New Physics in double Higgs production at future e+e− colliders

Andres Vasquez

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

Higgs and Effective Field Theory
Louvain-la-Neuve, Belgium

HEFT 2019
Higgs and Effective Field Theory

Goals

- Study effects of New Physics parametrized by SM dimension-six operators in $e^+e^- \to h\,h$ at future lepton colliders

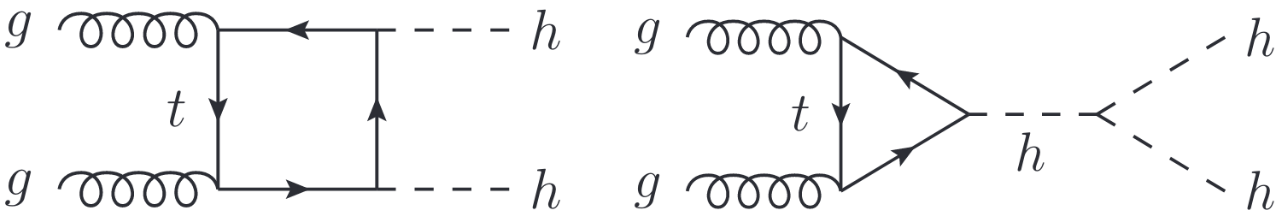
- Perform sensitivity study for several benchmark values of energy and integrated luminosity

Motivation

In the SM, the process $gg \to hh$ (Plehn, Spira & Zerwas, 1996) present interference between boxes and triangle topologies: the closer one gets to the threshold, the stronger the cancellation. (Li & Voloshin, 2013)

Small cross-section

Sensitive to New Physics effects

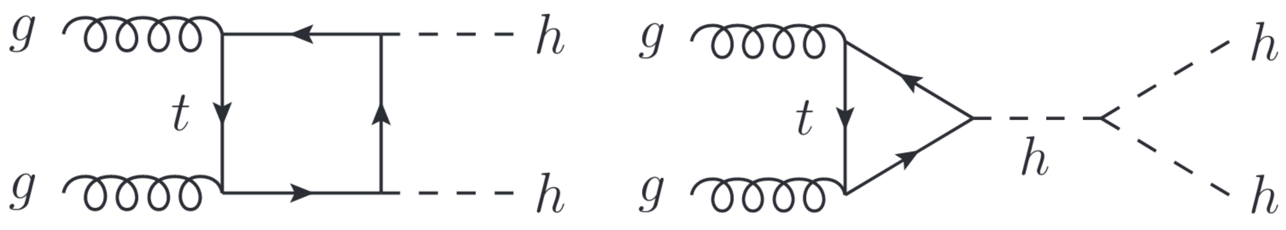


Motivation

In the SM, the process $gg \to hh$ (Plehn, Spira & Zerwas, 1996) present interference between boxes and triangle topologies: the closer one gets to the threshold, the stronger the cancellation. (Li & Voloshin, 2013)

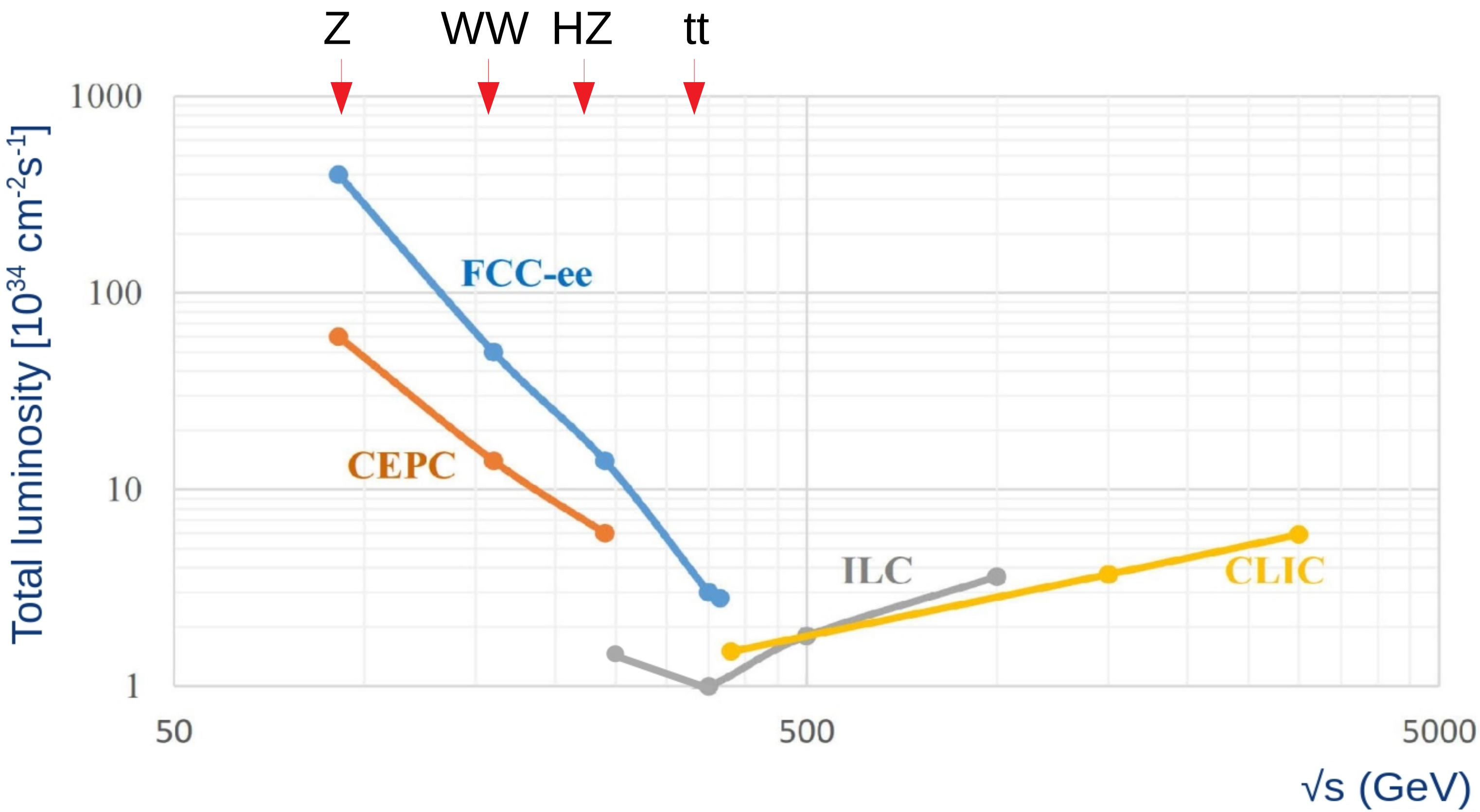
Small cross-section

Sensitive to New Physics effects



Does the process $e^+e^- \to hh$ show a similar behavior to the interference in production of di-Higgs through gluon fusion?

