Study of EFT effects in <u>nTGC</u> and <u>aQGC</u> in ElectroWeak processes

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nTGC? aQGC? Why?

• SM provides gauge boson coupling of:



Triple Gauge Coupling (TGC): WWZ, WW γ

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

• What if *prohibited* vertices exist?



BSM!

nTGC? aQGC? How?

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



- 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:

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

$$\chi^{2}$$
Nuisances parameter







nTGCs - Parameters



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

Basis of dim 8 operators for nTGCs:

$$\begin{split} \mathcal{O}_{\widetilde{B}W} &= i H^{\dagger} \widetilde{B}_{\mu\nu} W^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H, \\ \mathcal{O}_{B\widetilde{W}} &= i H^{\dagger} B^{\mu\nu} \widetilde{W}_{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H, \\ \mathcal{O}_{\widetilde{W}W} &= i H^{\dagger} \widetilde{W}_{\mu\nu} W^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H, \\ \mathcal{O}_{\widetilde{B}B} &= i H^{\dagger} \widetilde{B}_{\mu\nu} B^{\mu\rho} \left\{ D_{\rho}, D^{\nu} \right\} H. \end{split}$$

$$ie\Gamma_{ZZV}^{\alpha\beta\mu}(\mathbf{q}_{1},\mathbf{q}_{2},\mathbf{q}_{3}) = \frac{-e(\mathbf{q}_{3}^{2}-m_{V}^{2})}{M_{Z}^{2}} \left[f_{4}^{V}(\mathbf{q}_{3}^{\alpha}g^{\mu\beta}+\mathbf{q}_{3}^{\beta}g^{\mu\alpha}) - f_{5}^{V}\epsilon^{\mu\alpha\beta\rho}(\mathbf{q}_{1}-\mathbf{q}_{2})_{\rho} \right] , \quad (1.1)$$

$$ie\Gamma_{Z\gamma V}^{\alpha\beta\mu}(\mathbf{q}_{1},\mathbf{q}_{2},\mathbf{q}_{3}) = \frac{-e(\mathbf{q}_{3}^{2}-m_{V}^{2})}{M_{Z}^{2}} \left\{ h_{1}^{V}(\mathbf{q}_{2}^{\mu}g^{\alpha\beta}-\mathbf{q}_{2}^{\alpha}g^{\mu\beta}) + \frac{h_{2}^{V}}{M_{Z}^{2}}\mathbf{q}_{3}^{\alpha}[(\mathbf{q}_{3}\mathbf{q}_{2})g^{\mu\beta}-\mathbf{q}_{2}^{\mu}\mathbf{q}_{3}^{\beta}] - h_{3}^{V}\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_{4}^{V}}{M_{Z}^{2}}\mathbf{q}_{3}^{\alpha}\epsilon^{\mu\beta\rho\sigma}\mathbf{q}_{3\rho}q_{2\sigma} \right\}$$

$$(1.2)$$

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



< 0

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



• Sensitive to two nTGCs: ZZZ, $ZZ\gamma$.

 $CMS - ZZ(\rightarrow 4l)$

- 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	$17.0 \pm 0.5 ({\rm stat})^{+0.6}_{-0.5} ({\rm syst}) \pm 0.4 ({\rm theo}) \pm 0.4 ({\rm lumi})$
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 ± 0.3 (stat) ± 0.5 (syst) ± 0.4 (theo) ± 0.3 (lumi)

• Consistent with the NNLO prediciton

 $\mathcal{L} = 137 \, f b^{-1} @ 13 \, \text{TeV}$



$CMS - ZZ(\rightarrow 4l)$ $\mathcal{L} = 137 \, f b^{-1} @13 \, \text{TeV}$

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

 σ_{SMEFT}

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

- 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



-0.001

-0.002

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

0.001

-0.001

-0.002

Expected 68% CL

Observed 95% CL

Observed 95% CL (1D)

0

0.001

0.002

 f_4^{γ}

— — Expected 95% CL

-0.002 -0.001

0.001

0.002

 f_5^{γ}

Observed 95% CL

Best fit

-0.002 -0.001

Observed 95% CL (1D)

