Results on VBS Production (Part 1 ATLAS)

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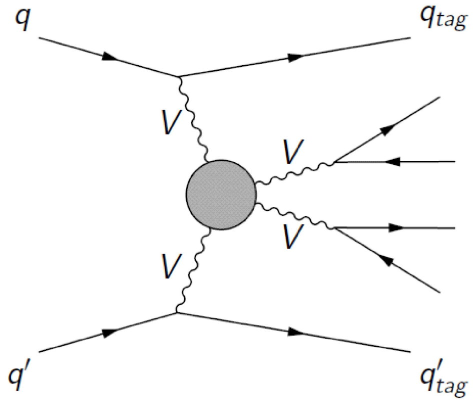
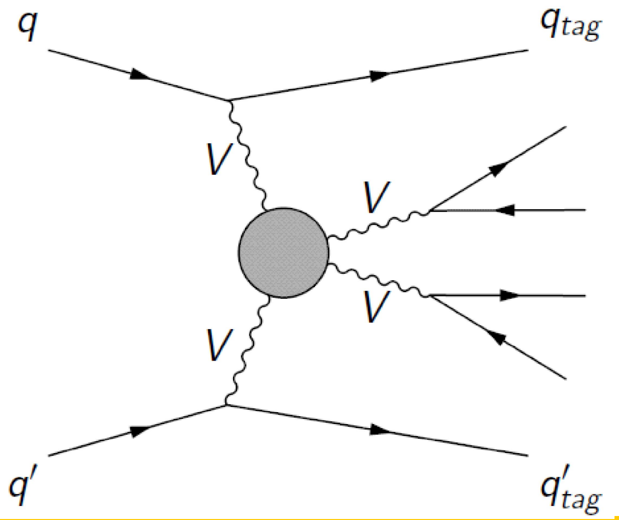
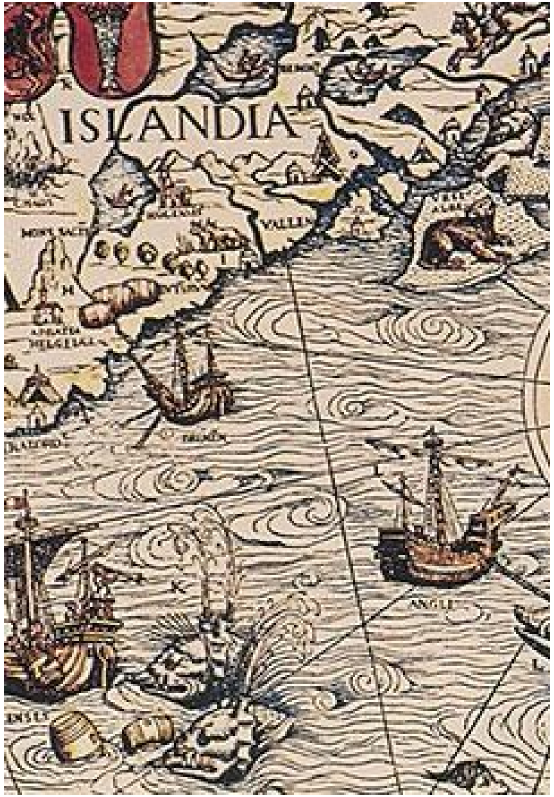


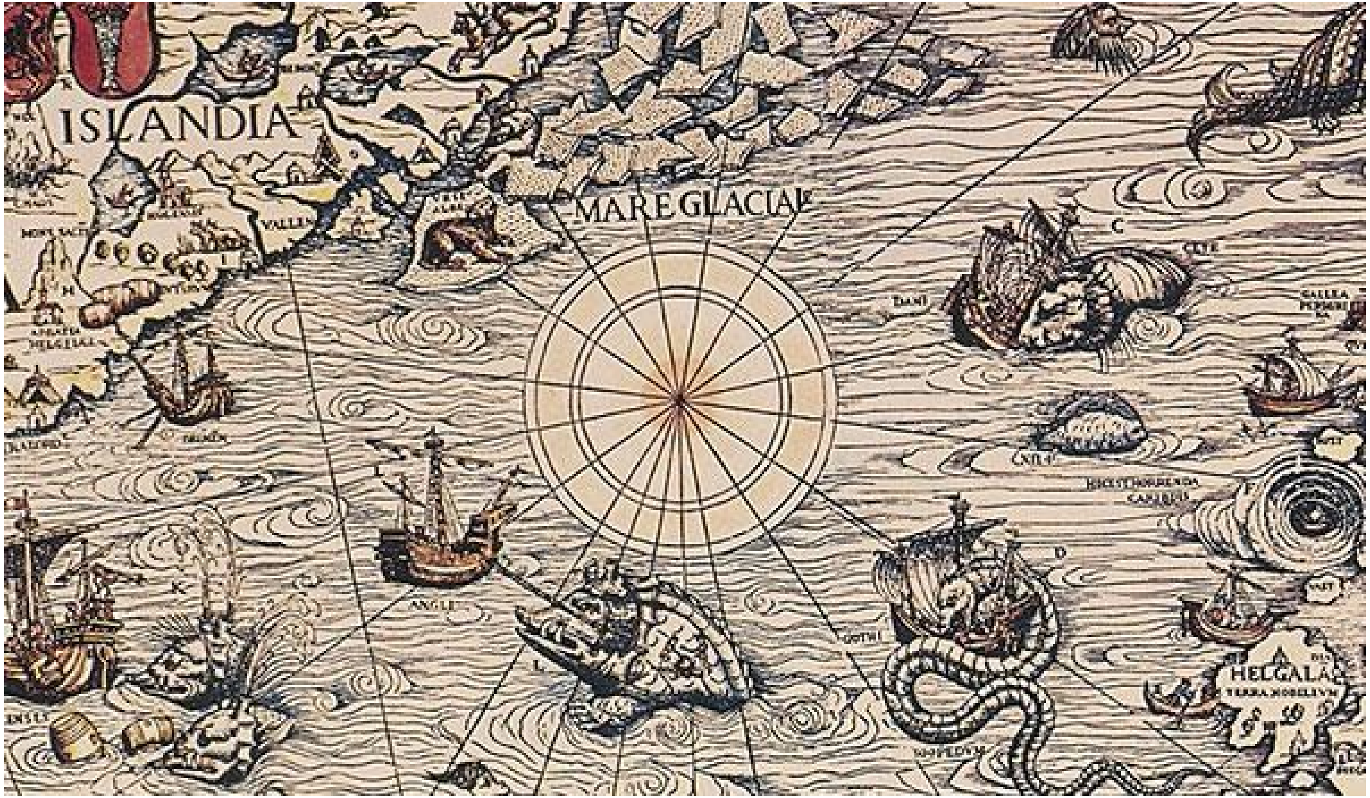
Why Quartic Interactions

- Longitudinal polarization of the W and Z directly related to electroweak symmetry breaking
  - Could be an excellent place to find new physics
- **We have never been able to do it before**





