Jets in electroweak production of W,Z bosons

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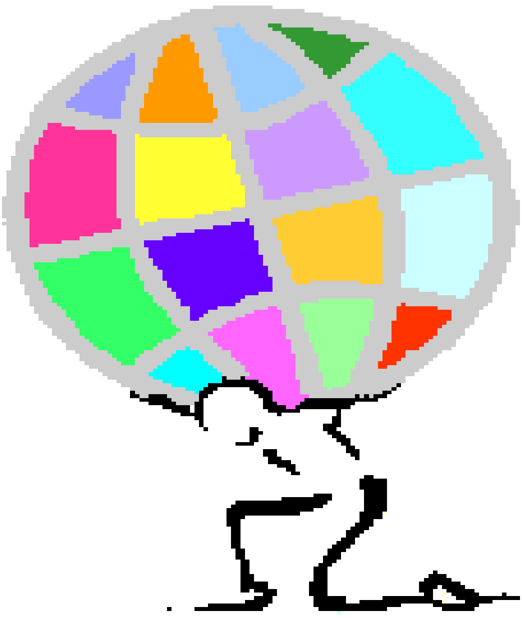
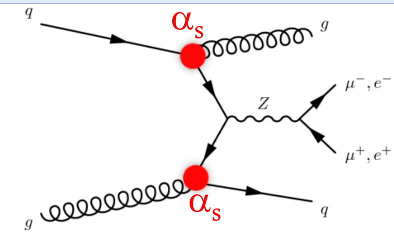
On behalf of the
ATLAS Collaboration

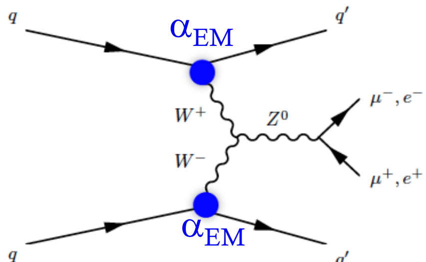


Motivations

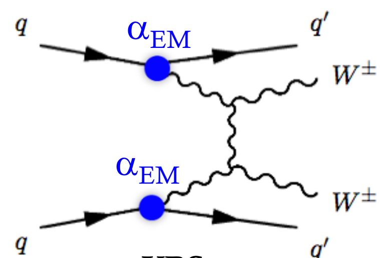
Jet production in association with W/Z bosons is dominated by strong interactions (see talk of A. Ruiz Marinez soon after)



Production via purely electroweak processes is rarer.
Mainly interested in:



VBF



VBS

→What we can learn from them?

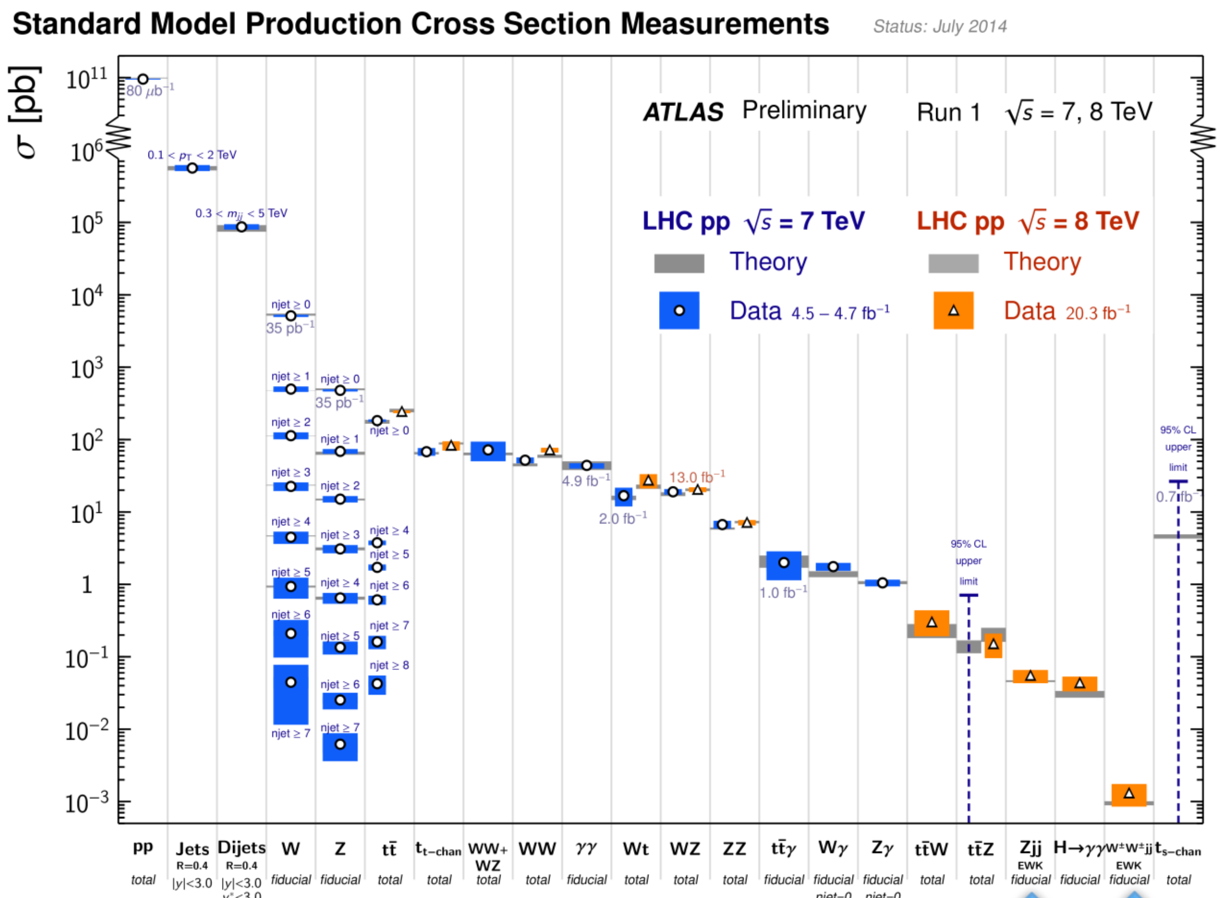
- Probe triple and quadratic gauge boson self-interactions
  → Can be used in a model independent approach to explore new physics, that modifies gauge boson self-interactions (anomalous couplings)
- Probe the nature of the EW symmetry breaking, testing the unitarization in VV scattering by HVV contribution (VBS)
- Understand irreducible background to Higgs and beyond-SM searches
  → Constrain MC modelling of QCD-initiated processes in VBF-like regions

Outline

2 measurements recently published by ATLAS:

-EW production of Zjj
JHEP04 (2014) 031

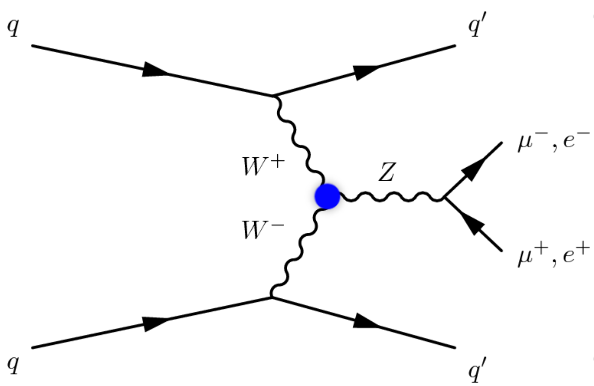
- EW production of $W^{\pm}W^{\pm}jj$ with same sign W
arXiv:1405.6241
acc by Phys. Rev. Lett.
→First evidence!



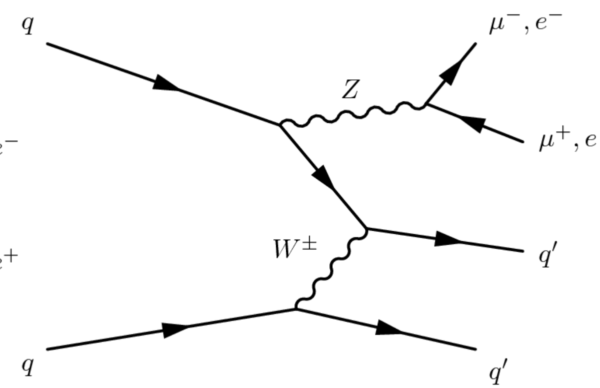
Both done at 8 TeV with 2012 dataset

EW Zjj

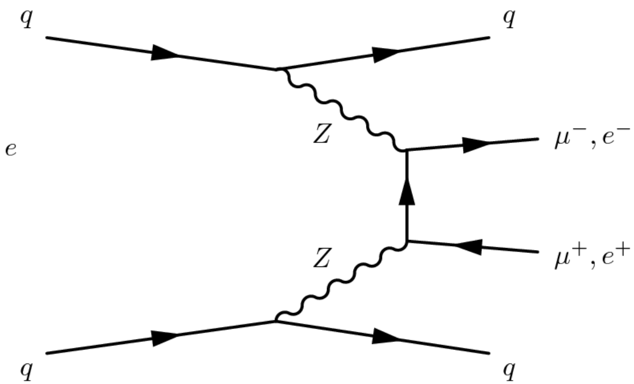
Electroweak processes:



VBF



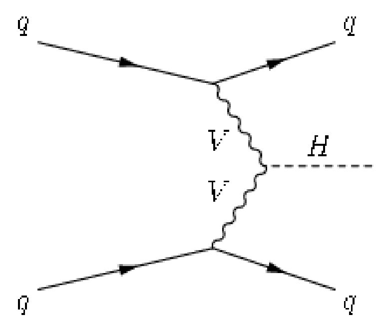
Z-boson bremsstrahlung



Non resonant processes

Sensitive to anomalous WWZ triple gauge couplings (aTGCs)

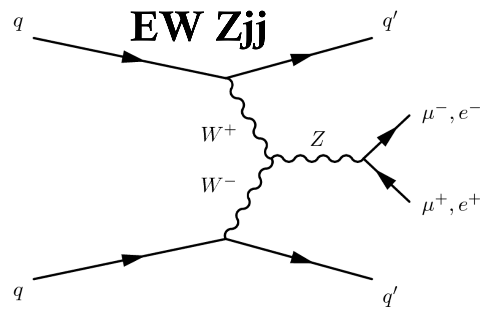
Similar to VBF production of a Higgs boson

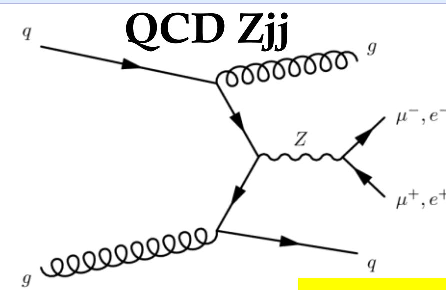


Rare processes
~1% of inclusive Zjj cross-section

EW Zjj vs QCD Zjj

How disentangle EW Zjj from QCD Zjj?





