New Physics in double Higgs Production at future e+e- colliders

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C. Degrande, A.Tonero, R. Rosenfeld, A. V. - arXiv: 1901.05979 [hep-ph]

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Goals

- Study the effects of New Physics parametrized by SM dimension-six operators in $e^+e^- \rightarrow hh$ at future lepton colliders

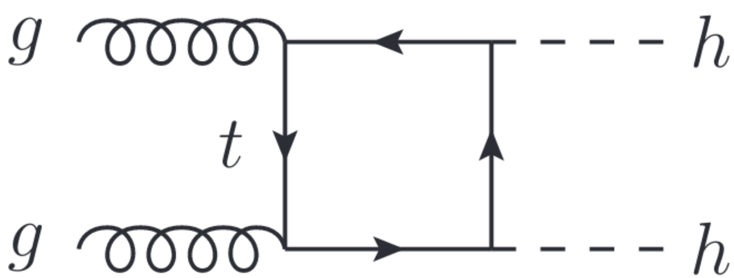
- Perform sensitivity study for several benchmark values of energy and integrated luminosity

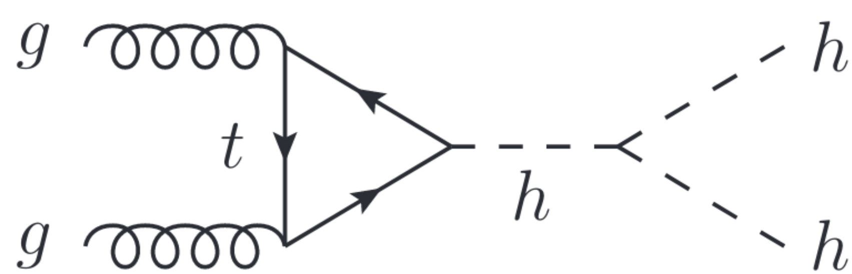
Motivation

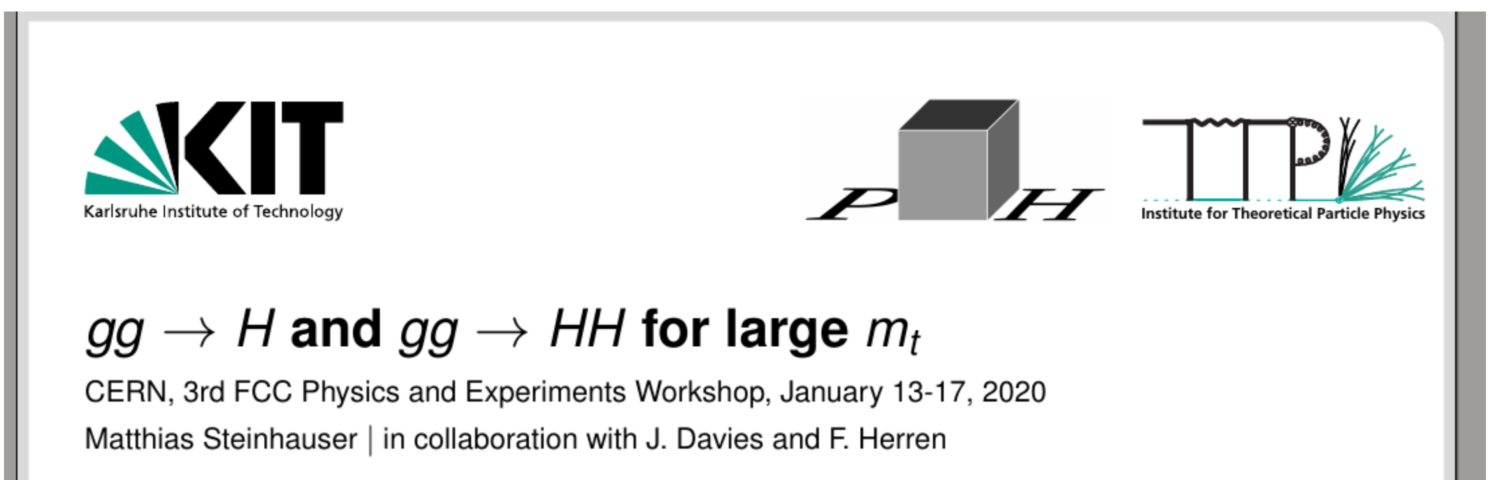
[Plehn, Spira & Zerwas, 1996]

In the SM, the process $gg \to hh$ presents destructive interference between boxes and triangle topologies: the closer to the threshold, the stronger the cancellation.

[Li & Voloshin, 2013]







Motivation

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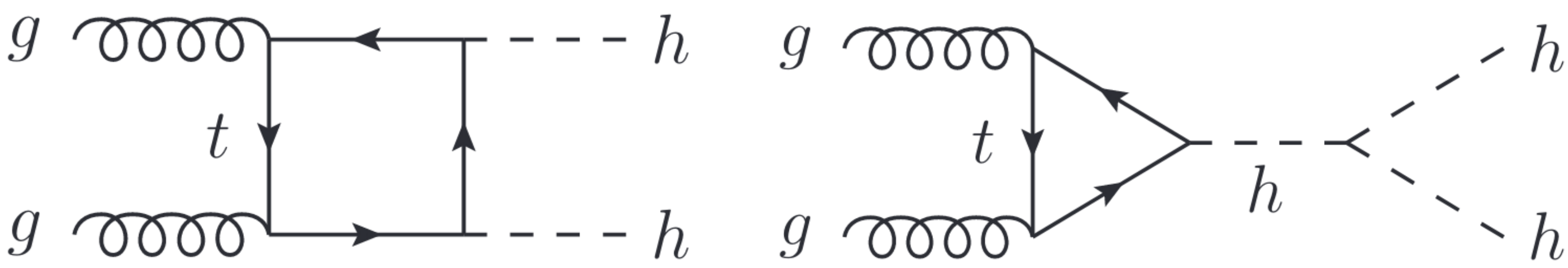
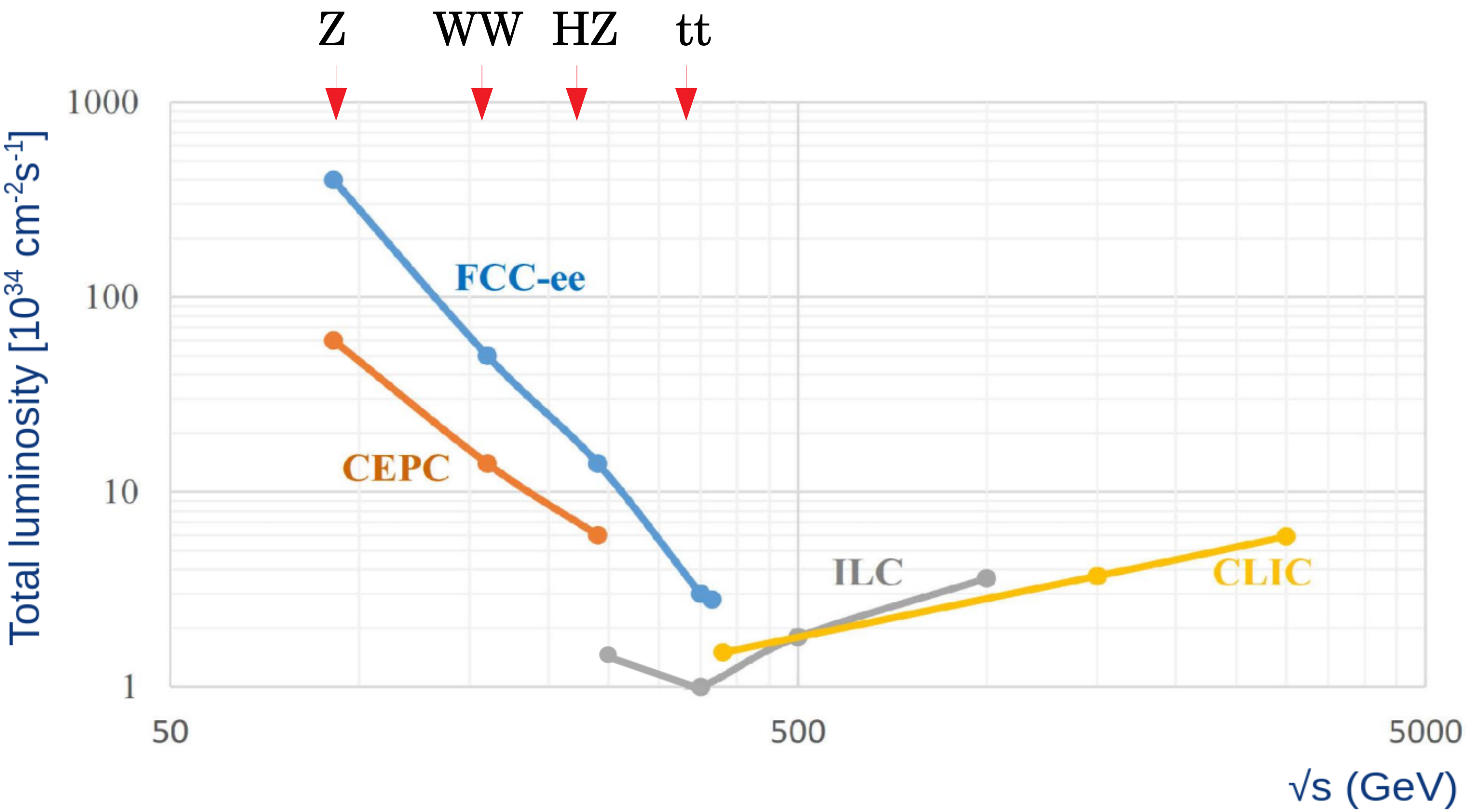


