Multiboson Measurements in CMS

PHENO 2026

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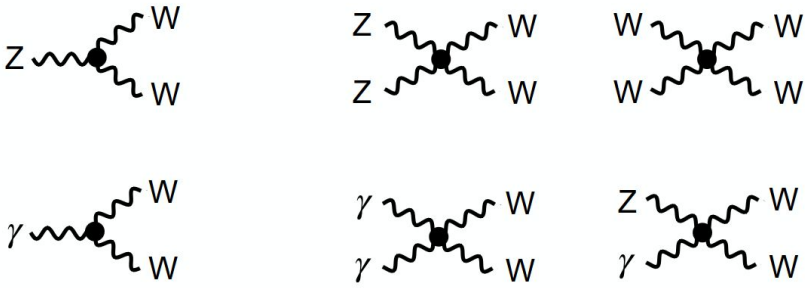
Multiboson Physics

- Production of multiboson processes at the LHC provides insight into EW symmetry breaking. These are some of the most rare observed SM processes.



- New CMS multiboson results since PHENO 2025. I will discuss **four of them:**
  - **VVV**: First EFT search with dim-6 Wilson coefficients (WCs) along with dim-8 WCs [SMP-24-017] *arXiv:2605.XXXXX – in submission queue as of this morning!*
  - **γ-fusion W^+W^-**: Observation and measurement of production cross section and constraints on dim-8 WCs [arXiv:2601.21574]
  - **VBS ZZ**: First observation in CMS of EW ZZ and constraints on dim-8 WCs [SMP-23-001]
  - ■ **VBS $W^\pm W^\mp$ and $W^\pm Z$**: production cross section and differential cross section measurements [SMP-25-013]
  - EFT Combination: Higgs, V, top, and multijet measurements combined to constrain dim-6 WCs [arXiv:2504.02958]

○ Run 2 ■ Run 3

Effective Field Theory

VVV:
- 12 dim-6 WCs (Warsaw basis)
- 20 dim-8 WCs (Éboli basis)

Effective Lagrangian:

Wilson coefficient (WC) (dimensionless)

Effective Operators

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

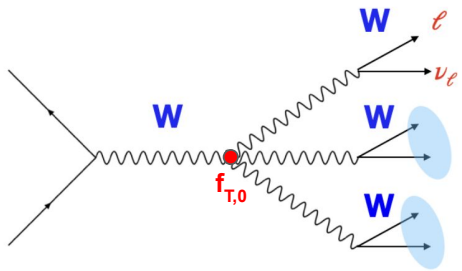
dim-6 dim-8

Mass scale (large)

e.g. $f_{T,0}$ is a genuine QGC operator

$$\mathcal{O}_{T,0} = \mathrm{Tr}(\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}) \times \mathrm{Tr}(\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta})$$

SR-ℓ-2fj Final State

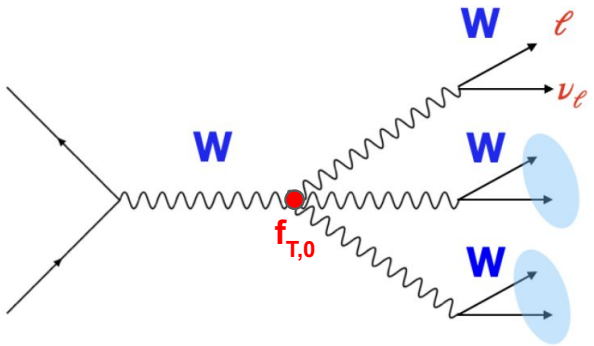


EFT Impact on VVV

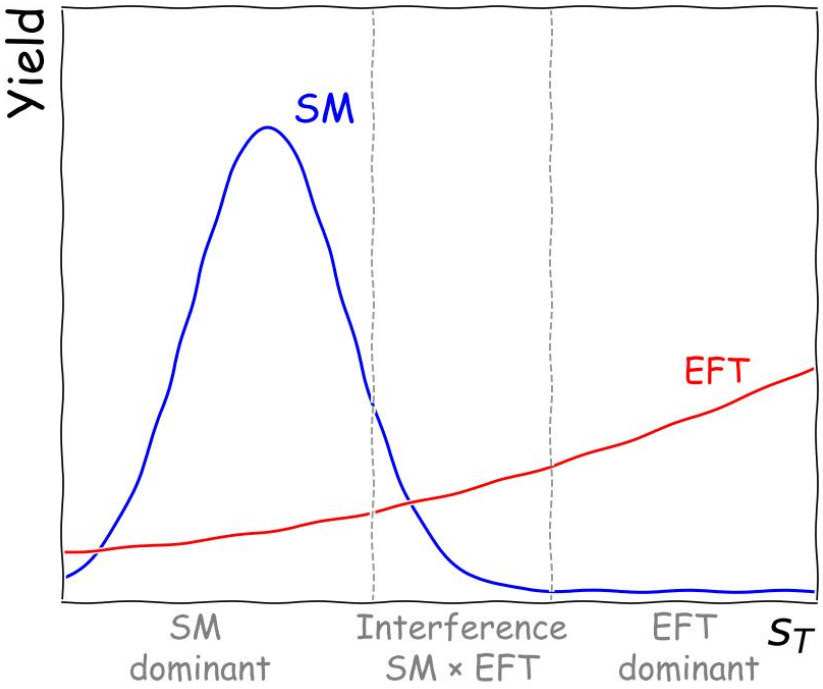
- Large pure BSM contribution, small SM interference contribution
- Enhancement for large m_{VVV} (~$\hat{s}$)

→**Analysis targets boosted objects (leptons, jets)**

SR-ℓ-2fj Final State



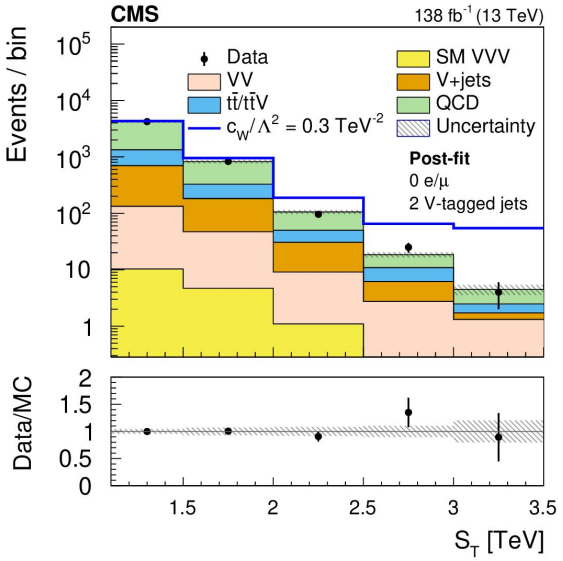
Sketch



Analysis Channels

Channel label	# leptons	# V-tagged jets (VTJ)	# τ_h	Variable of Interest
SR-0ℓ-2VTJ	0	2	0	S_T
SR-0ℓ-3VTJ	0	≥ 3	0	S_T
SR-1ℓ-2VTJ	1	≥ 2	0	$m_{JJ\ell\nu}$
SR-2ℓ-OS-1VTJ	2	1	0	S_T
SR-2ℓ-OS-2VTJ	2	≥ 2	0	S_T
SR-2ℓ-SS-1VTJ	2	≥ 1	0	S_T
SR-1T-1ℓ-1VTJ	1	1	1	S_T and BDT score (2D)
SR-1T-2ℓ-0VTJ	2	0	1	S_T and BDT score (2D)

SR-0ℓ-2VTJ

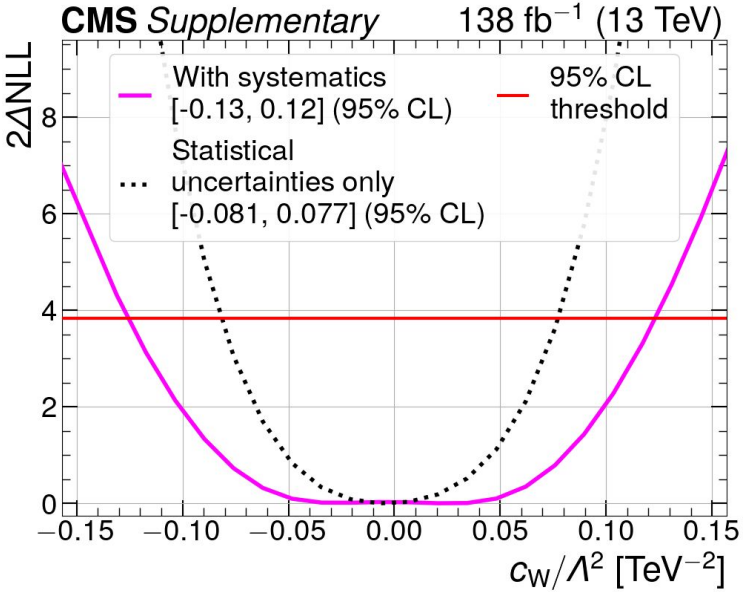


- Binned signal distributions (~s_T) from each channel combined in the statistical analysis
- Dominant backgrounds modeled with data-driven techniques (e.g. ABCD for SR-0l-2VTJ QCD) and MC for all others.
- Total of 37 signal bins

