Anomalous Quartic Couplings Studies at ATLAS

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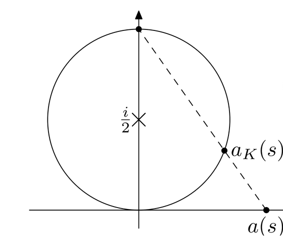
Introduction

- In the Standard Model, the quartic gauge boson couplings originate from non-Abelian nature of the theory.
  - Allowed couplings: WWWW, WWZZ, WWZγ, WWγγ
- Measuring the effect of quartic couplings is challenging
  - The cross section is at the order of femto barn.
  - The quartic coupling diagrams can not be separated from other diagrams due to gauge invariance requirement.
- Vector boson scattering and triboson processes are sensitive to quartic couplings effects
  - Low energy effect from new physic phenomena can result in anomalous quartic couplings (aQGC) → new physics evidences if deviations from SM are observed.

- Effective field theory to describe the aQGC effect:

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

- The higher-oder terms break gauge invariance → Use form factor or K-matrix scheme to restore unitarity
  - K-matrix unitarization scheme: project the elastic scattering eigenamplitude on the Argand circle

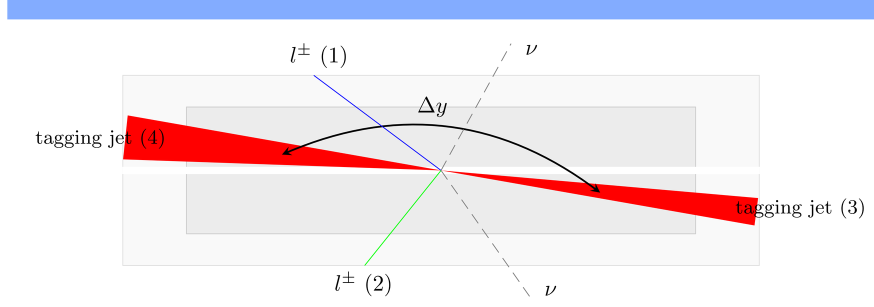


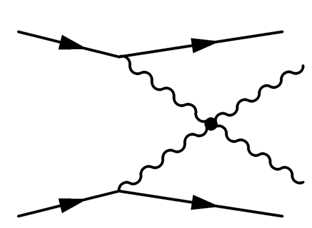
$$a_K(s) = \frac{1}{\mathrm{Re}(1/a(s)) - i} = \frac{a(s)}{1 - ia(s)} \quad \text{if } a(s) \text{ is real}$$

