The 2026 International Workshop on the High Energy Circular Electron Positron Collider

CEPC 2026

Overview of Electroweak Experimental Results

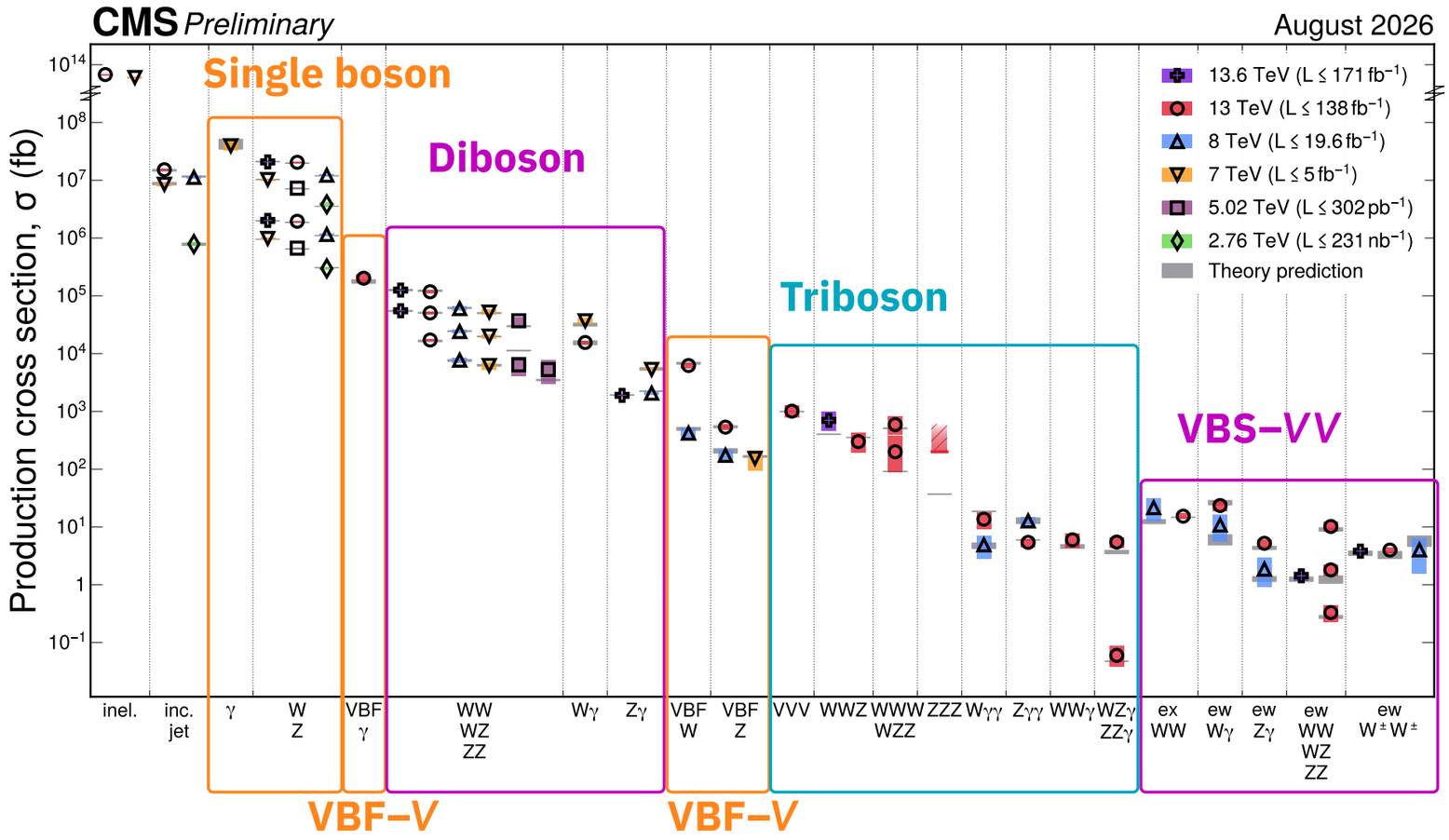
Jie Xiao[1,2] on behalf of the ATLAS and CMS Collaborations

[1] *IPPP, Durham University*
[2] *Imperial College London*

Shanghai · 22–26 October 2026



Landscape of electroweak measurements at the LHC



Single boson + VBF–*V*

- **Single boson**:
  - Abundant samples
  - Precise EW parameters
- **VBF**
  - Forward jets + central *V*
  - Triple-gauge couplings (TGCs)

Diboson + VBS–*VV*

- **Diboson**
  - Large cross sections
  - Precise measurements
  - Polarisation and TGCs
- **VBS**
  - Rare
  - TGCs / Quartic gauge couplings (QGCs)
  - Polarisation

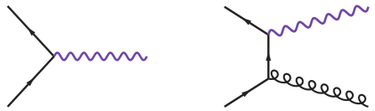
Triboson

- Rare
- TGCs / QGCs

More summary plots ATLAS CMS

Single boson & VBF–*V* programme

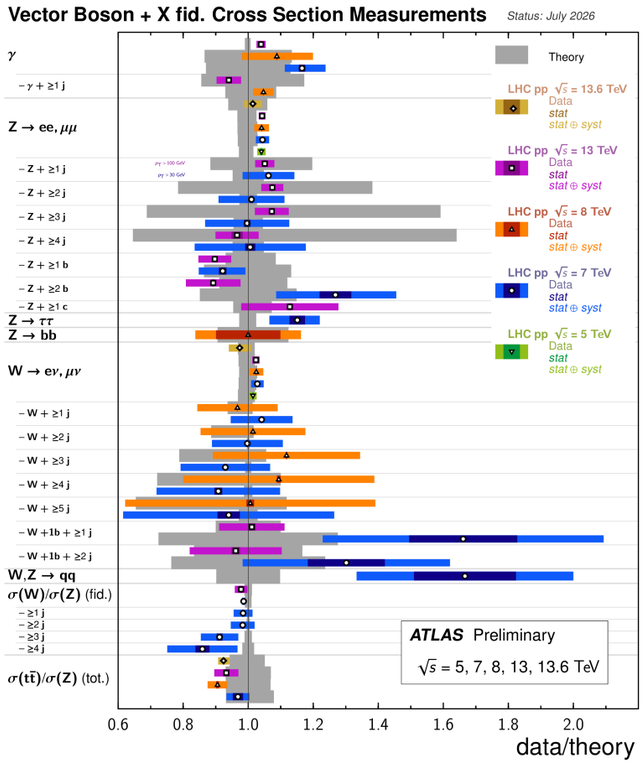
Single boson + jets



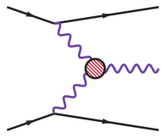
$W/Z/\gamma$ + jets

- Abundant **precision samples**
- EW parameters, PDFs and QCD modelling

ATLAS
single-boson cross-section summary



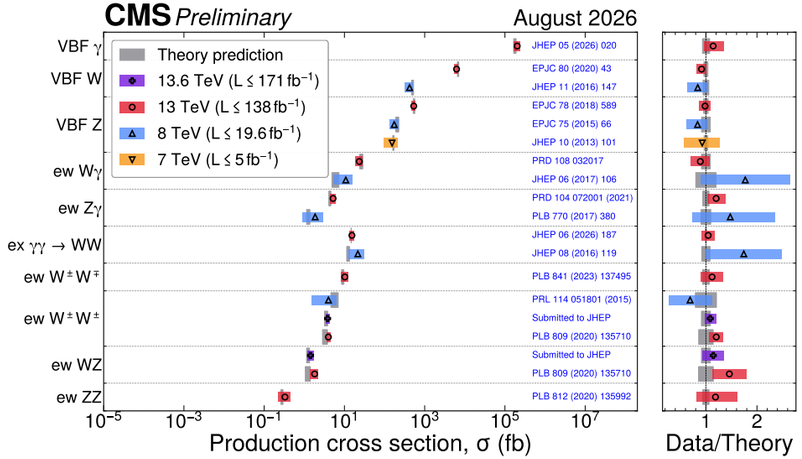
VBF–*V*: electroweak *Vjj*



Wjj Zjj γjj

- Forward jets: **large rapidity separation** and m_{jj}
- Small EW production; probes **TGCs** and **EFT**

CMS
EW VBF/VBS cross-section summary



Deviations from the SM can be parametrised model-independently in an **EFT** expansion

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

W mass and width

Test self-consistency of the SM

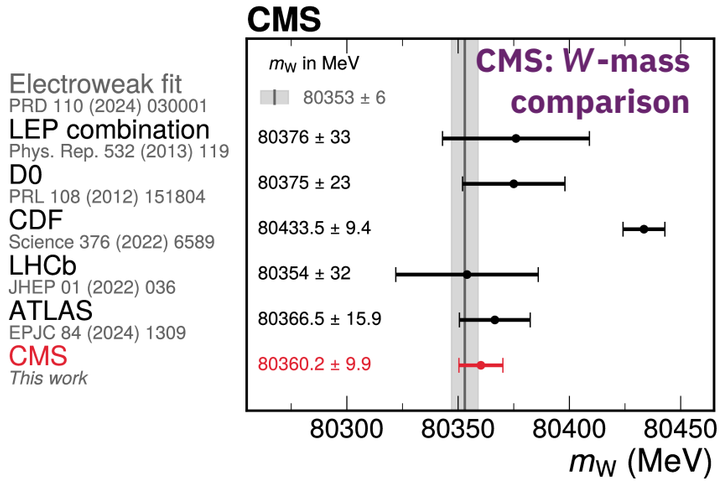
- Precision inputs test the SM at loop level

CMS Nature 652 (2026) 321

- $m_W = 80.3602 \pm 0.0099$ **GeV**
- Important uncertainties:
  - **Muon momentum** calibration
  - High order **EW corrections**
  - **PDFs**

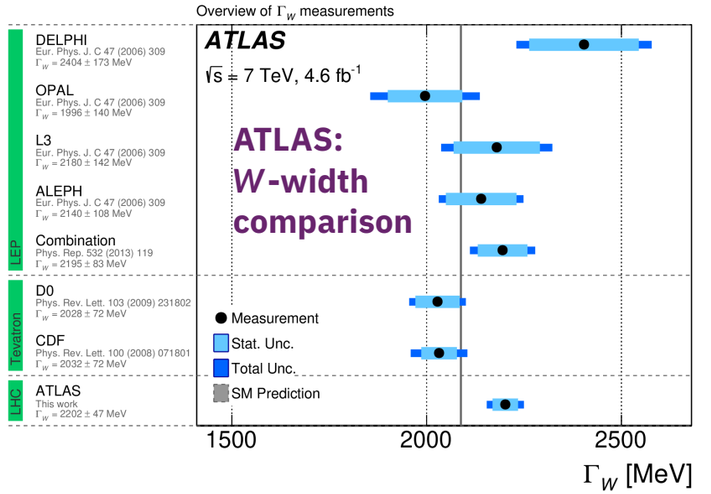
ATLAS EPJC 84 (2024) 1309

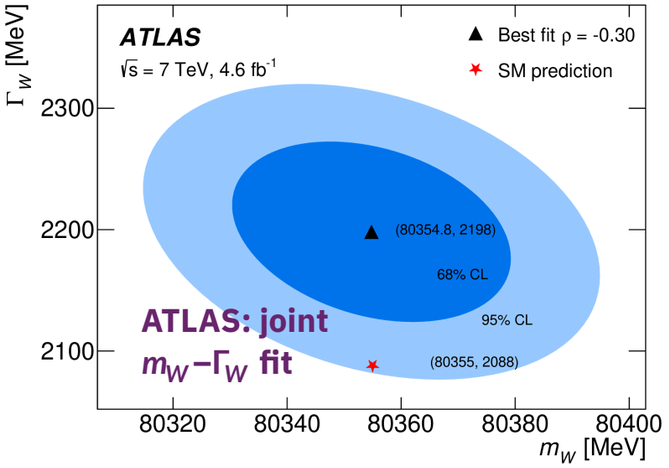
- **7 TeV** re-analysis
- $m_W = 80.3665 \pm 0.0159$ **GeV**
- $\Gamma_W = 2202 \pm 47$ **MeV**



