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A study on Higgs-Gauge Boson Anomalous couplings via $\gamma\gamma Z$ Production at the FCC-ee

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Introduction

- The discovery of the new resonance with mass around 125 GeV in the searches for the Standard Model Higgs boson has been reported by the ATLAS and CMS Collaborations.
- All of the properties of the new particle measured so far are consistent with that of the Standard Model (SM) Higgs boson.
- In particular, the couplings of the Higgs boson have recently been analyzed using the combined ATLAS and CMS data, with no evidence of physics beyond the SM [*].

[*] ATLAS-CONF-2015-044

- In view of the kinematic reach of the Large Hadron Collider (LHC), it is natural to suppose that the threshold for any new physics may lie substantially above the masses of the Standard Model particles.

- A future e+e− linear collider, such as the projected TLEP*, will have the potential to probe the Standard Model (SM) Higgs sector with higher precision than its predecessors, LEP and the LHC at CERN.

- In this case, the new physics may be analyzed in the decoupling limit, and its effects may be parameterized in terms of higher-dimensional operators composed of Standard Model fields [*].

*("TLEP" a.k.a. FCC-ee)

[*] W. Buchmüller and D. Wyler, Nucl. Phys. B 268 (1986) 621

- The proposed Fcc-ee e+e− collider [*], which could be hosted in a new 80 to 100 km tunnel would be able to produce collisions at centre-of-mass energies from 90 to 350 GeV and beyond, at several interaction points, and make precision measurements at the Z pole, at the WW threshold, at the HZ cross section maximum, and at the tt threshold, with an unequalled accuracy.

	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L (10^{34} $cm^{-2}s^{-1}$/IP)	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

[*] M. Bicer et al. [TLEP Design Study Working Group Collaboration],
"First Look at the Physics Case of TLEP,"JHEP 1401,164 (2014)

The most general effective Higgs Lagrangian in the Gauge Eigenbasis

- A powerful tool for analyzing such models of physics beyond the SM is provided by the SM Effective Field Theory (SM EFT), which parametrizes possible new physics via a systematic expansion in a series of higher-dimensional operators composed of SM fields.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \bar{c}_i \mathcal{O}_i = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm SILH} + \mathcal{L}_{CP} + \mathcal{L}_{F_1} + \mathcal{L}_{F_2} + \mathcal{L}_{G} \, ,$$

- $\mathcal{L}_{\rm SILH}$: (SILH=Strongly Interacting Light Higgs) is inspired by scenarios where the Higgs field is part of a strongly interacting sector,
- $\mathcal{L}_{CP}$: contains CP-violating operators
- $\mathcal{L}_{F_1}$: contains interactions between two Higgs fields and a pair
- $\mathcal{L}_{F_2}$:contains interactions among a pair of fermions with a single Higgs field and a gauge-boson that originate from different NP scenarios (other than the heavy vector exchanges),
- $\mathcal{L}_{G}$:contains new gauge-boson self-interactions

- We focus on the effects of New Physics in production of the Higgs in association with a vector boson. Hence, we are interested in three-point functions involving the Higgs and two vector bosons. The Lagrangian leads to the following CP-conserving and CP-violating parts in the unitary gauge and mass basis [*]

$$
\begin{aligned}
\mathcal{L}_3 = & -\frac{m_H^2}{2v} g^{(1)}_{hhh} h^3 + \frac{1}{2} g^{(2)}_{hhh} h \partial_\mu h \partial^\mu h \\
& - \frac{1}{4} g_{hgg} G^a_{\mu\nu} G_a^{\mu\nu} h - \frac{1}{4} \tilde{g}_{hgg} G^a_{\mu\nu} \tilde{G}^{\mu\nu} h - \frac{1}{4} g_{h\gamma\gamma} F_{\mu\nu} F^{\mu\nu} h - \frac{1}{4} \tilde{g}_{h\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} h \\
& - \frac{1}{4} g^{(1)}_{hzz} Z_{\mu\nu} Z^{\mu\nu} h - g^{(2)}_{hzz} Z_\nu \partial_\mu Z^{\mu\nu} h + \frac{1}{2} g^{(3)}_{hzz} Z_\mu Z^\mu h - \frac{1}{4} \tilde{g}_{hzz} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h \\
& - \frac{1}{2} g^{(1)}_{haz} Z_{\mu\nu} F^{\mu\nu} h - \frac{1}{2} \tilde{g}_{haz} Z_{\mu\nu} \tilde{F}^{\mu\nu} h - g^{(2)}_{haz} Z_\nu \partial_\mu F^{\mu\nu} h - \frac{1}{2} g^{(1)}_{hww} W^{\mu\nu} W^\dagger_{\mu\nu} h \\
& - \left[g^{(2)}_{hww} W^\nu \partial^\mu W^\dagger_{\mu\nu} h + \text{h.c.} \right] + g(1 - \frac{1}{2} \bar{c}_H) m_W W^\dagger_\mu W^\mu h - \frac{1}{2} \tilde{g}_{hww} W^{\mu\nu} \tilde{W}^\dagger_{\mu\nu} h \\
& - \left[\tilde{y}_u \frac{1}{\sqrt{2}} [\bar{u} P_R u] h + \tilde{y}_d \frac{1}{\sqrt{2}} [\bar{d} P_R d] h + \tilde{y}_\ell \frac{1}{\sqrt{2}} [\bar{\ell} P_R \ell] h + \text{h.c.} \right],
\end{aligned}
$$

[*] A. Alloul, B. Fuks, and V. Sanz, JHEP 04 (2014) 110.