0

q $Z^{(*)}/\gamma^*$ ℓ^+ g Q000





• Measure the ZZ polarization in 4l channel (extract the LL component)

• Measure the spin correlation between ZZ bosons

 $Z^{(*)}/\gamma^*$

ATLAS – ZZ($\rightarrow 4l$) Angular

• Search for CP-violation and nTGCs in ZZ(4l) on-shell events (dim-8 EFT)





ATLAS – ZZ($\rightarrow 4l$) Angular

• 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 fourlepton system.

aNTGC parameter	Interfere	ence 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]	



 $\mathcal{L} = 140 \, f b^{-1} @13 \, \text{TeV}$

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: $Z_L Z_L$ (Signal) || $Z_T Z_L Z_T Z_T$ (Background)
- Fiducial cross section (4.3 σ for $Z_L Z_L$):
 - $\sigma_{Z_L Z_L}^{obs.} = 2.45 \pm 0.56(stat.) \pm 0.21(syst.)$ fb
 - $\sigma^{pred.}_{Z_L Z_L} = 2.10 \pm 0.09 \, {\rm fb}$





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$\mathbf{CMS} - \mathbf{Z} (\rightarrow \nu \bar{\nu}) \gamma$



- 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:





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

- 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
$\mathcal{L}_{S,0},\mathcal{L}_{S,1}$	Х	Х	Х	0	0	0	0	0	0
$\mathcal{L}_{M,0},\mathcal{L}_{M,1},\!\mathcal{L}_{M,6},\!\mathcal{L}_{M,7}$	Х	Х	Х	Х	Х	Х	Х	0	0
$\mathcal{L}_{M,2} \; , \! \mathcal{L}_{M,3}, \; \mathcal{L}_{M,4} \; , \! \mathcal{L}_{M,5}$	0	Х	Х	Х	Х	Х	Х	0	0
$\mathcal{L}_{T,0} \;, \! \mathcal{L}_{T,1} \;, \! \mathcal{L}_{T,2}$	Х	Х	Х	Х	Х	Х	Х	Х	Х
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	0	Х	Х	Х	Х	Х	Х	Х	Х
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	0	0	Х	0	0	Х	Х	Х	Х



anomalous QGC (aQGC)

- 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 <u>PRD 101, 113003 (2020)</u>.
- The bounds on each Wilson coefficient is related to the centerof-mass energy (\sqrt{s}) of the two-to-two scattering system.

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

Bound 1 operator

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.

EW production

W



q'



- 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



ATLAS – VBS ZZ($\rightarrow 4l$)



- 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. PRD 101, 113003 (2020)
- Clip scan is performed via $E_c = m_{4l}$ to check the unitarity bound (if violated).

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 .



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

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

 $\mathcal{L} = 140 \, f b^{-1} @13 \, {
m TeV}$

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

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



ATLAS – VBS Z($\rightarrow \nu \bar{\nu}$ **)** γ $\mathcal{L} = 139 \, f b^{-1} @ 13 \, \text{TeV}$

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- 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	$E_{\rm c}$ [TeV]	Observed limit $[\text{TeV}^{-4}]$	Expected limit $[\text{TeV}^{-4}]$
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	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] imes 10^{-1}$
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	$[-3.3, 3.2] imes 10^1$	$[-3.0, 3.0] \times 10^1$



ATLAS – VBS WZ

 $\mathcal{L} = 140 \, f b^{-1} @13 \, \text{TeV}$

Events

10⁴

10

10²

10

10⁻¹

1.4

0.8



-0.25 < BDT score < 0.1

W[±]Z-EW

ZZ Misid. leptons

W[±]7-OCD+INT

tZj and VVV

Tot. unc.

-0/Λ⁴ = 2.5 TeV⁻⁴

ATLAS

Post-fit SM

BDT score < -0.25

√s = 13 TeV, 140 fb⁻



- Boost Decision Tree (BDT) for separating QCD WZjj and VBS WZ. 15 input variables are used, including jetkinematics 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 garranged in a one-dimensional histogram of 20 statistically independent bins for EFT re-interpretation.



