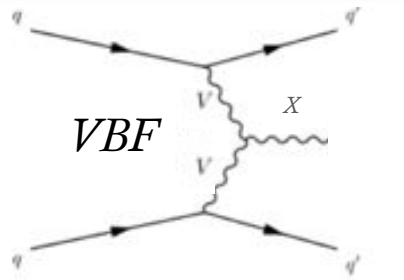
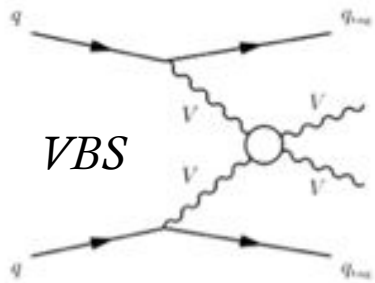
Measurements of Vector Boson Fusion and Scattering and Triboson production with the ATLAS detector

Narei Lorenzo Martinez
on behalf of ATLAS collaboration
Indiana University

Introduction





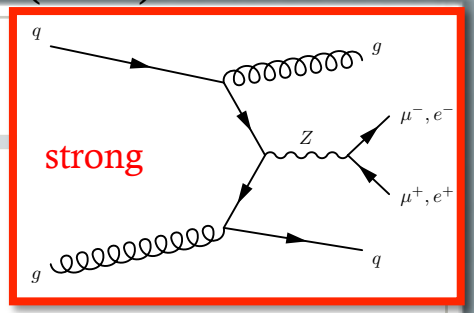
- Vector boson fusion (VBF) and scattering (VBS): important test of electroweak (EW) sector of the standard model (SM)
  - How Higgs boson unitarizes scattering amplitude
  - Irreducible background for new physics searches
- Sensitive probe of anomalous triple and quartic gauge boson coupling (aTGC and aQGC)
  - New physics would appear as enhancements in high p_T regions
  - **Tri-boson production is also sensitive to aQGC**
- Distinctive signature of VBF/VBS
  - Presence of two **energetic hadronic jets in the forward and backward directions** wrt the proton beamline.
  - No QCD colour exchanged in the processes → suppressed hadronic activity between the two jets ("**rapidity gap**")

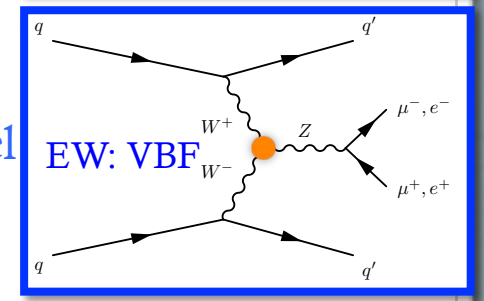
In this talk,
• probe TGC via Vector Boson Fusion process (see **L.Chevalier's talk** for a probe with diboson production)
• probe QGC via Vector Boson Scattering and tri-boson production

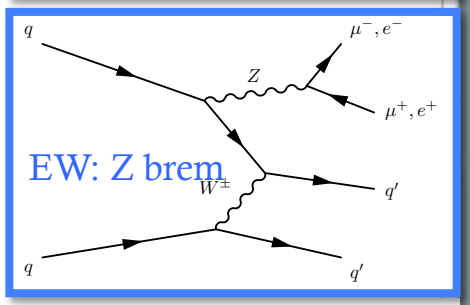
JHEP 04(2014)031

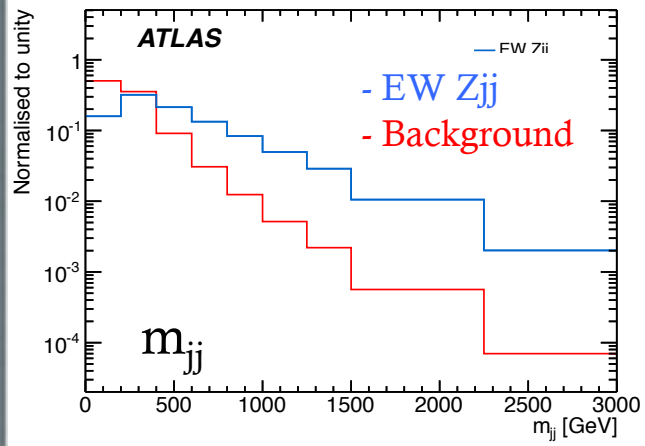
Z+2jets

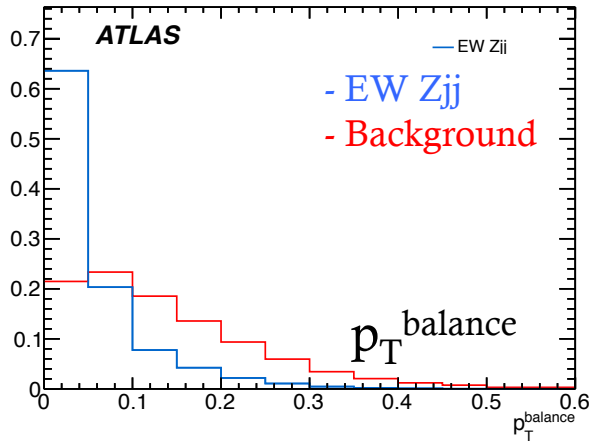
- Many processes give final state with a Z boson and two jets
  - dominated by strong production → data can provide important constraints on theoretical modeling
- Much rarer but very interesting: pure electroweak Zjj (t-channel exchange of a EW boson) in particular the vector boson fusion
  - similarity with VBF Higgs
  - sensitivity to anomalous WWZ triple gauge couplings
- Signature of pure EWK process: harder m_{jj}, smaller jet activity in rapidity gap, better p_T balance of the system Z+2jets

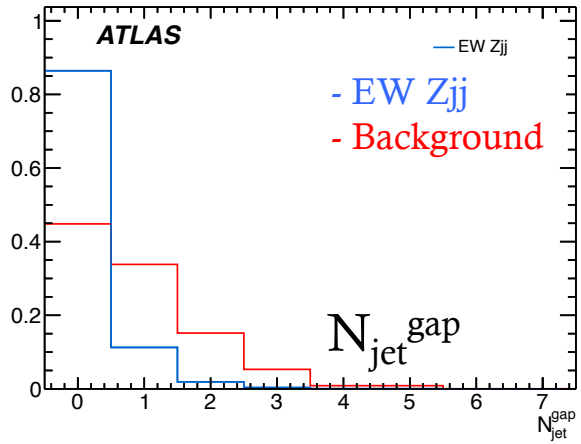












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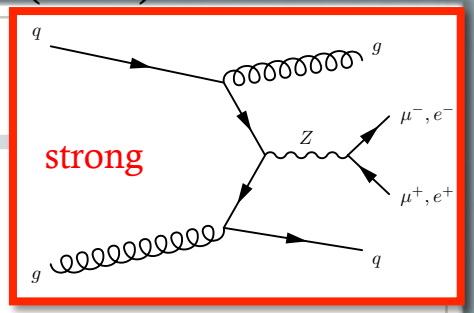
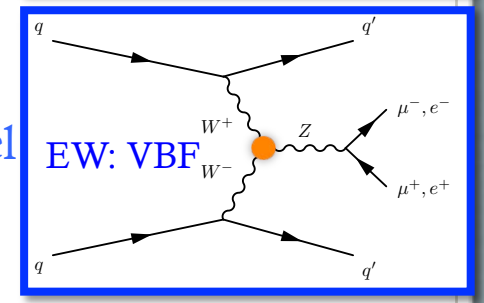
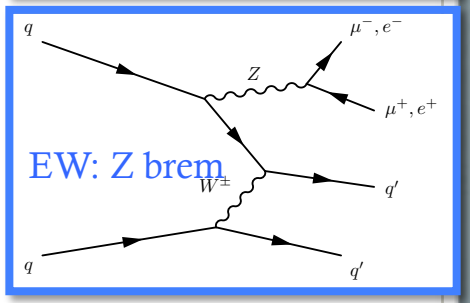
Z+2jets







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  - dominated by strong production → data can provide important constraints on theoretical modeling
- Much rarer but very interesting: pure electroweak Zjj (t-channel exchange of a EW boson) in particular the vector boson fusion
  - similarity with VBF Higgs
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- Signature of pure EWK process: harder m_{jj}, smaller jet activity in rapidity gap, better p_T balance of the system Z+2jets

