Electroweak measurements at the LHC and HL-LHC with ATLAS and CMS

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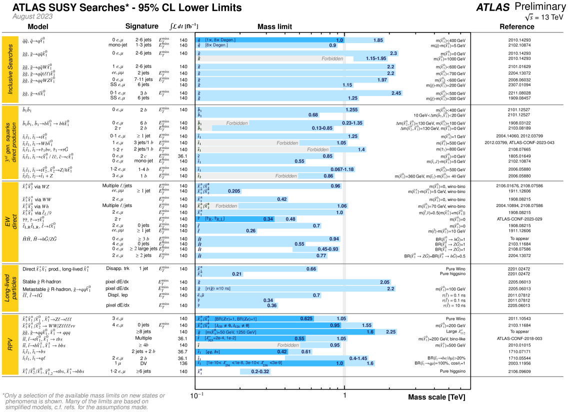
IMPERIAL

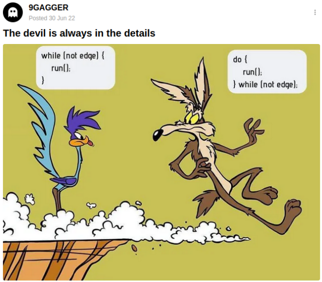
on behalf of the ATLAS and CMS Collaborations

8$^{\text{th}}$-11$^{\text{th}}$ July 2024, LCWS 2024, Tokyo, Japan

Why Precision Measurements Matter

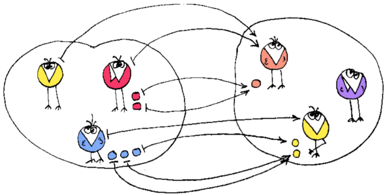
- Hadron colliders: discovery machines.
- But what happens if all the "obvious" BSM signals are excluded ?
- The devil hides in the details!





The EW sector of the SM

- EW sector: 5 parameters ⇒ α_{EM}, G_F, m_W, m_Z, $sin^2\theta_W$
- Parameters are not independent.
- Precise predictions ⇒ high sensitivity to new physics !



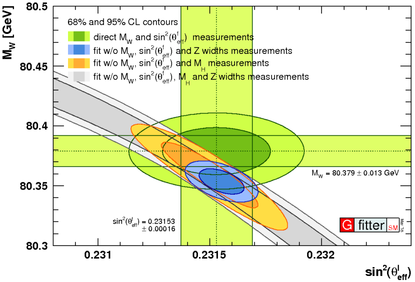
At tree level

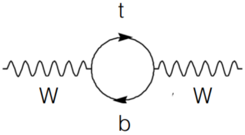
$$sin^2\theta_W = (1 - \frac{m_W^2}{m_Z^2})$$

$$m_W^2 sin^2\theta_W = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F}$$

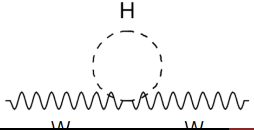
Experimental inputs to the Theory

- The Standard Model is not self-contained: needs experimental inputs!
- Tree-level not sufficient: radiative corrections.
- Global EW fits ⇔ SM self-consistency check
- Any tension between direct and indirect constraints ⇒ new physics in higher order corrections.





$\sim m^2_{top}$



$\sim \ln(m^2_H)$

With EW form factors

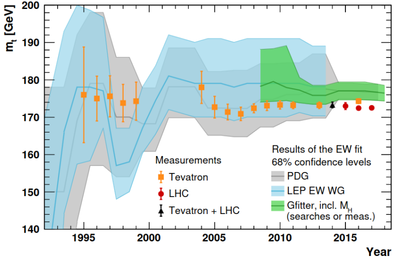
$$\sin^2\theta^{\ell}_{\rm eff} = \sin^2\theta_{\rm W}(1+\Delta\kappa)$$

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$$

The Theory-Experiment feeding loop

- Despite being hadron colliders, LHC and HL-LHC have much more to bring to the EW sector picture before the next generation of lepton collider comes into life.
- MC predictions and theory calculations confronted to new highs every data-taking year.

Eur. Phys. J. C78, 675 (2018)



- If ILC or CLIC or FCC-ee/CEPC came into life tomorrow, we would be in deep trouble for comparing with theory! Years ahead are crucial to build the required accuracy.

EW results shown today

DISCLAIMER

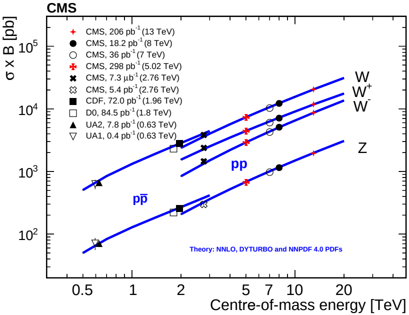
- Not possible to fully acknowledge the plethore of ATLAS and CMS results.
- Will concentrate on newest results mainly.
- Others flashed in summary plots.

Outline


SM PARAMETERS
TOP
H MASSES
GF
αQED
W MASS
WIDTH
Z MASS
WIDTH
W,Z
CROSS
SECTIONS

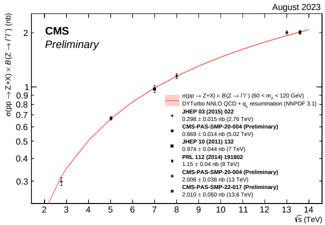
W and Z vs $\sqrt{s}$

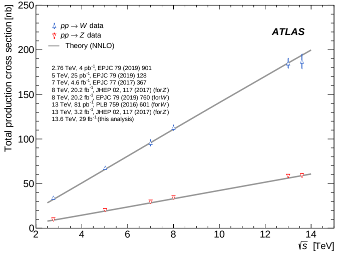
- Since their discovery at UA1, excellent agreement data-MC from 0.63 TeV up to 13.6 TeV hadron collisions, using DYTURBO@NNLO in QCD + NNPDF4.0.
- At LHC, special low PU datasets for best accuracy.



arXiv:2405.1866

CMS-PAS-SMP-22-017, $\mathcal{L} = 5.04$ fb^{-1}





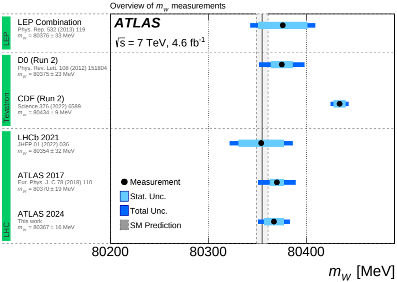
PLB 854 (2024) 13872

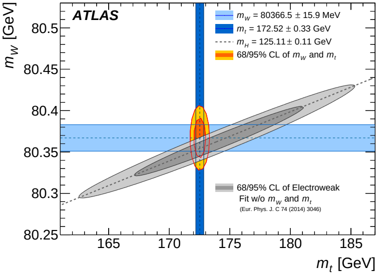
W boson mass measurement

- Leptonic (e,μ) decays of the W.
- Challenging measurement at hadron colliders.
- Reanalysis of data used for 2017 measurement.
- Profile likelihood fits to p_T^ℓ and m_T.
- Signal MC templates for a range of m_W values, reweighted to the Breit-Wigner parametrisation of the W mass.

	ATLAS m_W 2017	ATLAS m_W 2023
Statistical interpretation	χ^2 fit with stat-only uncertainties, systematics added aposteriori	Profile max. likelihood (ML) fit - for the first time in context of m_W measurements; O(1000) NPs reduced to ~200 NPs with PCA
Baseline PDF	CT10	CT18
Electroweak theory unc.	Evaluated at truth level	Evaluated at detector level
Multijet background	2023: Systematic shape variations using PCA, new transfer function from CR to SR	
Detector calibration	Unchanged	
EW and top background	Unchanged	

Courtesy of O. Kuprash

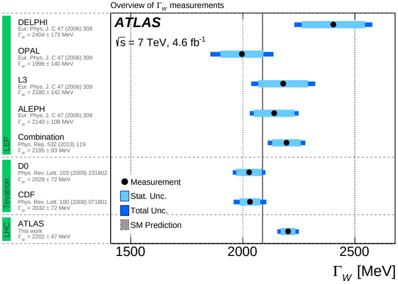


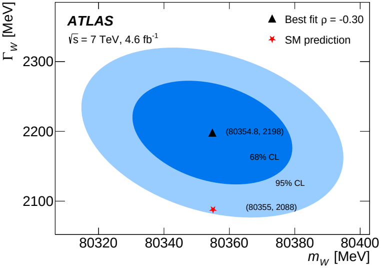


W boson width measurement

arXiv:2403.1508

- First measurement of Γ_W at LHC.
- Best single-experiment measurement to date.
- Modelling (PS tune) and recoil dominate uncertainties.





	1 param. fits		2 param. fit	
m_W	80366.5 ± 15.9	⇒	80354.8 ± 16.1	↓12 MeV
Γ_W	2202 ± 47		2198 ± 49	↓4 MeV

Small impact on uncertainties

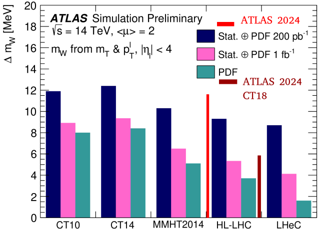
Systematic uncertainties

arXiv:2403.1508

m_W uncertainties

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

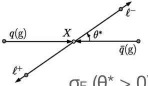
Snowmass report, ATL-PHYS-PUB-2022-018/CMS-FTR-22-00



- At HL-LHC: increased lepton acceptance.
- But need a dataset with low instantaneous luminosity.
- Final precision will depend on PDFs and amount of data.

The weak mixing angle at the LHC

CMS-PAS-SMP-22-010

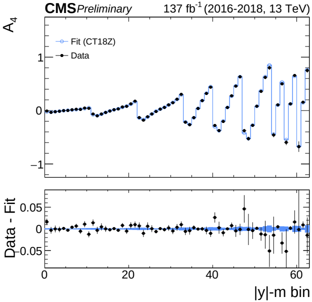


σ_F (θ* > 0)
σ_B (θ* < 0)

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Measured via $Z/\gamma^* \to ee, \mu\mu$ asymmetry in lepton decay angle θ_{CS}.
- Fit of data using templates from POWHEG MiNNLO.
- Addition of forward electrons.
- Use 9 $|y_{\ell\ell}|$ times 11 $m_{\ell\ell}$ bins.
- 3 measurements: fits to measured $A_{FB}(y, m)$, unfolded $A_4(Y, M) = 8/3\ A_{FB}(Y, M)$, observed $\cos\theta_{CS}$.

Channel	$\|\eta\|$		min p_T^{lead} (GeV)	min p_T^{trail} (GeV)
$\mu\mu$	0.00–2.40		20	10
ee	0.00–2.50		25	15
	$\|\eta_e\|$	$\|\eta_{g,h}\|$	min p_T^e (GeV)	min $p_T^{g,h}$ (GeV)
eg	0.00–2.50	2.50–2.87	30	20
eh	1.57–2.50	3.14–4.36	30	20



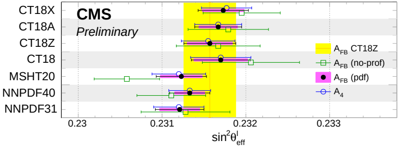
Best measurement at hadron collider to date

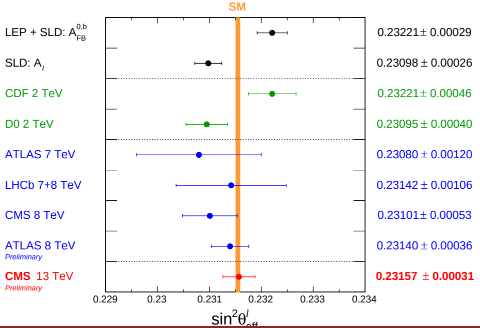
$$\sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23157 \pm 0.00010\,(\mathrm{stat}) \pm 0.00015\,(\mathrm{exp}) \pm 0.00009\,(\mathrm{theo}) \pm 0.00027\,(\mathrm{PDF})$$

- Uncertainties dominated by PDF.
- Exp. systematics: MC stat (0.00008), lepton efficiency (0.00006), calibrations (0.00006), bkg (0.00004), others (0.00003).

CMS-PAS-SMP-22-010

PDF profiling reduces PDF set differences.



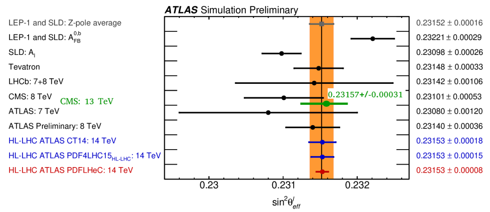


ATLAS 8 TeV [ATLAS-CONF-2018-037]

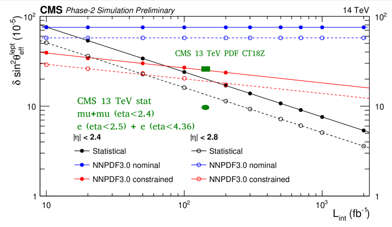
$$\sin^2\theta^{\ell}_{\mathrm{eff}} = \mathbf{0.23140 \pm 0.00036}$$

The weak mixing angle at HL-LHC

ATLAS: ee only extended to $|y| < 4.0$



CMS: $\mu\mu$ only extended to $|y| < 2.8$

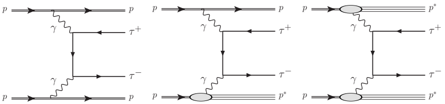


ATL-PHYS-PUB-2022-018/FTR-22-001

- New CMS measurement already better than expectations in YR2018.

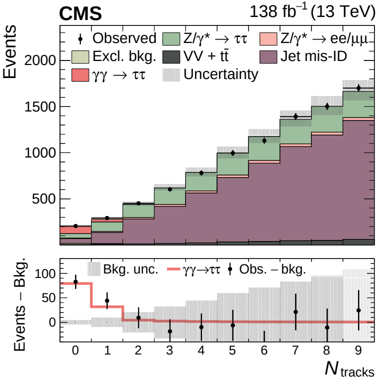
[We are never better beaten than by oneself]

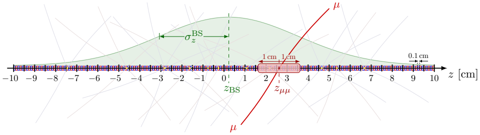
Exclusive production (p)$\gamma\gamma$(p)$\rightarrow \tau\tau$ with CMS



arXiv:2406.03975

- Pure QED process.
- In SM, anomalous magnetic moment $a_\tau = 117721.10^{-8}$, electric dipole moment $d_\tau = -7.3.10^{-38} e$cm.
- Combine eμ, eτ_h, $\mu\tau_h$, $\tau_h\tau_h$.
- Backgrounds reduced by requiring no track around di-tau vertex and low acoplanarity A$= 1 - |\Delta\phi(\ell, \ell')|/\pi$.
- Corrections for track multiplicity from $\mu\mu$ CRs.

