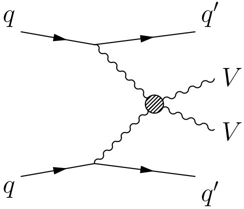
VBS-VV Results from ATLAS



Lulu Liu
University of Michigan

Multi-Boson Workshop

BNL, Oct 29, 2014

why vector boson scattering? (I)

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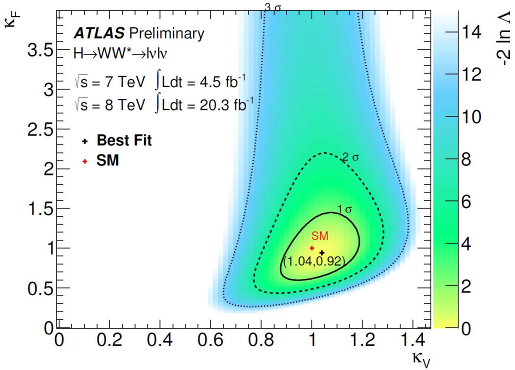
why vector boson scattering? (I)

- $V_L V_L \to V_L V_L$ scattering violates unitarity $\sim \mathrm{TeV}$ if there is no Higgs.
- Now we've found a Higgs particle with mass 125 GeV.
- Is it fully responsible for the EWSB?
- Or some new physics could share the job?

- The Higgs couplings have been measured. Take the ATLAS $H \to WW^*$ as an example:

ATLAS-CONF-2014-060

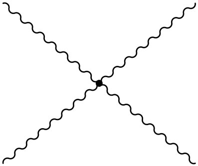


- Best fit:
  $\kappa_F = 0.92^{+0.31}_{-0.23}$,
  $\kappa_V = 1.04^{+0.10}_{-0.11}$
- Prospects at HL-LHC for $\kappa_V \sim 5\%$ precision

- Still room for new physics! If the Higgs is only partially responsible for the EWSB, the $V_L V_L$ scattering amplitude still grows as $\mathcal{O}(s/m_W^2)$ until new physics kicks in.

why vector boson scattering? (II)

- Gauge boson self interactions are an important part of the electroweak sector
- Triple-gauge-boson coupling (TGC) has been studied extensively
- No direct evidence for a process involving QGC vertex in previous experiments
- Probe to quartic-gauge-boson couplings (QGC) through VBS:



- QGC can be also studied in tri-boson production

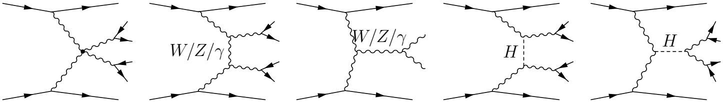
VBS at ATLAS

Final State	Status
$W^{\pm}W^{\pm} \to \ell^{\pm}\nu\ell^{\pm}\nu$	ATLAS-STDM-2013-06. Evidence for VBS!
$WZ \to \ell\nu\ell\ell$	In progress
$WW/WZ \to \ell\nu jj$	In progress
$V\gamma$	In progress
$pp \to pWWp$	In progress
$H \to WW^{*} \to \ell^{+}\nu\ell^{-}\nu$	ATLAS-CONF-2014-060. Evidence for VBF production!
$H \to ZZ^{*} \to \ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$	ATLAS-HIGG-2013-21

- This talk will focus on the same-sign WW analysis and briefly discuss the VBF part of the $H \to WW^{*}$ analysis.
- More to come in the future.

VBS at LHC

- VBS production at LHC with $\mathcal{O}(\alpha_{EW}^6)$:



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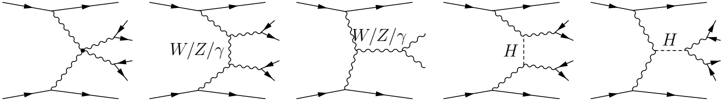
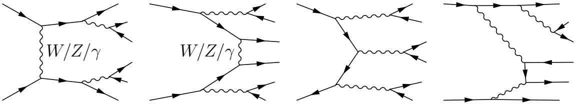


- non-VBS production of the same final state with $\mathcal{O}(\alpha_{EW}^6)$:



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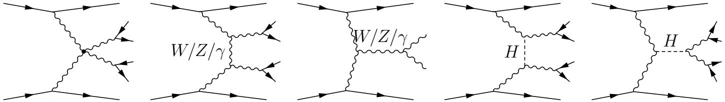

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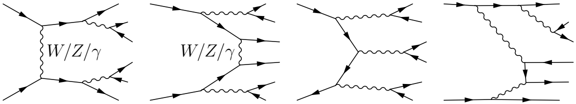
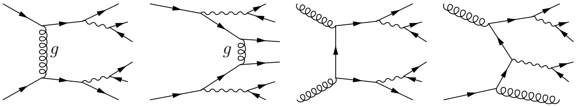


- strong production of the same final state with $\mathcal{O}(\alpha_S^2\alpha_{EW}^4)$:



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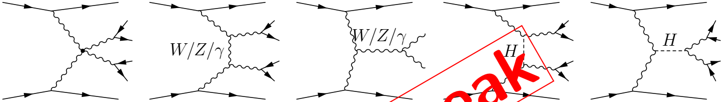

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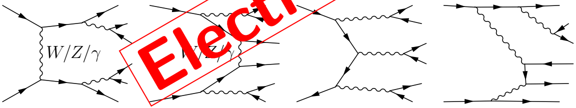

