Measurements of quartic coupling and vector boson scattering in ATLAS

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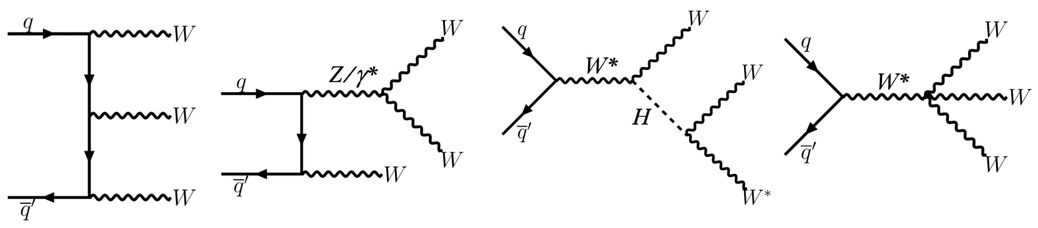
Introduction

- $SU(2)_L \times U(1)_Y$ symmetry breaking $\rightarrow$ allowed gauge couplings:
  - **Triple:** WWZ, $WW\gamma$;
  - **Quartic:** $WWWW$, $WWZZ$, $WW\gamma\gamma$, $WWZ\gamma$.
- Multiboson processes are very rare at the LHC.
- Sensitivity to BSM via anomalous quartic gauge couplings (aQCGs) evaluated with the model independent framework of Effective Field Theory [1]:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j^8.$$

- At leading order $\mathcal{O}_j^8$ are the lowest dimension operators inducing only QGCs without triple gauge-boson vertices.
- Presented studies use ATLAS 2015-2018 pp collision data ($\sqrt{s} = 13$ TeV, 139 fb^{-1}).

$pp \rightarrow WWW$



Previous studies: evidence, combined VVV production studies [2, 3].

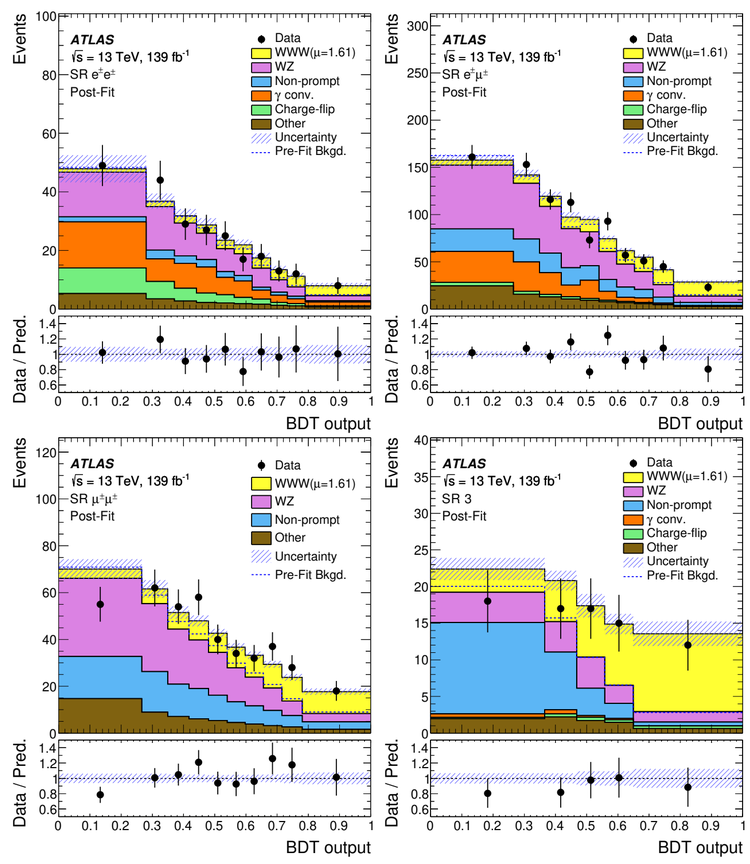
Final states:

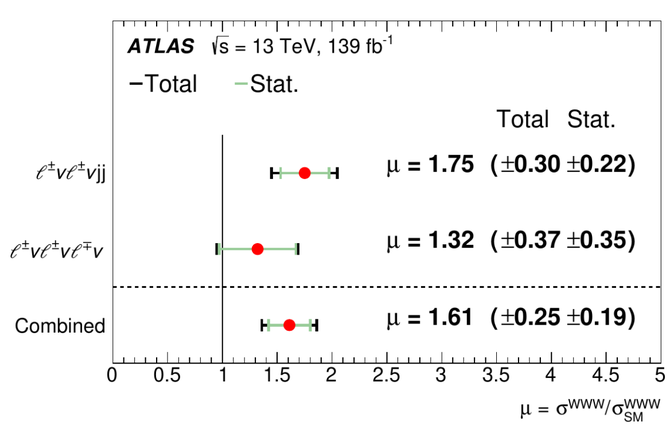
- 2ℓ: $e^\pm e^\pm/\mu^\pm e^\pm/\mu^\pm\mu^\pm$, $E_{\mathrm{T}}^{\mathrm{miss}}$, ≥ 2 jets.
- 3ℓ: $e^\pm e^\pm \mu^\mp/\mu^\pm\mu^\pm e^\mp$, $E_{\mathrm{T}}^{\mathrm{miss}}$

Main backgrounds: $WZ(\ell\nu\ell\ell)$+jets, ℓ from hadron decays and $j \rightarrow \ell$ misidentification.

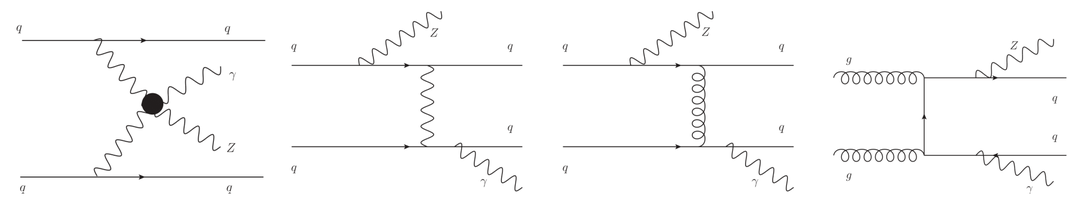
Signal extraction: 2 BDT classifiers for each channel, maximum-likelihood fit for signal and WZ+jets processes.

Results: $\sigma_{\mathrm{fid}}^{WWW} = 820 \pm 100(\mathrm{stat.}) \pm 80(\mathrm{syst.})$ fb with observed (expected) significance of 8.0σ (5.4σ) [4].





$pp \rightarrow Z(\nu\nu)\gamma jj$



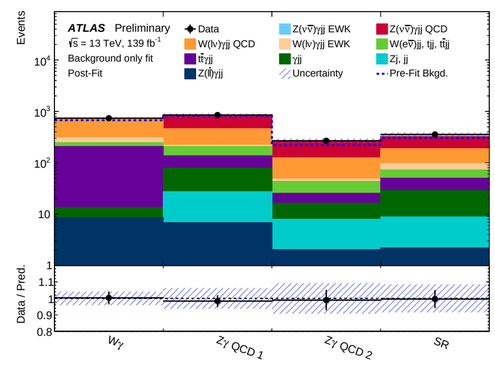
Previous studies: observation and aQGC limits for $Z(\ell\ell)\gamma jj$ [5], observation for $Z(\nu\nu)\gamma jj$ with $E_{\mathrm{T}}^{\gamma} \in [15; 110]$ GeV [6].

Final states: photon with $E_{\mathrm{T}}^{\gamma} > 150$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$ and ≥ 2 jets.

Main backgrounds: QCD $Z(\nu\nu)\gamma jj$ and $W(\ell\nu)\gamma jj$.

Signal extraction: BDT classifier, maximum-likelihood fit for signal $Z(\nu\nu)\gamma jj$ QCD and $W(\ell\nu)\gamma jj$ processes.