CMS: uncertainty breakdown

Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum calibration	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9





⟹ Precision requires control of theory, proton structure and detector calibration

Weak mixing angle from Drell–Yan

Forward–backward asymmetry in $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$

$$A_{\mathrm{FB}} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$$

- Fit A_{FB} versus dilepton mass and rapidity

Effective leptonic mixing angle

$$\sin^2\theta^{\ell}_{\mathrm{eff}} = \frac{1}{4}\left(1 - \frac{g^{\ell}_V}{g^{\ell}_A}\right) = \kappa_{\ell}\sin^2\theta_W$$

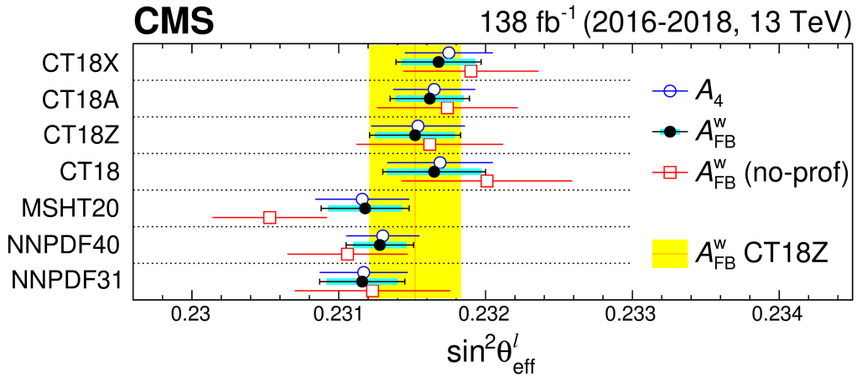
- On-shell: $\sin^2\theta_W = 1 - m_W^2/m_Z^2$
- Encodes the Z couplings to charged leptons

CMS 13 TeV PLB 866 (2025) 139526

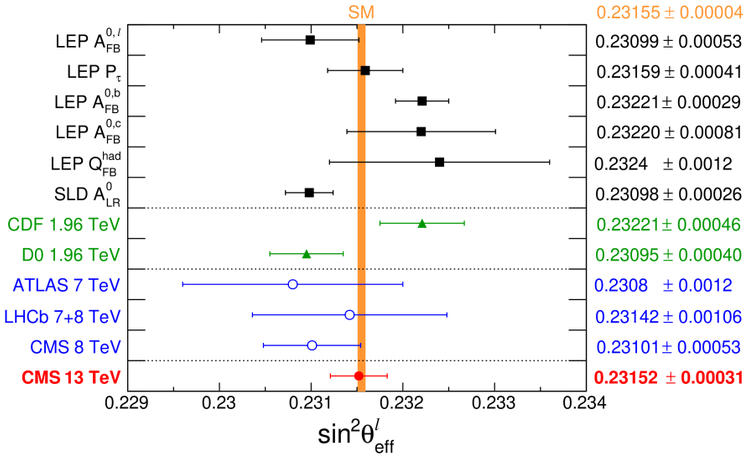
$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23152 \pm 0.00031$

ATLAS 8 TeV ATLAS-CONF-2018-037

$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23140 \pm 0.00036$



CMS: fits with PDF profiling versus unprofiled PDFs

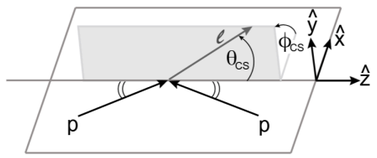


An independent cross-check of LEP/SLD measurements

⟹ Precision extraction requires control of proton PDFs

Single boson: angular measurements test QCD

Lepton decay angles probe boson polarisation and QCD radiation



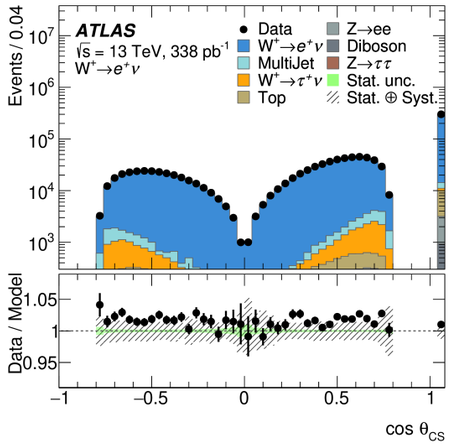
Collins–Soper frame

$$\frac{d\sigma}{dp_T^W\,dy^W\,dm^W\,d\cos\theta\,d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^W\,dy^W\,dm^W}\left[\left(1+\cos^2\theta\right)+\frac{1}{2}A_0\left(1-3\cos^2\theta\right)+A_1\sin 2\theta\cos\varphi\right.$$
$$\left.+\frac{1}{2}A_2\sin^2\theta\cos 2\varphi+A_3\sin\theta\cos\varphi+A_4\cos\theta+A_5\sin^2\theta\sin 2\varphi+A_6\sin 2\theta\sin\varphi+A_7\sin\theta\sin\varphi\right]$$

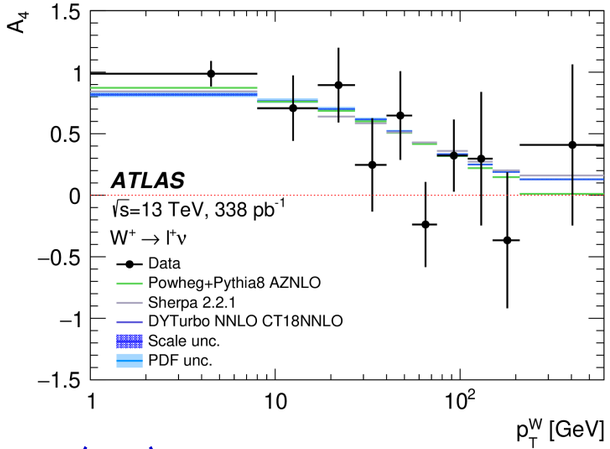
A_0: longitudinal polarisation · A_4: forward–backward asymmetry

ATLAS EPJC 86 (2026) 483

Angular templates extract W coefficients versus p_T^W



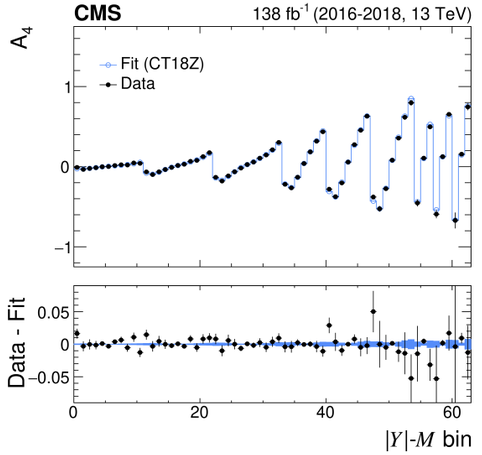
$W^+ \to e^+\nu$: angular distribution



$A_4\left(p_T^W\right)$: comparison with QCD predictions

CMS SMP-22-010

Drell–Yan A_4: input to $\sin^2\theta_{\text{eff}}^{\ell}$



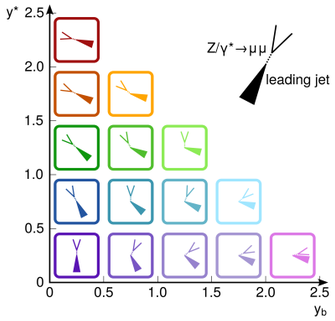
Unfolded A_4 in dilepton $|Y|$–M bins

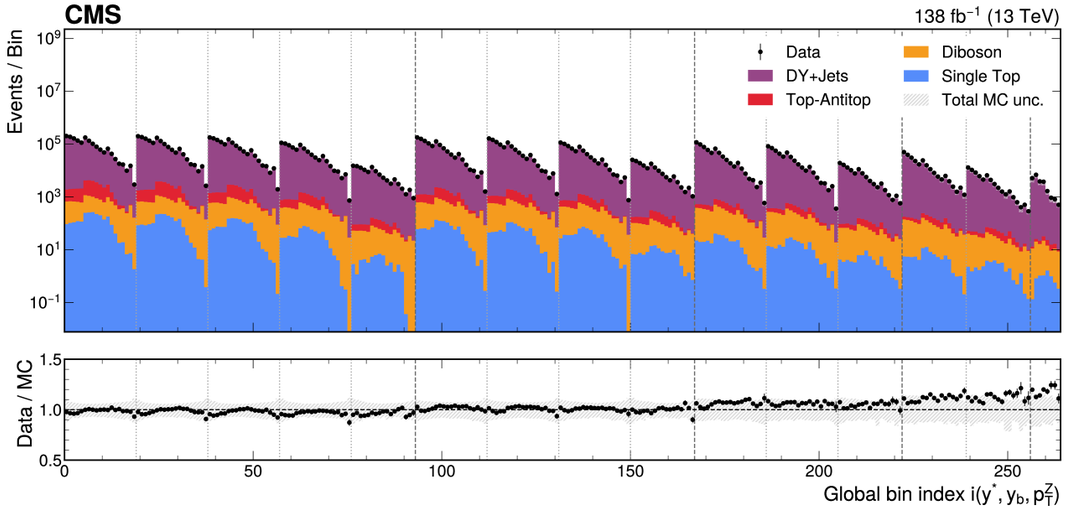
Triple-differential Z + jet production

Differential production cross section of $Z(\rightarrow \mu\mu)$ + jets `CMS SMP-24-010`