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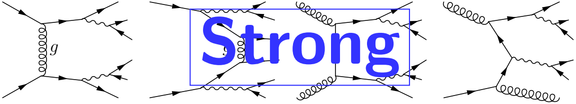

- VBS not separately gauge invariant. Look at electroweak production as a whole.

why same-sign WW: electroweak vs. strong

- Electroweak vs. Strong production at LHC. (Sherpa prediction with two leptons $p_{\mathrm{T}} > 5$ GeV, $m_{\ell\ell} > 4$ GeV and two jets $p_{\mathrm{T}} > 10$ GeV.)

final state	process	$VVjj$−Ewk [fb]	$VVjj$−Strong [fb]	Ewk/Strong
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign)	$W^{\pm}W^{\pm}$	19.5	18.8	1.04
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3	3030	0.030
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2	687	0.043
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5	106	0.014
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4	162	0.015

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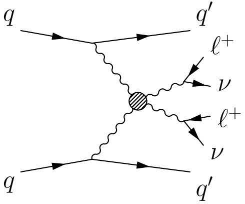
- Experimentally, the same-sign lepton pair requirement also greatly suppresses other SM backgrounds.
- Analysis goals:
  - measure the inclusive Ewk+Strong $W^{\pm}W^{\pm}jj$ production cross section,
  - extract the electroweak $W^{\pm}W^{\pm}jj$ component,
  - place constraints on aQGC's.

signal simulation

- $W^{\pm}W^{\pm}jj$-Ewk and -Strong are simulated using Sherpa up to one extra parton.
- Interference (7%-12%) is added to electroweak production, assuming "No electroweak production, no interference".
- Normalized to NLO cross section calculated using PowhegBox in the fiducial regions.

event selection



- Exactly 2 isolated leptons (e, μ) of the same electric charge with $p_{\mathrm{T}} > 25$ GeV and $m_{\ell\ell} > 20$ GeV
- missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
- at least 2 jets with $p_{\mathrm{T}} > 30$ GeV

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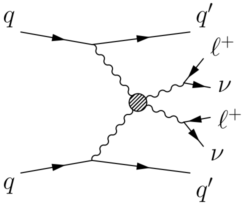

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- b jet veto $\Rightarrow$ suppress $t\bar{t}$

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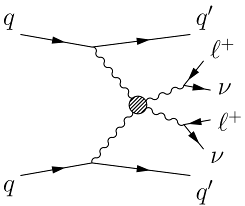

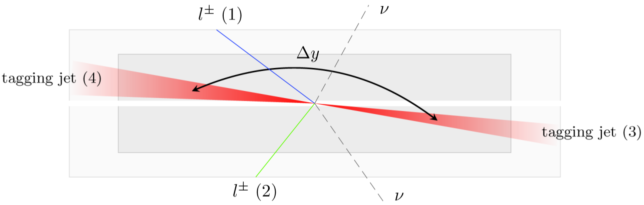

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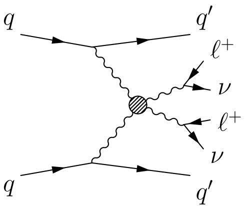

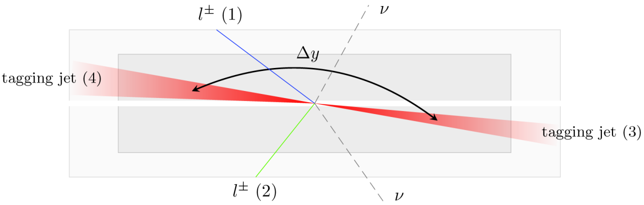

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- $m_{jj} > 500$ GeV $\Rightarrow$ **Inclusive Signal Region**

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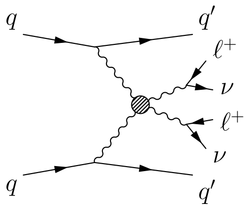

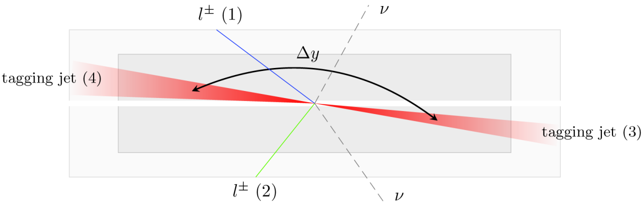

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- $\Delta y(jj) > 2.4$ $\Rightarrow$ **VBS Signal Region**

background overview

- Prompt backgrounds:
  - WZ+jets
  - ZZ+jets
  - $t\bar{t} + V$
- Photon conversions:
  - $W\gamma$+jets
  - Z+jets and $t\bar{t}$ events with electron charge mis-ID
- Other non-prompt:
  - Leptons originating from hadronic jets

background overview

- Prompt backgrounds:
  - WZ+jets: Sherpa
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(Prompt backgrounds and $W\gamma$+jets: MC)

(Z+jets and $t\bar{t}$ charge mis-ID, and leptons from hadronic jets: data-driven)