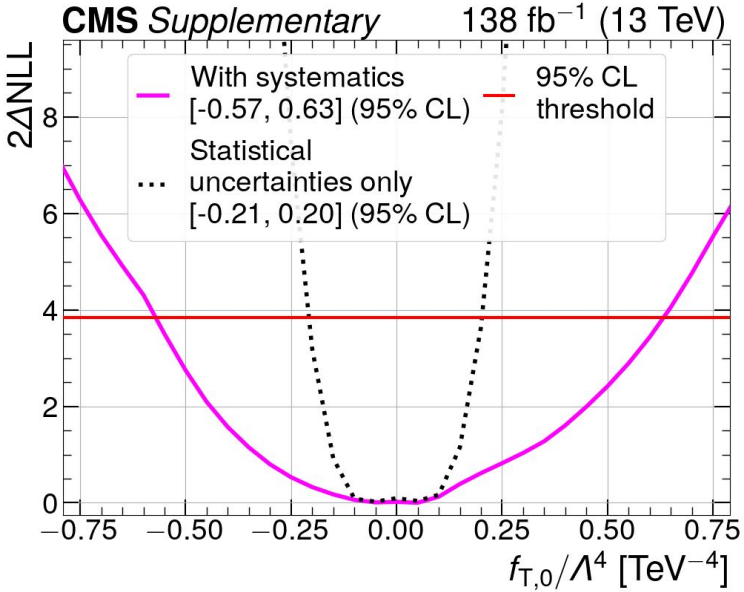
ΔNLL

All signal bins combined in a single likelihood fit using the CMS COMBINE tool [Comput Softw Big Sci 8, 19]

c_W (dim-6)



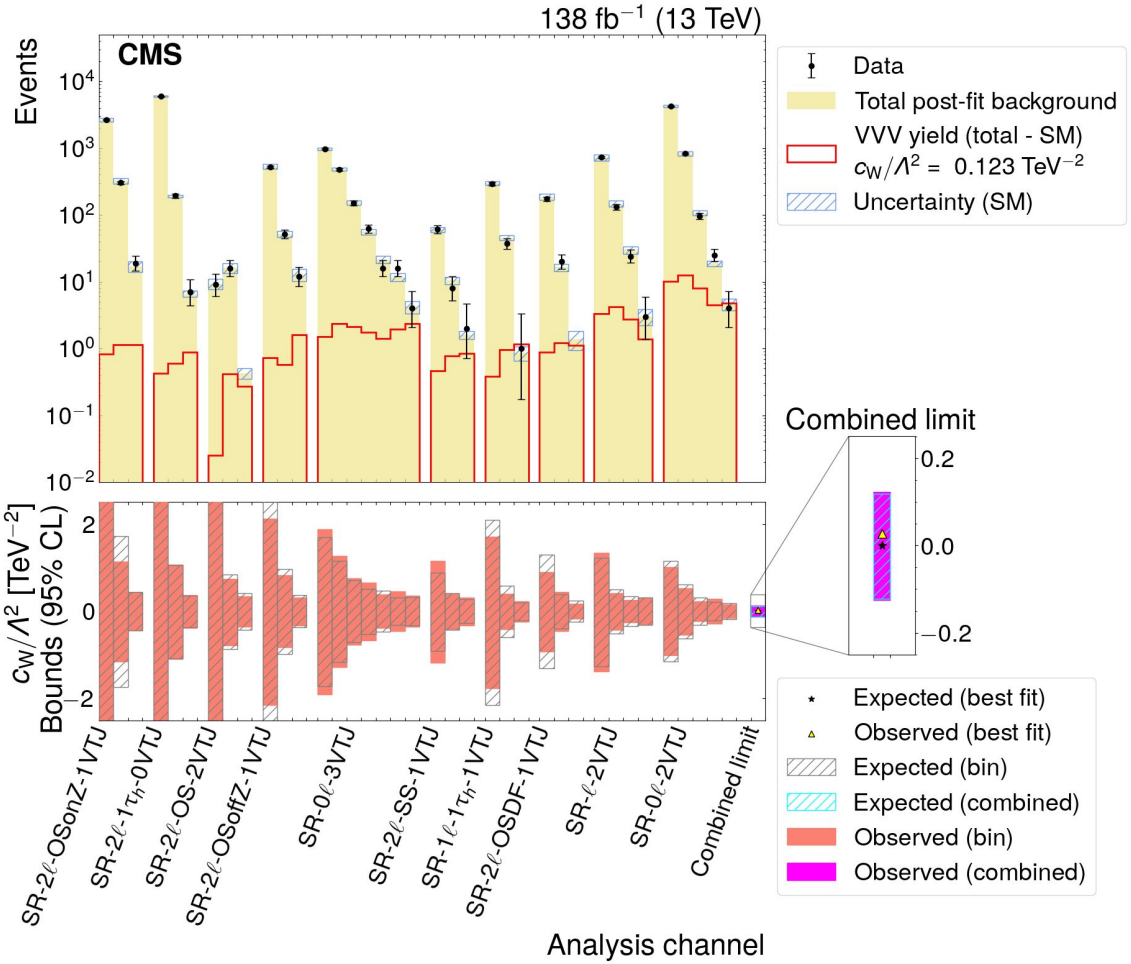
$f_{T,0}$ (dim-8)



- Impact of systematics driven by theoretical PDF and QCD scales uncertainties, particularly in dim-8.

Results – c_W

- Sensitivity driven by high-s_T bins
- Many final states contribute significantly (leading final state depends on WC)
- Data compatible with the SM prediction (p = 0.74)



Bounds: dim-6

Competitive bounds →

Wilson coefficient	Freeze other WCs 95% CL Bounds [TeV^{-2}] Observed	Freeze other WCs 95% CL Bounds [TeV^{-2}] Expected	Profile other WCs 95% CL Bounds [TeV^{-2}] Observed	Profile other WCs 95% CL Bounds [TeV^{-2}] Expected
c_W/Λ^2	$[-0.13, 0.12]$	$[-0.12, 0.12]$	$[-0.11, 0.12]$	$[-0.13, 0.12]$
c_{Hq3}/Λ^2	$[-0.24, 0.21]$	$[-0.23, 0.20]$	$[-0.44, 0.37]$	$[-0.30, 0.25]$
c_{Hq1}/Λ^2	$[-0.34, 0.34]$	$[-0.32, 0.32]$	$[-0.39, 0.42]$	$[-0.33, 0.33]$
c_{Hu}/Λ^2	$[-0.60, 0.59]$	$[-0.61, 0.59]$	$[-0.89, 0.83]$	$[-0.74, 0.73]$
c_{Hd}/Λ^2	$[-0.79, 0.79]$	$[-0.79, 0.79]$	$[-0.98, 1.04]$	$[-0.86, 0.88]$
c_{HW}/Λ^2	$[-1.60, 1.55]$	$[-1.63, 1.55]$	$[-3.2, 3.6]$	$[-2.1, 2.3]$
c_{HWB}/Λ^2	$[-5.2, 5.0]$	$[-5.5, 5.2]$	$[-9.6, 9.7]$	$[-7.6, 7.4]$
$c_{H\ell 3}/\Lambda^2$	$[-3.7, 1.2] \cup [9, 17]$	$[-3, 15]$	$[-5, 22]$	$[-4, 18]$
c_{HB}/Λ^2	$[-11, 11]$	$[-12, 12]$	$[-11, 12]$	$[-13, 13]$
$c_{\ell\ell 1}/\Lambda^2$	$[-32, -13] \cup [-9, 10]$	$[-30, 7]$	$[-34, 10]$	$[-32, 8]$
$c_{H\Box}/\Lambda^2$	$[-76, 69]$	$[-69, 61]$	$[-71, 68]$	$[-56, 54]$
c_{HDD}/Λ^2	$[-114, 71]$	$[-108, 68]$	$[-164, 81]$	$[-130, 72]$

