Electroweak production of Zjj and $W^{\pm}W^{\pm}jj$ states at the LHC

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arXiv:1405.6241

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On behalf of the ATLAS Collaboration

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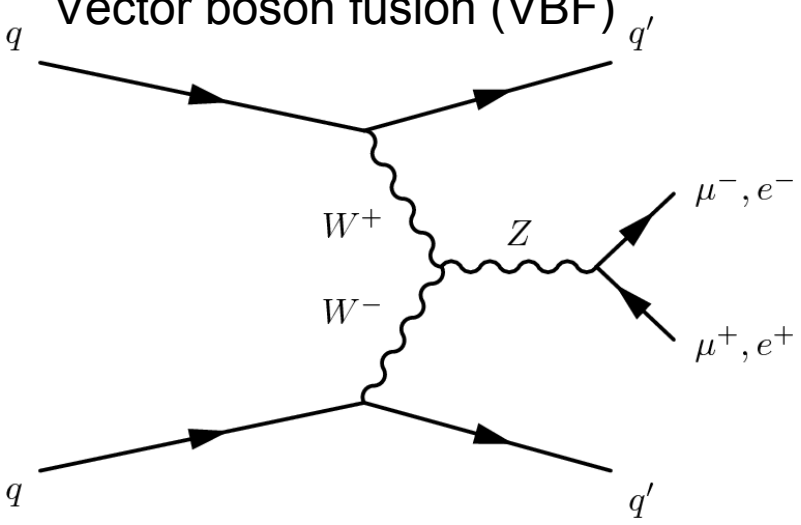
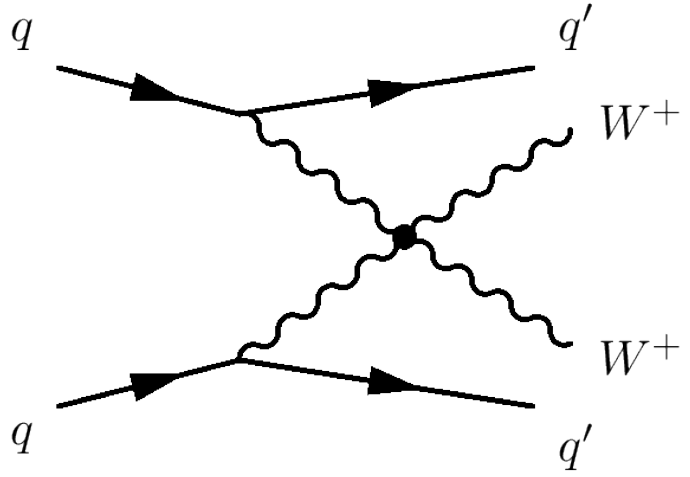
Motivation

Vector boson fusion (VBF)



$\sigma^{\text{fid.}}(Zjj - \text{Electroweak}) = 46.1 \pm 1.0$ fb

Vector boson scattering (VBS)

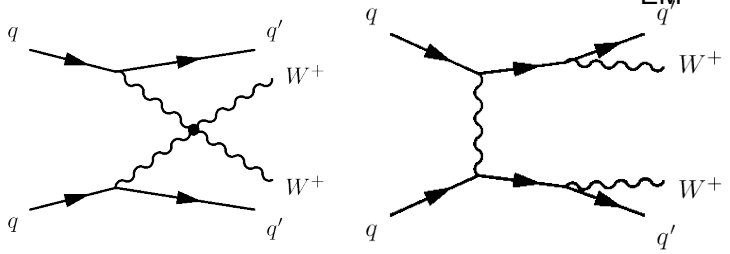


$\sigma^{\text{fid.}}(W^{\pm}W^{\pm}jj - \text{Electroweak}) = 0.95 \pm 0.06$ fb

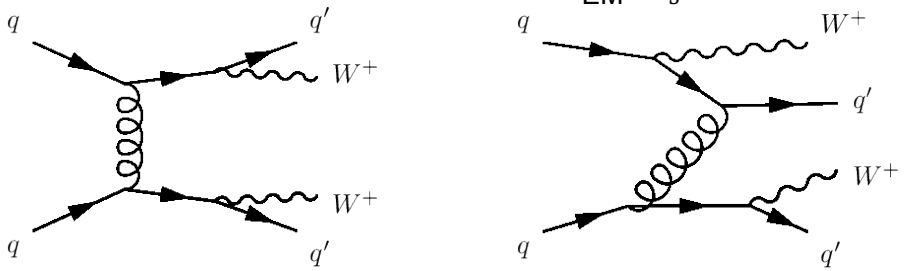
- **Rare Standard Model processes**
- **Insight on Electroweak symmetry breaking mechanism**
  - $W_L W_L \rightarrow W_L W_L$ violates unitarity without a SM Higgs
  - Zjj background for VBF Higgs measurements
- **Sensitive to triple/quartic gauge couplings**

Electroweak and Strong production

Electroweak production: $O(\alpha_{EM}^4)$ @ LO

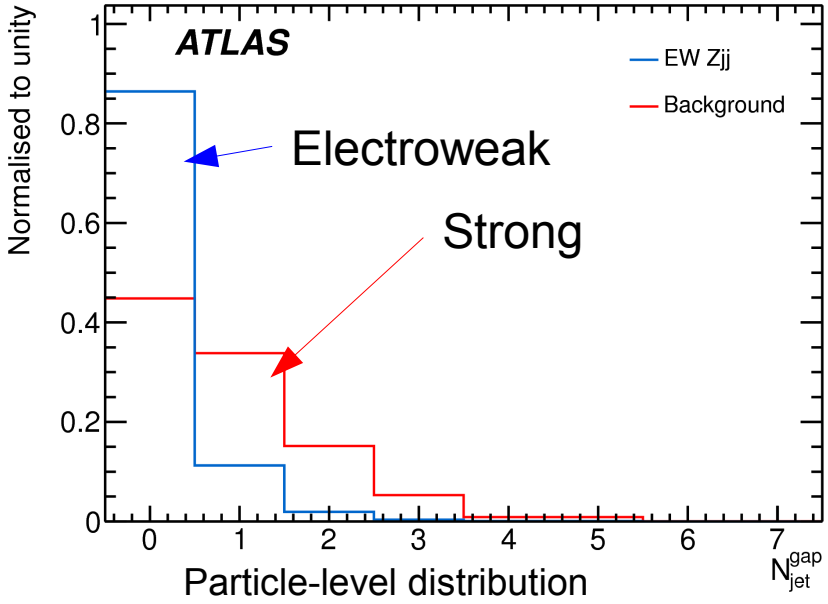


Strong production: $O(\alpha_{EM}^2\alpha_s^2)$ @ LO



Analogous classification for Zjj production

- **Study the whole EWK production (interference, gauge invariance)**
- **EWK production leads to**
  - Large invariant mass of *tagging* jets
  - Large rapidity difference (lack of "color-flow" b/w tagging jets)



Electroweak and Strong production

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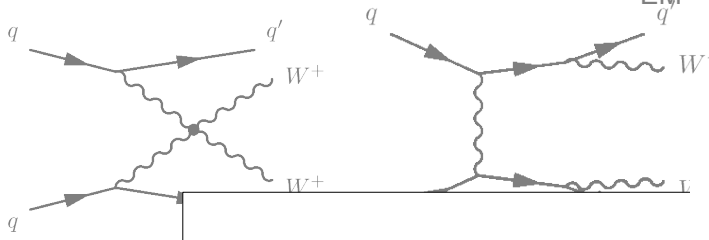
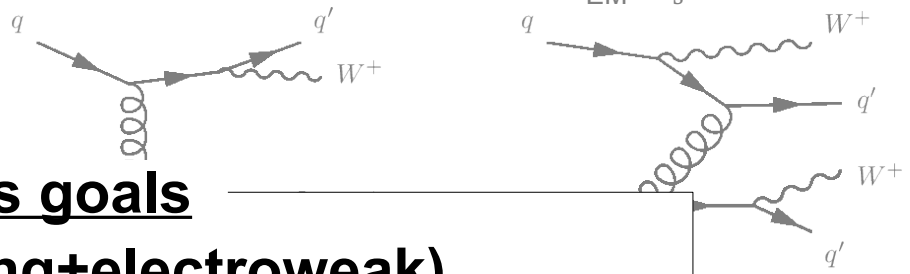


