Experimental overview of EFT at LHC

Aram Apyan
on behalf of the ATLAS and CMS collaborations

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Effective Field Theory

> "The present educated view of the standard model, and of general relativity, is again that these are the leading terms in effective field theories." S. Weinberg, hep-th/9702027

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda_i^2} O_i^{(6)} + \sum_j \frac{f_i^{(8)}}{\Lambda_i^4} O_j^{(8)} + \dots ,$$

$$\sigma = |\mathcal{A}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

SM

Interference of SM and NP

Pure NP

- For dim=6 Warsaw basis often used to define complete set of independent operators
  - 59 operators for CP-even and restricted-flavor scenario

Outlook

See the talks by G. Callea and S. Chatterjee for Higgs EFT
See the talks by L. Keszeghová and J. Li for Top EFT

- Impossible to cover the wealth of interesting ATLAS and CMS results in a 15 minute talk
- Identify some interesting themes and topics of discussion:
  - Selected highlights of recent results
  - Impact of differential cross sections on dim-6 (interference)
  - Dealing with the unitarity violation
  - The interplay between dim-8 and dim-6 operators
  - Towards a global combination

$$\sigma = |\mathcal{A}_{\rm SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_{\rm SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j}\frac{c_i^{(6)}c_j^{(6)}}{\Lambda^4} 2{\rm Re}\left(\mathcal{A}_i^{(6)}\mathcal{A}_j^{(6)*}\right)$$

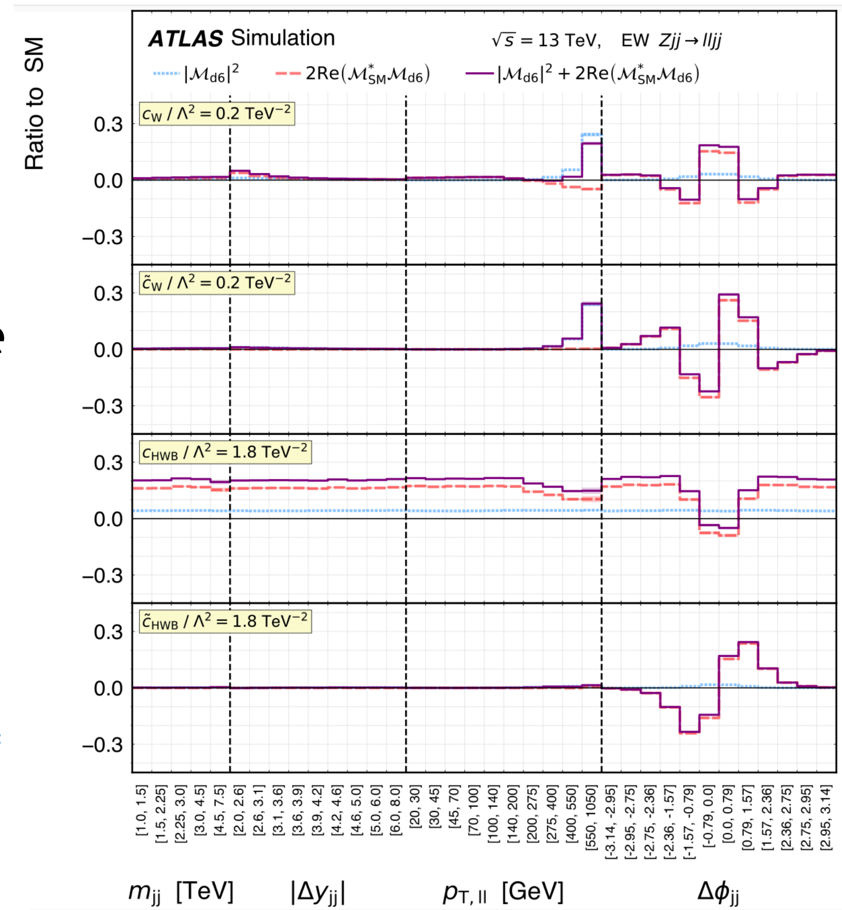
SM

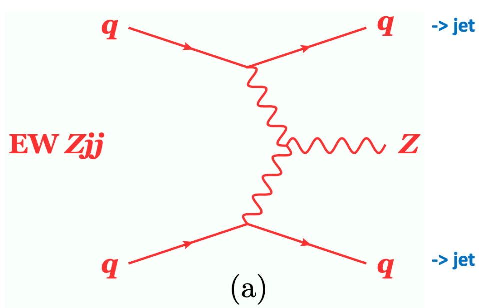
Interference of SM and NP

Pure NP

Dim-6 and differential cross sections

- Inclusive Diboson (VV) and V+2j processes probe triple gauge couplings
  - Effect of the interference is not detectable when considering only invariant mass and momentum observables
- Increasing the sensitivity to interference (which scales as Λ^{-2}) is important for improving the validity of constraints
  - The leading dim-8 contributions also enter at Λ^{-4} and unclear how to interpret the pure dim-6 BSM contribution

