Study of EFT effects in nTGC and aQGC in ElectroWeak processes

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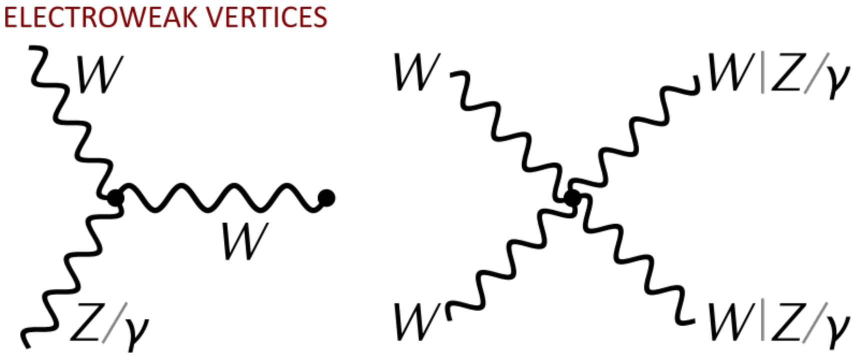
On behalf of the ATLAS and CMS Collaborations

nTGC? aQGC? Why?

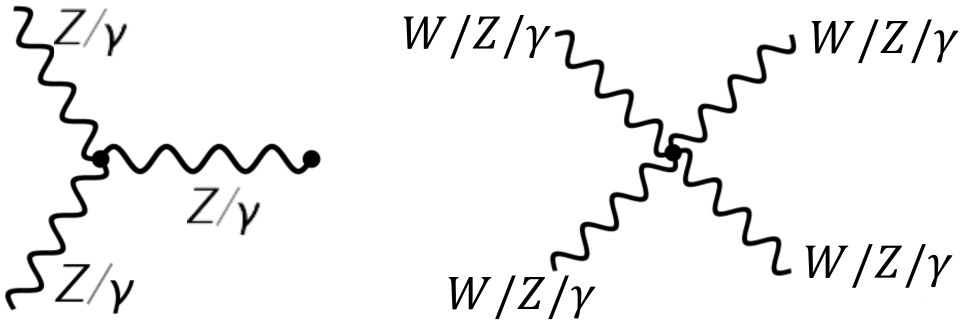
- SM provides gauge boson coupling of:



Triple Gauge Coupling (TGC):
WWZ, WWγ

Quartic Gauge Coupling (QGC):
WWWW, WWZZ, WWZγ,
WW$\gamma\gamma$

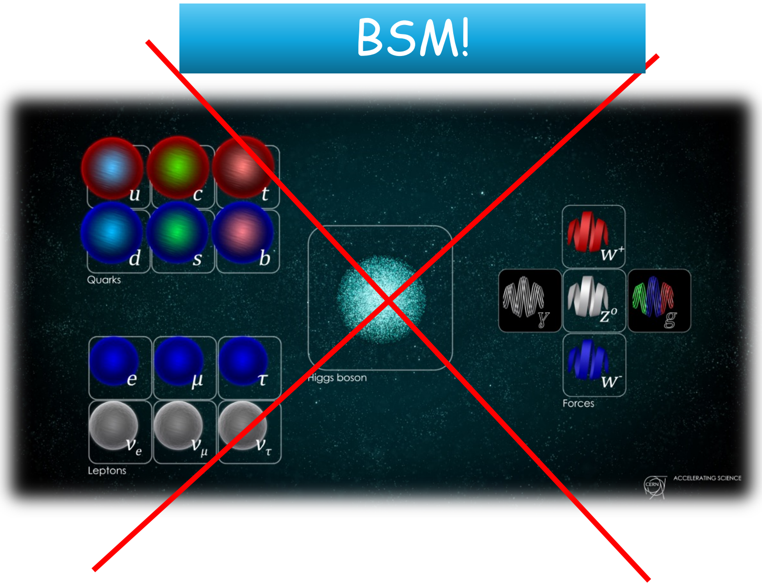
- What if *prohibited* vertices exist?



Neutral TGC (nTGC):
ZZZ, ZZγ, Z$\gamma\gamma$

anomalous QGC (aQGC)

A direct hint to



nTGC? aQGC? How?

- Standard Model Effective Field Theory (SMEFT) based on Taylor expansion in local operators with mass dimension > 4

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{d=6}}{\Lambda^2} \mathcal{O}_i^{d=6} + \sum_j \frac{c_j^{d=8}}{\Lambda^4} \mathcal{O}_j^{d=8} + \cdots$$

dimension

Wilson Coefficient

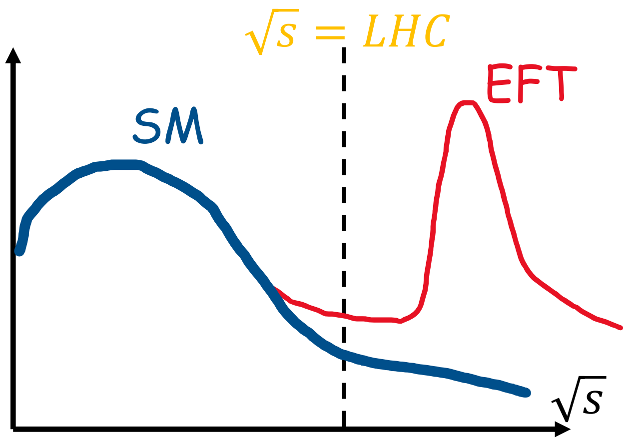
Energy Scale

Operators

- The nTGCs and aQGCs (without aTGCs counterpart), which is today's focus, are described in diemension-8. While dimension-5 has one operators for neutrino mass and aTGCs arises from dimension-6.

- When the energy scale parameter $\Lambda \gg \sqrt{s}$ the expansion term can be truncated.

- Growth of amplitude with $\sqrt{s}$ can violate unitarity



nTGC? aQGC? How? – The Basic Way

- Cross-section with single operator

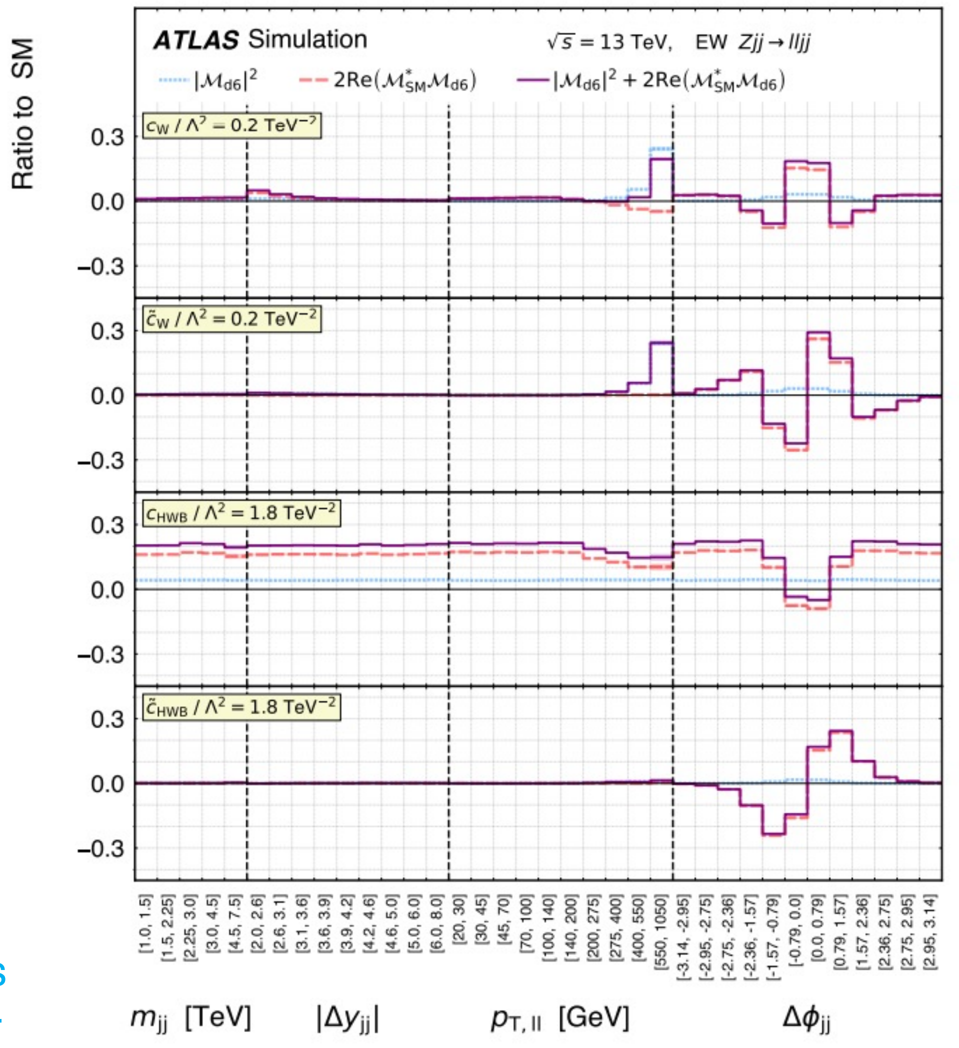
$$\sigma_{SMEFT} = \sigma_{SM} + \left(\frac{c^{d=8}}{\Lambda^4}\right)\sigma_{int} + \left(\frac{c^{d=8}}{\Lambda^4}\right)^2 \sigma_{EFT}$$

- Cross-section of interference term is proportional to coefficient.
- Cross-section of pure EFT contribution is proportional to the square of coefficient
- With cross-section of σ_{int} and σ_{EFT} from MC when $c = 1$, a likelihood test can be performed to the measured cross-section:

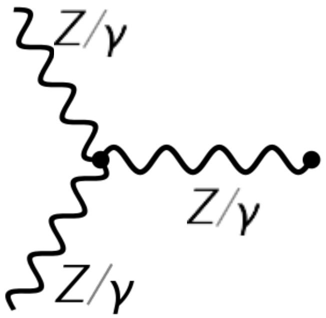
$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k |Cov|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{data} - \vec{\sigma}_{SMEFT} - \sum_i \theta \cdot \vec{e}_\theta\right)^T Cov^{-1}\left(\vec{\sigma}_{data} - \vec{\sigma}_{SMEFT} - \sum_i \theta \cdot \vec{e}_\theta\right)\right) \times \prod_i \mathcal{N}(\theta_i)$$

χ^2

Nuisances parameter



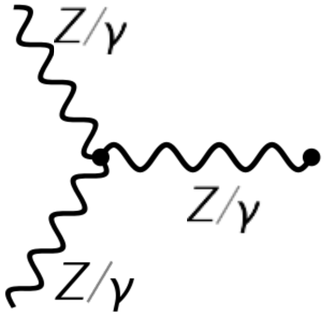
arxiv: 2006.15458



nTGCs

nTGCs - Parameters

JHEP 1402 (2014) 101



Neutral TGC (nTGC):
ZZZ, ZZγ, Z$\gamma\gamma$

$$ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,q_3) = \frac{-e(q_3^2 - m_V^2)}{M_Z^2}\left[f_4^V\,(q_3^\alpha g^{\mu\beta} + q_3^\beta g^{\mu\alpha}) - f_5^V\,\epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right], \quad (1.1)$$

$$ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,q_3) = \frac{-e(q_3^2 - m_V^2)}{M_Z^2}\Big\{h_1^V\,(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{M_Z^2} q_3^\alpha[(q_3 q_2)g^{\mu\beta} - q_2^\mu q_3^\beta] - h_3^V\,\epsilon^{\mu\alpha\beta\rho} q_{2\rho} - \frac{h_4^V}{M_Z^2} q_3^\alpha\,\epsilon^{\mu\beta\rho\sigma} q_{3\rho} q_{2\sigma}\Big\} \quad (1.2)$$

