UCLouvain
Institut de recherche en mathématique et physique
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New physics in double Higgs production

Celine Degrande

Plan

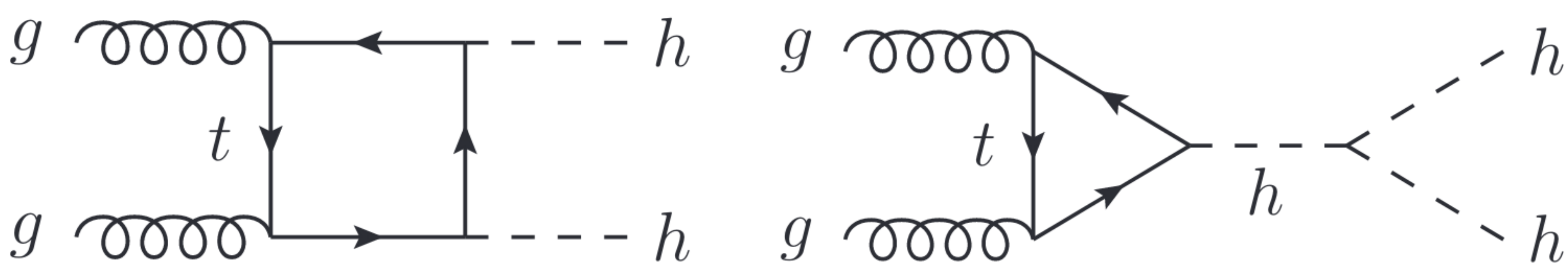
C. D., A. Tonero, R. Rosenfeld, Andres Vasquez, JHEP 1905 (2019) 020

- Introduction : HH
- SMEFT operators for HH
- Results
- Other constraints
- Summary

Introduction: double HH

HH at hadron colliders

Plehn, Spira & Zerwas, 1996



Stronger cancellation close to threshold

Li & Voloshin, 2013

Small in the SM = good for NP

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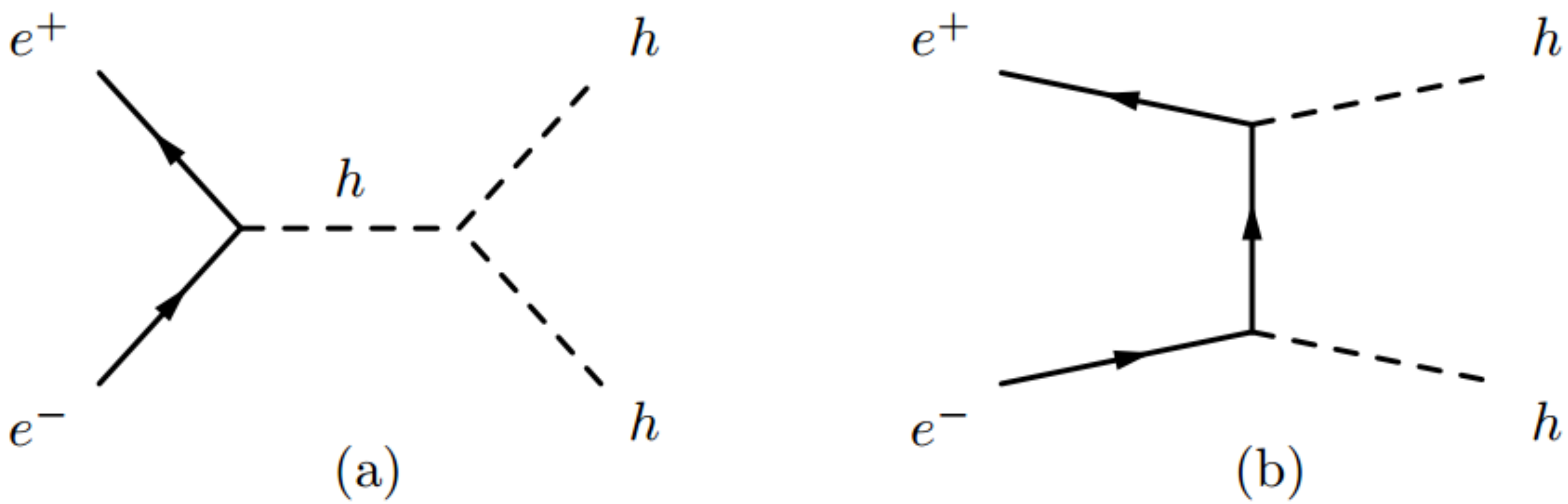
HH at lepton colliders

