Electroweak analyses at the LHC: status and prospects

EFTs at the LHC: Theory and Experiment

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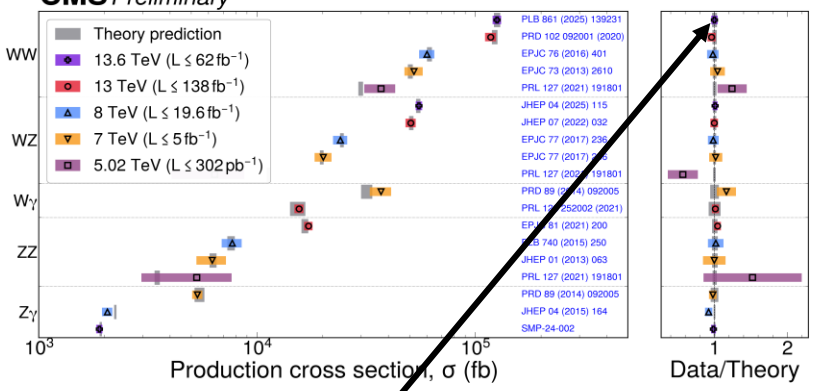
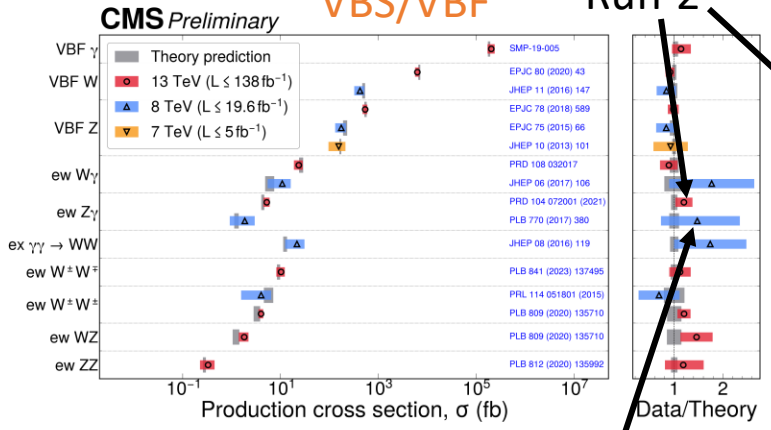
Multiboson production at the LHC

- We are entering the precision era for multiboson measurements

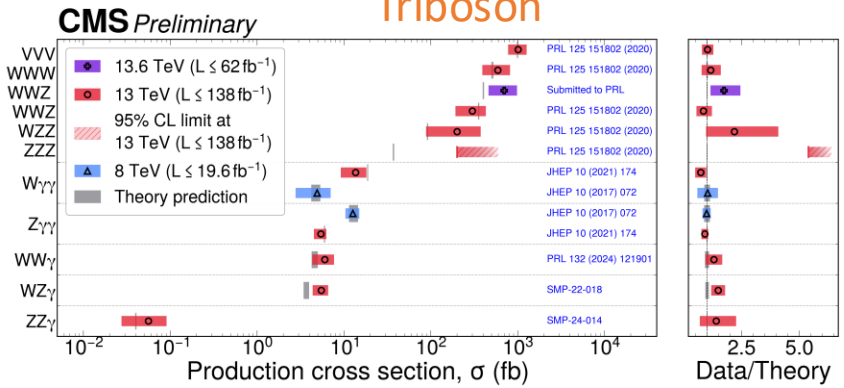
Diboson (inclusive)



VBS/VBF



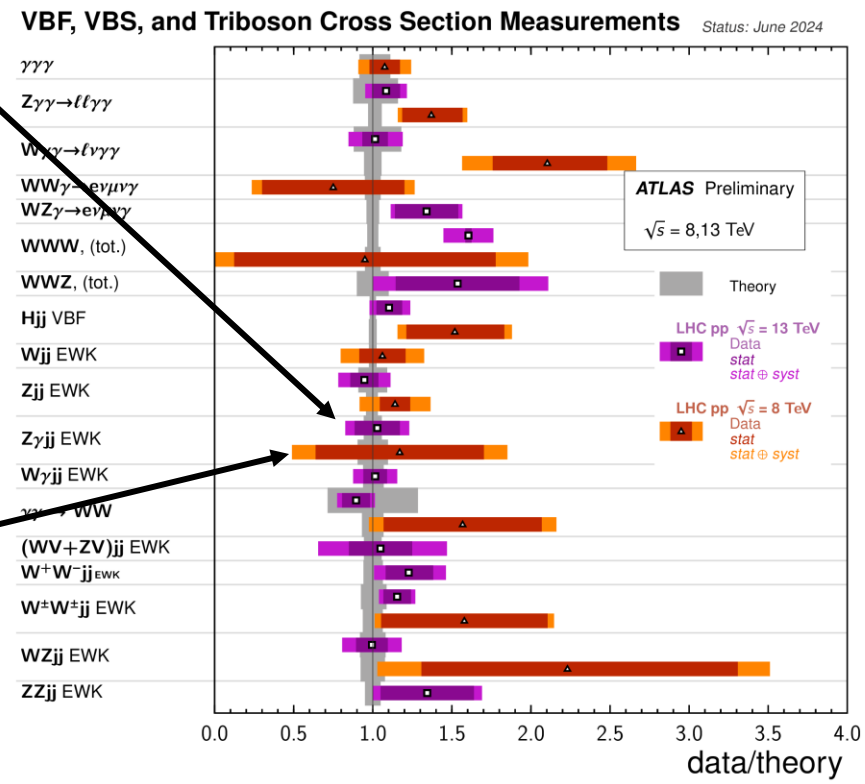
Triboson



Run-3

Run-2

Run-1

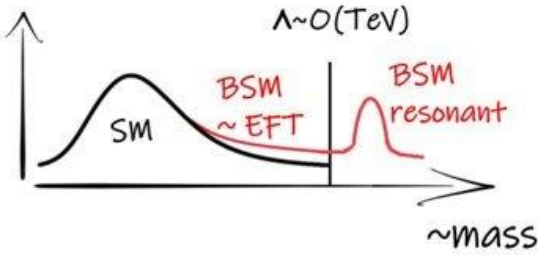


ATL-PHYS-PUB-2024-011

CMS results

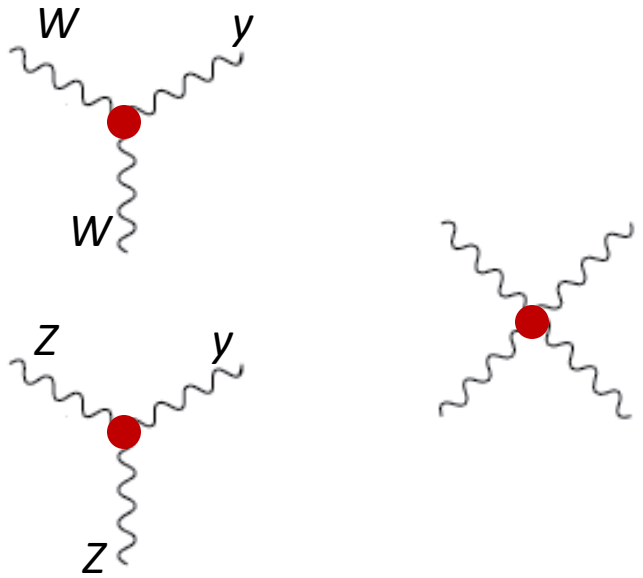
- Look for deviations from SM prediction: new physics ?

Effective Field Theory (EFT) approach



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

- Dimension-6 operators
  - Charged anomalous triple gauge couplings (aTGCs)
  - Anomalous quartic gauge couplings (aQGCs)
  - Mainly probed by inclusive diboson measurements
- Dimension-8 operators
  - aTGCs including neutral triple gauge couplings (nTGCs)
    - Mainly probed by inclusive neutral diboson measurements
  - aQGCs without affecting TGCs
    - Probed by vector boson scattering (VBS) and triboson measurements



- Odd-dimension operators usually ignored in EW analyses
  - Violate lepton/baryon number conservation
  - Weinberg operator (dimension-5) probed in search for Majorana neutrinos with diboson final states

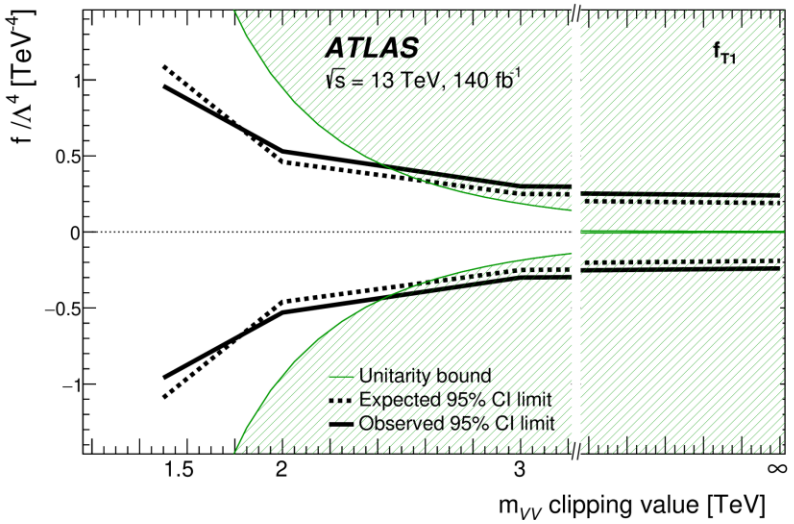
Bases

- Dimension-6
  - Warsaw basis
  - Covers EW, diboson, Higgs and Top operators

- Dimension-8
  - aQGCs: Eboli model used in Run-2, complete basis including C/P odd operators (superset of Eboli model) recommended for Run-3
  - nTGCs: bases from Degrande and Ellis *et al.*
  - Dimension-6 usually ignored when constraining dimension-8 operators

Unitarity

- aQGCs: violation of unitarity at high energy
- Can be prevented by reducing theory phase space
- Option used in many Run-2 analyses: clipping
  - Introduce a cut-off energy beyond which the Wilson coefficient is set to zero
  - Can perform clipping scans of experimental limits
  - Limits physically meaningful up to intersection with theoretical unitarity bounds: unitarized limits



Covered results

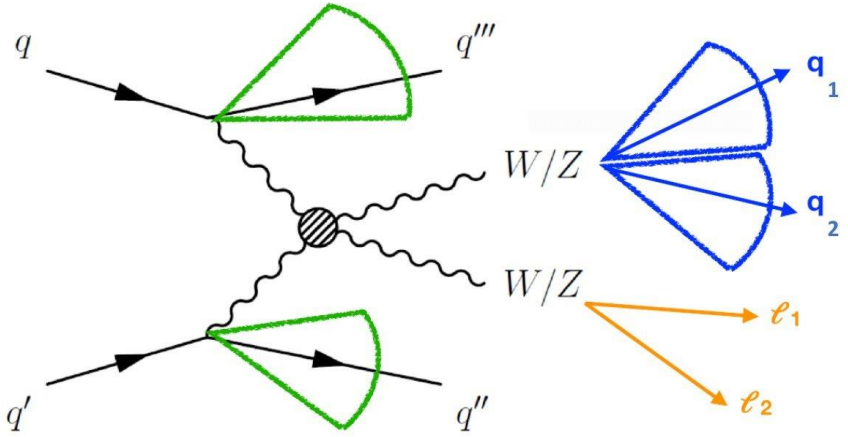
- Electroweak diboson production in association with a high-mass dijet system in semileptonic final states from *pp* collisions at 13 TeV (ATLAS)
- Study of semileptonic vector boson scattering and anomalous quartic gauge coupling from proton-proton collisions at 13 TeV (CMS)
- Observation of *WZy* production and constraints on new physics scenarios in proton-proton collisions at 13 TeV (CMS)
- Measurement of the photon-fusion production cross section of a pair of *W* bosons (CMS)
- Measurements of *Zy* differential cross sections and search for neutral triple gauge couplings in *pp* collisions at 13 TeV (ATLAS)
- Study of same-sign *W* boson scattering and anomalous couplings in events with one tau lepton from *pp* collisions at 13 TeV (CMS)
- Measurements and interpretations of *WZ* production cross-sections in *pp* collisions at 13 TeV (ATLAS)
- Combined effective field theory interpretation of Higgs boson, electroweak vector boson, top quark, and multi-jet measurements (CMS)