- f_i^V require on shell ZZ, while h_i^V require on shell Zγ.
- A recent paper point out that extra operators and form factor should be introduced in nTGCs.-> PRD 107 (2023) 035005

Basis of dim 8 operators for nTGCs:

$$\mathcal{O}_{\widetilde{B}W} = i\,H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H,$$
$$\mathcal{O}_{B\widetilde{W}} = i\,H^\dagger B^{\mu\nu} \widetilde{W}_{\mu\rho}\,\{D_\rho, D^\nu\}\,H,$$
$$\mathcal{O}_{\widetilde{W}W} = i\,H^\dagger \widetilde{W}_{\mu\nu} W^{\mu\rho}\,\{D_\rho, D^\nu\}\,H,$$
$$\mathcal{O}_{\widetilde{B}B} = i\,H^\dagger \widetilde{B}_{\mu\nu} B^{\mu\rho}\,\{D_\rho, D^\nu\}\,H.$$

ZZ production

Zγ production

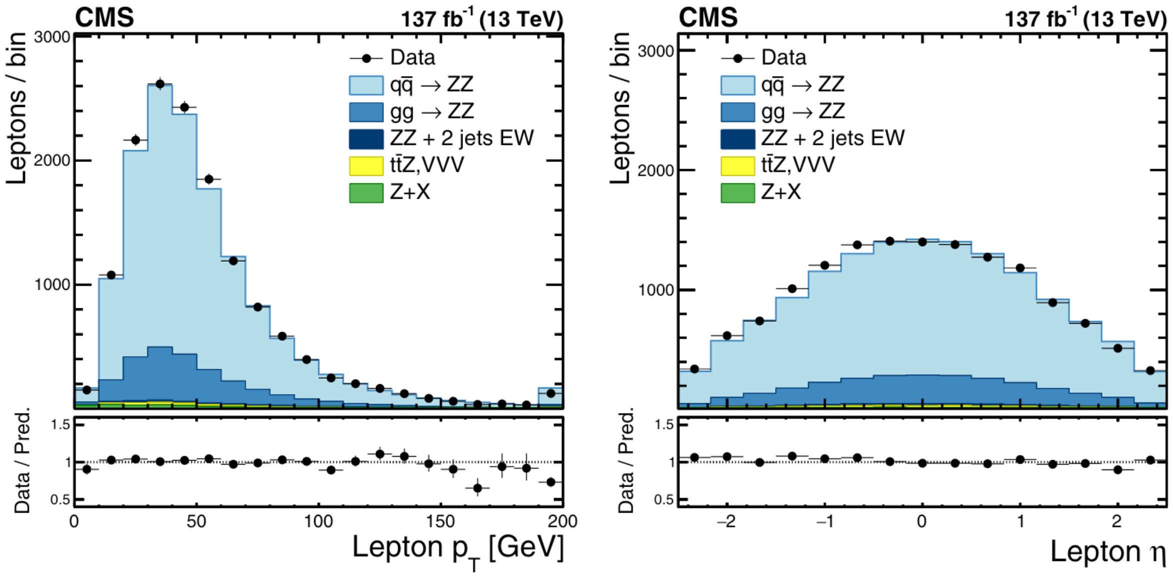
	CP-odd	CP-even
ZZZ	f_4^Z	f_5^Z
ZZγ	f_4^γ, h_1^Z, h_2^Z	f_5^γ, h_3^Z, h_4^Z
Z$\gamma\gamma$	h_1^γ, h_2^γ	h_3^γ, h_4^γ

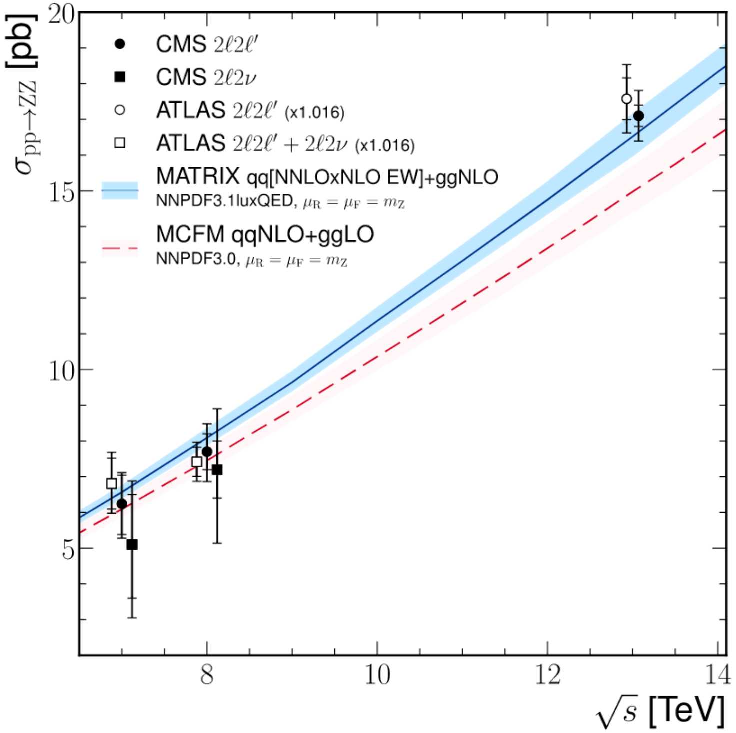
CMS – ZZ($\rightarrow 4l$)

$\mathcal{L} = 137\ fb^{-1}$@13 TeV

Eur. Phys. J. C (2021) 81:200

- Sensitive to two nTGCs: ZZZ, ZZγ.
- Test predictions at next-to-next-to-leading order (NNLO) in QCD.
- Low background contribution (~3%) due to the requirement for four well-reconstructed and isolated leptons.





- Cross section measurement:

Year	Total cross section, pb
2016	$18.1 \pm 0.6\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo})^{+0.5}_{-0.4}\,(\text{lumi})$
2017	$17.0 \pm 0.5\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$17.1 \pm 0.4\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.4 \pm 0.3\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

- Consistent with the NNLO prediciton

CMS – ZZ($\to 4l$)

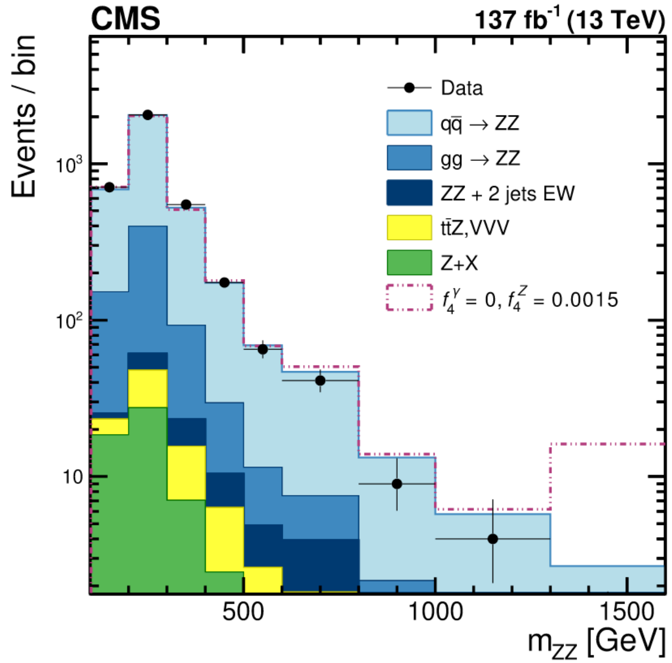
$\mathcal{L} = 137\ fb^{-1}$@13 TeV   Eur. Phys. J. C (2021) 81:200

- 2-D constraints, set limit to two parameters simultaneously. Predicted cross section:

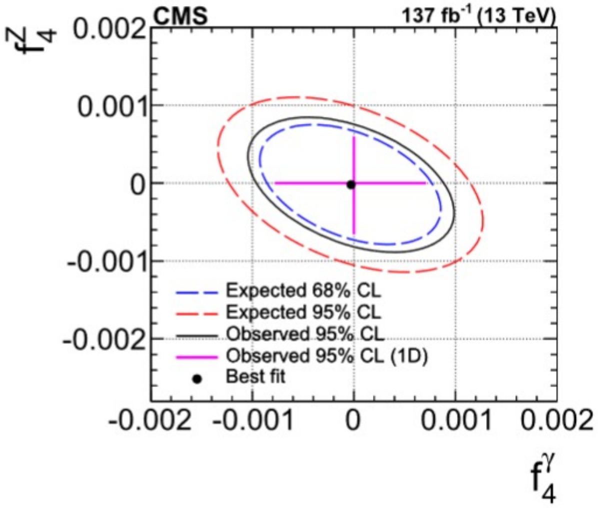
$$\sigma_{SMEFT} = \sigma_{SM} + c_1\sigma_{int1,SM} + c_2\sigma_{int2,SM} + c_1c_2\sigma_{int1,2} + {c_1}^2\sigma_{EFT,1} + {c_2}^2\sigma_{EFT,2}$$

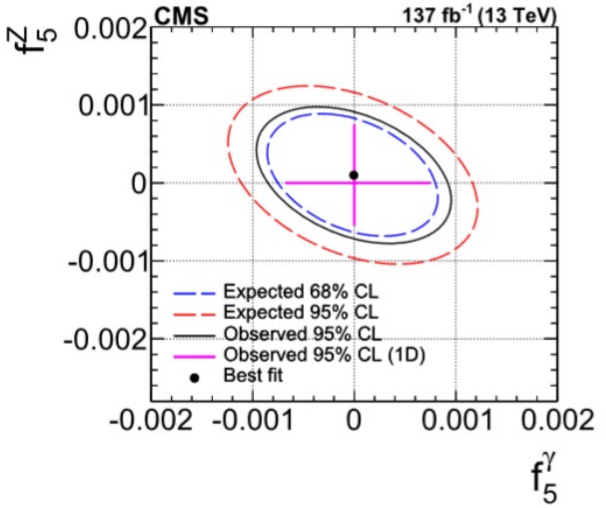
- Constraints are set on m_{ZZ}, CP-even variable. Hence CP-odd parameters (f_4^V) interference term are vanished.

- Overflow contribution are included in the last bin.