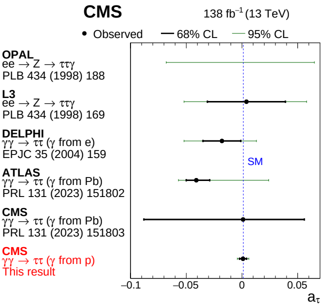


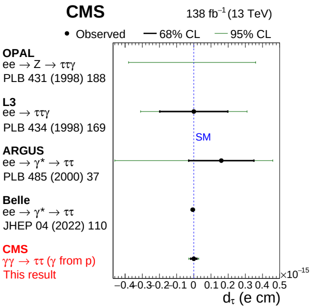


Extraction of the anomalous coupling $g_\tau - 2$

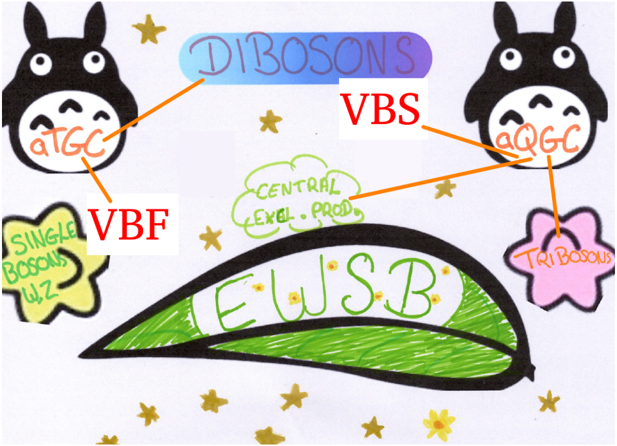
arXiv:2406.03975

- First-time observation in p-p collisions !
- Best-fit $\mu = 0.75^{+0.17}_{-0.14}$(syst)$\pm$0.11(stat).
- Observed significance: 5.3 (expected 6.5) s.d.
- Fiducial cross section (Ntracks=0): $\sigma^{\rm obs}_{\rm fid} = 12.4^{+3.8}_{-3.1}$ fb.
- Prediction from GAMMA-UPC elastic production, corrected for dissociative prod using data-CR: $\sigma^{\rm pred}_{\rm fid} = 16.5 \pm 1.5$ fb.



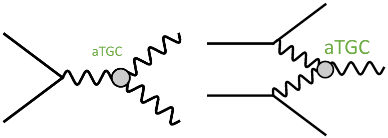


Outline



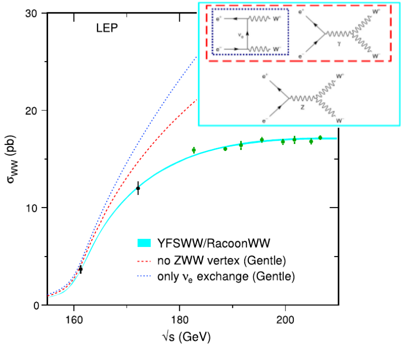
DIBOSONS
VBS
aTGC
aQGC
CENTRAL EXCL. PROD.
VBF
SINGLE BOSONS W,Z
EWSB
TRIBOSONS

Triple Gauge Couplings in the SM



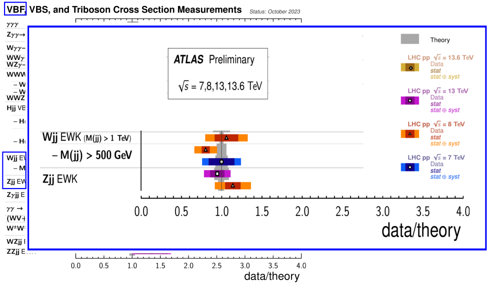
- Only charged TGC allowed in SM: $WW\gamma$ and WWZ.
- Fully determined by the structure of the EW sector of SM.
- Subtle cancellations involved $\Rightarrow$ extremely sensitive to new physics through anomalous couplings.
- Experimentally, %-level precision for VV with clean multi-lepton FS.
- Diboson production: state of the art MC predictions at NNLO in pQCD, with NLO EW corrections (MATRIX).

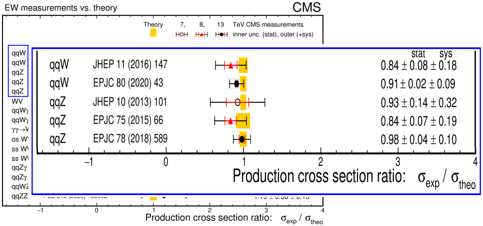
- First evidence from LEP data in WW production, confirmation of non-Abelian nature of EW sector of SM.

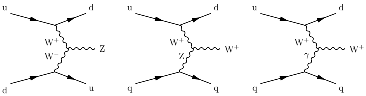


Physics Reports 532 (2013) 119

EW production of single bosons

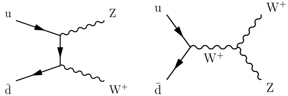


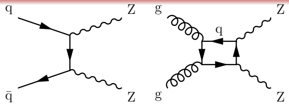




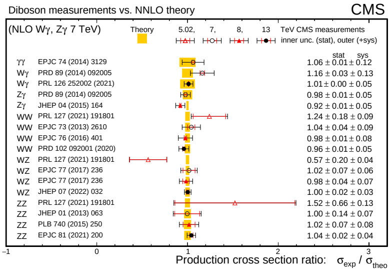
- Good Data/Theory consistency
- Already systematics limited.
- Measured to about 10% precision.
- With 13 TeV data, stat uncertainties $\simeq$ theory uncertainties !
- MC predictions still at LO.

Diboson production

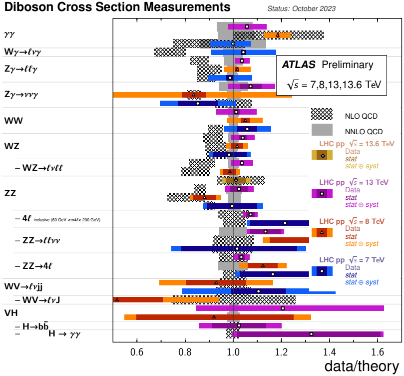




- All 13 TeV measurements: syst. dominated.
- Theory uncertainties $\simeq$ exp. uncertainties for WW,WZ and ZZ.
- Theory $>$ exp. for Wγ.



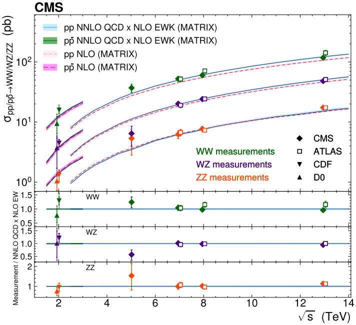
arXiv:2405.18661

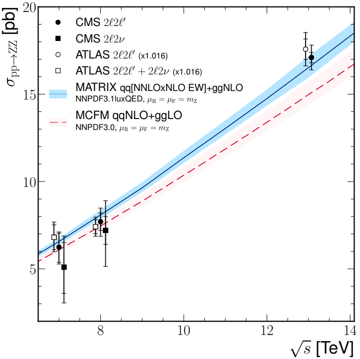


ATL-PHYS-PUB-2023-039

ATLAS/CMS comparison

arXiv:2405.18661



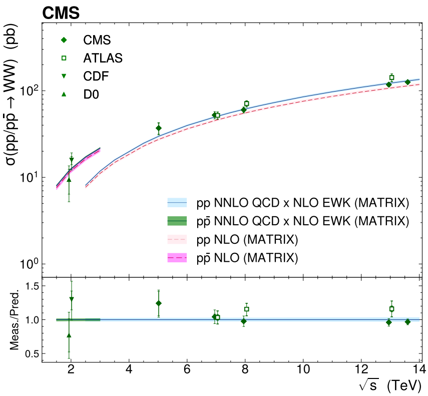


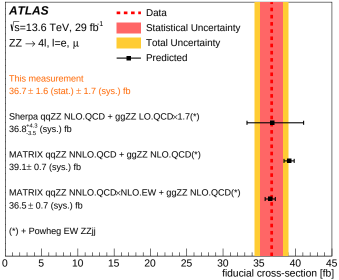
- Globally good agreement with MC predictions ⇒ NNLO (QCD) + NLO (EW) predictions necessary to match experimental precision!
- Already many new results out with full Run-2 dataset for both experiments.

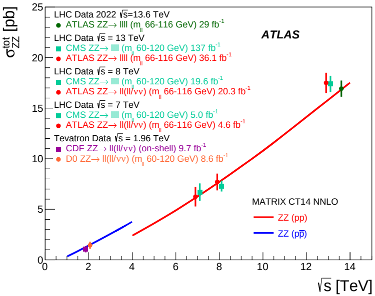
WW and ZZ at $\sqrt{s} = 13.6$ TeV

ATLAS ZZ: PLB 855 (2024) 138764

CMS WW: arXiv:2406.05101



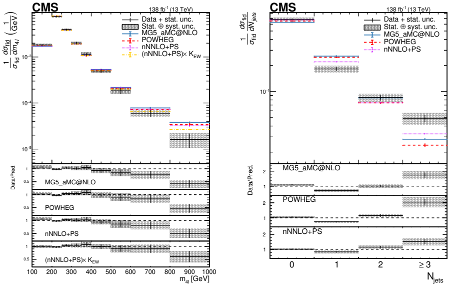




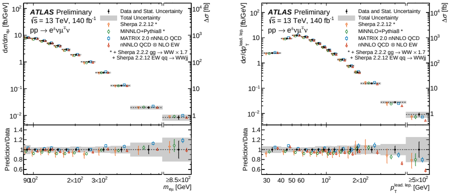
Differential cross sections at $\sqrt{s} = 13$ TeV

- Test of higher order corrections. For e.g. diboson invariant mass, large enhancement in XS from NNLO QCD correction, but reduction expected from NLO EW corrections.
- Higher-order QCD corrections needed to model jet multiplicity in ZZ events (CMS)
- Limitation of multiplicative EW correction, mixing mixed EW/QCD contributions, visible at high lepton pT in WW events (ATLAS).
- PDF choice important for the overall XS !

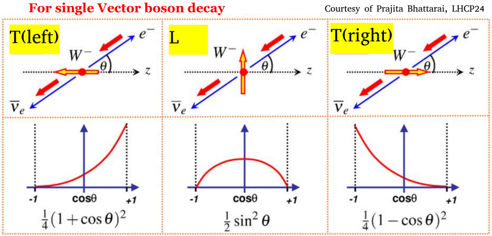
ZZ, arXiv:2404.02711



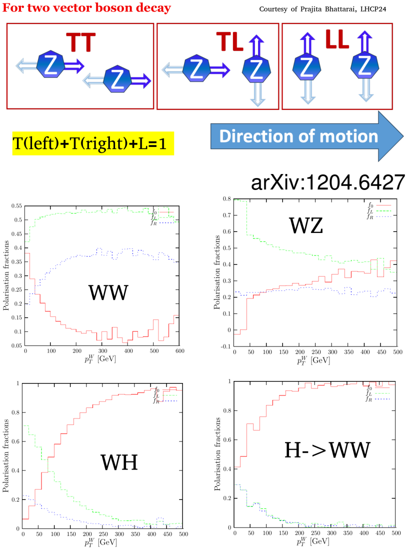
WW, ATLAS-CONF-23-012



Polarisation measurements in inclusive VV

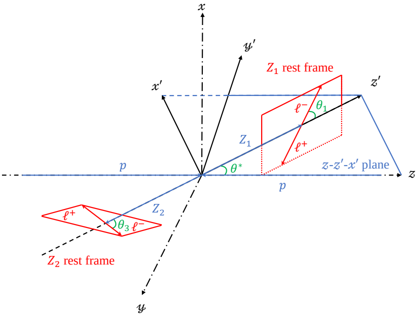


- V polarisation ⇒ underlying physics of the interaction + helicities of other particles.
- **Frame-dependent!** Measured via angular distributions of W/Z decay leptons.
- Fractions depend on $p_T^{V/VV}$.
- Fractions predicted by SM ⇒ New physics would change the picture!

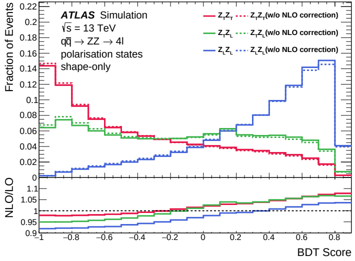


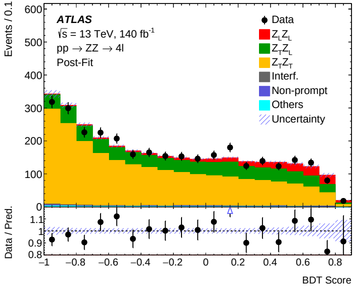
Evidence for $Z_L Z_L$ production

JHEP 12 (2023) 107



- ATLAS with 140 fb^{-1} 13 TeV data.
- $4\ell(\ell=$e,$\mu)$ from 2 on-shell Z: m$_{4\ell} > 180$ GeV, $|$m$_{\ell\ell}-$m$_Z| < 10$ GeV.
- BDT to enhance LL, using angular variables.
- Challenge! get higher-order QCD and EW corrections for polarisation templates.





Result for $Z_L Z_L$ production

JHEP 12 (2023) 107

- Profile likelihood fit to BDT discriminant.
- Extract signal strength and cross section: significance 4.3σ (exp 3.8σ).
- Prediction: NLO QCD $\times$ NLO EW $q\bar{q} \to ZZ$ + LO $gg \to ZZ$ [MoCaNLO] + LO EW $qq \to ZZ+2j$.

$$\mu_{LL} = 1.15 \pm 0.27(stat) \pm 0.11(syst) = 1.15 \pm 0.29$$

$$\mu_{LL}(exp) = 1.00 \pm 0.27$$

$$\sigma^{\text{obs}}_{Z_L Z_L} = 2.45 \pm 0.56(stat) \pm 0.21(syst)\ fb = 2.45 \pm 0.60\ fb$$

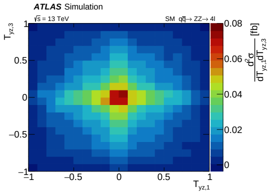
$$\sigma^{\text{pred}}_{Z_L Z_L} = 2.10 \pm 0.09\ fb$$

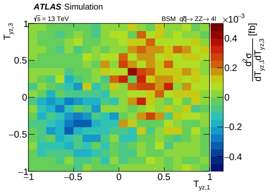
- Limited by data statistics.
- Leading systematics: theoretical modelling of the polarisation templates.
- Leading theoretical uncertainties on prediction: QCD scales and PDF.

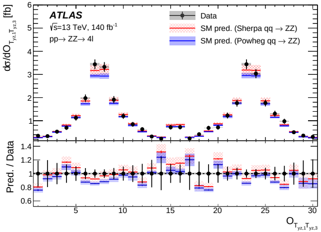
CP-sensitive observables in ZZ production

JHEP 12 (2023) 107

- Existing constraints on anomalous neutral TGC normally use high-pT observables ⇒ very strong constraints but insensitive to CP properties.
- Construct CP-sensitive observable $T_{yz,1(3)} = sin\phi_{1(3)} \times cos\theta_{1(3)}$.
- Symmetric for SM, asymmetric for CP-odd ANTGC.
- Construct 1-D map out of 2-D distribution.



