Observation of electroweak Z+2j production at ATLAS

[a.k.a Z-boson production via weak boson fusion]

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Outline

1) Cross sections and distributions for inclusive Z+2j production
2) Extracting the electroweak Z+2j component

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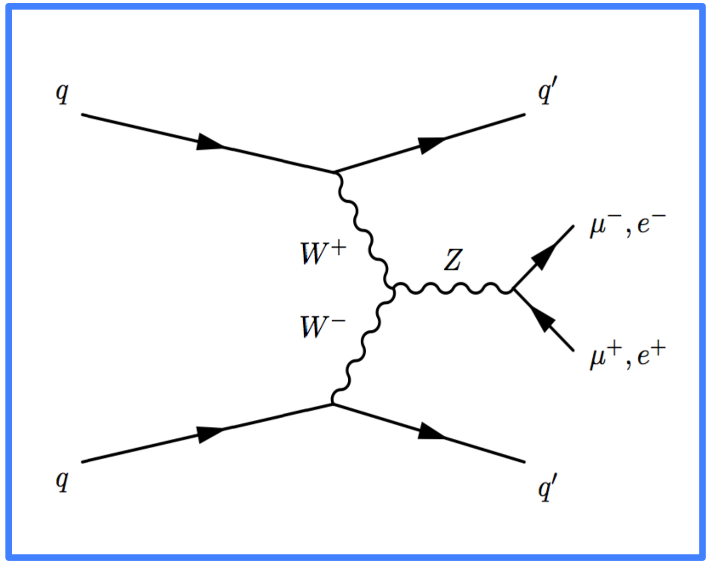
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2013-02/

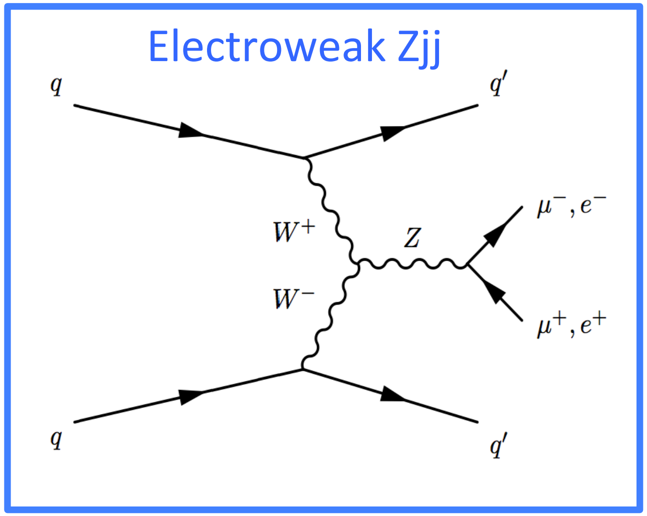
Why bother with electroweak Z+2j production?

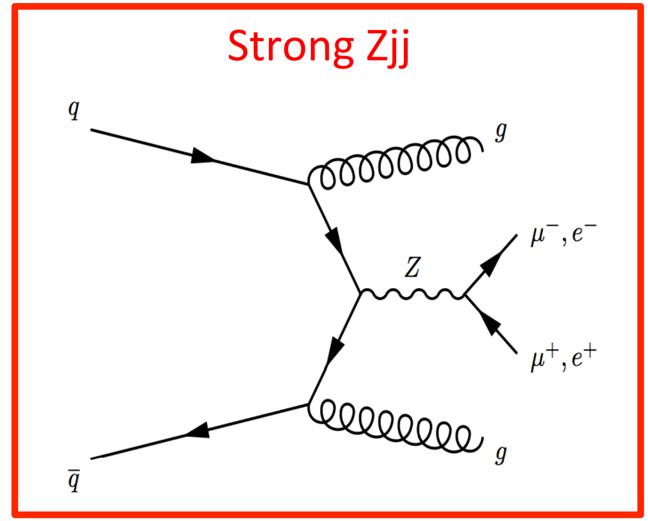


- Weak-boson fusion/scattering plays an important role in Higgs measurements (couplings, ττ) and searches for anomalous quartic gauge couplings.

- Z-production via weak boson fusion is a *standard candle* for these processes
  - first observation of weak boson fusion at a hadron collider
  - a direct test of the ZWW coupling.