Bounds: dim-8

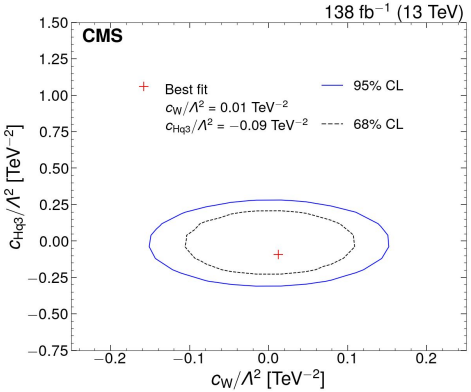
Wilson coefficient	95% CL bounds [TeV^{-4}] Observed	Expected	Measurement [TeV^{-4}] Observed
$f_{T,0}/\Lambda^4$	$[-0.57, 0.63]$	$[-0.48, 0.54]$	$-0.05^{+0.34}_{-0.28}$
$f_{T,1}/\Lambda^4$	$[-0.63, 0.70]$	$[-0.54, 0.62]$	$0.05^{+0.26}_{-0.41}$
$f_{T,3}/\Lambda^4$	$[-1.22, 1.32]$	$[-1.04, 1.18]$	$0.10^{+0.48}_{-0.82}$
$f_{T,2}/\Lambda^4$	$[-1.29, 1.39]$	$[-1.10, 1.24]$	$0.10^{+0.50}_{-0.85}$
$f_{M,0}/\Lambda^4$	$[-3.8, 4.0]$	$[-2.8, 3.2]$	$-0.4^{+2.9}_{-1.8}$
$f_{T,5}/\Lambda^4$	$[-4.0, 3.9]$	$[-3.1, 3.0]$	$0.0^{+2.6}_{-2.7}$
$f_{T,6}/\Lambda^4$	$[-4.9, 4.8]$	$[-3.8, 3.7]$	$0.0^{+3.2}_{-3.3}$
$f_{M,1}/\Lambda^4$	$[-6.7, 6.4]$	$[-5.0, 5.1]$	$-1.0^{+4.7}_{-3.0}$
$f_{T,4}/\Lambda^4$	$[-9.2, 9.0]$	$[-7.1, 7.0]$	$0.0^{+6.0}_{-6.0}$
$f_{T,7}/\Lambda^4$	$[-10, 10]$	$[-8, 8]$	$0.1^{+6.8}_{-7.1}$
$f_{M,7}/\Lambda^4$	$[-10, 11]$	$[-8, 9]$	$-1.0^{+6.7}_{-4.4}$
→ $f_{M,5}/\Lambda^4$	$[-11, 11]$	$[-9, 9]$	$0.0^{+7.3}_{-7.0}$
$f_{T,8}/\Lambda^4$	$[-11, 12]$	$[-7, 7]$	5^{+3}_{-13}
→ $f_{M,4}/\Lambda^4$	$[-13, 13]$	$[-11, 11]$	$0.0^{+8.7}_{-8.4}$
→ $f_{M,2}/\Lambda^4$	$[-14, 14]$	$[-11, 11]$	$0.0^{+9.7}_{-9.7}$
$f_{T,9}/\Lambda^4$	$[-22, 23]$	$[-14, 14]$	11^{+5}_{-27}
→ $f_{M,3}/\Lambda^4$	$[-23, 23]$	$[-18, 18]$	0^{+16}_{-15}
$f_{S,1}/\Lambda^4$	$[-26, 26]$	$[-24, 25]$	-2^{+16}_{-13}
$f_{S,0}/\Lambda^4$	$[-38, 38]$	$[-35, 35]$	-2^{+22}_{-20}
$f_{S,2}/\Lambda^4$	$[-38, 39]$	$[-36, 36]$	-2^{+22}_{-20}

Bounds compatible with recent ATLAS VVZ EFT search [arXiv:2412.15123]

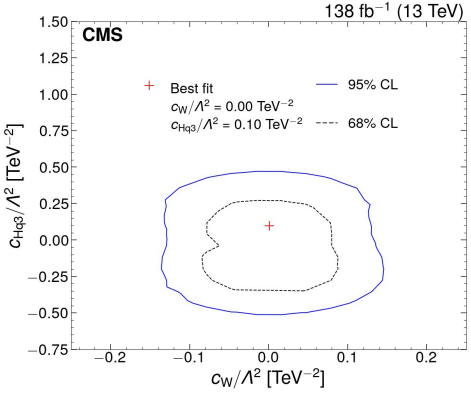
Additional Results

2D Scans

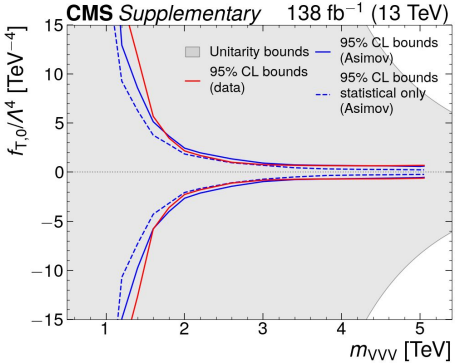
Freeze other WCs



Profile other WCs

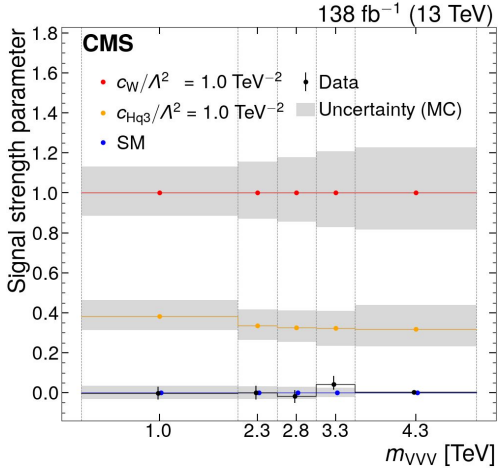


Clipping / Unitarity Bounds*

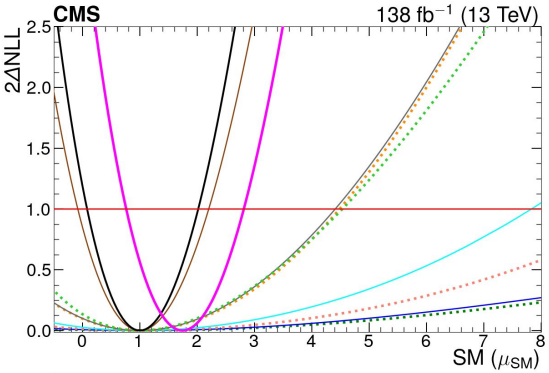


* Unitarity bounds from [arXiv:2601.07920]

Template Fit (pseudo-unfolding)

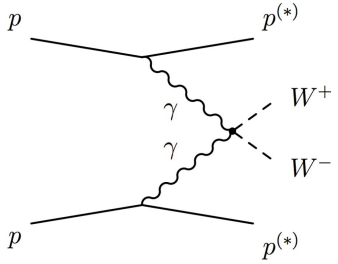


SM VVV Sensitivity



Full analysis Asimov $\hat{\mu}_{SM} = 1.00^{+1.02}_{-0.92}$	SR-2ℓ-1τ_h-0VTJ $\hat{\mu}_{SM} = 1.0^{+3.4}_{-3.1}$	SR-0ℓ-3VTJ $\hat{\mu}_{SM} = 1^{+17}_{-15}$
Full analysis data $\hat{\mu}_{SM} = 1.74^{+1.07}_{-0.98}$	SR-2ℓ-OS-1VTJ $\hat{\mu}_{SM} = 1.0^{+3.5}_{-3.1}$	SR-0ℓ-2VTJ $\hat{\mu}_{SM} = 1^{+17}_{-16}$
SR-2ℓ-SS-1VTJ $\hat{\mu}_{SM} = 1.00^{+1.20}_{-1.08}$	SR-2ℓ-OS-2VTJ $\hat{\mu}_{SM} = 1.0^{+6.8}_{-5.6}$	2ΔNLL threshold 68% CL
SR-1ℓ-1τ_h-1VTJ $\hat{\mu}_{SM} = 1.0^{+3.5}_{-2.4}$	SR-ℓ-2VTJ $\hat{\mu}_{SM} = 1.0^{+9.0}_{-8.7}$	

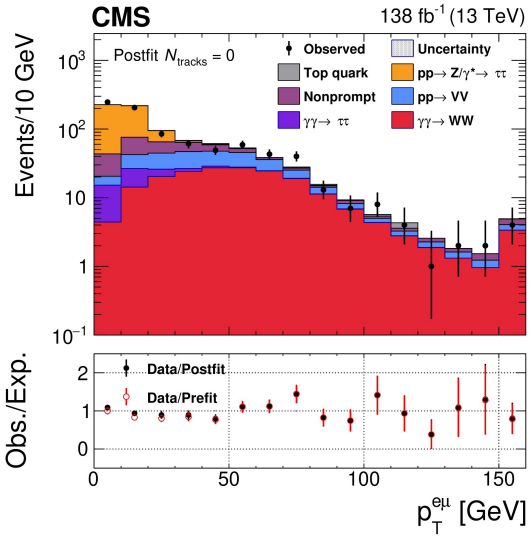
γγ-fusion W^+W^-



- Select $e^{\pm}\mu^{\mp}$ + p_T^{miss}
- Require no nearby tracks (N_{tracks} = 0)