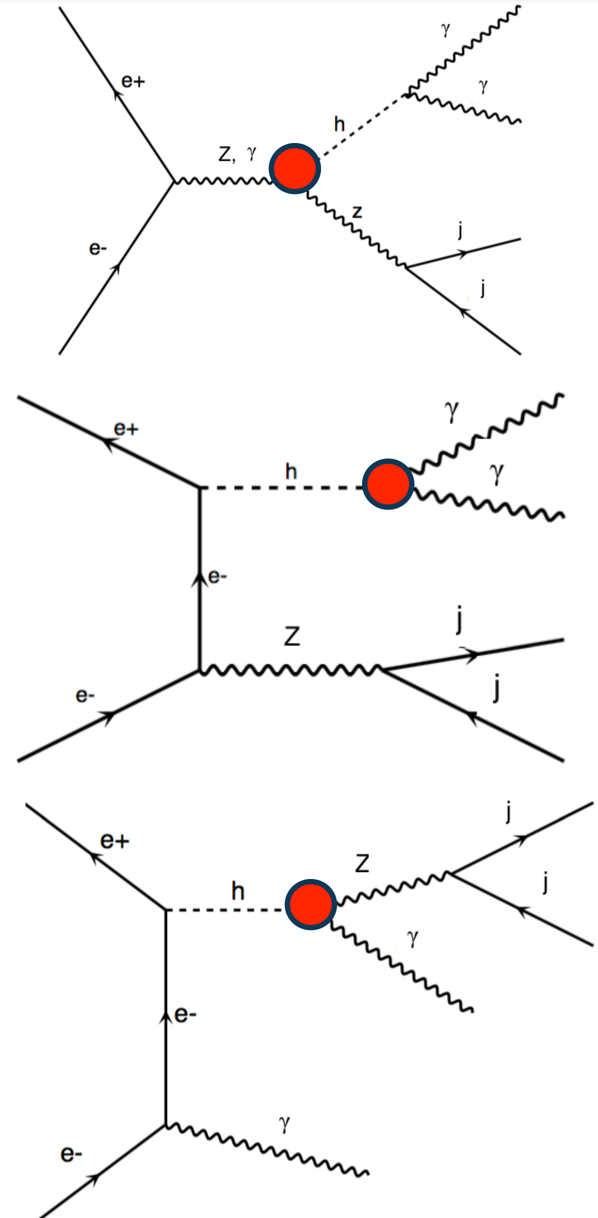
The Lagrangian is expressed in the mass basis, and those associated with the operators expressed in the gauge basis.

g_{hgg}	$g_H - \frac{4\bar{c}_g g_s^2 v}{m_W^2}$
$\tilde{g}_{hgg}$	$-\frac{4\tilde{c}_g g_s^2 v}{m_W^2}$
$g_{h\gamma\gamma}$	$a_H - \frac{8g\bar{c}_\gamma s_W^2}{m_W}$
$\tilde{g}_{h\gamma\gamma}$	$-\frac{8g\tilde{c}_\gamma s_W^2}{m_W}$
$g_{hzz}^{(1)}$	$\frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4 + c_W^2\bar{c}_{HW}\right]$
$\tilde{g}_{hzz}$	$\frac{2g}{c_W^2 m_W}\left[\tilde{c}_{HB}s_W^2 - 4\tilde{c}_\gamma s_W^4 + c_W^2\tilde{c}_{HW}\right]$
$g_{hzz}^{(2)}$	$\frac{g}{c_W^2 m_W}\left[(\bar{c}_{HW} + \bar{c}_W)c_W^2 + (\bar{c}_B + \bar{c}_{HB})s_W^2\right]$
$g_{hzz}^{(3)}$	$\frac{gm_W}{c_W^2}\left[1 - \frac{1}{2}\bar{c}_H - 2\bar{c}_T + 8\bar{c}_\gamma\frac{s_W^4}{c_W^2}\right]$
$g_{haz}^{(1)}$	$\frac{gs_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\bar{c}_\gamma s_W^2\right]$
$\tilde{g}_{haz}$	$\frac{gs_W}{c_W m_W}\left[\tilde{c}_{HW} - \tilde{c}_{HB} + 8\tilde{c}_\gamma s_W^2\right]$
$g_{haz}^{(2)}$	$\frac{gs_W}{c_W m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$
$g_{hww}^{(1)}$	$\frac{2g}{m_W}\bar{c}_{HW}$
$\tilde{g}_{hww}$	$\frac{2g}{m_W}\tilde{c}_{HW}$
$g_{hww}^{(2)}$	$\frac{g}{m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$

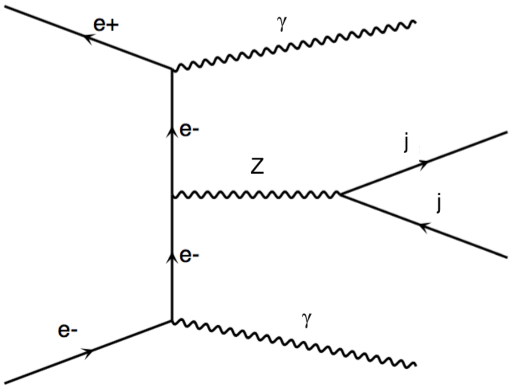
The contributed Feynman diagrams

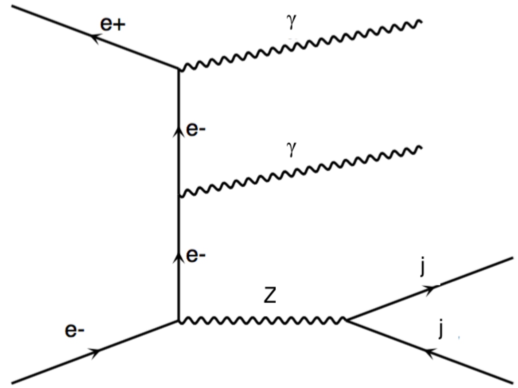
- In this study, we focus on searching for effective Higgs-neutral boson couplings via $e^+e^- \to \gamma\ \gamma\ Z \to \gamma\ \gamma\ j\ j$ process. (where j is light quarks or anti quarks)

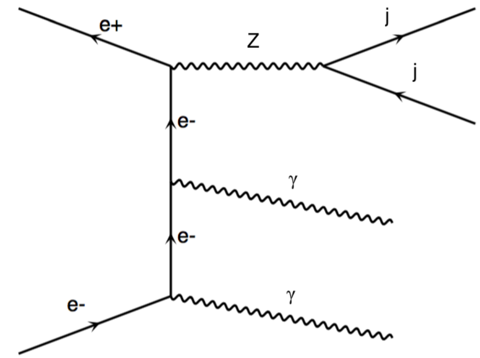
- This process is mainly sensitive hZZ, hγγ and hZγ couplings, apart from the effective fermionic couplings which are taken to be the standard couplings in our study.