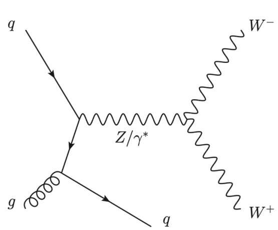


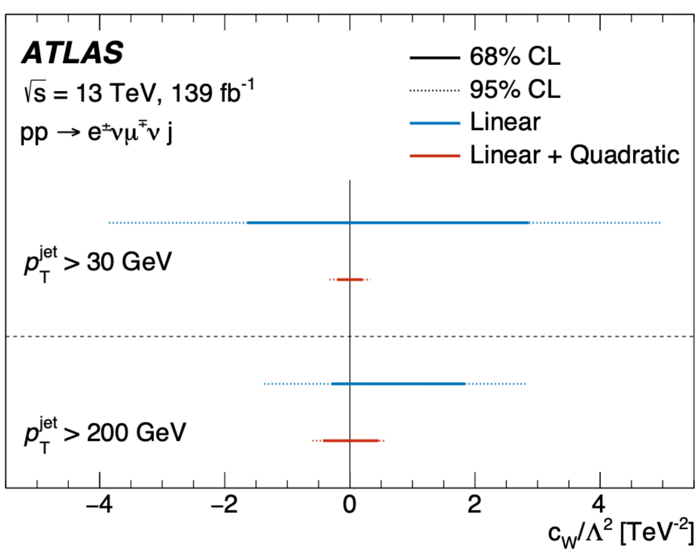


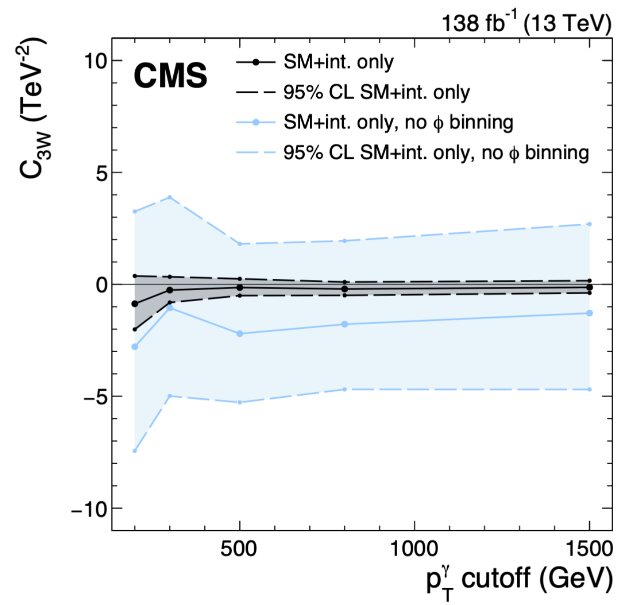
Arxiv:2006.15458

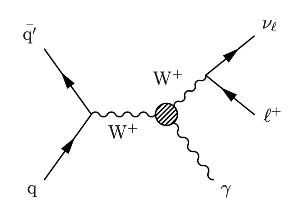
Dim-6 and differential cross sections

- Different approaches employed to enhance the interference (linear) contribution:
  - ATLAS WW result requires presence of an high pT jet to partially mitigate the interference suppression
  - CMS Wγ result uses a simultaneous measurement of the photon pT and the azimuthal angle of the charged lepton to enhance the interference