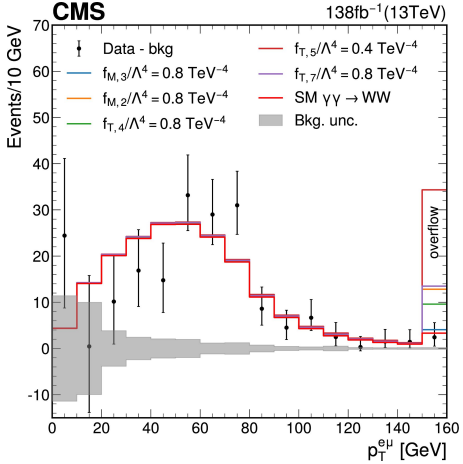
Process	$N_{tracks} = 0$ (SR)	$1 \leq N_{tracks} \leq 5$ (CR)
$Z/\gamma^* \to \tau\tau$	361 ± 22	$11\,260 \pm 170$
Jet mis-ID	119 ± 10	$2\,160 \pm 180$
Inclusive VV	117 ± 10	$3\,770 \pm 220$
$\gamma\gamma \to \tau\tau$	34.2 ± 1.5	37.3 ± 1.5
Top	6.6 ± 1.4	673 ± 98
EW WW +2 jets	3.6 ± 0.7	28.9 ± 4.9
Nonfiducial $\gamma\gamma \to$ WW	11.4 ± 0.4	70.4 ± 2.4
Total bkg.	653 ± 30	$18\,000 \pm 160$
Fiducial $\gamma\gamma \to$ WW	183 ± 22	121 ± 15
Total	835 ± 29	$18\,120 \pm 170$
Observed	829	18 112

SR



Measured: σ^{fid} = 3.96+0.53-0.51 fb
Predicted: σ^{fid} = 3.87±0.77 fb

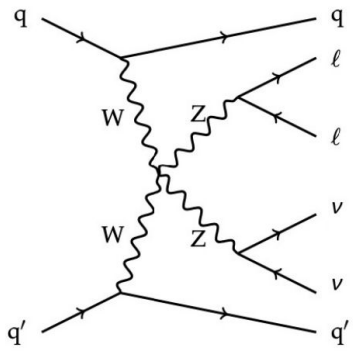
SR - Backgrounds



	Expected 95% CL (TeV^{-4})	Observed 95% CL (TeV^{-4})
f_{M0}/Λ^4	[−4.03, 4.10]	[−3.24, 3.25]
f_{M1}/Λ^4	[−15.46, 14.93]	[−12.31, 12.03]
$f_{\overline{M1}}/\Lambda^4$	[−0.62, 0.62]	[−0.50, 0.49]
f_{M2}/Λ^4	[−0.61, 0.63]	[−0.49, 0.50]
$f_{\overline{M2}}/\Lambda^4$	[−2.24, 2.24]	[−1.80, 1.79]
f_{M3}/Λ^4	[−2.36, 2.28]	[−1.88, 1.84]
f_{M4}/Λ^4	[−2.22, 2.26]	[−1.79, 1.80]
$f_{\overline{M4}}/\Lambda^4$	[−4.49, 4.49]	[−3.59, 3.58]
f_{M5}/Λ^4	[−4.12, 4.27]	[−3.32, 3.40]
$f_{\overline{M5}}/\Lambda^4$	[−2.03, 2.03]	[−1.63, 1.62]
f_{M7}/Λ^4	[−29.86, 30.92]	[−24.06, 24.62]
f_{T0}/Λ^4	[−0.65, 0.53]	[−0.53, 0.42]
f_{T1}/Λ^4	[−2.13, 2.00]	[−1.71, 1.59]
f_{T2}/Λ^4	[−2.50, 2.01]	[−2.04, 1.56]
$f_{\overline{T2}}/\Lambda^4$	[−0.090, 0.090]	[−0.03, 0.03]
f_{T3}/Λ^4	[−3.28, 2.49]	[−2.69, 1.90]
$f_{\overline{T3}}/\Lambda^4$	[−0.089, 0.089]	[−0.071, 0.071]
f_{T4}/Λ^4	[−1.00, 0.76]	[−0.82, 0.58]
$f_{\overline{T4}}/\Lambda^4$	[−0.38, 0.38]	[−0.30, 0.30]
f_{T5}/Λ^4	[−0.20, 0.16]	[−0.16, 0.13]
$f_{\overline{T5}}/\Lambda^4$	[−0.21, 0.21]	[−0.17, 0.17]
f_{T6}/Λ^4	[−0.65, 0.61]	[−0.52, 0.48]
$f_{\overline{T6}}/\Lambda^4$	[−0.62, 0.62]	[−0.50, 0.50]
f_{T7}/Λ^4	[−0.76, 0.61]	[−0.62, 0.47]

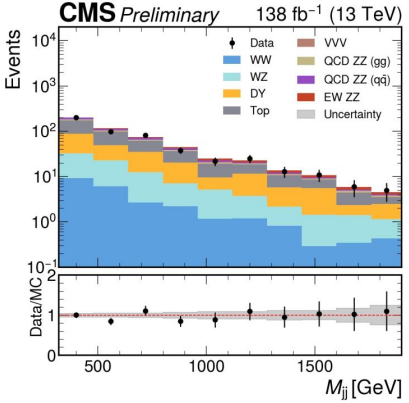
VBS ZZ

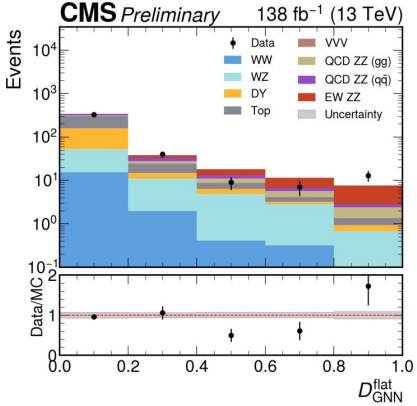
- 2ℓ, 2ν final state primary target for the analysis
- Cross section measurement: combined with previous ZZ→4ℓ evidence (4.0σ) [arXiv:2008.07013] for combined significance of 5.0σ



Process	Yield (events)
DY	111 ± 7
Top	159 ± 23
WW	18 ± 3
WZ	55 ± 3
QCD ZZ ($q\bar{q}$)	31 ± 3
QCD ZZ (gg)	20 ± 1
VVV	2 ± 0.1
Total background	395 ± 26
Total signal (EW ZZ)	22 ± 2
Total processes	416 ± 23
Data	400

SR for cross section measurement



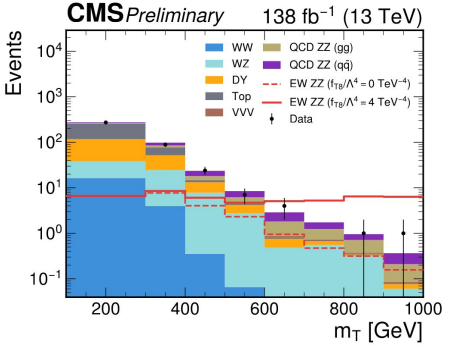


ZZ →2ℓ

Measured: σ^{fid} = 0.37+0.15-0.13 fb

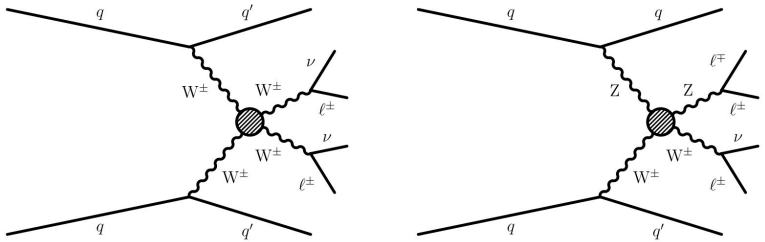
Predicted: σ^{fid} = 0.39±0.06 fb

SR for EFT bounds



Coupling	Expected 95% CL (TeV^{-4})	Observed 95% CL (TeV^{-4})	Unitarity limit (TeV)
f_{S0}/Λ^4	[−40, 40]	[−36, 37]	1.3
f_{S1}/Λ^4	[−31, 32]	[−28, 28]	1.1
f_{S2}/Λ^4	[−39, 40]	[−35, 37]	1.1
f_{M0}/Λ^4	[−6.9, 6.9]	[−6.5, 6.6]	1.6
f_{M1}/Λ^4	[−24, 24]	[−23, 23]	1.6
f_{M2}/Λ^4	[−8.3, 8.4]	[−7.8, 7.8]	1.5
f_{M3}/Λ^4	[−29, 29]	[−27, 27]	1.5
f_{M4}/Λ^4	[−20, 19]	[−18, 18]	1.5
f_{M5}/Λ^4	[−28, 28]	[−25, 26]	1.7
f_{M7}/Λ^4	[−44, 44]	[−40, 40]	1.7
f_{T0}/Λ^4	[−1.5, 1.2]	[−1.5, 1.1]	1.5
f_{T1}/Λ^4	[−1.7, 1.6]	[−1.6, 1.5]	1.7
f_{T2}/Λ^4	[−3.7, 3.2]	[−3.6, 2.8]	1.6
f_{T3}/Λ^4	[−3.8, 3.3]	[−3.7, 2.9]	1.7
f_{T4}/Λ^4	[−8.6, 7.8]	[−8.3, 7.1]	1.6
f_{T5}/Λ^4	[−3.3, 2.8]	[−3.1, 2.6]	1.5
f_{T6}/Λ^4	[−4.2, 4.1]	[−3.9, 3.8]	1.5
f_{T7}/Λ^4	[−11, 9.2]	[−10, 8.23]	1.6
f_{T8}/Λ^4	[−2.2, 2.2]	[−2.1, 2.1]	1.2
f_{T9}/Λ^4	[−4.6, 4.6]	[−4.3, 4.3]	1.2
f_{S0}/Λ^4	[−40, 40]	[−36, 37]	1.3
f_{S1}/Λ^4	[−31, 32]	[−28, 28]	1.1
f_{S2}/Λ^4	[−39, 40]	[−35, 37]	1.1

