EFT for Higgsstrahlung

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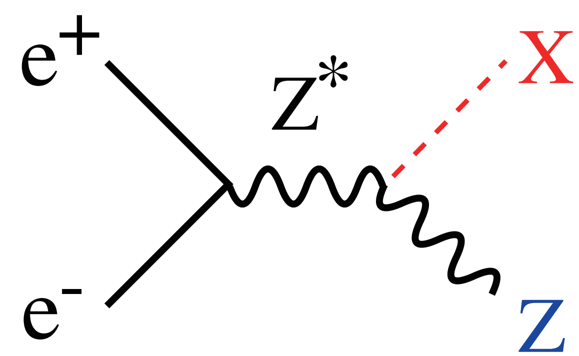
based on work with Nathaniel Craig, Marco Farina, and Matthew McCullough, 1411.0676, JHEP 1503:146

Introduction

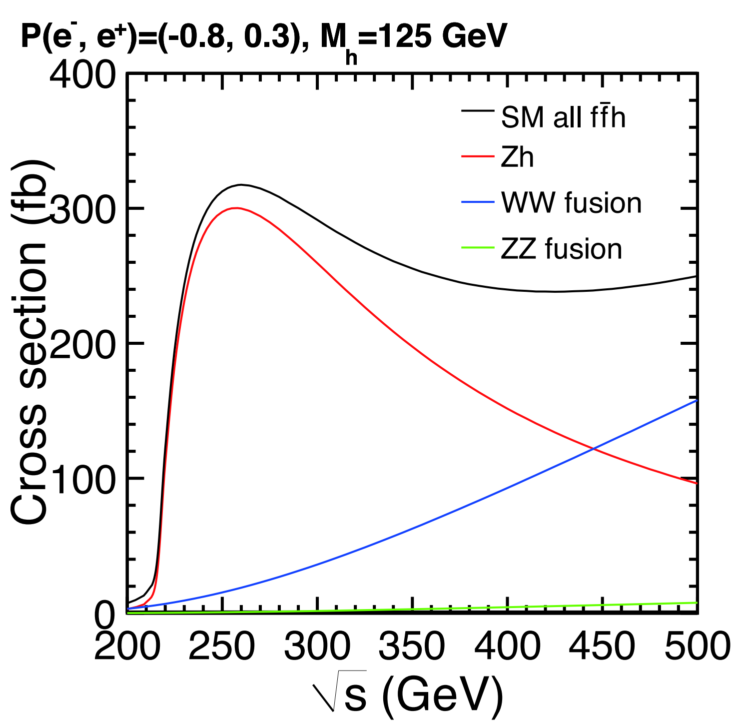
- What is Higgsstrahlung? (a.k.a. Bjorken process)

$e^+e^- \to Zh$



- What's so special about Higgsstrahlung?

1. The dominant channel of H production in e+e- collisions for $\sqrt{s}$ between 216 and ~400 GeV



$\sqrt{s} = 250$ GeV

$\sigma_{hZ} \approx 225$ fb (unpol.)

2. "Recoil Mass" technique allows for cross section measurement independent of the Higgs decay channel (no need to observe the Higgs at all!)