ATLAS – VBS $W\gamma$

- 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.



e<	ATLAS $\sqrt{s} = 13 \text{ TeV}. 1$	IO fb ¹	ATLAS	$\sqrt{s} = 13 \text{ TeV} \cdot 140 \text{ fb}^{1}$	Cofficients [TeV ⁻⁴]	Observable	$M_{W\gamma}$ cut-off [TeV]	Expected [TeV ⁻⁴]	Observed [TeV ⁻⁴]
vo 10 ⁻¹	EW $W(\rightarrow \nu)\gamma jj$ $N_{iets}^{gap} = 0, \xi_{i} < 0.3$	(SR)	$EW W(\rightarrow lv)\gamma jj$	$N_{\text{iets}}^{\text{gap}} = 0, \xi_{\perp} < 0.35 \text{ (SR)}$	f_{T0}/Λ^4	$p_{\mathrm{T}_{\mathrm{I}}}^{jj}$	1.4	[-2.5, 2.6]	[-1.9, 1.9]
£	γ	nc. 兰兰		• Data, stat. unc.	f_{T1}/Λ^4	p_{T}^{jj}	1.9	[-1.6, 1.6]	[-1.1, 1.2]
þ	Total unc.	ੇ ਹ ੀ	$0^{-1} = -$	Total unc.	f_{T2}/Λ^4	p_{T}^{jj}	1.6	[-4.9, 5.3]	[-3.6, 4.0]
α /	Sherpa 2.2	12 1 b		o Sherpa 2.2.12	f_{T3}/Λ^4	p_{T}^{jj}	1.9	[-3.4, 3.6]	[-2.5, 2.7]
^o 10 ^{−2}	🗖 📕 💼 MadGraph	+Pythia8 0		MadGraph5+Pythia8	f_{T4}/Λ^4	p_{T}^{jj}	2.2	[-3.1, 3.1]	[-2.2, 2.3]
		1		-	f_{T5}/Λ^4	$p_{\mathrm{T}}^{\hat{j}j}$	1.8	[-1.8, 1.8]	[-1.3, 1.3]
	-	- 10	0 ⁻²		f_{T6}/Λ^4	$p_{\mathrm{T}}^{\hat{j}j}$	2.1	[-1.5, 1.5]	[-1.1, 1.1]
	•	1		1	f_{T7}/Λ^4	p_{T}^{jj}	2.1	[-4.0, 4.1]	[-2.9, 3.0]
10 ⁻³	- • •	-			f_{M0}/Λ^4	p_{T}^{l}	1.1	[-45, 44]	[-32, 31]
			e-3	1 🔤	f_{M1}/Λ^4	p_{T}^{l}	1.4	[-60, 62]	[-43, 44]
ta -	<u></u> <u></u> <u></u>			F++++	f_{M2}/Λ^4	p_{T}^{l}	1.4	[-15, 15]	[-11, 11]
C. Da		Dat			f_{M3}/Λ^4	p_{T}^{l}	1.8	[-22, 22]	[-16, 16]
2		Q		•	f_{M4}/Λ^4	p_{T}^{l}	1.5	[-28, 27]	[-20, 20]
otio otio)€ ليبيا	0.5		f_{M5}/Λ^4	p_T^l	1.9	[-21, 23]	[-14, 17]
ñ	0 100 200 300 400 500 600 700		40 50 60 70 10 ²	2×10^2 3×10^2	f_{M7}/Λ^4	p_{T}^{l}	1.5	[-100, 99]	[-73, 71]
	Ļ			p _T [GeV]					



CMS – VBS ssWW with hadronic τ

- VBS same-sign (ss) WW with one W decays to e or μ , another W decays to hadronic τ . Signal: $\tau v_{\tau} l v_{l} j j$ $(l = e, \mu)$
- 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: $\sigma_{SMEFT} = \sigma_{SM} + c_{d-6}\sigma_{int} + c_{d-6}^2\sigma_{d-6} + c_{d-8}\sigma_{int} + c_{d-8}^2\sigma_{d-8}$