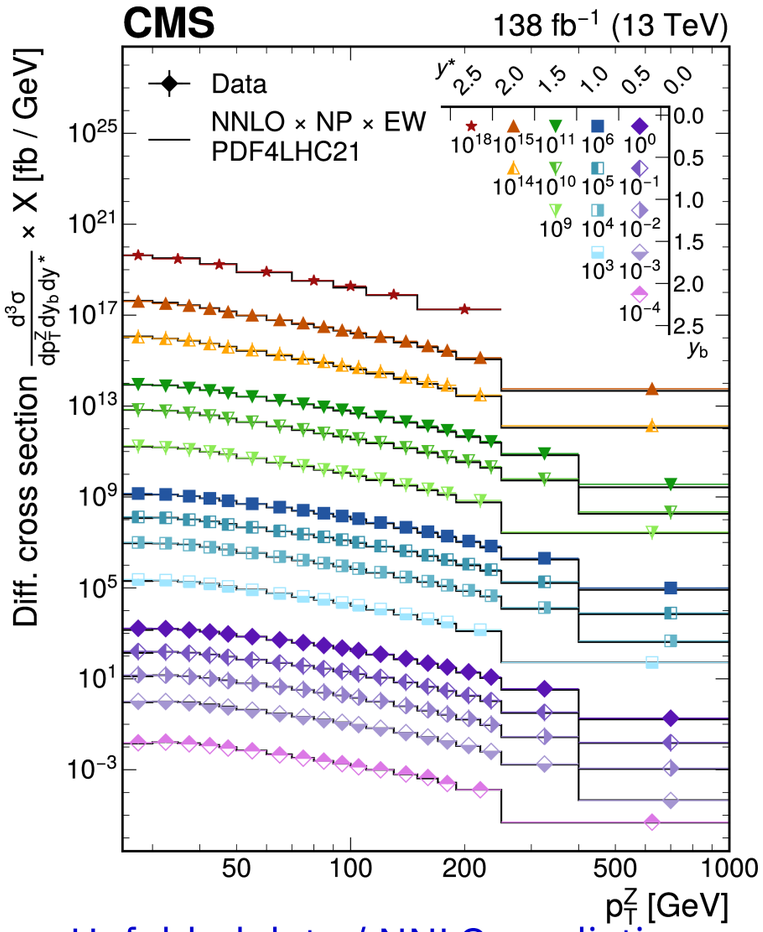
Three observables probe proton structure

- p_T^Z: energy scale of the process
- $y^* = \frac{1}{2}|y_Z - y_{\text{jet}}|$: rapidity separation / scattering angle
- $y_b = \frac{1}{2}|y_Z + y_{\text{jet}}|$: system boost / incoming parton momenta
- **3D unfolding**; **NNLO QCD + EW + NP** comparison
- **1.5–5%** precision for $p_T^Z > 50$ GeV in central / boosted regions





Event topology and (y_b, y^*) binning

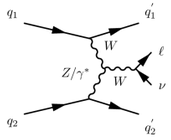


Unfolded data / NNLO prediction across rapidity bins

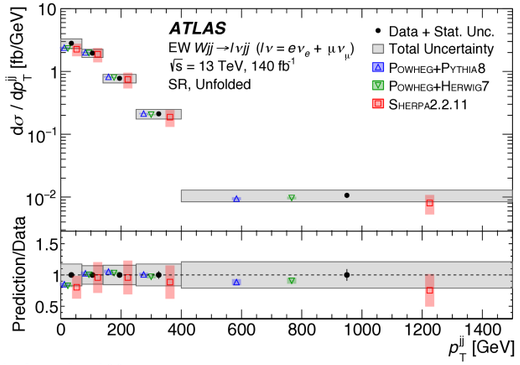
Single boson: VBF V probes gauge interactions

Forward tagging jets + a central boson: **large m_{jj}** and rapidity separation enrich EW Vjj

EW $W(\to e\nu/\mu\nu)jj$ ATLAS STDM-2021-04



- $\sigma^{\text{fid}} = 480 \pm 12(\text{stat}) \pm 39(\text{exp}) \pm 53(\text{theory})$ fb



Unfolded dijet transverse momentum p_T^{jj}

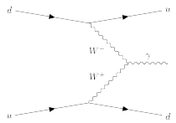
$\mathcal{O}_W$ modifies the triple and quartic EW gauge-boson self-couplings

Operator	Corresponding WC
X^3	
$\mathcal{Q}_W = \varepsilon^{ijk} W_\mu^{iv} W_v^{jp} W_\rho^{k\mu}$	c_W
$\mathcal{Q}_{\widetilde{W}} = \varepsilon^{ijk} \widetilde{W}_\mu^{iv} W_v^{jp} W_\rho^{k\mu}$	$c_{\widetilde{W}}$

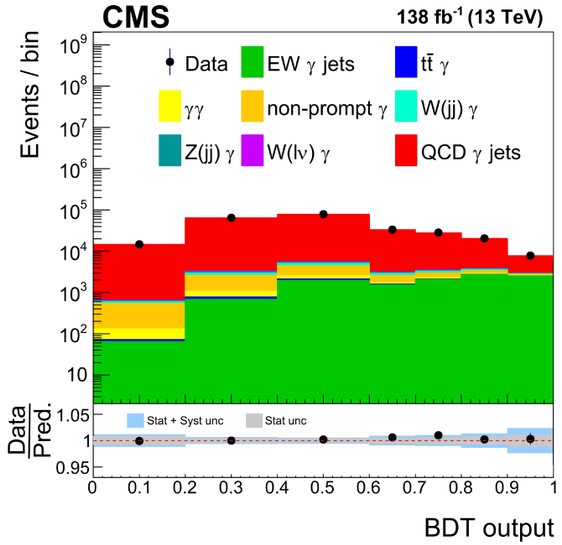
	Expected interval [TeV^{-2}]		Observed interval [TeV^{-2}]	
Wilson coefficient	Linear-only	Linear+quadratic	Linear-only	Linear+quadratic
c_W/Λ^2	$[-0.17, 0.17]$	$[-0.17, 0.16]$	$[-0.17, 0.12]$	$[-0.15, 0.10]$
$\tilde{c}_W/\Lambda^2$	$[-0.19, 0.19]$	$[-0.18, 0.19]$	$[-0.083, 0.25]$	$[-0.079, 0.18]$
c_{HWB}/Λ^2	$[-5.6, 4.3]$	$[-3.4, 5.4]$	$[-4.1, 4.4]$	$[-2.2, 2.9]$
$\tilde{c}_{HWB}/\Lambda^2$	$[-10, 10]$	$[-4.1, 4.1]$	$[-11, 7.3]$	$[-2.8, 2.5]$

EFT intervals: linear-only and linear + quadratic

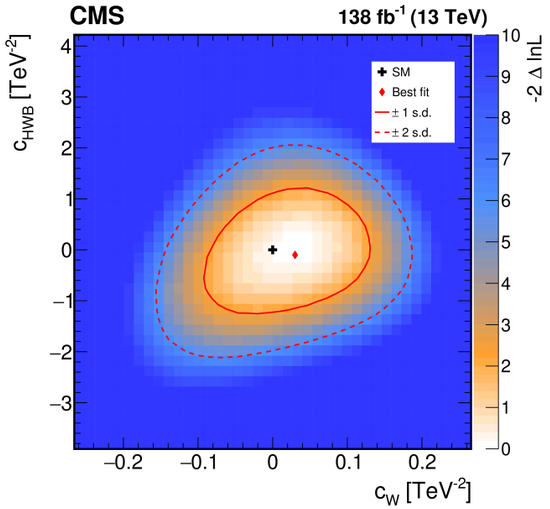
EW γjj (photon $p_T > 200$ GeV) CMS SMP-19-005



- **First observation**: $> 5\sigma$
- $\sigma^{\text{fid}} = 202^{+36}_{-32}$ fb



Post-fit BDT discriminant

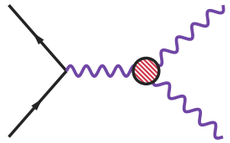


EFT: $c_W - c_{HWB}$ likelihood

⟹ EW Vjj tests triple gauge interactions

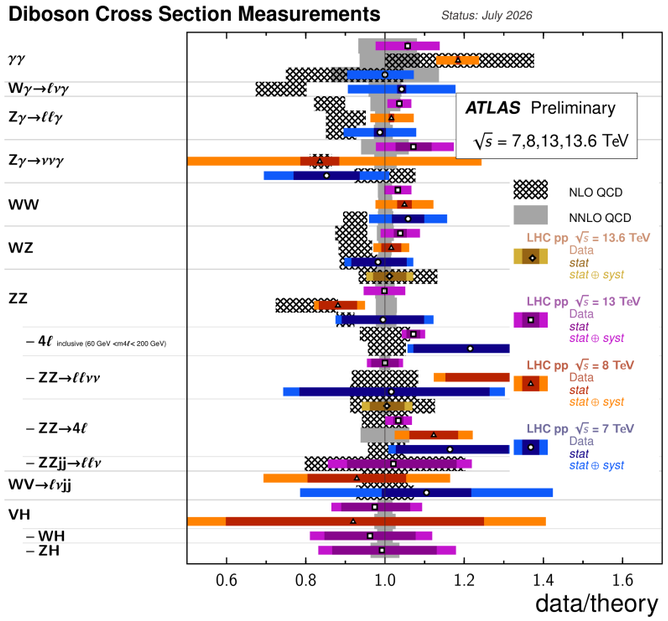
The diboson + VBS programme

Diboson: large cross sections



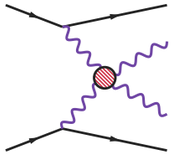
WW WZ ZZ
$W\gamma$ $Z\gamma$ $\gamma\gamma$

- Precision measurements
- Boosted regimes probe **TGCs/EFT**



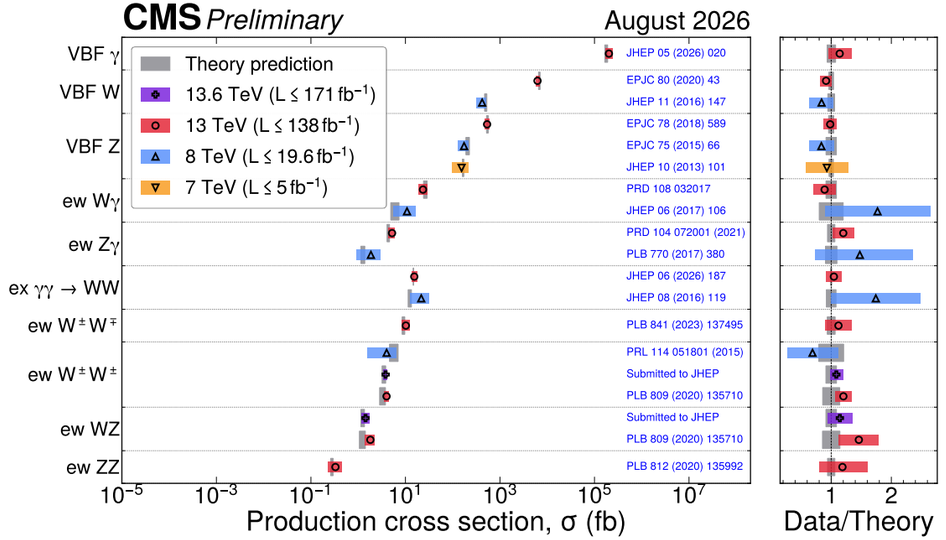
ATLAS diboson cross-section summary

VBS: rare electroweak $VVjj$



$W^{\pm}W^{\pm}$ $W^{+}W^{-}$ WZ ZZ
$W\gamma$ $Z\gamma$ $\gamma\gamma$

- Probes **TGCs / QGCs** and **EWSB**
- **Polarisation**: resolve helicities and test gauge–Higgs cancellations



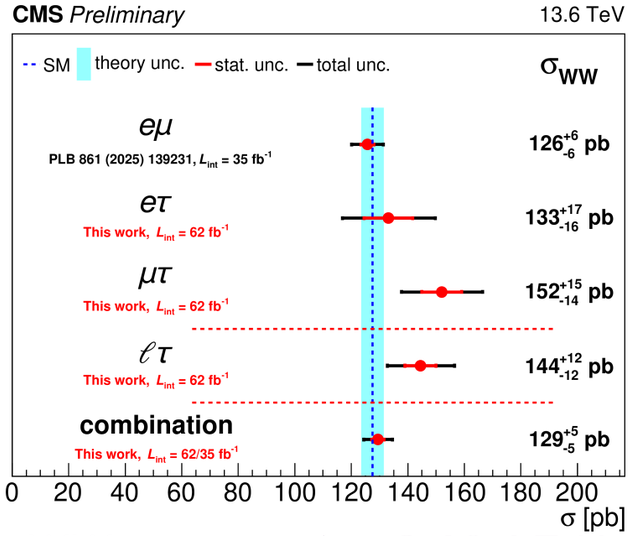
CMS electroweak VBF / VBS cross-section summary