We don’t know what we will see

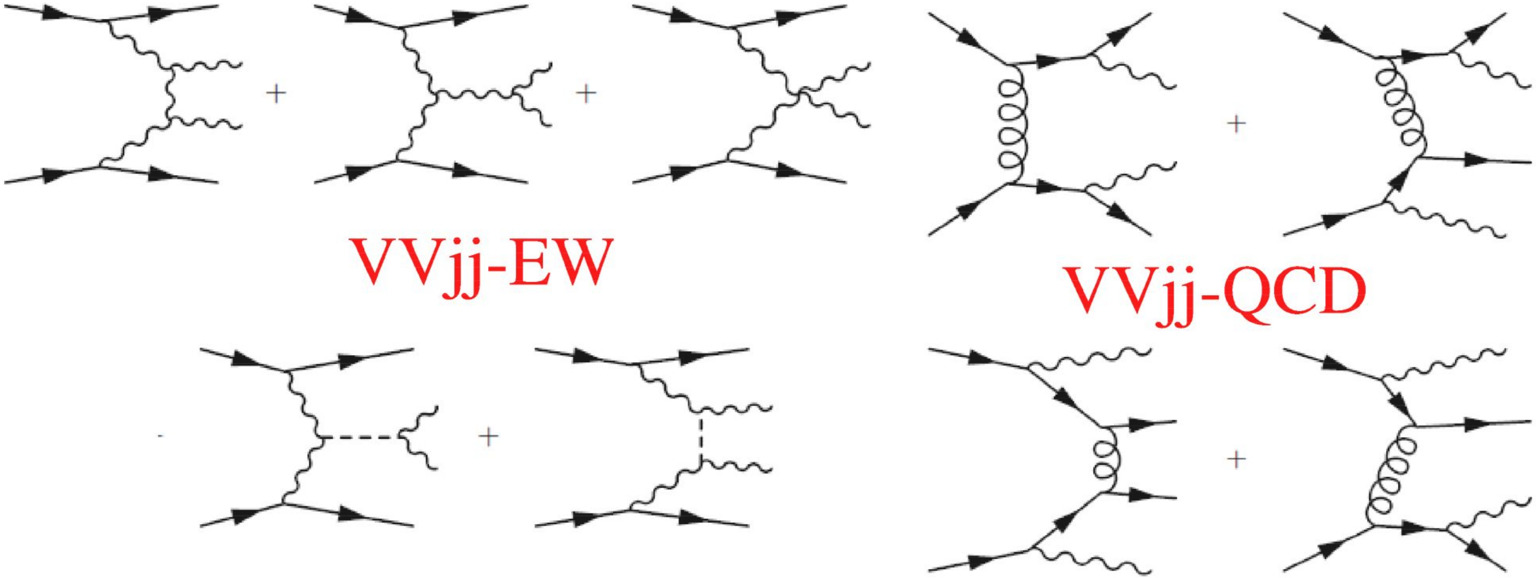


ATLAS's Measurements

- Just at the start of exploring this interesting sector, so far results are just for 8 TeV
  - Same Sign WW + jj
    - ATLAS-STDM-2013-06
  - WZ+jj
    - ATLAS-STDM-2014-02
  - WV (Semi-leptonic VBS) + jj
    - Preliminary Plots:STDM-2015-09
  - $\gamma\gamma \rightarrow WW$
    - ATLAS-STDM-2015-10

VBS: Experimental challenge finding EWK signal

- Final state signatures with two “tag” jets come from two categories*

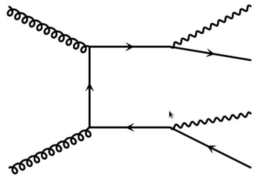


*at tree level

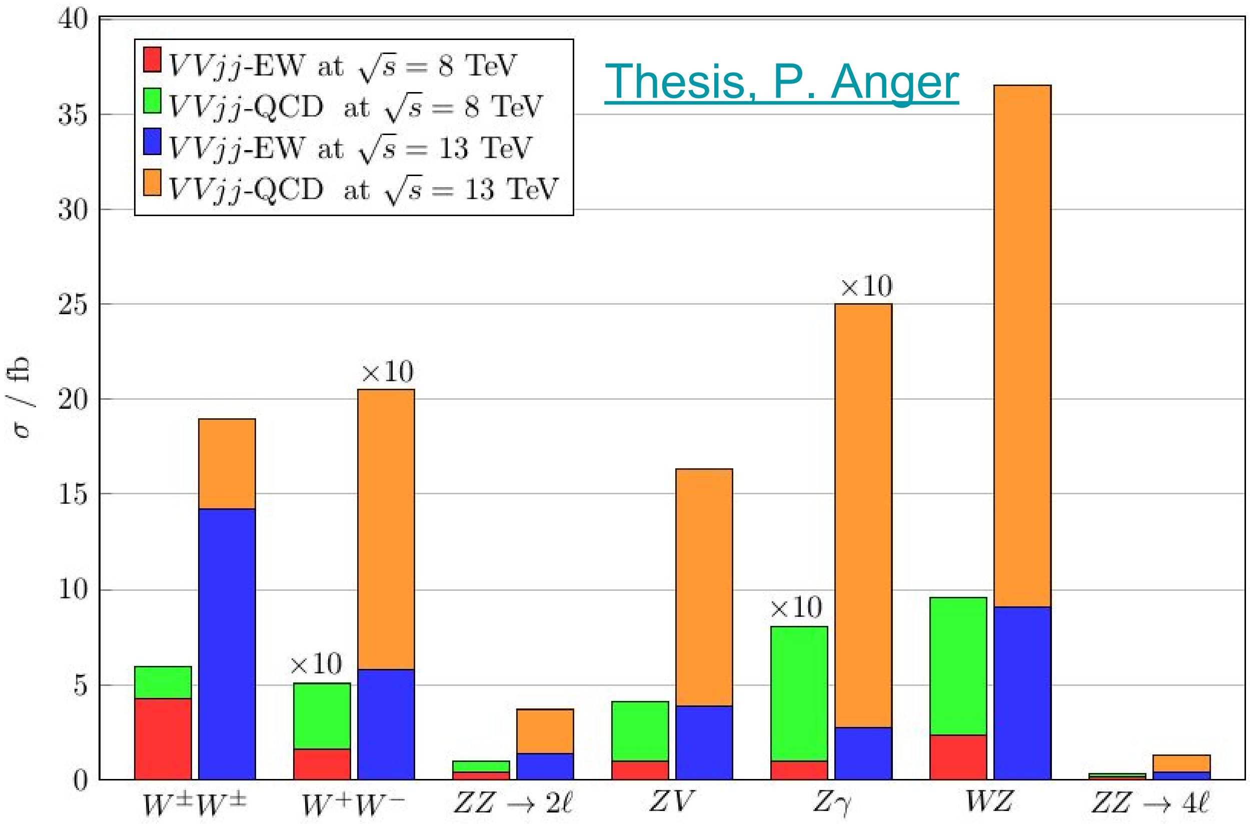
A few example diagrams

Electroweak vs. Strong cross section by process

- EWK and Strong Production by channel
  - **After some analysis cuts to suppress QCD**
- Same Sign W+W+ has no gluon initial states

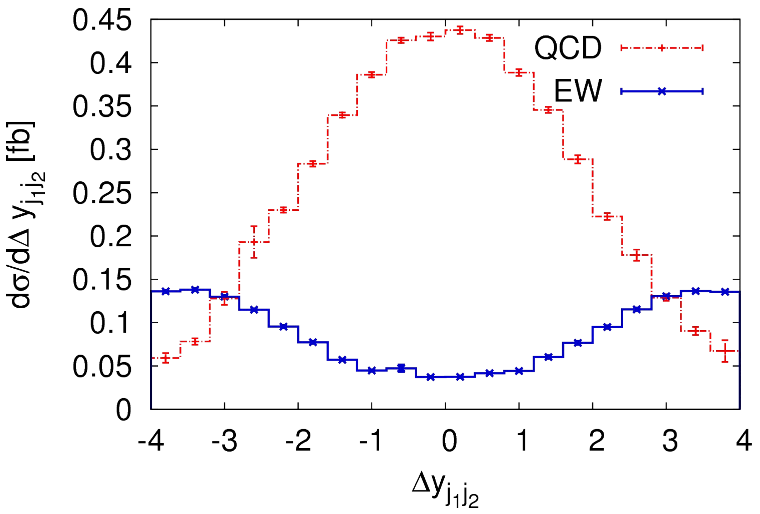


- Others experimentally challenging

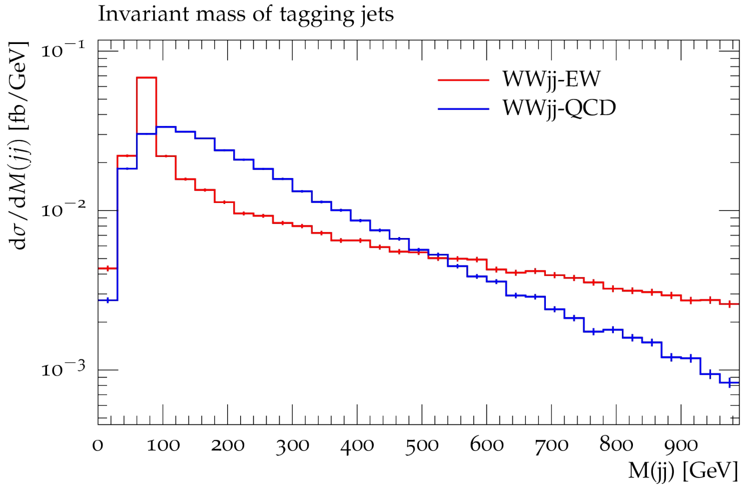


QCD VS. Electroweak

- Experimental Signatures
  - 2 Jets with large M(j,j)
  - 2 Jets with large rapidity separation