EW diboson production in semileptonic final states

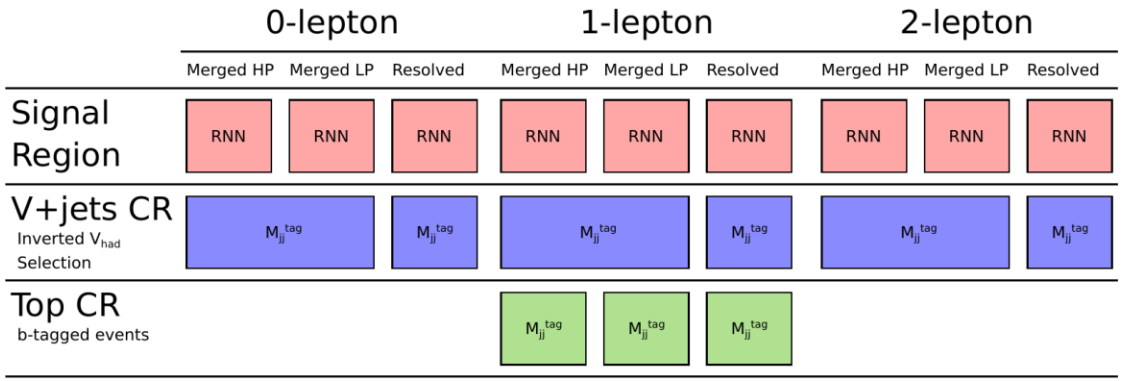
- EW diboson production: includes VBS processes

ATLAS EXPERIMENT arXiv:2503.17461

- High statistics compared to fully lepronic final states (but higher backgrounds)
- One boson decays leptonically
  - 0-lepton channel $\mathrm{V}\to q\bar{q}'$, $\mathrm{Z}\to \nu\bar{\nu}$.
  - 1-lepton channel $\mathrm{V}\to q\bar{q}'$, $\mathrm{W}\to l\nu$.
  - 2-lepton channel $\mathrm{V}\to q\bar{q}'$, $\mathrm{Z}\to l^{+}l^{-}$.
- The other one decays hadronically
  - Merged (boosted) regime: 1 large-*R* jet (*R*=1.0)
  - Resolved regime: 2 small-*R* jets (*R*=0.4)
- 9 Signal Regions (SRs) + 9 Control Regions (CRs)



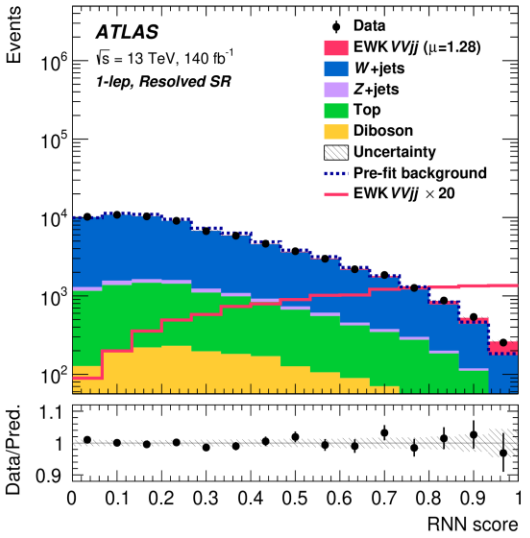
Tagging jets: forward, high invariant mass



High Purity (HP): passes 50% working point of *W*/*Z* tagger
Low Purity (LP): fails 50%, passes 80%

EW diboson production in semileptonic final states

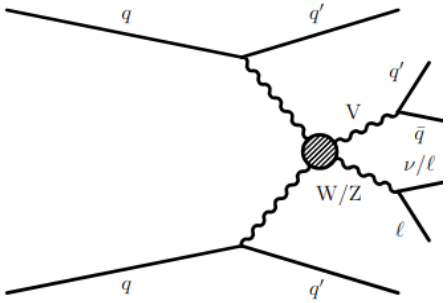
- Recurrent Neural Network (RNN) fitted
- Measured signal strength: $\mu_{\text{EW } VVjj} = 1.28 \pm 0.22$
  - Compatible with SM prediction
- Background-only hypothesis rejected with 7.4σ significance
  - First observation of EW diboson production in semileptonic final states
- $\sigma^{\text{fiducial}} = 29.2 \pm 4.9$ fb
- aQGC interpretation
  - All operators of Eboli model constrained
  - Unitarization
  - No deviation from SM
  - Probed scale at the TeV level for f=1
  - Competitive aQGC limits



Wilson coefficient	Expected limit [TeV^{-4}]	Observed limit [TeV^{-4}]	Expected limit unitarized [TeV^{-4}]	Observed limit unitarized [TeV^{-4}]
f_{T0}/Λ^4	[-0.20, 0.18]	[-0.25, 0.22]	[-0.79, 0.47] at [1.76, 1.96] TeV	[-0.85, 0.47] at [1.73, 2.00] TeV
f_{T1}/Λ^4	[-0.19, 0.19]	[-0.24, 0.24]	[-0.34, 0.34] at [2.59, 2.59] TeV	[-0.43, 0.43] at [2.43, 2.43] TeV
f_{T2}/Λ^4	[-0.44, 0.44]	[-0.55, 0.55]	[-0.95, 0.96] at [2.22, 2.22] TeV	[-1.16, 1.17] at [2.12, 2.11] TeV
f_{T3}/Λ^4	[-0.38, 0.38]	[-0.48, 0.48]	[-0.62, 0.62] at [2.71, 2.71] TeV	[-0.88, 0.88] at [2.49, 2.48] TeV
f_{T4}/Λ^4	[-1.46, 1.32]	[-1.51, 1.37]	[-3.03, 2.60] at [2.02, 2.09] TeV	[-3.03, 2.60] at [2.02, 2.10] TeV
f_{T5}/Λ^4	[-0.57, 0.53]	[-0.64, 0.58]	-	[-2.65, 2.57] at [1.53, 1.54] TeV
f_{T6}/Λ^4	[-0.76, 0.72]	[-0.74, 0.71]	[-2.82, 2.01] at [1.66, 1.73] TeV	[-2.98, 2.62] at [1.64, 1.69] TeV
f_{T7}/Λ^4	[-1.78, 1.52]	[-1.94, 1.70]	[-7.88, 4.29] at [1.65, 1.90] TeV	[-6.70, 4.11] at [1.72, 1.91] TeV
f_{T8}/Λ^4	[-0.59, 0.59]	[-0.48, 0.48]	-	-
f_{T9}/Λ^4	[-1.22, 1.22]	[-1.02, 1.03]	-	-
f_{S02}/Λ^4	[-3.22, 3.22]	[-3.96, 3.96]	[-5.53, 5.54] at [2.07, 2.67] TeV	[-6.16, 6.17] at [2.01, 2.01] TeV
f_{S1}/Λ^4	[-6.84, 6.86]	[-8.06, 8.06]	-	-
f_{M0}/Λ^4	[-1.13, 1.12]	[-1.26, 1.25]	[-2.61, 2.58] at [2.00, 2.00] TeV	[-2.71, 2.65] at [1.97, 1.98] TeV
f_{M1}/Λ^4	[-3.23, 3.24]	[-3.95, 3.95]	[-6.22, 6.22] at [2.27, 2.27] TeV	[-7.42, 7.43] at [2.17, 2.17] TeV
f_{M2}/Λ^4	[-1.66, 1.67]	[-1.85, 1.85]	-	-
f_{M3}/Λ^4	[-5.29, 5.29]	[-5.68, 5.71]	[-23.69, 23.39] at [1.57, 1.57] TeV	[-18.62, 19.10] at [1.66, 1.65] TeV
f_{M4}/Λ^4	[-2.62, 2.62]	[-2.96, 2.97]	-	-
f_{M5}/Λ^4	[-3.81, 3.82]	[-4.41, 4.44]	[-6.80, 6.80] at [2.33, 2.33] TeV	[-7.28, 7.30] at [2.29, 2.29] TeV
f_{M7}/Λ^4	[-5.32, 5.20]	[-6.60, 6.43]	[-9.47, 9.38] at [2.43, 2.43] TeV	[-11.91, 11.11] at [2.29, 2.33] TeV

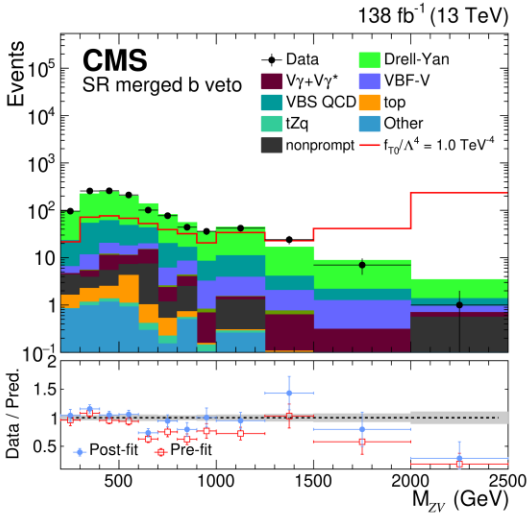
Semileptonic VBS and aQGCs

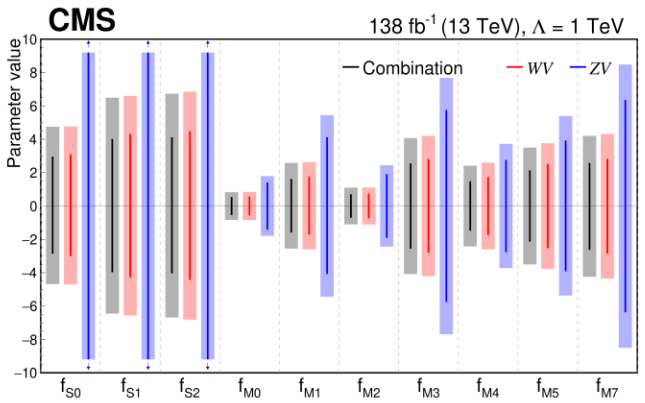
1-lepton: *lvqq*
2-lepton: *llqq*
No 0-lepton