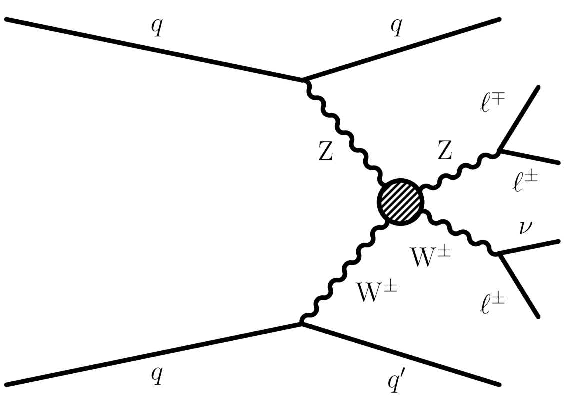


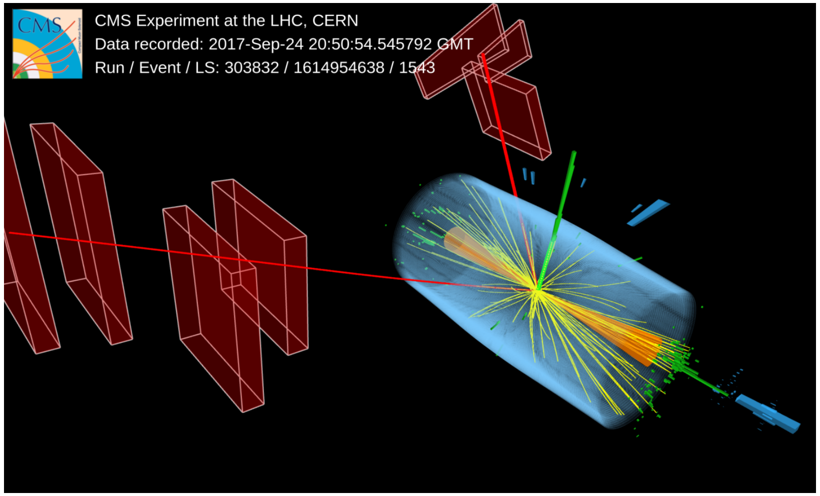
Arxiv:2103.10319

Arxiv:2111.13948

Unitarity

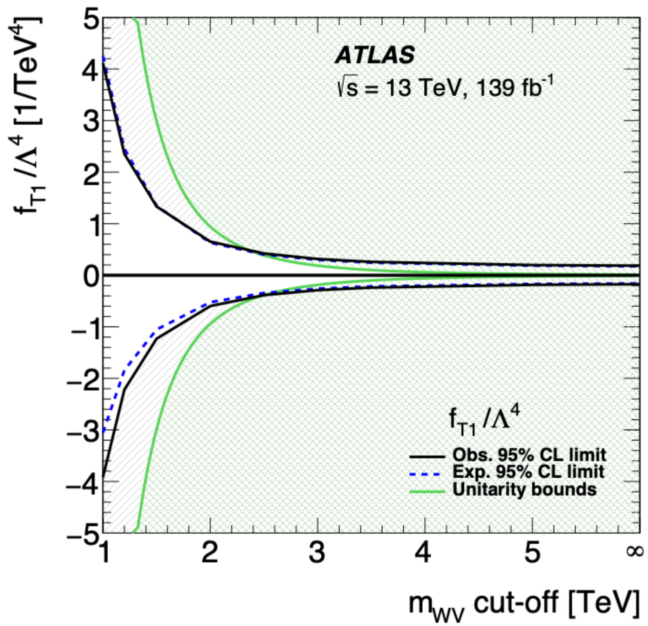
- A truncated EFT expansion violates unitarity at some energy scale
- Recent ATLAS and CMS results dealt with unitarity in number of ways
  - Do nothing and report the constraints without unitarity considerations
  - Report a unitarity bound corresponding to the observed limit
  - Report constraints as a function of cut-off scale (clipping)
- Vector boson scattering (VBS) processes
  - Contributions to quartic vertex appear first at dim-8 in EFT



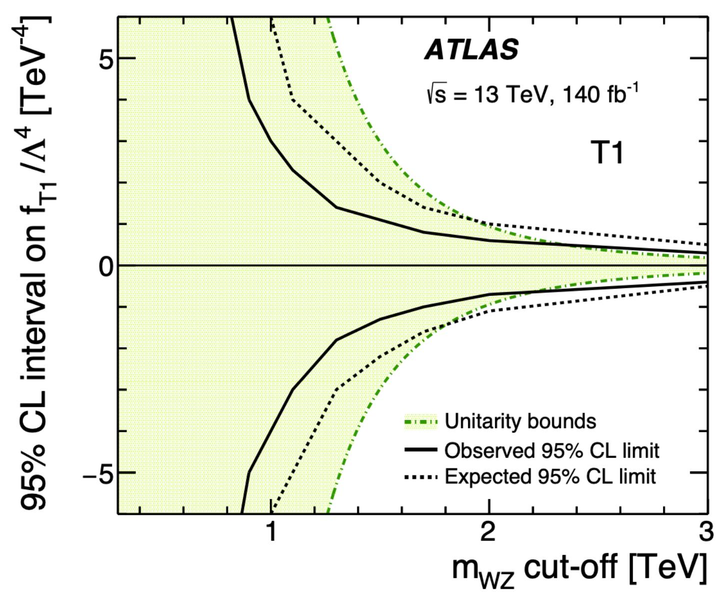


Dim-8 operators

- Typically 18 independent charge-conjugate and parity conserving operators are considered
  - EFT model generated at leading order. NLO EW and QCD effects are important in VBS
- Recent ATLAS same-sign WW and WZ EFT results
  - Similar competitive results from CMS in Arxiv:2005.01173



Arxiv:2312.00420



Arxiv:2403.15296

Interplay of dim-8 and dim-6 operators

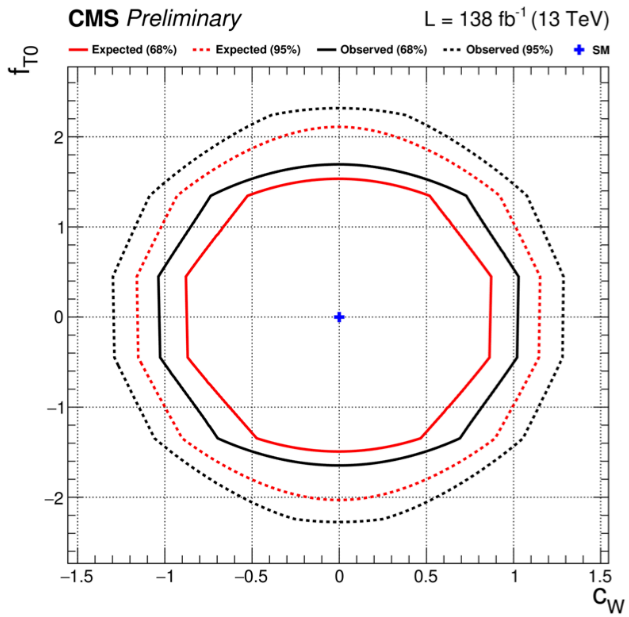
- Effects of dim-6 operators affecting the triple gauge couplings has been previously ignored in VBS results
  - The effect of dim-6 operators in VBS results is an interesting question
- New CMS VBS same-sign WW result with one W boson decaying to hadronic tau lepton
  - First simultaneous extraction of dim-6 and dim-8 constraints

- Significance of EW same-sign WW with tau decays is 2.7 standard deviations

Cross section for dim-6 + dim-8 operator:

$$\sigma_{SMEFT} = \sigma_{SM} + c_{d-6}\sigma_{int} + c_{d-6}^2\sigma_{d-6} + c_{d-8}\sigma_{int} + c_{d-8}^2\sigma_{d-8}$$