Highly Correlated



arXiv:1108.0864

Anomalous Quartic Gauge Couplings (aQGCs)

- Often how we describe sensitivity to new physics
  - Allow for new operators in the Lagrangian typically Dimension 8 for aQGC
  - Generally produces production enhancements at high boson pT

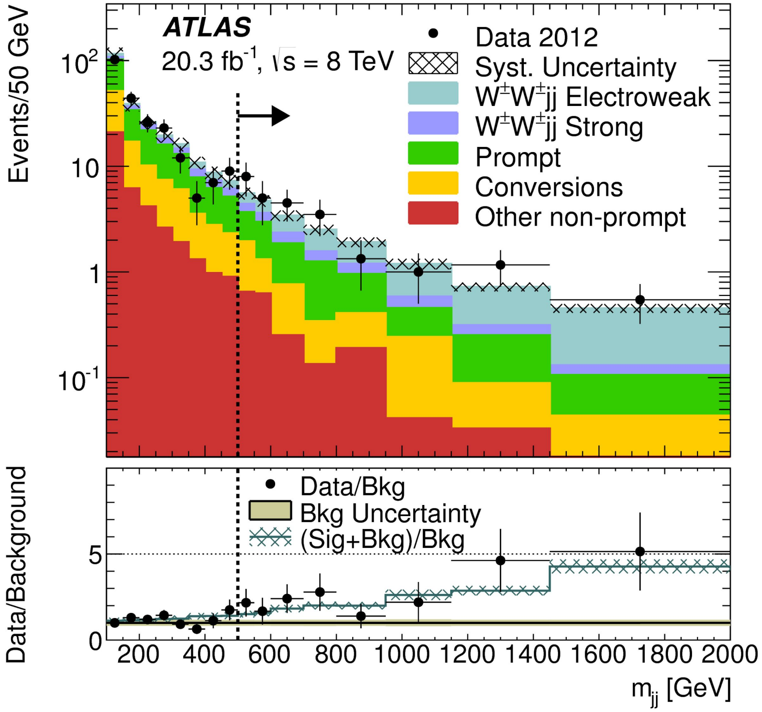
- ATLAS has been using the α_4,α_5 parameterization
  - A. Alboteanu, W. Kilian, and J. Reuter, J. High Energy Phys. 11 (2008) 010.
  - T. Appelquist and C. Bernard,Phys. Rev. D 22, 200 (1980);
  - A. C. Longhitano, Phys. Rev. D22, 1166 (1980); Nucl. Phys. B188, 118 (1981)

- If α_4,α_5 become too large these models become unphysical (are un-unitarized)
  - ATLAS addresses this with a K-Matrix procedure
    - A. Alboteanu, W. Kilian, and J. Reuter, J. High Energy Phys. 11 (2008) 010

Same Sign W^+W^+jj

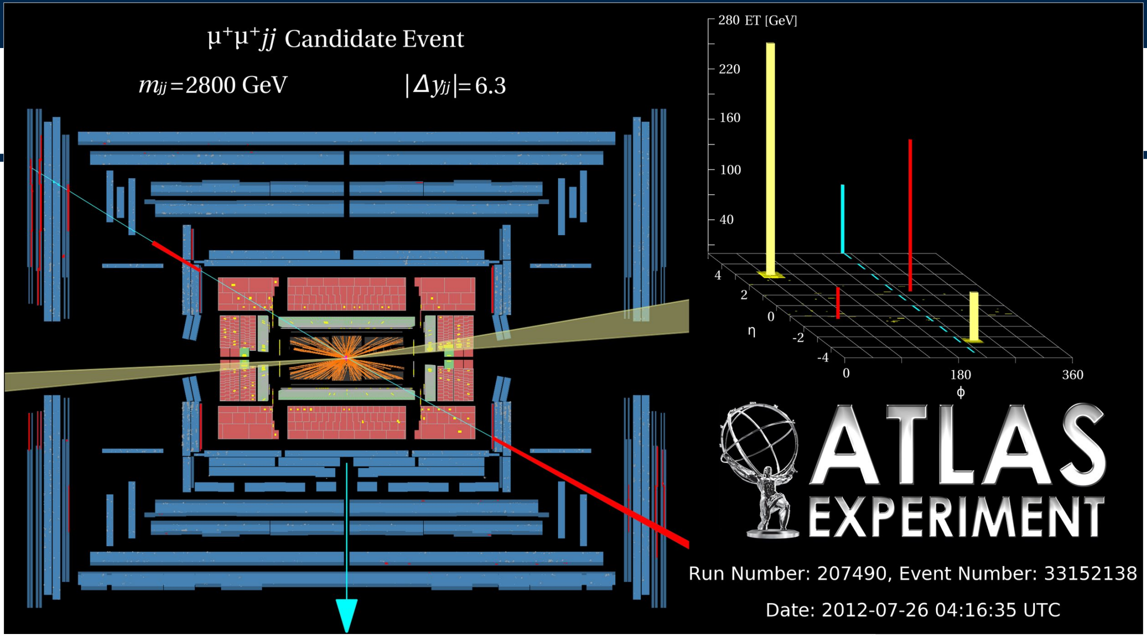
ATLAS-STDM-2013-06

- Reminder of the first evidence for electroweak diboson production
- Look for two leptons (*e*/μ) with identical electric charge
- 2 jets with large M(j,j) and dY(j,j)
  - Slight excess in data seen over SM prediction
  - 3.6 Sigma over background only prediction
- Set limits on α_4,α_5 coupling s
  - Unitarized with a k-matrix



Example

- $\mu^+\mu$ cleanest channel
  - No charge mis-id
- $e^+\mu$ has the most events



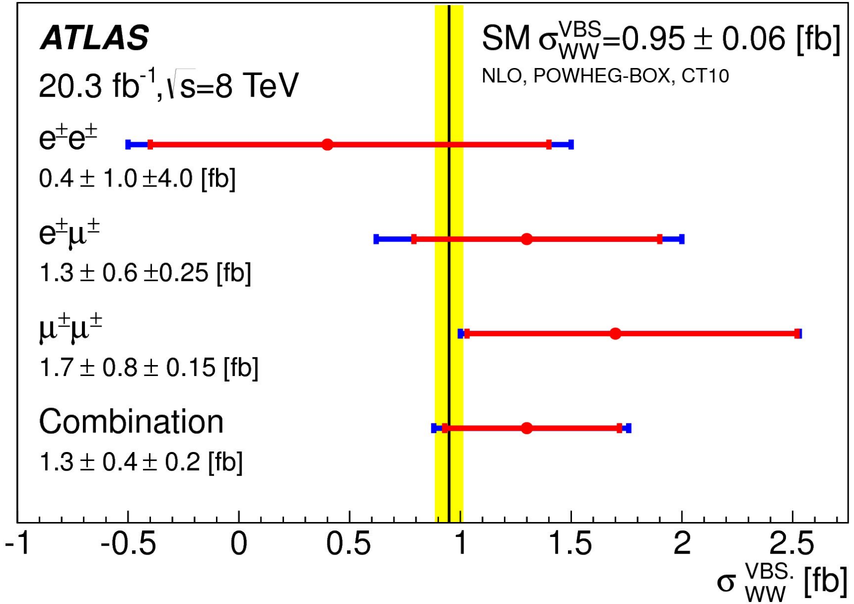
	Inclusive Region			VBS Region		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	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 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