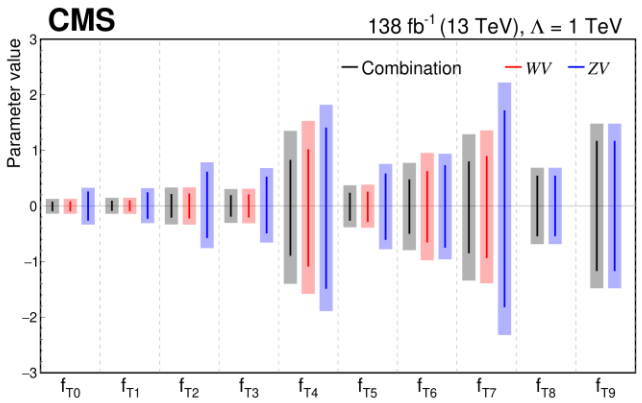


arXiv:2510.00118

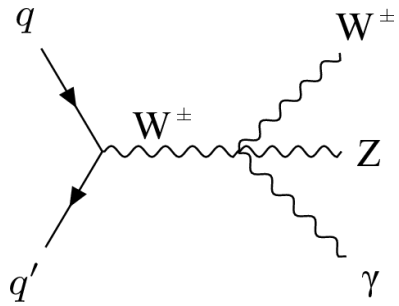
- Equivalent measurement, focused on aQGCs
- *ZVjj* EW production measurement
  - Boosted (*R*=0.8 jet) and resolved (*R*=0.4 jets) categories
  - 4 SRs (*b*-tag boosted, *b*-tag boosted, *b*-veto boosted, *b*-veto resolved)
  - CRs to constrain Drell-Yan and Top backgrounds
  - DNN fitted: $\mu_{\mathrm{EW}\,ZVjj} = 0.63 \pm 0.52$, 1.3σ significance
- Combined with *WVjj* measurement to constrain aQGCs
  - Only boosted events
  - Invariant mass of diboson system fitted
  - Current best limits for most Wilson coefficients of Eboli model
  - No unitarization procedure







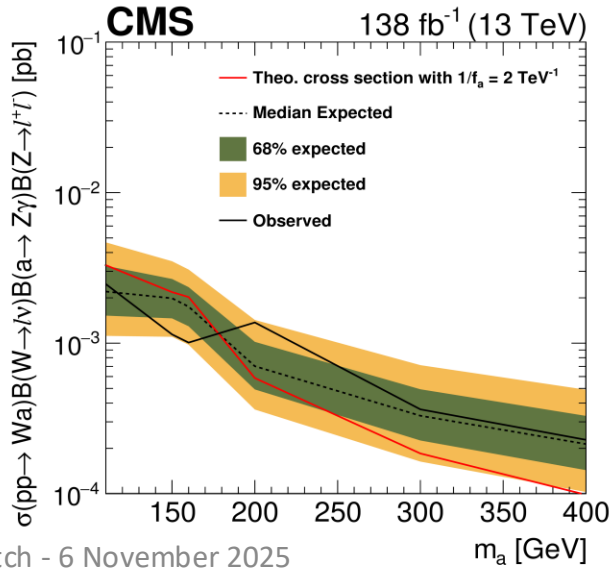
WZy production

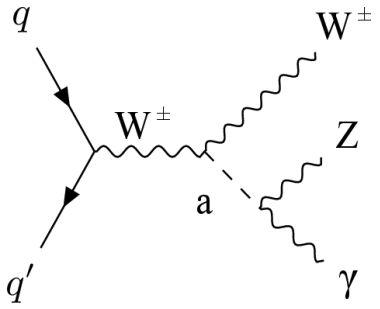


- *WZy* triboson production measurement
  - Signal involves *WWZy* vertex
- Final states with three charged leptons and one photon
  - One SR, CRs for *ZZ* and non-prompt lepton/photon
  - Fits to m_{Zy} in SR and non-prompt *y* CR, m_{lll} in *ZZ* and non-prompt lepton CRs
- Measured signal strength: $\mu_{WZy} = 1.47 \pm 0.31$, 5.4σ significance
- aQGC constraints
  - Not competitive with VBS

Operators	Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[-2.60, 2.60]	[-2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[-3.28, 3.24]	[-3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[-7.15, 7.05]	[-6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[-2.54, 2.56]	[-2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[-3.18, 3.22]	[-3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[-6.85, 7.05]	[-6.65, 6.85]	1.71

- Limits for massive axion-like particles





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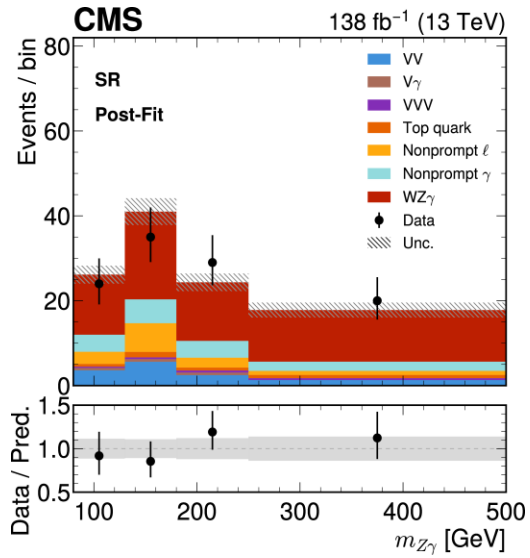
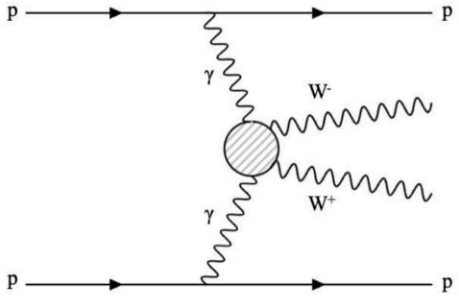
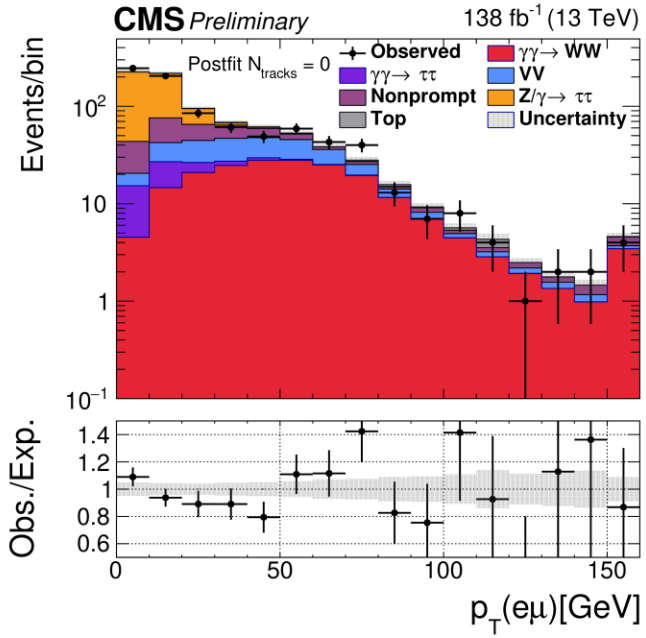


Photon-fusion production of *W* bosons

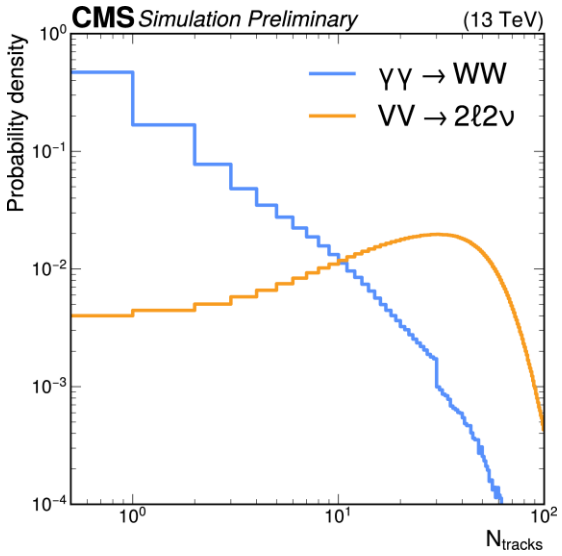
- $\gamma\gamma W^+W^-$ production
  - Look for leptonic decay
  - Limited track multiplicity
  - Angular selection to reduce $\tau\tau$ background

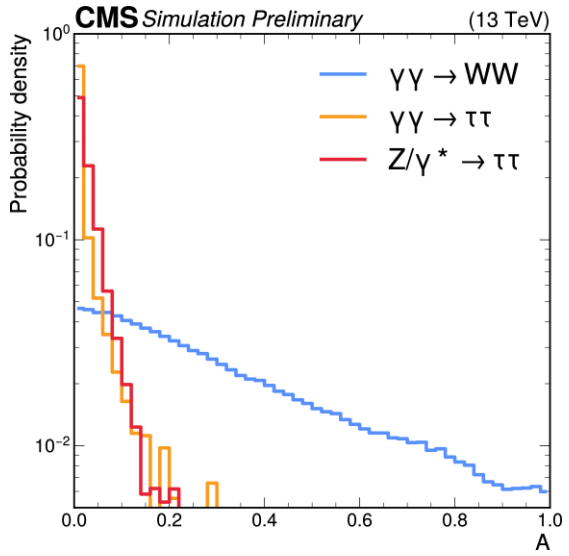




- SR + CR fit
  - 7.4σ significance
  - $\sigma^{\text{inclusive}}$ = 659 ± 80 fb (all decay modes)
  - σ^{fiducial} = 4.1 ± 0.5 fb

CMS-PAS-SMP-24-019



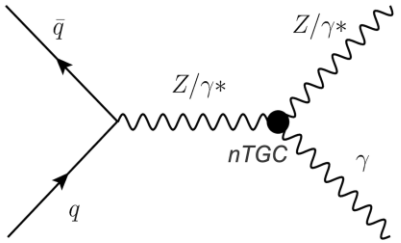


Photon-fusion production of *W* bosons

- aQGC interpretation
- First use of the new basis
- Curent best constraints on M2, M3, T4, T7 (and newly introduced M̃/T̃ operators)
- No unitarization procedure

	Expected 95% CL (TeV^{-4})	Observed 95% CL (TeV^{-4})
$f_{\mathrm{M0}}/\Lambda^4$	[-3.95, 4.02]	[-3.47, 3.47]
$f_{\mathrm{M1}}/\Lambda^4$	[-15.19, 14.66]	[-13.11, 12.88]
$f_{\widetilde{\mathrm{M1}}}/\Lambda^4$	[-0.61, 0.61]	[-0.53, 0.53]
$f_{\mathrm{M2}}/\Lambda^4$	[-0.60, 0.61]	[-0.53, 0.53]
$f_{\widetilde{\mathrm{M2}}}/\Lambda^4$	[-2.20, 2.20]	[-1.92, 1.91]
$f_{\mathrm{M3}}/\Lambda^4$	[-2.32, 2.24]	[-2.00, 1.96]
$f_{\mathrm{M4}}/\Lambda^4$	[-2.18, 2.22]	[-1.91, 1.92]
$f_{\widetilde{\mathrm{M4}}}/\Lambda^4$	[-4.41, 4.41]	[-3.84, 3.82]
$f_{\mathrm{M5}}/\Lambda^4$	[-4.05, 4.20]	[-3.56, 3.62]
$f_{\widetilde{\mathrm{M5}}}/\Lambda^4$	[-1.99, 1.99]	[-1.74, 1.73]
$f_{\mathrm{M7}}/\Lambda^4$	[-29.31, 30.38]	[-25.76, 26.22]
$f_{\mathrm{T0}}/\Lambda^4$	[-0.64, 0.52]	[-0.56, 0.45]
$f_{\mathrm{T1}}/\Lambda^4$	[-2.09, 1.97]	[-1.82, 1.70]
$f_{\mathrm{T2}}/\Lambda^4$	[-2.46, 1.97]	[-2.15, 1.68]
$f_{\widetilde{\mathrm{T2}}}/\Lambda^4$	[-0.088, 0.088]	[-0.076, 0.076]
$f_{\mathrm{T3}}/\Lambda^4$	[-3.23, 2.44]	[-2.84, 2.07]
$f_{\widetilde{\mathrm{T3}}}/\Lambda^4$	[-0.088, 0.088]	[-0.076, 0.076]
$f_{\mathrm{T4}}/\Lambda^4$	[-0.99, 0.74]	[-0.87, 0.63]
$f_{\widetilde{\mathrm{T4}}}/\Lambda^4$	[-0.37, 0.37]	[-0.32, 0.32]
$f_{\mathrm{T5}}/\Lambda^4$	[-0.20, 0.16]	[-0.17, 0.14]
$f_{\widetilde{\mathrm{T5}}}/\Lambda^4$	[-0.21, 0.21]	[-0.18, 0.18]
$f_{\mathrm{T6}}/\Lambda^4$	[-0.64, 0.60]	[-0.56, 0.52]
$f_{\widetilde{\mathrm{T6}}}/\Lambda^4$	[-0.61, 0.61]	[-0.53, 0.53]
$f_{\mathrm{T7}}/\Lambda^4$	[-0.75, 0.60]	[-0.66, 0.51]

