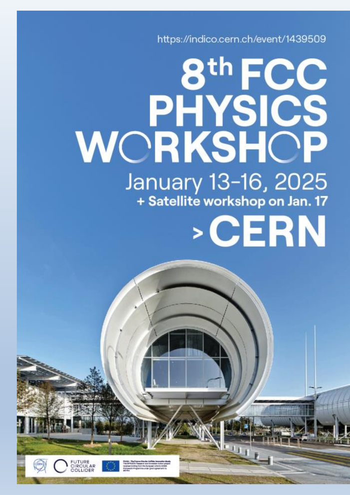
Constraining Anormal Quartic Gauge Couplings via $pp \rightarrow Z\gamma\gamma$ Process at FCC-hh



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ABSTRACT

We study on dimension-8 anomalous couplings related to the quartic vertices of neutral gauge bosons, defined by the effective field theory framework, in $Z\gamma\gamma$ production with Z-boson decaying to charged leptons at Future Circular hadron-hadron collider (FCC-hh). The analysis is performed using Monte Carlo event sampling with a realistic detector effect and a cut-off-based method, taking into account centre-of-mass energy of 100 TeV and integrated luminosity parameters of 30 ab^{-1} or the FCC-hh. The sensitivity limits for anomalous quartic couplings f_{T8}/Λ^4 and f_{T9}/Λ^4 (f_{T0}/Λ^4, f_{T1}/Λ^4 and f_{T2}/Λ^4) at 95% C.L. for FCC-hh with without systematic errors is two (one) order better than the current experimental limits of ATLAS and CMS results. Considering a realistic systematic uncertainty such as 10% from possible experimental sources, the sensitivity of all anomalous quartic couplings gets worsen by about 1.5% compared to those without systematic uncertainty for FCC-hh.

THEORY

The three classes of dimension-eight effective operators containing; i) covariant derivatives of Higgs doublet only ($O_{S,j}$), ii) two field strength tensors and two derivatives of Higgs doublet ($O_{M,j}$) and iii) field strength tensors only ($O_{T,j}$) are added SM Lagrangian [1]

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{\substack{j=0 \\ j\neq 8}}^{9} \frac{f_{T,j}}{\Lambda^4} \mathcal{O}_{T,j}$$

$$\mathcal{O}_{T0} = \mathrm{Tr}[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}] \times \mathrm{Tr}[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}]$$
$$\mathcal{O}_{T1} = \mathrm{Tr}[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}] \times \mathrm{Tr}[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}]$$
$$\mathcal{O}_{T2} = \mathrm{Tr}[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}] \times \mathrm{Tr}[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}]$$
$$\mathcal{O}_{T8} = [\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}]$$
$$\mathcal{O}_{T9} = [\widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}]$$

	$WWWW$	$WWZZ$	$ZZZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{T0}, \mathcal{O}_{T1}, \mathcal{O}_{T2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T8}, \mathcal{O}_{T9}$			✓			✓	✓	✓	✓