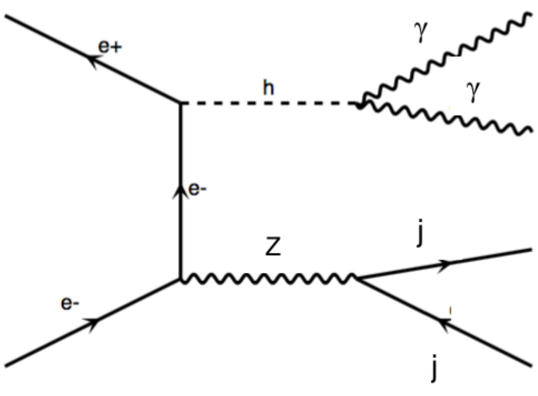


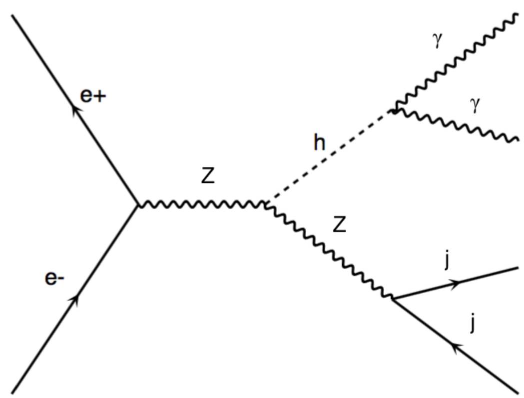
- and tree-level SM diagrams for the $e^+e^- \to \gamma\,\gamma\,Z \to \gamma\,\gamma\,j\,j$ process











Analysis Setup

- We use MadGraph5 [*] to generate the signal & background events with the effective Lagrangian implemented through FEYNRULES [**]

- The signal and background events are generated in the center-of-mass energies of 240 GeV .

- We apply the following pre-selection cuts on the final state photons and two jets to generate unweighted events;

$p_T^j > 20$ GeV , $|\eta^j| < 5$ $\Delta R_{jj} > 0.4$

$p_T^\gamma > 10$ GeV, $|\eta^\gamma| < 2.5$ $\Delta R_{\gamma\gamma} > 0.4$, $\Delta R_{j\gamma} > 0.4$

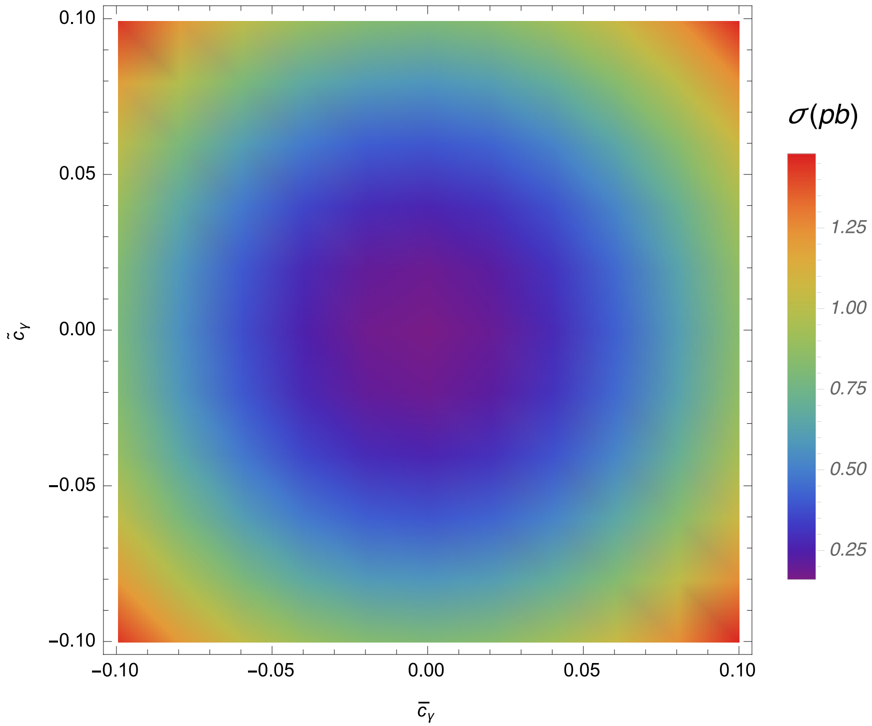
j=u, d, c, s

$\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2}$ with φ representing the azimuthal angle with respect to the beam directions.

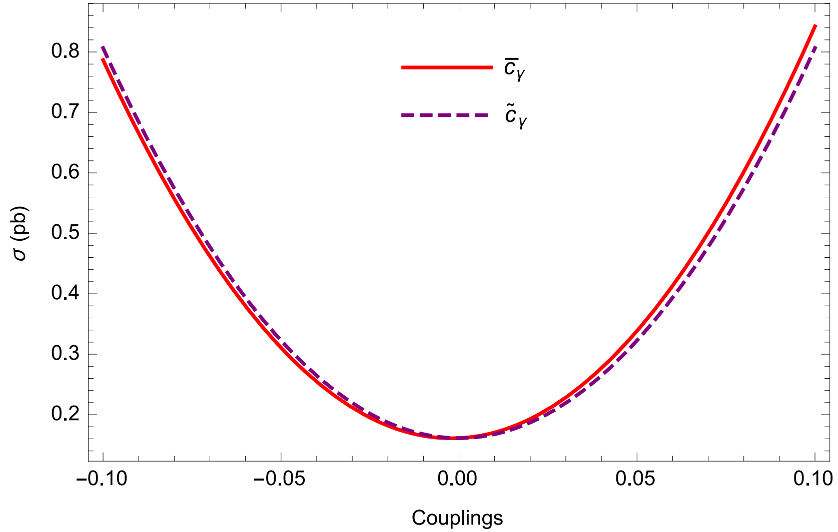
[*] J. Alwall et al., JHEP 1407 (2014) 079.

[**] A. Alloul, B. Fuks, and V. Sanz, J. High Energy Phys. 04 (2014) 110.