$$M_{rec}^2 = (p_{e^+} + p_{e^-} - p_Z)^2$$

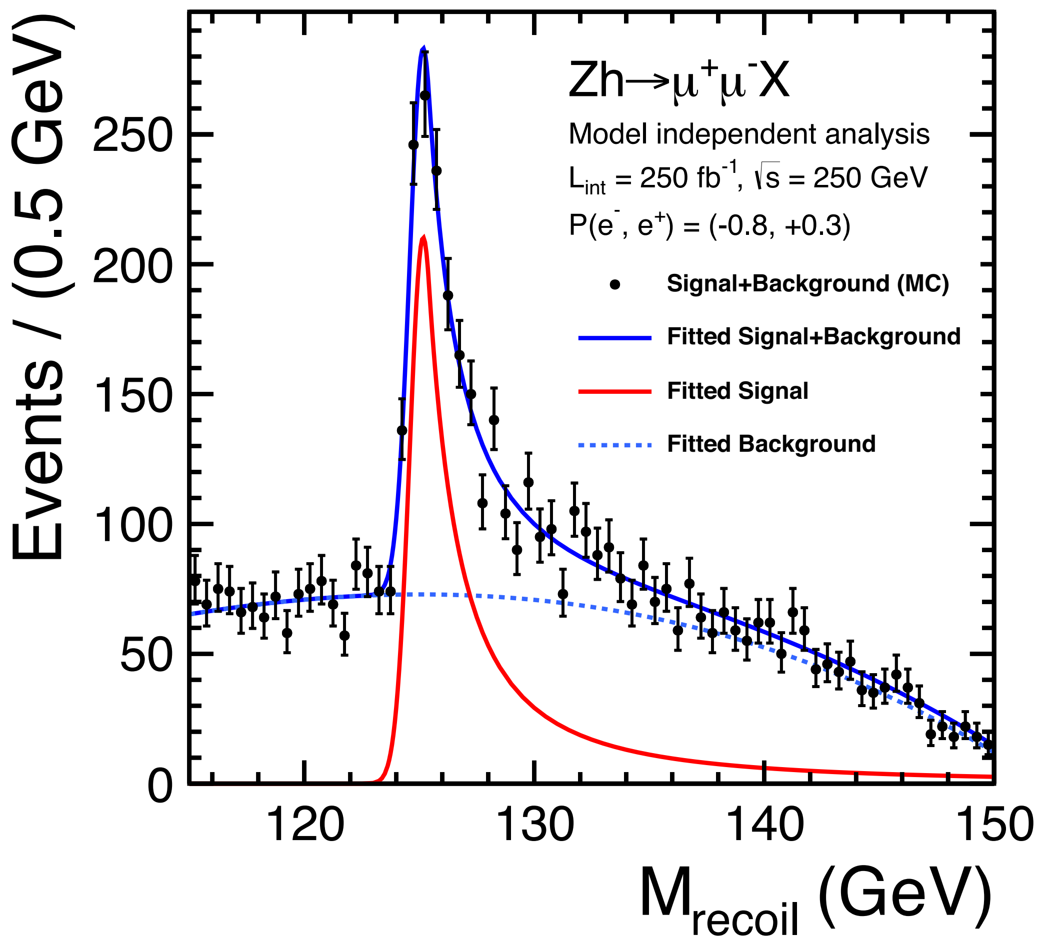
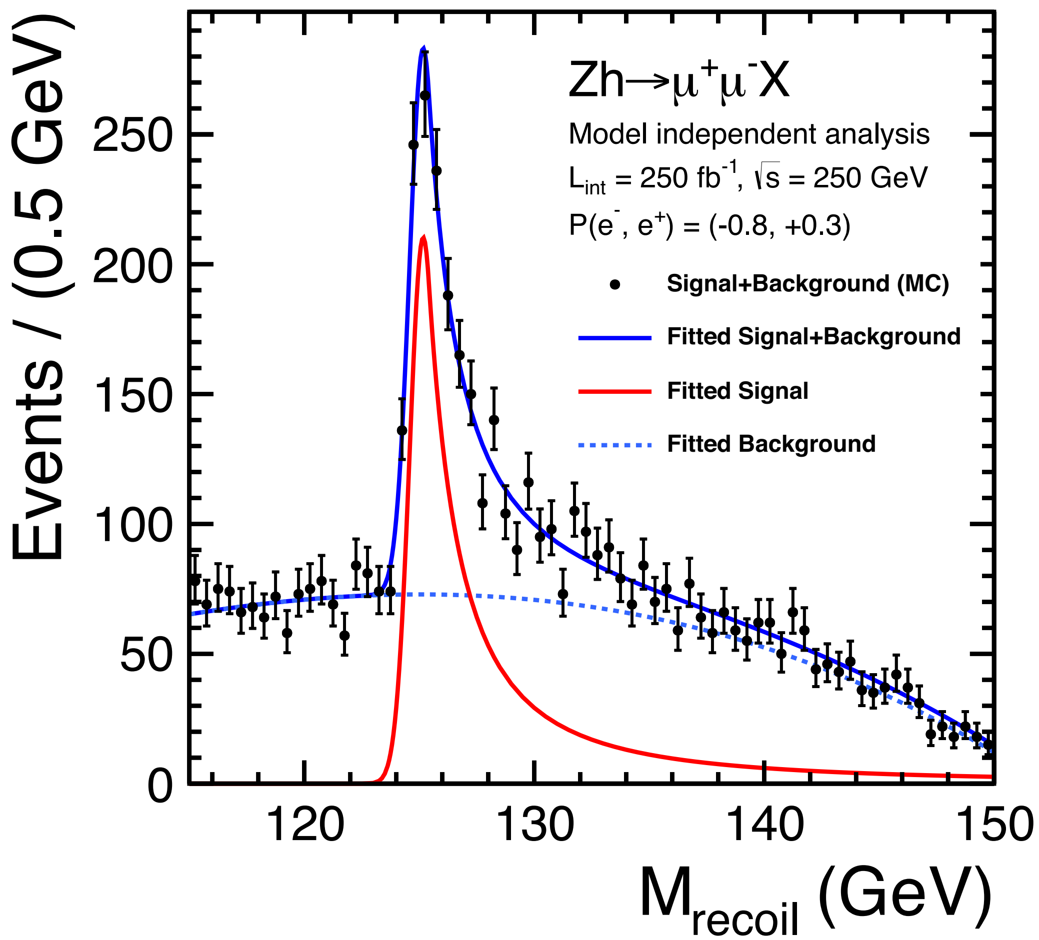