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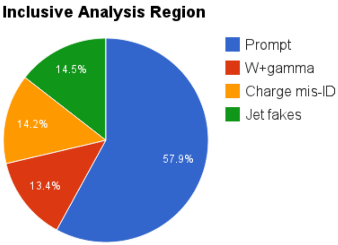
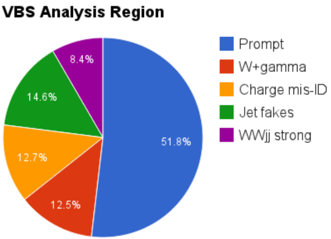
- Background composition:

MC

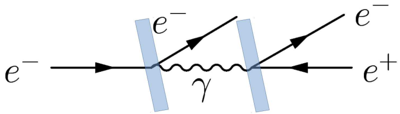
data-driven





lepton charge mis-ID

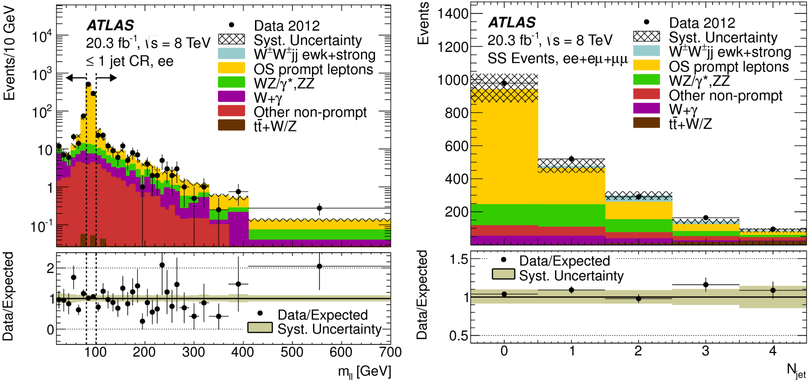
- Mostly through photon conversion. Negligible for muons.



- Charge mis-ID rate measured using $Z \to ee$ events in data.
- Scale opposite-sign data sample by the charge mis-ID rate to estimate the background in same-sign signal regions.
- Electron energy loss applied according to MC studies.

lepton charge mis-ID

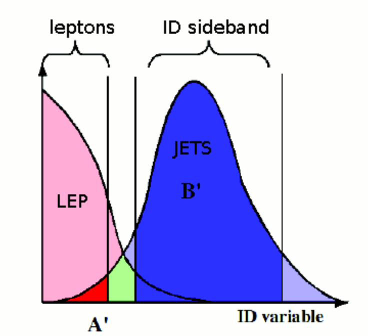
ATLAS-STDM-2013-06



- $m_{\ell\ell}$ shape validates charge mis-ID rate and energy loss correction.
- Jet distributions correctly predicted by charge mis-ID background estimation.

non-prompt background

- Non-prompt leptons come from hadronic jets: mis-reconstruction or hadron decay.
- Use lepton isolation sideband to extrapolate from non-prompt dominated region to signal region: fake factor method.



- Measure fake factors in dijet sample.

non-prompt bkg. estimation

- Not easy to find a non-prompt-dominated CR given the tight lepton isolation. Use a $b-$tag SS CR with 20%-40% from non-prompt.

non-prompt bkg. estimation

- Not easy to find a non-prompt-dominated CR given the tight lepton isolation. Use a $b-$tag SS CR with 20%-40% from non-prompt.
- Event yields in $b-$tag SS CR: ATLAS-STDM-2013-06

b-tag Control Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
Non-prompt	6.7 ± 2.5	20 ± 8	10 ± 5	37 ± 10
Total Predicted	40 ± 6	75 ± 13	25 ± 7	141 ± 22
Data	46	82	36	164

non-prompt bkg. estimation

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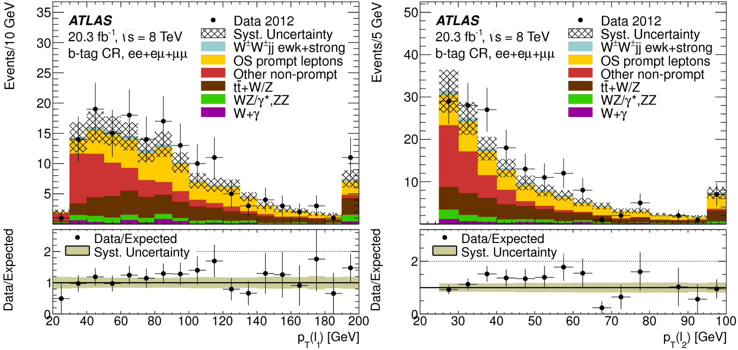
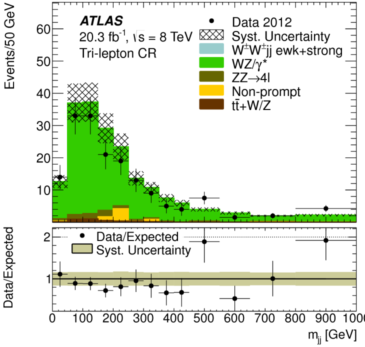
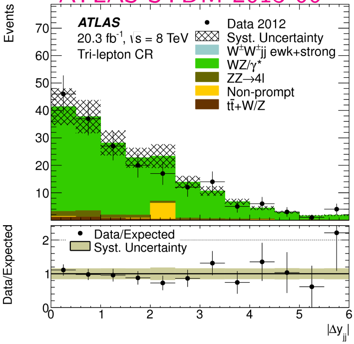


- The largest background in both signal regions.
- Estimated using MC. Checked in trilepton control region.
  - Instead of vetoing a third lepton, require exactly one third lepton passing the veto lepton definition,
  - m_{jj} and $\Delta y(jj)$ cuts not applied.