	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	−8.8 ; 8.3	−6.6 ; 6.0
f_5^Z	−8.0 ; 9.9	−5.5 ; 7.5
f_4^γ	−9.9 ; 9.5	−7.8 ; 7.1
f_5^γ	−9.2 ; 9.8	−6.8 ; 7.5

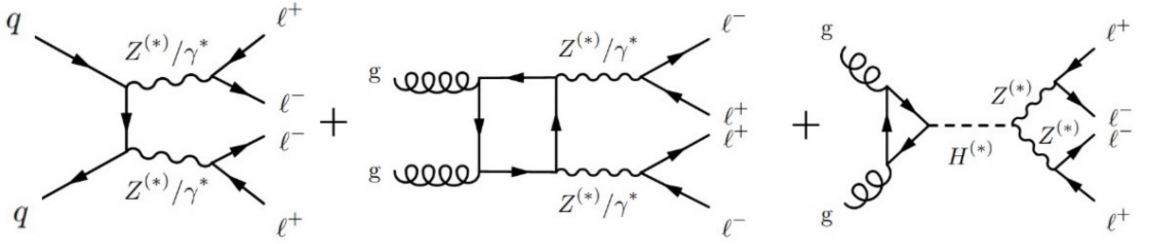




ATLAS – ZZ($\rightarrow 4l$) Angular

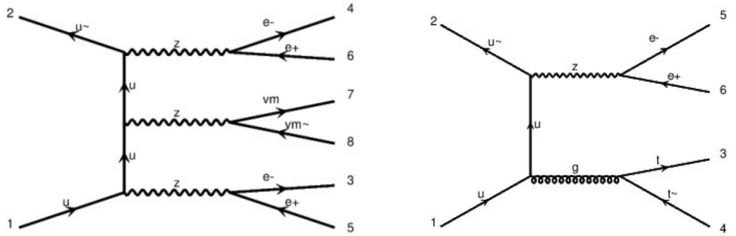
$\mathcal{L} = 140\ fb^{-1}$@13 TeV   JHEP 12 (2023) 107

- Search for CP-violation and nTGCs in ZZ(4l) on-shell events (dim-8 EFT)
- Measure the ZZ polarization in 4l channel (extract the LL component)
- Measure the spin correlation between ZZ bosons



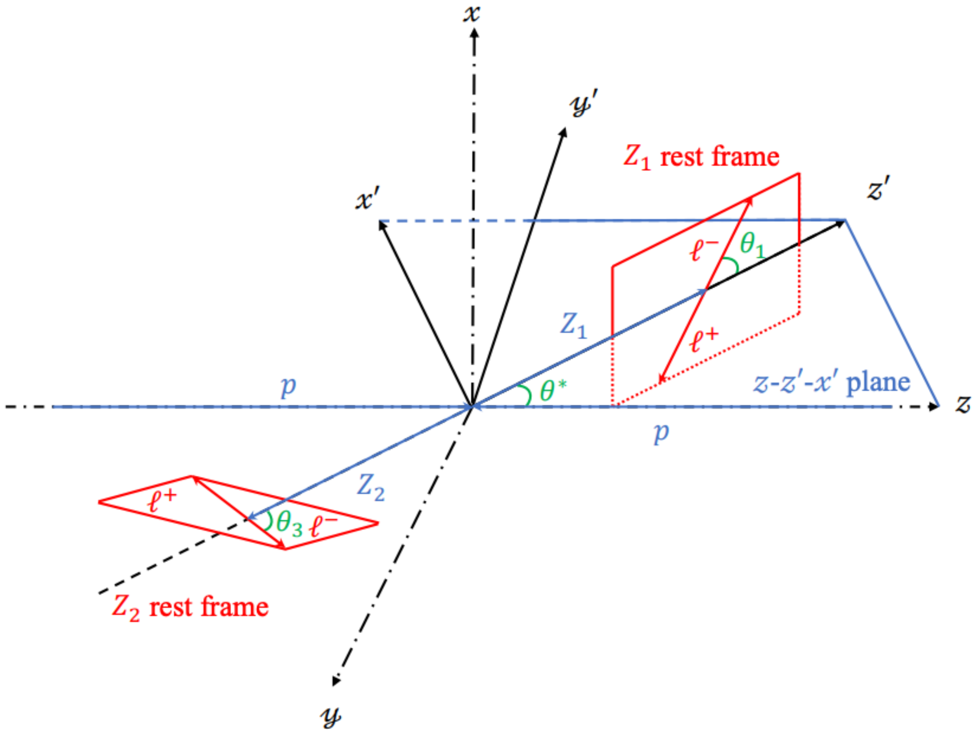
qq → ZZ → 4l   gg → ZZ → 4l   gg → H → ZZ → 4l

Signal



Triboson (VVV)   ttbar + Z

Background



ATLAS – ZZ($\rightarrow 4l$) Angular

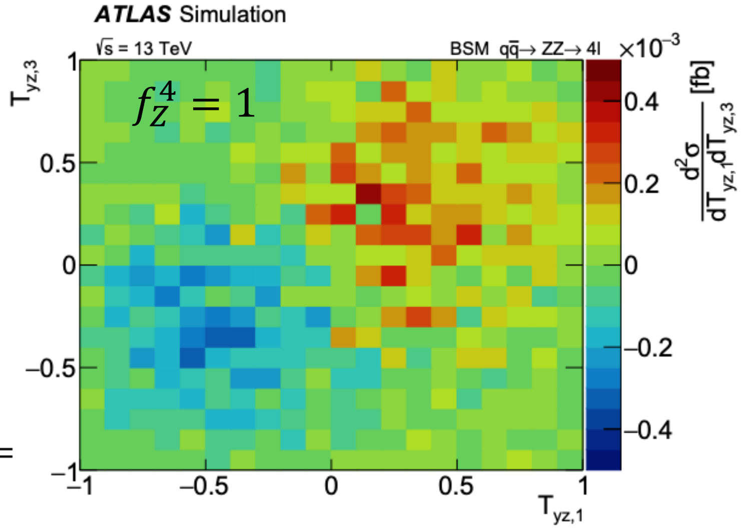
$\mathcal{L} = 140\ fb^{-1}$@13 TeV JHEP 12 (2023) 107

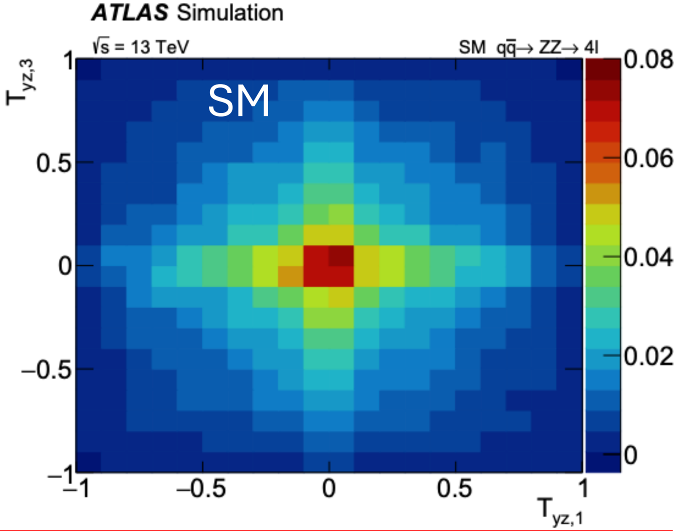
- To improve sensitivity, the two CP sensitive angles are combined as:

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

- An Optimal Observable (OO) is defined from the 2D distribution of $T_{yz,1}\ V.S.\ T_{yz,3}$ to maximise the sensitivity for the four-lepton system.

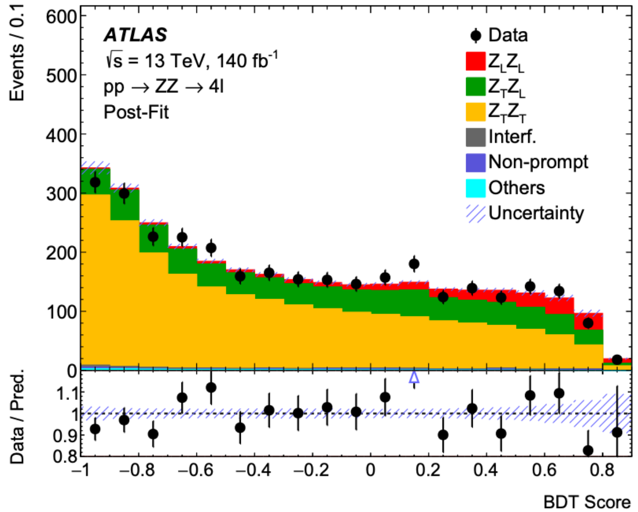
aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	[−0.16, 0.16]	[−0.12, 0.20]	[−0.013, 0.012]	[−0.012, 0.012]
f_γ^4	[−0.30, 0.30]	[−0.34, 0.28]	[−0.015, 0.015]	[−0.015, 0.015]





Angular observable allows direct probe to the interference term and CPV effects, although it is of magnitude weaker in full EFT.

- A BDT is used to determine the three different ZZ polarisation pairs: Z_LZ_L (Signal) || Z_TZ_L Z_TZ_T (Background)
- Fiducial cross section (4.3σ for Z_LZ_L):
  - $\sigma^{obs.}_{Z_LZ_L} = 2.45 \pm 0.56(stat.) \pm 0.21(syst.)$ fb
  - $\sigma^{pred.}_{Z_LZ_L} = 2.10 \pm 0.09$ fb

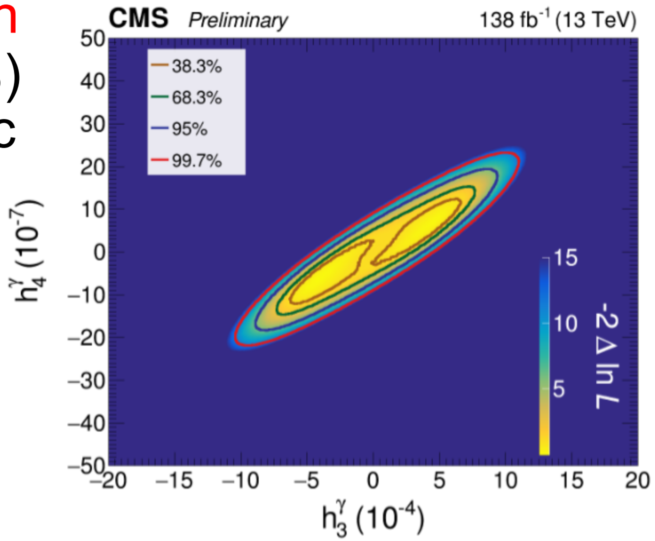


CMS – Z($\to \nu\bar{\nu}$)γ

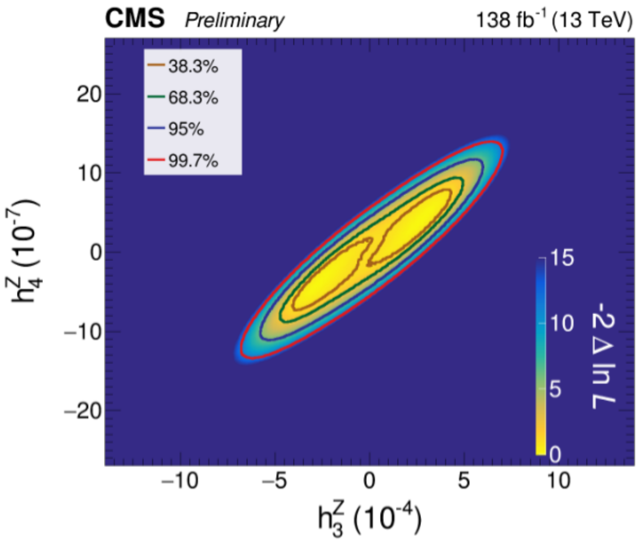
$\mathcal{L} = 138\ fb^{-1}$@13 TeV   CMS PAS SMP-22-009

- Invisible Z decay has a higher branching fraction (20%) compared to the leptonic Z channel (10%) and cleaner signature compared to both leptonic Z decay and hadronic decay.

