Studies of quartic electroweak interactions in the ATLAS experiment

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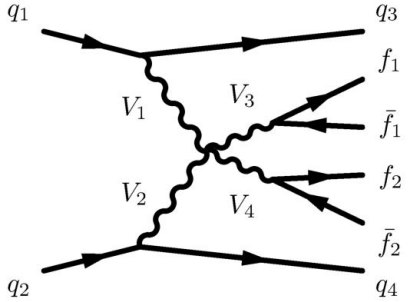
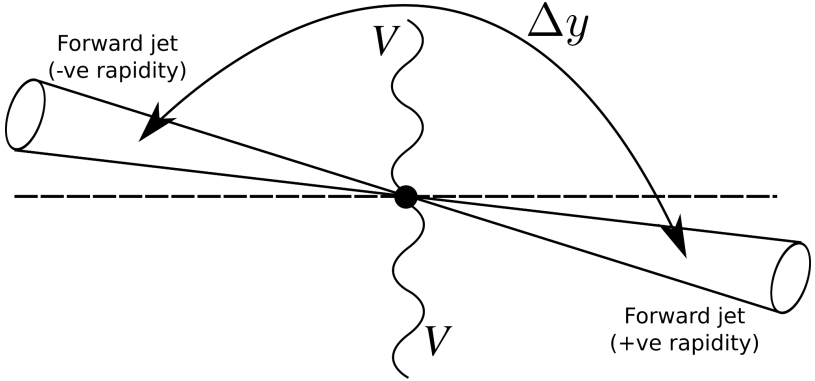
Measuring electroweak interactions at the LHC

- Quartic electroweak (EW) interactions appear in **Vector Boson Scattering** (VBS) and **triboson** processes at LO
- Some of the rarest processes measured at the LHC
- Often a large QCD-induced background
- Allow for searches of new physics through Anomalous Quartic Gauge Couplings (AQGC)

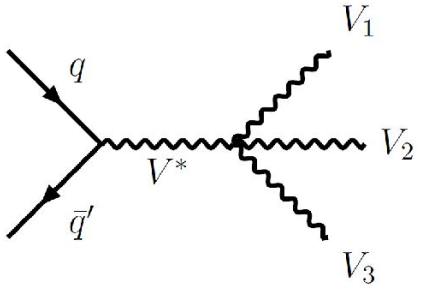
VBS



Characteristic VBS event topology:



Triboson



Observation of electroweak production of W+W− jj

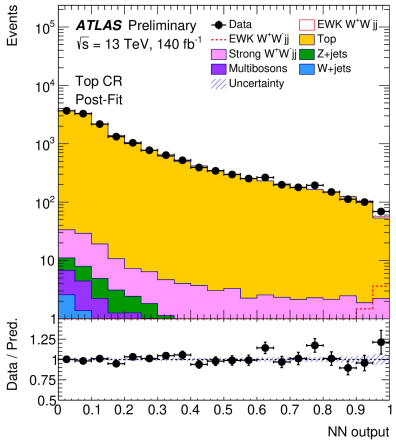
ATLAS-CONF-2023-039

- EW production of opposite-sign WW sensitive to **VBS**, and **quartic EW interactions**

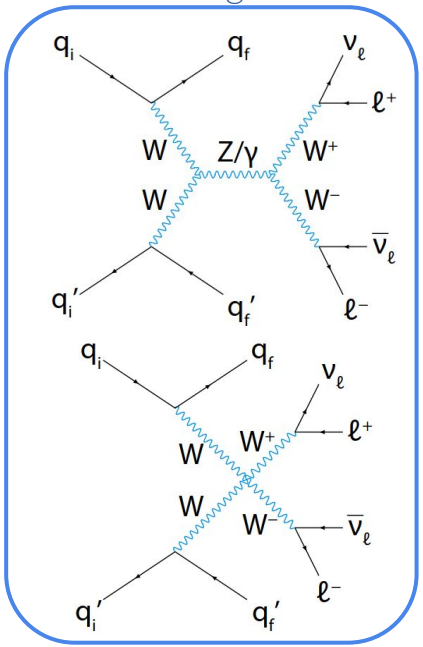
- Train neural network (NN) to distinguish signal from **top** and **QCD** backgrounds
- Select for:
  - 2-3 jets
  - Opposite sign electron muon pair
  - MET

