EFT studies of hZ & hhZ production @ the ILC/CLIC

the case of contact interactions

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Based on:

"Contact interactions in Higgs-vector boson associated production at the ILC":

Jonthan Cohen (PhD student), SBS, Gad Eilam, PRD2016 (arxiv: 1602.01698)

Outline

- ee colliders & ee $\rightarrow$ hZ,hhZ: quick notes
- The SMEFT & application to ee $\rightarrow$ hZ,hhZ
  the $\psi^2\varphi^2 D$ class op's from heavy vector-boson exchanges
- NP(ee $\rightarrow$ hZ,hhZ)$_{\psi 2\varphi 2D}$:expectations @ a 0.5-3 TeV ILC/CLIC
- Some extra handles
  - Validity of the EFT
  - An hZ – hhZ correlation
- Summary & outlook

ee colliders: a pathway to precision

Some benchmark expectations for leading BSM scenarios

- SUSY (tanβ=5): $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$

- Composite Higgs: $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$

- Top partners: $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$

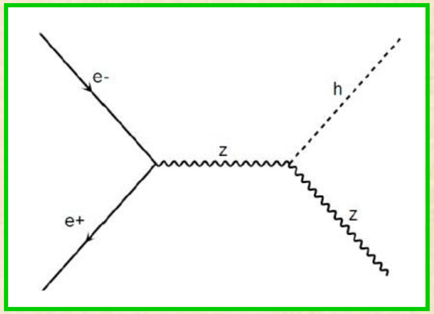
"stolen" from Paulo Meridiani's talk @ EPS-HEP2017

given the present status of BSM searches, need percent level accuracies to hunt for the tail of potential multi-TeV NP

ee → hZ & hhZ: some basic facts

SM

$e^+e^- \to hZ$



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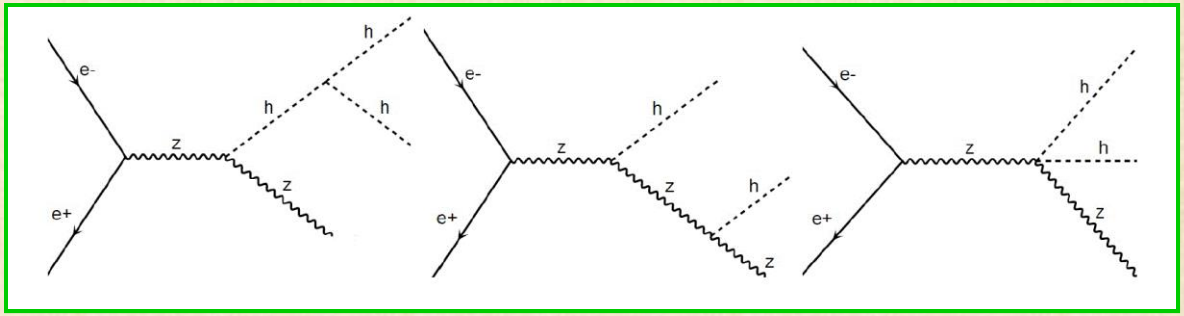

$\sigma(E_{cm} \sim 250$ GeV$) \sim O(100$ fb$)$
dropping to $O(10$ fb$)$ @ $E_{cm} \sim 1$ TeV
& to $O(1$ fb$)$ @ $E_{cm} \sim 3$ TeV

$\sigma(E_{cm} \sim 500 - 1000$ GeV$) \sim O(0.1$ fb$)$
dropping to $O(0.01$ fb$)$ @ $E_{cm} \sim 3$ TeV

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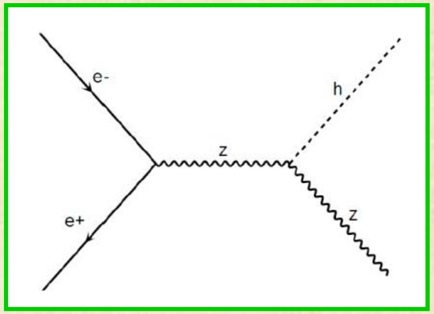

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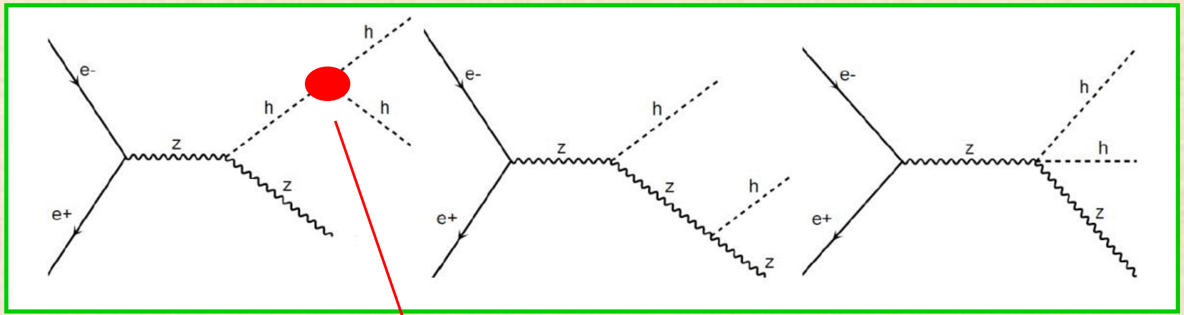

$\sigma(E_{cm} \sim 250$ GeV) ~ O(100 fb)
dropping to O(10 fb) @ E_{cm} ~ 1 TeV
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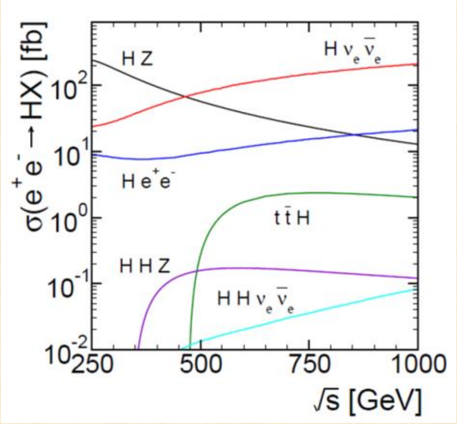
Dominant Higgs prod. Channel
@ E_{cm} ~ 250 -350 GeV



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One of the main motivation for hhZ:
potential sensitivity to the Higgs trilinear self coupling

ee → hZ & hhZ: some basic facts

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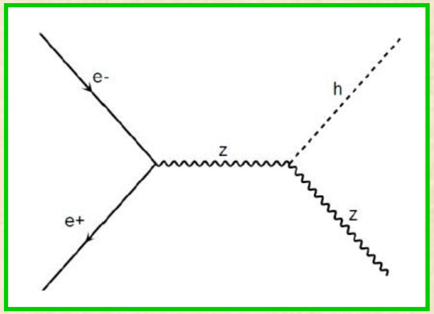