ATLAS-STDM-2013-06

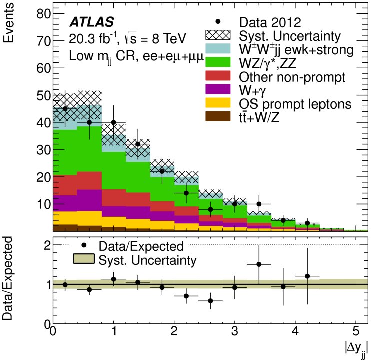


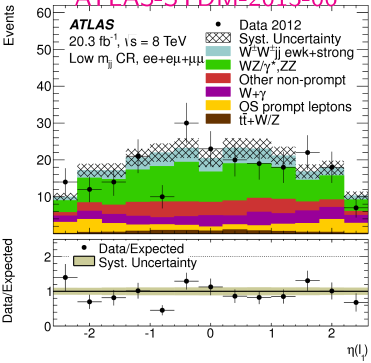


low m_{jj} control region

- Same as the Inclusive Signal Region up to the $m_{jj} > 500$ GeV cut. Require instead $m_{jj} < 500$ GeV.
- Good test of the overall background estimation.

ATLAS-STDM-2013-06





systematic uncertainties

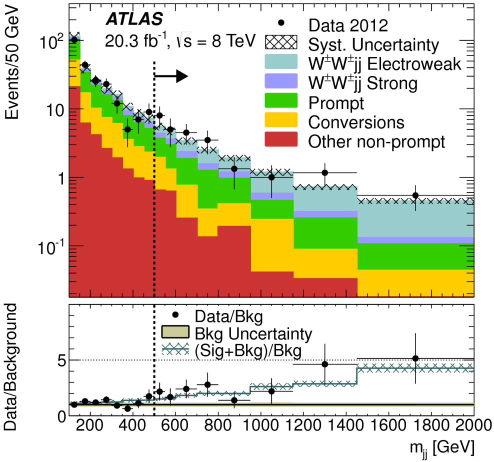
- Summary of systematics in Inclusive analysis region:

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background	$ee/e\mu/\mu\mu$	Signal	$ee/e\mu/\mu\mu$
Jet reconstruction	**11/13/13**	**Jet reconstruction**	**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		

- The uncertainties in the VBS analysis region are of the same order.

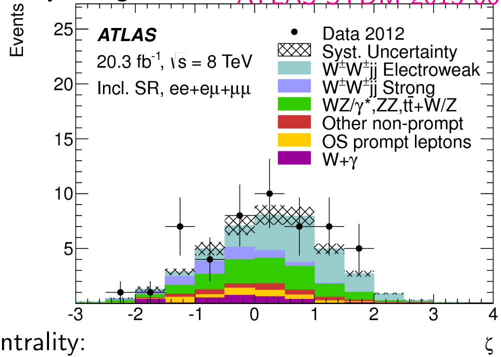
- Inclusive analysis region:

ATLAS-STDM-2013-06

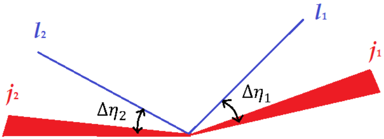


signal region plots (II)

- Inclusive analysis region: ATLAS-STDM-2013-06

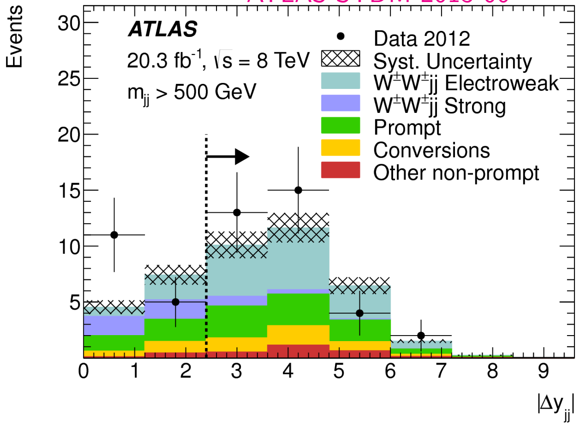


- lepton centrality:
  $\zeta = min\{\eta(j_1) - \eta(\ell_1), \eta(\ell_2) - \eta(j_2)\}$ where $\eta(j_1) > \eta(j_2)$ and $\eta(\ell_1) > \eta(\ell_2)$
- $\zeta > 0$ for VBS and centers around 0 for other processes.



- VBS analysis region:

ATLAS-STDM-2013-06



signal region event yields

- Event yields in the signal region

ATLAS-STDM-2013-06

	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**

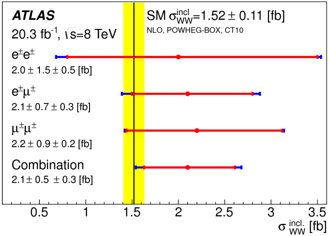
- Significant excess when comparing observed data with backgrounds only.
- Good agreement between data and signal+background.