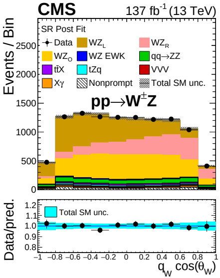


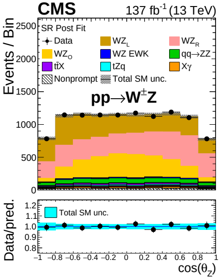


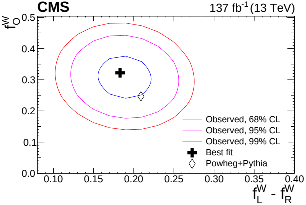
Polarisation fractions in WZ production

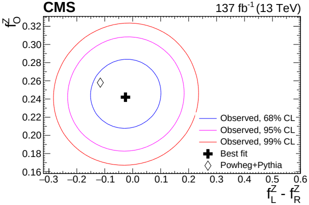
JHEP 07 (2022) 032

- 3-lepton decays, $m_{WZ} > 100$ GeV.
- Likelihood fit to $\cos(\theta_W)$ and $\cos(\theta_Z)$.
- Polarisation templates from MC: longitudinal "0", transverse "L"/"R".
- 3 params: total norm, f_0 and $f_{LR} = f_L - f_R$.
- $\Rightarrow$ Decorrelation between L and T components for both W and Z.
- Also first observation of W_L in WZ: significance 5.6σ (exp. 4.3σ). Significance for $Z_L >> 5\sigma$





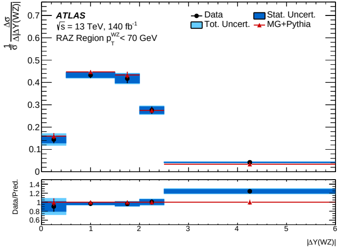


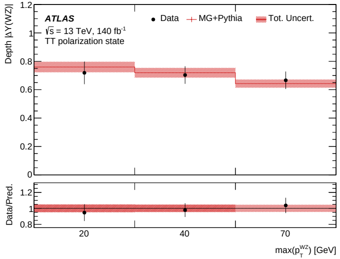


Radiation Amplitude Zero in WZ production

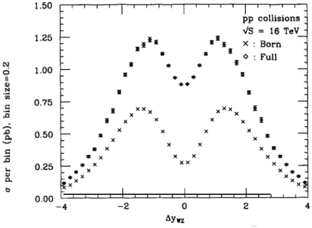
arXiv:2402.16365

- ATLAS full Run-2 data, 3-lepton decays
- AT LO: expect exact 0 yield for TT events with $\Delta Y(WZ) \simeq 0$.
- Effect enhanced for low jet activity $\Rightarrow$ select events at low p_T^{WZ}
- Bkg ($\simeq$ 10%) and 00+0T+T0 ($\simeq$ 27%) subtracted + unfolding.
- Good agreement with simulation!





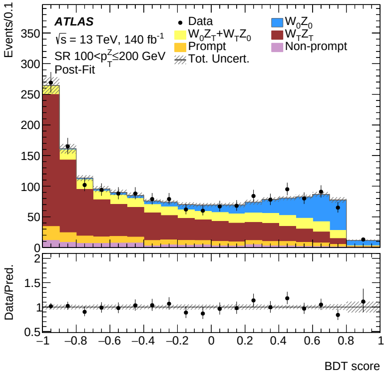
S. Frixione et al. / WZ production at hadron colliders



Longitudinal polarisation in WZ production

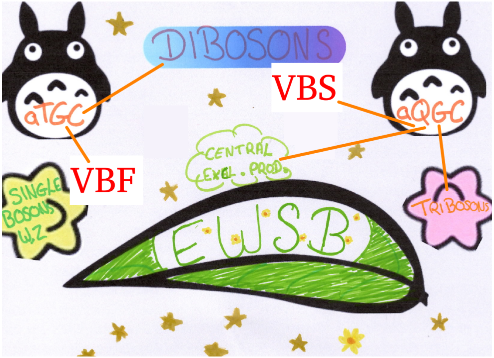
arXiv:2402.16365

- Enhance 00 contribution with high p_T^Z selection.
- BDT to separate 00 from TT+0T+T0.
- Likelihood fit of BDT discriminant ⇒ extract f_{00}, f_{0T+T0}, total norm.
- Pol. templates + predicted fractions: MADGRAPH_aMC@NLO WZ+0j,WZ+1j at LO + higher-order QCD corrections (from data) + NLO EW corrections.



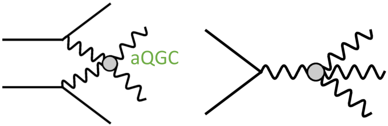
	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

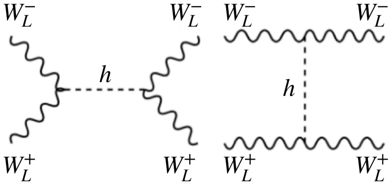
Outline



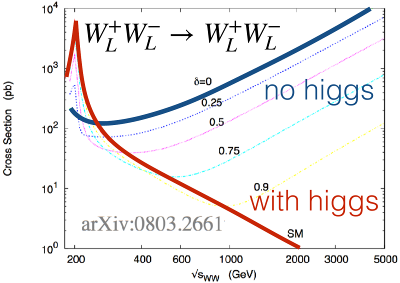
DIBOSONS
VBS
aTGC
aQGC
VBF
CENTRAL EXCL. PROD.
SINGLE BOSONS W,Z
TRIBOSONS
EWSB

Quartic Gauge Couplings

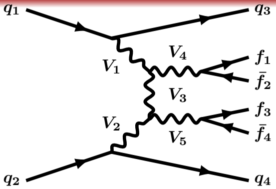




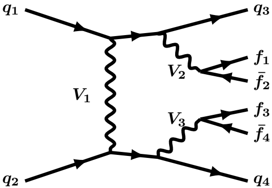
- Allowed in SM: WWWW, WWZZ, WWZγ, WW$\gamma\gamma$.
- VBS/Tribosons: rare processes, again crucial to test EWSB.
- VV to VV scattering: separating longitudinal polarisation of V and measure vs m_{VV} $\Rightarrow$ unique measurement of HVV coupling.



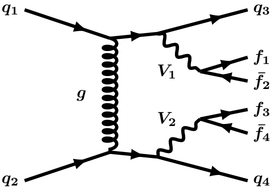
Characteristics of the VBS production



- Final state with 2 jets: specific topology with large m_{jj} ($\geq$ 500 GeV) and large $\Delta\eta_{jj}$ ($\geq$ 2).

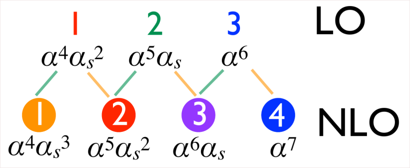


- Background from non-VBS but O(α^6) part of the signal.



- Background from O($\alpha^4\alpha_s^2$) and interference O($\alpha^5\alpha_s$).

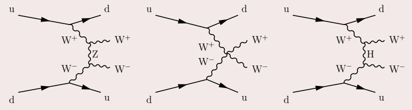
Mixing between QCD and EW corrections

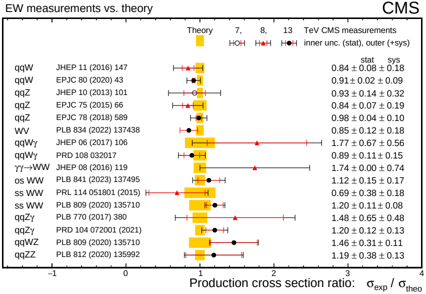


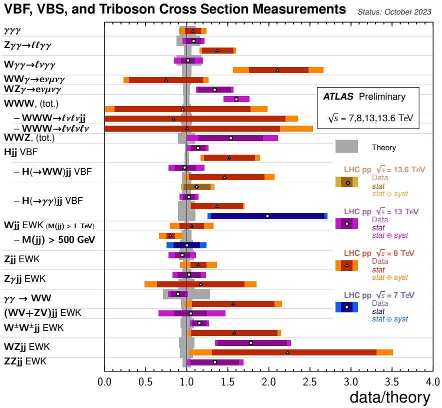
- NLO EW for strong production ⇔ NLO QCD for interference
- NLO EW for interference ⇔ NLO QCD for EW production
- Complication for MC event generators !
- VBS approximation: unique assignement as "EW" or "QCD" corrections.

Overview of LHC results

The VBS topology



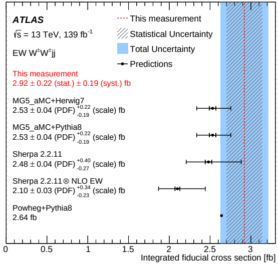


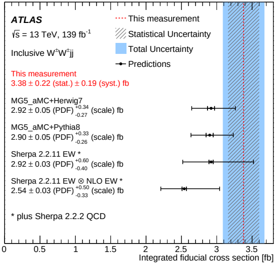


Golden channel: $W^{\pm}W^{\pm}$+2j

ATLAS 139 fb^{-1} JHEP 04 (2024) 026

- Best EW/strong production ratio, $\simeq$ 5 in fiducial area.
- Main background: WZ+2j $\Rightarrow$ can measure both processes together, CMS strategy in [PLB 809 (2020) 135710]
- Extract inclusive and differential XS.





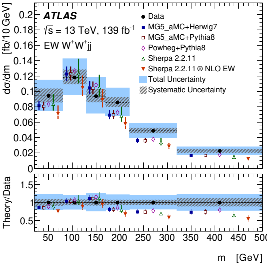
Source	Impact [%]
Experimental	4.6
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.9
E_T^{miss} scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.4
Background, charge misrec.	1.0
Pile-up modelling	0.1
Luminosity	1.9
Modelling	4.5
EW $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.7
EW $W^{\pm}W^{\pm}jj$, QCD corrections	1.9
EW $W^{\pm}W^{\pm}jj$, EW corrections	0.9
Int $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	0.6
QCD $W^{\pm}W^{\pm}jj$, shower, scale, PDF & α_s	2.6
QCD $W^{\pm}W^{\pm}jj$, QCD corrections	0.8
Background, WZ scale, PDF & α_s	0.3
Background, WZ reweighting	1.5
Background, other	1.3
Model statistical	1.8
Experimental and modelling	6.4
Data statistical	7.4
Total	9.8

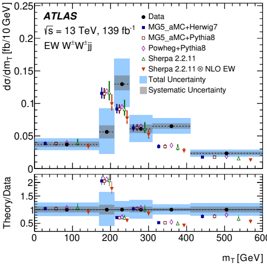
Differential cross sections for $W^{\pm}W^{\pm}$+2j

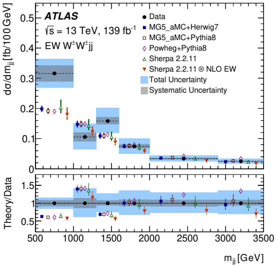
JHEP 04 (2024) 026

Variable	EW $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	EW $W^{\pm}W^{\pm}jj$ p-value	Inclusive $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	Inclusive $W^{\pm}W^{\pm}jj$ p-value	Max. value in data
$m_{\ell\ell}$	4.5/6	0.605	7.34/6	0.291	1081 GeV
m_{T}	13.0/6	0.043	16.33/6	0.012	1270 GeV
m_{jj}	7.6/6	0.266	8.67/6	0.193	6328 GeV
$N_{\text{gap jets}}$	2.5/2	0.282	2.53/2	0.282	5
ξ_{j_3}	4.2/5	0.517	4.93/5	0.424	1.74

- Some discrepancy with MC: underestimates the data, generally.
- Statistically limited.







- Corresponding CMS results: 137 fb^{-1}: PLB 809 (2020) 135710

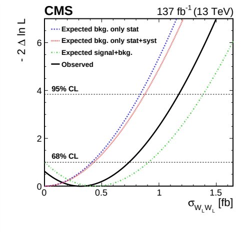
Other measurements with $W^{\pm}W^{\pm}$+2j

Phys. Lett. B 812 (2020) 136018, 137 fb^{-1}

CMS-PAS-SMP-22-008, 137 fb^{-1}

CMS: polarisation fractions

- Measure independently $W^{\pm}_{L}W^{\pm}_{L}$ vs $W^{\pm}_{X}W^{\pm}_{T}$ and $W^{\pm}_{T}W^{\pm}_{T}$ vs $W^{\pm}_{X}W^{\pm}_{L}$ with BDT.
- 2 ref. frames: $W^{\pm}W^{\pm}$ and parton-parton c.o.m.

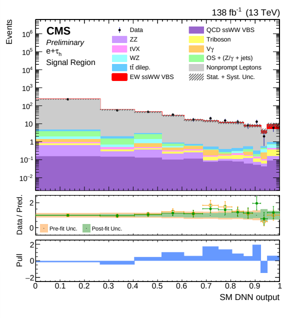


Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_{X}W^{\pm}_{T}$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$ 2.3 s.d.	1.63 ± 0.18 3.1 s.d.
$W^{\pm}_{T}W^{\pm}_{T}$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

CMS: final state with a τ lepton

- Extend sensitivity to BSM.
- DNN to enhance signal.
- Stat. limited.

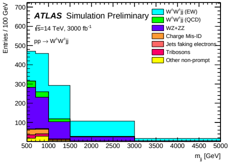
	Observed	Expected
EW μ	$1.44^{+0.63}_{-0.56}$	$1.00^{+0.60}_{-0.53}$
Signif.	2.7σ	1.9σ

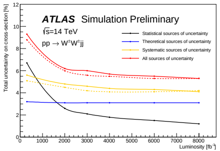


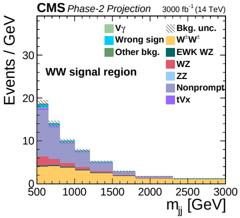
Prospects for $W^{\pm}W^{\pm}$ at HL-LHC

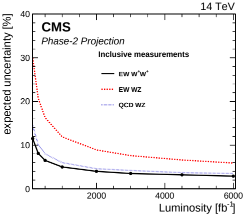
ATLAS: ATL-PHYS-PUB-2018-052 CMS: FTR-21-001

- Flagship channel for HL-LHC physics program.
- Using 3000 fb^{-1}, 3 leptons (e,μ) + 2j $m_{jj} > 500$ GeV
- ATLAS: extended lepton acceptance to $|\eta| < 4$. CMS: same as Run 2.









	Run-2	HL-LHC
ATLAS	10% (stat 8%)	6% (stat 2%)
CMS	11% (stat 9%)	3% (stat 2%)

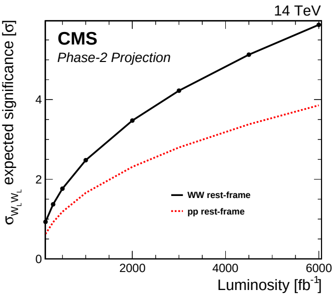
Source	Uncertainty (%) Baseline	Uncertainty (%) Optimistic
$W^{\pm}W^{\pm}jj$ (EW)	3	
Luminosity	1	
Trigger efficiency	0.5	
Lepton reconstruction and identification	1.8	
Jets	2.3	
Flavour tagging	1.8	
Jets faking electrons	20	
Charge mis-ID	25	
$W^{\pm}W^{\pm}jj$ (QCD)	20	5
Top	15	10
Diboson	10	5
Triboson	15	10

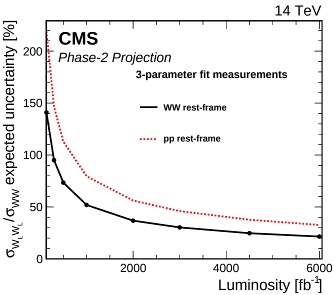
Source of uncertainty	EW $W^{\pm}W^{\pm}$	EW WZ	QCD WZ
Integrated luminosity	1.1	1.0	1.0
Lepton measurement	1.1	1.5	1.5
Jet energy scale and resolution	0.3	2.0	0.4
Pileup	0.1	0.5	0.3
b tagging	1.2	1.2	1.2
Limited sample size	0.8	1.0	0.5
Nonprompt lepton rate	1.2	1.7	1.3
Theory	1.7	2.6	1.4
Total systematic uncertainty	3.0	4.4	3.0
Statistical uncertainty	1.8	6.1	2.8
Total uncertainty	3.5	7.6	4.2

Prospects for $W^{\pm}_{L}W^{\pm}_{L}$ at HL-LHC

- CMS selection using BDTs (Run 2 strategy).