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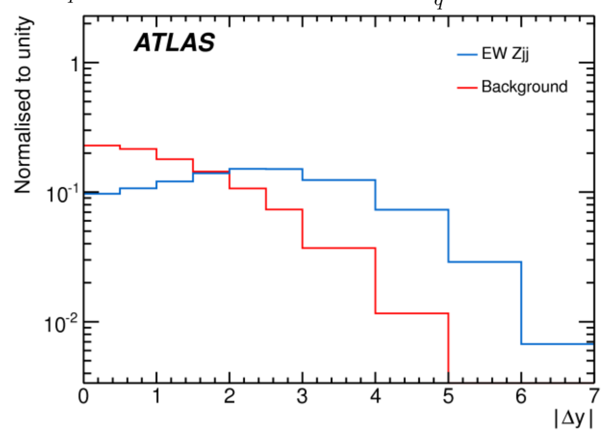
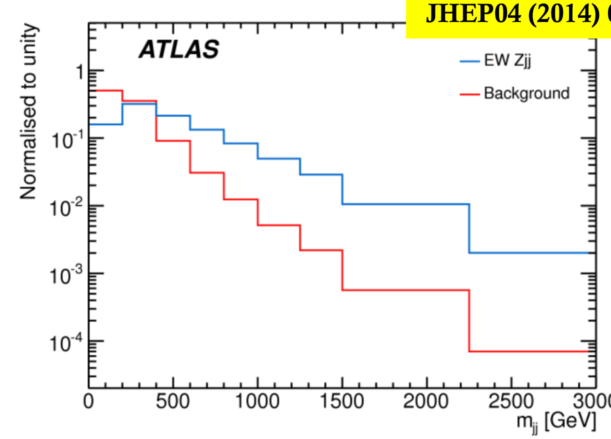
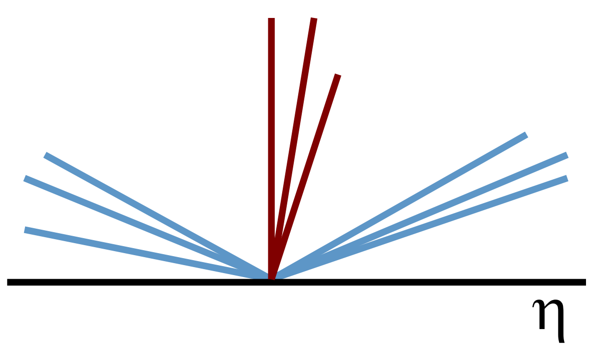
VBF selection:

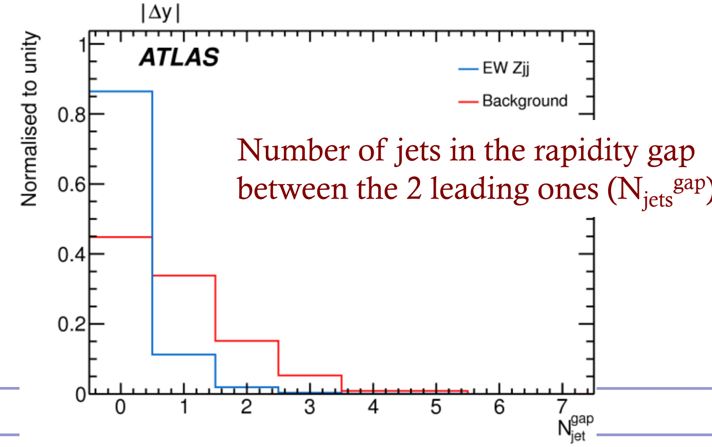
-large Δy_{jj} and m_{jj}

-veto central jet activity







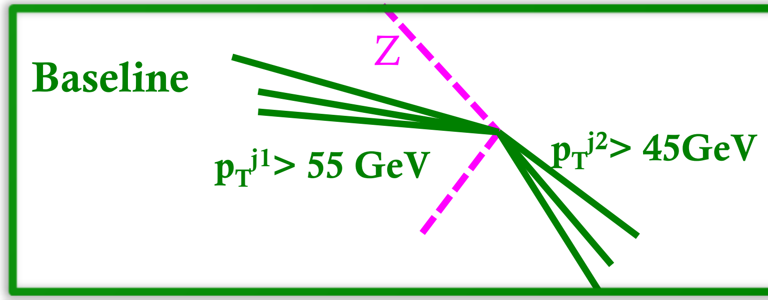


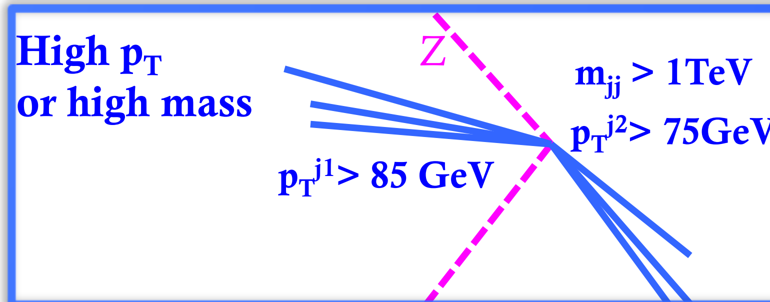
Zjj : strategy of the measurement

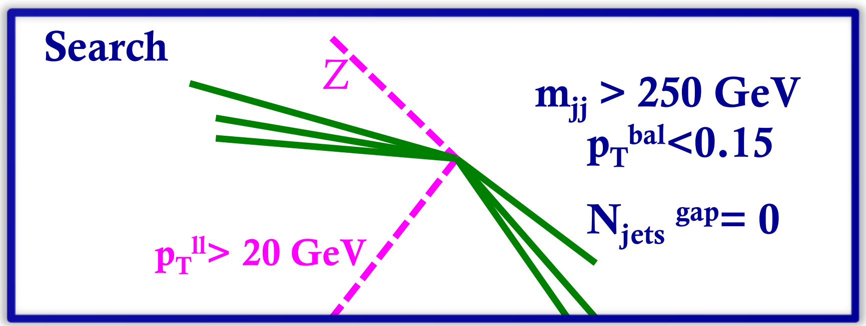
1) Measure inclusive (QCD+EW) Zjj cross section and differential distributions in 5 fiducial regions with varying sensitivity to the EW component:

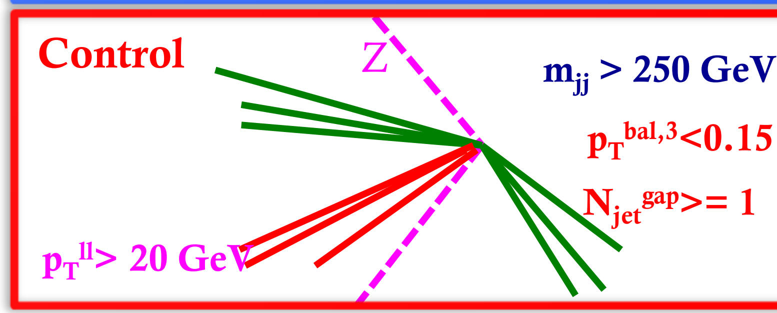
- 3 regions with simple topologies:
  - **"baseline"**
  - **"high p_T"** and **"high mass"**
    → probe impact of EW component
- 2 ad hoc selections**:**

  "search region" and **"control region"**









2) Extract electroweak component cross section from "search region", constraining the modeling on the background (QCD Zjj) from the "control region"

3) Set limits on anomalous triple gauge couplings

Zjj: Detector Level

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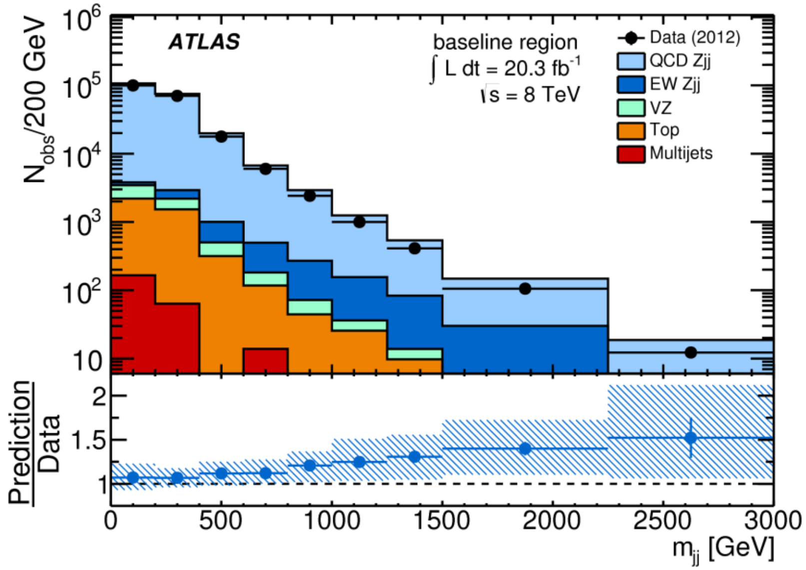
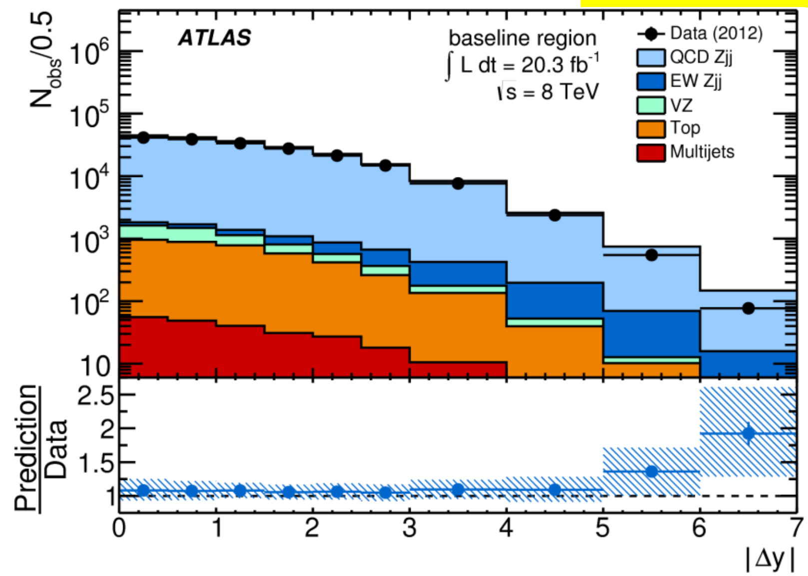




- QCD Zjj and EW Zjj with Sherpa (v1.4.3) normalized with Powheg
- WZ and ZZ with Sherpa
- ttbar and single top with MC@NLO+Herwig/Jimmy
- Multijets: data-driven

Sherpa describes adequately the data, apart some mismodelling at high m_{jj} and large angular separation

Zjj: Particle level

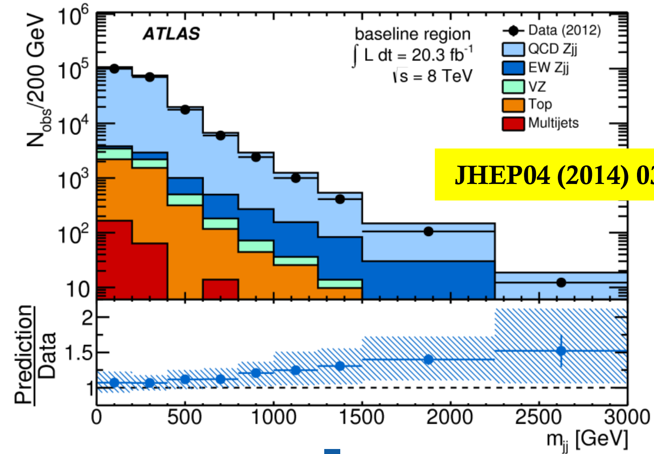
The Detector Level

Signal= Data –BKGs
BKGs partially from MCs
partially with data-driven techniques

Correct for detector effects (trigger and reconstruction efficiency, resolution, scales) (**UNFOLDING** with Sherpa (QCD+EW Zjj))

The Particle Level

-Measurement presented in a kinematic phase space well covered by the detector acceptance (close to the phase space of the detector level measurement):
-Comparisons :
data corrected – Predictions



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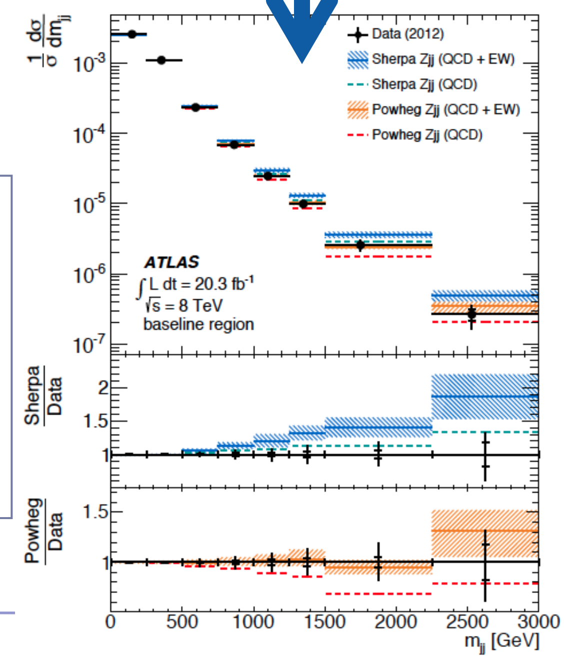