Z+2j production at the LHC

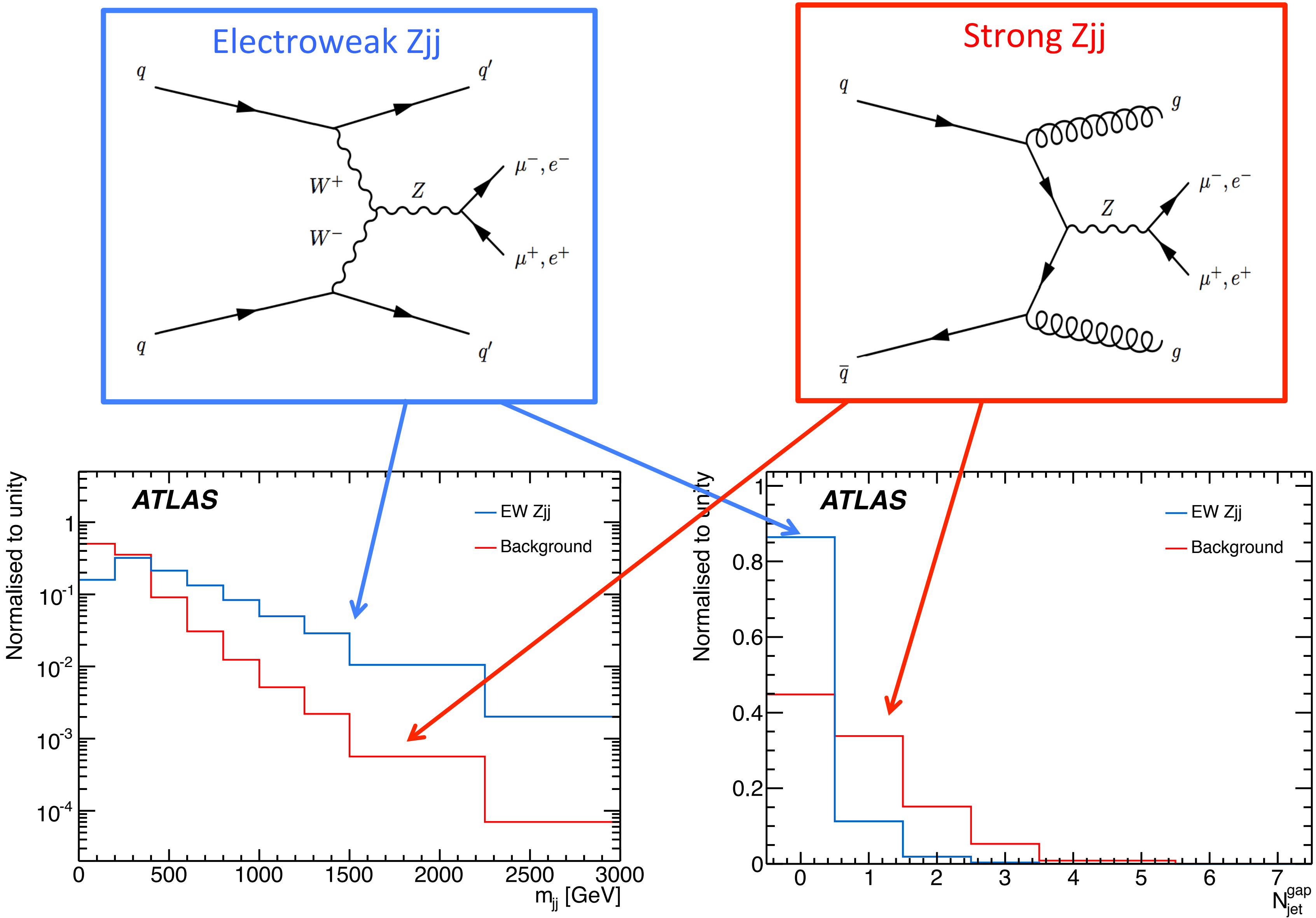




- Electroweak Z+2j production is *rare*: only ~1% of the inclusive Z+2j cross section

- Electroweak Z+2j has two characteristic features:
  - Dijet system covering a large rapidity interval and large invariant mass
  - Little additional jet activity in the rapidity interval

Z+2j production at the LHC



Cross sections and distributions for inclusive Z+2j production

Detector-corrected measurements at √s=8TeV

1) Cross sections measured in five fiducial regions
2) Differential distributions sensitive to dijet kinematics (m_{jj}, Δy)
3) Differential distributions sensitive to 'in-gap' jet activity

Five fiducial regions: different sensitivity to electroweak Zjj

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^{\ell}\rvert < 2.47,\ p_{\mathrm{T}}^{\ell} > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_{\mathrm{T}}^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^{j}\rvert < 4.4,\ \Delta R_{j,\ell} \geq 0.3$				
	$p_{\mathrm{T}}^{j1} > 55$ GeV				$p_{\mathrm{T}}^{j1} > 85$ GeV
	$p_{\mathrm{T}}^{j2} > 45$ GeV				$p_{\mathrm{T}}^{j2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} \geq 1$	—
Zjj system	—		$p_{\mathrm{T}}^{\mathrm{balance}} < 0.15$	$p_{\mathrm{T}}^{\mathrm{balance,3}} < 0.15$	—