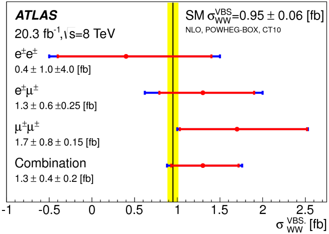
"Cut and count" experiment:

ATLAS-STDM-2013-06

	Inclusive analysis region		**VBS** analysis region	
channel	Significance Z (expected)	$\sigma^{\text{Ewk+Strong}}_{W^\pm W^\pm jj}$ [fb]	Significance Z (expected)	$\sigma^{\text{Ewk}}_{W^\pm W^\pm jj}$ [fb]
ee channel	1.6/(1.3)	$2.0^{+1.54}_{-1.32}$	0.4/(1.1)	$0.4^{+1.1}_{-0.4}$
$e\mu$ channel	3.3/(2.6)	$2.1^{+0.78}_{-0.71}$	2.4/(2.0)	$1.3^{+0.6}_{-0.6}$
$\mu\mu$ channel	3.5/(2.5)	$2.2^{+0.94}_{-0.78}$	3.2/(2.1)	$1.7^{+0.8}_{-0.7}$
combined	**4.5**/(3.4)	$2.1^{+0.58}_{-0.56}$	**3.6**/(2.8)	$1.3^{+0.46}_{-0.42}$

First evidence for both the inclusive and electroweak production of same-sign $W^\pm W^\pm jj$



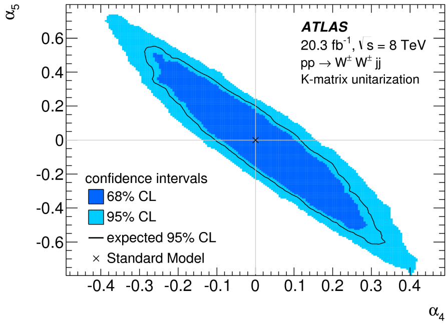


Measured cross sections agree with the SM prediction within 1 σ

anomalous quartic gauge coupling

- Low energy effects from new physics at scales beyond our LHC reach can be parameterized by effective field theories with higher-dimensional operators: $\mathcal{L}_{eff} = \mathcal{L}_{\text{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{L}_i^{(d)}$
- Use WHIZARD to simulate different aQGC points (non-linear representation). K-matrix method is adopted to restore unitarity.
- Our analysis is sensitive to the dimensional 4 parameters α_4 $((\text{tr}\{V_\mu V_\nu\})^2))$ and α_5 $((\text{tr}\{V_\mu V^\mu\})^2)$.
- Limits are extracted using the VBS signal region.

ATLAS-STDM-2013-06



Observed 1D limits:

$\alpha_4 \in [-0.14, 0.16]$

$\alpha_5 \in [-0.23, 0.24]$

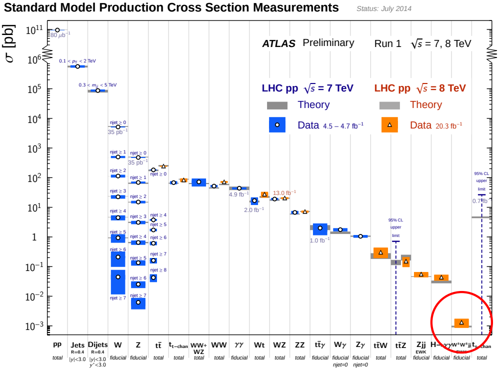
Expected 1D limits:

$\alpha_4 \in [-0.10, 0.12]$

$\alpha_5 \in [-0.18, 0.20]$

summary of same-sign WW VBS

- The fiducial cross section of the inclusive $W^{\pm}W^{\pm}jj$ and $W^{\pm}W^{\pm}jj$−Ewk has been measured using the 2012 8 TeV data set, consistent with the SM prediction within 1 σ.
- First evidence for both inclusive $W^{\pm}W^{\pm}jj$ (4.5σ) and $W^{\pm}W^{\pm}jj$−Ewk (3.6σ)! Evidence for VBS!
- aQGC limits are set on α_4, α_5 parameters in the effective field theory (with K-matrix unitarisation).



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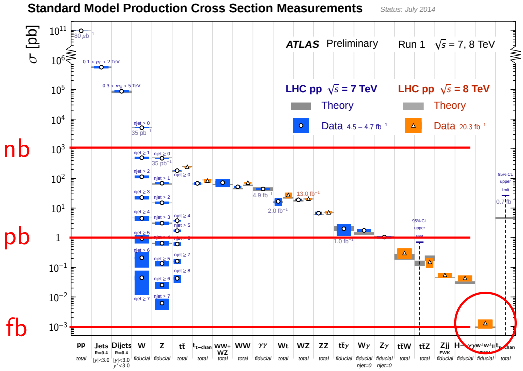
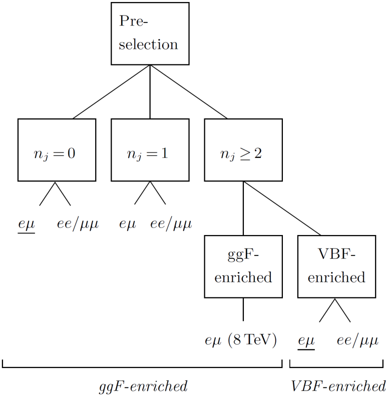


