Multiboson LHC

Multiboson and VBS measurements

S. Folgueras (Universidad de Oviedo)

on behalf of the CMS and ATLAS Collaborations

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AGENCIA ESTATAL DE INVESTIGACIÓN

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European Research Council
Established by the European Commission

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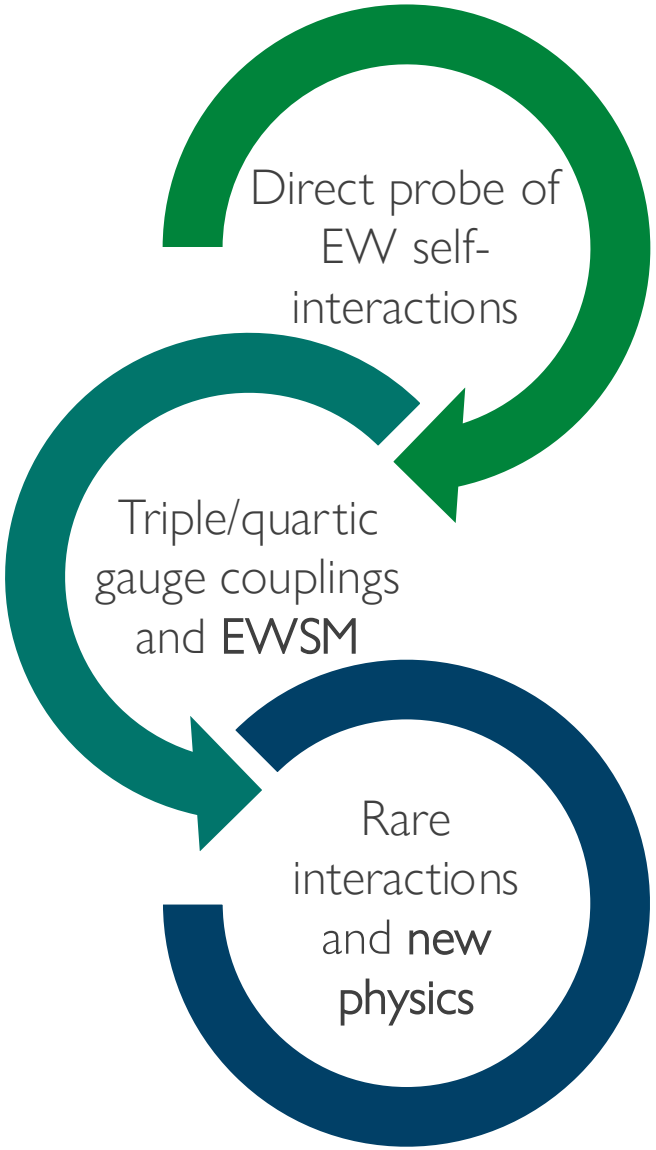
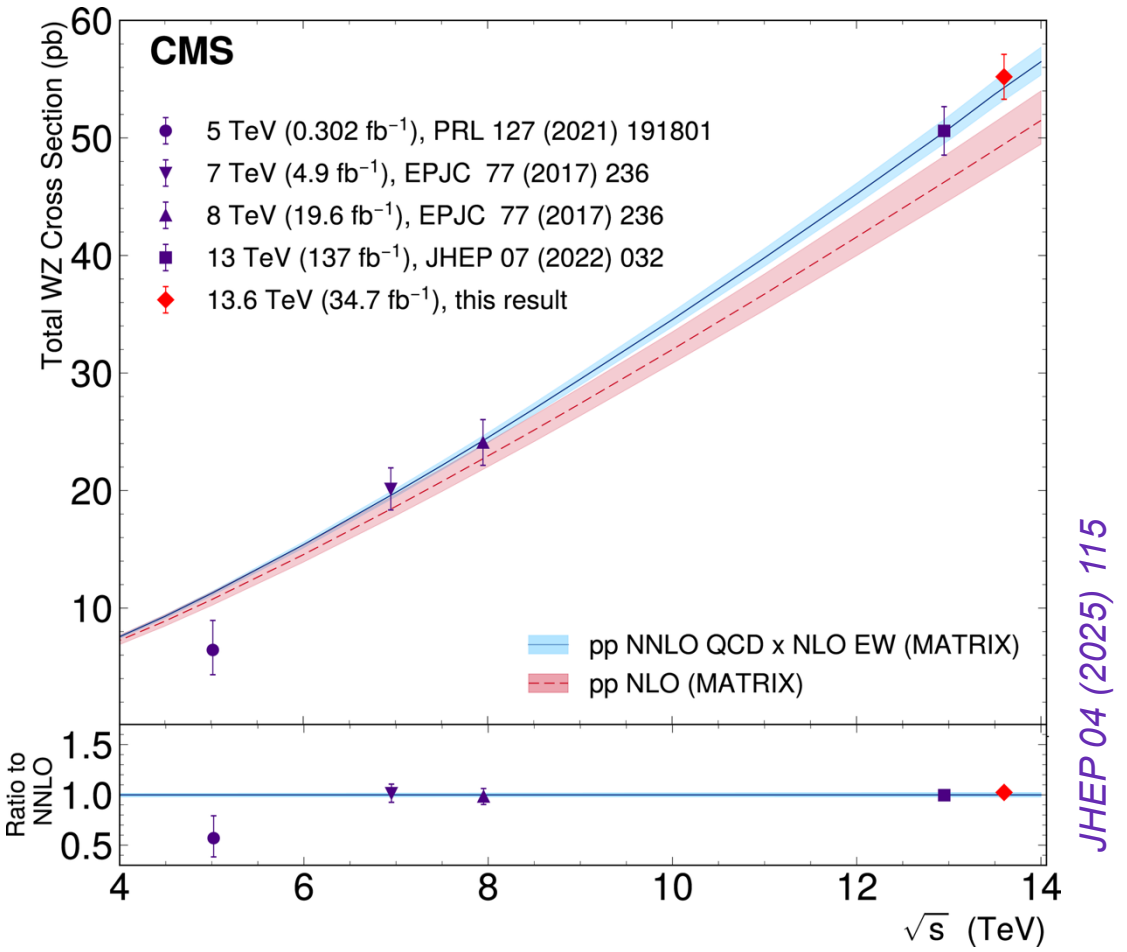
Why multiboson & VBS?



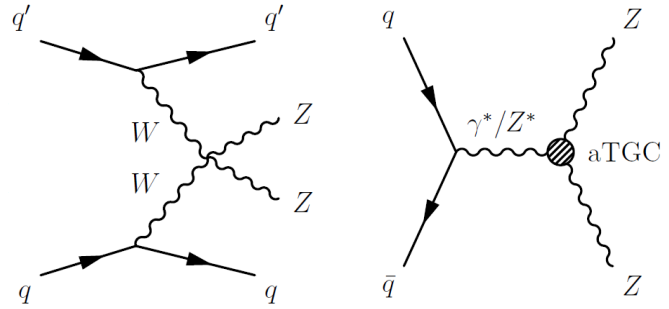


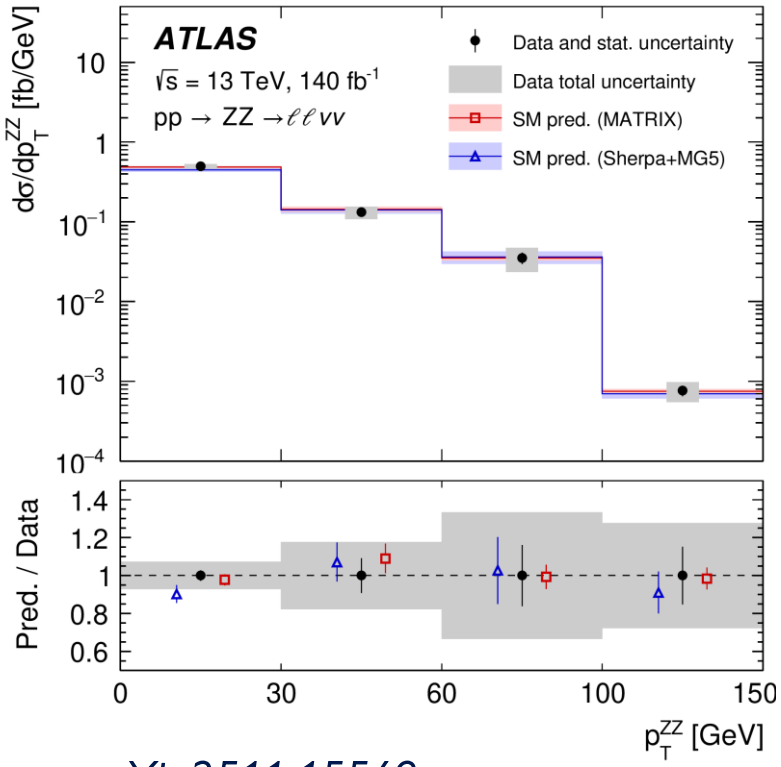
JHEP 04 (2025) 115

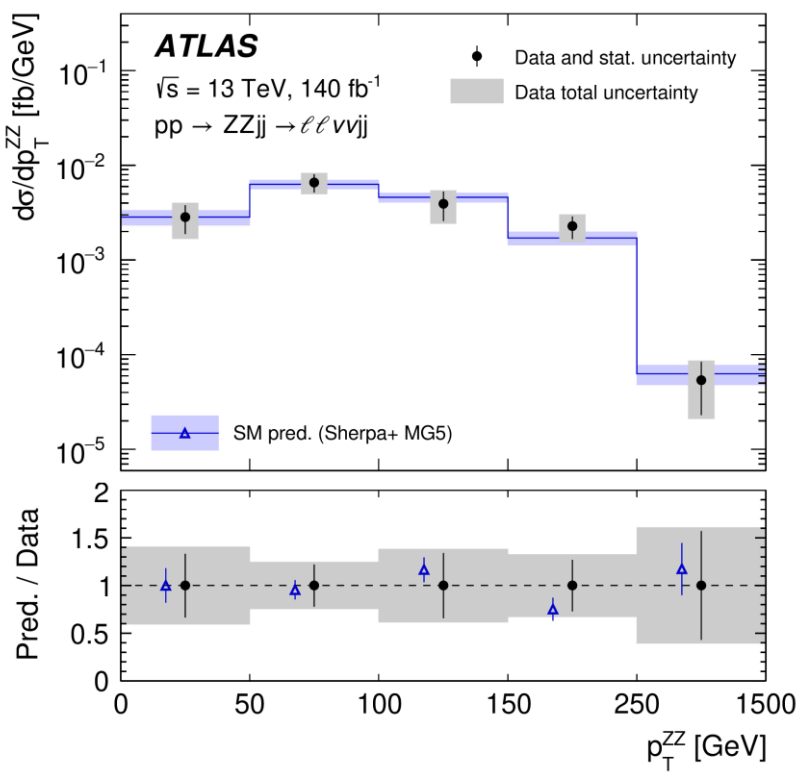
Multiboson measurements offer a **comprehensive test of the electroweak sector at the LHC**

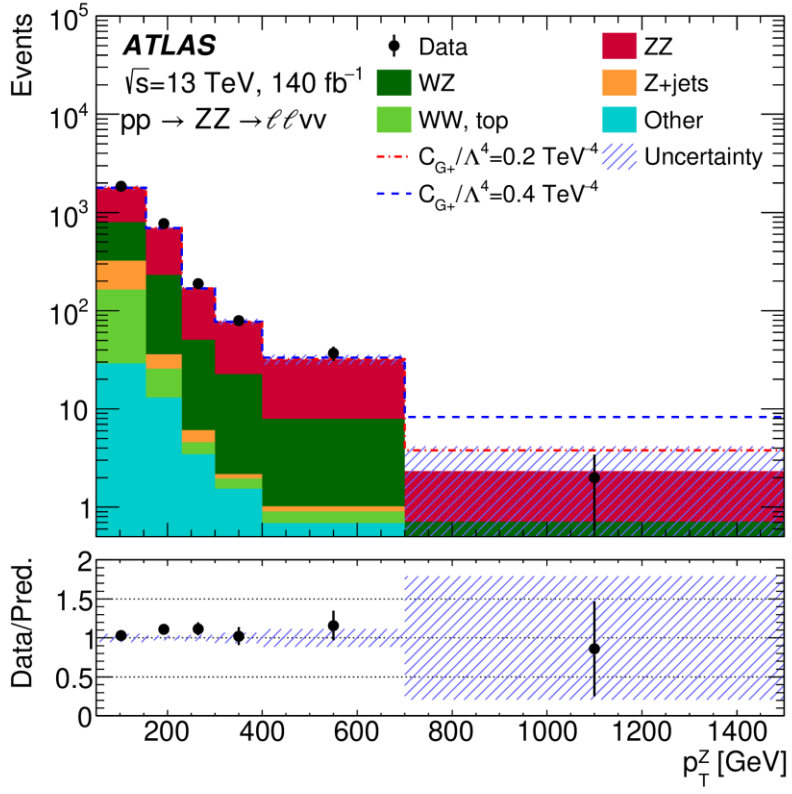
Differential diboson

- Inclusive ZZ and ZZjj
- Differential distributions in agreement with NLO
- Sensitivity to neutral TGC and QGC









arXiv:2511.15569

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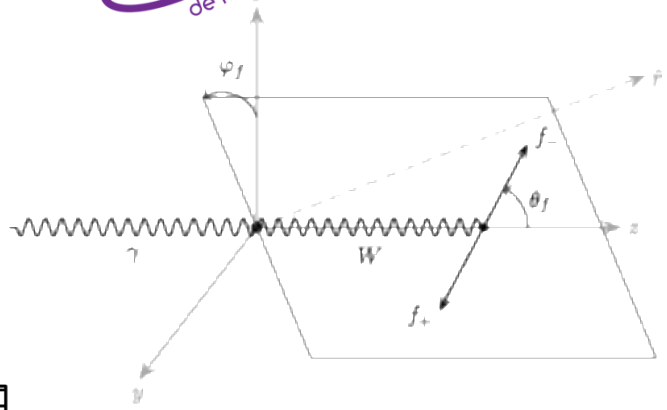
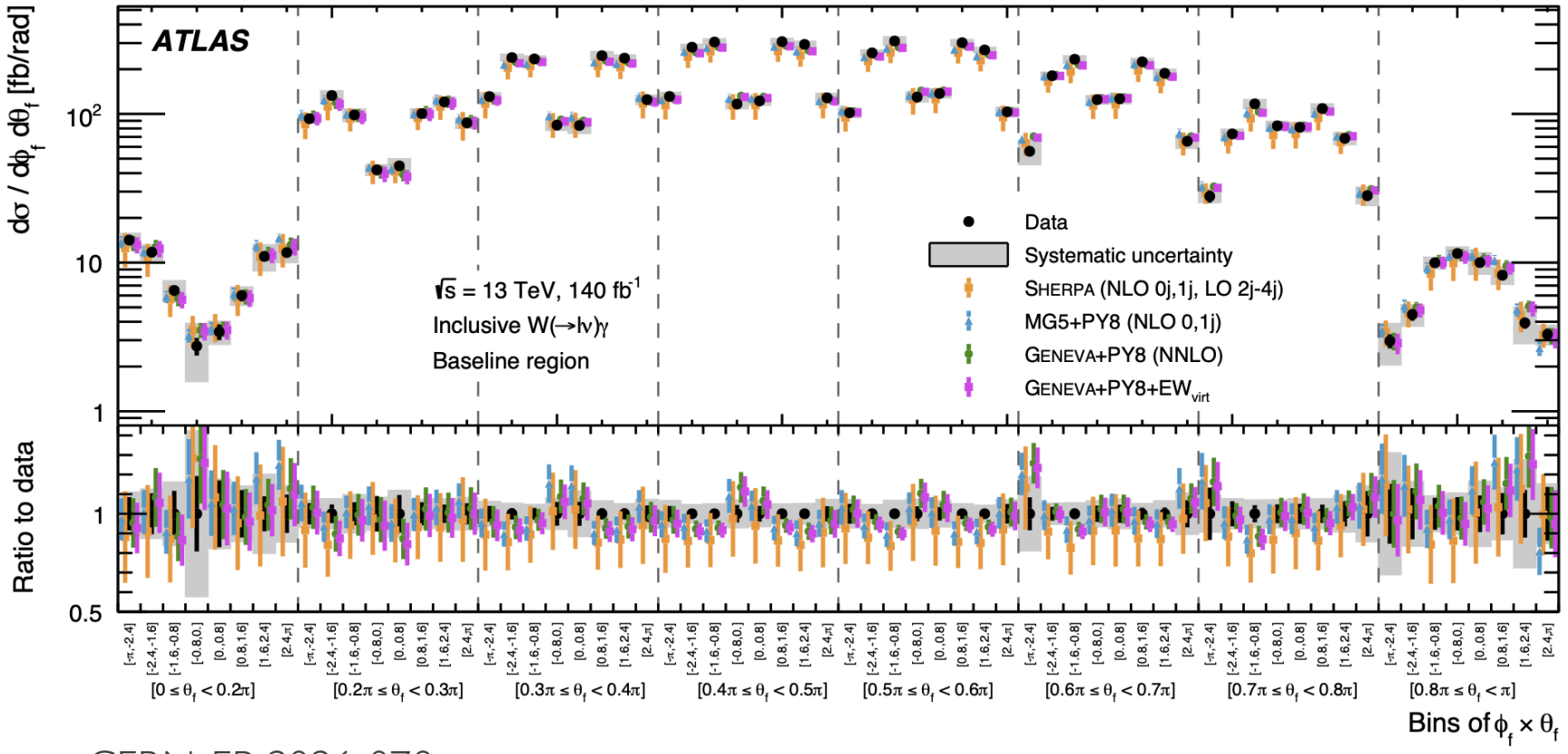
Wγ production: precision probe

- Sufficient precision to discriminate between state-of-the-art theoretical predictions including higher-order NNLO QCD and (virtual) NLO EW.
- Inclusive $W\gamma$ kinematic observables. RAZ probed.