CMS: FTR-21-001



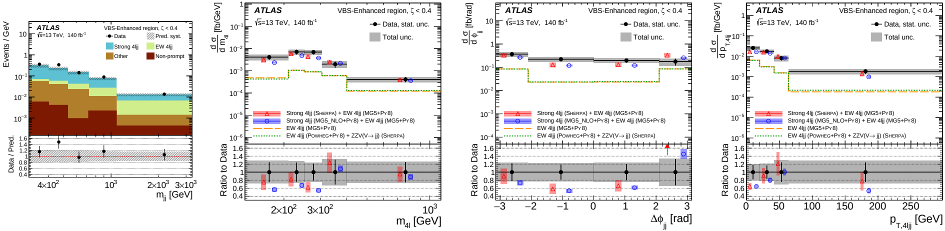


- Expected significance @ 3 ab^{-1}: 4σ.
- Expected precision: 30%.

EW production of ZZ(4ℓ)+2j

ATLAS: JHEP 01 (2024) 004

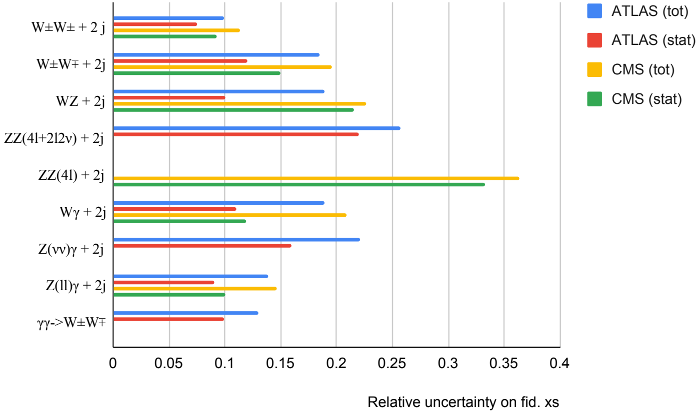
- 140 fb^{-1}, 4ℓ (e,μ) + 2j with $m_{jj} > 300$ GeV, $\Delta y_{jj} > 2.0$.
- First observation in N.P. 19 (2023) 237 (ATLAS, 5.7σ, 26% precision) and evidence in PLB 812 (2020) 135992 (CMS, 4σ, 36% precision)
- New! Differential xs with 3 types of observables: VBS, polarisation+CP prop., QCD-sensitive.
- Cut on centrality $\zeta = \left|\frac{[y_{4\ell} - 0.5(y_{j1}+y_{j2})]}{\Delta y_{jj}}\right| < 0.4$ (> 0.4) to enhance (suppress) EW contribution.
- Better agreement for SHERPA (larger theory unc.) over MG5_NLO+Py8.
- At HL-LHC, expect 10% precision on cross section with 3 ab^{-1}.



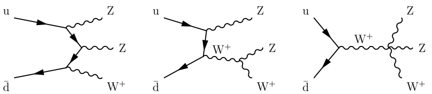
Other VBS results with full run-2 dataset

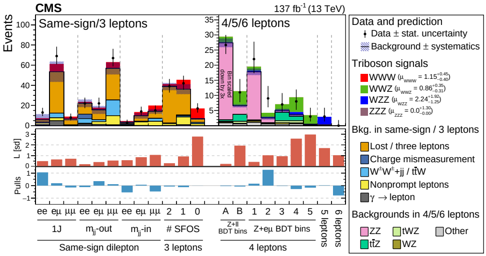
Channel	Final state	ATLAS	CMS
WZ+2j	3ℓ (e,μ)	arXiv:2403.15296	PLB 809 (2020) 135710
W^+W^-+2j	e+μ	arXiv:2403.04869	PLB 841 (2023) 137495
Wγ+2j	W$\rightarrow$ e, mu	arXiv:2403.02809	PRD 108 (2023) 032017
Zγ+2j	Z$\rightarrow$ $\nu\nu$	EPJC 82 (2022) 105	-
Zγ+2j	Z$\rightarrow$ $\ell\ell$ (e,μ)	PLB 846 (2023) 138222	PRD 104 (2021) 072001

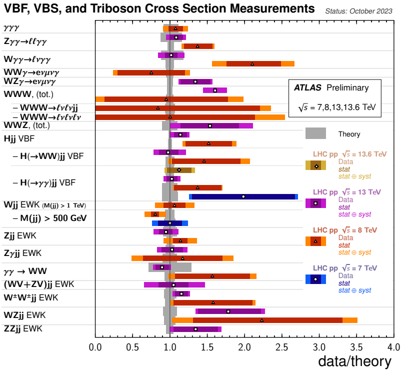
$\Rightarrow$ See backup slides for details on a selection.



Overview of LHC tribosons results







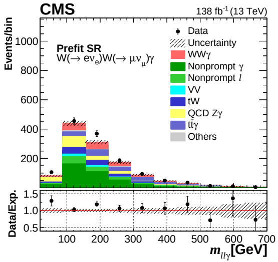
First observation of WWγ in p-p collisions

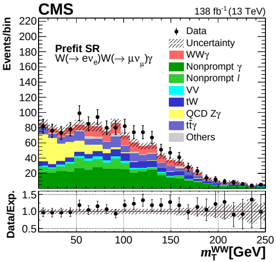
PRL 132 (2024) 121901

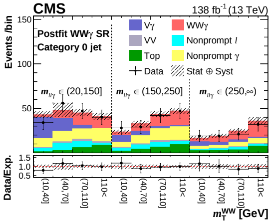
- 138 fb^{-1}, e$\mu\gamma$+MET, likelihood fit in 2D m_T^{WW} and $m_{\ell\ell\gamma}$.
- Signal modelled at NLO QCD with MADGRAPH_aMC@NLO.
- Enhance sensitivity with 2 categories: 0 and ≥ 1 jet.
- Observed (expected) significance of 5.6 (4.7) σ.

$$\sigma_{obs} = 5.9 \pm 0.8(\text{stat}) \pm 0.8(\text{syst}) \pm 0.7(\text{modeling})\ \text{fb}$$

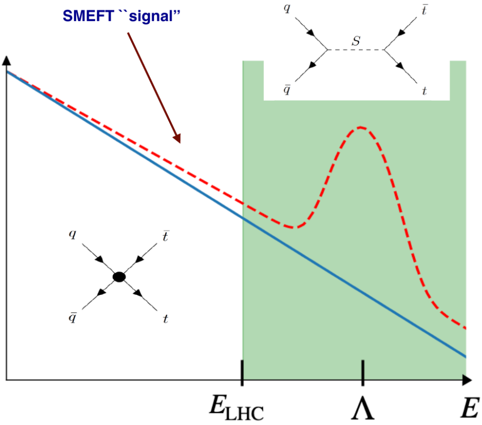
$$\sigma_{theo} = 5.33 \pm 0.34(\text{scale}) \pm 0.05(\text{PDF})\ \text{fb}$$







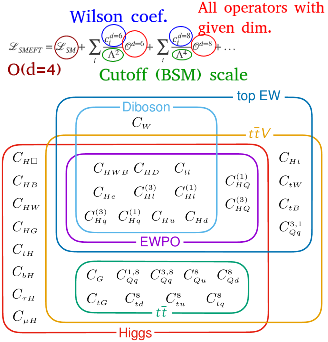
Outline



J. Rojo, LHCP2024

LHC results and global fit

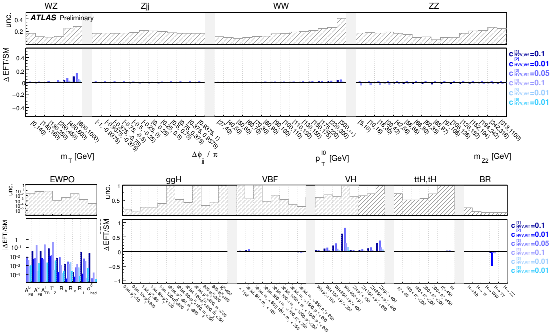
- Many new results from ATLAS and CMS with limits on anomalous SMEFT dim-6 and dim-8 operators with full run-2 dataset ⇒ See backup slides for a selection.
- Many differential cross sections available to improve sensitivity.
- One observable ⇒ several contributing operators
- One operator ⇒ affects several observables.
- Ultimately ⇒ global analysis, efforts already ongoing.



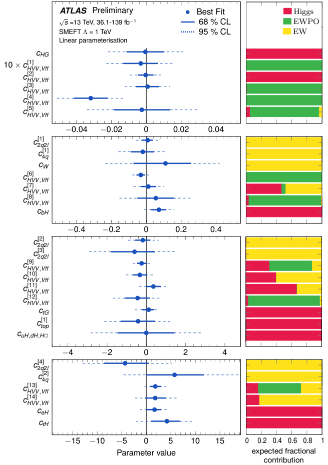
arXiv:2012.02779

First global fit by ATLAS

- Includes also LEP EW Precision Observables.
- New VBS results with full run-2 to be added / similar effort from CMS ongoing !



ATL-PHYS-PUB-2022-037

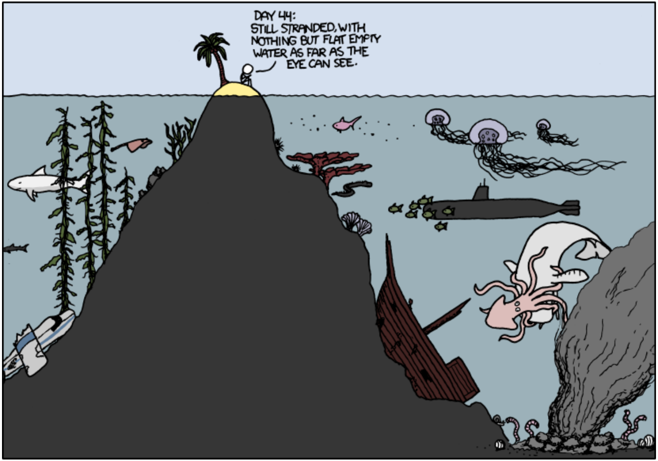


Conclusion

- Reaching precision era for SM parameters, even at hadron collider !
- Precision measurements are already limited by PDF uncertainties.
- %-level predictions on VV production and high statistics: can measure differentially.
- VBS processes now measured at both ATLAS and CMS with $\mathcal{O}(10\%)$ precision for golden same-sign WW production and exclusive production, 20% for others.
- Many new results with first polarisation measurements in inclusive ZZ, WZ and $W^{\pm}W^{\pm}$+2j productions.

- First differential distributions for VBS processes!
- Many new constraints on EFT parameters $\Rightarrow$ experimental/theory collaboration for global fits.
- HL-LHC expected to reach 3-10%-level precision on golden VBS channels.
- Adding a "boost" factor, $W_L^{\pm}W_L^{\pm}$ should be observed at HL-LHC.
- More work needed on reducing theory modelling uncertainties, and analysing ALL LHC data available !

Thank you for your attention



Backups

BACKUPS

Systematic uncertainties in W and Z measurement

PLB 854 (2024) 13872,
$\sqrt{s} = 13.6$ TeV, $\mathcal{L} = 29$ fb^{-1}.

Category	$\sigma(Z \to ee)$	$\sigma(Z \to \mu\mu)$	$\sigma(Z \to \ell\ell)$	$\sigma(W^- \to e^-\bar{\nu})$	$\sigma(W^+ \to e^+\nu)$	$\sigma(W^- \to \mu^-\bar{\nu})$	$\sigma(W^+ \to \mu^+\nu)$
Luminosity	2.2	2.2	2.2	2.5	2.5	2.5	2.4
Pile-up	1.2	0.3	0.8	1.1	1.1	0.3	0.4
MC statistics	< 0.2	< 0.2	< 0.2	< 0.2	0.4	< 0.2	0.4
Lepton trigger	0.2	0.4	0.2	1.2	1.3	1.0	1.0
Electron reconstruction	1.4	–	0.9	0.7	0.8	–	–
Muon reconstruction	–	2.1	1.4	–	–	1.0	1.0
Multi-jet	–	–	–	2.9	2.4	1.3	1.1
Other background modelling	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.5	0.4
Jet energy scale	–	–	–	1.4	1.4	1.3	1.4
Jet energy resolution	–	–	–	< 0.2	0.3	0.2	0.2
NNJVT	–	–	–	1.6	1.5	1.3	1.3
E_T^{miss} track soft term	–	–	–	< 0.2	0.4	< 0.2	< 0.2
PDF	0.2	0.2	< 0.2	0.8	0.8	0.6	0.5
QCD scale (ME and PS)	0.6	< 0.2	0.3	1.3	1.2	0.6	0.6
Flavour tagging	–	–	–	–	–	–	–
$t\bar{t}$ modelling	–	–	–	–	–	–	–
Total systematic impact [%]	3.0	3.1	2.7	5.0	4.5	3.8	3.6
Statistical impact [%]	0.04	0.03	0.02	0.02	0.01	0.01	0.01

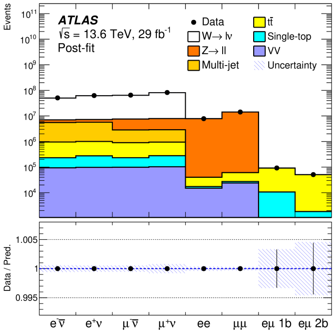
Category	$\sigma(W^- \to \ell^-\bar{\nu})$	$\sigma(W^+ \to \ell^+\nu)$	$\sigma(W^\pm \to \ell\nu)$	R_{W^+/W^-}	$R_{W^\pm/Z}$	$R_{t\bar{t}/W^\pm}$
Luminosity	2.5	2.4	2.4	< 0.2	0.3	< 0.2
Pile-up	0.5	0.7	0.6	< 0.2	< 0.2	< 0.2
MC statistics	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
Lepton trigger	1.0	0.9	0.9	< 0.2	0.7	0.8
Electron reconstruction	0.4	0.5	0.4	< 0.2	0.5	0.4
Muon reconstruction	0.6	0.6	0.6	0.2	0.8	0.6
Multi-jet	1.2	1.2	1.2	1.6	1.1	1.0
Other background modelling	0.4	0.4	0.4	< 0.2	0.3	0.9
Jet energy scale	1.3	1.3	1.3	< 0.2	1.3	1.3
Jet energy resolution	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
NNJVT	1.4	1.3	1.3	< 0.2	1.3	< 0.2
E_T^{miss} track soft term	< 0.2	0.3	0.3	< 0.2	0.3	0.3
PDF	0.5	0.5	0.3	0.5	0.2	0.4
QCD scale (ME and PS)	0.8	0.7	0.6	< 0.2	0.7	0.7
Flavour tagging	–	–	–	–	–	< 0.2
$t\bar{t}$ modelling	–	–	–	–	–	1.1
Total systematic impact [%]	3.7	3.5	3.5	1.7	2.4	2.5
Statistical impact [%]	0.01	0.01	0.01	0.01	0.02	0.32

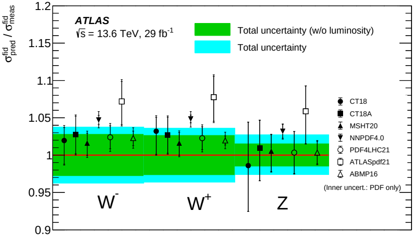
CMS-PAS-SMP-22-017,
$\sqrt{s} = 13.6$ TeV, $\mathcal{L} = 5.04$ fb^{-1}.