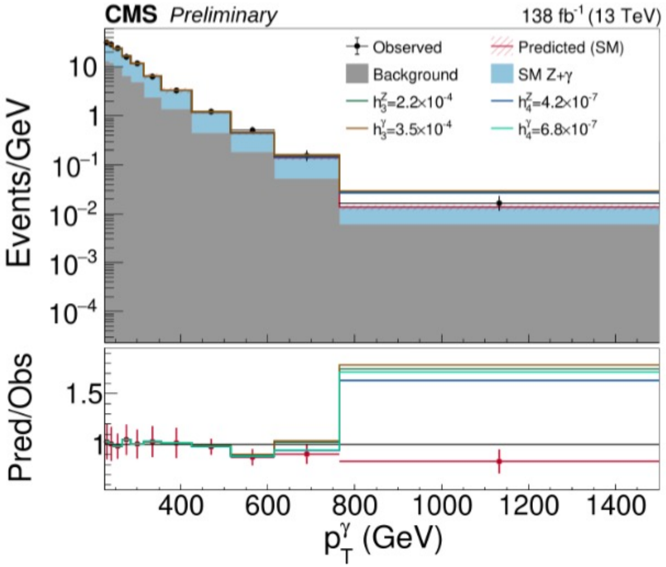
- Measurement divided into barrel and endcaps due to different detector response on fake backgrounds:

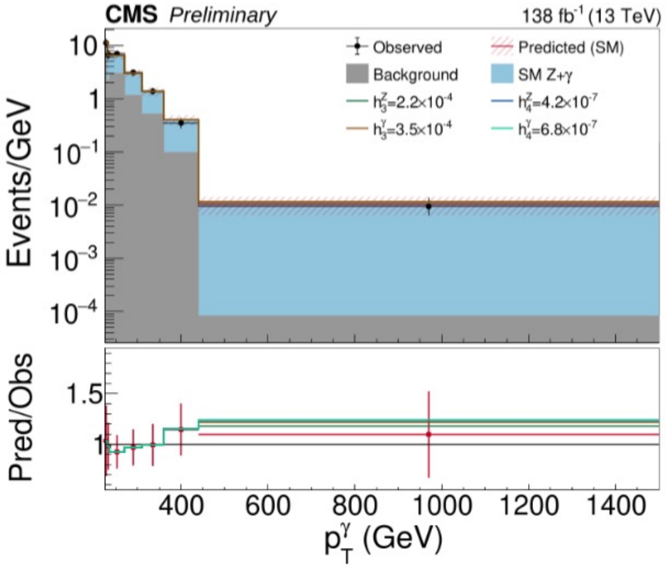


Z$\gamma\gamma$ Vertex



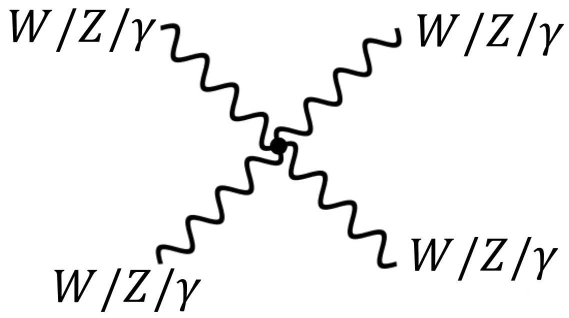
ZZγ Vertex





Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)

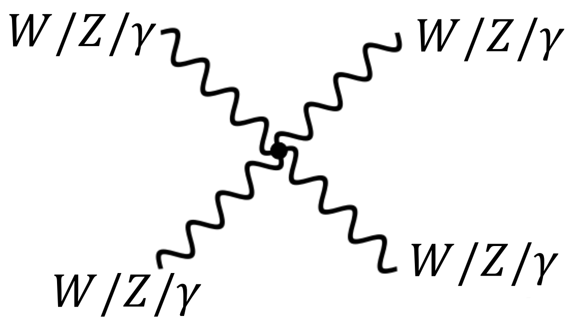
The sensitivities to CP-conserving and CP- violating couplings are comparable in the probed p_T regime.



aQGCs

aQGCs - Parameters

PRD 93, 093013 (2016)



anomalous QGC (aQGC)

- The Eboli Model:
  - tensor (T): EWK field strength tensors derivatives
  - scalar (S): Higgs doublet derivatives
  - mixed (M): both

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

- To guarantee consistency of the analyses, it is essential to verify whether perturbative partial-wave unitarity is satisfied when probing aQGCs.
- Partial wave unitarity for two-to-two scattering is calculated in PRD 101, 113003 (2020).
- The bounds on each Wilson coefficient is related to the center-of-mass energy ($\sqrt{s}$) of the two-to-two scattering system.

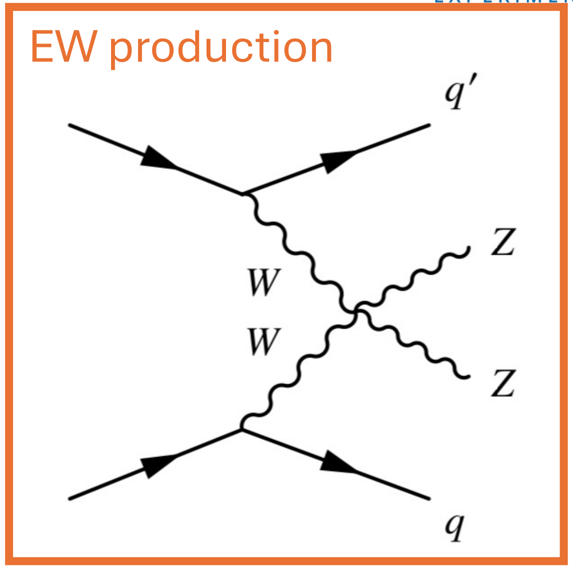
	Bound	
	1 operator	
Wilson coefficient		For $\sqrt{s} < 1.5(3)$ TeV
$\lvert\frac{f_{S,0}}{\Lambda^4}\rvert$	$32\pi s^{-2}$	$20(1.2)$ TeV^{-4}
$\lvert\frac{f_{S,1}}{\Lambda^4}\rvert$	$\frac{96}{7}\pi s^{-2}$	$8.5(0.53)$ TeV^{-4}
$\lvert\frac{f_{S,2}}{\Lambda^4}\rvert$	$\frac{96}{5}\pi s^{-2}$	$8.5(0.53)$ TeV^{-4}

Clip Scan: constraints on each Wilson coefficient can be obtained after restricting EFT contribution within $\sqrt{s} < E_c$, and the unitarity bound of E_c can be calculated and compared with the constraints.

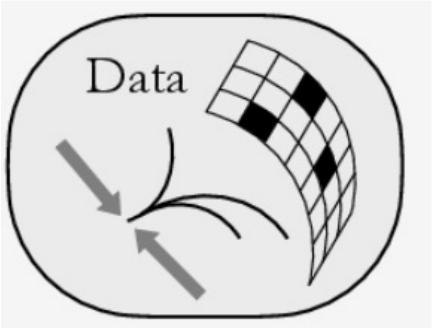
ATLAS – VBS ZZ($\rightarrow 4l$)

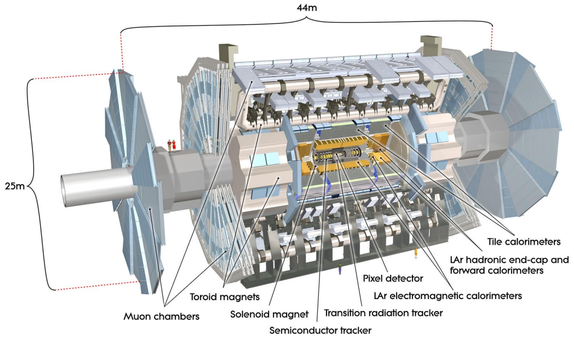
$\mathcal{L} = 140\ fb^{-1}$@13 TeV   JHEP. 2024, 4 (2024)

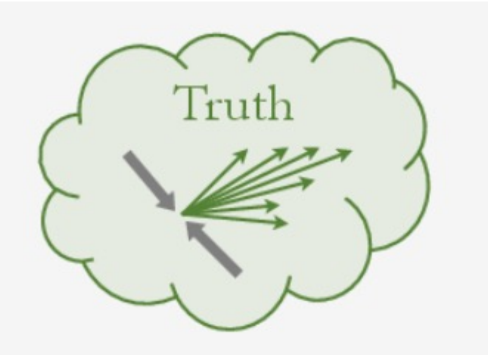
- Motivation and goal
  - Sensitive to 3 and 4-weak boson self-interactions
  - Differential cross-sections can probe New Physics (aTGC, aQGC)
  - Unfolded differential cross section measurement.
    - Remove detector response
    - Allow different models to perform re-interpretation directly



Reconstruction distribution (Detector-level) = Detector Response ⊗ Physics distribution y_i (Particle-level)

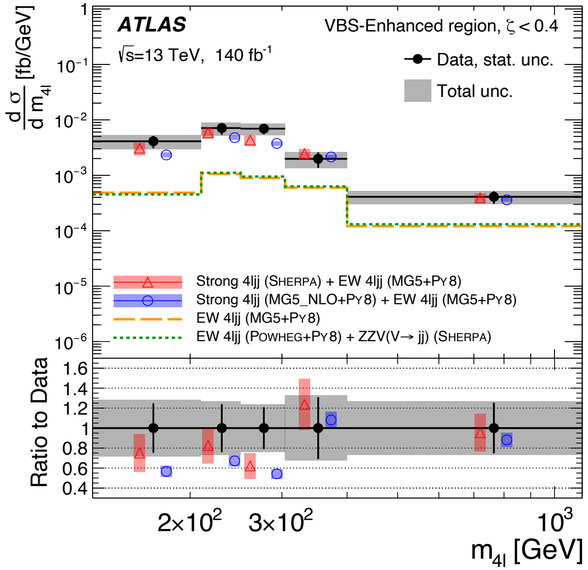






Reconstruction

Unfold



ATLAS – VBS ZZ($\to 4l$)

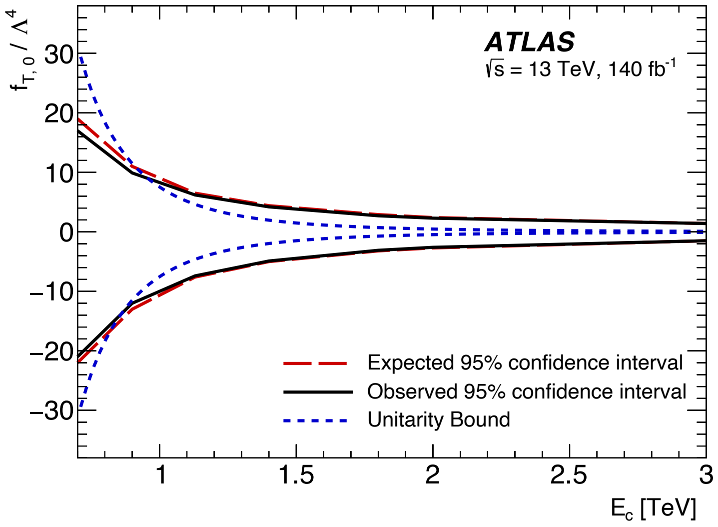
$\mathcal{L} = 140\ fb^{-1}$@13 TeV

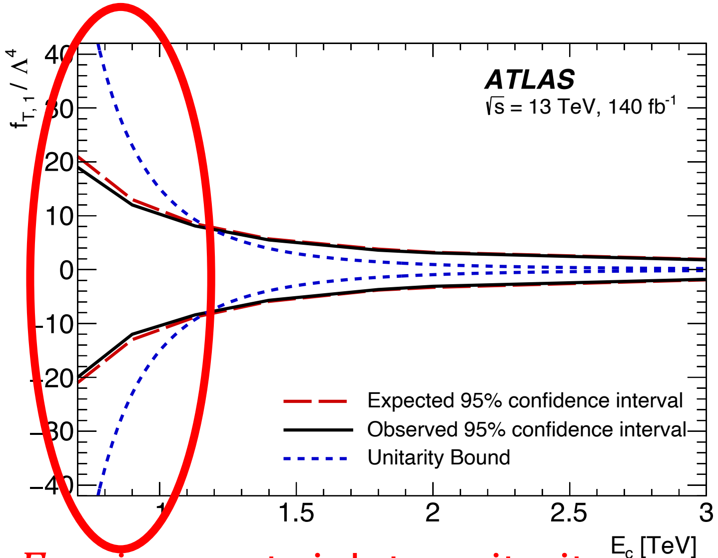
JHEP. 2024, 4 (2024)

- Unfolded cross-sections in agreement with predictions (some underestimation from MG5+PY8 strong production)
- Limits to dim-8 operators from a combined $m_{jj} + m_{4\ell}$ fit with overflow contributions.
- Clip scan is performed via $E_c = m_{4l}$ to check the unitarity bound (if violated).