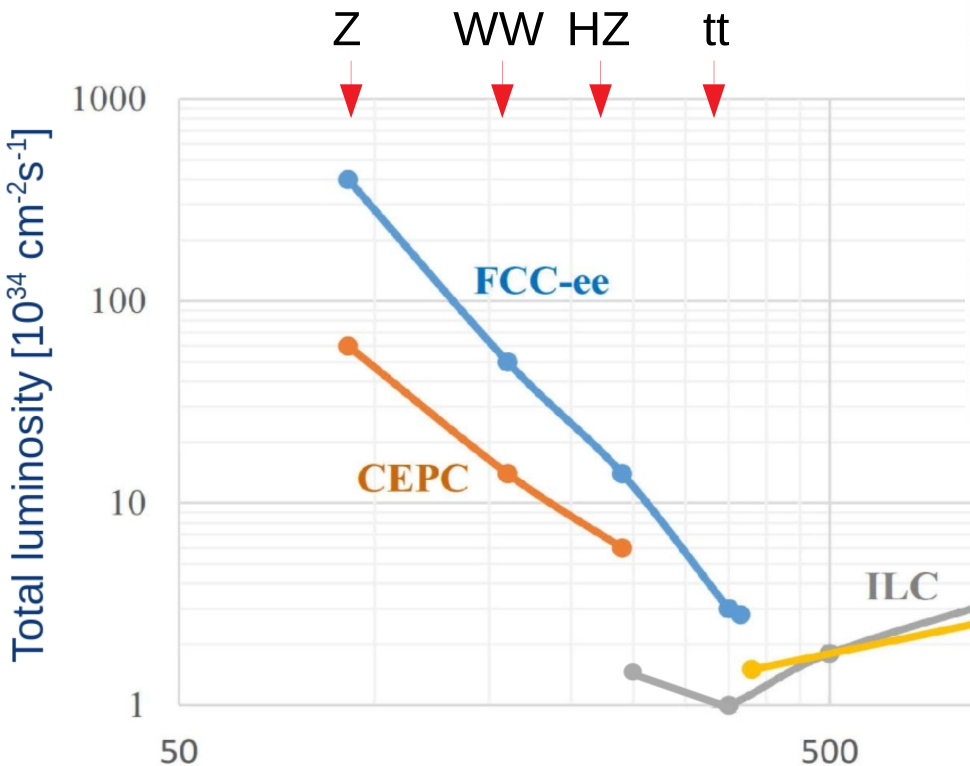
Lepton Colliders

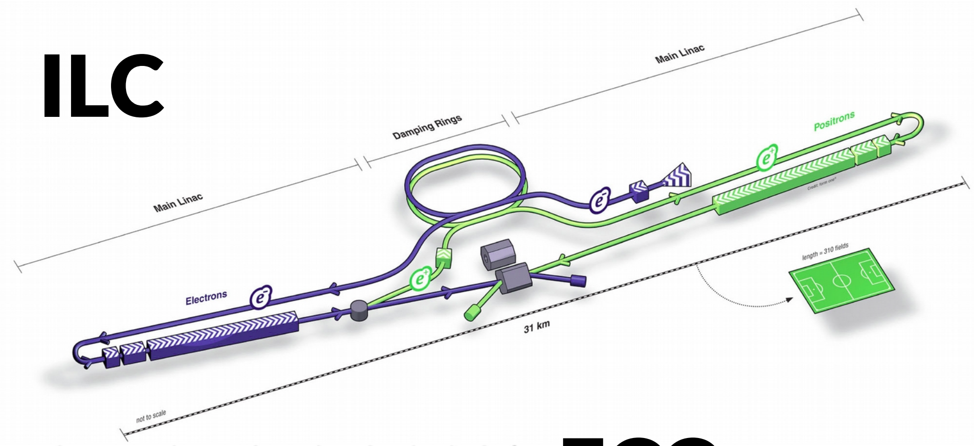


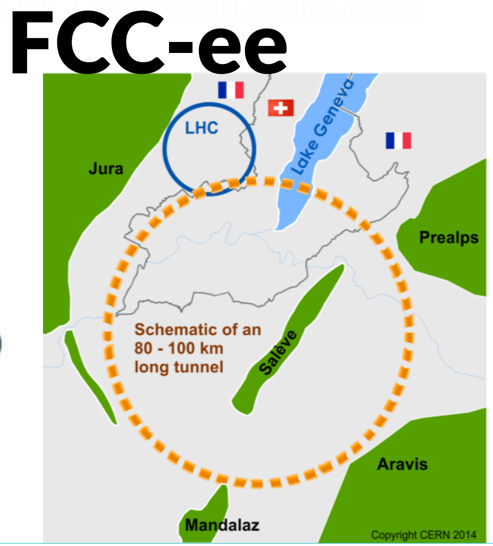
(Giacomelli, 2018 EOS Solstice meeting)

Higher luminosities for circular colliders than for linear. Linear colliders reach higher energies.

