First Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ at ATLAS

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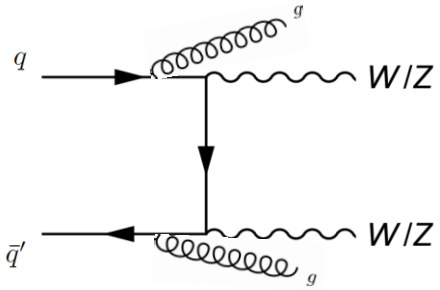
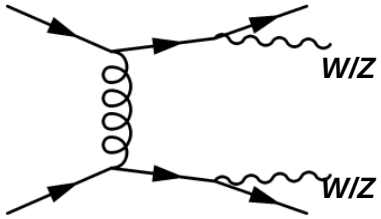
Introduction

- Two categories for production of vector boson pair + dijet (VVjj) at LHC:
  - Strong production : $\mathcal{O}(\alpha_s) = 2$





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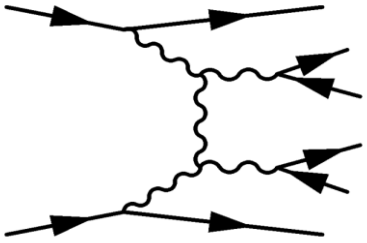
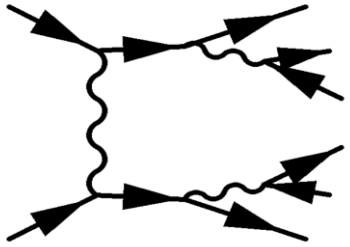
  - Electroweak (EWK) production : $\mathcal{O}(\alpha_s) = 0$





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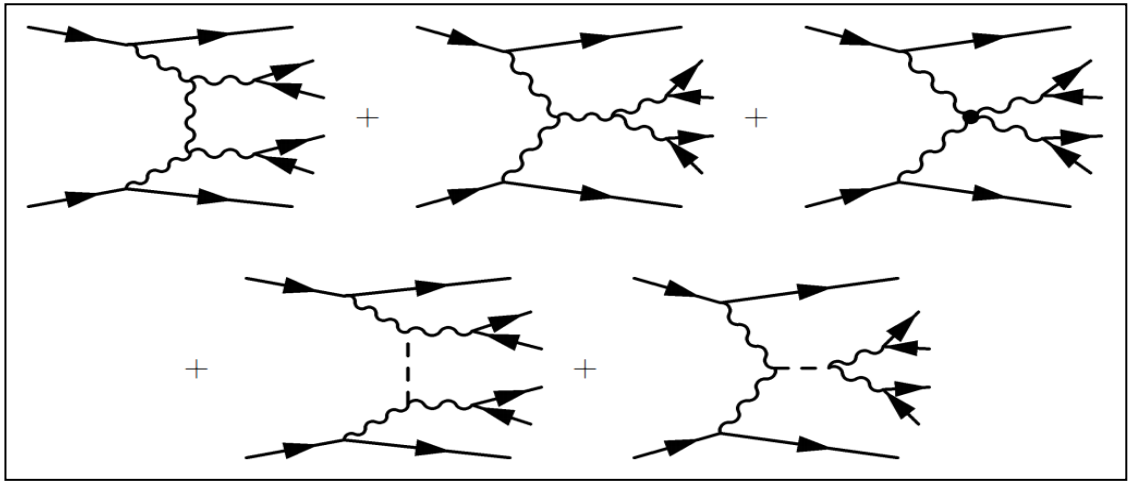
Purely electroweak interactions at born level

Why study EWK VVjj production

Vector Boson Scattering (VBS)

Never observed yet!

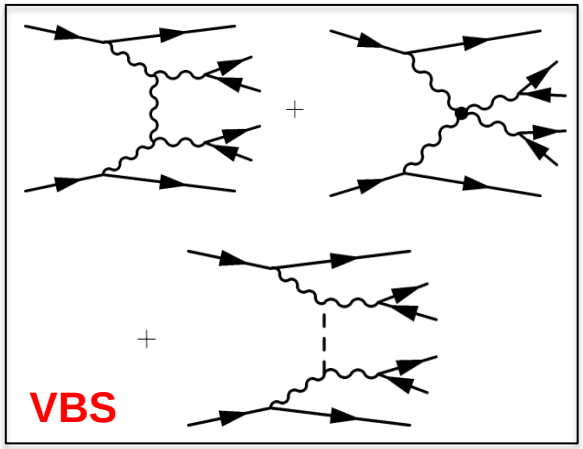


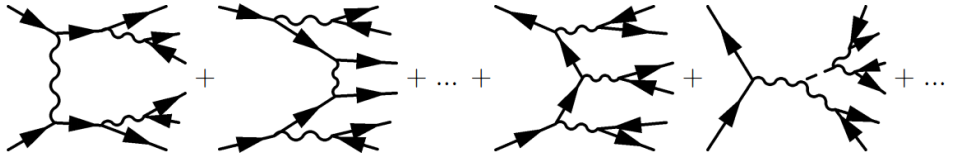
- **Crucial to studies of the electroweak symmetry breaking mechanism regardless of the Higgs discovery**
  - Verify the unitarity in $V_L V_L$ scattering
  - Search for alternative EWSB mechanisms
    - new VV resonances, strong VV interactions …
- Ideal laboratory for measuring HVV couplings
- Sensitive to anomalous quartic gauge couplings (aQGC)

