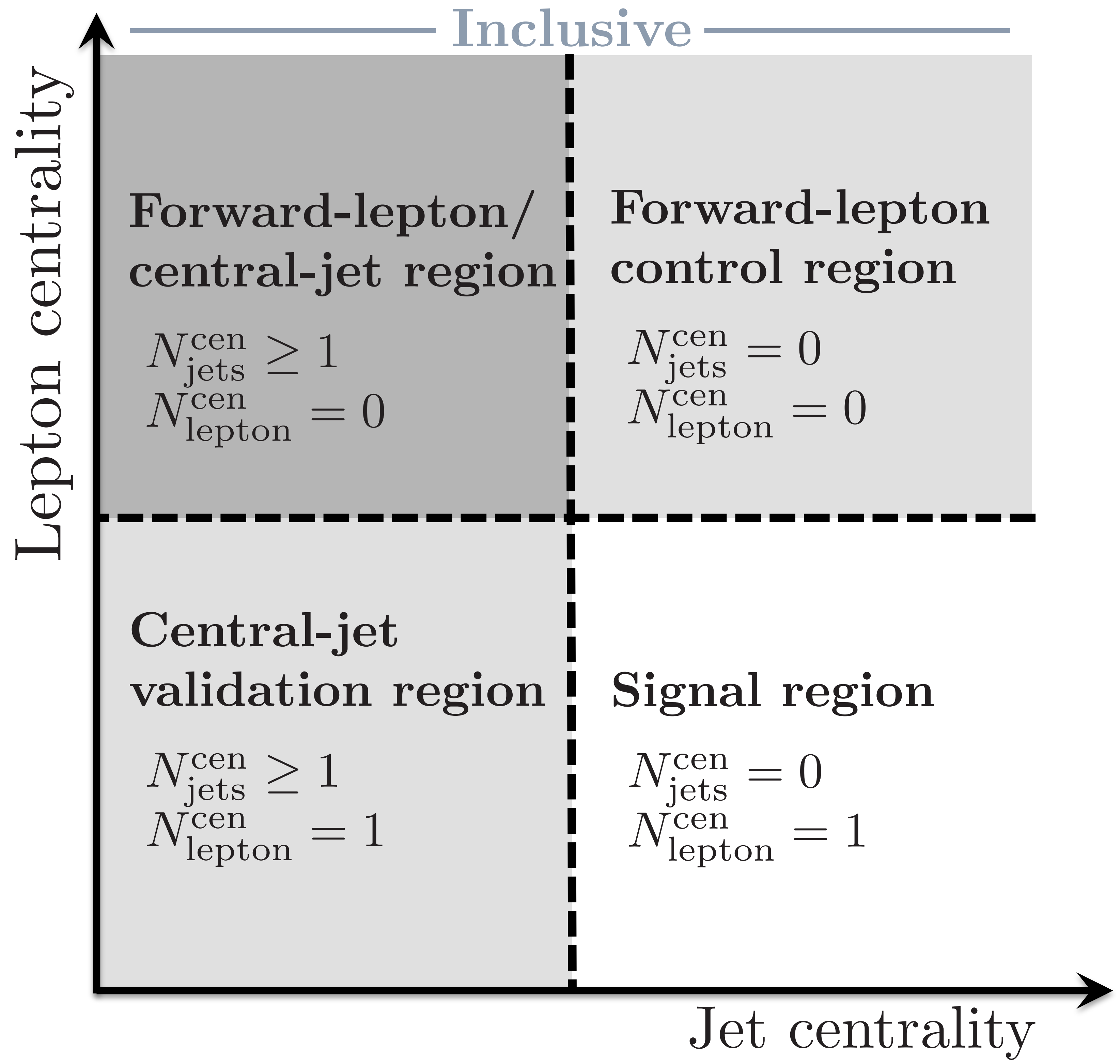
7&8 TeV EW Wjj | Analysis strategy

- The analysis defines measurement regions varying in EW *Wjj* purity.
- Signal EW *Wjj* process characterised by a lepton and no jets in the central rapidity range.

$$C_{\ell\,(j)} \equiv \left| \frac{y_{\ell\,(j)} - \frac{y_1+y_2}{2}}{y_1 - y_2} \right|$$



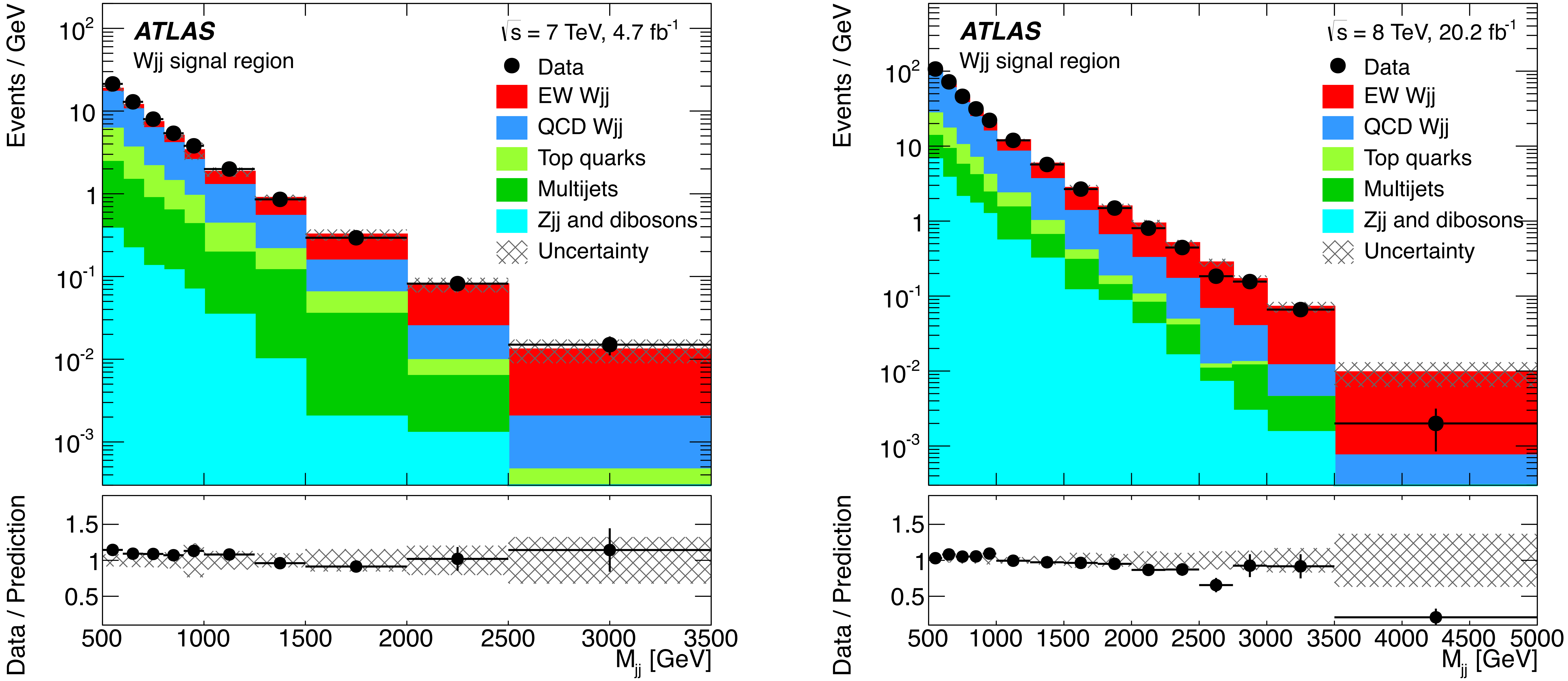




[arXiv:1703.04362]

7&8 TeV EW Wjj | Backgrounds

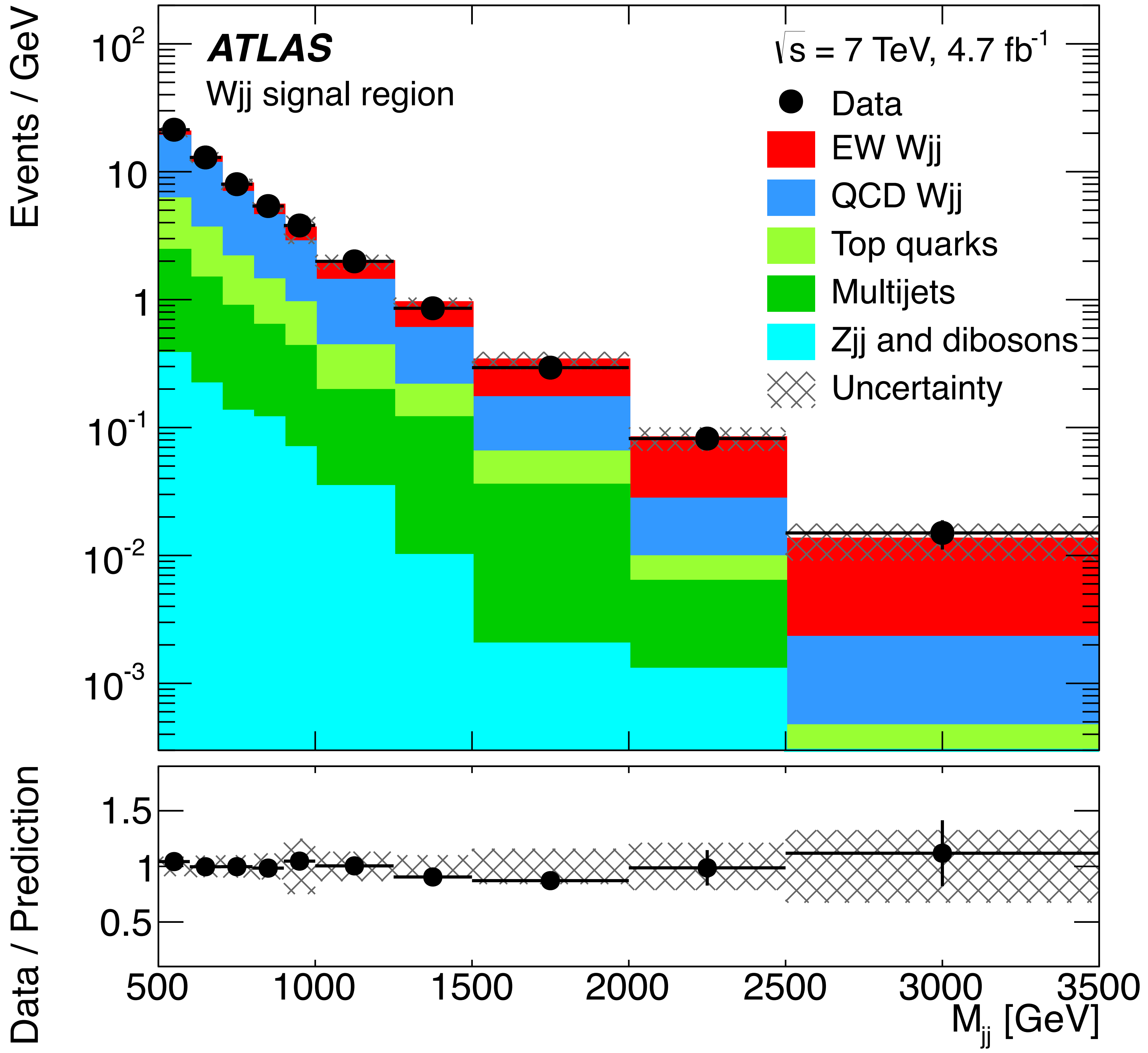
- MC samples are used to model *Wjj* production
  - Small data-derived corrections are applied to reduce systematic uncertainties.
- Other processes producing a prompt charged lepton are also modelled with MC
- The multijet background is modelled using data.

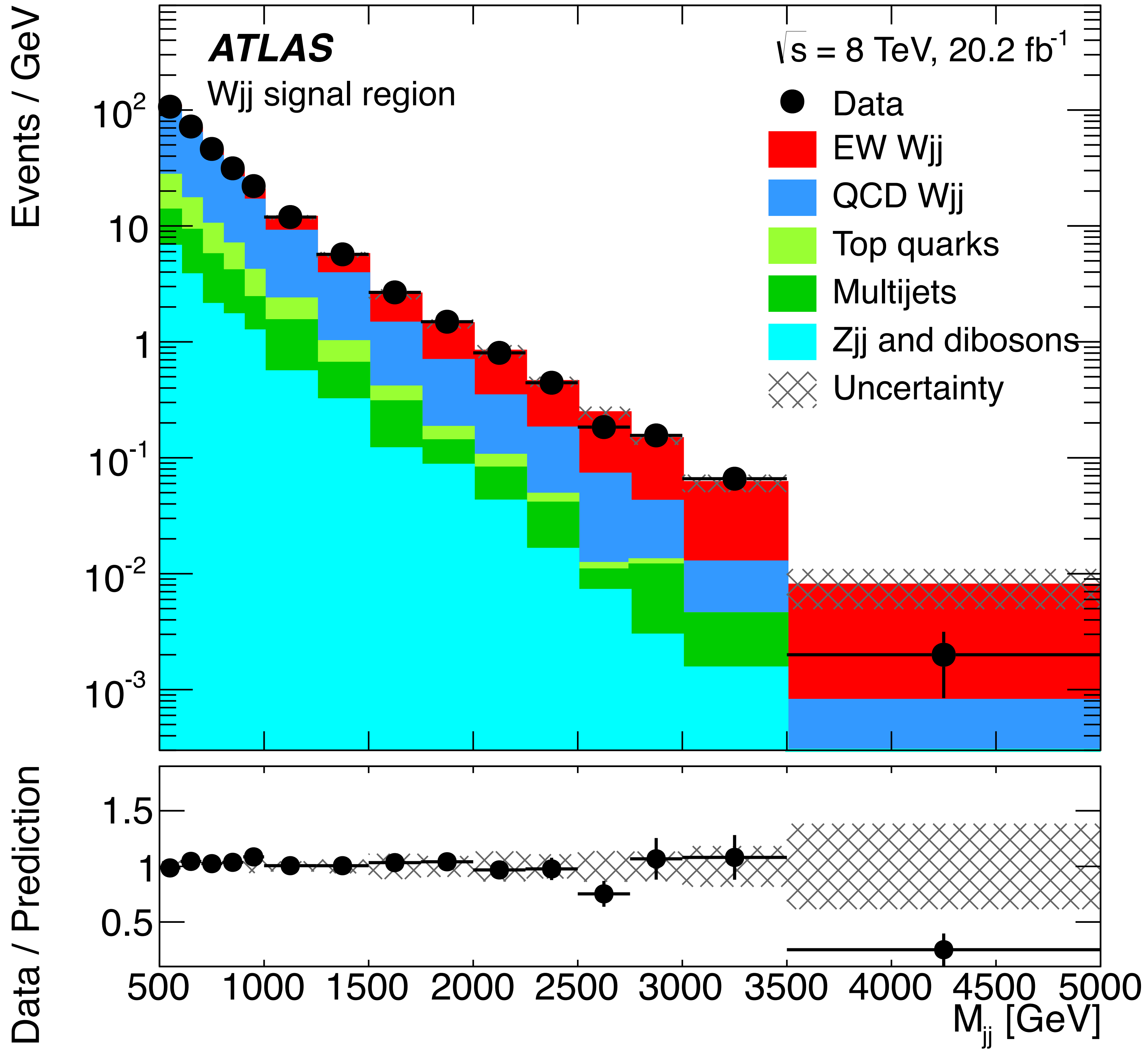


[arXiv:1703.04362]

7&8 TeV EW Wjj | Backgrounds

- MC samples are used to model *Wjj* production
  - Small data-derived corrections are applied to reduce systematic uncertainties.
- Other processes producing a prompt charged lepton are also modelled with MC
- The multijet background is modelled using data.
- The dijet mass distributions in 7 and 8 TeV data are fitted for μ_{EW} and μ_{QCD}.