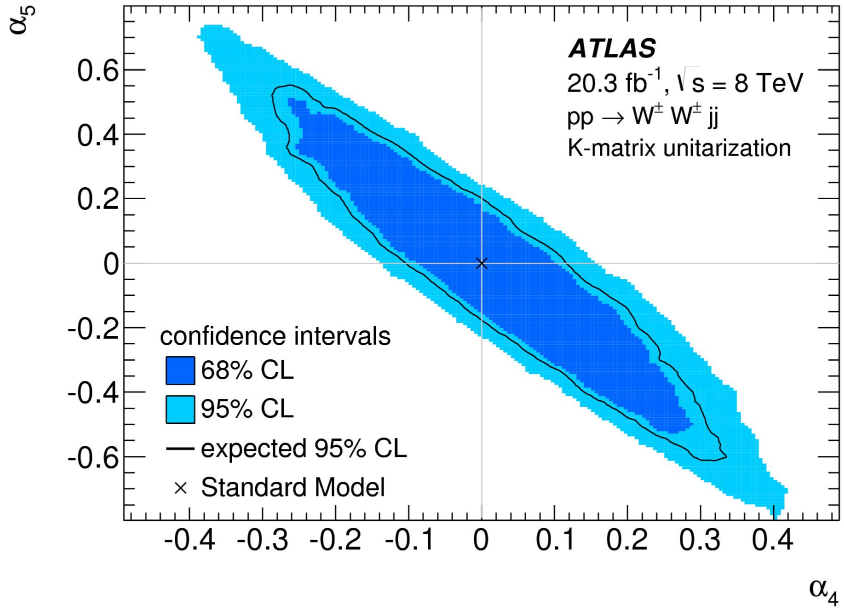
ATLAS-STDM-2013-06

Cross Section Results

ATLAS-STDM-2013-06

- Use a simple counting experiment to extract cross section and limits

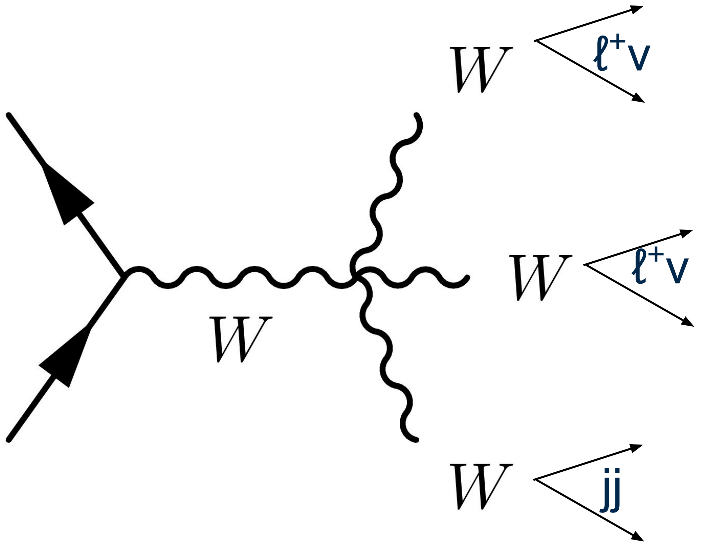


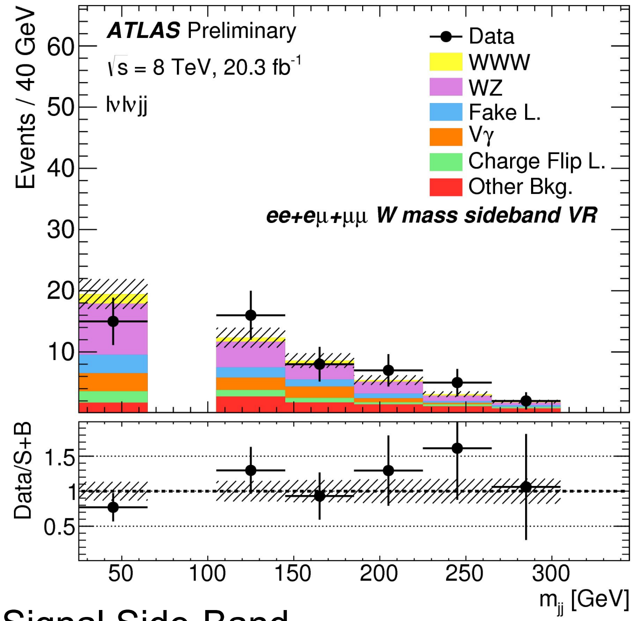


- This limit is frequently used as a baseline comparison for newer studies

Quick Plug for WWW

- Very preliminary plots available for same-sign leptons + 2 jets from tri-boson production. Signal at M(j,j) = M_W instead at large M(j,j), probes same coupling
    - See Tri-boson talk by Julia Djuvsland





Signal Side-Band

WZ + Two Jets

ATLAS-STDM-2014-02

- Three lepton selection with two jets
  - One region optimized to measure standard model VBS production
    - High M(j,j)
  - A second region is optimized to observe contributions from anomalous couplings
    - High pT, and high ΔΦ

Variable	Total	Fiducial and aTGC	VBS	aQGC
Lepton $\|\eta\|$	—	< 2.5	< 2.5	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	—	> 15, > 20	> 15, > 20	> 15, > 20
m_Z range [GeV]	$66 - 116$	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	—	> 30	> 30	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	—	> 0.2, > 0.3	> 0.2, > 0.3	> 0.2, > 0.3
p_T two leading jets [GeV]	—	—	> 30	> 30
$\|\eta_j\|$ two leading jets	—	—	< 4.5	< 4.5
Jet multiplicity	—	—	≥ 2	≥ 2
m_{jj} [GeV]	—	—	> 500	> 500
$\Delta R(j, \ell)$	—	—	> 0.3	> 0.3
$\|\Delta\phi(W, Z)\|$	—	—	—	> 2
$\sum \|p_T^\ell\|$ [GeV]	—	—	—	> 250

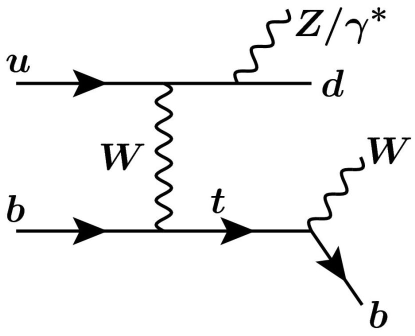
WZ - VBS Results

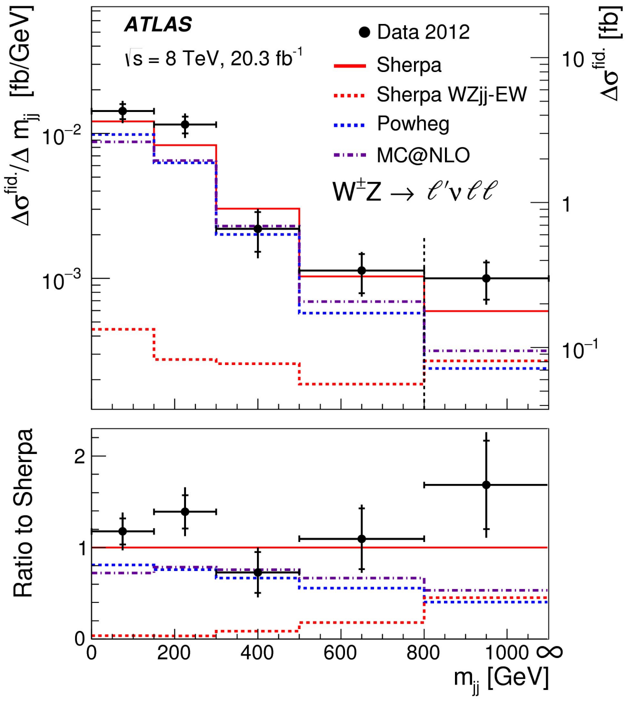
ATLAS-STDM-2014-02

- Slight excess seen in data consistent with expectation
  - Not yet sensitive to the SM
  - 95% limits are quoted
- Quoted with and without the tZ+j