- Dedicated top enriched control Region (CR) to constrain top backgrounds

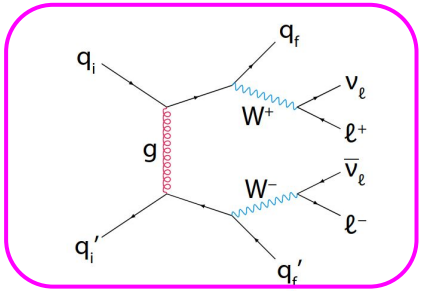
- CR defined by Inverting b-veto



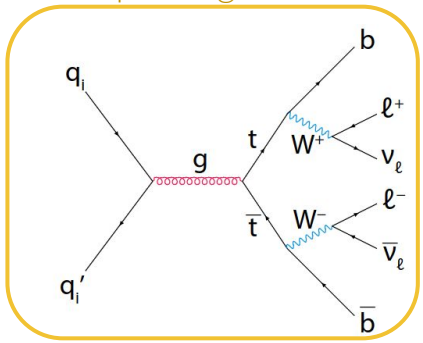
EW Signal



QCD background



Top backgrounds



Observation of electroweak production of W+W− jj

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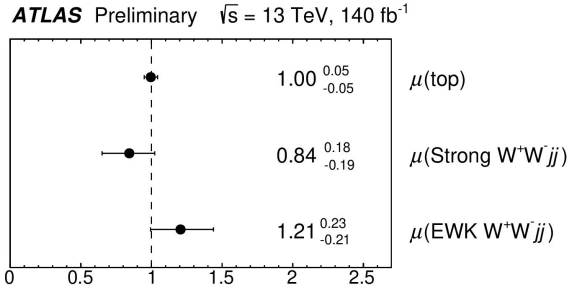
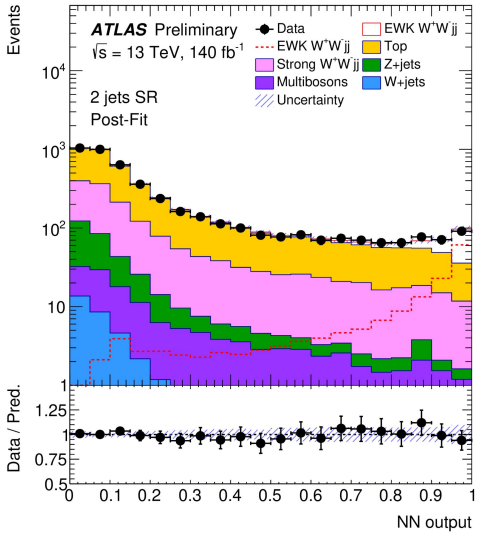
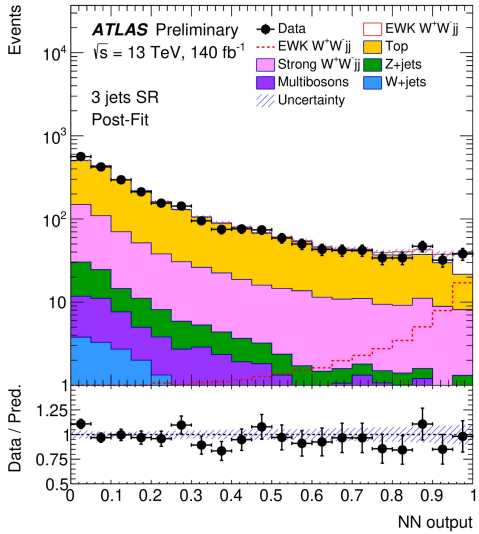
- Profile likelihood fit in NN score performed in signal region and CR simultaneously
- Constrain signal strength and strong, top background normalisations
- Dominant sources of uncertainty: data stats, MC stats, top background modelling, signal modelling, JES/JER



★ **EW W+W-jj observed at 7.1σ**

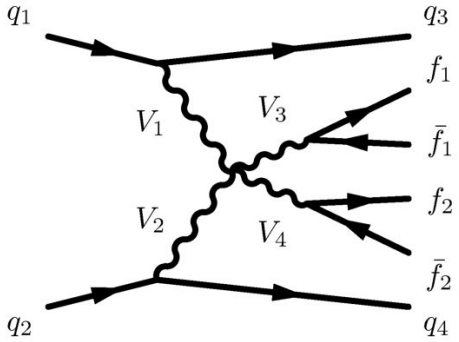
★ Fiducial cross-section:
σ_{EW} = 2.65 + 0.52 - 0.48 fb



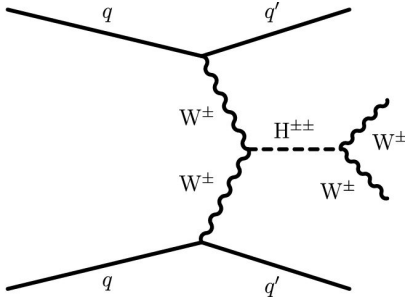


Measurement of same-sign WWjj production

EW Production, **VBS**



Possible BSM EW Production with **doubly charged Higgs**



ATLAS-CONF-2023-023

- Sensitive to VBS, quartic electroweak interactions, $H^{\pm\pm}$ interactions
- Dominant background from QCD WZjj production
- Selections:
  - Two same-sign leptons; third lepton veto
  - $m_{\ell\ell}$, MET
  - VBS topology: hard jets, large m_{jj}, large Δy
- QCD-WZjj enhanced CR to constrain dominant background