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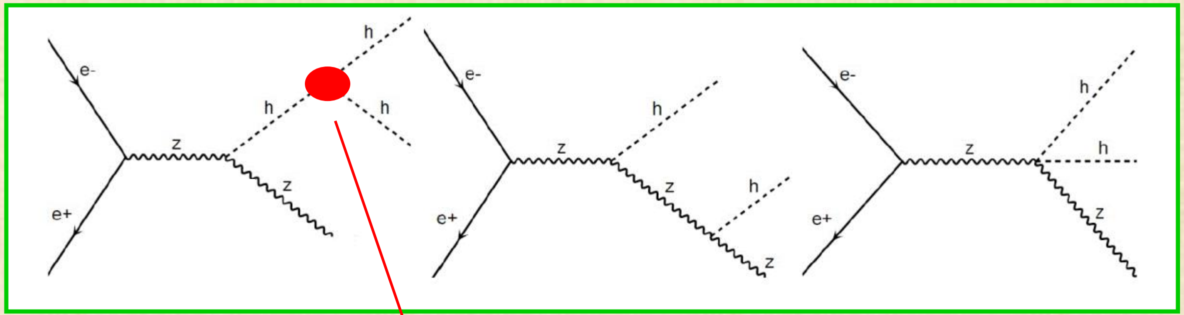

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One of the main motivation for hhZ:
potential sensitivity to the Higgs trilinear self coupling

Indeed, both are sensitive to a variety of BSM scenarios
but: sensitivity to multi-TeV NP requires TeV-scale energies where CSX's are small

⇒ needs an O(1000 fb^{-1}) luminosity

The SMEFT

perhaps the only not-speculated NP framework by definition …

The "art" of EFT in a nutshell:

Conventional practice: physics at E $\leq \Lambda$ is described by

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \frac{1}{\Lambda^{(n-4)}} \sum_i f_i^{(n)} \mathcal{O}_i^{(n)}$$

- ✓ "light fields" [@ E $\leq \Lambda$] = SM fields
- ✓ Gauge-symmetry [@ E $\leq \Lambda$] = SM: SU(3)xSU(2)xU(1)
- ✓ Underlying NP ($\phi_{\rm heavy}$) is weakly coupled, renormalizable, obeys gauge-invariance & preserves symmetries of the known dynamics (SM) (useful for classifying the higher dim operators)

The "art" of EFT in a nutshell:

on top of that:

use 3 more guiding principles which further simplify/reduce the # of relevant operators
(we don't know the precise form of the underlying heavy physics ⇒ ambiguities in selecting relevant operators …):
Arzt, Einhorn & Wudka, Nucl.Phys. B433 (1995), 41; Einhorn & Wudka, Nucl.Phys. B876 (2013) 556

1. **Equations of Motion (EoM):** an "equivalence theorem"

2. **Integration by Parts (IbP):** dismiss surface terms

3. **Loop Classification of operators:** loop-gen. (LG) vs potentially tree-level gen. (PTG) operators

Many operators can be constructed under these conditions,
O(50) @ dim 6
but only several of them directly apply to hZ & hhZ prod …

The SMEFT & heavy vector-boson exchanges: the $\psi^2\varphi^2 D$ class operators

The GIMR (Warsaw) basis (Grzadkowski et at., arxiv:1008.4884)

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}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
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$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

+ 4 fermion interactions …

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+ 4 fermion interactions …

$\psi^2\varphi^2 D$ op's:
heavy vector-boson exchanges (singlets & triplets)

generate llhZ & llhhZ contact terms and therefore expected to give the dominant higher-dim. EFT effect in ee →hZ,hhZ

The SMEFT & heavy vector-boson exchanges: the $\psi^2\varphi^2 D$ class operators

For practical reasons use HEL package (FeynRules) → UFO file for MG5 …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \bar{c}_i \mathcal{O}_i \equiv \mathcal{L}_{SM} + \mathcal{L}_{SILH} + \mathcal{L}_{F_1} + \mathcal{L}_{F_2} + \mathcal{L}_G$$

Alloul, Fuk, JHEP2014 (arxiv: 1310.5150)

$$\begin{aligned}
\mathcal{L}_{F_1} = \; & \frac{i\bar{c}_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu Q_L\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \frac{4i\bar{c}'_{HQ}}{v^2}\left[\bar{Q}_L\gamma^\mu T_{2k} Q_L\right]\left[\Phi^\dagger T_2^k \overleftrightarrow{D}_\mu \Phi\right] \\
& + \frac{i\bar{c}_{Hu}}{v^2}\left[\bar{u}_R\gamma^\mu u_R\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \frac{i\bar{c}_{Hd}}{v^2}\left[\bar{d}_R\gamma^\mu d_R\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] \\
& - \left[\frac{i\bar{c}_{Hud}}{v^2}\left[\bar{u}_R\gamma^\mu d_R\right]\left[\Phi \cdot \overleftrightarrow{D}_\mu \Phi\right] + h.c.\right] \\
& + \frac{i\bar{c}_{HL}}{v^2}\left[\bar{L}_L\gamma^\mu L_L\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right] + \frac{4i\bar{c}'_{HL}}{v^2}\left[\bar{L}_L\gamma^\mu T_{2k} L_L\right]\left[\Phi^\dagger T_2^k \overleftrightarrow{D}_\mu \Phi\right] \\
& + \frac{i\bar{c}_{He}}{v^2}\left[\bar{e}_R\gamma^\mu e_R\right]\left[\Phi^\dagger \overleftrightarrow{D}_\mu \Phi\right]
\end{aligned}$$

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→ leptonic $\psi^2\varphi^2 D$ op's

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→ leptonic $\psi^2\varphi^2 D$ op's

"mapping" HEL → GIMR: $\bar{c}_i = \frac{v^2}{\Lambda^2} f_i$ $f_i \sim O(1)$ …

The SMEFT & heavy vector-boson exchanges: the $\psi^2\varphi^2 D$ class operators

Constraints: e.g., Contino et al., JHEP2013 (arxiv: 1303.3876)

- $\psi^2\varphi^2 D$ class operators modify couplings of Z to quarks and leptons

$$\frac{\delta g_{L\psi}}{g_{L\psi}} = \frac{1}{2}\frac{(-\bar{c}_{H\Psi} + 2\,T_{3L}\,\bar{c}'_{H\Psi})}{T_{3L} - Q\sin^2\theta_W}\,, \qquad \frac{\delta g_{R\psi}}{g_{R\psi}} = \frac{1}{2}\frac{\bar{c}_{H\psi}}{Q\sin^2\theta_W}$$

- Tightly constrained by Z-pole measurements at LEP1
- Independent of Higgs physics

use PEWD

$$-0.0009 < \bar{c}_{He} < 0.003,$$

$$-0.0003 < \bar{c}_{HL} + \bar{c}'_{HL} < 0.002$$

$$-0.002 < \bar{c}_{HL} - \bar{c}'_{HL} < 0.004$$

in terms of Λ (e.g., for O_{HL}):