Quartic gauge boson vertices modified by the related dimension-8 operator

CROSS SECTIONS fot pp → Zγγ PROCESS

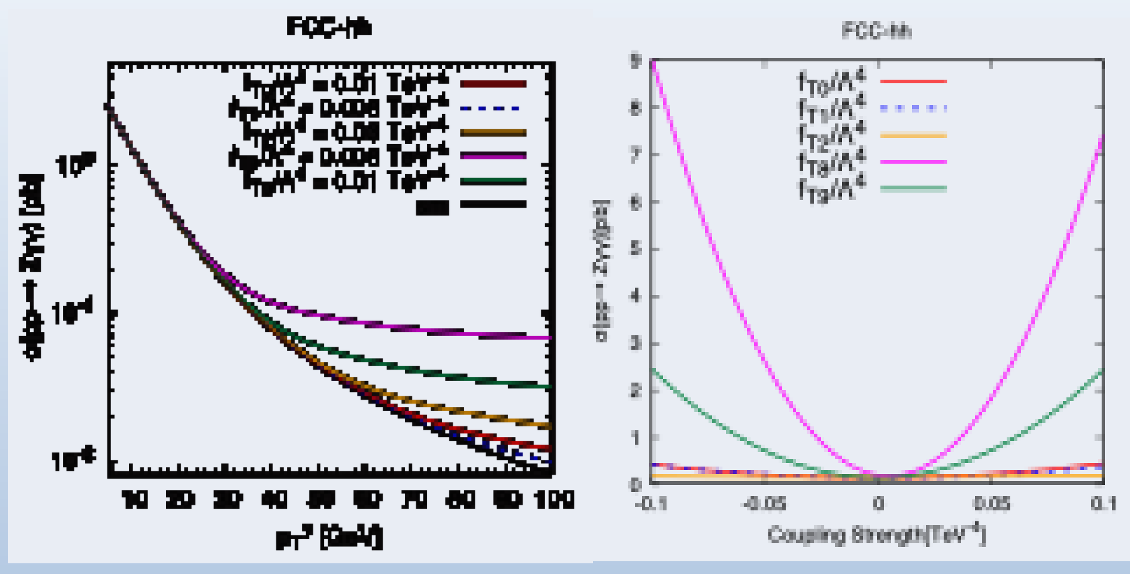

Fig.1 : The cross section of the pp → Zγγ process as function of the lower cut on photon transverse momentum (left panel) and production cross section of the Zγγ process in terms of the anomalous quartic gauge couplings for FCC-hh (in the right panel)

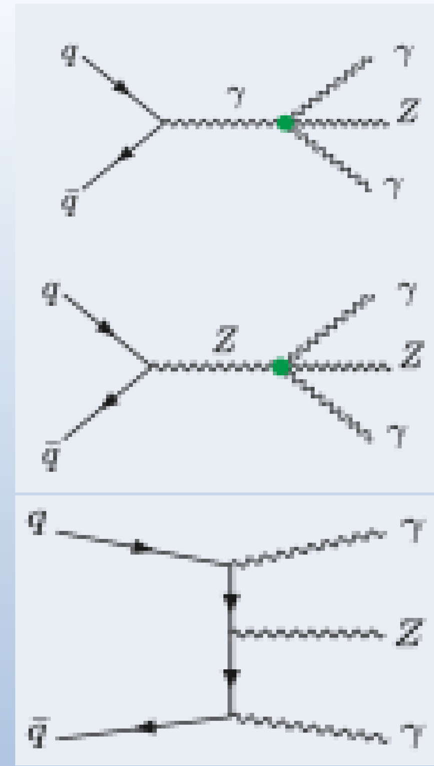

Fig.2: Feynman diagrams for the tree-level Zγγ production of anomalous quartic gauge-boson coupling vertex (represented with green circle) and the SM contributions.

EVENT SELECTION AND DETAILS OF ANALYSIS

Event generation by **MadGraph5_aMC@NLO 3.1.1 [2]** signal and all background process → Parton Shower and Hadronization by **Pythia 8.20 [3]** → Fast Simulation by **Delphes 3.4.2 [4]** with FCC Detector Card → Jets are reconstructed by using clustered energy deposits with **FastJet 3.3.2** [5] using **anti-kt** algorithm [6]