PRD 101, 113003 (2020)

Clip scan is performed by estimating the limit of Wilson coefficient when clipping all the EFT event with the energy higher than the given E_c.





The E_c reigon not violate unitarity

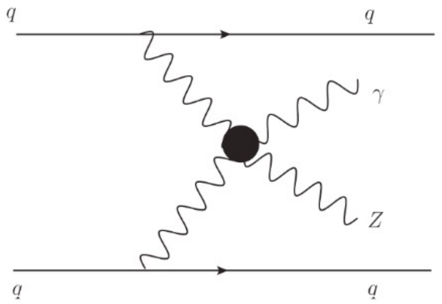
Wilson coefficient	$\lvert\mathcal{M}_{d8}\rvert^2$ Included	95% confidence interval [TeV^{-4}] Expected	Observed
$f_{T,0}/\Lambda^4$	yes	[-1.00, 0.97]	[-0.98, 0.93]
	no	[-19, 19]	[-23, 17]
$f_{T,1}/\Lambda^4$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-140, 140]	[-160, 120]
$f_{T,2}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-63, 62]	[-74, 56]
$f_{T,5}/\Lambda^4$	yes	[-2.6, 2.5]	[-2.5, 2.4]
	no	[-68, 67]	[-79, 60]
$f_{T,6}/\Lambda^4$	yes	[-4.1, 4.1]	[-3.9, 3.9]
	no	[-550, 540]	[-640, 480]
$f_{T,7}/\Lambda^4$	yes	[-8.8, 8.4]	[-8.5, 8.1]
	no	[-220, 220]	[-260, 200]
$f_{T,8}/\Lambda^4$	yes	[-2.2, 2.2]	[-2.1, 2.1]
	no	[-3.9, 3.8]$\times 10^4$	[-4.6, 3.1]$\times 10^4$
$f_{T,9}/\Lambda^4$	yes	[-4.7, 4.7]	[-4.5, 4.5]
	no	[-6.4, 6.3]$\times 10^4$	[-7.5, 5.5]$\times 10^4$

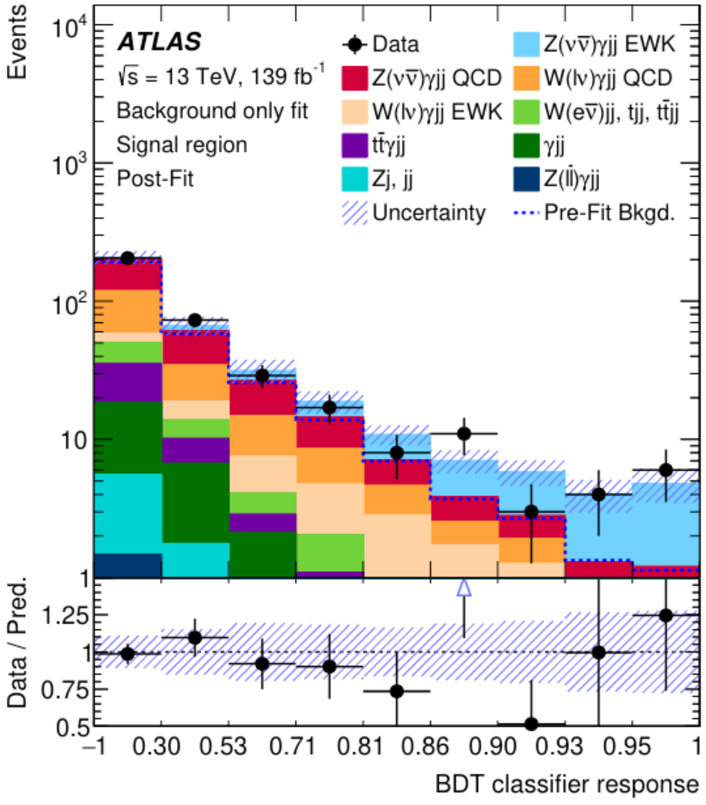
ATLAS – VBS Z($\rightarrow \nu\bar{\nu}$)γ

$\mathcal{L} = 140\ fb^{-1}$@13 TeV JHEP 06(2023)082

- VBS Z($\rightarrow \nu\bar{\nu}$)γ is observed in low energy phase space ($15 < E_T^\gamma < 110$ GeV) by ATLAS (EPJC 82 (2022) 105). But low energy phase space has no sensitivity to aQGCs.
- This analysis conduct the VBS Z($\rightarrow \nu\bar{\nu}$)γ in high energy phase-space ($E_T^\gamma > 150$ GeV). Both phase-space can be combined to obtain higher sensitivity to aQGCs.
- Dominant background from QCD Z($\rightarrow \nu\bar{\nu}$)γjj and W($\rightarrow l\nu$)γjj.
- Combined measurement has found a 6.3σ (6.6σ) significance on signal strength of VBS Z($\rightarrow \nu\bar{\nu}$)γ and the fiducial cross section of high energy phase space is measured:

$$\sigma_{Z\gamma\mathrm{EWK}} = 0.77^{+0.34}_{-0.30}\ \mathrm{fb} = 0.77^{+0.25}_{-0.23}\ (\mathrm{stat.})^{+0.22}_{-0.18}\ (\mathrm{syst.})\ \mathrm{fb}.$$



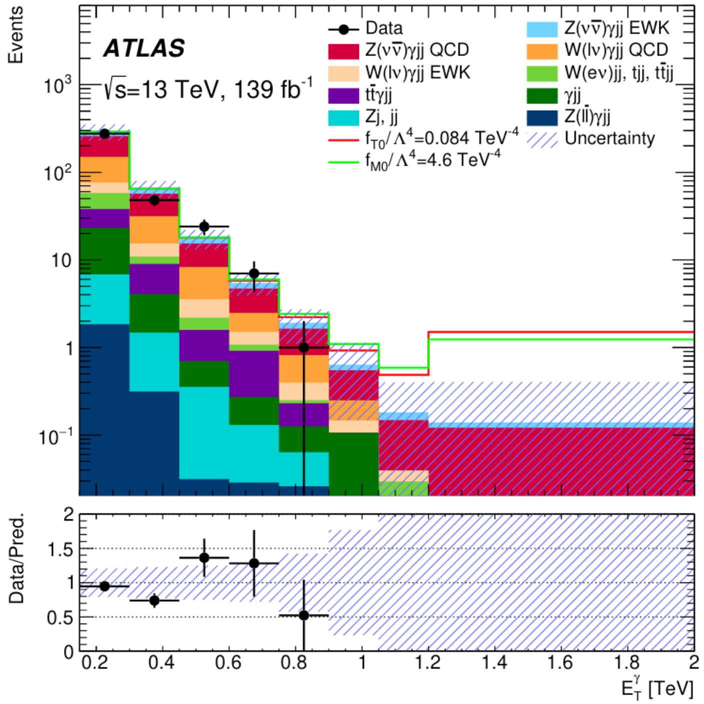


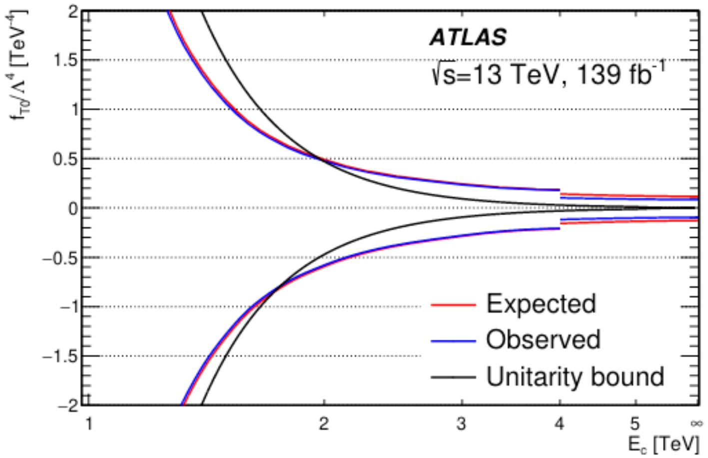
ATLAS – VBS $Z(\rightarrow \nu\bar{\nu})\gamma$

$\mathcal{L} = 139\ fb^{-1}$@13 TeV JHEP 06(2023)082

- Probed for nQGCs via E_T^{γ}.
- Clip scan performed by setting clip energy $E_c = m_{Z\gamma}$ (using particle-level information).
- The regime in which E_c is less than 4 TeV is obtained with an E_T^{γ} threshold of 600 GeV (400 GeV) for f_T (f_M).
- The regime in which E_c exceeds 4 TeV is obtained with an E_T^{γ} threshold of 900 GeV.

Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$



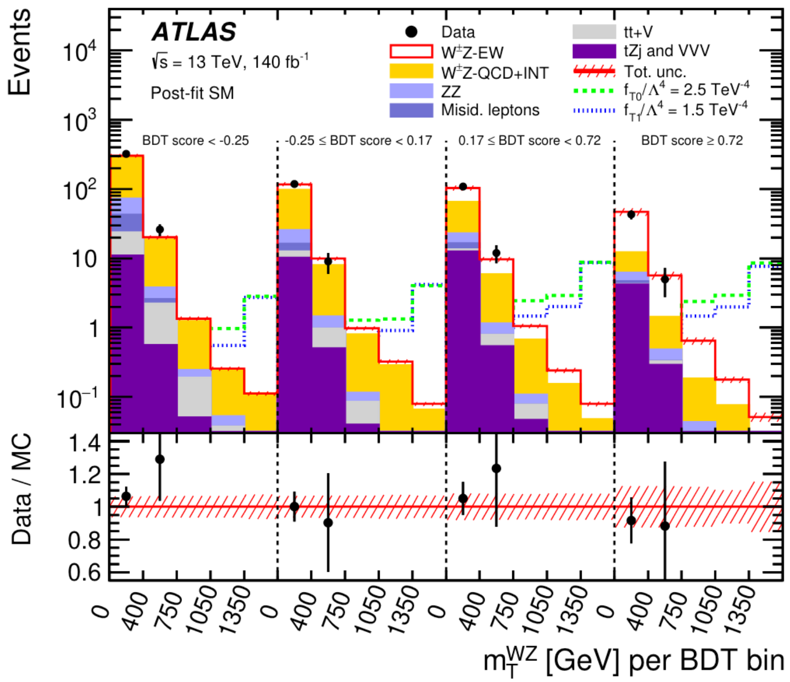


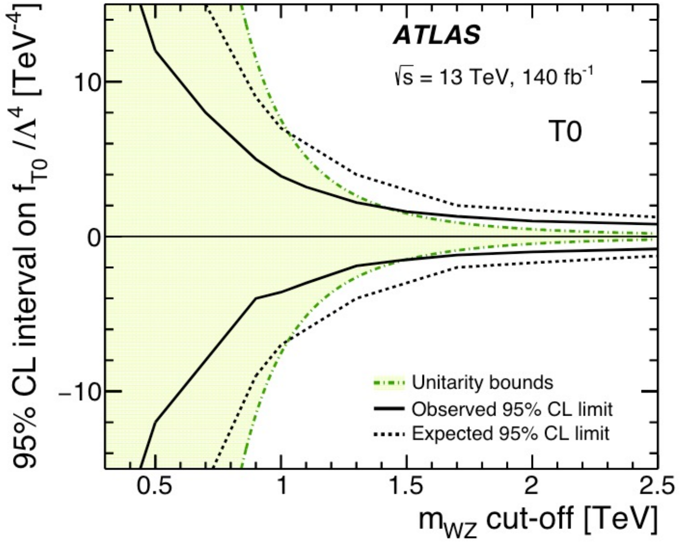
ATLAS – VBS WZ

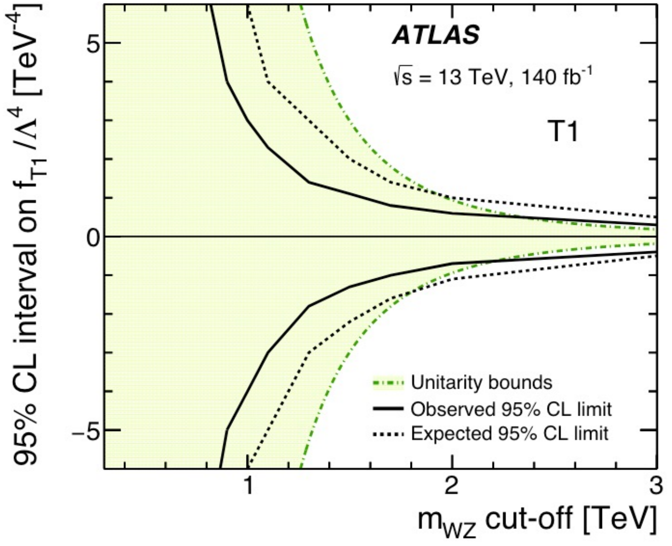
$\mathcal{L} = 140\ fb^{-1}$@13 TeV   arXiv: 2403.15296 [hep-ex]

- Boost Decision Tree (BDT) for separating QCD WZjj and VBS WZ. 15 input variables are used, including jet-kinematics variables, vector-bosons-kinematics variables, and variables related to both jets and leptons kinematics.