Lepton Colliders

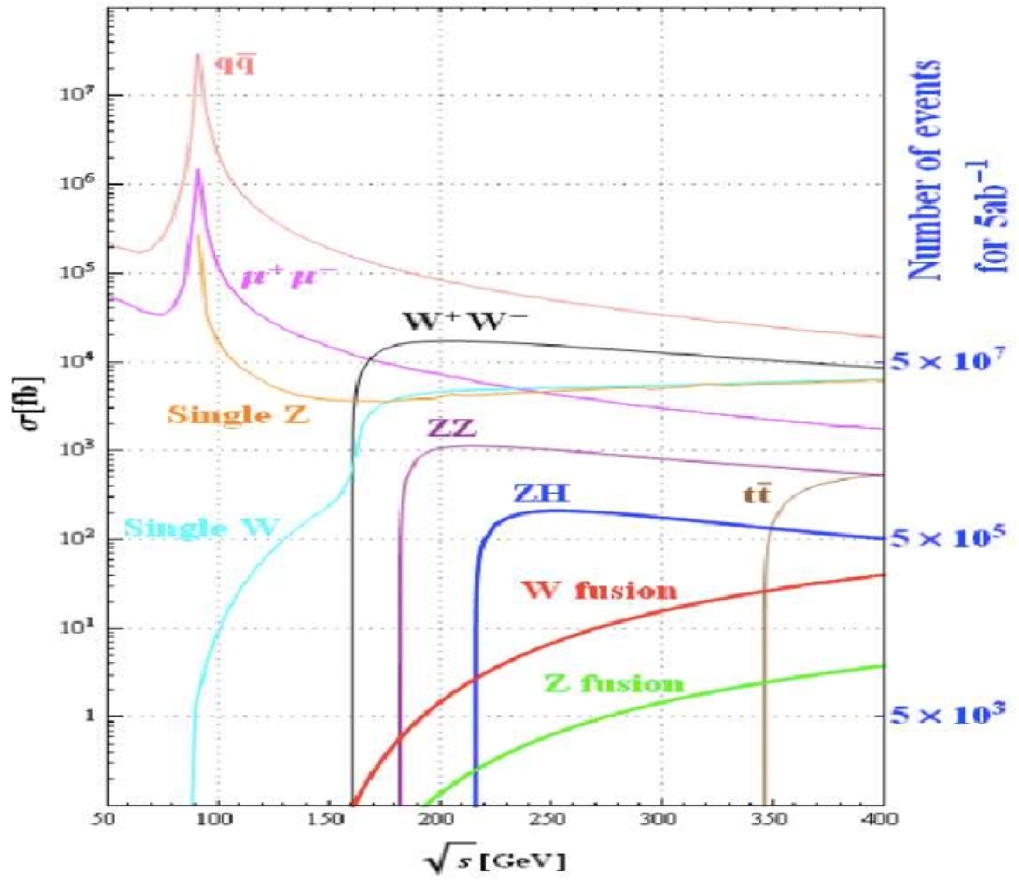






Lepton Colliders

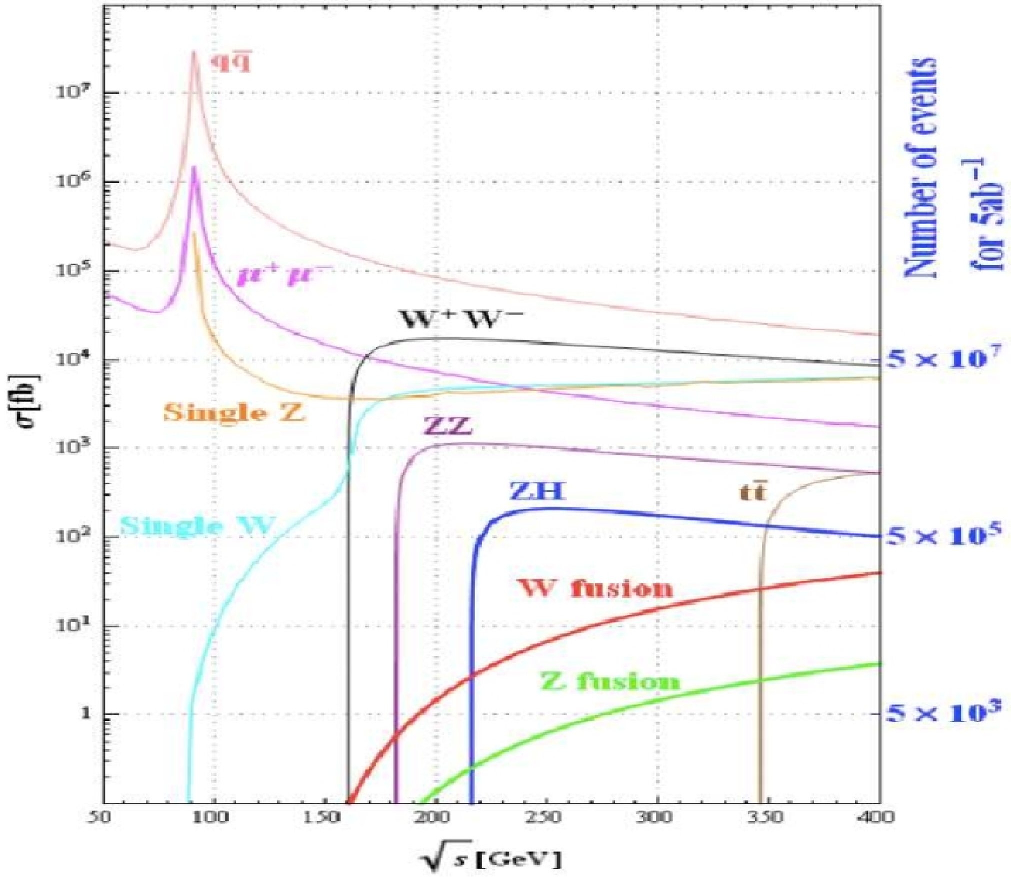
Different process that will provide clean data to probe new physics.



Lepton Colliders

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

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



Lepton Colliders

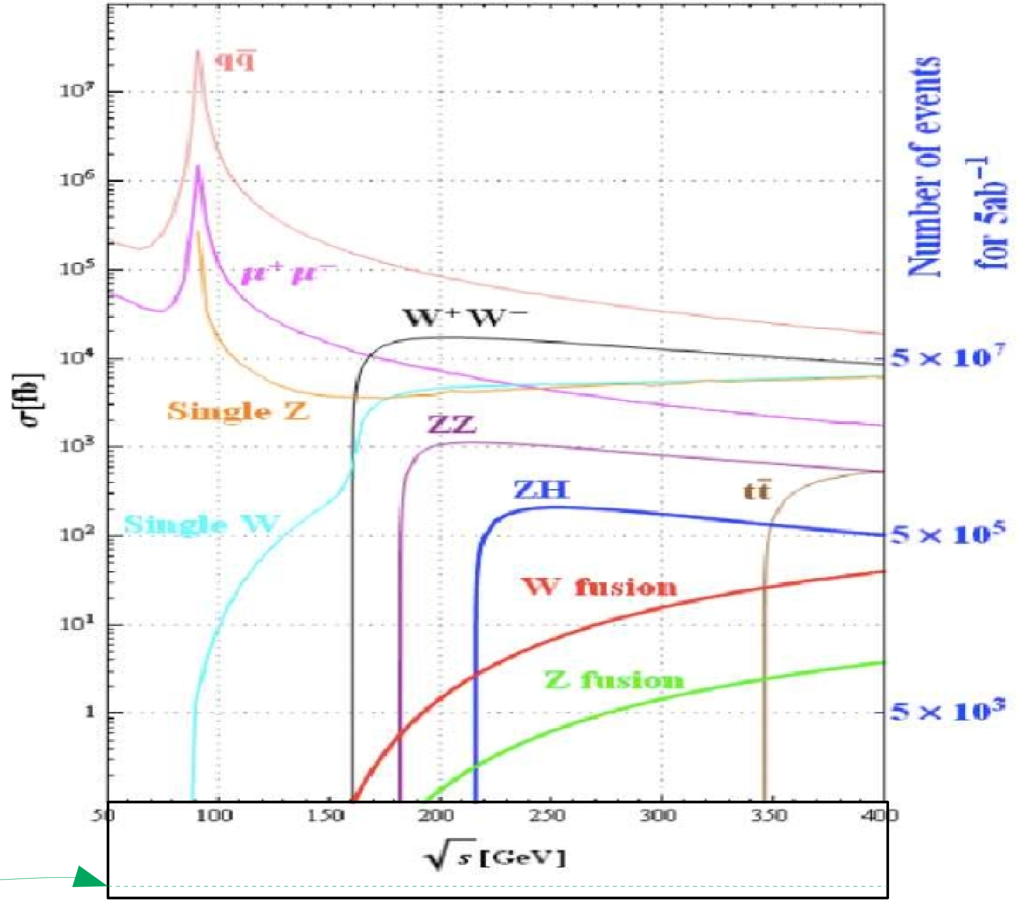
Different process that will provide clean data to probe new physics.

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

Cross-section too small,
doesn’t even appear in the plot.

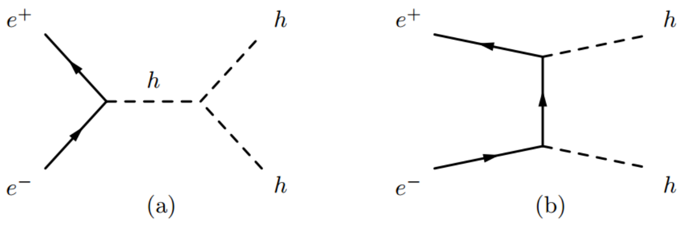
It is of order 10^{-2} fb

Why is it too small?