  - Form factor

$$\left(1 + \frac{s}{\Lambda^2}\right)^{-n}$$

Vector Boson Scattering in WWjj Final State





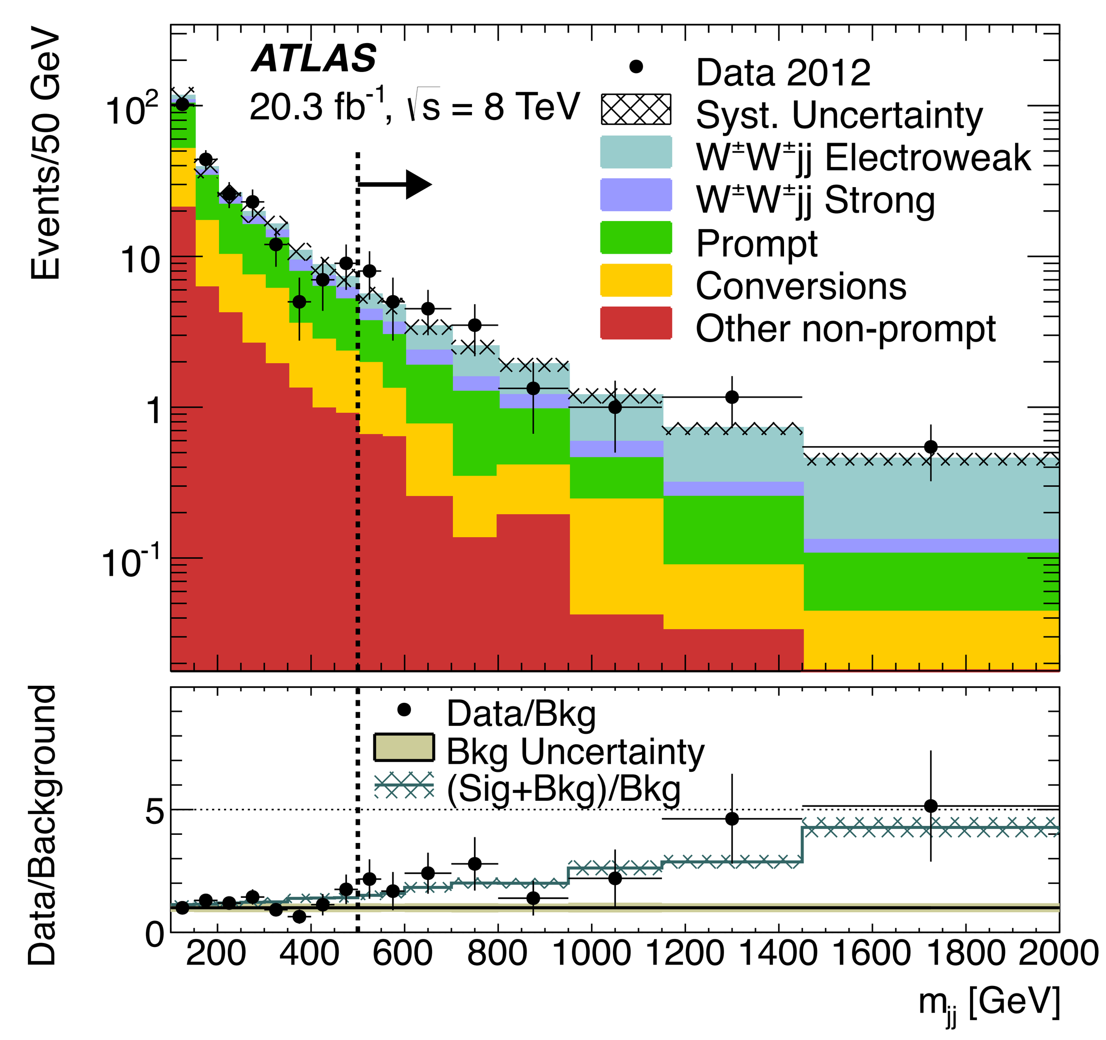
- The VBS WWjj process is ideal for QGC at WWWW vertex studies:
  - The SM backgrounds are controlled by tagging two jets with large rapidity gap.
  - Use same-sign leptonic WW channel to further reduce SM backgrounds.
- The quartic couplings contribution are measured together with other EWK and strong diagrams resulting in the same final states.
- VBS signal region: M_{jj} > 500 GeV and Δy_{jj} > 2.4

	ee	eμ	μμ
Total backgrounds	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
EWK WWjj	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	6	18	10

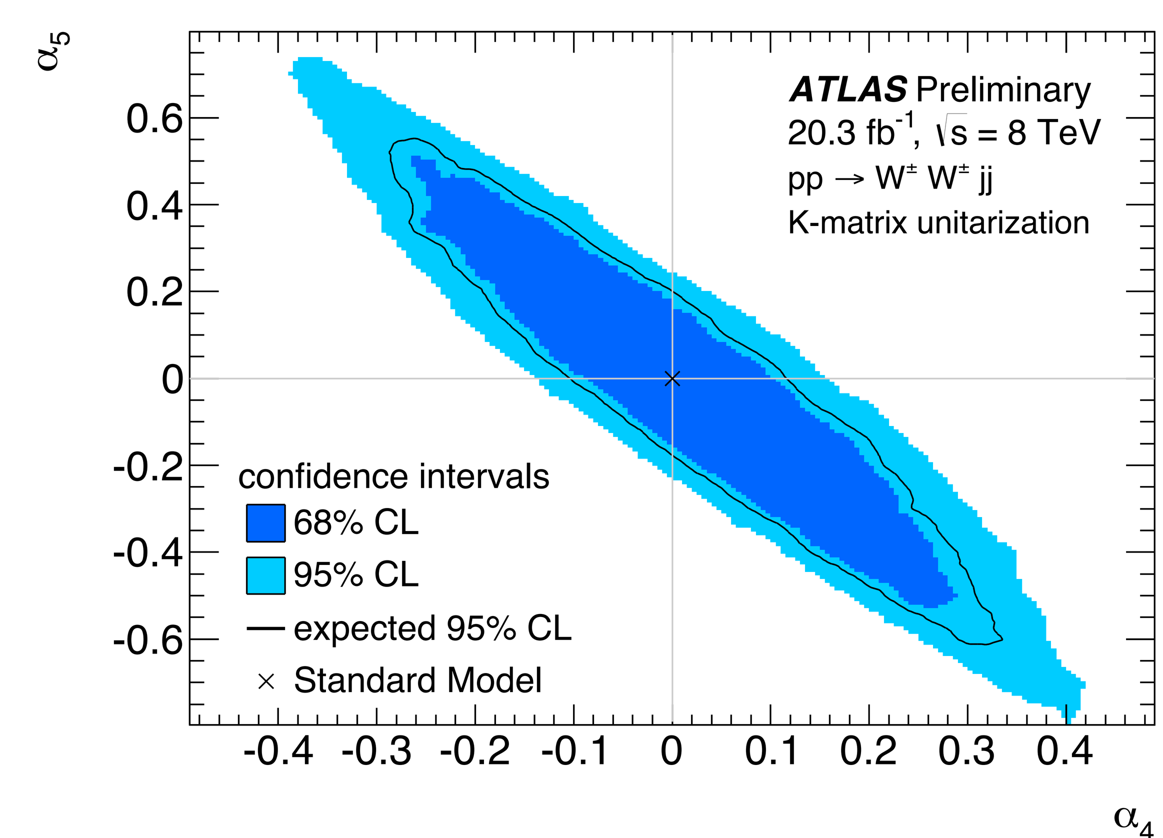
- Effective electroweak chiral Lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_{\mathrm{SM}} + \beta_1 \mathcal{L}_0'^{(2)} + \sum_i \alpha_i^{(4)} \mathcal{L}_i^{(4)} + \frac{1}{\Lambda}\sum_i \alpha_i^{(5)} \mathcal{L}_i^{(5)}$$