Zjj: Baseline selection

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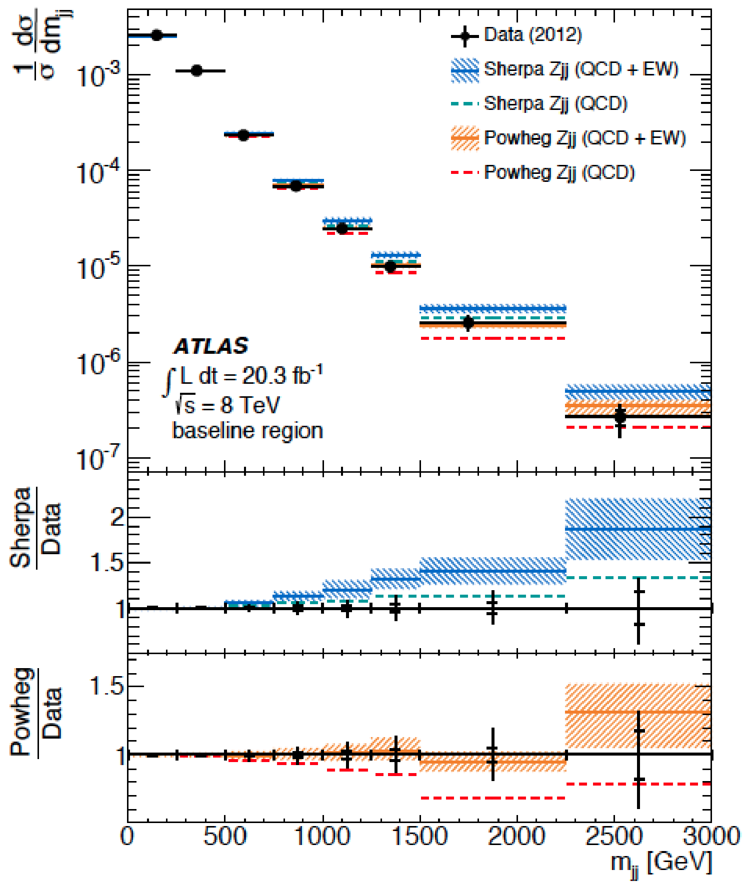
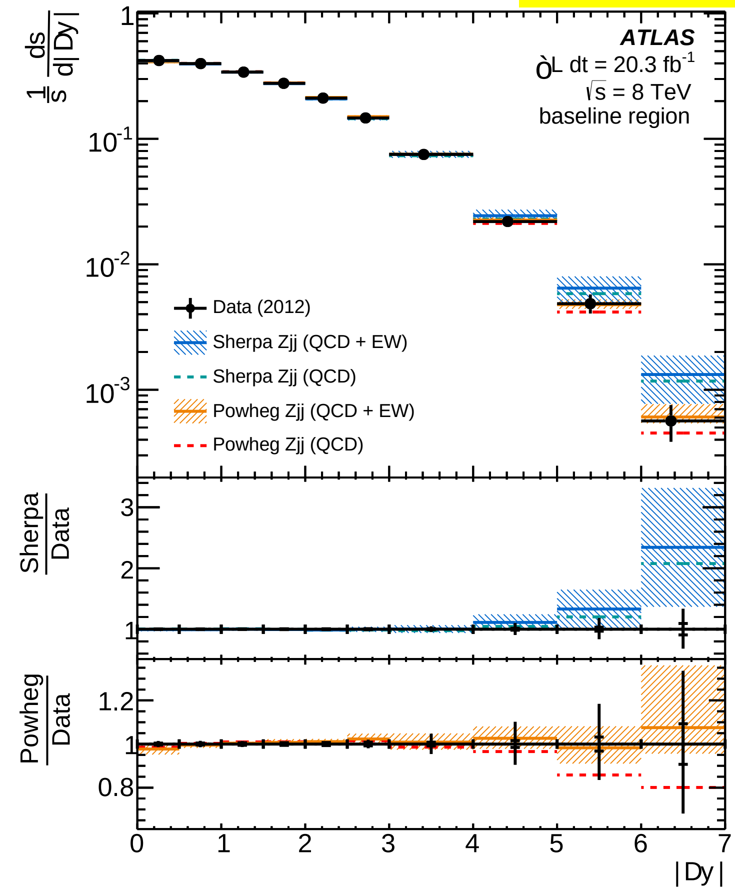


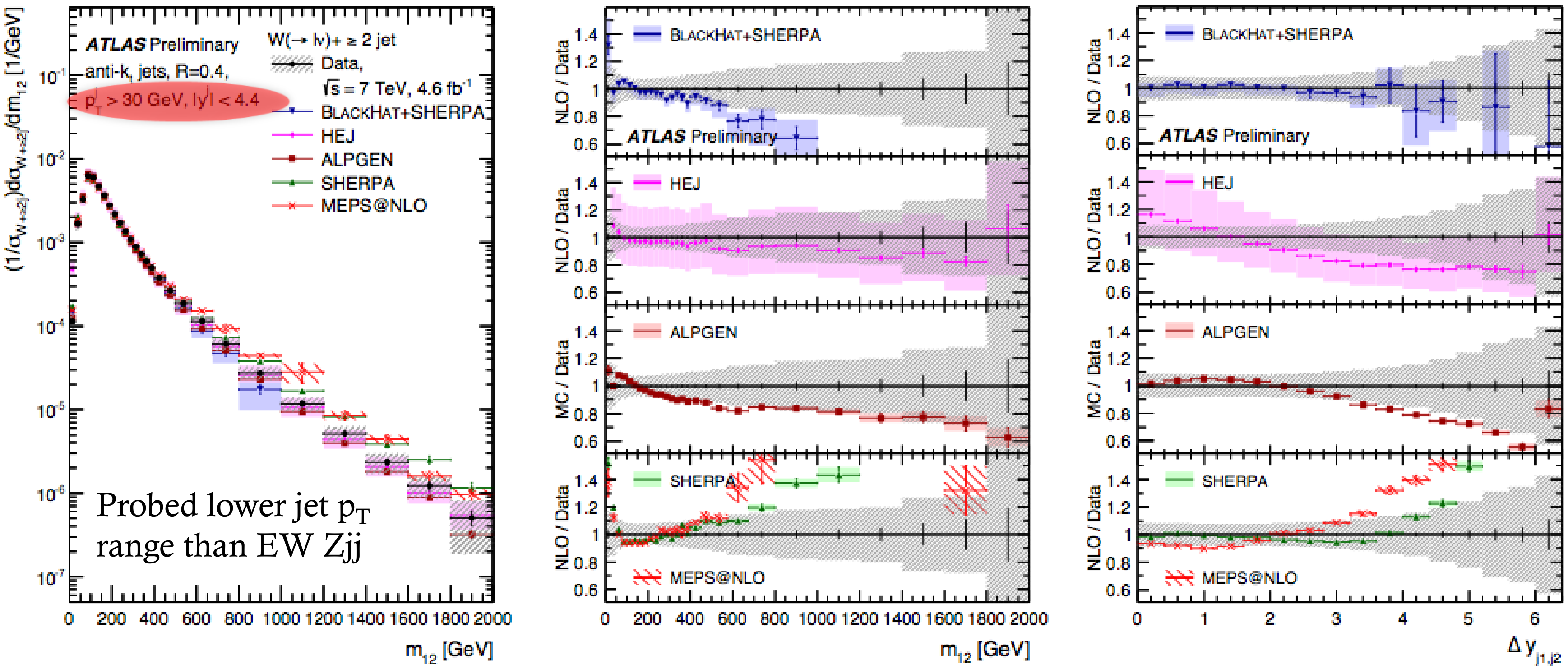


Powheg (NLO in pQCD) better describe the data than Sherpa (LO)
Sherpa predicts an harder mass spectrum and larger separation between the jets

Dijets in W/Z+jets analyses

m_{jj} (W+jets , 7 TeV) **ATLAS-CONF-2014-035** **Δy (W+jets , 7 TeV)**

2011 dataset



Sherpa (v1.4.1, LO) shows a similar trend in W+jets analysis at 7 TeV.
MEPS@NLO (NLO MC implemented in Sherpa2) doesn' t show improved agreement with data.
None of the predictions fully describes the data.

More results in the talk of A. Ruiz Martinez

Zjj: Jet Veto

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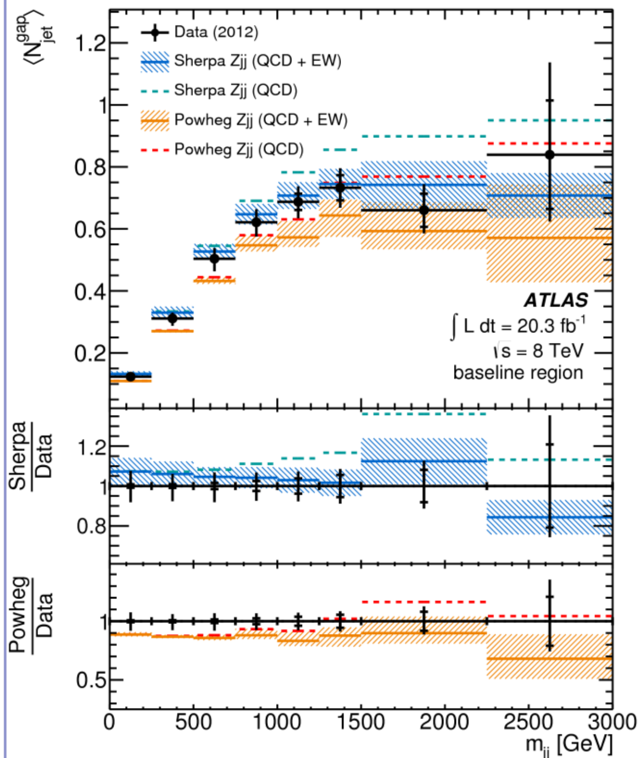
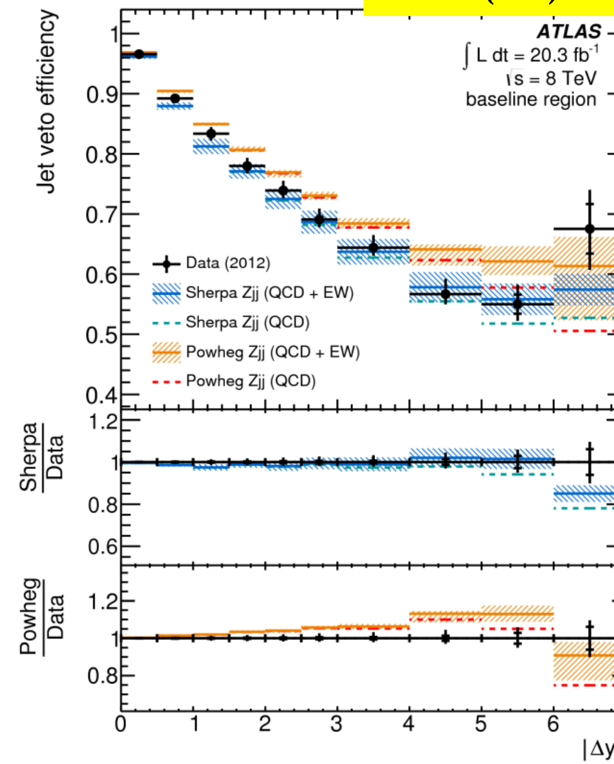


Jet veto efficiency defined as the fraction of events without additional jets with p_T>25 GeV in Δy