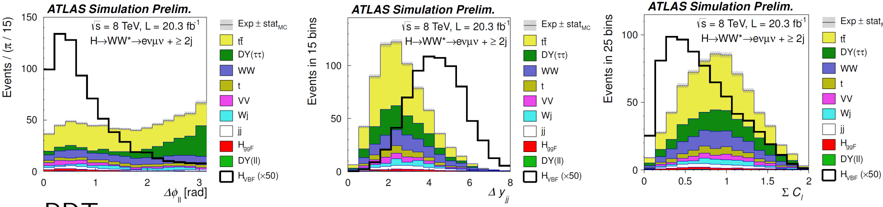
$H \to WW^* \to \ell^+\nu\ell'^-\nu'$

- The ATLAS $H \to WW^*$ analysis using 7 and 8 TeV data is recently updated with 6.1 σ for total production and 3.2 σ for VBF production.
- Improvements of the analysis:
  - track-based missing transverse momentum: better $m_{\mathrm{T}}(WW)$ resolution, better background suppression
  - likelihood ID for electron: same signal efficiency with better background suppression
  - lower sub-leading lepton p_{T}: increase in signal acceptance
- Major backgrounds:
  - Drell-Yan, top, SM W^+W^-, other diboson processes: MC estimation
  - Non-prompt ($W + jets$ and multijet): data-driven

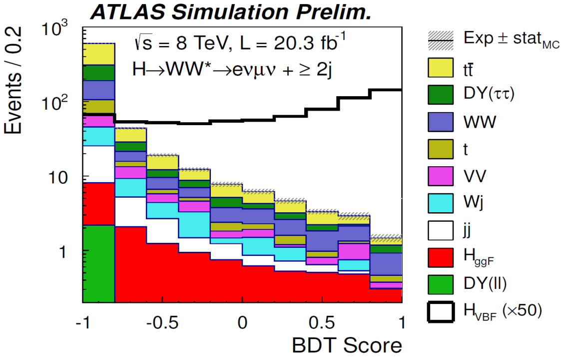
- The VBF-enriched region is defined based on BDT after di-lepton, p_T^{miss}, $N_{jet} \geq 2$ and central jet veto.
- Input variables to BDT:
  - VBS topology: m_{jj}, Δy_{jj}, sum of lepton centrality $\left(C_\ell = \left|\eta_\ell - \frac{\sum \eta_{jj}}{2}\right| / \frac{\Delta\eta_{jj}}{2}\right)$, $\sum m_{\ell j}$
  - Higgs decay topology: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T
  - others: vector sum of all p_T



- Input variables: $\Delta\phi_{\ell\ell}$, Δy_{jj}, $\sum C_\ell$ ATLAS-CONF-2014-060

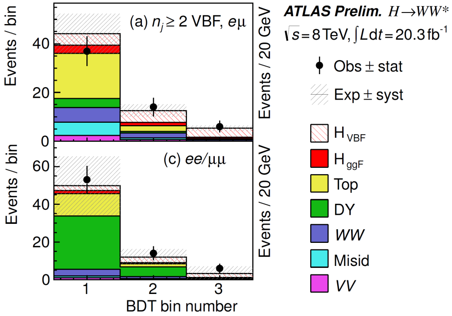


- BDT score:



ATLAS-CONF-2014-060

- Observed BDT:



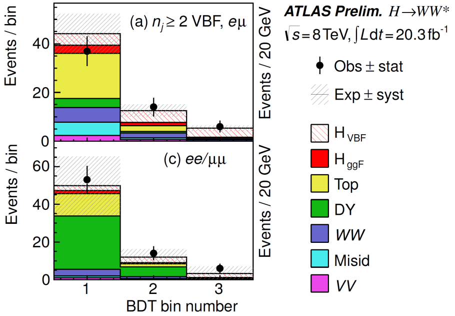
- Event yields:

Channel	Obs.	Sig.	Bkg.
$n_j \geq 2$, VBF (8 TeV)	130	29±4	99±9
$e\mu$ bin 1	37	8.2±1.3	36±4
$e\mu$ bin 2	14	6.3±0.8	6.5±1.3
$e\mu$ bin 3	6	4.2±0.8	1.2±0.3
$ee/\mu\mu$ bin 1	53	4.2±0.7	46±6
$ee/\mu\mu$ bin 2	14	3.6±0.5	8.4±1.8
$ee/\mu\mu$ bin 3	6	2.3±0.4	1.1±0.4
$n_j \geq 2$, VBF (7 TeV)	9	3.6±0.4	7.8±1.8
$e\mu$ bin 1	6	1.0±0.2	3.0±0.9
$e\mu$ bin 2-3	0	1.3±0.2	0.7±0.2
$ee/\mu\mu$ bins 1-3	3	1.2±0.2	4.1±1.3

VBF $H \to WW^*$

ATLAS-CONF-2014-060

- Observed BDT:



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$ee/\mu\mu$ bins 1-3	3	1.2±0.2	4.1±1.3

- Measured VBF production cross section:
  $\sigma_{\rm VBF}^{\rm 8TeV} \times \mathcal{B}_{H\to WW^*} = 0.51^{+0.17}_{-0.15}({\rm stat.})^{+0.13}_{-0.08}({\rm syst.}) = 0.51^{+0.22}_{-0.17}$ pb
  SM prediction: 0.35 ± 0.02 pb
- Observed significance: 3.2 σ; Expected significance: 2.7 σ
- Evidence for VBF $H \to WW^*$ production!

