Results and Prospects in VBS-VV Production in Charged Diboson Channels (including aQGCs): WW, WZ, WY

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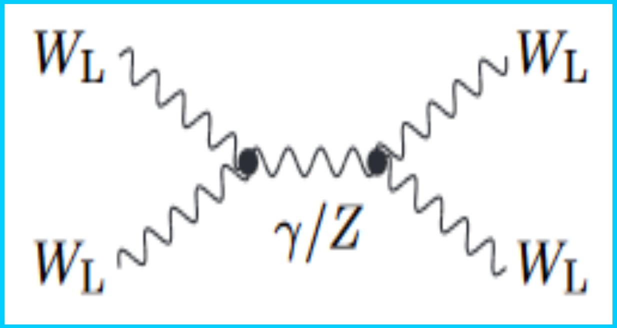
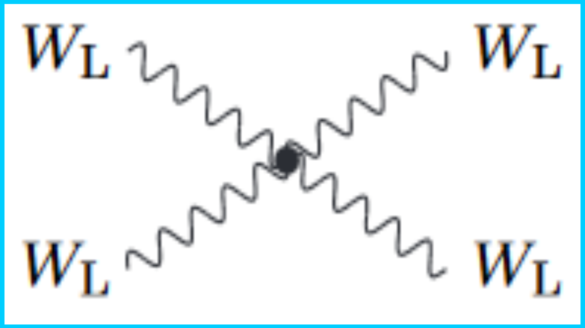
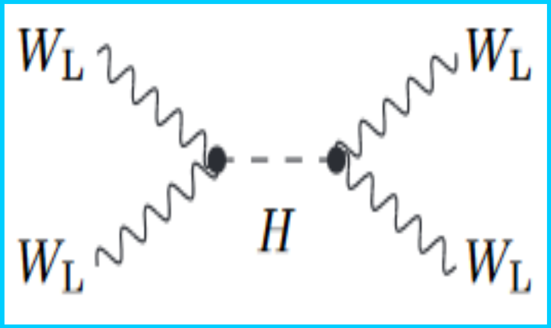
Vector Boson Scattering (VBS)

- **Production involving scattering of massive vector bosons**
- Produced via **Triple Gauge Coupling (TGC)**, **Quartic Gauge Coupling (QGC)**, or **Higgs exchange** in s- and t- channel







❖ **Longitudinal scattering of massive gauge bosons (V) is unitarized by interference with Higgs diagrams in SM**

⇒ **The V_L are coupled to the Higgs and they are the ones sensitive to the EWSB.**

⇒ **The behavior of the LL cross section can give information on the scale at which the symmetry breaks.**

VBS and New Physics

● The non-abelian nature $SU(2)_L x U(1)_Y$ of SM predicts the existence of the tri-linear as well as quartic gauge couplings.

● SM allows only charged couplings, i.e. WWZ, WWγ, WWWW, etc :
○ pure neutral couplings, i.e. ZZZ type are not allowed at SM tree level since Z/γ has no charge or isospin

➢ Conceptually, trilinear coupling probe the non-abelian gauge structure, while quartic coupling can be a window on the mechanism of the spontaneous symmetry breaking

● Physics beyond SM can introduce anomalous TGC or QGC which may allow neutral couplings or increase the charged TGC and QGC strength in a model-independent way

➢ **BSM physics can be parameterized in an effective field theory (EFT):**

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Results in enhancement at large scattering energies

Anomalous Quartic Gauge Couplings

Dimension 8 operators: Lowest dimension operators that modify the quartic boson interactions but do not affect the two or three weak gauge boson vertices.

Scalar operators only involve Higgs doublet

$$\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

Mixed operators mix scalar and tensor

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right]$$

$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \hat{W}^{\nu\alpha} \right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\alpha\mu} \hat{W}^{\beta\nu} \right] \times B_{\beta\nu}$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}$$

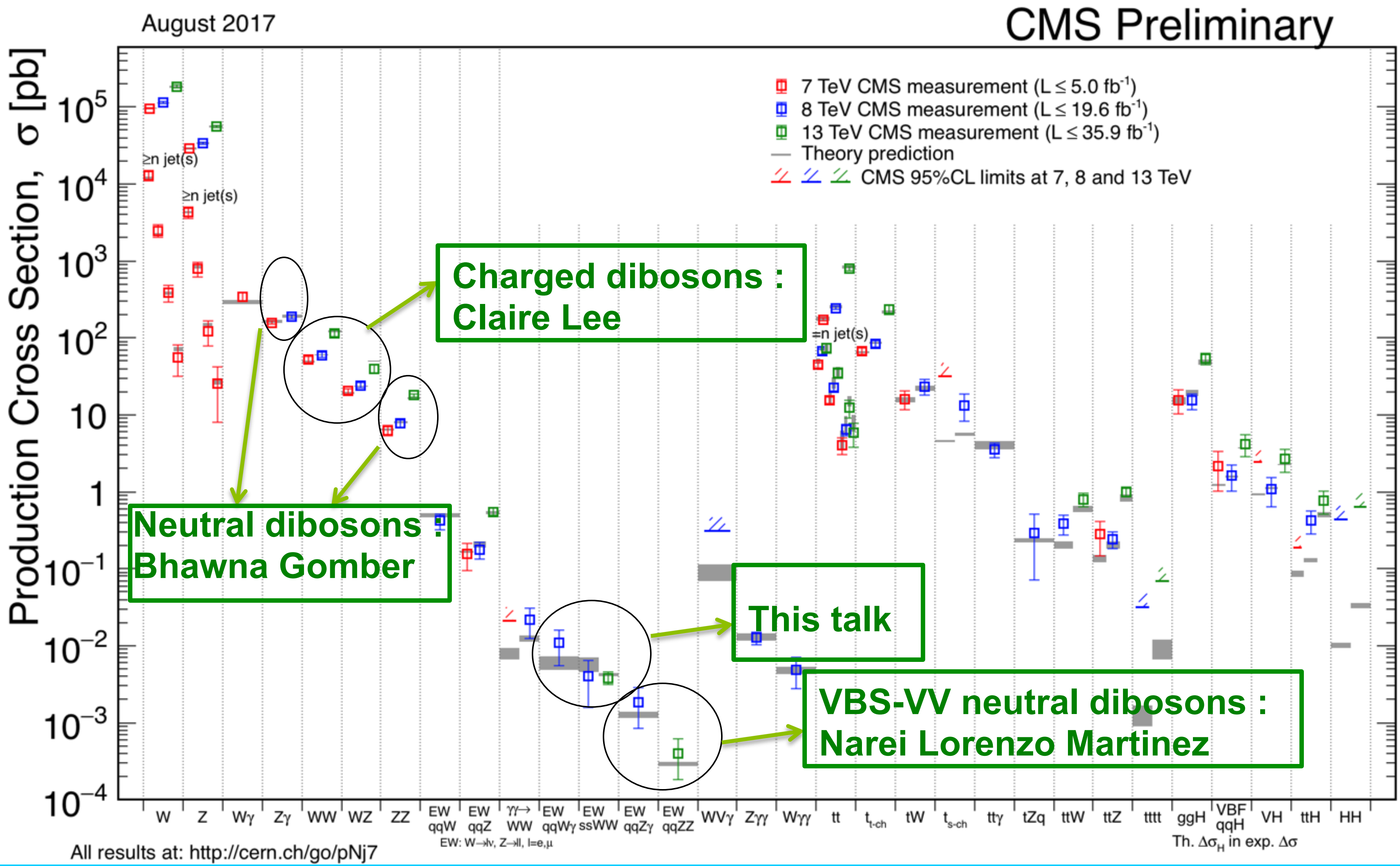
$$\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

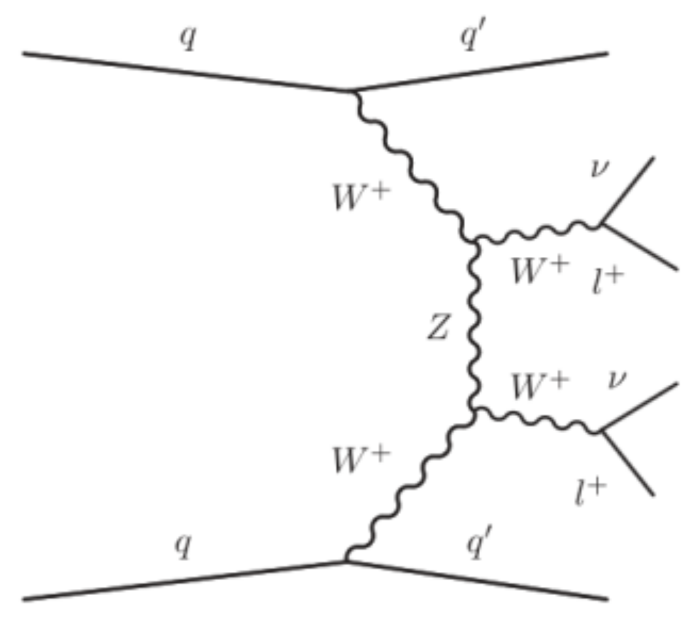
Tensor operators only field strength tensors

Ref: Phys.Rev. D74 (2006) 073005

Cross Sections



$W^{\pm}W^{\pm}$ – Signal selection



Large cross section x branching ratio
- Irreducible background low, S/B ~ 1

- Further background suppression via b-jet veto (ttbar) and anti-Z cuts in electron channels (DY)
- Data-driven estimates for reducible backgrounds
- Lepton fake rates extrapolate from ttbar-enriched to signal region
- WZ normalization from trilepton control region
- Data-driven charge mis-ID rates correct the simulation

- **Event selection:**
- Two and only two leptons ($\ell = \mu, e$) of same charge with pT 1(2) > 25(20) GeV $m_{\ell\ell}$ > 20 GeV
- Two jets with pT > 30 GeV, leading jets taken as tagging jets, m_{jj} > 500 GeV, $|\Delta\eta_{jj}|$ > 2.5, max ($z\ell^*$) < 0.75, where $z\ell^* = |\eta_l - (\eta_{j1} - \eta_{j2})/2|/|\Delta\eta_{jj}|$ is Zeppenfeld variable
- ET miss > 40 GeV

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$W^{\pm}W^{\pm}$ Cross Section

	$\mu^+\mu^+$	e^+e^+	$e^+\mu^+$	$\mu^-\mu^-$	e^-e^-	$e^-\mu^-$	Total
Data	40	14	63	26	10	48	201
Signal+Total bkg.	44.1 ± 3.4	19.0 ± 1.9	67.6 ± 3.8	23.9 ± 2.8	11.8 ± 1.8	38.9 ± 3.3	204.8 ± 7.2
Signal	18.3 ± 0.4	6.2 ± 0.2	24.7 ± 0.4	6.5 ± 0.2	2.5 ± 0.1	8.7 ± 0.2	66.9 ± 0.7
Total bkg.	25.7 ± 3.4	12.8 ± 1.9	42.9 ± 3.8	17.4 ± 2.8	9.4 ± 1.8	30.2 ± 3.3	137.9 ± 7.1
Non-prompt	18.4 ± 3.3	5.6 ± 1.7	24.9 ± 3.6	14.2 ± 2.8	5.0 ± 1.6	19.9 ± 3.2	87.9 ± 6.9
WZ	4.4 ± 0.2	3.0 ± 0.2	8.5 ± 0.3	2.2 ± 0.1	1.9 ± 0.2	5.2 ± 0.3	25.1 ± 0.6
QCD WW	1.3 ± 0.1	0.6 ± 0.1	1.7 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	4.8 ± 0.2
$W\gamma$	0.2 ± 0.2	1.4 ± 0.5	3.6 ± 0.9	-	0.8 ± 0.4	2.3 ± 0.7	8.3 ± 1.3
Triboson	1.2 ± 0.3	0.8 ± 0.2	2.2 ± 0.4	0.5 ± 0.2	0.3 ± 0.1	0.9 ± 0.3	5.8 ± 0.7
Wrong sign	-	1.5 ± 0.6	1.4 ± 0.4	-	1.1 ± 0.5	1.2 ± 0.4	5.2 ± 1.0

- Only statistical uncertainties listed above
- Signal contributions include only electroweak productions. QCD production is considered as background.
- The interference between the EW and QCD processes is of a few percent in the signal region and considered as systematic uncertainty.

➢ **An excess of events could signal the presence of anomalous quartic gauge couplings (aQGC) or the existence of a new resonance, such as a doubly charged Higgs boson.**

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Major Systematics

- The normalization processes for misidentified leptons - 30%.
- The WZ normalization uncertainty is 20-40% (dominated by the small number of events in the trilepton control region)
- Theoretical uncertainties of 12% for the signal normalization and 20% for the triboson background normalization (estimated by varying the renormalization and factorization scales up and down by a factor of two from their nominal value in the event)
- The interference between the EW signal and the QCD background processes taken up to 4.5%.
- A PDF uncertainty of 5% in the normalization of the signal is included.