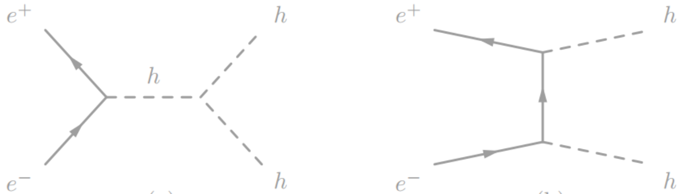
Standard Model Process

Tree Level diagrams suppressed being proportional to the electron mass



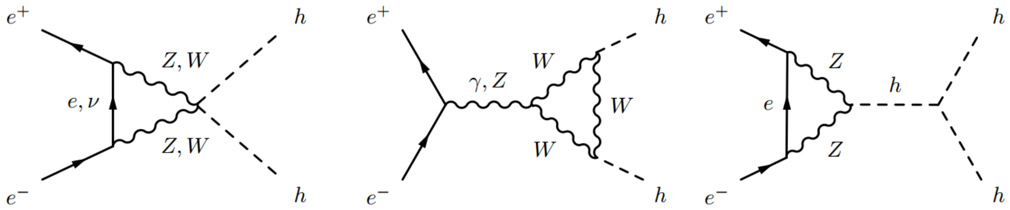
Standard Model Process

Tree Level diagrams suppressed being proportional to the electron mass

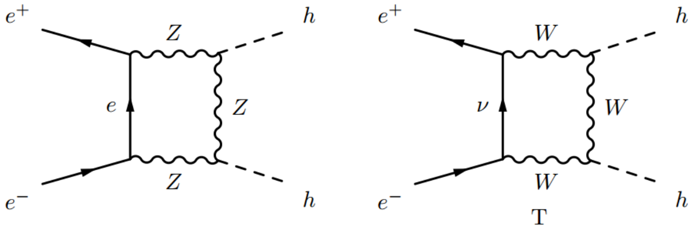


(a) (b)

The leading order is at 1-loop.



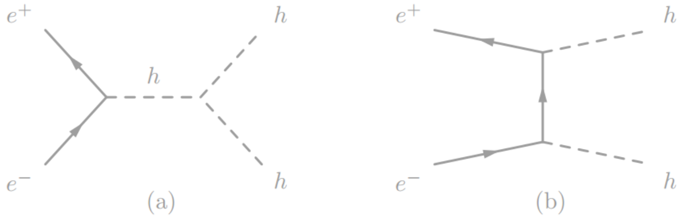
(a) (b) (c)



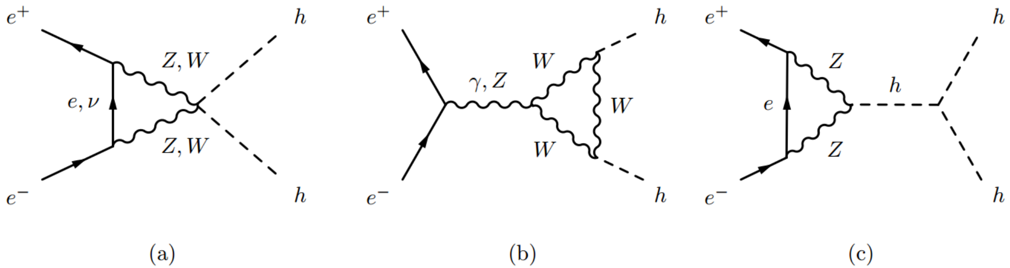
(a) (b)

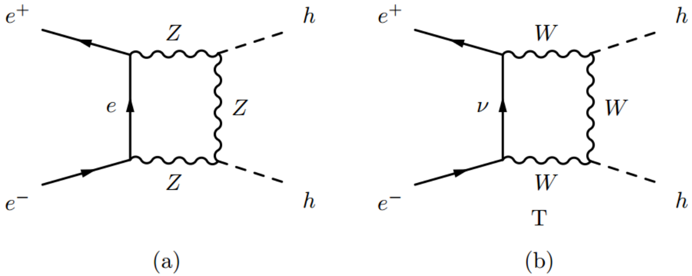
Standard Model Process

Tree Level diagrams suppressed being proportional to the electron mass



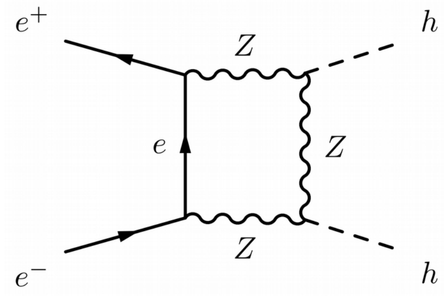
Do the boxes and triangles interfere?



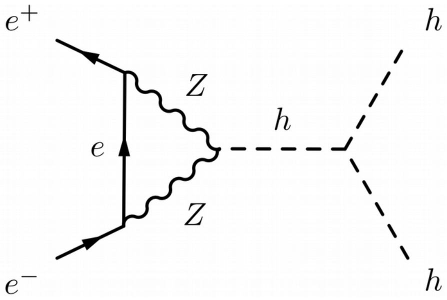


Standard Model Process

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



$+$

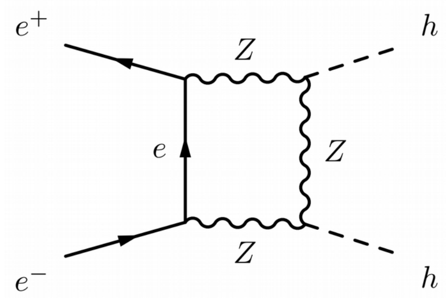


$\Bigg|^2$

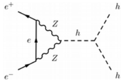
Answer: NO

Standard Model Process

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



$+$

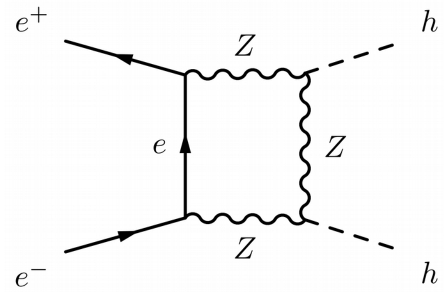


$$\Bigg|^2$$

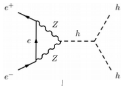
Triangle diagrams are negligible.

Standard Model Process

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



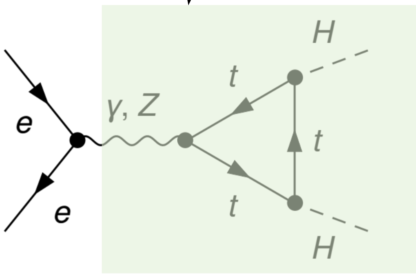
+



$$\Bigg|^2$$

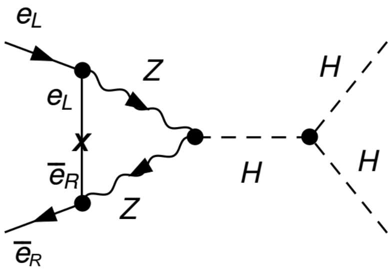
Triangle diagrams are negligible.