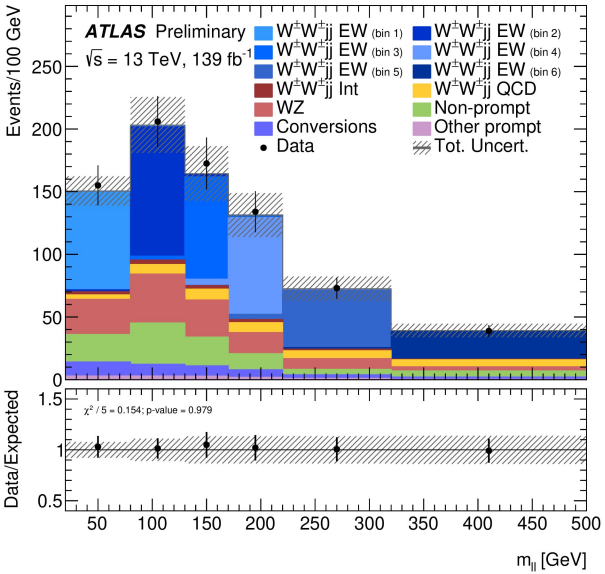
- Measure integrated fiducial cross-sections through likelihood fit of m_{jj} spectrum. EW and inclusive measurements.

Observed fiducial integrated cross-sections

★ $\sigma_{EW} = 2.88 \pm 0.21\ (stat.) \pm 0.19\ (syst.)$ fb
★ $\sigma_{EW+Int+QCD} = 3.35 \pm 0.22\ (stat.) \pm 0.20\ (syst.)$ fb

Measurement of same-sign WWjj production

- Differential signal extraction, WZ background normalisation, and unfolding performed simultaneously in likelihood fit.



EW

QCD+ INT + EW

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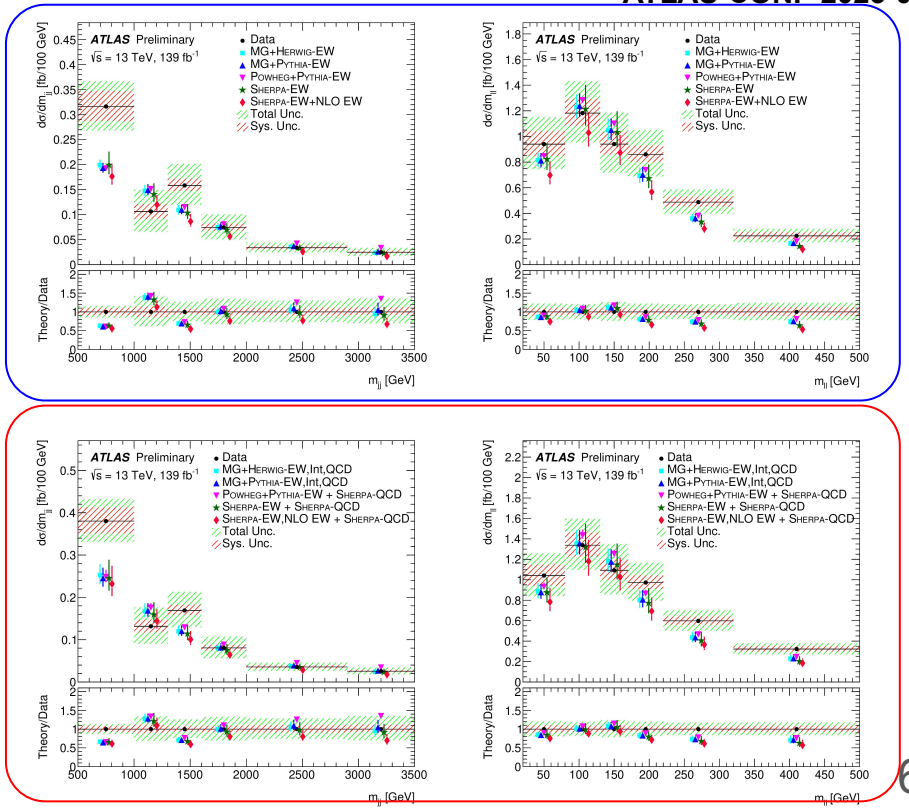


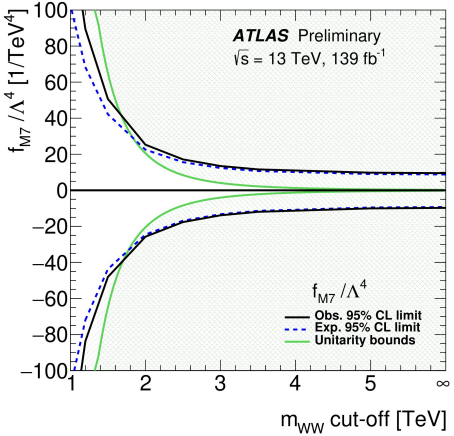
Measurement of same-sign WWjj production