Zγ and nTGCs

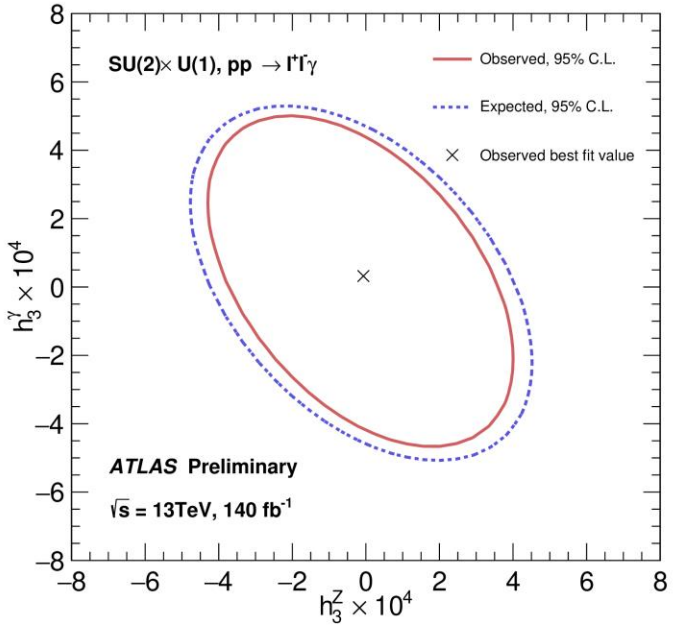


ATLAS EXPERIMENT ATLAS-CONF-2025-001

- Inclusive *Zγ* production, *Z* decaying to charged leptons
- Measurement focused on nTGC contraints: one region optimized for EFTs
  - nTGC vertex expressed as function of form factors, related to dimension-8 operators
  - First use of recent model respecting gauge symmetry
  - 1D and 2D limits obtained from p_T^γ fit

Parameters	Limits at 95% C.L.	
	Observed 95% C.L. [TeV^{-4}]	Expected 95 % C.L. [TeV^{-4}]
C_{G+}/Λ^4	[-0.022, 0.020]	[-0.025, 0.023]
C_{G-}/Λ^4	[-1.41, 1.08]	[-1.50, 1.23]
C_{BB}/Λ^4	[-0.37, 0.37]	[-0.44, 0.44]
$C_{\tilde{B}W}/\Lambda^4$	[-0.54, 0.53]	[-0.62, 0.61]
C_{BW}/Λ^4	[-0.87, 0.95]	[-1.05, 1.14]
C_{WW}/Λ^4	[-1.90, 1.78]	[-2.26, 2.13]

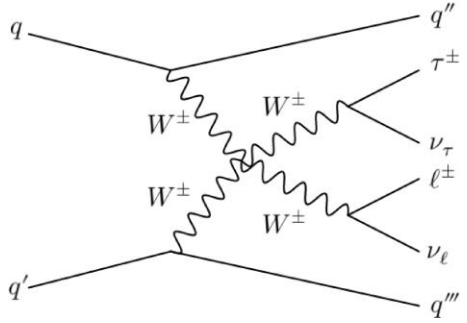
Parameters	Limits at 95% C.L.	
	Observed 95% C.L.	Expected 95 % C.L.
h_4^γ	$[-1.3 \times 10^{-5}, 1.4 \times 10^{-5}]$	$[-1.5 \times 10^{-5}, 1.6 \times 10^{-5}]$
h_4^Z	$[-2.4 \times 10^{-5}, 2.6 \times 10^{-5}]$	$[-2.8 \times 10^{-5}, 3.0 \times 10^{-5}]$
h_3^γ	$[-3.5 \times 10^{-4}, 4.6 \times 10^{-4}]$	$[-4.0 \times 10^{-4}, 4.9 \times 10^{-4}]$
h_3^Z	$[-3.2 \times 10^{-4}, 3.2 \times 10^{-4}]$	$[-3.7 \times 10^{-4}, 3.6 \times 10^{-4}]$



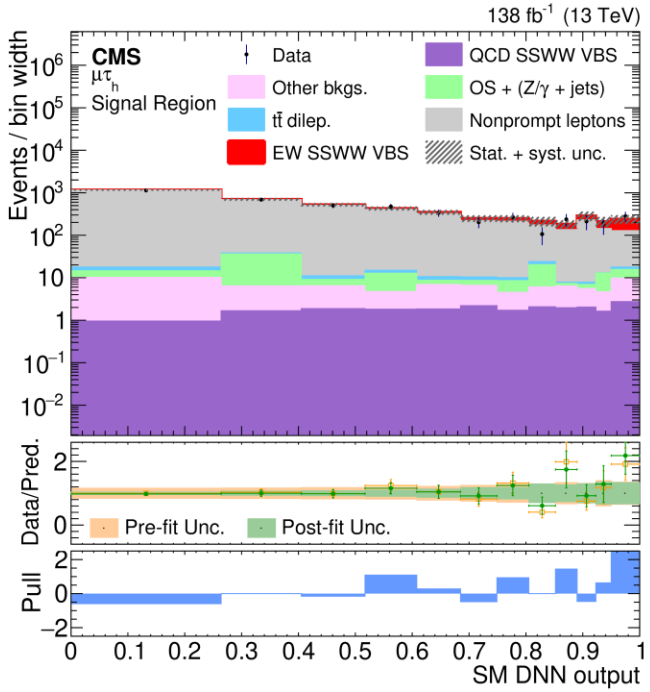
WW scattering in final states with tau leptons

arXiv:2410.04210

- First EW diboson production measurement with τ in final states
- Same-sign *WW* production
  - One W decays to a τ
    - Targetting hadronic τ
  - The other one decays to $e\nu/\mu\nu$

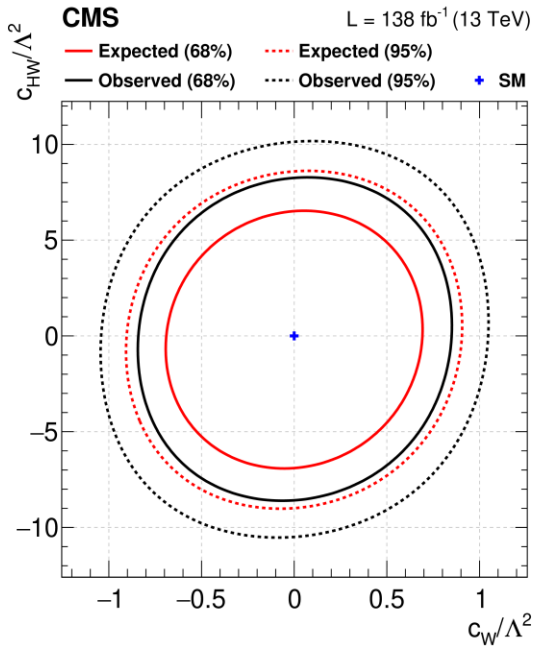


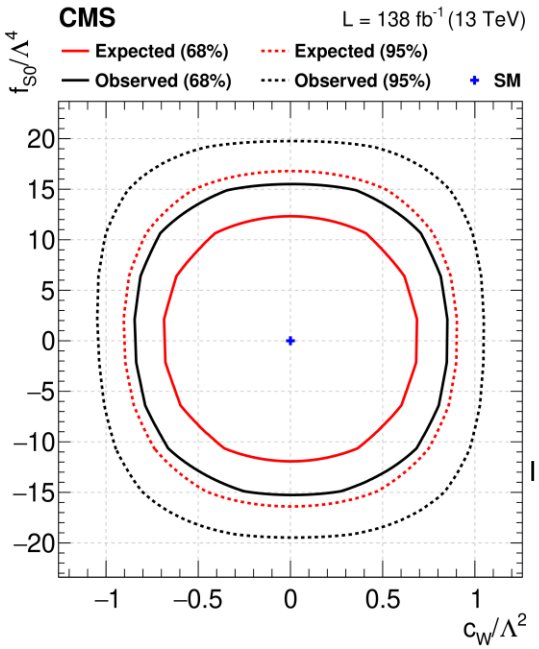
- One SR
- CRs to constrain Top, QCD, opposite-sign and fakes backgrounds
- DNN fit in SR, Top CR and opposite-sign CR
  - Measured signal strength: $\mu_{EW} = 1.44 \pm 0.58$
  - 2.7σ significance



WW scattering in final states with tau leptons

- EFT interpretation in dimension-6 and dimension-8
  - First time in a VBS analysis
- 1D and 2D limits obtained
  - VBS not competitive for dimension-6
  - Dimension-8 limits better in other channels
  - Dimension-6 vs dimension-6, dimension-6 vs dimension-8