Figure credit: "Physics at the e+e- Linear Collider", 1504.01726

2. "Recoil Mass" technique allows for cross section measurement independent of the Higgs decay channel (no need to observe the Higgs at all!)

$$M^2_{rec} = (p_{e^+} + p_{e^-} - p_Z)^2$$

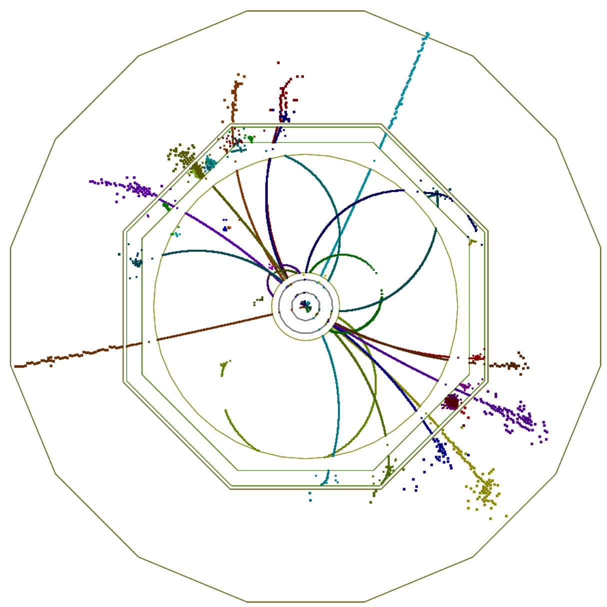
LHC cannot do this, no matter how much data!!!



Collider Shape Doesn't Matter!!!

