New Physics in double Higgs production at future e^+e^- colliders

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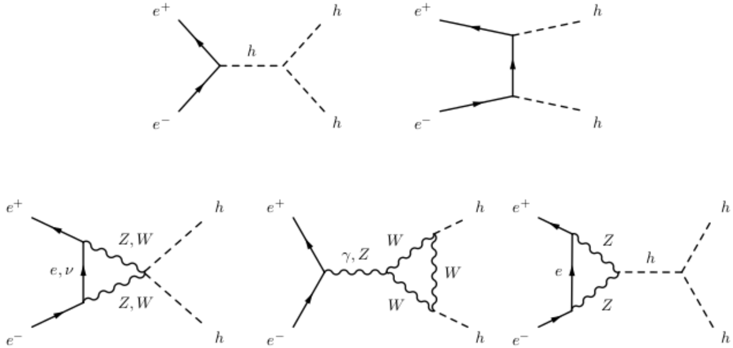
GOALS

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

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

SM $e^+e^- \to hh$

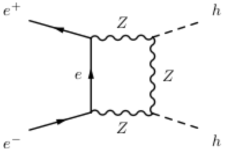
- Tree-level and loop triangle diagrams



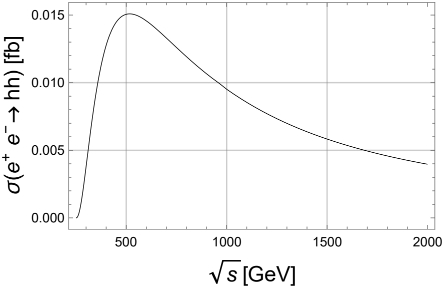
vanishing in the limit $m_e \to 0$

SM $e^+e^- \to hh$

- Loop box diagrams



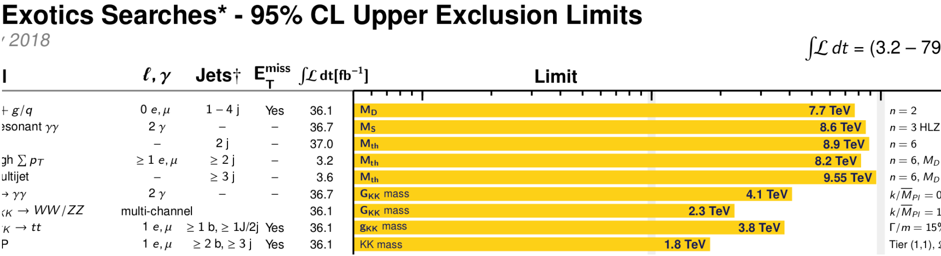
provide the leading contribution $\sigma_{\text{SM}} \sim \mathcal{O}(10^{-3}\text{-}10^{-2}\text{fb})$



- With large luminosities expected at future e^+e^- colliders, a few hundred events might be collected

- Cross sections can be enhanced by contributions coming from physics beyond the SM

No signs of New Physics so far at LHC



LHC results point to a new physics scale $\Lambda \gtrsim 1$ TeV

Standard Model EFT

- If new particles lie at a scale $\Lambda \gg v, E$ their effects at low energies are best parametrized by an effective Lagrangian $\mathcal{L}_{\text{eff}}$ (SMEFT)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \ldots$$

where

$$\mathcal{L}^{(5)} = \frac{c^{(5)}}{\Lambda}\mathcal{O}^{(5)} \qquad \mathcal{L}^{(6)} = \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} \qquad \mathcal{L}^{(8)} = \ldots$$

59 dimension-6 operators *[W. Buchmuller and D. Wyler, Nucl. Phys. B268 (1986) 621–653; B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP 10 (2010) 085]*

SMEFT contributions to $e^+e^- \to hh$

- In principle, all dimension-six operators relevant for Higgs/electron interactions should be considered

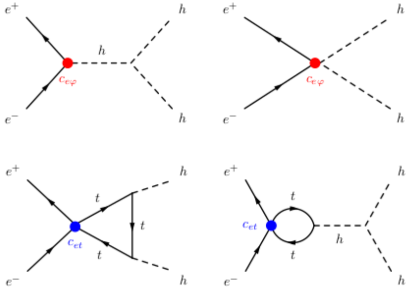
- Several of these operators (ones that modify $\bar{e}eZ$, $e\nu W$, hZZ and hWW) already (strongly) constrained from other observables at LHC/LEP and we set them to zero

- We are left with two classes of operators: ones that induce an effective $\bar{e}ehh$ and $\bar{e}e\bar{t}t$ couplings

Our study

- Just two EFT operators contribute (currently unconstrained)

$$\frac{c_{e\varphi}}{\Lambda^2}(\varphi^\dagger\varphi - \frac{v^2}{2})\bar{l}_L\varphi e_R + \text{h.c.} \qquad \frac{c_{et}}{\Lambda^2}\epsilon_{ij}\bar{l}^i_L e_R \bar{q}^j_L t_R + \text{h.c.}$$



Sensitivity study: expected bounds

- We compute $\sigma(e^+e^- \to hh)$ as function of $(\frac{c_{e\varphi}}{\Lambda^2}\ ,\ \frac{c_{et}}{\Lambda^2}\ ,\ \sqrt{s})$
- Chi-squared