 $\mathcal{L} = 138 \, f b^{-1} @13 \, \text{TeV}$

CMS

CMS – VBS ssWW with hadronic τ



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

Milcon	afficient	68% CL interval	(s)	95% CL	interval
vviison c	coentcient	Expected	Observed	Expected	Observed
	$c_{ll}^{(1)}$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	[-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]
1	c_{HWB}	[-41.7, 69.6]	[30.7, 89.2]	[-66.6, 96.4]	[-49.7, 110]
dim-6	$c_{H\square}$	[-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]
	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]
dim-8	f_{M1}	[-12.5, 13.3]	[-9.54, 11.15]	[-18.7, 19.6]	[-16.4, 17.7]
unn-0	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

 $qq \rightarrow ZZ \rightarrow 4l$ $gg \rightarrow ZZ \rightarrow 4l$

 $gg \rightarrow H \rightarrow ZZ \rightarrow 4I$





CMS – Triboson $V\gamma\gamma$ $\mathcal{L} = 137 \, fb^{-1}@13 \, \text{TeV}$ <u>JHEP 10(2021)174</u>

- 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 $p_{T,\gamma\gamma}$

	$W\gamma\gamma$ (TeV^{-4})	$Z\gamma\gamma$ (2	${ m FeV}^{-4}$)
Parameter	Expected	Observed	Expected	Observed
$f_{ m M2}/\Lambda^4$	[-57.3, 57.1]	[-39.9, 39.5]	<u></u>	_
$f_{ m M3}/\Lambda^4$	[-91.8, 92.6]	[-63.8,65.0]		
$f_{ m T0}/\Lambda^4$	[-1.86, 1.86]	[-1.30, 1.30]	[-4.86, 4.66]	[-5.70, 5.46]
$f_{ m T1}/\Lambda^4$	[-2.38, 2.38]	[-1.70, 1.66]	[-4.86, 4.66]	[-5.70, 5.46]
$f_{ m T2}/\Lambda^4$	[-5.16, 5.16]	[-3.64, 3.64]	[-9.72, 9.32]	[-11.4, 10.9]
$f_{ m T5}/\Lambda^4$	[-0.76, 0.84]	[-0.52,0.60]	[-2.44, 2.52]	[-2.92, 2.92]
$f_{ m T6}/\Lambda^4$	[-0.92,1.00]	[-0.60, 0.68]	[-3.24, 3.24]	[-3.80, 3.88]
$f_{ m T7}/\Lambda^4$	[-1.64, 1.72]	[-1.16, 1.16]	[-6.68, 6.60]	[-7.88, 7.72]
$f_{ m T8}/\Lambda^4$	_	_	[-0.90,0.94]	[-1.06, 1.10]
$f_{ m T9}/\Lambda^4$		3	[-1.54, 1.54]	[-1.82, 1.82]





CMS

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 Zγ 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.