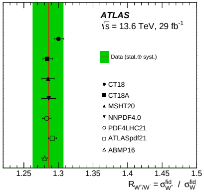
Source	Uncertainty (%)
Muon efficiencies	0.83
PDF, QCD scale and parton shower	0.53
Finite size of MC samples (bin-by-bin)	0.35
$t\bar{t}$ background	0.16
EWK background	0.12
Pileup	0.08
Muon momentum correction	0.08
Combined syst. uncertainty	0.92
Luminosity	2.3
Stat. uncertainty	0.06

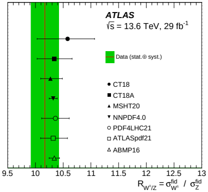
W and Z at $\sqrt{s} = 13.6$ TeV with ATLAS

PLB 854 (2024) 13872









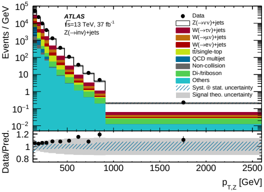
Electron selections	$p_T > 27$ GeV $\lvert\eta\rvert < 2.47$ and veto of $1.37 < \lvert\eta\rvert < 1.52$
Muon selections	$p_T > 27$ GeV $\lvert\eta\rvert < 2.5$
W-boson selections	Exactly one lepton $E_T^{miss} > 25$ GeV $m_T > 50$ GeV
Z-boson selections	Exactly two same flavour opposite charged leptons $66 < m_{\ell\ell} < 116$ GeV

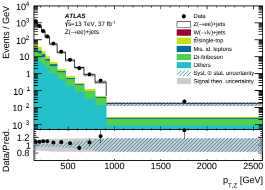
$\gamma\gamma \to \tau\tau$ systematic uncertainties and fiducial cuts

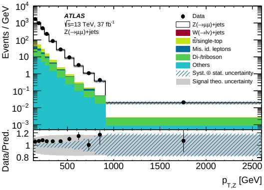
	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
p_T^e (GeV)	$> 15/24$	> 25	—	—
$\|\eta^e\|$	< 2.5	< 2.5	—	—
p_T^μ (GeV)	$> 24/15$	—	> 21	—
$\|\eta^\mu\|$	< 2.4	—	< 2.4	—
$p_T^{\tau_h}$ (GeV)	—	> 30	> 30	> 40
$\|\eta^{\tau_h}\|$	—	< 2.3	< 2.3	< 2.3
$\Delta R(\ell, \ell')$	> 0.5	> 0.5	> 0.5	> 0.5
$m_T(e/\mu, \vec{p}_T^{miss})$ [GeV]	—	< 75	< 75	—
A	< 0.015	< 0.015	< 0.015	< 0.015
m_{vis} (GeV)	< 500	< 500	< 500	< 500
N_{tracks}	0	0	0	0

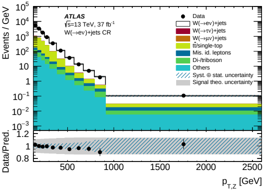
Uncertainty	Process	Magnitude
Luminosity	All simulations	1.6%
DY cross section	DY	2%
Inclusive diboson cross section	WW, WZ, ZZ	5%
e ID, iso, trigger	All simulations	up to 2%
e ID low-N_{tracks} correction	All simulations	1%
μ ID, iso, trigger	All simulations	<2%
τ_h ID	All simulations	1–5%
τ_h trigger	All simulations	up to 5%
$e \to \tau_h$ mis-ID	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	<10%
$\mu \to \tau_h$ ID	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	<10%
τ_h energy scale	All simulations	<1.2%
$e \to \tau_h$ energy scale	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	<5%
$\mu \to \tau_h$ energy scale	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	<1%
τ_h ID low-N_{tracks} correction	All simulations	2.1%
e ID low-N_{tracks} correction	All simulations	2.0%
$e \to \tau_h$ ID low-N_{tracks} correction	$Z/\gamma* \to ee$ and $\gamma\gamma \to ee$	22%
$\mu \to \tau_h$ ID low-N_{tracks} correction	$Z/\gamma* \to \mu\mu$ and $\gamma\gamma \to \mu\mu$	15%
N_{tracks}^{PU} reweighting	All simulations	2%
N_{tracks}^{HS} reweighting	DY and inclusive VV	1.5–6.5%
Acoplanarity correction	DY	5%
DY extrapolation from $N_{tracks} < 10$	DY simulation	1.4–2.0%
μ_R, μ_f	DY simulation	Shape
PDF	DY simulation	Shape
jet→ τ_h MF, extrapolation with $p_T^{\tau_h}$	jet→ τ_h mis-ID bkg.	<50%
jet→ τ_h MF, N_{tracks} extrapolation (stat.)	jet→ τ_h mis-ID bkg.	6–18%
jet→ τ_h MF, inversion of CR selection	jet→ τ_h mis-ID bkg.	<10%
jet→ τ_h MF, x^{QCD} fraction	jet→ τ_h mis-ID bkg.	9%
jet→ τ_h MF, N_{tracks} extrapolation (syst.)	jet→ τ_h mis-ID bkg.	<10%
jet→ e/μ OS-to-SS (stat.)	jet→ e/μ mis-ID bkg.	<20%
jet→ e/μ OS-to-SS (syst.)	jet→ e/μ mis-ID bkg.	10%
jet→ e/μ OS-to-SS N_{tracks} extrapolation	jet→ e/μ mis-ID bkg.	8%
Elastic rescaling (stat.)	$\gamma\gamma \to \tau\tau/\mu\mu$/ee, WW	1.3–3.7%
Elastic rescaling (syst., shape)	$\gamma\gamma \to \tau\tau/\mu\mu$/ee, WW	Mass-dependent
Limited statistics	All processes	Bin-dependent
Pileup reweighting	All simulations	Event-dependent

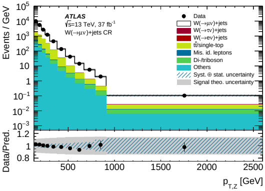
Z boson invisible width: backgrounds



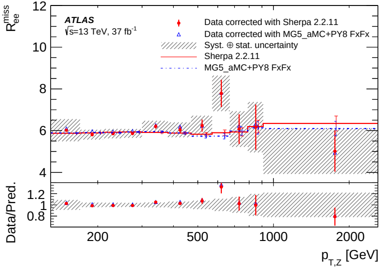


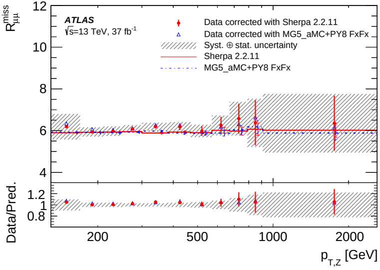


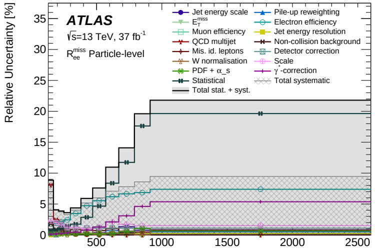


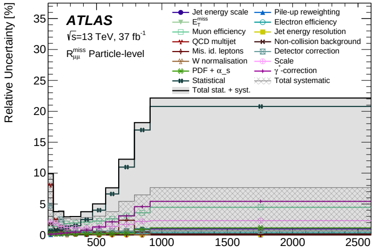


Z boson invisible width: ratio





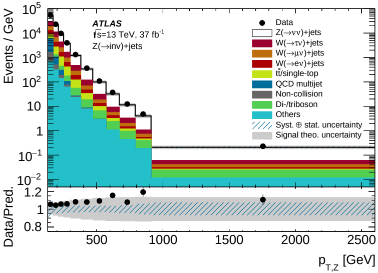


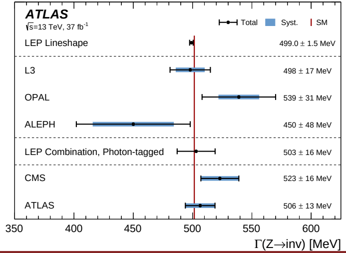


Invisible Z width

PLB 854 (2024) 138705

- Important test of the SM related to number of ν.
- Very precise prediction from SM, $\Gamma(Z \to \text{inv}) = 501.445 \pm 0.047\,\text{MeV}$ [PDG2022]$\Rightarrow$ sensitivity to new physics.
- Using ratio of invisible to (ee,$\mu\mu$) decays corrected to common phase-space: dominant syst. uncertainties cancel.
- Z+jets generated with SHERPA2.2.11 at NLO (up to 2 partons)+LO (up to 5 partons), and also MG5_aMC@NLO at NLO (up to 3 partons).
- Selection: $p_{T,Z} > 130$ GeV and ≥ 1 jet with $p_T > 110$ GeV and $|\eta| < 2.4$, $\Delta\phi(\text{jet},p_{T,Z}) > 0.4$
- Binning in $p_{T,Z}$ ($\Leftrightarrow$ recoil).





Z invisible width: systematic uncertainties

ATLAS 37 fb^{-1}, PLB 854 (2024) 138705

Systematic Uncertainty	Impact on $\Gamma(Z \to \text{inv})$ in [MeV]	in [%]
Muon efficiency	7.4	1.5
Renormalisation & factorisation scales	5.9	1.2
Electron efficiency	4.9	1.0
Detector correction	4.4	0.9
QCD multijet	3.2	0.6
E_T^{miss}	2.4	0.5
$Z(\to \mu\mu)$+jets misid. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\to \ell\nu)$+jets normalisation	1.5	0.3
Pile-up reweighting	1.5	0.3
Non-collision background estimate	1.3	0.3
Jet energy scale	1.3	0.3
γ^*-correction	1.0	0.2
$Z(\to ee)$+jets misid. lepton estimate	1.0	0.2
Luminosity	1.0	0.2
Parton distribution functions + α_s	0.7	0.1
$\Gamma(Z \to \ell\ell)$	0.5	0.1
Tau energy scale	0.4	0.1
Muon momentum scale	0.3	0.1
$W(\to \ell\nu)$+jets misid. lepton estimate	0.3	0.1
(Forward) jet vertex tagging	0.2	< 0.1
Top subtraction scheme	0.2	< 0.1
Electron energy scale	0.1	< 0.1
Systematic	12	2.4
Statistical	2	0.4
Total	13	2.5

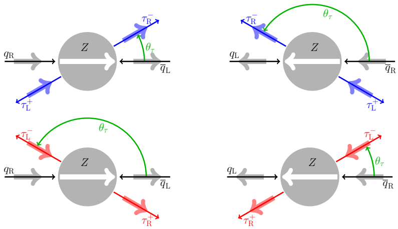
CMS 36.3 fb^{-1}, Phys. Lett. B 842 (2023) 137563

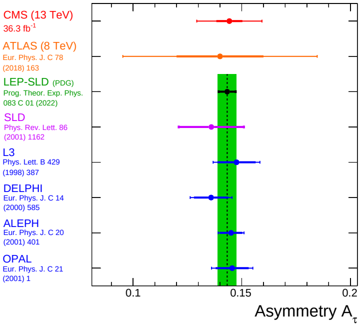
Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0
Electron trigger efficiency	0.7
τ_h veto efficiency	0.6–0.7
p_T^{miss} trigger efficiency (jets plus p_T^{miss} region)	0.7
p_T^{miss} trigger efficiency ($Z/\gamma^* \to \mu\mu$ region)	0.6
Boson p_T dependence of QCD corrections	0.5
Jet energy resolution	0.3–0.5
p_T^{miss} trigger efficiency (μ+jets region)	0.4
Muon identification efficiency (stat.)	0.3
Electron reconstruction efficiency (syst.)	0.3
Boson p_T dependence of EW corrections	0.3
PDFs	0.2
Renormalization/factorization scale	0.2
Electron reconstruction efficiency (stat.)	0.2
Overall	3.2

- QCD scale uncertainty much reduced by CMS global simultaneous fit strategy.
- CMS selects $p_{T,Z} > 200$ GeV.
- Overall lower exp. syst in ATLAS.

Tau polarisation in Z$\rightarrow \tau\tau$ decays

JHEP 01 (2024) 101





- CMS 35.9 fb^{-1} 2016 dataset.
- Most precise measurement at hadron colliders !
- Precision comparable to SLD.

MC for dibosons results

arXiv:2405.18661

Process	$\sqrt{s}$ (TeV)	Theory calculation	Other results
Wγ [285]	13	MG5_aMC 1p NLO	aTGC
W$^\pm$W$^\mp$ [289]	13	MATRIX	aTGC, σ: with jet veto
WZ [290]	13	MATRIX	aTGC, boson polarization, 9 dist.
ZZ [292]	13	MATRIX	aTGC, 6 dist.
EW W$^\pm$W$^\mp$,WZ [329]	13	MG5_aMC Py8 LO	aQGC
$\gamma\gamma \to$ W$^\pm$W$^\pm$ [330]	13	MADGRAPH 5 LO rescaled	aQGC
EW Wγ [311]	13	MG5_aMC Py8 LO	aQGC, m_{jj}, 6 dist.
EW Zγ [312]	13	MG5_aMC Py8 LO	aQGC, $m_{jj}x\Delta\eta(jj)$ + 3 1D dist.
EW W$^\pm$ W$^\pm$ [334]	13	MG5_aMC Py8 corr NLO QCD and EW [335,336]	aQGC, m_{jj}, 3 dist.
EW W$^+$ W$^-$ [337]	13	MG5_aMC Py8 LO	—
EW WZ [338]	13	MG5_aMC Py8 corr NLO QCD and EW [339]	aQGC, m_{jj}
EW ZZ [277]	13	POWHEG BPX NLO [340]	aQGC

Diboson State	N_{jets}	$\sqrt{s}$ (TeV)	Generator	Partons total	Partons NLO	PS	ME-PS scheme
Wγ [311]	2	13	MG5_aMC (NLO)	2	1	Py8	FxFx
Zγ [312]	2	13	MG5_aMC (NL0)	2	1	Py8	FxFx
W$^+$W$^-$ [289]	0–2	13	(POWHEG (NLO) + MCFM (LO)) * K_{NNLO} [314]	1	0	Py8	—