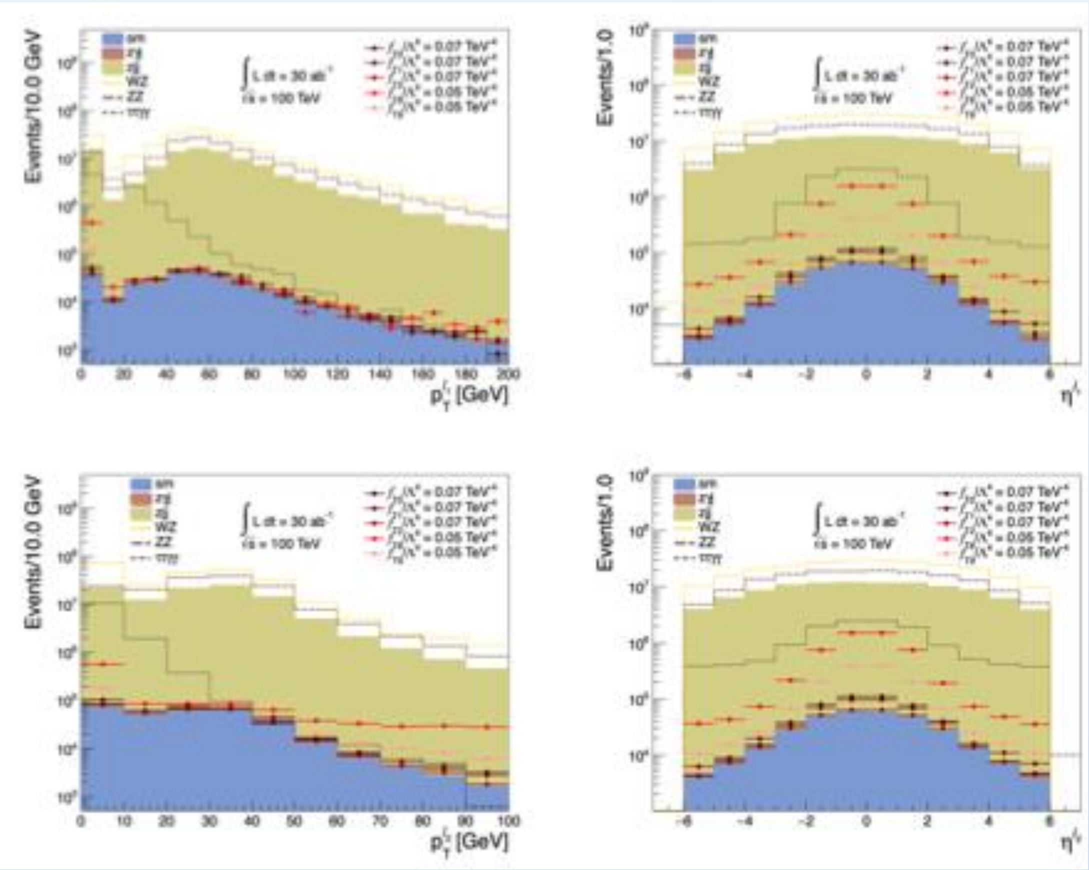

Fig.3 Normalized distributions of transverse momentum and pseudo-rapidity of the leading (l1) and sub- leading leptons (l2) after the event selection (Cut-0) for the signals and background with L_{int} = 30 ab^{-1}.

Cuts	Event selection criteria and applied kinematic cuts
Cut-0	$N_l \geqslant 2$ and same flavour but opposite charge, $N_\gamma \geqslant 2$
Cut-1	$p_T^{l_1,l_2} > 25$ GeV, $\lvert\eta^{l_1,l_2}\rvert \leqslant 2.5$
Cut-2	$p_T^{\gamma_1,\gamma_2} > 20$ GeV $\quad \lvert\eta^{\gamma_1,\gamma_2}\rvert \leqslant 2.5$
Cut-3	$\Delta R(\gamma_1,\gamma_2) > 0.4$, $\Delta R(\gamma_1,l_1) > 0.4$, $\Delta R(l_1,l_2) < 1.4$
Cut-4	81 GeV $< M_{l^+l^-} < 101$ GeV
Cut-5	$p_T^{\gamma_1} > 300$ GeV