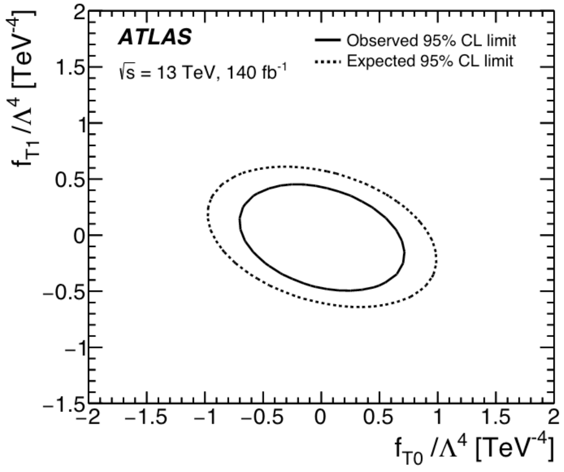
- Four bins in BDT score ([−1, −0.25, 0.17, 0.72, 1]) and five bins in m_T^{WZ}([0, 400, 750, 1050, 1350, ∞] GeV) are used and arranged in a one-dimensional histogram of 20 statistically independent bins for EFT re-interpretation.







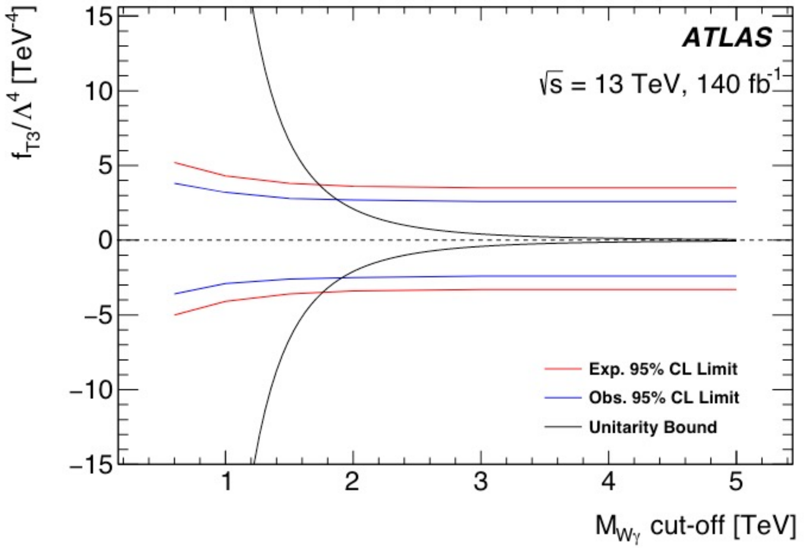
	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-0.80, 0.80]	[-0.57, 0.56]
f_{T1}/Λ^4	[-0.52, 0.49]	[-0.39, 0.35]
f_{T2}/Λ^4	[-1.6, 1.4]	[-1.2, 1.0]
f_{M0}/Λ^4	[-8.3, 8.3]	[-5.8, 5.6]
f_{M1}/Λ^4	[-12.3, 12.2]	[-8.6, 8.5]
f_{M7}/Λ^4	[-16.2, 16.2]	[-11.3, 11.3]
f_{S02}/Λ^4	[-14.2, 14.2]	[-10.4,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

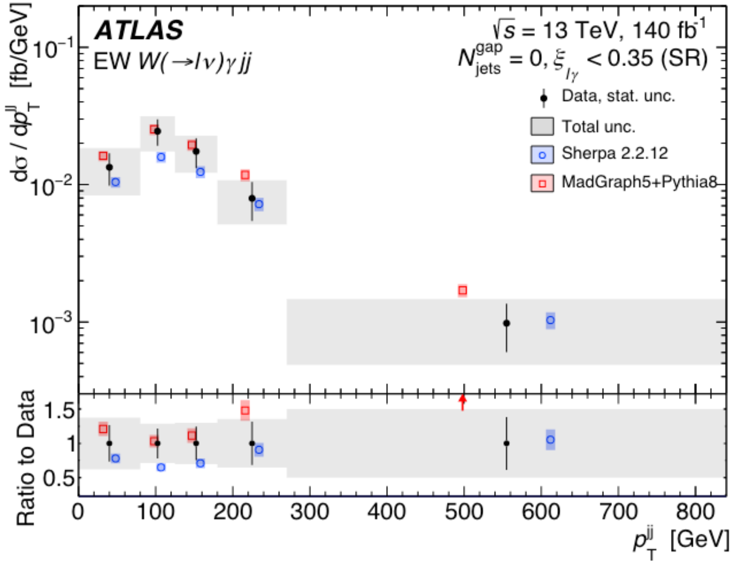


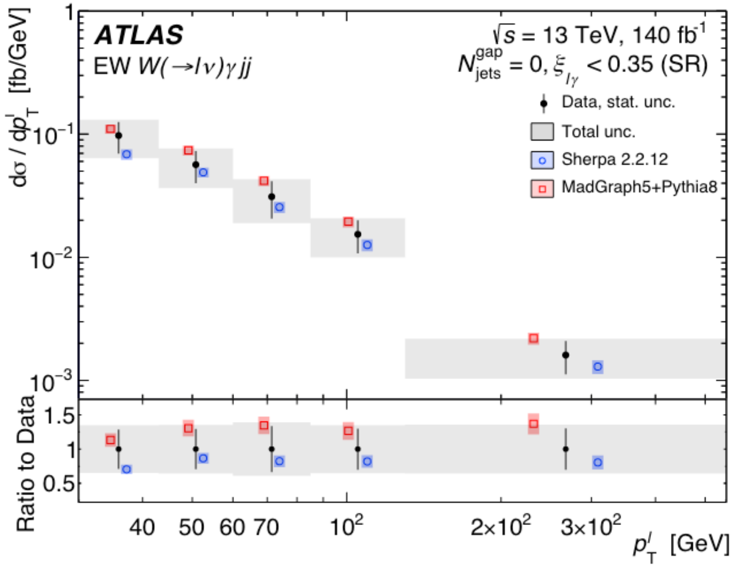
ATLAS – VBS Wγ

$\mathcal{L} = 140\ fb^{-1}$@13 TeV arXiv: 2403.02809 [hep-ex]

- Setting f_T constraints via unfolded p_T^{jj} distribution, f_M constraints via unfolded p_T^{l} distribution.
- Clip scan cut-off performed via $M_{W\gamma}$
- A first measurement on f_{T3} and f_{T4} in LHC.







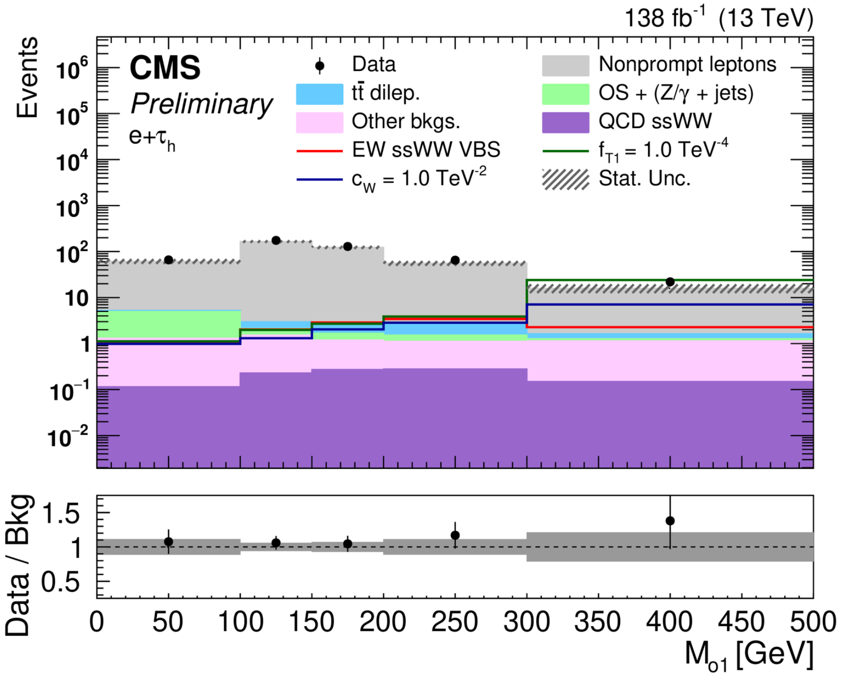
Cofficients [TeV^{-4}]	Observable	$M_{W\gamma}$ cut-off [TeV]	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	1.4	[-2.5, 2.6]	[-1.9, 1.9]
f_{T1}/Λ^4	p_T^{jj}	1.9	[-1.6, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	1.6	[-4.9, 5.3]	[-3.6, 4.0]
f_{T3}/Λ^4	p_T^{jj}	1.9	[-3.4, 3.6]	[-2.5, 2.7]
f_{T4}/Λ^4	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]

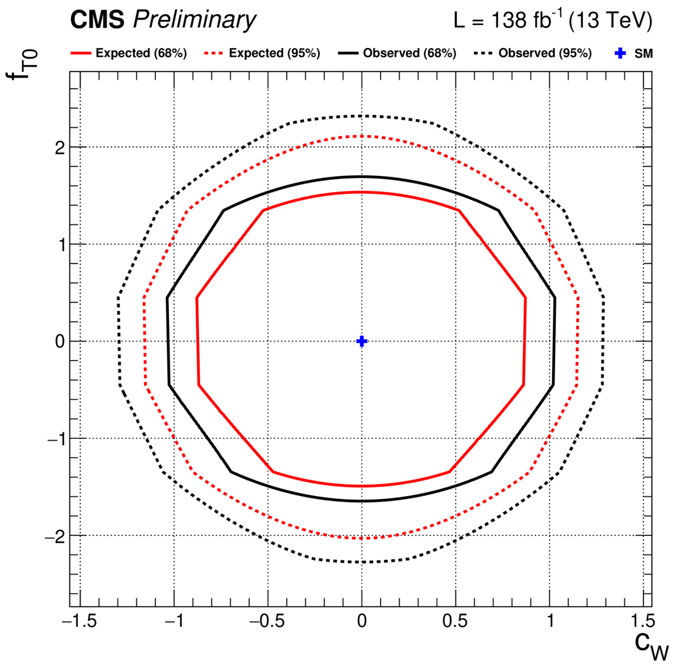
CMS – VBS ssWW with hadronic τ

$\mathcal{L} = 138\ fb^{-1}$@13 TeV

CMS PAS SMP-22-008

- VBS same-sign (ss) WW with one W decays to e or μ, another W decays to hadronic τ. Signal: $\tau\nu_\tau l\nu_l jj\ (l = e, \mu)$
- Significance of SM process at 2.7 σ, signal strength: $1.44^{+0.63}_{-0.56}$
- First simultaneous extraction of dim-6 and dim-8 constraints