- Measurements with 8 TeV data (20.3fb^{-1}) with ATLAS (e and μ channels)
- **Basic event selection:**
  - 2 isolated leptons with pT>25 GeV and |η|<(2.4,2.47) (μ,e)
  - 2 antikT0.4 jets with pT>25 GeV, |y|<4.4
- **Dominant backgrounds:**
  - VZ, Top (estimated from simulation)
  - multijets (estimated from data by reversing electron ID or muon isolation criteria)

Inclusive fiducial cross section

$$\sigma_{fid} = \frac{N_{obs} - N_{bkg}}{\int Ldt \cdot C}$$

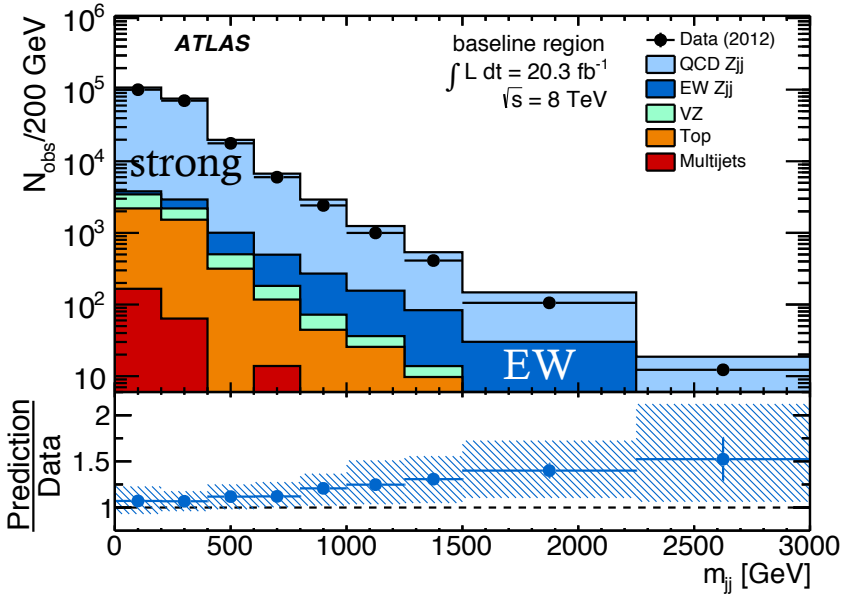
C=correction factor for difference between reconstruction and particle level (0.8-0.9 muons, 0.4-0.7 electrons)

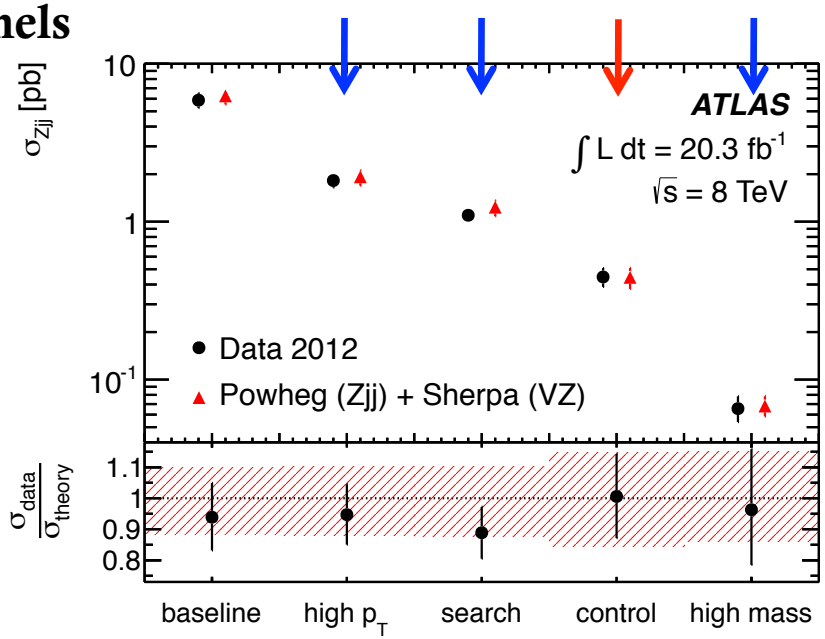
Measured in five fiducial regions:

- Baseline : most inclusive one
- Control : supress EW contribution, >=1jet in rapidity gap
- Search : no jet in rapidity gap
- High-mass : mjj>1 TeV
- High pT : harder cut on jet pT

probe impact of EW

Combination of electron and muon channels



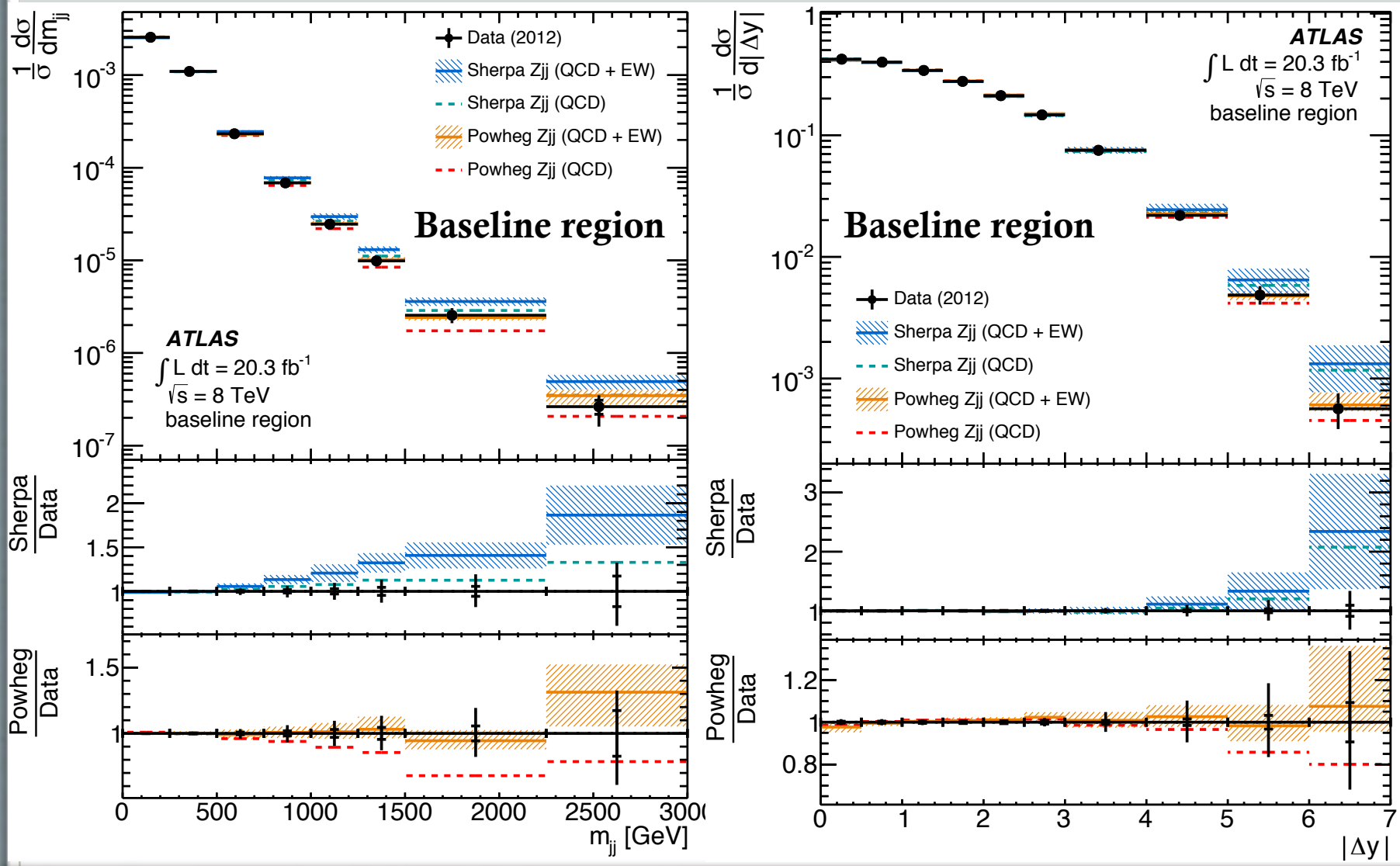


- Overall good description of data
- But indication of mismodelling **at high mjj**