Two possible structures



Parity violation: Vector boson = -1

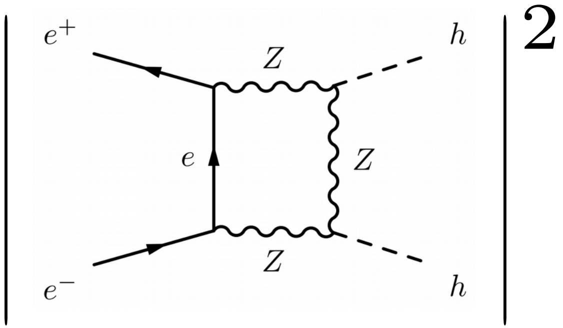
Final state = +1



Mass insertion ~ m_e

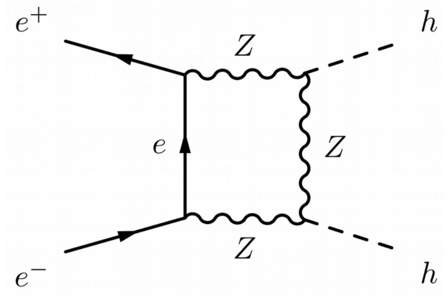
Standard Model Process

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



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

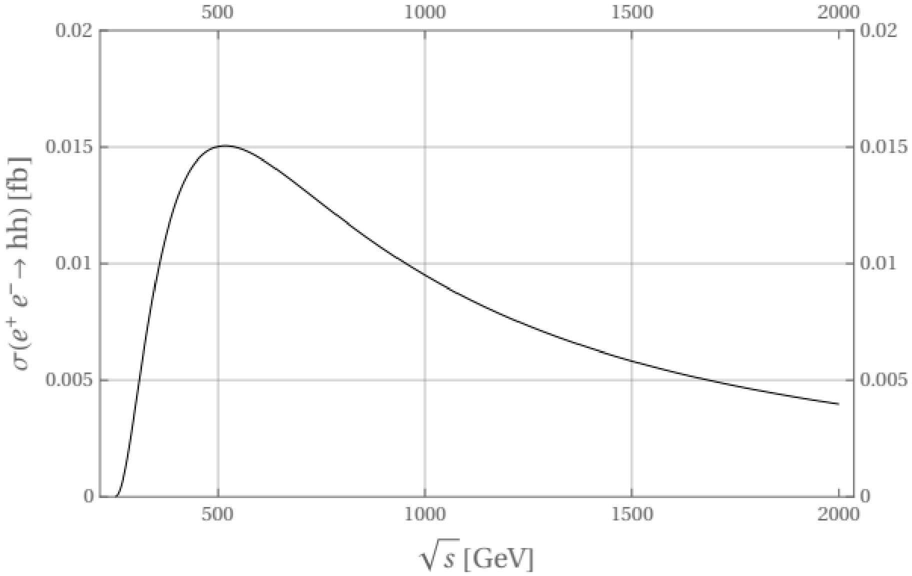
Standard Model Process

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

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-EFT

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	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.

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)

The process in the SM-EFT

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.

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.

The process in the SM-EFT

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.

A second class of dim-6 operators are those that introduce a direct coupling beween 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.

The process in the SM-EFT

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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

The process in the SM-EFT

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

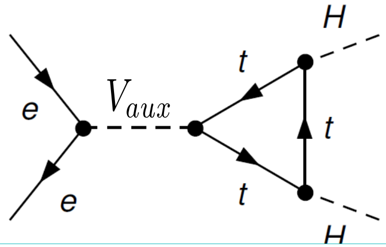
Table 3: Four-fermion operators.

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

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

Just one operator survives.



The process in the SM-EFT

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

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

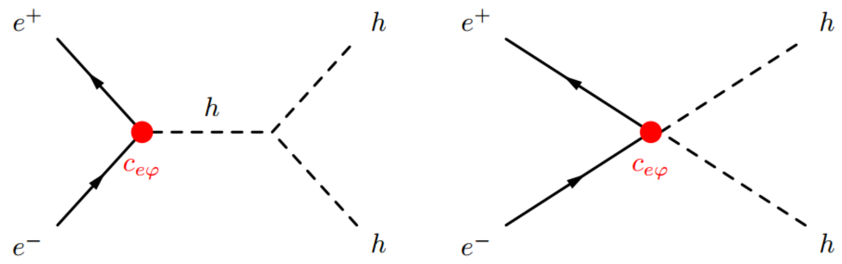
$$\mathcal{L} = \frac{c_{e\varphi}}{\Lambda^2}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{l}_L\varphi e_R + \frac{c_{et}}{\Lambda^2}\epsilon_{ij}\left(\bar{l}_L^i e_R\right)\left(\bar{q}_L^j t_R\right)$$

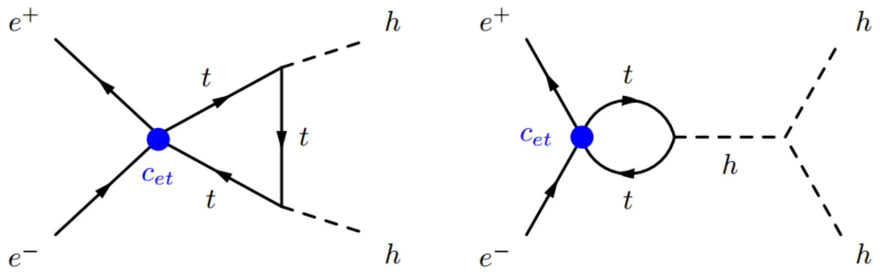
The process in the SM-EFT

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

$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$

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





The process in the SM-EFT

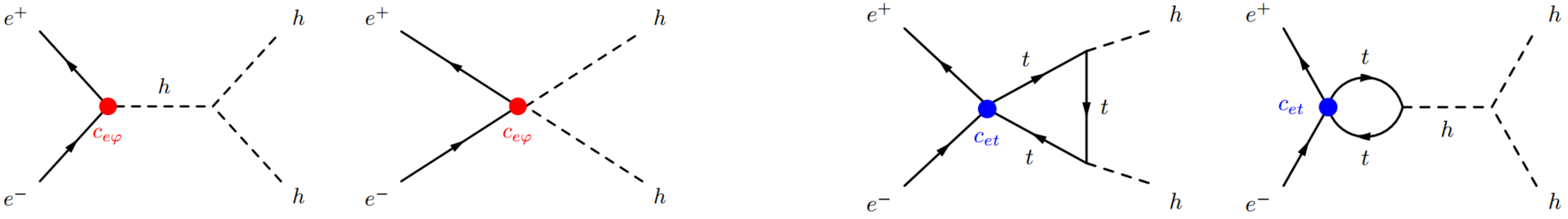
	$\psi^2\varphi^3$
$Q_{e\varphi}$	$\boxed{(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)}$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$

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

Redefinition to keep
the tree-level SM relation

$$m_e = y_e \frac{v}{\sqrt{2}}$$

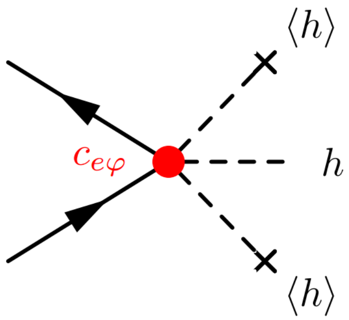
$$\mathcal{L} = \frac{c_{e\varphi}}{\Lambda^2}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)\bar{l}_L \varphi e_R + \frac{c_{et}}{\Lambda^2}\epsilon_{ij}\left(\bar{l}^i_L e_R\right)\left(\bar{q}^j_L t_R\right)$$