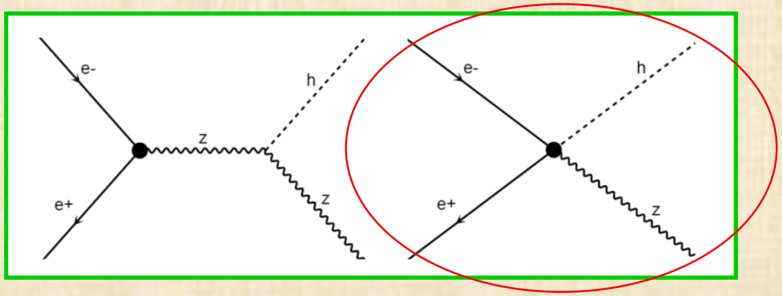
$$\bar{c}_i = \frac{v^2}{\Lambda^2} f_i$$

$$-0.0003 < \bar{c}_{HL} < 0.002$$

$f_i = -1$	$f_i = 1$
$\Lambda \gtrsim 14\,TeV$	$\Lambda \gtrsim 5.5\,TeV$

$e^+e^- \to hZ, hhZ$ *& the* $\psi^2\varphi^2 D$ class operators

$e^+e^- \to hZ$



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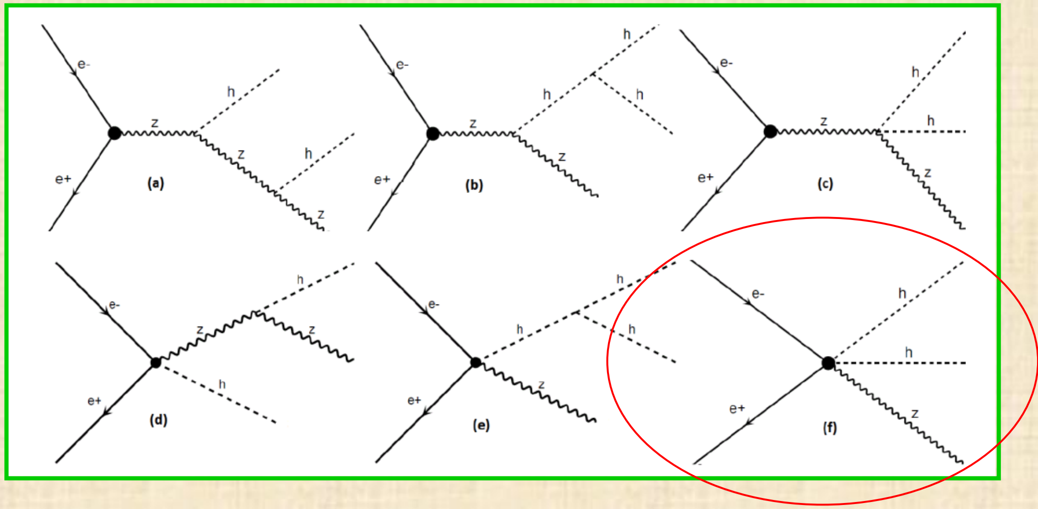

$e^+e^- \rightarrow hZ, hhZ$ *& the* $\psi^2\varphi^2D$ class operators

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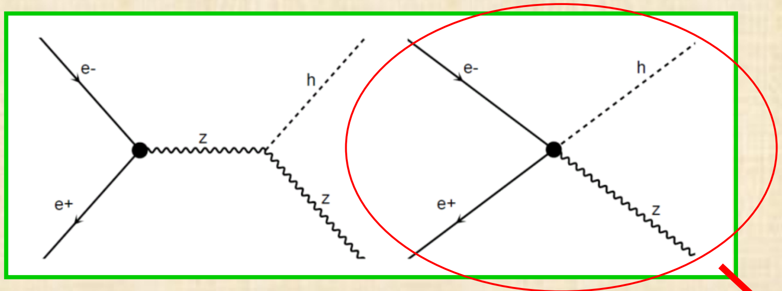
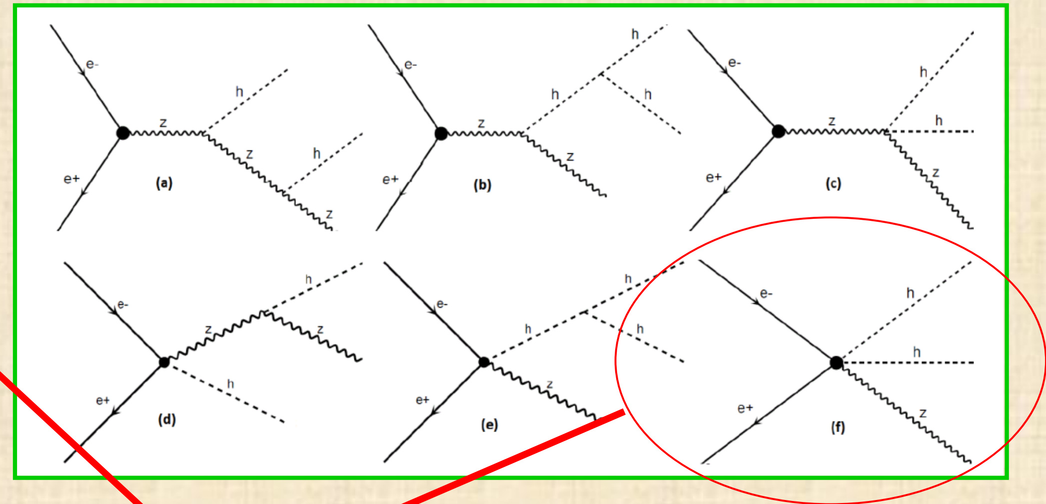


$e^+e^- \rightarrow hhZ$



$$d\sigma(hZ,hhZ) = d\sigma_{SM}(hZ,hhZ)\left(1+\frac{s}{\Lambda^2}\delta_1(f_i)+\frac{s^2}{\Lambda^4}\delta_2(f_i)\right)$$

$$\delta_1(s,f_i) = \frac{1}{2c_W s_W}\,\frac{a_e\left[(f_{HL}+f'_{HL})-\frac{f_{He}}{2}\right]+v_e\left[(f_{HL}+f'_{HL})+\frac{f_{He}}{2}\right]}{a_e^2+v_e^2}\,\frac{v^2}{M_Z^2}\,,$$

$$\delta_2(s,f_i) = \left(\frac{1}{4c_W s_W}\right)^2\frac{\left[(f_{HL}+f'_{HL})-\frac{f_{He}}{2}\right]^2+\left[(f_{HL}+f'_{HL})+\frac{f_{He}}{2}\right]^2}{a_e^2+v_e^2}\left(\frac{v^2}{M_Z^2}\right)^2$$

- An interesting hZ – hhZ correlation …
- Same sensitivity to f_{HL} & f'_{HL}

$e^+e^- \to$ hZ, hhZ: *numerical analysis*

Sensitivity:

$$N_{SD}\left(\sqrt{s}, f_i, \Lambda\right) \equiv \frac{N^T - N^{SM}}{\sqrt{N^T}}$$

$$N^{T,SM} = \sigma^{T,SM} L$$

Benchmark designs:

E_{cm} [TeV]	L [fb^{-1}]
0.5	500
1	1000
2	2000
3	2500

$e^+e^- \longrightarrow hZ, hhZ$: *numerical analysis*

"Validity" function:

$$\mathcal{R} \equiv \frac{\Delta\sigma_2}{\sigma_1}$$

$$\sigma = \sigma_{SM}\left(1 + \underbrace{\frac{\delta_1(s,f_i)}{\Lambda^2}}_{\sigma_1} + \underbrace{\frac{\delta_2(s,f_i)}{\Lambda^4}}_{\Delta\sigma_2}\right)$$

Values of Λ for which R>1 are considered to be inconsistent with the EFT prescription …