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

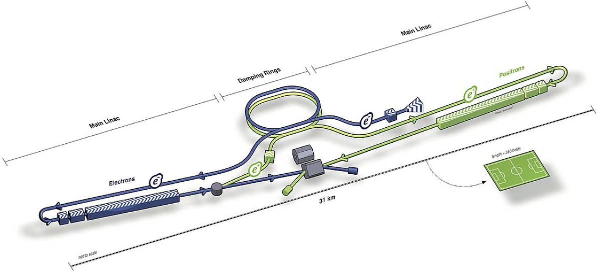
- Uncertainty $\delta\sigma^2 = \delta\sigma^2_{\mathrm{stat}} + \delta\sigma^2_{\mathrm{sys}}\ (\alpha = 0.1)$

$$\delta\sigma_{\mathrm{stat}} = \sqrt{\sigma_{\mathrm{SM}}/L} \qquad \delta\sigma_{\mathrm{sys}} = \alpha\,\sigma_{\mathrm{SM}}$$

- To consider Higgs decays rescale σ by

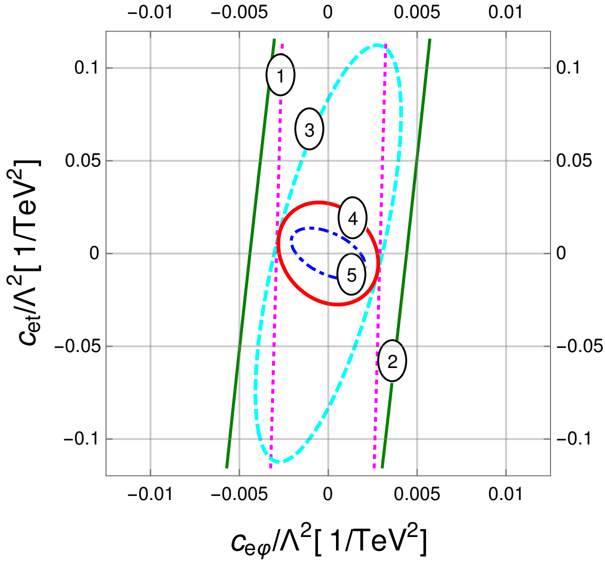
$$k = \mathrm{BR}(h \to f_1\bar{f}_1) \times \mathrm{BR}(h \to f_2\bar{f}_2)$$

Future e^+e^- colliders



Exp	$\sqrt{s}$ (GeV)	L (ab^{-1})	$\lvert c_{e\varphi}/\Lambda^2\rvert(\text{TeV}^{-2})$	$\lvert c_{et}/\Lambda^2\rvert(\text{TeV}^{-2})$
1 FCC-ee	350	2.6	$< 0.003 \quad (0.004)$	$< 1.020 \quad (1.280)$
2 CLIC	380	0.5	$< 0.004 \quad (0.006)$	$< 0.352 \quad (0.453)$
3 ILC	500	4	$< 0.003 \quad (0.004)$	$< 0.083 \quad (0.101)$
4 CLIC	1500	1.5	$< 0.003 \quad (0.003)$	$< 0.027 \quad (0.035)$
5 CLIC	3000	3.0	$< 0.002 \quad (0.002)$	$< 0.012 \quad (0.015)$

Results: expectd 95% CL bounds $(k = 1)$



Conclusions

- Double Higgs production at future e^+e^- colliders is sensitive to dimension-6 operators not yet constrained
- The small SM cross section and the clean environment makes this process an ideal laboratory for NP studies
- We derived 95% bounds on $c_{e\varphi}$ and c_{et} considering several benchmarks for these future colliders
- Bounds on $c_{e\varphi}$ typically probes scales of $\mathcal{O}(10$ TeV$)$ while the c_{et} operator probes scales of $\mathcal{O}(1$ TeV$)$
- Searches for $e^+e^- \to hh$ should be pursued in addition to the more traditional single and double Higgs production

Thank you

BACK UP

Electron mass and coupling to Higgs

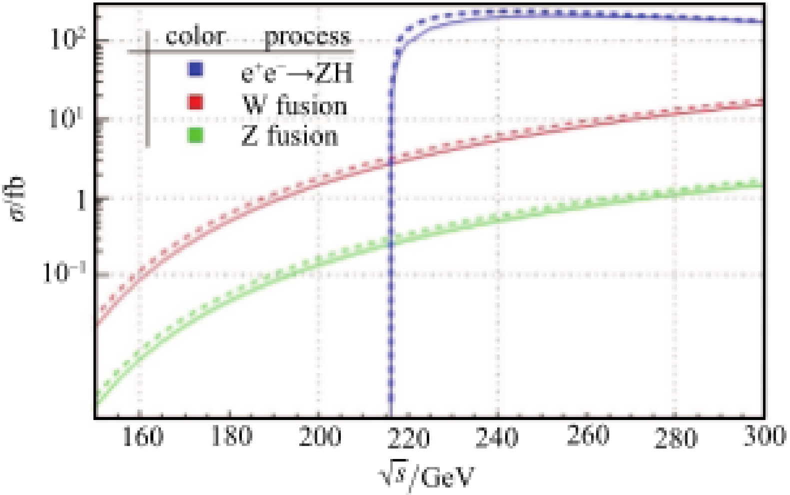
- Physical electron mass in $\bar{\mathrm{M}}\mathrm{S}$

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

- Higgs-electron coupling

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

Single Higgs production cross section at e^+e^-



Dimension 6 operators

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	