- Fiducial cross section measurement:

$$\sigma_{fid}\,(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66(stat) \pm 0.35(syst)\ fb$$

- In agreement with the SM expectation 4.25±0.21 fb.

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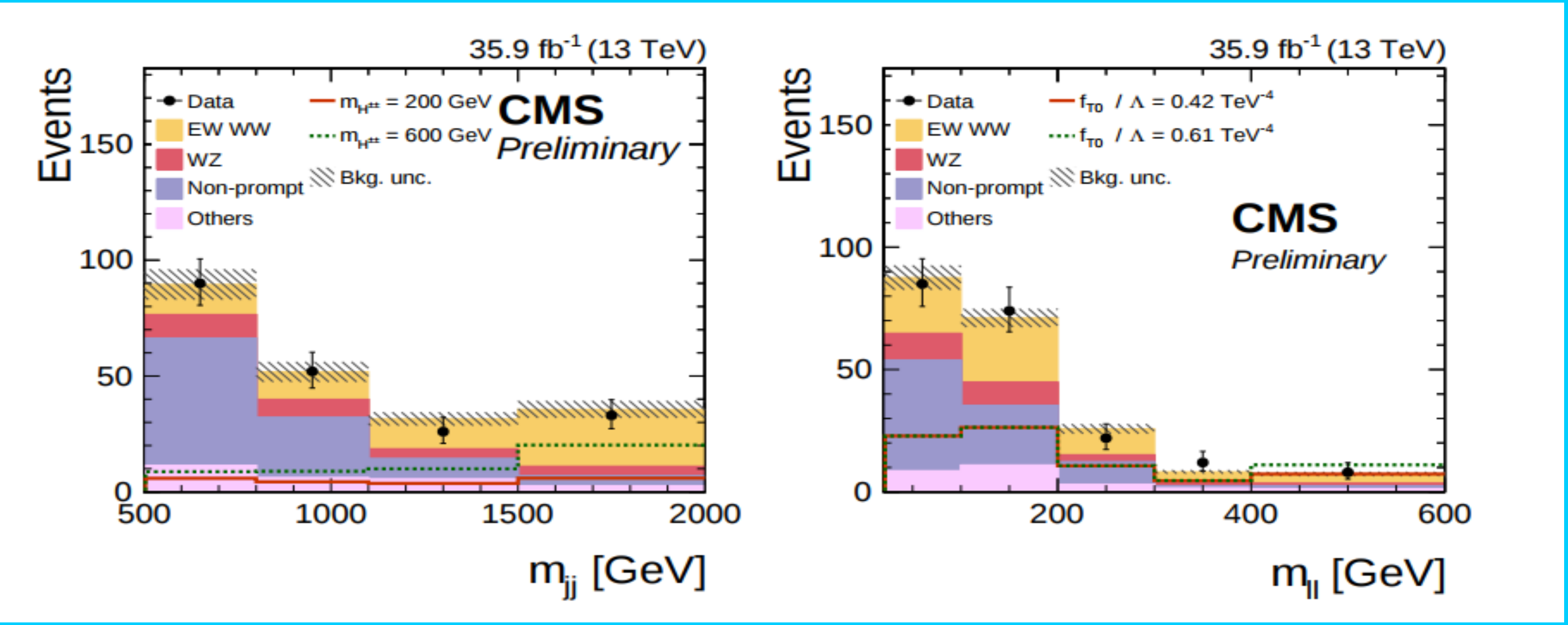
Observation of EW Production of W±W±



- **Major Backgrounds: Nonprompt leptons, WZ**

✓ **Signal strength evaluated by a simultaneous fit of signal region and WZ control region. The fit utilizes signal region with 2-D m_{jj} and m_{ll} distribution and 1-D m_{jj} distribution for control region.**

- **Observation at 5.5 standard deviations (5.7 expected)**

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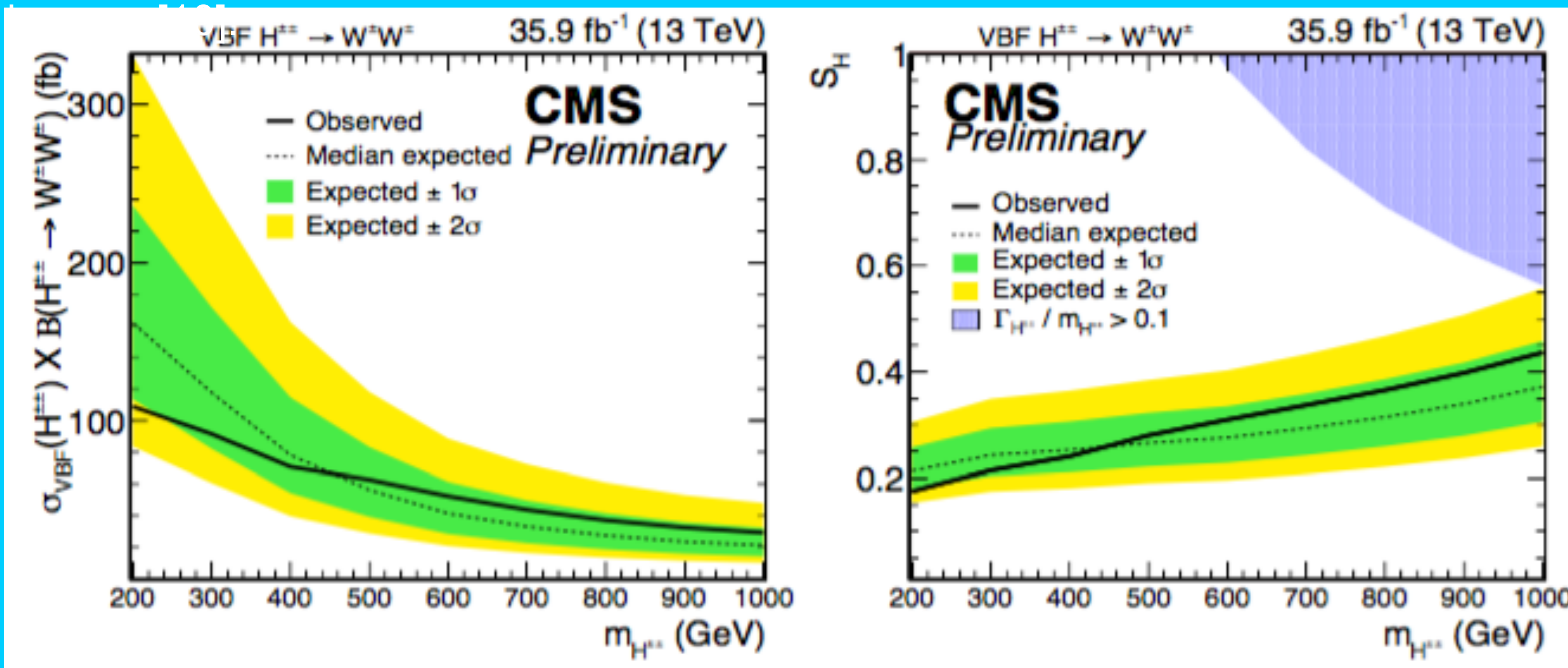
Limits on Doubly Charged Higgs boson

- Predicted in Higgs sectors beyond the SM where weak isotriplet scalars are included.
- They can be produced via weak vector-boson fusion (VBF) and decay to pairs of same-sign W



95% CL upper limits on doubly charged Higgs production and decay $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$.

Ratio of Higgs boson vacuum expectation values S_H

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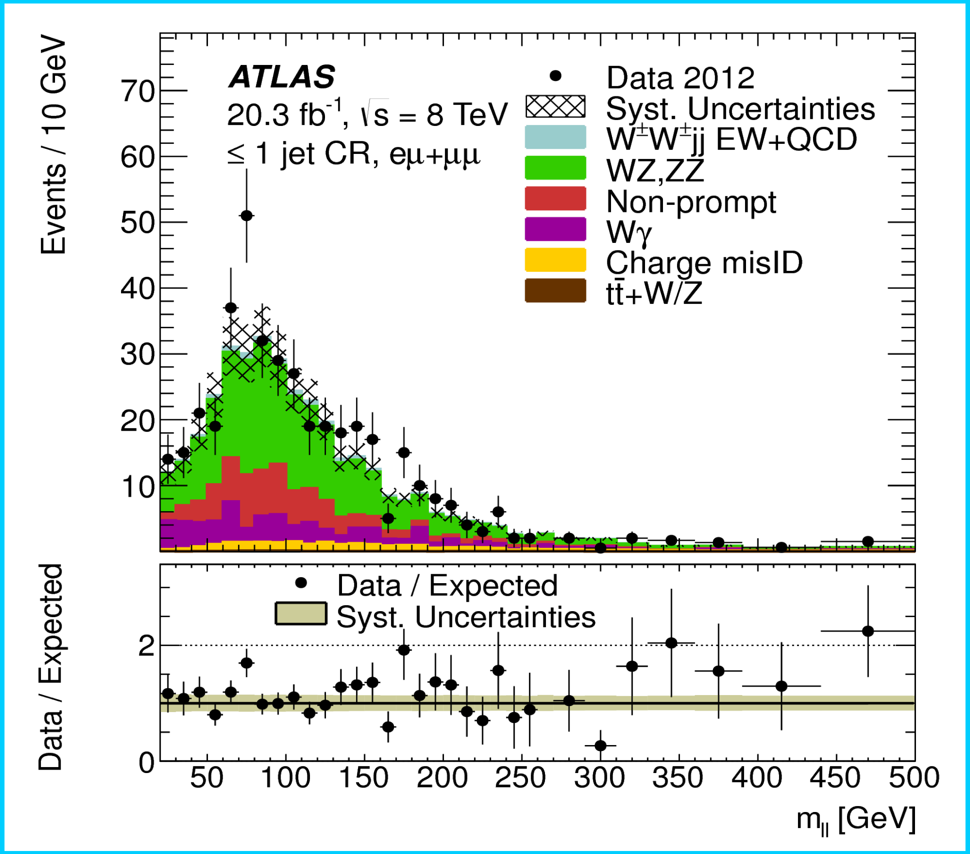
$W^{\pm}W^{\pm}$ – Signal Selection

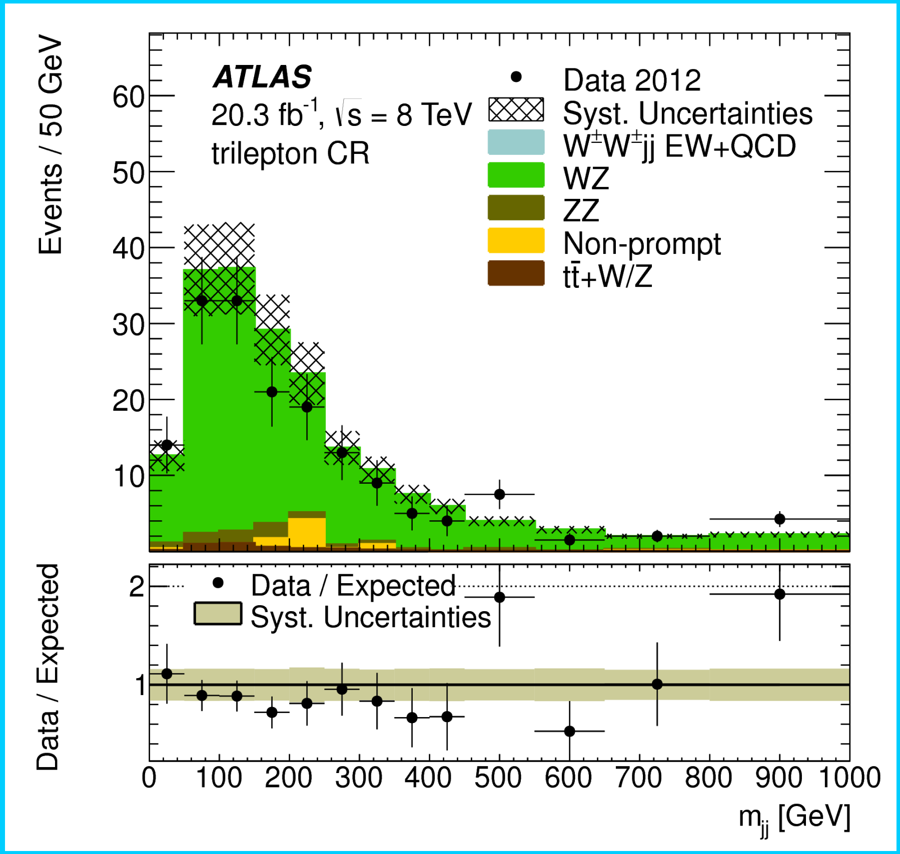
Signal Region		Selection Criteria
Inclusive	Lepton	Exactly two tight same-electric-charge leptons with $p_T > 25$ GeV
	Jet	At least two jets with $p_T > 30$ GeV and $\|\eta\| < 4.5$
	$m_{\ell\ell}$	$m_{\ell\ell} > 20$ GeV
	E_T^{miss}	$E_T^{miss} > 40$ GeV
	Z veto	$\|m_{\ell\ell} - m_Z\| > 10$ GeV (only for the $e^{\pm}e^{\pm}$ channel)
	Third-lepton veto	No third veto-lepton
	b-jet veto	No identified b-jets with $p_T > 30$ GeV and $\|\eta\| < 2.5$
	m_{jj}	$m_{jj} > 500$ GeV
VBS	Δy_{jj}	$\|\Delta y_{jj}\| > 2.4$
aQGC	$m_{WW,T}$	$m_{WW,T} > 400$ GeV

Four control regions (CRs) "≤ 1 jet CR", "trilepton CR", "b-tag CR", and "low-m_{jj} CR", are used to validate background predictions.