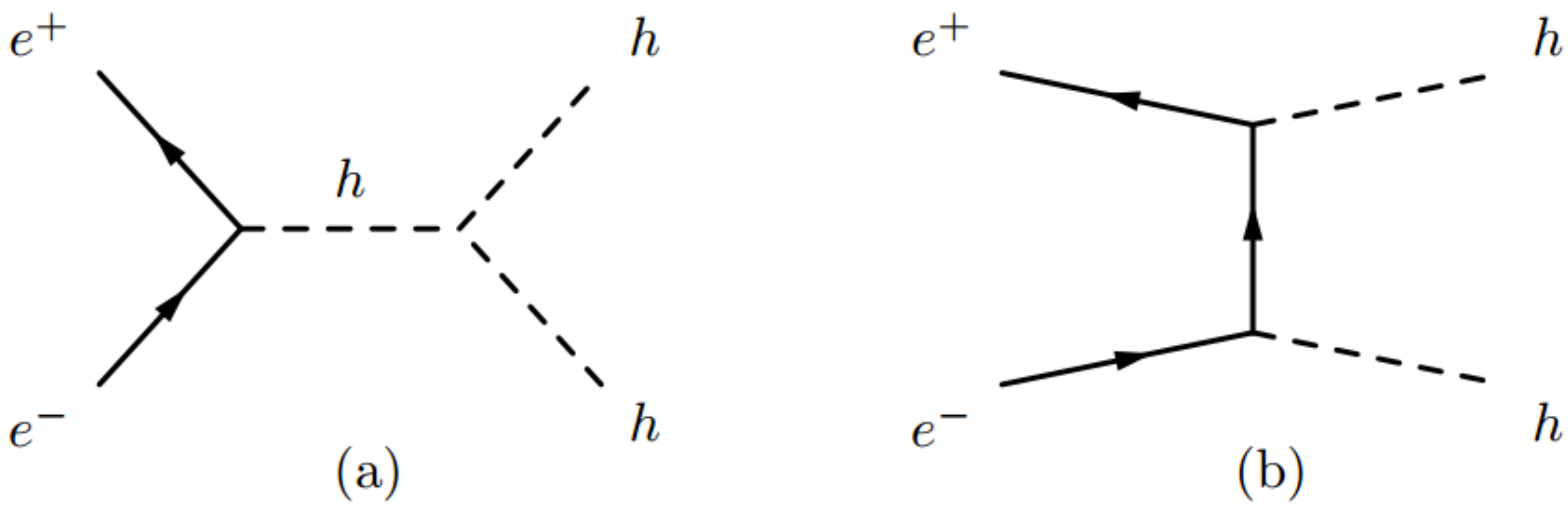
Tree-level



$$\propto m_e \approx 0$$

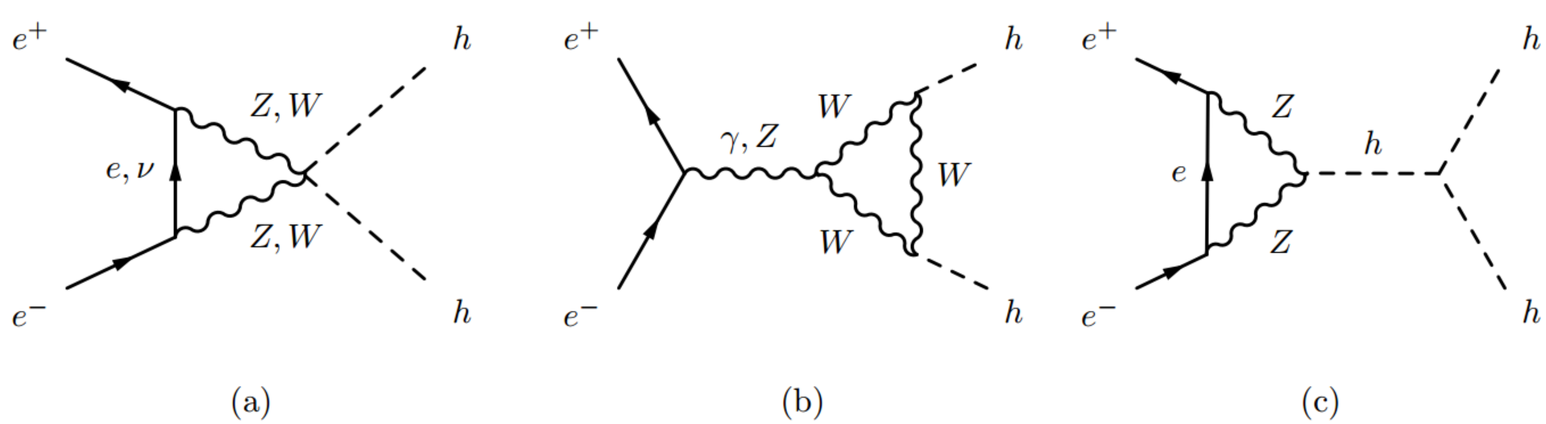
HH at lepton colliders

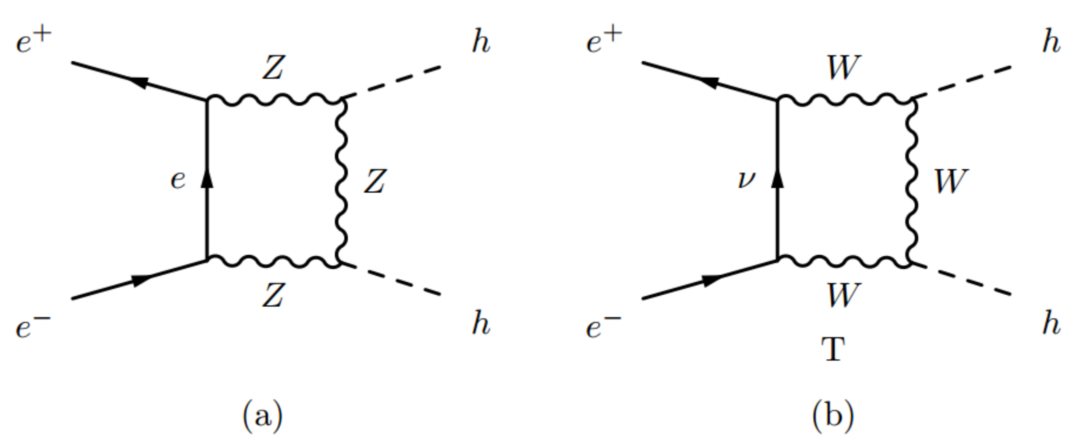