Diboson production: WW, WV and ZZ

CMS SMP-24-011

$WW \to \ell\tau_h\nu\bar{\nu}$

- **First** LHC WW measurement with **hadronic τ decays**
- $\sigma_{WW} = 144 \pm 12$ pb
- With $e\mu$ **channel**: 129 ± 5 pb

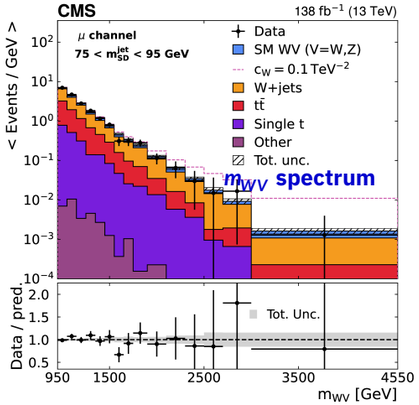


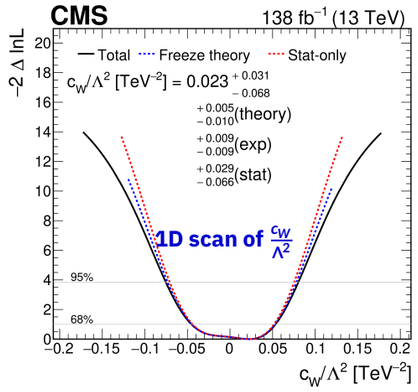
WW cross section @ 13.6 TeV

CMS SMP-25-001

$WV \to \ell\nu q\bar{q}$

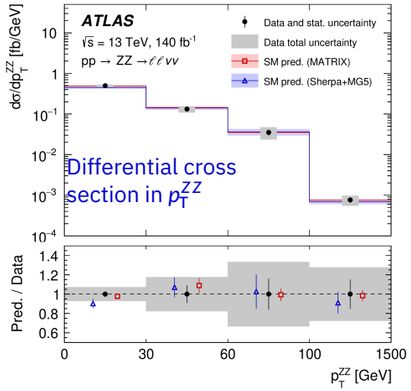
- Probe **dimension-six EFT** operators

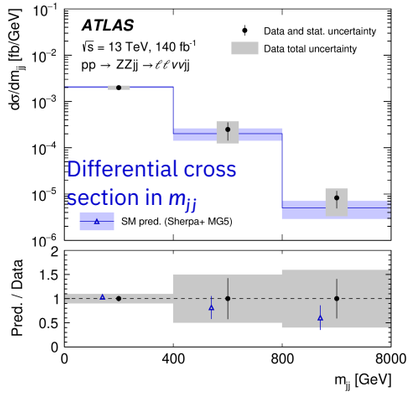




ATLAS STDM-2019-27

$ZZ \to \ell\ell\nu\nu$



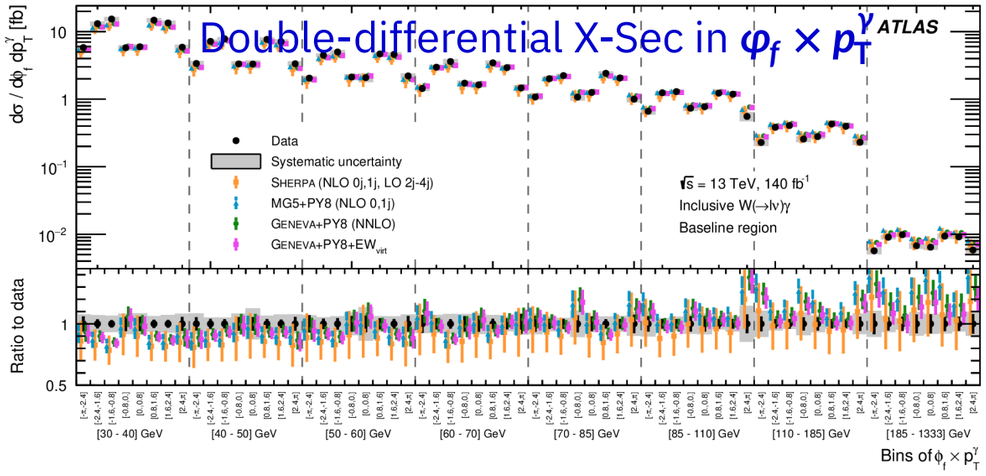


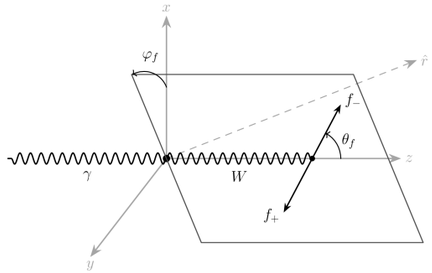
Dijet enriched phase space

Photon final states: $W\gamma$, $Z\gamma$ and EW $\gamma\gamma jj$

$W(\to \ell\nu)\gamma$ ATLAS STDM-2022-15

- Differential cross sections and $WW\gamma$ TGCs





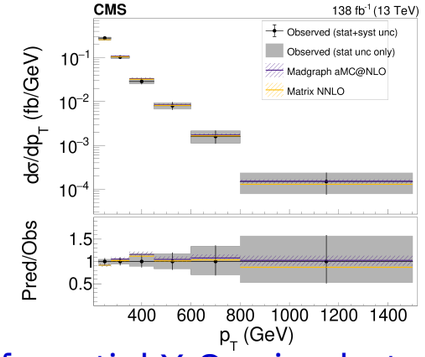
Wilson coefficient	Observable	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	k-factor	95% CL [TeV^{-2}] Expected	Observed
c_W/Λ^2	$\phi_f \times p_T^\gamma$	no	no	$[-0.37, 0.38]$	$[-0.42, 0.36]$
		yes	no	$[-0.12, 0.11]$	$[-0.06, 0.06]$
		no	yes	$[-0.23, 0.25]$	$[-0.28, 0.21]$
		yes	yes	$[-0.09, 0.09]$	$[-0.05, 0.05]$
$c_{\tilde{W}}/\Lambda^2$	$O_{NN}^{\tilde{W}}$	no	no	$[-0.53, 0.54]$	$[-0.74, 0.23]$
		yes	no	$[-0.61, 0.36]$	$[-0.67, 0.19]$
		no	yes	$[-0.32, 0.32]$	$[-0.45, 0.14]$
		yes	yes	$[-0.43, 0.25]$	$[-0.54, 0.11]$

1D limits on dimension-six Wilson coefficients

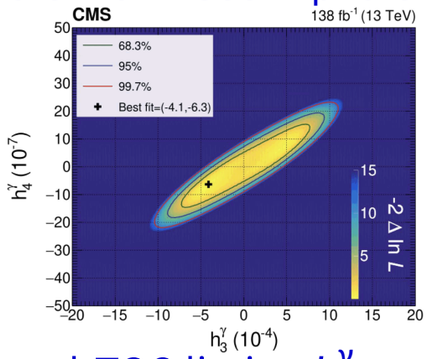
CMS SMP-22-009

$Z(\to \nu\bar{\nu})\gamma$

- $p_T^\gamma > 225$ & $p_T^{miss} > 200$ GeV



Differential X-Sec in photon p_T

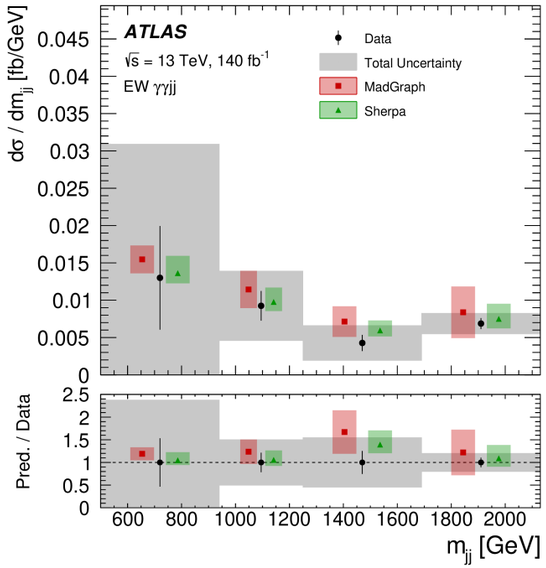


Neutral-TGC limits: h_3^γ and h_4^γ

ATLAS STDM-2022-16

EW $\gamma\gamma jj$

- **Two isolated photons** and **large m_{jj}**
- **First observation: 6.2σ**
- $\sigma_{EW}^{fid} = 13.8^{+3.0}_{-2.6}$ **fb**



Differential X-Sec in m_{jj}

Decomposition of the diboson polarisation

Strong independent probe of the electroweak gauge sector & **EWSB**

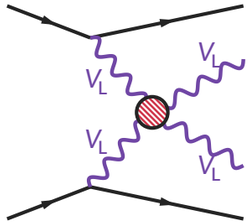
- Direct connection to **Higgs mechanism** via **longitudinal polarization**
- BSM effects might influence only certain polarization components
- **Delicate cancellation in longitudinal VBS to rescue unitarity**

Decomposition of the vector boson polarisation

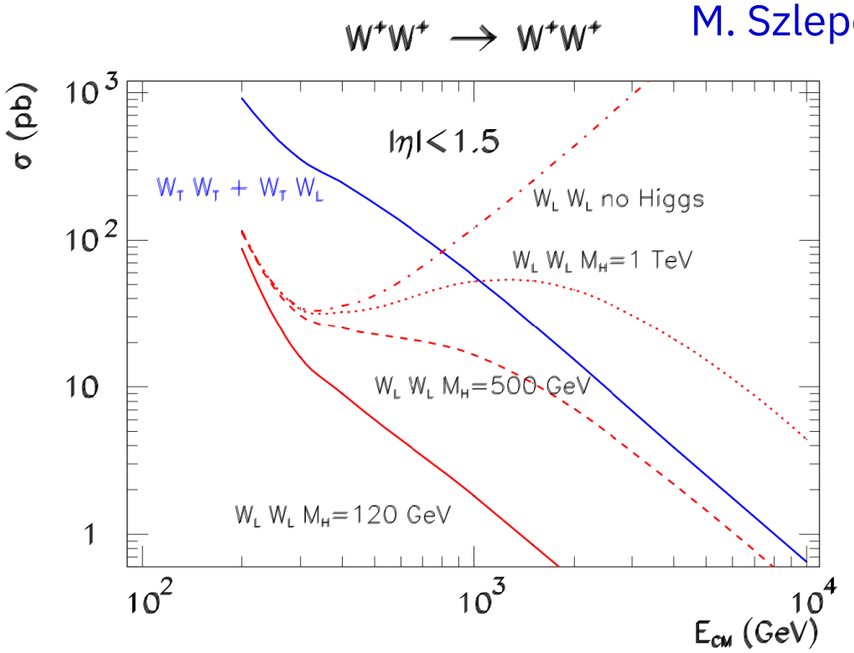
$$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{\text{int.}} \frac{d\sigma_{\text{int.}}}{dX} \right)$$