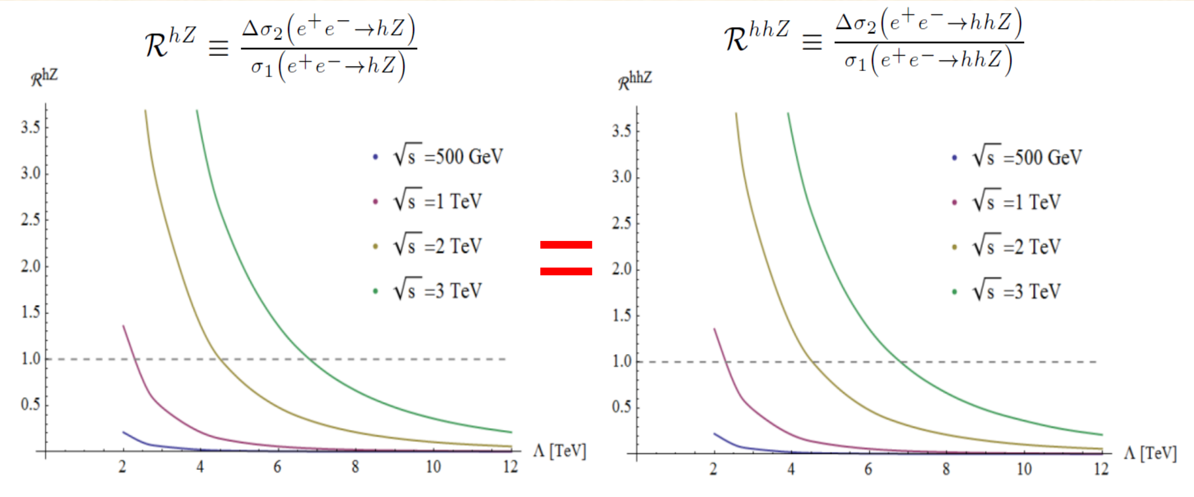
Limitations of the EFT

"Validity" function:

$$\mathcal{R} \equiv \frac{\Delta\sigma_2}{\sigma_1} \qquad \sigma = \sigma_{SM}\left(1 + \underbrace{\frac{\delta_1(s,f_i)}{\Lambda^2}}_{\sigma_1} + \underbrace{\frac{\delta_2(s,f_i)}{\Lambda^4}}_{\Delta\sigma_2}\right)$$

*Values of Λ for which **R>1** are considered to be inconsistent with the EFT prescription …*

E_{cm}=0.5 TeV	√
E_{cm}=1 TeV	Λ > 2.5 TeV
E_{cm}=2 TeV	Λ > 4.5 TeV
E_{cm}=3 TeV	Λ > 7 TeV



Results for the $\psi^2\varphi^2 D$ op's cannot be "trusted" below these values without knowing the full dim 8 effect …

Naive Analysis

$\sigma\ (e^+e^- \to hZ,\ hhZ) \cdot BR(h,Z \to F)$

Realistic Background Analysis

full simulation of backg with appropriate kinematic & acceptance cuts

(but still a theorist analysis …)

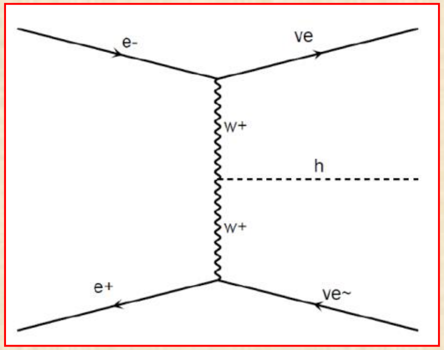
NA ~ RBA

BG considerations

BG depends on the subsequent decays of h & Z:

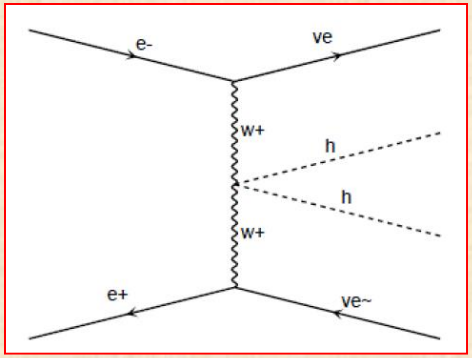
$Z \rightarrow \nu\nu$: dominant BG from WW-fusion
(in particular @ $E_{cm} \geq 1$ TeV)
$Z \rightarrow ee$: dominant BG from ZZ-fusion

e+e- → hZ → hνν



e.g., BG for the hνν & hhνν fs

e+e- → hhZ → hhνν



BG considerations

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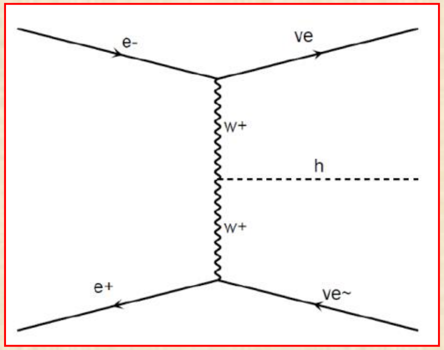
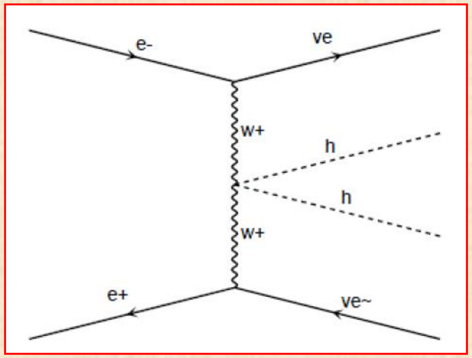
$Z \to \nu\nu$: dominant BG from WW-fusion
(in particular @ $E_{cm} \geq 1$ TeV)
$Z \to ee$: dominant BG from ZZ-fusion

$e^+e^- \to hZ \to h\nu\nu$



e.g., BG for the $h\nu\nu$ & $hh\nu\nu$ fs

$e^+e^- \to hhZ \to hh\nu\nu$

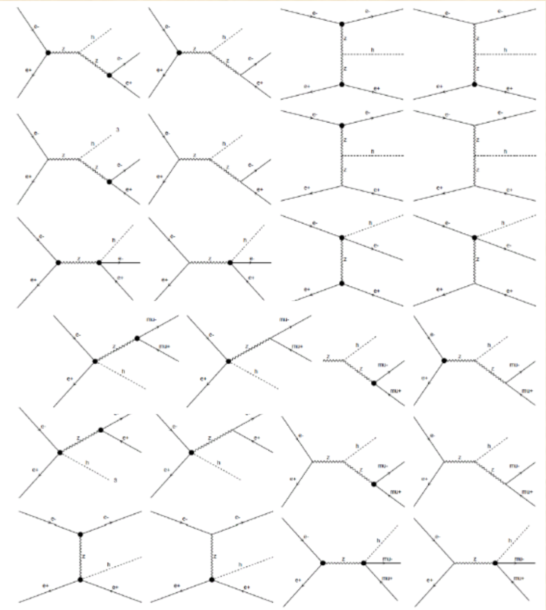


Consider all SM + NP(O_{HL}) diagrams for any of the final states and optimize with a set of kinematic + acceptance cuts:

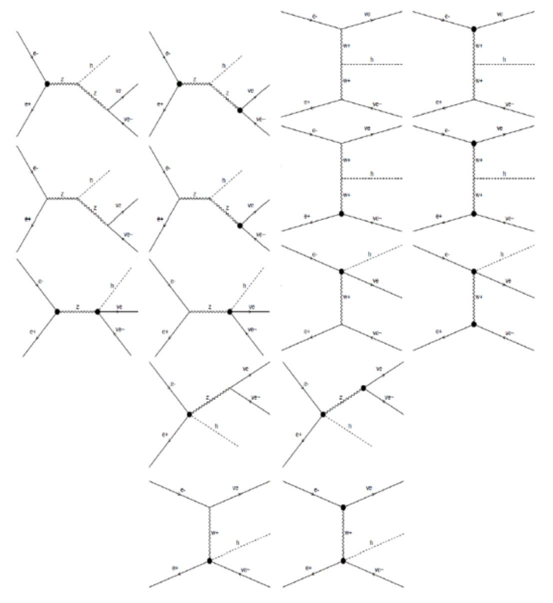
e.g., for $e^+e^- \to hZ \to hee$: 85 GeV < M_{ee} < 95 GeV
$p_T(e)$ > 15 GeV, $p_T(ee)$ > 80 GeV

e+e- → hZ: *full set of SM + NP diagrams*

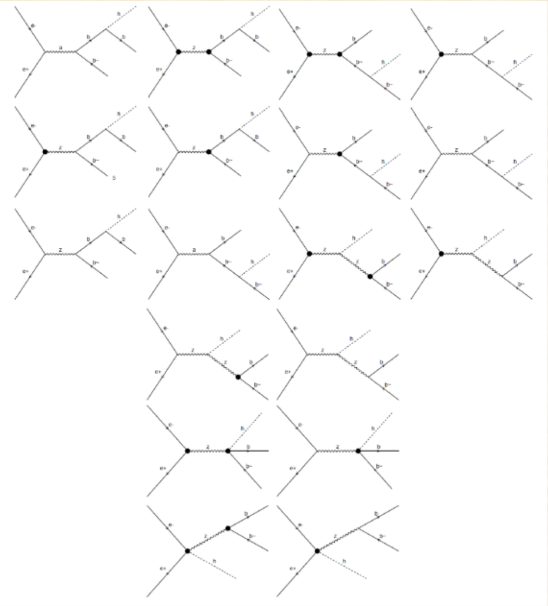
e+e- → hZ → hee+hμμ: 24 diag's



e+e- → hZ → hνν: 16 diag's

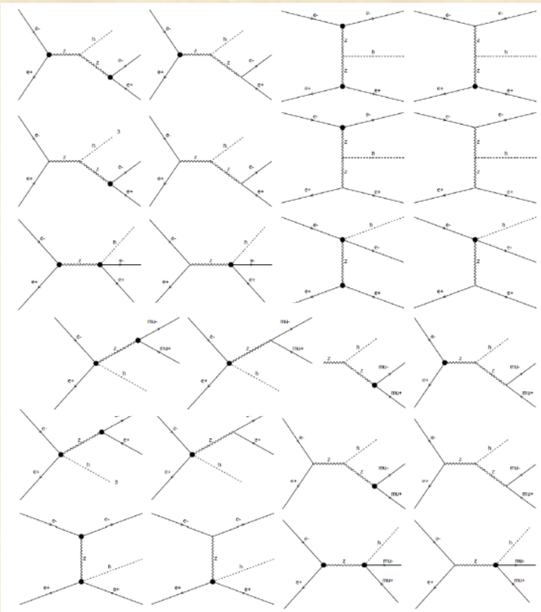


e+e- → hZ → hbb: 18 diag's

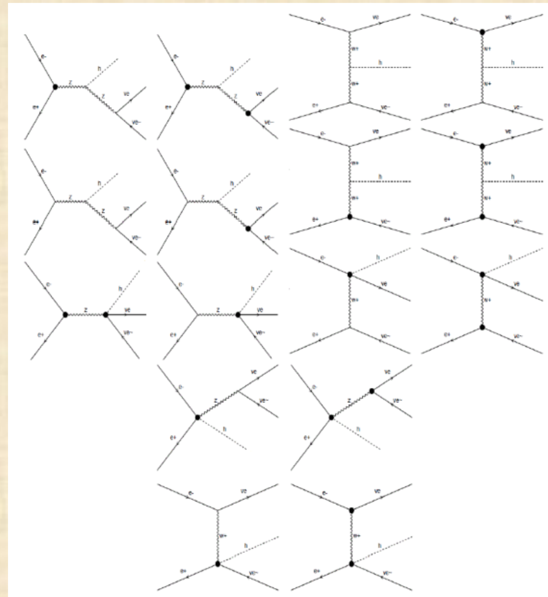


e+e- → hZ: *full set of SM + NP diagrams*

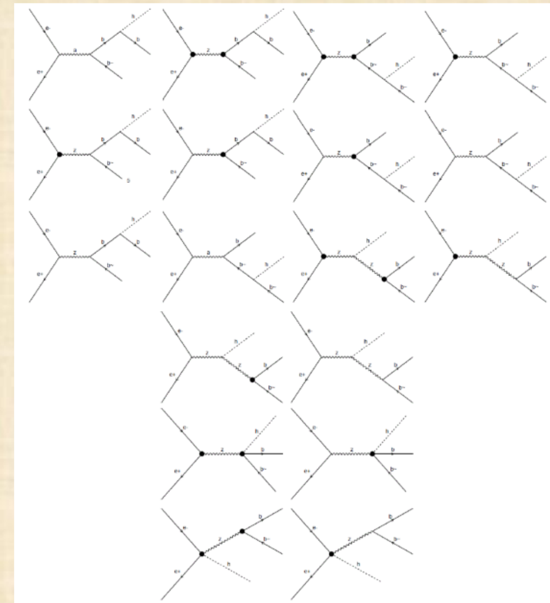
e+e- → hZ → hee+hμμ: 24 diag's



e+e- → hZ → hνν: 16 diag's



e+e- → hZ → hbb: 18 diag's



e+e- → hZ → hνν: comparison with naive estimates

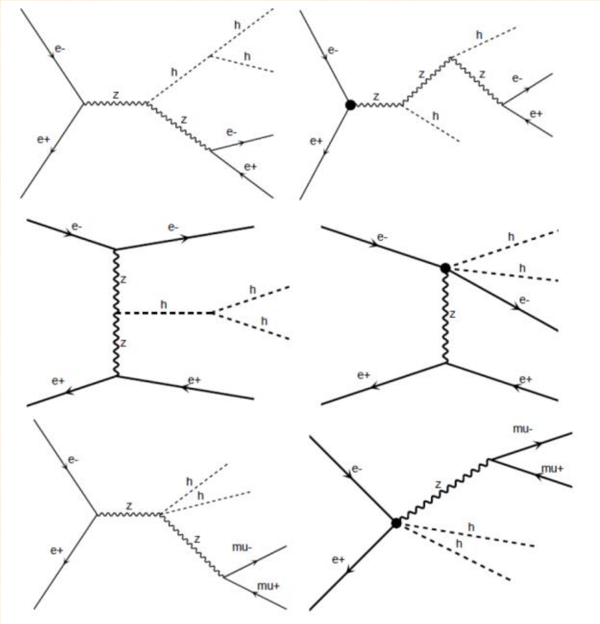
	$\sqrt{s}$=500 GeV			$\sqrt{s}$=1 TeV		
	Before cuts	After cuts	$\sigma_{hZ} \times \mathcal{BR}_Z$	Before cuts	After cuts	$\sigma_{hZ} \times \mathcal{BR}_Z$
σ^{SM} [fb]	757	3.64	3.74	205.7	0.7874	0.840
$(\sigma^T)_{\Lambda=6\,TeV}$ [fb]	759	4.029	4.16	206.7	1.182	1.127

	$\sqrt{s}$=2 TeV			$\sqrt{s}$=3 TeV		
	Before cuts	After cuts	$\sigma_{hZ} \times \mathcal{BR}_Z$	Before cuts	After cuts	$\sigma_{hZ} \times \mathcal{BR}_Z$
σ^{SM} [fb]	374.9	0.1889	0.203	483.6	0.0834	0.0898
$(\sigma^T)_{\Lambda=6\,TeV}$ [fb]	376	0.7574	0.8190	485.8	0.9561	1.03