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

- Processes involved

Electroweak production

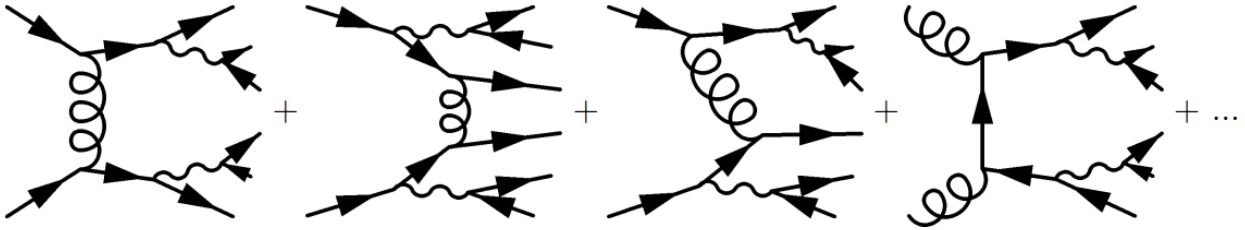




Gauge-invariantly inseparable with VBS

Triple-boson production gauge-invariantly separable

Strong production



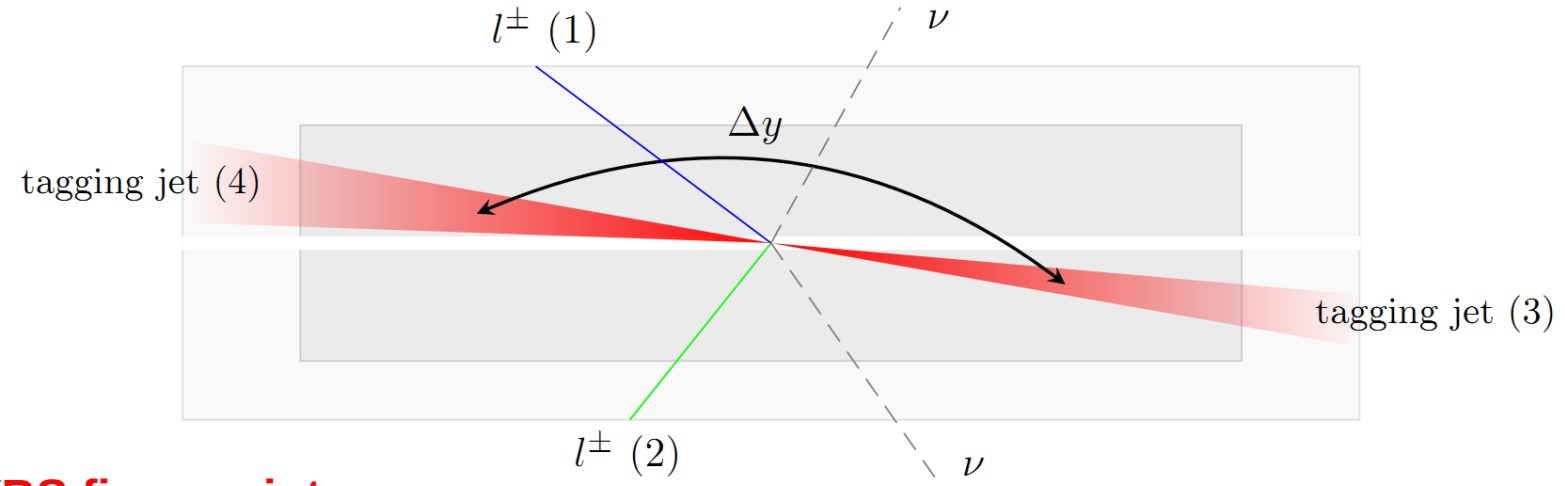
Why same-sign WW ?

- Good final state for studying VBS due to low cross section for strong production
  - High signal-to-background ratio with reasonable signal cross section
  - Very promising channel to first observe VBS at LHC !