For all CRs, the contributions from $W^{\pm}W^{\pm}$ jj-EW and $W^{\pm}W^{\pm}$ jj-QCD production are normalized to the SM prediction

$W^{\pm}W^{\pm}$ – Signal Selection





The invariant mass distribution of the dilepton pair for the $e^{\pm}\mu^{\pm}$ and $\mu^{\pm}\mu^{\pm}$ channels in the ≤ 1 jet CR without the Z boson veto requirement

The m_{jj} distribution of the two jets with the highest p_T is shown summed over all lepton channels for the trilepton CR

Major systematics for $W^{\pm}W^{\pm}$

- Inclusive signal region (SR) treats both electroweak and strong production of $W^{\pm}W^{\pm}jj$ as signal.
- VBS signal region consists of events in inclusive SR with separation between two leading-pT jets greater than 2.4 in rapidity ($|\Delta y_{jj}|$).

Major Systematics

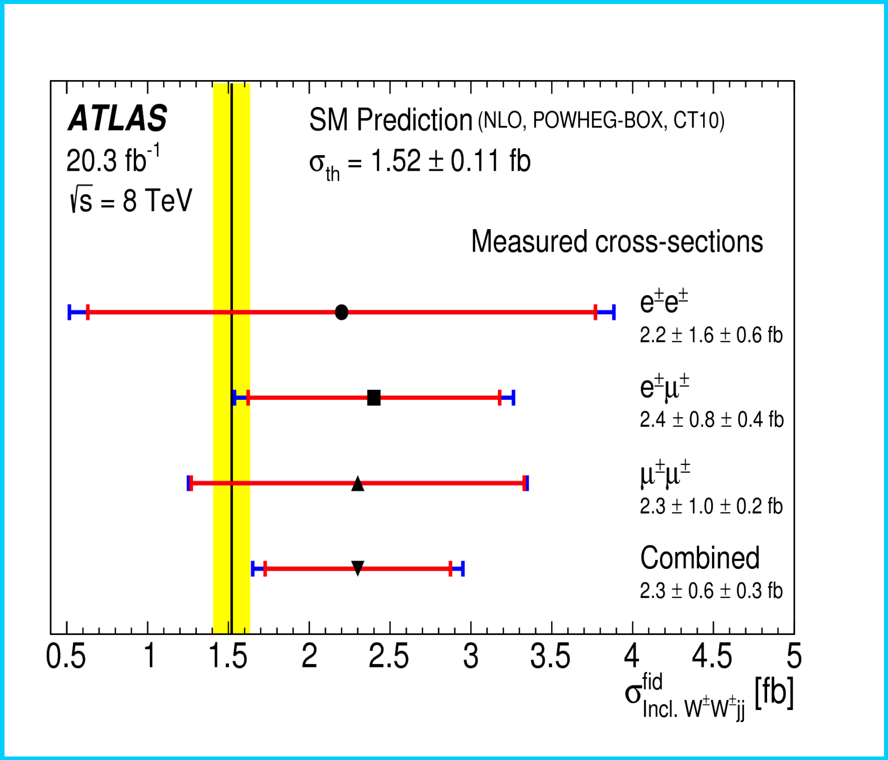
On Background Yield

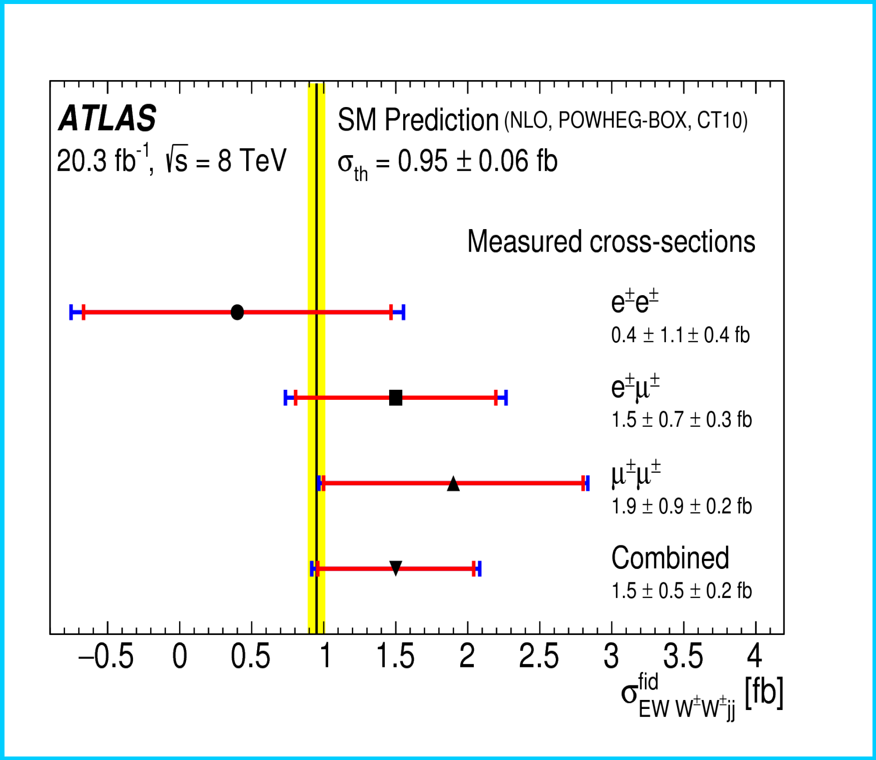
	Inclusive SR ee/eμ/μμ (%)	VBS SR ee/eμ/μμ (%)
Jet related uncertainty	11/13/13	13/20/20
W+-Zjj-EW cross section	6/8/11	5/5/8
MC sample size	8/6/8	9/6/8
Non-prompt	4/7/7	4/7/7

Signal Yield	Inclusive SR	VBS SR
Jet-related Unc.	6	5
W+-W=-jj-EW cross section	5	6
WWjj-QCD cross section	3.1	–
Luminosity	2.8	2.8

 https://arxiv.org/pdf/1611.02428

Measured cross section for $W^{\pm}W^{\pm}$





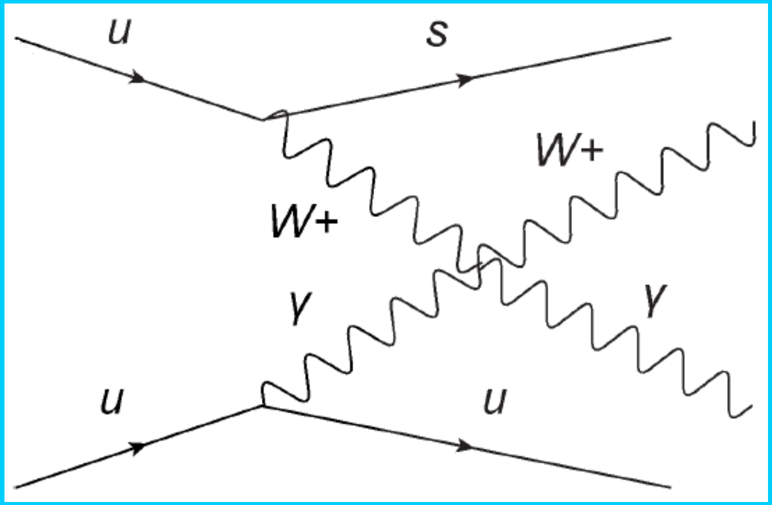
The observed combined significance over the background- only hypothesis is 4.5σ in the Inclusive SR and 3.6σ in the VBS SR, while the corresponding expected significances for a SM $W^{\pm}W^{\pm}$ jj signal are 3.1σ and 2.3σ, respectively.

https://arxiv.org/pdf/1611.02428

Wγ+2jet – Signal Selection

Final state considered: μ(e) + γ+ ET + 2 jets

Single-lepton (e, μ) trigger	$|M_{e\gamma} - M_Z| > 10\,\text{GeV}$ (electron channel)
Lepton, photon ID and isolation	$p_T^{j1} > 40\,\text{GeV}$, $p_T^{j2} > 30\,\text{GeV}$
Second lepton veto	$|\eta^{j1}| < 4.7$, $|\eta^{j2}| < 4.7$
Muon (electron) $p_T > 25\ (30)\,\text{GeV}$, $|\eta| < 2.1\ (2.4)$	$|\Delta\phi_{j1,\vec{p}_T^{\text{miss}}}| > 0.4$, $|\Delta\phi_{j2,\vec{p}_T^{\text{miss}}}| > 0.4\,\text{rad}$
Photon $p_T^{\gamma} > 22\,\text{GeV}$, $|\eta| < 1.44$	b quark jet veto for tag jets
W boson transverse mass $> 30\,\text{GeV}$	Dijet invariant mass $m_{jj} > 200\,\text{GeV}$
$|\vec{p}_T^{\text{miss}}| > 35\,\text{GeV}$	$\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell}, \Delta R_{\ell\gamma} > 0.5$



Process	Muon channel	Electron channel
EW-induced Wγ+2 jets	5.8 ± 1.8	3.8 ± 1.2
QCD-induced Wγ+jets	11.2 ± 3.2	10.3 ± 3.2
W+jets, 1 jet $\rightarrow \gamma$	3.1 ± 0.7	2.2 ± 0.5
MC $t\bar{t}\gamma$	1.2 ± 0.6	0.4 ± 0.2
MC single top quark	0.5 ± 0.5	0.6 ± 0.4
MC WVγ, V$\rightarrow$ two jets	0.3 ± 0.2	0.3 ± 0.2
MC Zγ+jets	0.2 ± 0.2	0.3 ± 0.2
Total prediction	22.1 ± 3.8	17.9 ± 3.5
Data	24	20

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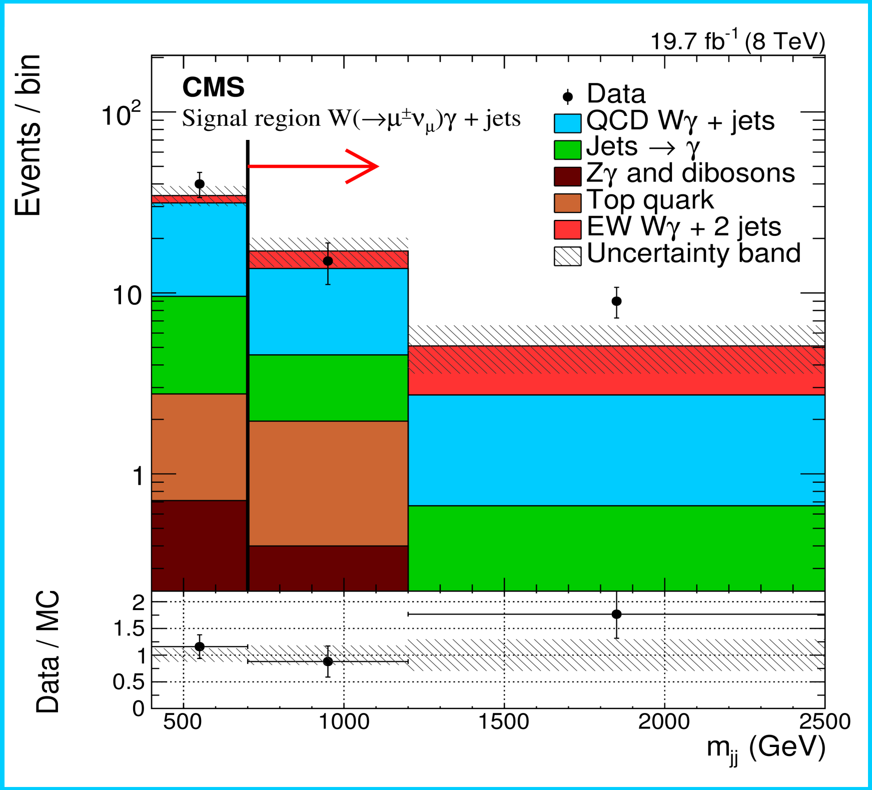
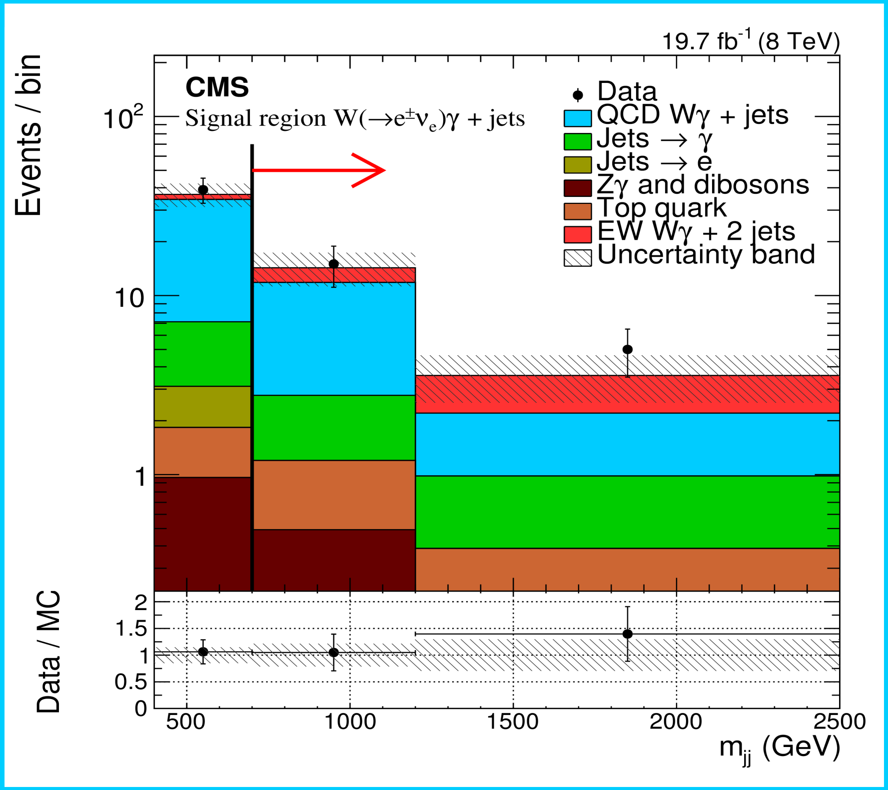
Wγ+2jet Cross Section