Tree-level



$\propto m_e \approx 0$

One-loop





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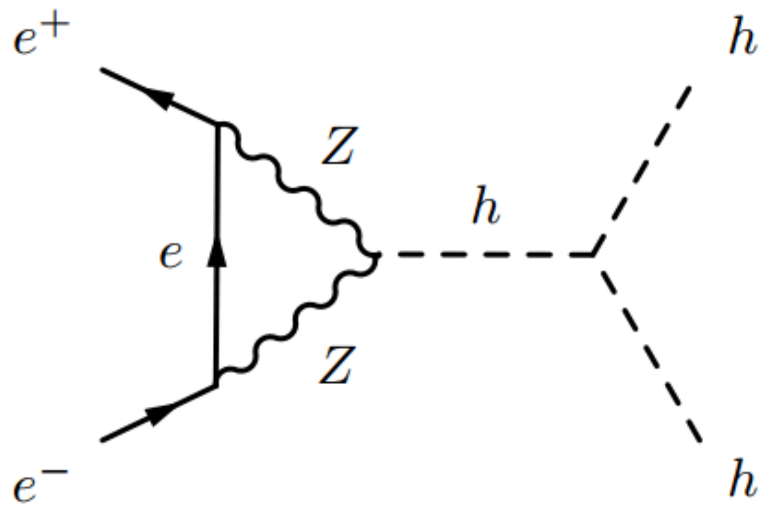
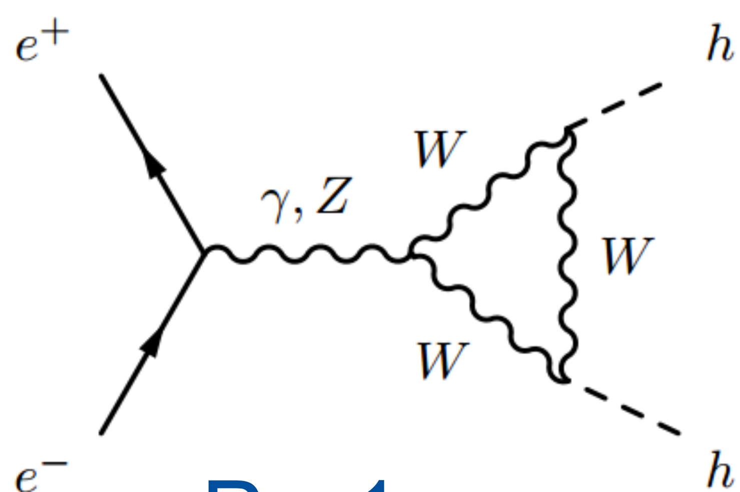