Cross sections at 8 TeV

Final state	Process	$VVjj$-EW	$VVjj$-QCD
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb

$W^{\pm}W^{\pm}$ VBS topology and selection



VBS fingerprint

- Two high energy forward jets in opposite hemispheres with large invariant mass → two powerful VBS discriminating variables: **m_{jj}** and **dY_{jj}**
- Less hadronic activity in between the two forward jets

$W^{\pm}W^{\pm}$ signature

- Two isolated same-sign high p_T central leptons
- Large missing transverse energy (MET)

Event selection at 8 TeV

- $p_T(l) > 25$ GeV (l=e/μ), $N_l == 2$, $q_{l1} \times q_{l2} > 0$
- $p_T(jet) > 30$ GeV, b-jet veto, $N_{jet} >= 2$
- $|m_{ee} - m_Z| > 10$ GeV, MET > 40 GeV

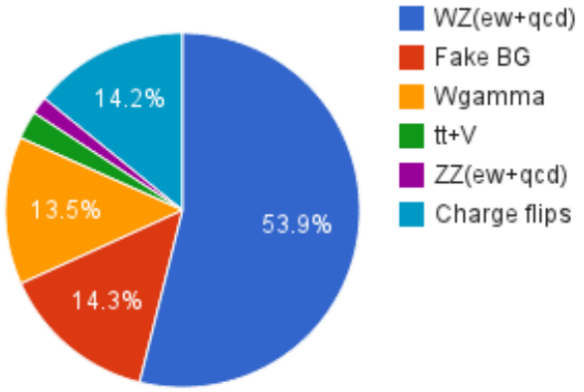
- mjj > 500 GeV
  - **inclusive phase space region**
- dYjj > 2.4
  - **VBS phase space region**

Backgrounds

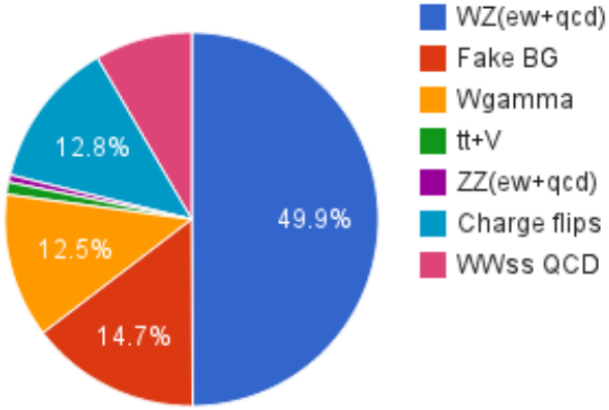
- Prompt backgrounds
  - WZ/γ* (most important)
  - ZZ, tt+W/Z, DPI
- Conversions
  - Electron charge mis-identification
    - Z, top, WW
  - W+(γ→e)
- Jet-fakes
  - W+jets, top, QCD multi-jet

Rather complicated background composition. Control regions were heavily used to validate background estimations.

Inclusive analysis region

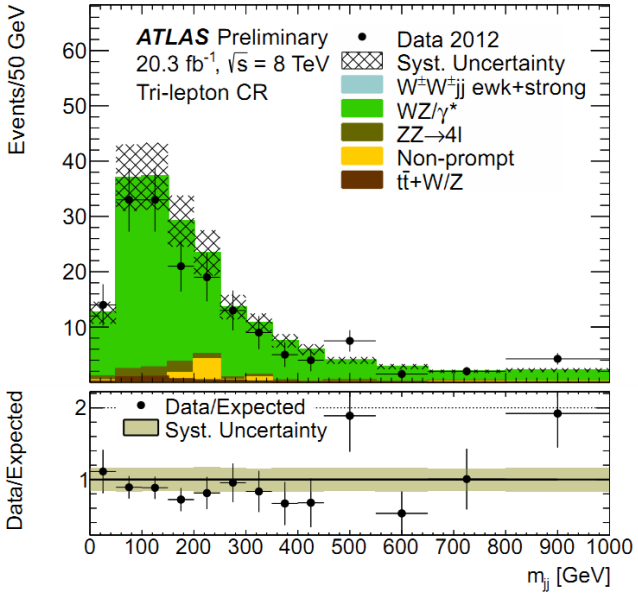


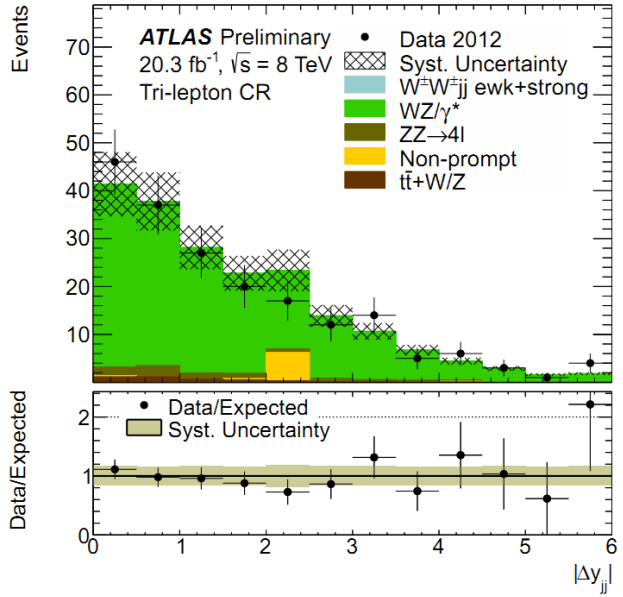
VBS analysis region



WZ/γ* background

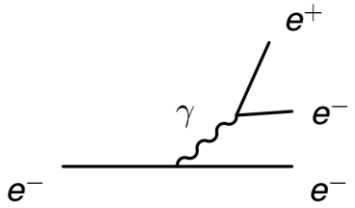
- Introduced a veto on any loose third lepton to suppress its contribution.
- Estimated using MC and normalized with NLO cross section.
- Validated using control regions