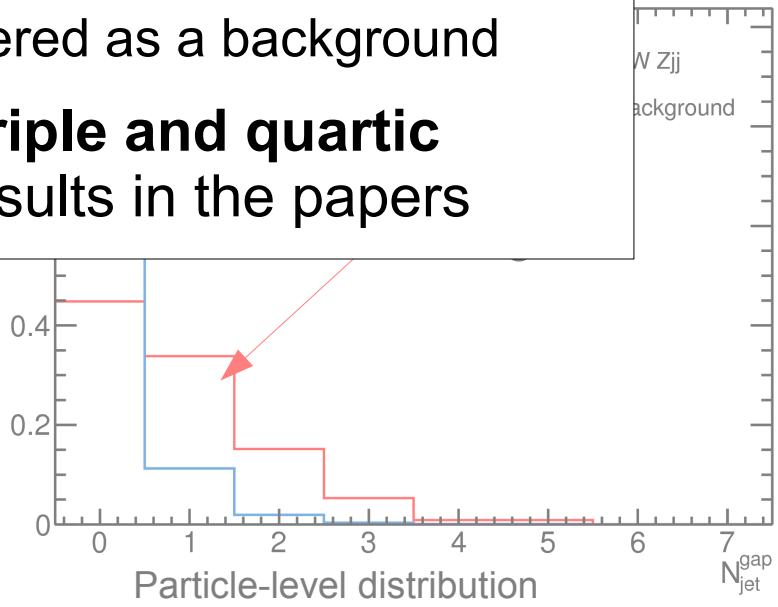
Strong production: $O(\alpha_{EM}^2\alpha_s^2)$ @ LO

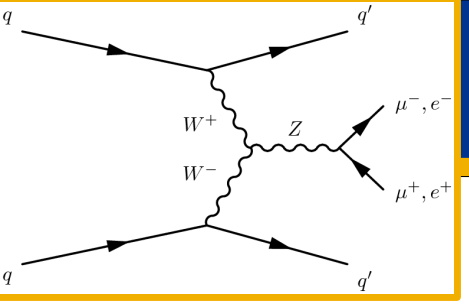


Analyses goals

- **Measure inclusive (strong+electroweak) production cross section (and kinematic)**
- **Extract electroweak component cross section**
  - strong production considered as a background
- **Set limits on anomalous triple and quartic gauge couplings** ← see results in the papers

- Stu… …nce)
- EW…
  - …
  - Large rapidity difference (lack of "color-flow" b/w tagging jets)





Zjj: data sample and selections

- **20.3/fb @ 8 TeV; μμjj, eejj final states**
- **single/di-lepton triggers**

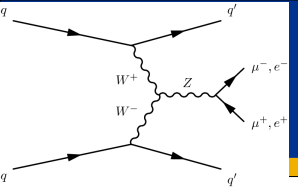
Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\|\eta^\ell\| < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \le m_{\ell\ell} \le 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		—
Jets	$\|y^j\| < 4.4$, $\Delta R_{j,\ell} \ge 0.3$				
	$p_T^{j1} > 55$ GeV				$p_T^{j1} > 85$ GeV
	$p_T^{j2}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

Z selection

jets selection

= probe high-p_T, high m(jj) = extract EWK component

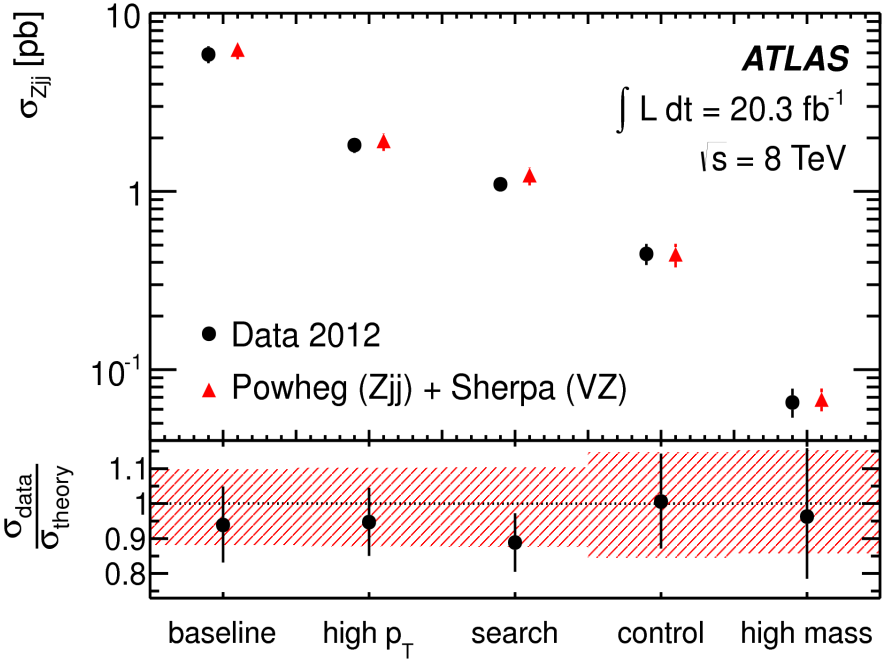
- **Strong Zjj production dominates (85-96%)**
- **Electroweak Zjj (1-12%), other processes (1-4%)**

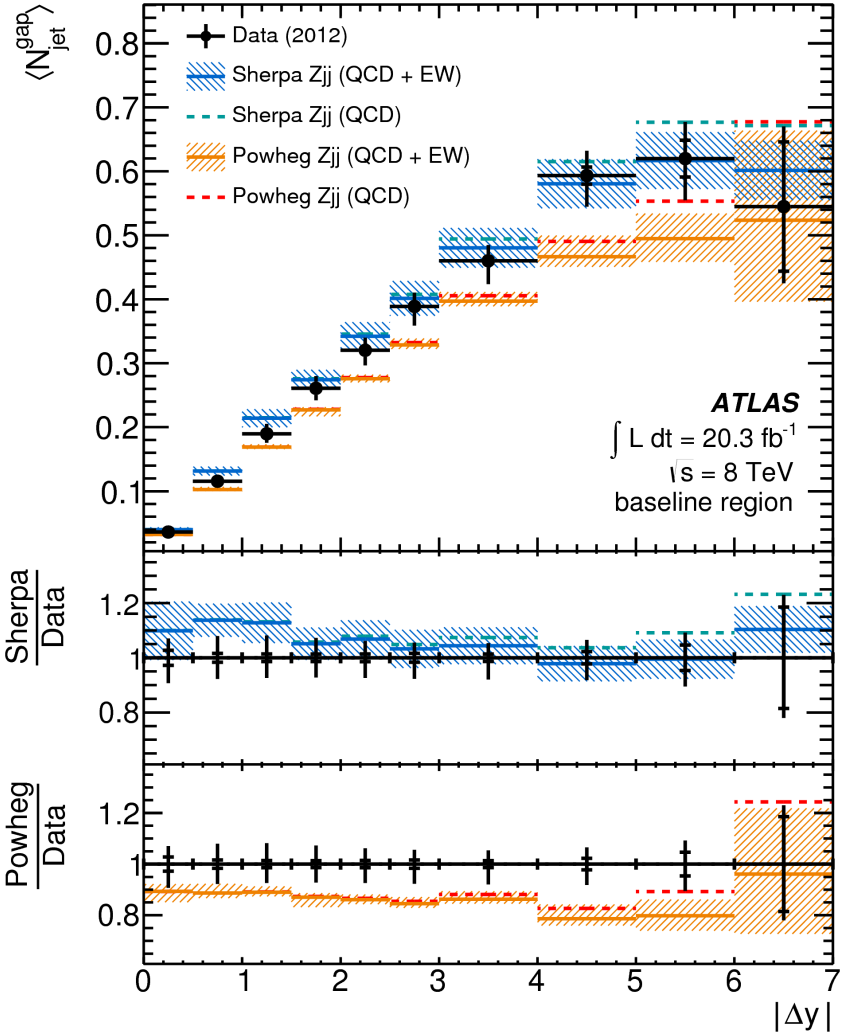


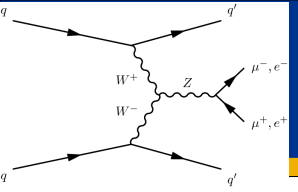
Fiducial cross section (strong+ewk)

- **Measure fiducial cross section**
- **Unfold sensitive kinematic distributions to particle-level**

$$\sigma^{\text{fid.}} = \frac{N(\text{ewk} + \text{strong})}{\int \mathcal{L} \cdot \mathcal{C}}$$