$\propto m_e \approx 0$

correction to the electron Yukawa



P=-1

P=+1

= 0 by parity conservation

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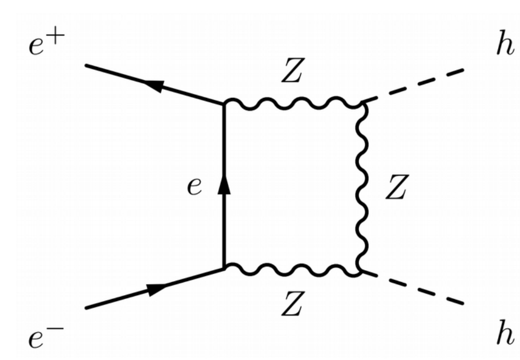
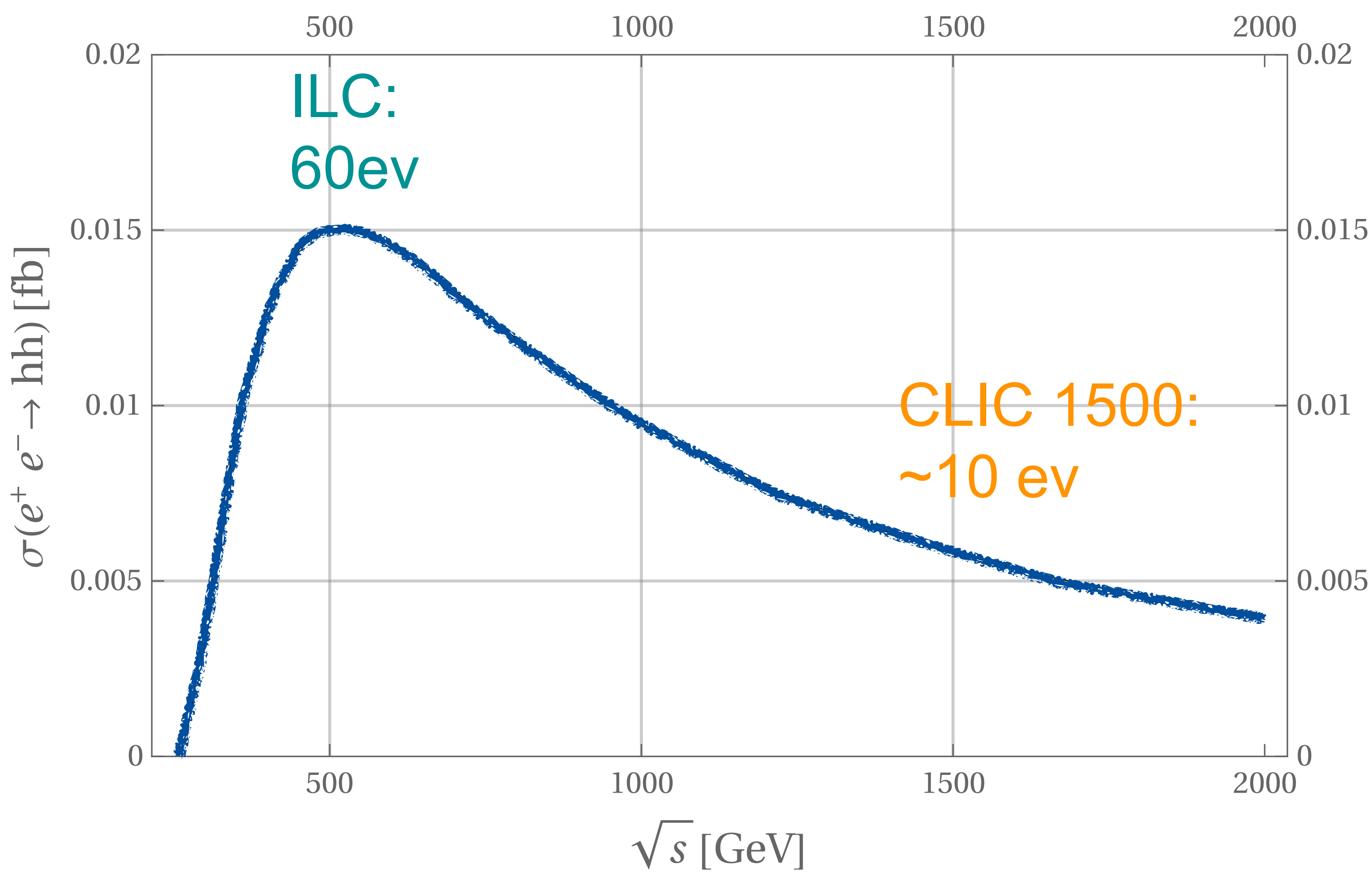
HH at lepton colliders

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

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



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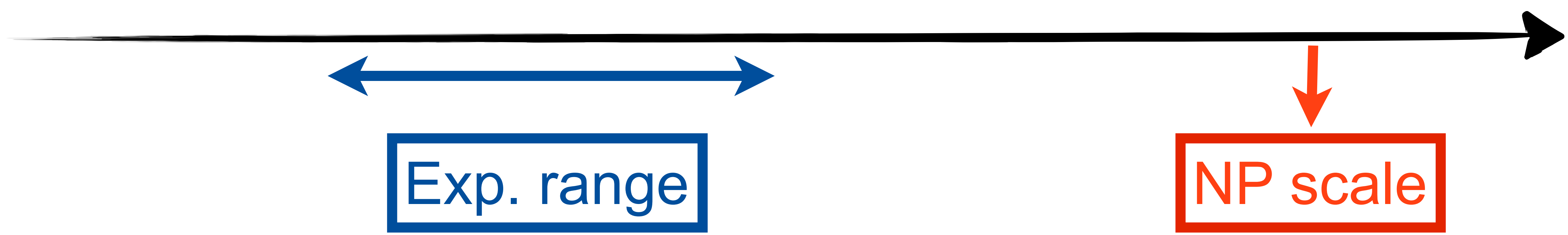
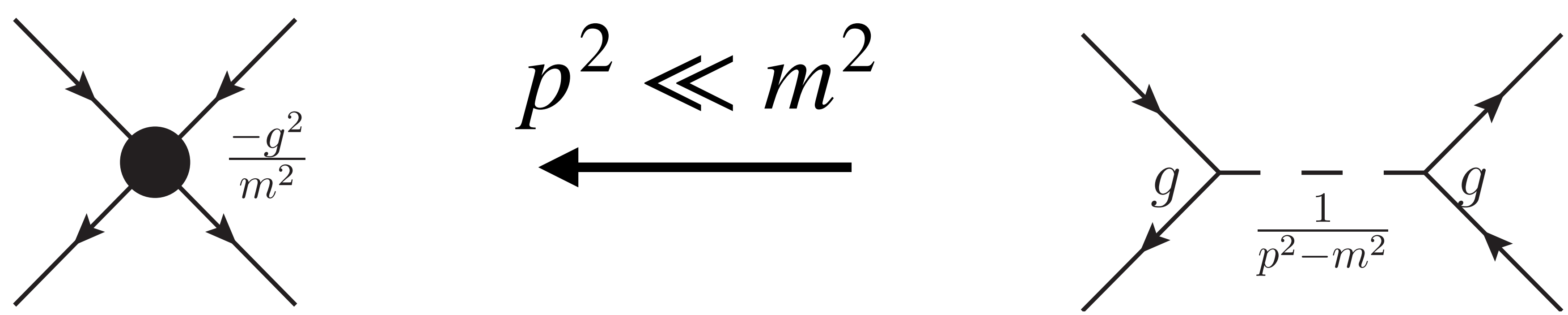
SMEFT operators for HH