- Good agreement found in the five regions
- Results compatible between the two channels

Differential m_{jj} and ΔY distributions

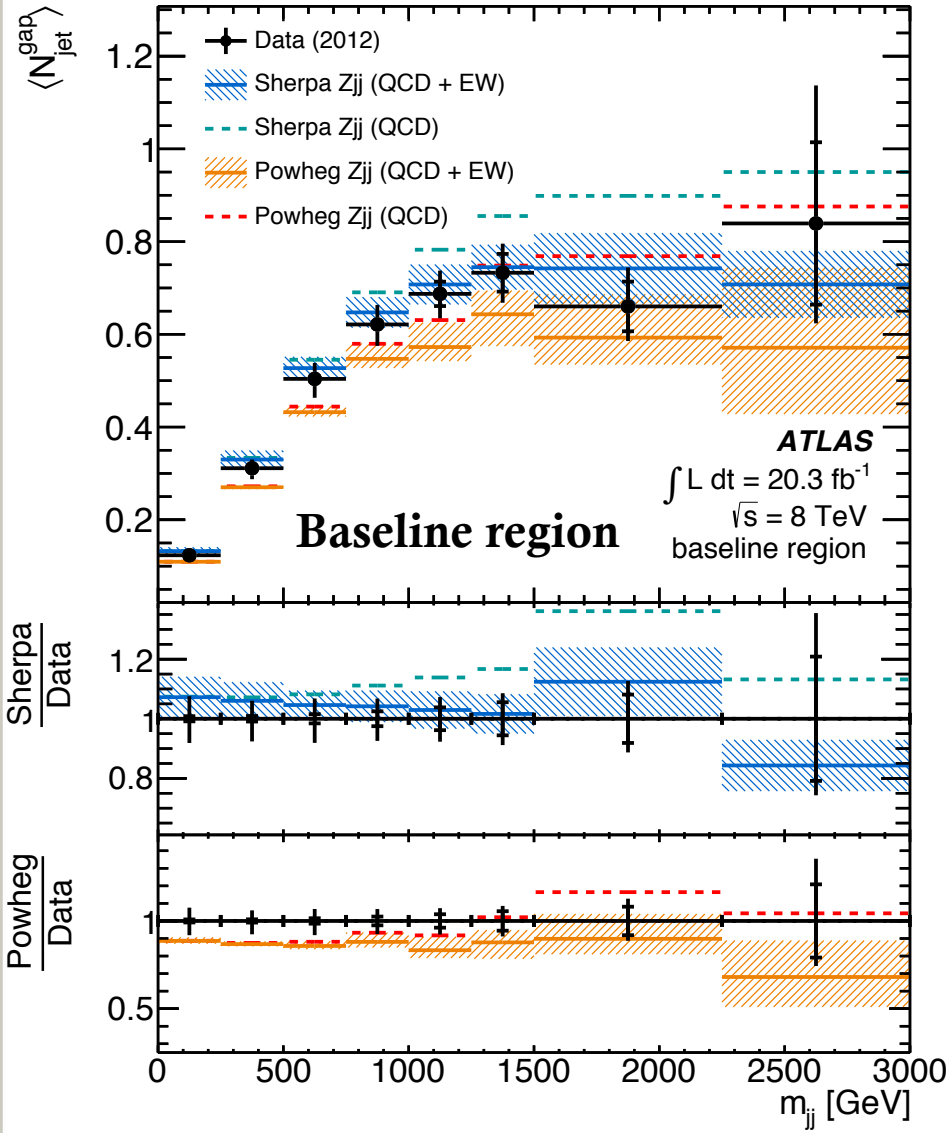
Comparison with Powheg and Sherpa 1.4.3



Powheg better describes m_{jj} and ΔY dist. than Sherpa in QCD dominated region.
New NLO version of Sherpa (2.1.0) should improve agreement [1].

Differential $<N_{jet}^{gap}>$ distribution

Comparison with Powheg and Sherpa 1.4.3



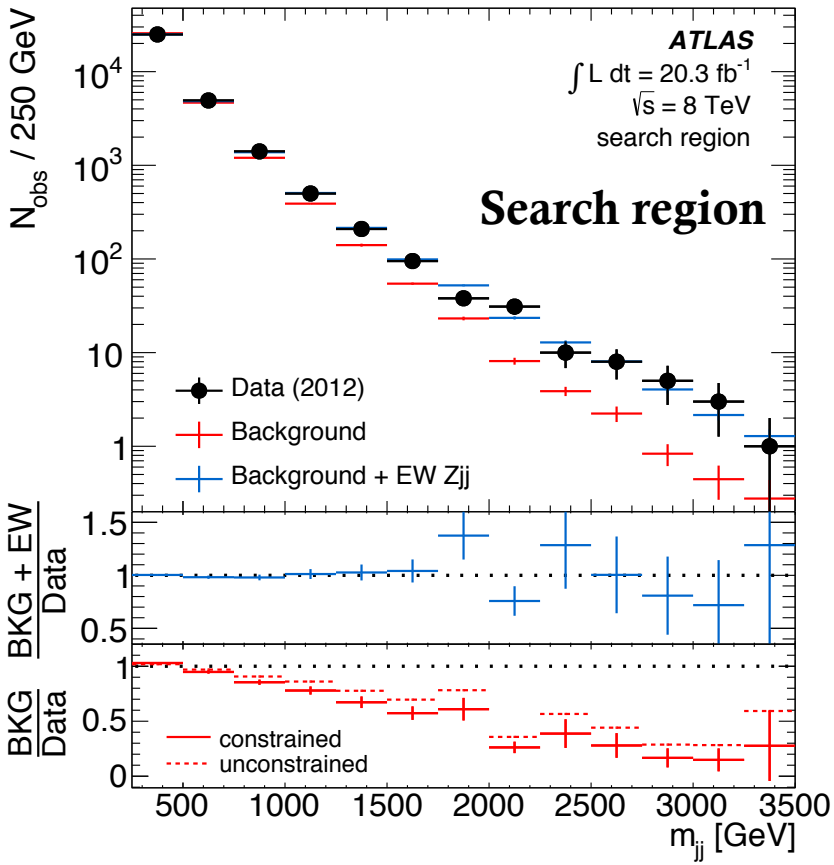
- Smaller jet activity in EW process than in strong one as expected
- Sherpa better describes variables sensitive to additional jet activity in event

None of the two generators can fully reproduce data for all distributions in all fiducial regions

→ data can be used to constrain modelling of Zjj production

Observation of EW Zjj

- Extract number of electroweak Zjj events by a fit to mjj distribution in **search region**
- Data in control region used to constrain generator modelling of the background m_{jj} shape → minimize experimental and theory uncertainties.
- Dominant systematics: JES and lepton identification
- Fiducial cross section for EW component:
  - electron and muon channels compatible within 1.7σ
  - in good agreement with Powheg prediction



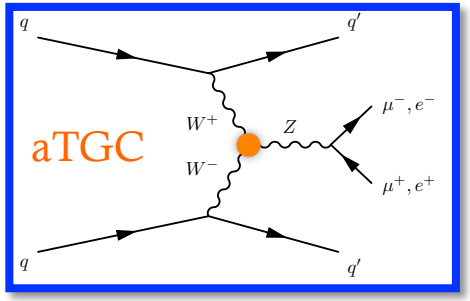
Background-only hypothesis rejected with >5σ significance

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

$$\sigma_{EW,Powheg} = 46.1 \pm 0.2\,(\text{stat}) \pm 0.8\,(\text{PDF}) \pm 0.5\,(\text{model})\text{fb}$$

Limits on aTGC

- Measured in search region + cut on mjj> 1TeV
  (region least affected by background normalisation)



- Effective Lagrangian for aTGC

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

analysis sensitive to these parameters (=1 and =0 in SM)

- Modify couplings by a dipole form factor, depending on unitarization scale Λ

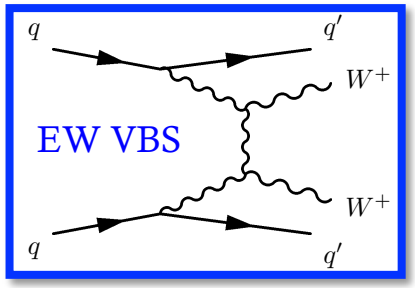
aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

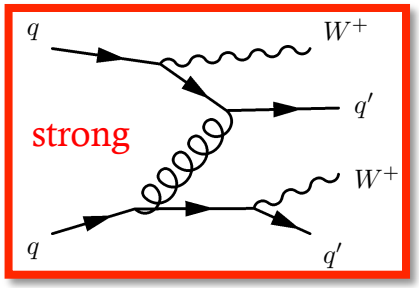
Complementary to measurements made with di-boson WZ [2] (space-like vs time-like propag.)