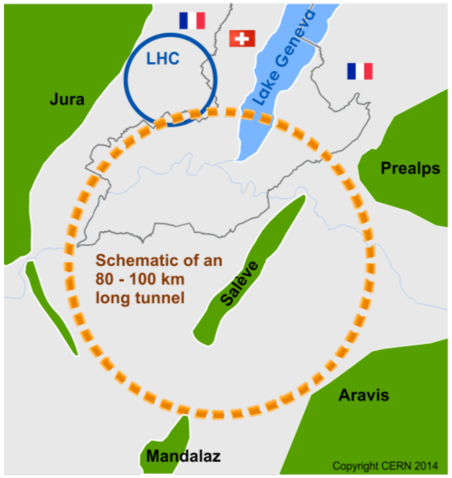
Small cross-section → Sensitive to New Physics effects

→ Does the process $e^+e^- \to hh$ follow a similar behavior?

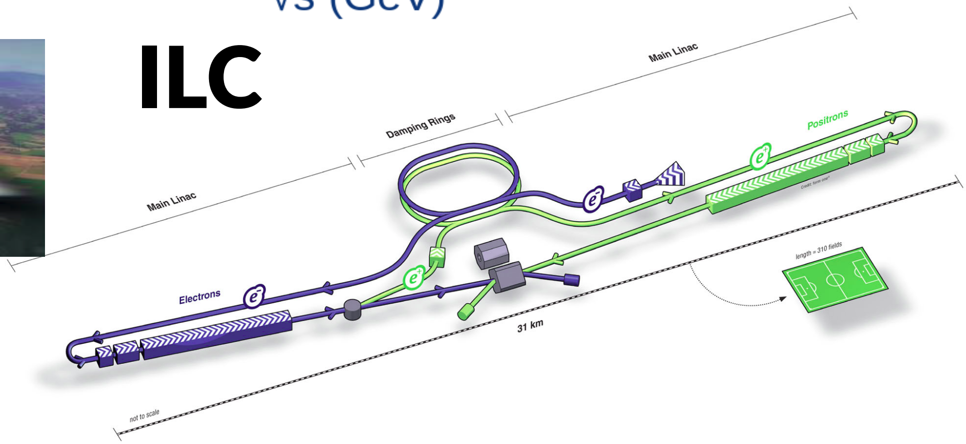
Lepton Colliders



FCC-ee



ILC

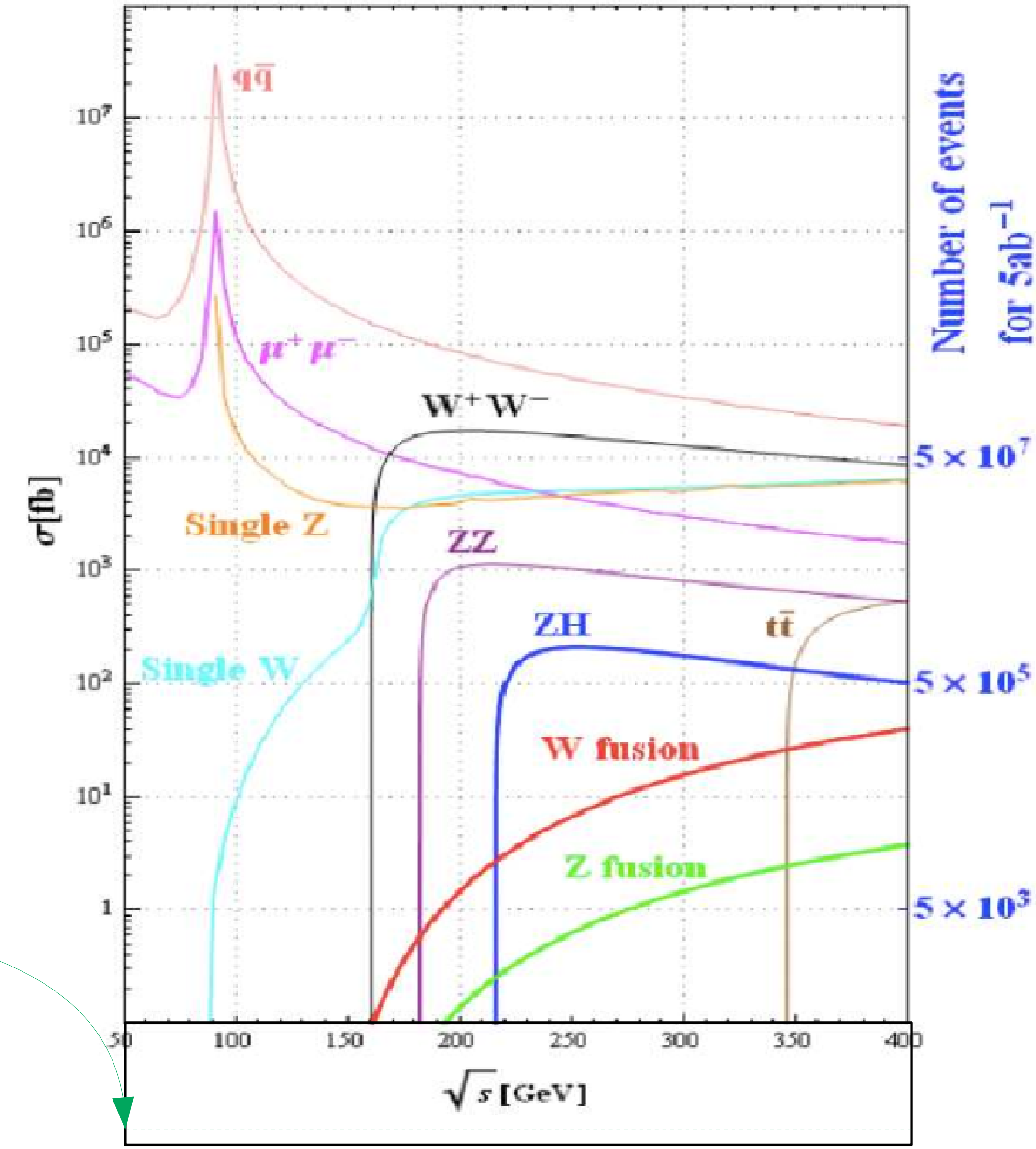


Lepton Colliders

- Different process that will provide clean data to probe new physics.

- What about the process $e^+e^- \to hh$?

  Cross section is too small. It is of order 10^{-2} fb.