The m_{jj} distribution in the muon and electron channels (signal region lies above 700 GeV, indicated by the horizontal arrows).

σ_{fid} = 10.8 ± 4.1 (stat) ± 3.4 (syst) ± 0.3 (lumi) fb **(for VBS-like fiducial region)**

✓ **consistent with the SM prediction of EW- induced signal**

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Constrains on anomalous Quartic Gauge Couplings

Constrains on aQGC from $W^{\pm}W^{\pm}$

	Observed limits (TeV $^{-4}$)	Expected limits (TeV $^{-4}$)	Run-I limits (TeV $^{-4}$)
f_{S0}/Λ	[-7.7, 7.7]	[-7.0, 7.2]	[-38 , 40] [11]
f_{S1}/Λ	[-21.6,21.8]	[-19.9,20.2]	[-118 , 120] [11]
f_{M0}/Λ	[-6.0, 5.9]	[-5.6, 5.5]	[-4.6 , 4.6] [29]
f_{M1}/Λ	[-8.7 ,9.1]	[-7.9, 8.5]	[-17 , 17] [29]
f_{M6}/Λ	[-11.9,11.8]	[-11.1,11.0]	[-65 , 63] [11]
f_{M7}/Λ	[-13.3,12.9]	[-12.4,11.8]	[-70 , 66] [11]
f_{T0}/Λ	[-0.62,0.65]	[-0.58,0.61]	[-3.8 , 3.4] [30]
f_{T1}/Λ	[-0.28,0.31]	[-0.26,0.29]	[-1.9 , 2.2] [11]
f_{T2}/Λ	[-0.89,1.02]	[-0.80,0.95]	[-5.2 , 6.4] [11]

✓ **Much improved limits compared to RunI 8 TeV.**

- Numbers in [ ] are references to published RunI limits.

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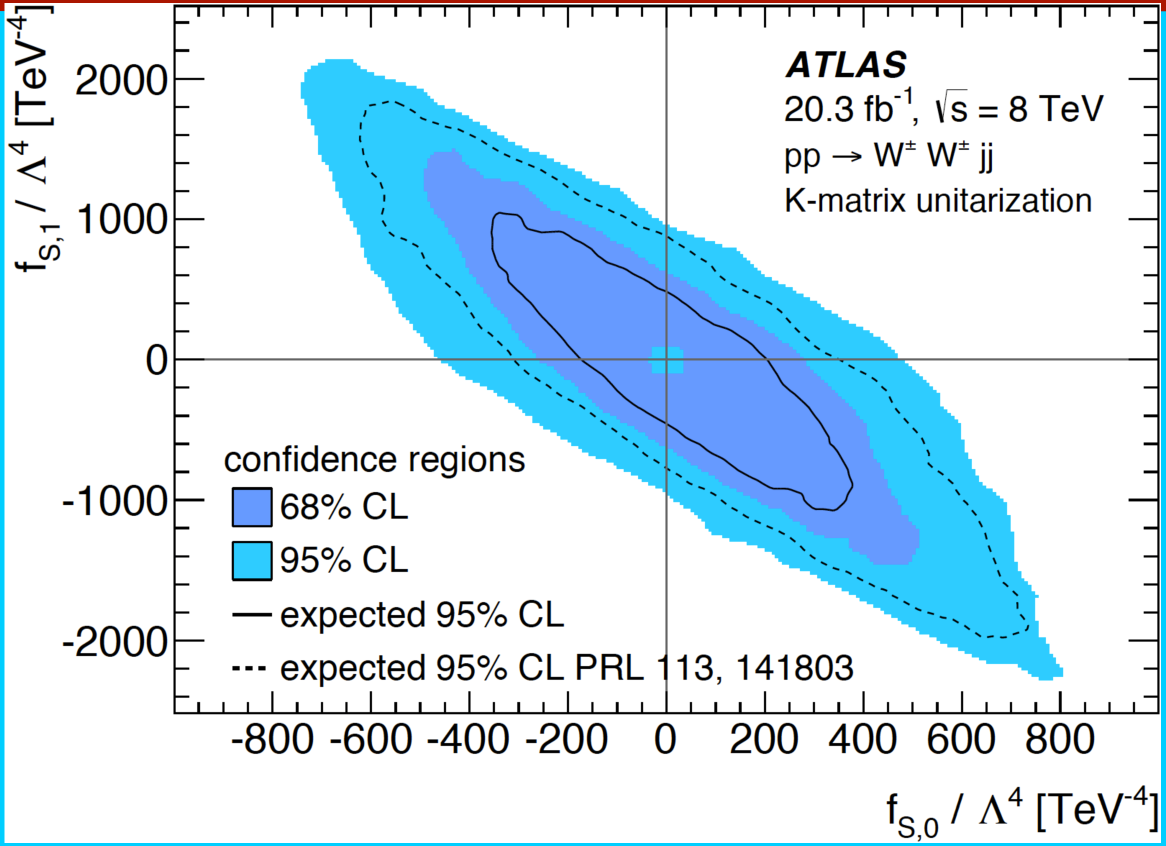
aQGC Selection from $W^\pm W^\pm$

	aQGC Signal Region
Non-prompt	$0.2 \pm 0.1 \pm 0.1$
Conversions	$0.7 \pm 0.2 \pm 0.1$
Prompt	$0.8 \pm 0.1 \pm 0.3$
SM $W^\pm W^\pm jj$-EW	$1.7 \pm 0.1 \pm 0.2$
SM $W^\pm W^\pm jj$-QCD	$0.4 \pm 0.0 \pm 0.1$
Total background	$3.8 \pm 0.3 \pm 0.5$
$\alpha_4 = 0.1,\ \alpha_5 = 0$	$7.3 \pm 0.4 \pm 0.6$
Data	8

An excess of data events with a significance of 1.8σ.

 https://arxiv.org/pdf/1611.02428

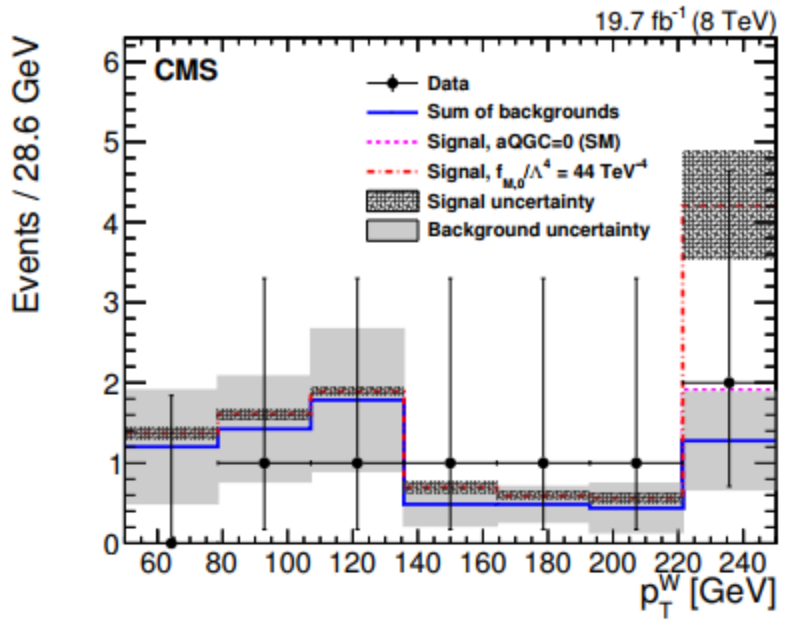
Constraints on aQGC from $W^{\pm}W^{\pm}$



Two-dimensional limits on $f_{S,0}/\Lambda^4$ and $f_{S,1}/\Lambda^4$. The limits on α_4 and α_5 are converted to the limits on coefficients of dimension-eight operators, $f_{S,0}/\Lambda^4$ and $f_{S,1}/\Lambda^4$, following the formalism defined in the Appendix of Phys. Rev. D 74 (2006) 073005 using Eqns. (60) and (61) in arXiv:1309.7890.

 https://arxiv.org/pdf/1611.02428

$W\gamma$+2jet – aQGC Constraints



Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 74$	$-47 < f_{M,0}/\Lambda^4 < 44$
$-125 < f_{M,1}/\Lambda^4 < 129$	$-72 < f_{M,1}/\Lambda^4 < 79$
$-26 < f_{M,2}/\Lambda^4 < 26$	$-16 < f_{M,2}/\Lambda^4 < 15$
$-43 < f_{M,3}/\Lambda^4 < 44$	$-25 < f_{M,3}/\Lambda^4 < 27$
$-40 < f_{M,4}/\Lambda^4 < 40$	$-23 < f_{M,4}/\Lambda^4 < 24$
$-65 < f_{M,5}/\Lambda^4 < 65$	$-39 < f_{M,5}/\Lambda^4 < 39$
$-129 < f_{M,6}/\Lambda^4 < 129$	$-77 < f_{M,6}/\Lambda^4 < 77$
$-164 < f_{M,7}/\Lambda^4 < 162$	$-99 < f_{M,7}/\Lambda^4 < 97$
$-5.4 < f_{T,0}/\Lambda^4 < 5.6$	$-3.2 < f_{T,0}/\Lambda^4 < 3.4$
$-3.7 < f_{T,1}/\Lambda^4 < 4.0$	$-2.2 < f_{T,1}/\Lambda^4 < 2.5$
$-11 < f_{T,2}/\Lambda^4 < 12$	$-6.3 < f_{T,2}/\Lambda^4 < 7.9$
$-3.8 < f_{T,5}/\Lambda^4 < 3.8$	$-2.3 < f_{T,5}/\Lambda^4 < 2.4$
$-2.8 < f_{T,6}/\Lambda^4 < 3.0$	$-1.7 < f_{T,6}/\Lambda^4 < 1.9$
$-7.3 < f_{T,7}/\Lambda^4 < 7.7$	$-4.4 < f_{T,7}/\Lambda^4 < 4.7$

The dash-dotted line depicts a representative signal distribution with anomalous coupling parameter $f_{M,0}/\Lambda^4 = f_{M,0}/\Lambda^4$=44 TeV and the dashed line shows the same distribution corresponding to the SM case

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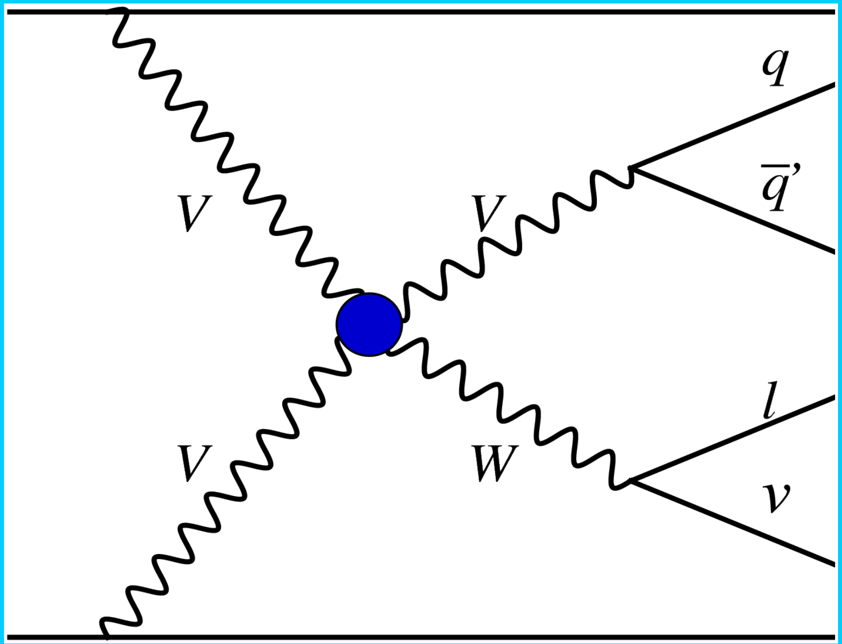
WW/WZ - Selection

- Searches for anomalous contributions to electroweak (EWK) production of two vector bosons plus two jets.