Phys. Rev. Lett. 113, 141803 (2014)

VBS WW+2j same sign

- First evidence for electroweak WWjj production
  - **very interesting channel because strong production does not dominate**



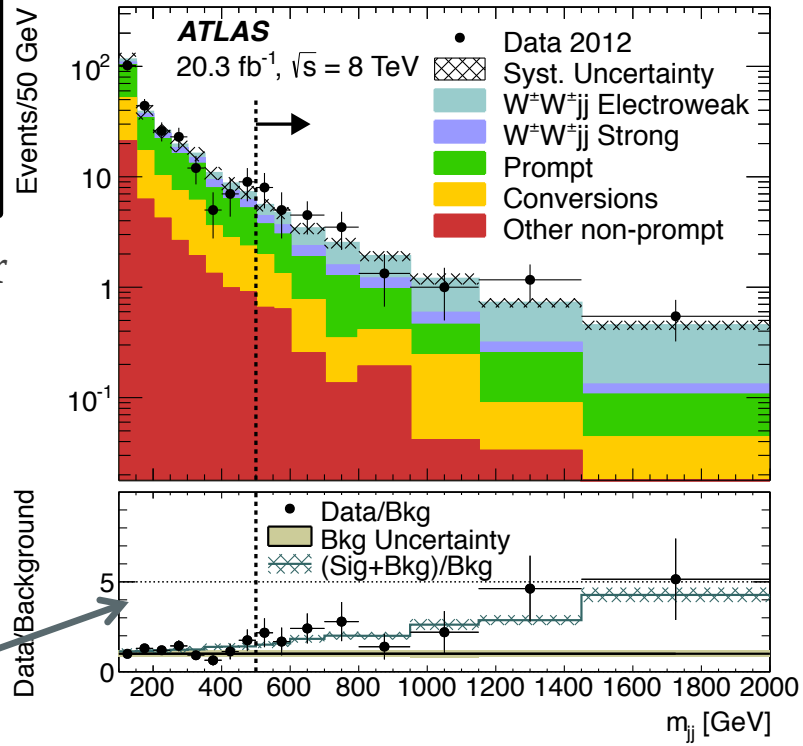


Two fiducial regions defined:
- Inclusive: 2 leptons with pT>25 GeV eta<2.5, 2jets with pT>30 GeV, η<4.5, m_{jj}>500 GeV
- VBS : add cut on $\Delta Yjj > 2.4$

- Background = dominant uncertainty. Four different control regions built to test the different background predictions → **good consistency found in all regions for all channels.**

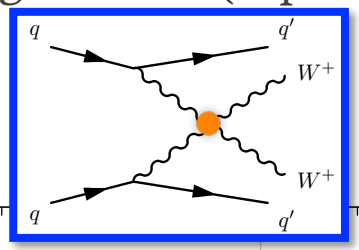
- Three decay channels: μμ, ee, μe

Excess of events over background expectation

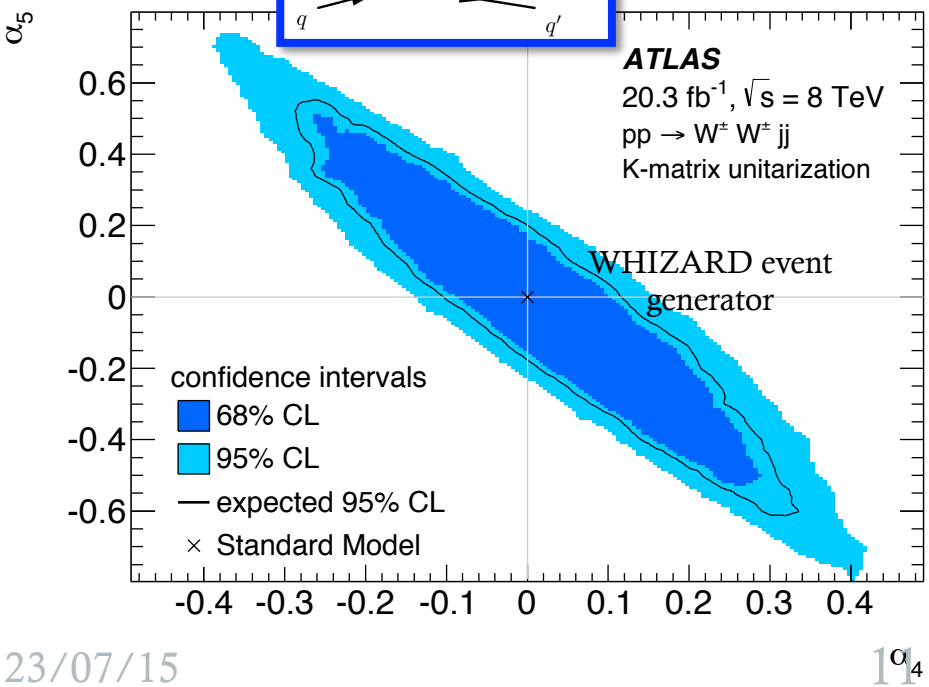


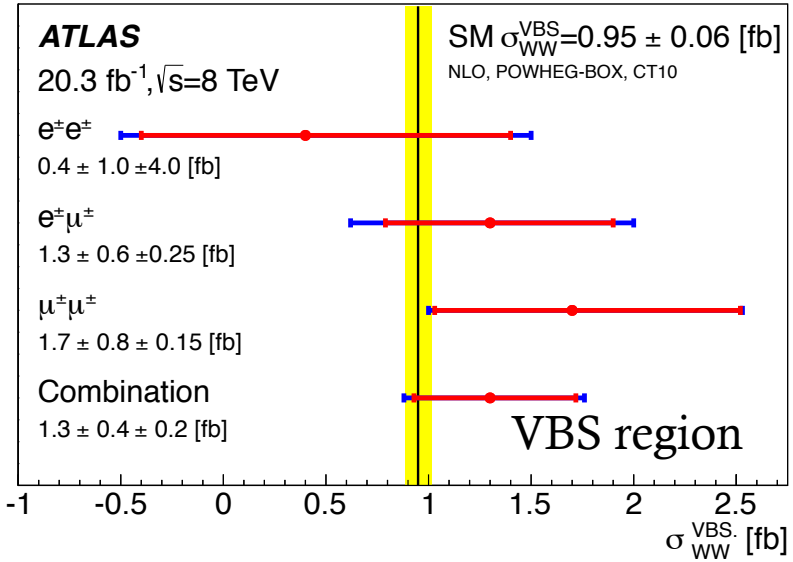
Fiducial cross section and limit on aQGC

- Combined significance over background only hypothesis:
  - Inclusive region (EW+strong): 4.5σ (exp: 3.4σ)
  - VBS region: 3.6σ (exp: 2.8σ)



aQGC





- Additional contribution to WWjj can be expressed in model-independent way using higher dim. operators → anomalous quartic gauge couplings (aQGC)
- VBS region used to set limits
- Deviation from SM parametrized in term of (α_4,α_5) (both 0 in SM)