CERN-EP-2026-078

Polarization:

- Double differential measurement W decay angles.
- Probe the polarisation state of the W and provide direct sensitivity to the W boson spin-density matrix.
- Agreement with SM

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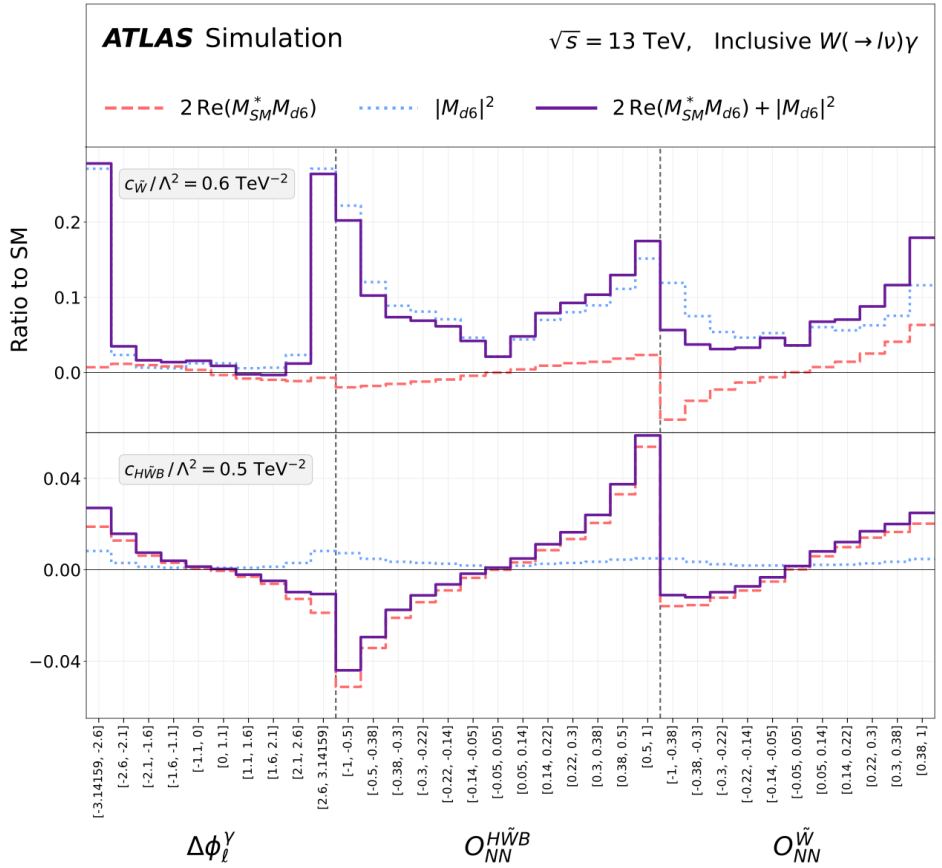

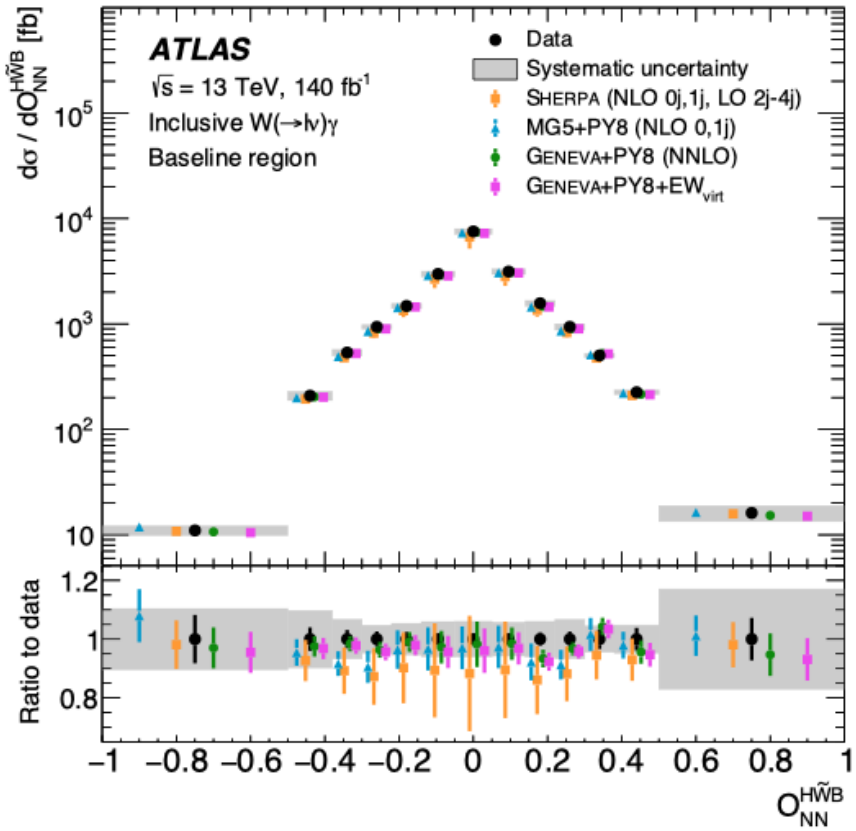

CP-sensitive observables:

- sensitive to interference caused by CP-violating $WW\gamma$ interactions
- O_{NN}, constructed from the outputs of a multi-class NN trained to separate interference for a given operator.

$$O_{NN} = P_+ - P_-$$

- In agreement with SM
- Improve the expected limits on the CP-odd operators by x2 compared to the use of $\Delta\phi_\ell^\gamma$ alone

CERN-EP-2026-078

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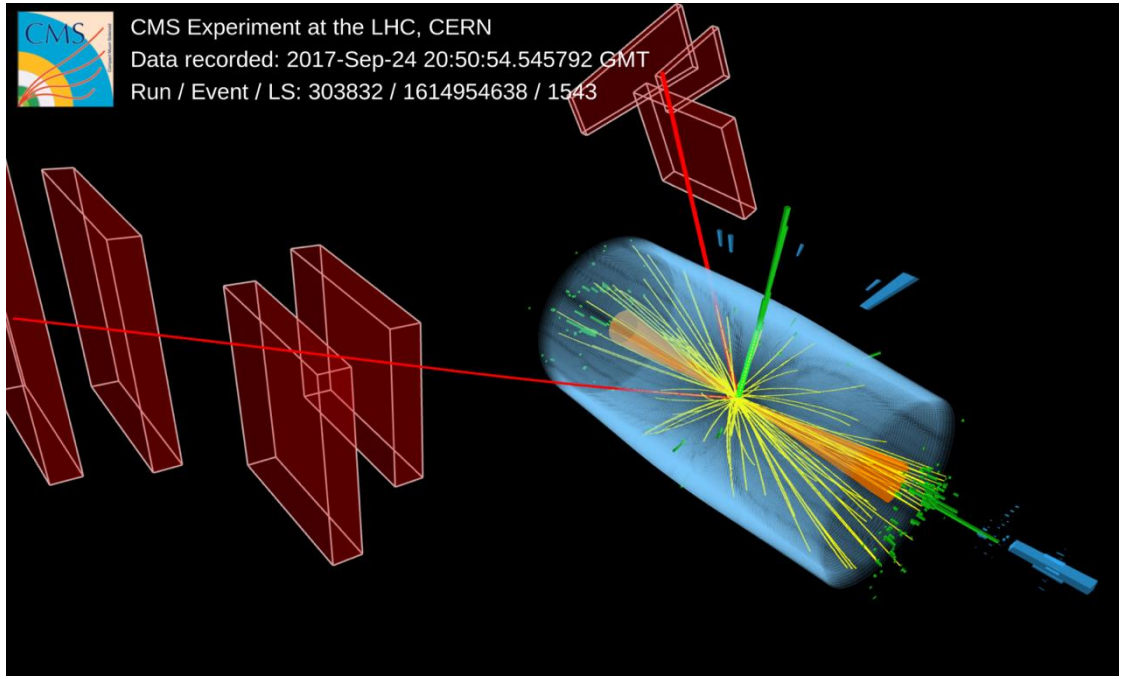
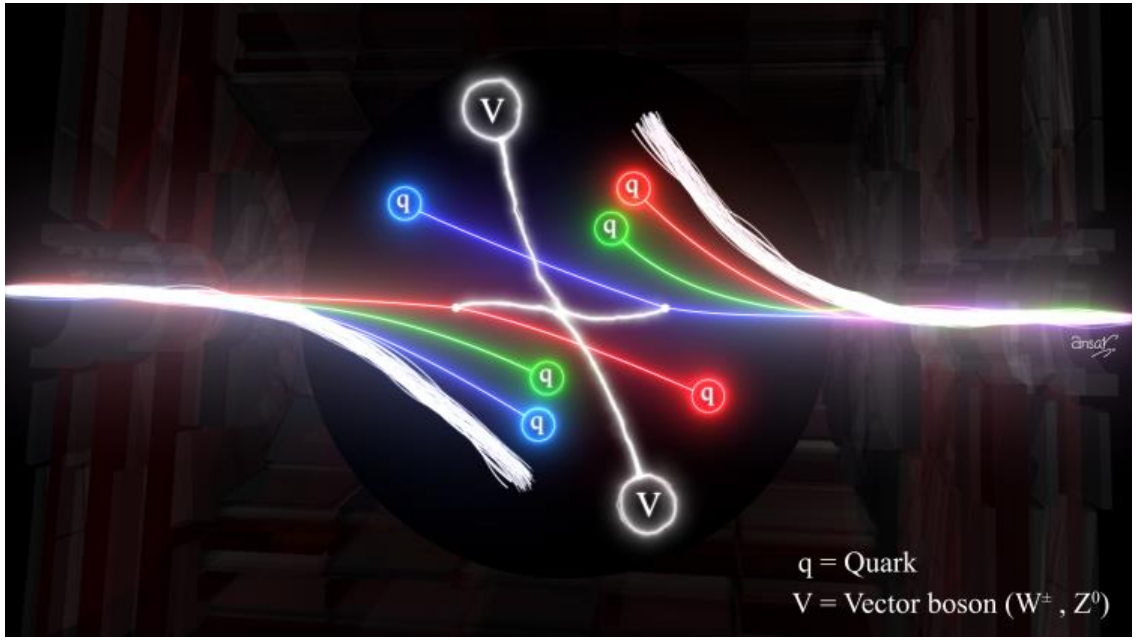
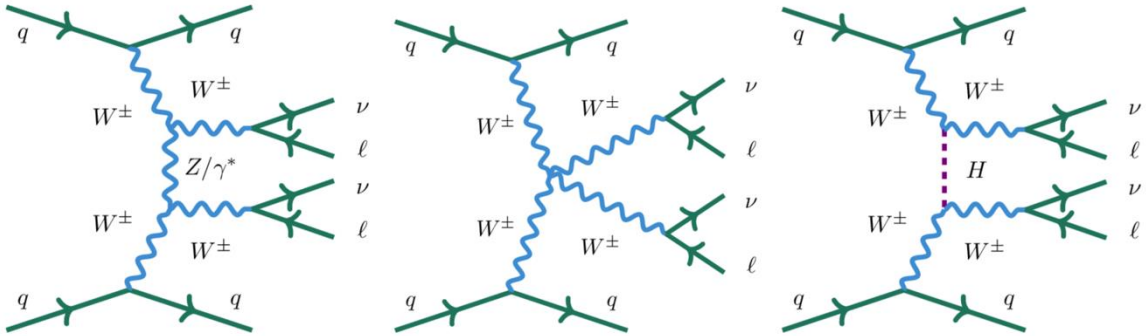
VBS topology

- Two vector bosons
- Two forward jets
- Large m_{jj},
- Large $\Delta\eta_{jj}$
- VBS directly probes quartic gauge couplings and electroweak symmetry breaking.





https://cms.cern/news/piecing-together-puzzle-comprehensive-look-vector-boson-scattering



VBS is now established experimentally, and Run 3 is the bridge to precision and EFT reach

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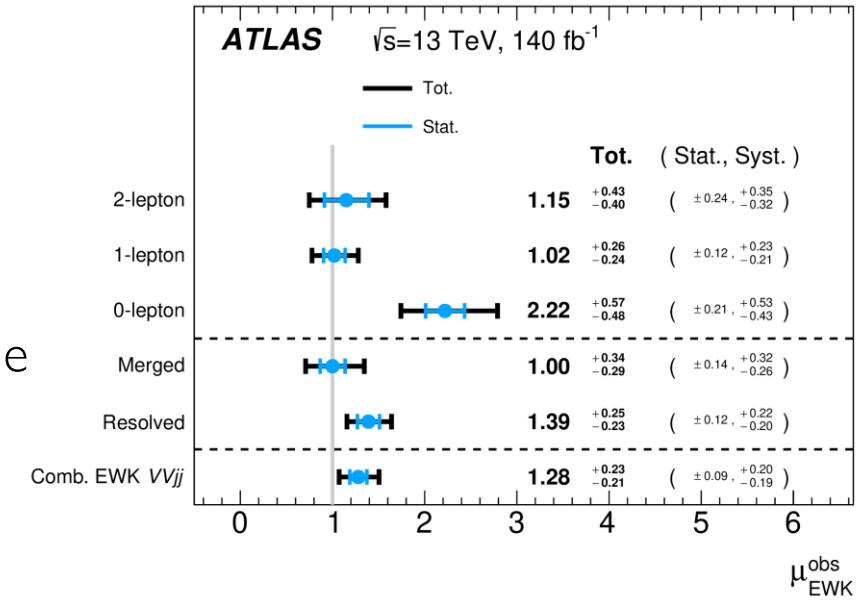
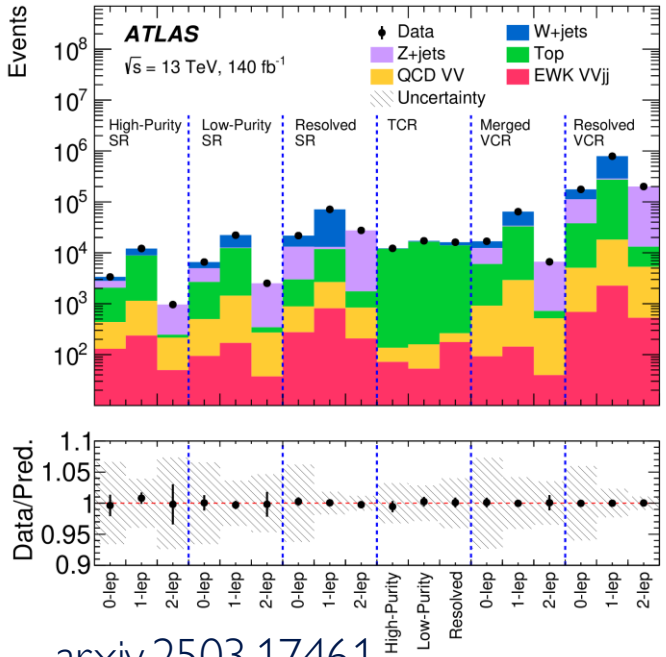
VBS observation in semileptonic modes

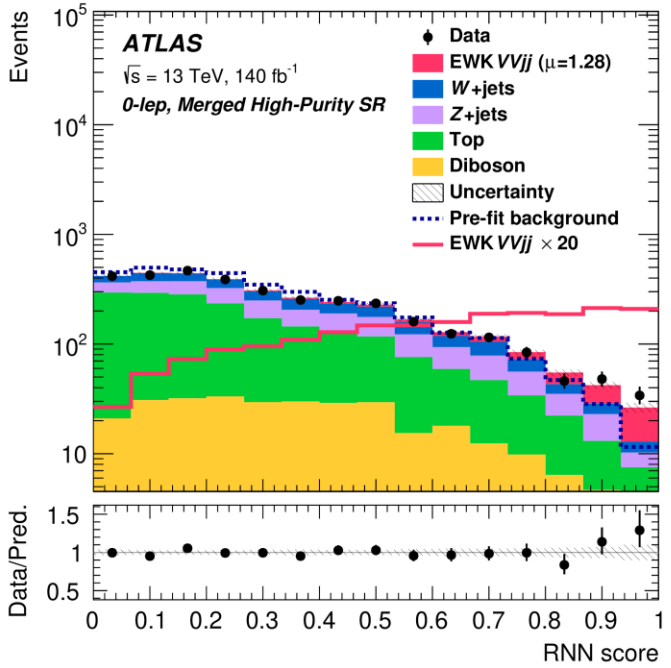
- Combined $\ell\ell$qq / ℓvqq / vvqq (resolved + merged)
- RNN-based extraction