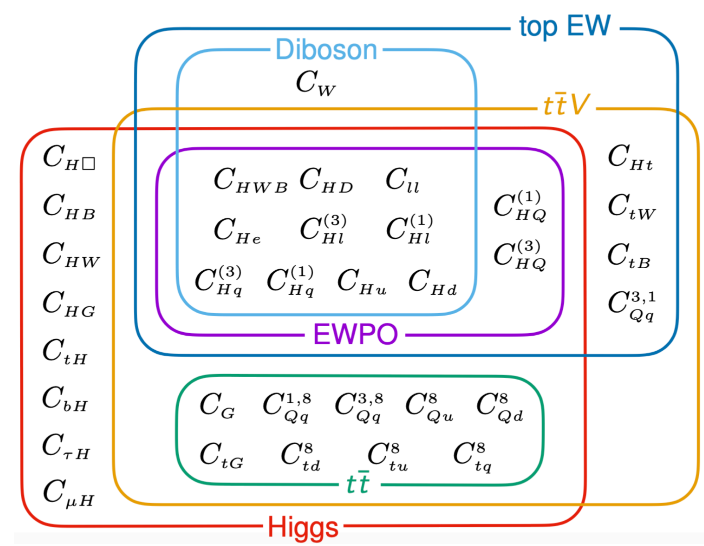
CMS-SMP-22-008



Global combined fits

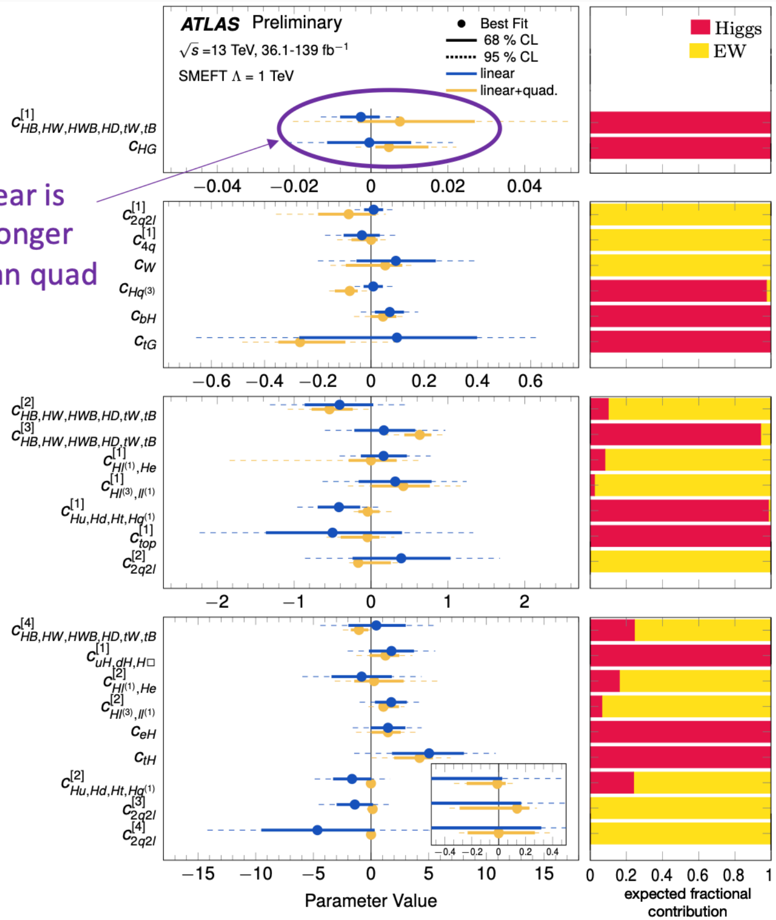
- Our target is to perform a global fit of many operators with many input physics measurements
  - Ultimately in the future try to simultaneously fit dim-6 and dim-8 operators with many measurements
- Significant step towards this direction performed by ATLAS in 2022
  - Dim-6 fit using Higgs+Diboson+EWPO data

- Great care taken to get details right:
  - Indirect impact of operators on Higgs BRs
  - Take propagator effects into account
  - Handle acceptance effects in certain Higgs decay kinematics
  - Consider impact of certain operators on Fermi constant