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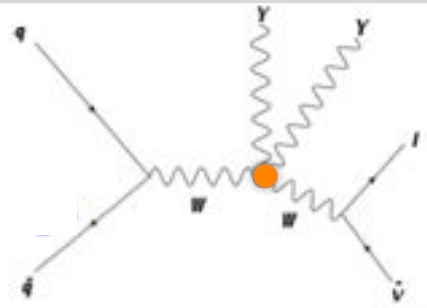
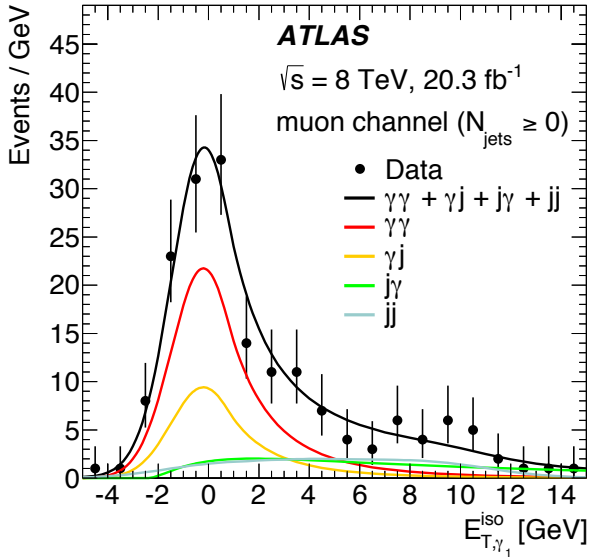
Triboson Wγγ

NEW



- First evidence for tri-boson production in Wγγ final state
  - allow test of quartic gauge couplings (QGC)
- Measurement of inclusive and exclusive cross sections
  - exclusive: veto on event with >=1jet
- **Main background:**
  - "fakes" (jet reco. as γ or lepton): Wjγ, Wjj, γγ+jets
    → *from data driven (DD) techniques*
  - prompt leptons/γ
    - Zγ, Zγγ, WZ, W(τν)γγ *(from Sherpa)*
    - ttbar, single top, WW *(from MC@NLO)*
    - ZZ *(from POWHEG)*



Definition of the fiducial region
$p_T^\ell > 20\,GeV$, $p_T^\nu > 25\,GeV$, $\lvert\eta_\ell\rvert < 2.5$
$m_T > 40\,GeV$
$E_T^\gamma > 20\,GeV$, $\lvert\eta^\gamma\rvert < 2.37$, iso. fraction $\epsilon_h^p < 0.5$
$\Delta R(\ell,\gamma) > 0.7$, $\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\ell/\gamma, \text{jet}) > 0.3$
Exclusive: no anti-k_t jets with $p_T^{jet} > 30\,GeV$, $\lvert\eta^{jet}\rvert < 4.4$

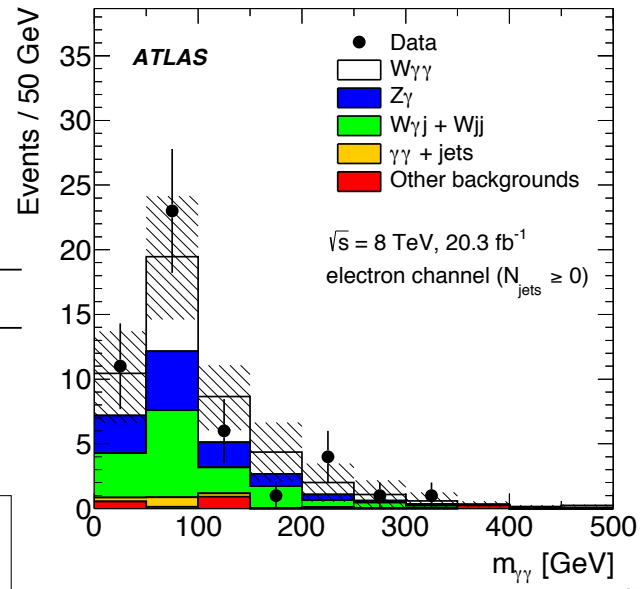
Main uncertainties on fiducial cross section: 1) DD background (14-23%) 2) JES (5-7%) 3) Luminosity (3%)

Cross section and limits on aQGC

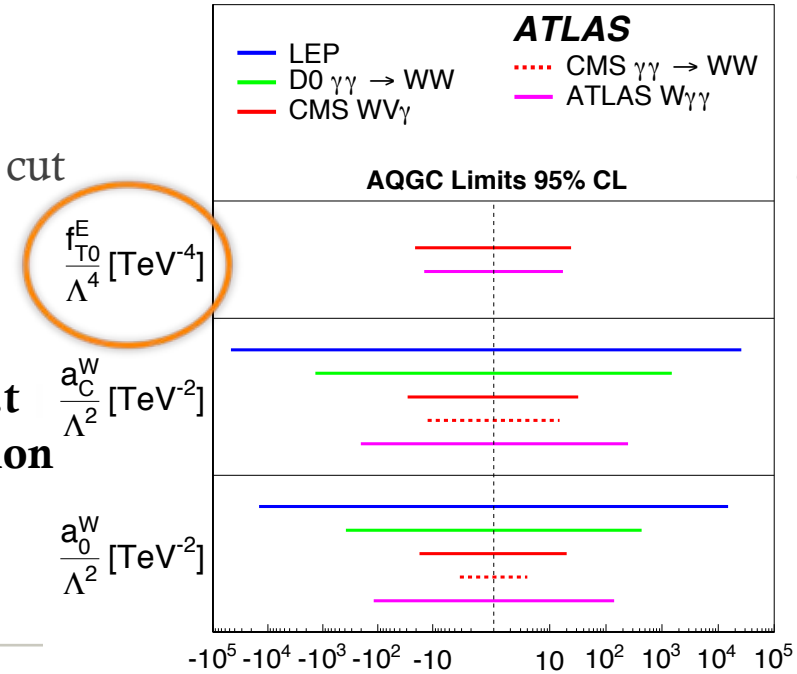
- Combined significance over background only scenario: **>3σ**
- Fiducial cross section:

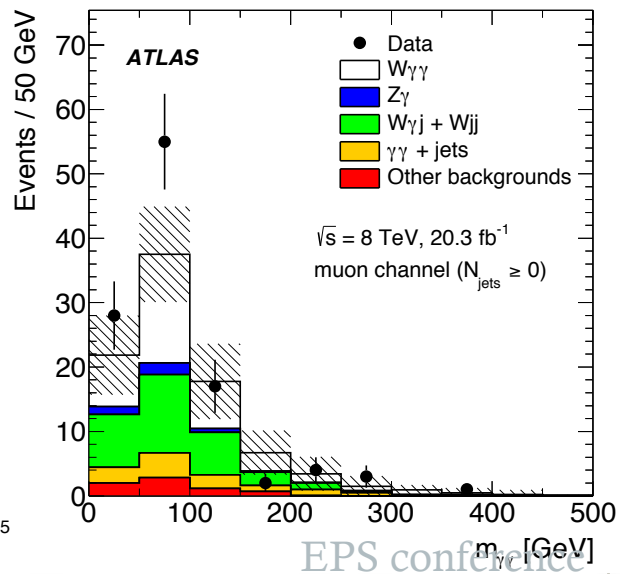
	σ^{fid}[fb]	σ^{MCFM} [fb]
Incl.	$6.1^{+1.1}_{-1.0}(\text{stat}) \pm 1.2(\text{syst}) \pm 0.2(\text{lumi})$	2.90 ± 0.16
Excl.	$2.9^{+0.8}_{-0.7}(\text{stat})^{+1.0}_{-0.9}(\text{syst}) \pm 0.1(\text{lumi})$	1.88 ± 0.20