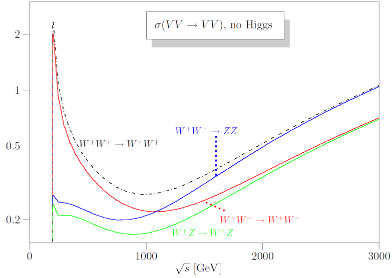
conclusion

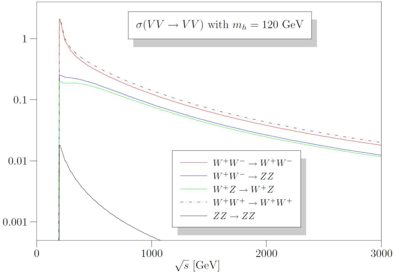
- The VBS is a process essential to the understanding of the EWSB; Sensitivity to aQGC.
- First evidence has been obtained for VBS!
- It's finally the time to study VBS at LHC. With higher energy and more data in the next three years, more to expect!

Backup Slides

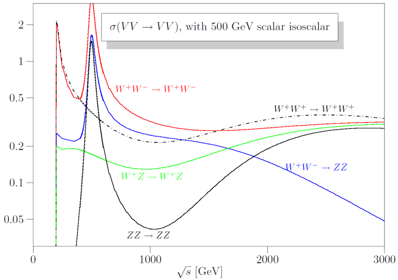
WW scattering

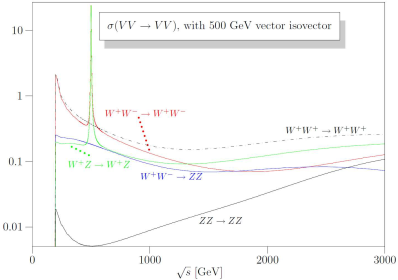
- J. Chang, K Cheung, CT Lu, TC Yuan, PRD 87 (2013) 093005:
  - $i\mathcal{M}_{QGC} = i\frac{g^2}{4m_W^4}\left[s^2 + 4st + t^2 - 4m_W^2(s+t) - \frac{8m_W^2}{s}ut\right]$
  - $i\mathcal{M}^{Z/\gamma}_{s-channel} = -i\frac{g^2}{4m_W^4}\left[s(t-u) - 3m_W^2(t-u)\right]$
  - $i\mathcal{M}^{Z/\gamma}_{t-channel} = -i\frac{g^2}{4m_W^4}\left[(s-u)t - 3m_W^2(s-u) + \frac{8m_W^2}{s}u^2\right]$
  - $i\mathcal{M}_H = -i\frac{g^2}{4m_W^2}\left[\frac{(s-2m_W^2)^2}{s-m_H^2} + \frac{(t-2m_W^2)^2}{t-m_H^2}\right]$
- Alboteanu et al. JHEP: 0811.010 (2008):





- Higgs mechanism is not the only solution to the unitarization. BSM resonances can also contribute: (Alboteanu et al. JHEP: 0811.010 (2008))





definition of fiducial regions

- object definitions:
  - dressed leptons: leptons summed with all four-vectors of any photon within ΔR =0.1; leptons are selected before dressing to avoid over-dressing with the photons from jet fragmentation; leptons are dressed before passed to event selections
  - jets: reconstructed with the anti-k_T algorithm with radius parameter R =0.4, clustering all particles but neutrinos and muons; jets overlapping with dressed electrons within ΔR =0.05 are removed
- Inclusive region:
  - No ME-level τ lepton
  - Two leptons (e or μ) with $p_\mathrm{T} > 25$ GeV and $|\eta| <2.5$
  - Two leptons have same electric charge with $m_{\ell\ell'} > 20$ GeV
  - Two leptons are separated with $\Delta R(\ell\ell') > 0.3$
  - Truth $E_\mathrm{T}^\mathrm{miss} > 40$ GeV
  - At least two jets with p_T >30 GeV and $|\eta| <4.5$
  - Selected leptons and jets are separated with min($\Delta R(\ell, jet)$)>0.3
  - The two leading p_T jets have $m_{jj} > 500$ GeV
- VBS region:
  - On top of the inclusive region, reguire the two leading p_T jets separated with $|\Delta y_{jj}| > 2.4$

lepton definitions

- nominal leptons

	electron	muon
p_{T}	$>$25 GeV	
$\|\eta\|$	$<$2.47, $\notin [1.37, 1.52]$	$<$2.5
ID/quality	author = 1 or 3 OQ cleaning `tight++`	staco MCP hits combined and tight same ID/MS trk. charge
impact parameter	$|z_0 \times sin\theta| <$0.5 mm, $|d_0/\sigma(d_0)| <$3	
isolation	$p_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.06 topo-$E_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.14	$p_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.07 $E_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.07

- veto leptons

	electron	muon
p_{T}	$>$7 GeV	$>$6 GeV
ID/quality	`loose++`	loose no trk. charge requirement
isolation	$p_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.13	$p_{\mathrm{T}}^{cone30}/p_{\mathrm{T}} <$0.15

jets and overlap removal

- jets

algorithm	AntiKt4TopoEM
p_{T}	$>$30 GeV
$\|\eta\|$	$<$4.5
quality	NOT looserBad
pileup removal	$|JVF| >$0.5 when $|\eta| <$2.4 && $p_{\mathrm{T}} <$50 GeV
$b-$jets	MV1 tagger, 70% eff. working point, $|\eta| <$2.5

- overlap removal

if $\Delta R(e, jet) < 0.3$	remove jet
if $\Delta R(e, \mu) < 0.1$	remove electron
if $\Delta R(\mu, jet) < 0.3$	remove event