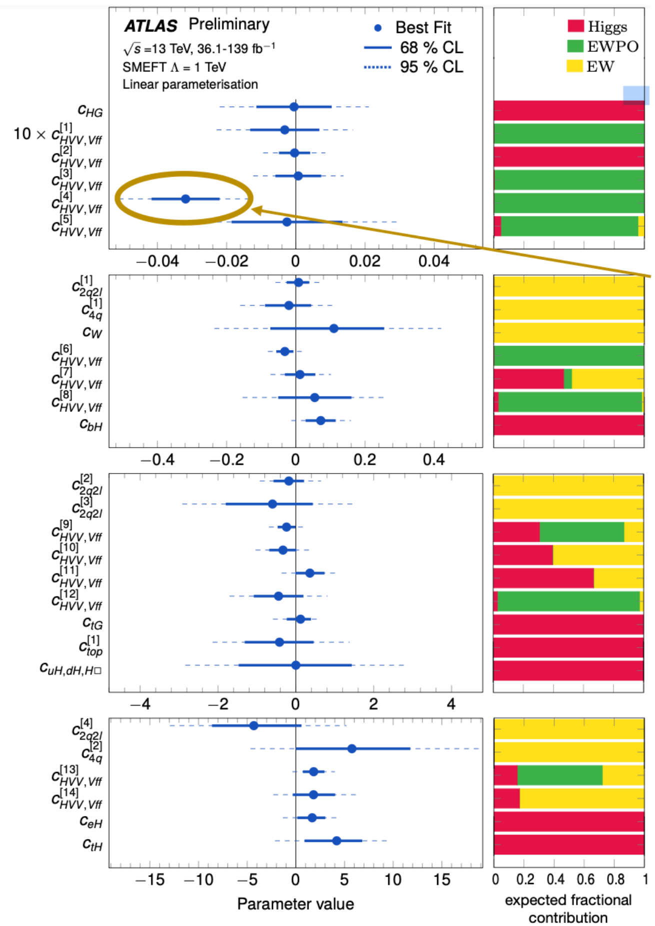


ATL-PHYS-PUB-2022-037

Global combined fits



linear is stronger than quad

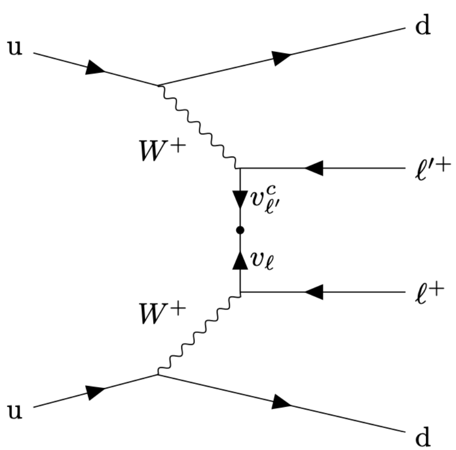


offset due to A_{FB}^b & A_{FB}^c

PCA analysis to extract the relevant eigenvectors

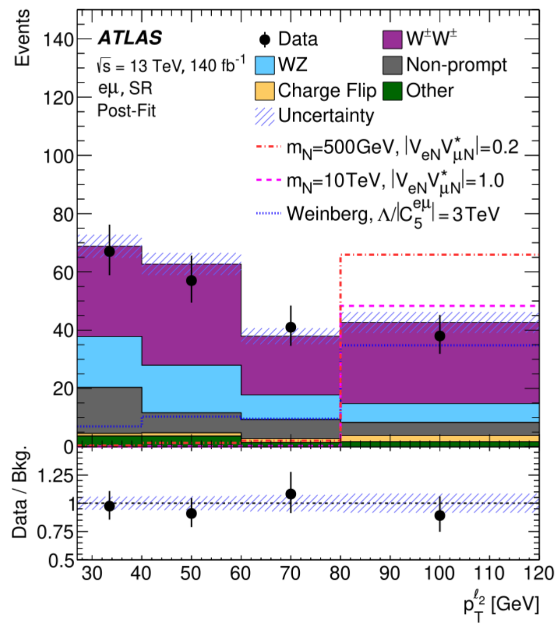
Dim-5 operators

- Dim-5 Weinberg operator
  - Violates lepton conservation and can generate neutrino mass
- ATLAS and CMS studied same-sign lljj final state to set constraints
  - μμ, eμ, and ee final states



$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda}[\Phi\cdot\overline{L}_\ell^c][L_{\ell'}\cdot\Phi]$$

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$$

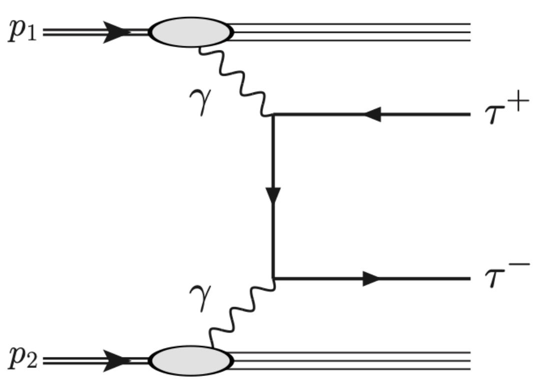


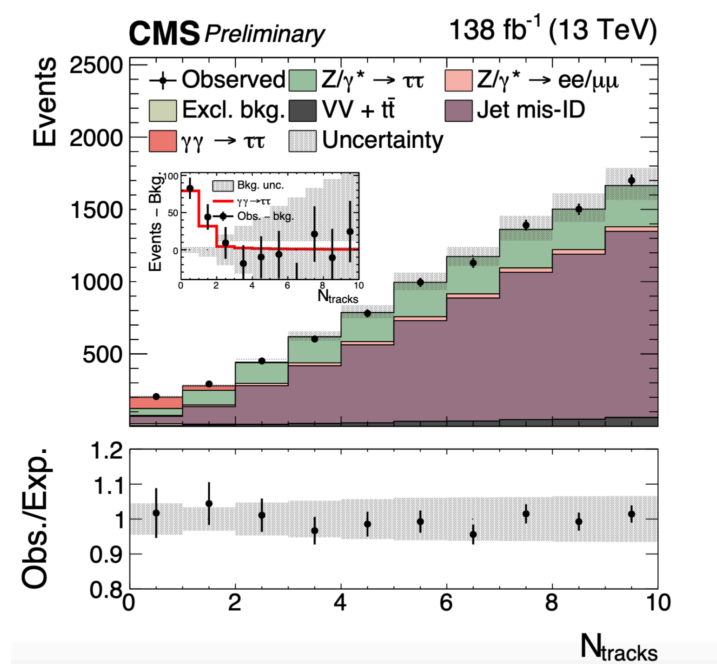
- Upper limits on effective Majorana mass in μμ
  - ATLAS: 16.7 GeV
  - CMS: 10.8 GeV