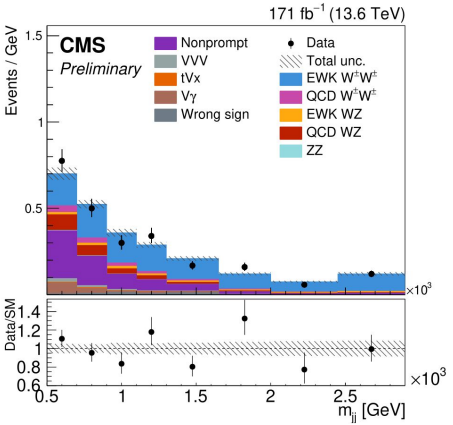
VBS: $W^{\pm}W^{\mp}$ and $W^{\pm}Z$ (Run 3)

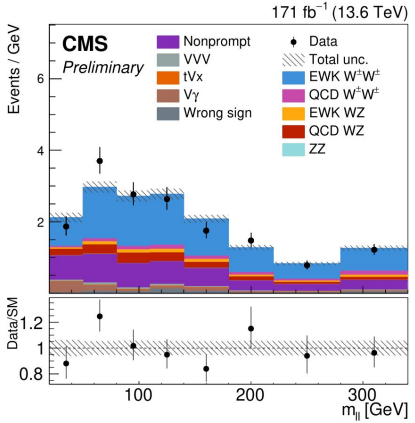


- Select leptonic final states + jets
- SRs, CRs included in ML fit
  - Cross sections for EW WW, EW WZ, and QCD WZ floated. Normalizations for nonprompt lepton and tZq floated

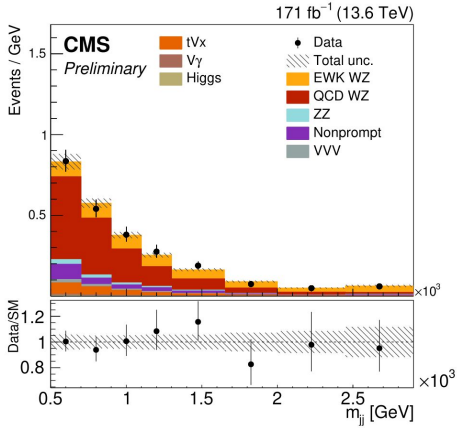
Process	$W^{\pm}W^{\pm}$ SR	Nonprompt lepton CR	WZ SR	tZq CR
EW $W^{\pm}W^{\pm}$	282 ± 36	98 ± 13	—	—
QCD $W^{\pm}W^{\pm}$	25.5 ± 3.0	17.9 ± 2.0	—	—
EW WZ	20.8 ± 4.5	9.7 ± 1.9	131 ± 25	0.8 ± 0.2
QCD WZ	48.6 ± 9.1	40.9 ± 6.0	288 ± 49	11.4 ± 2.3
ZZ	1.6 ± 0.3	1.3 ± 0.2	18.8 ± 3.8	0.8 ± 0.1
Nonprompt	142 ± 39	348 ± 47	47 ± 23	17.0 ± 8.4
VVV	9.8 ± 2.6	20.8 ± 3.9	11.3 ± 2.6	0.4 ± 0.1
tVx	3.7 ± 1.4	49.7 ± 8.4	44 ± 13	102 ± 16
$W\gamma$	23 ± 10	12.5 ± 4.2	4.6 ± 2.3	0.2 ± 0.1
Wrong-sign	13.6 ± 7.1	36.5 ± 9.8	—	—
Higgs boson	—	—	2.6 ± 1.3	1.4 ± 0.3
Total SM	571 ± 24	636 ± 25	548 ± 23	134 ± 12
Data	578	629	547	135

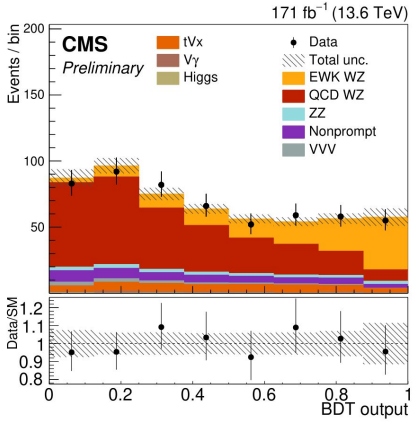
WW SR ($+\Delta\eta_{jj}$, $\Delta\phi_{jj}$, n_j distributions)





WZ SR



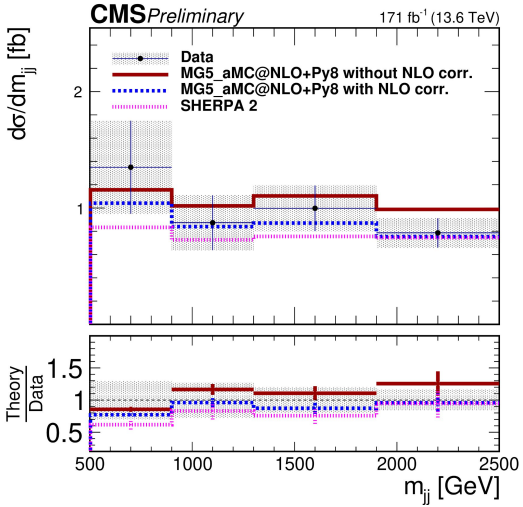


VBS: $W^{\pm}W^{\mp}$ and $W^{\pm}Z$ (Run 3)

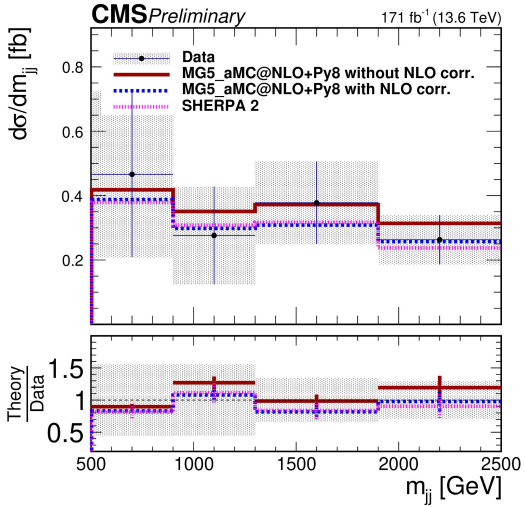
Inclusive production cross sections

Process	$\sigma\,\mathcal{B}$ (fb)	MadGraph5_aMC@NLO prediction without NLO corrections (fb)	MadGraph5_aMC@NLO prediction with NLO corrections (fb)	SHERPA prediction without NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.81 ± 0.38 (0.33 (stat) $\pm$ 0.18 (syst))	4.27 ± 0.38	3.51 ± 0.31	3.06 ± 0.46
EW+QCD $W^{\pm}W^{\pm}$	4.32 ± 0.40 (0.36 (stat) $\pm$ 0.18 (syst))	4.75 ± 0.52	3.99 ± 0.44	—
EW WZ	1.43 ± 0.26 (0.23 (stat) $\pm$ 0.12 (syst))	1.45 ± 0.13	1.25 ± 0.11	1.24 ± 0.19
EW+QCD WZ	4.75 ± 0.35 (0.27 (stat) $\pm$ 0.22 (syst))	4.59 ± 1.07	4.39 ± 1.05	—

WW



WZ



Additional WW differential distributions:

m_{ll}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, n_j

Summary

- Multiboson production provides stringent tests of the SM and access to potential new physics (aTGC, aQGC)
- Several new results from CMS
- Run 2 analyses setting bounds on dim-8 WCs:
  - VVV [SMP-24-017] – *on arXiv ASAP!*
  - γγ-fusion W^+W^- [arXiv:2601.21574]
  - VBS ZZ [SMP-23-001]
- Run 3 analysis:
  - VBS $W^\pm W^\mp$ and $W^\pm Z$ [SMP-25-013]
- Stay tuned!