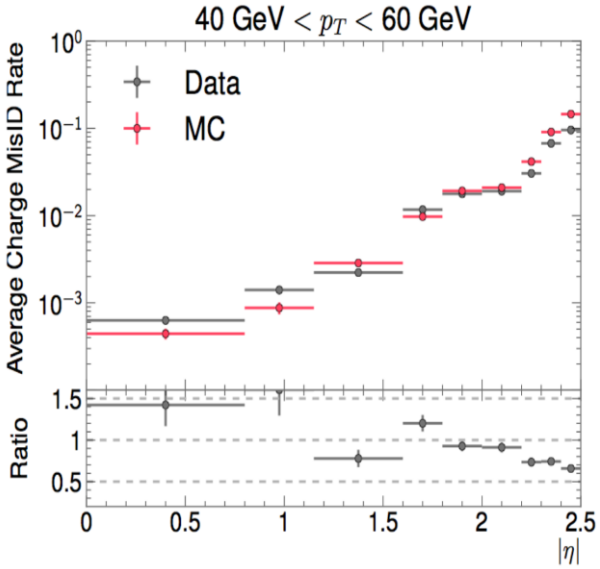


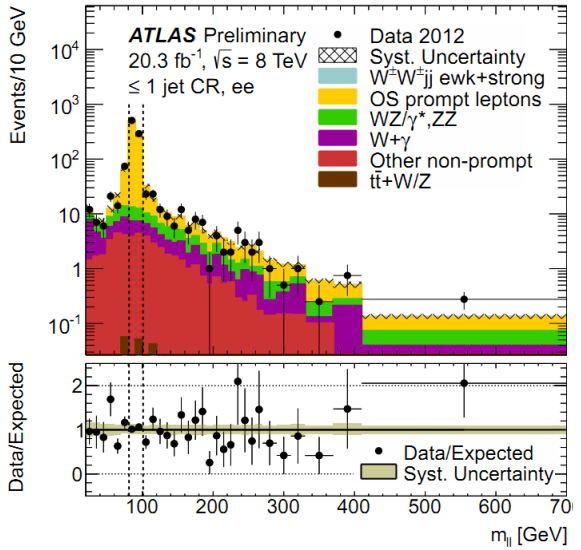


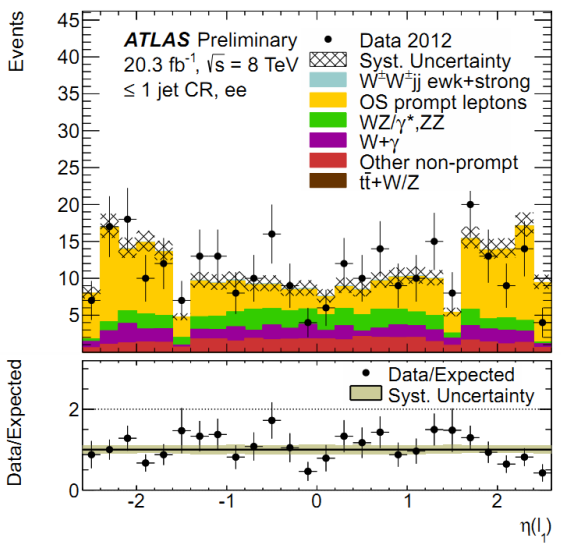
Backgrounds due to Charge Mis-ID

- Measure electron charge mis-ID rate using Z→ee data events
- Apply the rate to each electron in opposite-sign data events passing all other selection cuts
- Correct electron energy for loss due to bremsstrahlung + conversion in charge flip process