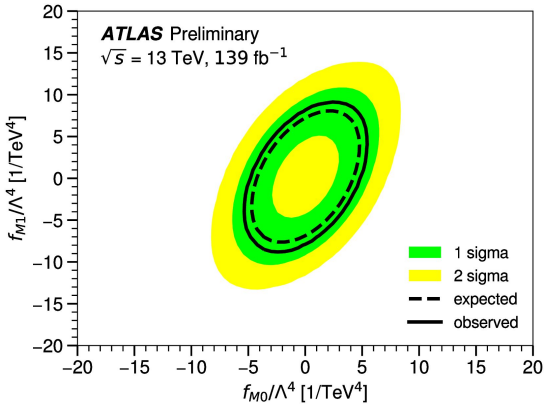
ATLAS-CONF-2023-023

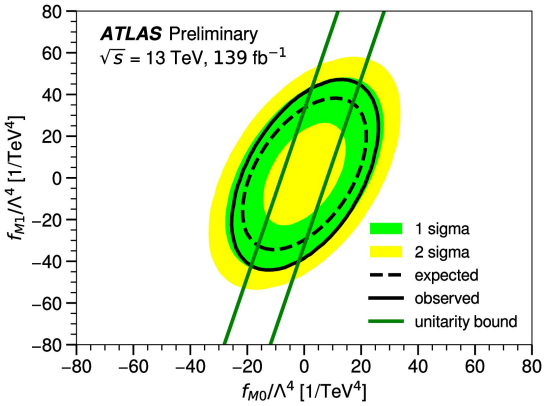
- Limits on AQGC through Eboli parametrisation of dim-8 EFT operators modifying EW $W^{\pm}W^{\pm}$ and EW WZ
- Dim > 4 operators can lead to scattering amplitudes that violate unitarity. Apply unitary constraint from theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)} \qquad |\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\,\text{Re}(\mathcal{M}_{\text{SM}}{}^* \mathcal{M}_{\text{d8}}) + |\mathcal{M}_{\text{d8}}|^2$$

Constraints on these Wilson coefficients at different cut-off energies







Measurement of same-sign WWjj production

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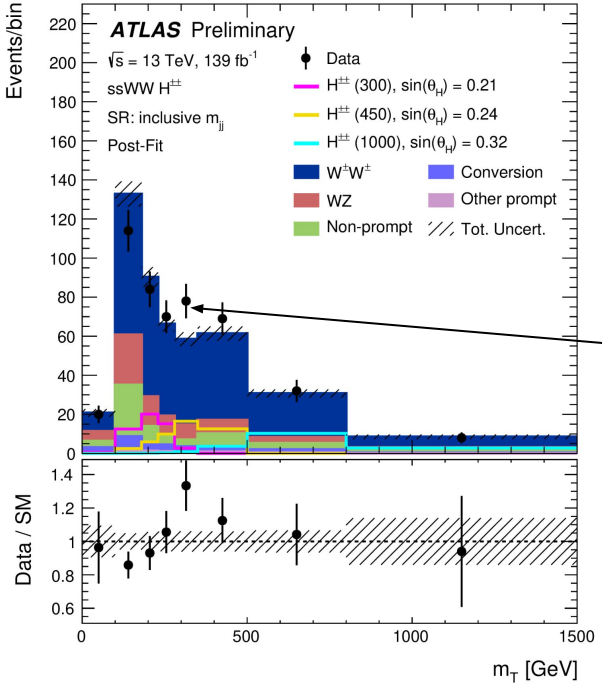
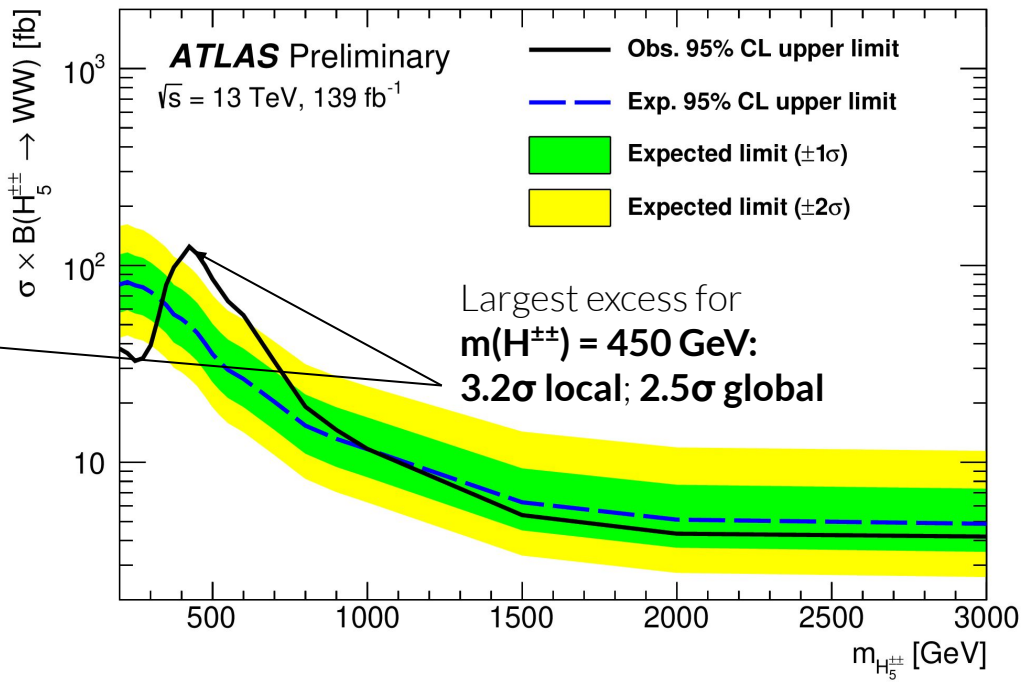
- Limits on production of $H^{\pm\pm}$ decaying to a pair of W bosons, within the Georgi–Machacek (GM) model.
- Limit setting performed using m_T distribution.