- $E_{\mathrm{T}}^{\mathrm{miss}}$: MET_RefFinal, recalculated using calibrated objects

systematic uncertainties in the VBS analysis region

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background		Signal	
Jet reconstruction	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^{*}	4.5/5.4/7.8	Jet reconstruction	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 $W+\gamma$	2.6/2.6/–	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		

signal efficiency

Inclusive analysis region			
	ee channel	$e\mu$ channel	$\mu\mu$ channel
$W^{\pm}W^{\pm}jj$ EW	$(56.7 \pm 1.5)\%$	$(73.0 \pm 0.9)\%$	$(80.4 \pm 1.1)\%$
$W^{\pm}W^{\pm}jj$ QCD	$(54.5 \pm 2.3)\%$	$(68.1 \pm 1.4)\%$	$(77.3 \pm 1.8)\%$
$W^{\pm}W^{\pm}jj$ EW+QCD	$(56.2 \pm 1.3)\%$	$(71.7 \pm 0.8)\%$	$(77.0 \pm 0.9)\%$
VBS analysis region			
	ee channel	$e\mu$ channel	$\mu\mu$ channel
$W^{\pm}W^{\pm}jjj$ EW	$(57.2 \pm 1.6)\%$	$(72.7 \pm 1.0)\%$	$(82.7 \pm 1.2)\%$
$W^{\pm}W^{\pm}jjj$ QCD	$(53.4 \pm 3.8)\%$	$(70.2 \pm 2.4)\%$	$(73.7 \pm 3.2)\%$
$W^{\pm}W^{\pm}jjj$ EW+QCD	$(56.8 \pm 1.4)\%$	$(72.4 \pm 0.9)\%$	$(81.8 \pm 1.3)\%$

cross section calculation

- Two signal regions: In the Inclusive analysis region, the same sign $W^{\pm}W^{\pm}jj$ Ewk+Strong is taken as the signal. In the VBS analysis region, Ewk is the signal.
- Cut and count experiment: Likelihood function is constructed using numbers of events in all three dilepton channels assuming Poisson distributions and nuisance parameters representing the systematic uncertainties. $L(\sigma_{W^{\pm}W^{\pm}jj}, \mathcal{L}, \alpha_j) = \mathrm{Gaus}(\mathcal{L}_0|\mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i\in\{ee,\mu\mu,e\mu\}} \mathrm{Pois}(N_i^{\mathrm{obs}}|N_{i,\mathrm{tot}}^{\mathrm{exp}}) \prod_{j\in\mathrm{syst}} \mathrm{Gaus}(\alpha_j^0|\alpha_j, 1)$

cross sections

combined:

$$\sigma^{\text{EWQCD}}_{W^\pm W^\pm jj} = 2.1 \pm^{0.5}_{0.5} (\text{stat.}) \pm^{0.3}_{0.3} (\text{sys.})\ \text{fb.} \tag{1}$$

$$\sigma^{\text{EW+INT}}_{W^\pm W^\pm jj} = 1.3 \pm^{0.4}_{0.4} (\text{stat.}) \pm^{0.2}_{0.2} (\text{sys.})\ \text{fb.} \tag{2}$$

in separate channels:

$$\sigma^{\text{EWQCD, } ee\text{, Incl. SR}}_{W^\pm W^\pm jj} = 2.0 \pm^{1.5}_{1.2} (stat.) \pm^{0.5}_{0.5} (sys.)\ \text{fb.} \tag{3}$$

$$\sigma^{\text{EWQCD, } e\mu\text{, Incl. SR}}_{W^\pm W^\pm jj} = 2.1 \pm^{0.7}_{0.6} (stat.) \pm^{0.3}_{0.3} (sys.)\ \text{fb.} \tag{4}$$

$$\sigma^{\text{EWQCD, } \mu\mu\text{, Incl. SR}}_{W^\pm W^\pm jj} = 2.2 \pm^{0.9}_{0.8} (stat.) \pm^{0.2}_{0.2} (sys.)\ \text{fb.} \tag{5}$$

$$\sigma^{\text{EW+INT, } ee\text{, VBS SR}}_{W^\pm W^\pm jj} = 0.37 \pm^{1.0}_{0.80} (stat.) \pm^{0.36}_{0.40} (sys.)\ \text{fb.} \tag{6}$$

$$\sigma^{\text{EW+INT, } e\mu\text{, VBS SR}}_{W^\pm W^\pm jj} = 1.26 \pm^{0.60}_{0.51} (stat.) \pm^{0.24}_{0.25} (sys.)\ \text{fb.} \tag{7}$$

$$\sigma^{\text{EW+INT, } \mu\mu\text{, VBS SR}}_{W^\pm W^\pm jj} = 1.74 \pm^{0.82}_{0.67} (stat.) \pm^{0.15}_{0.15} (sys.)\ \text{fb.} \tag{8}$$

$K-$matrix unitarization

- Project the scattering amplitude $\mathcal{A}(s)$ onto the Argand circle: saturation of the amplitude to achieve unitarity
- Amplitudes satisfying unitarity are invariant under $K-$matrix unitarization
- $\mathcal{A}_K(s) = \dfrac{\mathcal{A}(s)}{1 - i\mathcal{A}(s)}$

arXiv:1310.6708

arXiv:1307.8170