Figure credit: "Physics at the e+e- Linear Collider", 1504.01726

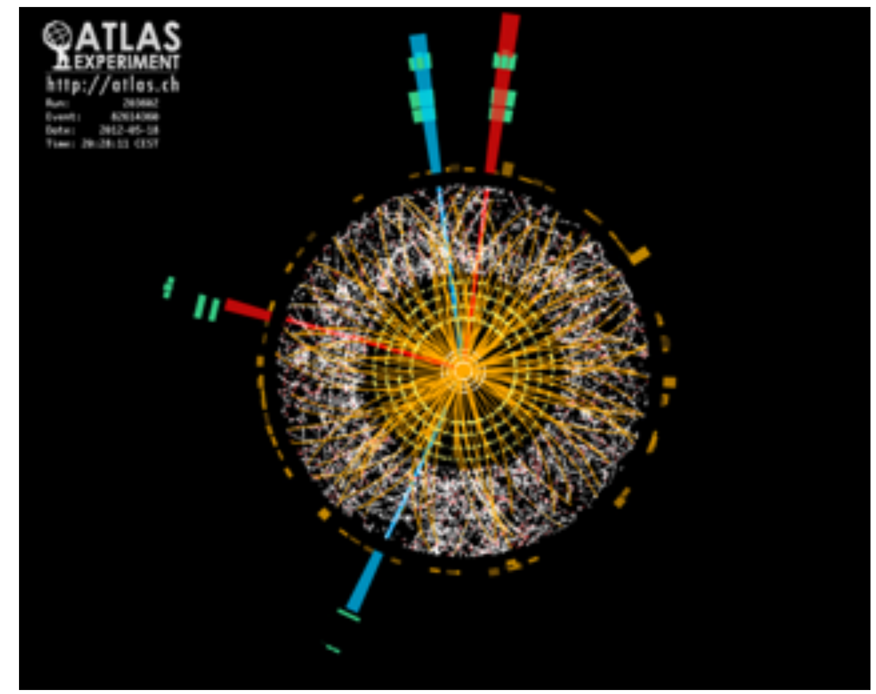
3. Clean events with low occupancy and no pile-up
→ precision measurements are possible!



ILC simulation

$e^+e^- \to hZ, Z \to \mu^+\mu^-, h \to b\bar{b}$

vs.



Assuming statistical errors dominate cross-section measurement ($\sqrt{s}$ =250 GeV, no polarization):

$L_{int} = 200\ \text{fb}^{-1}$ → $\delta\sigma_{Zh}/\sigma_{Zh} \approx 0.5\%$

$L_{int} = 5000\ \text{fb}^{-1}$ → $\delta\sigma_{Zh}/\sigma_{Zh} \approx 0.1\%$

Higgs EFT

- Use precision Higgsstrahlung measurement as a tool to search for new physics beyond the SM
- Assume new physics appears only at scales (motivated by the LHC, although not required by it)
- Effective Field Theory framework to parametrize effects of NP in a model-independent way:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

An irreducible basis for the 9 CP-conserving d=6 ops →

Other bases possible

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{a,\mu\nu}$$
$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{WB} = gg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_H = \tfrac{1}{2}(\partial_\mu|H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_L^{(3)\ell} = (iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu\sigma^a L_L)$$
$$\mathcal{O}_{LL}^{(3)\ell} = (\bar{L}_L\gamma_\mu\sigma^a L_L)(\bar{L}_L\gamma^\mu\sigma^a L_L)$$
$$\mathcal{O}_L^{\ell} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$$
$$\mathcal{O}_R^{e} = (iH^\dagger\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$

- We calculate shifts in $\sigma(e^+e^- \to Zh)$ due to these 9 ops
- Previous work (partial operator sets and/or incomplete calculations, except #12):

1. Hagiwara, Strong, '93
2. Gounaris, Renard, Vlachos, '95
3. Killian, Kramer, Zerwas, '96
4. Gonzales-Garcia, '99
5. Hagiwara, Ishihara, Kamoshita, Kniehl, '00
6. Barger, Han, Langacker, McElrath, Zerwas, '03
7. Biswal, Godbole, Singh, Choudhury, '05
8. Kile, Ramsey-Musolf, '07
9. Dutta, Hagiwara, Matsumoto, '08
10. Contino, Grojean, Pappadopulo, Rattazzi, Thamm, '13
11. Amar, Banerjee, von Buddenbrock, et.al., '14
12. Beneke, Boito, Wang, '14

Calculation

- Post-EWSB Effective Lagrangian:

$$\mathcal{L}_{\text{post}-\text{EWSB}} = \frac{d_1 v^3}{2\Lambda^2} h Z_\mu Z^\mu + \frac{d_2 v}{4\Lambda^2} h \mathcal{Z}_{\mu\nu}\mathcal{Z}^{\mu\nu} + \frac{d_3 v}{2\Lambda^2} h F^{\mu\nu}\mathcal{Z}_{\mu\nu} + \frac{v}{\Lambda^2}\bar{\psi}\gamma^\mu\left(d_4 P_L + d_5 P_R\right)\psi Z_\mu h,$$