Indirect detection of NP

- Assumption : NP scale >> energy probed in experiments





One assumption : $p^2 \ll m^2$

Ex : Fermi theory $-\frac{G_F}{Sqrt[2]} J^\mu J_\mu, \quad J_\mu = J^l_\mu + J^h_\mu, \quad J^l_\mu = \nu_l \gamma_\mu (1-\gamma_5) l$

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Dim6 operators for HH

Grzadkowski et al., 2010

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i^6$$

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}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	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.

Tree-level

One-loop thanks to eeZ, evW, hZZ, hWW modification: Constrained by LEP/LHC

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Dim6 operators for HH

Most operators do not contribute (Parity/ $\propto m_e \approx 0$)

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

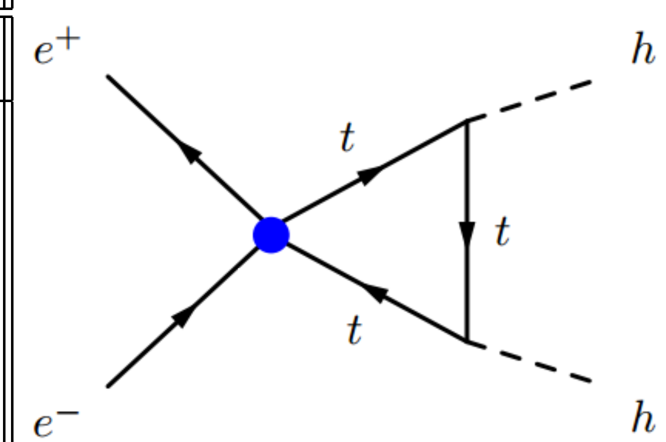

Table 3: Four-fermion operators.

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Dim6 operators for HH

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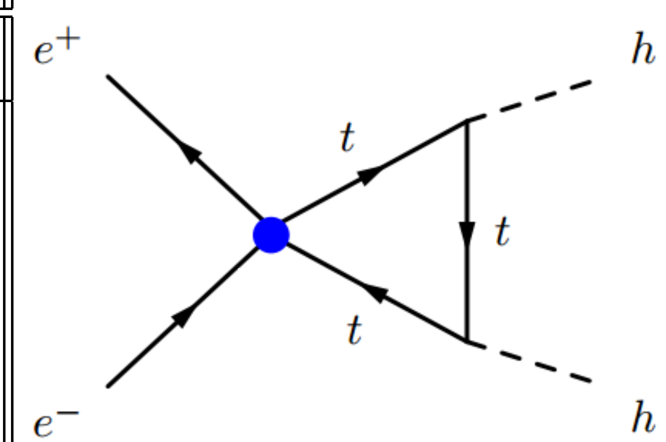
Table 3: Four-fermion operators.



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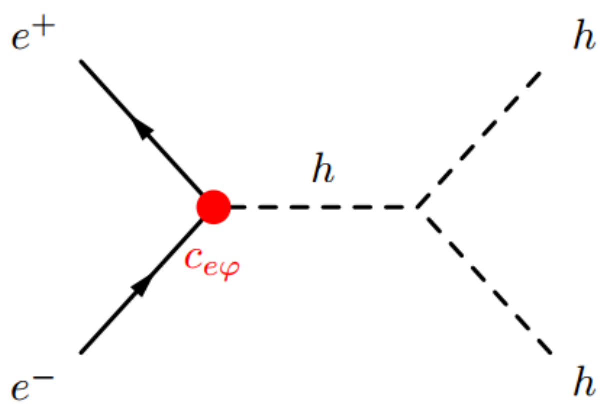
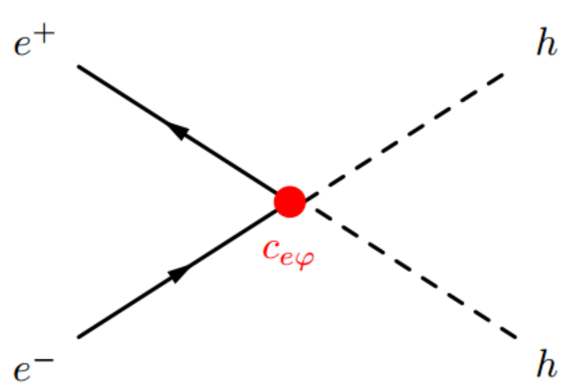
Dim6 operators for HH