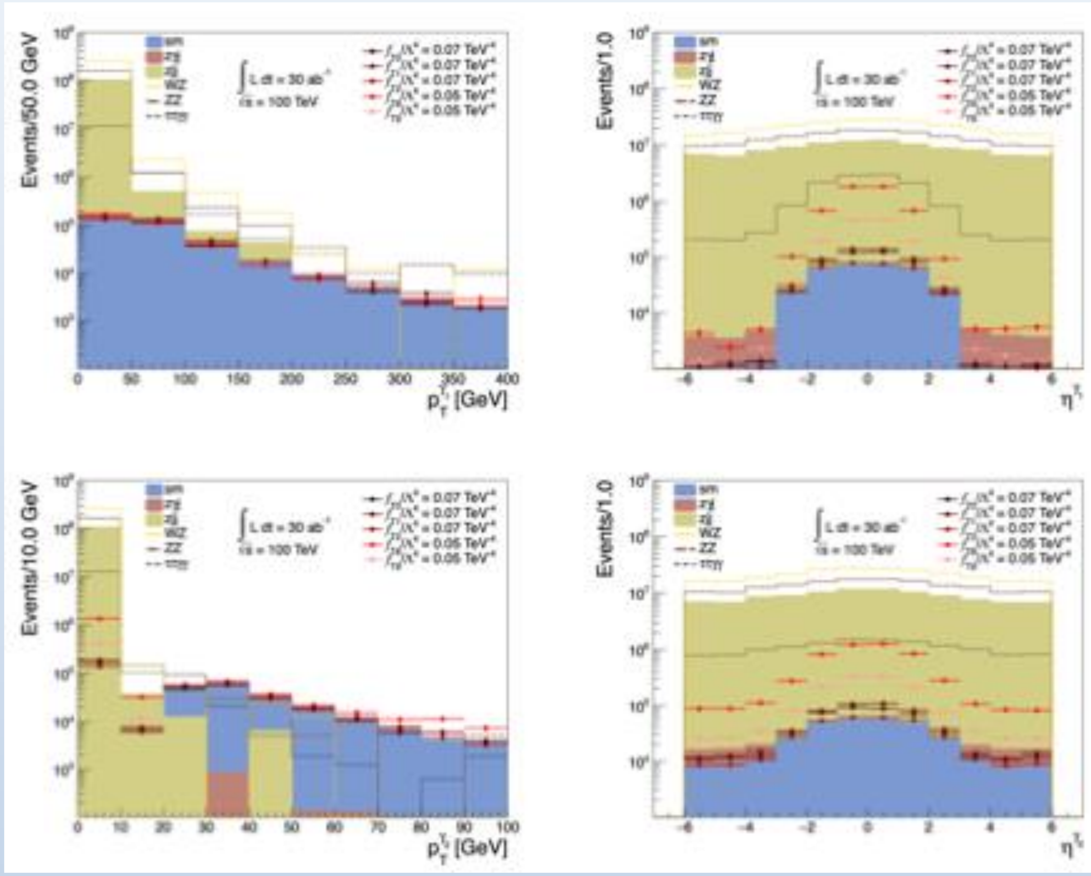

Fig4. Normalized distributions of transverse momentum and pseudo-rapidity of the leading (γ1) and sub- leading leptons (γ2) after the event selection(Cut-0) for the signals and backgrounds processes with Lint = 30 ab^{-1}