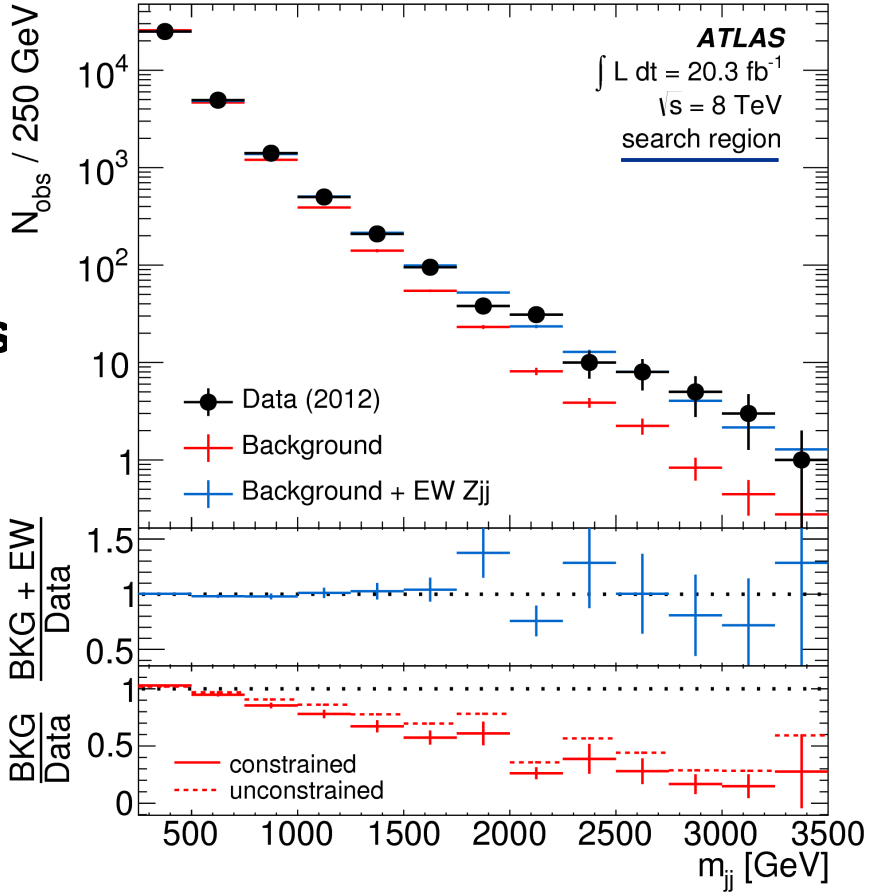
ewk Zjj extraction

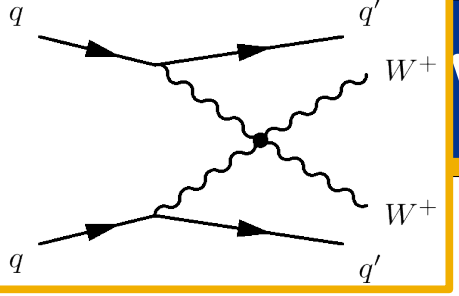
- **Constrain strong Zjj using events with >= 1 jet within tag jets**
- **Fit m(jj) in signal region**

$$\sigma^{\text{fid.}}_{\text{ewk}}(Zjj) = 54.7 \pm 4.6(\text{stat})^{+9.8}_{-10.4}(\text{syst}) \pm 1.5(\text{lumi})\ \text{fb}$$

→ **result in agreement with SM**

- **Background-only excluded at more than 5σ**
- **Leading systematic uncertainties**
  - Background modeling
    - Control region statistics
    - Theory uncertainties
  - Jet Energy Scale
  - Similar situation as for $W^{\pm}W^{\pm}jj$...

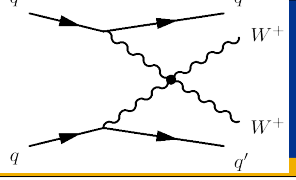




$W^{\pm}W^{\pm}jj$: data sample and selections

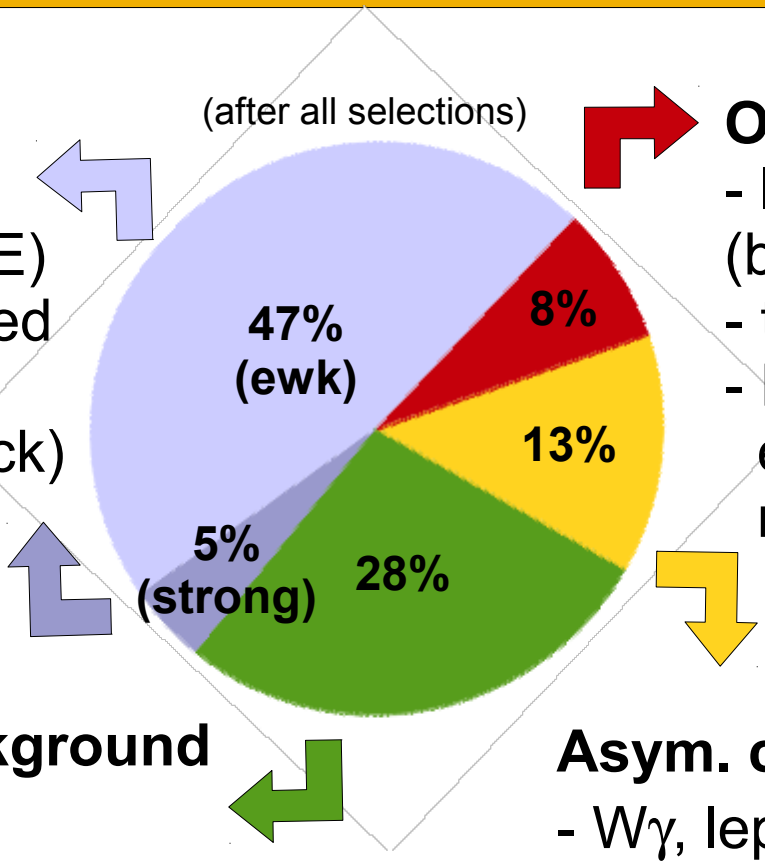
- **20.3/fb @ 8 TeV, single-lepton triggers**
- **$\mu^{\pm}\mu^{\pm}jj$, $e^{\pm}e^{\pm}jj$, $e^{\pm}\mu^{\pm}jj$ final states**
- **Leptons $p_T > 25$ GeV, $|\eta| < 2.5$, Jets $p_T > 30$ GeV, $|\eta| < 4.5$**
- **Veto events with any additional electron (muon) with $p_T > 7(6)$ GeV** ← Reduce WZ/ZZ
- **Missing Transverse Energy > 40 GeV** ← Reduce DY with charge mis-identification
- **$|\, m(ee) - m_Z \,| > 10$ GeV**
- **Veto events containing b-jets** ← Reduce $t\bar{t} \rightarrow l\nu jj\ bb$ (lepton from b-decays)

- **m(jj) > 500 GeV → Measure strong+EWK**
- **$|\Delta y(jj)| > 2.4$ → Extract EWK component**



Sample composition

(after all selections)

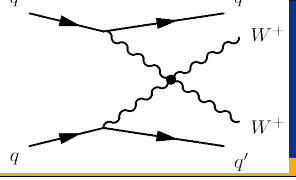


$W^{\pm}W^{\pm}jj$ ewk+strong
- Sherpa (3jets @ ME) prediction normalized with Powheg (VBFNLO as x-check)

Other non-prompt
- leptons from (b-)hadron decays
- top, W+jets, multi-jets
- Data-driven using events with one non-isolated lepton

Prompt lepton background
- mainly WZ/γ^*, ZZ
- 75% strong WZ/γ^*, 15% ewk WZ/γ^*
- Sherpa (3 jets @ ME) normalized with VBFNLO calculation when available (WZ/γ^*)

Asym. conversions ($\gamma \rightarrow ee$)
- Wγ, lepton bremsstrahlung (mostly Drell-Yan, top)
- affects mostly ee channel
- Data-driven from opposite sign leptons (DY, top)
- Simulation (Wγ)



Background control regions

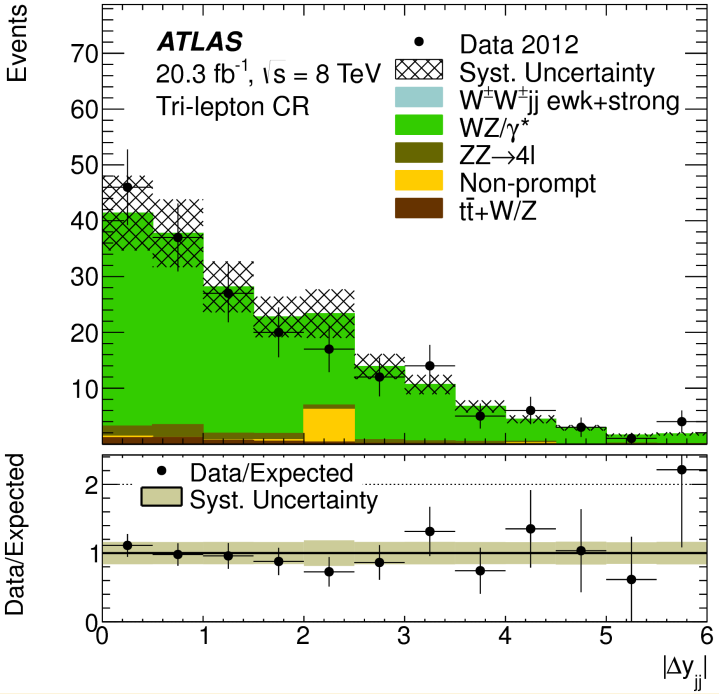
Prompt

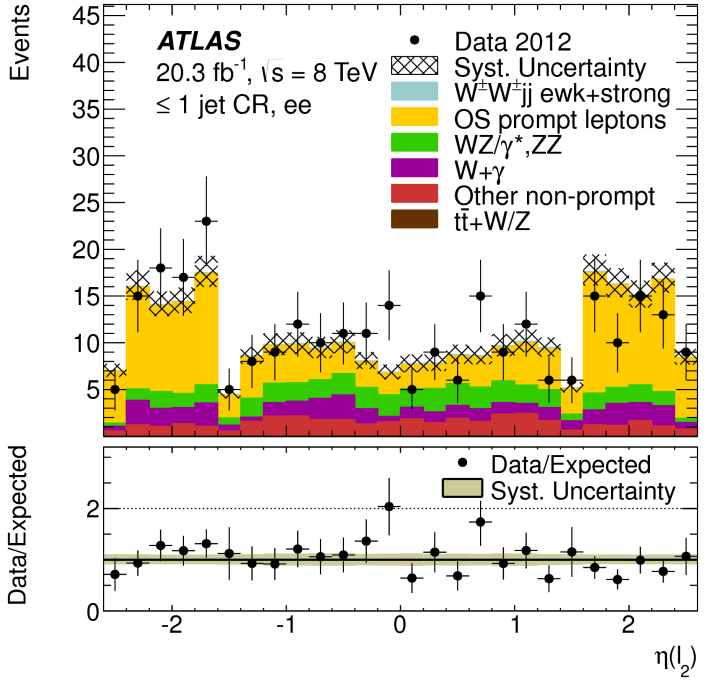
Conversions (ee), prompt (μμ)