Arxiv:2403.15016 Arxiv:2305.14931 Arxiv:2206.08956

Observation of γγ -> $\tau\tau$

- CMS observation of photon induced production of pair of τ leptons in pp collisions
  - Previously observed by ATLAS and CMS in PbPb collisions
  - Run 2 data sample at 13 TeV and integrated luminosity of 138 fb^{-1}
  - Events with small number of tracks are close to the di-tau vertex are selected to isolate photon induced processes
    - Correct the number of tracks in simulation





Anomalous magnetic moment

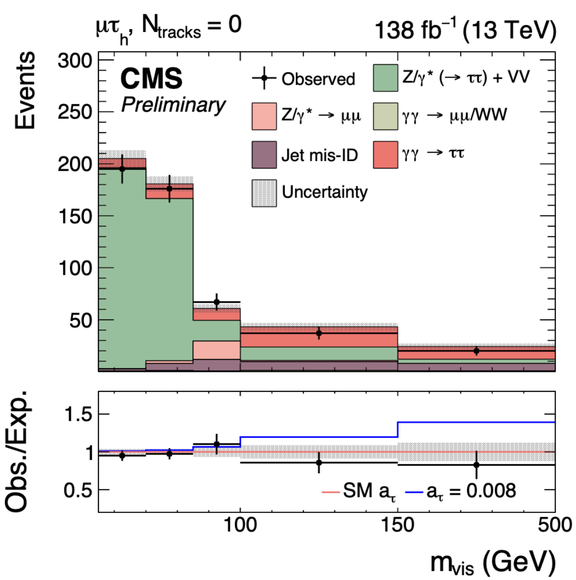
- CMS observation of photon induced production of pair of τ leptons in pp collisions
  - γγ -> $\tau\tau$ in pp: 5.3 (6.5) observed (expected) standard deviations
  - Constrain the anomalous electromagnetic moments of τ lepton using the visible mass distribution

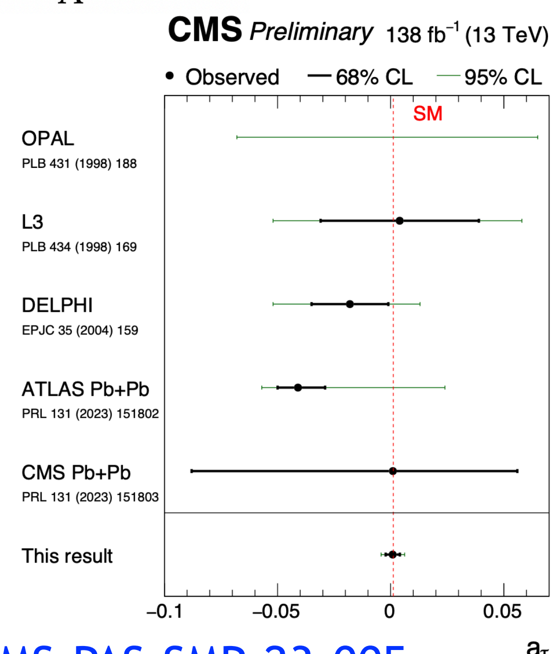
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}\left[C_{\tau\gamma}\right]$$

$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}\left[C_{\tau\gamma}\right]$$

$$C_{\tau\gamma} = \left(cos\theta_W C_{\tau B} - \sin\theta_W C_{\tau W}\right)$$

$$a_\tau = 0.0009^{+0.0016}_{-0.0015}\,(\mathrm{syst})^{+0.0028}_{-0.0027}\,(\mathrm{stat}).$$





CMS-PAS-SMP-23-005

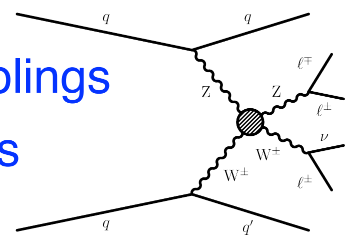
Summary

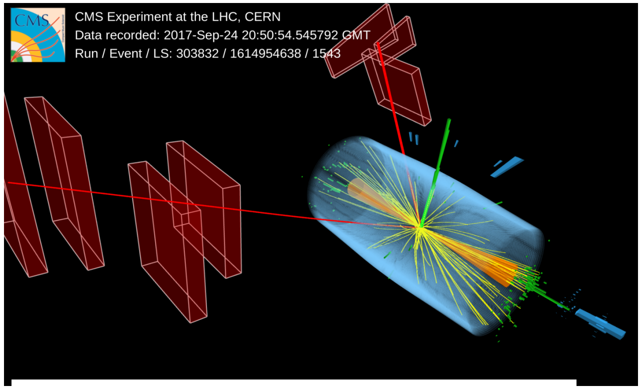
- Wealth of EFT fit results by ATLAS and CMS
  - Diverse range of analyses are used to set constraints
  - Many interesting recent results not covered in this talk
- Detailed differential measurements can lead to greater sensitivity for the interference (linear) terms
- The dim-6 and dim-8 operator interplay in certain measurements (VBS) is an important consideration
  - The unitarity of the constraints needs to be taken into account
- A combined global fit is challenging but an important goal
  - Progress towards this goal in recent results