Non-trivial to measure

- Template-fits based on polarized templates from MC



M. Szleper 2015



CMS Run 2 same-sign WW

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^{\pm}W_L^{\pm}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^{\pm}W_T^{\pm}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^{\pm}W_X^{\pm}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^{\pm}W_T^{\pm}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

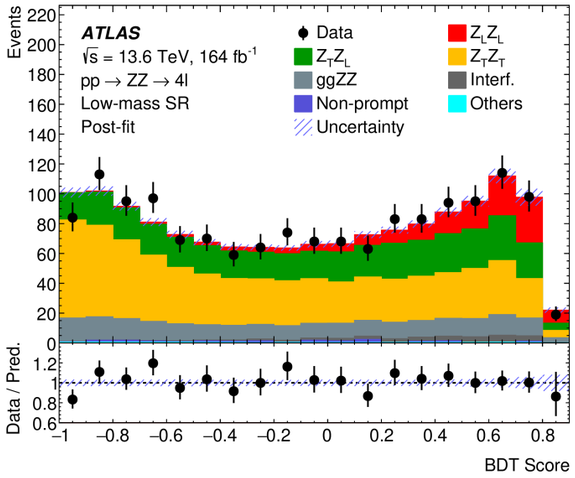
ATLAS same-sign WW polarisation

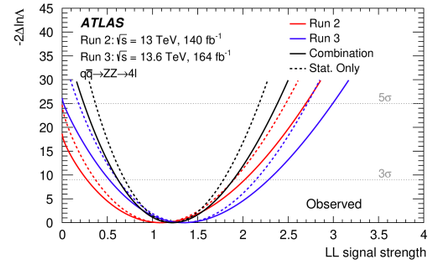
Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)
$W_L^{\pm}W_L^{\pm}jj$	0.29 ± 0.07	0.01 ± 0.21 (tot.)
$W_T^{\pm}W^{\pm}jj$	2.56 ± 0.64	3.39 ± 0.35 (tot.)
$W_L^{\pm}W^{\pm}jj$	1.18 ± 0.29	0.88 ± 0.30 (tot.)
$W_T^{\pm}W_T^{\pm}jj$	1.67 ± 0.40	2.49 ± 0.32 (tot.)

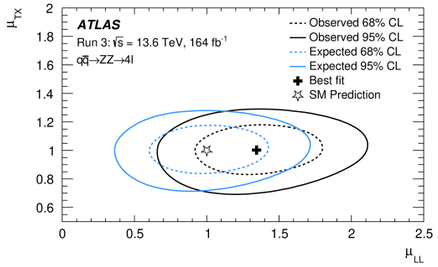
Polarisation of inclusive ZZ and VBS WZ productions

ATLAS STDM-2024-01

First observation of joint $Z_L Z_L$





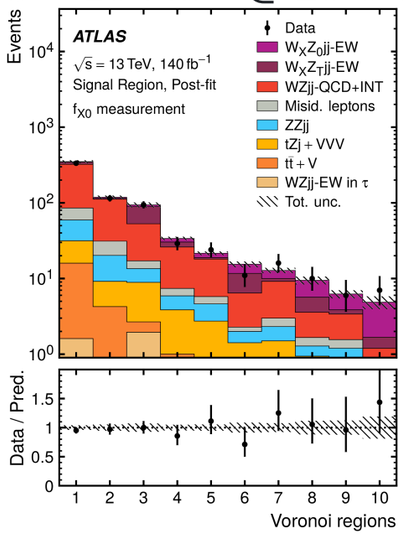


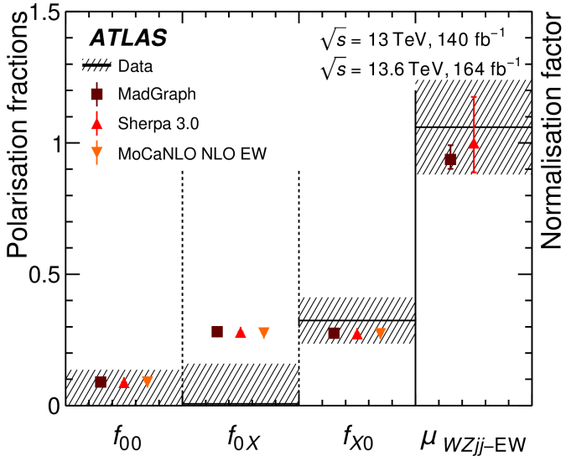
- Measured $Z_L Z_L$ fraction: $f_{LL} = 0.080 \pm 0.017$
- SM-consistent: **6.6σ** obs. (5.6σ exp.)

ATLAS STDM-2024-03

Evidence for WZ_L in VBS WZ

- Run2+Run3 data
  - $\mathcal{L} = 140$ fb^{-1} @ 13 TeV
  - $\mathcal{L} = 164$ fb^{-1} @ 13.6 TeV





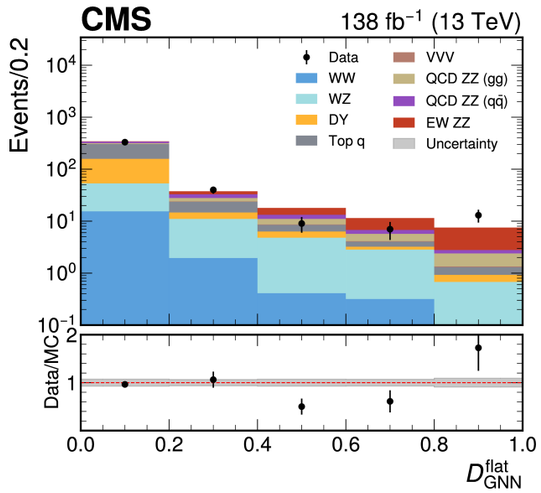
Observed significance of VBS WZ_L is **4.0σ**

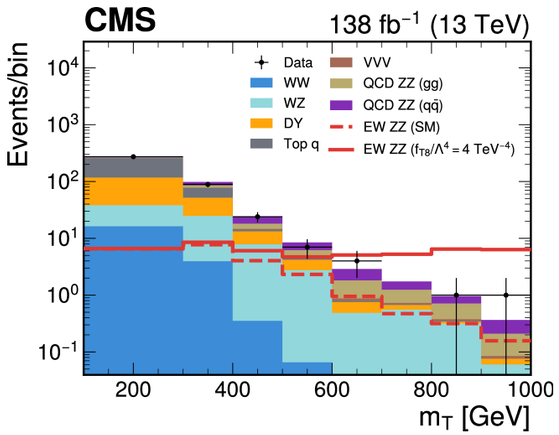
⟹ Single-boson longitudinal sensitivity is a step towards longitudinal VBS

VBS $ZZ(\to \ell\ell\nu\nu)$ and Run–3 VBS $W^{\pm}W^{\pm}$

EW $ZZ(\to \ell\ell\nu\nu)jj$ CMS SMP-23-001

- Focus on the **semi-invisible** decay of the VBS ZZ
- **Two leptons**, **large** p_T^{miss}, large $|\Delta\eta_{jj}|$, and **large** m_{jj}





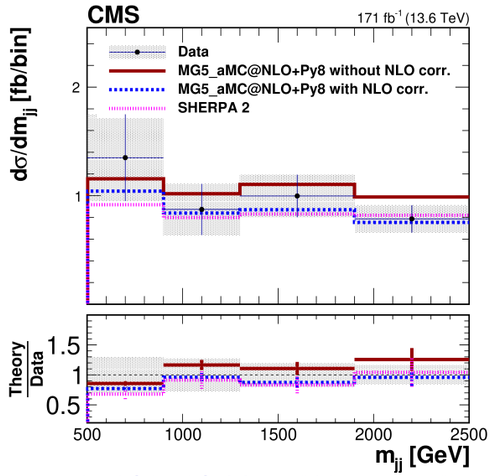
First evidence for EW $ZZ \to \ell\ell\nu\nu$: 3.1 σ

- $\sigma_{EW}^{fid} = 0.37^{+0.14}_{-0.12}(stat)^{+0.06}_{-0.06}(syst)$ **fb**
- Combined with EW $ZZ \to \ell\ell\ell'\ell'$: **5.0** σ
- Use m_T to set limits on **dimension-8 EFT operators WCs**

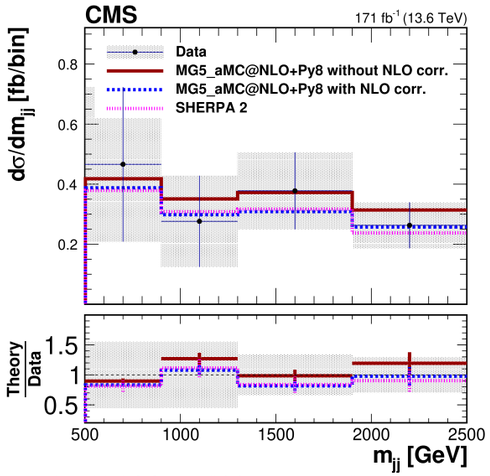
CMS SMP-25-013

Same-sign WW and WZ VBS in Run 3

- First Run 3 measurements at 13.6 TeV
- Unfolded distributions test predictions in the VBS phase space