Selection	VBS	aQGC
Data	45	9
Total Expected	37.2 ± 1.1	4.9 ± 0.3
$WZjj$-EW	7.4 ± 0.2	1.1 ± 0.1
$WZjj$-QCD	20.8 ± 0.8	2.8 ± 0.3
tZ	3.0 ± 0.1	0.3 ± 0.0
Misid. leptons	2.5 ± 0.6	0.1 ± 0.1
ZZ	1.9 ± 0.3	0.2 ± 0.1
$t\bar{t} + V$	1.6 ± 0.1	0.3 ± 0.0

95% CL upper limit on $\sigma^{\text{fid.}}_{W^\pm Zjj\text{-EW} \to \ell'\nu\ell\ell}$ [fb]		
	VBS only	VBS + tZj
VBS phase space		
Observed	0.63	0.67
Expected	0.45	0.49
$\pm 1\sigma$ Expected	[0.28 ; 0.62]	[0.33 ; 0.67]
$\pm 2\sigma$ Expected	[0.08 ; 0.80]	[0.19 ; 0.84]

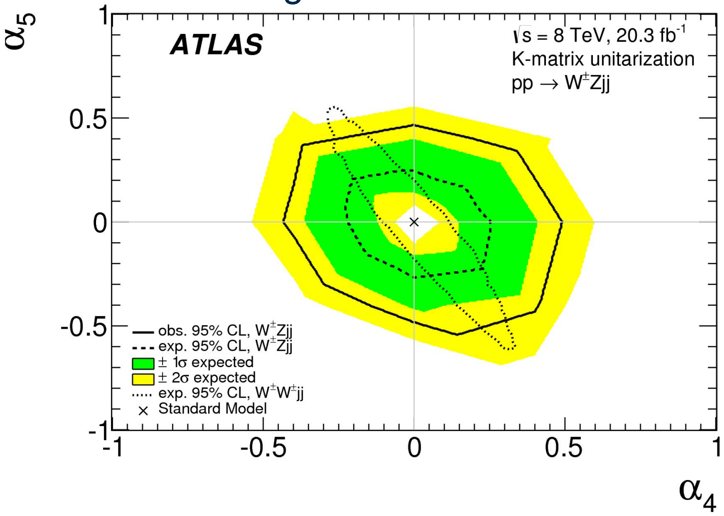


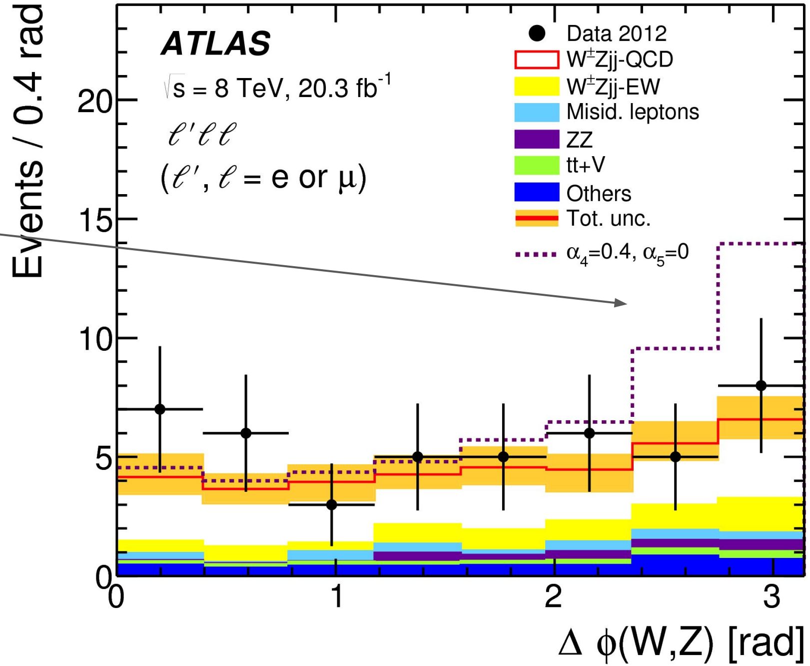


WZ - aQGC

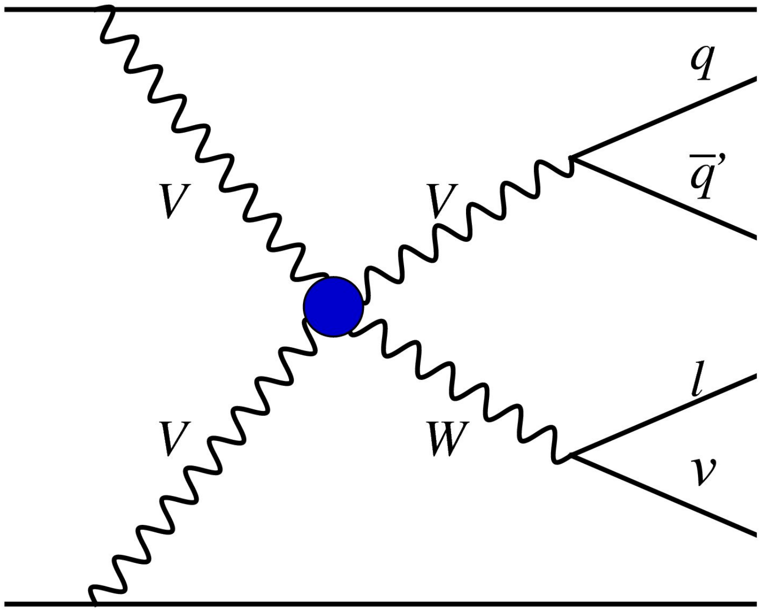
ATLAS-STDM-2014-02

- Complementary to ssWW
  - Different shape in the α_4,α_5 plane
- No sign of aQGC yet
  - One place we could have seen it is at large $\Delta\Phi$





VBS WV+jj



- Measuring VBS in a semi-leptonic channel has many advantages
  - Signal from multiple sources
    - OS WW
    - SS WW
    - WZ
  - Can reconstruct boson kinematics
- Tends to suffer from higher background
  - Makes SM measurements hard
  - Background falls as you move to higher pTs, making this channel ideal for aQGC measurements

Analysis

- Resolved (small-R jet) selection:
  - At least 4 small-R jets
  - Select jet pair with 64<m(jj)<96 GeV as W-jet candidates.
  - From the non W-jets, max mjj pair are the VBS "tagging" jets
- Merged (large-R jet) selection:
  - At least 2 small-R jets and 1 large-R jet.
  - 64 < m(J) < 96 GeV
  - Large-R jet with mass closest to W-mass is chosen to be V->qq candidate.
  - max mjj pair -> VBS "tagging" jets
- Event Selection
  - M(j,j) > 900 GeV (tag jets)
  - MET > 30 GeV
  - Boson Centrality > 0.9

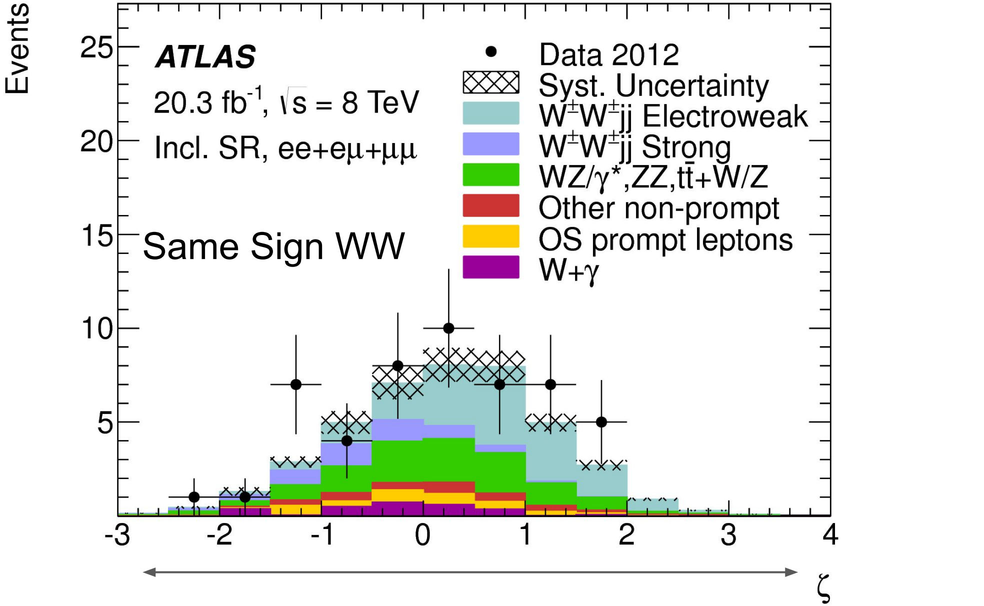
$$\zeta = min\{\Delta\eta_-, \Delta\eta_+\},$$