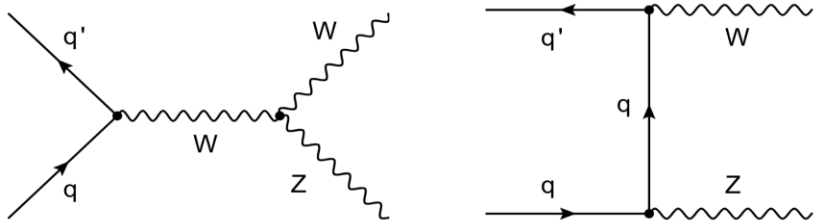




Wilson coefficient		68% CL interval(s)		95% CL interval	
		Observed	Expected	Observed	Expected
dim-6	$c_{ll}^{(1)}/\Lambda^2$	$[-11.6, 0.045]$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	$[-13.5, 2.11]$	$[-14.6, 3.53]$
	$c_{qq}^{(1)}/\Lambda^2$	$[-0.341, 0.416]$	$[-0.501, 0.576]$	$[-0.605, 0.681]$	$[-0.742, 0.818]$
	c_W/Λ^2	$[-0.513, 0.481]$	$[-0.681, 0.669]$	$[-0.842, 0.818]$	$[-0.987, 0.974]$
	c_{HW}/Λ^2	$[-5.48, 4.31]$	$[-7.00, 6.09]$	$[-8.68, 7.60]$	$[-9.99, 9.05]$
	c_{HWB}/Λ^2	$[-30.7, 89.2]$	$[-41.7, 69.6]$	$[-49.7, 110]$	$[-66.6, 96.4]$
	$c_{H\Box}/\Lambda^2$	$[-12.0, 14.0]$	$[-16.6, 18.1]$	$[-20.9, 22.7]$	$[-24.7, 26.3]$
	c_{HD}/Λ^2	$[-15.3, 31.5]$	$[-24.6, 34.7]$	$[-31.4, 45.5]$	$[-38.2, 48.8]$
	$c_{Hl}^{(1)}/\Lambda^2$	$[-38.2, 39.5]$	$[-28.8, 29.9]$	$[-69.3, 68.3]$	$[-49.4, 49.7]$
	$c_{Hl}^{(3)}/\Lambda^2$	$[-0.045, 8.58]$	$[-1.43, 2.23] \cup [5.88, 9.54]$	$[-1.59, 9.94]$	$[-2.64, 10.8]$
	$c_{Hq}^{(1)}/\Lambda^2$	$[-3.27, 3.44]$	$[-4.53, 4.42]$	$[-5.55, 5.60]$	$[-6.56, 6.44]$
	$c_{Hq}^{(3)}/\Lambda^2$	$[-1.88, 0.705]$	$[-2.39, 1.37]$	$[-2.82, 1.61]$	$[-3.24, 2.16]$
dim-8	f_{T0}/Λ^4	$[-0.774, 0.842]$	$[-1.02, 1.08]$	$[-1.32, 1.38]$	$[-1.52, 1.58]$
	f_{T1}/Λ^4	$[-0.319, 0.381]$	$[-0.426, 0.480]$	$[-0.552, 0.613]$	$[-0.640, 0.695]$
	f_{T2}/Λ^4	$[-0.851, 1.12]$	$[-1.15, 1.37]$	$[-1.51, 1.76]$	$[-1.75, 1.98]$
	f_{M0}/Λ^4	$[-8.07, 7.70]$	$[-9.89, 9.74]$	$[-13.1, 12.8]$	$[-14.6, 14.5]$
	f_{M1}/Λ^4	$[-9.54, 11.15]$	$[-12.5, 13.3]$	$[-16.4, 17.7]$	$[-18.7, 19.6]$
	f_{M7}/Λ^4	$[-17.6, 15.3]$	$[-20.3, 19.2]$	$[-27.6, 25.8]$	$[-29.9, 28.8]$
	f_{S0}/Λ^4	$[-9.60, 9.82]$	$[-11.6, 12.0]$	$[-15.9, 16.1]$	$[-17.4, 17.9]$
	f_{S1}/Λ^4	$[-40.9, 41.3]$	$[-37.4, 38.8]$	$[-60.9, 61.8]$	$[-57.2, 58.6]$
	f_{S2}/Λ^4	$[-40.9, 41.3]$	$[-37.4, 38.8]$	$[-60.9, 61.8]$	$[-57.2, 58.6]$

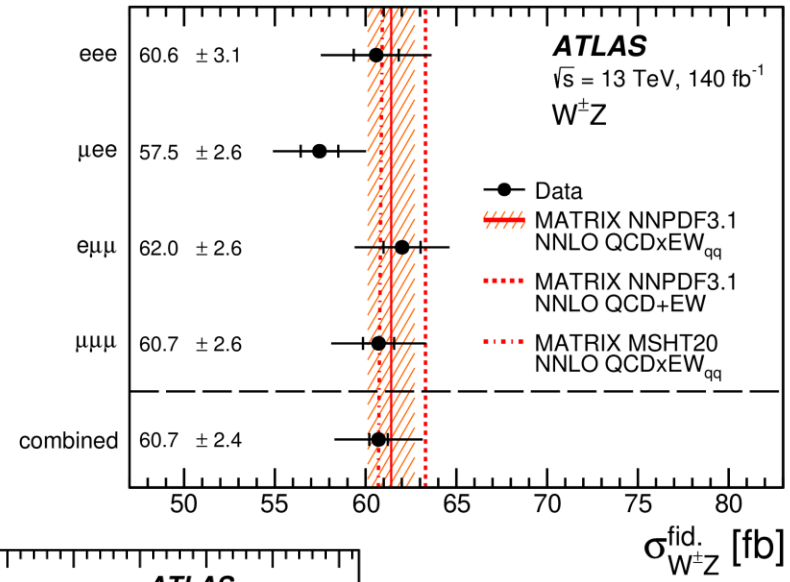
Interference between dimension-6 and dimension-8 not considered

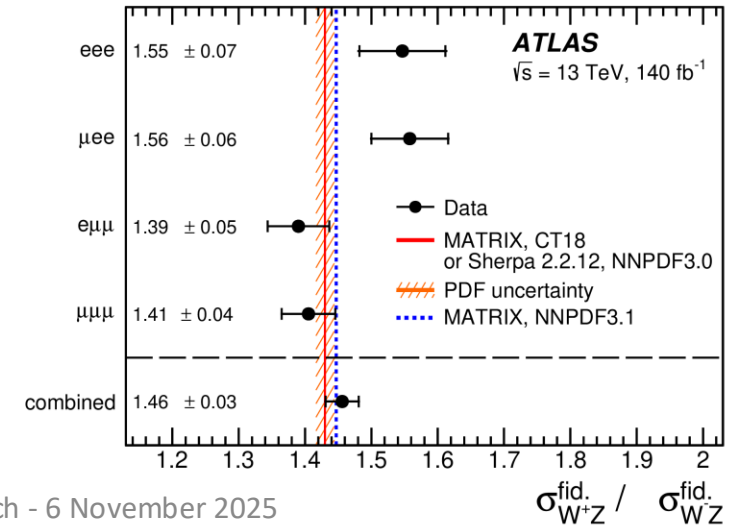
WZ production



- Inclusive diboson production measurement
  - Leptonic decays: *eee*, *μee*, *eμμ*, *μμμ* combined in single SR
  - CRs for *ZZ* and Top backgrounds
- Fiducial and differential cross-section measurements
  - Very good agreement with NNLO QCD NLO EW prediction
- Charge asymmetry study
  - Proton: two up valence quarks + one down valence quark
  - W^+Z/W^-Z ratio in good agreement with prediction

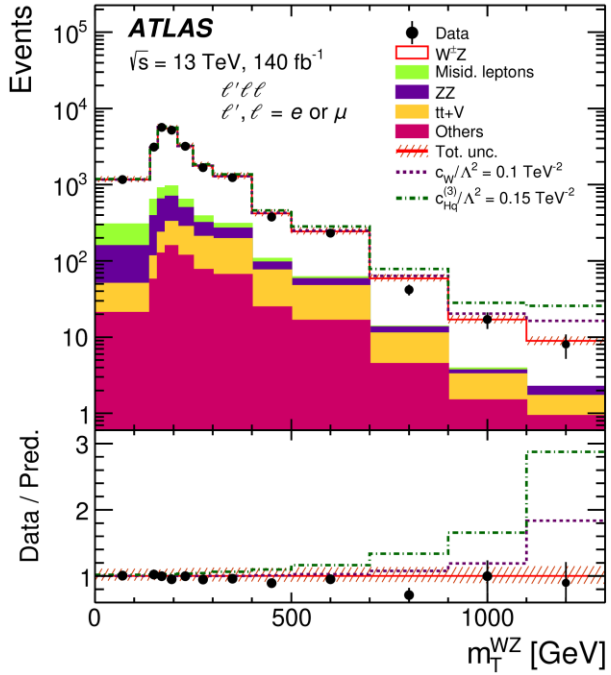
ATLAS EXPERIMENT arXiv:2507.03500

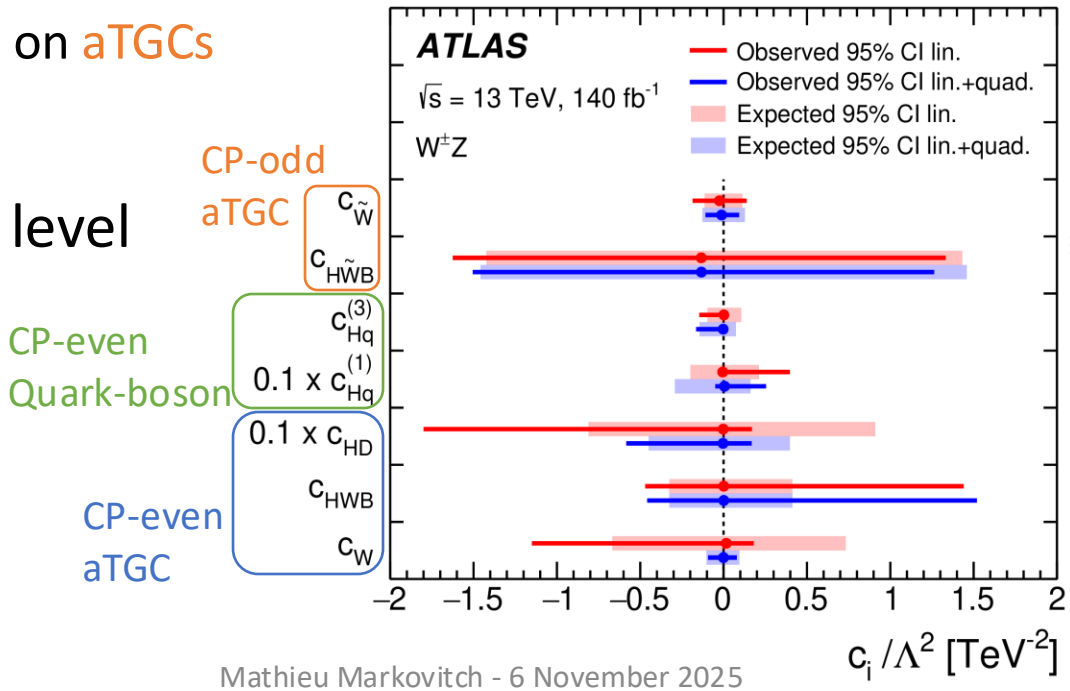


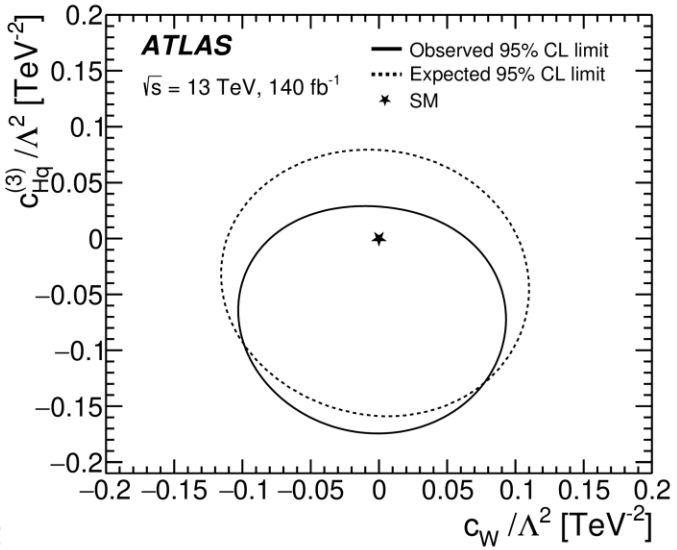


WZ production

- Constraints on CP-even dimension-6 EFT operators
  - Fit to m_T^{WZ} distribution
  - Competitive constraints on aTGCs and anomalous fermion-boson couplings
  - Some 2D limits obtained
- Constraints on CP-odd operators
  - Fit to combined BDT score S_{comb} sensitive to CP-odd effects
  - Competitive constraints on aTGCs
- No deviation from SM
- Probed scale at the TeV level