higher than theory by 1.9σ in inclusive case



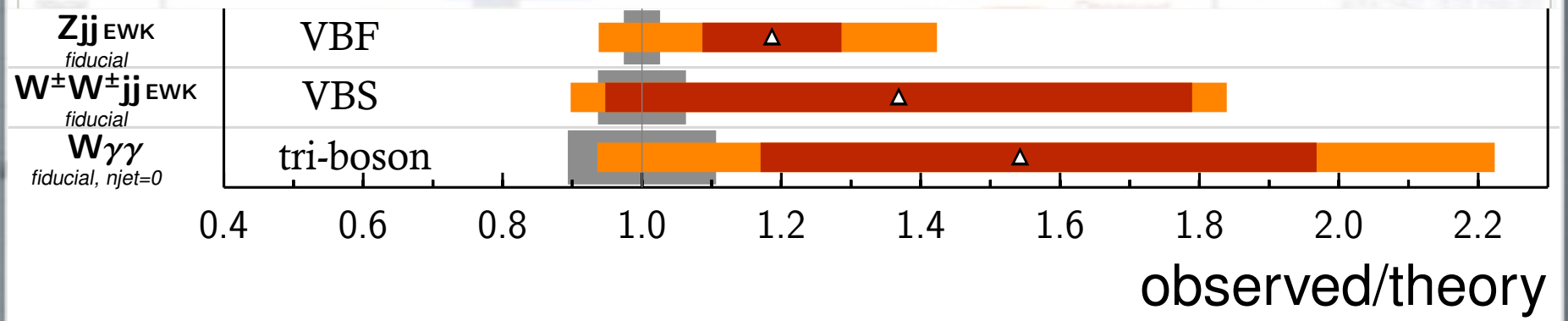
- Limits on aQGC obtained from exclusive region + cut $m_{\gamma\gamma}$>300 GeV
- Channel very sensitive to f_{T0} → **improve limit w.r.t previous publication [3]**





Conclusion

- Overall good agreement between data and simulation found in VBF, VBS and triboson cross section measurements and constrain on aTGC and aQGC limits have been set.
- Many other ATLAS measurements to come soon: VBF W, VBS WZ, tri-boson Zγγ



References

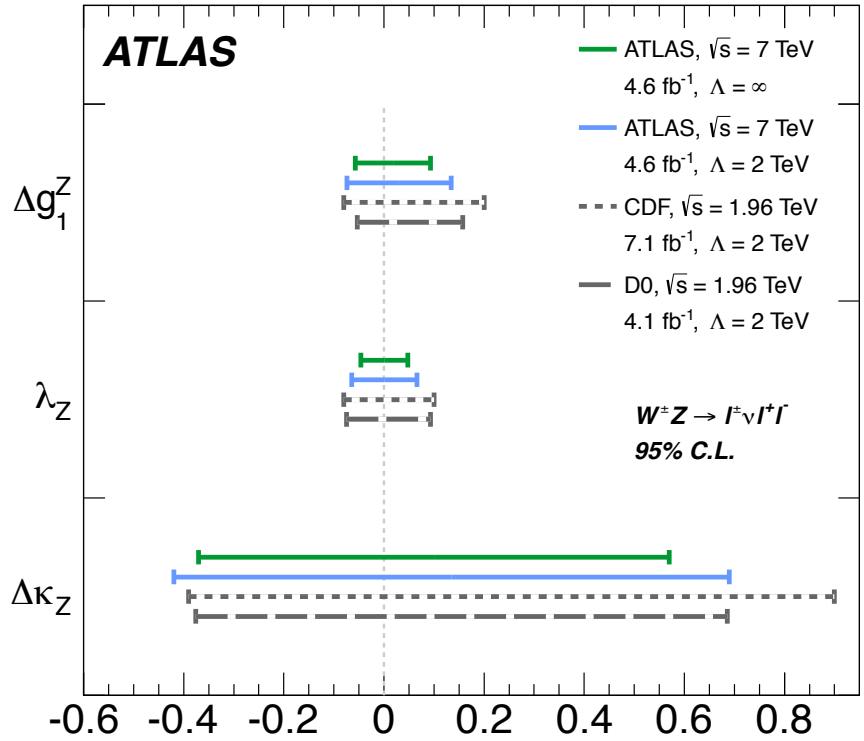
- [1]: MEPS@NLO merging: « QCD matrix elements + parton showers: The NLO case» arXiv:1207.5030

- [2]: Measurement of WZ production in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, Eur. Phys. J. C72 (2012) 2173

- [3]: A search for WW gamma and WZ gamma production and constraints on anomalous quartic gauge couplings in pp collisions at sqrt(s) = 8 TeV, Phys. Lett. B 740, 250 (2015)

Back-up

WZ aTGC



Measurement of WZ production in proton-proton collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector, Eur. Phys. J. C72 (2012) 2173, [arXiv:1208.1390]