$$d_1 = -\frac{g_z^2}{2}\left(\frac{1}{2}c_H + 2c_T\right),$$

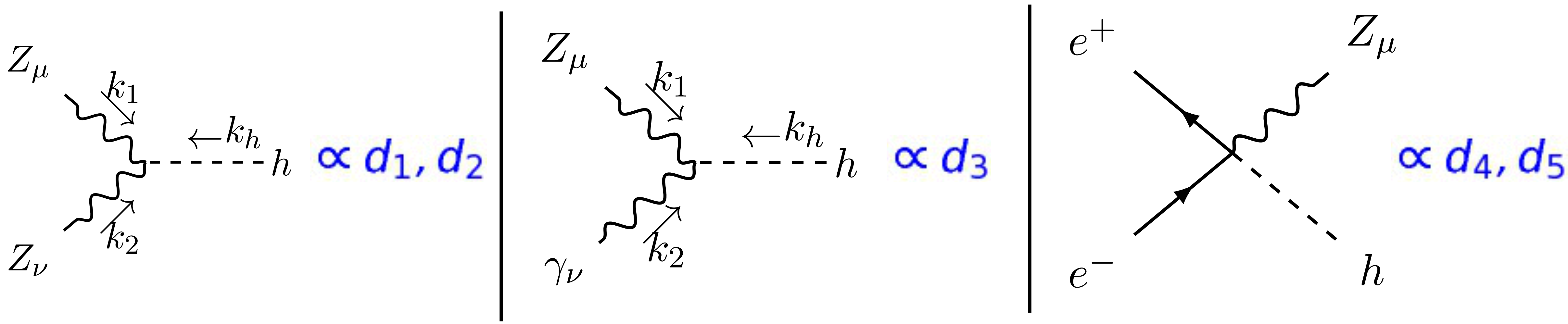
$$d_2 = 4g_z^2\left(s_\theta^4 c_{BB} + s_\theta^2 c_\theta^2 c_{WB} + c_\theta^4 c_{WW}\right),$$

$$d_3 = 2g_z^2 c_\theta s_\theta\left(-2s_\theta^2 c_{BB} - (c_\theta^2 - s_\theta^2)c_{WB} + 2c_\theta^2 c_{WW}\right),$$

$$d_4 = -g_z\left(c_L^{(3)\ell} + c_L^\ell\right),$$

$$d_5 = -g_z c_R^e,$$

- "Direct" Effects: correction to ZZh vertex + 2 new vertices



- "Direct" cross section shift:

$$\frac{d\Delta\sigma}{d\cos\theta} = \frac{g_Z m_Z v}{32\pi\Lambda^2}\frac{p_Z}{s^{3/2}}\sum_{i=1}^{5} d_i F_i(s,t)$$

$$g_Z = \frac{4\sqrt{\pi\alpha}}{\sin 2\theta_W},\ g_L = g_Z\left(-\frac{1}{2}+\sin^2\theta_W\right),$$

$$g_R = g_Z \sin^2\theta_W$$

F_1	$(g_L^2+g_R^2)v^2\frac{2s+\frac{tu}{m_Z^2}-m_h^2}{(s-m_Z^2)^2}$
F_2	$(g_L^2+g_R^2)\frac{s(s+m_Z^2-m_h^2)}{(s-m_Z^2)^2}$
F_3	$-e(g_L+g_R)\frac{s+m_Z^2-m_h^2}{s-m_Z^2}$
F_4	$g_L\frac{2s+\frac{tu}{m_Z^2}-m_h^2}{s-m_Z^2}$
F_5	$g_R\frac{2s+\frac{tu}{m_Z^2}-m_h^2}{s-m_Z^2}$

- Subtlety: need to carefully define "reference" SM cross section

$$\frac{d\sigma_{SM}}{d\cos\theta} = \frac{g_Z^2(g_L^2+g_R^2)m_Z^2}{64\pi}\frac{p_Z}{s^{3/2}}\frac{2s+\frac{tu}{m_Z^2}-m_h^2}{(s-m_Z^2)^2}$$

- At 0.1% precision, corrections to input parameters (g_L, g_R, g_Z) need to be included