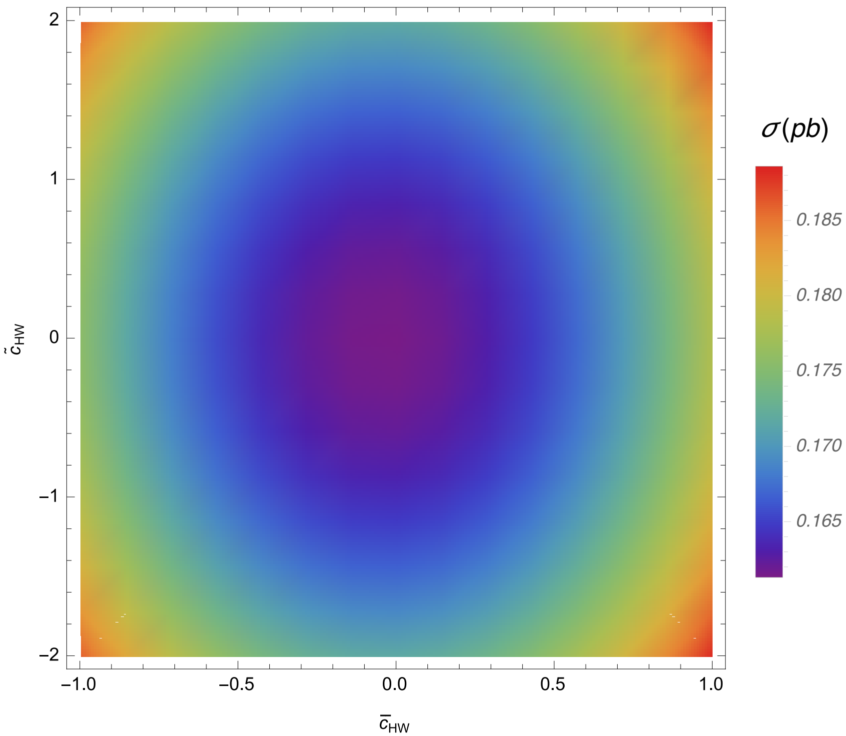
Cross Sections of $e^+e^- \to \gamma\gamma Z \to \gamma\gamma jj$ process



- The cross section of the $e^+e^- \to \gamma\gamma Z \to \gamma\gamma jj$ process for a two dimensional scan of $\bar{c}_\gamma$ and $\tilde{c}_\gamma$.
- All other Wilson coefficients are set to zero.



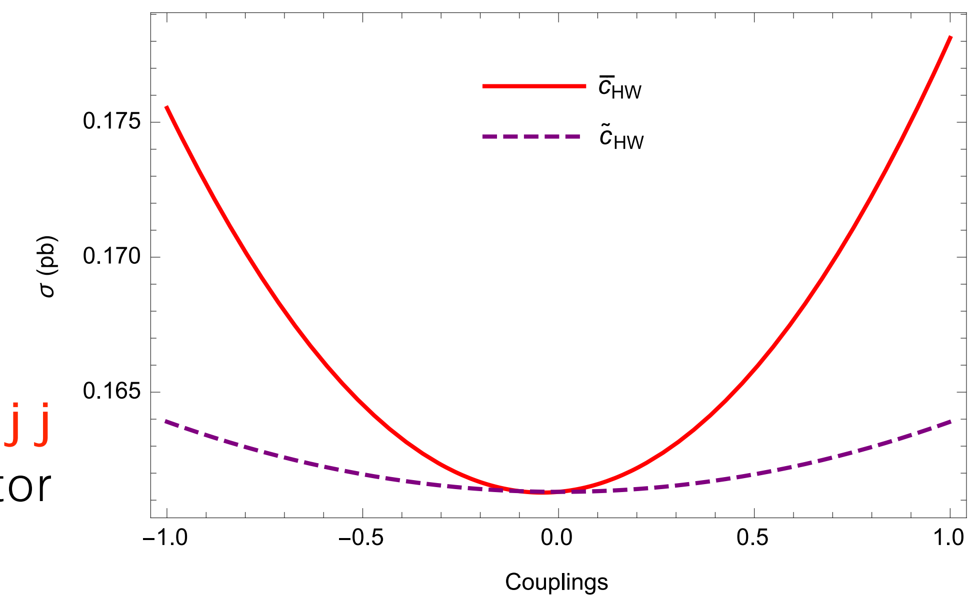
The cross section of the $e^+e^- \to \gamma\gamma Z \to \gamma\gamma jj$ process, switching on each operator individually and setting the others to zero.



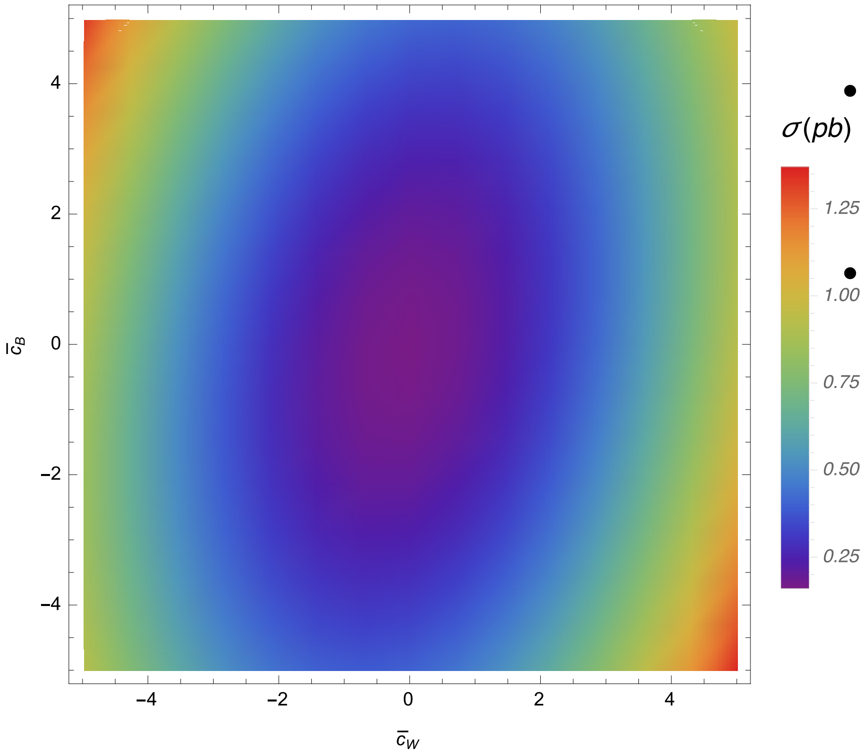
- The cross section of the $e^+e^- \to \gamma\gamma Z \to \gamma\gamma jj$ process for a two dimensional scan of $\bar{c}_{HW}$ and $\tilde{c}_{HW}$
- All other Wilson coefficients are set to zero except for $\bar{c}_{HB}$ and $\tilde{c}_{HB}$ which are set to be