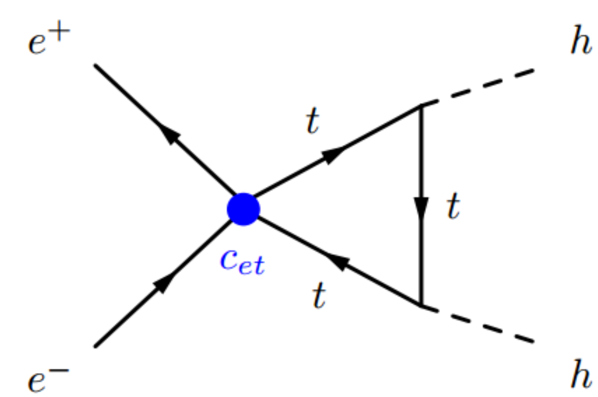
$$\frac{c_{e\varphi}}{\Lambda^2}(\varphi^\dagger\varphi - \frac{v^2}{2})\bar{l}_L\varphi e_R$$

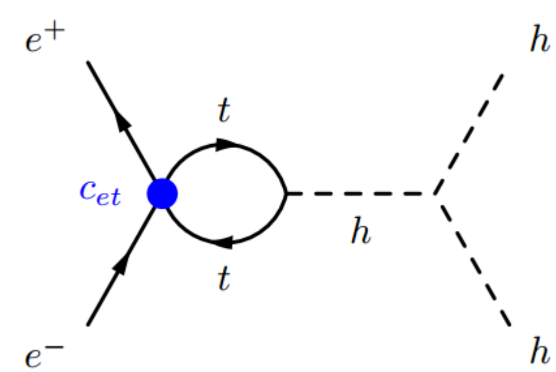


Correction to the electron Yukawa



$$\frac{c_{et}}{\Lambda^2}\epsilon_{ij}\bar{l}^i_L e_R \bar{q}^j_L t_R$$





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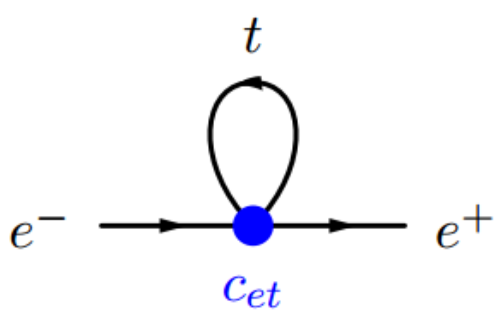
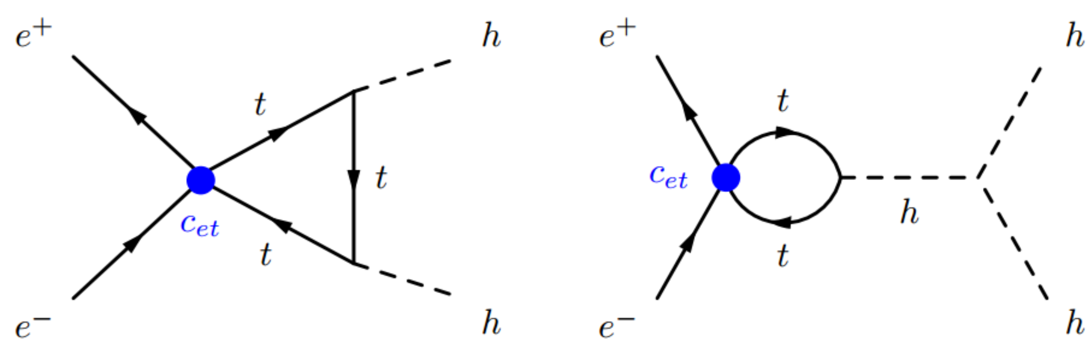
Results