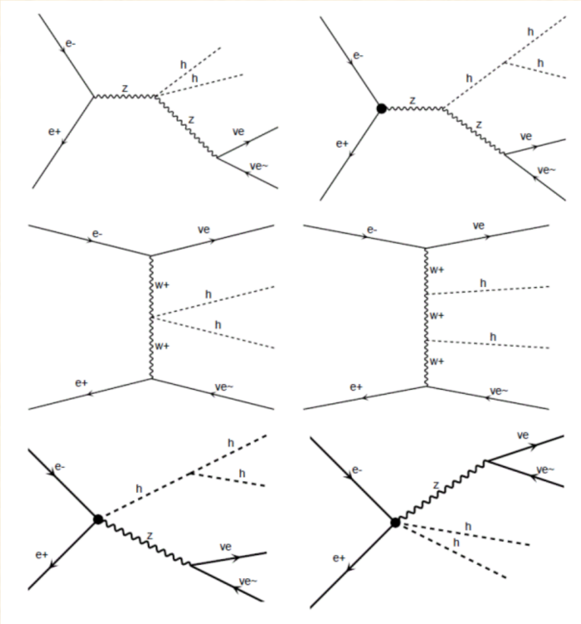
TABLE II: SM and SM+NP cross-sections in the $e^+e^- \to h\nu_e\overline{\nu}_e$ channel including all SM and NP diagrams, after imposing the cut on the missing invariant mass of the two neutrinos $m_Z - 4\Gamma_Z < \mathcal{M}_{\nu_e\overline{\nu}_e} < m_Z + 4\Gamma_Z$ (in order to suppress the WW-fusion BG, see Fig. 2 and Appendix C). Also shown are the corresponding naive cross-sections of section V: $\sigma_{hZ} \times \mathcal{BR}_Z$, where $\sigma_{hZ} \equiv \sigma\left(e^+e^- \to hZ\right)$ and $\mathcal{BR}_Z \equiv \mathcal{BR}\left(Z \to \nu_e\overline{\nu}_e\right) = 6.6\%$. Results are given for $\sqrt{s}$=500 GeV, 1 TeV (upper table) and 2 ,3 TeV (lower table). For the NP cross-section we take Λ =6 TeV.

e+e- → hhZ: *sample diagrams*

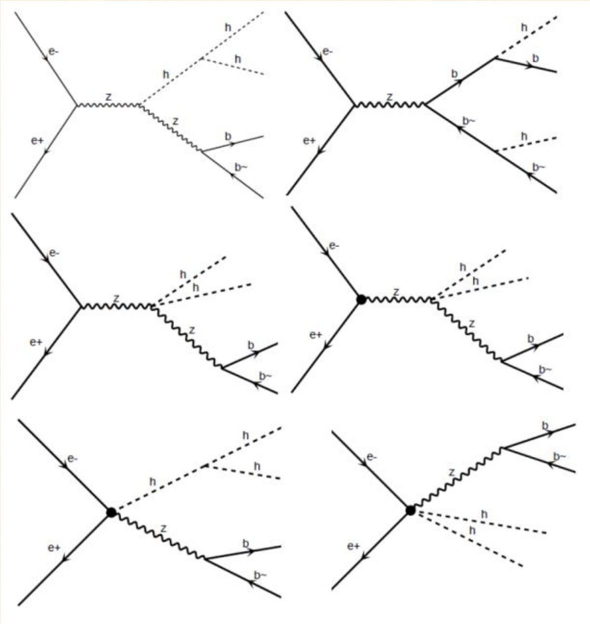
$e^+e^- \to hhZ \to hhee + hh\mu\mu$: ~ 100 diag's



$e^+e^- \to hhZ \to hh\nu\nu$: ~ 70 diag's



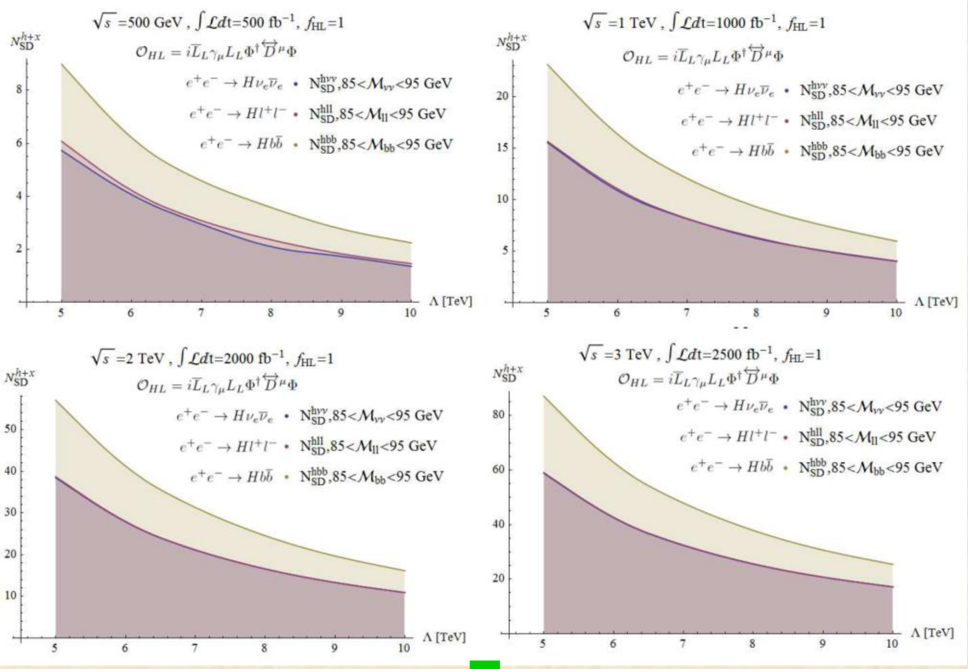
$e^+e^- \to hhZ \to hhbb$: ~ 100 diag's



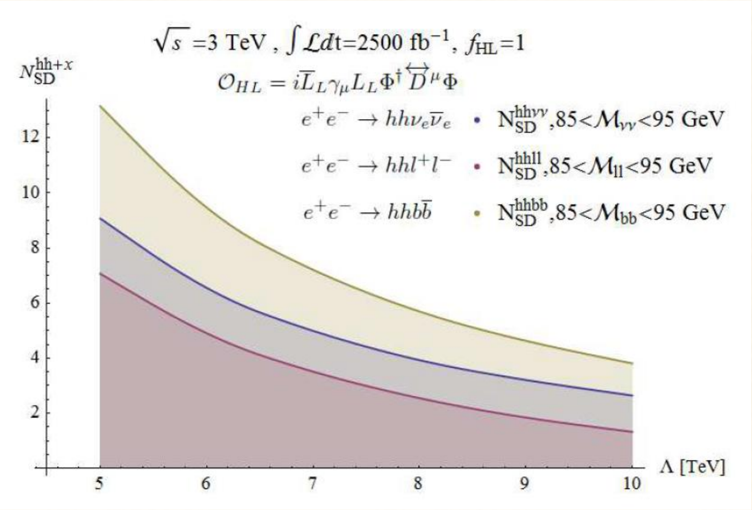
Sensitivities

$$\frac{1}{\Lambda^2} i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \overline{\psi}\gamma^\mu\psi$$

e+e- → hZ → hee+hμμ, hνν, hbb



e+e- → hhZ → hhee+hhμμ, hhνν, hhbb



$\sqrt{s}$	$N_{SD}^{hll}, N_{SD}^{h\nu\nu}$	Λ
500 GeV	6σ	5 TeV
1 TeV	10σ	6 TeV
2 TeV	20σ	7 TeV
3 TeV	25σ	8 TeV