$$\bar{c}_{HW} = -\bar{c}_{HB}$$

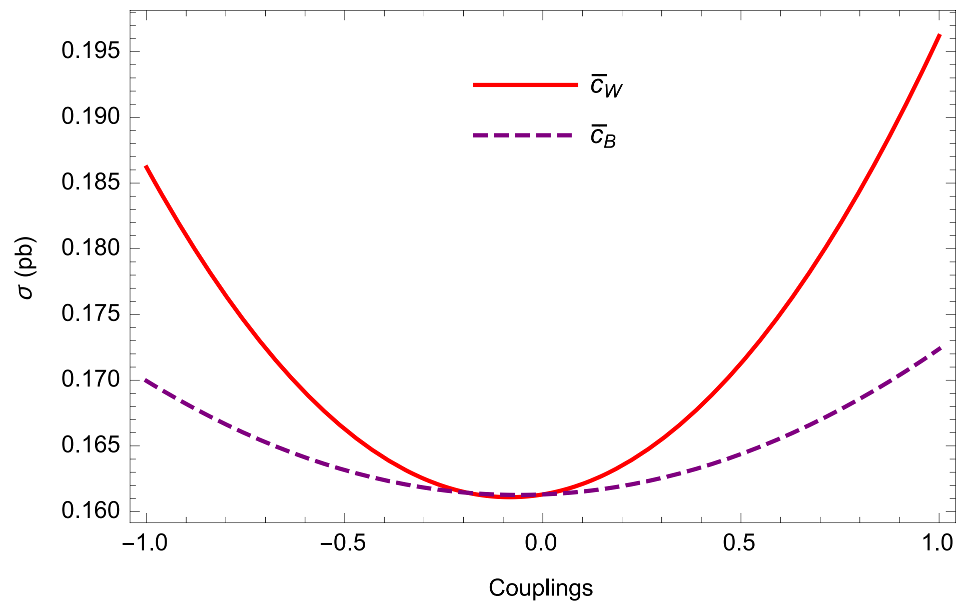
$$\tilde{c}_{HW} = -\tilde{c}_{HB}$$



The cross section of the $e^+e^- \to \gamma\gamma Z \to \gamma\gamma jj$ process, switching on each operator individually and setting the others to zero.



- The cross section of the $e^+e^- \to \gamma\,\gamma\,Z \to \gamma\,\gamma\,j\,j$ process for a two dimensional scan of $\bar{c}_B$ and $\bar{c}_W$
- All other Wilson coefficients are set tozero.



The cross section of the $e^+e^- \to \gamma\,\gamma\,Z \to \gamma\,\gamma\,j\,j$ process, switching on each operator individually and setting the others to zero.

Limits on Anomalous couplings

- In order to probe the sensitivity to the Wilson coefficients, we use one and two-dimensional χ^2 criterion without systematic error. The χ^2 function is defined as follows

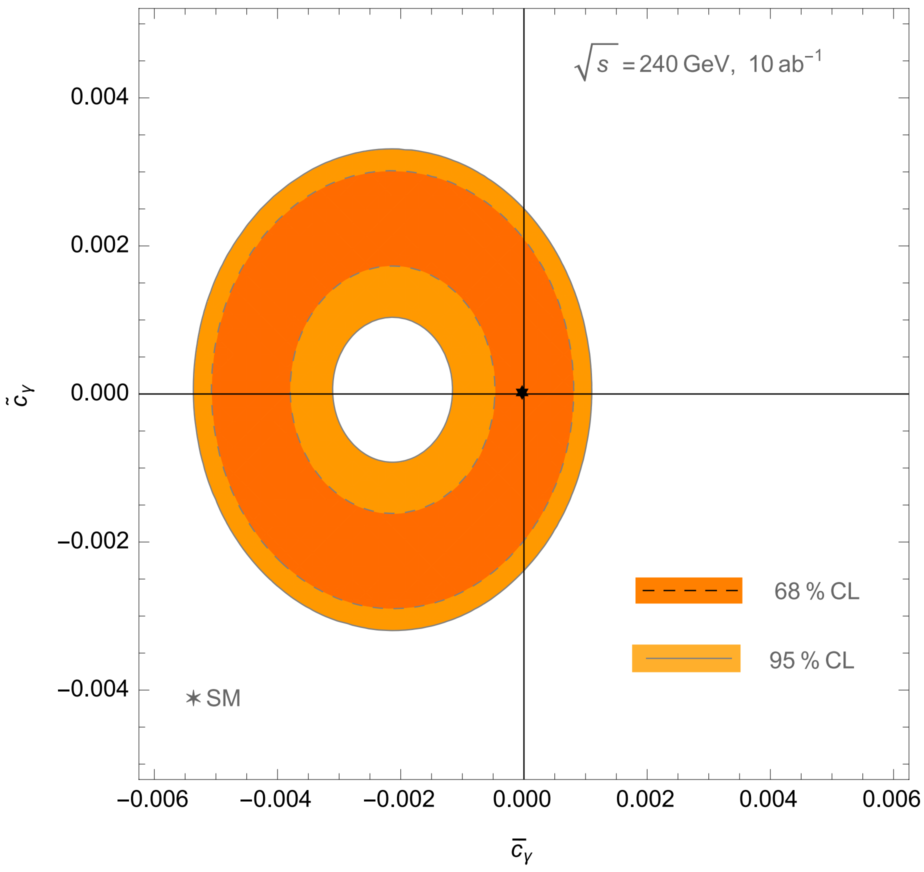
$$\chi^2 = \left(\frac{\sigma_{SM} - \sigma_{NP}}{\sigma_{SM}\delta_{stat}}\right)^2$$

where σ_{NP} is the cross section in the existence of new physics effects, $\delta_{stat} = \sqrt{N}$ is the statistical error, N is the number of events.