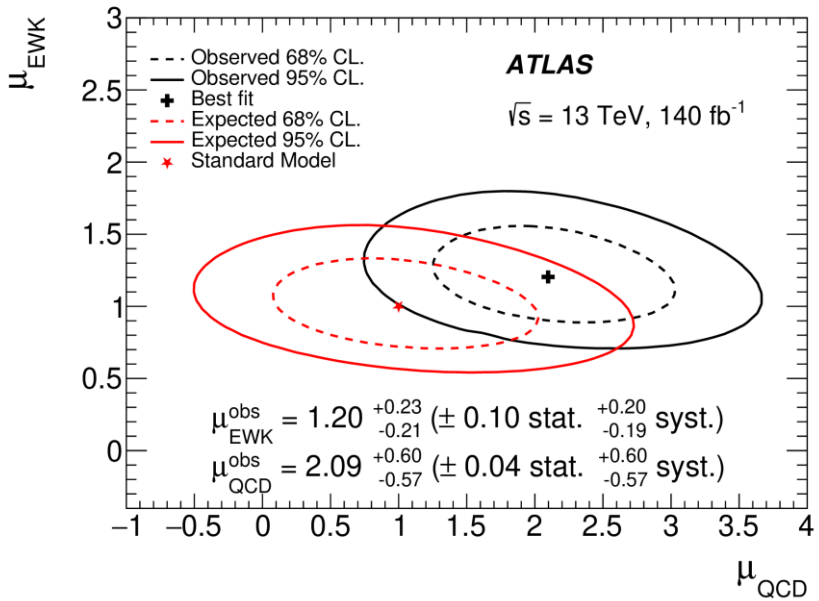
- Observed significance: 7.4σ (expected 6.1σ)
- ATLAS also sees 3.3σ evidence for ≥1 longitudinal W in SSWW: the next VBS frontier [Phys. Rev. Lett. 135 (2025) 111802]





arxiv.2503.17461





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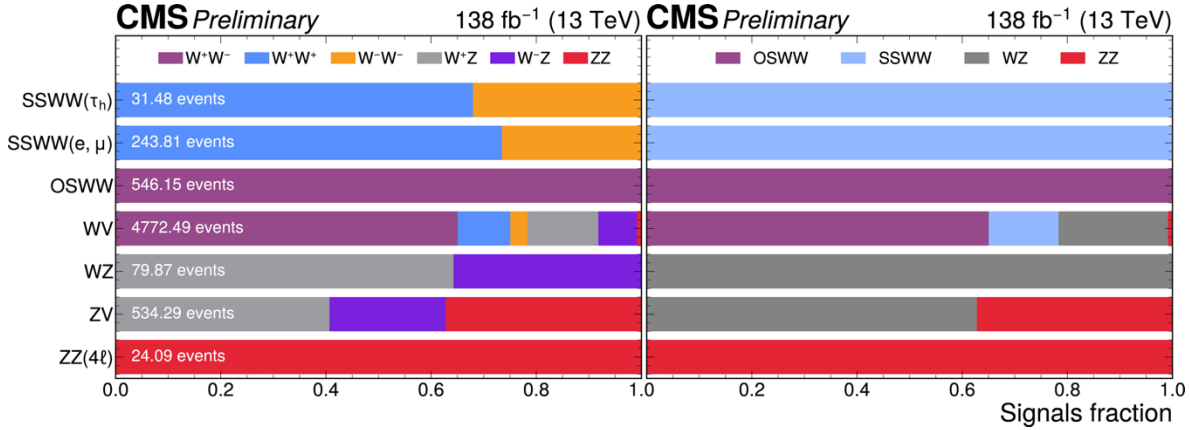
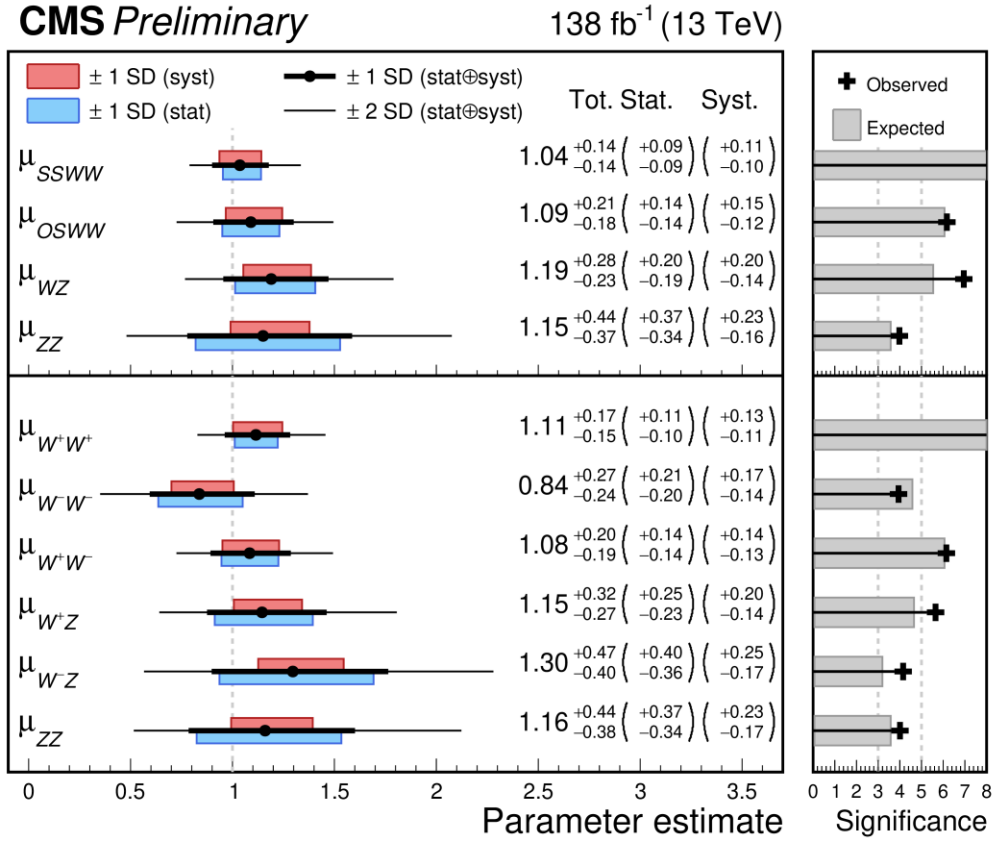
VBS: CMS combination across 7 channels

- Simultaneous fit to fully-leptonic (SSWW, OSWW, WZ, ZZ) and semi-leptonic (WV, ZV) final states
- Run-2 dataset: 138 fb^{-1} at 13 TeV
- Measured μ values (4-POI model) are all consistent with 1 within uncertainties





Provides a coherent baseline for EFT / aQGC interpretations and future Run-3 updates

CMS-PAS-SMP-24-013

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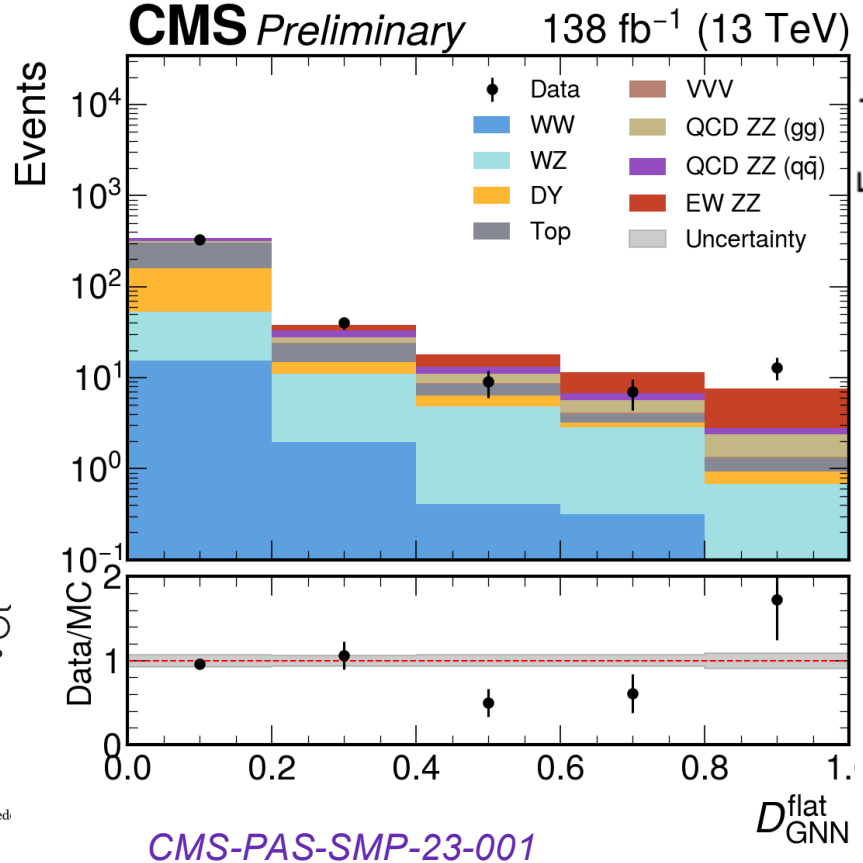
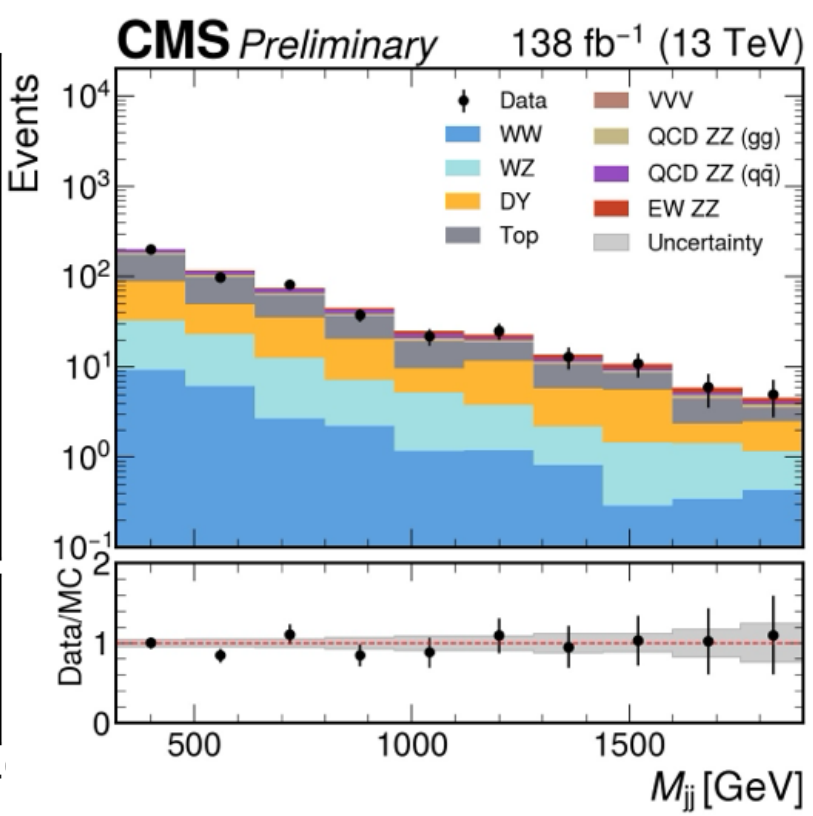
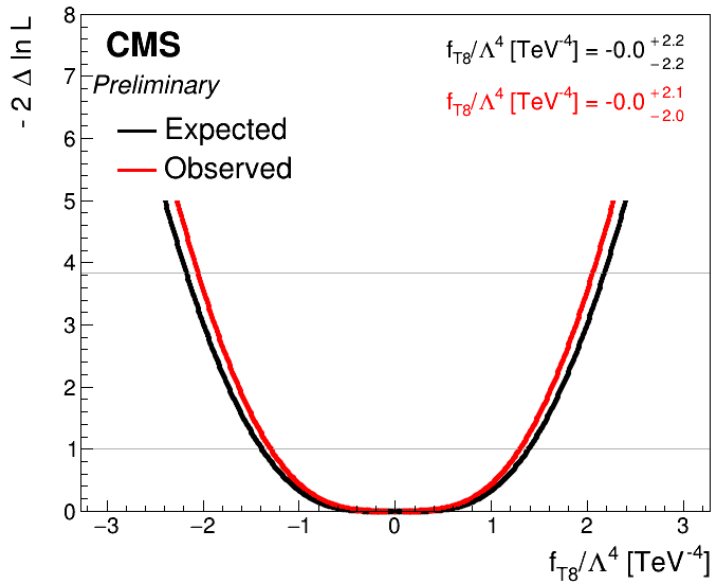
EW ZZ production:VBS fully established

- $\sigma_{EW} = 0.37^{+0.14}_{-0.12}(stat) \pm 0.06\ (syst)$
- 3.1 sigma in this channel alone, and 5 sigma when combined with the four-lepton channel,
  - establishing electroweak ZZ production.







Limits on aQGC are derived in terms of dimension-8 EFT operators.

CMS-PAS-SMP-23-001

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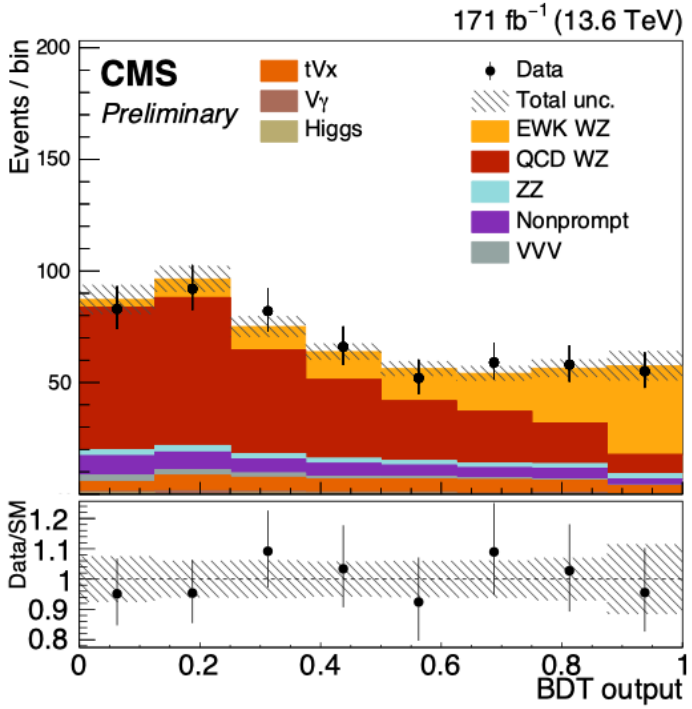
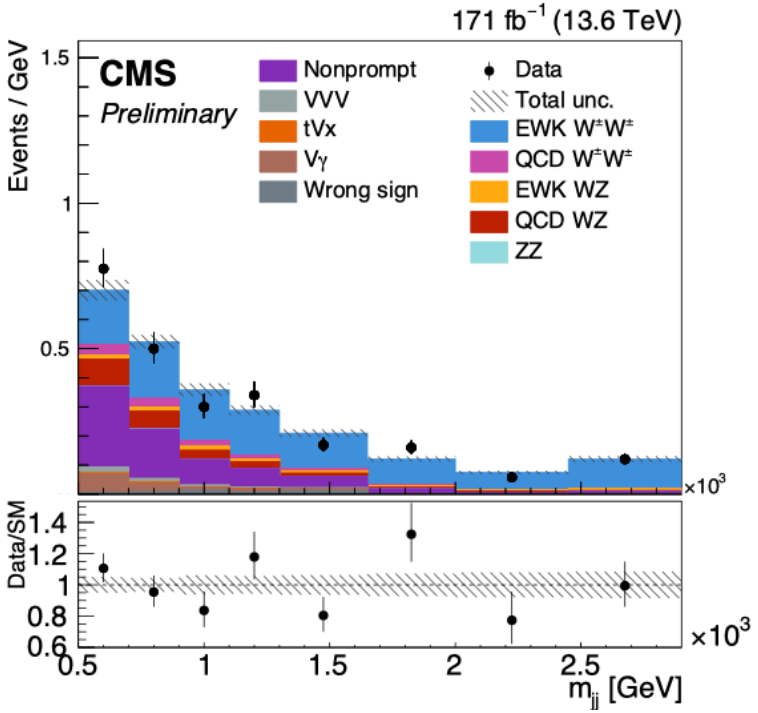
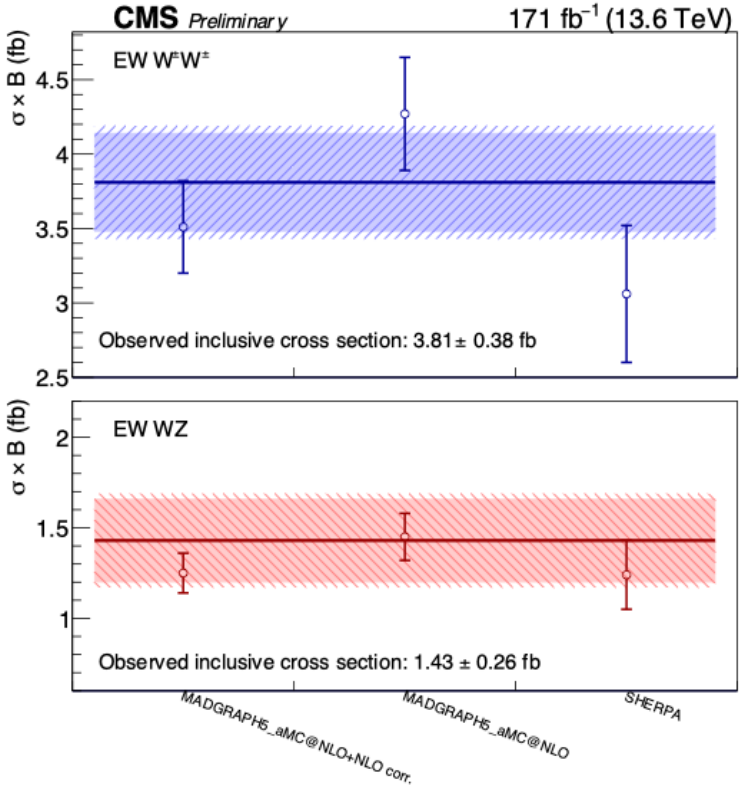
First measurement in VBS @13.6 TeV

- First Run-3 leptonic VBS measurement: both EW $W^{\pm}W^{\pm}$ and EW WZ observed with Run 3 data.
- **Analysis Strategy:** channels ($W^{\pm}W^{\pm}$ and WZ leptonic modes), VBS topology cuts, BDT-based WZ discrimination, and the simultaneous ML fit structure
- **Key Results:** >5σ and ~7σ observation significances. Inclusive fiducial cross sections. $W^{\pm}W^{\pm}$ differential.