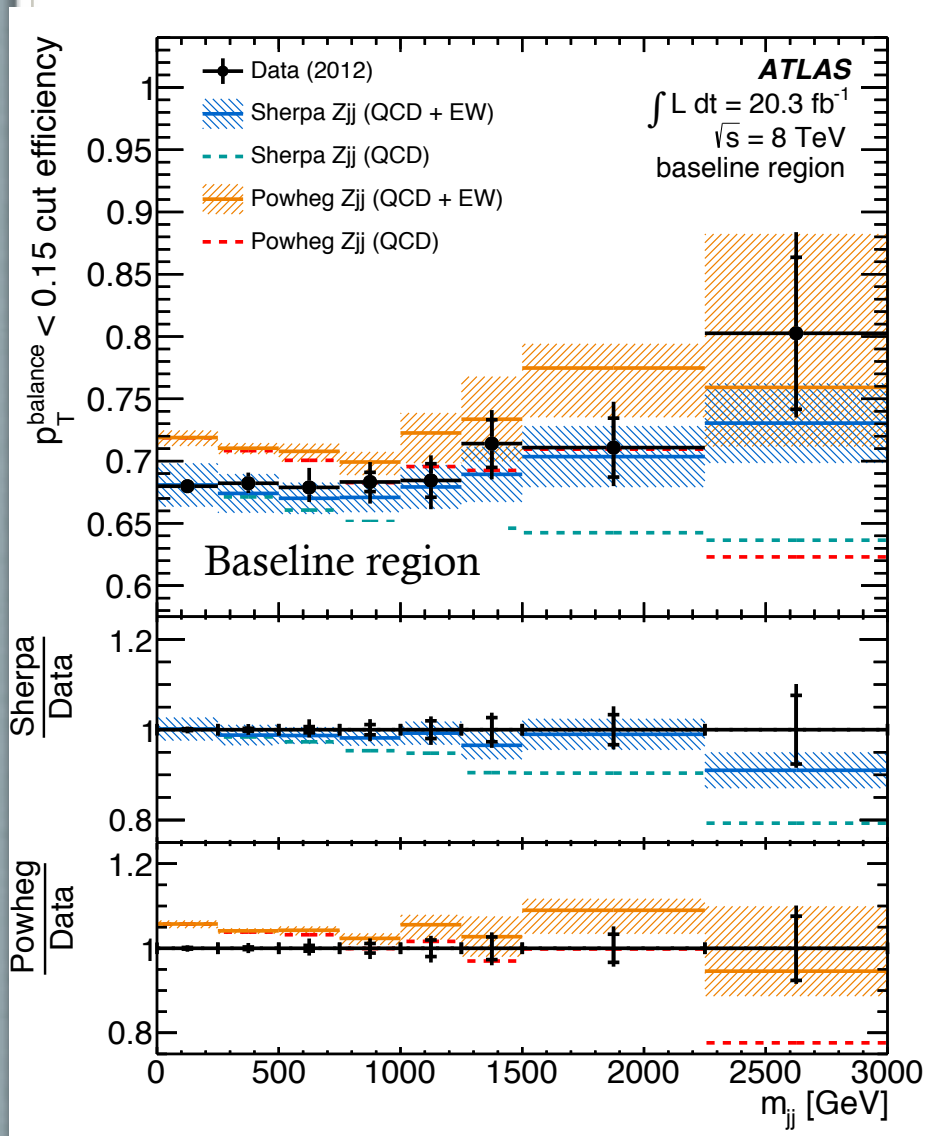
Z+2j, definition of fiducial regions

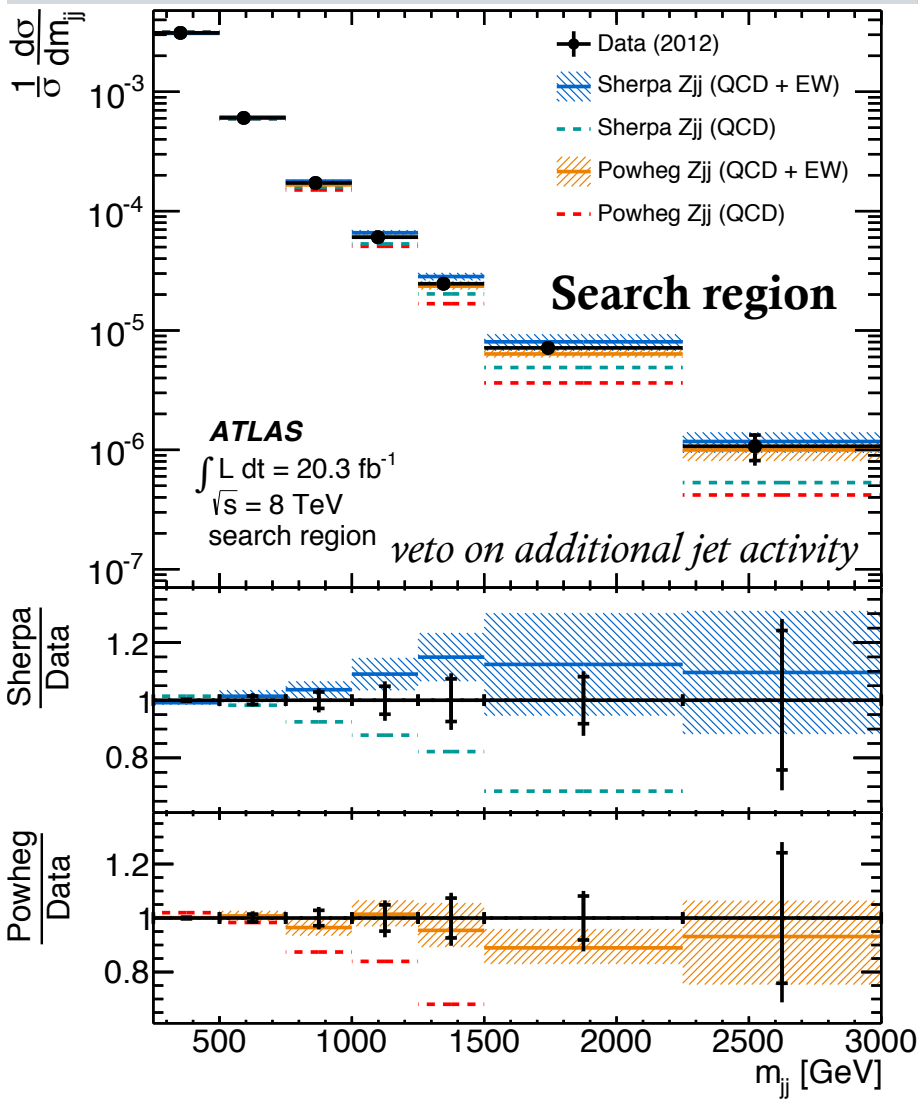
Table 1. Summary of the selection criteria that define the fiducial regions. 'Interval jets' refer to the selection criteria applied to the jets that lie in the rapidity interval bounded by the dijet system.

Object	baseline	high-mass	search	control	high-p_T
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{jet}^{BNP} = 0$	$N_{jet}^{BNP} \geq 1$	—
Zjj system	—		$p_T^{balance} < 0.15$	$p_T^{balance,3} < 0.15$	—

Differential distributions

- Sensible distributions to:
  - kinematics of the two tagging jets: mjj, deltaYjj, …
  - difference in colour flow between EW and strong production: N_{jet}^{gap}, p_T^{bal}, …
- Method: iterative Bayesian unfolding in same 5 regions as defined previously
  - 1st step, detector response matrix (=prior) from Sherpa
  - 2nd step prior = unfolded distribution from data
- Dominant systematic uncertainties
  - jet related uncertainties (energy scale, resolution, jet vertex fraction)
  - theoretical modelling
- Comparisons between Powheg (accurate to NLO in pQCD) and Sherpa (accurate to LO) generators
- Results:
  - Smaller jet activity in EW process than in strong one as expected
  - None of the two generators can fully reproduce data for all distributions in all fiducial regions → **unfolded data can be used to constrain modelling of Zjj production in specific phase-space**