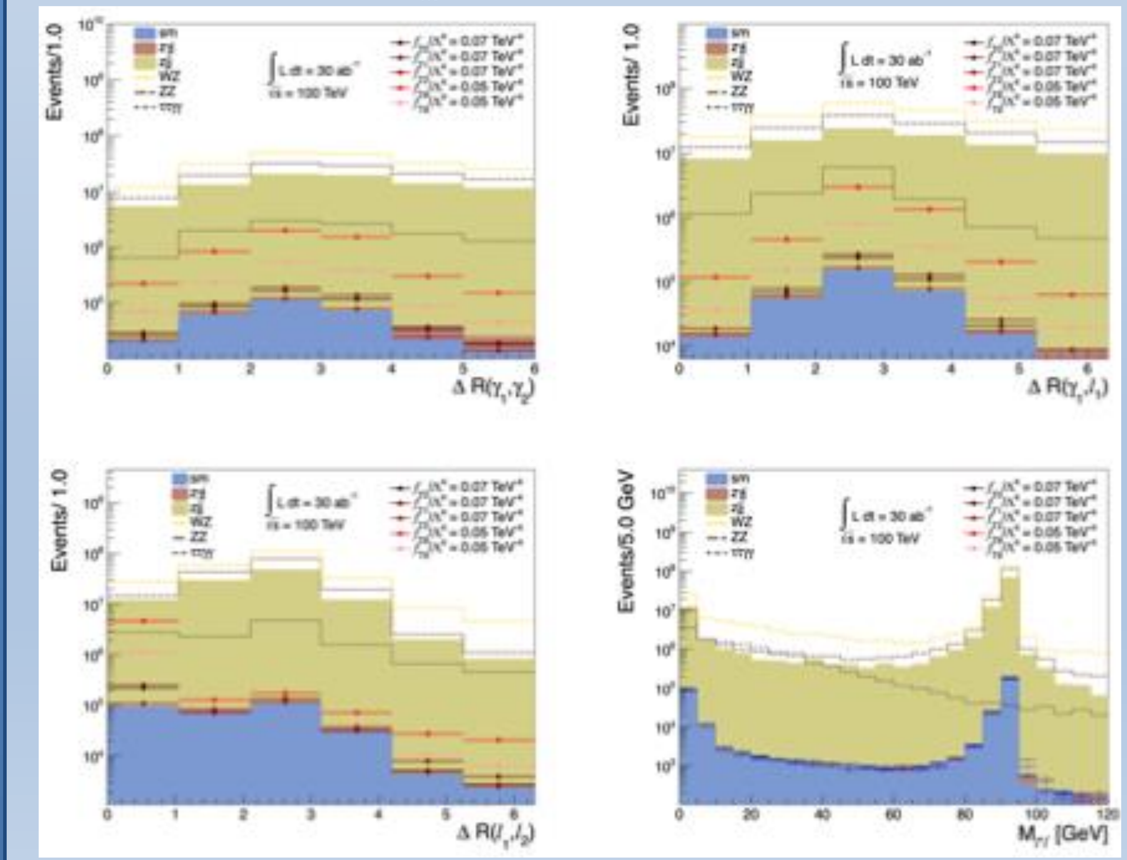

Fig.5 Normalized ΔR(γ1, γ2), ΔR(γ1, l1), ΔR(l1, l2) and charged lepton pair invariant mass distribution after the event selection (Cut-0) for the signals and backgrounds processes with Lint = 30 ab^{-1}.

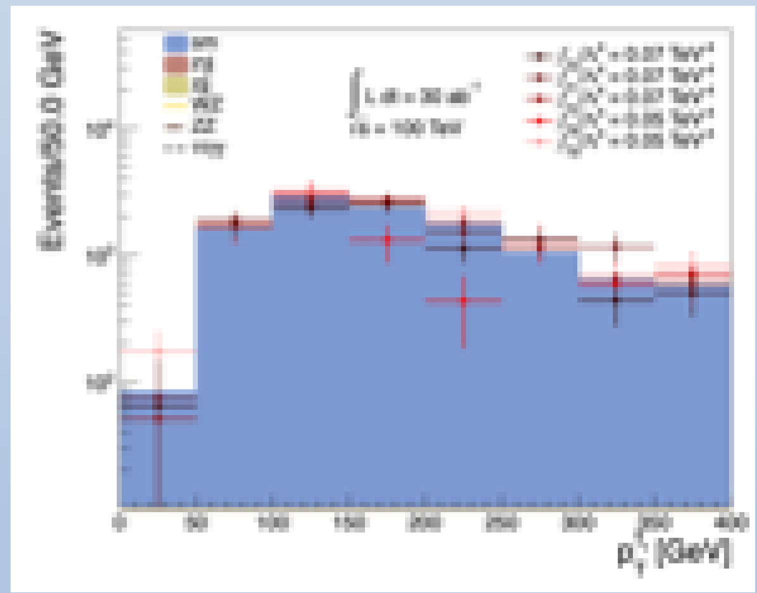

Fig.6 Normalized distributions of transverse momentum of the leading photon (γ1) after Cut-4 for the signals and backgrounds processes with L_{int} = 30 ab^{-1}