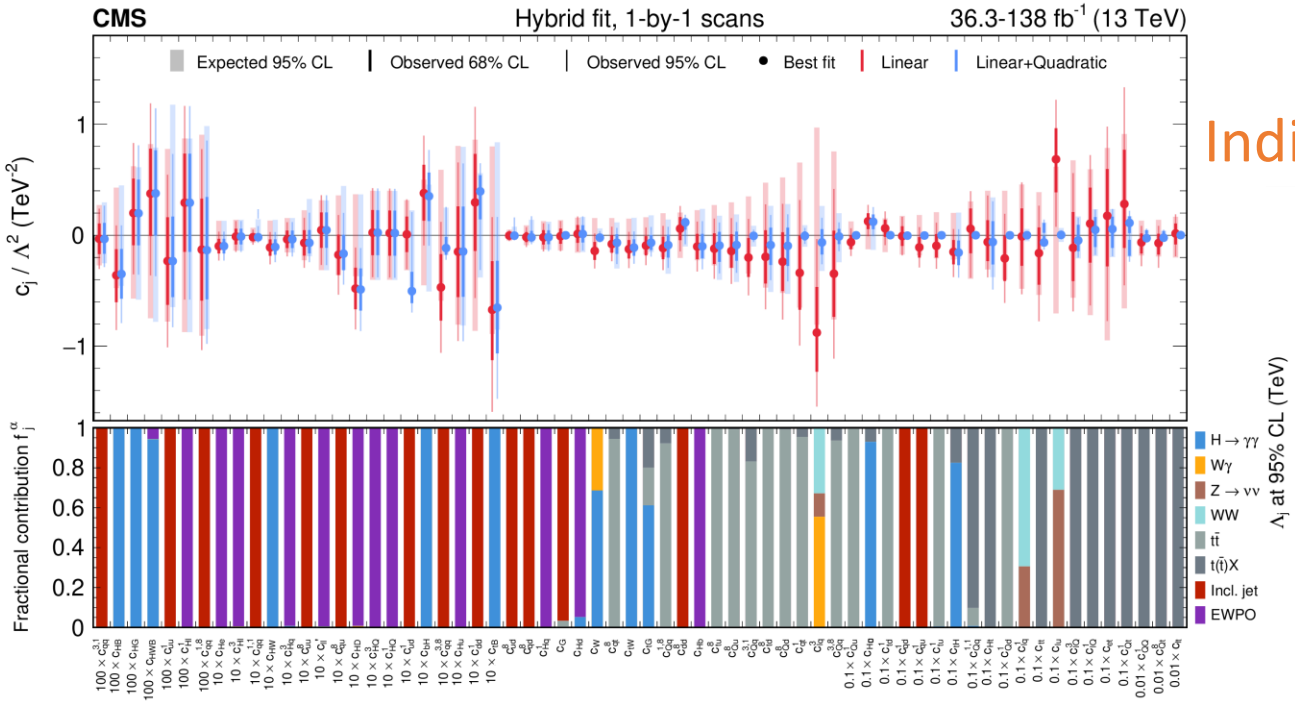


Combined EFT interpretation

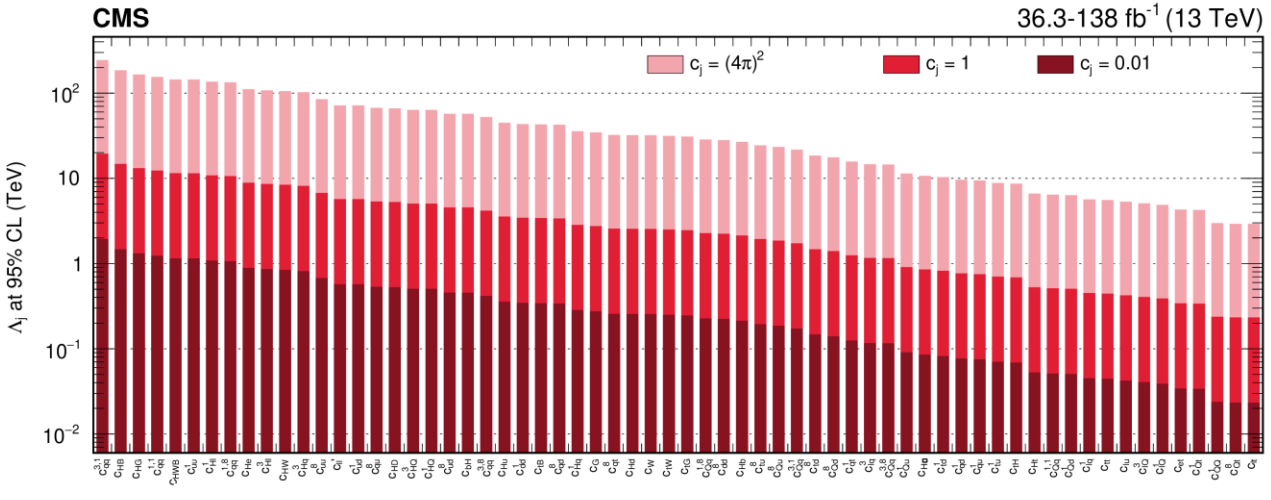
- Combination of seven CMS measurements (Higgs, EW, QCD, Top) + EW precision observables measured at LEP and SLC
- Constraints on 64 Wilson coefficients associated to dimension-6 SMEFT operators

arXiv:2504.02958

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Differential cross sections	STXS bins [54]	✓
$W\gamma$	Fiducial differential cross sections	$p_T^\gamma \times \lvert\phi_f\rvert$ [33]	✓
$Z \to \nu\nu$	Fiducial differential cross sections	p_T^Z	✓
WW	Fiducial differential cross sections	$m_{\ell\ell}$	✓ Diboson/VBF
$t\bar{t}$	Fiducial differential cross sections	$m_{t\bar{t}}$	×
$t(\bar{t})X$	Direct EFT	Yields in regions of interest	✓
Inclusive jet	Fiducial differential cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A_{FB}^{0,\ell}$, $A_{FB}^{0,c}$, $A_{FB}^{0,b}$ [36]	×

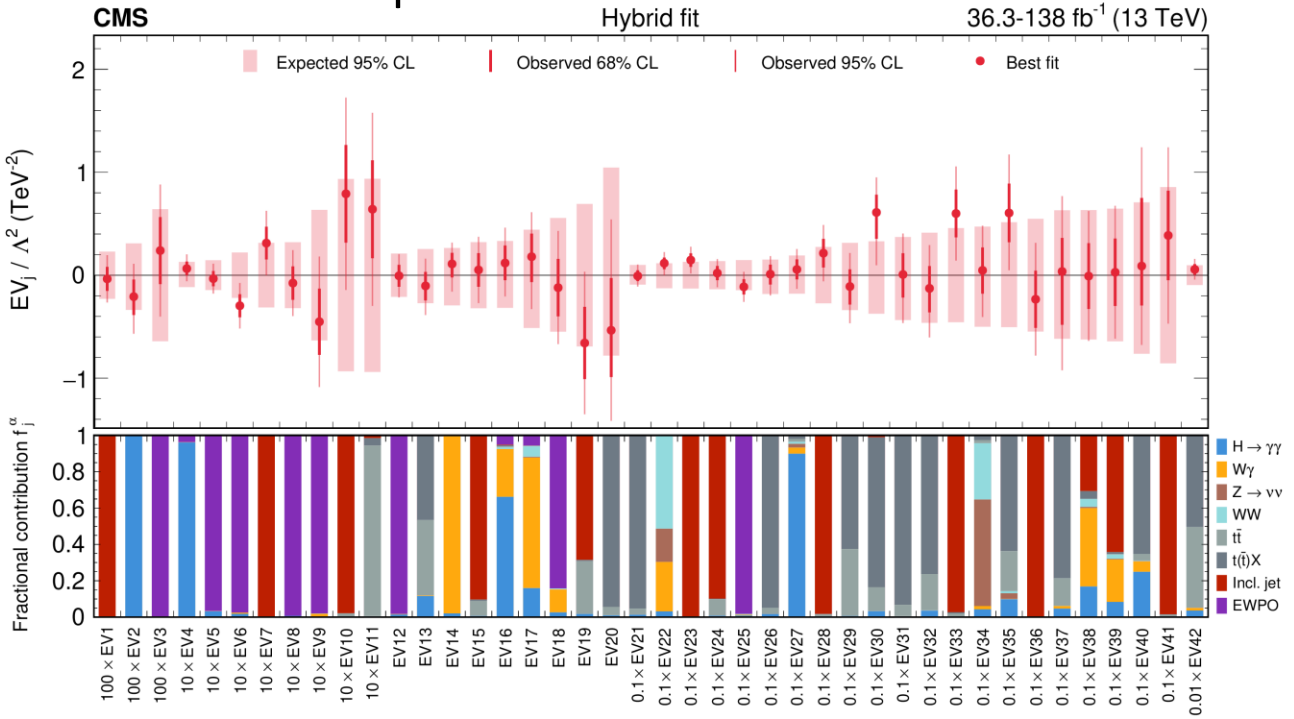


Individual constraints



Combined EFT interpretation

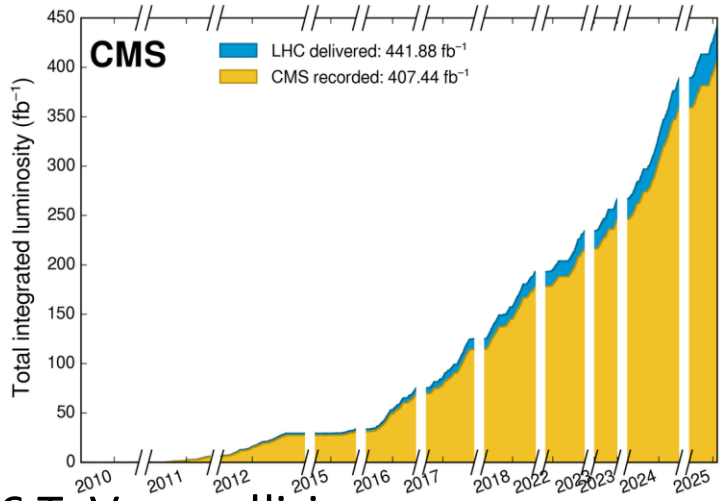
- Profiled constraints on 42 linear combinations of Wilson coefficients
  - 22 remaining combinations correspond to flat directions and are fixed to zero

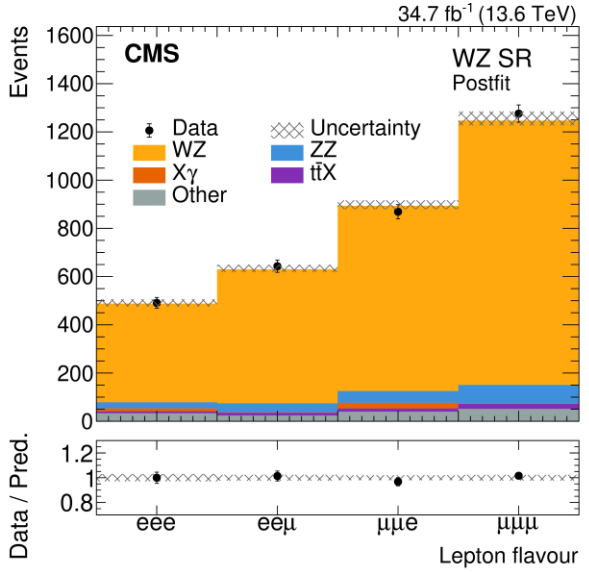


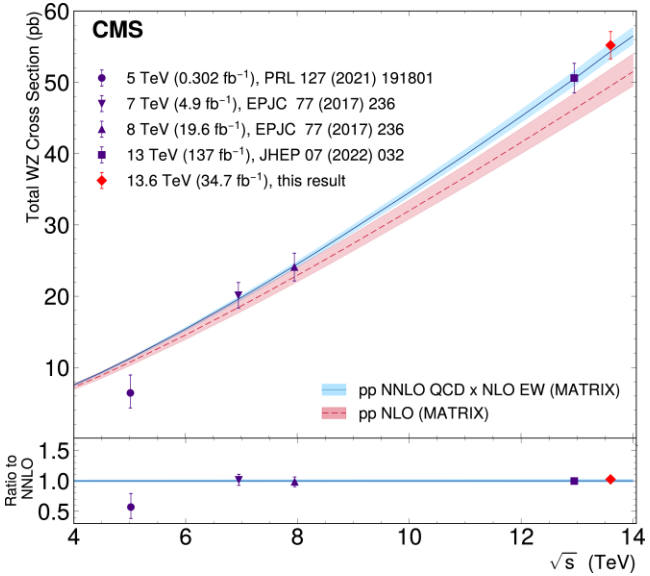
- Important improvement brought by the combination (*e.g.* on c_W)
- *p*-value for SM compatibility is 1.7% (26% when removing inclusive jet measurement)
- Probed scale between 0.2 and 20 TeV for *c*=1