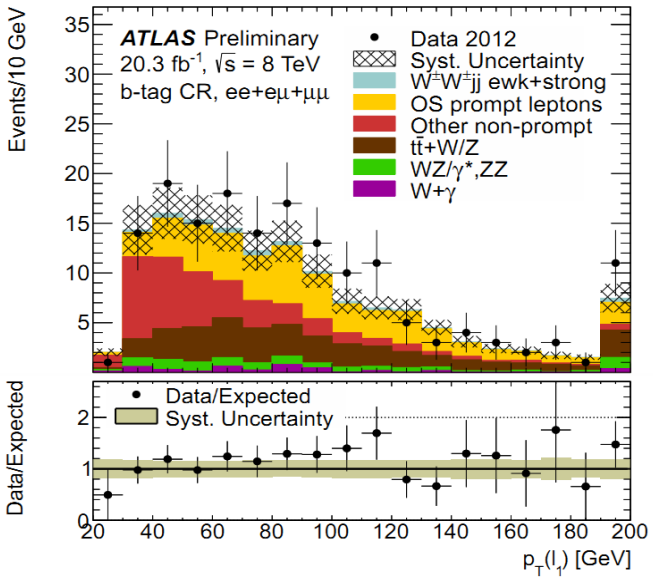


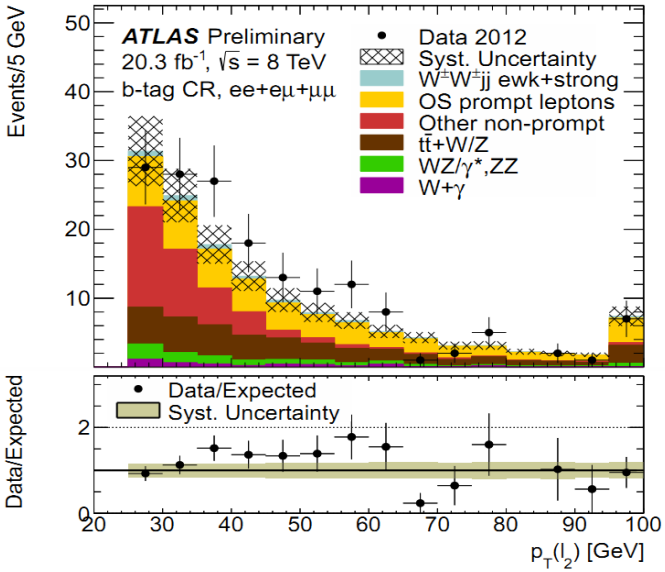


“Jet-fake” backgrounds

- One or both of the leptons originated from jets
- Estimated with the fake-factor method
  - Define 2 classes of leptons: tight and loose
  - Measure fake factor (# tight leptons)/(# loose leptons) in dijet events
  - Apply the factor to events with 1 tight lepton and 1 loose lepton

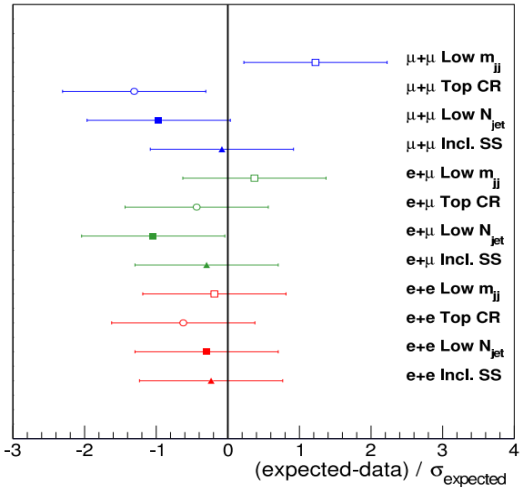
$$f_{lepton} \equiv \frac{N_{\text{full lepton ID}}}{N_{\text{fake lepton ID}}} \qquad N_{\text{fake Bkg}} = f_{lepton} \times N_{\text{full lepton ID + fake lepton ID}}$$

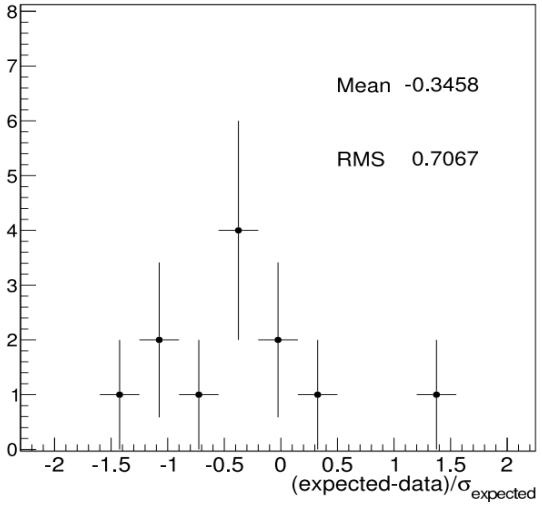




Control Regions Summary

Control Region		Tri-lepton	≤ 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