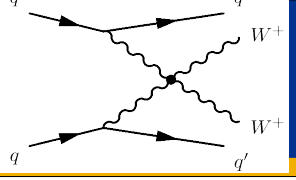
other non-prompt (b-decays)

Mix

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





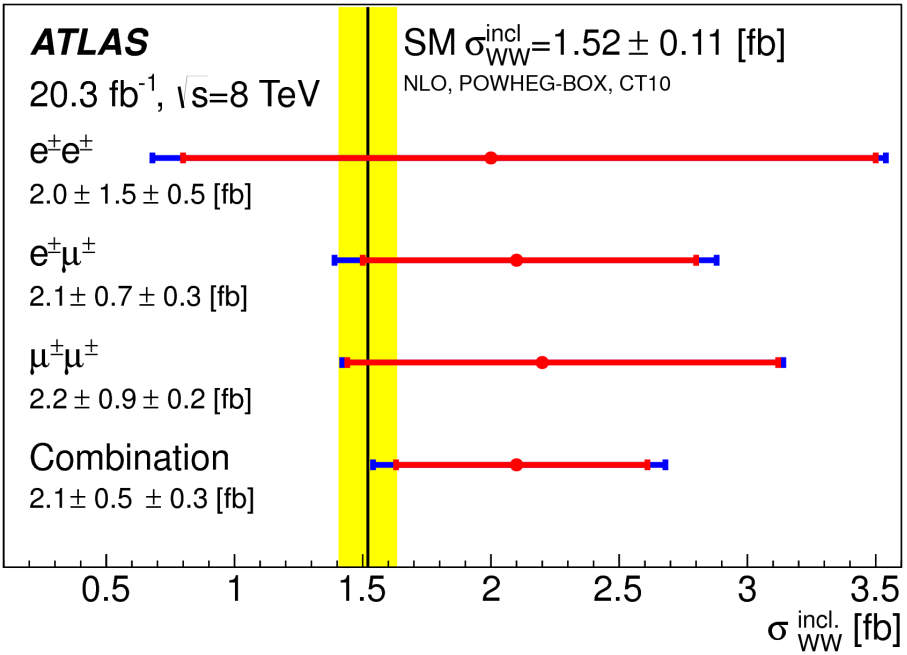


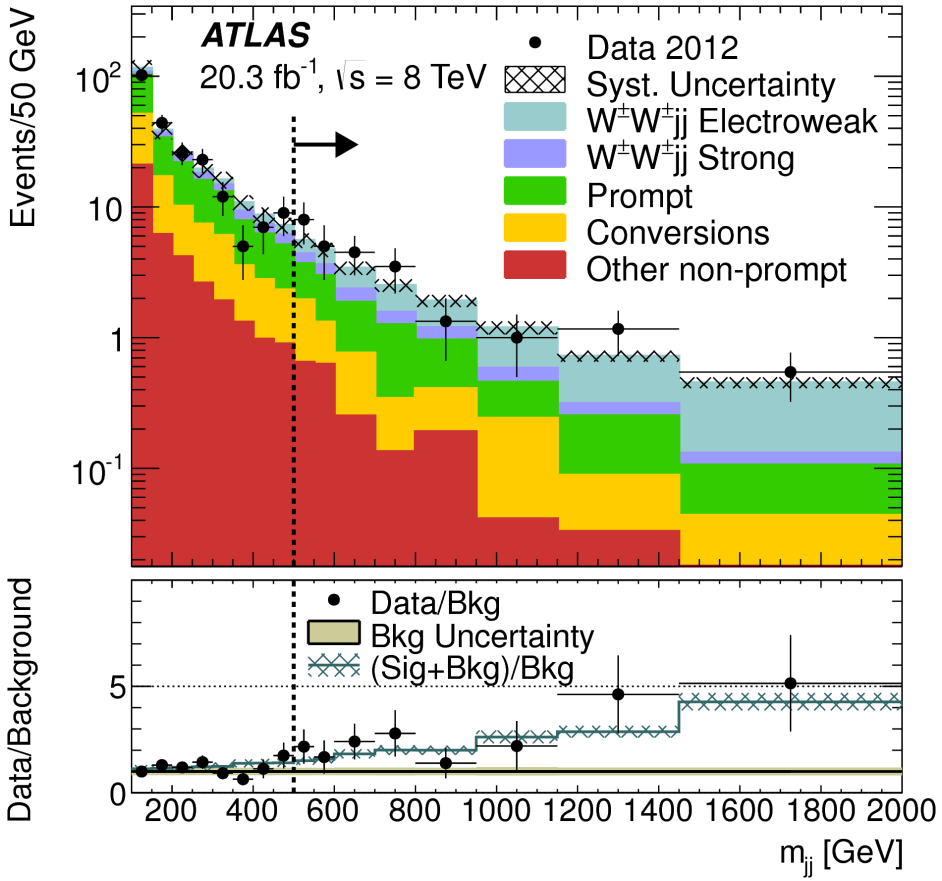
Fiducial cross section (strong+ewk)

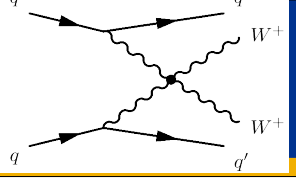
- **Background-only hypothesis excluded at 4.5σ**
- **Measure fiducial cross section in fiducial phase space close to experimental acceptance selections**

$$\sigma^{\text{fid.}} = \frac{N^{\text{obs.}} - N^{\text{bkg.}}}{\int \mathcal{L} \cdot \mathcal{C}}$$