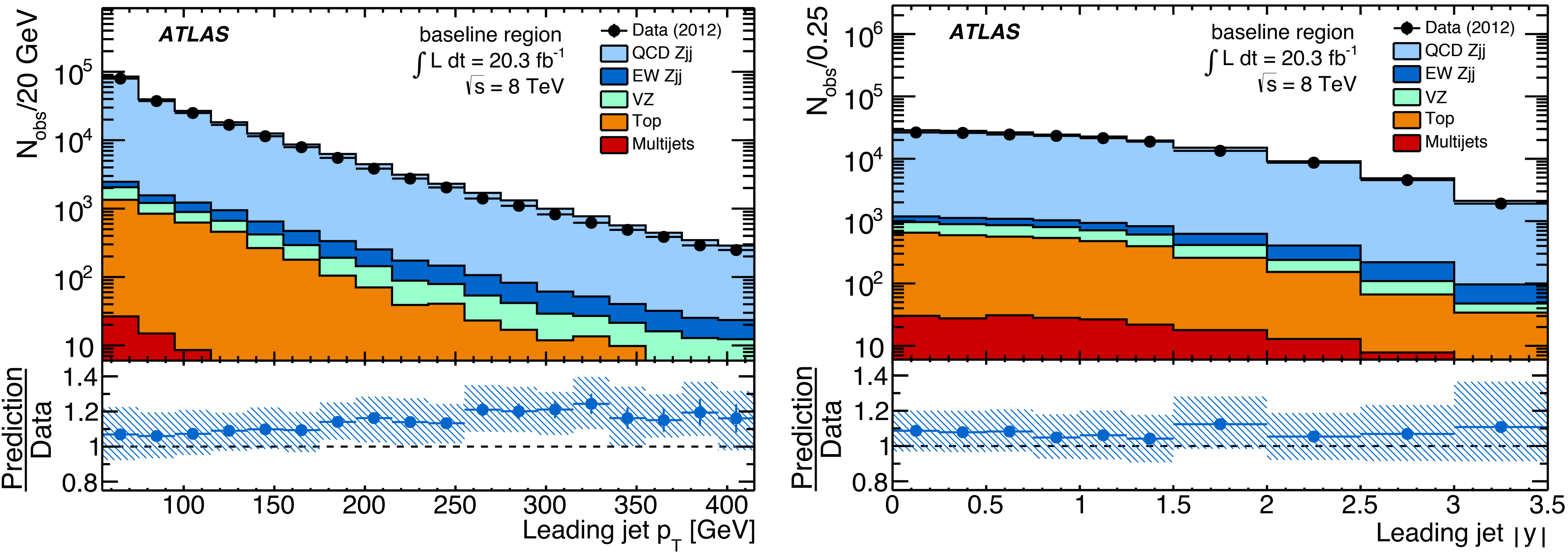
--- Z-boson selection

--- Baseline jet selection

--- Probe of high-p_T or high-mass

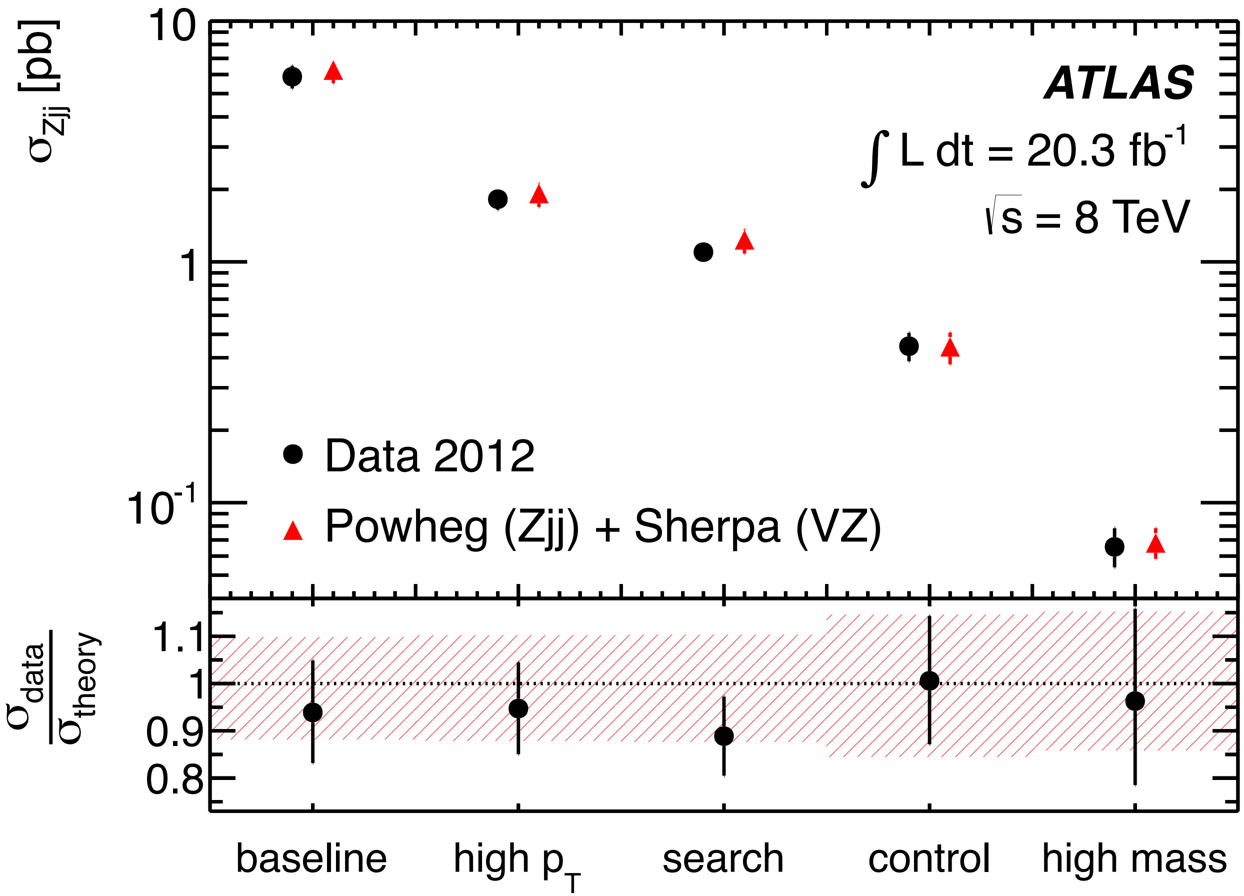
--- Search/control cuts for electroweak extraction

Example of data/simulation in the *baseline* region



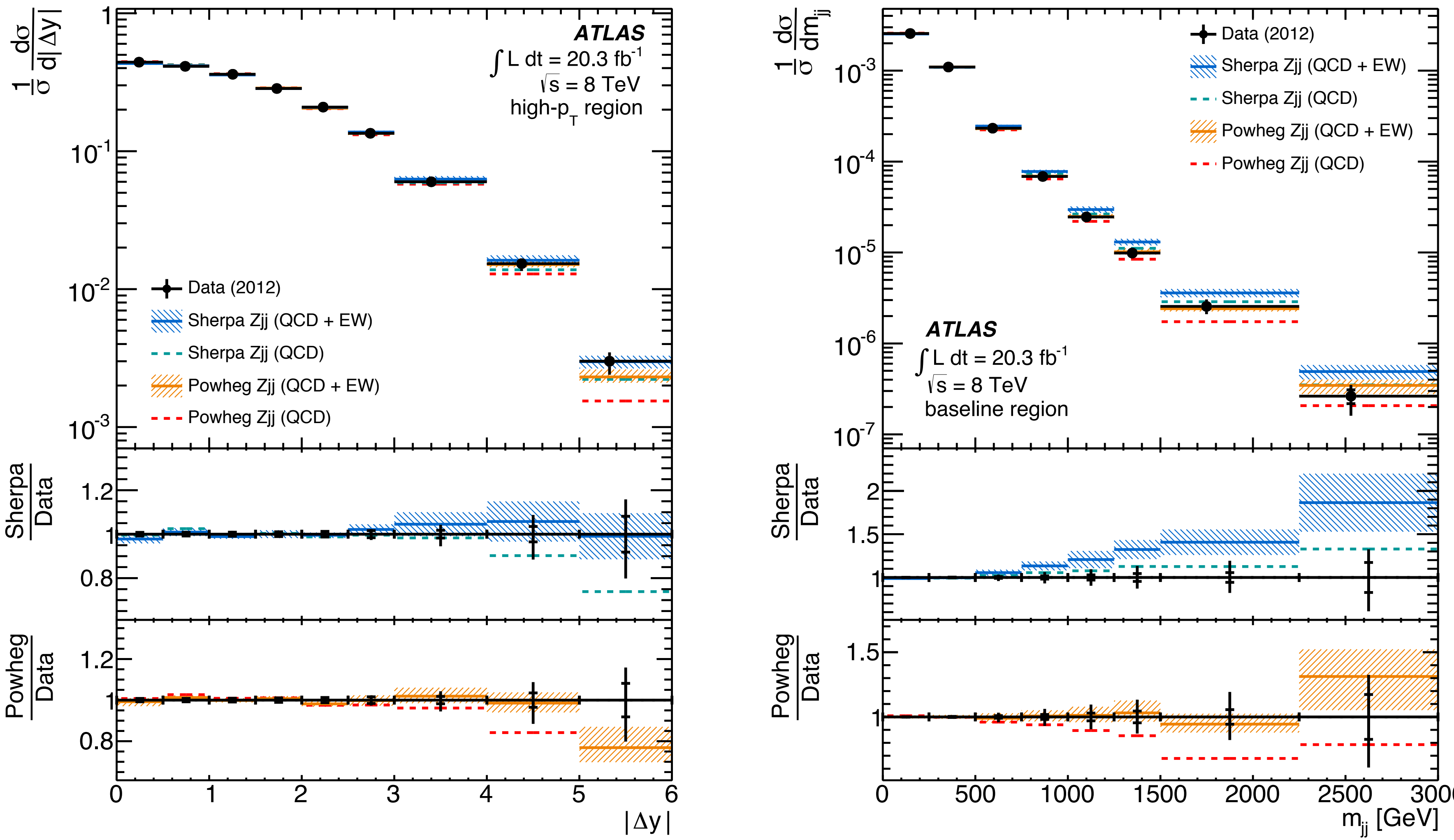
- Small non-Z backgrounds
- Reasonable agreement between data and simulation

Measurement of inclusive Z+2j cross sections (II)



Measure cross section by $\sigma_{\rm fid} = \dfrac{N_{\rm obs} - N_{\rm bkg}}{\int L\,{\rm d}t \cdot \mathcal{C}}$