JHEP 04 (2024) 026

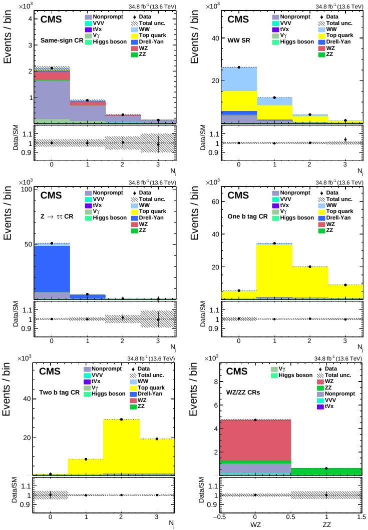
Process, short description	ME Generator + parton shower	Order	Tune	PDF set in ME
EW, Int, QCD $W^\pm W^\pm jj$, nominal signal	MadGraph5_aMC@NLO2.6.7 + Herwig7.2	LO	Herwig	NNPDF3.0nlo
EW, Int, QCD $W^\pm W^\pm jj$, alternative shower	MadGraph5_aMC@NLO2.6.7 + Pythia8.244	LO	A14	NNPDF3.0nlo
EW $W^\pm W^\pm jj$, NLO pQCD approx.	Sherpa2.2.11 & Sherpa2.2.2(WWW) & Powheg Box2+Pythia8.235 (WH)	+0,1j@LO NLO	Sherpa A14	NNPDF3.0nnlo
EW $W^\pm W^\pm jj$, NLO pQCD approx.	Powheg Boxv2 + Pythia8.230	NLO (VBS approx.)	AZNLO	NNPDF3.0nlo
QCD $W^\pm W^\pm jj$, NLO pQCD approx.	Sherpa2.2.2	+0,1j@LO	Sherpa	NNPDF3.0nnlo
QCD $VVjj$	Sherpa2.2.2	+0,1j@NLO; +2,3j@LO	Sherpa	NNPDF3.0nnlo
EW $W^\pm Z/\gamma^* jj$	MadGraph5_aMC@NLO2.6.2+Pythia8.235	LO	A14	NNPDF3.0nlo
EW $Z/\gamma^* Z/\gamma^* jj$	Sherpa2.2.2	LO	Sherpa	NNPDF3.0nnlo
QCD $V\gamma jj$	Sherpa2.2.11	+0,1j@NLO; +2,3j@LO	A14	NNPDF3.0nnlo
EW $V\gamma jj$	MadGraph5_aMC@NLO2.6.5+Pythia8.240	LO	A14	NNPDF3.0nlo
VVV	Sherpa2.2.1 (leptonic) & Sherpa2.2.2 (one $V \to jj$)	+0,1j@LO	Sherpa	NNPDF3.0nnlo
$t\bar{t}V$	MadGraph5_aMC@NLO2.3.3.p0 + Pythia8.210	NLO	A14	NNPDF3.0nlo
tZq	MadGraph5_aMC@NLO2.3.3.p1 + Pythia8.212	LO	A14	NNPDF2.3lo
$W^\pm W^\pm jj$ EFT	MadGraph5_aMC@NLO 2.6.5 + Pythia8.235	LO	A14	NNPDF3.0nlo
$H_5^{\pm\pm}$	MadGraph5_aMC@NLO 2.9.5 + Pythia8.245	LO	A14	NNPDF3.0nlo

Quick recap of new results since 2023

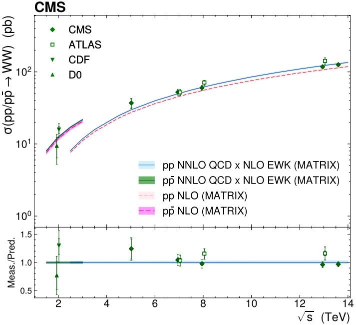
Final state	ATLAS	CMS
W^+W- 13 TeV	CONF-23-012 140 fb^{-1}, inclusive XS + differential XS	-
W^+W- 13.6 TeV	-	arXiv:2406.05101
WZ	arXiv:2402.16365 polarisation studies	[JHEP 07 (2022) 032]
ZZ 13.6 TeV	arXiv:2311.09715	-
ZZ 13 TeV	JHEP 12 (2023) 107 140 fb^{-1}, polarisation + CP properties	arXiv:2404.02711 138 fb^{-1}, ZZ+jets differential XS
$Z(\nu\nu)\gamma$ 13 TeV	-	CMS-PAS-SMP-22-009 138 fb^{-1}

WW at $\sqrt{s} = 13.6$ TeV

arXiv:2406.05101

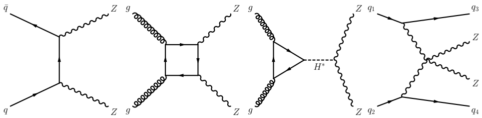


Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044

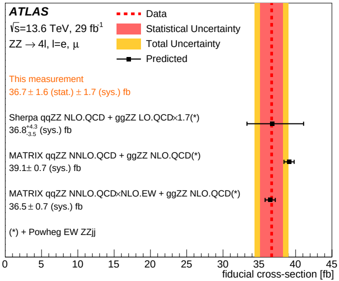


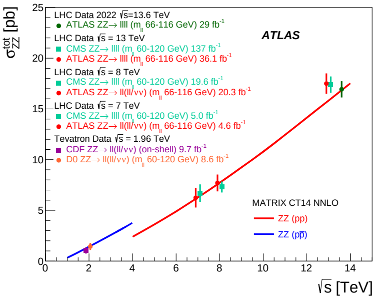
ZZ at $\sqrt{s} = 13.6$ TeV

arXiv:2311.09715



Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3





WW at $\sqrt{s} = 13.6$ TeV

arXiv:2406.05101

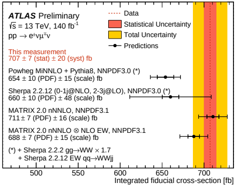
Quantity	WW	One/two b tags	$Z \to \tau\tau$	Same-sign
Number of tight leptons		Strictly 2		
Additional loose leptons		0		
Lepton charges		Opposite		Same
$p_T^{\ell\,\max}$		>25 GeV		
$p_T^{\ell\,\min}$		>20 GeV		
$m_{\ell\ell}$	>85 GeV	>85 GeV	<85 GeV	>85 GeV
$p_T^{\ell\ell}$	—	—	<30 GeV	—
Number of b-tagged jets	0	1/2	0	0
N_j		$0/1/2/\geq 3$		

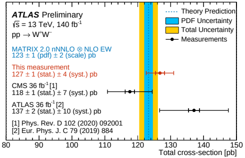
Variable	WZ	ZZ
Number of tight leptons	Strictly 3	Strictly 4
Additional loose leptons	0	
Lepton p_T	>25/10/20 GeV	>25/20/10/10 GeV (p_T ordered)
$\lvert m_{\ell\ell} - m_Z \rvert$	<15 GeV	<15 GeV (both pairs)
$m_{3\ell}$	>100 GeV	—
$m_{4\ell}$	—	>150 GeV
p_T^{miss}	>30 GeV	—
Number of b-tagged jets	0	

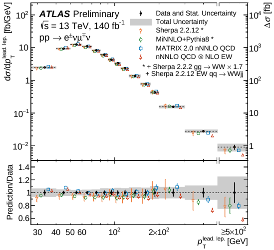
WW at $\sqrt{s} = 13$ TeV

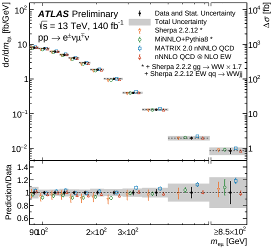
ATLAS-CONF-2023-012

- Excellent agreement with fixed-order MATRIX predictions.
- EW corr. improve modelling at high diboson mass but over-correct pT(leading lepton) ⇒ related to multiplicative treatment, need mixed QCD+EW effects, in particular for hard QCD radiations.
- PDF choice impacts overall XS prediction.









Evidence for $Z_L Z_L$ production

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		Pre-fit	Post-fit
ZZ	$Z_L Z_L$	189.3 ± 8.7	220 ± 54
	$Z_T Z_L$	710 ± 29	711 ± 29
	$Z_T Z_T$	2170 ± 120	2147 ± 60
	Interference	33.7 ± 2.8	33.4 ± 2.7
Non-prompt		18.7 ± 7.1	18.5 ± 7.0
Others		20.0 ± 3.7	19.9 ± 3.7
Total		3140 ± 150	3149 ± 57
Data		3149	3149

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

CP-sensitive observables in ZZ production

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- Existing constraints on anomalous neutral TGC normally use high-pT observables ⇒ very strong constraints but insensitive to CP properties.
- Construct CP-sensitive observable $T_{yz,1(3)} = sin\phi_{1(3)} \times cos\theta_{1(3)}$.
- Symmetric for SM, asymmetric for CP-odd ANTGC.
- Construct 1-D map out of 2-D distribution.

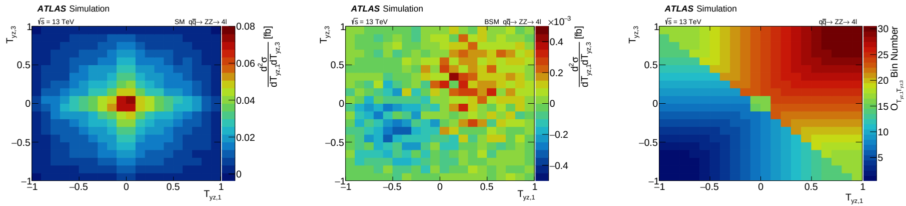
CP odd & main target of the analysis

SM cross-section

EFT only contribution

$$\sigma_{pred} = \sigma_{SM} + c\,.\,\sigma_{interf} + c^2\,.\,\sigma_{quad}$$

interference between SM & EFT



Anomalous couplings in ZZ production

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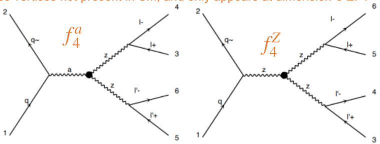
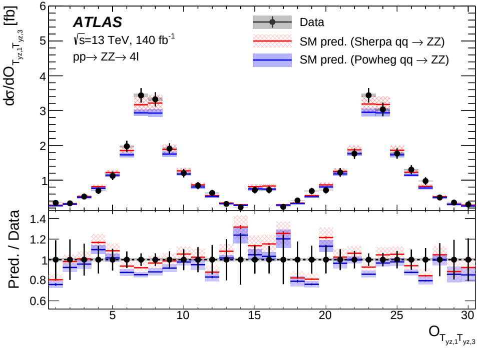
These vertices not present in SM, and only appears at dimension-8 EFT



- Unfolded differential cross section from 1-D map of 2-D distribution ⇒ constraints on ATGC parameters.
- Largest impact on 95%CL intervals: theo. unc. on QCD scales, PDF, α_s and PS.
- Constraints looser than those set using high-pT kinematic observables sensitive to quadratic terms, but sensitive to interference term!



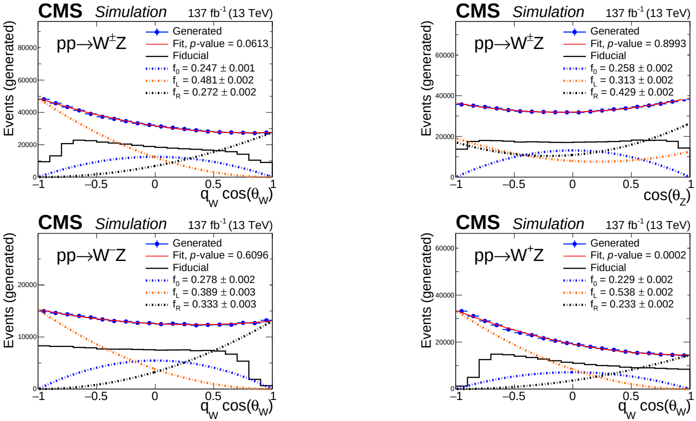
aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	$[-0.16, 0.16]$	$[-0.12, 0.20]$	$[-0.013, 0.012]$	$[-0.012, 0.012]$
f_γ^4	$[-0.30, 0.30]$	$[-0.34, 0.28]$	$[-0.015, 0.015]$	$[-0.015, 0.015]$

CMS 137fb-1 using m(4l) differential cross section [EPJC 81 (2021) 200]

aTGC parameter	Expected 95% CL $\times10^{-4}$	Observed 95% CL $\times10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1

Impact of fiducial cuts on polarisation fractions in WZ production

JHEP 07 (2022) 032



Systematics for f_{00} in WZ production

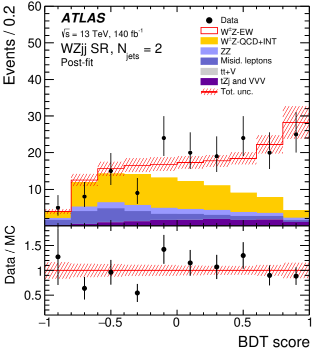
arXiv:2402.16365

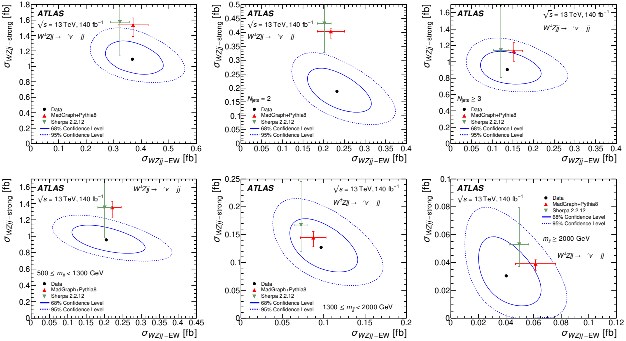
Source	Impact on f_{00} [%]	
Experimental	**100 < p_T^Z ≤ 200 GeV**	**p_T^Z > 200 GeV**
Luminosity	0.1	0.2
Electron calibration	1.0	0.9
Muon calibration	1.1	1.3
Jet energy scale and resolution	5.9	9.0
E_T^{miss} scale and resolution	1.0	0.6
Flavor-tagging inefficiency	0.1	0.2
Pileup modelling	1.6	1.1
Non-prompt background estimation	5.8	0.8
Modelling		
Background, other	1.4	1.6
Model statistical	2.5	5.6
NLO QCD effects	6.8	8.2
NLO EW effects	1.1	3.3
Effect of additive vs multiplicative QCD+EW combination	1.3	3.8
Interference impact	1.4	0.7
PDF, Scales, and shower settings	3.5	9.2
Experimental and modelling	12.1	17.7
Data statistical	18.0	64.5
Total	21.7	66.9

EW production of WZ+2j

ATLAS: arXiv:2403.15296 [CMS: PLB 809 (2020) 135710]

- Using 140 fb^{-1}, 3 leptons (e,μ) + 2j $m_{jj} > 500$ GeV
- BDT used to separate EW and strong productions.
- Extract cross section and differential distributions.
- Dominant uncertainties: syst from theory modelling.

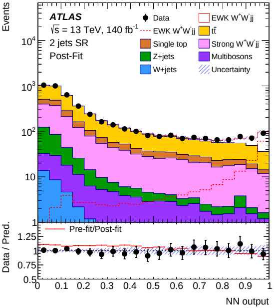


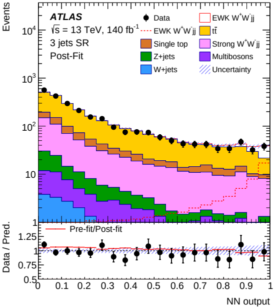


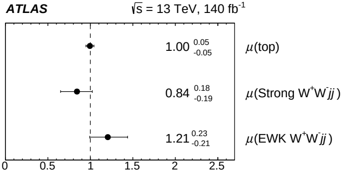
EW production of W^+W^-+2j

ATLAS: arXiv:2403.04869 [CMS result: PLB 841 (2023) 137495]

- Using 140 fb^{-1}, e+μ+2j final state, $=2$ and ≥ 3 jet categories.
- Signal extraction using a likelihood fit to Neural Network outputs.
- Top (66% of SR) and strong production (24% of SR) as free parameters.