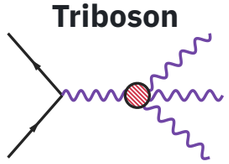


EW $W^{\pm}W^{\pm}jj$: differential cross section in m_{jj}



EW $WZjj$: differential cross section in m_{jj}

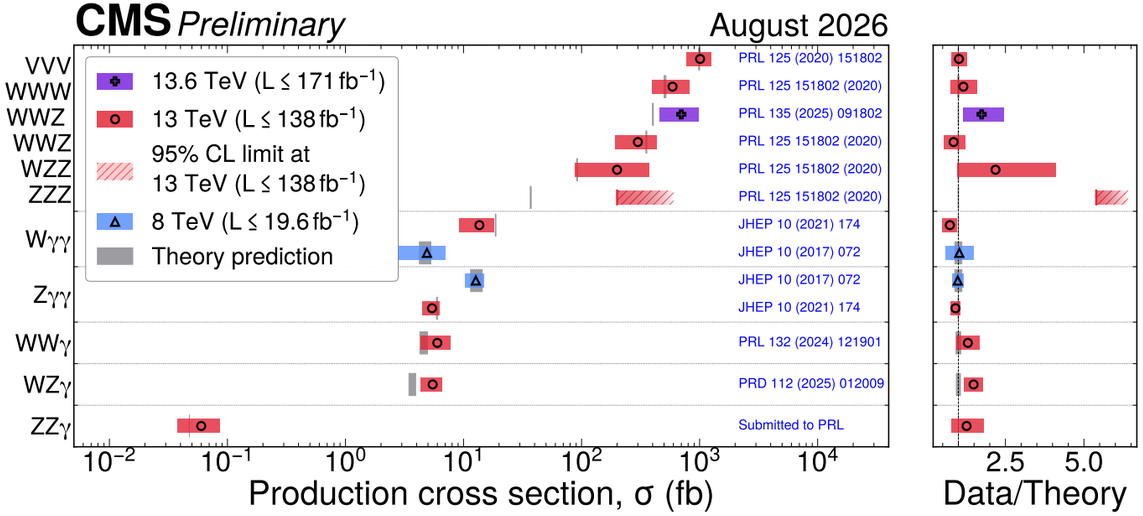
The triboson frontier



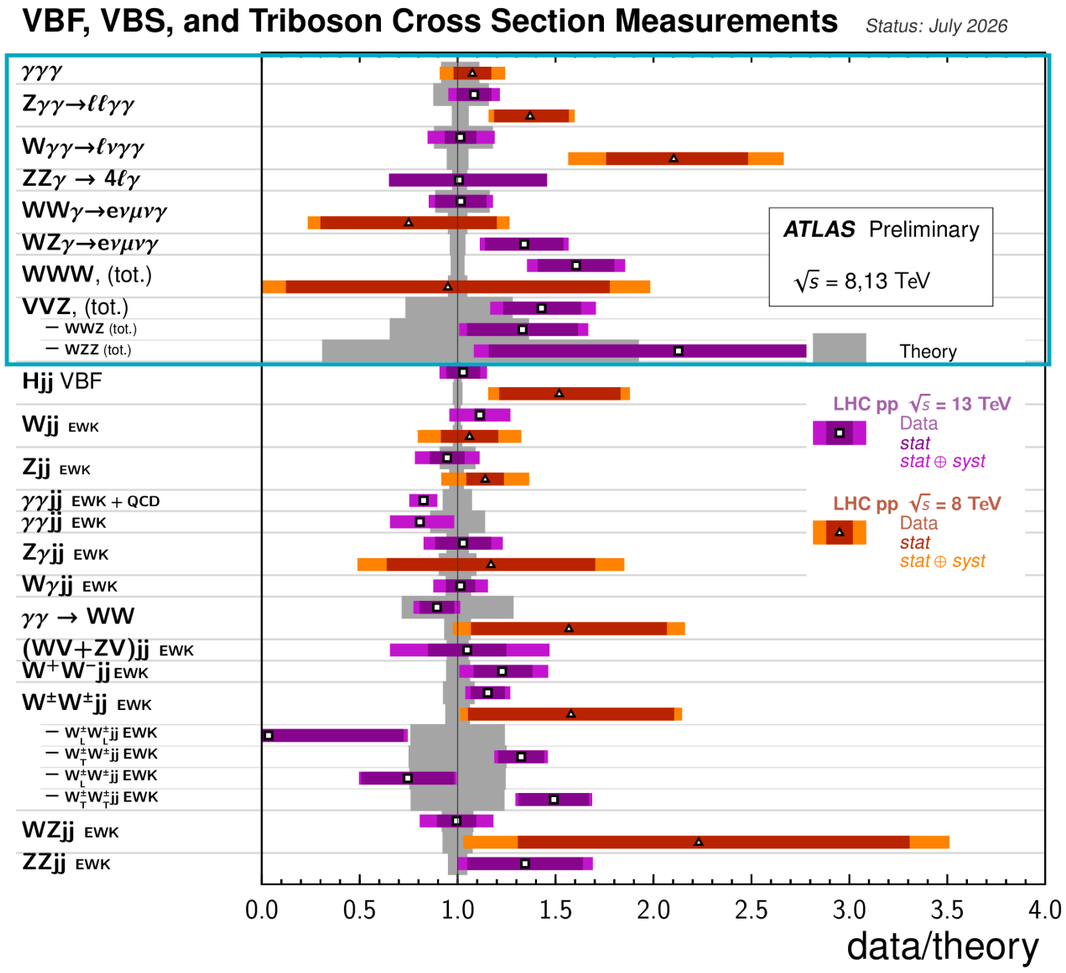
WWW WWZ WZZ ZZZ
$WW\gamma$ $WZ\gamma$ $ZZ\gamma$
$W\gamma\gamma$ $Z\gamma\gamma$ $\gamma\gamma\gamma$

Rare processes probing gauge self-interactions

- Rates far below inclusive diboson production
- Complementary sensitivity to **TGCs / QGCs** and **EFT**



CMS triboson cross-section summary



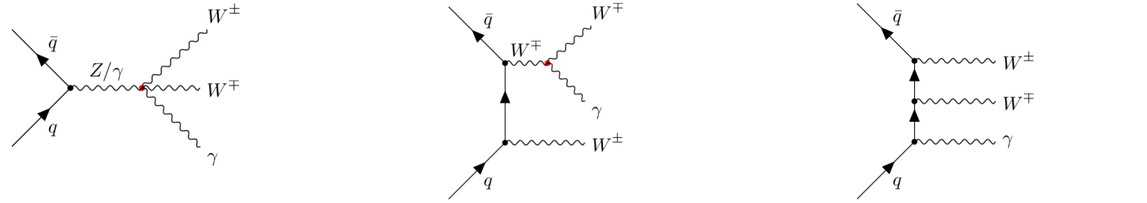
ATLAS VBF, VBS and **triboson** summary

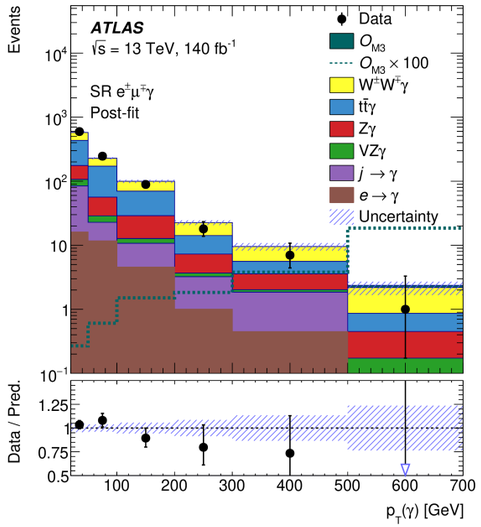
$VV\gamma$

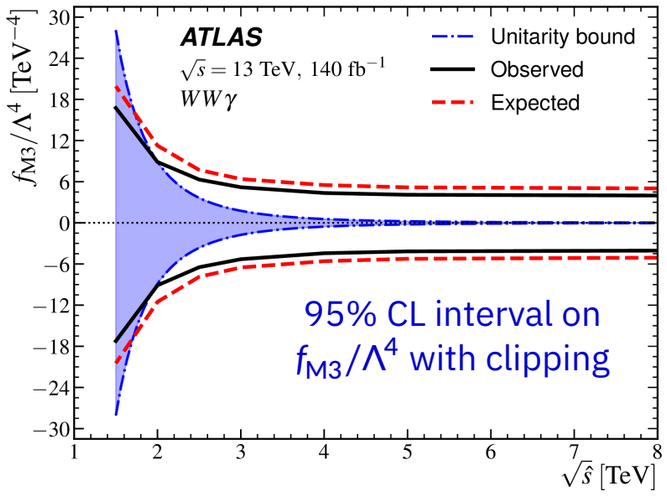
ATLAS PLB 873 (2026) 140050

$WW\gamma \to e\mu\nu\bar{\nu}\gamma$

- **Observation: 5.9σ** (6.0σ expected)
- $\sigma^{\text{fid}} = 6.2 \pm 1.0$ fb



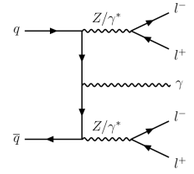


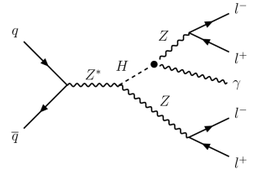


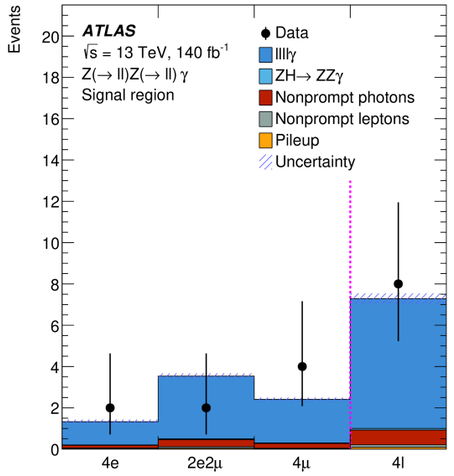
ATLAS PRL 137 (2026) 091804

$ZZ\gamma \to 4\ell\gamma$

- **Evidence: 4.4σ** (4.4σ expected)
- $\sigma^{\text{fid}} = 0.144^{+0.064}_{-0.051}(\text{stat})^{+0.007}_{-0.005}(\text{syst})$ fb







Yields by lepton flavour

	Number of events
Signal	6.36 ± 0.09 (stat.) ± 0.18 (syst.)
Nonprompt photons	0.71 ± 0.02 (stat.) ± 0.13 (syst.)
Nonprompt leptons	0.12 ± 0.02 (stat.) ± 0.08 (syst.)
Pileup	0.09 ± 0.002 (stat.) ± 0.02 (syst.)
Total background	0.92 ± 0.03 (stat.) ± 0.15 (syst.)
N_{tot} prediction	7.28 ± 0.09 (stat.) ± 0.23 (syst.)
N_{tot} **data**	8

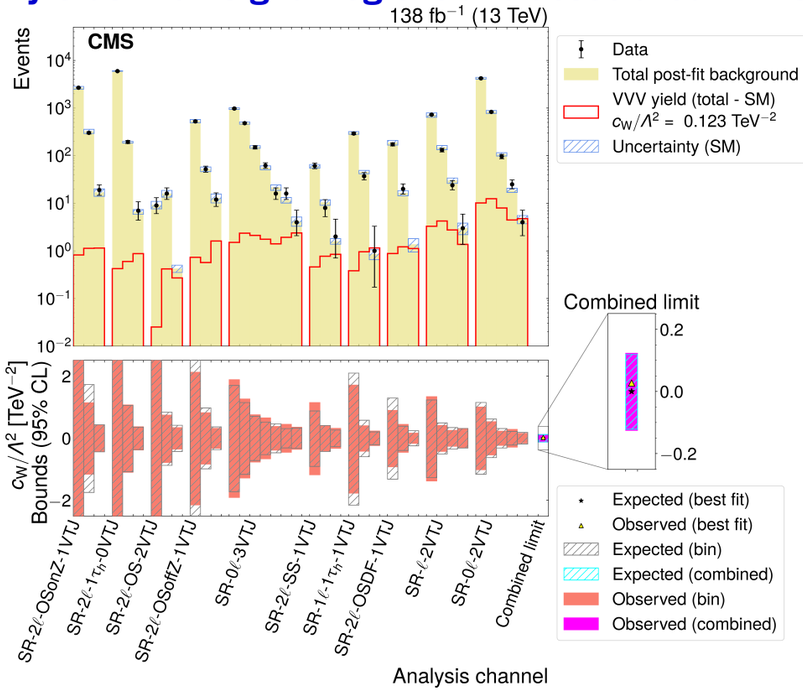
Search for new physics in triple boson production

Consider **three massive gauge bosons** (*VVV*, where *V* is a *W* or *Z* boson) production