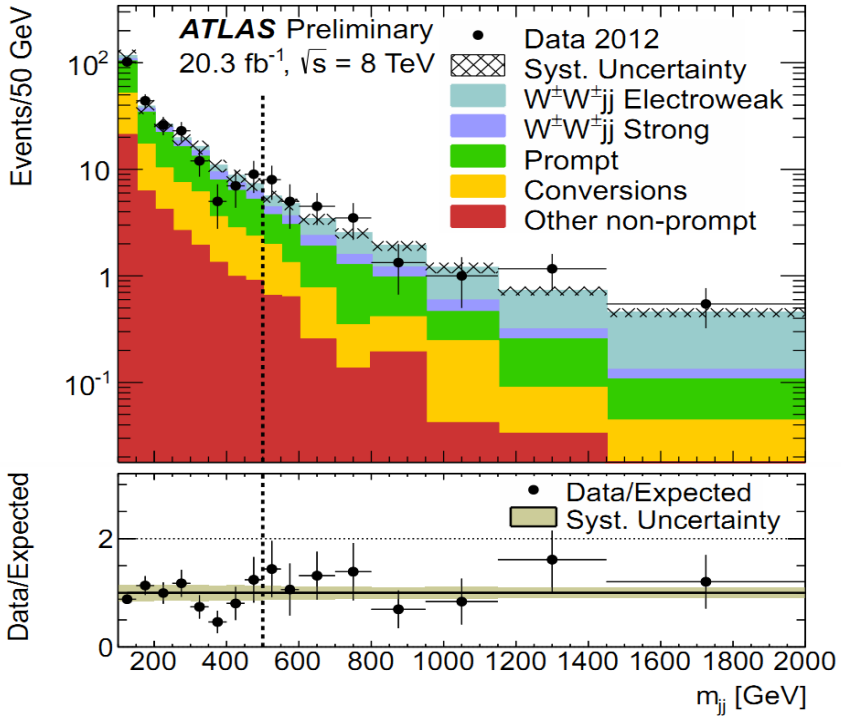




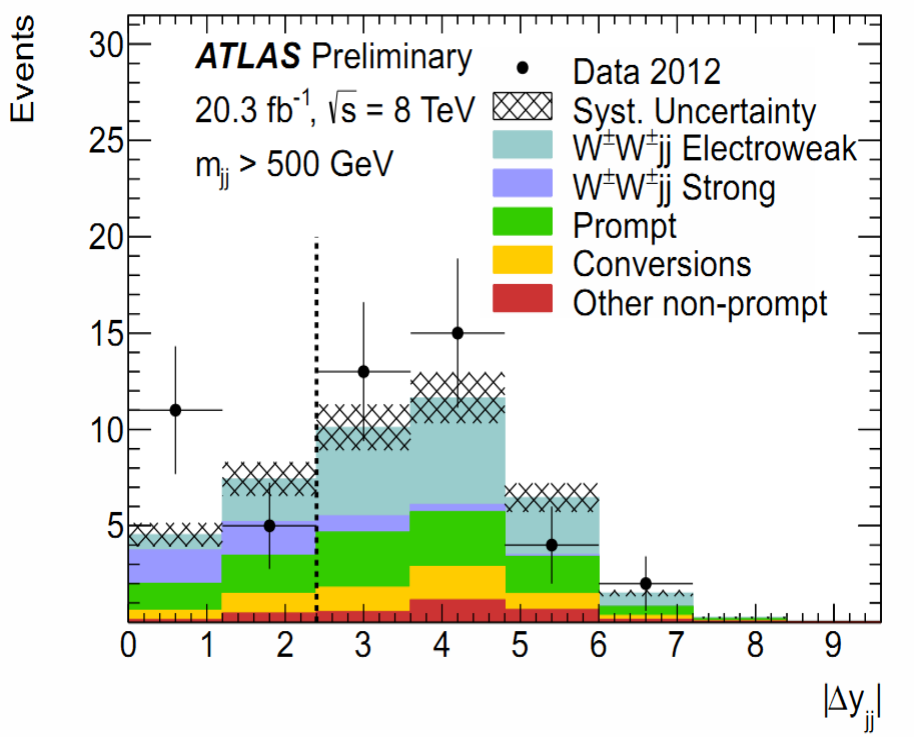
Good agreement in control regions → Background estimations well validated

Signal Regions

Inclusive region



VBS region



- *Data and prediction compatible in general*
- *Strong evidence for $W^{\pm}W^{\pm}jj$ production in inclusive region*
- *Electroweak component significantly enhanced in VBS region*

Observed and Predicted

	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

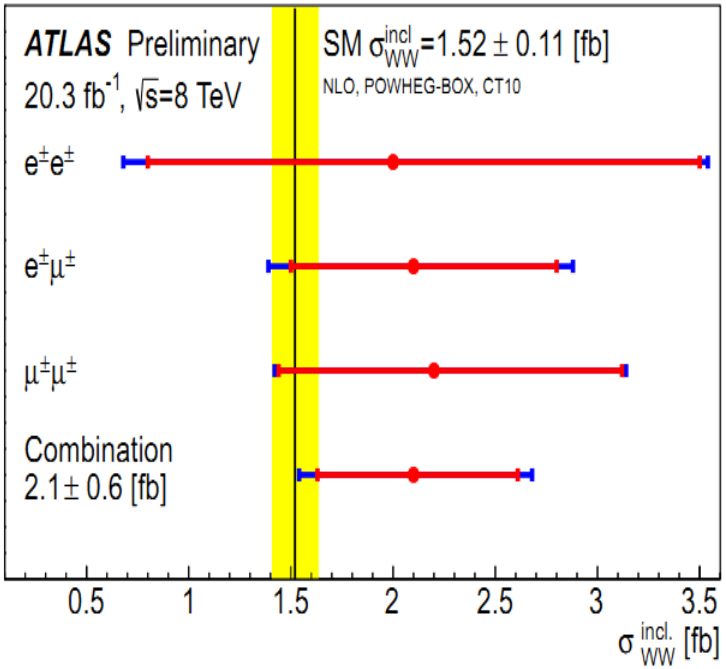
Leading source of systematic uncertainty : Jet energy scale