- 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

<u>CERN Twiki</u>

September 2020	CMS ATLAS				
	ATLAS+CMS	Channel	Limits	∫ <i>L</i> dt	√s
~ F		ZZ (41,212v)	[-1.5e-02, 1.5e-02]	4.6 fb ⁻¹	7 TeV
f ^r .	⊢−−−− 1	ZZ (4I,2I2v)	[-3.8e-03, 3.8e-03]	20.3 fb ⁻¹	8 TeV
•4	⊢ −−1	ZZ (4I)	[-1.8e-03, 1.8e-03]	36.1 fb ⁻¹	13 TeV
	⊢-I	ZZ (2l2v)	[-1.2e-03, 1.2e-03]	36.1 fb ⁻¹	13 TeV
	⊢−−−−−	ZZ (4I)	[-5.0e-03, 5.0e-03]	19.6 fb ⁻¹	8 TeV
	⊢−−−−	ZZ (2l2v)	[-3.6e-03, 3.2e-03]	24.7 fb ⁻¹	7,8 TeV
	⊢−−− 4	ZZ (4I,2I2v)	[-3.0e-03, 2.6e-03]	24.7 fb ⁻¹	7,8 TeV
	н	ZZ (4I)	[-7.8e-04, 7.1e-04]	137 fb ⁻¹	13 TeV
		ZZ (4I,2I2v)	[-1.0e-02, 1.0e-02]	9.6 fb ⁻¹	7 TeV
7		ZZ (4I,2I2v)	[-1.3e-02, 1.3e-02]	4.6 fb ⁻¹	7 TeV
f .	⊢−−−−	ZZ (4I,2I2v)	[-3.3e-03, 3.2e-03]	20.3 fb ⁻¹	8 TeV
-4	⊢	ZZ (4I)	[-1.5e-03, 1.5e-03]	36.1 fb ⁻¹	13 TeV
	н	ZZ (2l2v)	[-1.0e-03, 1.0e-03]	36.1 fb ⁻¹	13 TeV
	⊢ −−−−−−	ZZ (4I)	[-4.0e-03, 4.0e-03]	19.6 fb ⁻¹	8 TeV
	⊢−−− 4	ZZ (2l2v)	[-2.7e-03, 3.2e-03]	24.7 fb ⁻¹	7,8 TeV
	⊢ −−1	ZZ (4I,2I2v)	[-2.1e-03, 2.6e-03]	24.7 fb ⁻¹	7,8 TeV
	н	ZZ (4I)	[-6.6e-04, 6.0e-04]	137 fb ⁻¹	13 TeV
		ZZ (4I,2I2v)	[-8.7e-03, 9.1e-03]	9.6 fb ⁻¹	7 TeV
~		ZZ (41,212v)	[-1.6e-02, 1.5e-02]	4.6 fb ⁻¹	7 TeV
fr	► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ► ►	ZZ (41,212v)	[-3.8e-03, 3.8e-03]	20.3 fb ⁻¹	8 TeV
5	⊢ –−	ZZ (4I)	[-1.8e-03, 1.8e-03]	36.1 fb ⁻¹	13 TeV
	H	ZZ (2l2v)	[-1.2e-03, 1.2e-03]	36.1 fb ⁻¹	13 TeV
	⊢ −−−−−−−−−−−−	ZZ (4I)	[-5.0e-03, 5.0e-03]	19.6 fb ⁻¹	8 TeV
	⊢−−−−	ZZ(2l2v)	[-3.3e-03, 3.6e-03]	24.7 fb ⁻¹	7,8 TeV
	⊢ −−−4	ZZ(4I,2I2v)	[-2.6e-03, 2.7e-03]	24.7 fb ⁻¹	7,8 TeV
	Н	ZZ (4I)	[-6.8e-04, 7.5e-04]	137 fb ⁻¹	13 TeV
	├	ZZ (4I,2I2v)	[-1.1e-02, 1.1e-02]	9.6 fb ⁻¹	7 TeV
-7		ZZ (41,212v)	[-1.3e-02, 1.3e-02]	4.6 fb ⁻¹	7 TeV
ff	⊢ −−−−	ZZ (41,212v)	[-3.3e-03, 3.3e-03]	20.3 fb ⁻¹	8 TeV
5	H	ZZ (4I)	[-1.5e-03, 1.5e-03]	36.1 fb ⁻¹	13 TeV
	H	ZZ (2l2v)	[-1.0e-03, 1.0e-03]	36.1 fb ⁻¹	13 TeV
		ZZ (4I)	[-4.0e-03, 4.0e-03]	19.6 fb ⁻¹	8 TeV
		ZZ (2l2v)	[-2.9e-03, 3.0e-03]	24.7 fb ⁻¹	7,8 TeV
		ZZ (41,212v)	[-2.2e-03, 2.3e-03]	24.7 fb ⁻¹	7,8 TeV
	H	ZZ (4I)	[-5.5e-04, 7.5e-04]	137 fb ⁻¹	13 TeV
		ZZ (41,212v)	[-9.1e-03, 8.9e-0β]	9.6 fb ⁻¹	7 TeV
		0.00	0.04		
-0.02	0	0.02	0.04		0.06
aC summary plots	at: http://cern.ch/go/8ghC			imita @O	
ao ouninary plote			aluc		5% U.L.