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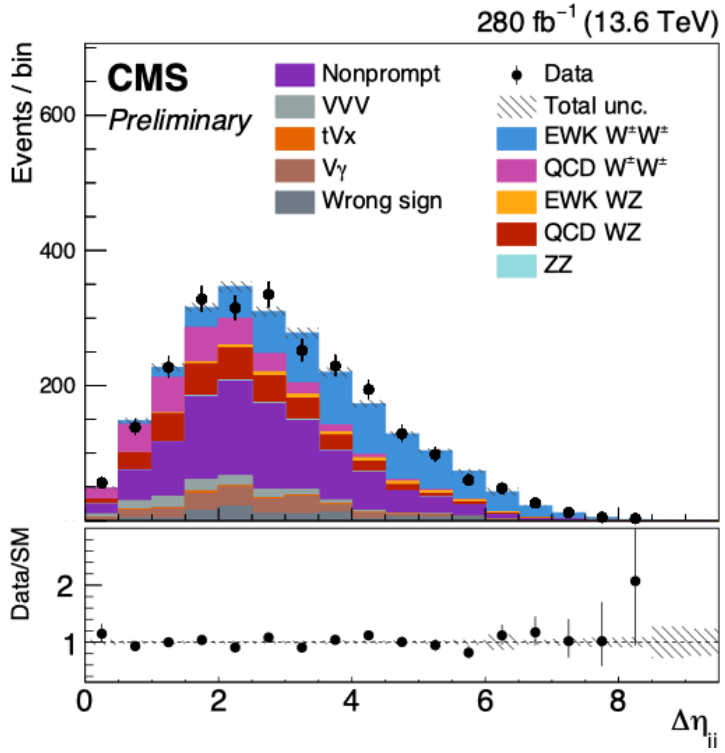
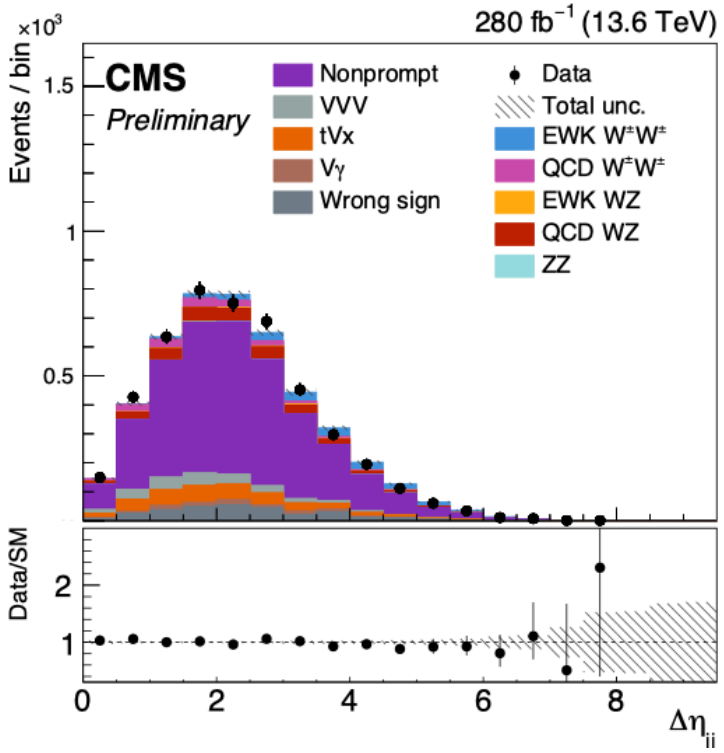
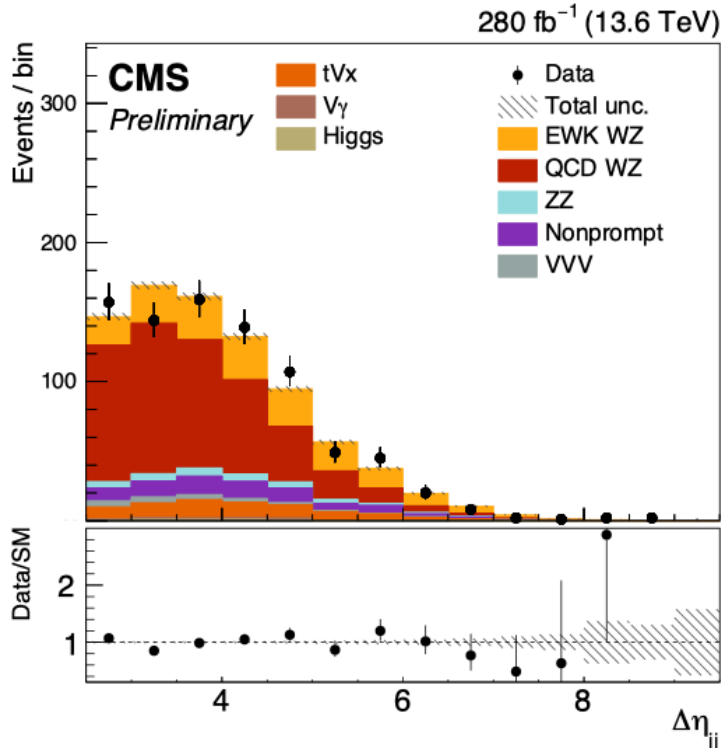
And already looking at 2025 data!

- More data is needed to improve sensitivity (to aQGC).
- Distributions in the 2022-25 data sample, both signal regions (with loose m_{jj} requirement) and control regions.





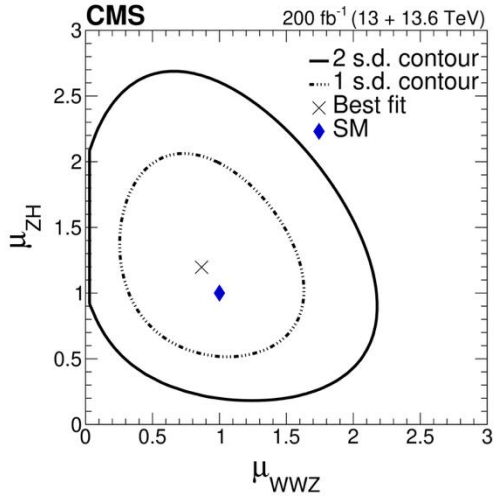


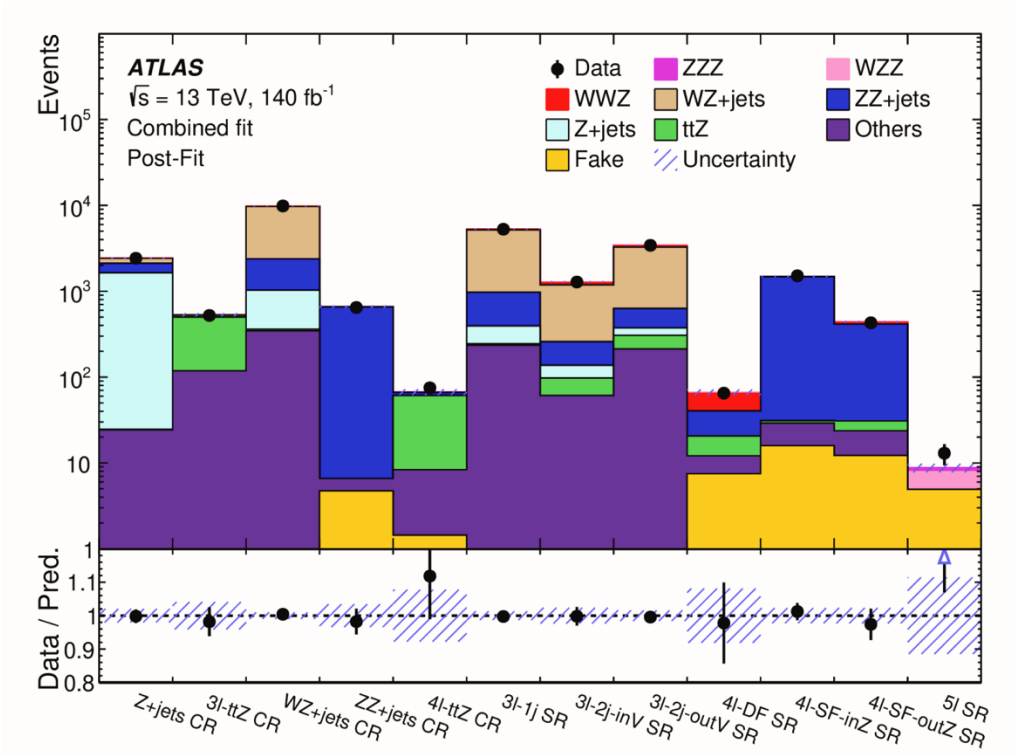
See Monika's talk this afternoon

CMS-PAS-SMP-25-013

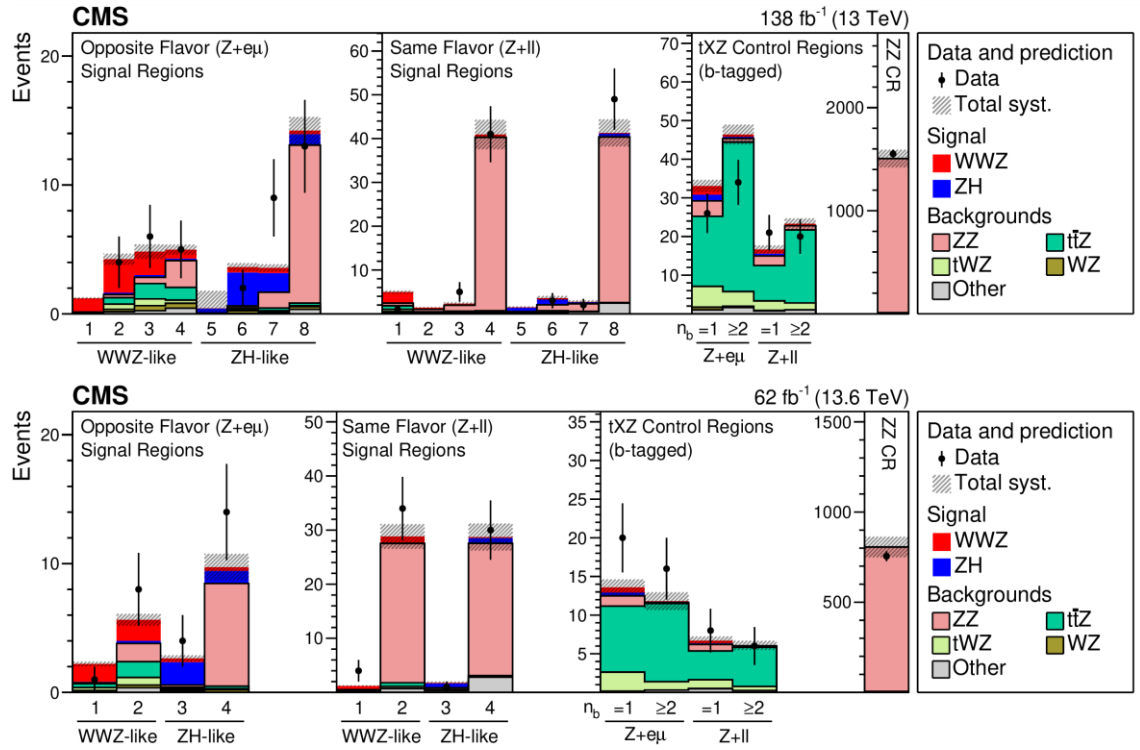
Triboson production: Run 2 + Run 3

- Triboson production directly probes quartic gauge couplings.
  - Extremely complex analyses, multiple final states to maximize sensitivity.
- CMS: evidence for triboson (WWZ) production at 13.6 TeV with 4.5σ (5σ) observed (expected) significance.
- ATLAS observed VVZ (6.4σ) and evidence of WWZ





Phys. Lett. B 866 (2025) 139527



PRL 135 (2025) 091802

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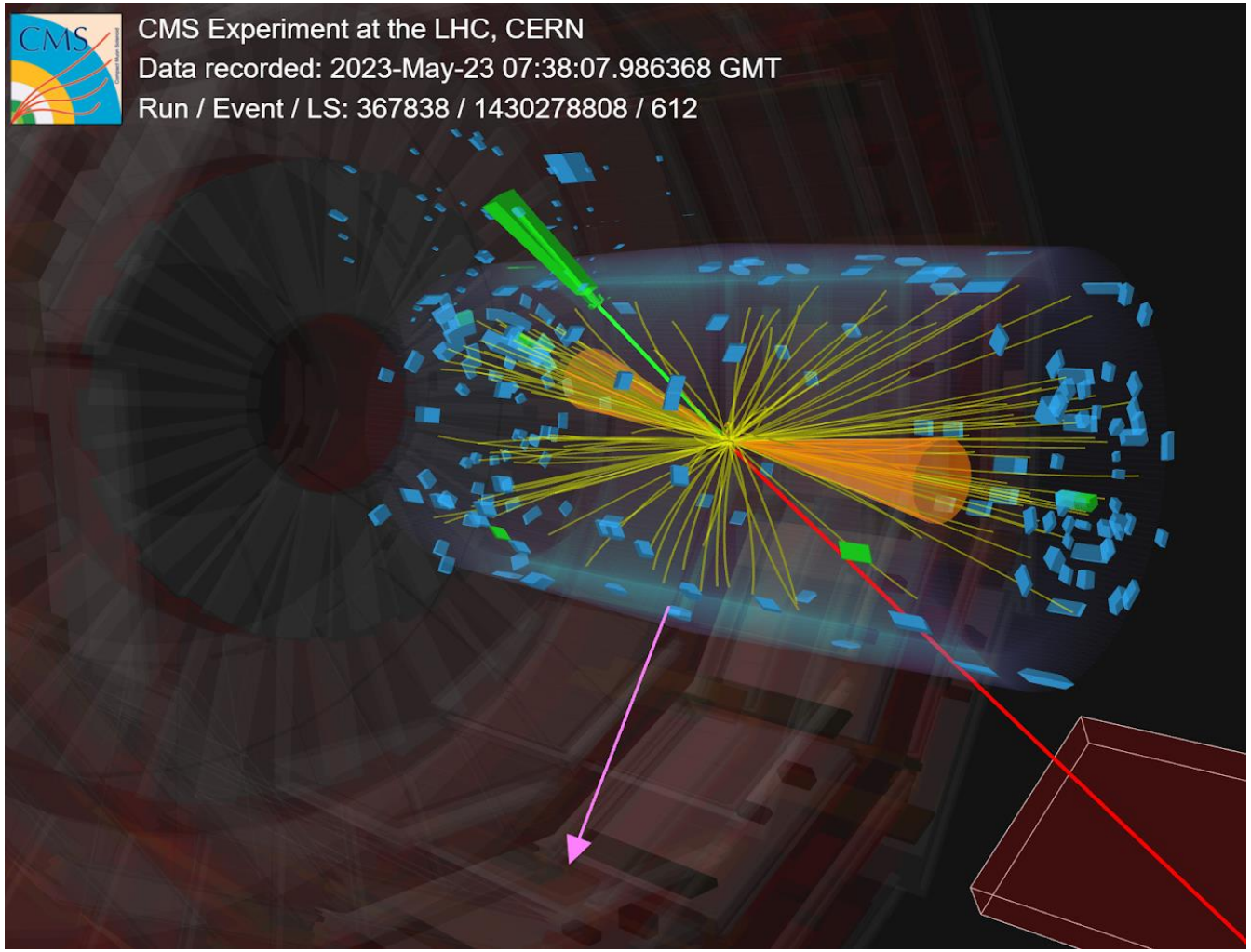
Outlook

- Diboson measurements validate electroweak sector at precision level.
- VBS now observed in several channels and probes electroweak symmetry breaking
- First Run-3 VBS measurements at $\sqrt{s}$ = 13.6 TeV
- Triboson and radiative processes extend sensitivity to rare gauge interactions
- Run-3 and HL-LHC will transform multiboson physics into a precision probe of the electroweak sector.