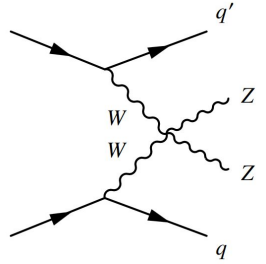


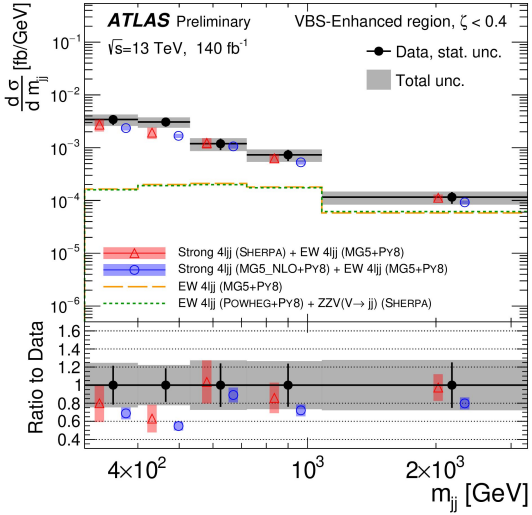


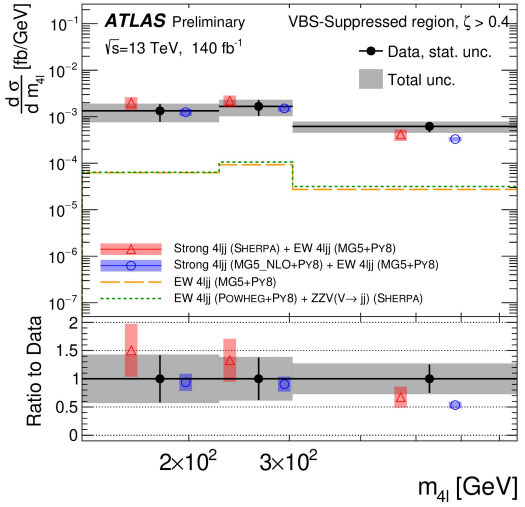
Measurement of inclusive ZZ(→4ℓ)jj production

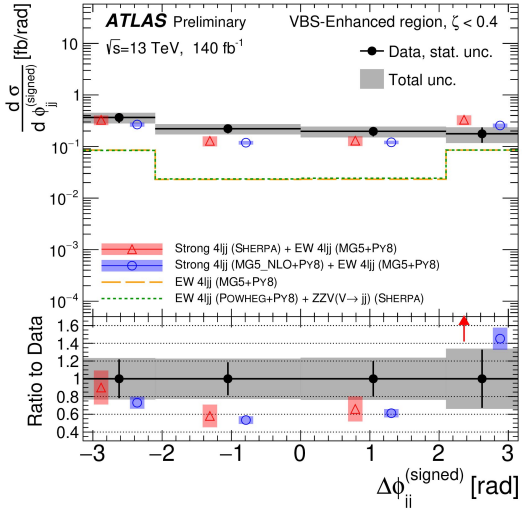
ATLAS-CONF-2023-024

- Sensitive to quartic EW gauge couplings, triple EW gauge couplings through VBS
- Measure differential cross-sections for the inclusive production, EFT limits
- Event selection:
  - 2SFOS lepton pairs and 2 jets
  - VBS event topology: large m_{jj}, $p_{T,j}$, Δy_{jj}, centrally produced 4-lepton system