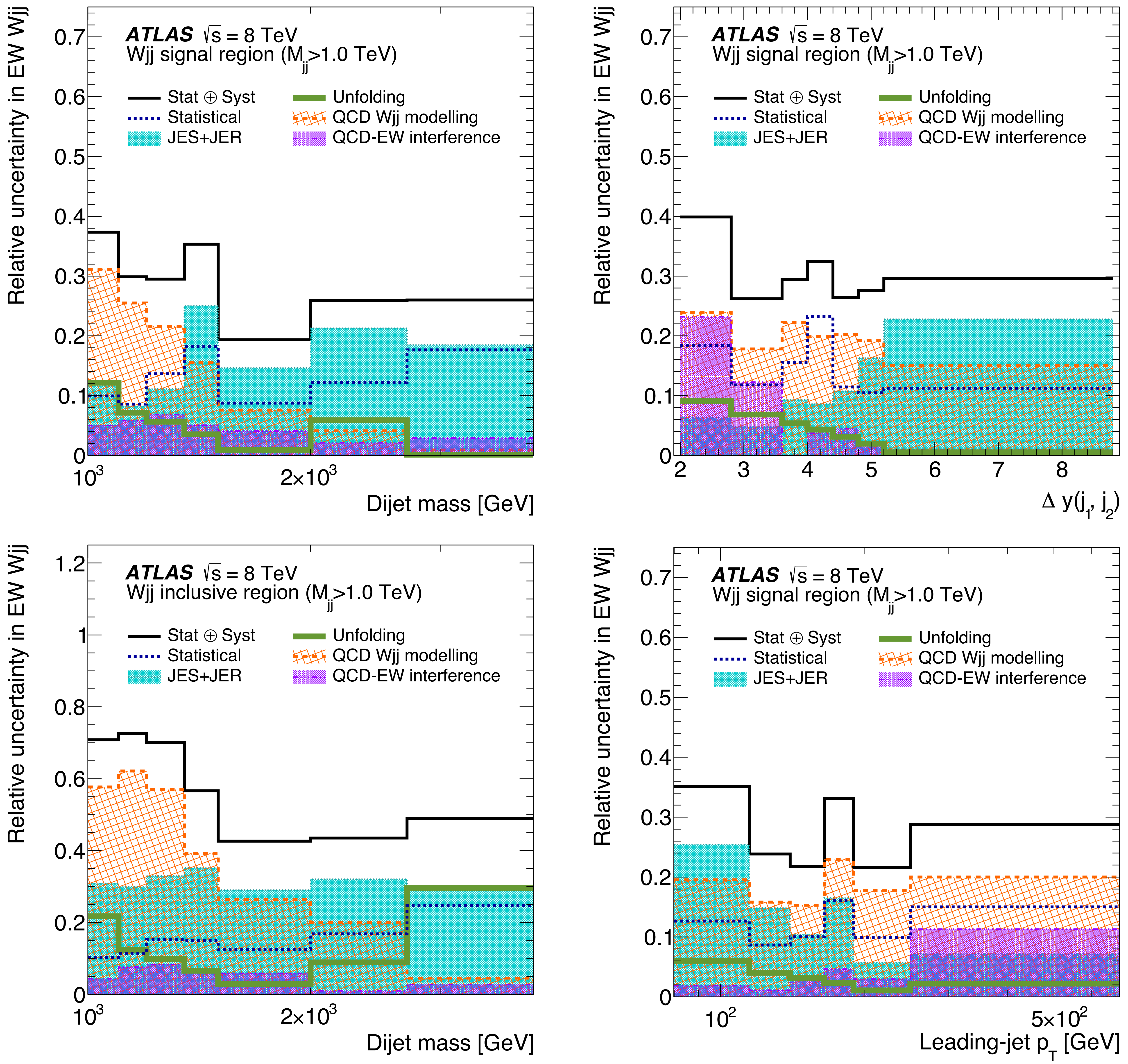




[arXiv:1703.04362]

7&8 TeV EW Wjj | Systematics

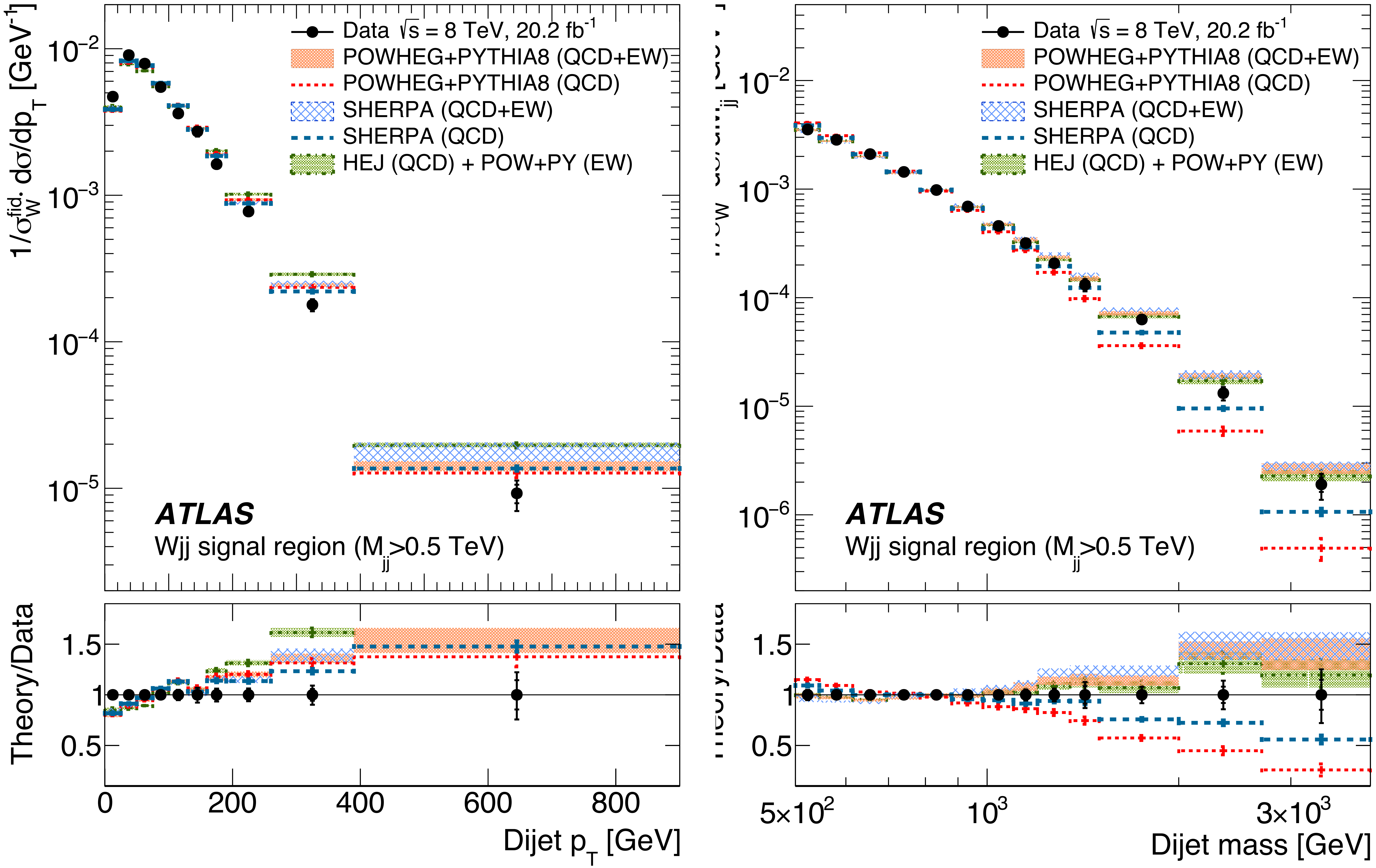
- Uncertainties in strong *Wjj* modelling are important at low dijet invariant mass
- Interference uncertainties become dominant at low dijet rapidity separation
- For most EW *Wjj* distributions, the leading sources of uncertainty are
  - Statistical
  - Strong *Wjj* modelling
  - Jet energy scale and resolution



[arXiv:1703.04362]

7&8 TeV EW Wjj | Results

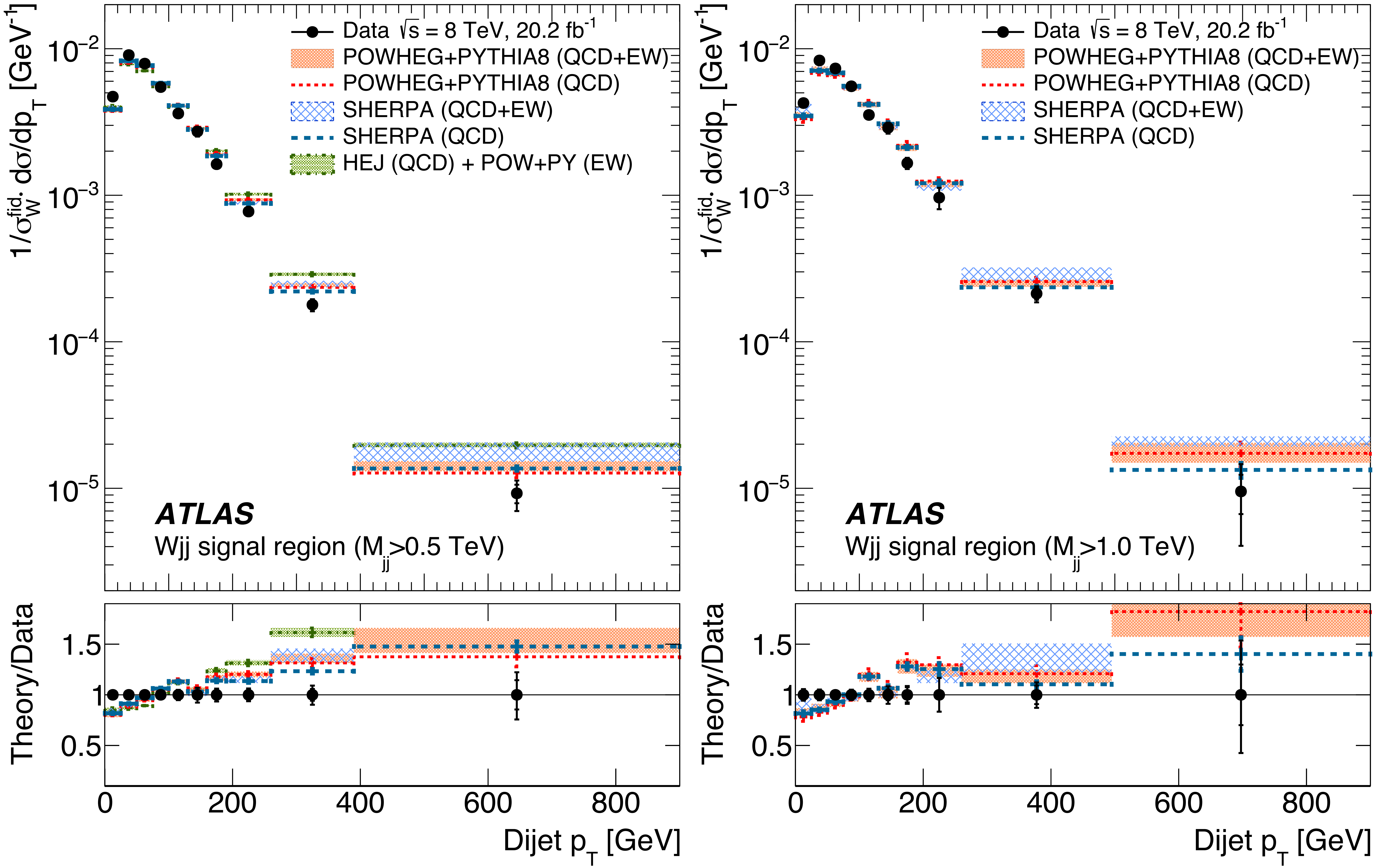
- Predictions:
  - Powheg+Py8 (NLO QCD&EW)
  - Sherpa (LO QCD&EW)
  - HEJ (all-order resummed)
- Discrimination between EW & strong *Wjj* enhanced in SR
- Data supports the presence of EW *Wjj* production.
  - Excess of Powheg+Py8 at high M_{jj} is consistent with a measured $\mu_{EW} < 1$.



[arXiv:1703.04362]

7&8 TeV EW Wjj | Results

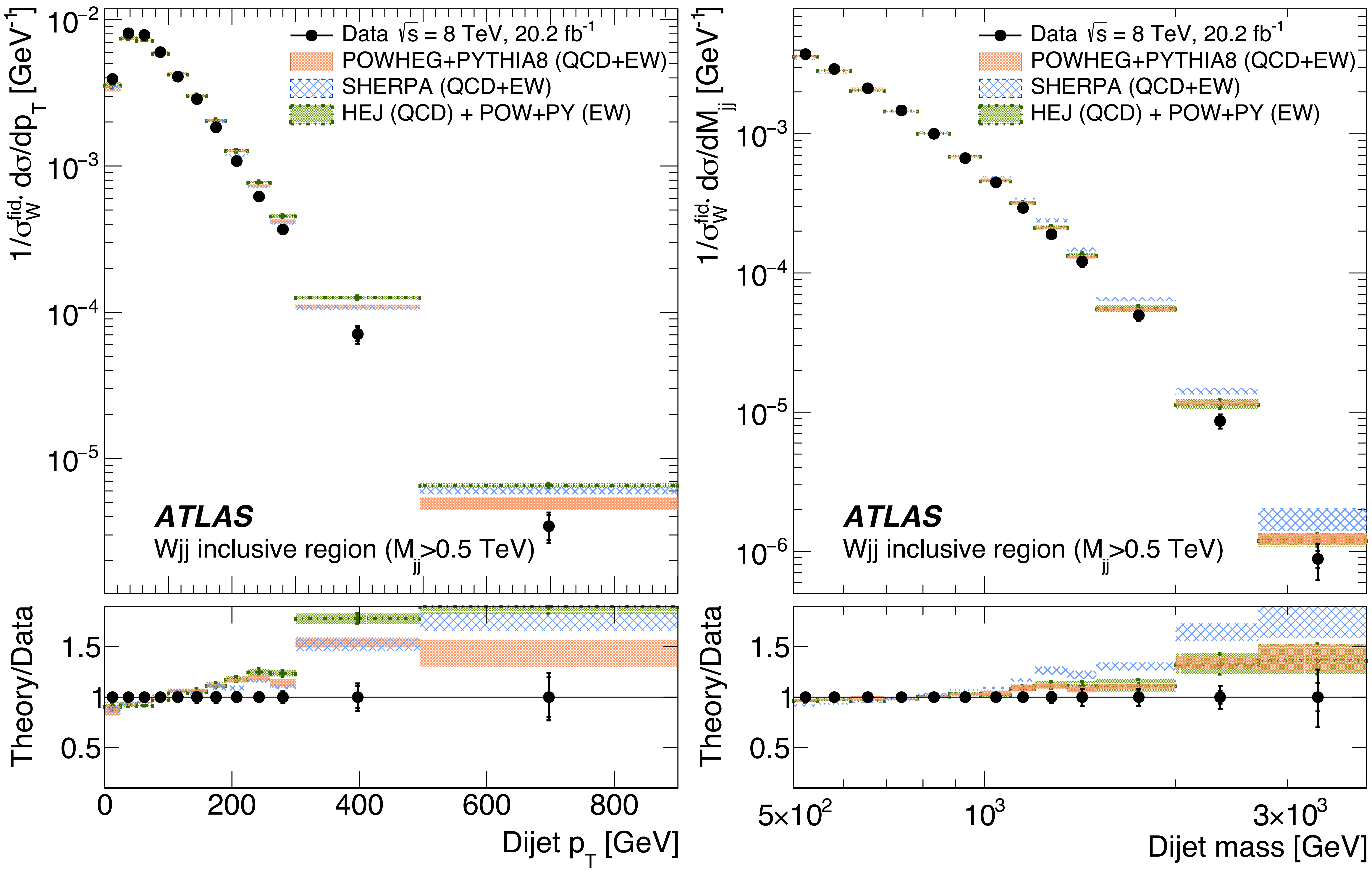
- All predictions overestimate at high dijet p_T in the incl. and signal-enhanced regions,
  - Not seen in the central-jet validation region
- Increasing the dijet invariant mass threshold to enhance the EW *Wjj* signal does not increase the disagreement
  - suggests difference related to modelling of strong *Wjj.*
  - NLO EW corrections to strong *Wjj* is a possible explanation.



[arXiv:1703.04362]

7&8 TeV EW Wjj | Results

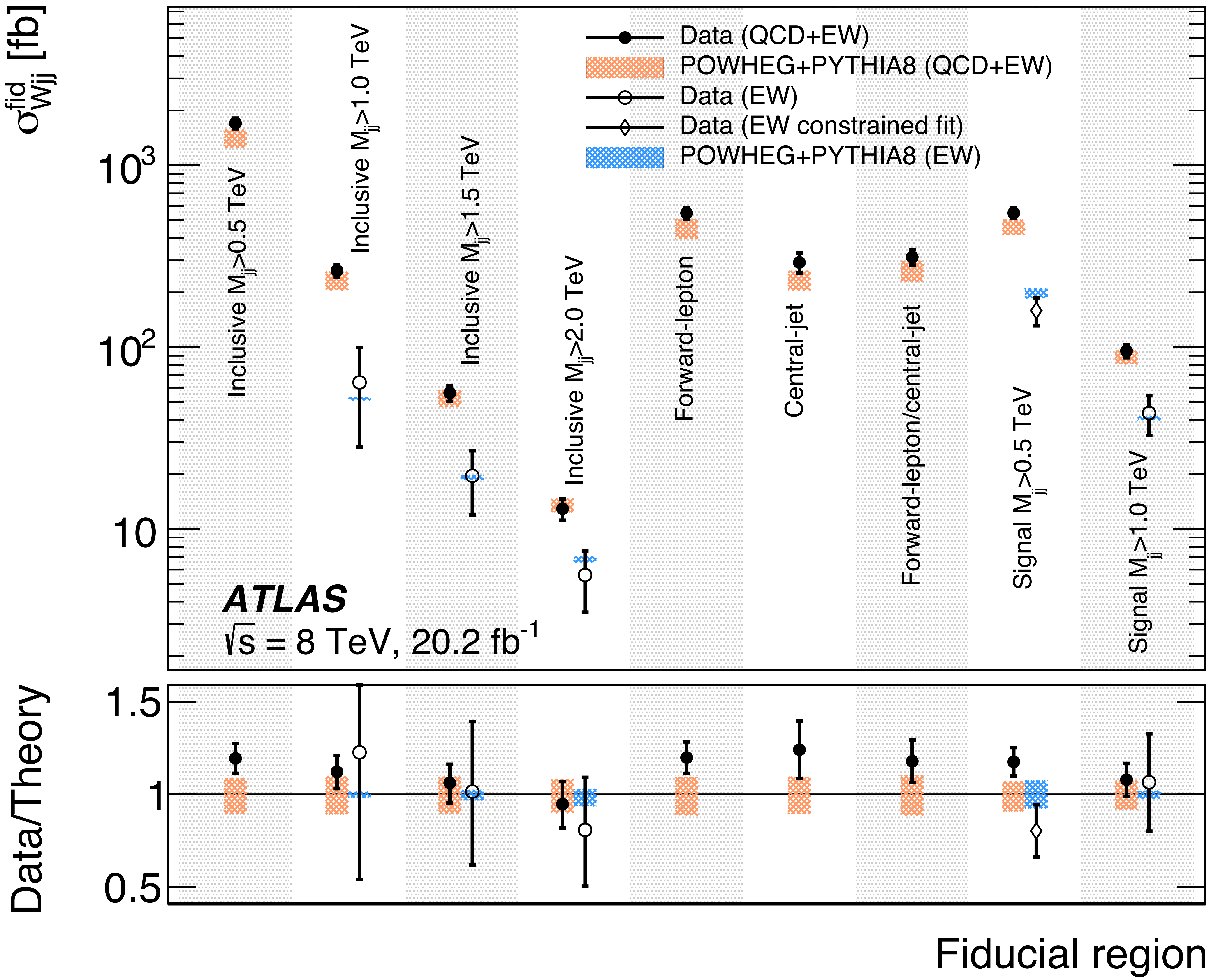
- **Inclusive selection** also shows significant mismodelling of dijet p_T.
- Dijet mass mismodelling is particularly striking
  - Strong production dominated region.
  - Sherpa is particularly discrepant.
- Important for VBF analyses e.g. Higgs.