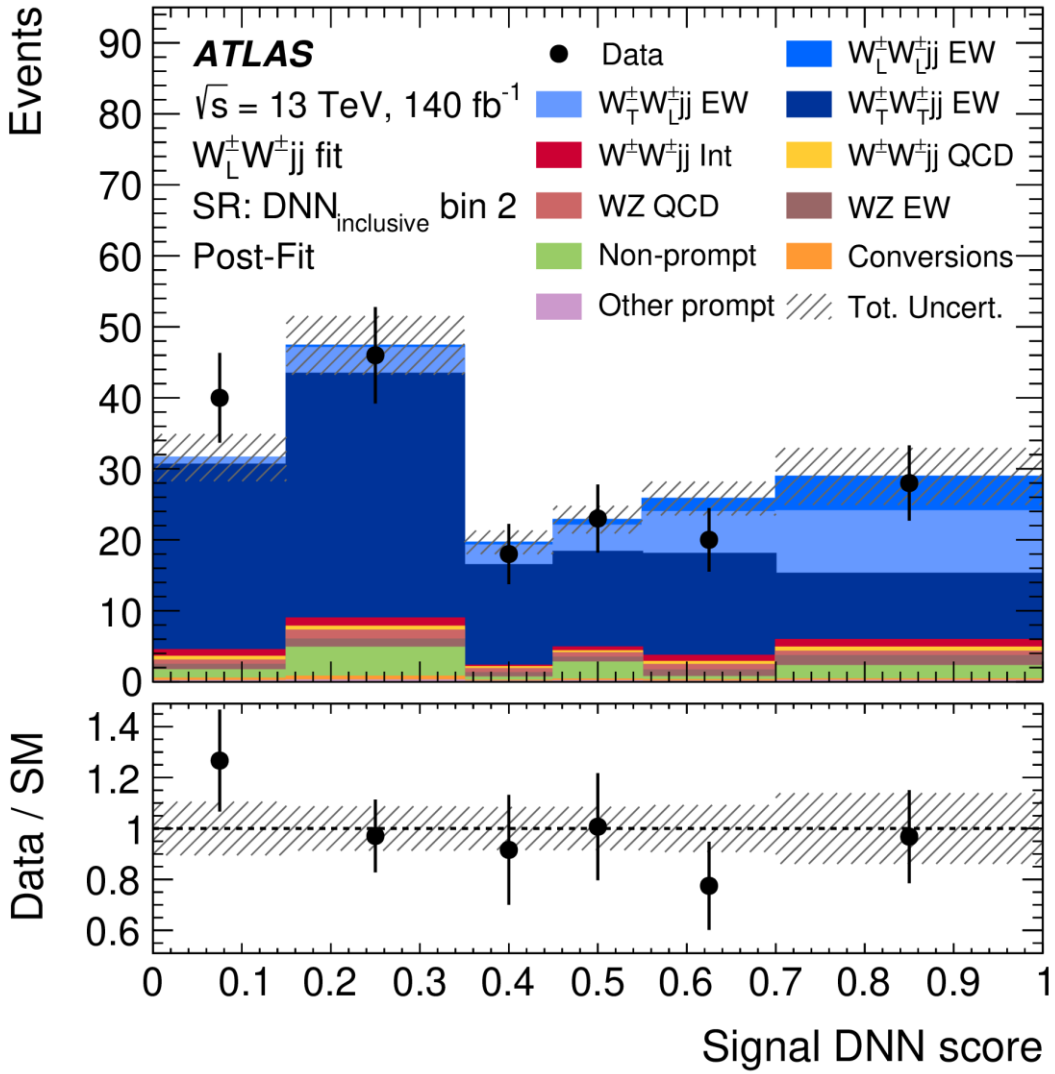


Back-up slides

Diboson
VBS
Triboson

Longitudinal VBS: same-sign WWjj

- **Same-sign dileptons + VBS jets** (high m_{jj}, large $\Delta\eta_{jj}$)
- Two-stage DNN strategy:
  - (i) inclusive EW SSWW vs backgrounds;
  - (ii) polarisation separation
- Evidence for ≥ 1 longitudinal W: 3.3σ (expected 4.0σ)
- Upper limit for doubly-longitudinal component in fiducial region: 0.45 fb (95% CL)



Polarisation measurements: disentangle the **longitudinal (L) and transverse (T)** helicity fractions of the produced bosons.

Phys. Rev. Lett. 135 (2025) 111802

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Diboson precision summary

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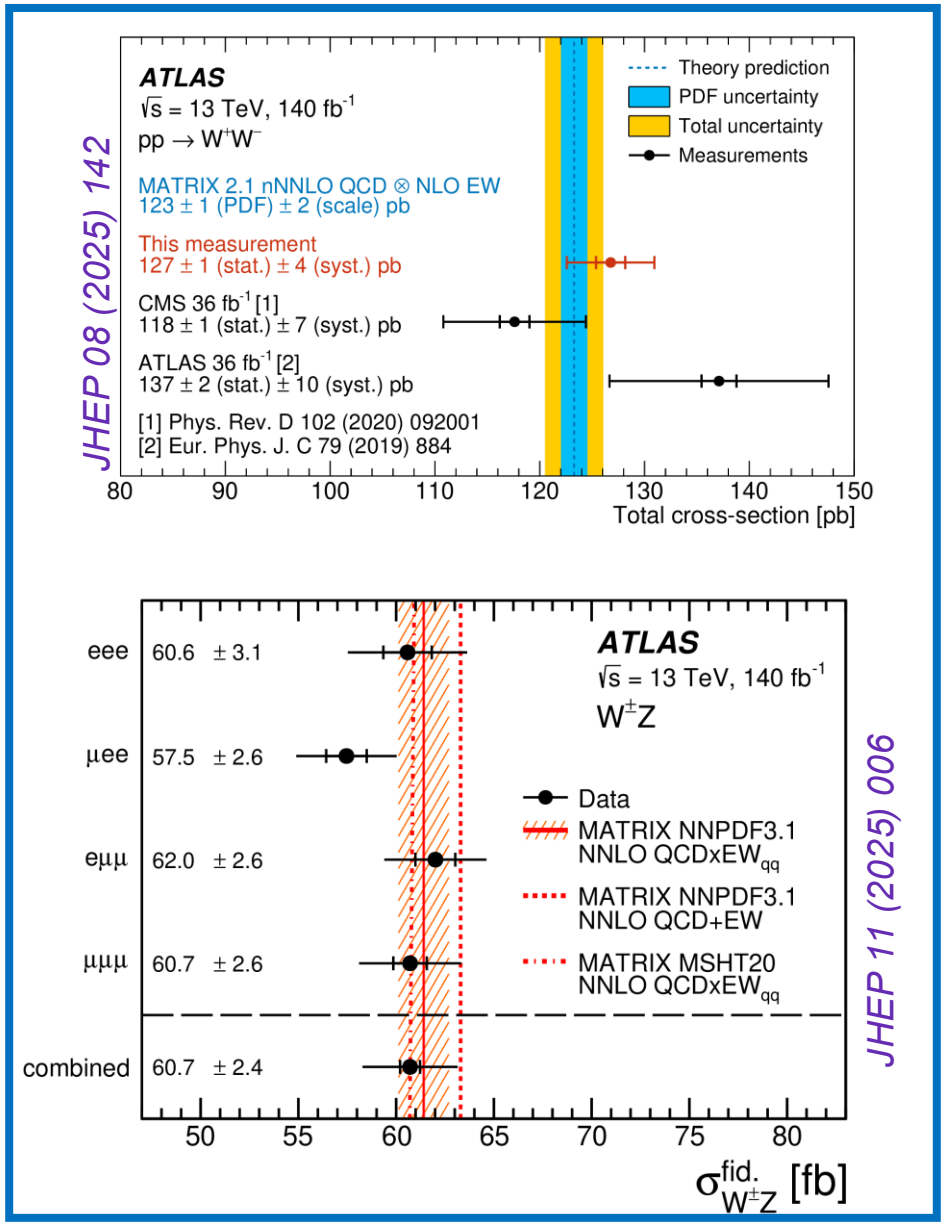
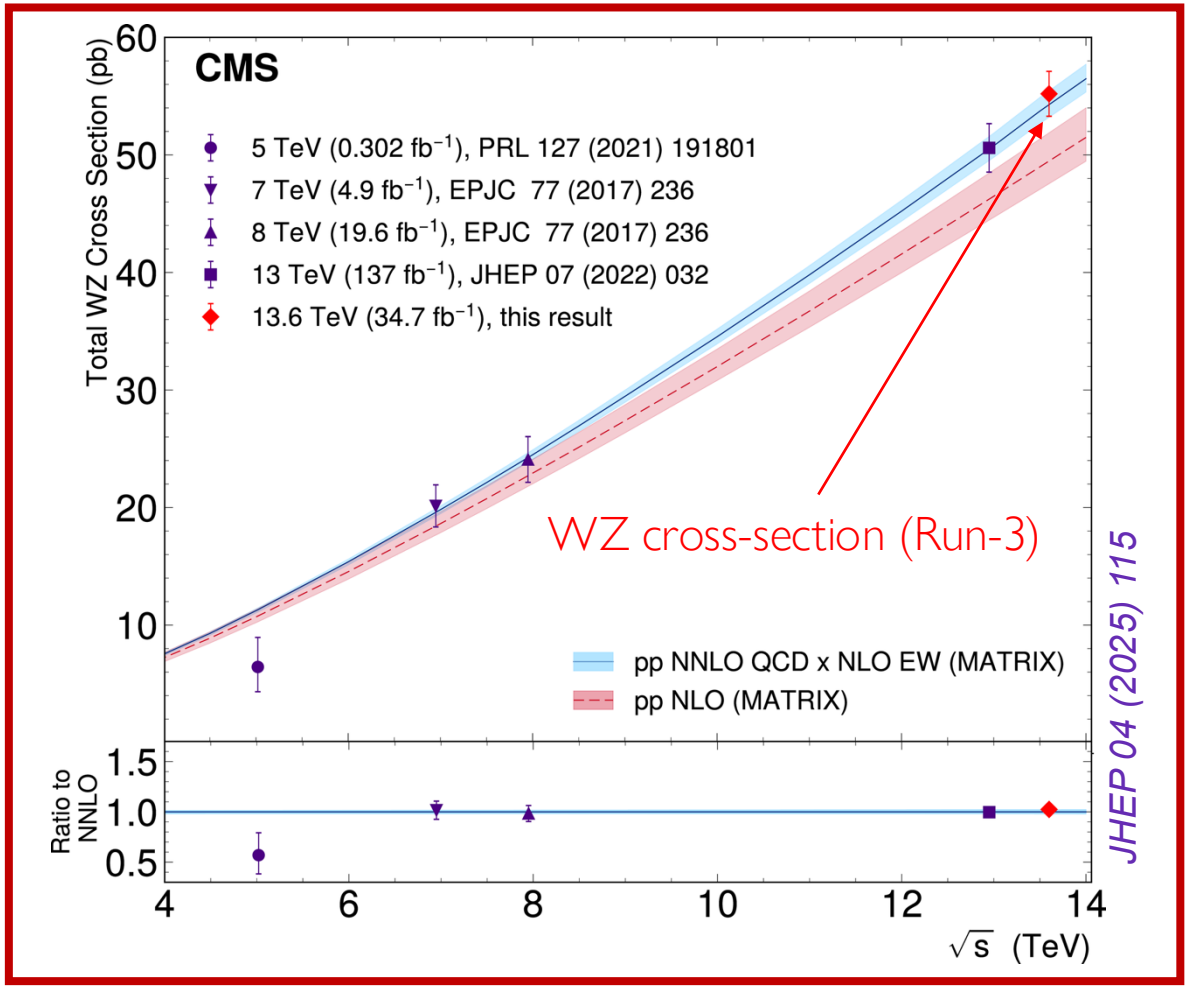
Diboson measurements validate EW gauge sector and provide precision baseline for exploring rarer multiboson and VBS processes.





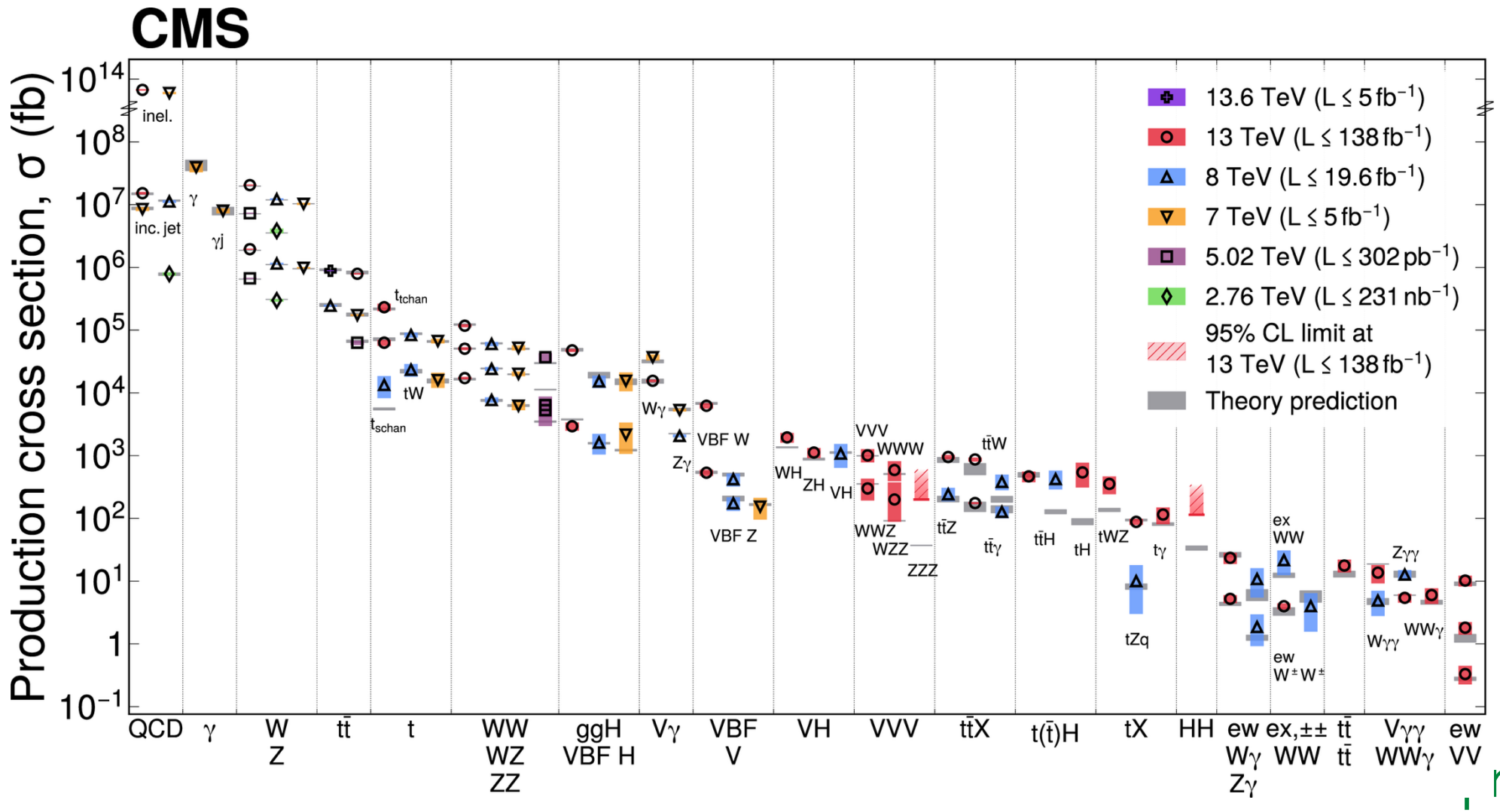
The "menu"

- WZ: JHEP 04 (2025) 115 (Run 3)
- Zg: 13 TeV (arXiv:2601.14102) and 13.6 TeV(arXiv:2512.08582)
- ZZg: CMS-PAS-SMP-24-014 (Run 2)
- VBF g: arXiv:2512.00502
- VBS ssWW and WZ:
- VBS ZV semileptonic: arXiv:2510.00118
- $\gamma\gamma \rightarrow WW$: arXiv:2601.21574
- WWZ: PRL 135 (2025) 091802 (Run 2 + Run 3)

- WW: JHEP 08 (2025) 142
- WZ: JHEP 11 (2025) 006
- ZZ: arXiv:2511.15569 (Run 2)
- Wg:
- ZZg: arXiv:2602.17165 (Run 2)
- VBS semileptonic: arxiv.2503.17461
- WWg: *Phys. Lett. B 873 (2026) 140050*
- *ZZg: arXiv:2602.17165*

Why multiboson & VBS?