$\mathcal{C}$ → 56–83%





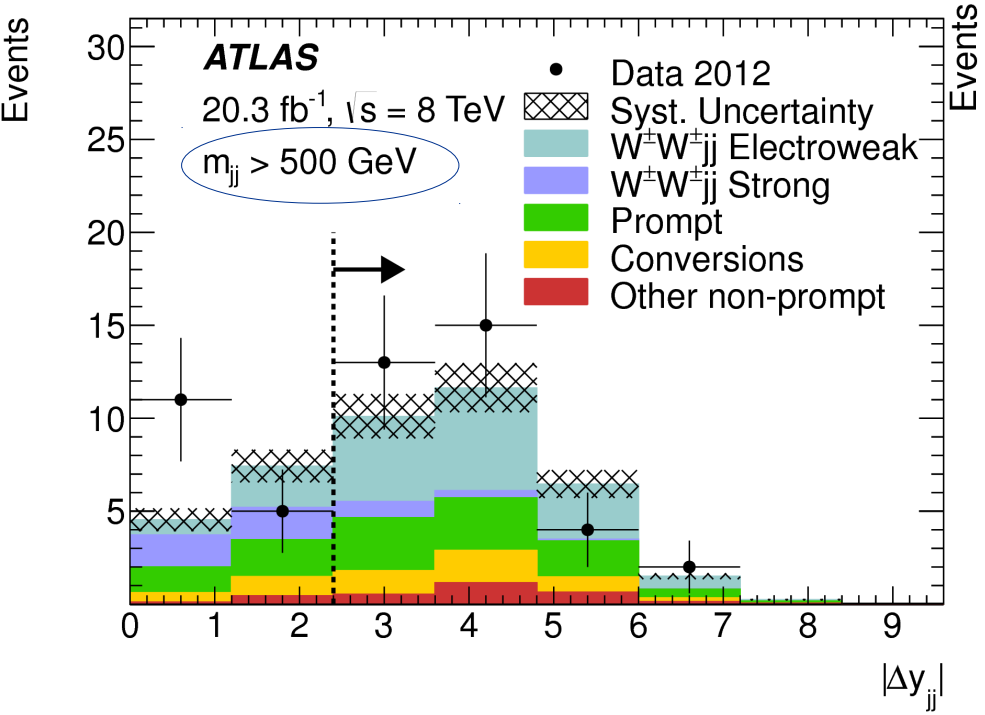


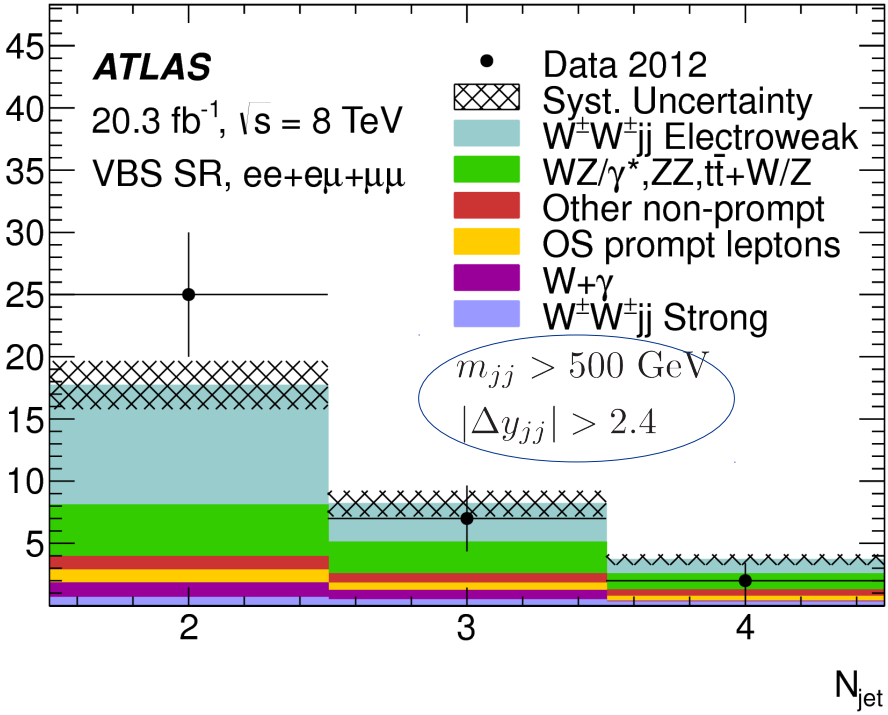
ewk $W^{\pm}W^{\pm}jj$ extraction

- **Background-only hypothesis excluded at 3.6σ**
  → first evidence of electroweak $W^{\pm}W^{\pm}jj$ production

$$\sigma^{\text{fid, VBS Region}}_{W^{\pm}W^{\pm}jj\ \text{Electroweak}} = 1.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst.})\ \text{fb}$$
$$0.95 \pm 0.06\ \text{fb}\quad (\text{expected})$$

- **Statistical error dominates**





Conclusions

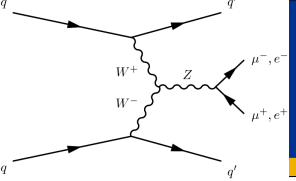
- **Observation of electroweak Zjj production**
- **Evidence of electroweak $W^{\pm}W^{\pm}jj$ production**

- **Measured fiducial cross sections in agreement with SM**
- **Milestones towards a full VBS program at the LHC**

- **WWjj statistically limited**
  - In Run-2 expect increase in cross section by a factor of ~ 4

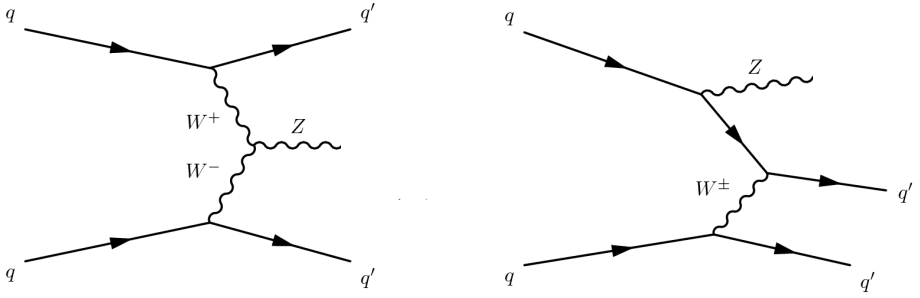
Looking forward to fully explore the physics behind VBS in the next years of operations of the LHC !!

BACKUP

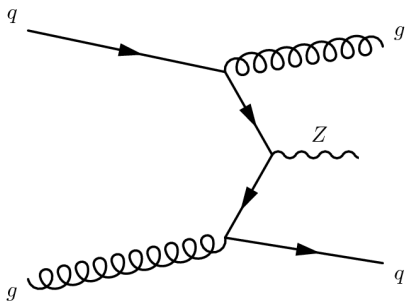


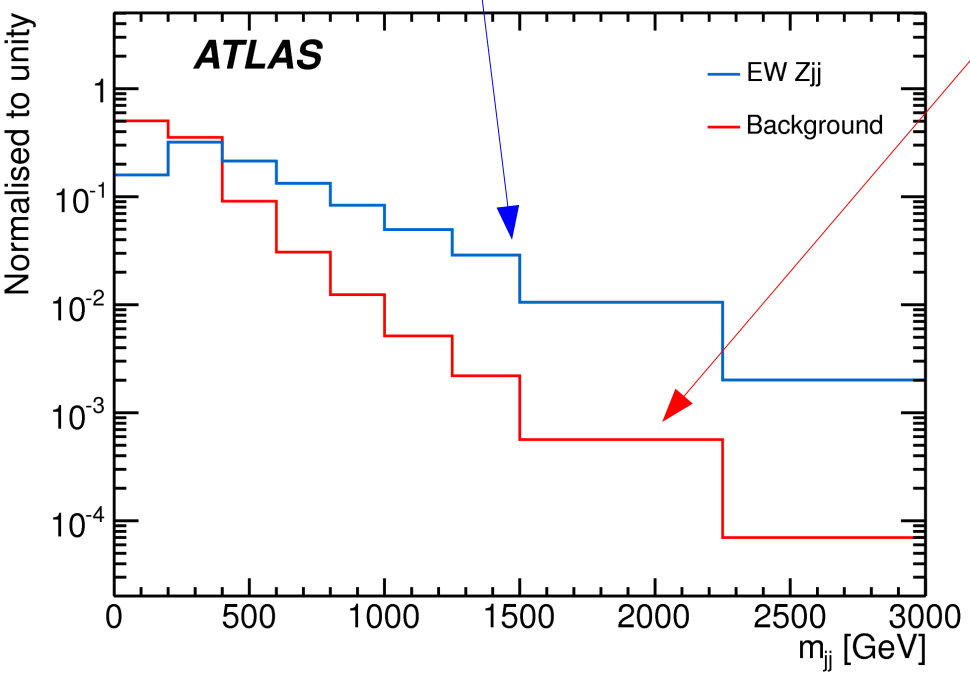
VBS/VBF @ LHC

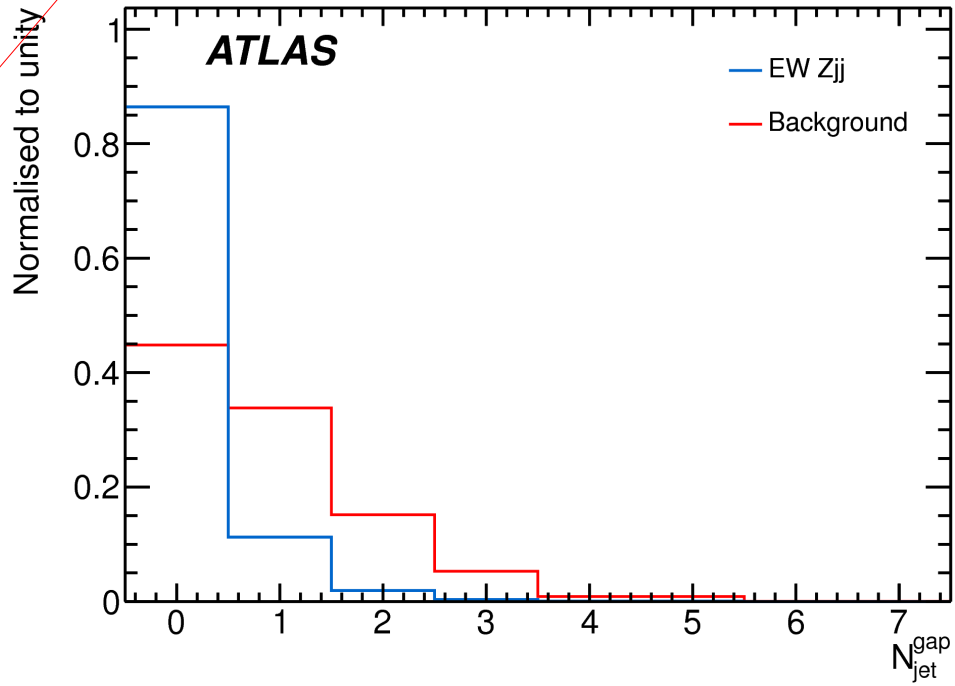
Electroweak production: $O(\alpha_{EM}^3)$ @ LO