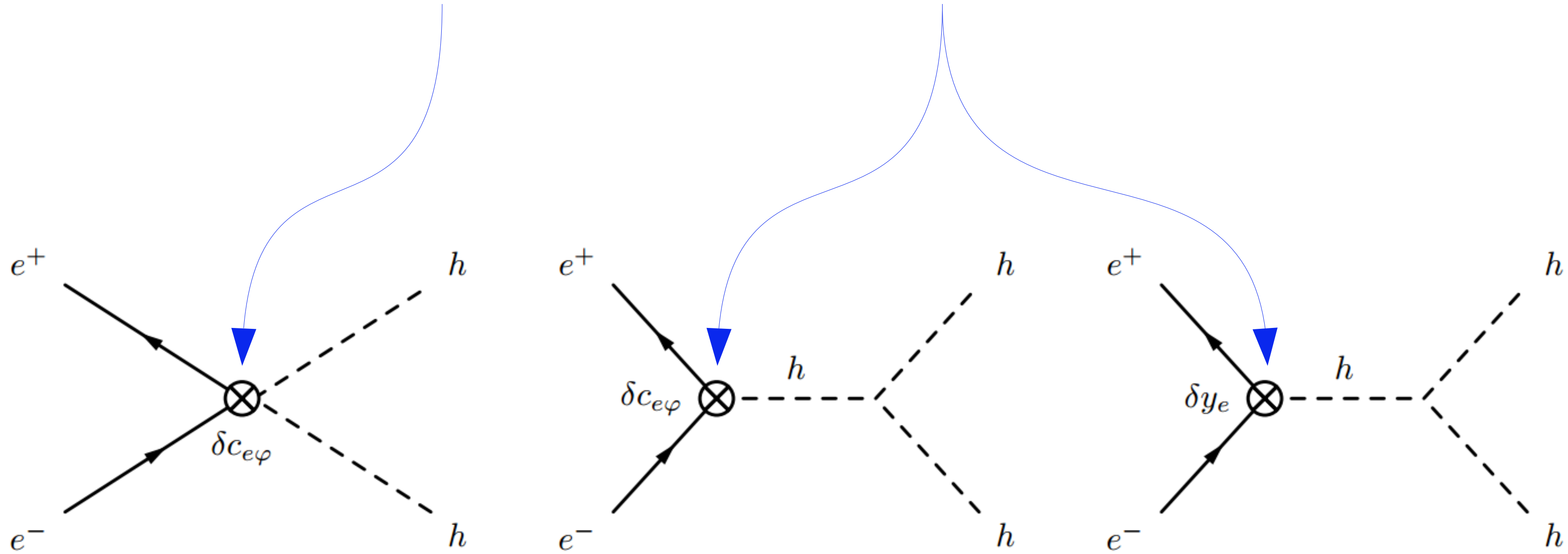
Comments on the top loop



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



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



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

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

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Results for future colliders

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

$$\delta\sigma^2 = \delta\sigma^2_{stat} + \delta\sigma^2_{sys} \qquad \delta\sigma_{stat} = \sqrt{\sigma^{SM}/L} \qquad \delta\sigma_{sys} = \alpha\sigma^{SM} \quad (\alpha = 0.1)$$

Ind. 95% CL

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	$< 0.002 \quad (< 0.002)$	$< 0.012 \quad (< 0.015)$

k = 1 (k = 0.35)

bottom decay

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

Results for future colliders

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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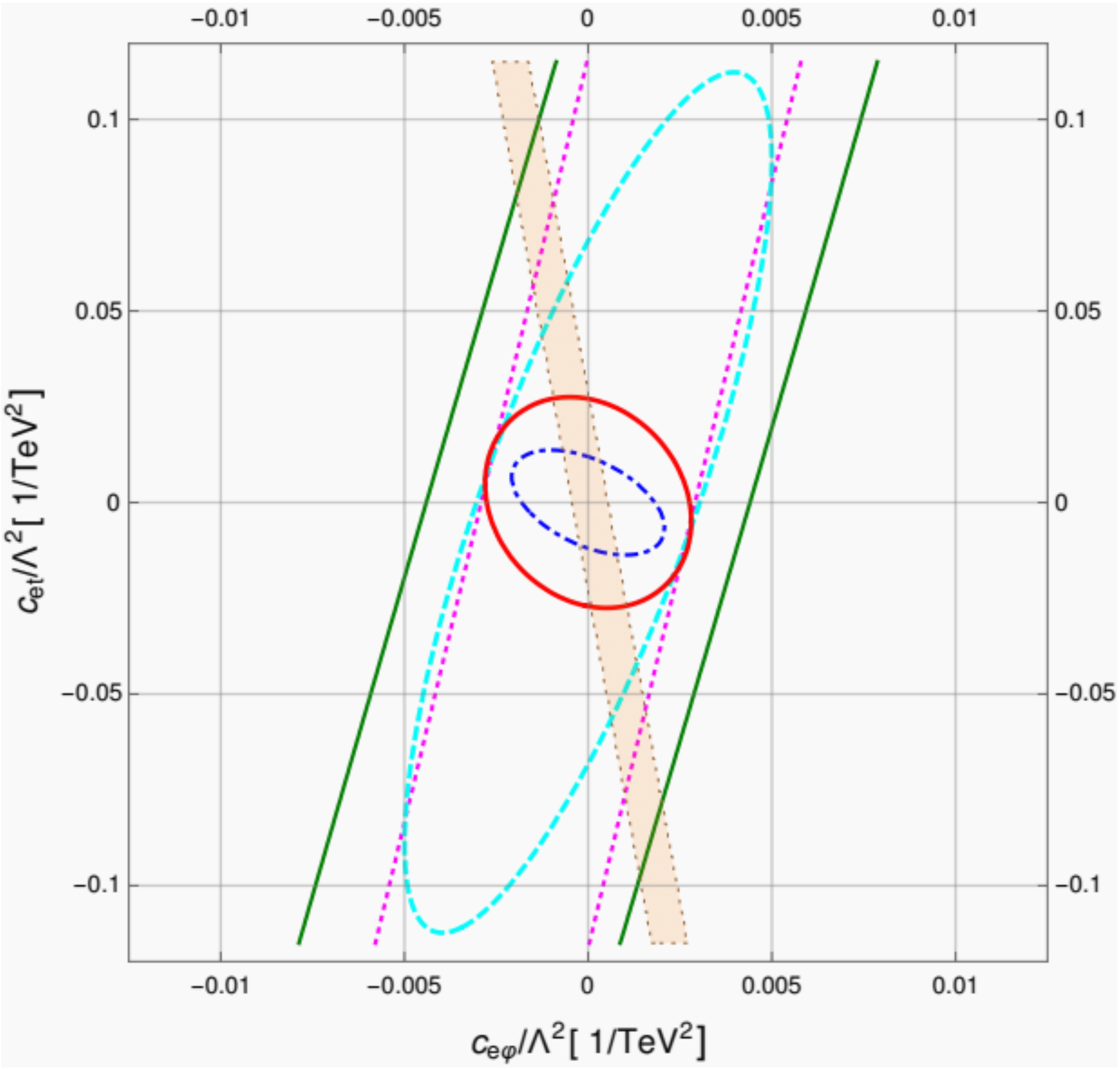
95%CL, k=1