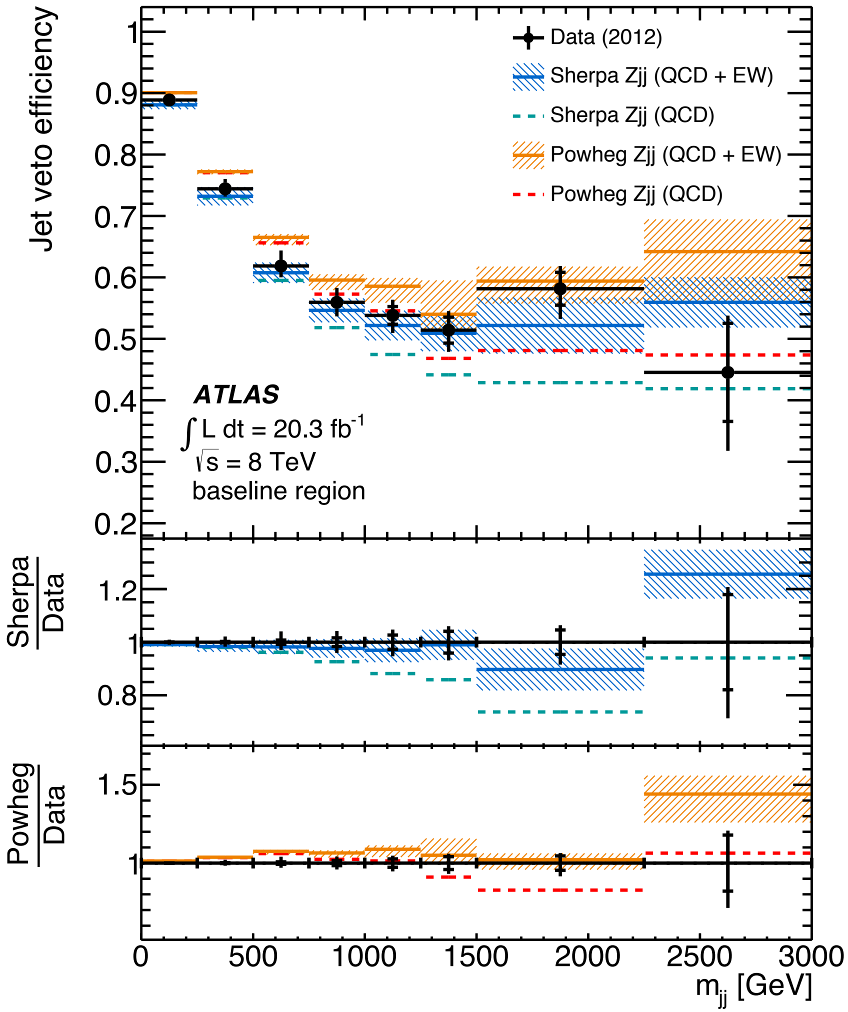
Measurement of dijet kinematics (unfolded)

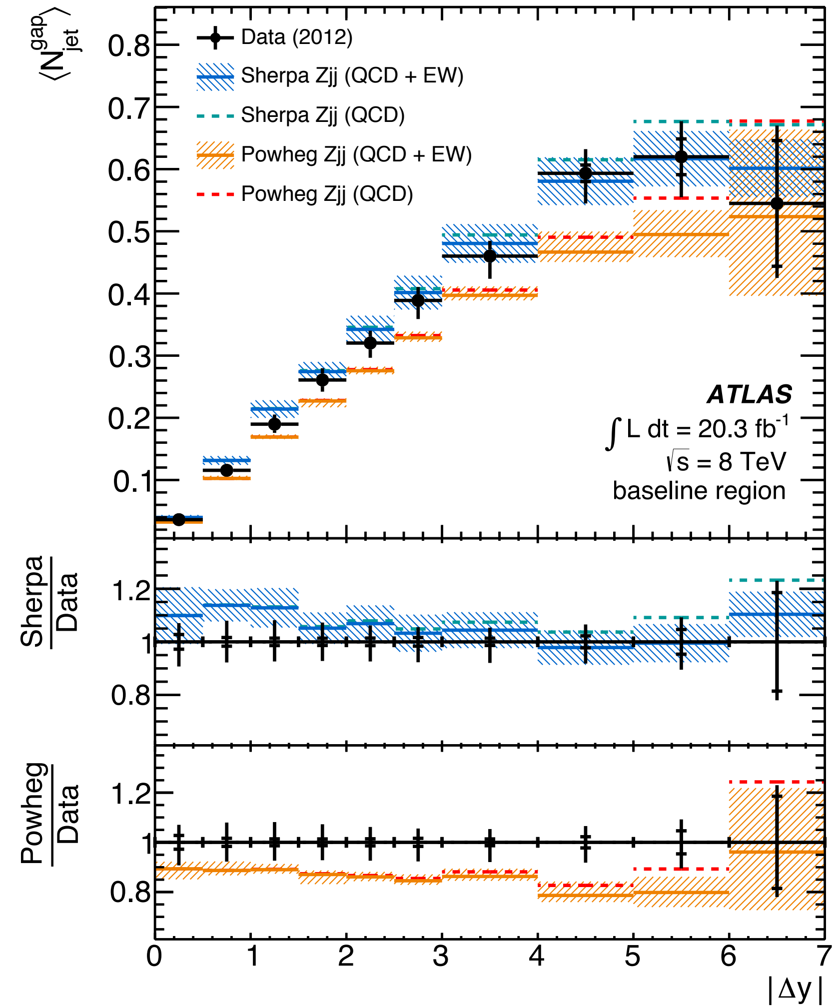


Powheg accurate to next-to-leading order (NLO) in QCD for Z+2j production

Sherpa accurate only to leading order (LO) in QCD for Z+2j production

Measurement of in-gap jet activity (unfolded)





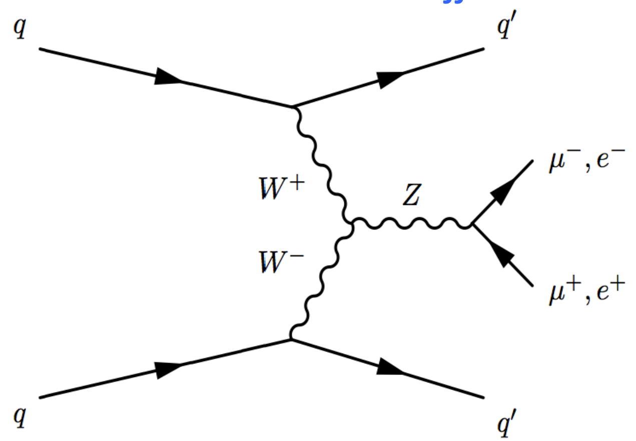
Sherpa accurate to LO in QCD for third and fourth jet emission

Powheg only accurate to LO in QCD for third jet emission

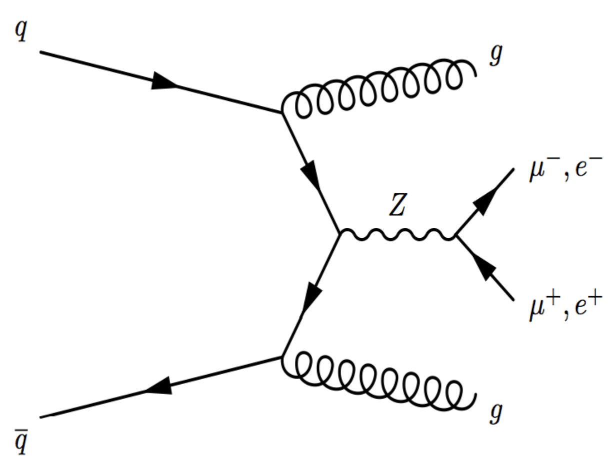
Extracting the electroweak Z+2j component ($\sqrt{s}$=8TeV)