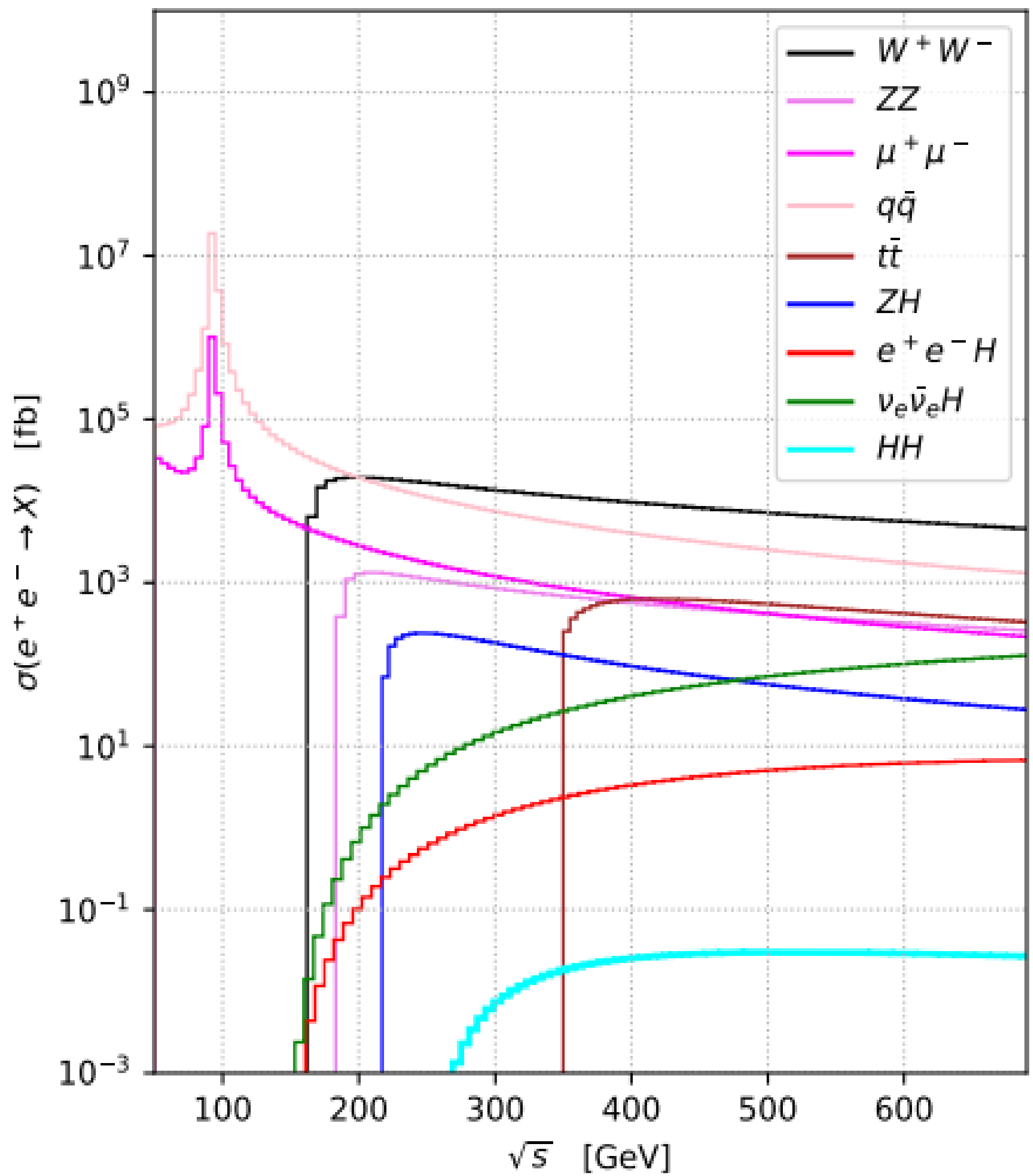
Lepton Colliders

- Different process that will provide clean data to probe new physics.

- What about the process $e^+e^- \to hh$?

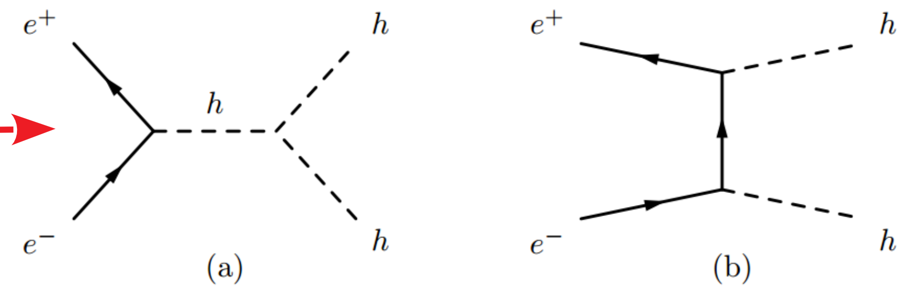
  Cross section is too small. It is of order 10^{-2} fb.

  Natural question: why is the cross section so small?

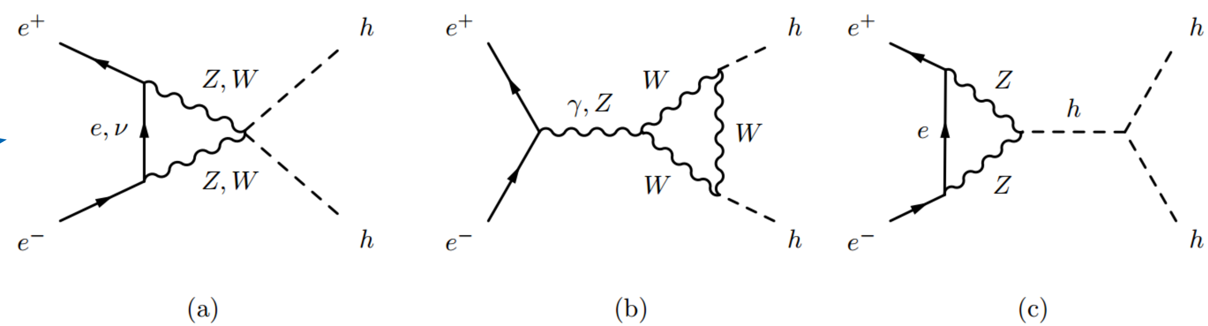


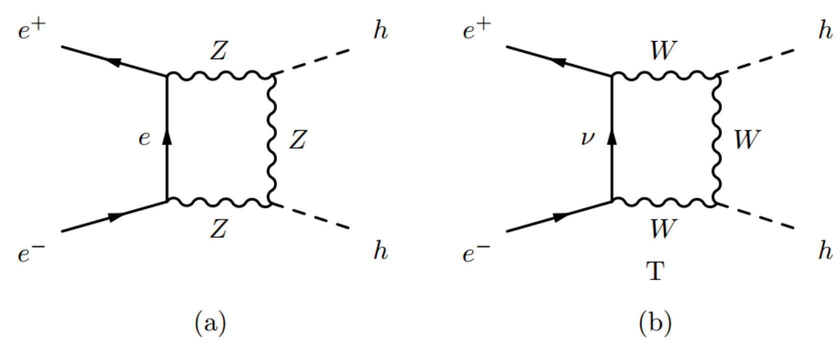
Di-Higgs in the SM

Tree Level diagrams suppressed being proportional to the electron mass



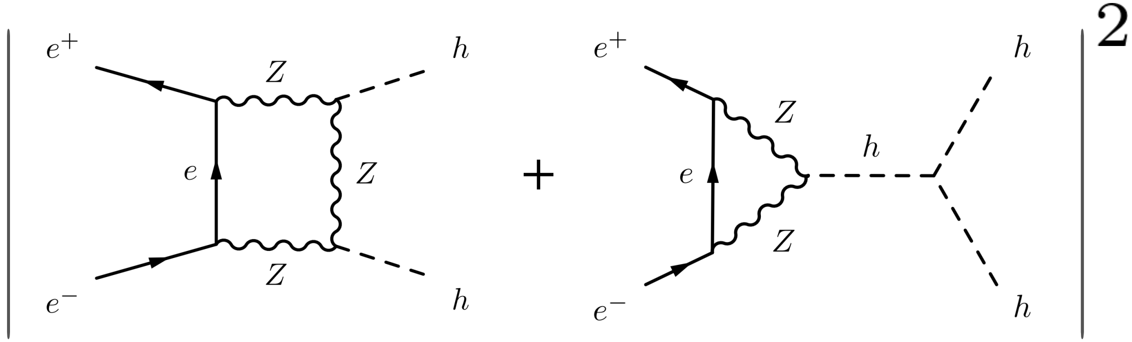
Do the boxes and triangles interfere?





Di-Higgs in the SM

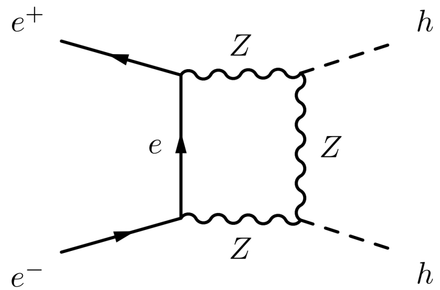
$$|\mathcal{M}|^2 \sim$$



Answer: NO

Di-Higgs in the SM

$|\mathcal{M}|^2 \sim \Bigg|$



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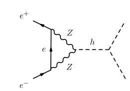
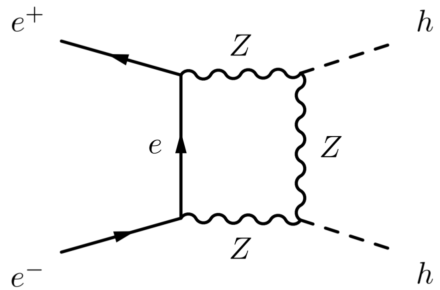


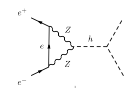
$\Bigg|^2$

Triangle diagrams are negligible.