Physics Report 1115 (2025) 3



Multiboson LHC

, rehensive test of the electroweak sector at the LHC

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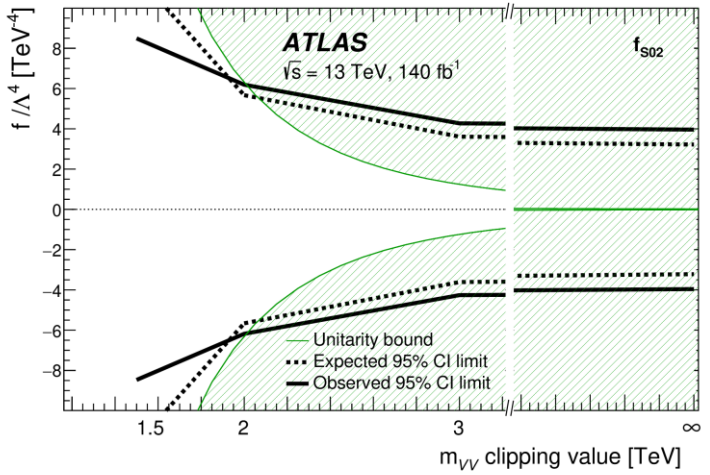
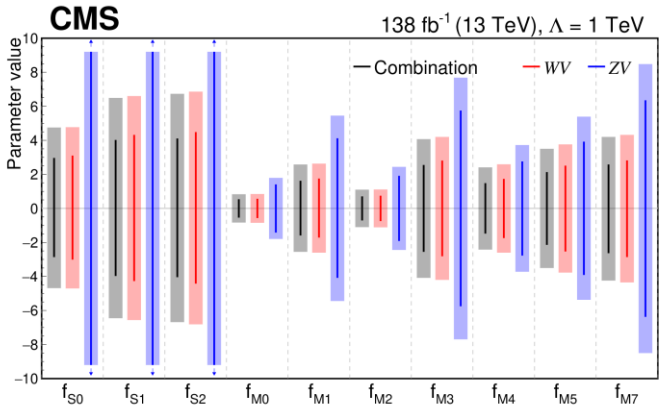
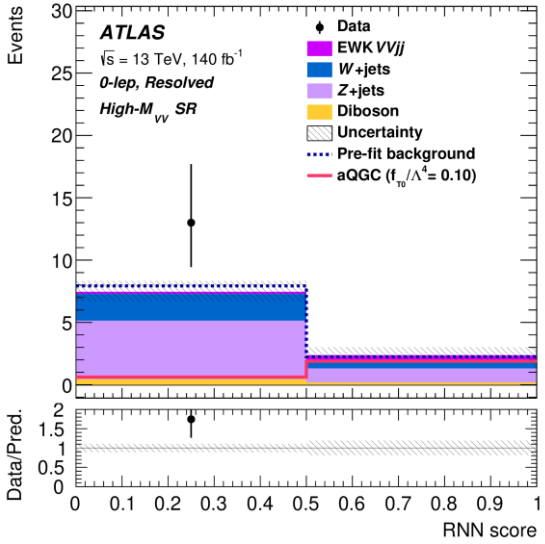
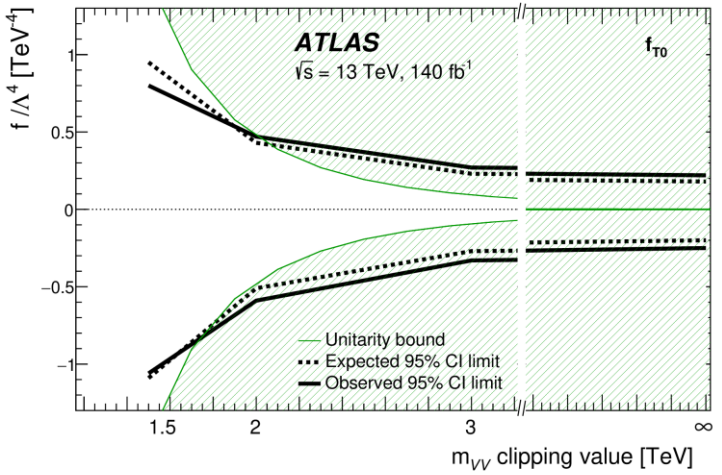
Searching for new physics

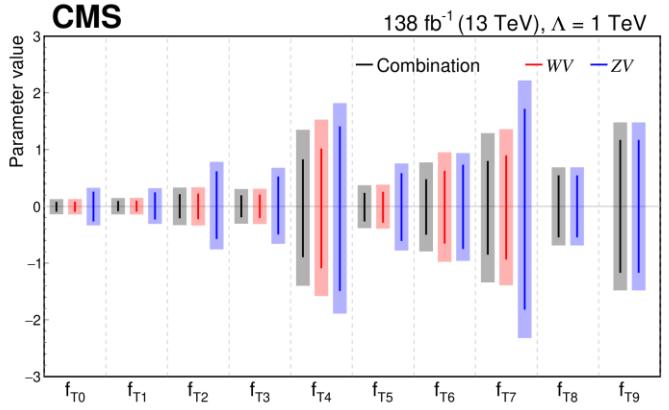
- High-energy tails provide strong sensitivity to dimension-8 EFT operators.
- Complementary strength across the operator basis between ATLAS and CMS











arXiv:2510.00118

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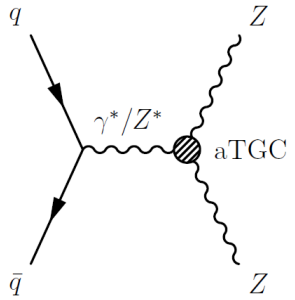
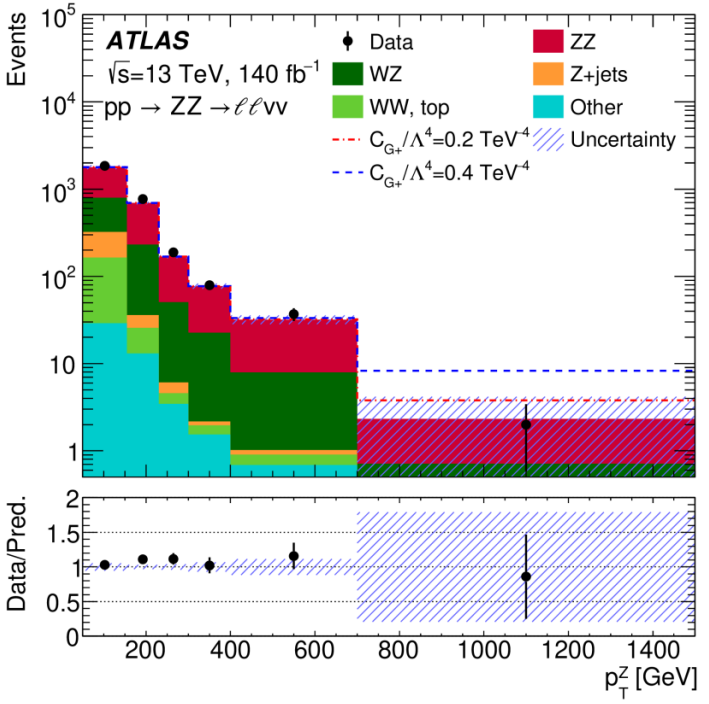
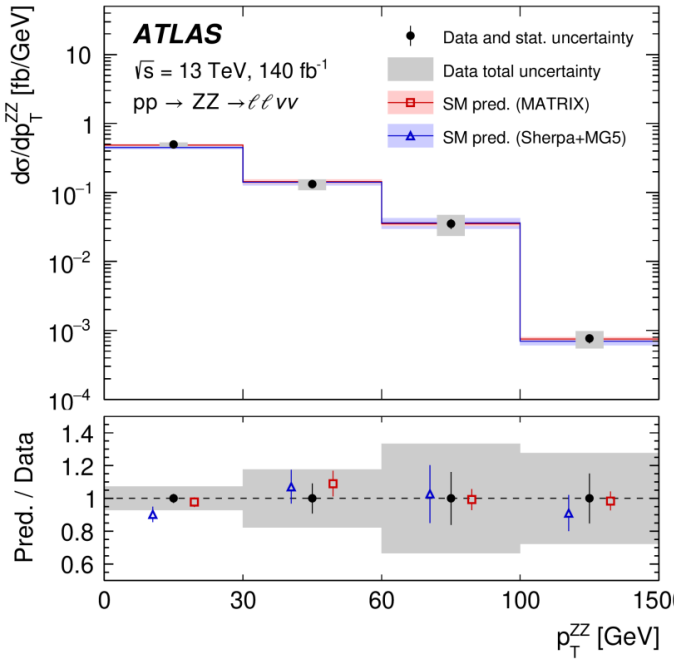
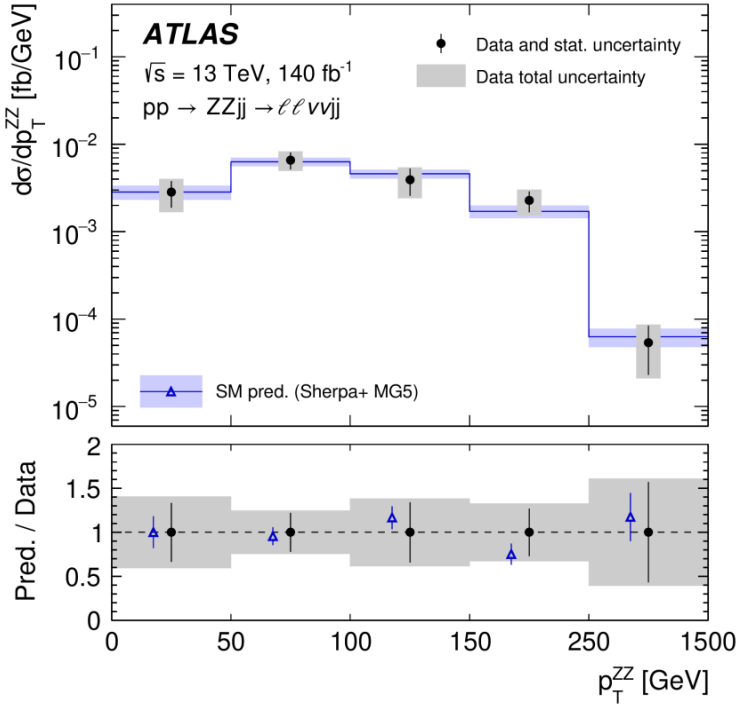
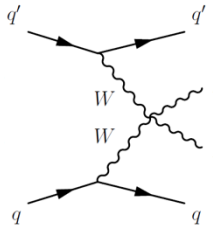
- Differential distributions in agreement with NLO
- Sensitivity to neutral TGC and QGC

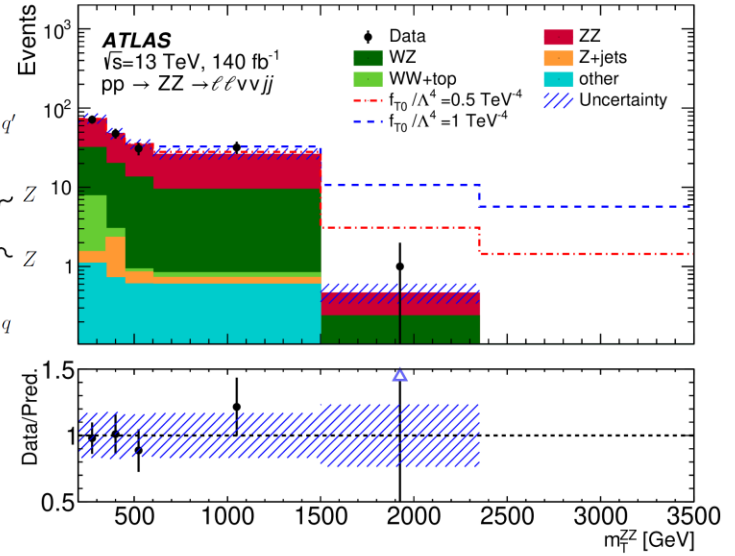












arXiv:2511.15569

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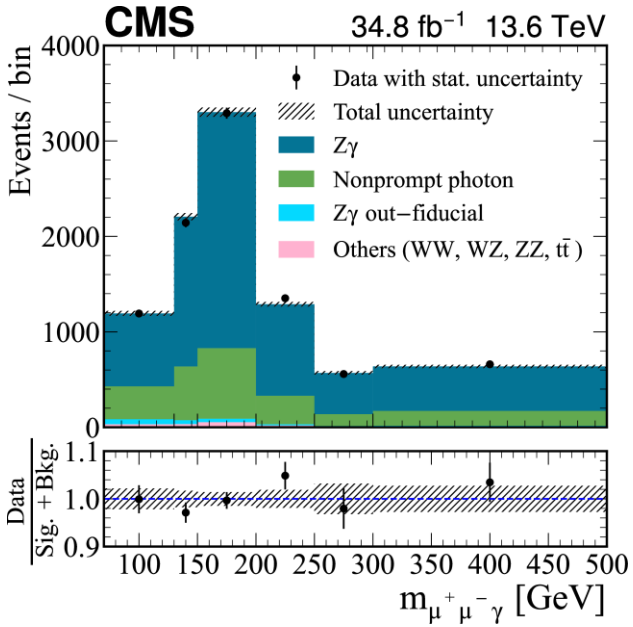
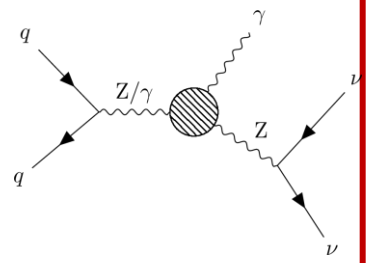
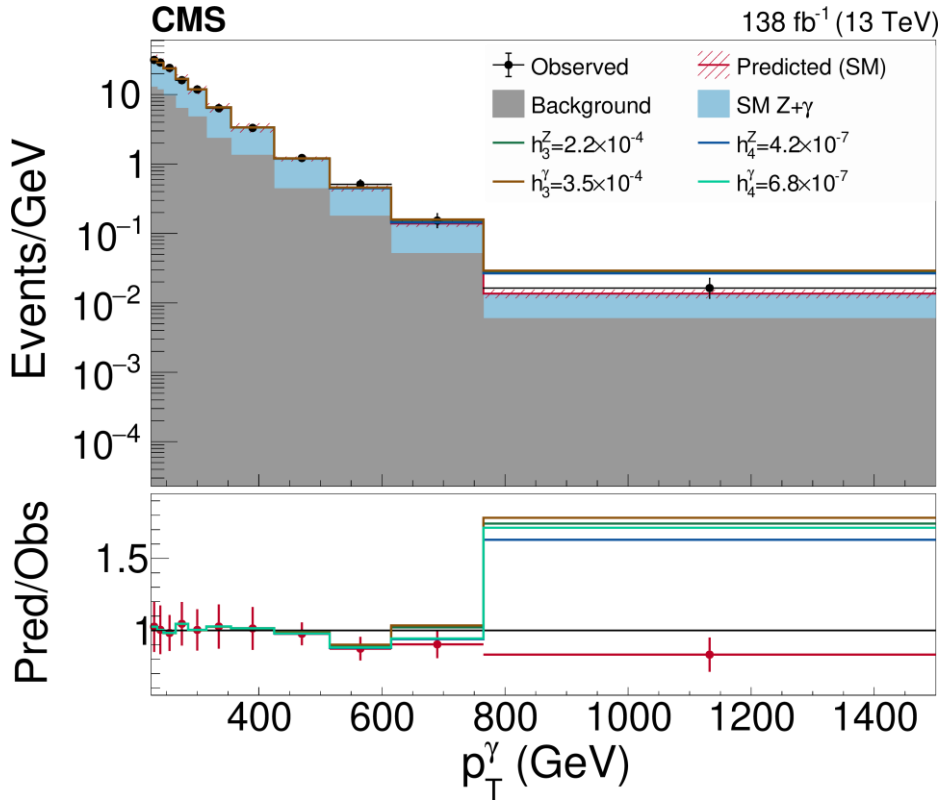
Neutral TGC sensitivity: $Z\gamma$ @ 13 and 13.6 TeV