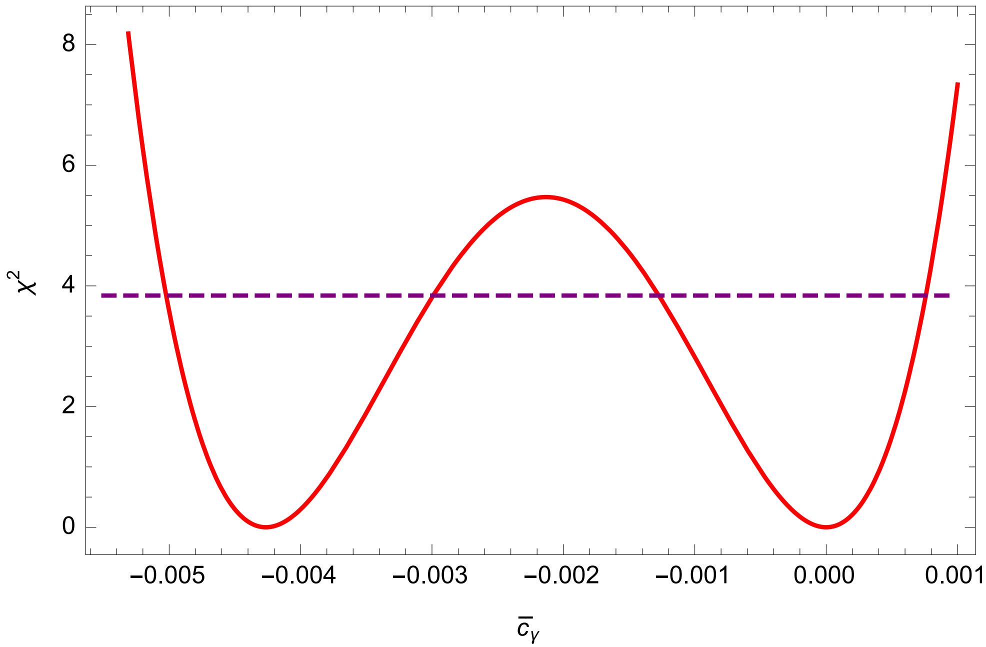
$N = L_{int} \times \sigma_{SM}$

σ_{SM} is the corresponding SM background cross section

- The 95% and 68% confidence region for a two-dimensional scan for CP-conserving and CP-violating parameters $\bar{c}_\gamma$ and $\tilde{c}_\gamma$



- All other Wilson coefficients are set to zero
- $\sqrt{s}$=240 GeV, L_{int}= 10 ab^{-1}



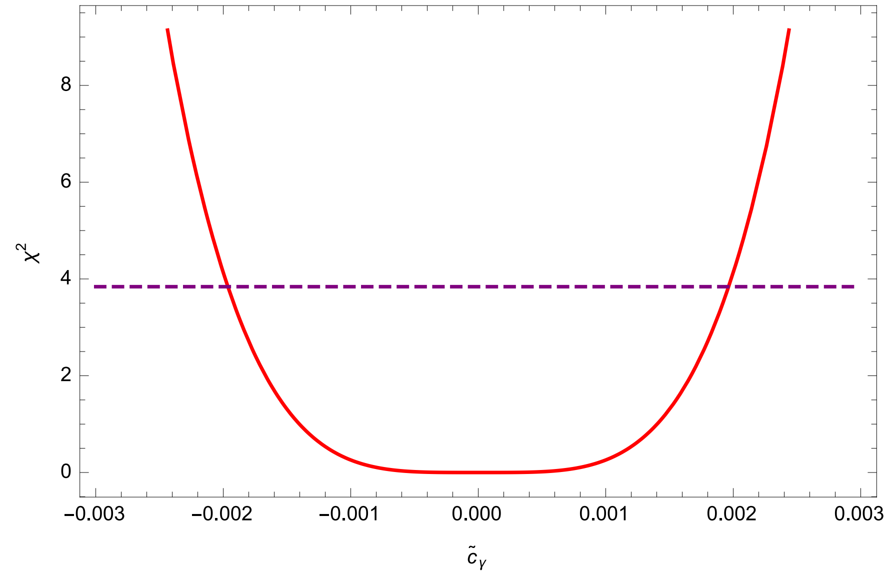
- The 95% C.L. limit for a one-dimensional scan of the $\bar{c}_\gamma$ are

[-5.0, -2.9] x10^{-3} U [-1.3, 0.76] x10^{-3}

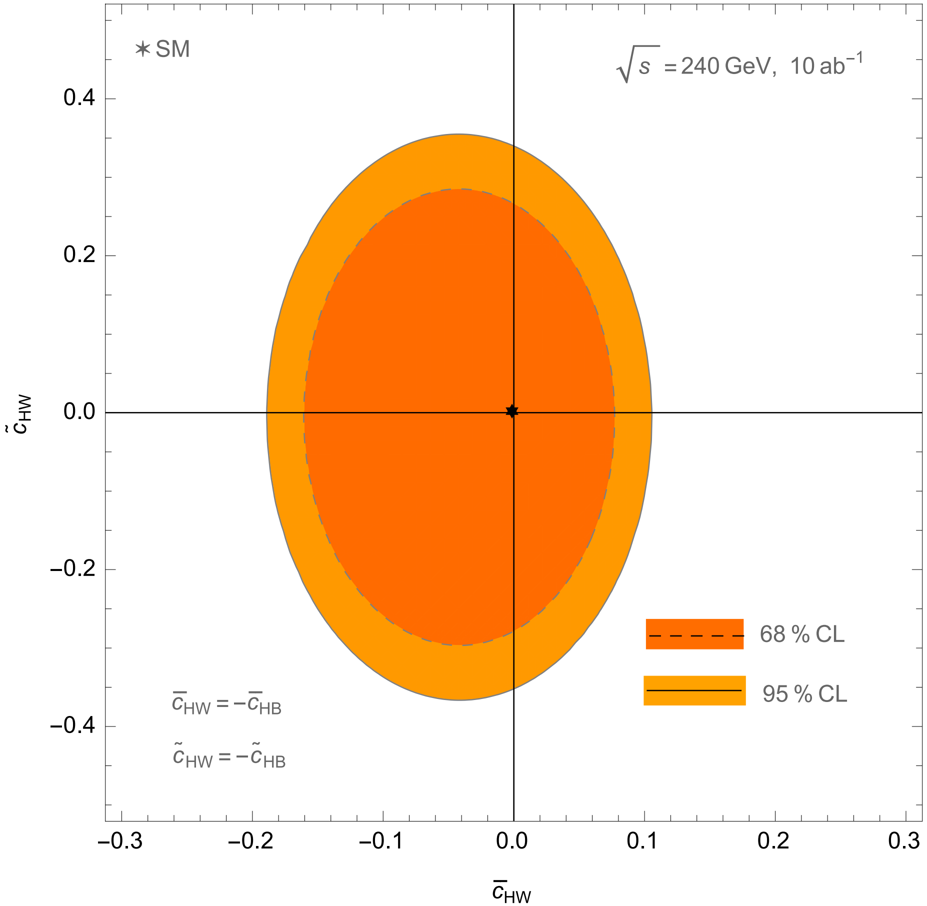
- These new interaction ($\bar{c}_\gamma$) can interfere with corresponding SM interactions. Destructive interference effect causes the $h\rightarrow\gamma\gamma$ decay is observed in the obtained limits of this coupling.