W → lv and V → jj + 2 additional jets

✓ Singal include tau leptonic decays



Event Selection:
pT(l) > 30 GeV, *E*miss > 30 GeV

- The hadronic portion of the event is selected with two criteria:

1. A "resolved" selection : Reconstructs the hadronically decaying *W*/*Z* candidate (*V*had) as two small-*R* jets (*V* → jj),

✓ Event should have least four small-*R* jets

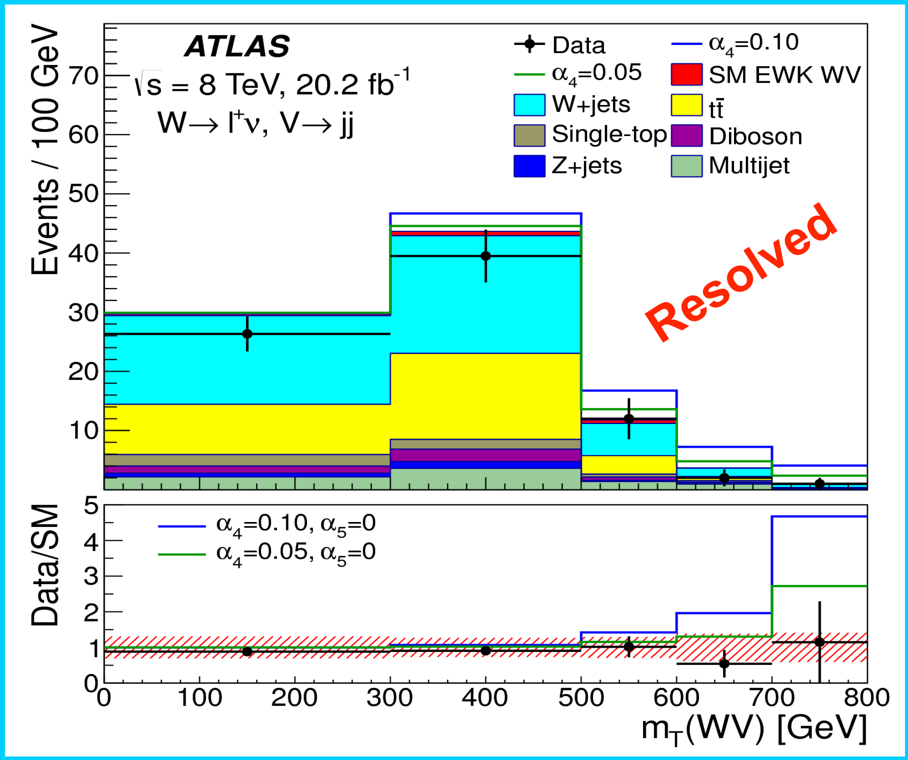
2. A "merged" selection: Reconstructs the *V*had as a single large-*R* jet (*V* → J)

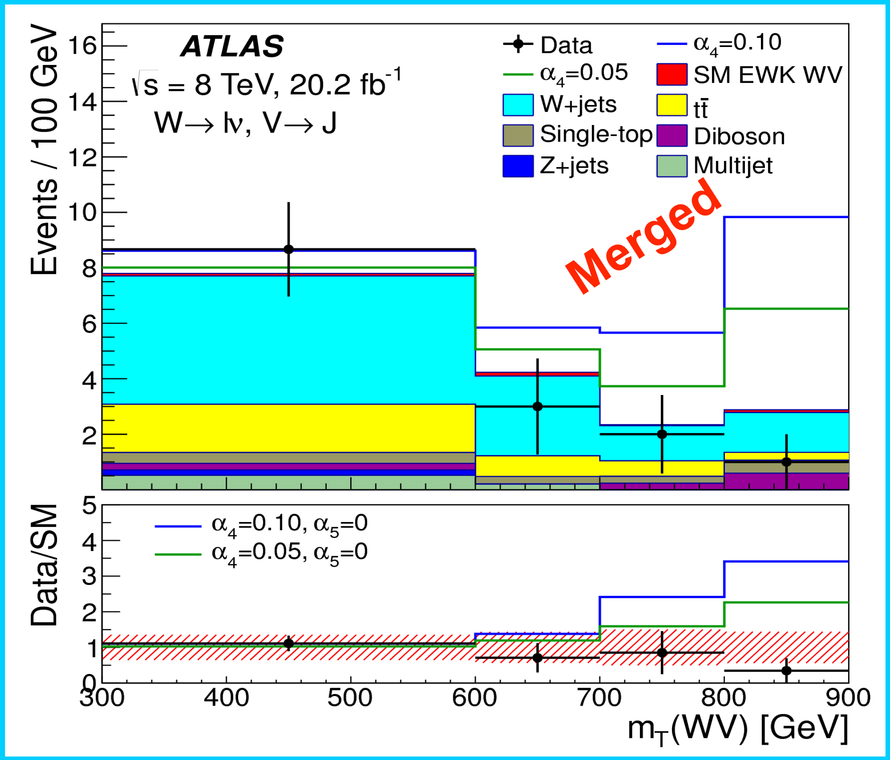
✓ Event should have at least one large-*R* jet

For Both criteria: 64 < *m*(*V*had) < 96 GeV , *m*jj,tag > 500 GeV

https://arxiv.org/pdf/1609.05122

WW / WZ - Selection





- The main backgrounds are due to W + jets and $t\bar{t}$ processes

Major systematics:

W/Z + jets modeling	13% (Resolved)	29% (Merged)
$t\bar{t}$ modeling	14% (Resolved)	7% (Merged)
Multijet yield	6% (Resolved)	5% (Merged)

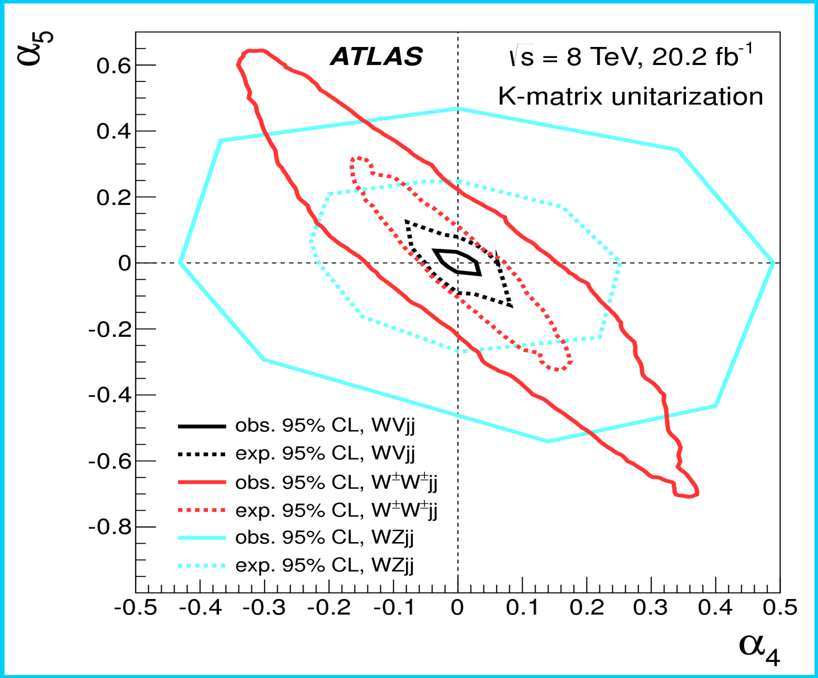
WW/WZ – Event Yield

	Resolved channel		Merged channel
	e^+ and μ^+	e^- and μ^-	e and μ
W + jets	92 ± 37	51 ± 29	19.4 ± 9.9
$t\bar{t}$	59 ± 18	63 ± 35	6.8 ± 2.8
Single-top	10.0 ± 5.6	5.5 ± 3.2	2.2 ± 1.2
Diboson	8.6 ± 5.7	10.8 ± 6.4	1.6 ± 1.2
Z + jets	4.5 ± 1.5	3.4 ± 2.4	0.58 ± 0.64
Multijet	16 ± 16	12 ± 12	1.8 ± 1.9
Total background	190 ± 53	145 ± 54	32 ± 12
EWK WV (SM)	3.66 ± 0.82	2.34 ± 0.56	0.54 ± 0.22
EWK WV ($\alpha_4 = 0.1, \alpha_5 = 0$)	21.0 ± 4.2	9.2 ± 1.9	15.1 ± 4.4
Data	173	131	32

- ✓ **The expected number of events passing the final event selection**
- ✓ **The quoted errors include all systematic uncertainties in the expected yields.**

https://arxiv.org/pdf/1609.05122

WW / WZ – aQGC Constraints

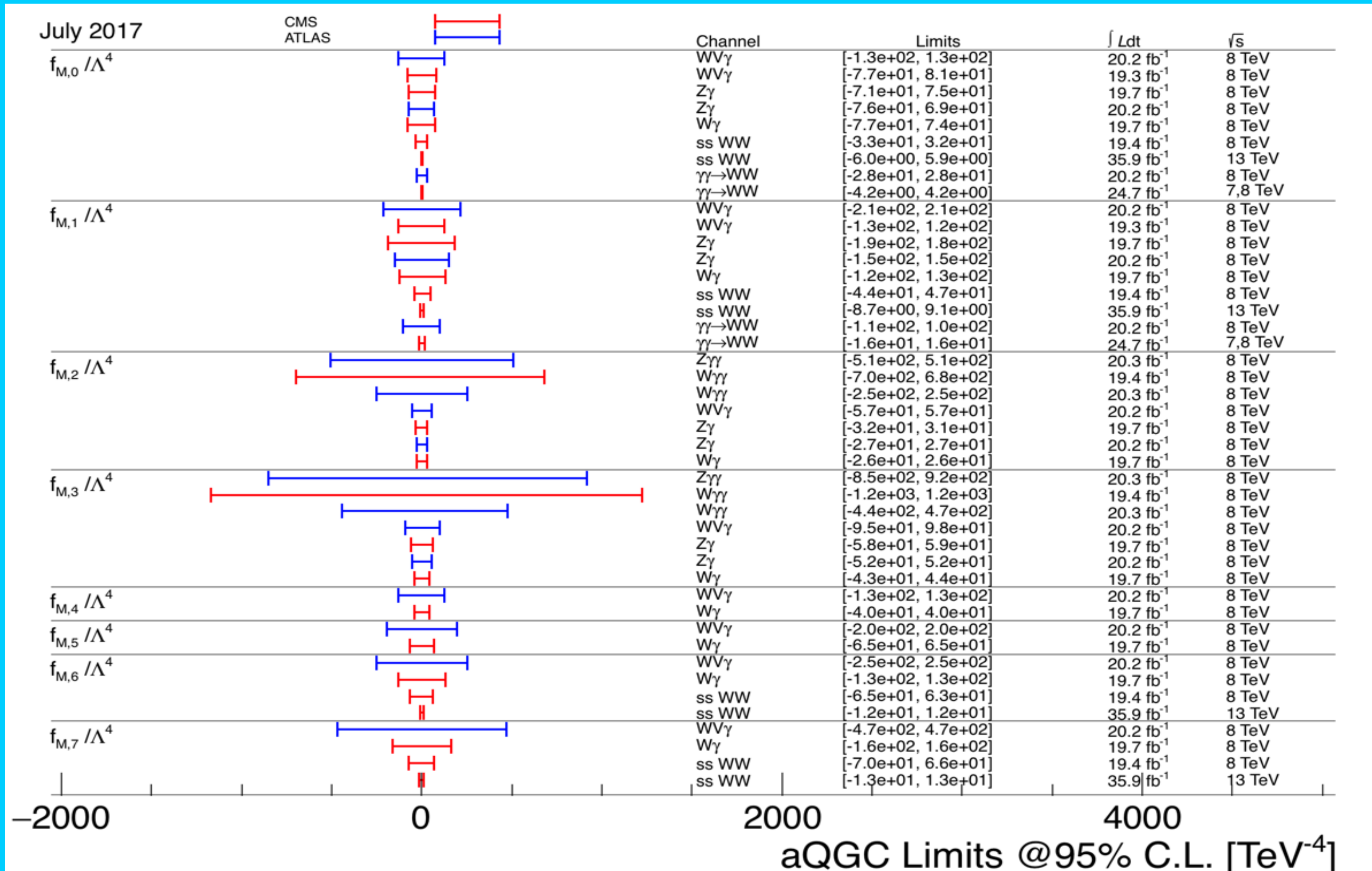


- ✓ At 95% CL, the observed confidence intervals are $-0.024 < \alpha 4 < 0.030$ and $-0.028 < \alpha 5 < 0.033$, where the confidence interval on each parameter is calculated while fixing the other parameter to zero.
- ✓ The expected 95% confidence intervals are $-0.060 < \alpha 4 < 0.062$ and $-0.084 < \alpha 5 < 0.080$.