$$\alpha_4 \mathcal{L}_4 = \alpha_4 \left(\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}_\nu\right\}\right)^2 \quad \text{and} \quad \alpha_5 \mathcal{L}_5 = \alpha_5 \left(\mathrm{tr}\left\{\mathbf{V}_\mu \mathbf{V}^\mu\right\}\right)^2$$



- The dimension-4 operator L_4 and L_5 are the lowest dimensional operators contributing to quartic vertex, conserving SU(2) and CP.
- Limit setting:
  - WHIZARD to simulate pure EWK processes for different aQGC points.
  - Unitarization with K-matrix method
  - Profile likelihood method for limit setting



- Sensitivity studies at 14 TeV in VBS WWjj
  - Dilepton channel: use eμν+2j channels. W+jets and Z+jets are suppressed

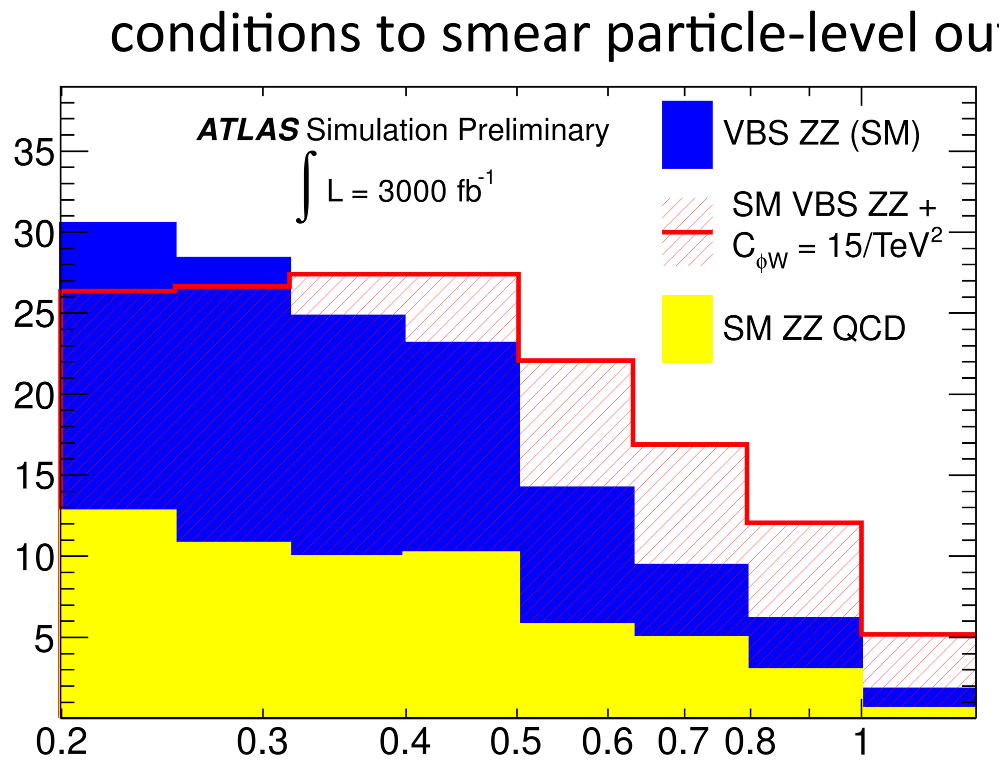
model	300 fb^{-1}	1 ab^{-1}	3 ab^{-1}
a_4	0.066	0.025	0.016