	f_{T8}/Λ^4=0.01 TeV^{-4}			FCC-hh			
Cut-0	339659 (336093)	316474	277688	104987000	255968000	162914000	13170400
Cut-1	135863 (132902)	125512	108020	29593500	66414700	52153500	280985
Cut-2	84834 (82976)	79066	793	0	24973	14963	0
Cut-3	19272 (17494)	16211	198	0	12486	0	0
Cut-4	18467 (16848)	15585	149	0	12486	0	0
Cut-5	5205 (4010)	2958	20	0	0	0	0

Table 1: The cumulative number of events for signal (f_{T8}/Λ^4 = 0.01 TeV $^{-4}$) and relevant background processes after applied cuts The number of events between the parenthesis are obtained after applying UV bounds for signals.

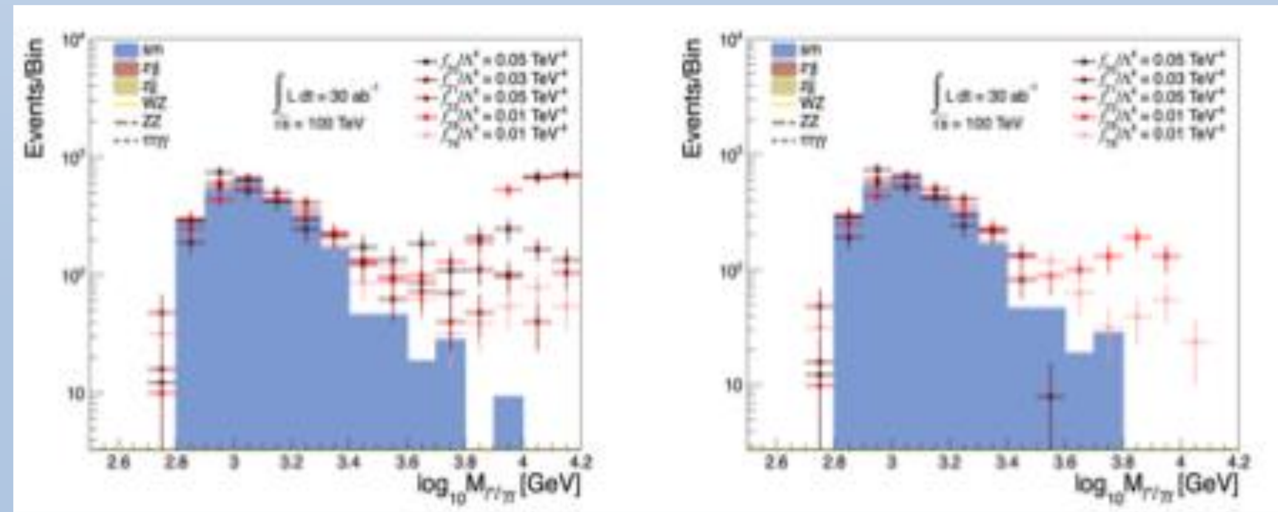

Fig.7 Reconstructed mass of the leading and sub-leading charged leptons and photons after cut-5 without the UV bound (left panels) and with the UV bound (right panels) for FCC-hh with a L_{int} = 30 ab^{-1}

RESULTS AND DISCUSSION

The obtaining of the 95% Confidence Level (C.L.) limit on a one-dimensional aQGC parameter is performed by χ2 test which corresponds to 3.84 integrating the invariant mass distribution of l⁺l⁻γγ system

$$\chi^2 = \sum_i^{n_{bins}} \left(\frac{N_i^{NP} - N_i^B}{N_i^B \Delta_i} \right)^2$$

$$\Delta_i = \sqrt{\delta_{sys}^2 + \frac{1}{N_i^B}}$$

NP is the total number of events in the existence of aQGC, NB is total number of events of the corresponding SM backgrounds in ith bin, ΔI is the combined systematic (δsys) and statistical uncertainties in each bin.