- ➢ The use of the "merged" category of events significantly improves the aQGC sensitivity
- ➢ Most of the aQGC sensitivity comes from the highest-mT(WV) bins ➔ merged category is powerful.
- ➢ The expected aQGC confidence intervals are about 40% more stringent by including merged category.

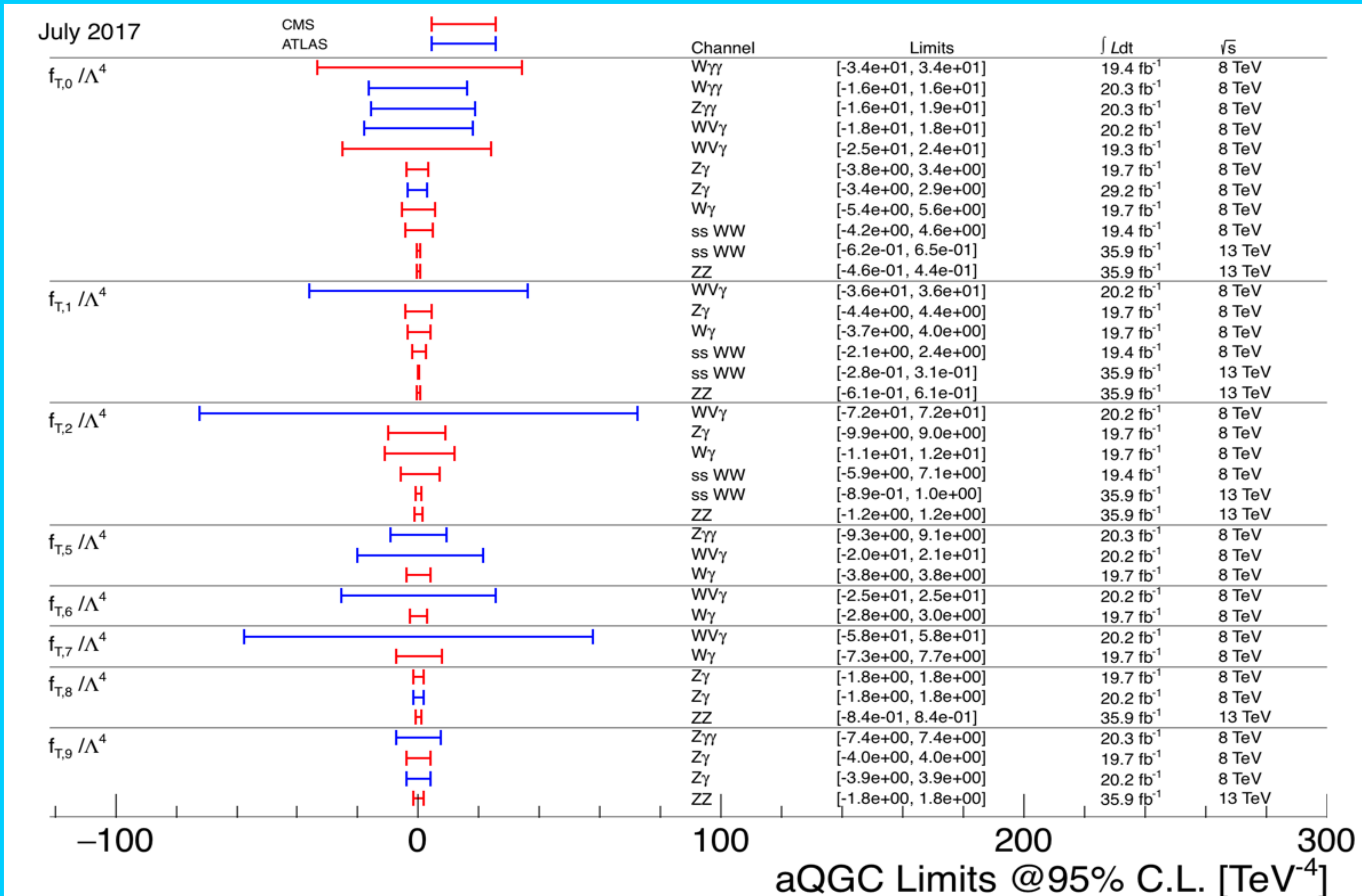
 https://arxiv.org/pdf/1609.05122

aQGC Summary



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSMPaTGC/aQGC_fm.pdf

aQGC Summary



https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsSMPaTGC/aQGC_ft.pdf

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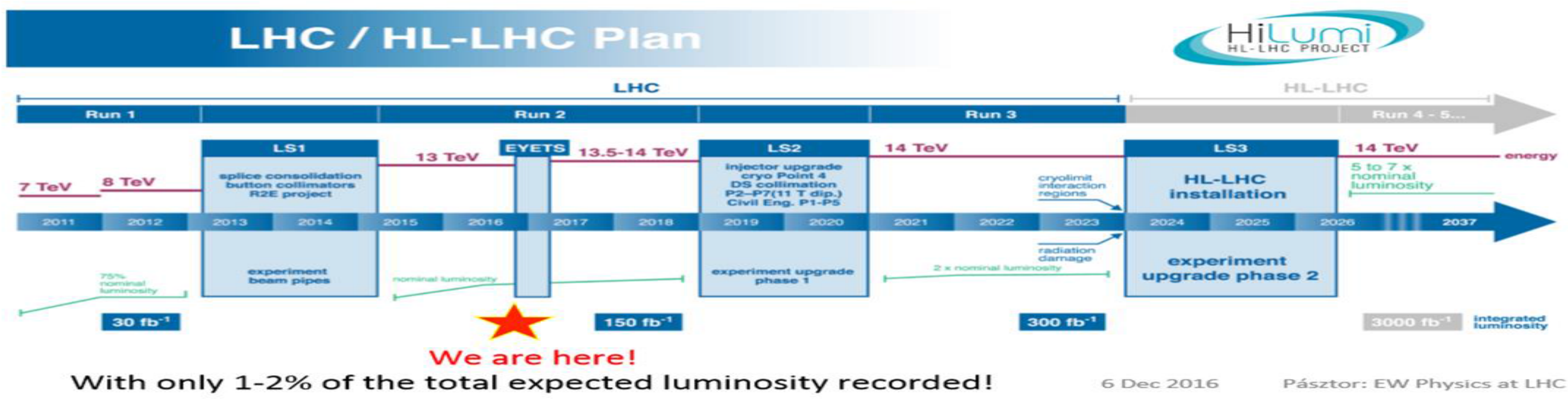
Future Prospects



- Both ATLAS and CMS are planning to upgrade the detector for Phase 2 for increased performance and to handle high pile-up situations.
- Almost all the detector systems, Calorimetry, Tracking system and Muon stations are planned to be upgraded – Wider acceptance.
- Both ATLAS and CMS have performed the sensitivity studies for various VBS channels for Phase2 HL-LHC.

✓ Will discuss WW and WZ prospects.

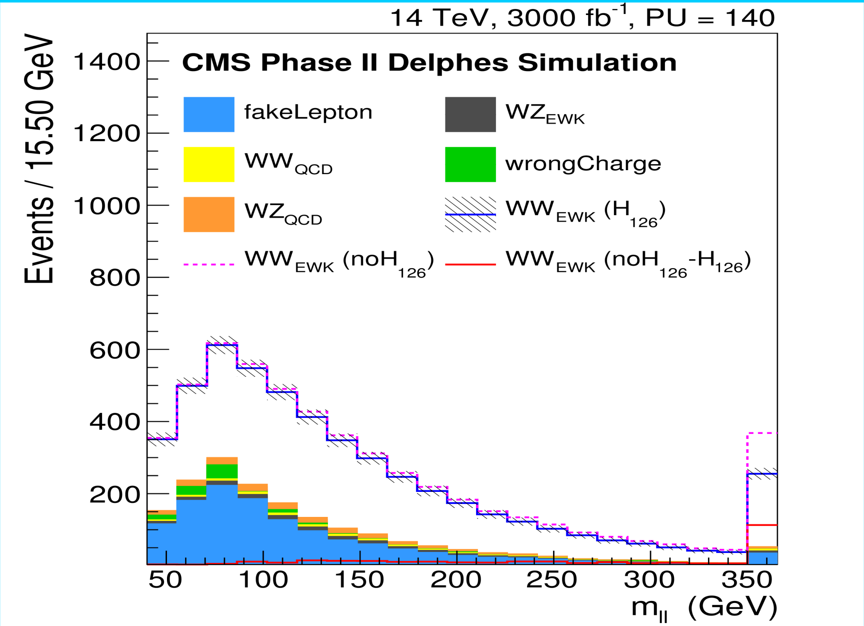
$W^{\pm}W^{\pm} \rightarrow l^{\pm}l^{\pm}\nu\nu$

lepton pT>20 GeV, mll>40 GeV

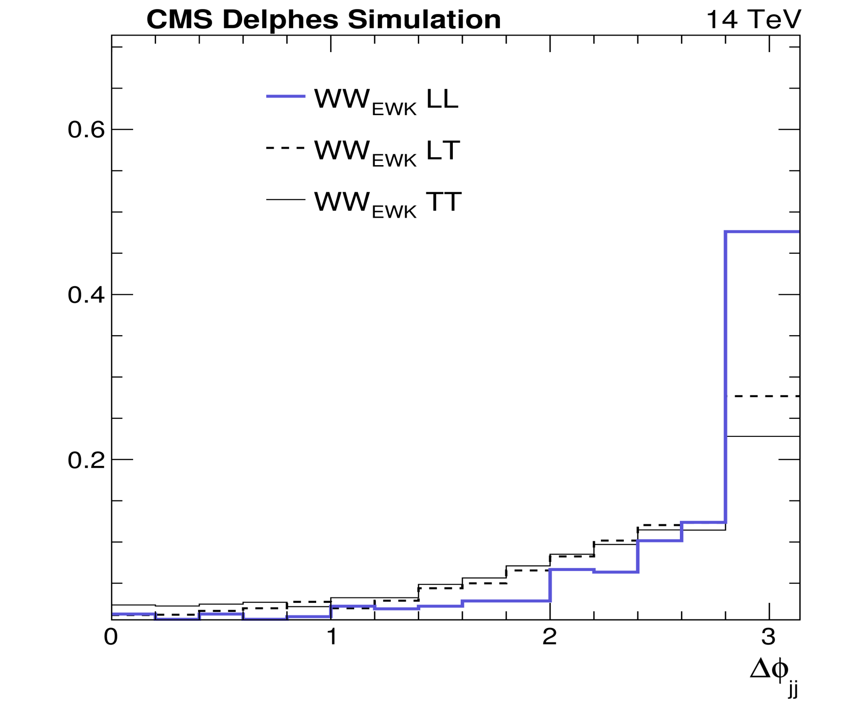
Δηll > 2, MET>40 GeV

Two jets with pT > 30 GeV, Δηjj>2.5

Mjj> 850 GeV



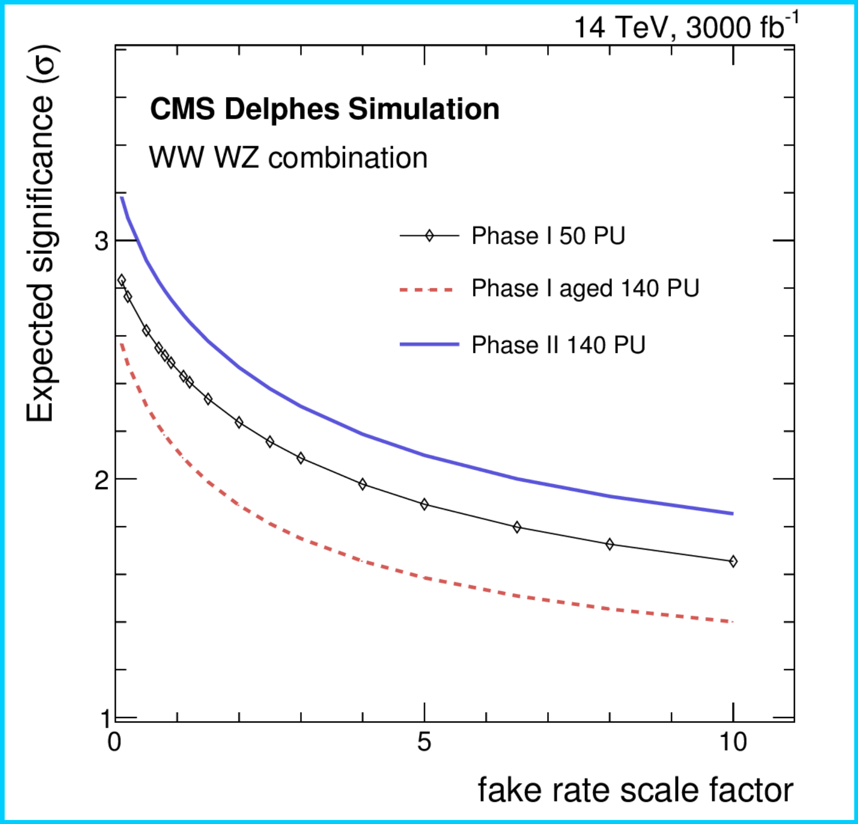
Di-lepton invariant mass m_{ll} for the Phase II detector, after the same-sign $W^{\pm}W^{\pm}$ selection.