Outlook

- Run-2 EW analyses to be finalized
  - Dataset of ~140 fb^{-1} of 13 TeV *pp* collisions
- Run-3 effort started already
  - Analyses starting with 2022-2024 dataset: ~180 fb^{-1} of 13.6 TeV *pp* collisions
    - Combination with Run-2 possible
  - Higher statistics, slightly higher energy
  - Improved object reconstruction
  - New analysis techniques
  - Boson polarization studies
- More and more interest in global fits
- Preparing for HL-LHC







CMS *WZ* at 13.6 TeV: JHEP04(2025)115

Conclusion

- Run-2 dataset
  - Allowed to observe most VBS processes and improve diboson measurements
  - Constraints on dimension-6 and dimension-8 EFT operators
- Run-3 dataset
  - Analyses are ramping up
  - More statistics, improved reconstruction and analysis techniques: tighter constraints expected
  - Benefit from lessons learnt during Run-2
- To be investigated
  - Combinations
  - EFT effects in polarization measurements
  - Interplay between dimension-6 and dimension-8 (in particular for VBS)
  - Theoretical constraints (unitarity and positivity bounds)
  - EFT-model matching

Backup

aQGC basis

	SM				Not SM				
Wilson coefficient	$WWWW$	$WWZZ$	$WW\gamma\gamma$	$WWZ\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
f_{S0}, f_{S1}, f_{S2}	✓	✓			✓				
f_{M0}, f_{M1}, f_{M7}	✓	✓	✓	✓	✓	✓	✓		
f_{M2}, f_{M3}, f_{M4}, f_{M5}		✓	✓	✓	✓	✓	✓		
f_{T0}, f_{T1}, f_{T2}, f_{T3}	✓	✓	✓	✓	✓	✓	✓	✓	✓
f_{T4}, f_{T5}, f_{T6}, f_{T7}		✓	✓	✓	✓	✓	✓	✓	✓
f_{T8}, f_{T9}					✓	✓	✓	✓	✓

	aQGC Operator Basis	C	P	Almeida, Éboli, Gonzalez-Garcia [3]	Remmen & Rodd [4]	Murphy [6]
$\mathcal{O}_0^S$	$[D_\mu H^\dagger D_\nu H][D^\mu H^\dagger D^\nu H]$	+	+	$\mathcal{O}_{S,0}$	$\mathcal{O}_2^{H^4}$	$Q^{(2)}_{H^4}$
$\mathcal{O}_1^S$	$[D^\mu H^\dagger D_\mu H][D^\nu H^\dagger D_\nu H]$	+	+	$\mathcal{O}_{S,1}$	$\mathcal{O}_3^{H^4}$	$Q^{(3)}_{H^4}$
$\mathcal{O}_2^S$	$[D_\mu H^\dagger D_\nu H][D^\nu H^\dagger D^\mu H]$	+	+	$\mathcal{O}_{S,2}$	$\mathcal{O}_1^{H^4}$	$Q^{(1)}_{H^4}$
$\mathcal{O}_0^M$	$\frac{1}{2}[D^\mu H^\dagger D_\mu H]W^I_{\nu\rho}W^{I\,\nu\rho}$	+	+	$\mathcal{O}_{M,0}$	$\frac{1}{2}\mathcal{O}_2^{H^2W^2}$	$\frac{1}{2}Q^{(2)}_{W^2H^2D^2}$
$\mathcal{O}_1^M$	$-\frac{1}{2}[D^\mu H^\dagger D^\nu H]W^I_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,1}$	$-\frac{1}{2}\mathcal{O}_1^{H^2W^2}$	$-\frac{1}{2}Q^{(1)}_{W^2H^2D^2}$
$\mathcal{O}_2^M$	$[D^\mu H^\dagger D_\mu H]B_{\nu\rho}B^{\nu\rho}$	+	+	$\mathcal{O}_{M,2}$	$\mathcal{O}_2^{H^2B^2}$	$Q^{(2)}_{B^2H^2D^2}$
$\mathcal{O}_3^M$	$-[D^\mu H^\dagger D^\nu H]B_{\mu\rho}B_{\nu}{}^{\rho}$	+	+	$\mathcal{O}_{M,3}$	$-\mathcal{O}_1^{H^2B^2}$	$-Q^{(1)}_{B^2H^2D^2}$
$\mathcal{O}_4^M$	$[D^\mu H^\dagger \tau^I D_\mu H]B^{\nu\rho}W^I_{\nu\rho}$	+	+	$\mathcal{O}_{M,4}$	$\mathcal{O}_1^{H^2BW}$	$\frac{1}{2}Q^{(1)}_{WBH^2D^2}$
$\mathcal{O}_5^M$	$[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho W^I_{\nu\rho} + B_\nu{}^\rho W^I_{\mu\rho})$	+	+	$\mathcal{O}_{M,5}$	$\mathcal{O}_3^{H^2BW}$	$\frac{1}{2}Q^{(4)}_{WBH^2D^2}$
$\mathcal{O}_7^M$	$[D^\mu H^\dagger \tau^I \tau^J D^\nu H]W^J_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,7}$	$\frac{1}{4}\mathcal{O}_1^{H^2W^2} - \frac{1}{2}\mathcal{O}_3^{H^2W^2}$	$\frac{1}{4}Q^{(1)}_{W^2H^2D^2} - \frac{1}{4}Q^{(4)}_{W^2H^2D^2}$
$\mathcal{O}_8^M$	$i[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho \widetilde{W}^I_{\nu\rho} - B_\nu{}^\rho \widetilde{W}^I_{\mu\rho})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2BW}$	$\frac{1}{2}Q^{(5)}_{WBH^2D^2}$
$\mathcal{O}_9^M$	$\epsilon^{IJK}[D^\mu H^\dagger \tau^I D^\nu H](W^J_{\mu\rho}\widetilde{W}^{K\,\rho}_{\nu} - \widetilde{W}^J_{\mu\rho}W^{K\,\rho}_{\nu})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2W^2}$	$\frac{1}{2}Q^{(5)}_{W^2H^2D^2}$
$\mathcal{O}_0^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\,\mu\nu}W^J_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,0}$	$\frac{1}{4}\mathcal{O}_1^{W^4}$	$\frac{1}{4}Q^{(1)}_{W^4}$
$\mathcal{O}_1^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\,\mu\nu}W^I_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,1}$	$\frac{1}{4}\mathcal{O}_3^{W^4}$	$\frac{1}{4}Q^{(3)}_{W^4}$
$\mathcal{O}_2^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\nu\alpha}W^J_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,2}$	$\frac{1}{16}\mathcal{O}_1^{W^4} + \frac{1}{16}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_4^{W^4}$	$\frac{1}{16}Q^{(1)}_{W^4} + \frac{1}{16}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(4)}_{W^4}$
$\mathcal{O}_3^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\nu\alpha}W^I_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,3}$	$\frac{1}{8}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_2^{W^4}$	$\frac{1}{8}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(2)}_{W^4}$
$\mathcal{O}_4^T$	$\frac{1}{2}W^I_{\mu\nu}B^{\nu\alpha}W^I_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,4}$	$\frac{1}{8}\mathcal{O}_2^{B^2W^2} + \frac{1}{4}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{8}Q^{(2)}_{W^2B^2} + \frac{1}{4}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_5^T$	$\frac{1}{2}B_{\mu\nu}B^{\mu\nu}W^I_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,5}$	$\frac{1}{2}\mathcal{O}_1^{B^2W^2}$	$\frac{1}{2}Q^{(1)}_{W^2B^2}$
$\mathcal{O}_6^T$	$\frac{1}{2}B_{\mu\nu}W^{I\,\mu\nu}B_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,6}$	$\frac{1}{2}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{2}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_7^T$	$\frac{1}{2}W^I_{\mu\nu}W^{I\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,7}$	$\frac{1}{8}\mathcal{O}_1^{B^2W^2} + \frac{1}{8}\mathcal{O}_3^{B^2W^2} + \frac{1}{8}\mathcal{O}_4^{B^2W^2}$	$\frac{1}{8}Q^{(1)}_{W^2B^2} + \frac{1}{8}Q^{(3)}_{W^2B^2} + \frac{1}{8}Q^{(4)}_{W^2B^2}$
$\mathcal{O}_8^T$	$B_{\mu\nu}B^{\mu\nu}B_{\rho\sigma}B^{\rho\sigma}$	+	+	$\mathcal{O}_{T,8}$	$\mathcal{O}_1^{B^4}$	$Q^{(1)}_{B^4}$
$\mathcal{O}_9^T$	$B_{\mu\nu}B^{\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,9}$	$\frac{1}{2}\mathcal{O}_1^{B^4} + \frac{1}{4}\mathcal{O}_2^{B^4}$	$\frac{1}{2}Q^{(1)}_{B^4} + \frac{1}{4}Q^{(2)}_{B^4}$

ATLAS semileptonic

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-electron triggers Single-muon or $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-lepton triggers
$V \to \nu\nu/\ell\nu/\ell\ell$	0 'Loose' leptons $p_{\mathrm{T}} > 7$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R \text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, V_{\mathrm{had}}) > \pi/9$	1 'Tight' lepton $p_{\mathrm{T}} > 27$ GeV 0 other 'Loose' leptons with $p_{\mathrm{T}} > 7$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 80$ GeV	2 'Loose' leptons $p_{\mathrm{T}} > 27$ GeV $83 < m_{ee} < 99$ GeV $-0.0117 \times p_{\mathrm{T}}^{\mu\mu} + 85.63\ \mathrm{GeV} < m_{\mu\mu}$ $0.0185 \times p_{\mathrm{T}}^{\mu\mu} + 94\ \mathrm{GeV} > m_{\mu\mu}$
VBS topology tagging jets	Largest m_{jj} pair with $\eta_{\mathrm{tag}\ j_1} \cdot \eta_{\mathrm{tag}\ j_2} < 0$ $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_{\mathrm{T}}^{tag\ j_{1,2}} > 30$ GeV		
$V \to J$	Leading p_{T} large-R jet $p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2$ V boson tagger requirements on m_J, D_2, and $n_{\mathrm{Tracks}}^{\mathrm{ungroomed}}$		
$V \to jj$	Two leading p_{T} small-R jets $p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$ $p_{\mathrm{T}}^{j_1} > 40$ GeV $64 < m_{jj} < 106$ GeV		
Top veto	$m_{jjj} > 220$ GeV (resolved only)		
Additional b-jet veto	No	Yes	No

CMS semileptonic

ZV

Preselection: $n_\ell = 2$, $m_{\ell\ell} \in [76, 106]\,\text{GeV}$, $p_\text{T}(\ell_1) > 35\,\text{GeV}$, $p_\text{T}(\ell_2) > 20\,\text{GeV}$, $p_\text{T}(\text{j}_{1,2}) > 30\,\text{GeV}$, $m_\text{jj} > 500\,\text{GeV}$, $|\Delta\eta_\text{jj}| > 2.5$