WC	VVV	$\gamma\gamma \to W^+W^-$	VBS ZZ
$f_{T,0}/\Lambda^4$	[-0.57,0.63]	**[-0.53,0.42]**	[-1.5,1.1]
$f_{T,1}/\Lambda^4$	**[-0.63,0.70]**	[-1.71,1.59]	[-1.6,1.5]
$f_{T,2}/\Lambda^4$	**[-1.29,1.39]**	[-2.04,1.56]	[-3.6,2.8]
$f_{T,3}/\Lambda^4$	**[-1.22,1.32]**	[-2.69,1.90]	[-3.7,2.9]
$f_{T,4}/\Lambda^4$	[-9.2,9.0]	**[-0.82,0.58]**	[-8.3,7.1]
$f_{T,5}/\Lambda^4$	[-4.0,3.9]	**[-0.16,0.13]**	[-3.1,2.6]
$f_{T,6}/\Lambda^4$	[-4.9,4.8]	**[-0.52,0.48]**	[-3.9,3.8]
$f_{T,7}/\Lambda^4$	[-10,10]	**[-0.62,0.47]**	[-10,8.23]
$f_{T,8}/\Lambda^4$	[-11,12]	–	**[-2.1,2.1]**
$f_{T,9}/\Lambda^4$	[-22,23]	–	**[-4.3,4.3]**
$f_{M,0}/\Lambda^4$	[-3.8,4.0]	**[-3.24,3.25]**	[-6.5,6.6]
$f_{M,1}/\Lambda^4$	**[-6.7,6.4]**	[-12.31,12.03]	[-23,23]
$f_{M,2}/\Lambda^4$	[-14,14]	**[-0.49,0.50]**	[-7.8,7.8]
$f_{M,3}/\Lambda^4$	[-23,23]	**[-1.88,1.84]**	[-27,27]
$f_{M,4}/\Lambda^4$	[-13,13]	**[-1.79,1.80]**	[-18,18]
$f_{M,5}/\Lambda^4$	[-11,11]	**[-3.32,3.40]**	[-25,26]
$f_{M,7}/\Lambda^4$	**[-10,11]**	[-24.06,24.62]	[-40,40]
$f_{S,0}/\Lambda^4$	[-38,38]	–	**[-36,37]**
$f_{S,1}/\Lambda^4$	**[-26,26]**	–	[-28,28]
$f_{S,2}/\Lambda^4$	[-38,39]	–	**[-35,37]**

Backups

Triboson (VVV) Production at the LHC

V = W,Z

- Triboson production provides a precision test of the EW sector
- Rare process with access to, e.g., aTGC and aQGC.
  - SM cross sections @ 13 TeV: 509 fb (WWW), 354 fb (WWZ), 91.6 fb (WZZ), 37.1 (ZZZ)

→ Prime candidate for an EFT search.

SM VVV:

- ATLAS evidence of WWW and WWZ (4.1σ) using Run 2 data [PLB 798, 134913] (2019)
- CMS observation of VVV (5.7σ) using Run 2 data [PRL 125, 151802] (2020)
- ATLAS observation of WWW (8.0σ) using Run 2 data [PRL 129, 061803] (2022)
- CMS evidence of WWZ and ZH (4.5σ) with Run 2 and partial Run 3 data [PRL 135, 091802] (2025)

EFT Analyses:

- ATLAS observation of VVZ production (6.4σ obs. significance) and bounds on several mixed dim-8 operators with Run 2 data [PLB 886, 139527] (2025)
- **CMS – first analysis of VVV that includes dimension-6 Wilson coefficients. [SMP-24-017]**
  - Analysis is designed to target boosted objects (leptons, jets): EFT effects grow with ŝ. Additionally, SM backgrounds fall as ŝ increases.
  - We set bounds on a 12 dimension-6 (dim6) and 20 dimension-8 (dim8) Wilson coefficients (WCs) and provide additional results (2D contours, clipping, template fit, SM sensitivity)

VVV: List of WCs

dim6

Warsaw basis [JHEP 2010, 85]

Operator $\mathcal{O}_i$	Wilson coefficient
Gauge boson self-interaction	
$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	c_W
$\Phi^\dagger \Phi \, W_{I\mu\nu} W^{I\mu\nu}$	c_{HW}
$\Phi^\dagger \Phi \, B_{\mu\nu} B^{\mu\nu}$	c_{HB}
$\Phi^\dagger \tau^I \Phi \, W^I_{\mu\nu} B^{\mu\nu}$	c_{HWB}
$(\Phi^\dagger \Phi) \Box (\Phi^\dagger \Phi)$	$c_{H\Box}$
$(\Phi^\dagger D_\mu \Phi)^\star (\Phi^\dagger D^\mu \Phi)$	c_{HDD}
Gauge boson and fermion interaction	
$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$	c_{Hq3}
$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{q}_p \gamma^\mu q_r)$	c_{Hq1}
$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_p \gamma^\mu u_r)$	c_{Hu}
$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{d}_p \gamma^\mu d_r)$	c_{Hd}
$(\Phi^\dagger i \overleftrightarrow{D}^I_\mu \Phi)(\bar{\ell}_p \tau^I \gamma^\mu \ell_r)$	$c_{H\ell 3}$
Four-fermion interaction	
$(\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t)$	$c_{\ell\ell 1}$

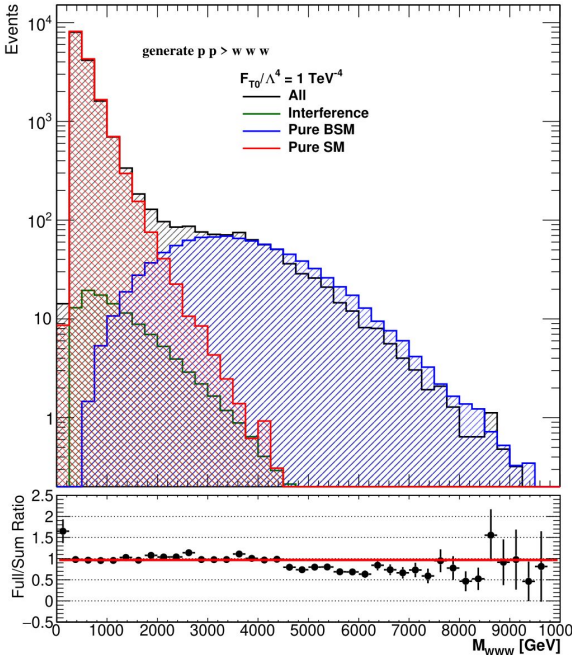
dim8

Éboli basis [PRD 93, 093013]

Operator $\mathcal{O}_j$	Wilson coefficient
Longitudinal operators	
$[(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\mu \Phi)^\dagger D^\nu \Phi]$	$f_{S,0}$
$[(D_\mu \Phi)^\dagger D^\mu \Phi] \times [(D_\nu \Phi)^\dagger D^\nu \Phi]$	$f_{S,1}$
$[(D_\mu \Phi)^\dagger D_\nu \Phi] \times [(D^\nu \Phi)^\dagger D^\mu \Phi]$	$f_{S,2}$
Transverse operators	
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times \mathrm{Tr}[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta}]$	$f_{T,0}$
$\mathrm{Tr}[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$	$f_{T,1}$
$\mathrm{Tr}[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha}]$	$f_{T,2}$
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}_{\alpha\beta}] \times \mathrm{Tr}[\hat{W}^{\alpha\nu} \hat{W}^{\mu\beta}]$	$f_{T,3}$
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}_{\alpha\beta}] \times B^{\alpha\nu} B^{\mu\beta}$	$f_{T,4}$
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times B_{\alpha\beta} B^{\alpha\beta}$	$f_{T,5}$
$\mathrm{Tr}[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times B_{\mu\beta} B^{\alpha\nu}$	$f_{T,6}$
$\mathrm{Tr}[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta}] \times B_{\beta\nu} B^{\nu\alpha}$	$f_{T,7}$
$B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$	$f_{T,8}$
$B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$	$f_{T,9}$
Mixed operators	
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi]$	$f_{M,0}$
$\mathrm{Tr}[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi]$	$f_{M,1}$
$[B_{\mu\nu} B^{\mu\nu}] \times [(D_\beta \Phi)^\dagger D^\beta \Phi]$	$f_{M,2}$
$[B_{\mu\nu} B^{\nu\beta}] \times [(D_\beta \Phi)^\dagger D^\mu \Phi]$	$f_{M,3}$
$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi] \times B^{\beta\nu}$	$f_{M,4}$
$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi] \times B^{\beta\mu} + \mathrm{H.c.}$	$f_{M,5}$
$[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi]$	$f_{M,7}$

VVV: Impact of EFT (generator level)

$f_{T,0}$



10 TeV

VVV: Final State Objects

Leptons (e / μ)

- e ID using MVA trained on: shower shape, track-cluster matching, track quality, …
- e selection algorithm distinguishes: e from hard scatter; e from mis-ID charged hadrons or from gamma conversion
- μ candidates reconstructed using information from tracker & muon chamber + requires minimal deposits in calorimeters
- e/μ isolation criteria applied to reduce non-prompt lepton backgrounds

Hadronic τ (τ_h)

- Hadrons-plus-strips (HPS) algorithm identifies candidate τ_h with 1 or 3 charged prongs from PF candidates
- Includes decays with $\leq 2\pi^0$
- HPS candidates fed into DeepTau algorithm for further discrimination from e, μ, jets

V-tagged jets (VTJ)

- anti-kT algorithm used to cluster jets using R=0.8 (i.e. AK-8 jets, “large radius”) and R=0.4 (i.e. AK-4 jets, “small radius”)
- Exclusions in clustering e.g. charged hadrons not from PV
- Jet energy correction applied; pileup mitigations applied; lepton isolation applied
- Jets groomed using soft drop (SD) algorithm
- ParticleNet algorithm used to identify jets from boosted V
- AK-8 jets that pass selections and pass the ParticleNet & m_{SD} requirements (channel dependent) are called “VTJ”

- Reconstructed particle-flow (PF) candidates analyzed to construct final states objects
- A variety of p_T thresholds & other kinematic requirements applied at pre-selection level. Channel specific cuts applied downstream.