$\sqrt{s}$	N_{SD}^{hbb}	Λ
500 GeV	6σ	6 TeV
1 TeV	10σ	8 TeV
2 TeV	20σ	9 TeV
3 TeV	25σ	10 TeV

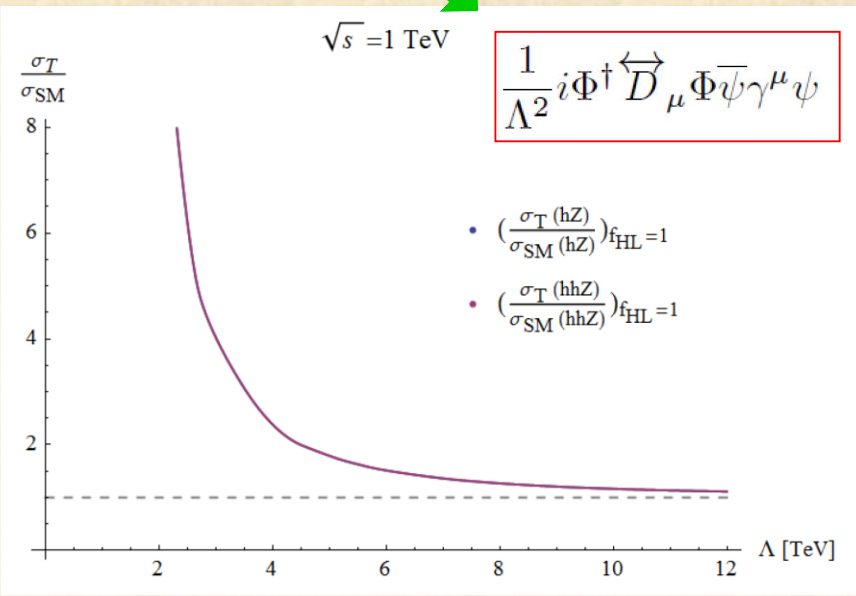
$e^+e^- \to hhz \to hh + x$ for $\Lambda = 7$ TeV			
	N_{SD}^{hhll}	$N_{SD}^{hh\nu\nu}$	N_{SD}^{hhbb}
$\sqrt{s} = 3$ TeV	3.5σ	5σ	7σ

Λ~O(10 TeV) easily probed @ ILC & CLIC

Λ ~ 7 TeV, borderline sensitivity @ CLIC energies

An hZ – hhZ correlation

Due to similarity of diff CSX's: $$\frac{\sigma^T(hZ)}{\sigma^{SM}(hZ)} = \frac{\sigma^T(hhZ)}{\sigma^{SM}(hhZ)}$$



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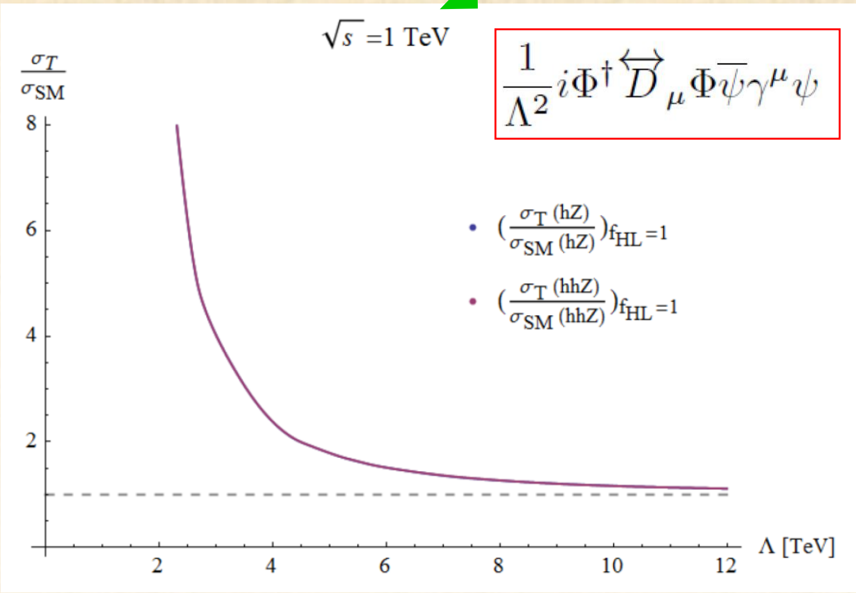
Due to similarity of diff CSX's: $$\frac{\sigma^T(hZ)}{\sigma^{SM}(hZ)} = \frac{\sigma^T(hhZ)}{\sigma^{SM}(hhZ)}$$



useful observable

$$R_{hZ/hhZ} = \frac{\frac{\sigma^T(hZ)}{\sigma^{SM}(hZ)}}{\frac{\sigma^T(hhZ)}{\sigma^{SM}(hhZ)}}$$

may play a key role in distinguishing between different NP scenarios!

e.g., NP in the form of anomalous Higgs trilinear couplings will exhibit a different behavior: $R_{hZ/hhZ} \neq 1$

SUMMARY

- The dim 6 $\psi^2\varphi^2D$ class op's (generated by tree-level exchanges of heavy vector-boson exchanges in the underlying UV theory) give rise to interesting new eehZ & eehhZ contact interactions.

- ee $\rightarrow$ hZ @ the ILC/CLIC is expected to be sensitive to $\Lambda_{\psi2\varphi2D} \sim O(10\ \text{TeV})$

- ee $\rightarrow$ hhZ: $\Lambda_{\psi2\varphi2D} \sim O(7\ \text{TeV})$ borderline at a 3 TeV CLIC, but
  - very useful for probing the NP type due to a potential correlation with ee $\rightarrow$ hZ
  - for $\Lambda_{\psi2\varphi2D} < 7$ TeV need to calculate/estimate the dim 8 contribution

- **Outlook:**
  - A full study of all dim 6 SMEFT effect in ee $\rightarrow$ hZ,hhZ (multiple operators)
  - Initial beam polarization effects
  - A study of the effects of dim 8 op's
  - A study of the sensitivity of pp $\rightarrow$ hV,hhV (LHC) to the $\psi^2\varphi^2D$ class op's

ADDITIONS

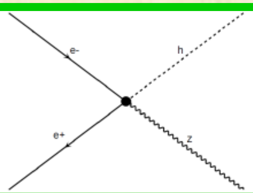
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{f_j^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

dim 8 operators

$$\frac{1}{\Lambda^2} i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \overline{\psi}\gamma^\mu\psi$$

$$\frac{1}{\Lambda^4} i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \overline{\psi}\gamma^\mu\psi (\Phi^\dagger\Phi)$$

$$\frac{v^2}{\Lambda^2}\times$$



$$\frac{1}{(\Box - M^2)} \underbrace{\approx}_{\Box \ll M^2} -\frac{1}{M^2}\sum_{k=0}^{\infty}\left(\frac{\Box}{M^2}\right)^k \approx -\frac{1}{M^2}\left(1+\frac{\Box}{M^2}\right)$$

$$\frac{1}{\Lambda^4} i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \Box\overline{\psi}\gamma^\mu\psi$$