Di-Higgs in the SM

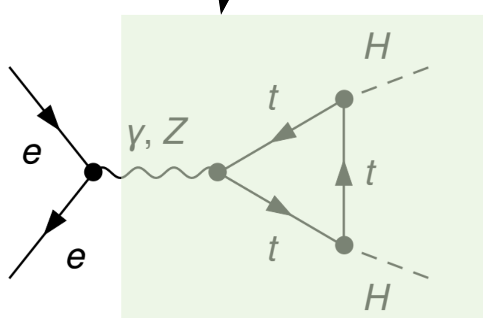
$$|\mathcal{M}|^2 \sim \left| \quad + \quad \right|^2$$

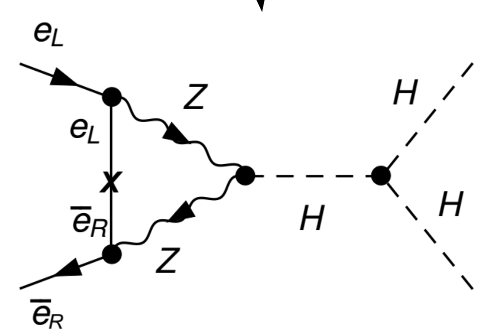




Triangle diagrams are negligible.

Two possible structures





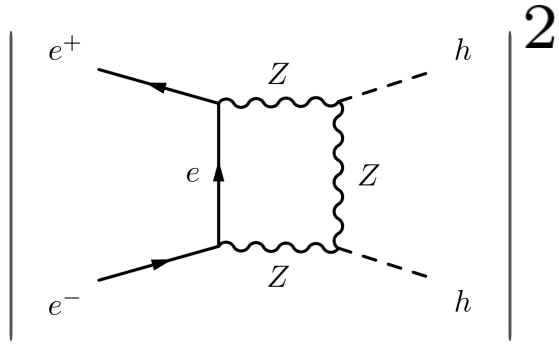
Parity violation: Vector boson = -1

Final state = +1

Mass insertion ~ m_e

Di-Higgs in the SM

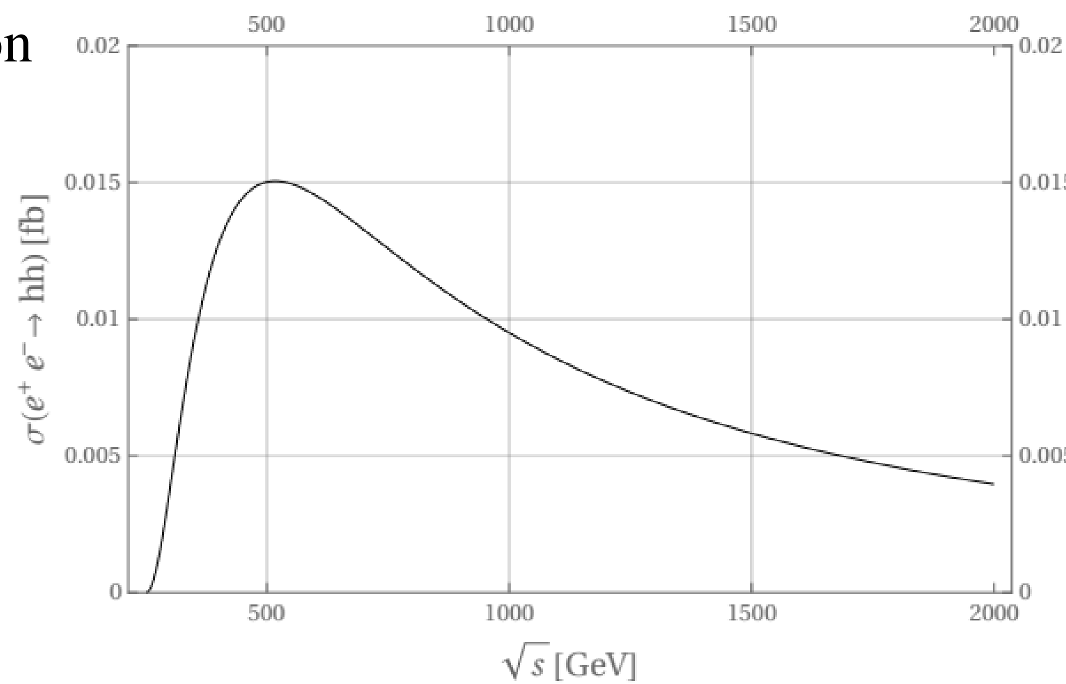
$|\mathcal{M}|^2 \sim$



In the end, the leading order is given just by 8 box-diagrams.

With the large luminosities at future lepton colliders, order one hundred of events might be collected in the course of few years.

Cross-section can be enhanced by BSM physics.



SM Effective Field Theory

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

We consider effects of new physics parametrized by the presence of higher dimensional operators in the SMEFT framework. We write the SMEFT lagrangian as

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)} + \dots$$

We focus on dimension-6 operators, and in particular we work in Warsaw basis.

[Grzadkowski et al., 2010]

Di-Higgs in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
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$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
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$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
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$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

A first class of dim-6 operators are those that modify the couplings eeZ , eνW , hZZ and hWW.

They are already well constrained from LEP and LHC data (Higgs decay measurement)

A first sensitivity study can safely neglect their contribution.

Di-Higgs in the SMEFT

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
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Table 2: Dimension-six operators other than the four-fermion ones.

A second class of dim-6 operators are those that introduce a direct coupling between ee and hh.

Tree-Level contribution.

A first class of dim-6 operators are those that modify the couplings eeZ , eνW , hZZ and hWW.

They are already well constrained from LEP and LHC data (Higgs decay measurement)

A first sensitivity study can safely neglect their contribution.

Di-Higgs in the SMEFT

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Table 3: Four-fermion operators.

A third class of dim-6 operators are those that introduce a direct coupling beween ee and ttbar.

1-Loop contributions proportional to the top mass

Di-Higgs in the SMEFT

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
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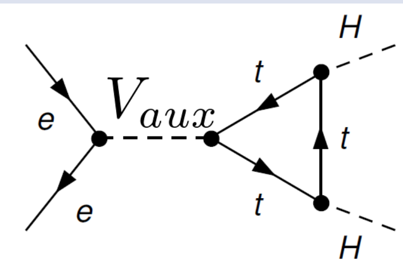
A third class of dim-6 operators are those that introduce a direct coupling beween ee and ttbar.

1-Loop contributions proportional to the top mass

Almost all of the seven operators give zero contribution due to spinor structures or Parity

Just one operator survives.



Di-Higgs in the SMEFT

	$\psi^2\varphi^3$
$\boxed{Q_{e\varphi}}$	$\boxed{(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)}$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$

$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$\boxed{Q_{lequ}^{(1)}}$	$\boxed{(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)}$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$$\mathcal{L} = \frac{c_{e\varphi}}{\Lambda^2}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{l}_L\varphi e_R + \frac{c_{et}}{\Lambda^2}\epsilon_{ij}\left(\bar{l}_L^i e_R\right)\left(\bar{q}_L^j t_R\right)$$

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	$\psi^2\varphi^3$
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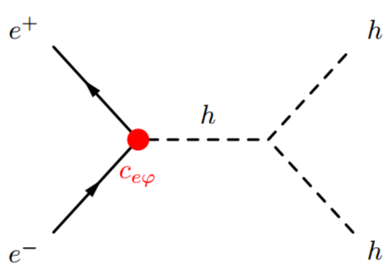