- **Significance for $W^{\pm}W^{\pm}jj$ production in inclusive region: 4.5 σ**
- **Significance for EWK $W^{\pm}W^{\pm}jj$ production in VBS region: 3.6 σ**

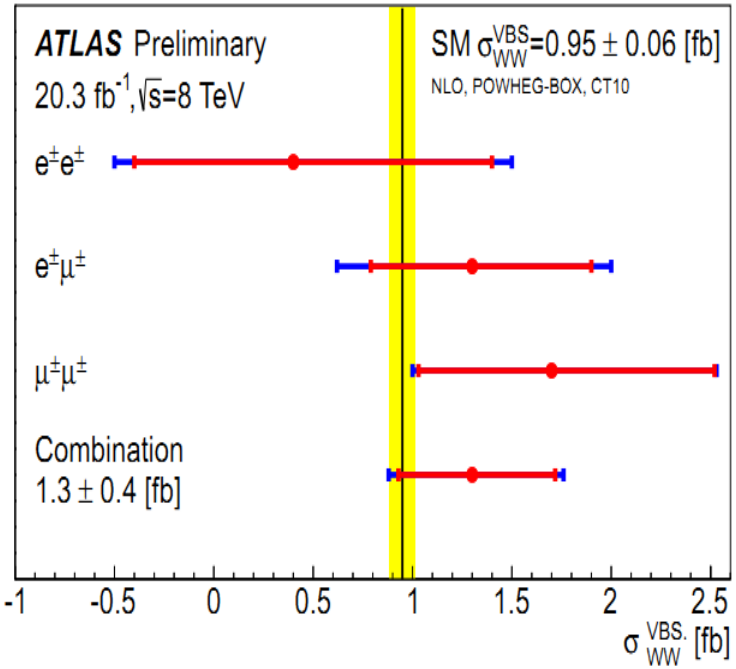
First evidence for EWK $W^{\pm}W^{\pm}jj$ production

Cross Sections

Inclusive region
(Both strong and EW components)

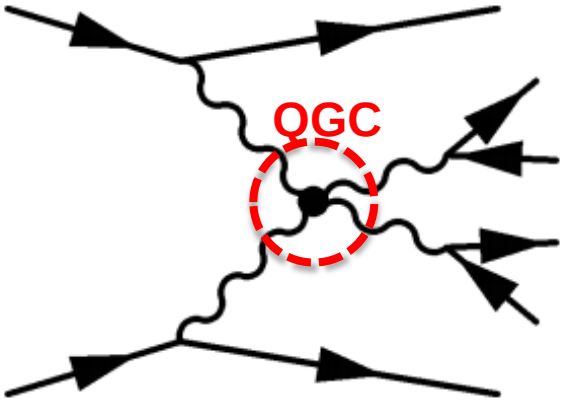


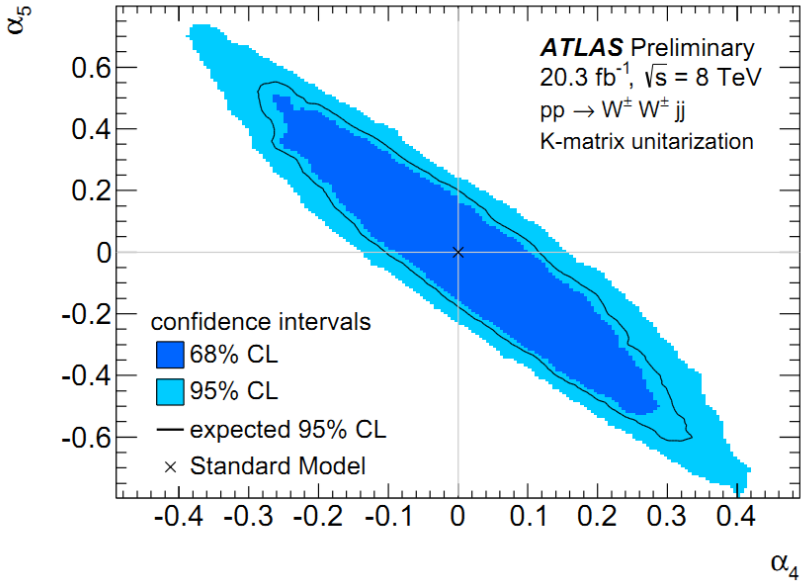
VBS region
(EW component only)