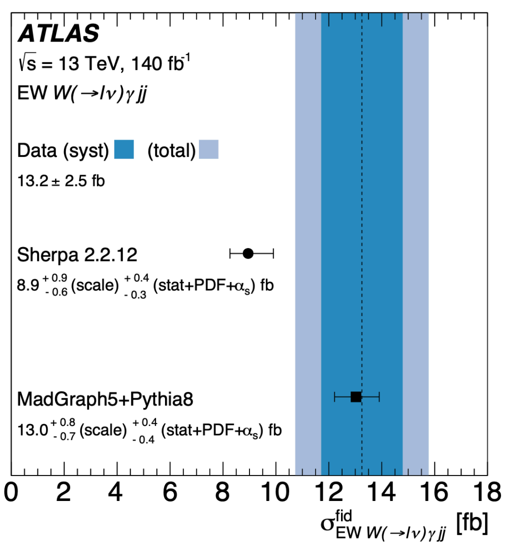
ADDITIONAL MATERIAL

VBS measurements

- From first observations->precision measurements
  - ATLAS and CMS completing Run 2 measurements
- Probe EW symmetry breaking
- Probe triple and quartic gauge couplings
- Theory predictions: NLO corrections
- Recent results to highlights:

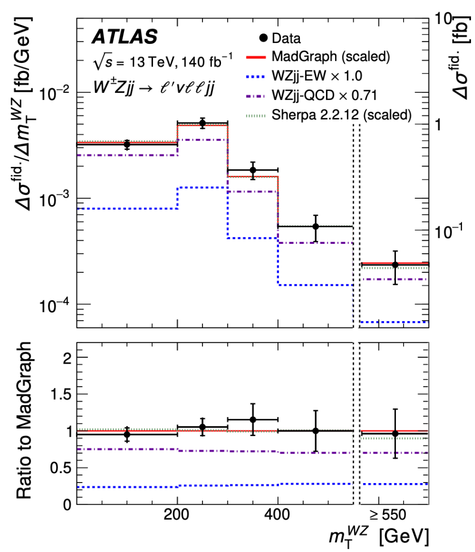






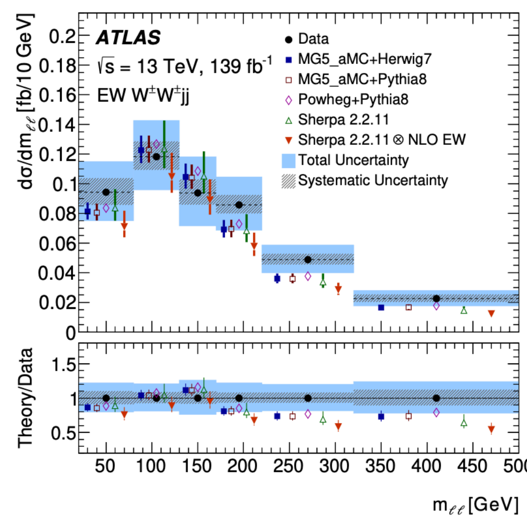
EW Wγjj

Arxiv:2403.02809



EW WZjj

Arxiv:2403.15296



EW W±W±jj

Arxiv:2312.00420

CMS-PAS-SMP-22-008

ATLAS global fit

Higgs data

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
	WH, ZH	139	[14,15,16]
$H \to b\bar{b}$	VBF	126	[17]
	$t\bar{t}H$	139	[18]

Z pole data

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{\text{FB}}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{\text{FB}}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{\text{FB}}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

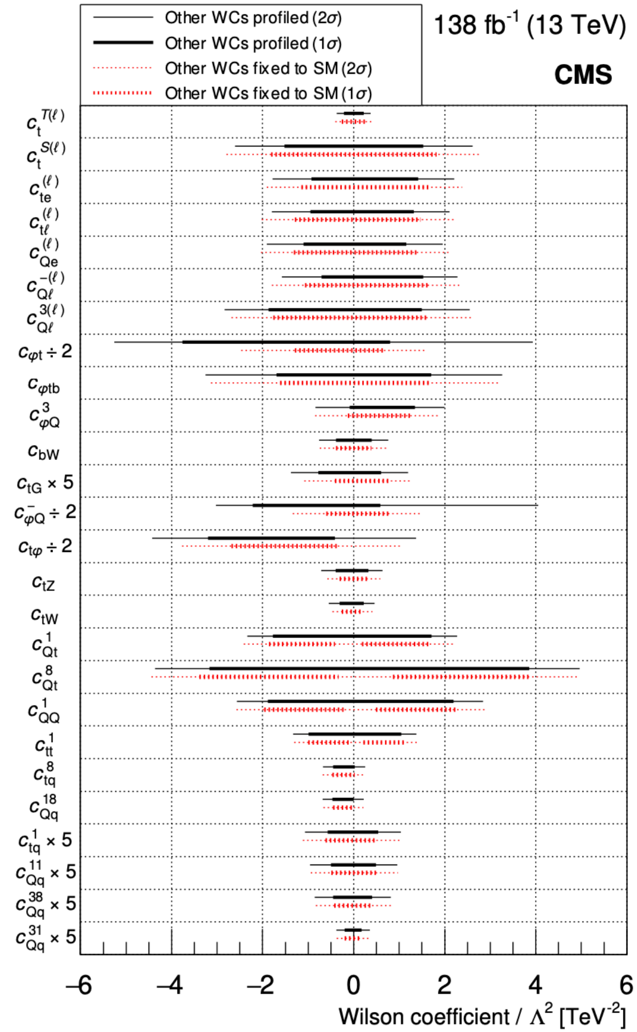
EW data

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^\pm\nu\mu^\mp\nu$	$m_{\ell\ell} > 55\,GeV,\ p_T^{\text{jet}} < 35\,GeV$	$p_T^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^\pm\nu\ell^+\ell^-$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_T^{WZ}	36	[20]
$pp \to \ell^+\ell^-\ell^+\ell^-$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139	[21]
$pp \to \ell^+\ell^- jj$	$m_{jj} > 1000\,GeV,\ m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139	[22]