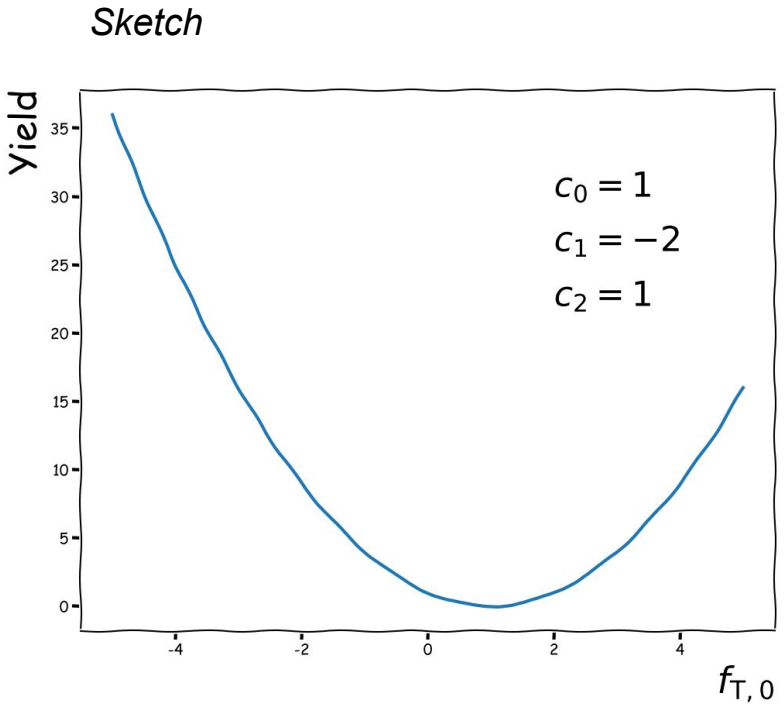
Statistical Combination

- VVV yields supplied as parabola parameter histograms, per final state bin:

  $y = c_0 + c_1 * WC + c_2 * WC^2$

  - c_0 = SM VVV
  - c_2 = pure EFT
  - c_1 = interference between SM and EFT

- Extension to multiple WCs varying is a paraboloid.
- All SR bins combined in one likelihood function. ΔNLL vs. WC computed using the CMS COMBINE tool [Comput Softw Big Sci 8, 19]



VVV: Measurements dim-6

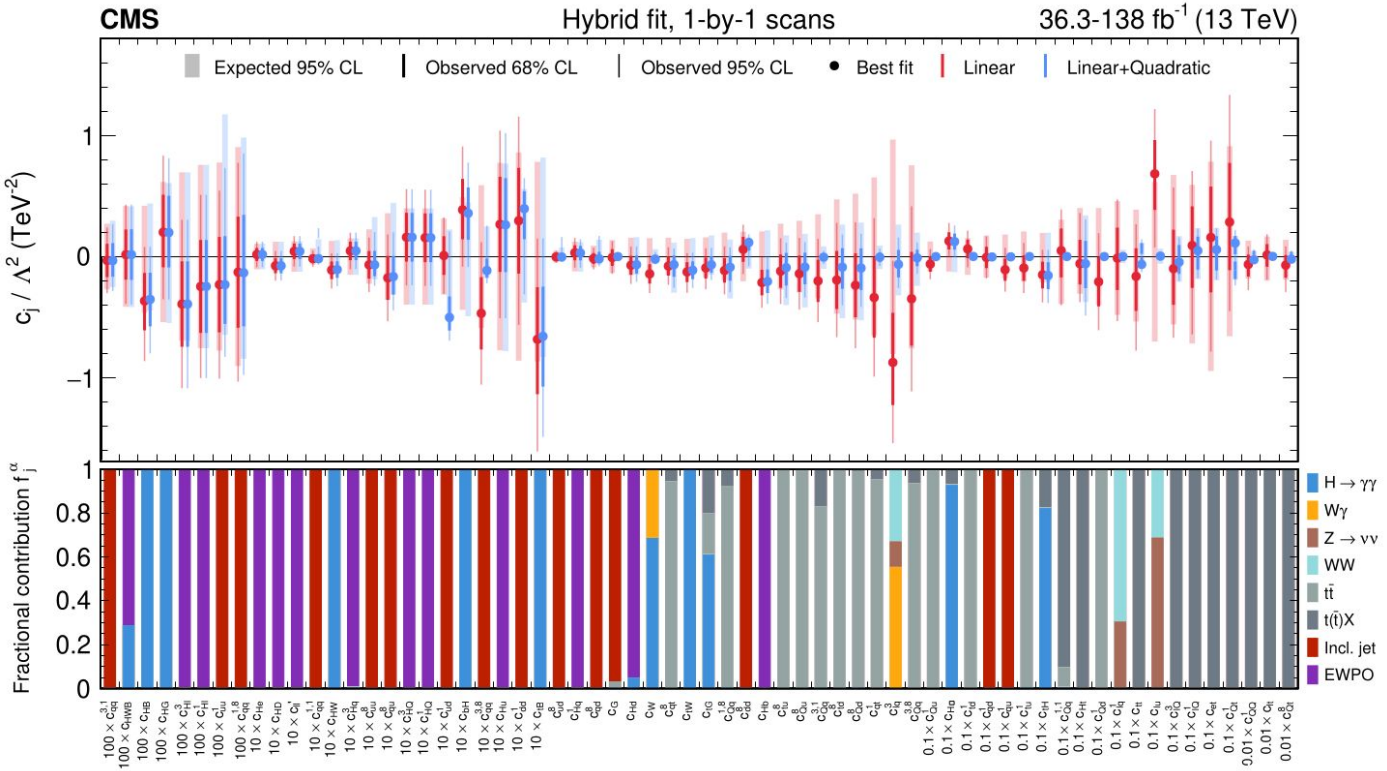
	Freeze other WCs	Profile other WCs
Wilson coefficient	Measurement [TeV^{-2}] Observed	Measurement [TeV^{-2}] Observed
c_W/Λ^2	$0.03^{+0.053}_{-0.11}$	$0.001^{+0.057}_{-0.055}$
c_{Hq3}/Λ^2	$0.05^{+0.09}_{-0.21}$	$-0.14^{+0.36}_{-0.16}$
c_{Hq1}/Λ^2	$0.10^{+0.12}_{-0.33}$	$-0.17^{+0.13}_{-0.11}$ or $0.19^{+0.10}_{-0.13}$
c_{Hu}/Λ^2	$0.09^{+0.29}_{-0.47}$	$0.04^{+0.40}_{-0.60}$
c_{Hd}/Λ^2	$0.10^{+0.39}_{-0.59}$	$-0.03^{+0.65}_{-0.46}$
c_{HW}/Λ^2	$0.17^{+0.84}_{-1.22}$	$0.5^{+1.8}_{-2.2}$
c_{HWB}/Λ^2	$0.5^{+2.7}_{-3.8}$	$1.6^{+5.3}_{-7.1}$
$c_{H\ell 3}/\Lambda^2$	$14.4^{+0.9}_{-2.7}$	$16.1^{+3.7}_{-5.9}$
c_{HB}/Λ^2	$0.7^{+6.4}_{-7.8}$	$0.7^{+5.7}_{-6.1}$
$c_{\ell\ell 1}/\Lambda^2$	-25^{+4}_{-4} or $5.1^{+1.6}_{-5.8}$	-25^{+5}_{-5} or $1.6^{+4.7}_{-3.1}$
$c_{H\Box}/\Lambda^2$	29^{+23}_{-85}	-32^{+82}_{-21}
c_{HDD}/Λ^2	-58^{+104}_{-32}	8^{+34}_{-138}

EFT Combination (dim-6)

- 7 Run 2 SM analyses combined: H→γγ, t tbar→lepton + jets, t tbar X, WW (l ν l ν), W (l ν) γ, Z →ν ν, inclusive jet production
  - EWPO included in the fit
- Most of the inputs are cross sections reinterpreted as bounds on WCs (except t tbar X)
- 64 dim-6 operators studied, primarily targeting linear term (bounds with quadratic term are also produced)
- PCA performed to also constrain 43 linear combinations of WCs