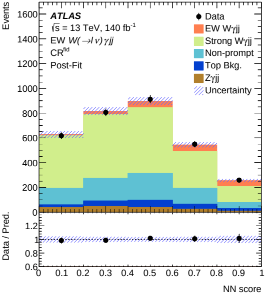
- Significance: 7.1σ (exp. 6.2σ).
- Observed fiducial cross section: $2.65^{+0.49}_{-0.46}$ fb.
- POWHEG BOX v2 prediction: $2.20^{+0.14}_{-0.13}$ fb.

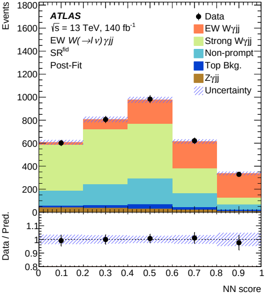
EW production of Wγ+2j

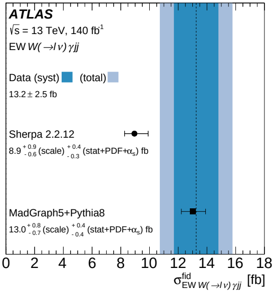
ATLAS: arXiv:2403.02809 [CMS: PRD 108 (2023) 032017]

- 140 fb^{-1}, ℓ (e,μ)+γ+2j $m_{jj} > 500$ GeV, $\Delta y_{jj} > 2.0$.

Fiducial cross-section	SR$^{\text{fid}}$		CR$^{\text{fid}}$	
	$N_{\text{jets}}^{\text{gap}} = 0$		$N_{\text{jets}}^{\text{gap}} > 0$	
Differential cross-section	SR	CR$_A$	CR$_B$	CR$_C$
$m_{jj} > 1$ TeV	$N_{\text{jets}}^{\text{gap}} = 0$ $\xi_{l\gamma} < 0.35$	$N_{\text{jets}}^{\text{gap}} > 0$ $\xi_{l\gamma} < 0.35$	$N_{\text{jets}}^{\text{gap}} > 0$ $0.35 < \xi_{l\gamma} < 1$	$N_{\text{jets}}^{\text{gap}} = 0$ $0.35 < \xi_{l\gamma} < 1$





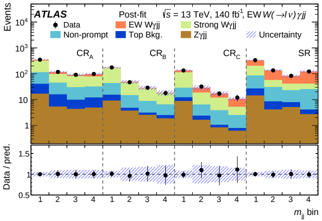


Uncertainty Source	Fractional Uncertainty [%]
Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
E_T^{miss}	1

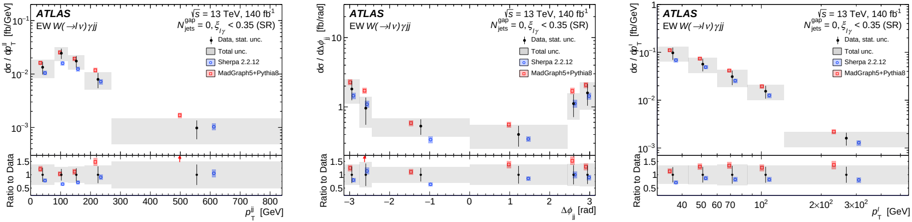
Differential distributions for Wγ+2j

ATLAS: arXiv:2403.02809

[CMS: PRD 108 (2023) 032017]



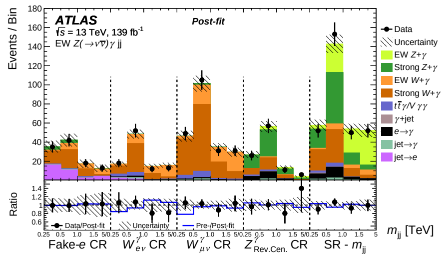
- Unfolded differential xs with 2 types of observables: VBS, polarisation+CP prop.
- SHERPA underestimates data, MG5+Py8 overestimates at high m_{jj} and p_T^{jj}



EW production of $Z\gamma$+2j

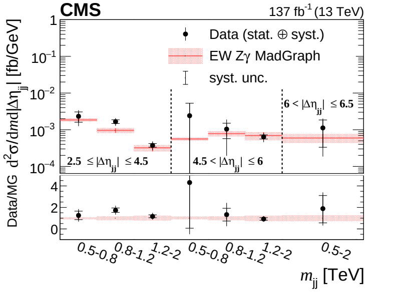
ATLAS: EPJC 82 (2022) 105

- 140 fb^{-1}, $Z \to \nu\nu + \gamma$+2j $m_{jj} > 500$ GeV, $\Delta y_{jj} > 3.0$.
- Significance: 5.2σ (exp. 5.1σ).
- $\sigma_{\text{meas}} = 1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})$ fb $\Rightarrow$ Precision 22%.



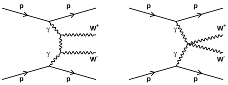
CMS: PRD 104 (2021) 072001

- 137 fb^{-1}, $Z \to \ell\ell + \gamma$+2j $m_{jj} > 500$ GeV, $\Delta y_{jj} > 2.5$.
- Significance: 9.4σ (exp. 8.5σ).
- $\sigma_{\text{meas}} = 5.21 \pm 0.52(\text{stat}) \pm 0.56(\text{syst})$ fb $\Rightarrow$ Precision 15%, syst dominated.



Exclusive production $\gamma\gamma \to WW$

ATL-PHYS-PUB-2021-026



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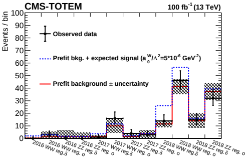
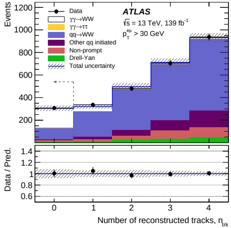
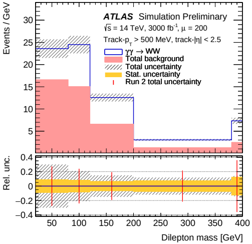
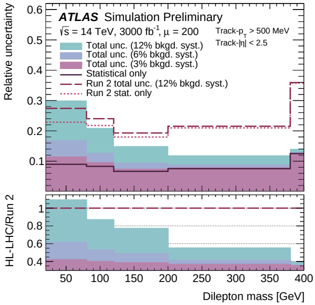


PLB 816 (2021) 136190







- Reconstruct forward protons $\Rightarrow$ use hadronic V decays.
- Target high m_{VV} region for new physics signals.

- 139 fb^{-1}, e+μ with track veto.
- Significance: 8.4σ (6.7σ exp.)
- Precision: $\simeq$ 13%

$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})$ f

MC for LHC tribosons results

arXiv:2405.18661

Process	Energy (TeV)	Theory calculation	Other results
$W\gamma\gamma$ [317]	8	MG5_aMC Py6 NLO	aQGC
$W\gamma\gamma$ [318]	13	MG5_aMC Py8 NLO	aQGC
$Z\gamma\gamma$ [317]	8	MG5_aMC Py6 NLO	aQGC
$Z\gamma\gamma$ [318]	13	MG5_aMC Py8 NLO	aQGC
$WV\gamma$ [319]	8	MG5_aMC Py8 NLO	aQGC
$WW\gamma$ [320]	13	MG5_aMC Py8 NLO	aQGC, $H\gamma$ search
VVV [316]	13	NLO [321,322,323]	VH production
WWW [316]	13	NLO [321,322,323]	VH production
WWZ [316]	13	NLO [321,322,323]	VH production
WZZ [316]	13	NLO [321,322,323]	VH production
ZZZ [316]	13	NLO [321,322,323]	VH production

Introduction to the SMEFT framework

- Model new physics in a general way.
- $\Rightarrow$ Allows precise calculations of cross sections.

Wilson coef. — All operators with given dim.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \sum_i \frac{c_i^{d=8}}{\Lambda^4}\mathcal{O}^{d=8} + \dots$$

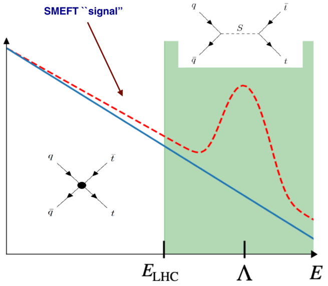
O(d=4) — Cutoff (BSM) scale

Interference SM-dim6 — Pure dim-6

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i^{\rm dim6}}{(\Lambda/1{\rm TeV})^2}\sigma_i^{(\rm dim6)} + \sum_{i\le j} \frac{C_i^{\rm dim6}C_j^{\rm dim6}}{(\Lambda/1{\rm TeV})^4}\sigma_{ij}^{(\rm dim6)} + \sum_i \frac{C_i^{\rm dim8}}{(\Lambda/1{\rm TeV})^4}\sigma_i^{(\rm dim8)} + \mathcal{O}(\Lambda^{-6}).$$

+ O(Λ-8)

Interference dim-8 — Pure dim-8



J. Rojo, LHCP2024

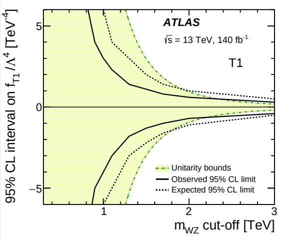
- New Physics $\simeq$ higher-order QCD/EW effects !
- Quadratic terms also important: VBS sensitive to dim-8 and quadratic dim-6.

EFT in practice and validity

- Usually: for ATGC, sensitive to dim-6 operators, for AGQC, sensitive to dim-8.
- Generation of events using MG5 for each coupling independently.
- Add events to SM predictions, and perform likelihood fit using most-sensitive variable.
- Variable: usually m_{VV} or CP sensitive variable to test CP-odd operators.
- Extract 95%CL limits on single / pair of operators.
- To test impact of missing higher-order terms: remove quartic couplings for the dimension considered ⇒ impact on limits ⇔ estimate from missing higher-orders.

Validity of this approach

- Validity limited to E<< Λ.
- Upper cut E_c on m_{VV} for EFT components, preserve unitarity at high energy scale.
- Study 95%CL interval vs E_c.
- More conservative limits at crossing btw observed limit and unitarity bound.

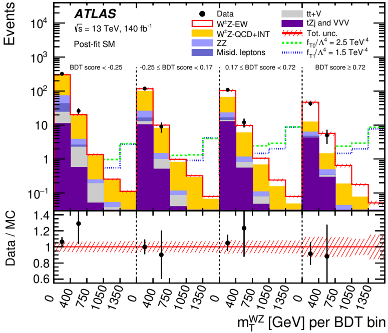


arXiv:2403.15296

Anomalous couplings in WZ+2j

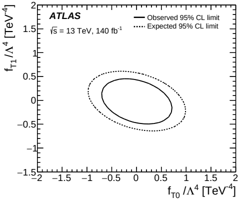
ATLAS: arXiv:2403.15296

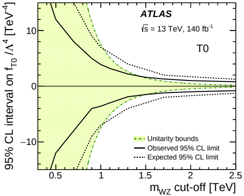
- 2-D BDT-m_T^{WZ} to look for dim-8 operators
- Limits competitive with CMS from [Phys. Lett. B 809 (2020) 135710].



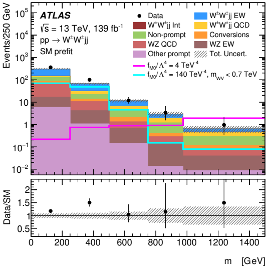
	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4, 10.4]
f_{S1}/Λ^4	[-42, 41]	[-30, 30]

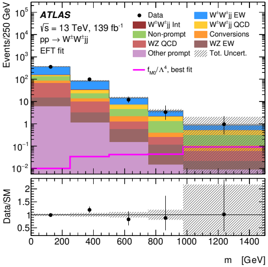
	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-7.0, 7.0]	[-1.5, 1.6]
f_{T1}/Λ^4	[-1.1, 1.0]	[-0.7, 0.6]
f_{T2}/Λ^4	[-12, 6]	[-2.4, 1.8]
f_{M0}/Λ^4	[-60, 60]	[-12, 12]
f_{M1}/Λ^4	[-32, 32]	[-15, 15]
f_{M7}/Λ^4	[-30, 30]	[-15, 15]
f_{S02}/Λ^4	[-41, 41]	[-18, 18]
f_{S1}/Λ^4	—	—





Anomalous couplings in $W^{\pm}W^{\pm}$+2j production





JHEP 04 (2024) 026

- Sensitive to WWWW interaction, using $m_{\ell\ell}$ distribution.
- Limits competitive with CMS from [Phys. Lett. B 809 (2020) 135710].

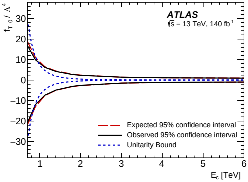
Coefficient	Type	No unitarisation cut-off [TeV^{-4}]	Lower, upper limit at the respective unitarity bound [TeV^{-4}]
f_{M0}/Λ^4	Exp.	[-3.9, 3.8]	-64 at 0.9 TeV, 40 at 1.0 TeV
	Obs.	[-4.1, 4.1]	-140 at 0.7 TeV, 117 at 0.8 TeV
f_{M1}/Λ^4	Exp.	[-6.3, 6.6]	-25.5 at 1.6 TeV, 31 at 1.5 TeV
	Obs.	[-6.8, 7.0]	-45 at 1.4 TeV, 54 at 1.3 TeV
f_{M7}/Λ^4	Exp.	[-9.3, 8.8]	-33 at 1.8 TeV, 29.1 at 1.8 TeV
	Obs.	[-9.8, 9.5]	-39 at 1.7 TeV, 42 at 1.7 TeV
f_{S02}/Λ^4	Exp.	[-5.5, 5.7]	-94 at 0.8 TeV, 122 at 0.7 TeV
	Obs.	[-5.9, 5.9]	–
f_{S1}/Λ^4	Exp.	[-22.0, 22.5]	–
	Obs.	[-23.5, 23.6]	–
f_{T0}/Λ^4	Exp.	[-0.34, 0.34]	-3.2 at 1.2 TeV, 4.9 at 1.1 TeV
	Obs.	[-0.36, 0.36]	-7.4 at 1.0 TeV, 12.4 at 0.9 TeV
f_{T1}/Λ^4	Exp.	[-0.158, 0.174]	-0.32 at 2.6 TeV, 0.44 at 2.4 TeV
	Obs.	[-0.174, 0.186]	-0.38 at 2.5 TeV, 0.49 at 2.4 TeV
f_{T2}/Λ^4	Exp.	[-0.56, 0.70]	-2.60 at 1.7 TeV, 10.3 at 1.2 TeV
	Obs.	[-0.63, 0.74]	–

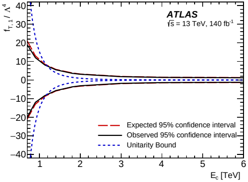
Anomalous couplings in ZZ+2j production

JHEP 01 (2024) 004

- Sensitive to dim-8 operators, using 2D $m_{4\ell}$-m_{jj} distributions.
- Limits also set on dim-6 operators - using $\Delta\phi_{jj}$ variable for CP-odd coefficients.