$$\Delta\eta_- = min\{\eta_i\} - min\{\eta_{j_{t1}}, \eta_{j_{t2}}\},$$

$$\Delta\eta_+ = max\{\eta_{j_{t1}}, \eta_{j_{t2}}\} - max\{\eta_i\}.$$

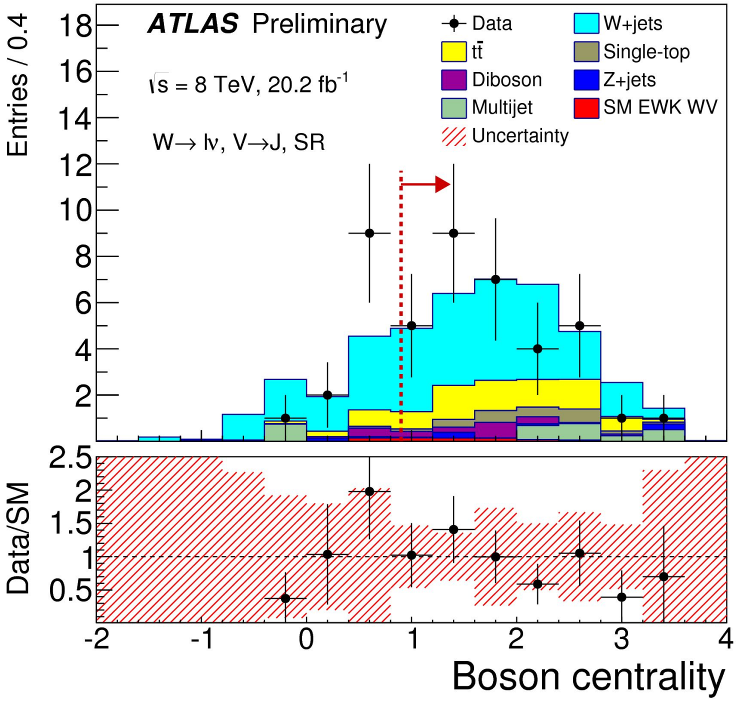
Boson Centrality

- Like M(j,j), and dY(j,j), boson centrality is a good VBS separator
  - Also correlated to M(j,j) / dY(j,j)



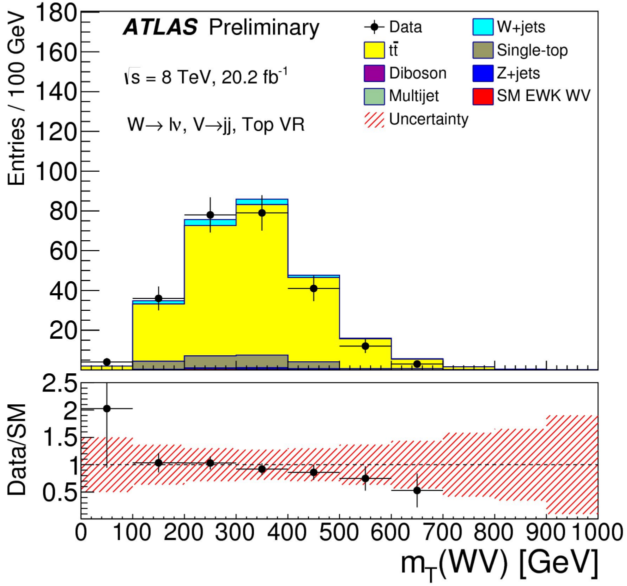
Lepton outside of jet pair (At higher eta)

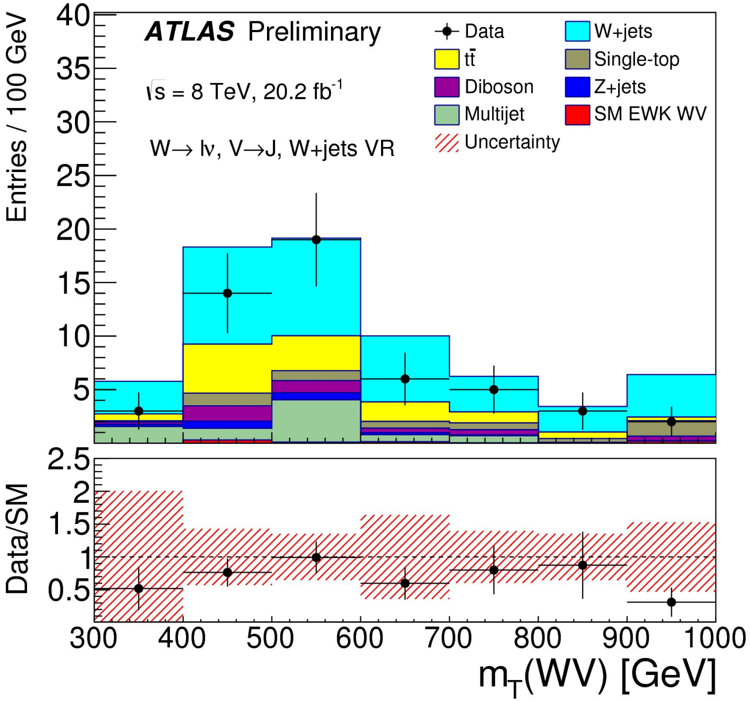
Lepton(s) inside of jet pair (At Lower eta)



Backgrounds and Modeling

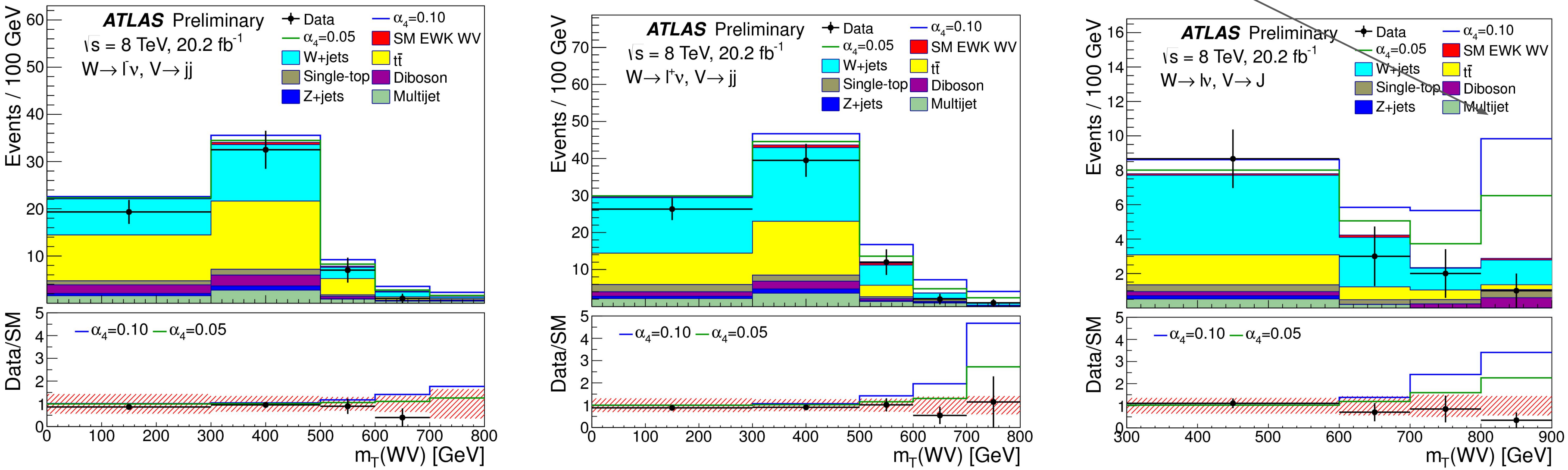
- Dominant backgrounds are top quark pair production and W+jets
  - Model with MC, but use data driven normalizations
  - Validate in control regions