The process in the SM-EFT

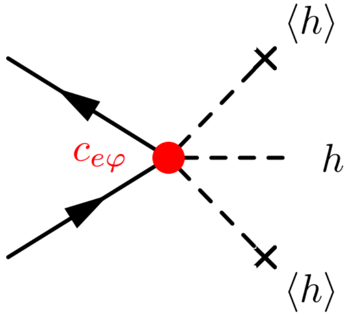
The electron-Higgs interaction gets modifications

at tree level from the operator $\mathcal{O}_{e\varphi}$



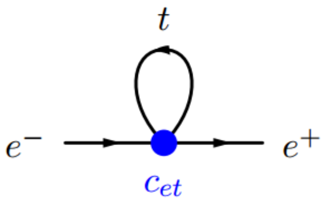
The process in the SM-EFT

The electron-Higgs interaction
gets modifications



at tree level from the operator $\mathcal{O}_{e\varphi}$

and at loop level from $\mathcal{O}_{et}$

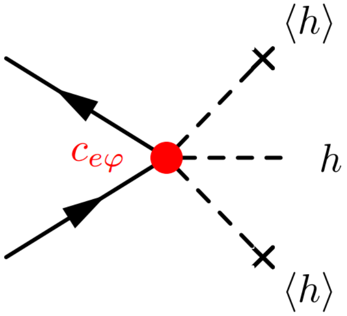


$$= \; -i\Sigma_e \; = \; -i\frac{6}{(4\pi)^2}\frac{c_{et}}{\Lambda^2}m_t^3\left(1 + \frac{1}{\bar{\epsilon}} + \log\frac{\mu^2}{m_t^2}\right)$$

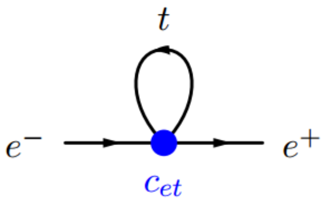
The process in the SM-EFT

The electron-Higgs interaction gets modifications

at tree level from the operator $\mathcal{O}_{e\varphi}$



and at loop level from $\mathcal{O}_{et}$



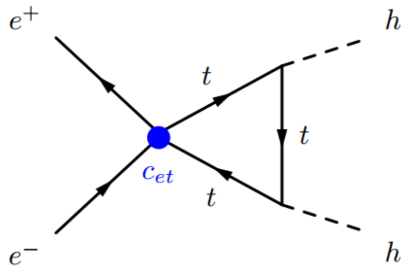
$$= -i\Sigma_e = -i\frac{6}{(4\pi)^2}\frac{c_{et}}{\Lambda^2}m_t^3\left(1+\frac{1}{\bar{\epsilon}}+\log\frac{\mu^2}{m_t^2}\right)$$

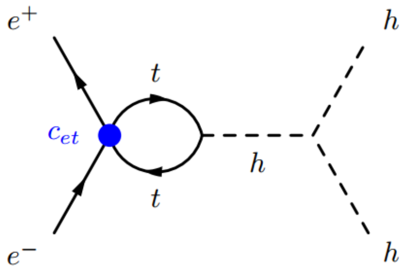
Tree-level diagrams in SMEFT are computed with the new Yukawa coupling