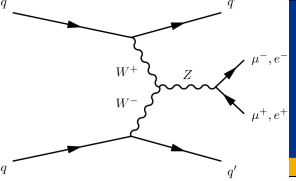
Strong production: $O(\alpha_{EM}\alpha_s^2)$ @ LO



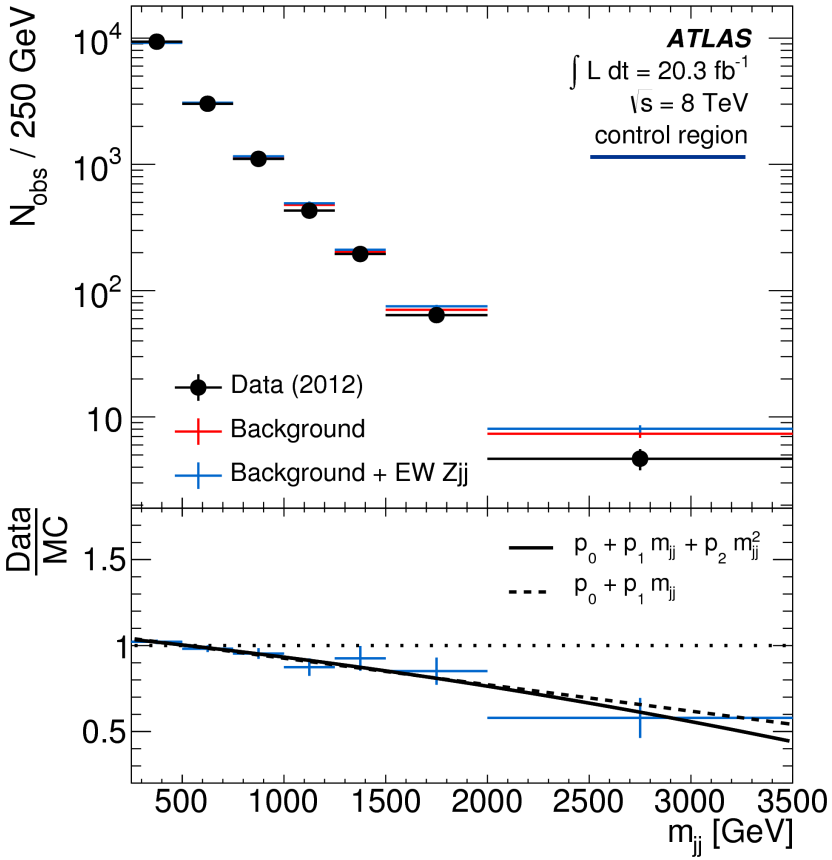


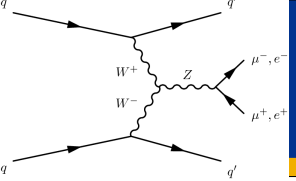


Particle-level distributions

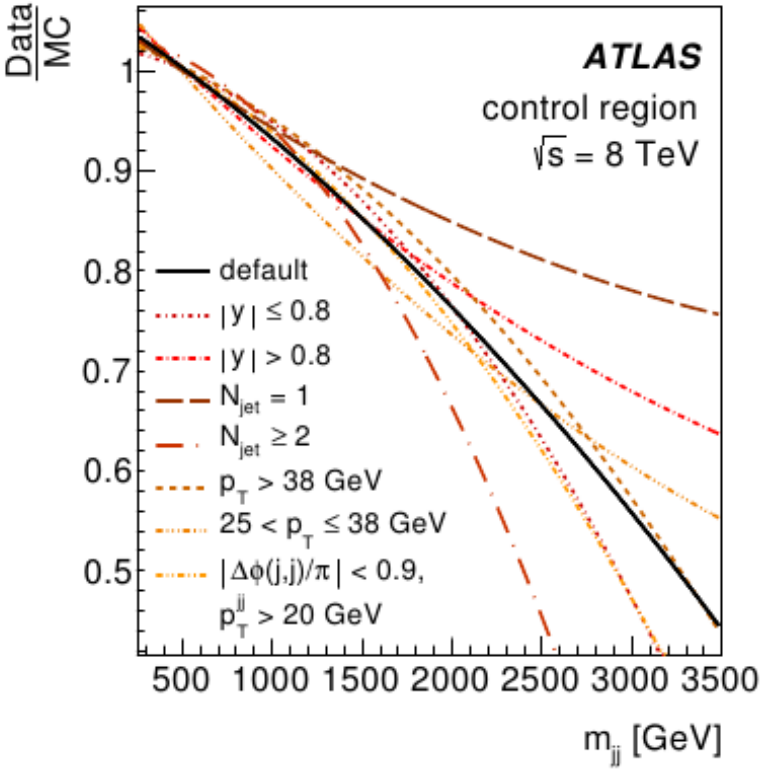


Strong Zjj control region

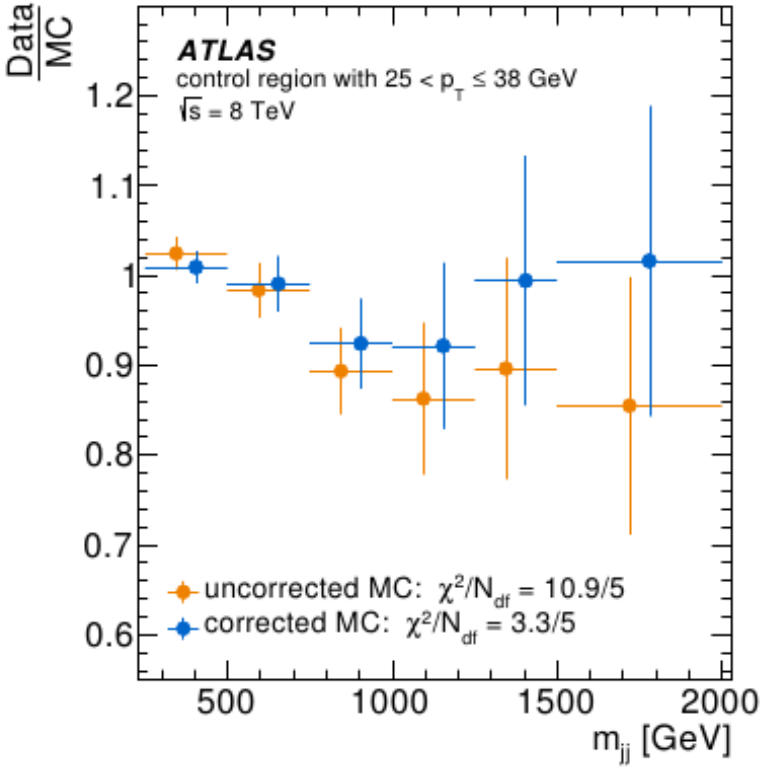




Strong Zjj control region

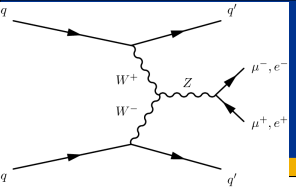


(a)

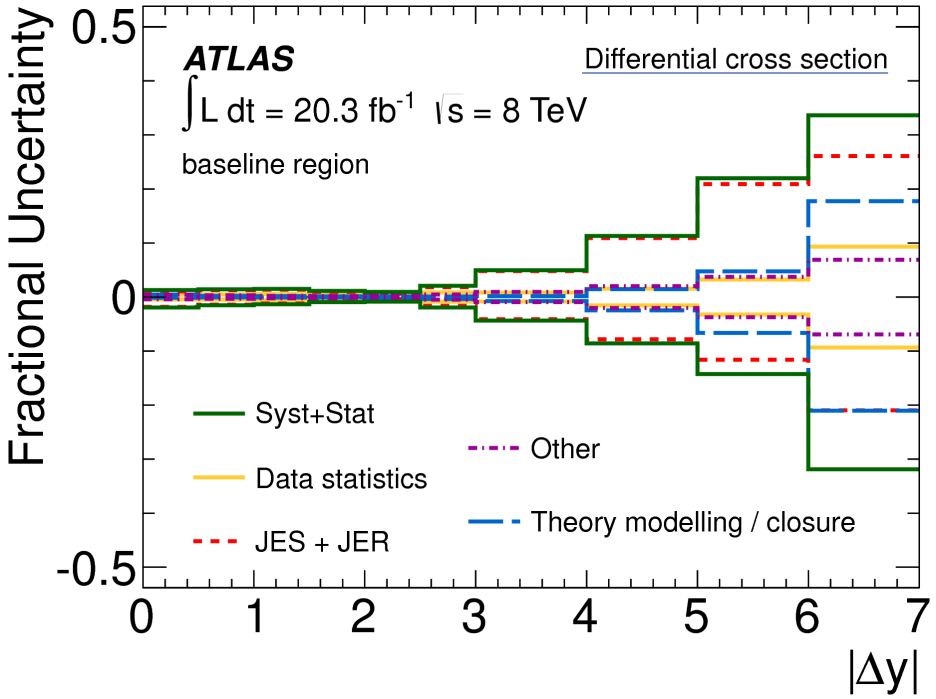


(b)

Figure 12. (a) Background reweighting functions obtained for different choices of *control* region. (b) The agreement between data and simulation in the $25 < p_{\mathrm{T}} \leq 38\,\mathrm{GeV}$ subregion both before and after applying a background reweighting function derived in the $p_{\mathrm{T}} > 38\,\mathrm{GeV}$ subregion.