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Other constraints

Other constraints

Higgs coupling to electron (will improve)

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

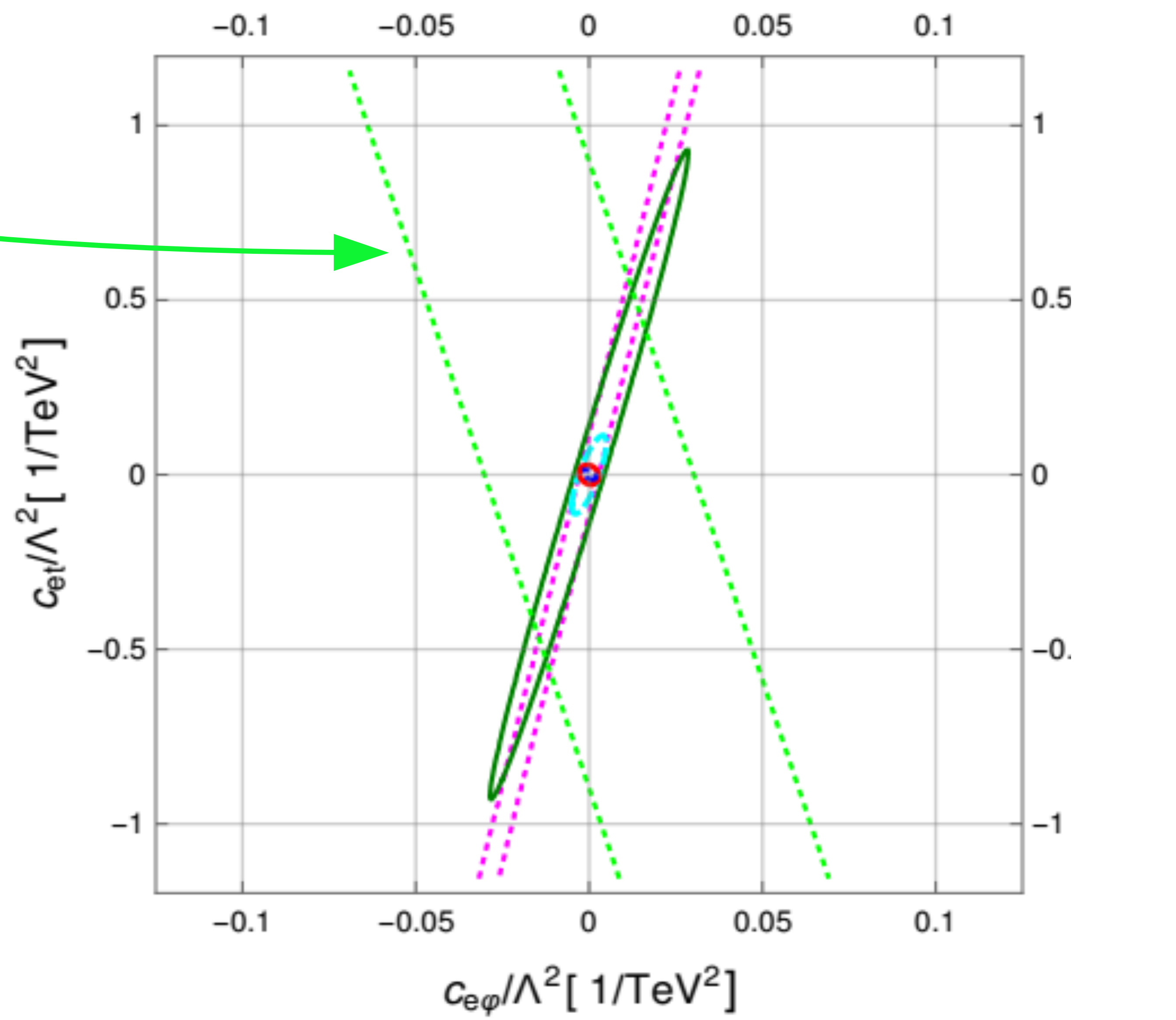
Fine tuning of the mass

$$|\delta m_e|\lesssim m_e$$

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

Top pair production

$$\frac{c_{et}}{\Lambda}\lesssim 10^{-2}-10^{-3}\ \mathrm{TeV}^{-2}$$



Durieux, Perello, Vos & Zhang, 2018

C. Degrande

Summary

Summary

- HH production is small in the SM
- 2 operators are relevant for ee > HH
- HH at lepton colliders: $\frac{c_{e\varphi}}{\Lambda^2} \lesssim 10^{-3}\text{TeV}^{-2}$ $\frac{c_{et}}{\Lambda^2} \lesssim 10^{-1} - 10^{-2}\text{TeV}^{-2}$
- They will be further constrained by ttbar, H