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

The process in the SM-EFT

These diagrams are UV divergent

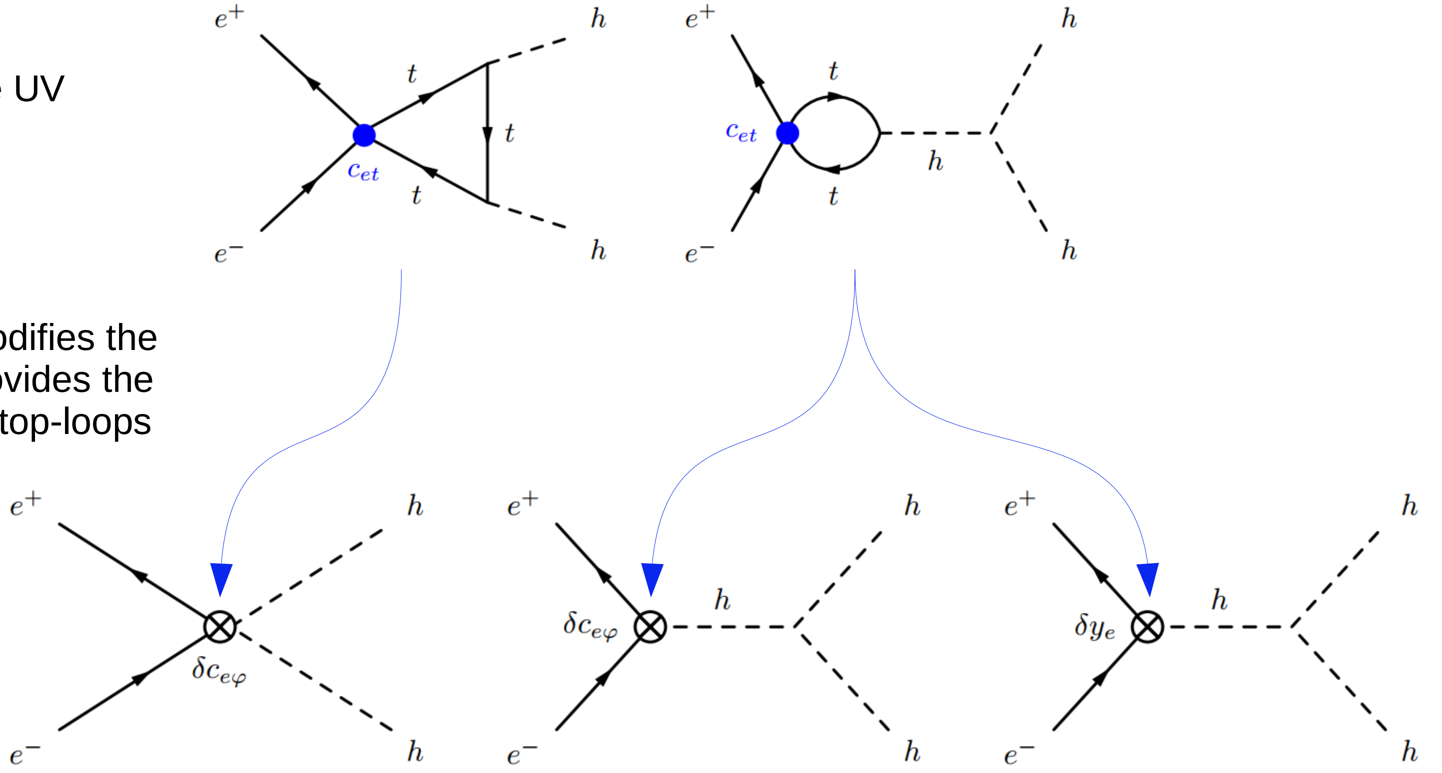




The process in the SM-EFT

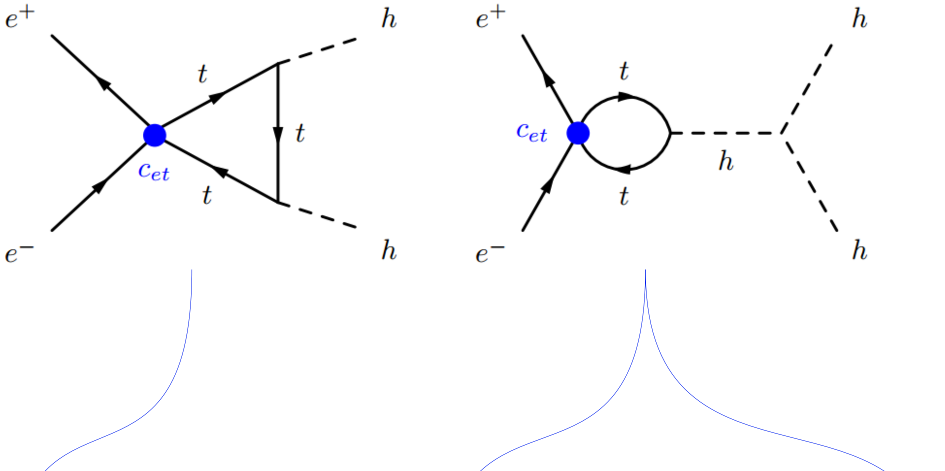
These diagrams are UV divergent

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

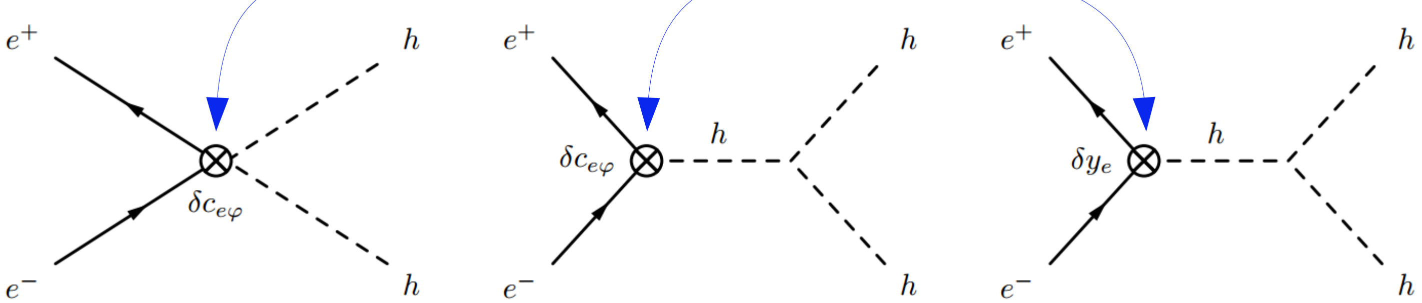


The process in the SM-EFT

These diagrams are UV divergent



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



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

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

Our Analysis

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

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

Thus, 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 $\delta\sigma^2 = \delta\sigma_{stat}^2 + \delta\sigma_{sys}^2$ and

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

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

Benchmark values & Results

Benchmark	Experiment	$\sqrt{s}$ (GeV)	L (ab^{-1})	$\lvert c_{e\varphi}/\Lambda^2\rvert(\mathrm{TeV}^{-2})$	$\lvert c_{et}/\Lambda^2\rvert(\mathrm{TeV}^{-2})$
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	$< 0.002 \quad (< 0.002)$	$< 0.012 \quad (< 0.015)$

Benchmark scenarios considered in our analysis.

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

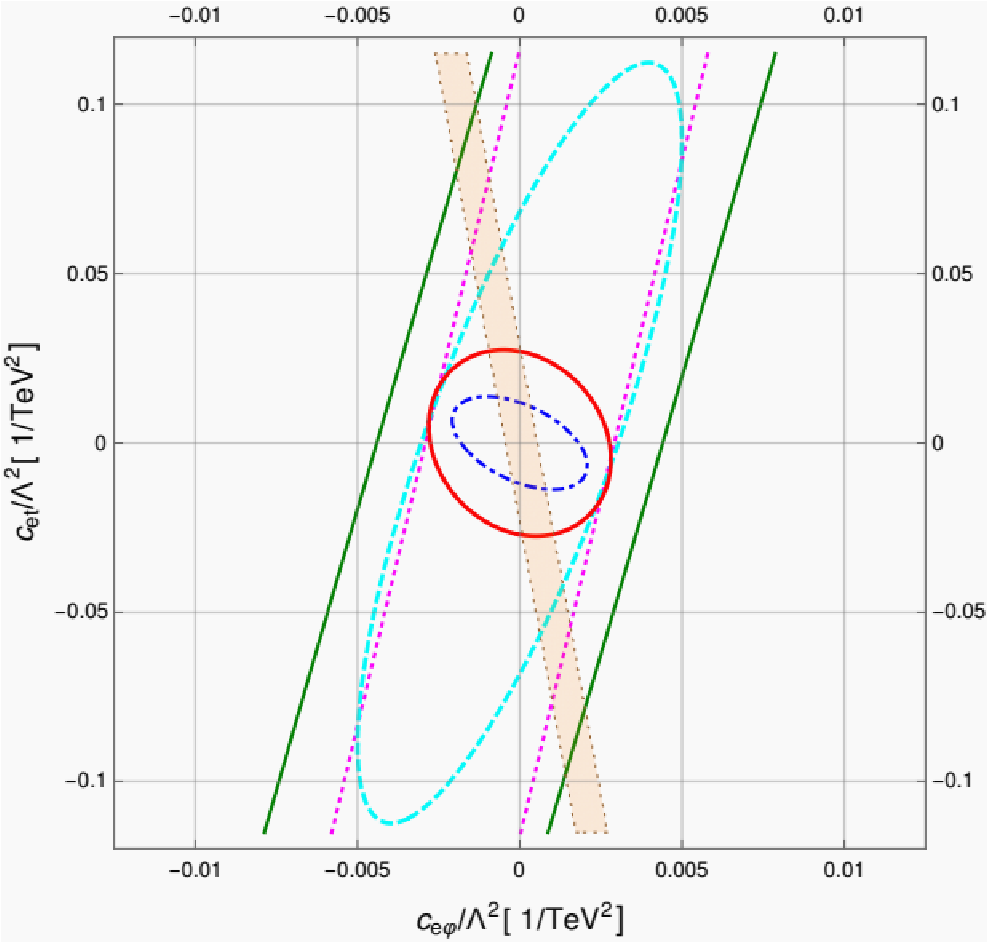
$$k = \mathrm{BR}(h \to f_1 \bar{f}_1) \times \mathrm{BR}(h \to f_2 \bar{f}_2)$$