nTGCs summary in 2018

<u>CERN Twiki</u>

oct 2018	CMS				
	ATLAS	Channel	Limits	∫ <i>L</i> dt	ſs
γ	⊢−−−−	Ζγ(ΙΙγ,ννγ)	[-9.5e-04, 9.9e-04]	20.3 fb ⁻¹	8 TeV
3	H	Ζγ(ννγ)	[-3.7e-04, 3.7e-04]	36.1 fb ⁻¹	13 TeV
	⊢ I	Ζγ(ΙΙγ,ννγ)	[-2.9e-03, 2.9e-03]	5.0 fb ⁻¹	7 TeV
H		Ζγ(ΙΙγ)	[-4.6e-03, 4.6e-03]	19.5 fb ⁻¹	8 TeV
	H	Ζγ(ννγ)	[-1.1e-03, 9.0e-04]	19.6 fb ⁻¹	8 TeV
7	⊢−−− 1	Ζγ(ΙΙγ,ννγ)	[-7.8e-04, 8.6e-04]	20.3 fb ⁻¹	8 TeV
3	н	Ζγ(ννγ)	[-3.2e-04, 3.3e-04]	36.1 fb ⁻¹	13 TeV
	⊢−−−−− −−−−−−−−−−−−−−−−−−−−−−−−−−−−1	Ζγ(ΙΙγ,ννγ)	[-2.7e-03, 2.7e-03]	5.0 fb ⁻¹	7 TeV
	L	Zγ(IIγ)	[-3.8e-03, 3.7e-03]	19.5 fb ⁻¹	8 TeV
	HH	Ζγ(ννγ)	[-1.5e-03, 1.6e-03]	19.6 fb ⁻¹	8 TeV
,	н	Ζγ(ΙΙγ,ννγ)	[-3.2e-06, 3.2e-06]	20.3 fb ⁻¹	8 TeV
Ļ	H Contraction of the second seco	Ζγ(ννγ)	[-4.4e-07, 4.3e-07]	36.1 fb ⁻¹	13 TeV
	H	Ζγ(ΙΙγ,ννγ)	[-1.5e-05, 1.5e-05]	5.0 fb ⁻¹	7 TeV
	HH	Zγ(IIγ)	[-3.6e-05, 3.5e-05]	19.5 fb ⁻¹	8 TeV
	H	Ζγ(ννγ)	[-3.8e-06, 4.3e-06]	19.6 fb ⁻¹	8 TeV
7	н	Ζγ(ΙΙγ,ννγ)	[-3.0e-06, 2.9e-06]	20.3 fb ⁻¹	8 TeV
- 1	H Contraction of the second seco	Ζγ(ννγ)	[-4.5e-07, 4.4e-07]	36.1 fb ⁻¹	13 TeV
	H	Ζγ(ΙΙγ,ννγ)	[-1.3e-05, 1.3e-05]	5.0 fb ⁻¹	7 TeV
	H	Ζγ(ΙΙγ)	[-3.1e-05, 3.0e-05]	19.5 fb ⁻¹	8 TeV
		Ζγ(ννγ)	[-3.9e-06, 4.5e-06]	19.6 fb ⁻¹	8 TeV
-0.5	5 0	0.5	1	1.5	x10 ⁻² (
			aTGC Limits @	295% C.	L. x10 ⁻⁴