- 2-D constraints set via transverse mass M_{o1} :

$$M_{o1}^2 = \left(p_T^\tau + p_T^l + p_T^{miss}\right)^2 - \left|\vec{p}_T^\tau + \vec{p}_T^l + \vec{p}_T^{miss}\right|^2$$

- 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 – VBS ssWW with hadronic τ

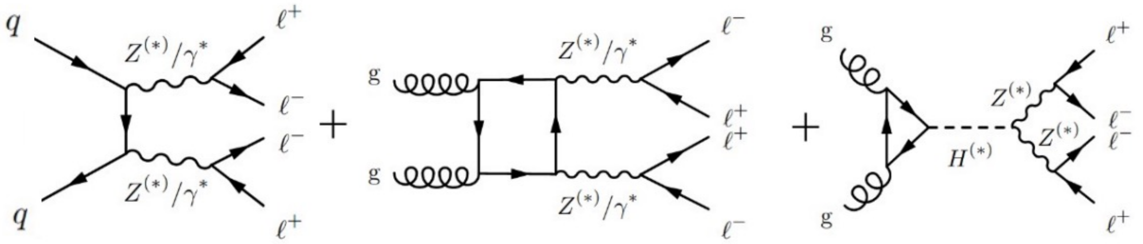
$\mathcal{L} = 138\ fb^{-1}$@13 TeV

CMS PAS SMP-22-008

- Also 1-D constraints are set via Deep Neural Network (DNNs) score

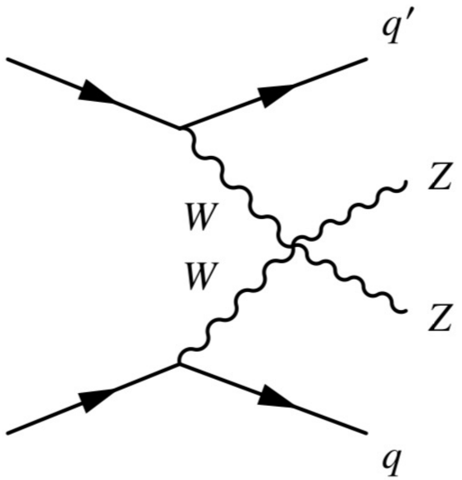
Wilson coefficient		68% CL interval(s) Expected	68% CL interval(s) Observed	95% CL interval Expected	95% CL interval Observed
dim-6	$c_{ll}^{(1)}$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	$[-11.6, 0.045]$	$[-14.6, 3.53]$	$[-13.5, 2.11]$
	$c_{qq}^{(1)}$	$[-0.501, 0.576]$	$[-0.341, 0.416]$	$[-0.742, 0.818]$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

Di-Boson Interaction



qq → ZZ → 4l   gg → ZZ → 4l   gg → H → ZZ → 4l

VBS



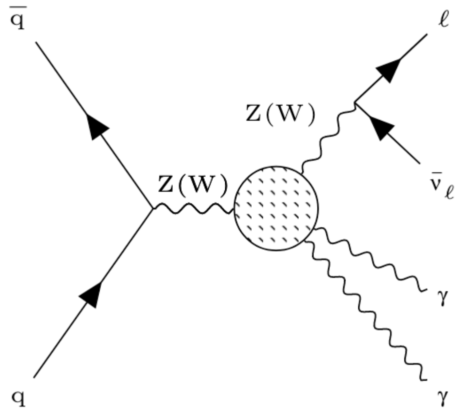
What Else?

CMS – Triboson $V\gamma\gamma$

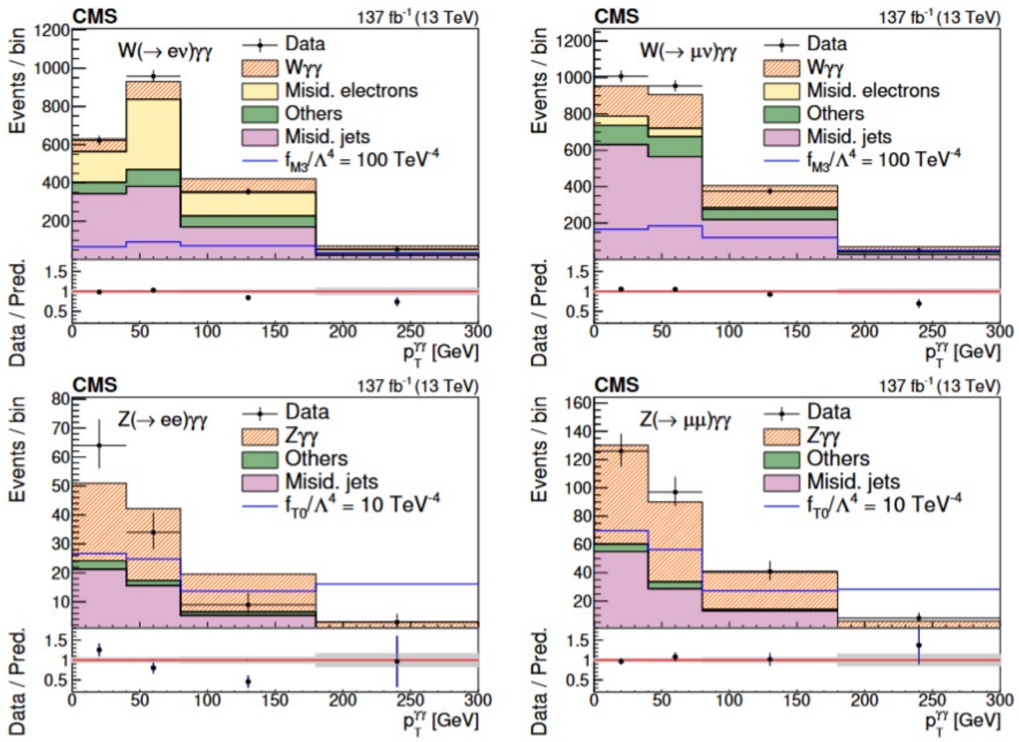
$\mathcal{L} = 137\ fb^{-1}$@13 TeV

JHEP 10(2021)174

- e/μ channels are used and combined in this measurement
- Background dominated by misid-jet and misid electrons
- Sensitive to the dim-6 and dim-8 operators, but lower statistics than di-bosons results in much weaker limits
- EFT constraints set via $p_{T,\gamma\gamma}$



Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]



Summary & Outlook

- As nTGCs and aQGCs are direct hints to BSM physics, the re-interpretation is become one main part of bosonic electroweak analysis.
- nTGCs limits are set by diboson ZZ or $Z\gamma$ production. aQGCs limits are obtain by VBS and Tri-boson production. All results are compatible with SM so far.
- Unfolded analysis allows test of new models in the future.

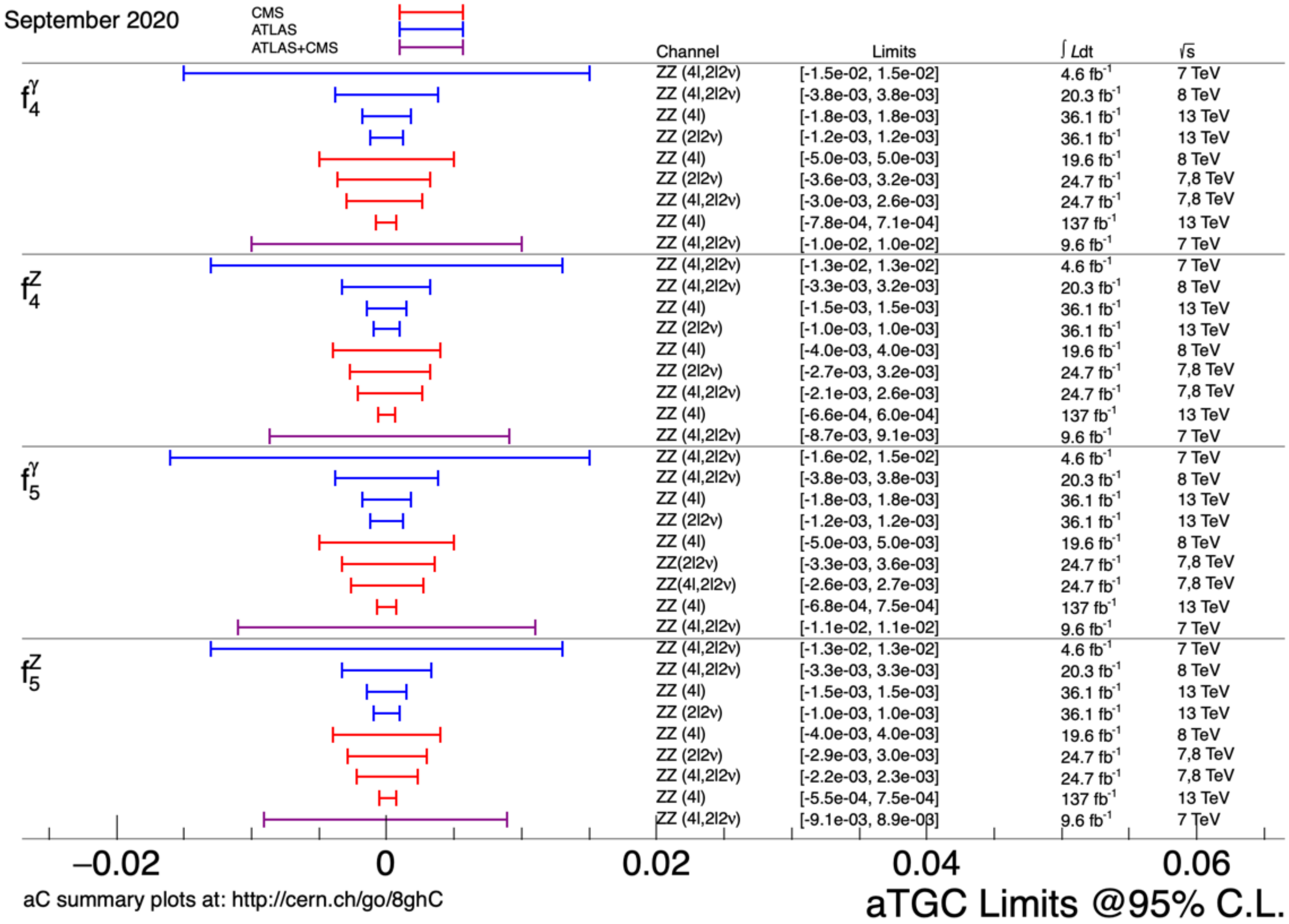
Thank you!

- Challenges:
  - Current analysis set constraints on one parameter / two parameters in simultaneously. How about more parameters and even full model?
  - Unitarity violation when including higher energy overflow contribution
  - Higher order correction of BSM model is absent, current analysis uses EFT model generated in tree-level
- LHC Run3 is on-going. Higher statistic and higher enegy → Higher sensitivity to BSM physics! Moreover, new global fit of Run 2 is await to be conducted.