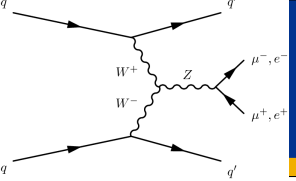
Systematic uncertainties



ewk cross section measurement

Source	ΔN_{EW}		ΔC_{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 %	

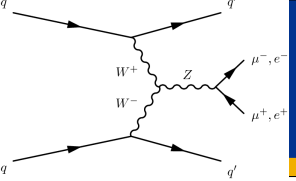
- **At large Δy(jj) largest uncertainty from Jet Energy Scale**
- **Theory uncertainty and background modeling important!**
- **Similar situation stands for $W^{\pm}W^{\pm}jj$ ...**



Electroweak Zjj fit results

	Electron	Muon	Electron+muon
Data	14248	17938	32186
MC predicted N_{bkg}	$13700 \pm 1200\,^{+1400}_{-1700}$	$18600 \pm 1500\,^{+1900}_{-2300}$	$32600 \pm 2600\,^{+3400}_{-4000}$
MC predicted N_{EW}	$602 \pm 27 \pm 18$	$731 \pm 29 \pm 22$	$1333 \pm 50 \pm 40$
Fitted N_{bkg}	$13351 \pm 144 \pm 29$	$17201 \pm 161 \pm 31$	$30530 \pm 216 \pm 40$
Fitted N_{EW}	$897 \pm 92 \pm 27$	$737 \pm 98 \pm 28$	$1657 \pm 134 \pm 40$

Table 5. The number of strong (N_{bkg}) and electroweak (N_{EW}) Zjj events as predicted by the MC simulation and obtained from a fit to the data. The number of events in data is also given. The first and second uncertainties on the fitted yields are due to statistical uncertainties in data and simulation, respectively. The first and second uncertainties in the MC prediction are the experimental and theoretical systematic uncertainties, respectively.

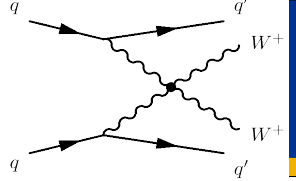


Anomalous gauge couplings limits

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

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	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

Table 7. The 95% confidence intervals obtained on the aTGC parameters from counting the number of events with $m_{jj} > 1$ TeV in the *search* region. Observed and expected intervals, labelled 'obs' and 'exp' respectively, are presented for unitarisation scales of $\Lambda = 6$ TeV and $\Lambda = \infty$. The parameter $\Delta g_{1,Z}$ refers to the deviation of $g_{1,Z}$ from the SM value.

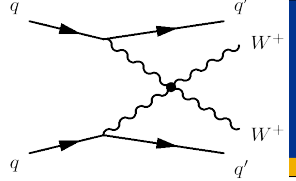


Signal expectation

- **NLO (in QCD) calculation available for electro-weak and strong $W^{\pm}W^{\pm}jj$ production**
  - VBFNLO and PowhegBox → interfaced with Pythia8 for parton shower, hadronization and underlying event
- **Constructive Interference of 7-12% (Sherpa, LO study)**
- **Main systematic from scale/PDF variations and parton shower uncertainties**

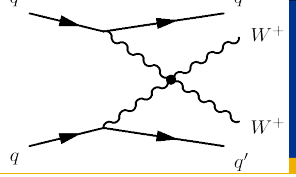
Expected cross section after selections that closely mimic experimental event selections:

fiducial x-section [fb]	Inclusive region	VBS region
Electroweak $W^{\pm}W^{\pm}jj$	1.00 ± 0.06	0.88 ± 0.05
Strong $W^{\pm}W^{\pm}jj$	0.35 ± 0.05	0.098 ± 0.018
Interference	0.16 ± 0.08	0.07 ± 0.04
Total Signal	**1.52 ± 0.11 fb**	**0.95 ± 0.06 fb**

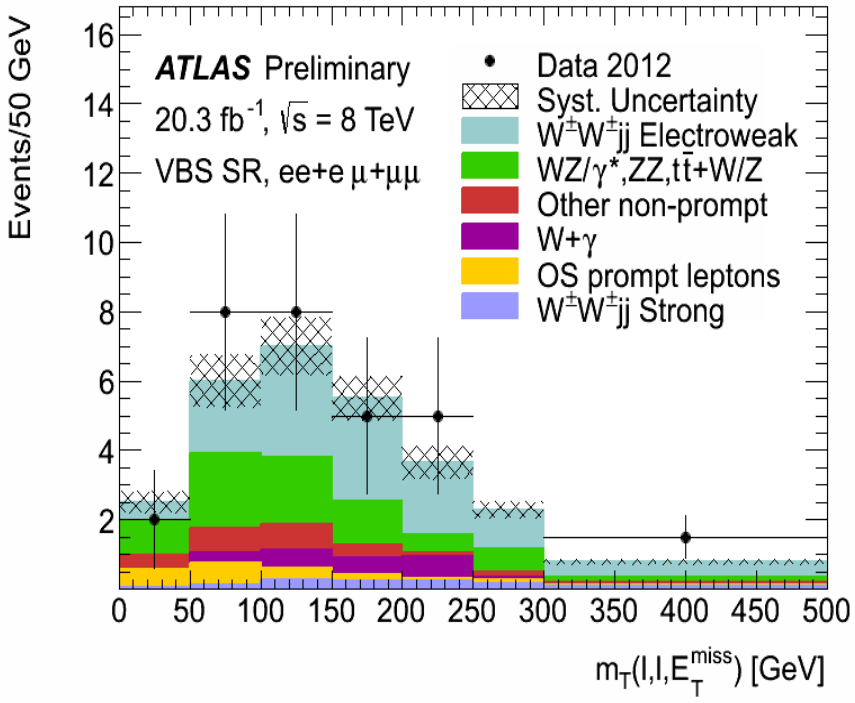


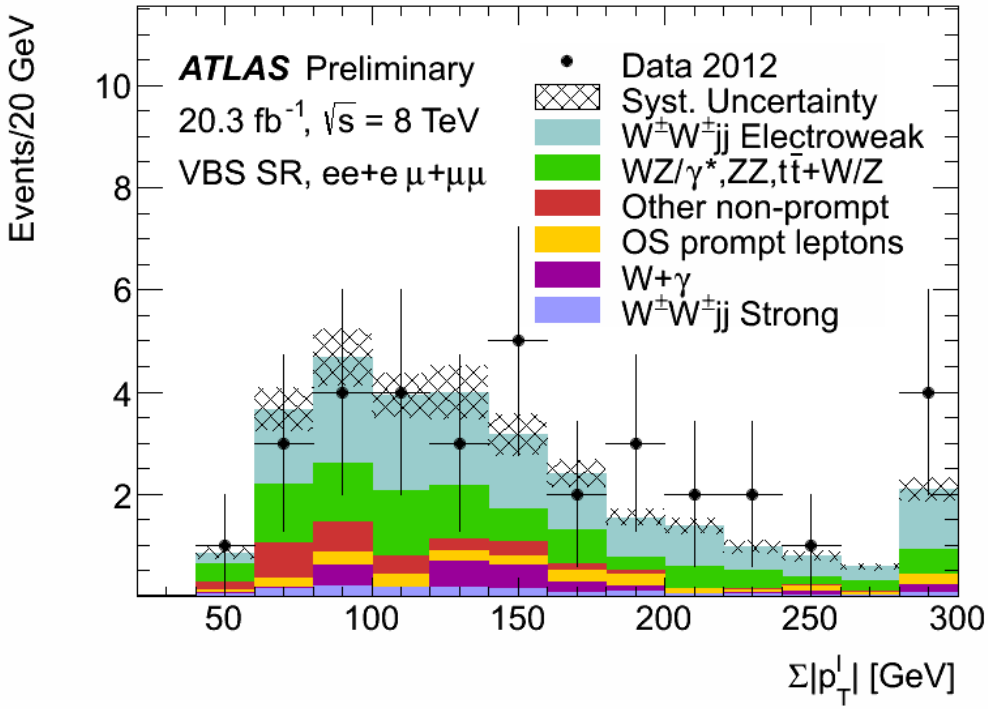
Signal region yields

	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	**0.89 ± 0.15**	**2.5 ± 0.4**	**1.42 ± 0.23**	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	**3.07 ± 0.30**	**9.0 ± 0.8**	**4.9 ± 0.5**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total signal	**4.0 ± 0.4**	**11.4 ± 1.2**	**6.3 ± 0.7**	**2.55 ± 0.25**	**7.3 ± 0.6**	**4.0 ± 0.4**
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