[arXiv:1703.04362]

7&8 TeV EW Wjj | Results

- Summary of cross section results:



[arXiv:1703.04362]

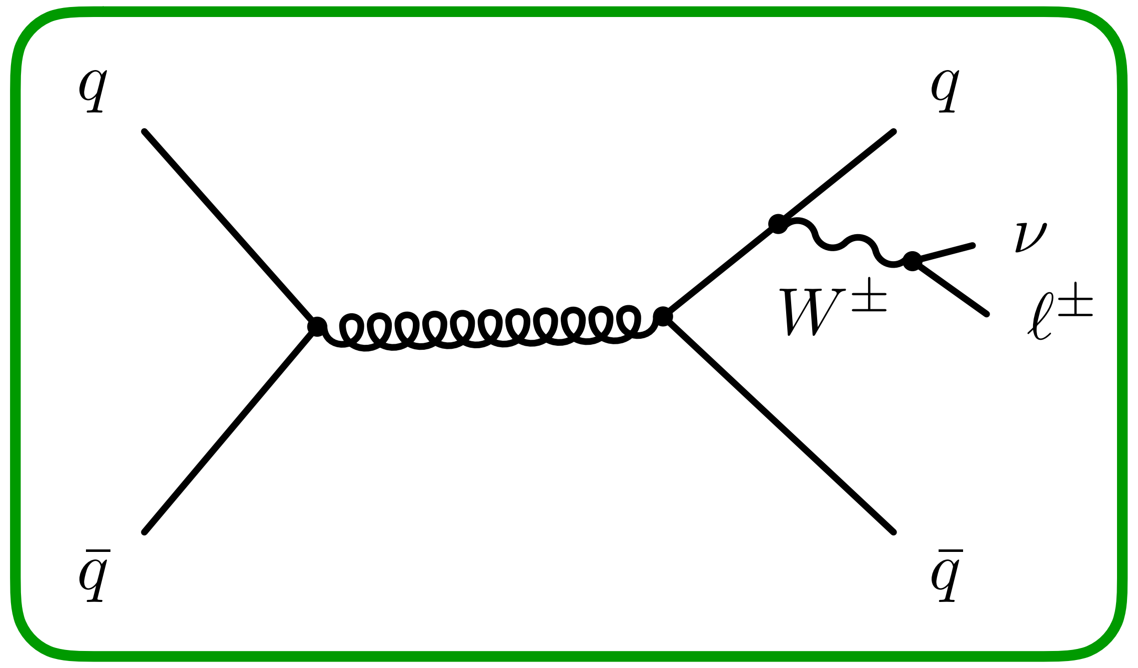
8 TeV W boson angular distributions

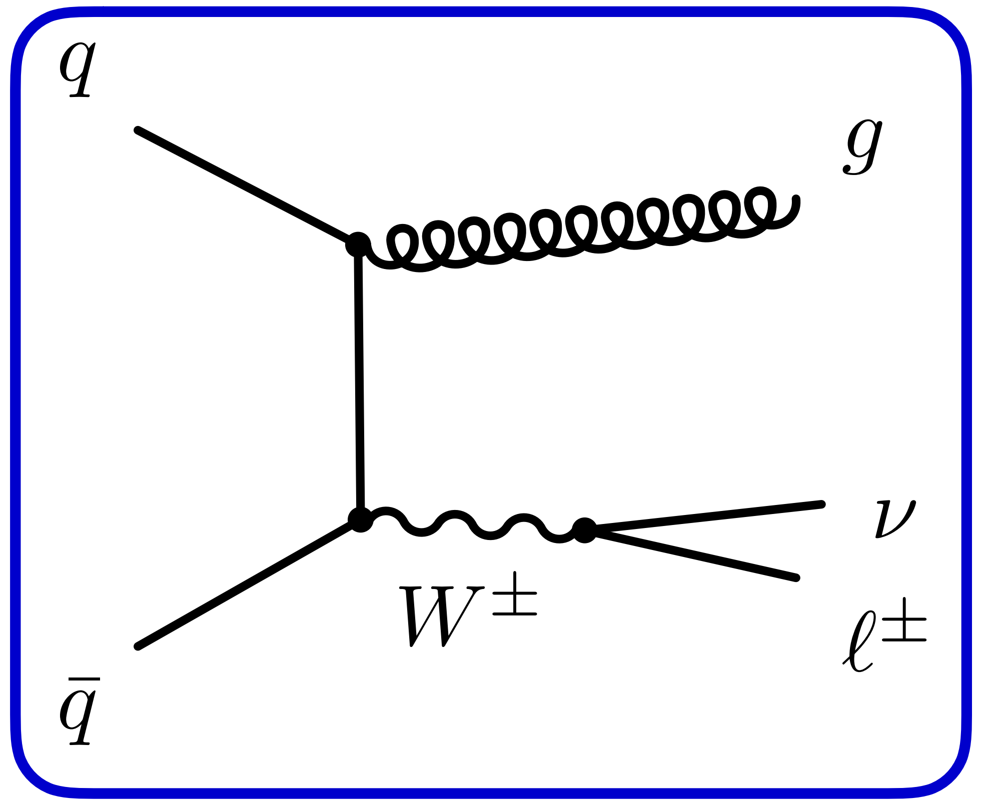
[Phys. Lett. B 765 (2017) 132
arXiv:1609.07045]

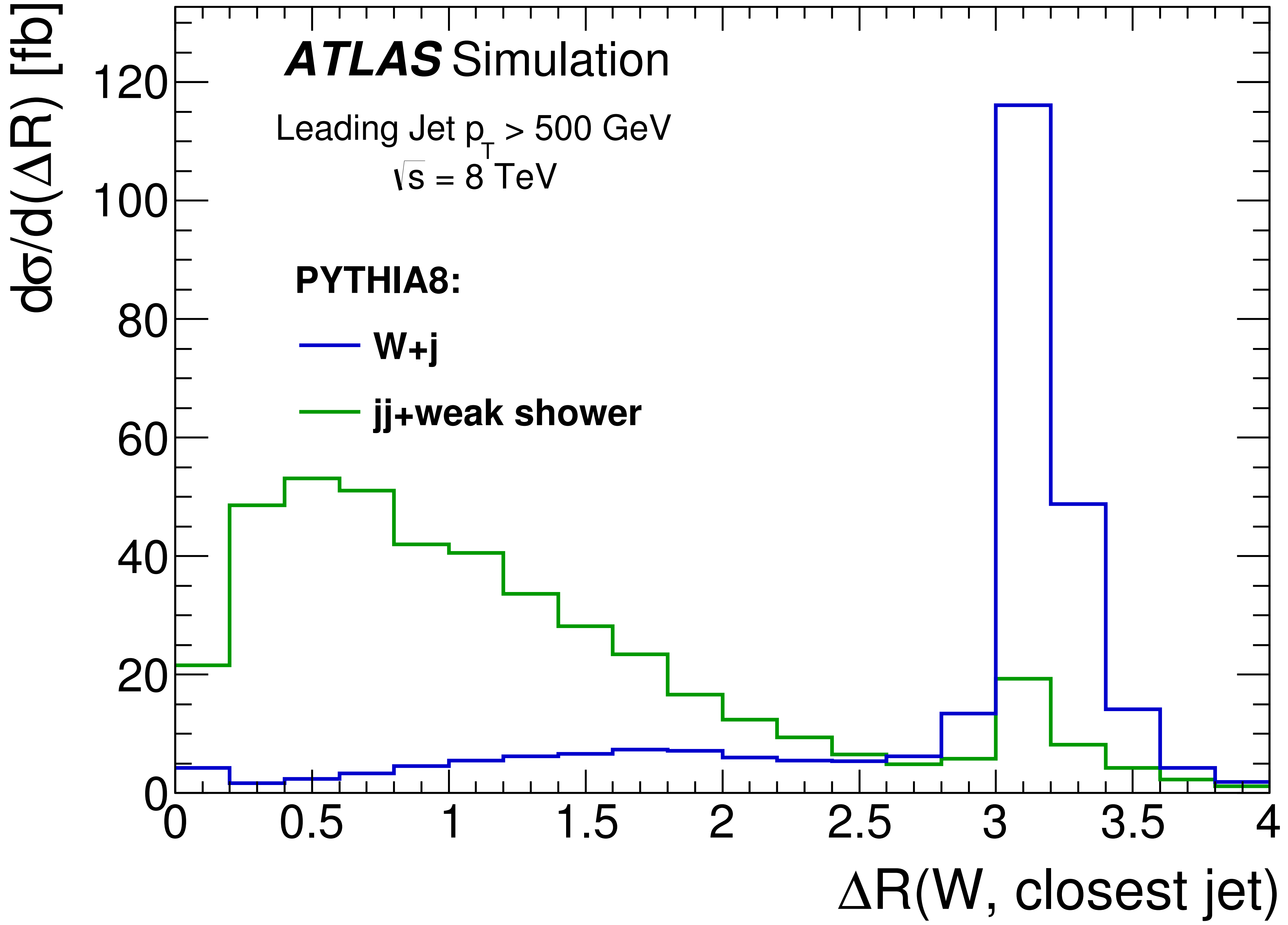
8 TeV W dR | Introduction

- Measure W+jets events kinematically consistent with a real W emission
  - A muon is observed close to a high transverse momentum jet.
  - At small angular separations the real W emissions contribution is expected to be large.

- Theoretical models are compared to the data for:
  - Absolute cross-section.
  - Angular distributions of the muon from the leptonic W decay.



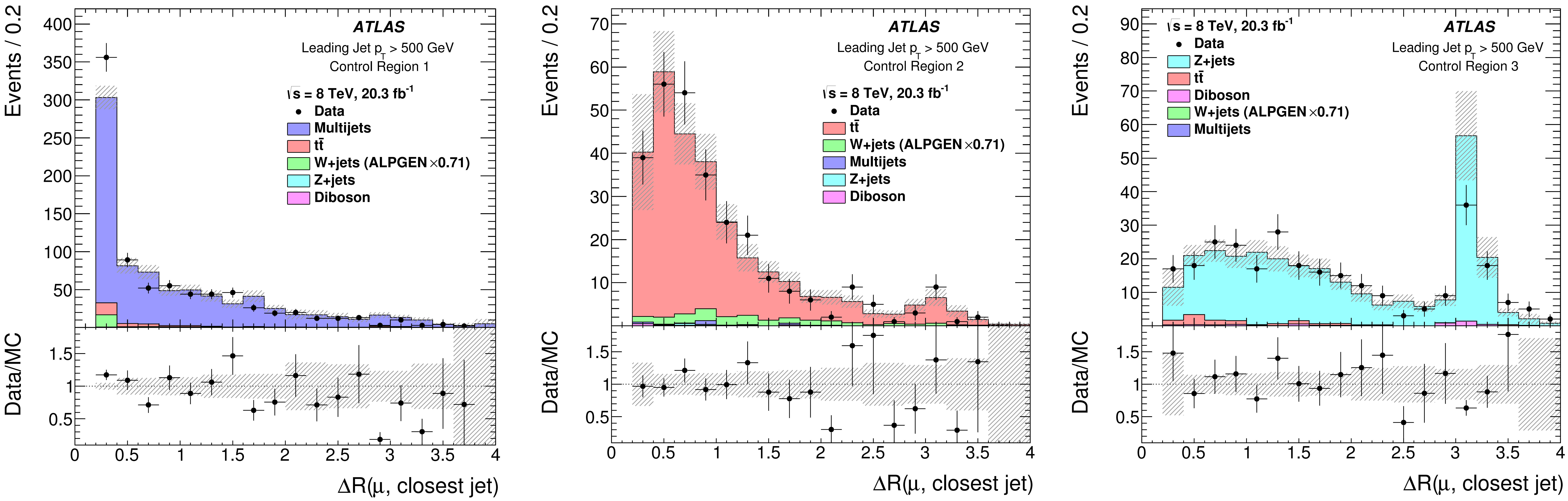




[arXiv:1609.07045]

8 TeV W dR | Backgrounds

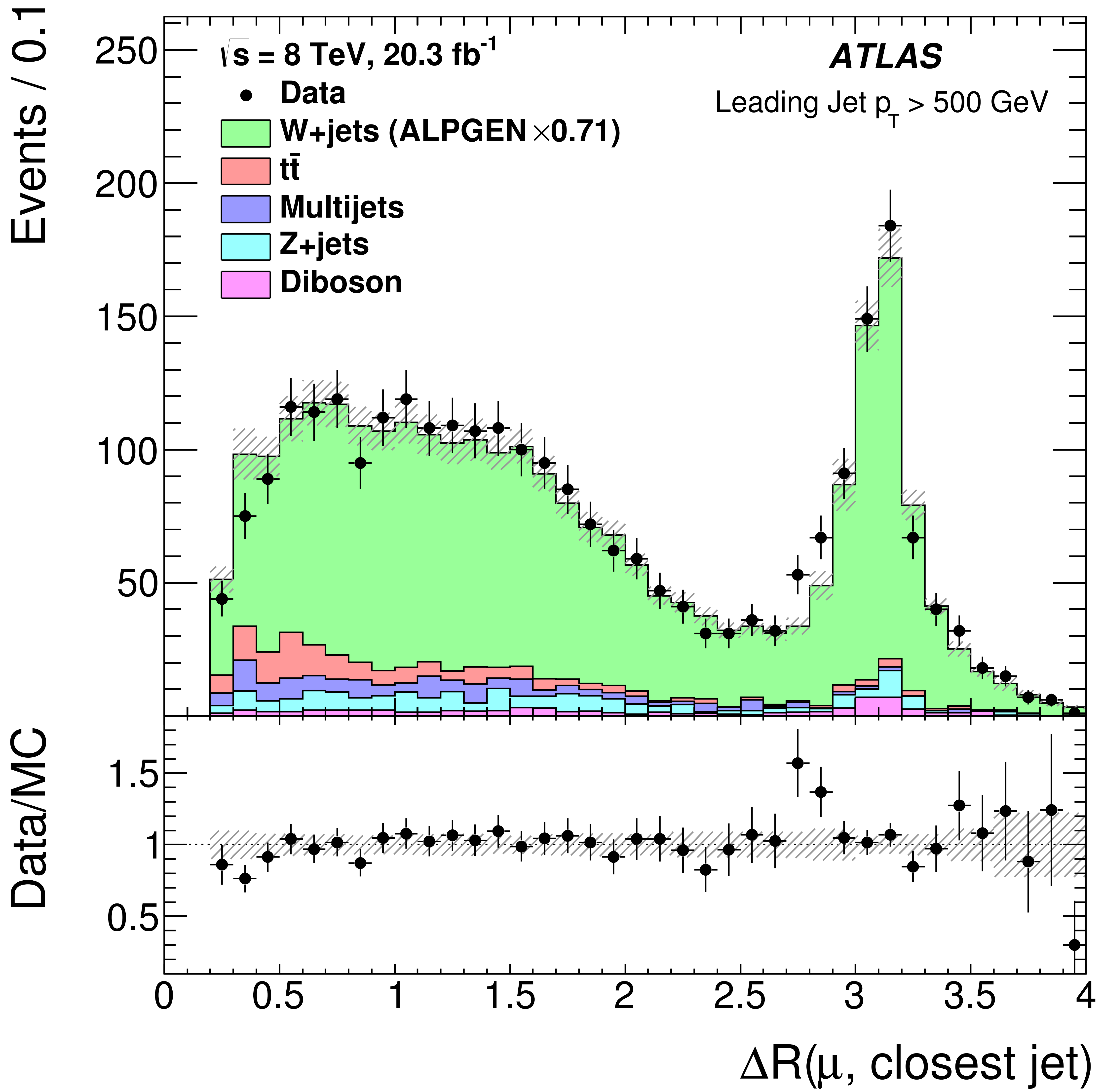
- Control regions defined for major backgrounds to derive MC scale factors:
  - **Multijet-enriched** (Pythia8) = 1.13
  - **ttbar-enriched** (Powheg+Pythia6) = 0.86
  - **Z+jets-enriched** (Alpgen+Pythia6) = 0.71



[arXiv:1609.07045]

8 TeV W dR | Results

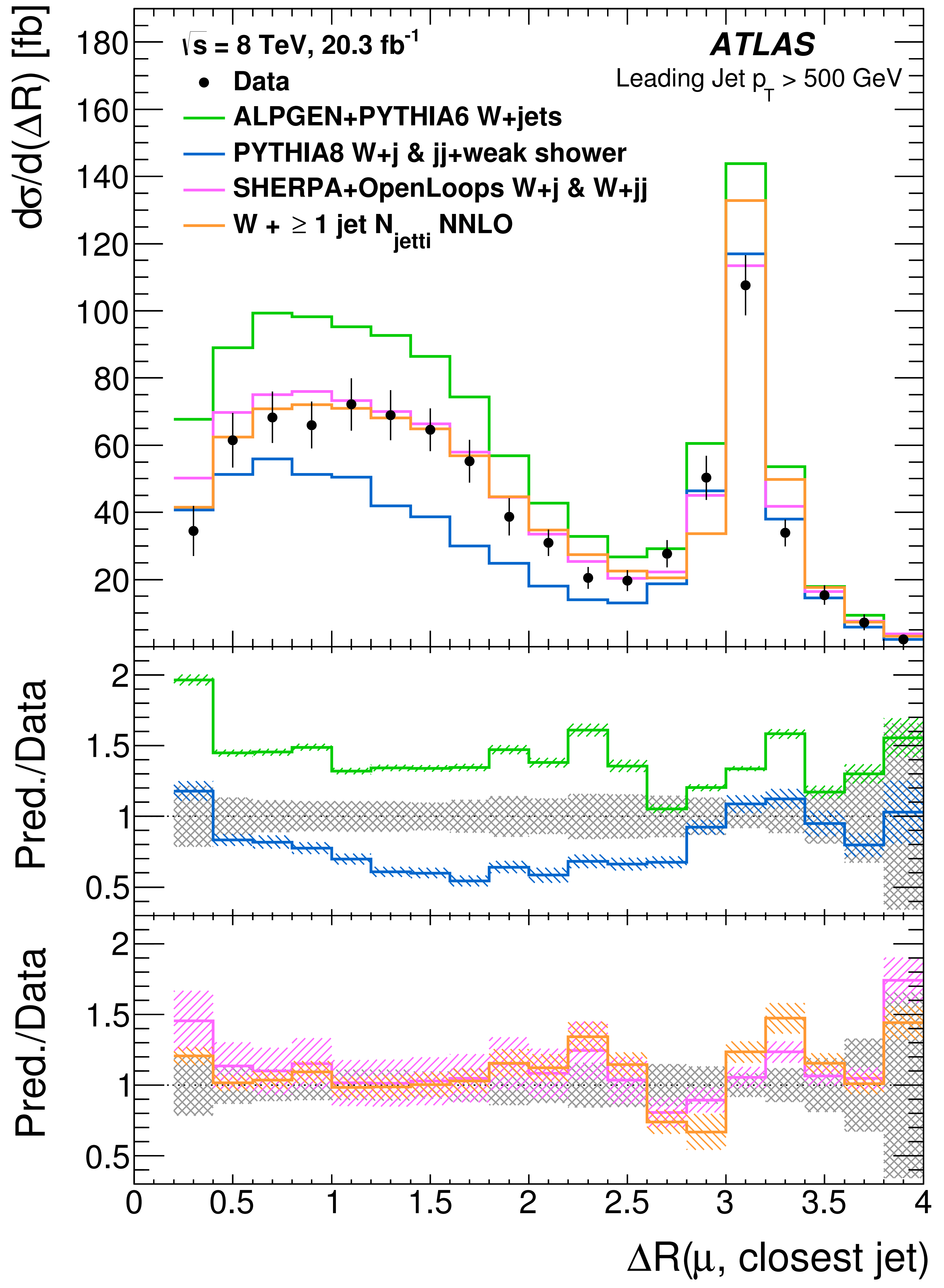
- All fed into signal region with signal scale-factor:
  - **W+jets** (Alpgen+Pythia6) = 0.71
  - Selection
    - >= 1 jet p_T > 500 GeV
    - ==1 muon, ==0 electrons
    - ==0 b-tagged jets
- Dominant systematic uncertainties are from:
  - b-tagging efficiency
    - From b-jet veto to reduce ttbar background
  - jet energy scale