Measured cross sections in agreement with SM

aQGC limits

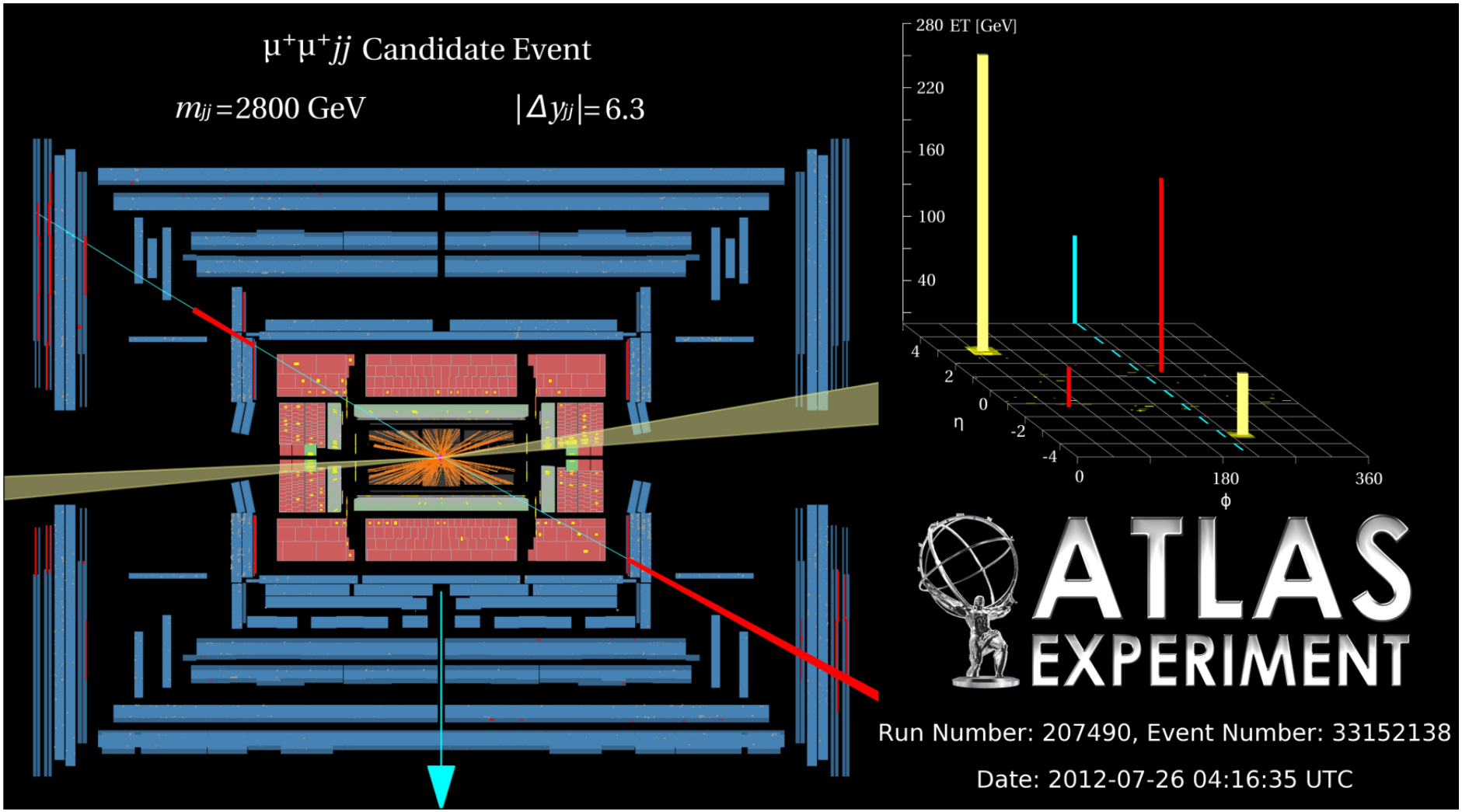




- $W^{\pm}W^{\pm}jj$ EWK production sensitive to aQGCs
- Non-linear parameterization ($\alpha 4$, $\alpha 5$) of aQGC effects with K-matrix unitarization
- aQGC limits derived using cross sections measured in VBS region.
- Profile likelihood method

$$\lambda(\alpha_4, \alpha_5) = -\log \frac{L(\alpha_4, \alpha_5, \hat{\hat{\vec{\theta}}})}{L(\hat{\alpha}_4, \hat{\alpha}_5, \hat{\vec{\theta}})}$$

A VBS candidate event !



Conclusions

- High-energy and high-luminosity LHC offers access to rare VVjj EW production processes.
- Of particular interest are VBS processes, which are crucial to understanding EWSB.
- We see first evidence of $W^{\pm}W^{\pm}jj$ production and of the EW production mode separately with LHC Run1 8TeV data.
- Measured cross sections in agreement with SM and limits set on aQGC.

Our ultimate goal is certainly VBS studies with LHC Run2 data and beyond.