EFT Combination (dim-6)

Bounds

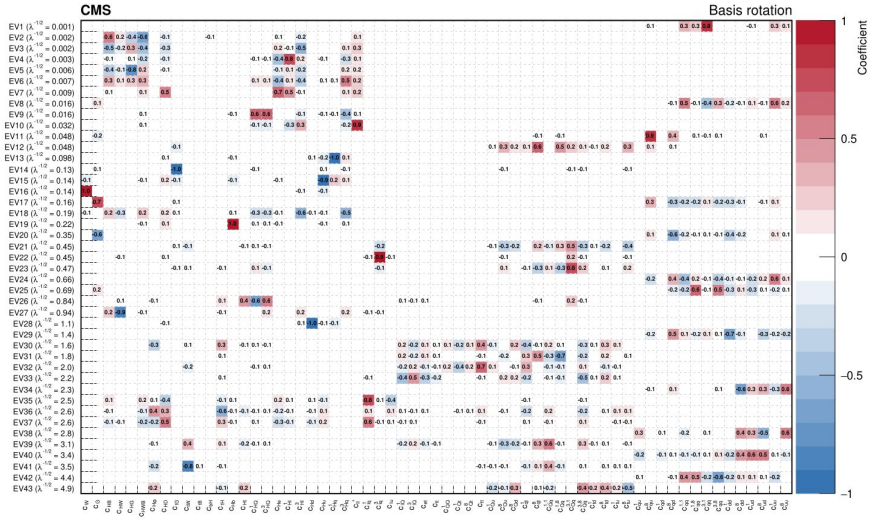


EFT Combination (dim-6)

POI	Expected (linear)	Observed (linear)	Best fit (linear)	Expected (lin.+quad.)	Observed (lin.+quad.)	Best fit (lin.+quad.)
$c_{qq}^{(3,1)}/\Lambda^2$	$[-0.003, 0.003]$	$[-0.003, 0.002]$	-0.000	$[-0.003, 0.003]$	$[-0.003, 0.003]$	-0.000
c_{HWB}/Λ^2	$[-0.004, 0.004]$	$[-0.004, 0.004]$	$+0.000$	$[-0.004, 0.004]$	$[-0.004, 0.004]$	$+0.000$
c_{HB}/Λ^2	$[-0.005, 0.004]$	$[-0.009, 0.001]$	-0.004	$[-0.004, 0.004]$	$[-0.008, 0.001]$	-0.004
c_{HG}/Λ^2	$[-0.005, 0.006]$	$[-0.004, 0.008]$	$+0.002$	$[-0.005, 0.006]$	$[-0.004, 0.008]$	$+0.002$
$c_{qq}^{(1,1)}/\Lambda^2$	$[-0.007, 0.007]$	$[-0.008, 0.005]$	-0.002	$[-0.005, 0.014]$	$[-0.007, 0.008]$	-0.002
$c_{Hl}^{(3)}/\Lambda^2$	$[-0.007, 0.007]$	$[-0.011, 0.003]$	-0.004	$[-0.007, 0.007]$	$[-0.011, 0.003]$	-0.004
$c_{Hl}^{(1)}/\Lambda^2$	$[-0.008, 0.008]$	$[-0.010, 0.005]$	-0.002	$[-0.008, 0.008]$	$[-0.010, 0.005]$	-0.002
$c_{uu}^{(1)}/\Lambda^2$	$[-0.008, 0.008]$	$[-0.010, 0.005]$	-0.002	$[-0.006, 0.012]$	$[-0.008, 0.007]$	-0.002
$c_{qq}^{(1,8)}/\Lambda^2$	$[-0.009, 0.009]$	$[-0.010, 0.008]$	-0.001	$[-0.008, 0.010]$	$[-0.010, 0.009]$	-0.001
c_{He}/Λ^2	$[-0.011, 0.011]$	$[-0.009, 0.012]$	$+0.002$	$[-0.011, 0.011]$	$[-0.009, 0.012]$	$+0.002$
c_{HD}/Λ^2	$[-0.012, 0.012]$	$[-0.020, 0.005]$	-0.008	$[-0.012, 0.012]$	$[-0.020, 0.005]$	-0.008
c_{ll}'/Λ^2	$[-0.013, 0.013]$	$[-0.008, 0.017]$	$+0.004$	$[-0.013, 0.013]$	$[-0.008, 0.017]$	$+0.004$
c_{HW}/Λ^2	$[-0.014, 0.013]$	$[-0.027, 0.003]$	-0.011	$[-0.014, 0.013]$	$[-0.025, 0.003]$	-0.011
$c_{Hq}^{(3)}/\Lambda^2$	$[-0.015, 0.015]$	$[-0.010, 0.020]$	$+0.005$	$[-0.015, 0.015]$	$[-0.010, 0.020]$	$+0.005$
$c_{uu}^{(8)}/\Lambda^2$	$[-0.022, 0.022]$	$[-0.029, 0.016]$	-0.007	$[-0.019, 0.033]$	$[-0.024, 0.020]$	-0.007
$c_{ud}^{(1)}/\Lambda^2$	$[-0.032, 0.032]$	$[-0.031, 0.032]$	$+0.001$	$[-0.054, 0.022]$	$[-0.070, 0.021]$	-0.050
$c_{qu}^{(8)}/\Lambda^2$	$[-0.036, 0.036]$	$[-0.054, 0.018]$	-0.018	$[-0.031, 0.044]$	$[-0.045, 0.020]$	-0.017
$c_{HQ}^{(3)}/\Lambda^2$	$[-0.040, 0.040]$	$[-0.024, 0.056]$	$+0.016$	$[-0.040, 0.040]$	$[-0.024, 0.056]$	$+0.016$
$c_{HQ}^{(1)}/\Lambda^2$	$[-0.040, 0.040]$	$[-0.024, 0.055]$	$+0.016$	$[-0.040, 0.040]$	$[-0.024, 0.055]$	$+0.016$
$\mathrm{Re}(c_{bH})/\Lambda^2$	$[-0.044, 0.049]$	$[-0.008, 0.091]$	$+0.039$	$[-0.049, 0.045]$	$[-0.008, 0.078]$	$+0.036$
$c_{ud}^{(8)}/\Lambda^2$	$[-0.049, 0.049]$	$[-0.052, 0.046]$	-0.003	$[-0.041, 0.075]$	$[-0.045, 0.160]$	-0.004
$c_{qq}^{(3,8)}/\Lambda^2$	$[-0.059, 0.059]$	$[-0.106, 0.012]$	-0.047	$[-0.018, 0.025]$	$[-0.022, 0.025]$	-0.012
c_{Hu}/Λ^2	$[-0.078, 0.077]$	$[-0.051, 0.104]$	$+0.027$	$[-0.078, 0.077]$	$[-0.051, 0.102]$	$+0.026$
$\mathrm{Re}(c_{tB})/\Lambda^2$	$[-0.087, 0.078]$	$[-0.161, 0.015]$	-0.068	$[-0.083, 0.082]$	$[-0.149, 0.015]$	-0.066
$c_{dd}^{(1)}/\Lambda^2$	$[-0.086, 0.086]$	$[-0.057, 0.116]$	$+0.030$	$[-0.038, 0.056]$	$[-0.031, 0.065]$	$+0.040$
$c_{qd}^{(8)}/\Lambda^2$	$[-0.089, 0.089]$	$[-0.106, 0.073]$	-0.017	$[-0.066, 0.138]$	$[-0.080, 0.171]$	-0.019
$c_{Hq}^{(1)}/\Lambda^2$	$[-0.12, 0.12]$	$[-0.09, 0.15]$	$+0.03$	$[-0.13, 0.12]$	$[-0.09, 0.14]$	$+0.03$
c_G/Λ^2	$[-0.14, 0.14]$	$[-0.14, 0.13]$	-0.01	$[-0.017, 0.015]$	$[-0.016, 0.014]$	-0.000
$\mathrm{Re}(c_{tW})/\Lambda^2$	$[-0.16, 0.15]$	$[-0.30, 0.03]$	-0.13	$[-0.15, 0.15]$	$[-0.26, 0.03]$	-0.11
$c_{qt}^{(8)}/\Lambda^2$	$[-0.15, 0.15]$	$[-0.23, 0.08]$	-0.08	$[-0.30, 0.12]$	$[-0.26, 0.07]$	-0.07
c_{Hd}/Λ^2	$[-0.15, 0.16]$	$[-0.23, 0.08]$	-0.07	$[-0.15, 0.16]$	$[-0.21, 0.08]$	-0.07
c_W/Λ^2	$[-0.16, 0.15]$	$[-0.30, 0.01]$	-0.14	$[-0.061, 0.061]$	$[-0.066, 0.037]$	-0.022

EFT Combination (dim-6)

PCA Rotation Matrix



Bounds