[arXiv:1609.07045]

8 TeV W dR | Comparison to predictions

- Unfolded data compared to several predictions:
  - Alpgen+Pythia6 (LO@5j)
  - Pythia8+Weak Shower (LO@2j+EWK PS)
  - Sherpa+OpenLoops Wj+Wjj (NLO in QCD & EW)
  - W + ≥ 1 jet N_{jetti} NNLO

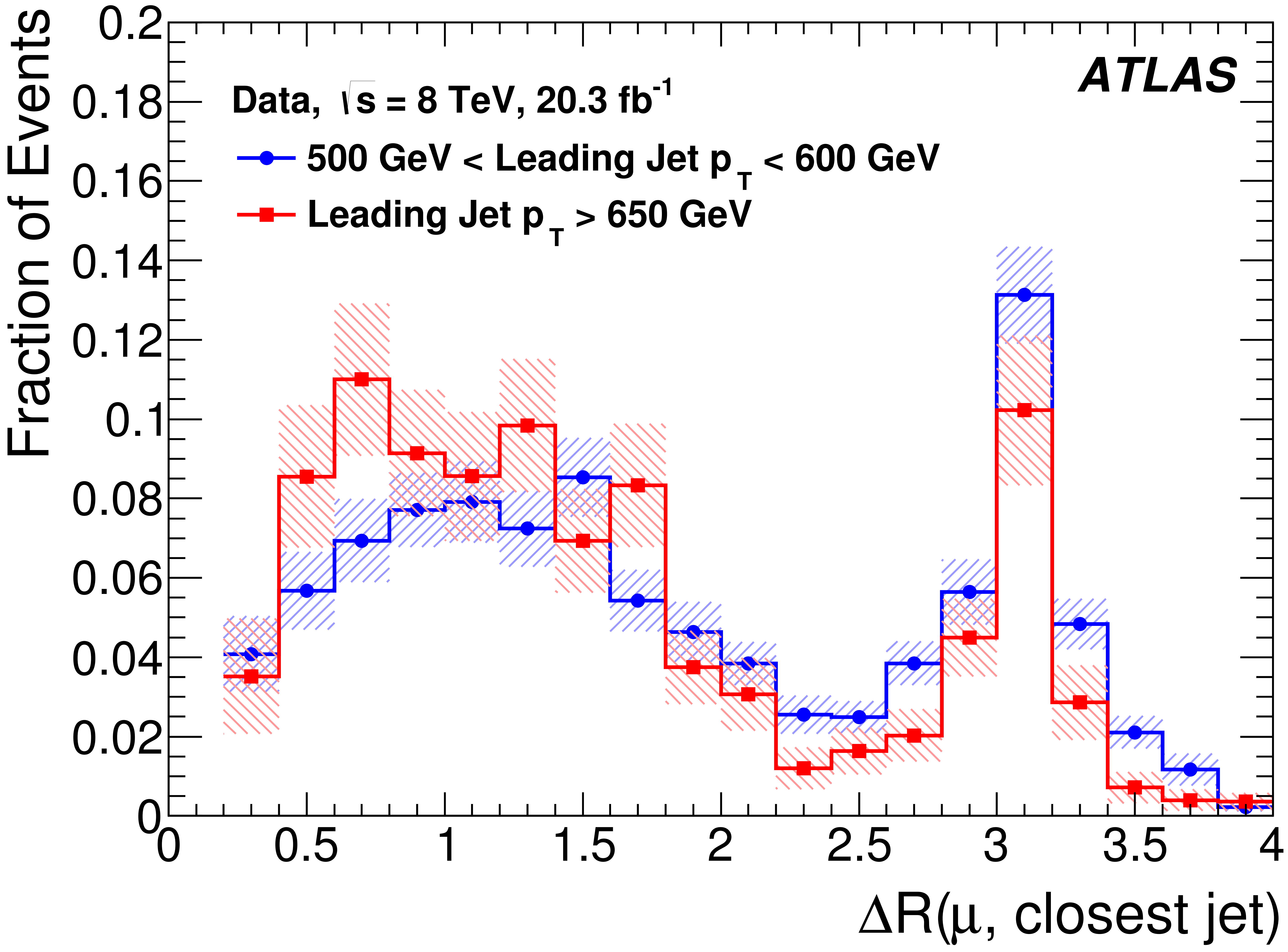


- At smaller *ΔR*, neither the shape nor the overall cross- section agree well for Alpgen or Pythia8.
- The predictions from Sherpa+OpenLoops and W + ≥ 1 jet N_{jetti} NNLO show much better agreement across the entire distribution.

[arXiv:1609.07045]

8 TeV W dR | Comparison to predictions

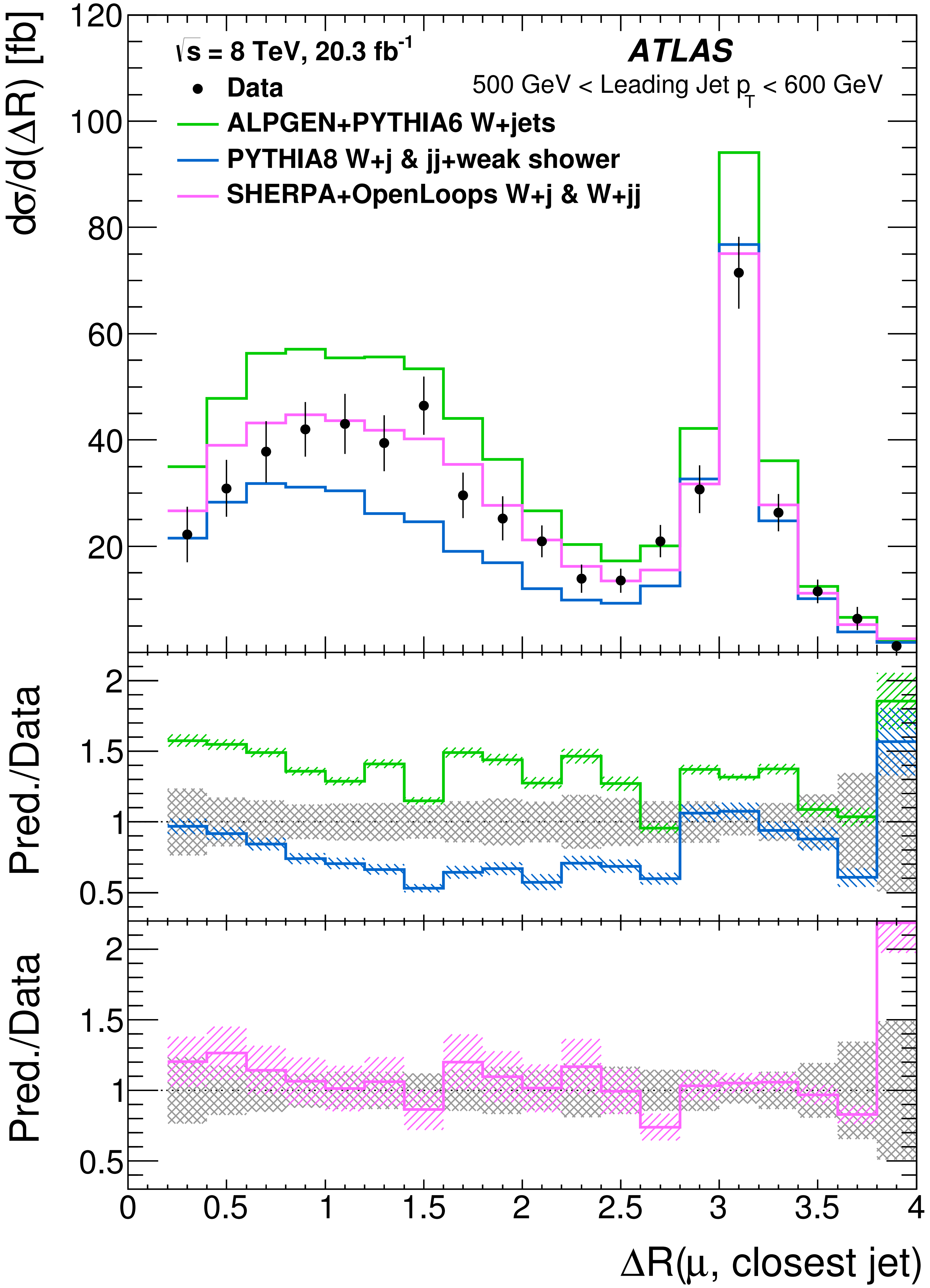
- Low and high leading jet p_T regions give different sensitivity to W emission.
- Sensitivity increases with increasing jet-p_T but the statistical uncertainty is also increasing.

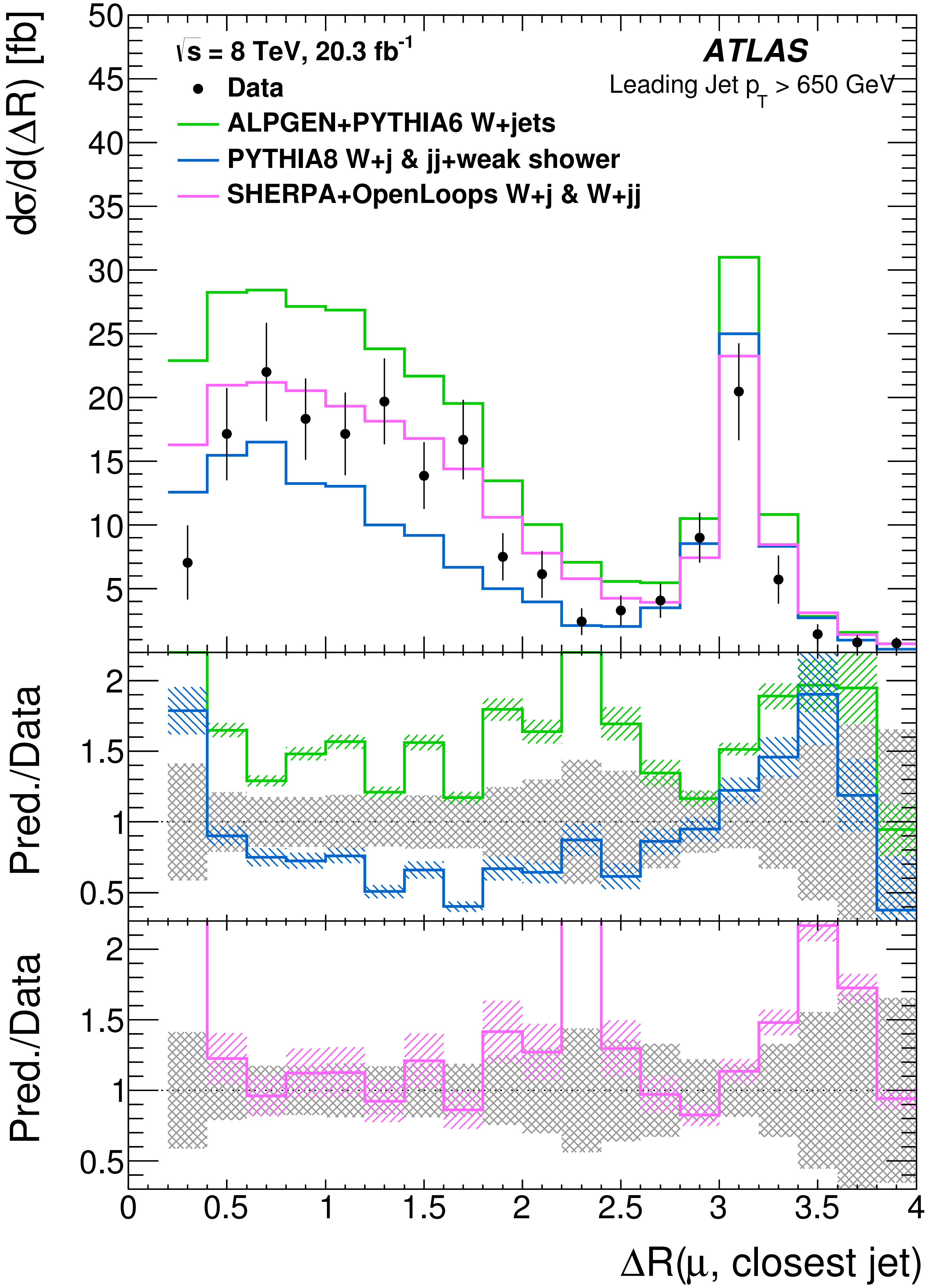


[arXiv:1609.07045]

8 TeV W dR | Comparison to predictions

- Low and high leading jet p_T regions give different sensitivity to W emission.
- Compared to several predictions:
  - Alpgen+Pythia6
  - Pythia8
  - Sherpa+OpenLoops
- The Sherpa prediction performs best.





[arXiv:1609.07045]

13 TeV Z+jets

[Eur. Phys. J. C77 (2017) 361
arXiv:1702.05725]

13 TeV Z+jets | Introduction

- Provides a clean signal with which to perform accurate measurements.

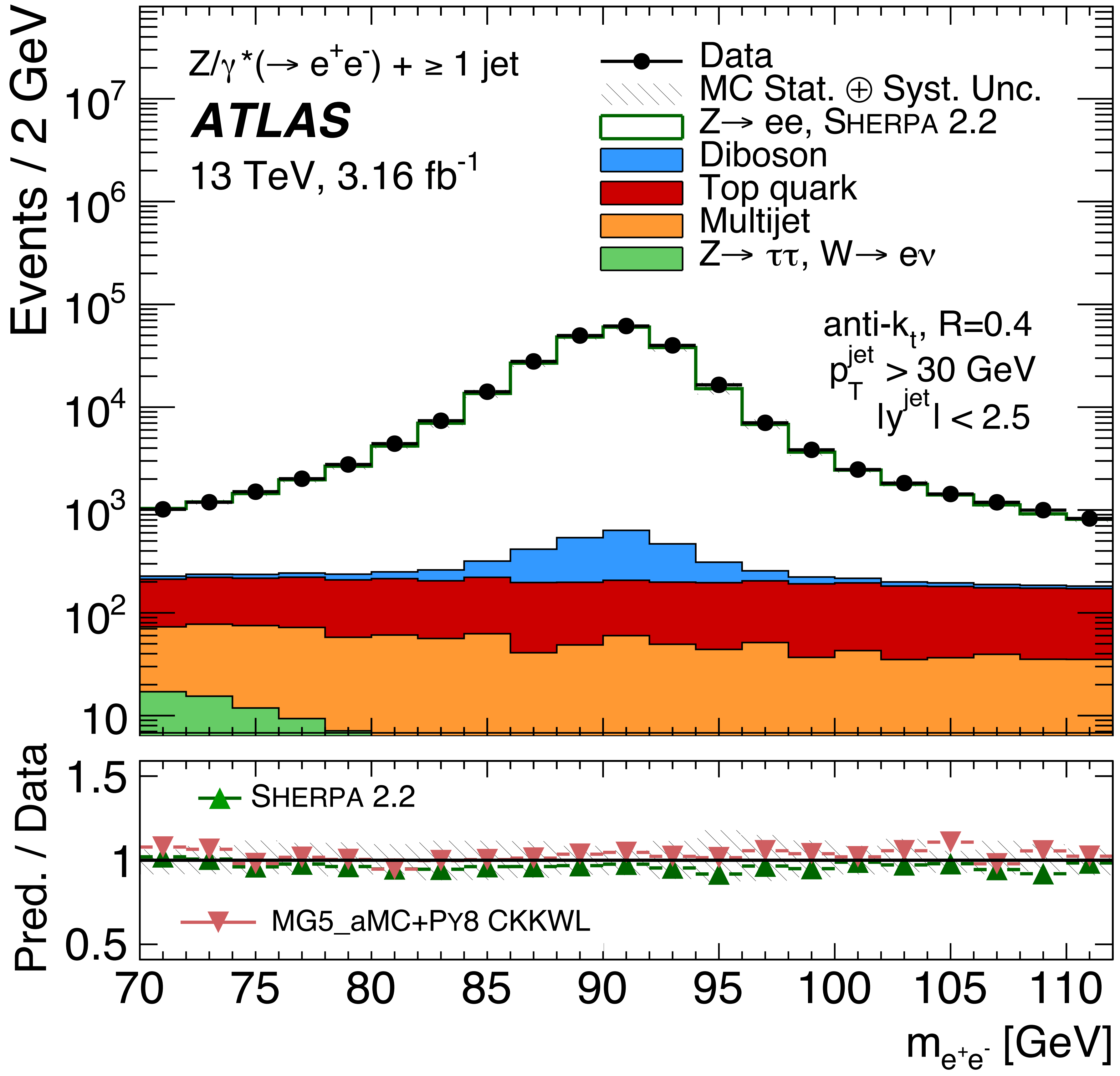
- Used as a powerful test of perturbative QCD.