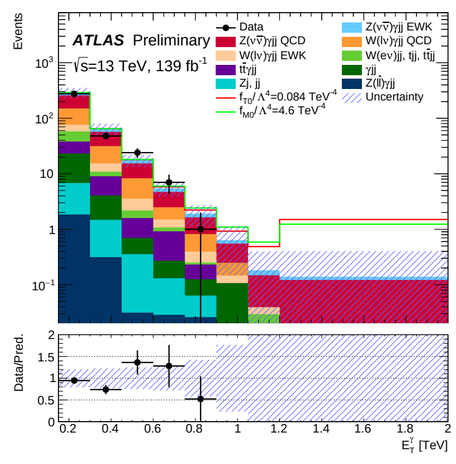
Results: $\sigma_{\mathrm{fid}}^{Z\gamma jj} = 0.77^{+0.34}_{-0.30}$ fb with observed (expected) significance of 3.2σ (3.7σ) [7]. This result is combined with Ref. [6] to obtain observed (expected) significance of 6.3σ (6.8σ).

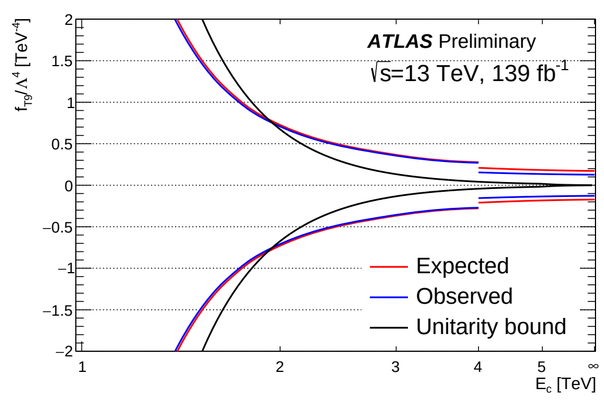


POI	Value		
	Current analysis	Ref. [6]	Combination
$\mu_{Z\gamma\mathrm{EWK}}$	0.78 ± 0.33	1.04 ± 0.23	0.96 ± 0.18
$\mu_{Z\gamma\mathrm{QCD}}$	1.21 ± 0.37	1.02 ± 0.41	1.17 ± 0.27
$\mu_{W\gamma}$	1.02 ± 0.22	1.01 ± 0.20	1.01 ± 0.13

High E_{T}^{γ} region is used to obtain both non-unitarised (presented) and unitarised limits on $\mathcal{O}_{T,j}^8$ and $\mathcal{O}_{M,j}^8$ [7].

Unitrisation is achieved using *clipping* method: setting the anomalous contribution to 0 for for $m_{Z\gamma} > E_c$ (estimated on particle level).





Coefficient	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
$f_{T,0}/\Lambda^4$	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
$f_{T,5}/\Lambda^4$	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
$f_{T,8}/\Lambda^4$	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
$f_{T,9}/\Lambda^4$	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
$f_{M,0}/\Lambda^4$	$[-4.6, 4.6]$	$[-6.2, 6.2]$
$f_{M,1}/\Lambda^4$	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
$f_{M,2}/\Lambda^4$	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Conclusion

- First observation of the $pp \rightarrow WWW$ process.
- Results of cross-section measurements of both WWW and $Z(\nu\nu)\gamma jj$ production are in agreement with the Standard Model.
- $Z(\nu\nu)\gamma jj$ production is used to obtain the most stringent up do date limits on the $\mathcal{O}_{T,j}^8$ coefficients.

References:

[1] Celine Degrande et al. In: *Annals of Physics* 335 (Aug. 2013), pp. 21–32. DOI: 10.1016/j.aop.2013.04.016.

[2] ATLAS Collaboration. In: *Phys. Lett. B* 798 (Nov. 2019), p. 134913. DOI: 10.1016/j.physletb.2019.134913.

[3] CMS Collaboration. In: *Phys. Rev. Lett.* 125.15 (Oct. 2020), p. 151802. DOI: 10.1103/PhysRevLett.125.151802.

[4] ATLAS Collaboration. 2022. DOI: 10.48550/ARXIV.2201.13045. URL: https://arxiv.org/abs/2201.13045.

[5] CMS Collaboration. In: *Phys. Rev. D* 104.7 (Oct. 2021), p. 072001. DOI: 10.1103/PhysRevD.104.072001.

[6] ATLAS Collaboration. In: *EPJC* 82.2 (2022), pp. 1–41. DOI: 10.1140/epjc/s10052-021-09878-z.

[7] ATLAS Collaboration. URL: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-59/.

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