Wilson coefficient	$\|\mathcal{M}_{d8}\|^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-0.98, 0.93]	[-1.00, 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]
$f_{T,2}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-74, 56]	[-63, 62]
$f_{T,5}/\Lambda^4$	yes	[-2.5, 2.4]	[-2.6, 2.5]
	no	[-79, 60]	[-68, 67]
$f_{T,6}/\Lambda^4$	yes	[-3.9, 3.9]	[-4.1, 4.1]
	no	[-64, 48]	[-55, 54]
$f_{T,7}/\Lambda^4$	yes	[-8.5, 8.1]	[-8.8, 8.4]
	no	[-260, 200]	[-220, 220]
$f_{T,8}/\Lambda^4$	yes	[-2.1, 2.1]	[-2.2, 2.2]
	no	[-4.6, 3.1]$\times10^4$	[-3.9, 3.8]$\times10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.5, 4.5]	[-4.7, 4.7]
	no	[-7.5, 5.5]$\times10^4$	[-6.4, 6.3]$\times10^4$



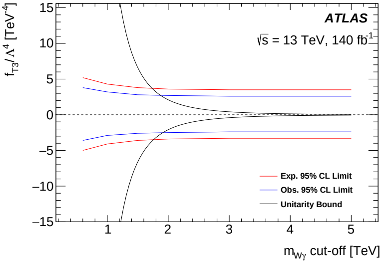


- CMS limits (Phys. Lett. B 812 (2020) 135992):

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24	0.22	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31	0.31	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63	0.59	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43	0.43	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92	0.92	1.8

Anomalous couplings in Wγ+2j

- Limits on dim-8 operators, using p_T^{ℓ} (mixed scalar operators) or p_T^{jj} (tensor-type operators).
- First limits on f_{T3} and f_{T4} at the LHC.
- Limits $\simeq$ insensitive to E_c.



ATLAS: arXiv:2403.02809

Cofficients [TeV^{-4}]	Observable	$M_{W\gamma}$ cut-off [TeV]	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	1.4	[-2.5, 2.6]	[-1.9, 1.9]
f_{T1}/Λ^4	p_T^{jj}	1.9	[-1.6, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	1.6	[-4.9, 5.3]	[-3.6, 4.0]
f_{T3}/Λ^4	p_T^{jj}	1.9	[-3.4, 3.6]	[-2.5, 2.7]
f_{T4}/Λ^4	p_T^{jj}	2.2	[-3.1, 3.1]	[-2.2, 2.3]
f_{T5}/Λ^4	p_T^{jj}	1.8	[-1.8, 1.8]	[-1.3, 1.3]
f_{T6}/Λ^4	p_T^{jj}	2.1	[-1.5, 1.5]	[-1.1, 1.1]
f_{T7}/Λ^4	p_T^{jj}	2.1	[-4.0, 4.1]	[-2.9, 3.0]
f_{M0}/Λ^4	p_T^{l}	1.1	[-45, 44]	[-32, 31]
f_{M1}/Λ^4	p_T^{l}	1.4	[-60, 62]	[-43, 44]
f_{M2}/Λ^4	p_T^{l}	1.4	[-15, 15]	[-11, 11]
f_{M3}/Λ^4	p_T^{l}	1.8	[-22, 22]	[-16, 16]
f_{M4}/Λ^4	p_T^{l}	1.5	[-28, 27]	[-20, 20]
f_{M5}/Λ^4	p_T^{l}	1.9	[-21, 23]	[-14, 17]
f_{M7}/Λ^4	p_T^{l}	1.5	[-100, 99]	[-73, 71]

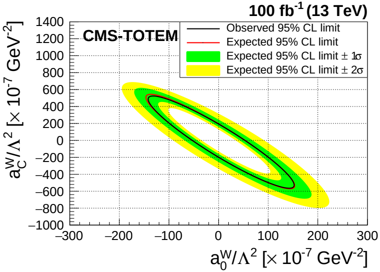
- CMS obtains better sensitivity using $m_{W\gamma}$ and strong+EW contributions [PRD 108 (2023) 032017]

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

Anomalous couplings in $\gamma\gamma \rightarrow$VV and Zγ+2j

JHEP 07 (2023) 229

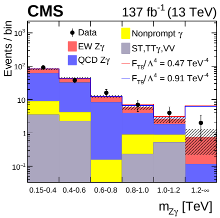
- Limits on dim-6 and dim-8 operators



Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

PRD 104 (2021) 072001

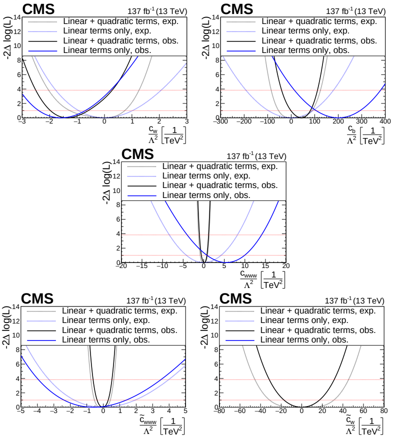
- Use $m_{Z\gamma}$ distribution.



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

Impact of quartic contrib. in ATGC from WZ

JHEP 07 (2022) 032



- Dimension-6 EFT: quadratic Λ^{-2} interference + quartic Λ^{-4} pure BSM.
- Dimension-8 EFT: additional quartic Λ^{-4} interference.
- test impact by dropping quartic contributions.

Anomalous couplings in ssWW and WZ+2j

CMS: Phys. Lett. B 809 (2020) 135710

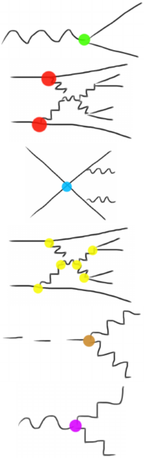
	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

	Observed ($W^\pm W^\pm$) (TeV^{-4})	Expected ($W^\pm W^\pm$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

Sensitivity to couplings

Individual contraints - Best variables

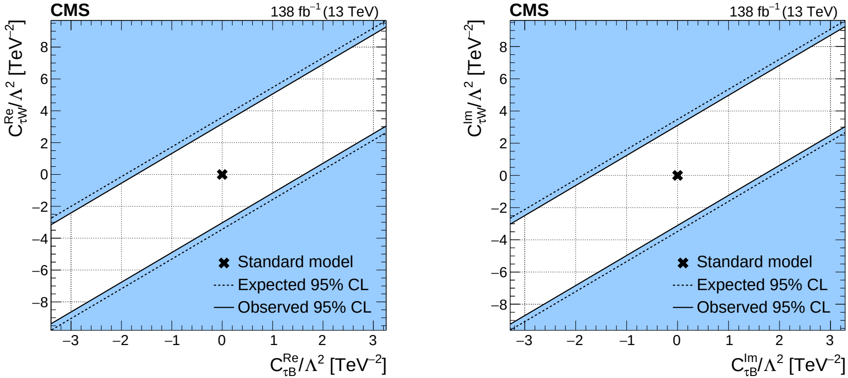
Op.	SSWW+2j L	SSWW+2j L+Q	OSWW+2j L	OSWW+2j L+Q	WZ+2j L	WZ+2j L+Q	ZZ+2j L	ZZ+2j L+Q	ZV+2j L	ZV+2j L+Q	WW L	WW L+Q
$c_{Hl}^{(1)}$	-	m_{ll}	-	MET	$m_{ee}{}^{\dagger}$	m_{WZ}	$p_{T,e^-\mu^-}{}^{\dagger}$	$p_{T,e^-\mu^-}{}^{\dagger}$	p^V_{T,j_1}	p^V_{T,j_1}	p_{T,l^1}	MET
$c_{Hq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	m_{jj}	m_{ll}	m_{jj}	p_{T,j^1}	m_{jj}	p_{T,j^1}	m_{jj}^{VBS}	m_{jj}^{VBS}	MET	MET
$c_{Hq}^{(3)}$	$\Delta\phi_{jj}$	$\Delta\phi_{jj}$	m_{ll}	m_{ll}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^1}	$\Delta\phi_{jj}{}^{\dagger}$	p_{T,l^4}	p^{VBS}_{T,j_2}	p^{VBS}_{T,j_2}	p_{T,l^1}	p_{T,l^1}
$c_{qq}^{(3)}$	$m_{ll}{}^{\dagger}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$p_{T,l^1}{}^{\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(3,1)}$	$\Delta\phi_{jj}$	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^2}	m_{jj}	p_{T,j^1}	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\phi_{jj}^{VBS}$	-	-
$c_{qq}^{(1,1)}$	$\Delta\phi_{jj}$	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{qq}^{(1)}$	p_{T,j^1}	p_{T,j^1}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	p_{T,j^2}	$\Delta\phi_{jj}^{VBS}$	p^{VBS}_{T,j_1}	-	-
$c_{Hl}^{(3)}$	$\Delta\eta_{jj}{}^{\dagger}$	$\Delta\eta_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	$m_{ll}{}^{\dagger}$	$m_{ll}{}^{\dagger}$
c_{HD}	p_{T,j^1}	m_{ll}	$\Delta\eta_{jj}$	$\Delta\eta_{jj}$	m_{ee}	$\Delta\eta_{jj}{}^{\dagger}$	$p_{T,e^+\mu^+}$	$p_{T,e^+\mu^+}{}^{\dagger}$	p_{T,l^2}	p_{T,l^2}	p_{T,l^1}	p_{T,l^1}
$c_{ll}^{(1)}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	m_{jj}	$m_{jj}{}^{\dagger}$	$m_{jj}{}^{\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$\Delta\eta_{jj}^{V\dagger}$	$p_{T,ll}{}^{\dagger}$	p_{T,l^2}
c_{HWB}	p_{T,j^1}	p_{T,j^1}	$\Delta\eta_{jj}$	m_{ll}	m_{ee}	m_{WZ}	$m_{\mu\mu}{}^{\dagger}$	$\Delta\eta_{jj}$	$\Delta\eta_{jj}^{V}$	$\Delta\eta_{jj}^{V}$	p_{T,l^1}	MET
$c_{H\Box}$	p_{T,j^1}	m_{ll}	m_{ll}	m_{ll}	-	m_{WZ}	-	$\Delta\eta_{jj}$	p^V_{T,j_2}	p^V_{T,j_2}	-	-
c_{HW}	$\Delta\phi_{jj}$	m_{ll}	$\Delta\phi_{jj}$	m_{ll}	$\eta_{l^3}{}^{\dagger}$	m_{WZ}	m_{jj}	m_{4l}	p^{VBS}_{T,j_1}	p^V_{T,j_2}	-	-
c_W	$\Delta\phi_{jj}$	$p_{T,ll}$	$\Delta\phi_{jj}$	m_{ll}	p_{T,l^1}	m_{WZ}	$\Delta\phi_{jj}$	p_{T,l^4}	$\Delta\phi_{jj}^{VBS\dagger}$	$\Delta\phi_{jj}^{VBS\dagger}$	MET	MET



Observables ranking change from Lin to Lin+Quad.
Best observable group usually match prior knowledge about the operator.

G. Boldrini, 07/07/2022, ICHEP2022

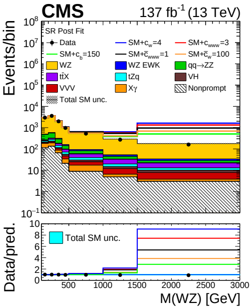
Anomalous couplings from $\gamma\gamma \to \tau\tau$

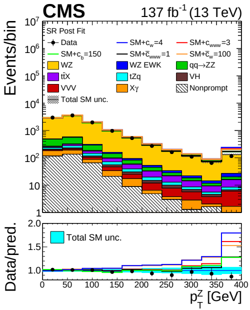


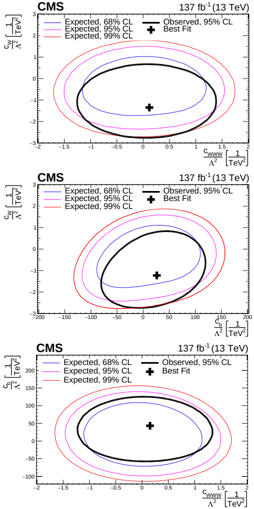
Anomalous couplings in WZ production

JHEP 07 (2022) 032

- Fit to m_{WZ} assuming dim-6+dim-8 operators. Study correlations for CP-conserving EFT parameters.
- Consider 3 CP-conserving + !NEW! 2 CP-violating parameters.



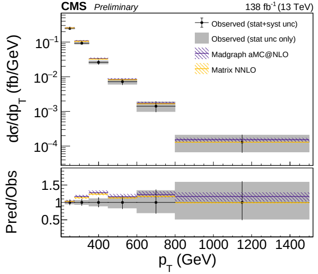




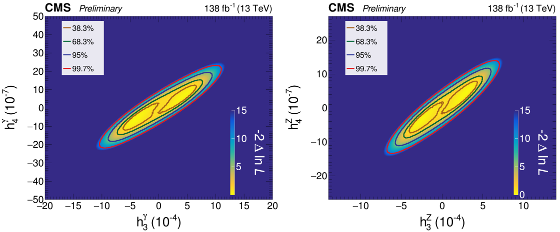
$Z\gamma \rightarrow \nu\nu\gamma$ and Neutral aTGC

CMS-PAS-SMP-22-009

Region	Measured	NLO (Madgraph5)	NNLO (MATRIX)
Barrel $\lvert\eta\rvert < 1.4442$	$16.74^{+1.05}_{-0.99}$	$19.61^{+0.73}_{-0.69}$	$19.33^{+0.27}_{-0.33}$
Endcaps $1.4442 < \lvert\eta\rvert < 2.5$	$7.84^{+0.76}_{-0.70}$	$6.45^{+0.27}_{-0.31}$	$6.21^{+0.07}_{-0.09}$
Combination of barrel and endcaps	$23.32^{+1.40}_{-1.32}$	$26.07^{+0.96}_{-0.97}$	$25.45^{+0.41}_{-0.33}$

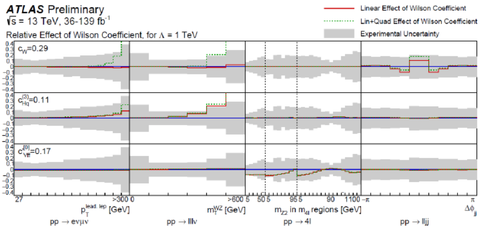


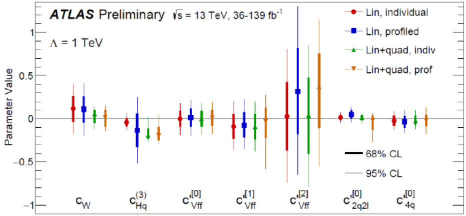
- Cross section in agreement with predictions.
- Anomalous couplings from vertex functions, 4 parameters for Z/γ in anomalous neutral TGC.
- Most stringent CMS limits to date !
- Using unfolded p_T^{γ} distribution.



EFT interpretation

ATL-PHYS-PUB-2021-022





$c'^{[0]}_{Vff} \simeq 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} - 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \simeq 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \simeq -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} - 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$

- Correlation of systematics between measurements taken into account

Correlated Uncertainty Source	WW	WZ	4ℓ	VBF Z
Luminosity (correlated part)	✓	✓	✓	✓
Luminosity 2015/16	✓	✓	✓	✓
Luminosity 2017/18			✓	✓
Lepton efficiency (correlated part)	✓	✓	✓	✓
Pile-up modelling	✓	✓	✓	✓
Pile-up jet suppression	✓			✓
Jet energy scale (Pile-up modelling)	✓			✓
Jet energy scale η-inter-calibration	✓			✓

- Limits at 95% CL for linear and linear+quadratic fits (to illustrate the effect of truncation of EFT expansion)
- Fits of individual coefficients (with others set to zero) as well as combined fit
- No deviations from SM found

Step forward towards global EFT interpretations!

21.10.2021 O. Kuprash - Multibosons & VBS at ATLAS 36

Extrapolation to HL-LHC/FCC-ee

SMEFIT3.0 arXiv:2404.12809