	δ_{sys}	FCC-hh Limits [TeV^{-4}]	Λ_{UV} [TeV]
f_{T0}/Λ^4	0%	[-1.29;1.05]$\times 10^{-2}$	3.6
	3%	[-1.73;1.50]$\times 10^{-2}$	
	5%	[-2.11;1.87]$\times 10^{-2}$	
	10%	[-2.86;2.63]$\times 10^{-2}$	
f_{T1}/Λ^4	0%	[-1.34;0.83]$\times 10^{-2}$	4.5
	3%	[-1.75;1.23]$\times 10^{-2}$	
	5%	[-2.08;1.56]$\times 10^{-2}$	
	10%	[-2.76;2.24]$\times 10^{-2}$	
f_{T2}/Λ^4	0%	[-2.15;1.52]$\times 10^{-2}$	4.3
	3%	[-2.83;2.20]$\times 10^{-2}$	
	5%	[-3.40;2.78]$\times 10^{-2}$	
	10%	[-4.57;3.94]$\times 10^{-2}$	
f_{T8}/Λ^4	0%	[-1.16;0.54]$\times 10^{-3}$	17.2
	3%	[-1.33;0.71]$\times 10^{-3}$	
	5%	[-1.50;0.89]$\times 10^{-3}$	
	10%	[-1.90;0.13]$\times 10^{-3}$	
f_{T9}/Λ^4	0%	[-1.26;1.09]$\times 10^{-3}$	17.7
	3%	[-1.35;1.18]$\times 10^{-3}$	
	5%	[-1.48;1.31]$\times 10^{-3}$	
	10%	[-1.84;1.66]$\times 10^{-3}$	

Table 2 95% C.L. limits on anomalous quartic gauge couplings in units of TeV^{-4} and the unitarity bounds (ΛUV) in units TeV considering δsys=0, 3%, 5% and 10% of systematic errors with L_{int} = 30 ab^{-1}

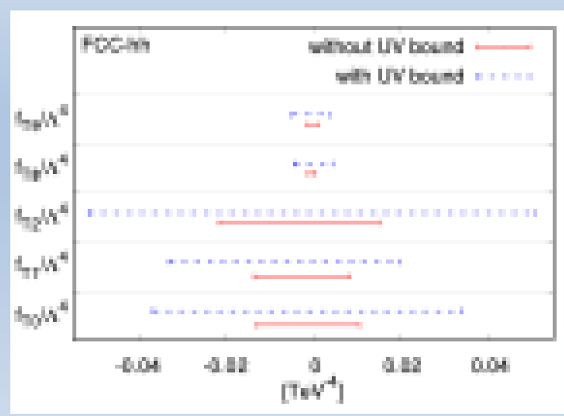

Fig. 8 95% C.L. limits on anomalous quartic gauge couplings with and without the unitarity bounds (ΛUV) considering δsys=0 of systematic errors with L_{int} = 30 ab^{-}

We have compared the current experimental limits with the results determined from this work, sensitivity on the couplings f_{T8}/Λ^4 and f_{T9}/Λ^4 (f_{T0}/Λ^4, f_{T1}/Λ^4 and f_{T2}/Λ^4) for FCC-hh without systematic errors with Lint with L_{int} = 30 ab^{-1} are two (one) order better than the current experimental limits obtained from different vector boson scattering process by ATLAS and CMS collaborations [7,8].

Comprable results related to HL-LHC ($\sqrt{s}$ =14 TeV) and HE-LHC ($\sqrt{s}$ =27 TeV) can be found in Ref[9].

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