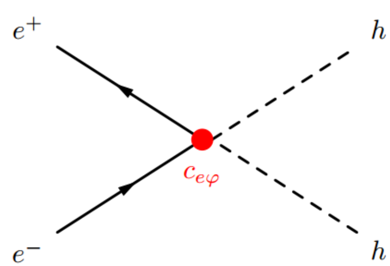

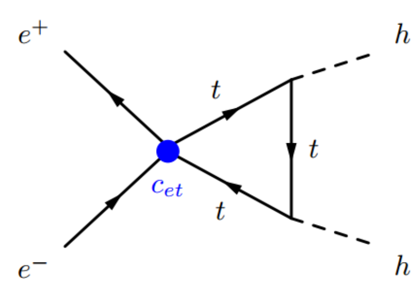

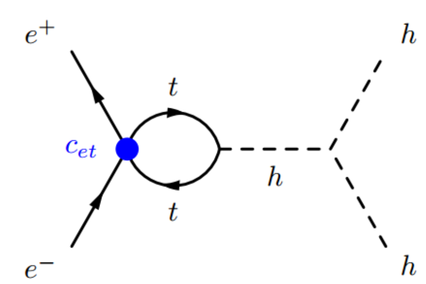

Di-Higgs in the SMEFT

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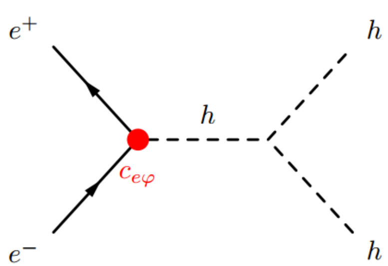
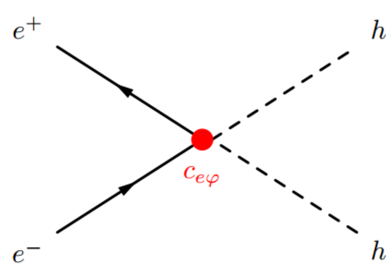
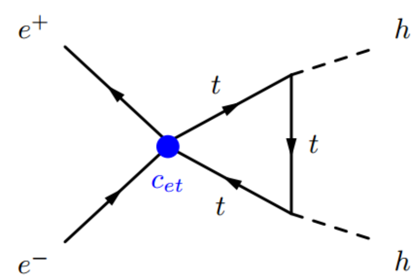
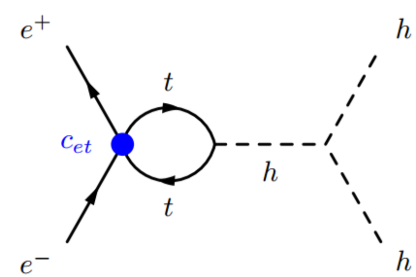
Redefinition to keep the tree-level SM relation $m_e = y_e \frac{v}{\sqrt{2}}$



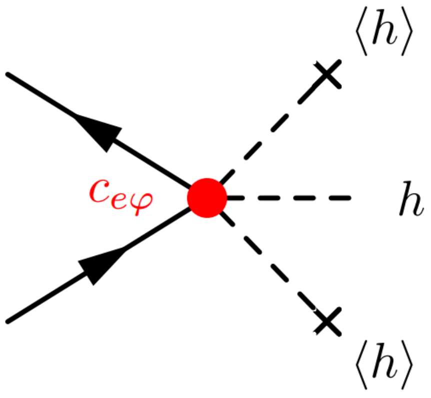






Di-Higgs in the SMEFT

- The electron-Higgs interaction gets modifications
  - At tree level from the operator $\mathcal{O}_{e\varphi}$



Di-Higgs in the SMEFT

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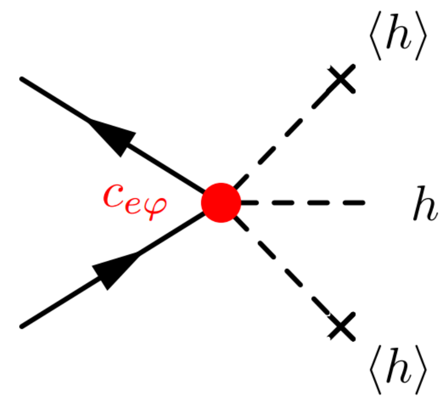
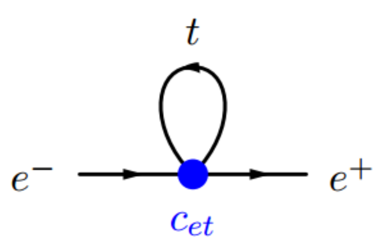


  - At tree level from the operator $\mathcal{O}_{e\varphi}$
  - At loop level from the operator $\mathcal{O}_{et}$



$$= \quad -i\Sigma_e \quad = \quad -i\frac{6}{(4\pi)^2}\frac{c_{et}}{\Lambda^2}m_t^3\left(1+\frac{1}{\bar{\epsilon}}+\log\frac{\mu^2}{m_t^2}\right)$$

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- The electron-Higgs interaction gets modifications
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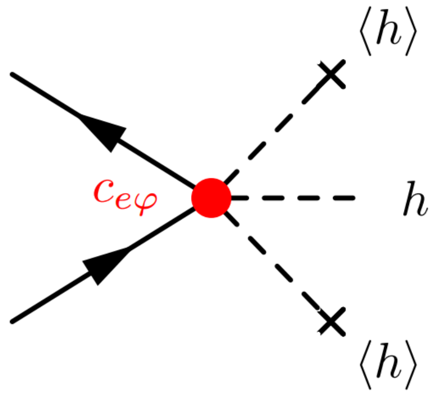
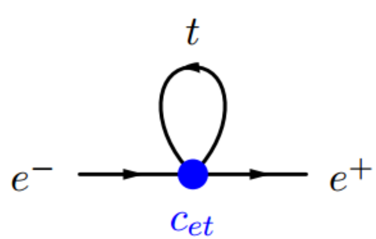




$$= \quad -i\Sigma_e \quad = \quad -i\frac{6}{(4\pi)^2}\frac{c_{et}}{\Lambda^2}m_t^3\left(1+\frac{1}{\bar{\epsilon}}+\log\frac{\mu^2}{m_t^2}\right)$$

Tree-level diagrams in SMEFT are computed with the new Yukawa coupling

$$-\frac{m_e}{v} \to -\frac{m_e}{v} + \frac{c_{e\varphi}v^2}{\Lambda^2\sqrt{2}} - \frac{6}{(4\pi)^2}\frac{c_{et}}{\Lambda^2}\frac{m_t^3}{v}\left(1+\log\frac{\mu^2}{m_t^2}\right)$$

Analysis Setup

- We compute the cross-section as a function of $\sqrt{s}$ and of the Wilson coefficient $c_{e\varphi}$ and c_{et}, such that

$$\sigma^{SMEFT}\left(\sqrt{s}, \frac{c_{e\varphi}}{\Lambda^2}, \frac{c_{et}}{\Lambda^2}\right) \sim \mathcal{O}\left(c_{e\varphi}^2\right) + \mathcal{O}\left(c_{e\varphi}c_{et}\right) + \mathcal{O}\left(c_{et}^2\right).$$

- The exclusion regions are computed through a χ^2- distribution analysis

$$\chi^2\left(\sqrt{s}, \frac{c_{e\varphi}}{\Lambda^2}, \frac{c_{et}}{\Lambda^2}\right) = \frac{\left[\sigma^{SMEFT}\left(\sqrt{s}, \frac{c_{e\varphi}}{\Lambda^2}, \frac{c_{et}}{\Lambda^2}\right) - \sigma^{SM}\left(\sqrt{s}\right)\right]^2}{\delta\sigma^2},$$

where the uncertainty is $\delta\sigma^2 = \delta\sigma_{stat}^2 + \delta\sigma_{sys}^2$

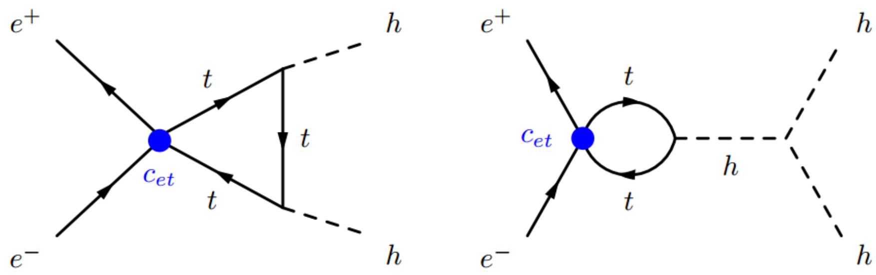
$$\delta\sigma_{stat} = \sqrt{\sigma^{SM}/L} \qquad \delta\sigma_{sys} = \alpha\sigma^{SM} \quad (\alpha = 0.1)$$

- The computations were done using `FeynRules`, `FeynArts` + `FormCalc` + `LoopTools` and cross-check with `NLOCT` and `MG5_aMC@NLO`

Di-Higgs in the SMEFT

- The SMEFT is renormalizable order by order, we have to take care of the divergences