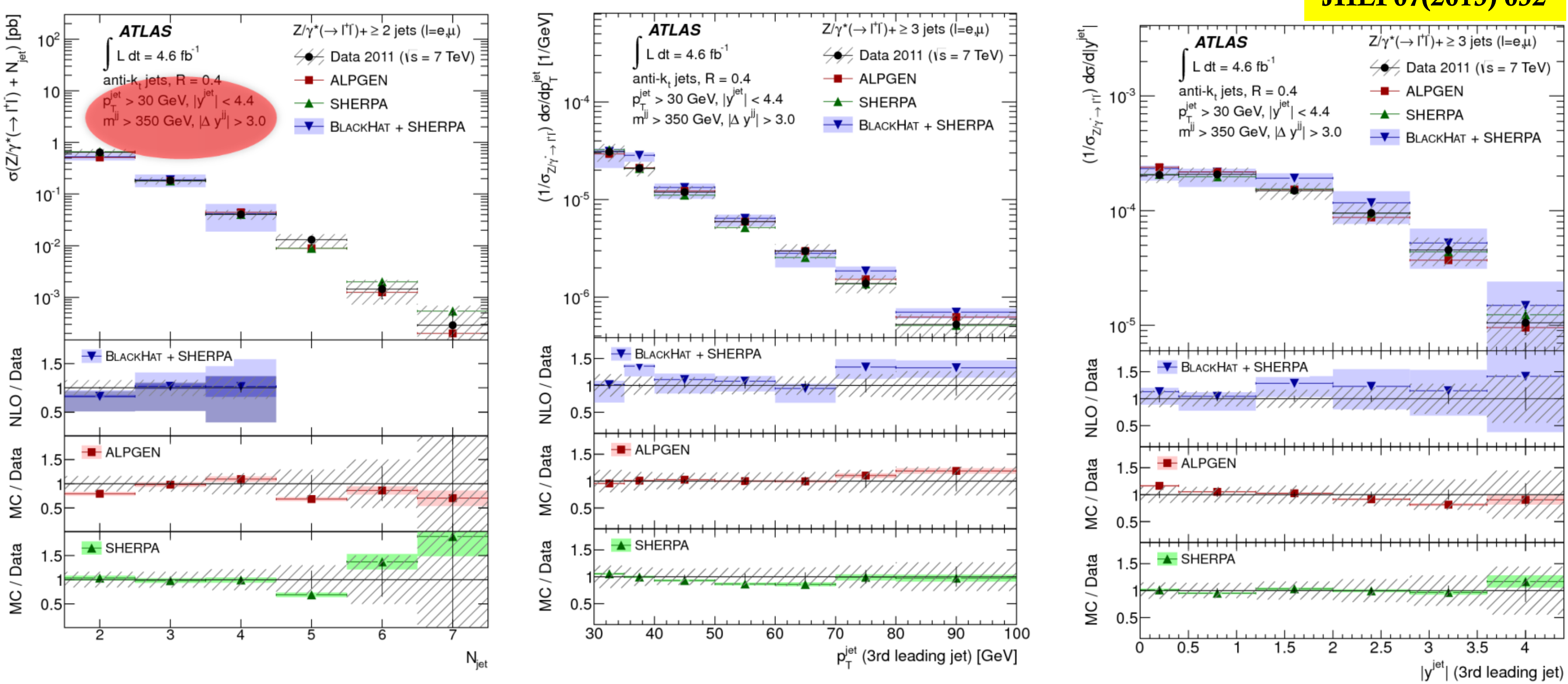
Probe wide-angle quark and gluon radiation in QCD Zjj as a function energy scale of dijet system, for EW processes little jet activity in the gap→ QCD Zjj has more activity (larger N_{jets}^{gap}, smaller fraction of events without additional jets)

Sherpa describes data quite better than Powheg for variable sensitive to additional jets

Jet veto in W/Z+jets analyses

Z+jets (7 TeV, 2011 dataset)

JHEP07(2013) 032



Probe modelling of the Z+jets for typical VBF phase-space regimes:
$m_{jj} > 350$ GeV, $\Delta y_{jj} > 3.0$

The predictions by BlackHat+Sherpa, Alpgen and Sherpa are consistent with the measurements

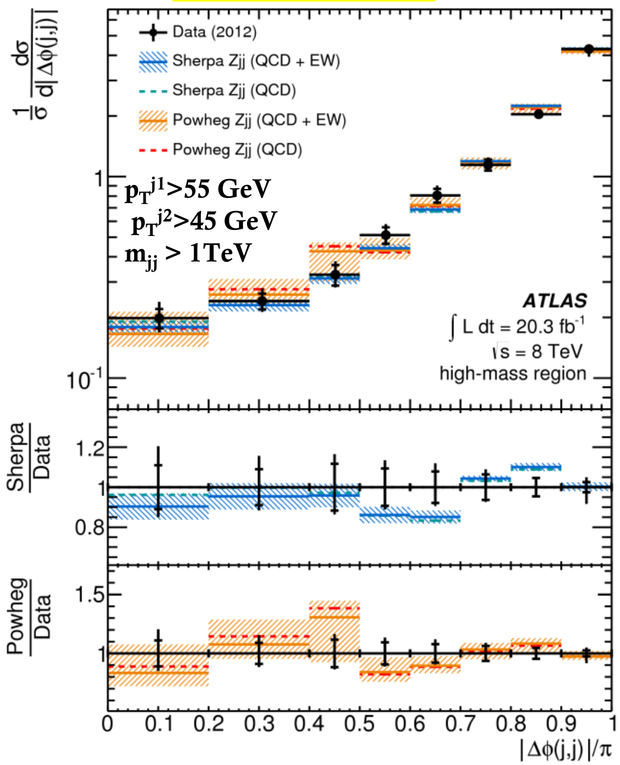
Zjj: High mass region

Δϕ not sensitive to EW and QCD separation in Zjj but discriminant variable in VBF Higgs measurements

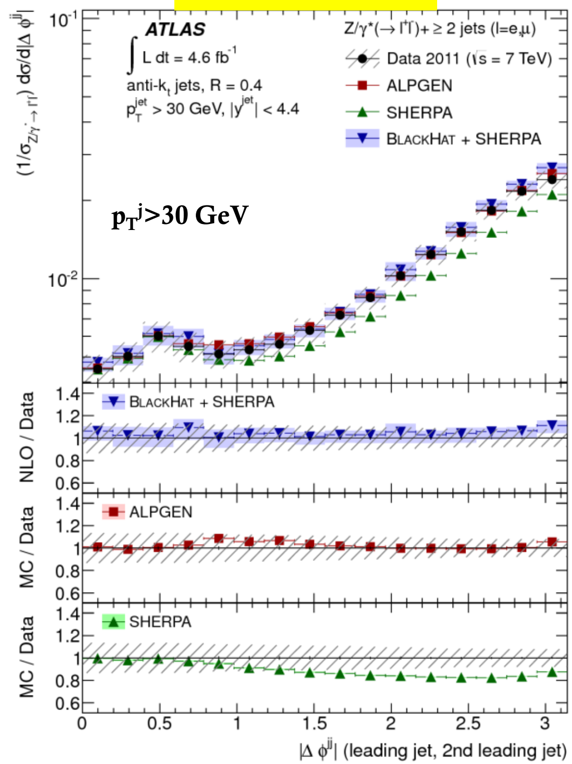
Z+jets (7 TeV) **W+jets (7 TeV)**

2011 dataset

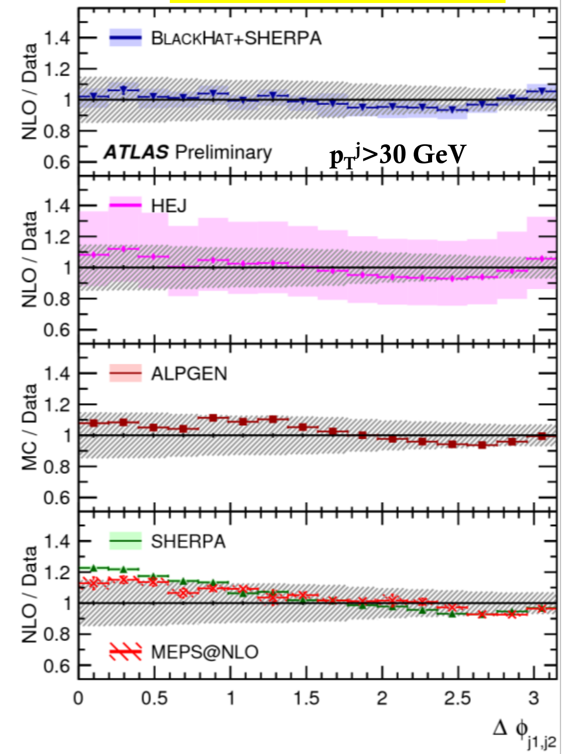
JHEP04 (2014) 031



JHEP07 (2013) 032



ATLAS-CONF-2014-035



Powheg and Sherpa describe the data in high m_{jj} region (extreme region)

While in low p_T region Sherpa shows a mismodelling

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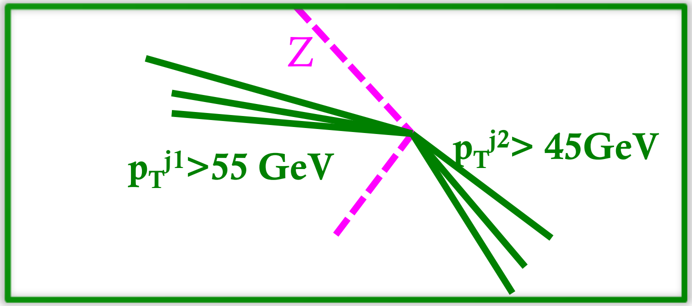
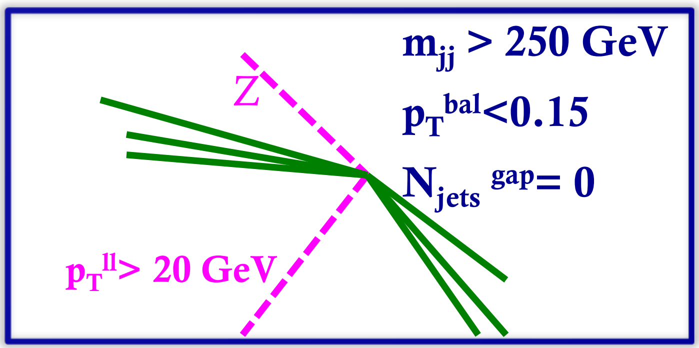
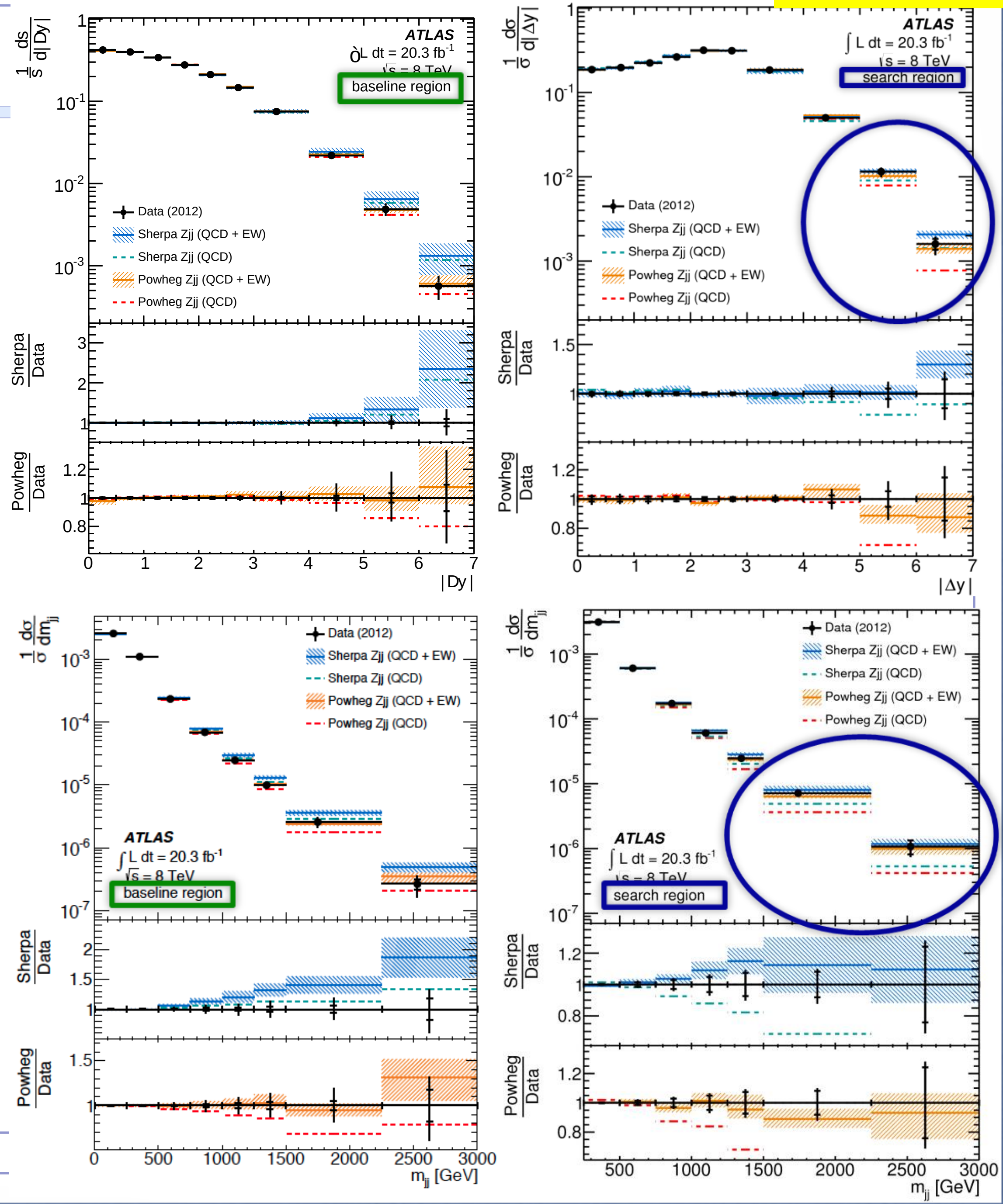
Zjj: Search