- V+jets processes constitute a non-negligible background for studies of the Higgs boson and in searches for new phenomena
  - Accurate modelling is vital for the sensitivity of these analyses

[arXiv:1702.05725]

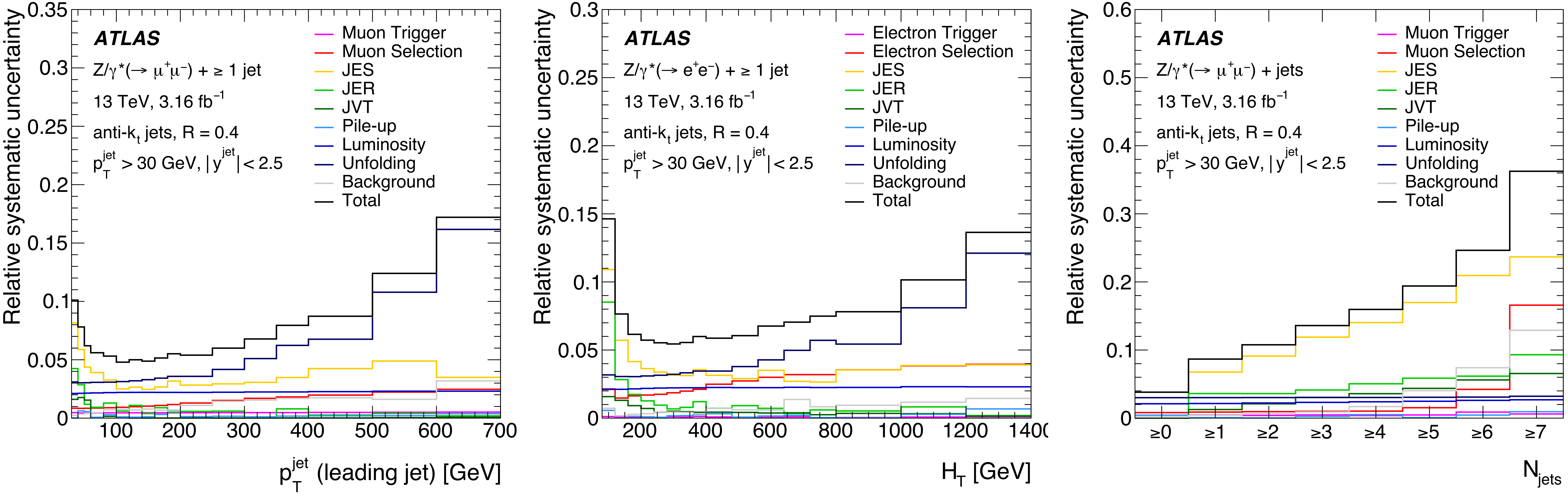
13 TeV Z+jets | Backgrounds

- Backgrounds from non-signal single-boson, diboson and top-quark (single top-quark and top- quark pair) production are estimated using MC
- Contributions from multijet events are evaluated with data-driven techniques.
  - Background-enriched multijet control regions in data are constructed by loosening the lepton identification and isolation requirements.
  - Templates are built from the dilepton invariant mass distribution
  - The templates are normalised to events passing the Z-boson signal selection.



13 TeV Z+jets | Systematics

- Dominant sources of systematic uncertainty are:
  - Jet energy scale and jet energy resolution
  - Unfolding uncertainty
  - Lepton selection uncertainties

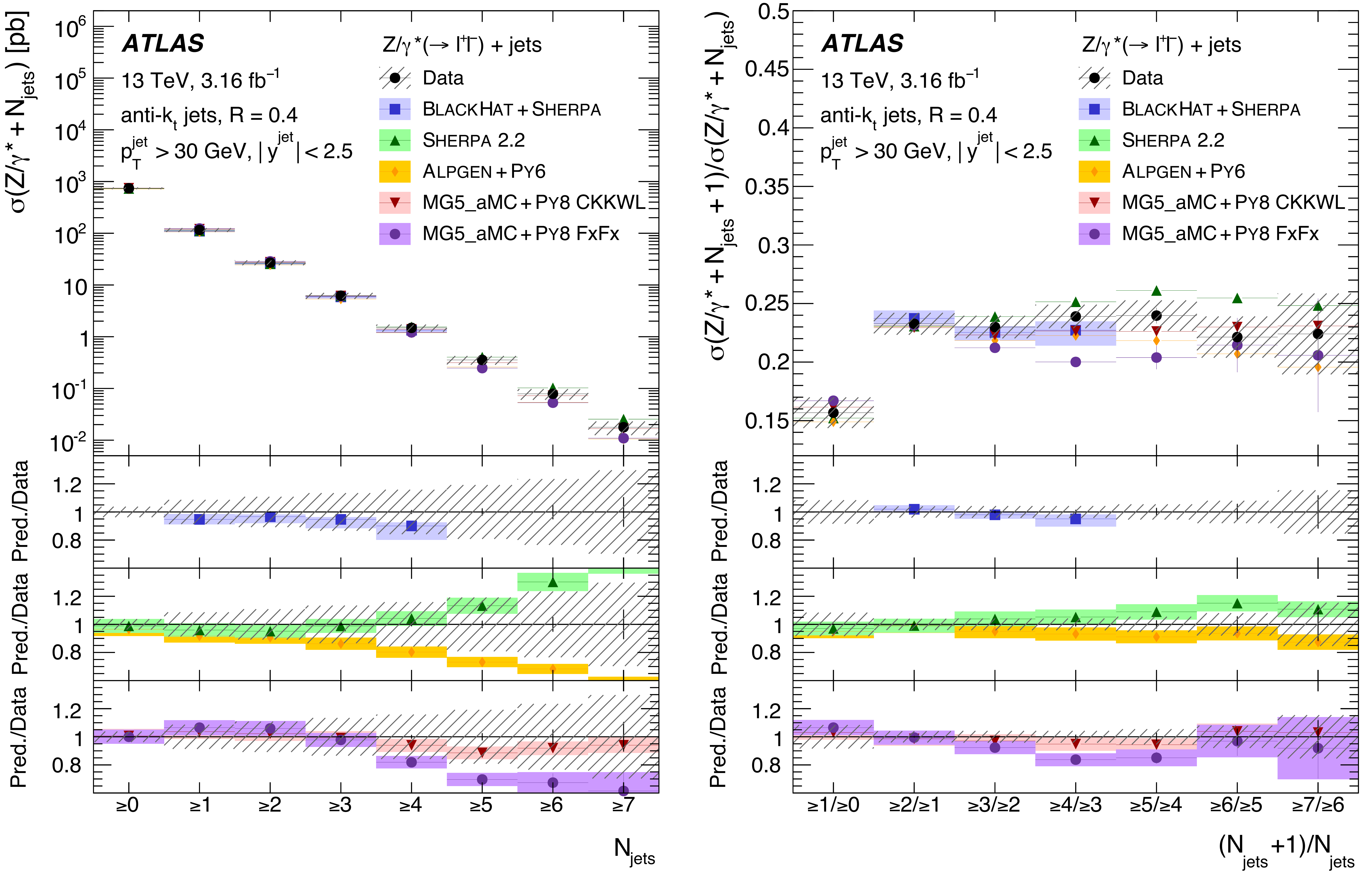


[arXiv:1702.05725]

13 TeV Z+jets | Results

- The unfolded differential cross sections are compared to several theoretical predictions:
  - BlackHat+Sherpa *(FO NLO@1-4j)*
  - Sherpa2.2 *(NLO@2j LO@4j)*
  - Alpgen+Pythia8 *(LO@5j)*
  - MG5_aMC+Py8 CKKW-L *(LO@4j)*
  - MG5_aMC+Py8 FxFx *(NLO@2j)*

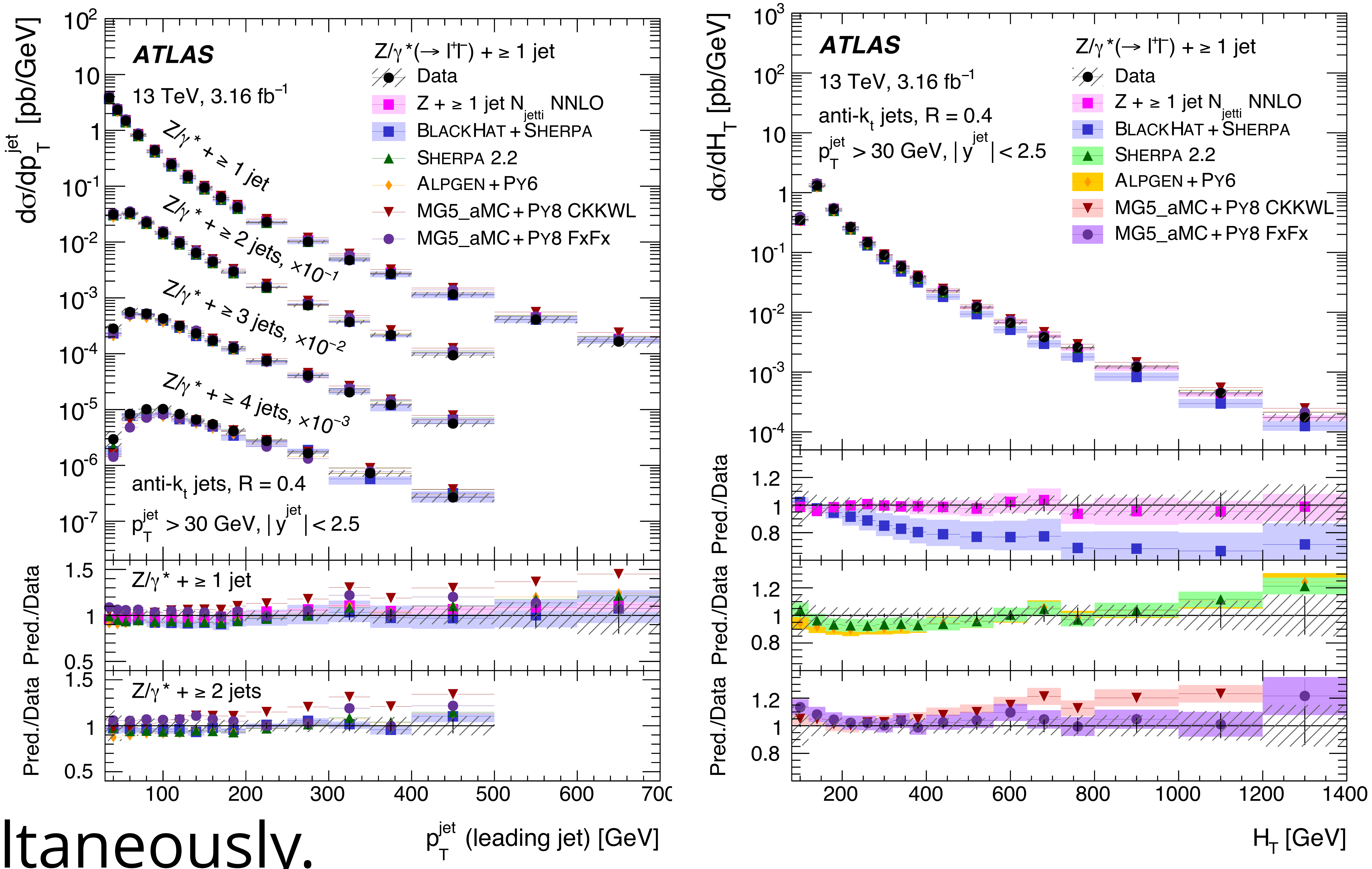
- Good agreement with the data except in higher multiplicity regions where a significant fraction of jets are produced by the parton shower.



[arXiv:1702.05725]

13 TeV Z+jets | Results

- The unfolded differential cross sections are compared to several theoretical predictions:
  - Njetti *(NNLO@1j)*
  - BlackHat+Sherpa *(FO NLO@1-4j)*
  - Sherpa2.2 (*NLO@2j LO@4j*)
  - Alpgen+Pythia8 *(LO@5j)*
  - MG5_aMC+Py8 CKKW-L *(LO@4j)*
  - MG5_aMC+Py8 FxFx *(NLO@2j)*

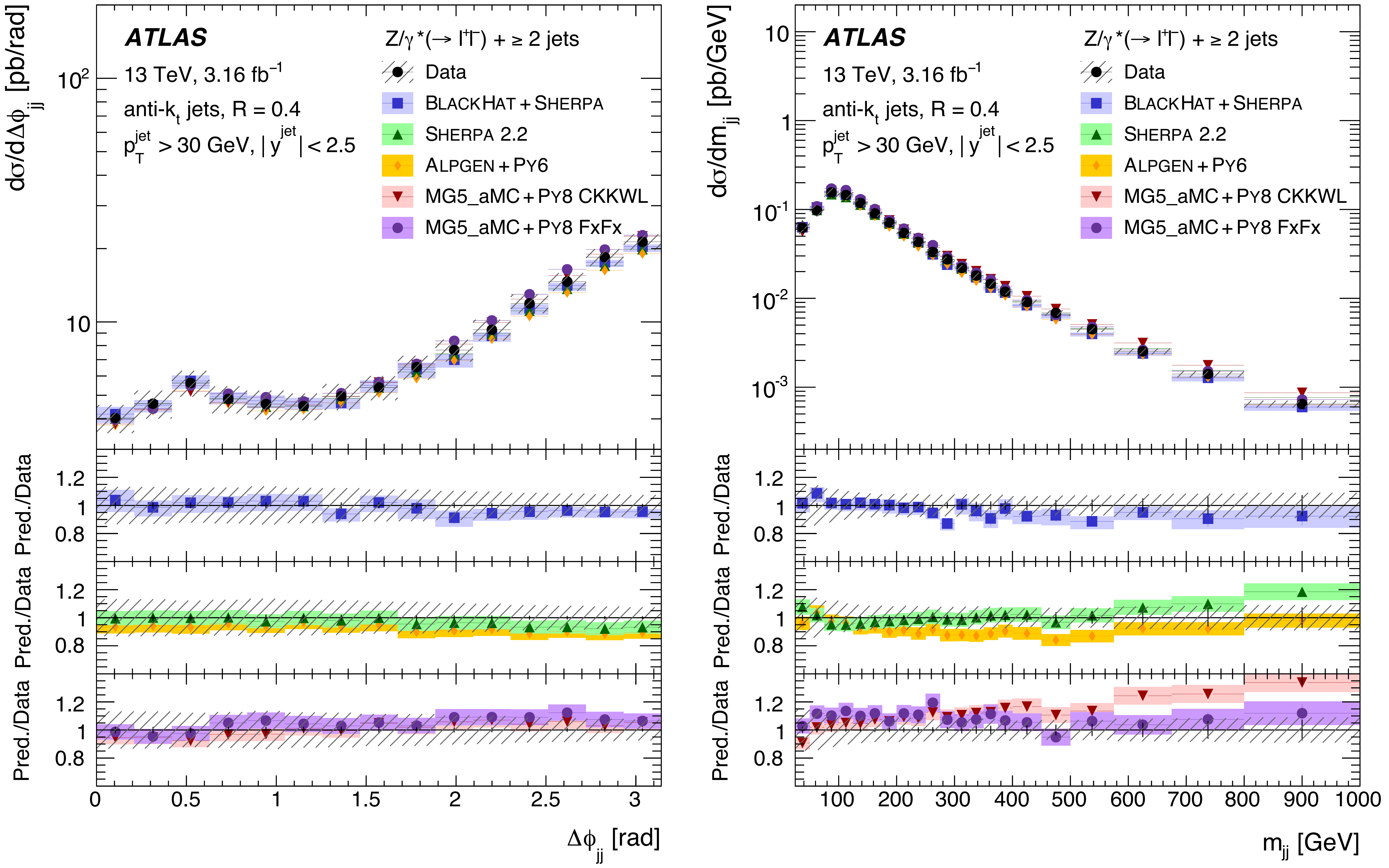


- **NLO**→**NNLO** scale uncertainty reduced!
- LO multileg setups too hard.
- Not easy to model N_{jets} & H_T simultaneously.

[arXiv:1702.05725]

13 TeV Z+jets | Results

- The unfolded differential cross sections are compared to several theoretical predictions:
  - BlackHat+Sherpa *(FO NLO@4j)*
  - Sherpa2.2 *(NLO@2j LO@4j)*
  - Alpgen+Pythia8 *(LO@5j)*
  - MG5_aMC+Py8 CKKW-L *(LO@4j)*
  - MG5_aMC+Py8 FxFx *(NLO@2j)*



- Good agreement with the data for $\Delta\varphi_{jj}$ as expected.
- Trends in m_{jj} not very strong in measured phase space, but known to be large beyond…

[arXiv:1702.05725]

13 TeV Z+jets | Further use of results

- Using these measurements to validate and tune the next generation of ATLAS V+jets samples.

[ATL-PHYS-PUB-2017-006]

Summary

Summary & outlook

- Many important tests of pQCD made with recent measurements.
- Lots of places where modelling could be improved.
- More measurements also required…
  - In the pipeline
    - 13 TeV V+HF
    - 13 TeV Z+jets at high p_T
- Advanced generator setups also in the pipeline:
  - Herwig7 NLO merging with Matchbox
  - MG5_aMC+Py8 UNLOPS
  - Geneva

Summary & outlook

- Many important tests of pQCD made with recent measurements.

- Lots of places where modelling could be improved.