Allowed range at 95% C.L. for $\tilde{c}_\gamma$

[-1.96, 1.96] x 10^{-3}



The 95% and 68% confidence region for a two-dimensional scan for $\bar{c}_{HW}$ and $\tilde{c}_{HW}$

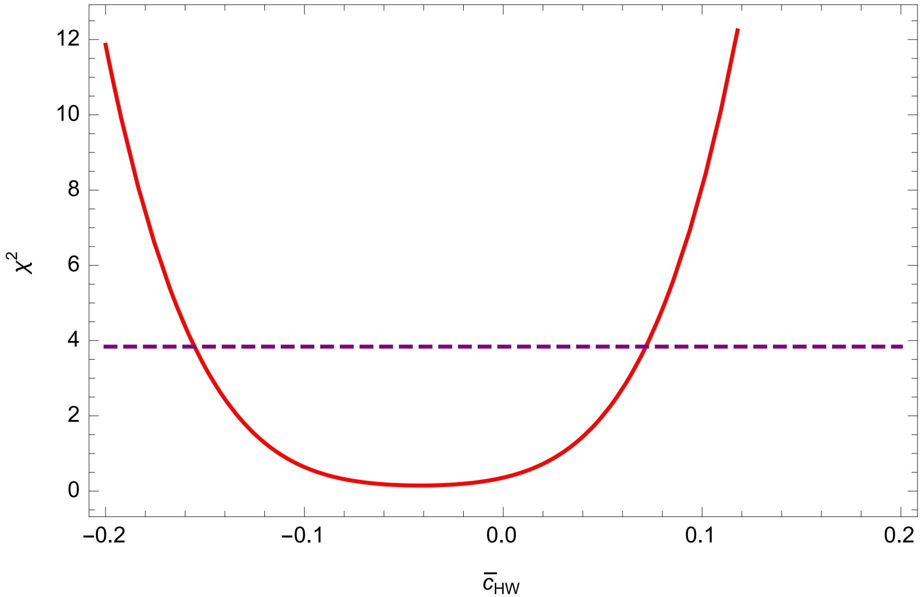


- All other Wilson coefficients are set to zero, except for $\bar{c}_{HB}$ and $\tilde{c}_{HB}$ which are set to be

$$\bar{c}_{HW} = - \bar{c}_{HB}$$

$$\tilde{c}_{HW} = - \tilde{c}_{HB}$$

- $\sqrt{s}$=240 GeV, L_{int}= 10 ab^{-1}

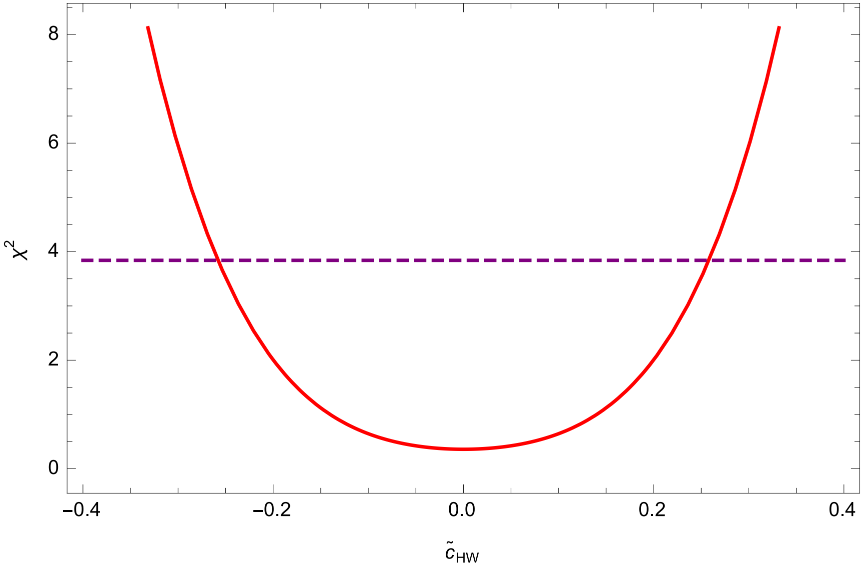


- The 95% C.L. limit for a one-dimensional scan of the $\bar{c}_{HW}$ is

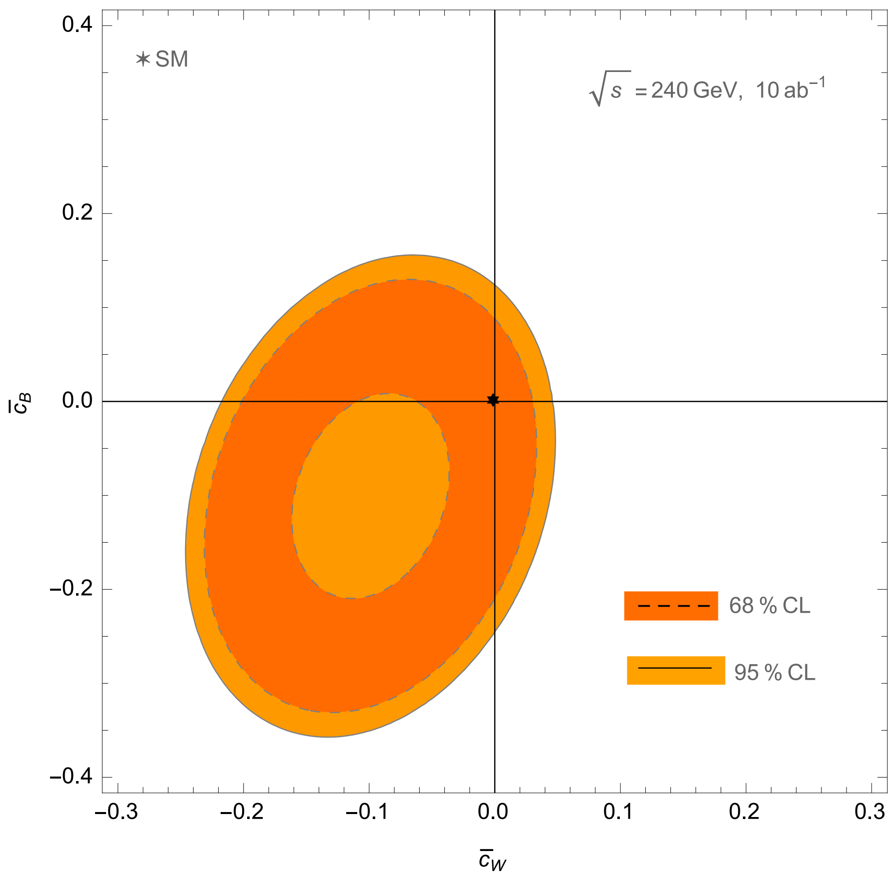
[-0.16, 0.07]