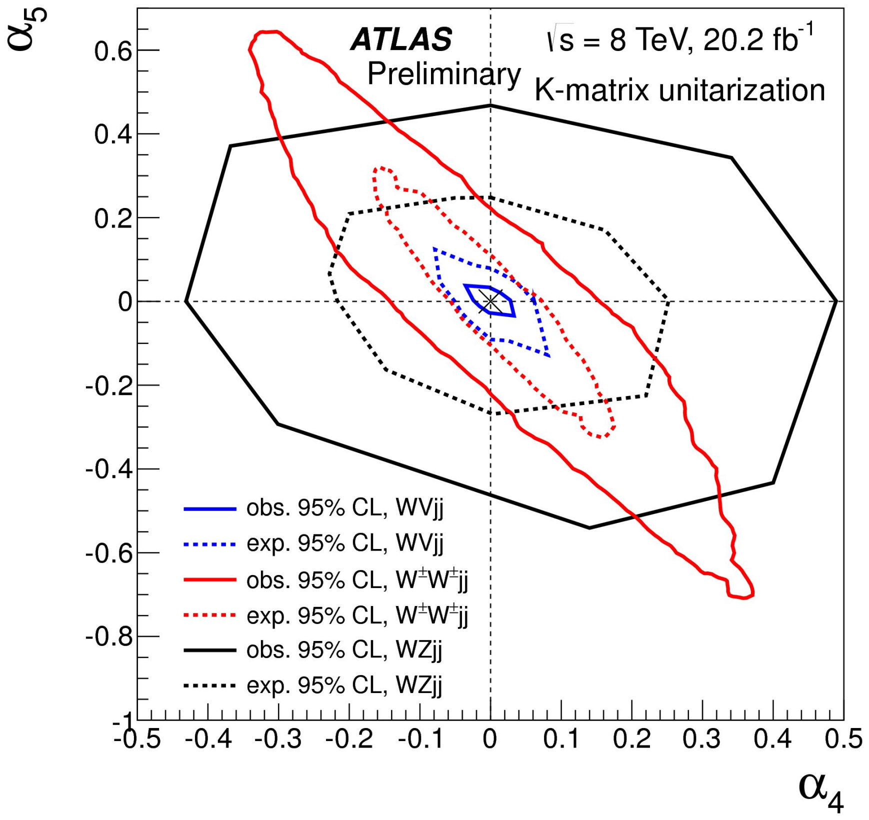
aQGC Fit

- After cut fit for aQGC points in three regions, resolved l^+, resolved l^-, merged
- Excellent aQGC sensitivity in resolved channel



aQGC Limit Comparison

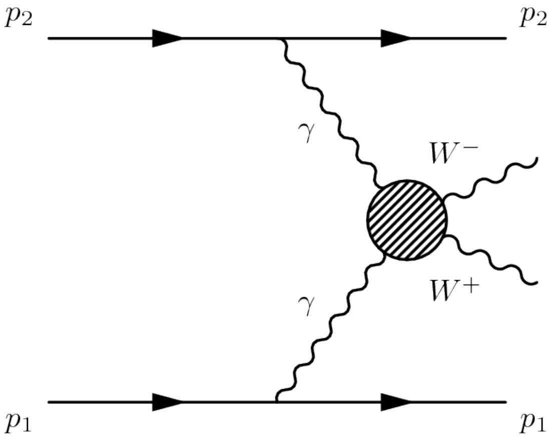
- Deficit seen in regions most sensitive to aQGC
  - Better limit than expect
- Most stringent limit to date on α_4, α_5 by significant margin
  - Both expected and observed
- Look for paper to be submitted soon

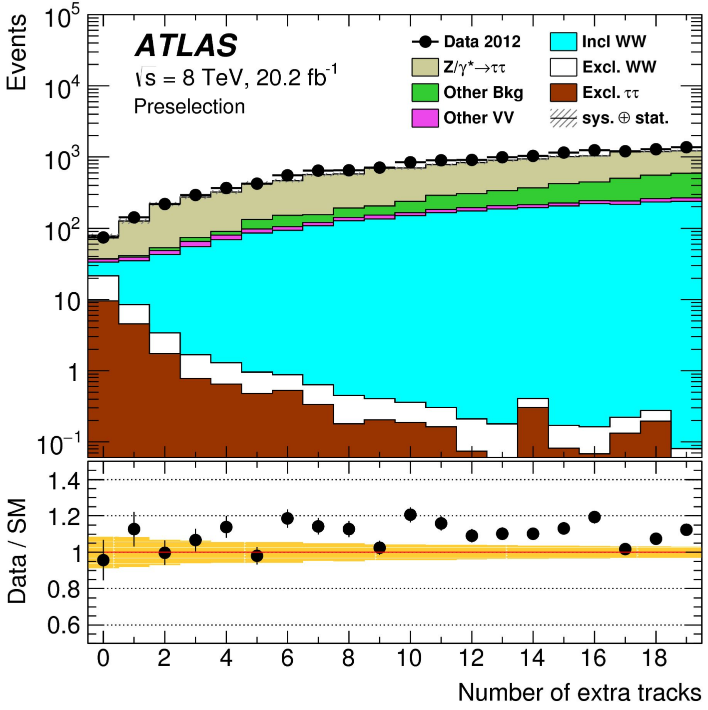


Exclusive WW production

ATLAS-STDM-2015-10

- A different set of aQGC involving photons and higgs production can be probed with exclusive production
- Protons can survive these interactions relatively intact, and go directly down the beam pipe
- Signature here is two leptons, with very little other activity in the event