From Baseline…



..to Search





In search region both predictions give a satisfactory descriptions of the data when QCD+EW processes are considered

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EW component extraction

EW component extracted by a 2 template fit of the dijet invariant mass

Fit done in the search region (EW dominated)

Background modelling (dominated by QCD Zjj) corrected in the search region using data/MC ratio in the control region

Background-only hypothesis rejected at greater than 5σ

Extracted cross sections in 2 search fiducial regions:

1) m_{jj}>250 GeV:

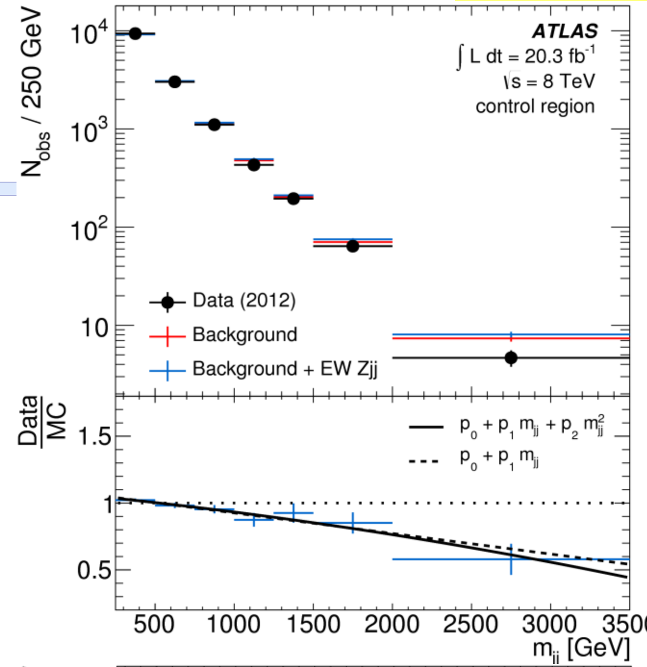
$$\sigma_{\mathrm{EW,measured}} = 54.7 \pm 4.6(\mathrm{stat})\,^{+9.8}_{-10.4}(\mathrm{syst}) \pm 1.5(\mathrm{lumi})\ \mathrm{fb}$$

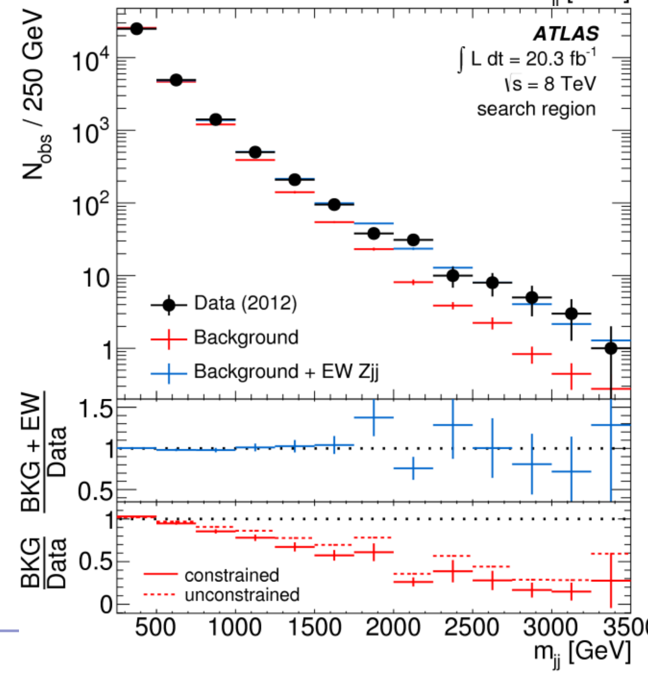
$$\sigma_{\mathrm{theory}} = 46.1 \pm 0.2(\mathrm{stat})\,^{+0.3}_{-0.2}(\mathrm{scale}) \pm 0.8(\mathrm{PDF}) \pm 0.5(\mathrm{model})\ \mathrm{fb}$$

2) m_{jj} > 1 TeV (most sensitive to EW Zjj component):

$$\sigma_{\mathrm{EW,measured}} = 10.7 \pm 0.9(\mathrm{stat}) \pm 1.9(\mathrm{syst}) \pm 0.3(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma_{\mathrm{theory}} = 9.38 \pm 0.05(\mathrm{stat})\,^{+0.15}_{-0.24}(\mathrm{scale}) \pm 0.24(\mathrm{PDF}) \pm 0.09(\mathrm{model})\ \mathrm{fb}$$

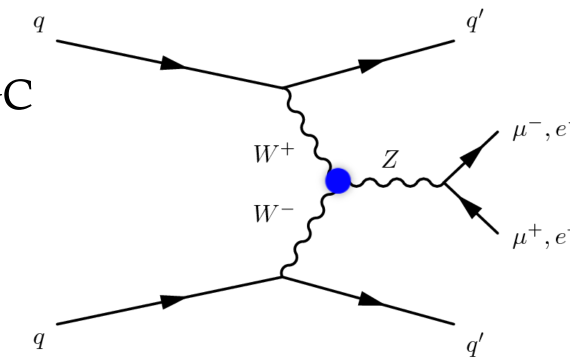




aTGC limit

- Zjj sensitive to TGC
- New physics in EW sector modify gauge boson self-interactions

Zjj measurement used to place limits on the aTGC



- In a generic aTGC model low energy effects from beyond SM physics can be parametrised by an effective Lagrangian (SM + higher-dimension operators):
  - 3 couplings describe the W,Z interaction strength:
    $g_{1,Z}$, λ_Z, κ_Z (in SM : $g_{1,Z}=1$, $\lambda_Z=0$, $\kappa_Z=0$)

Set 95% confidence intervals on $g_{1,Z}$, λ_Z from counting number of events in search region with $m_{jj}>1$TeV for 2 unitarization scales

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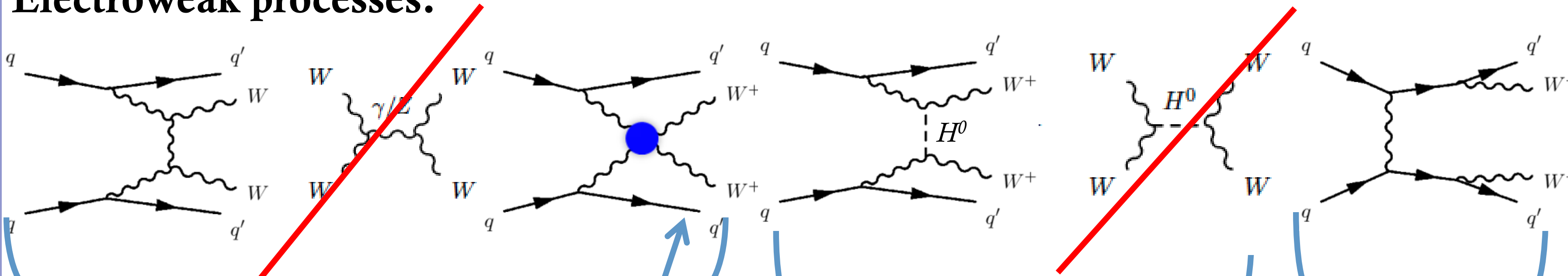
aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Not as stringent as limits set in diboson productions (~3 smaller for λ_Z in WZ) but complementary (2 Ws have space-like momentum transfer, while in diboson processes all 3 bosons have time-like momentum)

$W^{\pm}W^{\pm}jj$

Electroweak processes:



Self-interactions

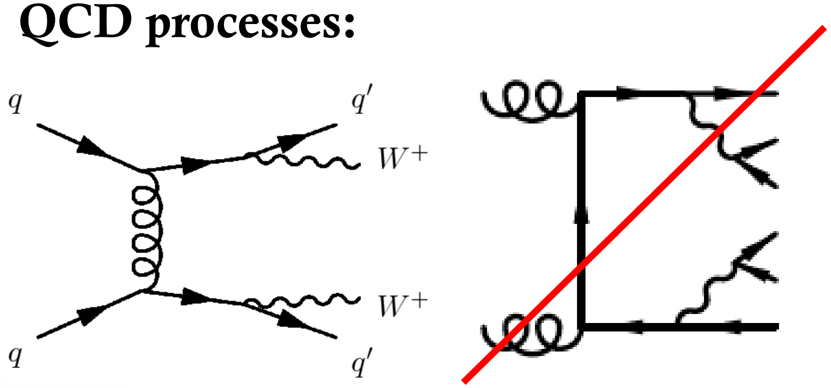
Higgs contributions

Non resonant

Sensitive to quadratic gauge couplings (QGCs)

$W_L W_L \rightarrow W_L W_L$ violates unitarity without a SM Higgs

QCD processes:



In $W^{\pm}W^{\pm}jj$ (same sign) production
some diagrams do not contribute

→Smaller cross-section than
$W^{+}W^{-}jj$ (opposite sign), but also large suppression of QCD processes
→ **Golden channel to study VBS**

$W^{\pm}W^{\pm}jj$: Strategy of the measurement

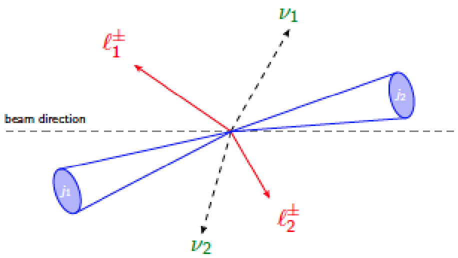
Strategy of the measurement is about the same of EW Zjj one:

1)Measure inclusive (QCD+EW) $W^{\pm}W^{\pm}jj$ cross section in 2 fiducial regions with varying sensitivity to the EW component
("inclusive region" and "VBS region")

2) Extraction on the EW $W^{\pm}W^{\pm}jj$ production from the "VBS region"

3) Set limits on anomalous quadratic gauge couplings

$W^{\pm}W^{\pm}jj$: selection



Basic selection:

-2 isolated same-sign leptons ($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$) with $p_T >$ 25 GeV
-Missing $E_T >$ 40 GeV
->=2 jets with $p_T >$ 30 GeV