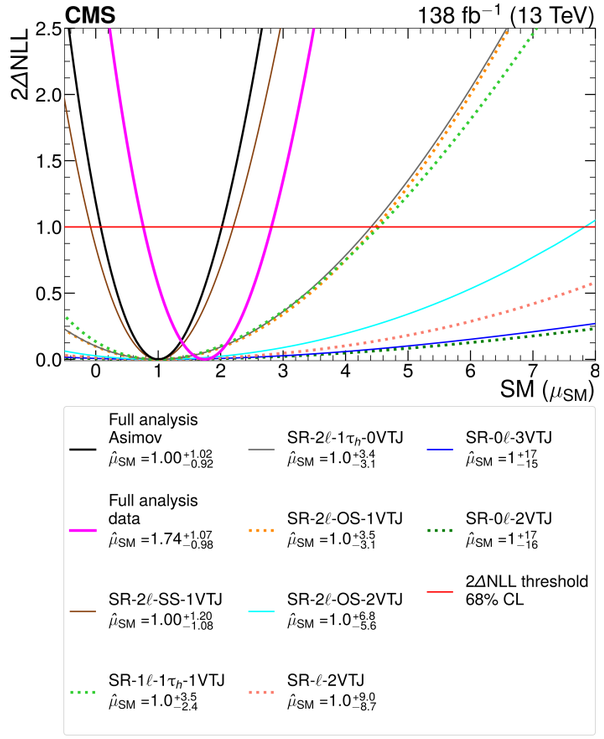
- SM processes contribute few events in **Lorentz-boosted regime**
- Require all three bosons have a p_T **above 200 GeV**
- Two **most stringent bounds** on dim-6 EFT operator WCs placed by **this analysis**
  - $-0.13 < c_W/\Lambda^{-2} < 0.12$ TeV^{-2}
  - $-0.24 < c_{Hq3}/\Lambda^{-2} < 0.21$ TeV^{-2}

CMS SMP-24-017

Bin-by-bin yields in all signal regions and associated limits on c_W/Λ^2



Sensitivity to the SM *VVV* production process

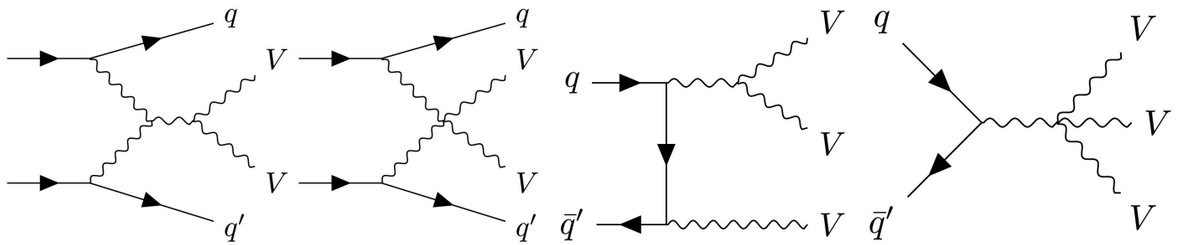


Multiboson EFT combination

Combining analyses **increases sensitivity**

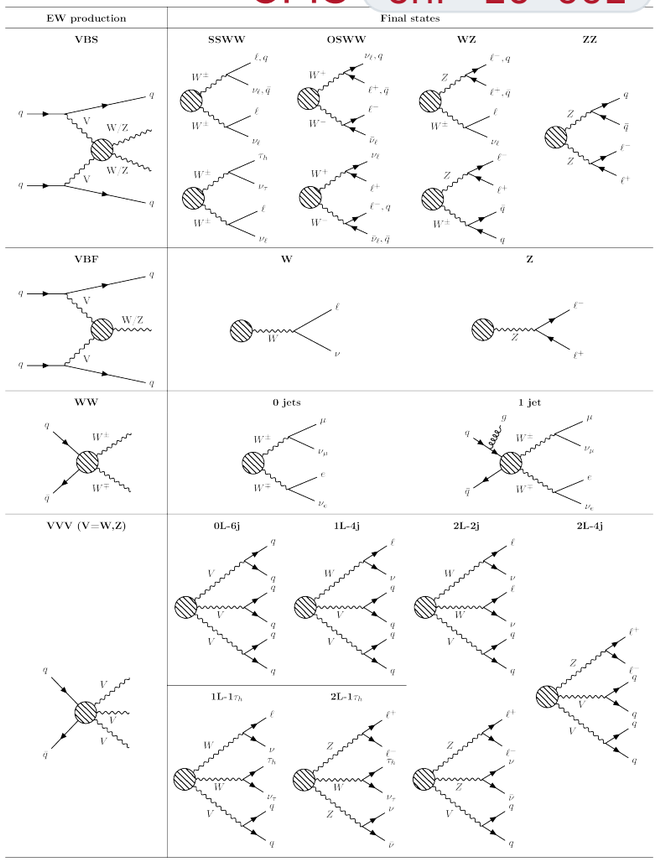
- The **first observation of *VVV*** combined the *WWW*, *WWZ*, *WZZ*, and *ZZZ* channels PRL 125(2020)151802
- With more individual channels now observed
  ⇒ combinations provide **stronger constraints on EFT operators**

ATLAS PLB 879(2026)140683



Analysis	Input type	Éboli operator results	Luminosity [fb^{-1}]	Reference
$VVjj \to (\ell\ell jj/\ell\nu jj/\nu\nu jj)jj$	Reco-level Differential	Full	140	
$WZjj \to l^+l^-l^\pm\nu jj$	Reco-level Differential	Partial	140	
$W^\pm W^\pm jj \to l^\pm\nu l^\pm\nu jj$	Reco-level Differential	Full	139	
$ZZjj \to l^+l^-l^+l^-jj$	Unfolded Differential	None	140	
$W\gamma jj \to l^\pm\nu\gamma jj$	Unfolded Differential	Full	140	
$Z\gamma jj \to \nu\bar{\nu}\gamma jj$	Reco-level Inclusive	Partial	139	
$Z\gamma jj \to l^+l^-\gamma jj$	Unfolded Differential	None	140	
$W\gamma\gamma \to l^\pm\nu\gamma\gamma$	Reco-level Differential	None	140	

CMS SMP-25-002

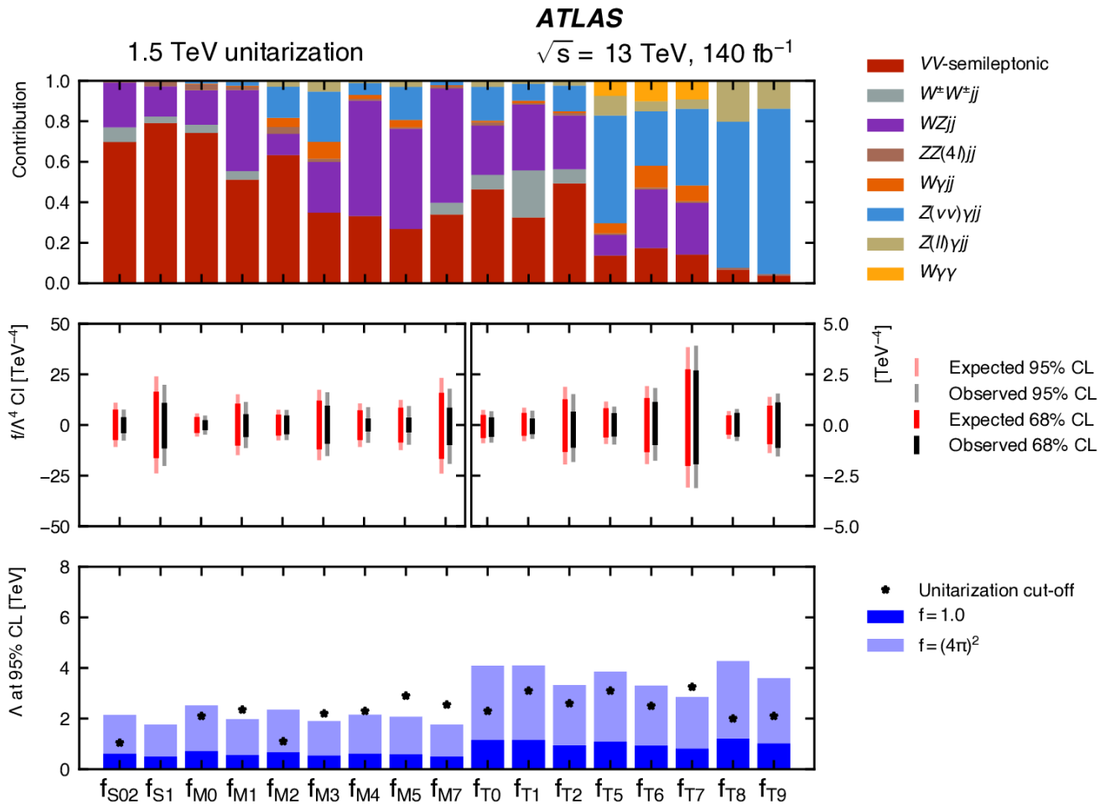


Multiboson EFT combination

Wilson-coefficient intervals and per-channel breakdown of the combined fit

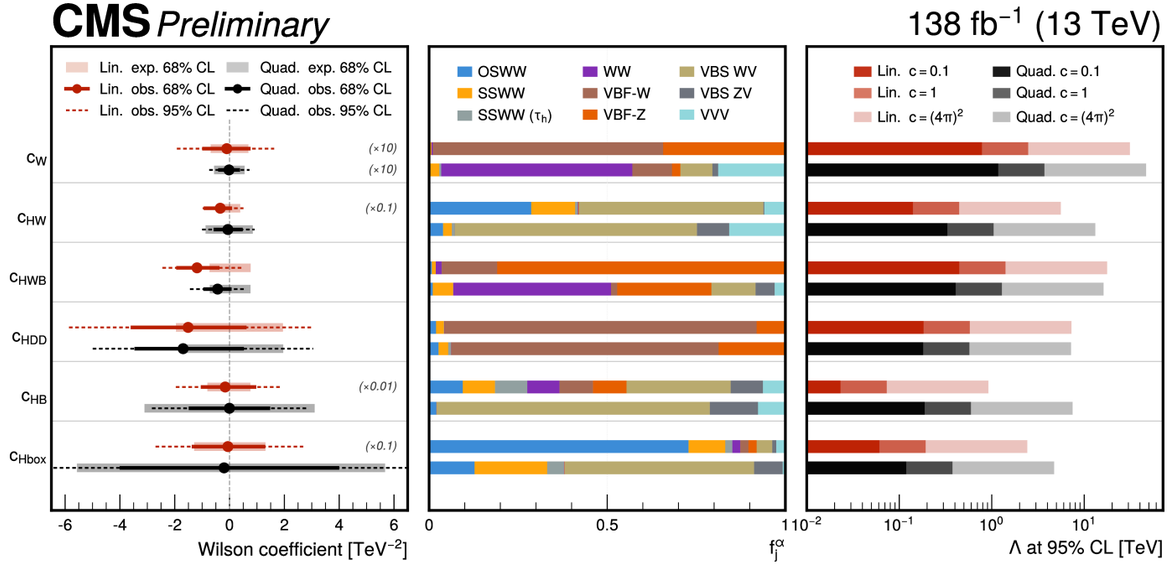
ATLAS PLB 879(2026)140683

- **Dimension-8 operator** · Éboli basis



CMS SMP-25-002

- **Dimension-6 operator** · Warsaw basis



$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\mathrm{SM}}|^2}_{\mathrm{SM}} + \underbrace{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}})}_{\text{interference (linear)}} + \underbrace{|\mathcal{M}_{\mathrm{BSM}}|^2}_{\text{BSM (quadratic)}}$$

Summary

Electroweak tests through precision, polarisation and rare processes

Single boson and VBF–V: precision tests of the electroweak sector

- m_W at $\sim$ 10 MeV; mixing-angle, angular and differential measurements sharpen theory and PDF inputs, EFT constraints