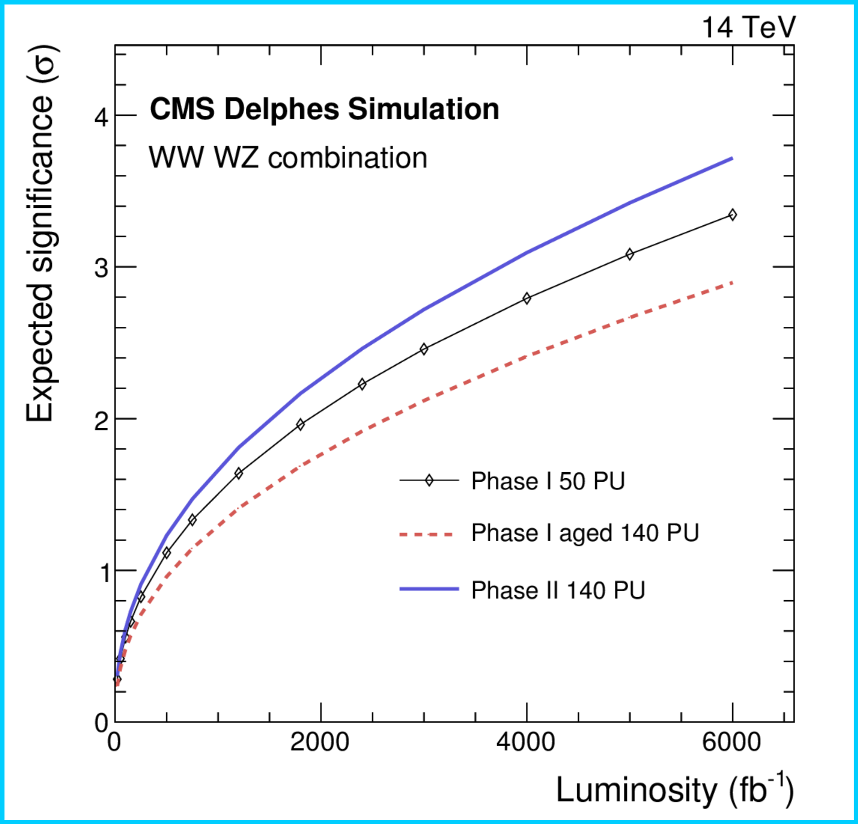


The ϕ angle between the tag jets ($\Delta\phi jj$), for LL, TL, and TT components of the EWK $W^{\pm}w^{\pm}$ after the same-sign $W^{\pm}W^{\pm}$ selection and for the Phase II detector.

CMS-SMP-14-008

$W^{\pm}W^{\pm} \rightarrow l^{\pm}l^{\pm}\nu\nu$





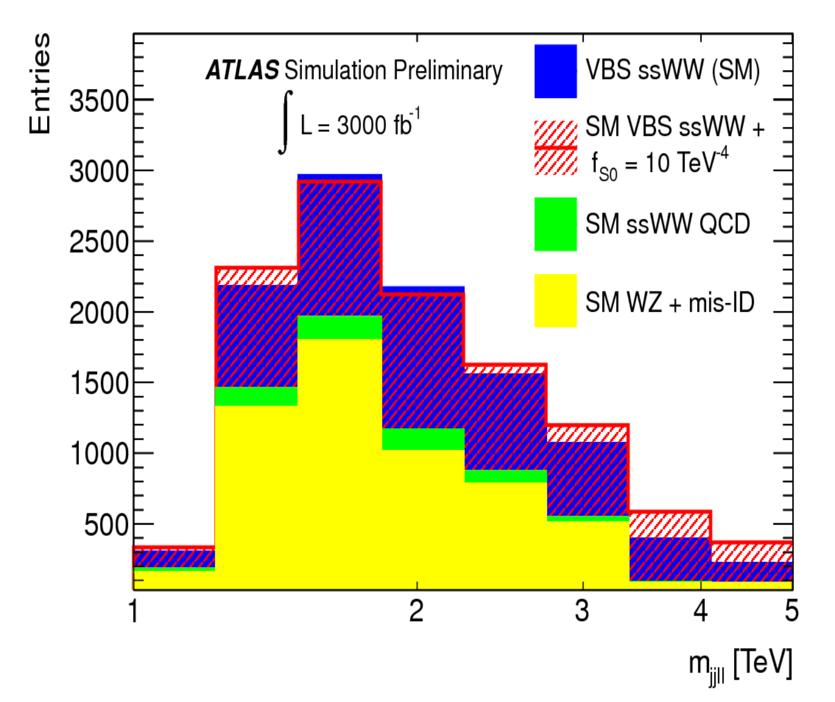
The expected discovery significance for the W_L scattering for the various detector scenarios with several possible scale factors to the fake rate after 3 ab^{-1} of data.

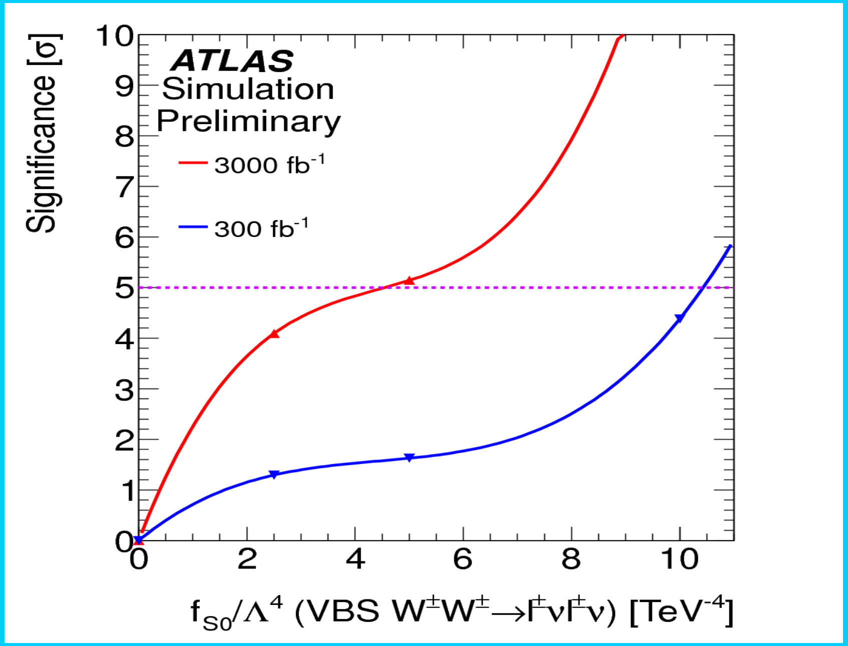
The evolution of the discovery sensitivity, for the fake rate scale factor of 1.

CMS-SMP-14-008

$W^{\pm}W^{\pm} \rightarrow l^{\pm}l^{\pm}\nu\nu$

- Exactly two selected leptons (each with pT > 25 GeV) with the same charge.
- At least one selected lepton must fire the trigger.
- At least two selected jets with pT > 50 GeV.
- m_{jj} > 1 TeV, where m_{jj} is the invariant mass of the two highest-pT selected jets.





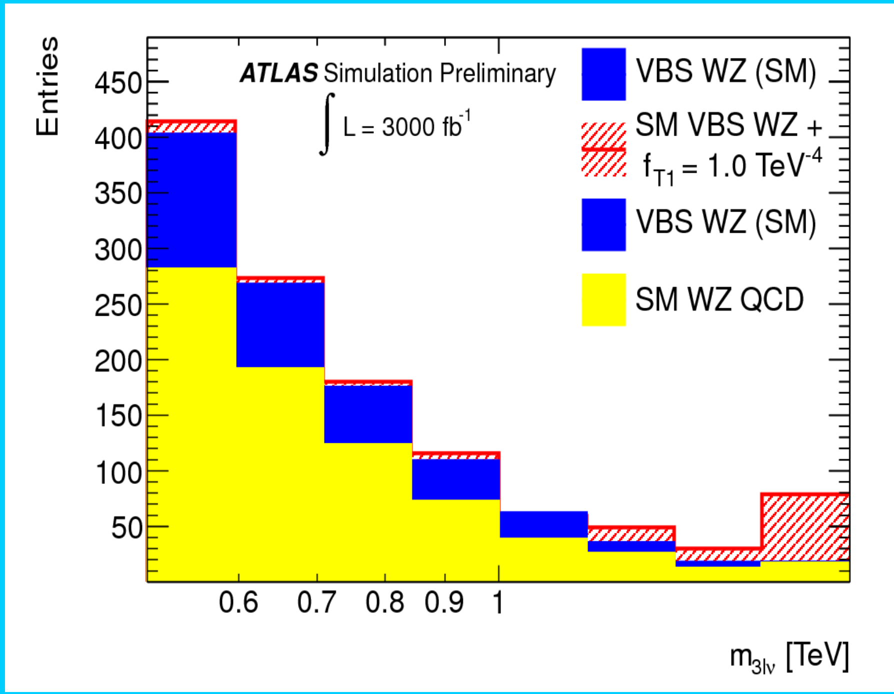
model	$300\ fb^{-1}$	$3\ ab^{-1}$
f_{S0}/Λ^4	$10\ TeV^{-4}$	$4.5\ TeV^{-4}$

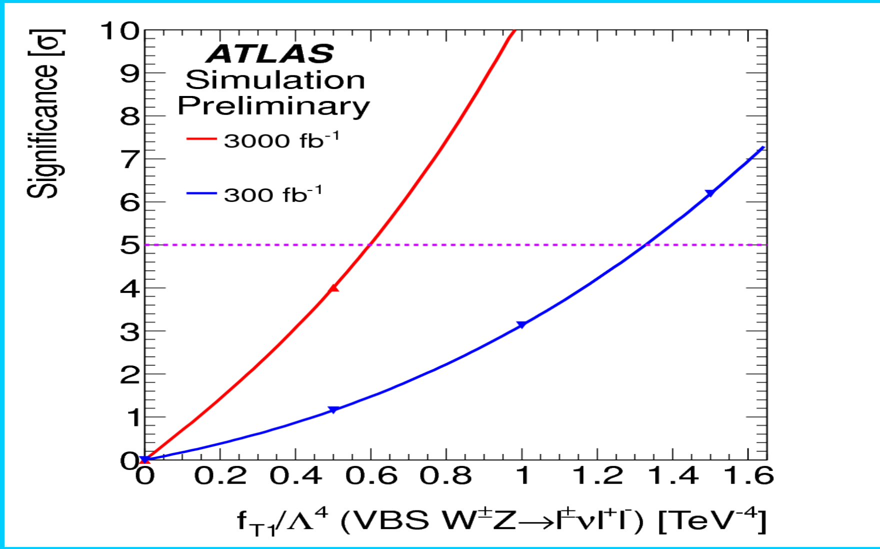
5σ discovery values of f_S0

 ATL-PHYS-PUB-2013-006

WZqq → 3lvjj

- Exactly three selected leptons (each with pT > 25 GeV) which can be separated into an opposite
sign, same flavor pair and an additional single lepton
- At least one selected lepton must fire the trigger.
- At least two selected jets with pT > 50 GeV.
- mj j > 1 TeV, where mj j is the invariant mass of the two highest-pT selected jets