Divergent diagrams involving effective operators



Di-Higgs in the SMEFT

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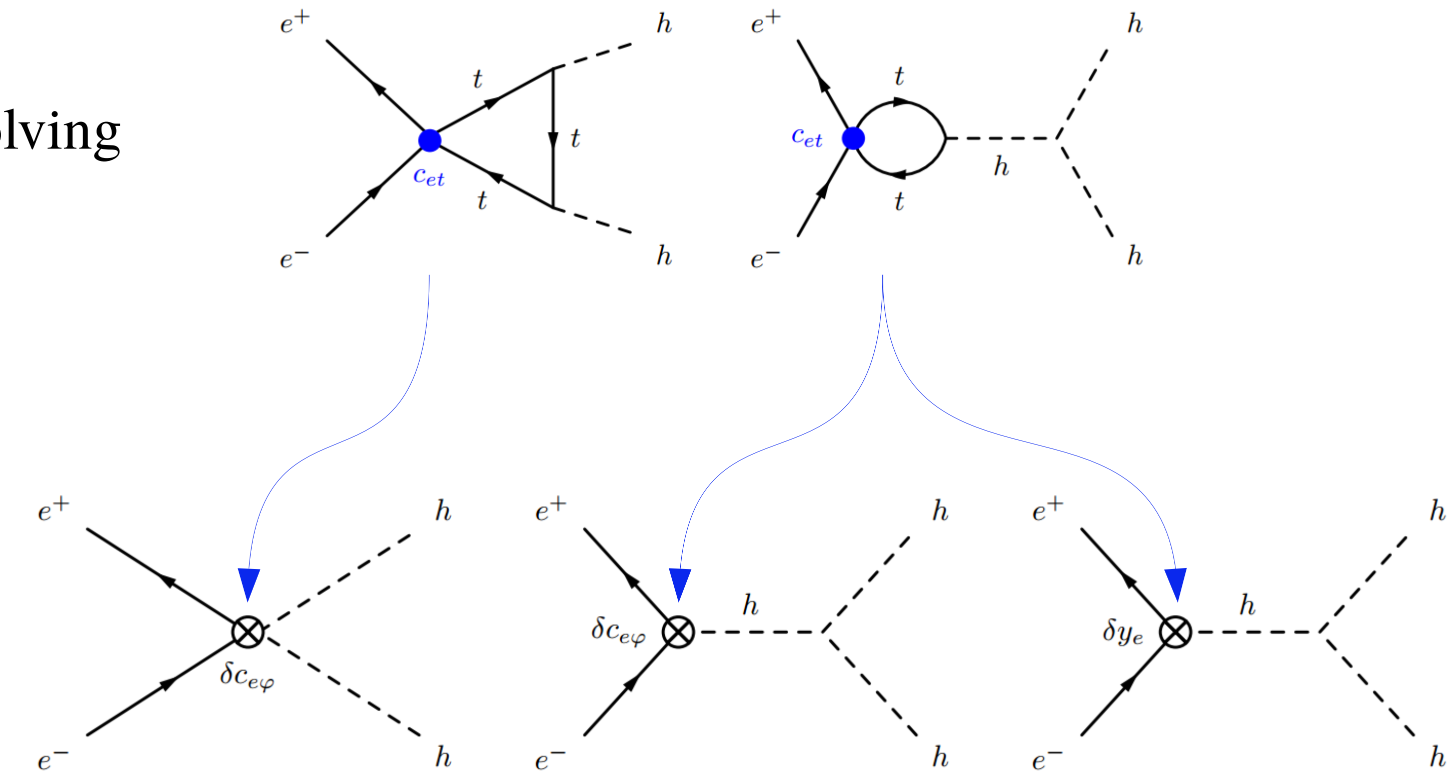
Divergent diagrams involving effective operators

The operator that modifies the Yukawa coupling provides the counter-term for the top-loops



$$\delta c_{e\varphi} = \frac{6}{(4\pi)^2} c_{et} y_t \left(y_t^2 - \lambda\right) \frac{1}{\bar{\epsilon}}$$

$$\delta y_e = -\frac{3}{(4\pi)^2} c_{et} v^2 y_t^3 \frac{1}{\bar{\epsilon}}$$

Benchmark Scenarios & Results

- Benchmark scenarios considered in our analysis.

Benchmark	Experiment	$\sqrt{s}$ (GeV)	L (ab^{-1})	$\|c_{e\varphi}/\Lambda^2\|(\mathrm{TeV}^{-2})$	$\|c_{et}/\Lambda^2\|(\mathrm{TeV}^{-2})$
1	FCC-ee	350	2.6	$< 0.003 \quad (< 0.004)$	$< 0.116 \quad (< 0.146)$
2	CLIC	380	0.5	$< 0.004 \quad (< 0.006)$	$< 0.143 \quad (< 0.184)$
3	ILC	500	4	$< 0.003 \quad (< 0.004)$	$< 0.068 \quad (< 0.083)$
4	CLIC	1500	1.5	$< 0.003 \quad (< 0.003)$	$< 0.027 \quad (< 0.035)$
5	CLIC	3000	3.0	$< 0.002 \quad (< 0.002)$	$< 0.012 \quad (< 0.015)$

- The last two columns represent the 95 % CL intervals for each operator coefficient taken individually in the analysis with k = 1 (k = 0.35).

$$k = \mathrm{BR}(h \to f_1 \bar{f}_1) \times \mathrm{BR}(h \to f_2 \bar{f}_2)$$

k factor keeps track of the Branching Ratio (k=0.35 just $b\bar{b}$ decay)

Results

Benchmark	Experiment	$\sqrt{s}$ (GeV)	L (ab^{-1})
1	FCC-ee	350	2.6
2	CLIC	380	0.5
3	ILC	500	4
4	CLIC	1500	1.5
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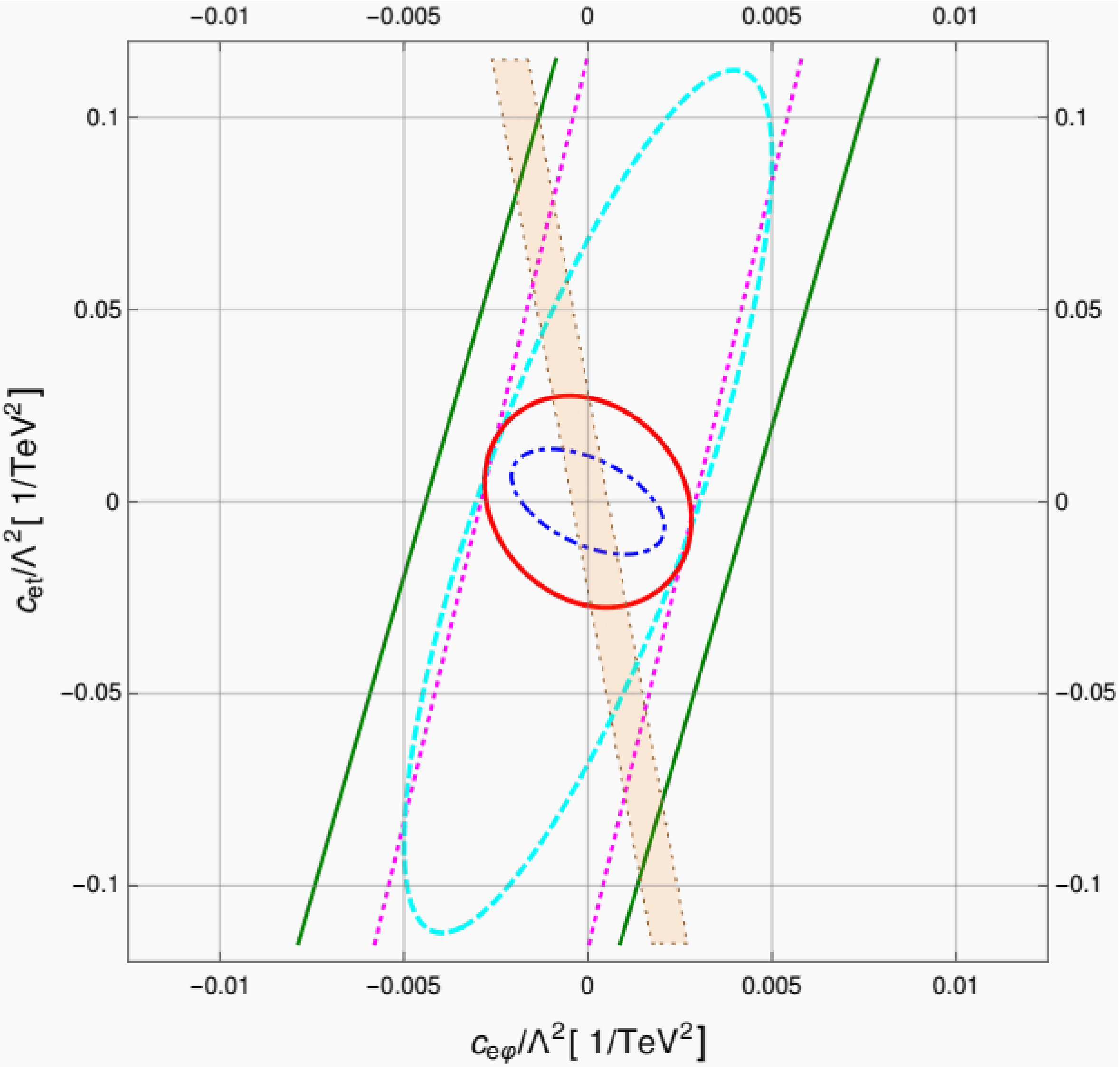