differential distributions

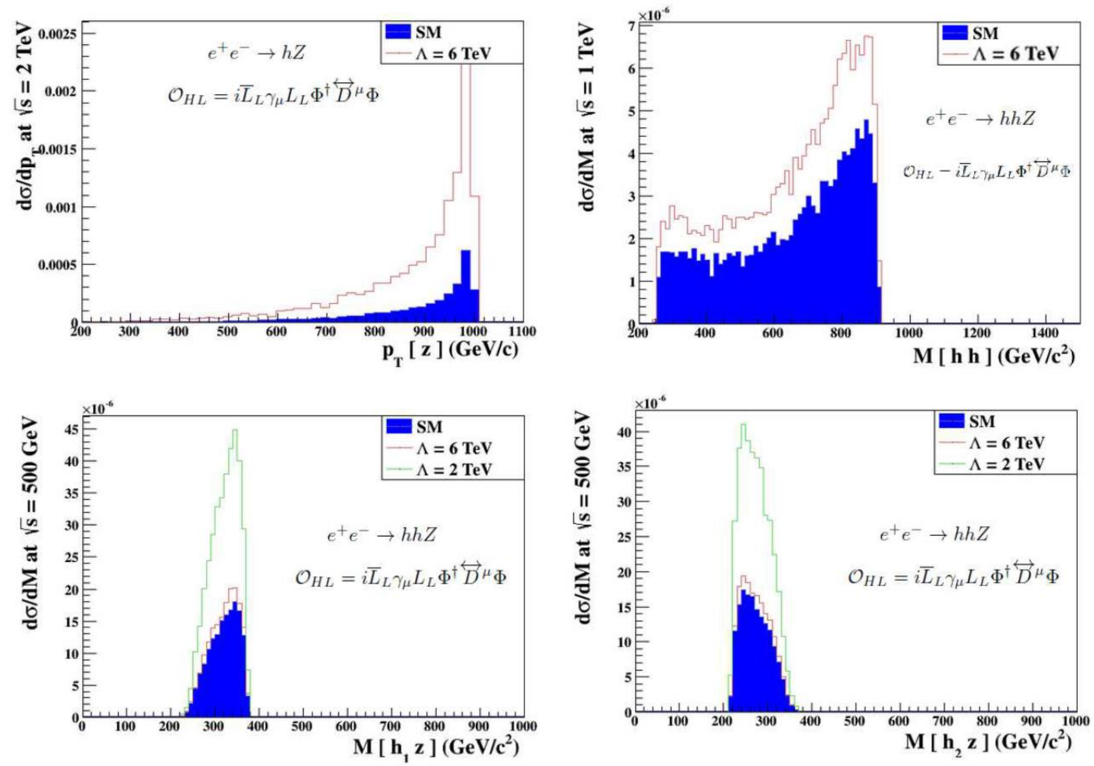
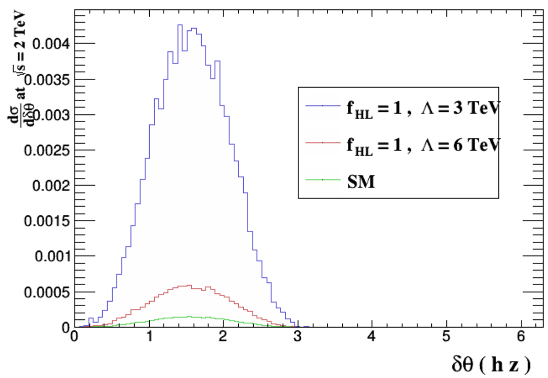
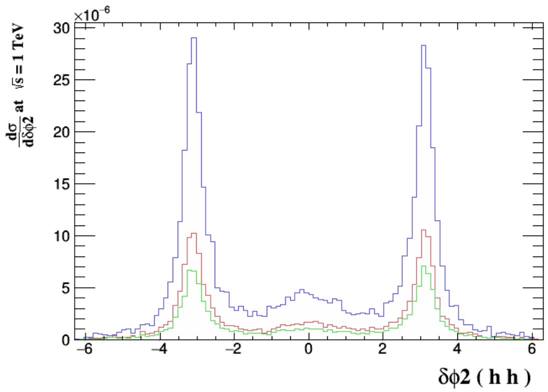


FIG. 12: The p_T (Z) distribution in $e^+e^- \to hZ$ at $\sqrt{s}$ =2 TeV (upper left), the invariant mass distribution of hh in $e^+e^- \to hhZ$ at $\sqrt{s}$ =1 TeV (upper right), the invariant mass distribution of Z + the Higgs with the largest-p_T in $e^+e^- \to hhZ$ at $\sqrt{s}$ =500 GeV (lower left) and the invariant mass of Z + the Higgs with the 2nd largest-p_T in $e^+e^- \to hhZ$ at $\sqrt{s}$ =500 GeV (lower right). The blue-solid histogram depicts the SM predictions while the red (green) solid lines correspond to the total cross-section including the effect of $\mathcal{O}_{HL}$, where $f_{HL} = 1$ and $\Lambda = 6$ TeV ($\Lambda = 2$ TeV).





heavy vectors operators

Consider for example the case where a new heavy vector singlet field V'_μ, with a mass $M \gg v$, is added to the SM lagrangian (the heavy vector can be thought of as some $U(1)'$ remnant of a higher broken symmetry). The lagrangian piece for V'_μ then reads:

$$\mathcal{L} = -\frac{1}{4}V'_{\mu\nu}V'^{\mu\nu} + \frac{1}{2}M^2 V'_\mu V'^\mu + V'_\mu \left(gi\Phi^\dagger \overleftrightarrow{D}^\mu \Phi + \tilde{g}\overline{\psi}\gamma^\mu\psi \right) , \qquad (2)$$

where, the "Hermitian derivative" in (2) is defined as $\Phi^\dagger \overleftrightarrow{D}_\mu \Phi \equiv \Phi^\dagger D_\mu \Phi - D_\mu \Phi^\dagger \Phi$.

Integrating out the heavy field V'_μ, by using its Equation of Motion (EOM), we can express V'_μ in terms of the SM light fields:

$$V'_\mu = -\frac{1}{(\Box - M^2)} \left(g\Phi^\dagger \overleftrightarrow{D}^\mu \Phi + \tilde{g}\overline{\psi}\gamma^\mu\psi \right) , \qquad (3)$$

so that, performing the propagator expansion:

$$\frac{1}{(\Box - M^2)} \underbrace{\approx}_{\Box \ll M^2} -\frac{1}{M^2} \sum_{k=0}^{\infty} \left(\frac{\Box}{M^2} \right)^k , \qquad (4)$$

and keeping only the first term, i.e, $k = 0$, we obtain:

$$V'_\mu \underbrace{\approx}_{\Box \ll M^2} \frac{1}{M^2} \left(g\Phi^\dagger \overleftrightarrow{D}^\mu \Phi + \tilde{g}\overline{\psi}\gamma^\mu\psi \right) . \qquad (5)$$

Plugging now V'_μ in (5) back into the original lagrangian of (2), we obtain the NP Lagrangian piece which emerges from the heavy vector-boson exchange:[2]

$$\Delta\mathcal{L}_{V'} = \frac{f_{V'}}{\Lambda^2}\mathcal{O}_{V'} , \qquad (6)$$

where $f_{V'} = g\tilde{g}$, $\Lambda = M$ and $\mathcal{O}_{V'}$ is the dimension 6 heavy vector singlet operator:

$$\mathcal{O}_{V'} = i\overline{\psi}\gamma^\mu\psi\Phi^\dagger \overleftrightarrow{D}^\mu \Phi . \qquad (7)$$