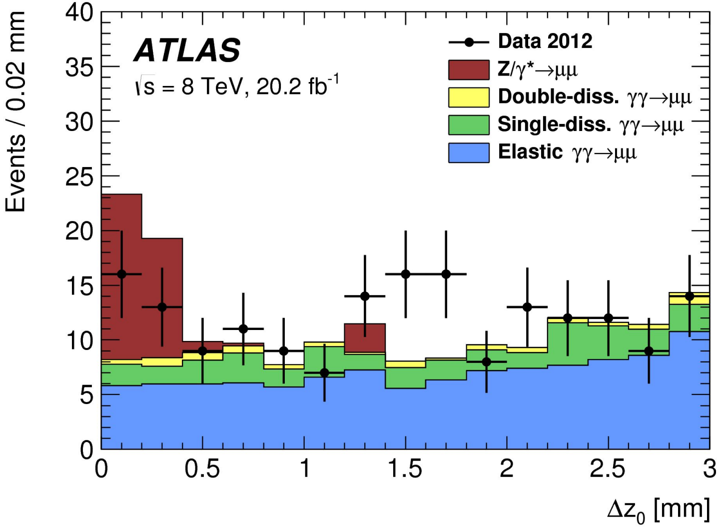




Exclusive WW production

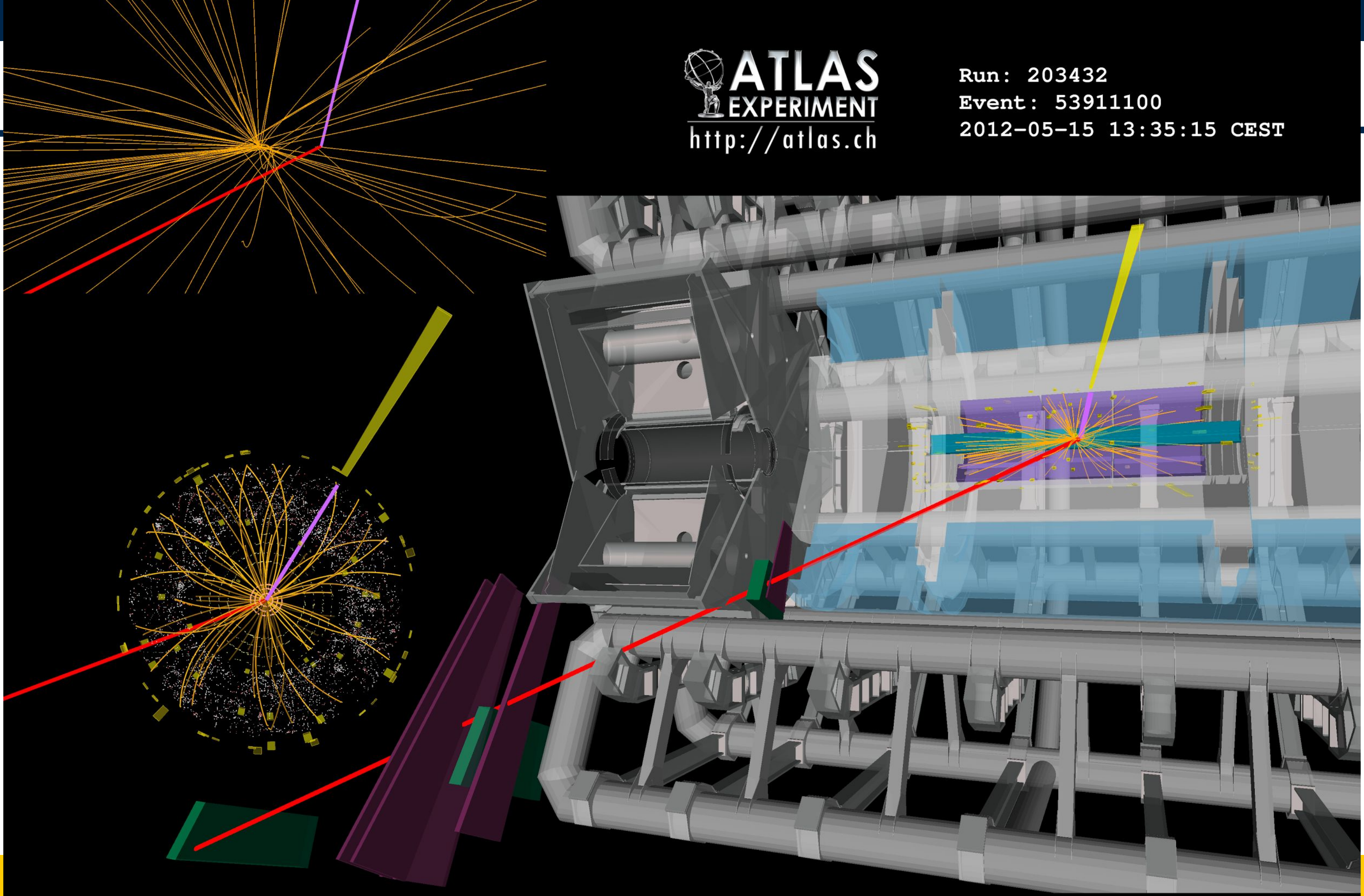
ATLAS-STDM-2015-10

- e+μ final state used to reduce Z□ℓℓ background
- "Extra tracks" are matched back to the lepton pair's vertex
  - ΔZ with the closest extra track used as a discriminant



	W^+W^- selection	Higgs boson selection
Preselection	Oppositely charged $e\mu$ final states	
	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 20$ GeV	$p_T^{\ell 1} > 25$ GeV and $p_T^{\ell 2} > 15$ GeV
	$m_{e\mu} > 20$ GeV	$m_{e\mu} > 10$ GeV
	$p_T^{e\mu} > 30$ GeV	
	Exclusivity selection, Δz_0^{iso}	
aQGC signal	$p_T^{e\mu} > 120$ GeV	–
Spin-0 Higgs boson	–	$m_{e\mu} < 55$ GeV
	–	$\Delta\phi_{e\mu} < 1.8$
	–	$m_T < 140$ GeV

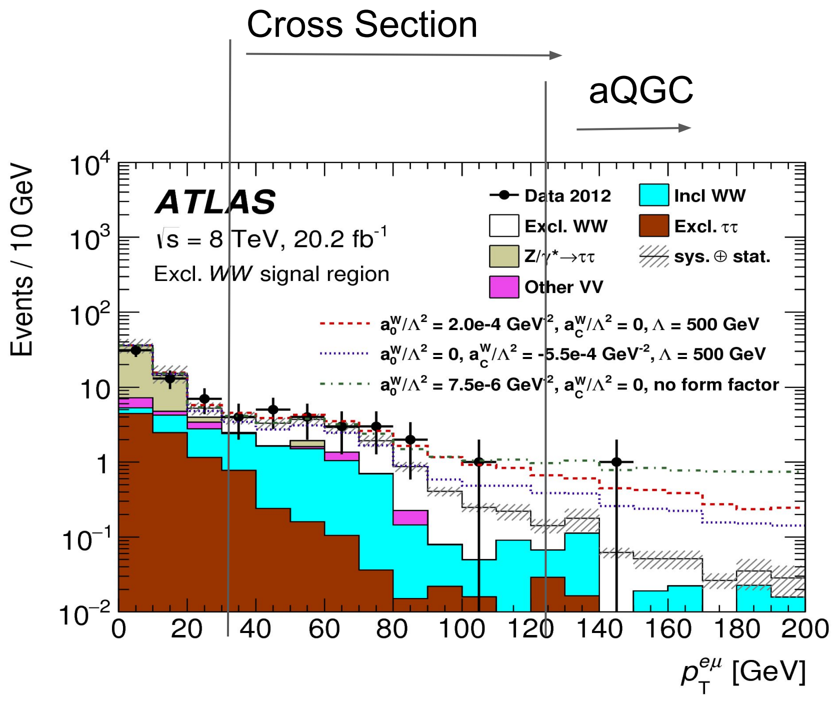
- $(1-|\Delta\phi_{\ell\ell}|/\pi) > 0.5$


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203432
Event: 53911100
2012-05-15 13:35:15 CEST

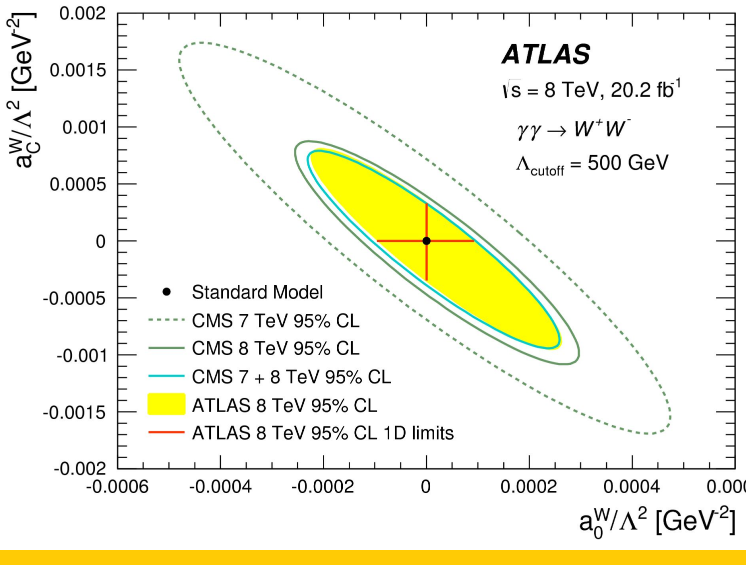
γγ→WW

ATLAS-STDM-2015-10

- Additional cuts on the pT of the e/mu system can be used to extract a cross section (> 30 GeV) and even tighter cuts can be used for the aQGC (> 120 GeV)
- Cross section (fiducial) agrees with SM prediction of 4.4 ± 0.3 fb



σ = 6.9± 2.2(stat.)±1.4(sys.) fb



Conclusions

- The LHC 8 TeV has provided a wealth of information about electroweak interactions
  - We've gone from having no experimental knowledge in this sector to some measurements and several good limits
  - So far predictions are not completely different from experiment, but it is hard to claim more than this with current precision
  - Statistics remain the dominant uncertainty

- There is still an awfully lot to do
  - With the LHC at 13 TeV expect more data and better precision
  - The data is coming in fast, so you may not have to wait long!