Diboson and VBS–VV : access to longitudinal polarisation

- Joint $Z_L Z_L$ observed in inclusive ZZ; evidence for Z_L in VBS WZ

Triboson: rare channels become probes of new physics

- Established multiboson signals and energetic final states constrain gauge interactions

Combinations: complementary channels strengthen EFT constraints

- The next gains require shared theory inputs and consistent treatment of correlations

Outlook

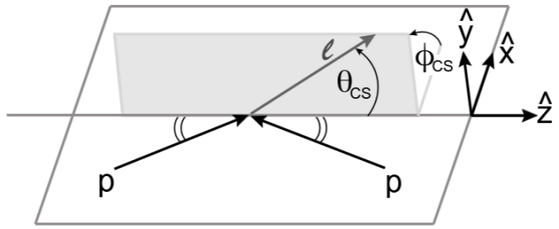
Polarisation, differential precision and combined EFT fits drive the next measurements

§ B

ADDITIONAL MATERIAL

Backup

Collins–Soper frame and A_{FB} definitions



Boson rest frame; after ATLAS, arXiv:1606.00689 Fig. 1

Lepton angles are measured in the boson rest frame, so they are insensitive to the boson p_T and boost

Axes: z bisects the quark direction $\vec{p}_1$ and $-\vec{p}_2$ (the reversed antiquark); x lies in the beam plane; $y = z \times x$

Angles: θ, φ of ℓ^- for Z and W^-, of the charged lepton in general; for $W \to \ell\nu$ the neutrino comes from p_T^{miss}

Quark direction in *pp*: the valence quark carries more momentum on average, so z points along the boson p_z; the wrong assignment at low $|y_{\ell\ell}|$ dilutes A_{FB}

Measured variables (CMS, Z/γ^*):

$$\cos\theta_{CS} = \frac{2\left(p_1^+ p_2^- - p_1^- p_2^+\right)}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2 + p_T^2}} \cdot \frac{p_z}{|p_z|}, \quad p^\pm = \frac{E \pm p_z}{\sqrt{2}}$$

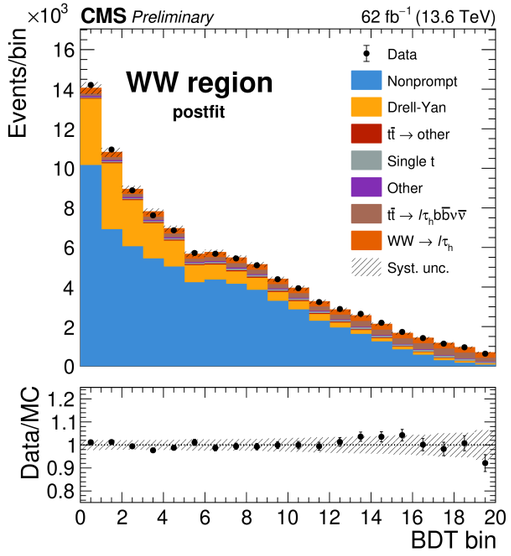
with 1 = ℓ^-, 2 = ℓ^+; $m_{\ell\ell}$, p_T, p_z of the dilepton system

Asymmetry: $A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$ with F (B): $\cos\theta_{CS} > 0$ (< 0); before FSR and in full phase space $A_{FB} = \frac{3}{8} A_4$

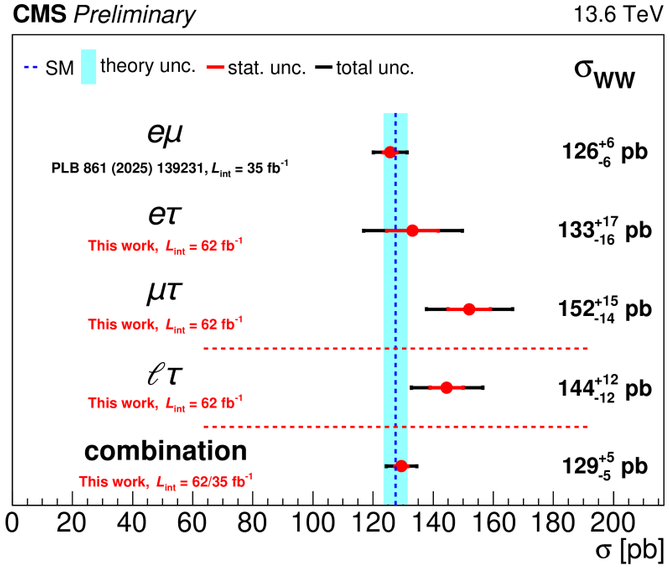
$WW \to \ell\tau_h\nu\bar{\nu}$ at 13.6 TeV

CMS · first LHC measurement of WW including hadronic τ decays `CMS SMP-24-011`

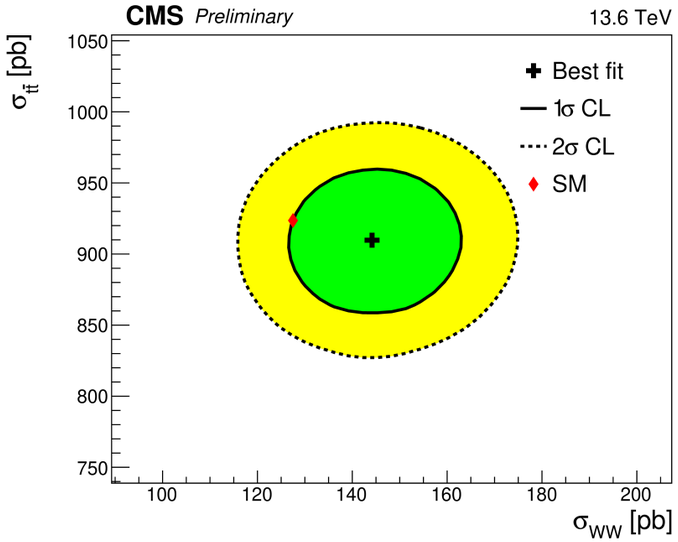
- Complements the established $e\mu$ final state; $t\bar{t}$ backgrounds treated simultaneously
- $\ell\tau_h$ channel: $\sigma_{WW} = 144 \pm 12$ pb; combined with $e\mu$ `PLB 861(2025)139231`: **$\sigma_{WW} = 129 \pm 5$ pb**



BDT separating prompt and nonprompt processes

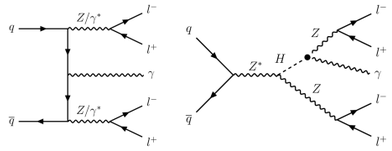


Inclusive WW cross-section comparison



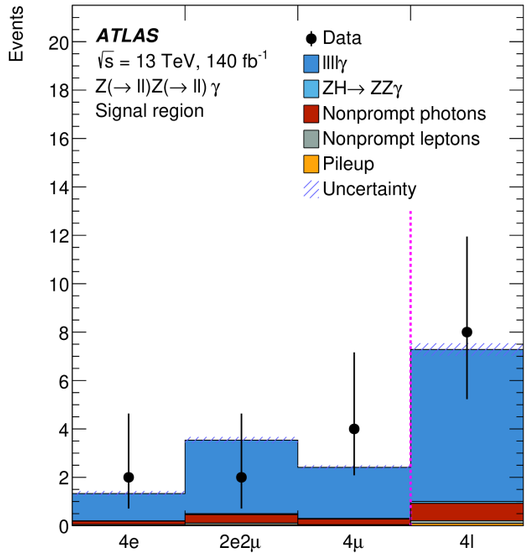
Simultaneous $t\bar{t}$ cross section

$ZZ\gamma$: evidence in the $4\ell\gamma$ final state

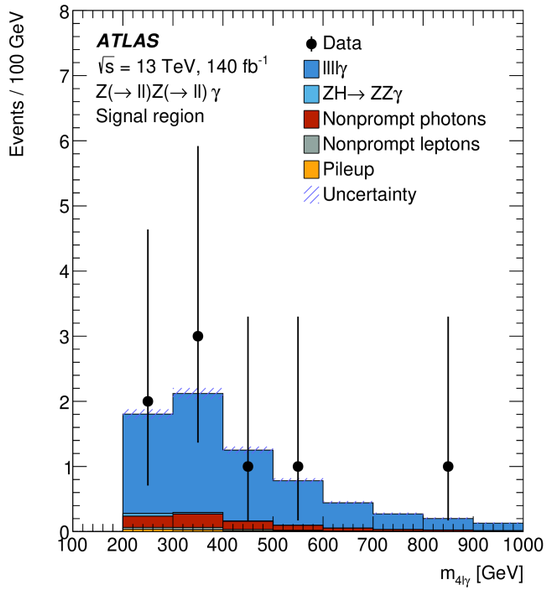


ATLAS · rare fully leptonic channel $ZZ\gamma \to \ell^+\ell^-\ell'^+\ell'^-\gamma$ PRL 137(2026)091804

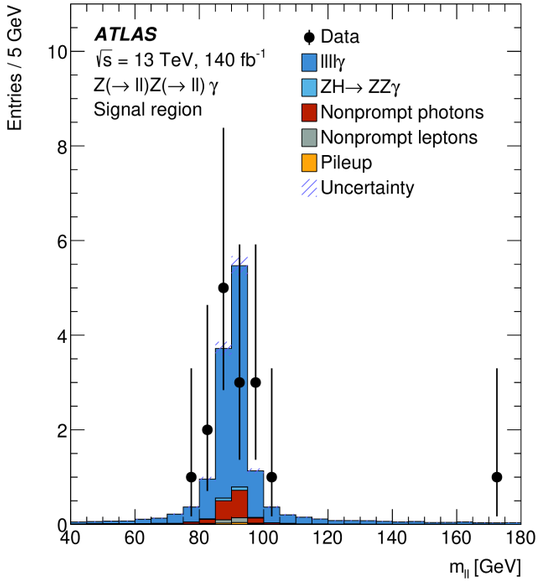
- Two reconstructed Z candidates and one photon; statistical precision is the dominant limitation
- $\sigma^{\text{fid}} = 0.144^{+0.064}_{-0.051}(\text{stat})^{+0.007}_{-0.005}(\text{syst})$ fb; observed (expected) significance 4.4σ (4.4σ)



Leptons in the final state



Invariant mass $m_{4\ell\gamma}$



Dilepton mass of the reconstructed Z bosons

	Number of events
Signal	6.36 ± 0.09 (stat.) ± 0.18 (syst.)
Nonprompt photons	0.71 ± 0.02 (stat.) ± 0.13 (syst.)
Nonprompt leptons	0.12 ± 0.02 (stat.) ± 0.08 (syst.)
Pileup	0.09 ± 0.002 (stat.) ± 0.02 (syst.)
Total background	0.92 ± 0.03 (stat.) ± 0.15 (syst.)
N_{tot} prediction	7.28 ± 0.09 (stat.) ± 0.23 (syst.)
N_{tot} **data**	8

Event selection in the signal region

EFT: interpret the assumptions with the intervals

SMEFT expansion

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

- Linear terms arise from interference with the SM amplitude
- Quadratic dimension-six terms and SM $\times$ dimension-eight terms share the Λ^{-4} order
- One-coefficient intervals differ from profiled multi-coefficient intervals
- High-energy clipping tests the validity dependence; it is not a UV completion
- Compare bounds only after matching basis, normalisation and fit assumptions

$\Longrightarrow$ An EFT interval is conditional on the model space and truncation