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
5	CLIC	3000	3.0

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



Results – Additional possible bounds

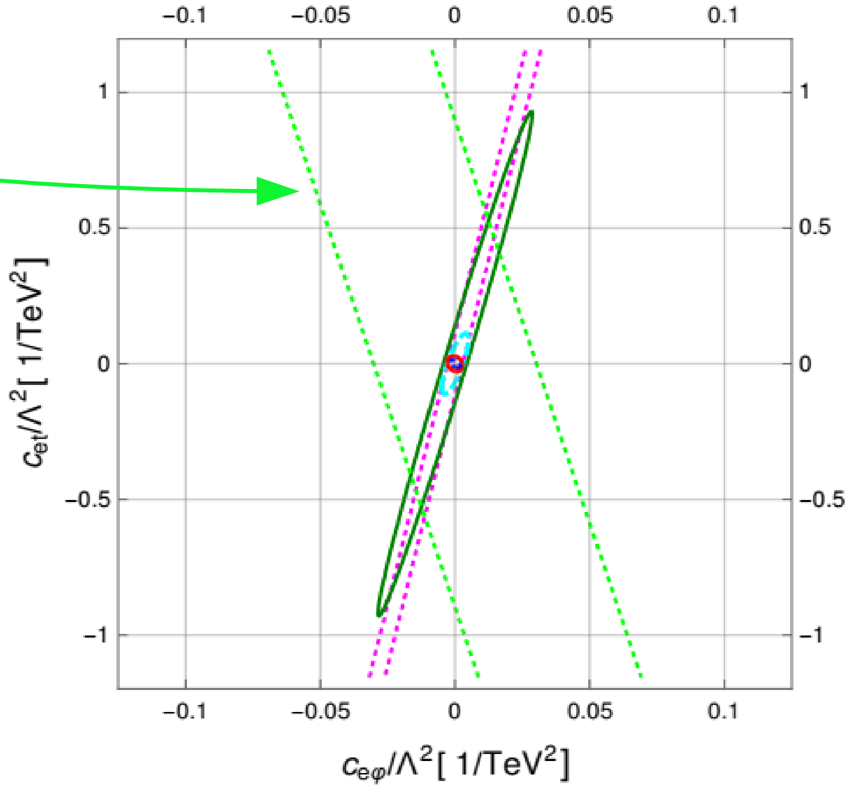
$$\left| -\frac{m_e}{v} + \frac{c_{e\varphi}(\mu)v^2}{\Lambda^2\sqrt{2}} - \frac{3}{(4\pi)^2}\frac{y_t}{\sqrt{2}}\frac{c_{et}}{\Lambda^2}(4m_t^2 - m_h^2)\left[f(m_h^2, m_t^2) + \log\frac{\mu^2}{m_t^2}\right]\right| \lesssim 600\frac{m_e}{v}$$

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)

Results – Additional possible bounds

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

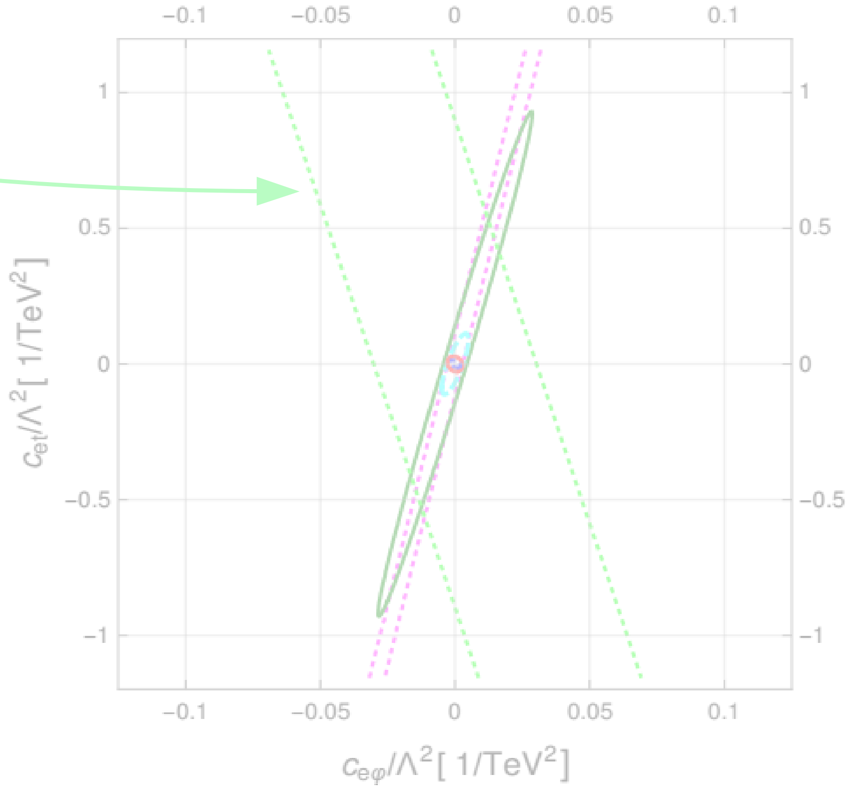
After considering all contributions to the eeh-vertex, the recent upper bound on the electron Yukawa coupling obtained from Higgs decay (Altmannshofer, Brod & Schmaltz, 2015)



Results – Additional 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)



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

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

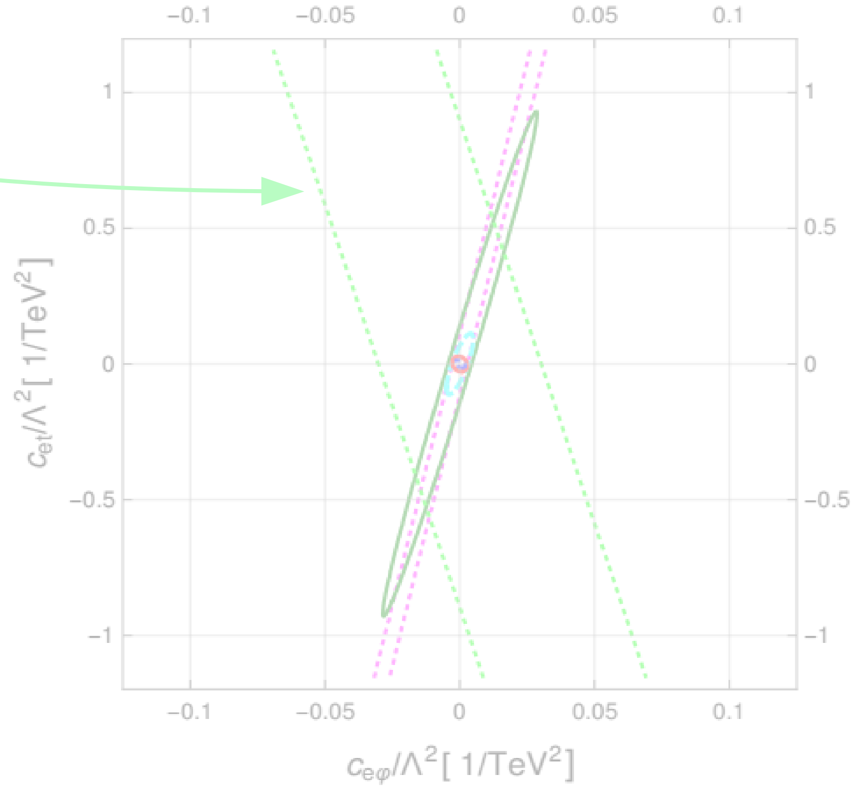
In this case we have that

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

Results – Additional 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)



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

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

Fine tuning is a guidance.

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.

  More stringent bounds can be found in the $e^+e^- \to t\bar{t}$ process for the coefficient c_{et} (Durieux, Perello, Vos & Zhang, 2018)

- 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 $c_{e\varphi}$ probe scales of O(10 TeV) while the c_{et} operator probes scales of O(1 TeV).

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.

  More stringent bounds can be found in the $e^+e^- \to t\bar{t}$ process for the coefficient c_{et} (Durieux, Perello, Vos & Zhang, 2018)

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

- We derived ... veral benchmark ... e bounds on $c_{e\varphi}$ probe ... tor probes scales of O

Thanks!!!