- $Z(\ell\ell)\gamma$ @ 13.6 TeV (34.8 fb^{-1})
  - σ_{fid} = 1.896 – 0.066 pb







arXiv:2512.08582

arXiv:2601.14102

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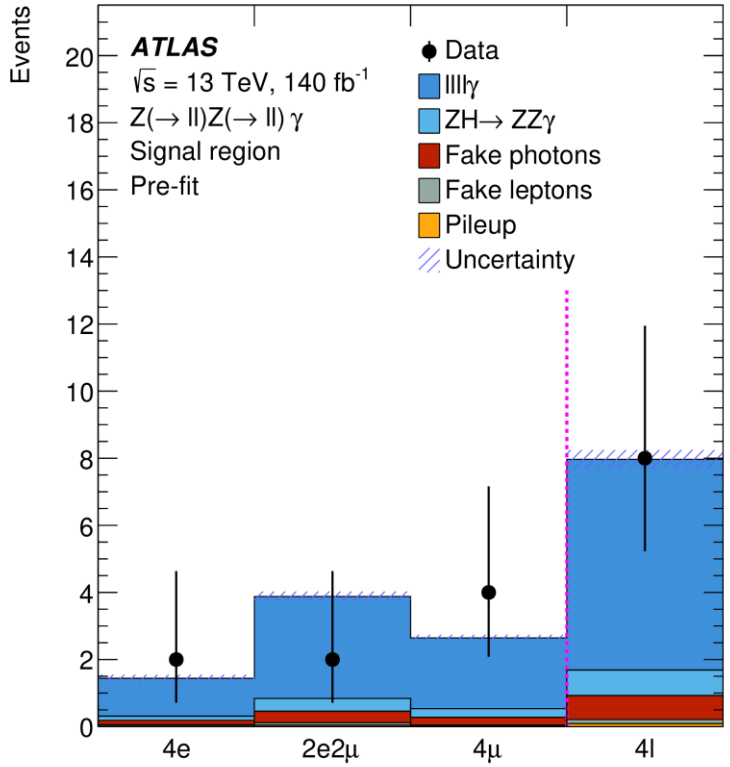
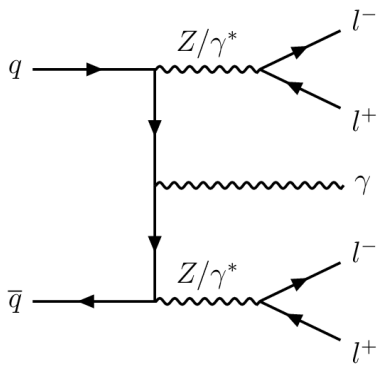
$ZZ\gamma$

This results in an observed (expected) significance of the $ZZ\gamma$ of 4.4σ (4.4σ).

$$p_T^{\gamma} > 20\ GeV;\ |\eta_{\gamma}| < 2.37; \Delta R(\ell,\gamma) > 0.4$$

$$\sigma_{ZZ\gamma} = 0.144^{+0.064}_{-0.051}(\text{stat.})^{+0.007}_{-0.005}(\text{syst.})\text{fb}$$



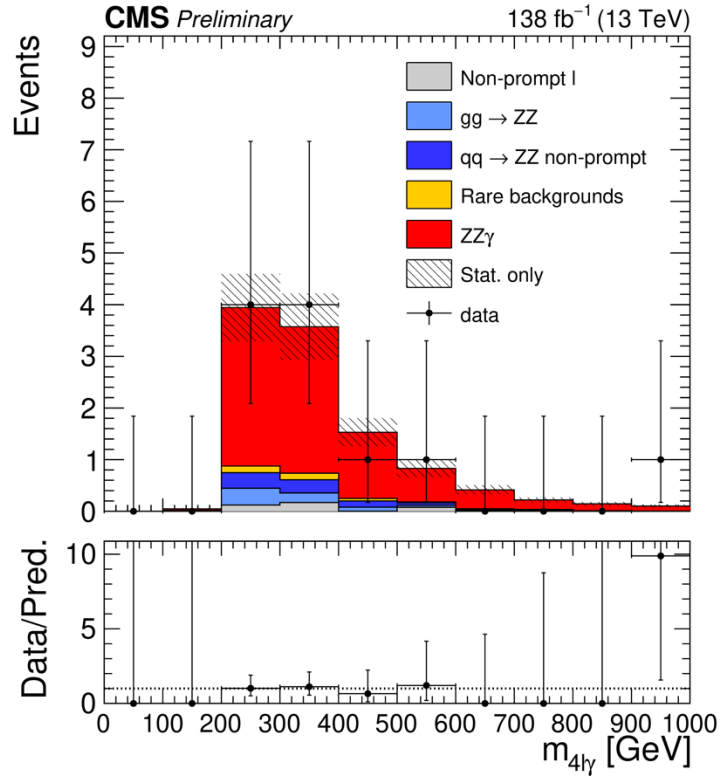


Consistent with SM prediction, Run 3 to reach observation

First observation of $4\ell\gamma$ (5.1σ) and evidence of $ZZ\gamma$ (3.7σ)

$$p_T^{\gamma} > 20\ GeV; |\eta_{\gamma}| < 2.4; \Delta R(\ell,\gamma) > 0.5$$

$$\sigma_{ZZ\gamma} = 0.06 \pm 0.03\ \text{fb}$$



arXiv:2602.17165

[CMS-PAS-SMP-24-014](CMS-PAS-SMP-24-014)

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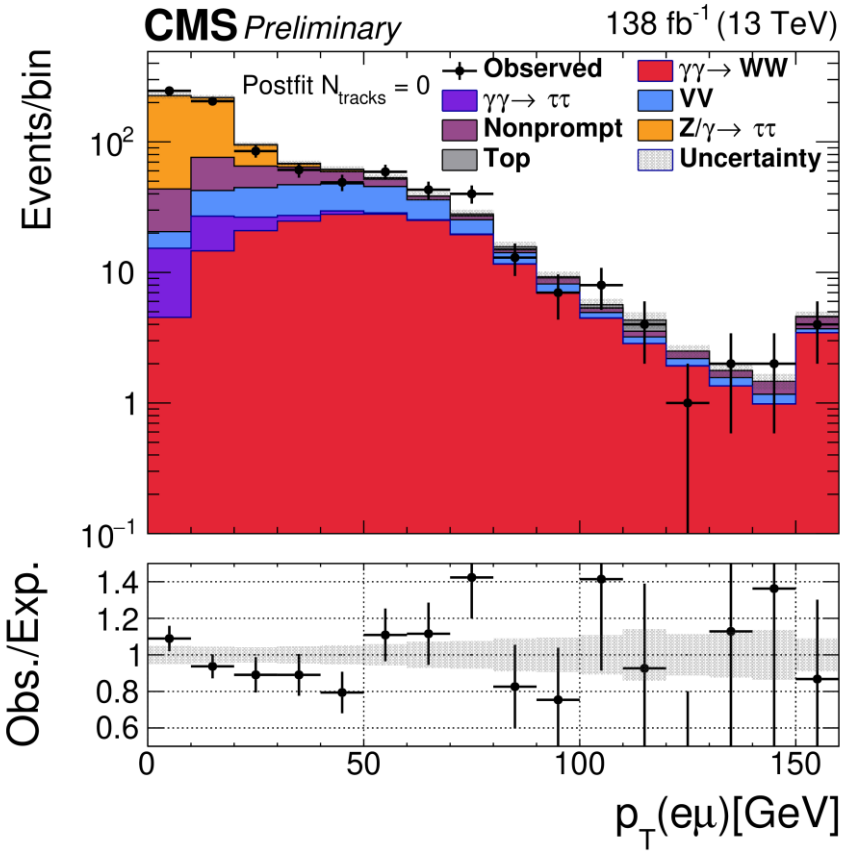
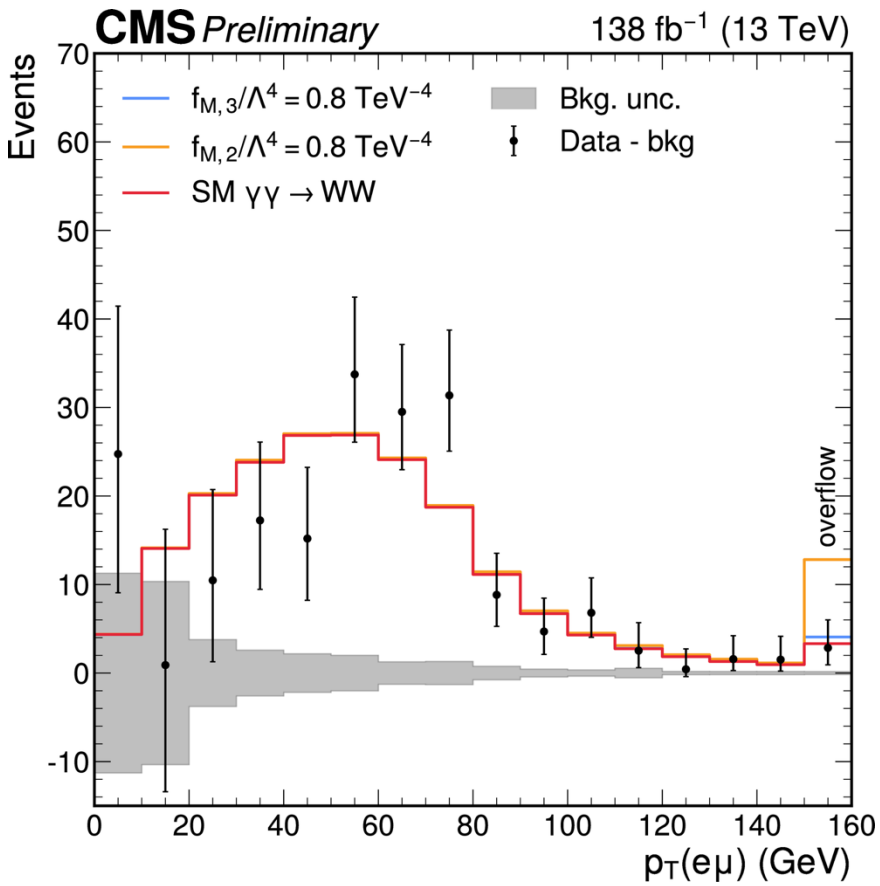
Rare EW interactions

- Define signal in events with eμ final state and no other tracks in the event.
- Detection of such exclusive events is still quite challenging due to the interaction of other protons in the beam (pileup).





first observation in CMS:

$$\sigma(\gamma\gamma \to W^+W^-) = 659 \pm 80\ \text{fb}$$

arXiv:2601.21574

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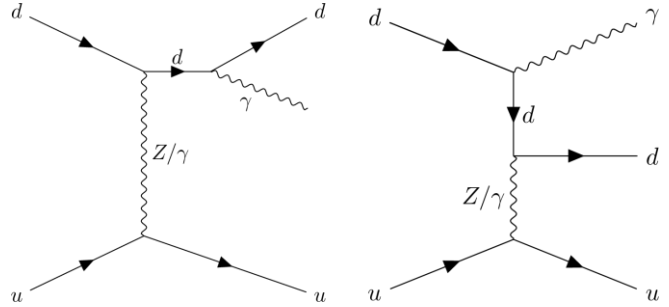
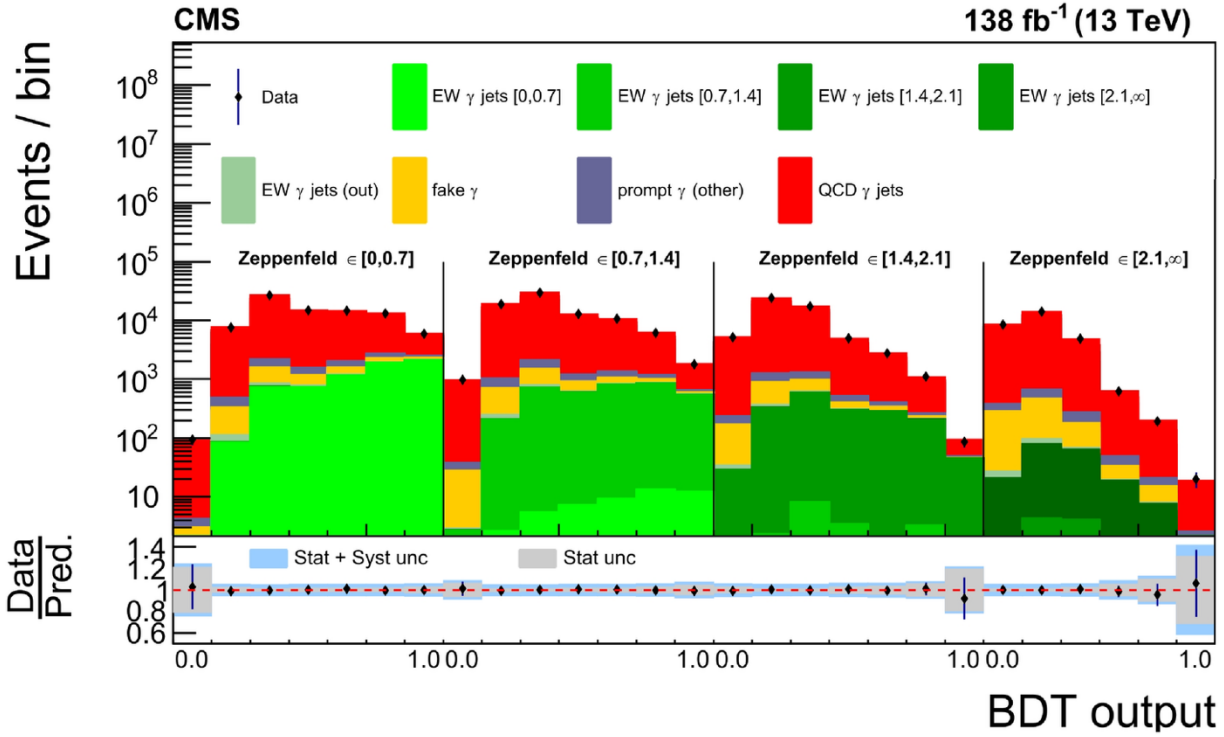
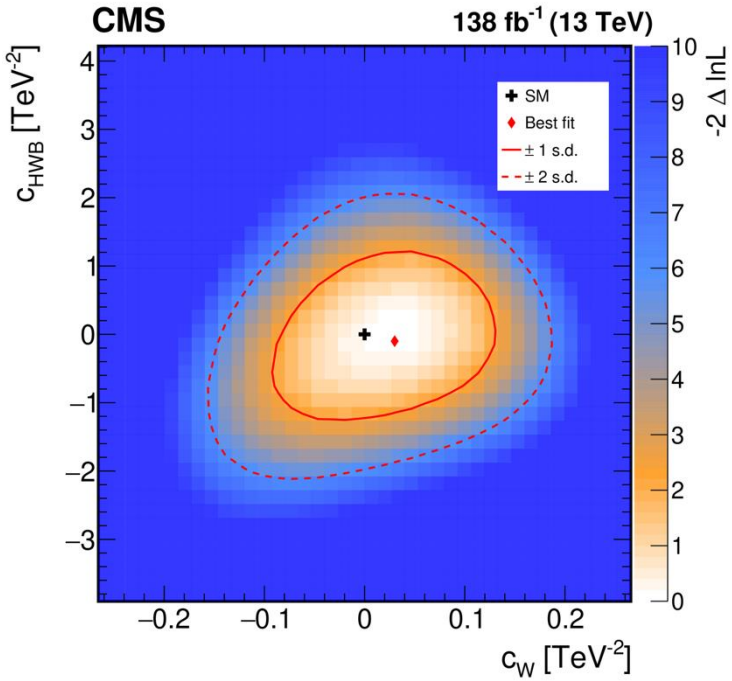
VBF gamma

- First observation of EW γjj @13 TeV
- Genuine VBF topology: large m_{jj}, large $\Delta\eta_{jj}$, central photon
- Direct probe of the $WW\gamma$ vertex in pure EWK process
- Significance $> 5\sigma$; $\sigma = 202 \pm 36$ fb
- Limits on the Warsaw basis coef.: $c_W = [-0.11, 0.16]$; $c_{HWB} = [-1.6, 1.5]$