- Need 3 measurements to fix the 3 Lagrangian parameters in the electroweak sector
- We considered two input "basis" choices:

(m_Z, G_F, α) (m_Z, m_W, α)

- In each basis, use SM relations to define the "reference" values of the couplings that enter $\sigma(e^+e^- \to Zh)$:

$$\hat{g}_z = \frac{4\sqrt{\pi\alpha}}{\sin 2\hat{\theta}_W} \qquad \hat{g}_{\mathrm{ZZh}} = \hat{g}_z m_Z, \quad \hat{g}_L = \hat{g}_z\left(-\frac{1}{2} + \sin^2\hat{\theta}_W\right), \quad \hat{g}_R = \hat{g}_z \sin^2\hat{\theta}_W$$

$$(m_Z, G_F, \alpha): \quad \sin 2\hat{\theta}_W = \left(\frac{4\pi\alpha}{\sqrt{2}G_F m_Z^2}\right)^{1/2},$$

$$(m_Z, m_W, \alpha): \quad \cos\hat{\theta}_W = \frac{m_W}{m_Z}.$$

- Numerical "SM prediction" is obtained by plugging reference coupling values into the SM cross section formula

- However, new physics modifies relation between input observables and SM Lagrangian couplings

$$g_{\rm ZZh} = \hat{g}_{\rm ZZh} + \delta g_{\rm ZZh}, \quad g_L = \hat{g}_L + \delta g_L, \quad g_R = \hat{g}_R + \delta g_R$$

- This results in a shift between the true and "reference" values of the SM cross section

- The observed "deviation from SM" is actually deviation from the reference SM value:

$$\frac{d\Delta\sigma}{d\cos\theta} = \frac{p_Z}{16\pi s^{3/2}}\left[2\left(\frac{\delta g_{\rm ZZh}}{g_{\rm ZZh}} + \frac{g_L\delta g_L + g_R \delta g_R}{g_L^2 + g_R^2}\right) F_{\rm SM}(s,t) + \frac{g_{\rm ZZh} v}{2\Lambda^2}\sum_{i=1}^{5} d_i F_i(s,t)\right]$$

"indirect": $\sigma_{\rm SM}(g_i) - \sigma_{\rm SM}(\hat{g}_i)$ direct

- Coupling shifts depend on the input basis:

Thanks to Michael Fedderke for spotting an error in v1!

$$(m_Z, G_F, \alpha): \quad \delta g_{\rm ZZh} = \frac{g_{\rm ZZh} v^2}{\Lambda^2}\left(c_T - c_L^{(3)\ell} + c_{LL}^{(3)\ell}\right),$$

$$\delta g_L = \frac{g_z v^2}{2\Lambda^2}\left[-\frac{1}{2(c_\theta^2 - s_\theta^2)}c_T + \frac{2e^2}{c_\theta^2 - s_\theta^2}c_{WB} + \frac{2s_\theta^2}{c_\theta^2 - s_\theta^2}c_L^{(3)\ell} - \frac{1}{c_\theta^2 - s_\theta^2}c_{LL}^{(3)\ell} - c_L^\ell\right],$$

$$\delta g_R = \frac{g_z v^2}{2\Lambda^2}\left[-\frac{s_\theta^2}{c_\theta^2 - s_\theta^2}c_T + \frac{2e^2}{c_\theta^2 - s_\theta^2}c_{WB} + \frac{2s_\theta^2}{c_\theta^2 - s_\theta^2}\left(c_L^{(3)\ell} - c_{LL}^{(3)\ell}\right) - c_R^e\right];$$

$$(m_Z, m_W, \alpha): \quad \delta g_{\rm ZZh} = \frac{g_{\rm ZZh} v^2}{\Lambda^2}\left[\left(1 - \frac{c_\theta^2}{2s_\theta^2}\right)c_T + g^2 c_{WB}\right],$$

$$\delta g_L = \frac{g_z v^2}{2\Lambda^2}\left[\frac{1}{2s_\theta^2}c_T - g^2 c_{WB} - c_L^{(3)\ell} - c_L^\ell\right],$$

$$\delta g_R = \frac{g_z v^2}{2\Lambda^2}\left[c_T - c_R^e\right]. \qquad (3.8)$$