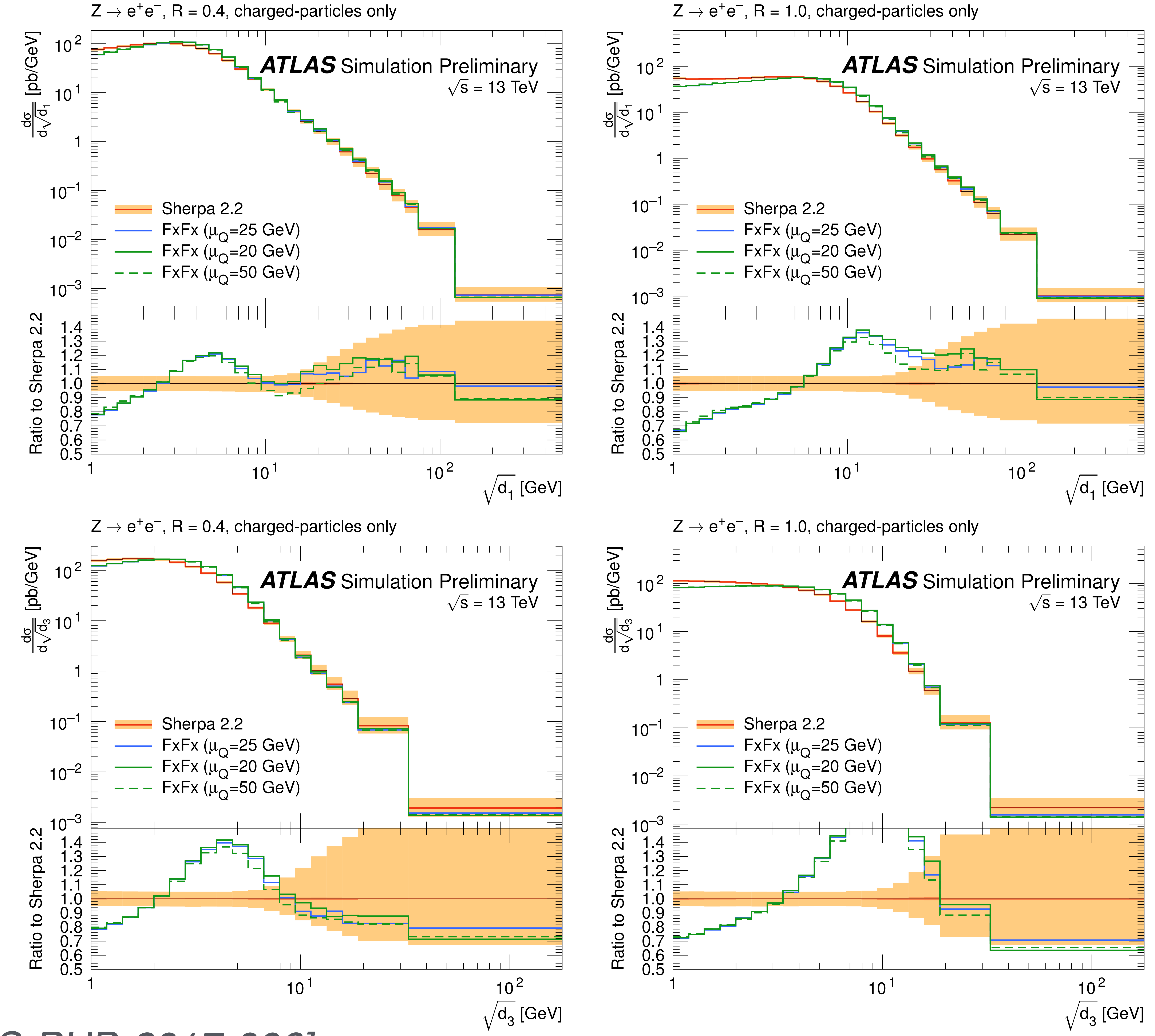
- More measurements also required…
  - In the pipeline
    - 13 TeV V+HF
    - 13 TeV Z+jets at high p_T

- Advanced generator setups also in the pipeline:
  - Herwig7 NLO merging with Matchbox
  - MG5_aMC+Py8 UNLOPS
  - Geneva

Thanks for your attention!

Back-ups

8TeV k_T-splittings | MC studies



[ATL-PHYS-PUB-2017-006]

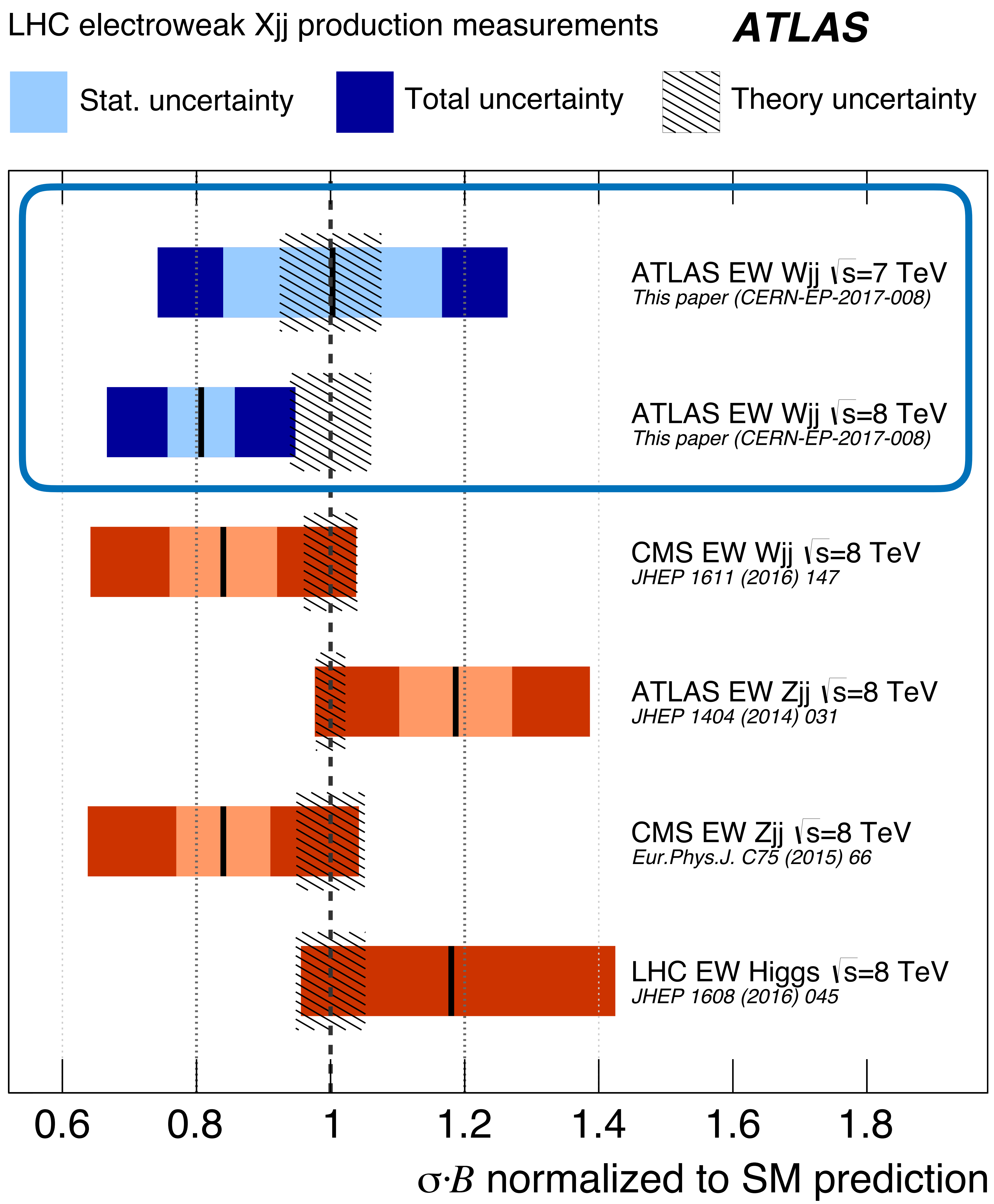
7&8 TeV EW Wjj | Results

- There is good overall agreement between the normalized distributions and the data.

- The fit results for μ_{QCD} are:
  - 1.16 ± 0.04 (stat) for 7 TeV data
  - 1.09 ± 0.02 (stat) for 8 TeV data.

- The measured values of μ_{EW} are:

$$\mu_{EW}\ (7\ \text{TeV}) = 1.00 \pm 0.16\ (\text{stat}) \pm 0.17\ (\text{exp}) \pm 0.12\ (\text{th}),$$
$$\mu_{EW}\ (8\ \text{TeV}) = 0.81 \pm 0.05\ (\text{stat}) \pm 0.09\ (\text{exp}) \pm 0.10\ (\text{th}).$$



[arXiv:1703.04362]

7&8 TeV EW Wjj

Region name	Requirements
Preselection	Lepton $p_T > 25$ GeV Lepton $\|\eta\| < 2.5$ $E_T^{miss} > 20$ GeV $m_T > 40$ GeV $p_T^{j_1} > 80$ GeV $p_T^{j_2} > 60$ GeV Jet $\|y\| < 4.4$ $M_{jj} > 500$ GeV $\Delta y(j_1, j_2) > 2$ $\Delta R(j, \ell) > 0.3$
Fiducial and differential measurements	
Signal region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Forward-lepton control region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} = 0$
Central-jet validation region	$N_{lepton}^{cen} = 1, N_{jets}^{cen} \geq 1$
Differential measurements only	
Inclusive regions	$M_{jj} > 0.5$ TeV, 1 TeV, 1.5 TeV, or 2 TeV
Forward-lepton/central-jet region	$N_{lepton}^{cen} = 0, N_{jets}^{cen} \geq 1$
High-mass signal region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0$
Anomalous coupling measurements only	
High-q^2 region	$M_{jj} > 1$ TeV, $N_{lepton}^{cen} = 1, N_{jets}^{cen} = 0, p_T^{j_1} > 600$ GeV

[arXiv:1609.07045]

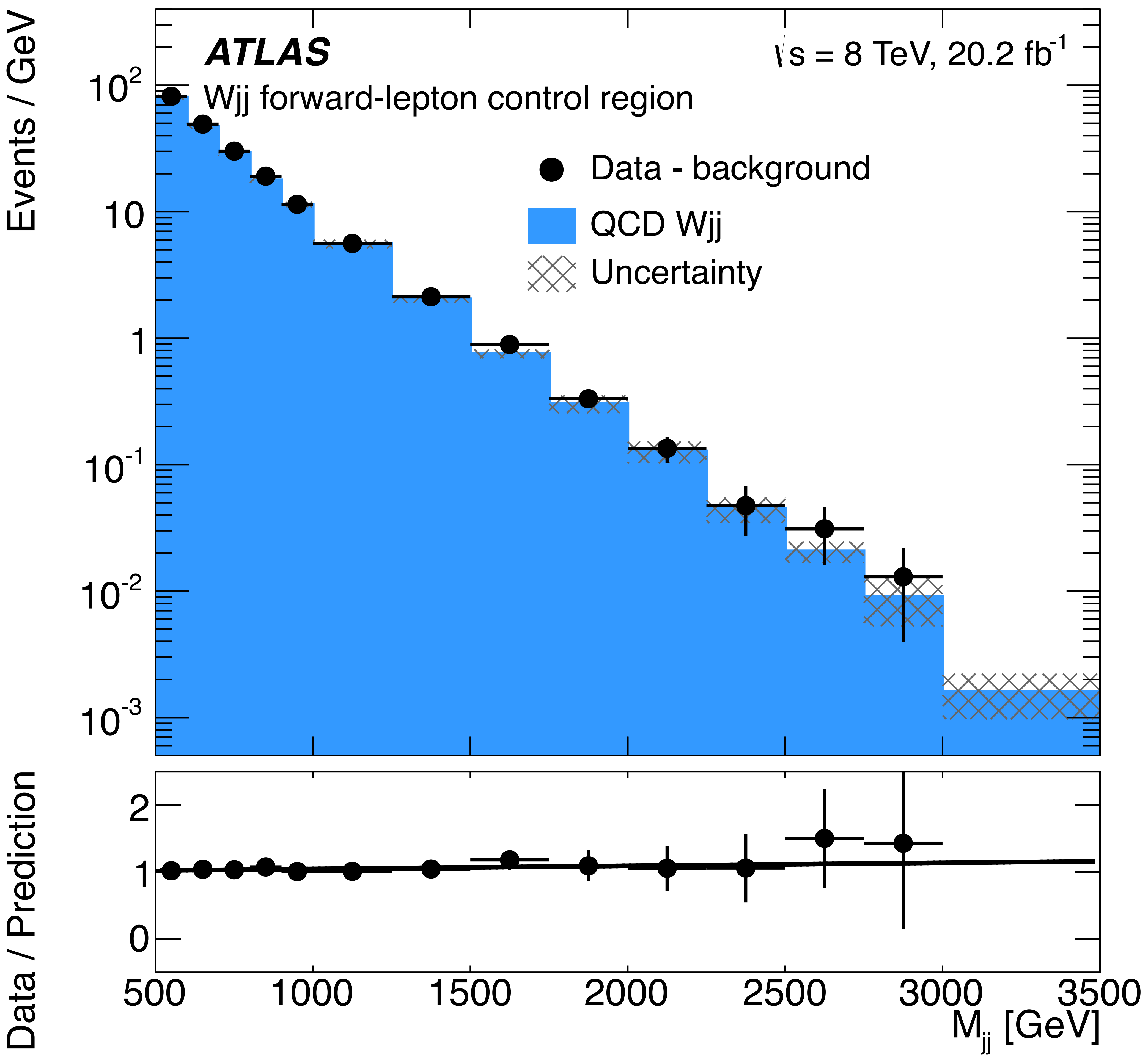
7&8 TeV EW Wjj

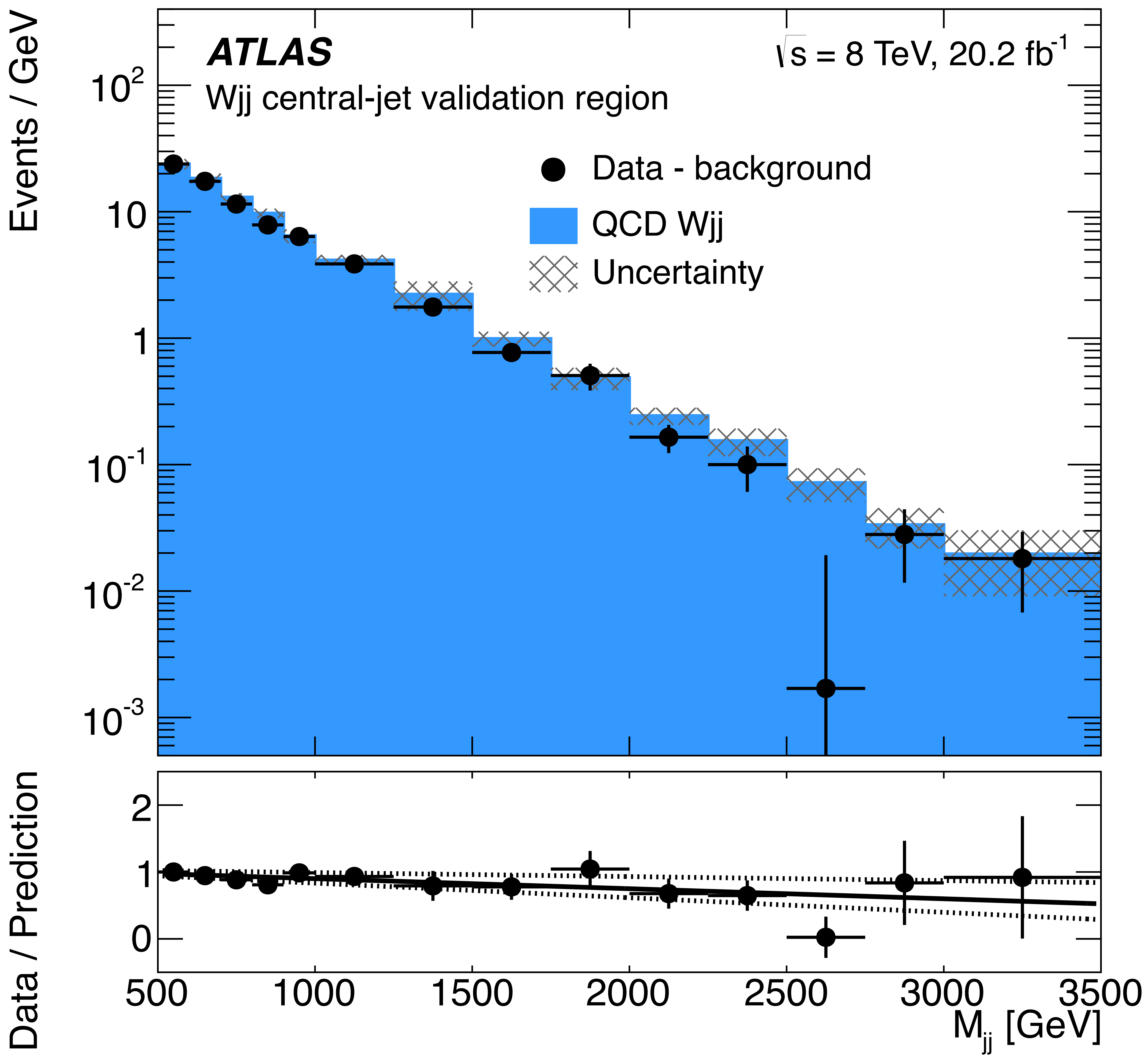
Process	MC generator	$\sigma \cdot \mathcal{B}$ [pb] 7 TeV	8 TeV
$W(\to e\nu, \mu\nu)$ + 2 jets			
2 EW vertices	Powheg + Pythia8	4670	5340
4 EW vertices (no dibosons)	Powheg + Pythia8	2.7	3.4
$W(\to \tau\nu)$ inclusive			
2 EW vertices	Sherpa	10100	11900
$W(\to \tau\nu)$ + 2 jets			
4 EW vertices (with dibosons)	Sherpa	8.4	
4 EW vertices (no dibosons)	Sherpa		4.2
Top quarks			
$t\bar{t}(\to \ell\nu b\bar{q}q\bar{b}, \ell\nu b\ell\nu\bar{b})$	MC@NLO + Herwig	90.0	
	Powheg + Pythia6		114
tW	AcerMC + Pythia6	15.3	
	MC@NLO + Herwig		20.7
$t\bar{b}q \to \ell\nu b\bar{b}q$	AcerMC + Pythia6	23.5	25.8
$t\bar{b} \to \ell\nu b\bar{b}$	AcerMC + Pythia6	1.0	
	MC@NLO + Herwig		1.7
$Z(\to \ell\ell)$ inclusive, $m_{\ell\ell} > 40$ GeV			
2 EW vertices	Sherpa	3140	3620
$Z(\to ee, \mu\mu)$ + 2 jets, $m_{ee,\mu\mu} > 40$ GeV			
4 EW vertices (no dibosons)	Sherpa	0.7	0.9
Dibosons			
WW	Herwig++	45.9	56.8
WZ	Herwig++	18.4	22.5
ZZ	Herwig++	6.0	7.2

[arXiv:1609.07045]

7&8 TeV EW Wjj

- No jet in gap (to derive correction) → With jet in gap (to validate correction)





- Correction reduces total uncertainty of σ/σSM from 0.18 to 0.14.

[arXiv:1609.07045]

7&8 TeV EW Wjj

Table 5: The statistical and systematic uncertainty contributions to the measurements of μ_{EW} in 7 and 8 TeV data.