Consistent with SM





arXiv:2512.00502

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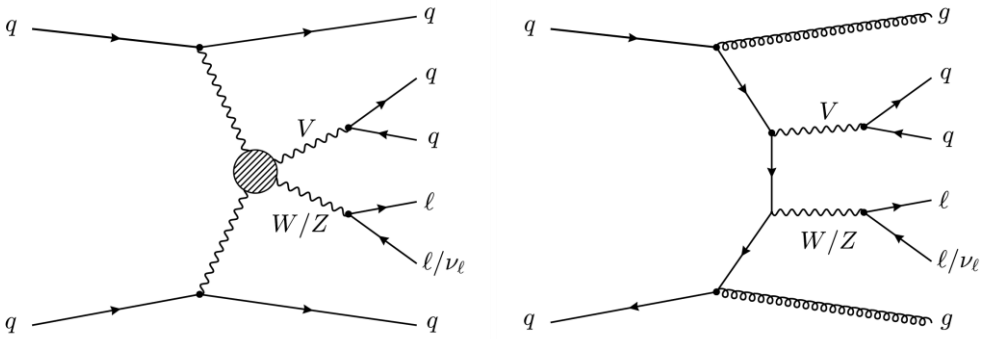
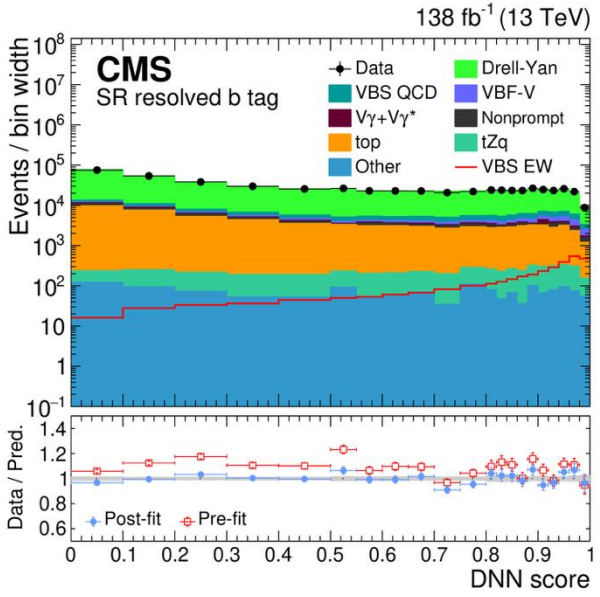
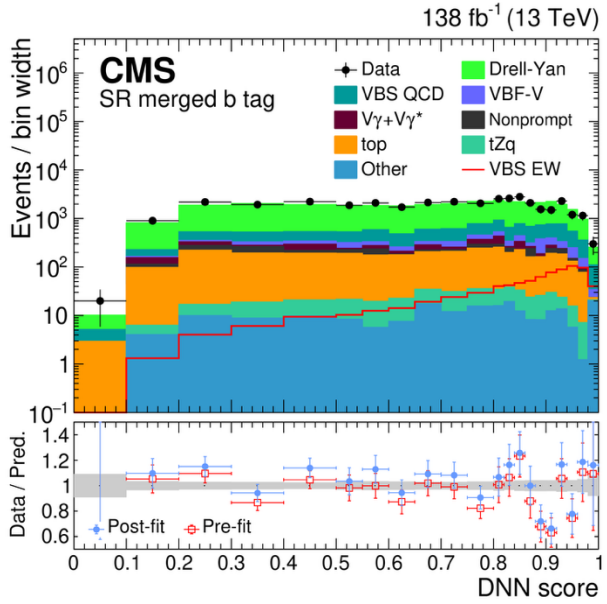
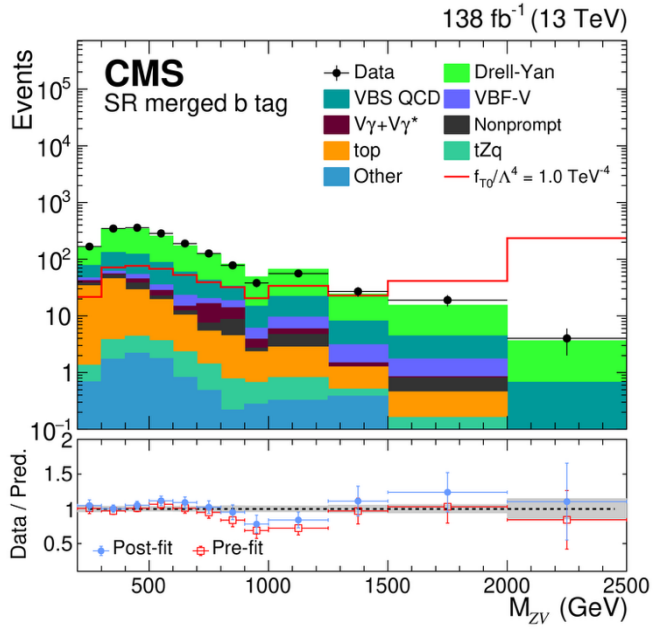
VBS ZV semileptonic and fully leptonic

- VBS ZV in $\ell\nu qq, \ell\ell qq$ @13 TeV (138 fb^{-1}) from CMS
- Resolved + merged topologies
- DNN-based signal extraction
- Statistically limited (1.3σ)









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Triboson production: VVZ and WWZ

ATLAS + CMS

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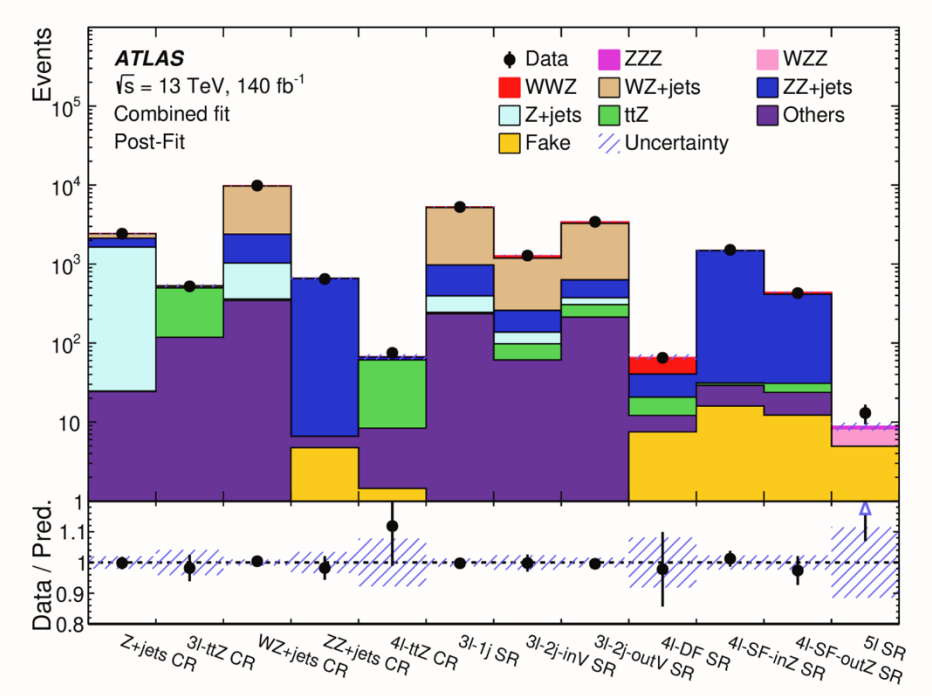
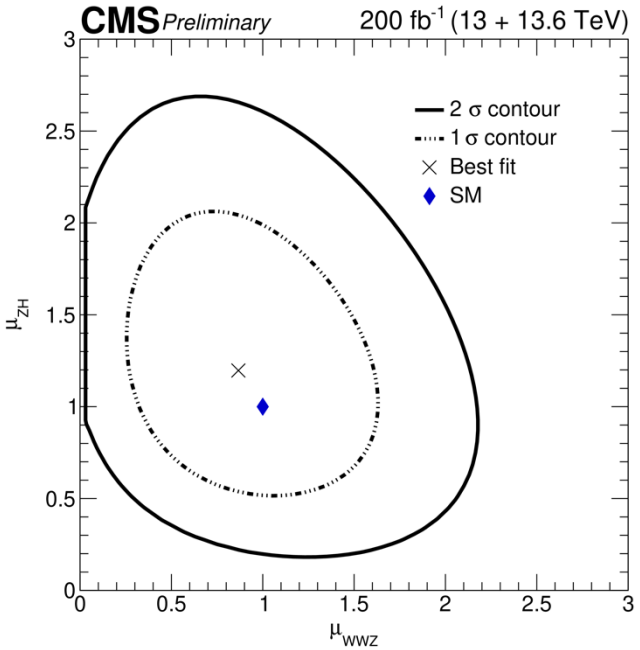
Rare SM processes with multiple gauge vertices; sensitive to EFT and high-energy behavior

ATLAS: VVZ observation (Run 2)



Observed significance: 6.4σ (VVZ); evidence for WWZ

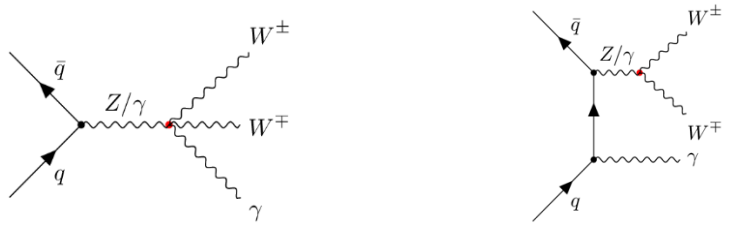
CMS: WWZ + ZH (H→WW) simultaneous fit (Run 2+3)

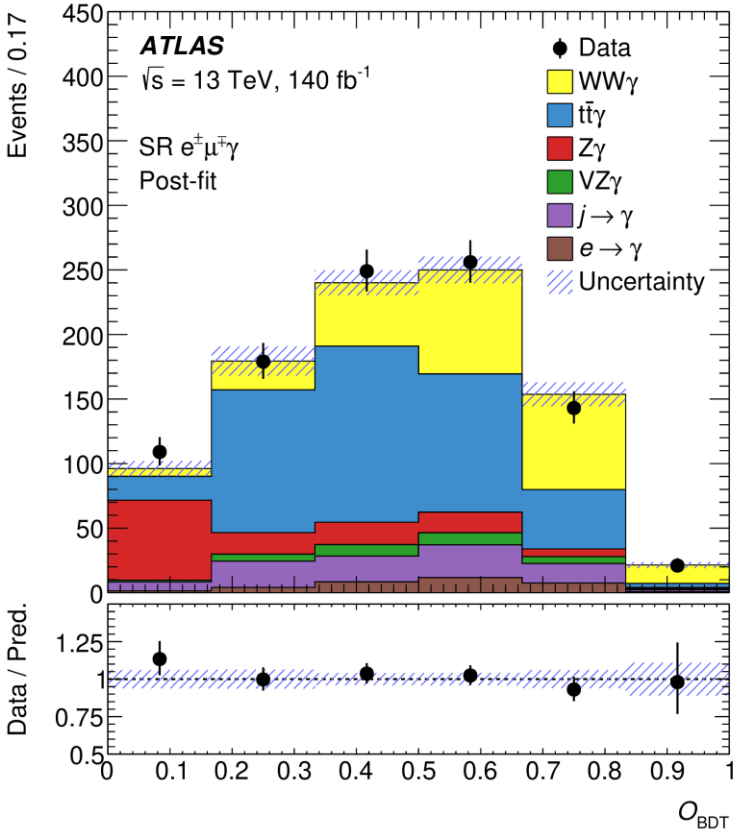


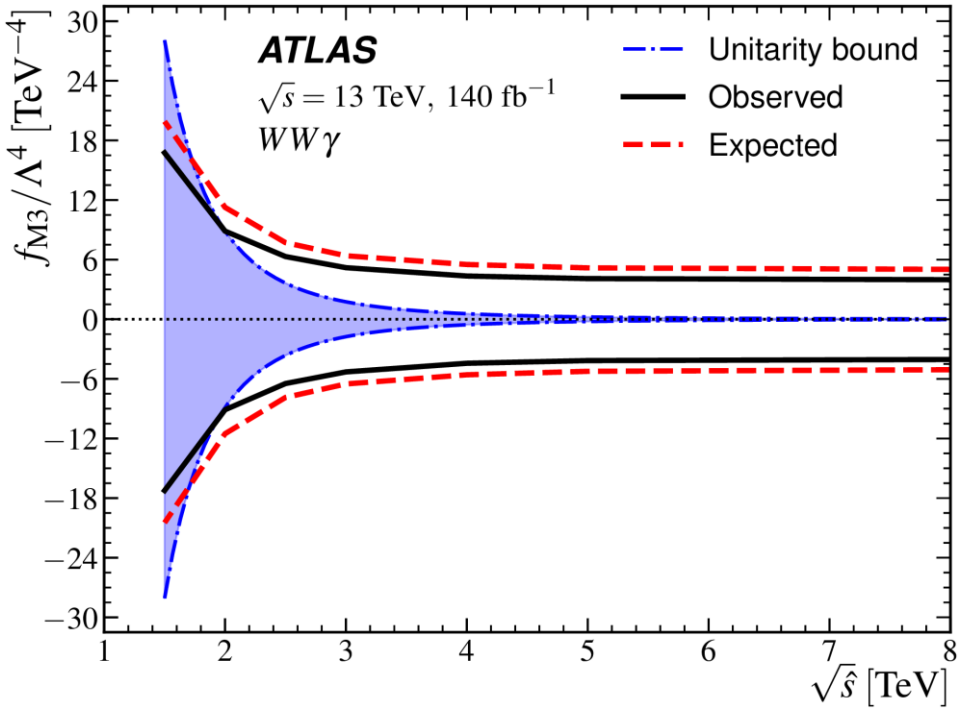
Overall μ ≈ 1.03 (Run 2+3); evidence at 13.6 TeV (Run 3)

Radiative triboson: $WW\gamma$

- WWγ Observation @13 TeV with 5.9σ
- Measured cross section: $\sigma_{\mathrm{fid}} = 6.2 \pm 1.0$ fb
- aQGC dim-8 limits







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Radiative triboson: WWγ (ATLAS) and WZγ (CMS)

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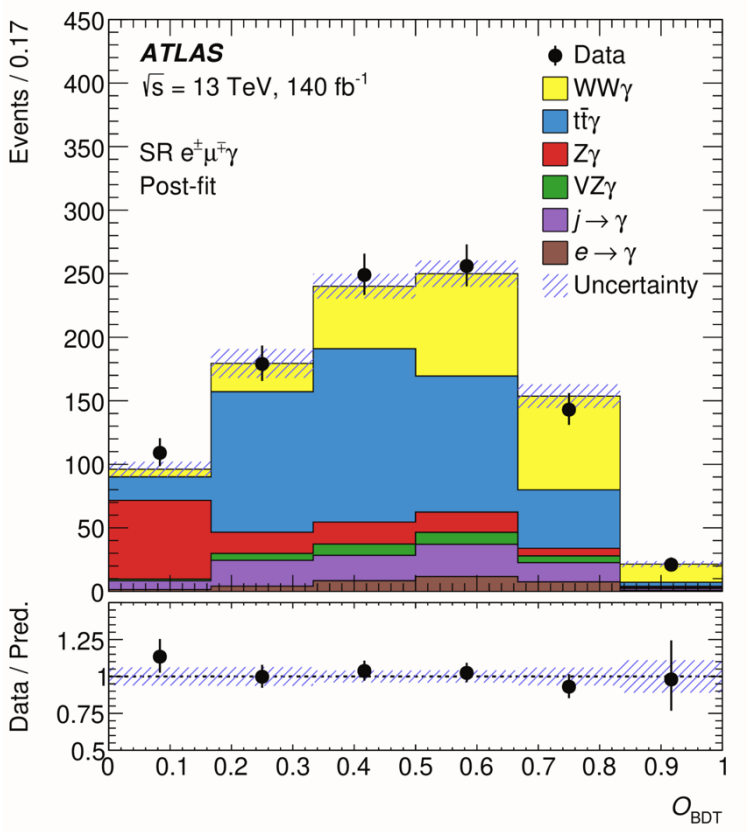
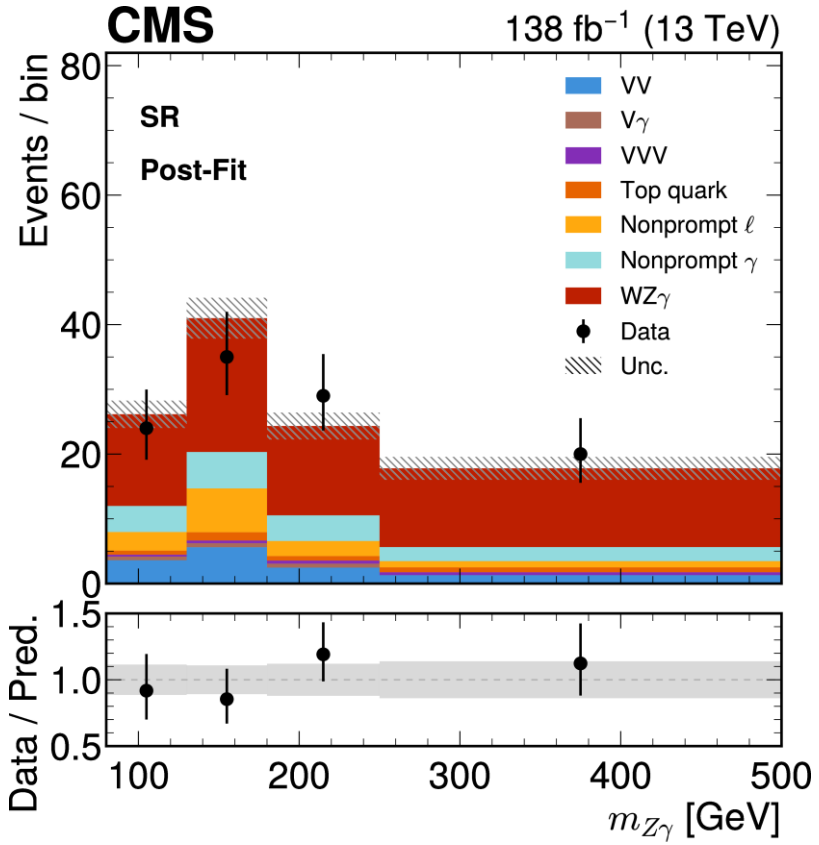
ATLAS: WWγ observation (Run 2)



Significance: 5.9σ; fiducial σ(eμνγ) measured

CMS: WZγ observation (Run 2)



Observed significance: 5.4σ; σ(fid) = 5.48 ± 1.11 fb