Regions	Variables	Lepton Selection	Other Requirements
SR	$65 < m_\text{V} < 105\,\text{GeV}$	Same-flavor	Split in b tag and b veto
DY CR	$m_\text{V} < 65$ or $m_\text{V} > 105\,\text{GeV}$	Same-flavor	Split in b tag and b veto
Top quark CR	$65 < m_\text{V} < 105\,\text{GeV}$	Different-flavor	—

WV

Preselection: $n_\ell = 1$, $p_\text{T}(\text{e}) > 30\,\text{GeV}$ (2016), $35\,\text{GeV}$ (2017, 2018), $p_\text{T}(\mu) > 30\,\text{GeV}$, $p_\text{T}^\text{miss} > 30\,\text{GeV}$, $m_\text{T}^\text{W} < 185\,\text{GeV}$, $p_\text{T}(\text{j}_1) > 50\,\text{GeV}$, $p_\text{T}(\text{j}_2) > 30\,\text{GeV}$, $m_\text{jj} > 500\,\text{GeV}$, $\Delta\eta_\text{jj} > 2.5$

Regions	Variables	Other Requirements
SR	$70 < m_\text{V} < 115\,\text{GeV}$	b veto
W+jets CR	$m_\text{V} < 70\,\text{GeV}$ or $m_\text{V} > 115\,\text{GeV}$	b veto
Top quark CR	$70 < m_\text{V} < 115\,\text{GeV}$	b tag

WZγ

TABLE I. Summary of the event selections in the SR, nonprompt CRs, and the ZZ CR. The nonprompt CRs are used to validate and constrain the nonprompt lepton and photon contributions, and the ZZ CR is used to constrain the ZZ contribution. A "…" indicates that no requirement is placed on the corresponding observable. The aQGC SR is the same as the SR with the exception that $p_{\mathrm{T}}^{\gamma} > 60$ GeV.

Region	N_ℓ	N_γ	N_{OSSF}	N_{btag}	$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$ [GeV]	$\min(m(\ell\ell'))$ [GeV]	$\lvert m(\ell_{Z1}, \ell_{Z2}) - m_Z \rvert$ [GeV]	$m(\ell_{Z1}, \ell_{Z2}, \ell_W)$ [GeV]	$m(\ell_W, \gamma)$ [GeV]
SR	$= 3$	≥ 1	≥ 1	$= 0$	> 30	$> \{25, 15, 25, -\}$	> 4	< 15	> 100	< 75 or > 105
ZZ CR	$= 4$	…	≥ 1	$= 0$	< 30	$> \{25, 15, 25, 15\}$	> 4	< 15	> 100	…
Nonprompt ℓ CR	$= 3$	…	≥ 1	> 0	> 30	$> \{25, 15, 25, -\}$	> 4	> 15	> 100	…
Nonprompt γ CR	$= 2$	≥ 1	$= 1$	> 0	< 30	$> \{25, 15, -, -\}$	> 4	> 15	…	…

Photon fusion

	$e\mu$ SR (CR)	$\mu\mu$
p_T^e (GeV)	$> 15/24$	—
$\lvert\eta^e\rvert$	< 2.5	—
$\lvert d_{xy}^e\rvert$ (cm)	< 0.05 in the barrel	—
	< 0.1 in the endcaps	
p_T^μ (GeV)	$> 24/15$	> 26–$29/10$
$\lvert\eta^\mu\rvert$	< 2.4	< 2.4
$\lvert d_{xy}^\mu\rvert$ (cm)	< 0.02	< 0.05
$m_{\ell\ell}$ (GeV)	> 20	> 50
OS	Yes	Yes
$\lvert dz(\ell,\ell)\rvert$ (cm)	< 0.04	< 0.1
ΔR	> 0.5	> 0.5
A	> 0.015	—
N_{tracks}	0 ([1, 5])	—

Zγ

Requirements	Signal region
Trigger	single or di-lepton triggers
N_{lepton}	≥ 2 OSSF leptons
Leading lepton p_T	> 30 GeV
Photon isolation	$p_T^{\text{iso}}/E_T < 0.05$, $E_T^{\text{iso}}/E_T < 0.065$
N_{photon}	≥ 1 photon
Leading photon p_T	> 200 GeV
N_{jet}	$= 0$
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV

WW VBS

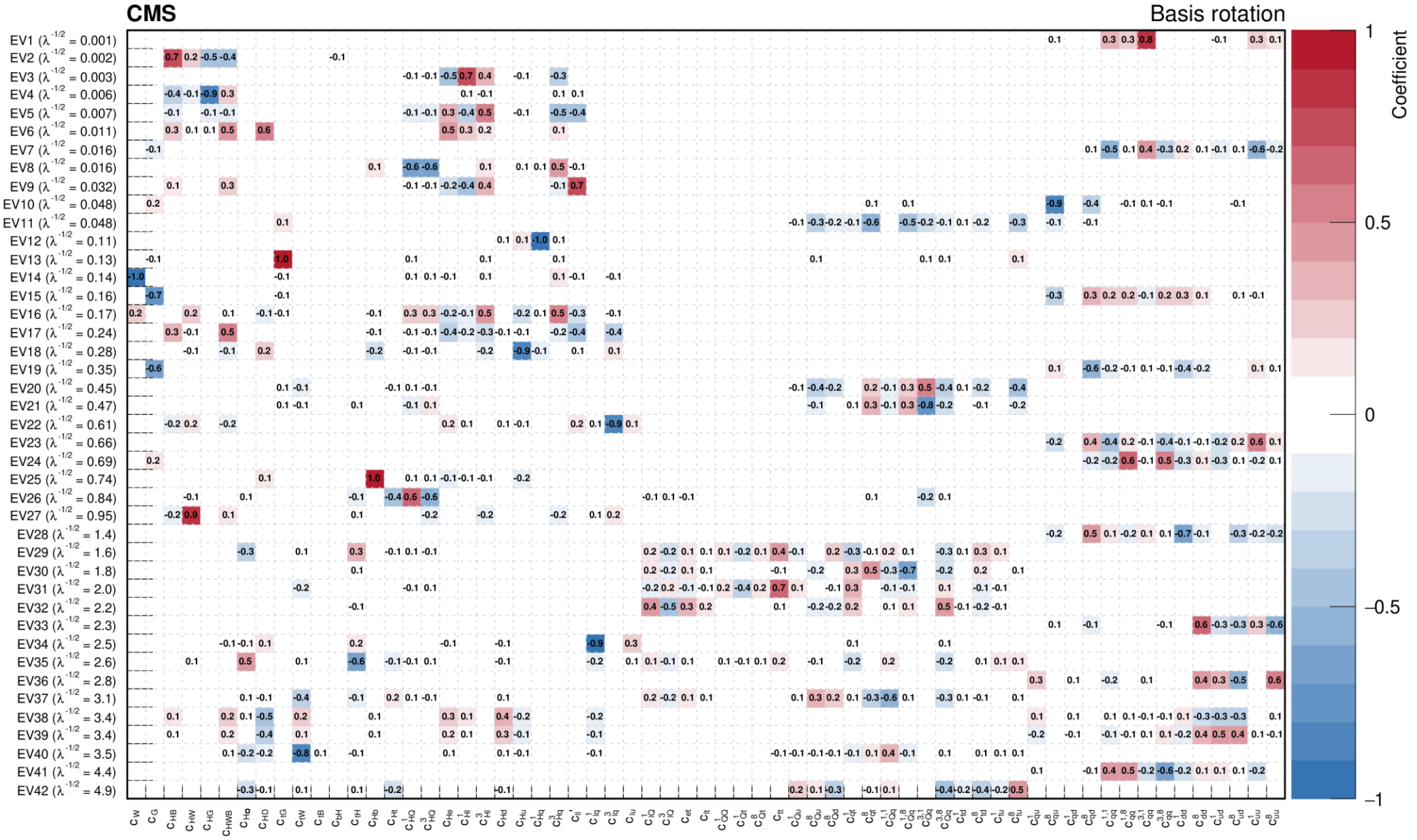
Region	1 T ℓ, 1 T τ_h, any L ℓ/τ_h	>= 2 jets with $\lvert\Delta\eta\rvert > 2.5$	SS ℓ, τ_h	p_T^{miss} >50 GeV	Additional requirements
SR	✓	✓	✓	✓	m_{jj} >500 GeV
Nonprompt CR	✓	✓	✓	×	
$t\bar{t}$ CR	✓	✓	×	✓	b-tagged jet ("medium")
OS CR	✓	✓	×	✓	b-tagged jet veto ("loose")

WZ

Variable	Fiducial inclusive
Lepton $\lvert\eta\rvert$	< 2.5
p_{T} of ℓ_Z, p_{T} of ℓ_W [GeV]	$> 15, > 20$
m_Z range [GeV]	$\lvert m_Z - m_Z^{\mathrm{PDG}}\rvert < 10$
m_{T}^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$

Inclusive event selection	
ZZ veto	Less than 4 loose leptons
N leptons	Exactly three leptons passing the medium lepton selection
Leading lepton p_{T}	$p_{\mathrm{T}}^{\mathrm{lead}} > 25$ GeV (in 2015) or $p_{\mathrm{T}}^{\mathrm{lead}} > 27$ GeV (2016–2018)
Z leptons	Two same flavor oppositely charged leptons passing the medium lepton selection
Mass window	$\lvert M_{\ell\ell} - M_Z\rvert < 10$ GeV
W lepton	Remaining lepton passes the tight lepton selection
W transverse mass	$m_{\mathrm{T}}^W > 30$ GeV

PCA


CMS
Basis rotation
Coefficient
1
0.5
0
−0.5
−1
EV1 (λ^-1/2 = 0.001)
EV2 (λ^-1/2 = 0.002)
EV3 (λ^-1/2 = 0.003)
EV4 (λ^-1/2 = 0.006)
EV5 (λ^-1/2 = 0.007)
EV6 (λ^-1/2 = 0.011)
EV7 (λ^-1/2 = 0.016)
EV8 (λ^-1/2 = 0.016)
EV9 (λ^-1/2 = 0.032)
EV10 (λ^-1/2 = 0.048)
EV11 (λ^-1/2 = 0.048)
EV12 (λ^-1/2 = 0.11)
EV13 (λ^-1/2 = 0.13)
EV14 (λ^-1/2 = 0.14)
EV15 (λ^-1/2 = 0.16)
EV16 (λ^-1/2 = 0.17)
EV17 (λ^-1/2 = 0.24)
EV18 (λ^-1/2 = 0.28)
EV19 (λ^-1/2 = 0.35)
EV20 (λ^-1/2 = 0.45)
EV21 (λ^-1/2 = 0.47)
EV22 (λ^-1/2 = 0.61)
EV23 (λ^-1/2 = 0.66)
EV24 (λ^-1/2 = 0.69)
EV25 (λ^-1/2 = 0.74)
EV26 (λ^-1/2 = 0.84)
EV27 (λ^-1/2 = 0.95)
EV28 (λ^-1/2 = 1.4)
EV29 (λ^-1/2 = 1.6)
EV30 (λ^-1/2 = 1.8)
EV31 (λ^-1/2 = 2.0)
EV32 (λ^-1/2 = 2.2)
EV33 (λ^-1/2 = 2.3)
EV34 (λ^-1/2 = 2.5)
EV35 (λ^-1/2 = 2.6)
EV36 (λ^-1/2 = 2.8)
EV37 (λ^-1/2 = 3.1)
EV38 (λ^-1/2 = 3.4)
EV39 (λ^-1/2 = 3.4)
EV40 (λ^-1/2 = 3.5)
EV41 (λ^-1/2 = 4.4)
EV42 (λ^-1/2 = 4.9)