- Allowed range at 95% C.L. for $\tilde{c}_{HW}$

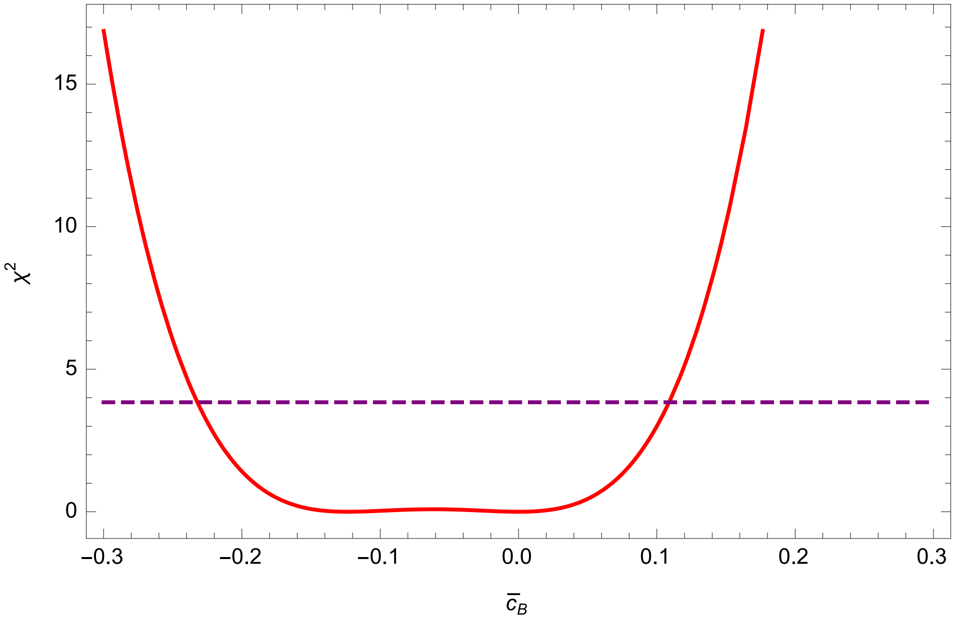
[-0.26, 0.26]



The 95% and 68% confidence region for a two-dimensional scan for $\bar{c}_B$ and $\bar{c}_W$



All other Wilson coefficients are set to zero and $\sqrt{s}$=240 GeV, L_{int}= 10 ab^{-1}

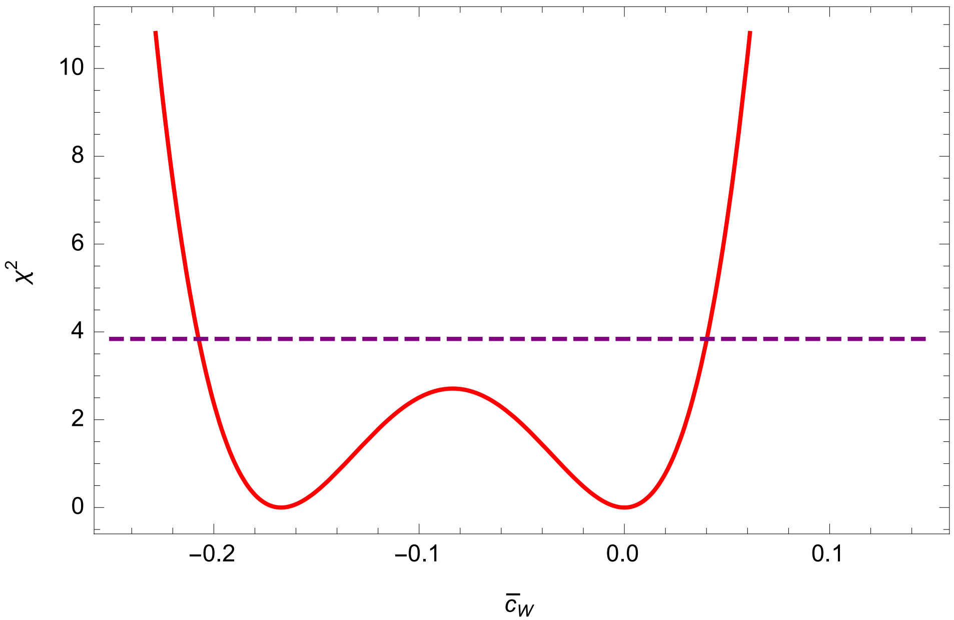


- The 95% C.L. limit for a one-dimensional scan of the $\bar{c}_B$ is

[-0.23, 0.11]

- Allowed range at 95% C.L. for $\bar{c}_W$

[-0.21,0.04]



Comparison with the LHC Results

Coefficient	LHC 8 TeV, 20.3 fb^{-1} [*]	FCC-ee 240 GeV, 10 ab^{-1} (our results)
$\bar{c}_\gamma$	[-7.4,-5.7] x 10^{-4} U [3.8, 5.1] x 10^{-3}	[-5.0, -2.9] x10^{-3} U [-1.3, 0.76] x10^{-3}
$\tilde{c}_\gamma$	[-1.8, 1.8] x 10^{-3}	[-1.96, 1.96] x 10^{-3}
$\bar{c}_{HW}$	[-8.6, 9.2] x 10^{-2}	[-0.16, 0.07]
$\tilde{c}_{HW}$	[-0.23, 0.23]	[-0.26, 0.26]
$\bar{c}_B$		[-0.23, 0.11]
$\bar{c}_W$	[-0.04, 0.035] [+]	[-0.21,0.04]

[*] ATLAS Collaboration / Physics Letters B 753 (2016) 69–85.

[+] J. Ellis, V. Sanz and T. You, ``The Effective Standard Model after LHC Run I", JHEP 1503, 157 (2015).

Summary and Conclusion

- The importance of improving precision tests of the SM, in particular in the Higgs sector, strongly motivates the construction of a future lepton collider.

- These indirect probes of new physics require a precise understanding of the SM contributions as well as the interplay between the SM and observable New Physics.

- We have shown that the $e^+e^- \rightarrow \gamma\gamma Z \rightarrow \gamma\gamma j j$ process is useful in detecting the anomalous couplings in Higgs-gauge boson interactions.

- Our results show that a 240 GeV-scale FCC-ee will be able to probe the anomalous couplings of Higgs-gauge boson interactions in $e^+e^- \rightarrow \gamma\gamma Z \rightarrow \gamma\gamma j j$ process at scales beyond the LEP bounds and become competitive with measurements at the LHC.

- The numerical study can be improved with more realistic collider and detector information.