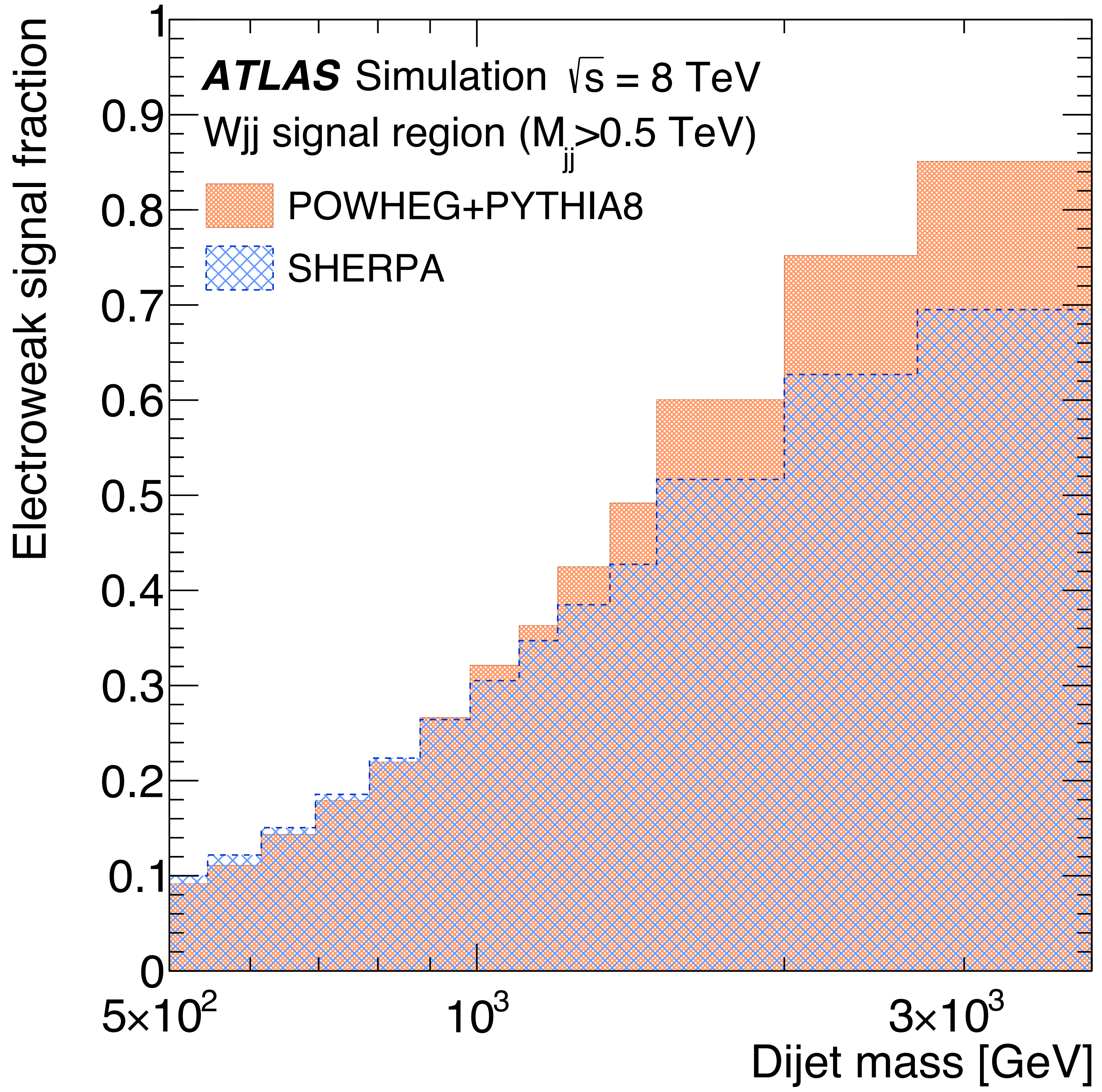
Source	Uncertainty in μ_{EW} 7 TeV	Uncertainty in μ_{EW} 8 TeV
Statistical		
Signal region	0.094	0.028
Control region	0.127	0.044
Experimental		
Jet energy scale (η intercalibration)	0.124	0.053
Jet energy scale and resolution (other)	0.096	0.059
Luminosity	0.018	0.019
Lepton and E_T^{miss} reconstruction	0.021	0.012
Multijet background	0.064	0.019
Theoretical		
MC statistics (signal region)	0.027	0.026
MC statistics (control region)	0.029	0.019
EW Wjj (scale and parton shower)	0.012	0.031
QCD Wjj (scale and parton shower)	0.043	0.018
Interference (EW and QCD Wjj)	0.037	0.032
Parton distribution functions	0.053	0.052
Other background cross sections	0.002	0.002
EW Wjj cross section	0.076	0.061
Total	0.26	0.14

[arXiv:1609.07045]

7&8 TeV EW Wjj

[arXiv:1609.07045]

7&8 TeV EW Wjj



[arXiv:1609.07045]

8 TeV W boson angular distributions

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%

Process	$0.2 < \Delta R < 2.4$	$\Delta R > 2.4$	Inclusive
Dijets	5%	2%	4%
$t\bar{t}$	7%	2%	5%
Z + jets	6%	4%	5%
Dibosons	2%	4%	3%
W + jets	80%	88%	82%
Data	1907	833	2740

[arXiv:1609.07045]

13 TeV Z+jets

Process	Generator	$(\sigma \cdot \mathrm{BR})$ [pb]	Normalisation order	Reference	Theory uncert.
$Z(\rightarrow \ell^+\ell^-) +$ jets ($\ell = e, \mu; m_{\ell\ell} > 40$ GeV)	SHERPA 2.2	2106	NNLO	[24–27]	5%
$Z(\rightarrow \ell^+\ell^-) +$ jets ($\ell = e, \mu, \tau; m_{\ell\ell} > 40$ GeV)	MG5_aMC@NLO+PY8	2103	NNLO	[24–27]	5%
$W \rightarrow \ell\nu$ ($\ell = e, \mu$)	MG5_aMC@NLO+PY8	20080	NNLO	[24–27]	5%
$t\bar{t}$ ($m_t = 172.5$ GeV)					
PERUGIA2012(RADHI/RADLO)	POWHEG+PY6	831	NNLO+NNLL	[28]	6%
UE-EE-5	MG5_aMC@NLO+Herwig++	831	NNLO+NNLL	[28]	6%
Single top quark (Wt)	POWHEG+PY6	72	NLO+NNLL	[29]	6%
Single top quark (t-channel)	POWHEG+PY6	136	NLO+NNLL	[30]	6%
Single top anti-quark (t-channel)	POWHEG+PY6	81	NLO+NNLL	[30]	6%
Dibosons	SHERPA 2.1	97	NLO	[31]	6%

[arXiv:1702.05725]

13 TeV Z+jets

	Electron channel							
	$+ \geq 0$ jets	$+ \geq 1$ jets	$+ \geq 2$ jets	$+ \geq 3$ jets	$+ \geq 4$ jets	$+ \geq 5$ jets	$+ \geq 6$ jets	$+ \geq 7$ jets
$Z \rightarrow e^+e^-$ [%]	99.3	97.6	93.9	90.3	87.3	85.2	83.3	81.2
Top quark [%]	0.2	1.2	3.8	6.5	8.6	9.7	10.5	11.6
Diboson [%]	0.2	0.8	1.6	2.4	3.4	4.4	5.5	6.6
$Z \rightarrow \tau^+\tau^-$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$W \rightarrow e\nu$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Multijet [%]	0.2	0.4	0.6	0.7	0.7	0.7	0.7	0.7
Expected	1,327,900	239,500	57,310	14,080	3637	978	252	63
Observed	1,347,900	248,816	59,998	14,377	3587	898	217	48

	Muon channel							
	$+ \geq 0$ jets	$+ \geq 1$ jets	$+ \geq 2$ jets	$+ \geq 3$ jets	$+ \geq 4$ jets	$+ \geq 5$ jets	$+ \geq 6$ jets	$+ \geq 7$ jets
$Z \rightarrow \mu^+\mu^-$ [%]	99.3	97.5	94.0	90.7	88.3	86.7	84.8	84.6
Top quark [%]	0.2	1.1	3.6	6.0	7.7	8.1	8.7	7.7
Diboson [%]	0.2	0.7	1.6	2.4	3.4	4.5	5.9	7.0
$Z \rightarrow \tau^+\tau^-$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$W \rightarrow \mu\nu$ [%]	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Multijet [%]	0.3	0.6	0.9	0.9	0.7	0.7	0.7	0.7
Expected	1,693,000	300,600	71,230	17,740	4523	1187	307	76
Observed	1,708,602	311,183	74,510	17,865	4387	1081	240	57

Table 2: Fraction of signal and background processes in % in the final selection and expected and observed numbers of events for the various inclusive jet multiplicities considered in the electron (top) and muon (bottom) channels.

[arXiv:1702.05725]

13 TeV Z+jets

Jet multiplicity	Measured cross section ± (stat.) ± (syst.) ± (lumi.) [pb]	
	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$
≥ 0 jets	743 ± 1 ± 24 ± 16	738 ± 1 ± 23 ± 16
≥ 1 jets	116.6 ± 0.3 ± 9.9 ± 2.5	115.7 ± 0.2 ± 9.7 ± 2.5
≥ 2 jets	27.1 ± 0.1 ± 2.9 ± 0.6	27.0 ± 0.1 ± 2.8 ± 0.6
≥ 3 jets	6.20 ± 0.06 ± 0.82 ± 0.14	6.22 ± 0.05 ± 0.83 ± 0.14
≥ 4 jets	1.49 ± 0.03 ± 0.23 ± 0.04	1.48 ± 0.03 ± 0.23 ± 0.04
≥ 5 jets	0.357 ± 0.013 ± 0.069 ± 0.009	0.354 ± 0.012 ± 0.068 ± 0.009
≥ 6 jets	0.082 ± 0.006 ± 0.019 ± 0.002	0.076 ± 0.005 ± 0.019 ± 0.002
≥ 7 jets	0.0180 ± 0.0029 ± 0.0051 ± 0.0005	0.0166 ± 0.0027 ± 0.0060 ± 0.0004

Table 3: Measured fiducial cross sections in the electron and muon channels for successive inclusive jet multiplicities. The total statistical and systematic uncertainties are given, along with the uncertainty in the luminosity.

[arXiv:1702.05725]

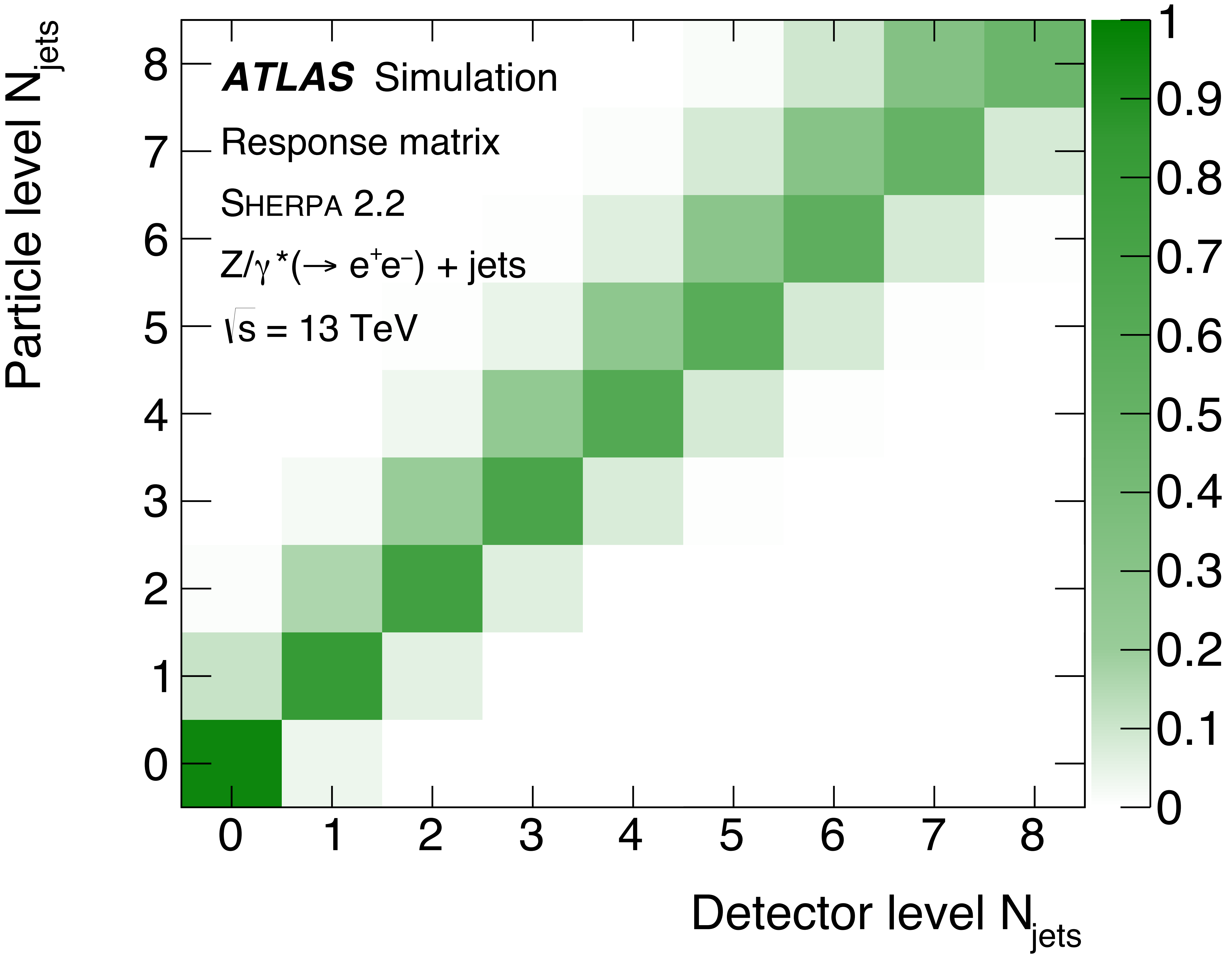
13 TeV Z+jets

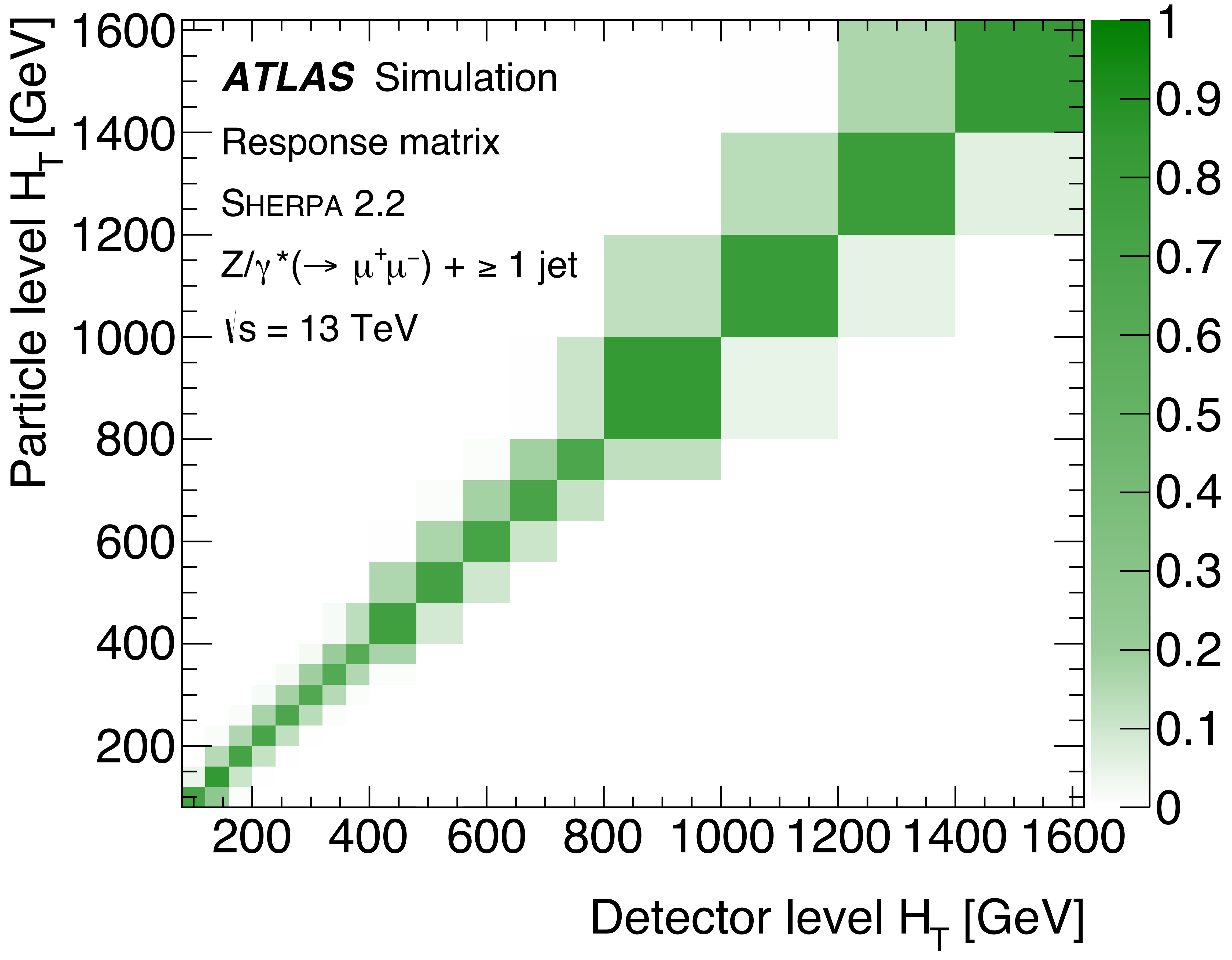
Relative uncertainty in $\sigma(Z(\to \ell^+\ell^-)+ \geq N_{\text{jets}})$ [%]								
	$Z \to e^+e^-$							
Systematic source	$+\geq 0$ jets	$+\geq 1$ jets	$+\geq 2$ jets	$+\geq 3$ jets	$+\geq 4$ jets	$+\geq 5$ jets	$+\geq 6$ jets	$+\geq 7$ jets
Electron trigger	0.1	0.1	0.1	0.2	0.2	0.2	0.3	0.3
Electron 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
Total 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
	$Z \to \mu^+\mu^-$							
Systematic source	$+\geq 0$ jets	$+\geq 1$ jets	$+\geq 2$ 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	< 0.1	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
Total syst. uncertainty	3.8	8.7	10.8	13.6	16.0	19.4	24.6	36.3
Stat. uncertainty	0.1	0.2	0.4	0.8	1.7	3.4	7.2	16.3

Table 4: Relative statistical and systematic uncertainties (in %) in the measured cross sections of Z+jets production for successive inclusive jet multiplicities in the electron (top) and muon (bottom) channels.