Data (2012)
Sherpa Zjj (QCD + EW)
Sherpa Zjj (QCD)
Powheg Zjj (QCD + EW)
Powheg Zjj (QCD)
ATLAS
∫L dt = 20.3 fb⁻¹
√s = 8 TeV
baseline region
Baseline region
$p_T^{balance}$ < 0.15 cut efficiency
Sherpa / Data
Powheg / Data
m_{jj} [GeV]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Search region
ATLAS
∫L dt = 20.3 fb⁻¹
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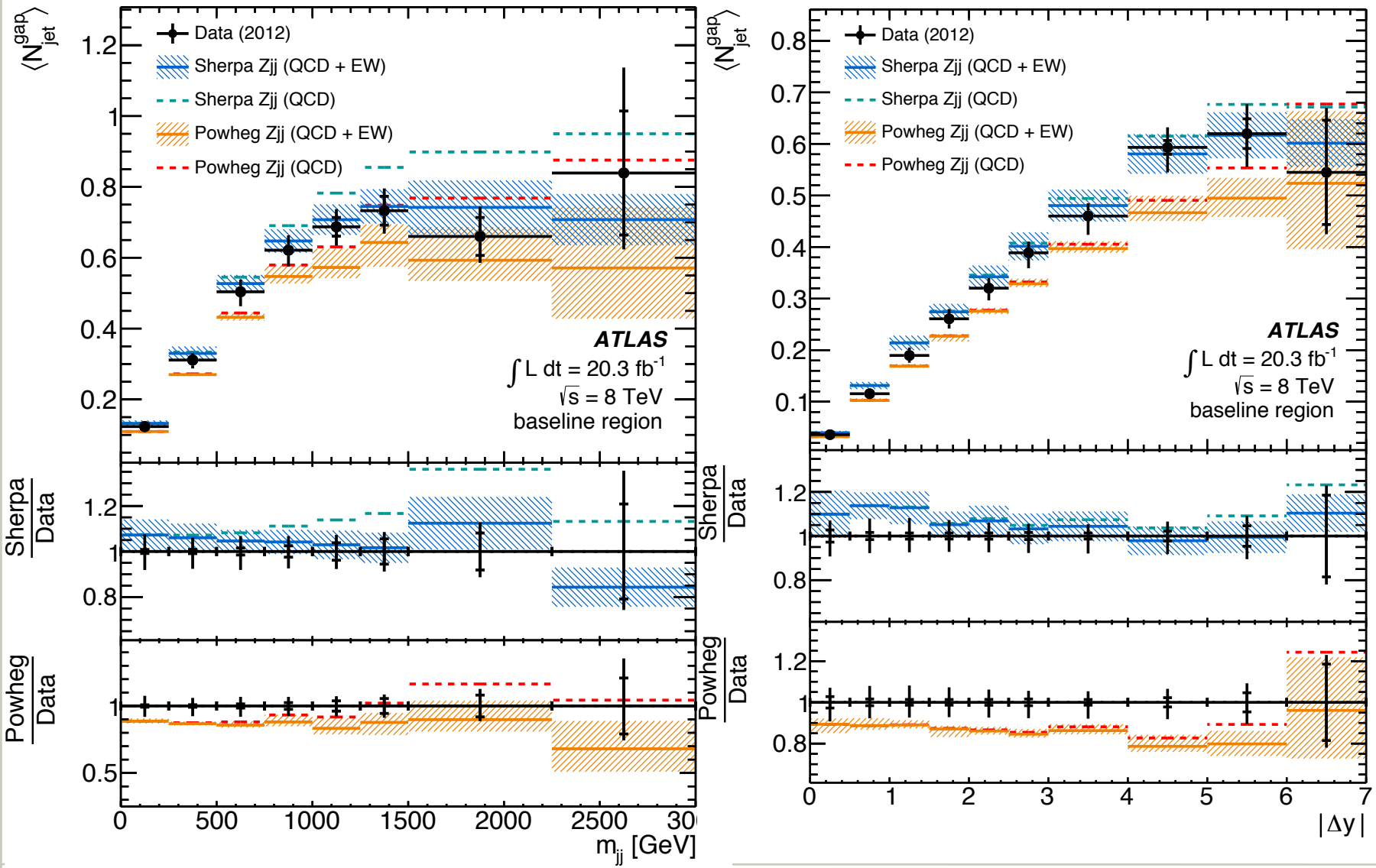
search region
veto on additional jet activity
$\frac{1}{\sigma}\frac{d\sigma}{dm_{jj}}$
Sherpa / Data
Powheg / Data
m_{jj} [GeV]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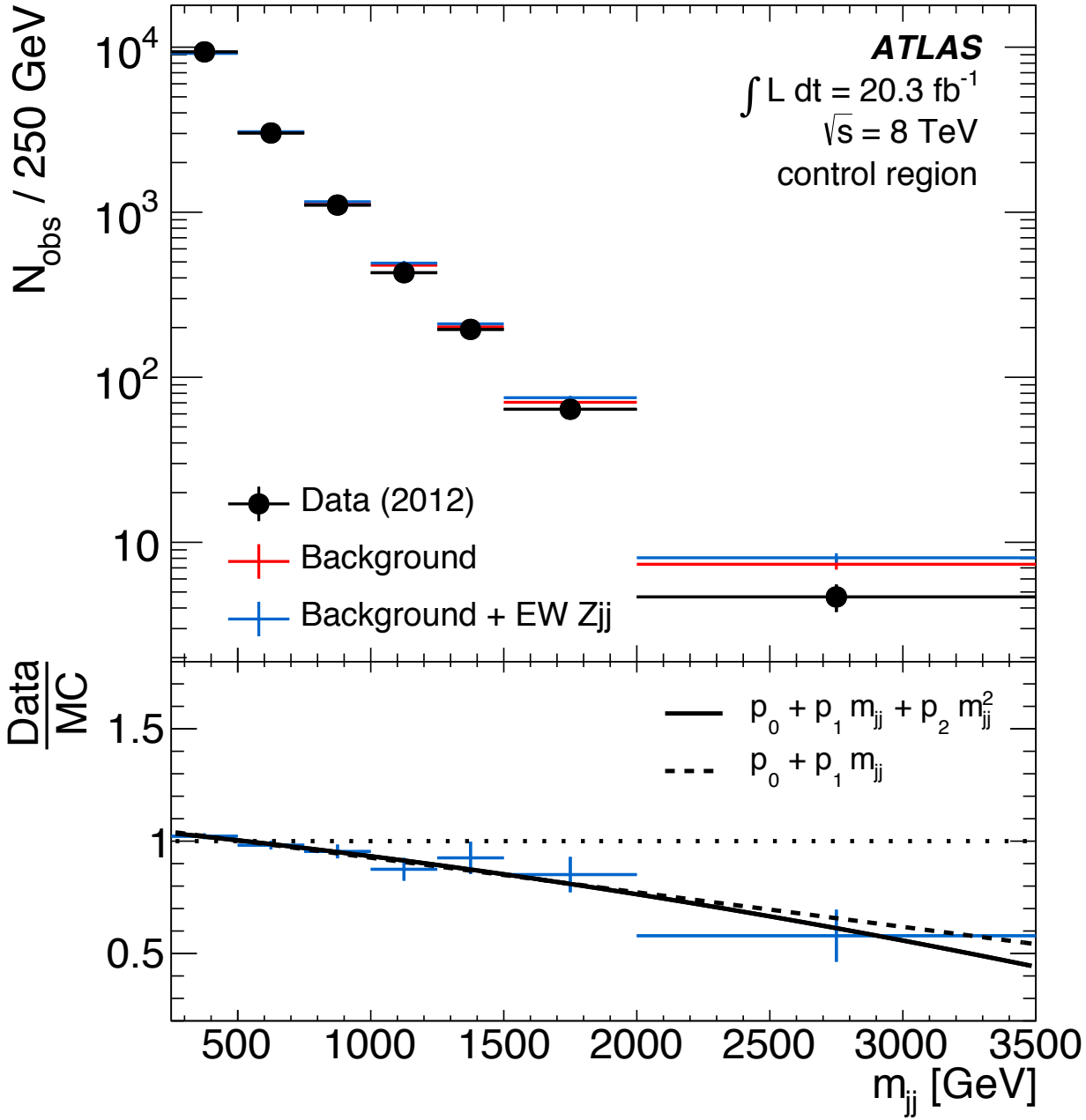
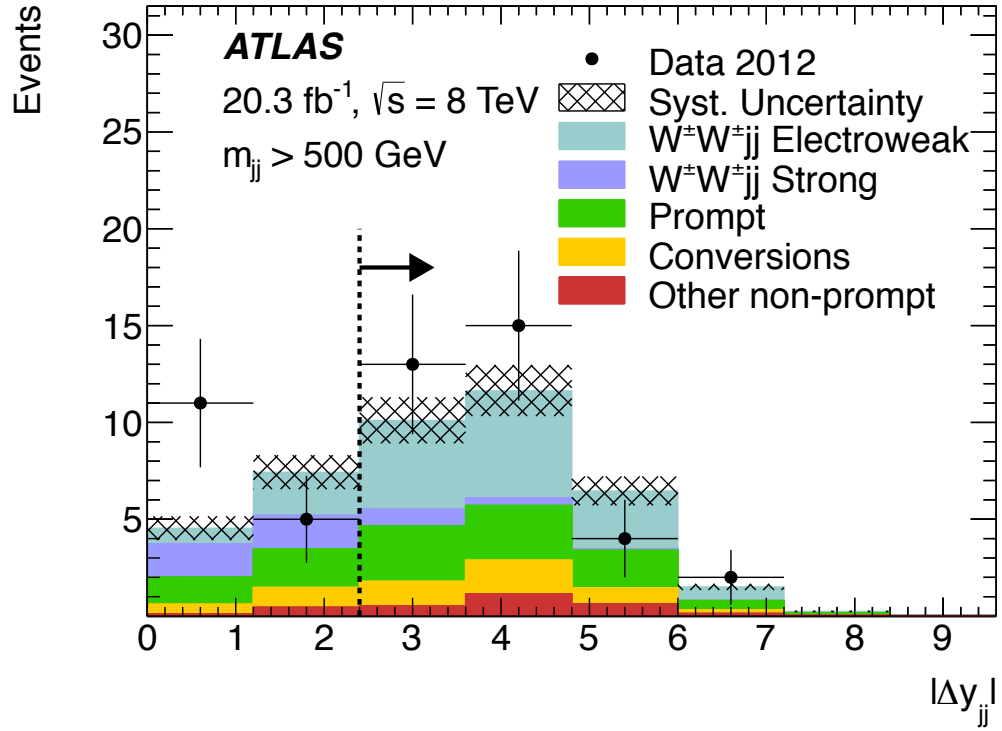
∫L dt = 20.3 fb-1
√s = 8 TeV
baseline region
⟨N_jet^gap⟩
Sherpa / Data
Powheg / Data
m_jj [GeV]
|Δy|


ATLAS
∫ L dt = 20.3 fb-1
√s = 8 TeV
control region
Data (2012)
Background
Background + EW Zjj
N_obs / 250 GeV
Data / MC
p0 + p1 mjj + p2 mjj2
p0 + p1 mjj
mjj [GeV]

- Prediction taken from Powheg+CT10 PDF + Pythia for parton showering
  - constructive interference between EW and strong process: +12% in inclusive region, +7% in VBS one

- Three decay channels: μμ, ee, μe



	Observed [TeV^{-4}]	Expected [TeV^{-4}]
$f_{\mathrm{T0}}/\Lambda^4$	$[-0.9,\ 0.9] \times 10^2$	$[-1.2,\ 1.2] \times 10^2$
$f_{\mathrm{M2}}/\Lambda^4$	$[-0.8,\ 0.8] \times 10^4$	$[-1.1,\ 1.1] \times 10^4$
$f_{\mathrm{M3}}/\Lambda^4$	$[-1.5,\ 1.4] \times 10^4$	$[-1.9,\ 1.8] \times 10^4$

no form factor applied