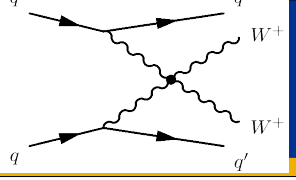


Signal kinematics

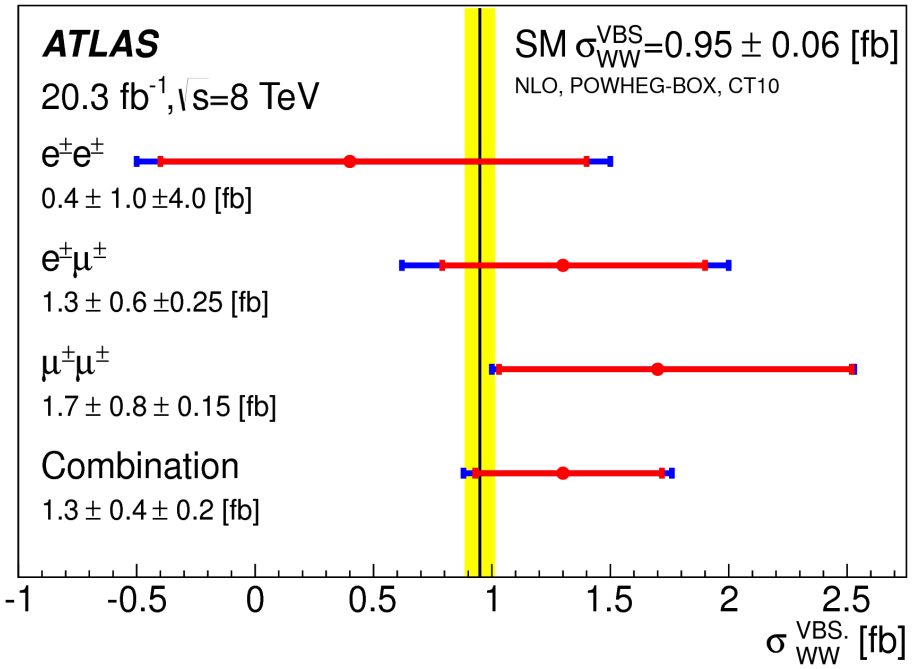


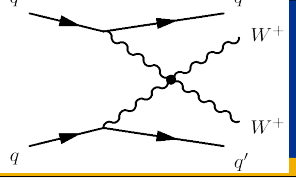


- **Kinematics sensitive to electroweak component**
- **Candidate distributions for differential cross section measurements with more data**



Electroweak fiducial cross section



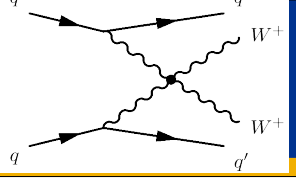


Cross section likelihood

$$L(\sigma_{W^\pm W^\pm jj}, \alpha_j) = \prod_{i \in \{ee,\mu\mu,e\mu\}} \mathrm{Pois}(N_i^{\mathrm{obs}} | N_{i,\mathrm{tot}}^{\mathrm{exp}}) \prod_{j \in \mathrm{syst}} \mathrm{Gaus}(\alpha_j^0 | \alpha_j, 1)$$

$$N_{i,\mathrm{tot}}^{\mathrm{exp}}(\sigma_{W^\pm W^\pm jj} \alpha_j) = \mathcal{L} \cdot \sigma_{W^\pm W^\pm jj} \cdot A_i \cdot \varepsilon_i(\alpha_j) + \sum_b N_{i,b}(\alpha_j)$$

- **α_j → nuisance parameters for systematic uncertainties**
- **A_i → relative acceptance for channel i (~ 1:2:1 for ee,eμ,μμ)**
- **ε_i → efficiency for channel i**
  - 56%, 72%, 77% for ee, eμ, μμ in Inclusive region
  - 57%, 73%, 83% for ee, eμ, μμ in VBS region



Fiducial region definition

Fiducial region: summary of selections

Two same-charge leptons (e,μ; veto τ decays), $p_T > 25$ GeV, $|\eta| < 2.5$

- includes photons in a cone of radius $\Delta R=0.1$ around the leptons

At least two jets $p_T > 30$ GeV, $|\eta| < 4.5$

- anti-k_T, R=0.4

$\Delta R(ll) = (\Delta\phi(ll)^2 + \Delta\eta(ll)^2)^{1/2} > 0.3$

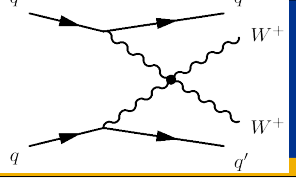
DR(l, jet) > 0.3

m(ll) > 20 GeV

Missing Transverse Energy > 40 GeV

m(jj) > 500 GeV → Inclusive fiducial region

$|\Delta y(jj)| > 2.4$ → VBS fiducial region



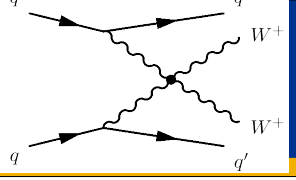
anomalous Quartic Gauge Couplings

- **Using electroweak $W^{\pm}W^{\pm}jj$ fiducial cross section in VBS phase space to constrain aQGC**
- **Effective field theory approach**

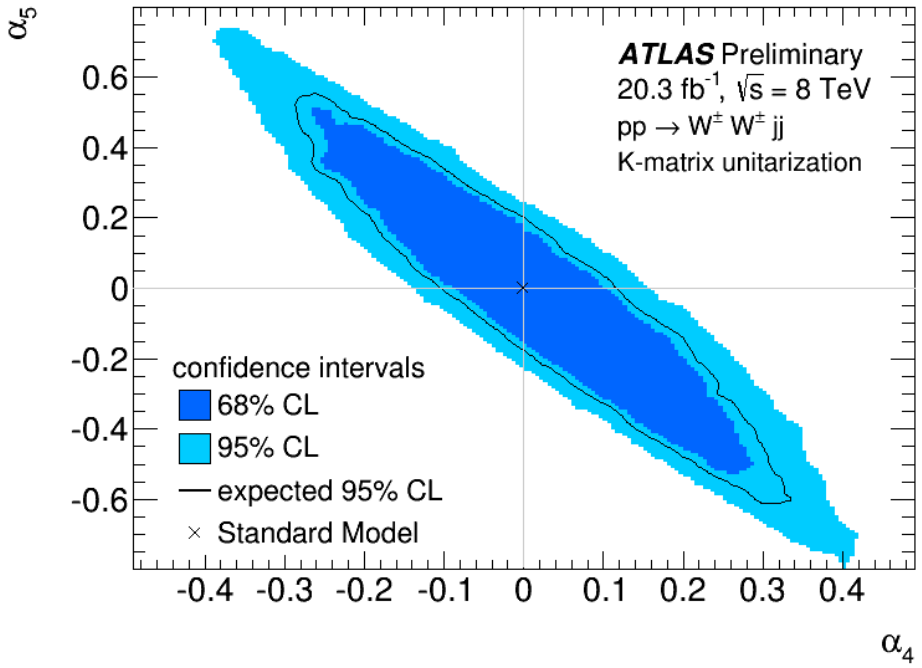
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{\text{dimension d}} \sum_{i} \frac{c_i^{(\mathrm{d})}}{\Lambda^{\mathrm{d}-4}} \mathcal{O}_i^{(\mathrm{d})}$$

  - Valid below energy scale Λ
- **Some d=8 operators can be mapped to d=4, d=6 ones**

d=4	d=6	d=8
WWWW, WWZZ	WWZγ,WWγγ	all VVVV
Chiral Lagrangian ("non-linear")	"non-linear" formalism	"linear" formalism
α_4, α_5	a_0 / Λ^2, a_C / Λ^2	$f_{S,i} / \Lambda^4$, $f_{M,i} / \Lambda^4$, $f_{T,i} / \Lambda^4$
Appelquist et al. (1980)	Belanger et al. (1992)	Eboli et al. (2006)



aQGC results



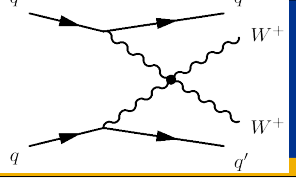
1-D observed 95% C.L. limits:

$-0.14 < \alpha_4 < 0.16$ (α_5=0)

$-0.23 < \alpha_5 < 0.24$ (α_4=0)

- **Simplified-model interpretation** (arXiv:1307.8170) **relates to energy scale of hypothetical contributing resonance:**

$$\Lambda = \frac{v}{\sqrt{\alpha_i}} \approx 500 - 650 \text{ GeV}$$



Process	σ^{fid} @ 8 TeV	σ^{fid} @ 14 TeV	Ratio 14 TeV / 8 TeV
electroweak $W^{\pm}W^{\pm}$jj	1.83 fb	7.3 fb	4
strong $W^{\pm}W^{\pm}$jj	0.74 fb	2.75 fb	4
strong $W^{\pm}Z$jj	3.11 fb	15.7 fb	5

Madgraph, LO; 2 same-charge lep p_T > 15 GeV, |η|<5; at least two jets p_T > 30 GeV, |η|<5; m(jj) > 500 GeV