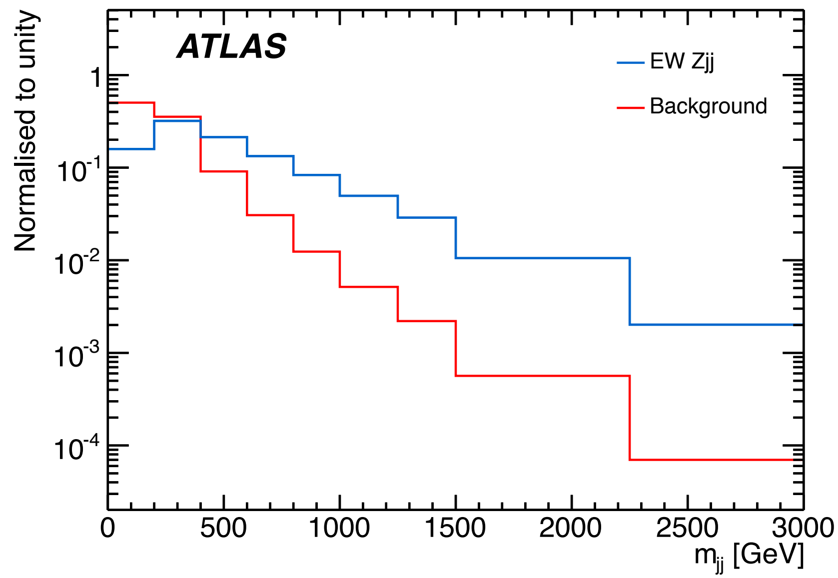
Extracting the signal - methodology

Electroweak Zjj



Strong Zjj

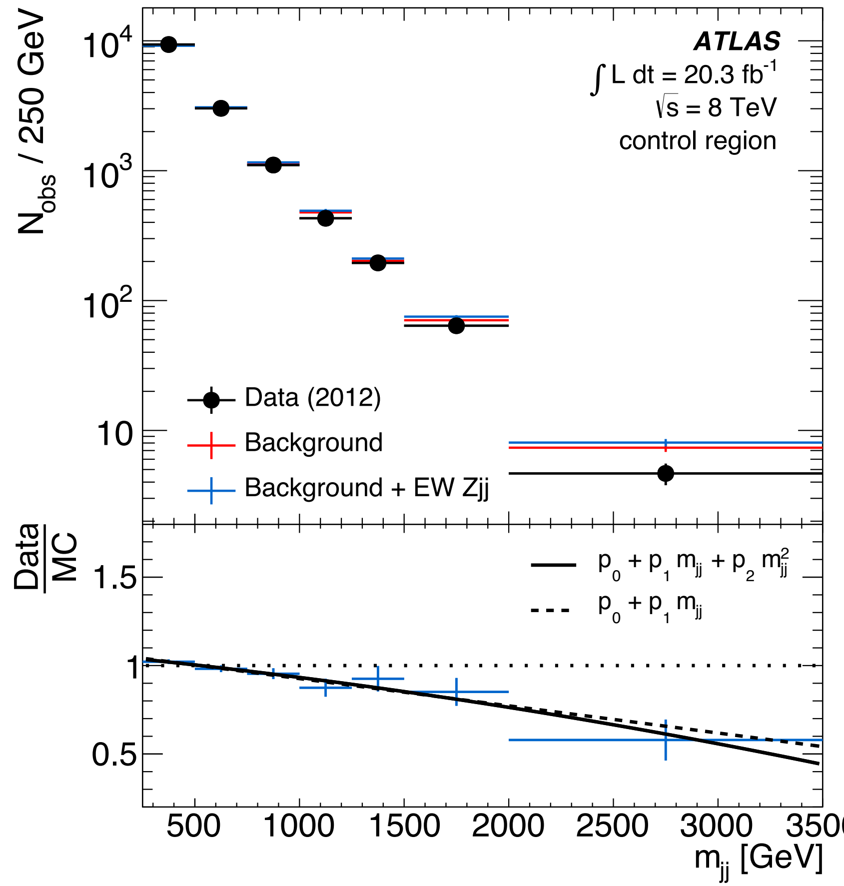




- Electroweak component is extracted by a two template fit to the dijet invariant mass
- This fit is carried out in the *search region*, which has a veto on additional central jet activity

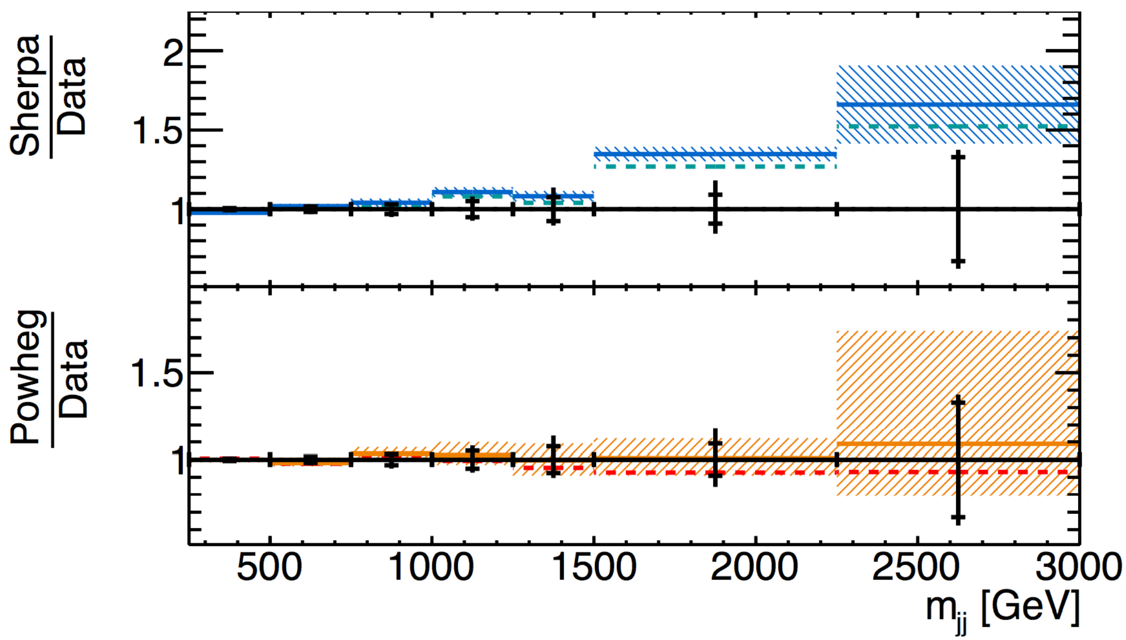
Data-driven constraint for the background model

- Control region defined by <u>reversing</u> the jet veto.
- Basic idea: correct the simulation in the *search* region using the data/MC ratio in the *control* region.
  - Plot shows correction derived for SHERPA
- Added bonus: limits the impact of jet energy scale uncertainties on the tagging jets
- Remaining experimental and theoretical uncertainties associated with the third jet modelling (extrapolation from *control -> search)*