Combined fits in top sector

- CMS tt+leptons analysis
  - ttZ, ttH, ttW, tttt, tZq, tHq
- Setting constraints on 26 independent Wilson coefficients
- Two scenarios are reported:
  - All Wilson coefficients are profiled
  - Only one/two are free and others are fixed to zero
- Limits don't degrade significantly going from individual to profiled

- More details in a talk given by Jack Li



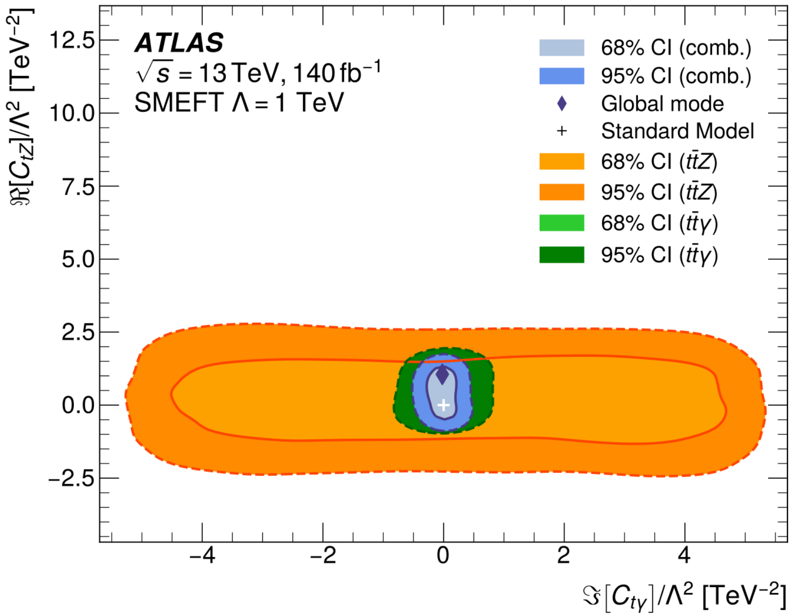
Arxiv:2307.15761

Combined fits in top sector

- ATLAS simultaneous analysis of ttZ and ttγ production to constrain EFT parameters
  - Use the distributions of the Z and γ bosons to simultaneously extract two complex Wilson Coefficients
  - Top EW dipole moments:

$$C_{tZ} = \cos\theta_W C_{tW} - \sin\theta_W C_{tB}$$
$$C_{t\gamma} = \sin\theta_W C_{tW} + \cos\theta_W C_{tB}$$

- Combination of the measurements significantly improves sensitivity
  - No sensitivity to linear interference term
  - Marginalized fits are obtained by integrating the posterior probability distribution over the other coefficients

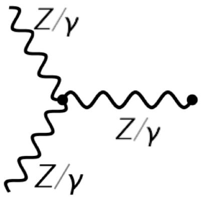


Arxiv:2403.09452

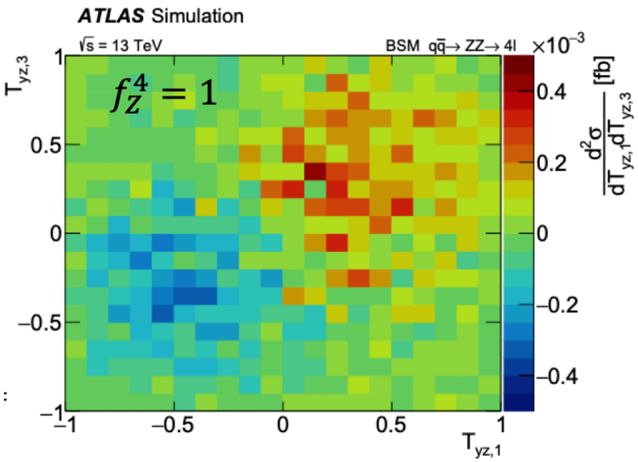
Anomalous neutral gauge couplings

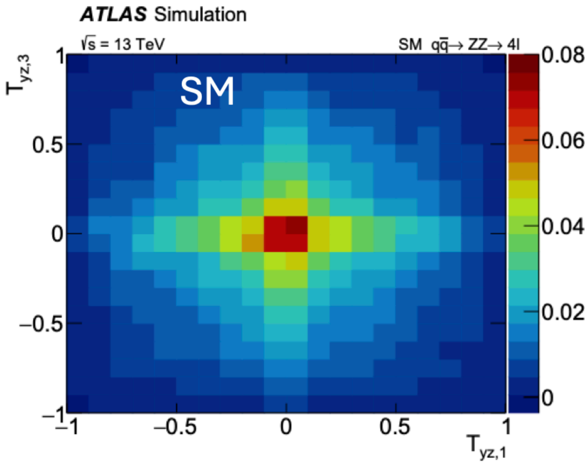
- ATLAS study on CP properties of the ZZ production
  - Results interpreted to constrain anomalous neutral triple gauge couplings
  - Direct probe of the interference term via angular optimal observables

$$T_{yz,1(3)} = \sin\phi_{1(3)} \cos\theta_{1(3)}$$



Neutral TGC (nTGC):
ZZZ, ZZγ, Zγγ





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]

Arxiv:2310.04350