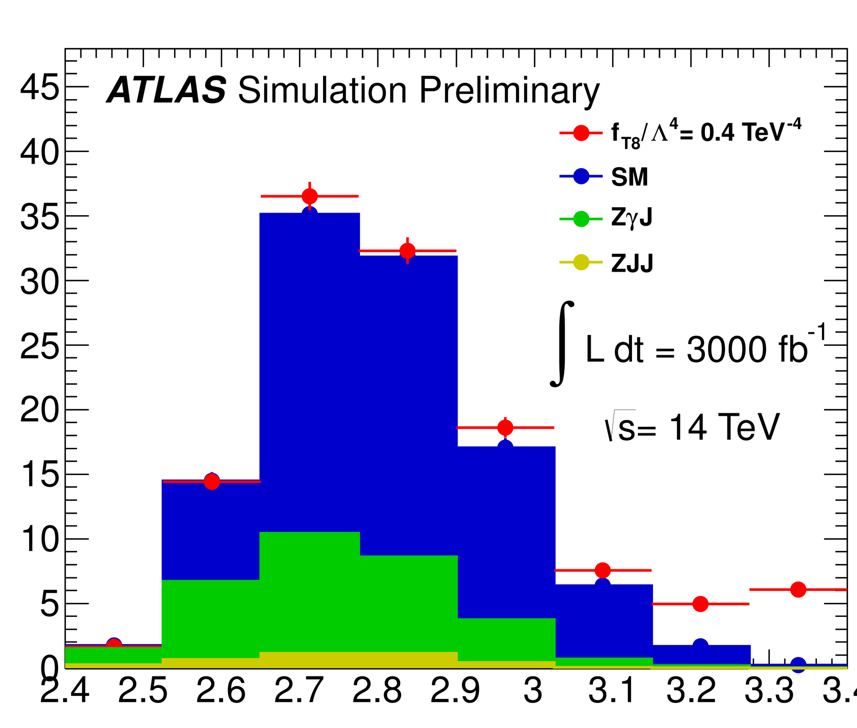
  - Lepton+jets channel: feasible to reconstruct WW mass. Dominant backgrounds are top pairs and dibosons

model	SM	500 GeV scalar	800 GeV vector	1150 GeV vector
(a_4, a_5)	(0, 0)	(0.01, 0.009)	(0.009, −0.007)	(0.004, −0.004)
S/B	(3.3 ± 0.3)%	(0.7 ± 0.1)%	(4.9 ± 0.3)%	(5.8 ± 0.3)%
$S/\sqrt{B}$ ($L = 300\mathrm{fb}^{-1}$)	2.3 ± 0.3	0.6 ± 0.1	3.3 ± 0.4	3.9 ± 0.4
$S/\sqrt{B}$ ($L = 3000\,\mathrm{fb}^{-1}$)	7.2 ± 0.1	1.6 ± 0.1	10.4 ± 0.7	12.4 ± 0.7

aQGC Sensitivity Studies at High Luminosity LHC

- Perform sensitivity studies in probing anomalous quartic gauge boson couplings via VBS and triboson channels at 14 TeV high luminosity scenarios (300 and 3000 fb^{-1}).
- The processes of interests are: VBS fully leptonic ZZ, WZ and triboson Zgg
- Simulations:
  - LO MADGRAPH generator, CTEQ6L1 PDF. Particle showers are simulated by PYTHIA
  - Jets are reconstructed using anti-kT R=0.4 algorithm from truth level particles.
  - Use parameterization of ATLAS detector performance at high pile-up conditions to smear particle-level output.





- VBS ZZ->llll:
  - Fully-leptonic channel (p_T > 25 GeV, two opposite sign, same flavor pairs), two tagged jets (p_T > 50 GeV, m_{jj} > 1 TeV)
  - Effective Lagrangian $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$
- VBS WZ->lnull:
  - Fully-leptonic channel (pT > 25 GeV), two tagged jets (p_T > 50 GeV with m_{jj} > 1 TeV)
  - Effective Lagrangian $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$
- Triboson Zgg:
  - Two leptons (p_T > 25 GeV, |η| < 2, |m_{ll} - 91| < 10 GeV) and one gamma (p_T > 160 GeV), lepton photon separation Δ > 0.4.
  - Effective Lagrangian

$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

- 5-sigma discovery values and 95% CL limits

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

References: ALT-PHYS-PUB-2012-005, ALT-PHYS-PUB-2013-006, arXiv:1405.6241

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