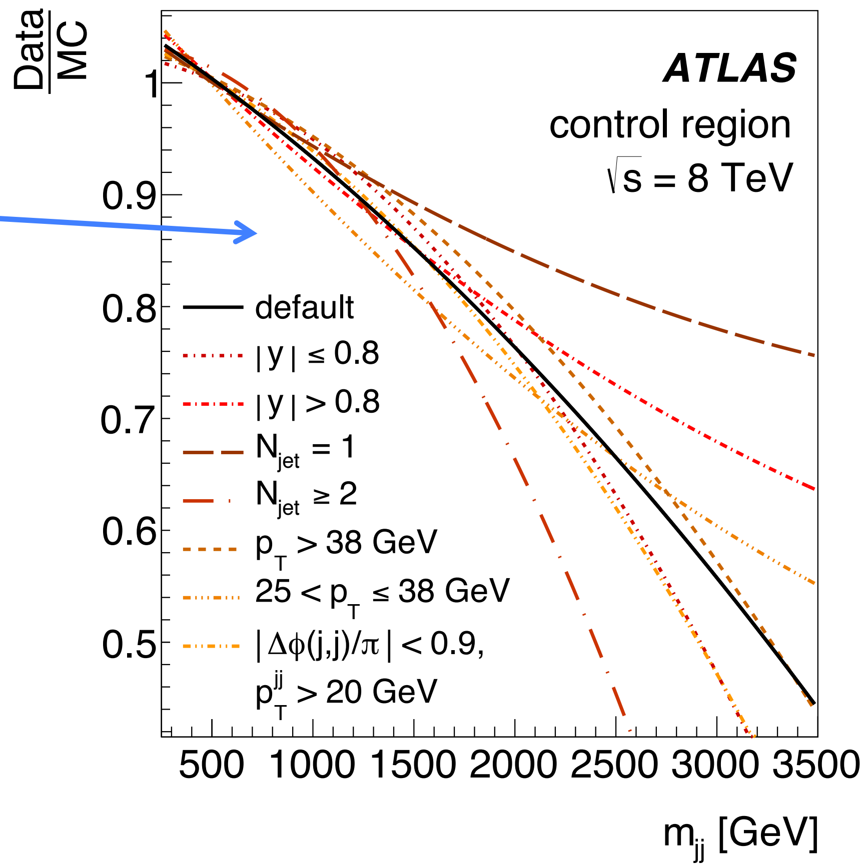
Data-driven constraint for the background model (I)

- Unfolded distributions show that POWHEG gives a better description that SHERPA as a function of m_{jj}
  - Choice of generator checked by reweighting SHERPA events to POWHEG in both the search and control regions.
  - Full analysis procedure repeated (i.e. new control region constraint derived)
  - <u>Extracted signal yields agree to 0.8%</u>



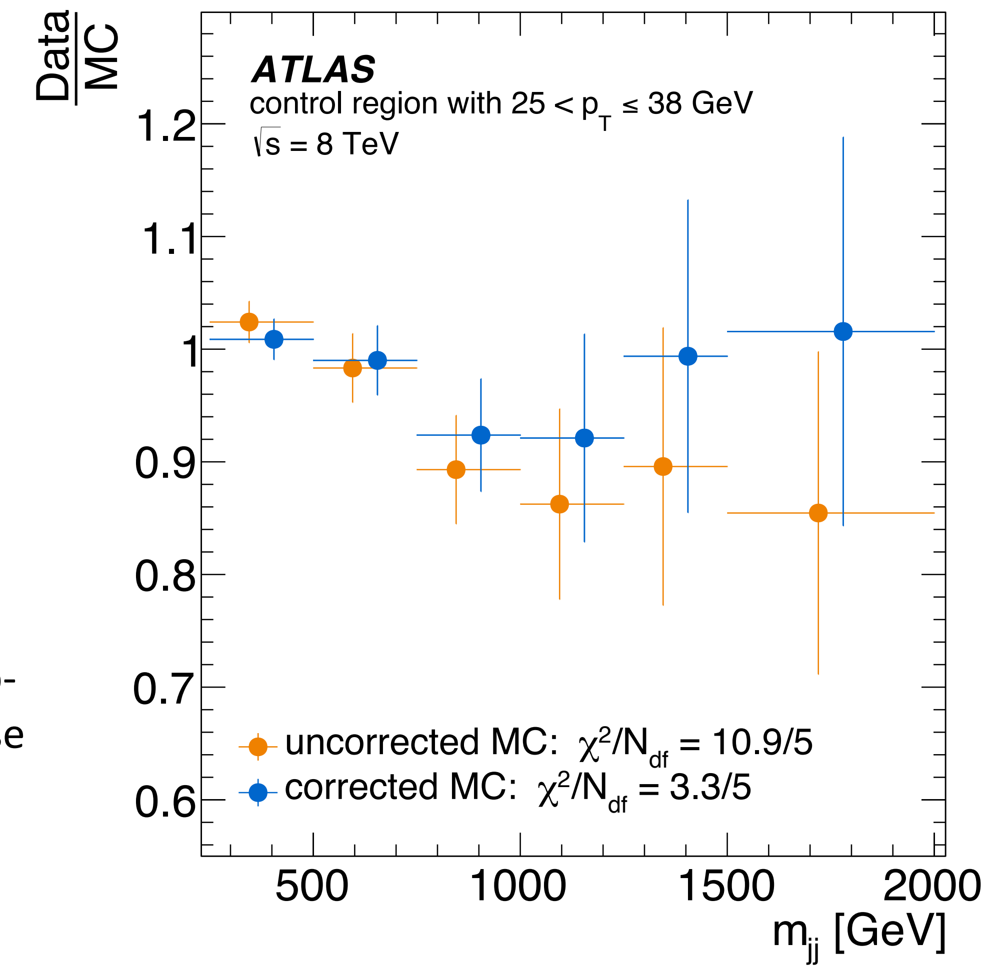
Data-driven constraint for the background model (II)

- Choice of control region validated by splitting it into seven sub-regions,
  - deriving new constraints,
  - repeating full analysis chain.
  - <u>extracted signal yields agree to within 5%.</u>



Data-driven constraint for the background model (III)

- The seven control regions are all signal-suppressed.
- Can use orthogonal sub-regions to test whether the reweighting function derived on one region improves the agreement between simulation and data in another region
- Agreement improved in all cases,
- Example, shown here is for orthogonal sub-regions that differ in the third jet transverse momentum.