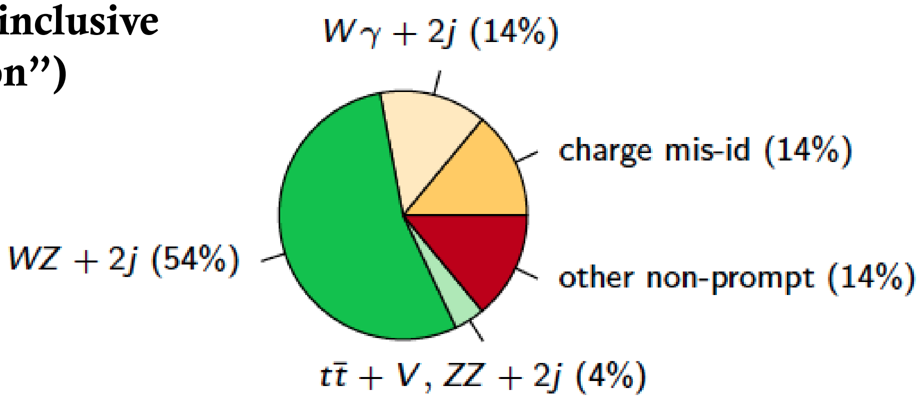
Further background reduction:

-additional leptons veto events → reduce background with prompt leptons
-Z veto in ee final state → reduce Z+jets background from charge mis-ID
-veto events containing b-jets → reduce ttbar

Final selection:

-m_{jj}> 500 GeV ("inclusive region")

Background (in "inclusive region")



Prompt backgrounds (from MC):
WZ + 2jets and ZZ +2 jets (Sherpa),
ttbar +W/Z (Madgraph)
Conversions:
- prompt photon conversion:
  $W\gamma$ (Alpgen and Sherpa)
- charge mis-ID (data-driven): Z+jets, W^+W^-
  ttbar (di-leptonic)

Other non-prompt backgrounds (data-driven):
W+jets, ttbar (semi-leptonic), dijet

$W^{\pm}W^{\pm}jj$: control regions

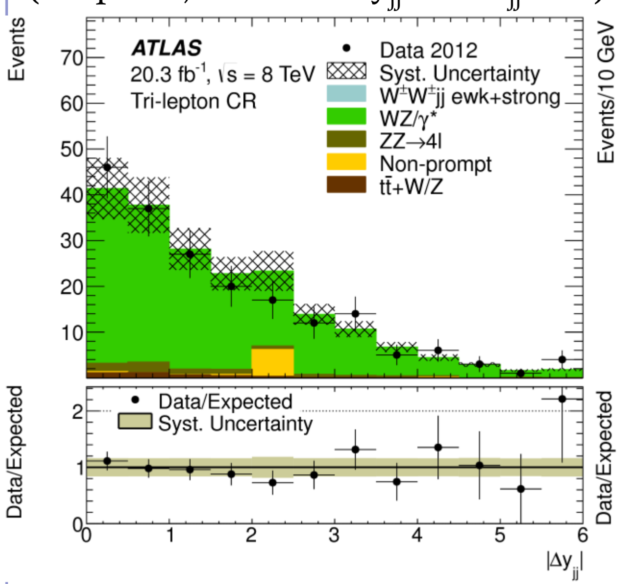
arXiv:1405.6241

Background predictions checked in several control regions targeting different background processes

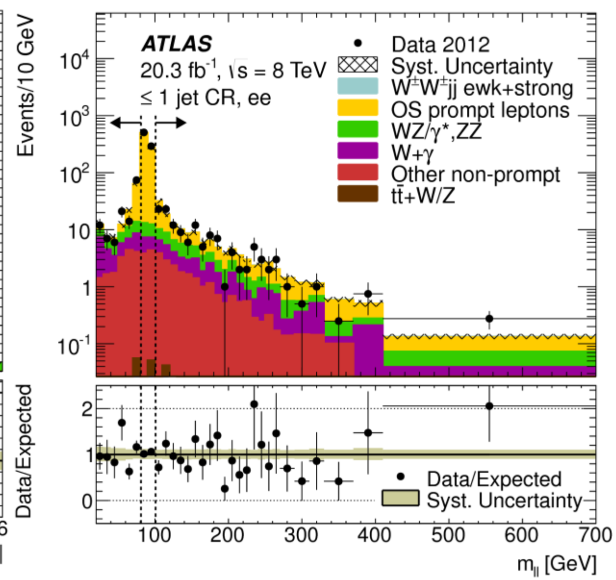
→good agreement with data observed

Control Region		Trilepton	≤ 1 jet	b-tagged	Low m_{jj}
$e^{\pm}e^{\pm}$	exp.	36 ± 6	278 ± 28	40 ± 6	76 ± 9
	data	40	288	46	78
$e^{\pm}\mu^{\pm}$	exp.	110 ± 18	288 ± 42	75 ± 13	127 ± 16
	data	104	328	82	120
$\mu^{\pm}\mu^{\pm}$	exp.	60 ± 10	88 ± 14	25 ± 7	40 ± 6
	data	48	101	36	30

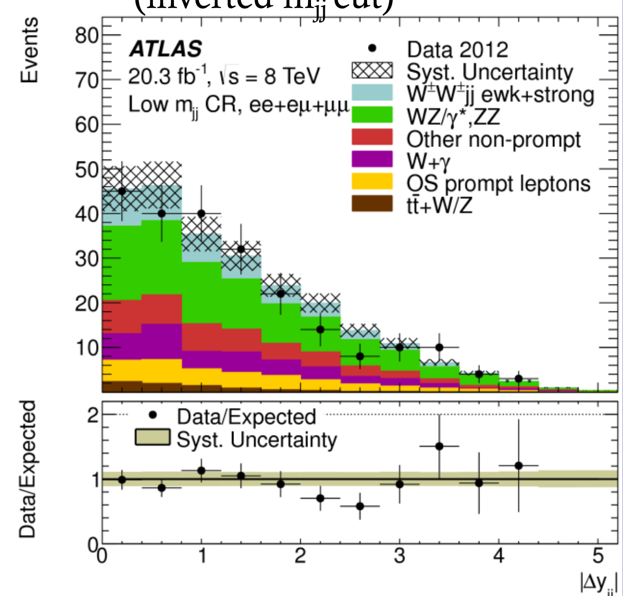
Test prompt backgrounds (3 leptons, removed Δy_{jj} and m_{jj} cuts)



Test conversion and prompt bkgs (at most 1 jet)

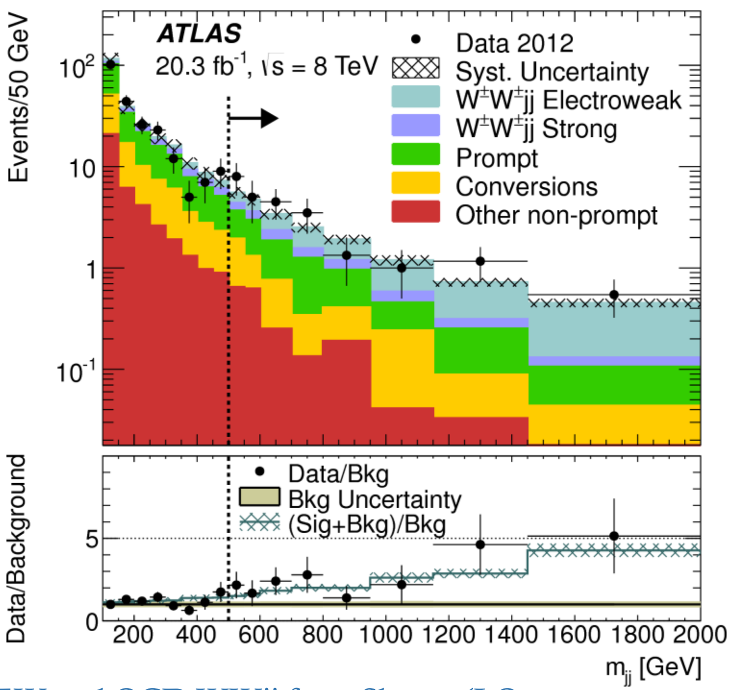


Test combined bkgs modeling (inverted m_{jj} cut)



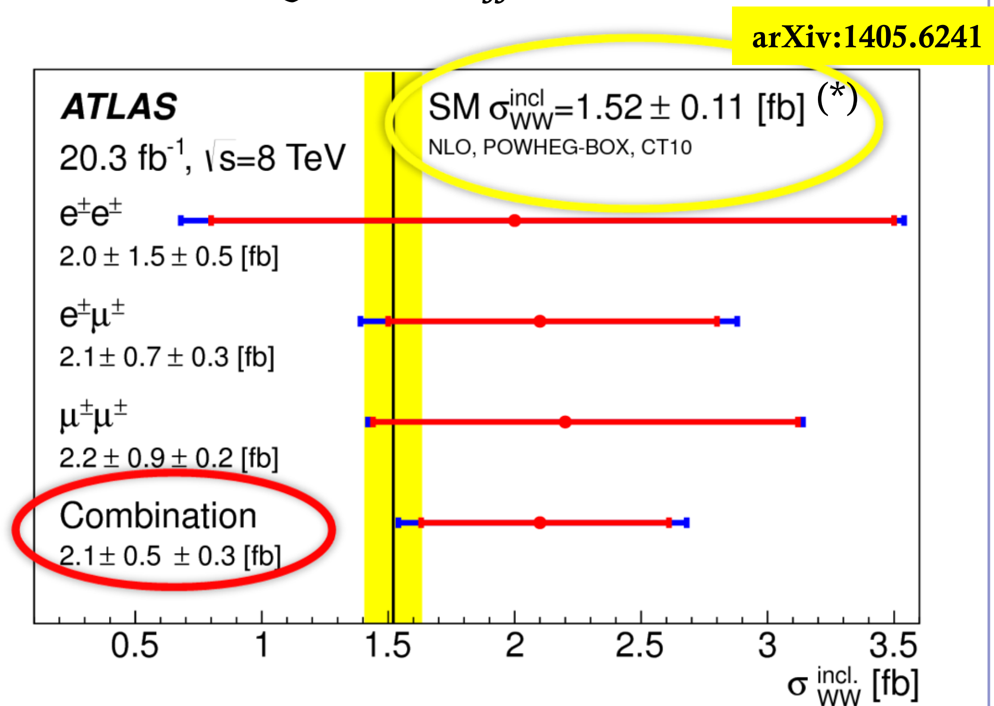
$W^{\pm}W^{\pm}jj$: inclusive

Inclusive region (m_{jj} > 500 GeV) : measured EW+QCD WWjj cross-section



EW and QCD WWjj from Sherpa (LO, up to 3 jets) normalized with Powheg (NLO)

Counted 50 events (background~20 events)



(*) Interference between EW and QCD production: 12 ± 6 % (LO, with Sherpa) included

Measurement in agreement with SM predictions

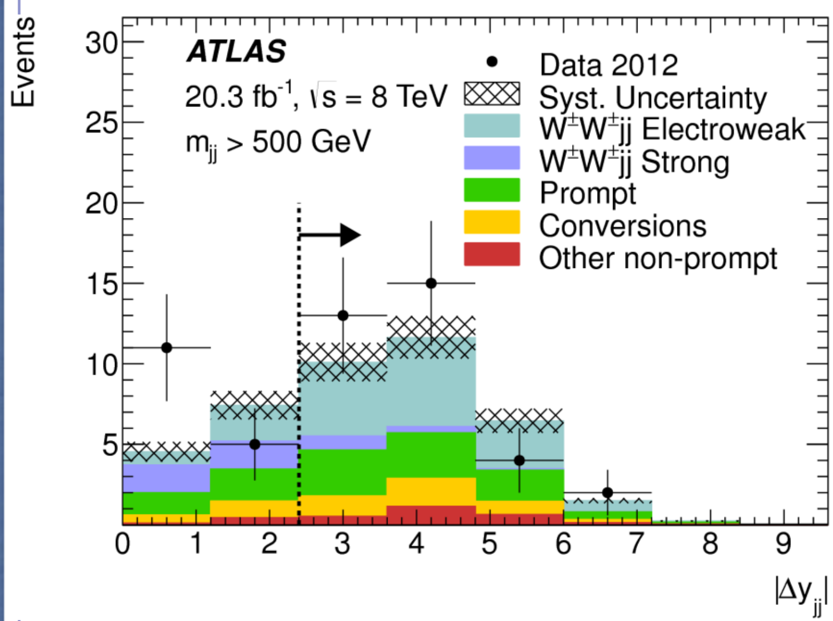
Background-only hypothesis excluded at 4.5σ (exp 3.4σ)