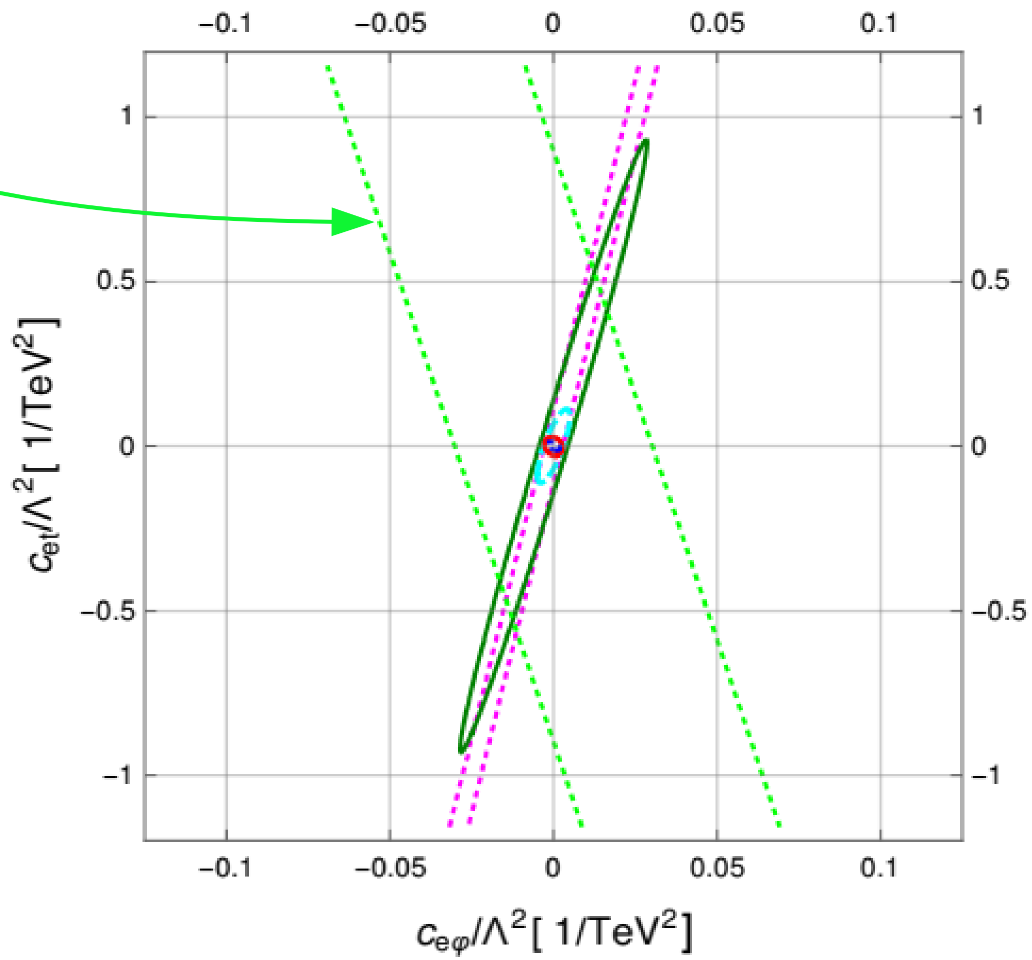
Bounds for 95% C.L. with k = 1

Other possible bounds

$$\left|-\frac{m_e}{v}+\frac{c_{e\varphi}(\mu)v^2}{\Lambda^2\sqrt{2}}-\frac{3}{(4\pi)^2}\frac{y_t}{\sqrt{2}}\frac{c_{et}}{\Lambda^2}(4m_t^2-m_h^2)\left[f(m_h^2,m_t^2)+\log\frac{\mu^2}{m_t^2}\right]\right|\lesssim 600\frac{m_e}{v}$$

After considering all contributions to the eeh-vertex, the recent upper bound on the electron Yukawa coupling obtained from Higgs decay.

[Altmannshofer, Brod & Schmaltz, 2015]



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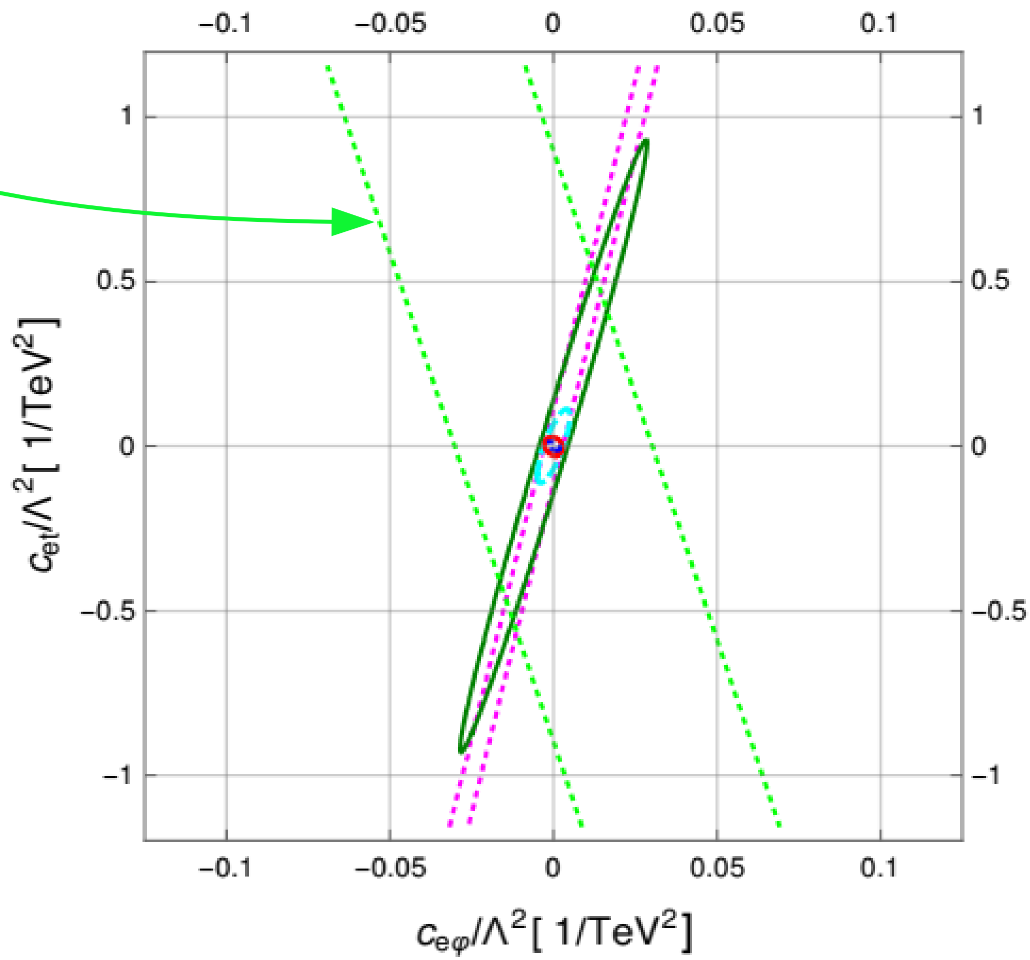

The correction to the electron mass may introduce a fine tuning problem and in order to avoid it one must require that

$$|\delta m_e| \leq m_e$$

In this case we have that

$$\left|\frac{c_{et}}{\Lambda^2}\right| \lesssim \frac{8\pi^2}{3}\frac{m_e}{m_t^3} \simeq 2\times 10^{-3}\mathrm{TeV}^{-2}$$