Backup

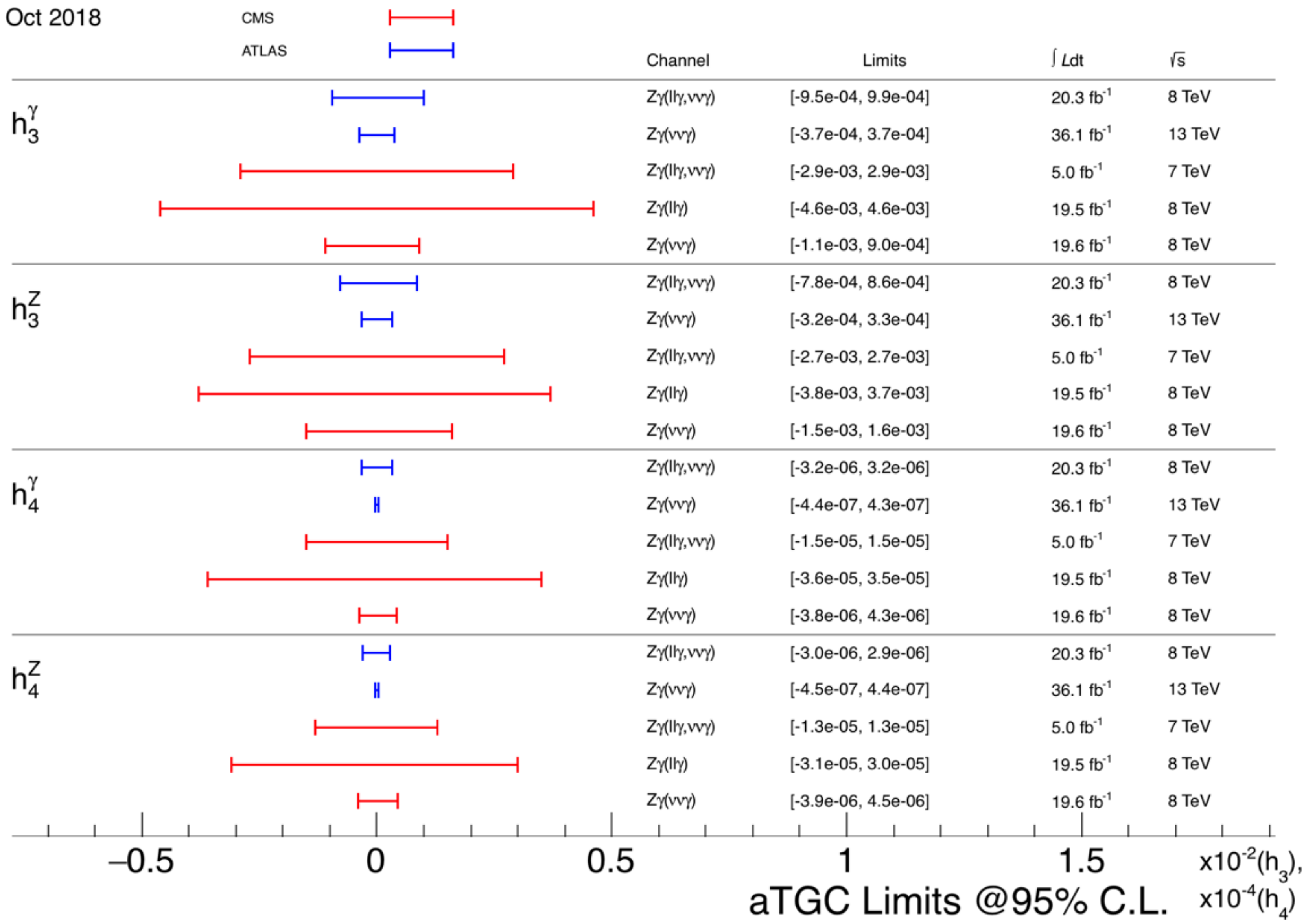
nTGCs summary in 2020

CERN Twiki



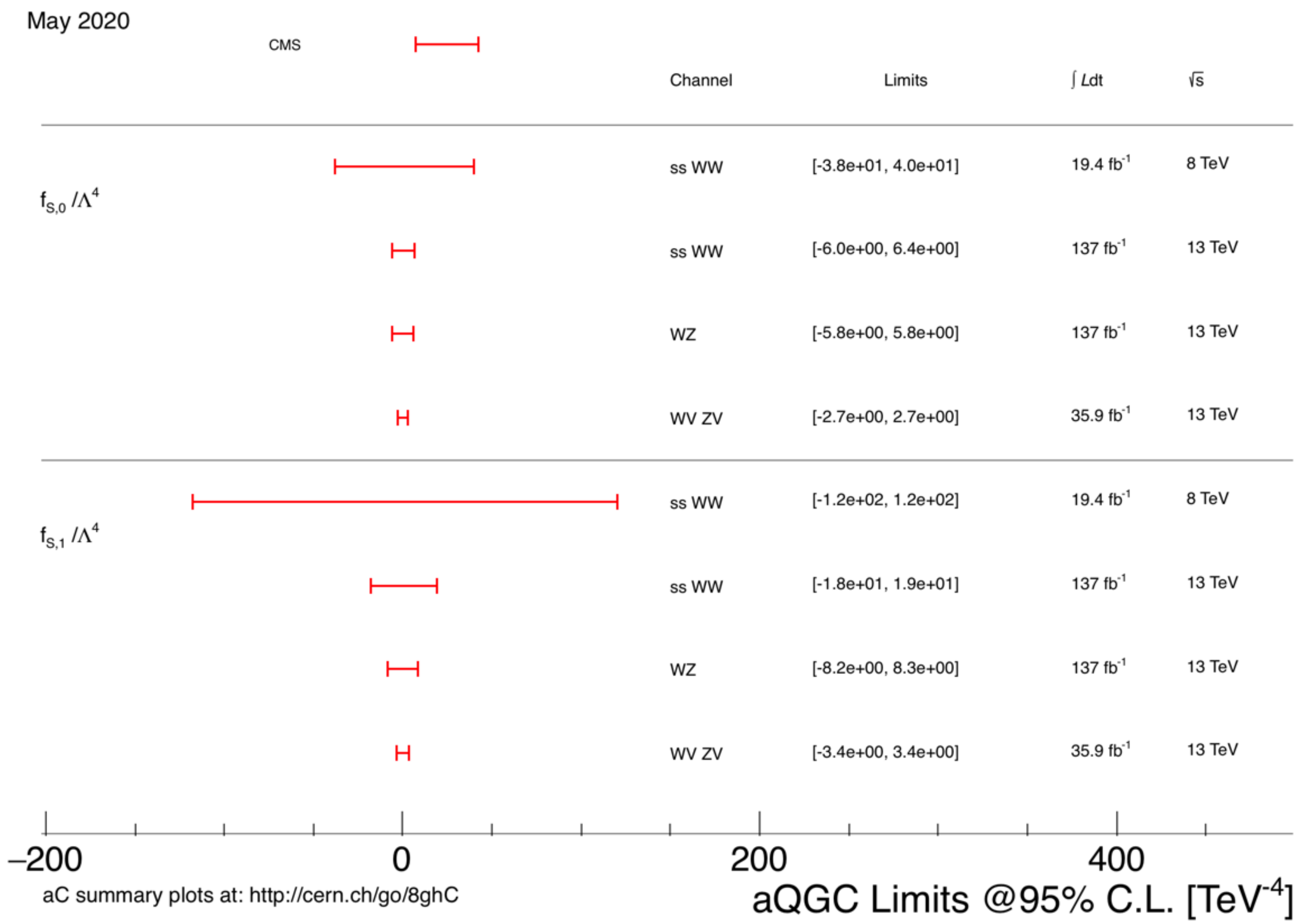
nTGCs summary in 2018

CERN Twiki



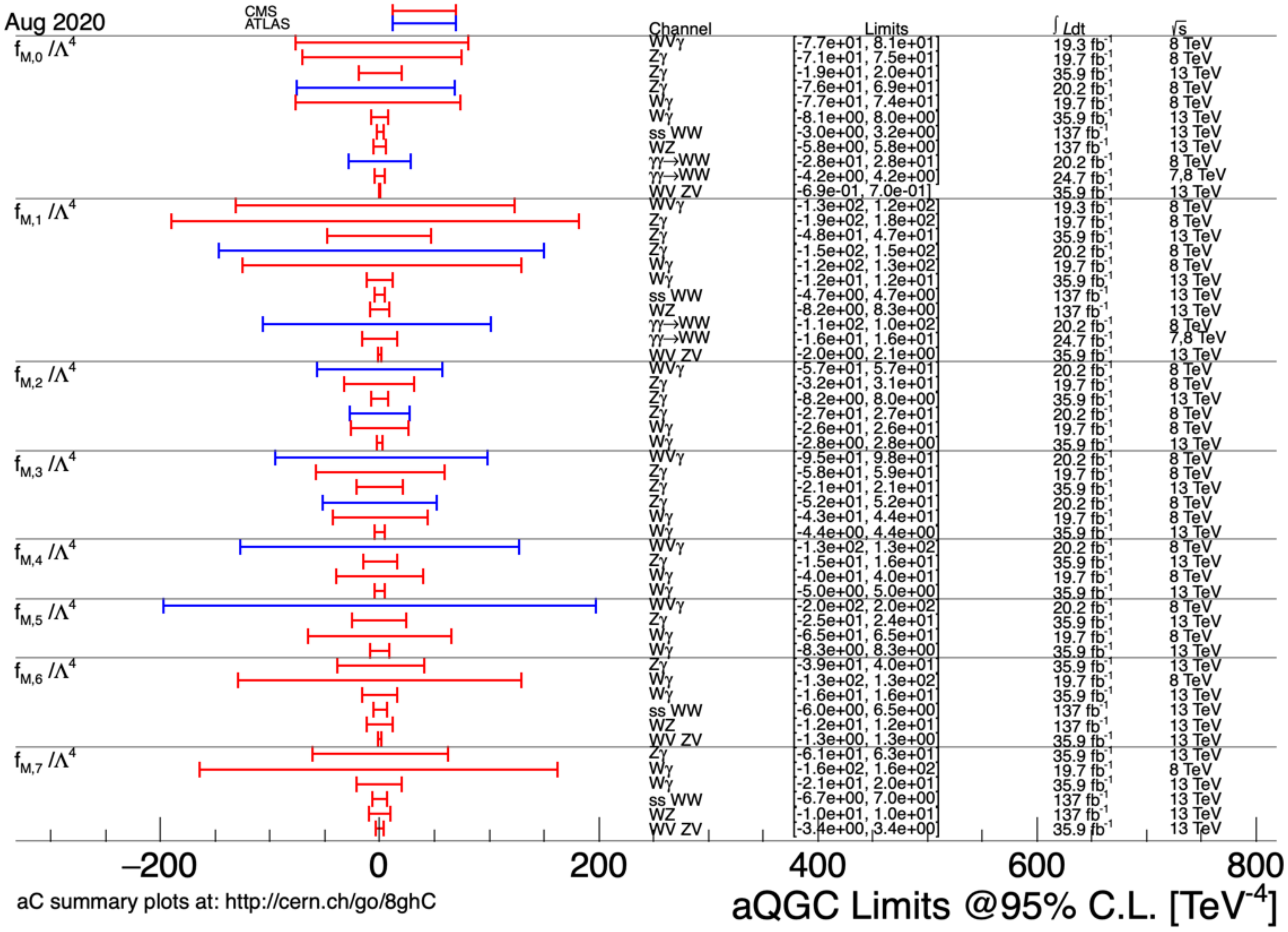
aQGCs summary in 2020

[CERN Twiki]



aQGCs summary in 2020

[CERN Twiki]



aQGCs summary in 2020

CERN Twiki