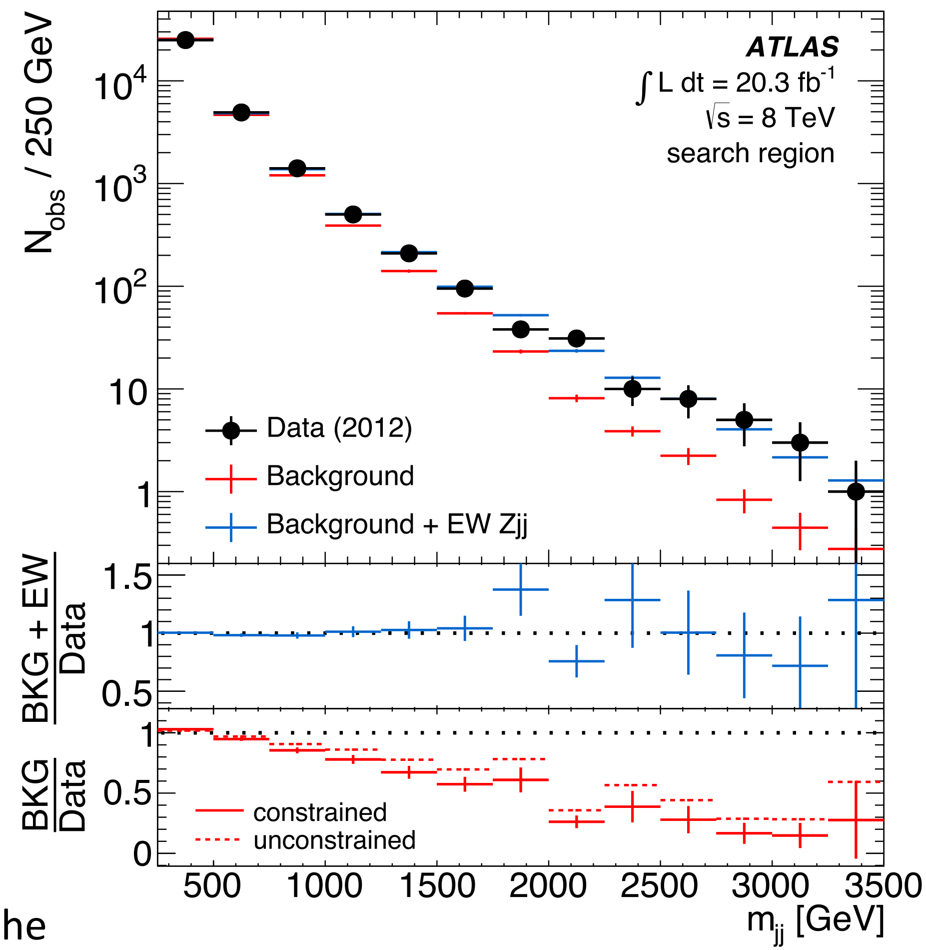


Extracting the signal - results

Fit results

	Electron+muon
Data	32186
MC predicted N_{bkg}	$32600 \pm 2600\,^{+3400}_{-4000}$
MC predicted N_{EW}	$1333 \pm 50 \pm 40$
Fitted N_{bkg}	$30530 \pm 216 \pm 40$
Fitted N_{EW}	$1657 \pm 134 \pm 40$

Background-only hypothesis rejected at greater than 5σ significance

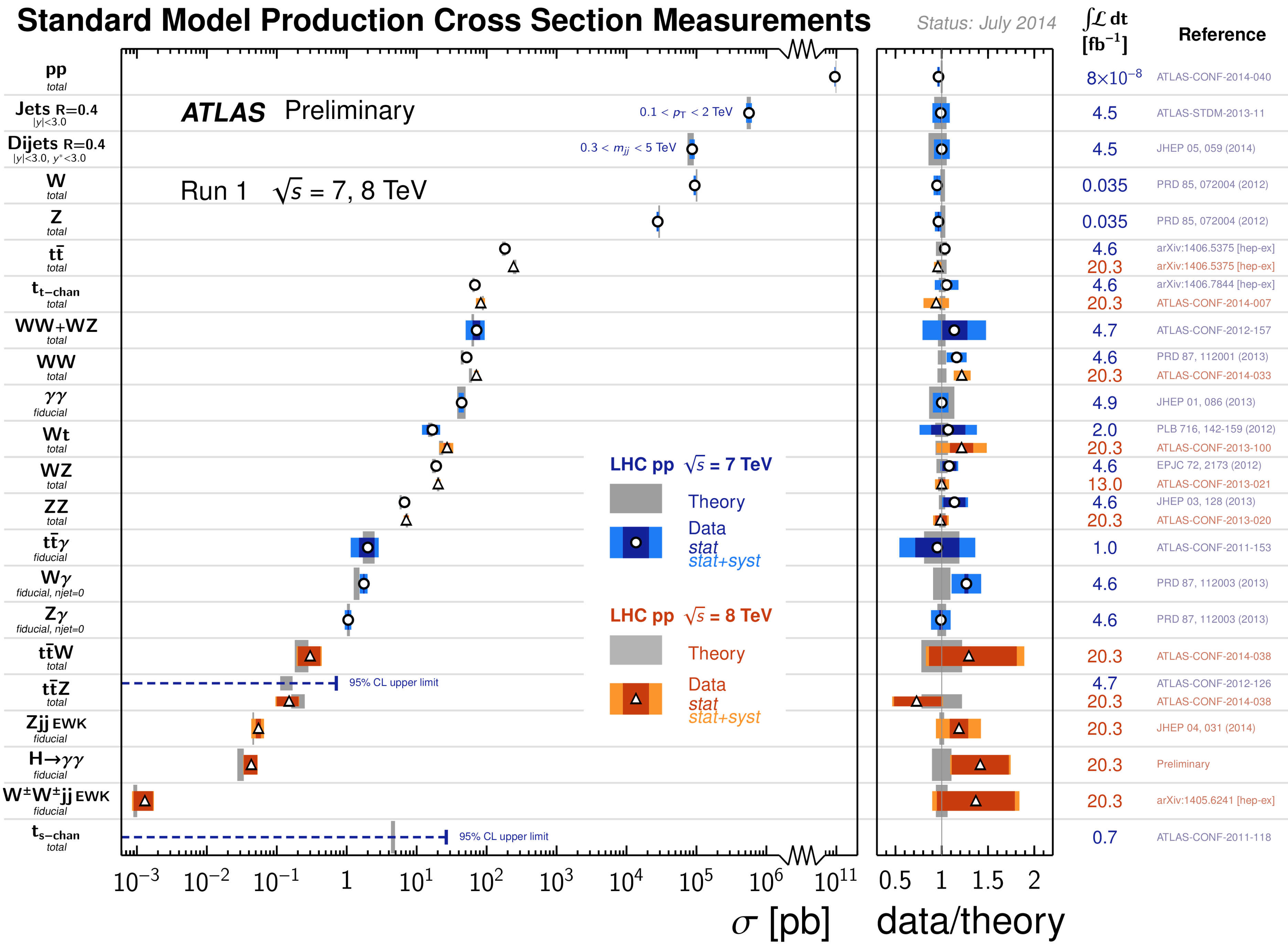


- Extracted yield converted to a cross section in the *search* fiducial region:

$$\sigma_{\mathrm{EW}} = 54.7 \pm 4.6\,(\mathrm{stat})\,^{+9.8}_{-10.4}\,(\mathrm{syst}) \pm 1.5\,(\mathrm{lumi})\ \mathrm{fb}.$$