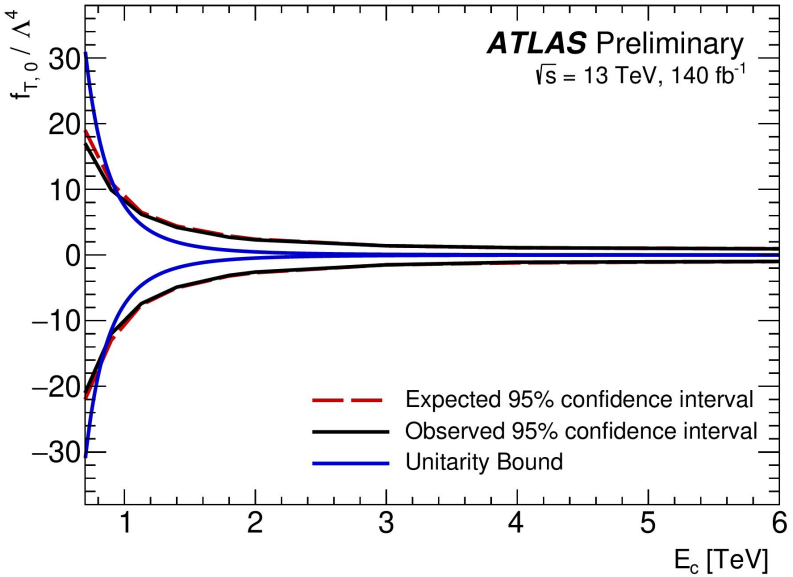




Measurement of inclusive ZZ(→4ℓ)jj production

ATLAS-CONF-2023-024

- Limits set on Wilson coefficients of dim-6 and dim-8 operators
- Use likelihood fit similar to same-sign WWjj
- Improved limits on dim-6 CP-odd operators though parity-odd **Δϕ**(j,j) observable



Use **Δϕ**(j,j)

Dim-8

Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98,0.93]	[-1.0,0.97]
	no	[-23, 17]	[-19, 19]
$f_{T,1}/\Lambda^4$	yes	[-1.2, 1.2]	[-1.3, 1.3]
	no	[-160, 120]	[-140, 140]

Dim-6

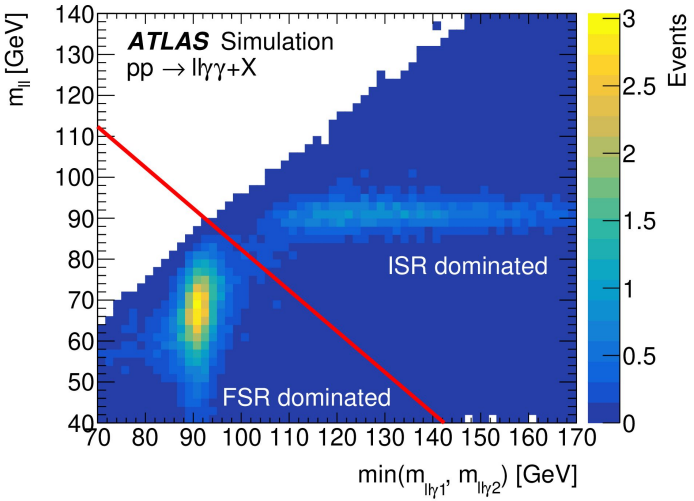
Wilson coefficient	$\lvert\mathcal{M}_{d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*

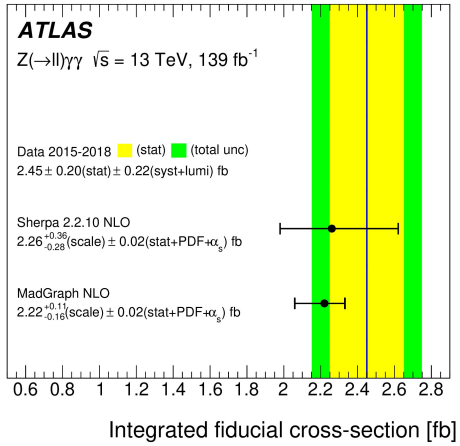
Measurement of Z(→ℓℓ)γγ production

EPJC 83 (2023) 539

- First measurement of **purely ISR** Z(→ℓℓ)γγ production!
  - Measured at 8TeV, **no FSR rejection** [PRD 93, 112002]
  - CMS measurement + EFT limits at 13 TEV, **no FSR rejection** [JHEP 10 174 (2021)]