	300 fb^{-1}	3000 fb^{-1}
f_{T1}/Λ^4	1.3 TeV^{-4}	0.6 TeV^{-4}

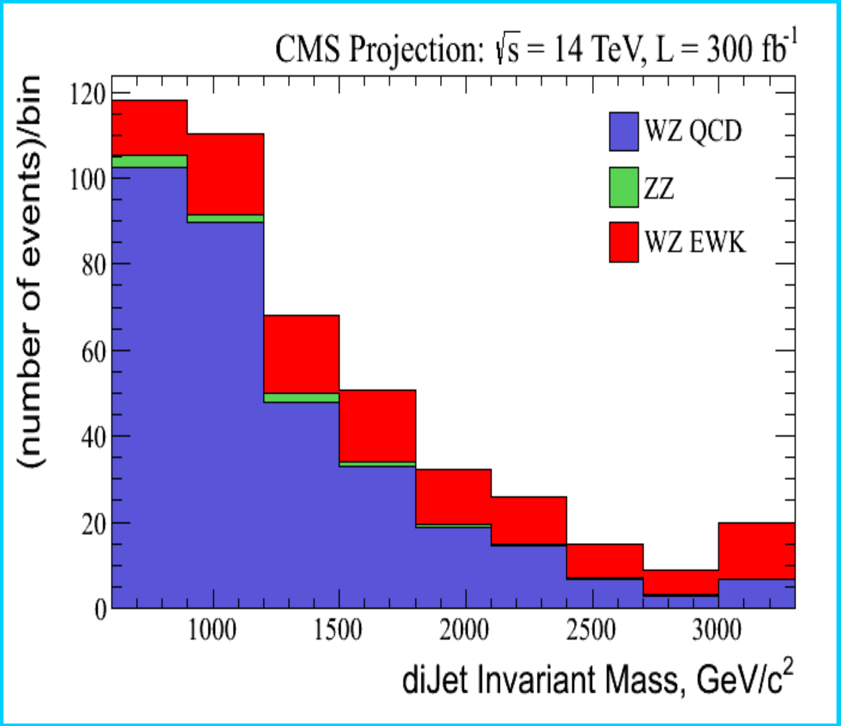
5σ discovery values of f_{T1}/Λ^4

WZqq → 3lνjj

➢ **300 fb-1 (Phase 1) with 50 pile-up event and current detector**

➢ **3000 fb-1 (Phase 2) with 140 pile-up events and with the detector upgrade, without extended acceptance.**

- lepton pT > 20 GeV/c, lepton |η |< 2.4
- **ΔR(ll')** > 0.04, **ΔR(lj')** > 0.4
- $\mathbf{m}_{ll}$ > 20 GeV/$\mathbf{c}^2$ for any same flavor opposite charge lepton pair
- MET > 30 GeV (300 fb^{-1} only)
- jet **pT** > 50 GeV/**c**, jet |η| < 4.7, Δη**jj** > 4.0
- $\mathbf{m}_{jj}$ > 600 GeV/**c**2



Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

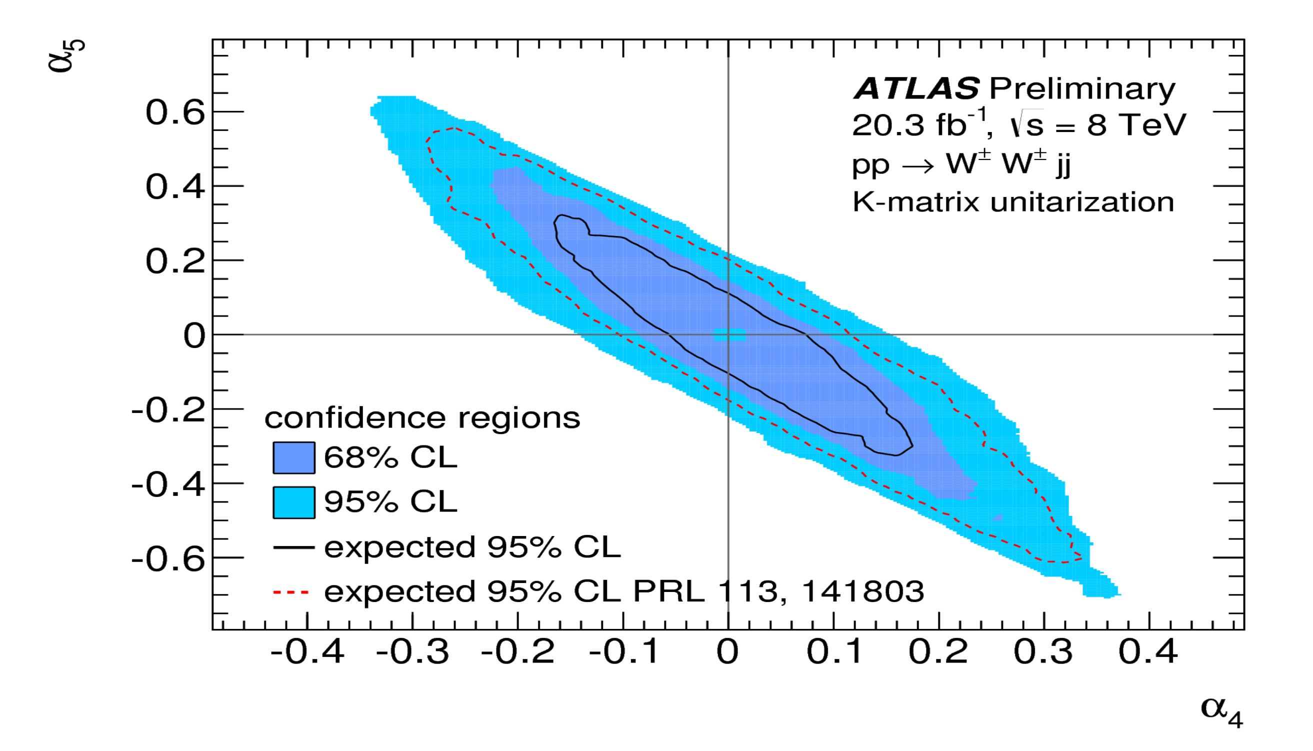
 CMS-FTR-13-006

Conclusions

- LHC is a discovery and precision measurement machine.
- VBS mechanism is becoming accessible now at LHC.
- Both ATLAS and CMS experiments have performed new and improved measurements.
- Observation of Same sign WW and stringent limits on aQGC.
- Upgraded detectors with HL-LHC will be able to measure the VBS and shed light on EWSB.

THANK YOU!

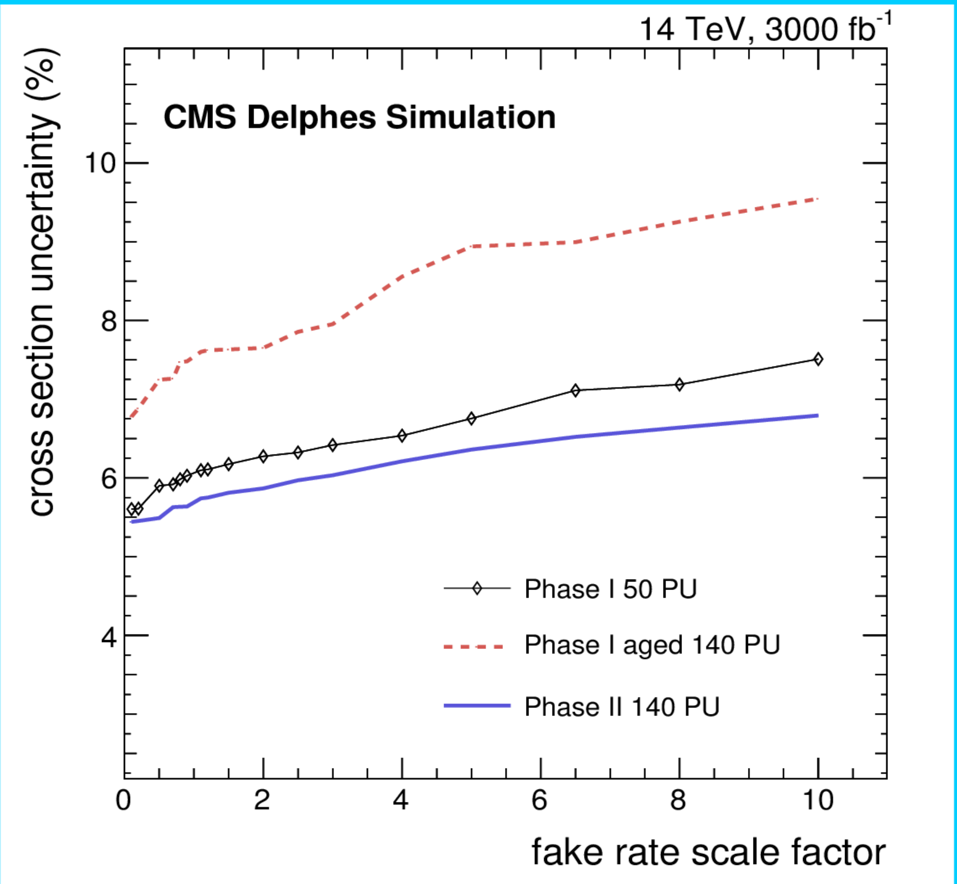
Constraints on aQGC

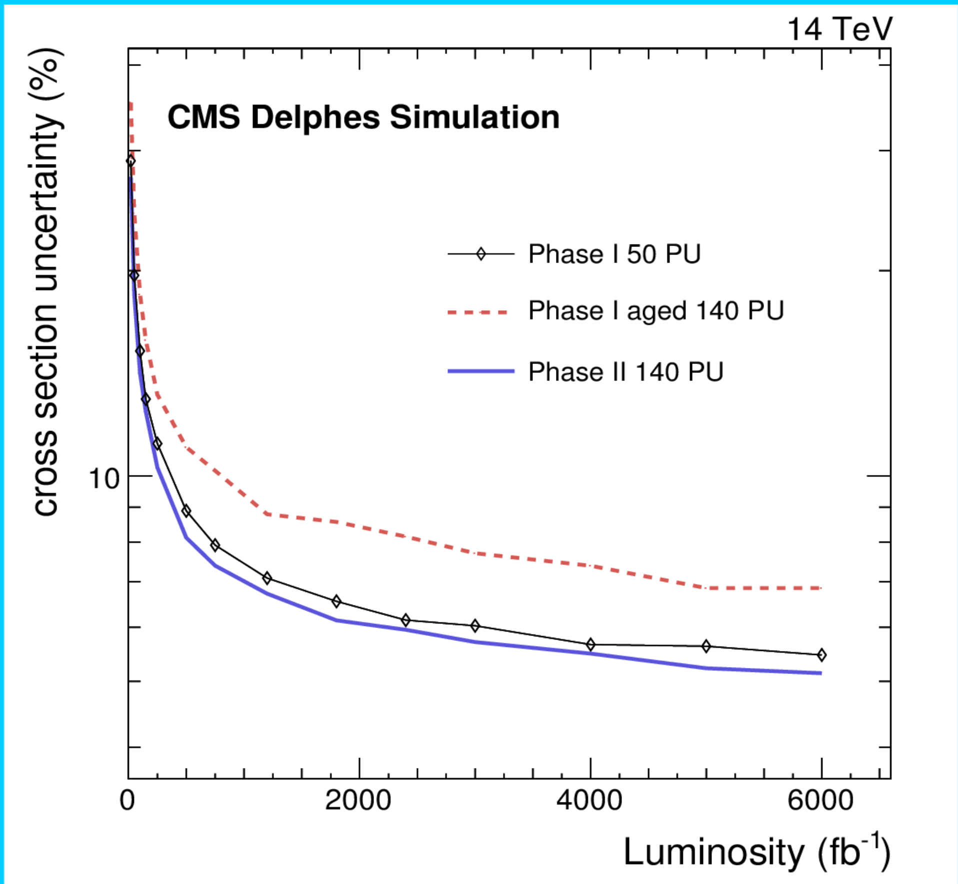


Two-dimensional confidence regions in the aQGC parameter plane (α_4,α_5). The area outside the solid light blue region is excluded by the data at the 95% CL. The area outside the solid dark blue region is excluded at the 68% CL. The expected exclusion contour at the 95% CL is marked by the solid black line. For comparison, the expected exclusion contour at the 95% CL from the previous analysis of this final state [Phys. Rev. Lett. 113 (2014) 141803] is shown as a black dashed line.

ATLAS

$W^{\pm}W^{\pm} \rightarrow l^{\pm}l^{\pm}\nu\nu$





The expected total uncertainty for the various scenarios with several possible scale factors to the fake rate, for the same-sign EWK WW cross section measurement.

The evolution of the analysis uncertainty, for the unity scale factor of the fake rate, as a function of the collected luminosity.

CMS-SMP-14-008

WW / WZ – aQGC Constraints

	Expected	Expected $\pm 1\sigma$	Expected $\pm 2\sigma$	Observed
lower limit, α_4	-0.060	$[-0.11, -0.030]$	$[-0.26, -0.015]$	-0.024
upper limit, α_4	0.062	$[0.034, 0.091]$	$[0.018, 0.20]$	0.030
lower limit, α_5	-0.084	$[-0.15, -0.034]$	$[-0.24, -0.018]$	-0.028
upper limit, α_5	0.080	$[0.039, 0.13]$	$[0.024, 0.23]$	0.033

The observed and expected lower and upper limits of the 95% confidence intervals for α_4 and α_5. The $\pm$ 1σ and ±2 σ uncertainty bands on the expected lower and upper limits are also shown for comparison. The α_4 confidence intervals are computed while fixing α_5 to zero, and vice-versa.