First evidence for $W^{\pm}W^{\pm}jj$ production

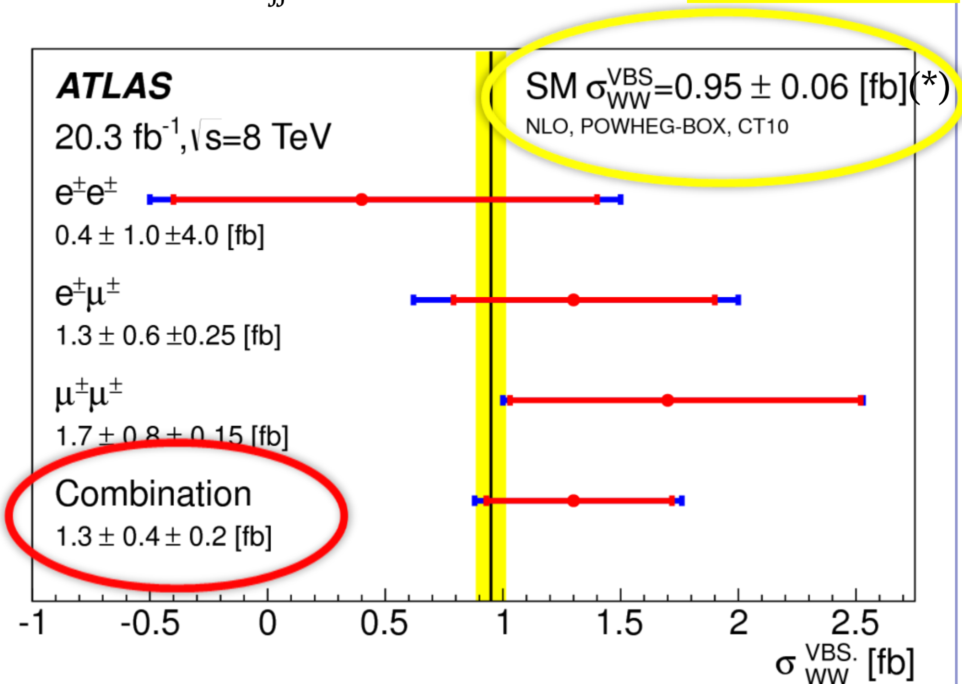
$W^{\pm}W^{\pm}jj$: EW measurement

Selection of VBS signature: $m_{jj} >$ 500 GeV && $|\Delta y_{jj}| >$ 2.4

arXiv:1405.6241



Counted 34 events (background~16 events)



(*) Interference between EW and QCD production:
7 ± 4 % (LO, with Sherpa) included

Measurement in agreement with SM predictions

Background-only hypothesis excluded at 3.6σ (exp 2.8σ)

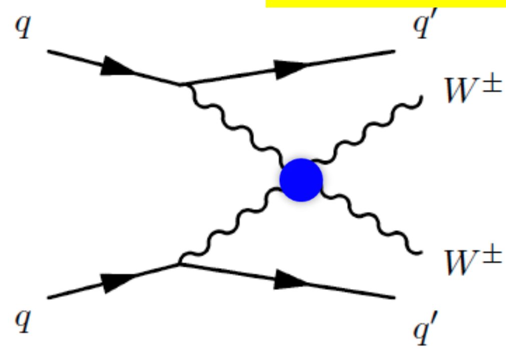
First evidence for EW $W^{\pm}W^{\pm}jj$ production

aQGC limits

arXiv:1405.6241

- $W^{\pm}W^{\pm}jj$ sensitive to QGC
- New physics in EW sector modify gauge boson self-interactions

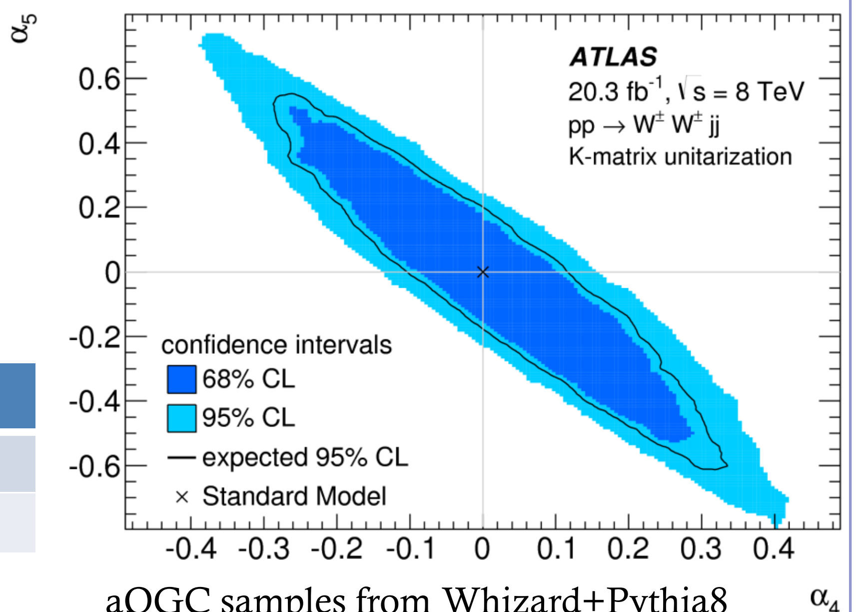
$W^{\pm}W^{\pm}jj$ measurement used to place limits on the aQGC



- Using an effective lagrangian to parametrise low energy effects from beyond SM physics, the aQGC couplings can be described by 2 parameters: α_4 and α_5

- Set 95% exclusion limits on α_4 and α_5 from cross section in VBS phase space

(95% CL)	α_4	α_5
Measured	[−0.14, +0.16]	[−0.23, +0.24]
Expected	[−0.10, +0.12]	[−0.18, +0.20]



aQGC samples from Whizard+Pythia8 with K-matrix unitarization (arxiv:0806.4145)

Conclusions

Jet production in association with W/Z bosons via purely electroweak processes is rare

2012 dataset (20 fb^{-1}) allows exploration of this field at ATLAS

ATLAS presented extremely interesting results:
-Evidence of EW Zjj, rejecting background-only hypothesis at greater than 5σ
-First evidence of $W^{\pm}W^{\pm}jj$ production and of EW component

In RunII, VBF and VBS will play a major part in tests of the electroweak sector of the Standard Model:
- VBS measurements and searches for anomalous gauge couplings
- Higgs production via weak boson fusion and HWW coupling determination

Finally, these measurements are complementary to the W/Z+jets measurements dominated by QCD: they constraint MC modelling in extreme phase-space regions

Backup Slides

Zjj: fiducial regions and their composition

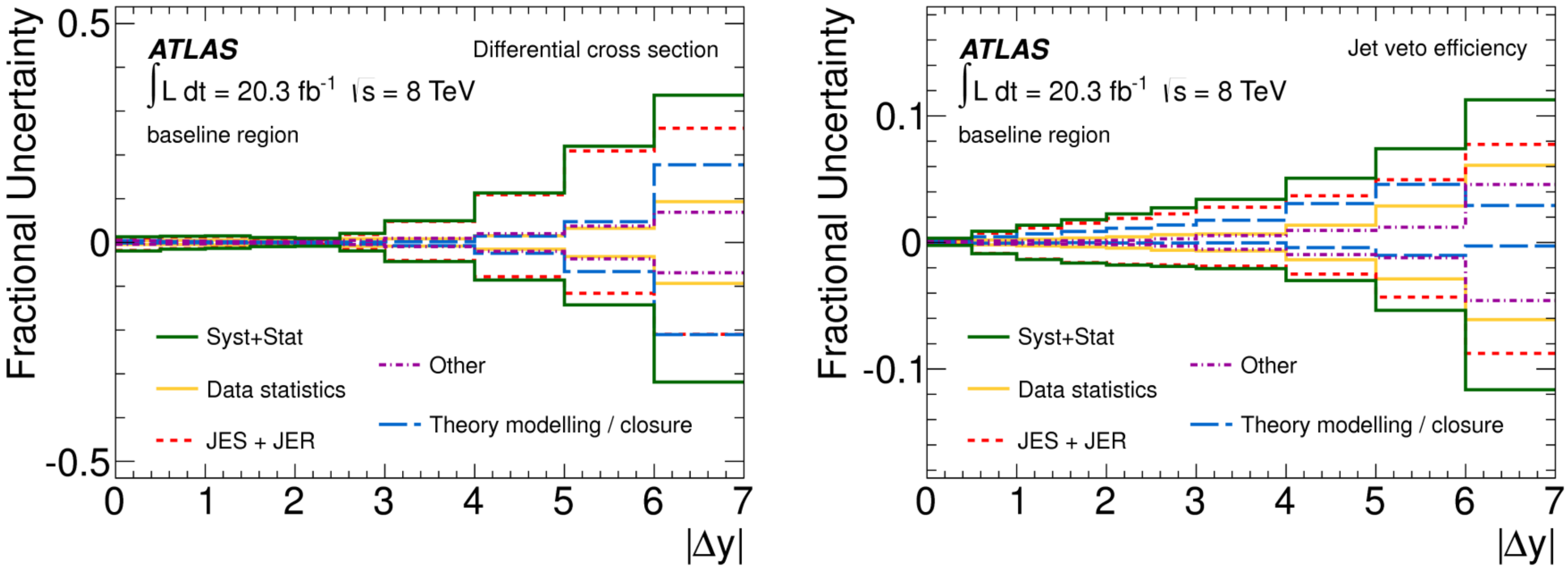
Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^{\ell}\rvert < 2.47$, $p_T^{\ell} > 25$ GeV				
Dilepton pair	$81 \leq m_{\ell\ell} \leq 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\lvert y^{j}\rvert < 4.4$, $\Delta R_{j,\ell} \geq 0.3$				
	$p_T^{j_1} > 55$ GeV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

Jets in the gap counted if : p_T>25 GeV

$$p_T^{\text{balance}} = \frac{\left|\vec{p}_T^{\,\ell_1} + \vec{p}_T^{\,\ell_2} + \vec{p}_T^{\,j_1} + \vec{p}_T^{\,j_2}\right|}{\left|\vec{p}_T^{\,\ell_1}\right| + \left|\vec{p}_T^{\,\ell_2}\right| + \left|\vec{p}_T^{\,j_1}\right| + \left|\vec{p}_T^{\,j_2}\right|}$$

	Composition (%)				
Process	*baseline*	*high-p_T*	*search*	*control*	*high-mass*
Strong Zjj	95.8	94.0	94.7	96.0	85
Electroweak Zjj	1.1	2.1	4.0	1.4	12
WZ and ZZ	1.0	1.3	0.7	1.4	1
$t\bar{t}$	1.8	2.2	0.6	1.0	2
Single top	0.1	0.1	< 0.1	< 0.1	< 0.1
Multijet	0.1	0.2	< 0.1	0.2	< 0.1
WW, W+jets	< 0.1	< 0.1	< 0.1	< 1.1	< 0.1

Zjj: uncertainties (1/2)



Zjj: uncertainties (2/2)