Breakdown of the electroweak cross section systematics

Source	ΔN_{EW}		$\Delta \mathcal{C}_{\mathrm{EW}}$	
	Electrons	Muons	Electrons	Muons
Lepton systematics	—	—	± 3.2 %	± 2.5%
Control region statistics	± 8.9 %	± 11.2 %	—	—
JES	± 5.6 %		$^{+2.7}_{-3.4}$ %	
JER	± 0.4 %		± 0.8 %	
Pileup jet modelling	± 0.3 %		± 0.3 %	
JVF	± 1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	± 8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	± 7.5 %		—	
Signal/background interference	± 6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		± 0.1 %	



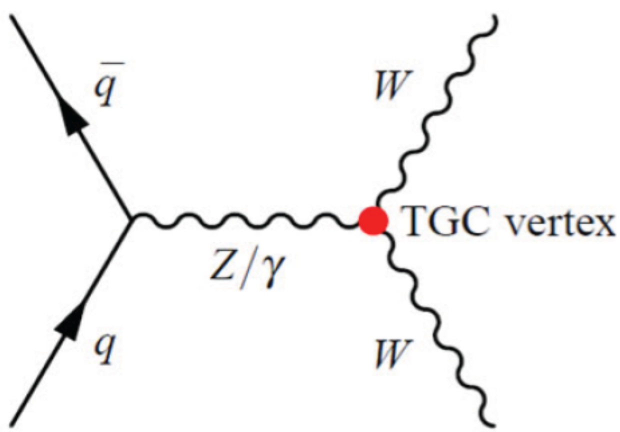
Standard Model Production Cross Section Measurements
Status: July 2014
∫ℒ dt [fb⁻¹]
Reference
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
pp total
Jets R=0.4 |y|<3.0
Dijets R=0.4 |y|<3.0, y*<3.0
W total
Z total
tt̄ total
t t−chan total
WW+WZ total
WW total
γγ fiducial
Wt total
WZ total
ZZ total
tt̄γ fiducial
Wγ fiducial, njet=0
Zγ fiducial, njet=0
tt̄W total
tt̄Z total
Zjj EWK fiducial
H→γγ fiducial
W±W±jj EWK fiducial
t s−chan total
0.1 < pT < 2 TeV
0.3 < mjj < 5 TeV
95% CL upper limit
95% CL upper limit
LHC pp √s = 7 TeV
Theory
Data
stat
stat+syst
LHC pp √s = 8 TeV
Theory
Data
stat
stat+syst
8×10⁻⁸ ATLAS-CONF-2014-040
4.5 ATLAS-STDM-2013-11
4.5 JHEP 05, 059 (2014)
0.035 PRD 85, 072004 (2012)
0.035 PRD 85, 072004 (2012)
4.6 arXiv:1406.5375 [hep-ex]
20.3 arXiv:1406.5375 [hep-ex]
4.6 arXiv:1406.7844 [hep-ex]
20.3 ATLAS-CONF-2014-007
4.7 ATLAS-CONF-2012-157
4.6 PRD 87, 112001 (2013)
20.3 ATLAS-CONF-2014-033
4.9 JHEP 01, 086 (2013)
2.0 PLB 716, 142-159 (2012)
20.3 ATLAS-CONF-2013-100
4.6 EPJC 72, 2173 (2012)
13.0 ATLAS-CONF-2013-021
4.6 JHEP 03, 128 (2013)
20.3 ATLAS-CONF-2013-020
1.0 ATLAS-CONF-2011-153
4.6 PRD 87, 112003 (2013)
4.6 PRD 87, 112003 (2013)
20.3 ATLAS-CONF-2014-038
4.7 ATLAS-CONF-2012-126
20.3 ATLAS-CONF-2014-038
20.3 JHEP 04, 031 (2014)
20.3 Preliminary
20.3 arXiv:1405.6241 [hep-ex]
0.7 ATLAS-CONF-2011-118
10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1 1.5 2
data/theory

Limits on aTGCs (I)

- Anomalous WWZ couplings parameterised using an effective lagrangian:

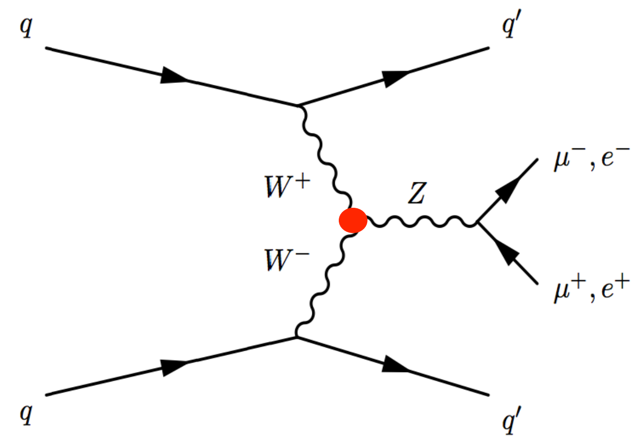
$$\frac{\mathcal{L}}{g_{WWZ}} = i\left[g_{1,Z}\left(W^{\dagger}_{\mu\nu}W^{\mu}Z^{\nu} - W_{\mu\nu}W^{\dagger\mu}Z^{\nu}\right) + \kappa_Z W^{\dagger}_{\mu}W_{\nu}Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2}W^{\dagger}_{\rho\mu}W^{\mu}_{\nu}Z^{\nu\rho}\right]$$

Diboson: WW



On-shell W's, off-shell Z
All bosons timelike, $Q^2>0$

Electroweak Zjj



Off-shell W's, on-shell Z
Z-boson timelike, $Q^2>0$
W-bosons space-like, $Q^2<0$

Limits on aTGCs (II)

- Number of observed events in data at $m_{jj} > 1$ TeV used to set limits on the aTGC parameters.
  - SHERPA used to parameterise the m_{jj} dependence on the aTGC.
  - Dipole form factor with two choices of unitarisation scale, Λ=6TeV and Λ=infinity
  - Electroweak cross section also measured in this region, for good measure:

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

$$\sigma_{\mathrm{EW}}^{m_{jj}>1\mathrm{TeV}} = 10.7 \pm 0.9\,(\mathrm{stat}) \pm 1.9\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})$$

Summary

- Inclusive Zjj production measured using ATLAS data at $\sqrt{s}$=8TeV
  - Cross sections in five fiducial regions
  - Differential distributions fully corrected for detector effects
- Observation of electroweak Zjj production at ATLAS
  - *A benchmark process for future studies of weak-boson fusion at the LHC*
  - Background-only hypothesis rejected at greater than 5σ
  - Cross section measured in two fiducial regions. Excellent agreement with NLO.
  - First limits placed on anomalous triple gauge couplings using weak boson fusion.
- See JHEP 1404 (2014) 031 [arXiv:1401.7610] for more details.