aQGCs summary in 2020

<u>CERN Twiki</u>



aQGCs summary in 2020

Aug 2020	CMS ATLAS	C	hannel	Limite	[/ dt	√e
$f_{M,0}/\Lambda^4$		W Zî	Wγ v	[-7.7e+01, 8.1e+01] [-7.1e+01, 7.5e+01]	19.3 fb ⁻¹ 19.7 fb ⁻¹	8 TeV
		Z,	ý	-1.9e+01, 2.0e+01	35.9 fb ⁻¹	13 TeV
	↓¥	Ŵ		-7.7e+01, 7.4e+01	19.7 fb ⁻¹	8 TeV
	Ж	SS	sww	[-3.0e+00, 3.2e+00]	137 fb	13 TeV
	► <u></u>	Ŷ	∕∠ ∕→₩₩	-2.8e+01, 2.8e+01	20.2 fb	8 TeV
	Ţ		/→vvv /V ZV	[-4.20+00, 4.20+00] [-6.9e-01, 7.0e-01]	24.7 fb 35.9 fb	13_TeV
f _{Μ,1} /Λ ⁴			γ	-1.3e+02, 1.2e+02 -1.9e+02, 1.8e+02	19.3 fb 19.7 fb	8 TeV 8 TeV
		Z	Y Y	-4.8e+01, 4.7e+01 [-1.5e+02, 1.5e+02]	35.9 fb ⁻ 20.2 fb ⁻	13 TeV 8 <u>T</u> eV
		Ŵ	ly ly	[-1.2e+02, 1.3e+02] [-1.2e+01, 1.2e+01]	19.7 fb ⁻ 35.9 fb ⁻	8 TeV 13 TeV
	Ц	SS W	s WW IZ	[-4.7e+00, 4.7e+00] [-8.2e+00, 8.3e+00]	137 fb ⁻¹ 137 fb ⁻¹	13 TeV 13 TeV
		22	/→WW /→WW	-1.1e+02, 1.0e+02 -1.6e+01, 1.6e+01	20.2 fb ⁻¹ 24 7 fb ⁻¹	8 TeV 7,8 TeV
£ / A 4	<u>H</u> `		N ZV N v	-2.0e+00, 2.1e+00 -5.7e+01, 5.7e+01	35.9 fb ⁻¹ 20.2 fb ⁻¹	13 TeV 8 TeV
I _{M,2} //X		Ž' Z'	Ϋ́,	-3.2e+01, 3.1e+01	19.7 fb ⁻¹ 35.9 fb ⁻¹	8 TeV
		Z	ý,	-2.7e+01, 2.7e+01	20.2 fb ⁻¹ 19 7 fb ⁻¹	8 TeV
5 (+4	Н '	Ŵ	Ιγ΄ Ν/~	-2.8e+00, 2.8e+00	35.9 fb ⁻¹	13 TeV
f _{M,3} /Λ		Ž	Ϋ́,	-5.8e+01, 5.9e+01	19.7 fb ⁻¹	8 TeV
	FH	Ž	Ý.	-5.2e+01, 5.2e+01	20.2 fb ⁻¹	8 TeV
		Ŵ	lý Klav	-4.4e+00, 4.4e+00	35.9 fb ⁻¹	
f _{M,4} /Λ ⁴		Z	Y.	-1.5e+02, 1.5e+02 [-1.5e+01, 1.6e+01]	20.2 fb 35.9 fb	13 TeV
	Н	Ŵ	ry ly l/a	-4.0e+01, 4.0e+01 -5.0e+00, 5.0e+00	35.9 fb ⁻¹	13 TeV
f _{M,5} /Λ ⁴	· - · ·		Y Y	-2.0e+02, 2.0e+02 -2.5e+01, 2.4e+01	20.2 fb 35.9 fb	8 IeV 13 TeV
		<u>v</u>	lý	-8.3e+00, 8.3e+00	19.7 fb 35.9 fb	
f _{M,6} /Λ ⁴		Į,	lγ	-3.9e+01, 4.0e+01 -1.3e+02, 1.3e+02	35.9 fb 19.7 fb	13 TeV 8 TeV
	.H.	SS	γ s_WW	[-1.6e+01, 1.6e+01] [-6.0e+00, 6.5e+00]	35.9 fb ⁺ 137 fb ⁺	13 TeV 13 TeV
	🐨	W	IZ IV ZV	-1.2e+01, 1.2e+01 -1.3e+00, 1.3e+00	137 fb ⁻ 35.9 fb ⁻	13 TeV 13 TeV
f _{M,7} /Λ ⁴		Z ² W	Ĭγ	[-6.1e+01, 6.3e+01] [-1.6e+02, 1.6e+02]	35.9 fb ⁻ 19.7 fb ⁻	13 TeV 8 TeV
	E F	W SS	/γ s WW	[-2.1e+01, 2.0e+01] [-6.7e+00, 7.0e+00]	35.9 fb ⁻ 137 fb ⁻	13 TeV 13 TeV
	- I - I - I - I - I - I - I - I - I - I		IZ IV ZV _I I	[-1.0e+01, 1.0e+01] [-3.4e+00, ₁ 3.4e+00]	137 fb ^{-'} 35.9 fb ⁻¹	13 TeV 13 TeV
	-200 0	200		400	600	800
	v ploto at: http://porp.ch/go/9ghC	200				IT-1/-41
ao summar	y plots at. http://cem.ch/go/ogno		ac		@95% C.L.	[lev]

aQGCs summary in 2020

CERN Twiki