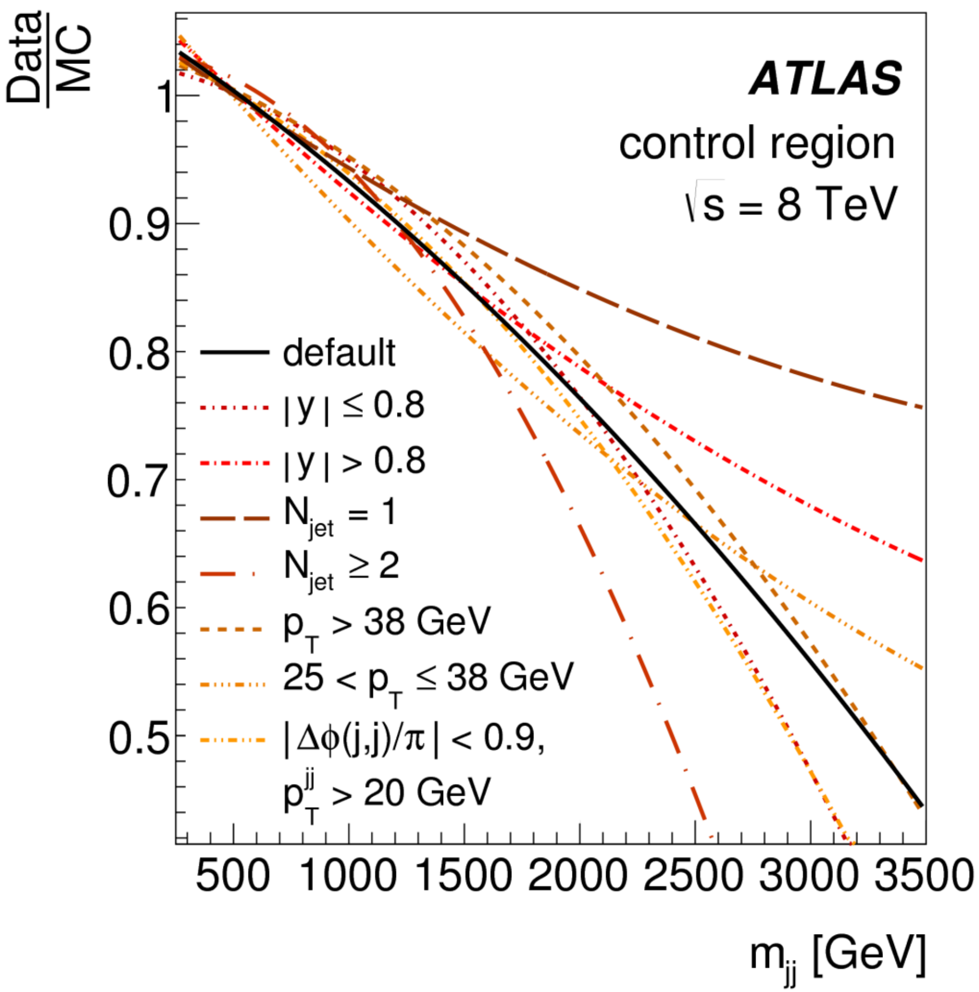
$$\sigma_{\mathrm{EW}} = \frac{N_{\mathrm{EW}}}{\int L\,\mathrm{d}t \cdot \mathcal{C}_{\mathrm{EW}}}$$

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 %	

Zjj: extraction of EW component

Validation of the constraint procedure:

- Variation of functional form (ΔN_{EW}<2%)
- Variation of generator (Powheg) (ΔN_{EW}<0.8%)
- Variation of the Control Region (maximum spread 5%)



Zjj: aTGC

Effective Lagrangian:

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

in SM : $g_{1,Z}=1$, $\lambda_Z=0$, $\kappa_Z=0$

To avoid tree-level unitarity violation, the anomalous couplings must vanish as the partonic centre-of-mass energy(s^) approaches infinity→ An arbitrary form factor may be introduced:

$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^2}$$

a_0 is the anomalous coupling at low energy.
Λ is a unitarization scale

- Limits extracted in "search region" with m_{jj}>1 TeV to limit the effect of bkg modelling (900 events in data, 261 expected for EW Zjj and 592 for background estimated with the m_{jj} fit)

-aTGC and form factors varied with Sherpa

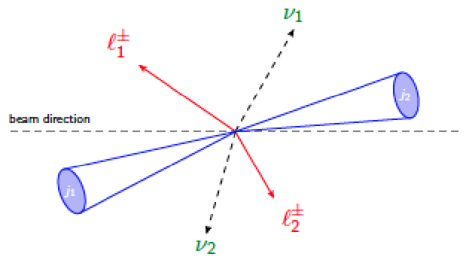
$W^{\pm}W^{\pm}jj$: selection

Basic selection:

-2 isolated same-sign leptons ($e^{\pm}e^{\pm}$,$\mu^{\pm}\mu^{\pm}$,$e^{\pm}\mu^{\pm}$) with
$p_T >$ 25 GeV, $m_{ll}>$ 20 GeV, $\Delta R_{ll}>0.3$

-Missing $E_T >$ 40 GeV

->=2 jets with $p_T >$ 30 GeV , $|\eta|<4.5$, $\Delta R_{lj} >0.3$



Further background reduction:

-additional leptons veto events ($p_T>$ 6 (μ)-7 (e) GeV) → reduce background with prompt leptons

-Z veto in ee final state → reduce Z+jets background from charge mis-ID

-veto events containing b-jets → reduce ttbar

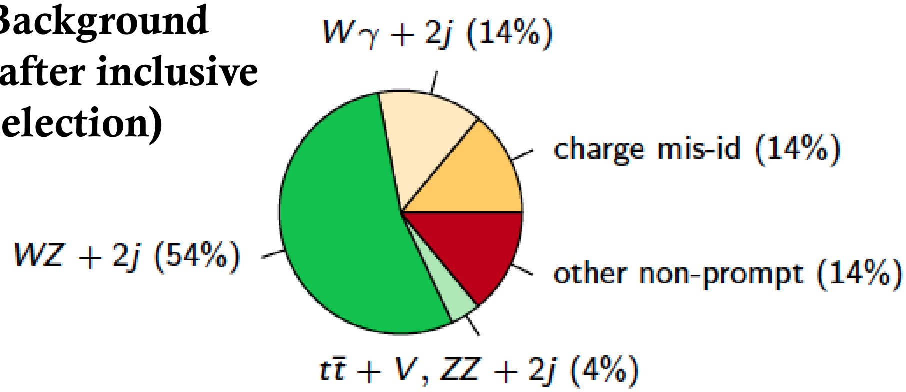
More info

Final selection:

-$m_{jj}>$ 500 GeV → further reduction of ttbar, WZ+jets ("inclusive region")

-$|\Delta y_{jj}|$ > 2.4 ("VBS region")

Background (after inclusive selection)



Prompt backgrounds:

WZ + 2jets and ZZ +2 jets (Sherpa), tZj (Sherpa)
ttbar +W/Z (Madgraph+Pythia8)

Conversions :

- prompt photon conversion:
  $W\gamma$ (Alpgen+Herwig/Jimmy and Sherpa for EW)
- charge mis-ID (data-driven): Z+jets,
  ttbar (di-leptonic) ,W^+W^-

Other non-prompt backgrounds (data-driven):
W+jets, ttbar (semi-leptonic), dijet

$W^{\pm}W^{\pm}jj$: sample composition

Inclusive Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
WZ/γ^*,ZZ,$t\bar{t}+W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5
Data	12	26	12	50

VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
WZ/γ^*,ZZ,$t\bar{t}+W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

$W^{\pm}W^{\pm}jj$: uncertainties

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background		Signal	
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^{\pm}W^{\pm}jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^{\pm}W^{\pm}jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

Background uncertainty around 20% dominated by Jet uncertainties (11-15%) and theory uncertainties (4-11%). Uncertainty of signal efficiency dominated by Jet uncertainties (6%)

$W^{\pm}W^{\pm}jj$: aQGC

Effective Lagrangian extended by additional operators of increasing dimension d, $\mathbf{L}^{(d)}_{i}$:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \beta_1 \mathcal{L}_0'^{(2)} + \sum_i \alpha_i^{(4)} \mathcal{L}_i^{(4)} + \frac{1}{\Lambda} \sum_i \alpha_i^{(5)} \mathcal{L}_i^{(5)} + \frac{1}{\Lambda^2} \sum_i \alpha_i^{(6)} \mathcal{L}_i^{(6)} + \ldots$$

α are the coupling parameters.

Form of $\mathbf{L_4}$ and $\mathbf{L_5}$ **:**

$$\alpha_4 \mathcal{L}_4 = \alpha_4 \left(\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}_\nu\right\}\right)^2 \quad \text{and} \quad \alpha_5 \mathcal{L}_5 = \alpha_5 \left(\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}^\mu\right\}\right)^2$$

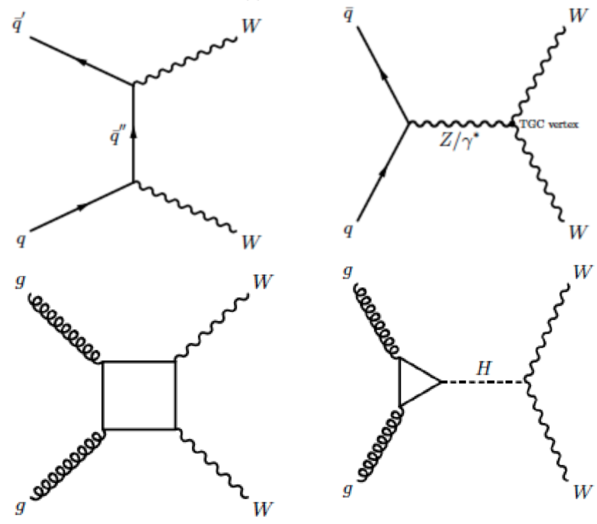
W⁺W⁻

Motivations:
- important test of EW theory and of QCD (sensitive to aTGC for WWγ and WWZ)
- irreducible background to H → WW

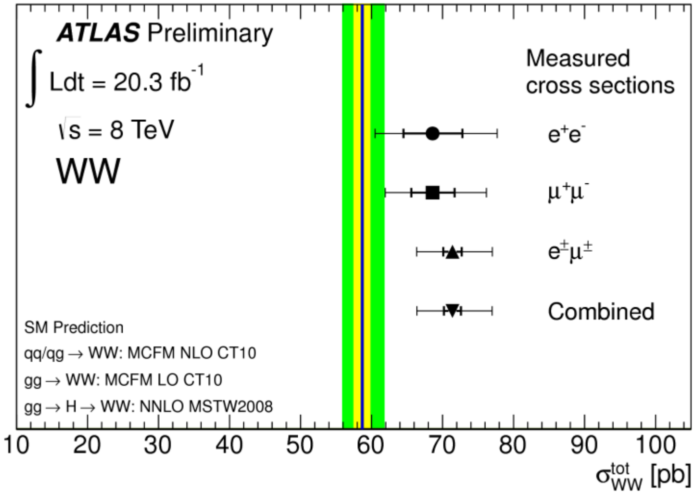
Selection
==2 isolated leptons with opposite sign and MET
- Veto events with jets

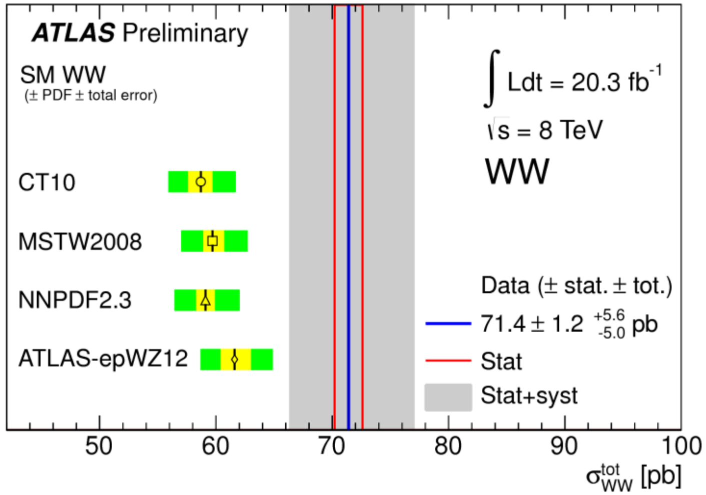
Backgrounds
Z, top and W+jets from data-driven Diboson from MC

Main processes



(WW production via VBS and double parton interactions neglected)





All measurements lie above the SM predictions