[arXiv:1702.05725]

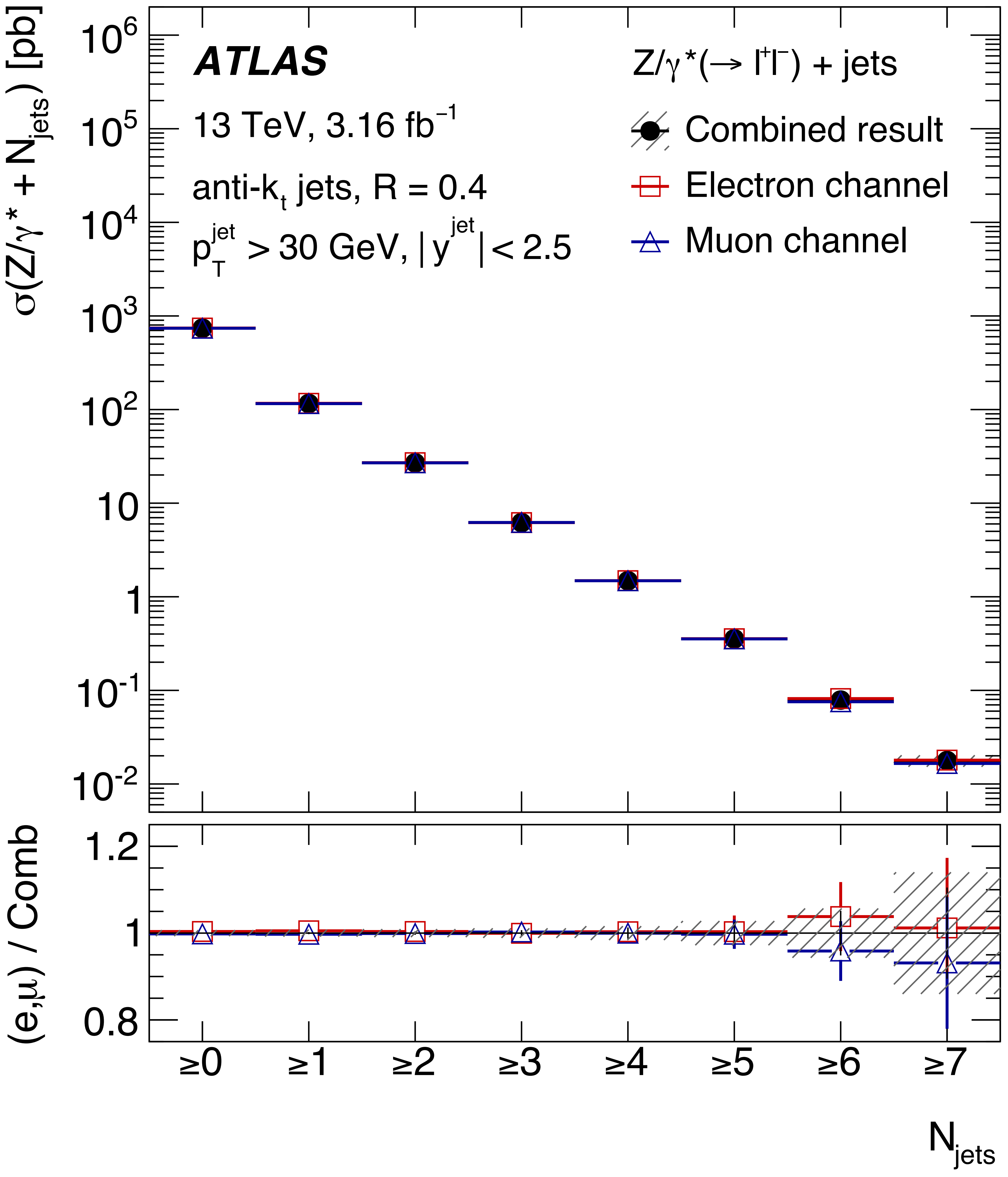
13 TeV Z+jets

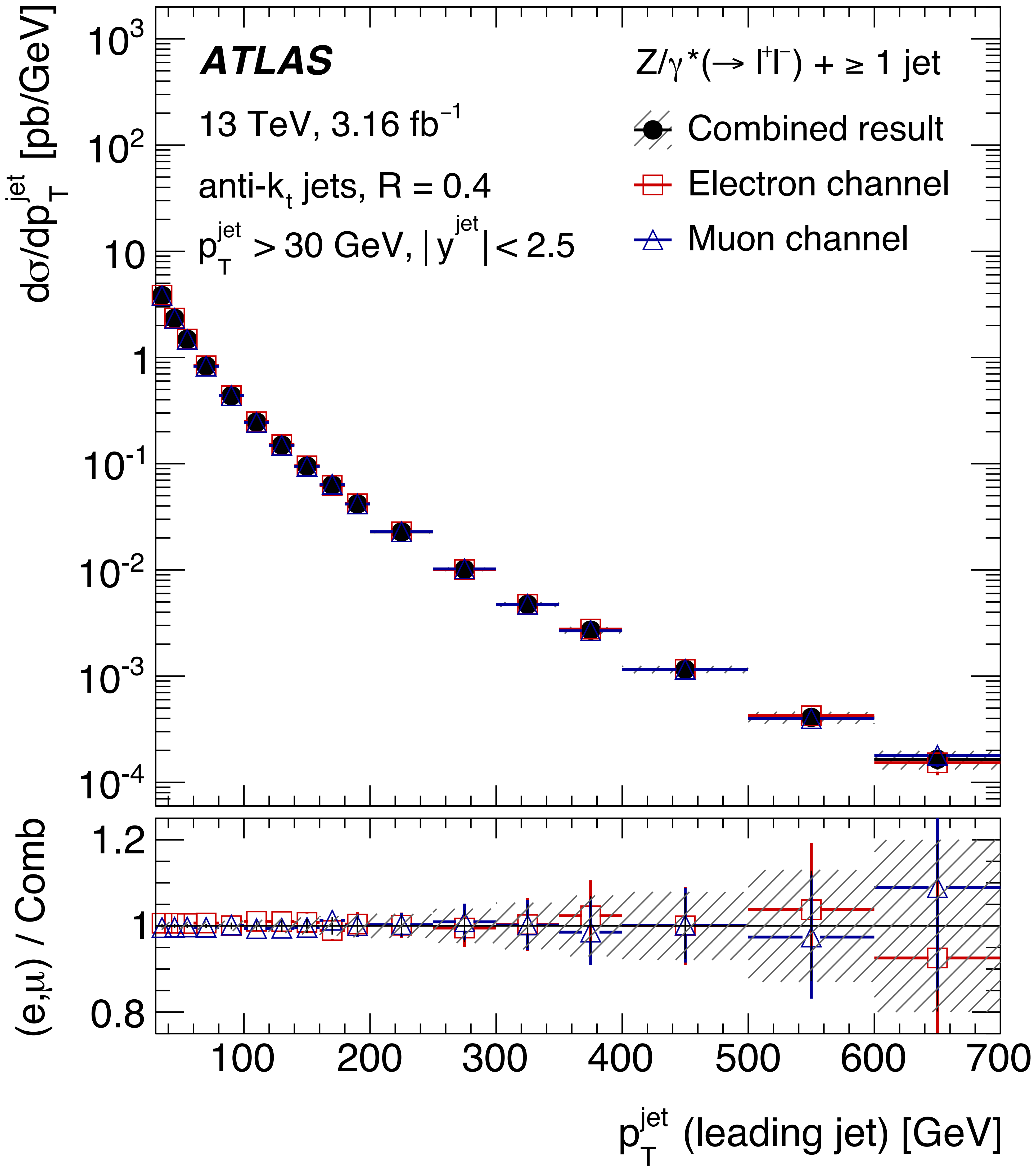




[arXiv:1702.05725]

13 TeV Z+jets





[arXiv:1702.05725]

13 TeV Z+jets

Jet multiplicity	Measured cross-section ratio $\pm$ (stat.) $\pm$ (syst.) $\pm$ (lumi.)
	$Z \rightarrow \ell\ell$
≥ 1 jets / ≥ 0 jets	$0.1568 \pm 0.0004 \pm 0.0131 \pm 0.0001$
≥ 2 jets / ≥ 1 jets	$0.2327 \pm 0.0011 \pm 0.0093 \pm 0.0002$
≥ 3 jets / ≥ 2 jets	$0.2299 \pm 0.0018 \pm 0.0095 \pm 0.0002$
≥ 4 jets / ≥ 3 jets	$0.2390 \pm 0.0035 \pm 0.0094 \pm 0.0002$
≥ 5 jets / ≥ 4 jets	$0.2397 \pm 0.0068 \pm 0.0111 \pm 0.0002$
≥ 6 jets / ≥ 5 jets	$0.2213 \pm 0.0127 \pm 0.0123 \pm 0.0003$
≥ 7 jets / ≥ 6 jets	$0.2240 \pm 0.0264 \pm 0.0222 \pm 0.0003$

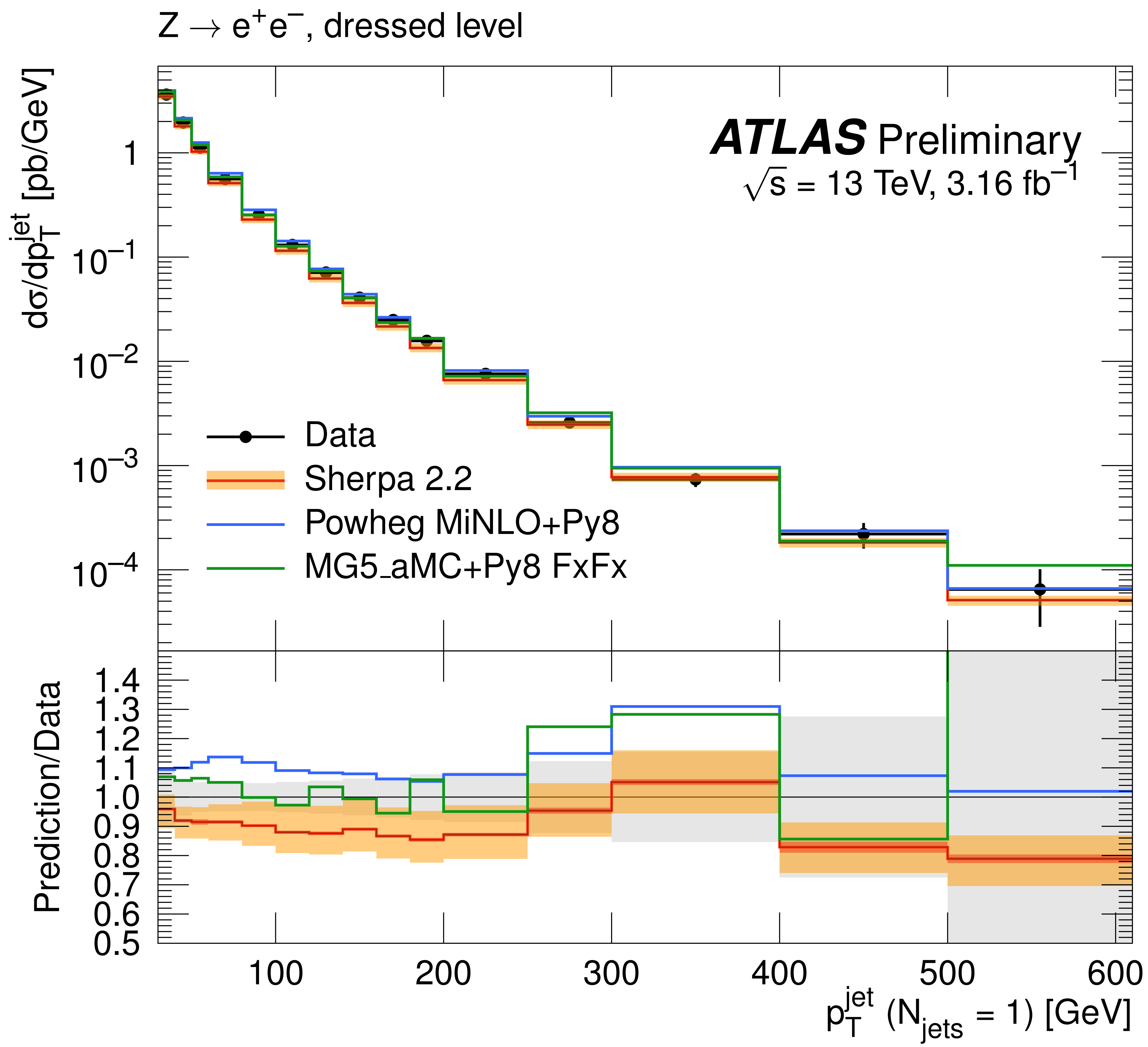
Table 6: Measured combined ratios of the fiducial cross sections for successive inclusive jet multiplicities. The statistical, systematic, and luminosity uncertainties are given.

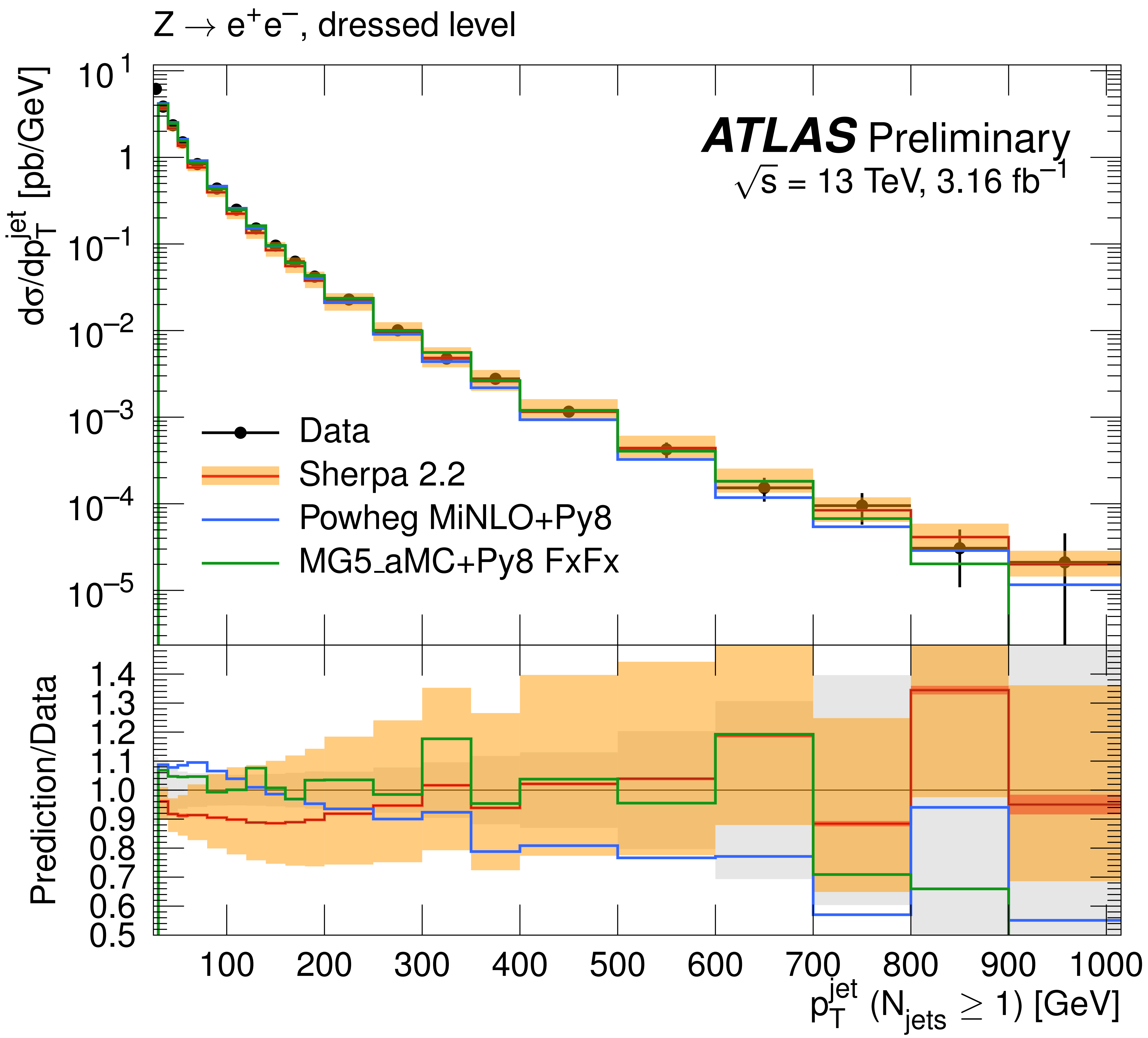
Jet multiplicity	Measured cross section $\pm$ (stat.) $\pm$ (syst.) $\pm$ (lumi.) [pb]
	$Z \rightarrow \ell\ell$
≥ 0 jets	$740 \pm 1 \pm 23 \pm 16$
≥ 1 jets	$116.0 \pm 0.3 \pm 9.7 \pm 2.5$
≥ 2 jets	$27.0 \pm 0.1 \pm 2.8 \pm 0.6$
≥ 3 jets	$6.20 \pm 0.04 \pm 0.82 \pm 0.14$
≥ 4 jets	$1.48 \pm 0.02 \pm 0.23 \pm 0.04$
≥ 5 jets	$0.36 \pm 0.01 \pm 0.07 \pm 0.01$
≥ 6 jets	$0.079 \pm 0.004 \pm 0.018 \pm 0.002$
≥ 7 jets	$0.0178 \pm 0.0019 \pm 0.0049 \pm 0.0005$

Table 5: Measured combined fiducial cross sections for successive inclusive jet multiplicities. The statistical, systematic, and luminosity uncertainties are given.

[arXiv:1702.05725]

13 TeV Z+jets





[arXiv:1702.05725]

The ATLAS detector