Other possible bounds

$$\left|-\frac{m_e}{v}+\frac{c_{e\varphi}(\mu)v^2}{\Lambda^2\sqrt{2}}-\frac{3}{(4\pi)^2}\frac{y_t}{\sqrt{2}}\frac{c_{et}}{\Lambda^2}(4m_t^2-m_h^2)\left[f(m_h^2,m_t^2)+\log\frac{\mu^2}{m_t^2}\right]\right|\lesssim 600\frac{m_e}{v}$$

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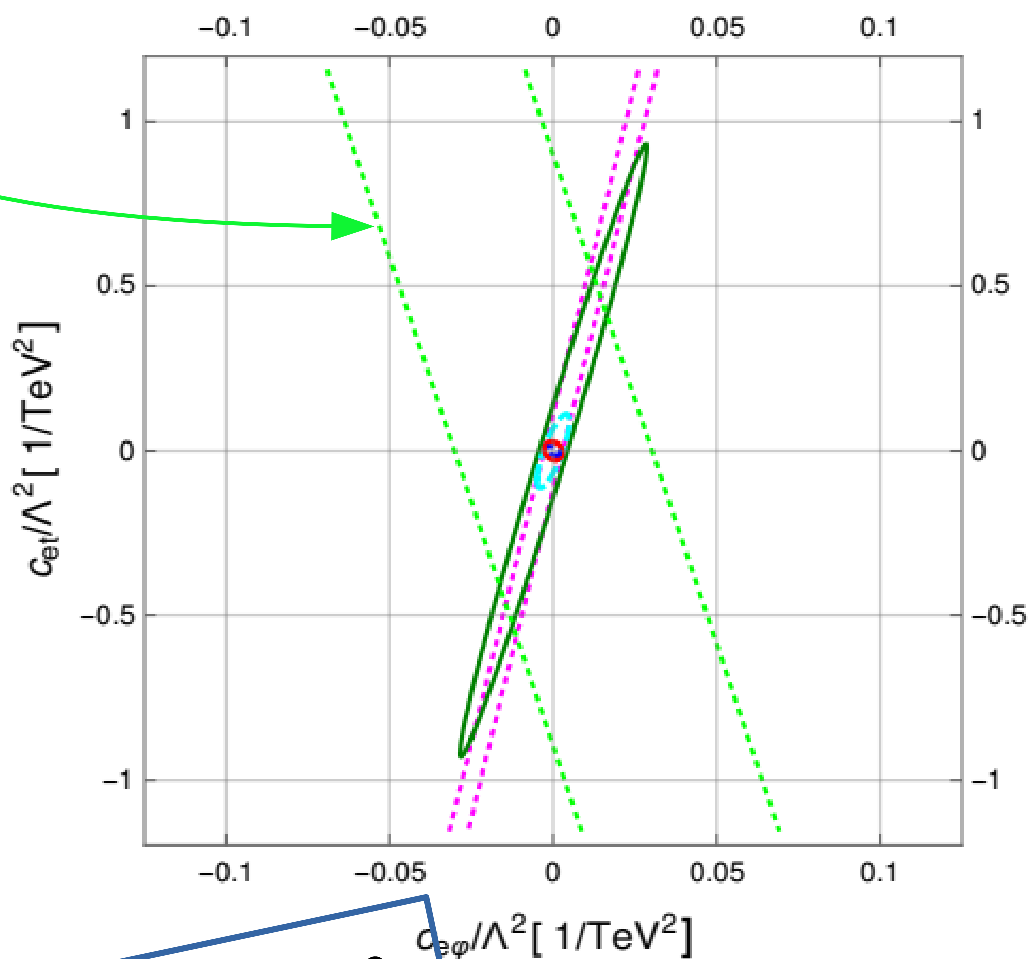

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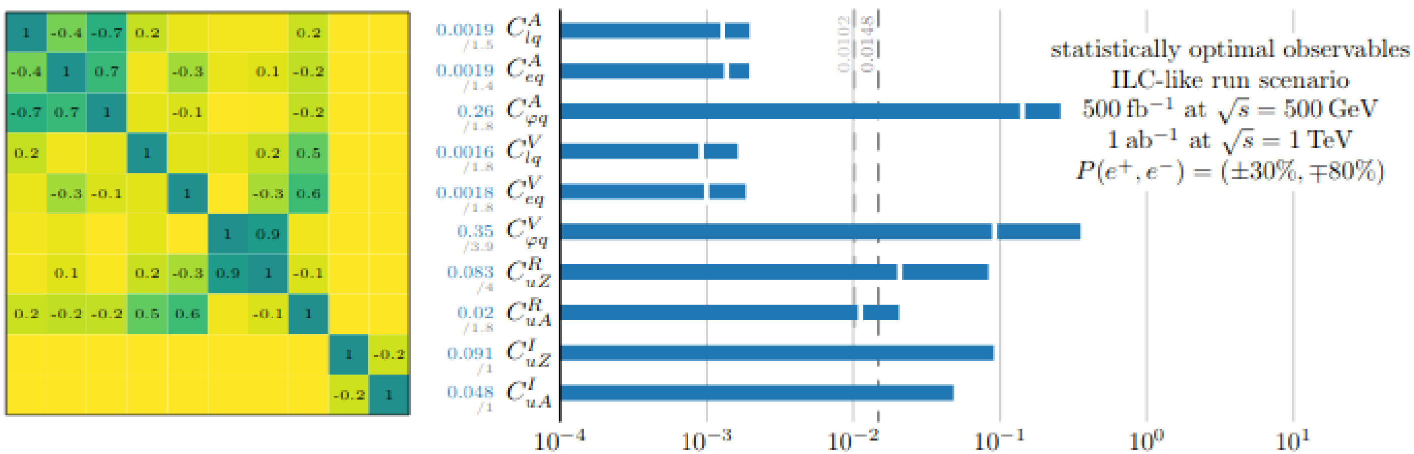
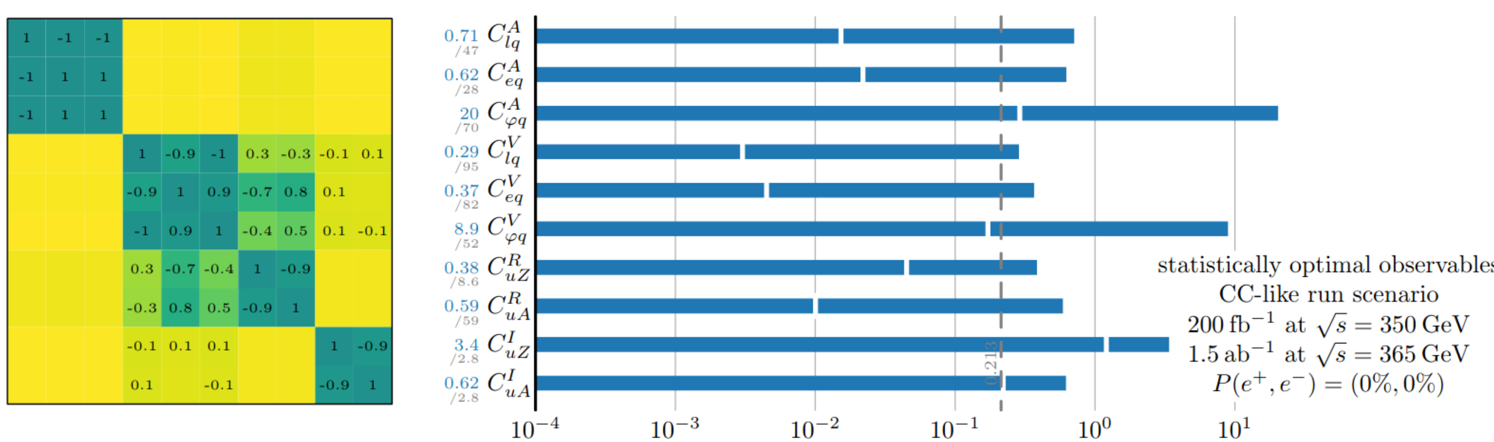
Fine tuning is a guidance.

Other possible bounds

More stringent bounds are found in the $e^+e^- \to t\bar{t}$ process for the coefficient c_{et}: order 10^{-3}TeV^{-2}

[Durieux, Perello, Vos & Zhang, 2018]





Summary

- Double Higgs production at future e+e− colliders offers the possibility to explore sensitivity to dim-6 operators involving electrons which have not been constrained yet.

- This process presents a small SM cross section, which could be useful in the clean environment of lepton accelerators for finding NP.

- We derived 95% bounds on $c_{e\varphi}$ and c_{et} for several benchmark set ups in future colliders, finding that the bounds on c_{et} probe scales of O(10 TeV) while the $c_{e\varphi}$ operator probes scales of O(1 TeV).