$$(m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z)$$

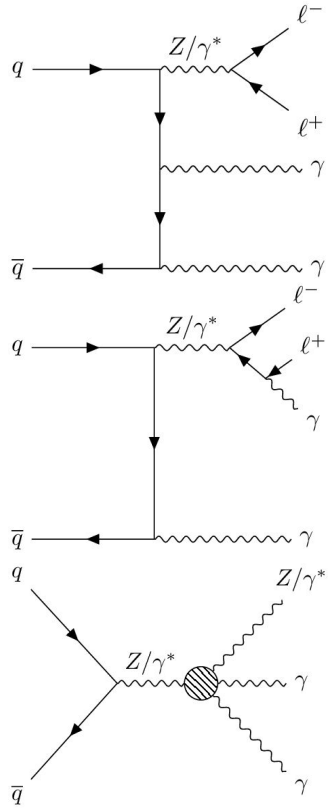




ISR

FSR

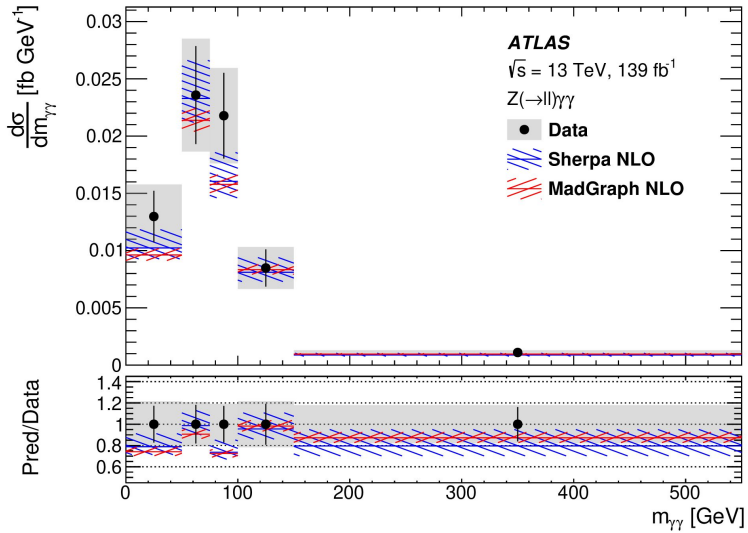
AQGC

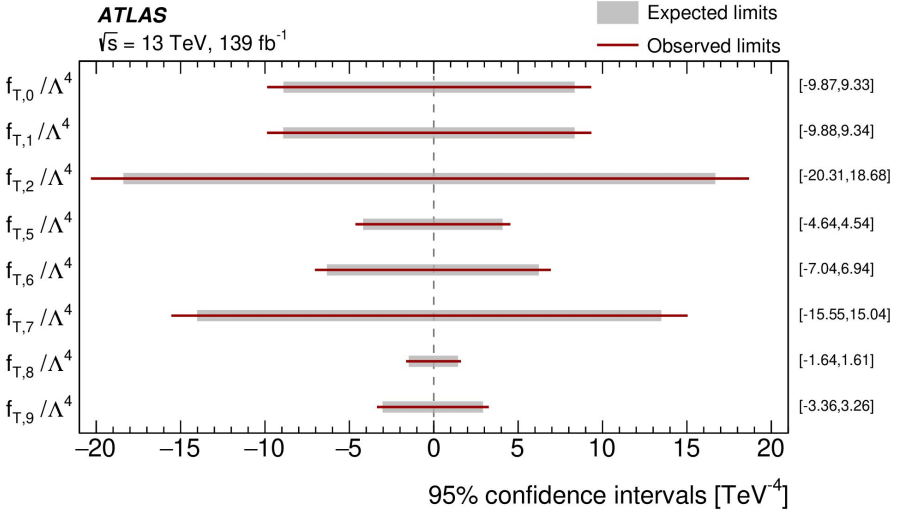


Measurement of Z(→ℓℓ)γγ production

EPJC 83 (2023) 539

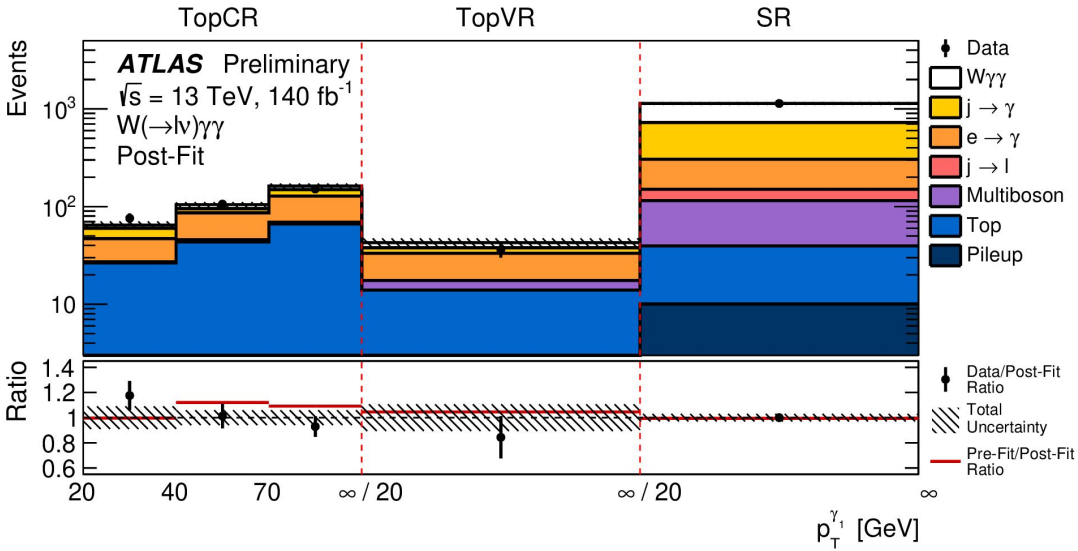
- First differential cross-section measurements of **ℓℓγγ** ($E_{T,\gamma}$, $p_{T,\ell\ell(\gamma\gamma)}$, $m_{\gamma\gamma(\ell\ell)}$)
- $m_{\gamma\gamma}$ distribution is important in the context of diphoton resonance searches in **ℓℓγγ** channels
- Limits on dim-8 AQGC



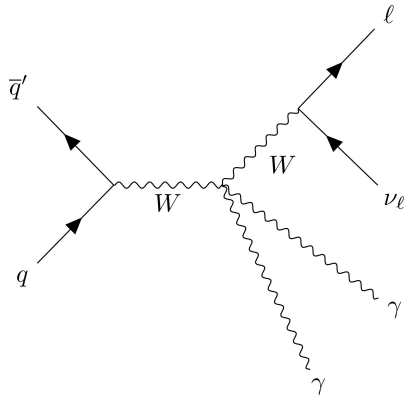


Observation of Wγγ production

- First observation of Wγγ production at the LHC!
- Largest background from hadronic fake photons
  - Dominant uncertainty from non-prompt background estimates



ATLAS-CONF-2023-005



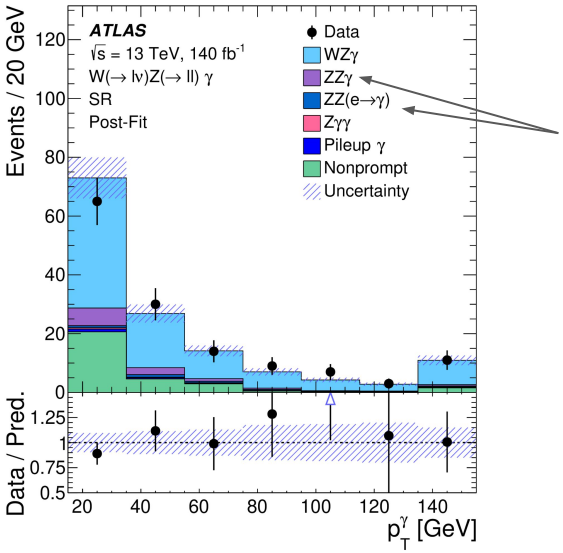
★ **Wγγ observed at 5.6σ**

★ Fiducial cross-section:
σ_{fid} = 12.2 + 2.1 - 2.0 fb

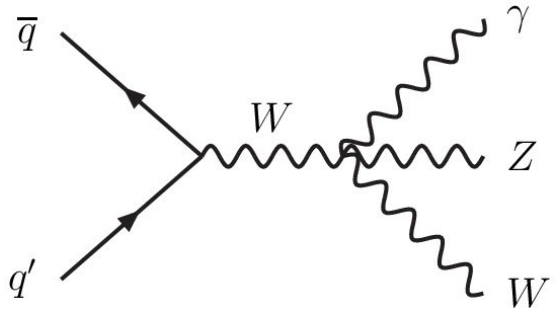
Observation of WZγ production

CERN-EP-2023-095

- Combined VVV observed by CMS, WWW by ATLAS, combined WWγ WZγ by ATLAS and CMS
- First fiducial cross-section measurement and observation of WZγ production
- Measurement **fully leptonic final states** performed in **FSR suppressed** and **ISR/TGC/QGC enhanced** phasespace ($m_{\ell\ell}$ >81GeV).



Dedicated Control Regions



★ **WZγ observed at 6.3σ**

★ Fiducial cross-section:
σ_{fid} = 2.01 ± 0.30 (stat.) ± 0.16 (syst.) fb

Conclusion

- A very productive year for Standard Model EW triboson and VBS analyses!
- Observations of processes of **σ** = 1-10fb, often with large irreducible or non-prompt backgrounds
- Differential cross-section measurements of rare EW processes in VBS-enriched regions
- Increasingly large body of constraints on anomalous quartic weak boson interactions
- Can expect more EW VBS/triboson results soon!