- $\Delta\sigma$ depends on the choice of the input basis; so do bounds on operators from $\sigma(e^+e^- \to Zh)$ alone

- Basis dependence should disappear in a global fit (i.e. propagate errors on input observables, include as constraints observables used as input in other bases)

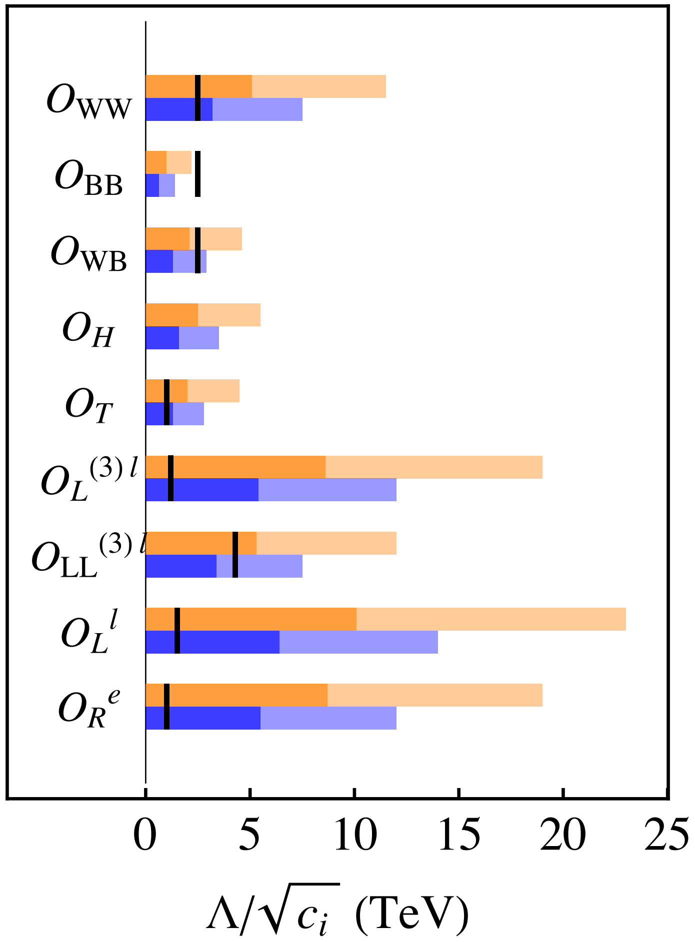
Results

- We find (in (m_Z, G_F, α) basis, at $\sqrt{s} = 250$ GeV):

$$\frac{\Delta\sigma}{\sigma} \approx \Big(0.26c_{WW} + 0.01c_{BB} + 0.04c_{WB} - 0.06c_H - 0.04c_T + 0.74c_L^{(3)\ell} + 0.28c_{LL}^{(3)\ell} + 1.03c_L^\ell - 0.76c_R^e\Big)\Lambda_{\text{TeV}}^{-2},$$

- Sensitivity (2/5 sigma) with 1 operator at a time:

	$\delta\sigma/\sigma = 0.5\%$	$\delta\sigma/\sigma = 0.1\%$	PEW	LHC
$\mathcal{O}_{WW}$	5.1/3.2	11.5/7.5	-	2.5
$\mathcal{O}_{BB}$	1.0/0.64	2.2/1.4	-	2.5
$\mathcal{O}_{WB}$	2.1/1.3	4.6/2.9	0.3	2.5
$\mathcal{O}_H$	2.5/1.6	5.5/3.5	-	-
$\mathcal{O}_T$	2.0/1.3	4.5/2.8	1.0	-
$\mathcal{O}_L^{(3)\ell}$	8.6/5.4	19/12	1.2	-
$\mathcal{O}_{LL}^{(3)\ell}$	5.3/3.4	12/7.5	4.3	-
$\mathcal{O}_L^\ell$	10.1/6.4	23/14	1.5	-
$\mathcal{O}_R^e$	8.7/5.5	19/12	1.0	-

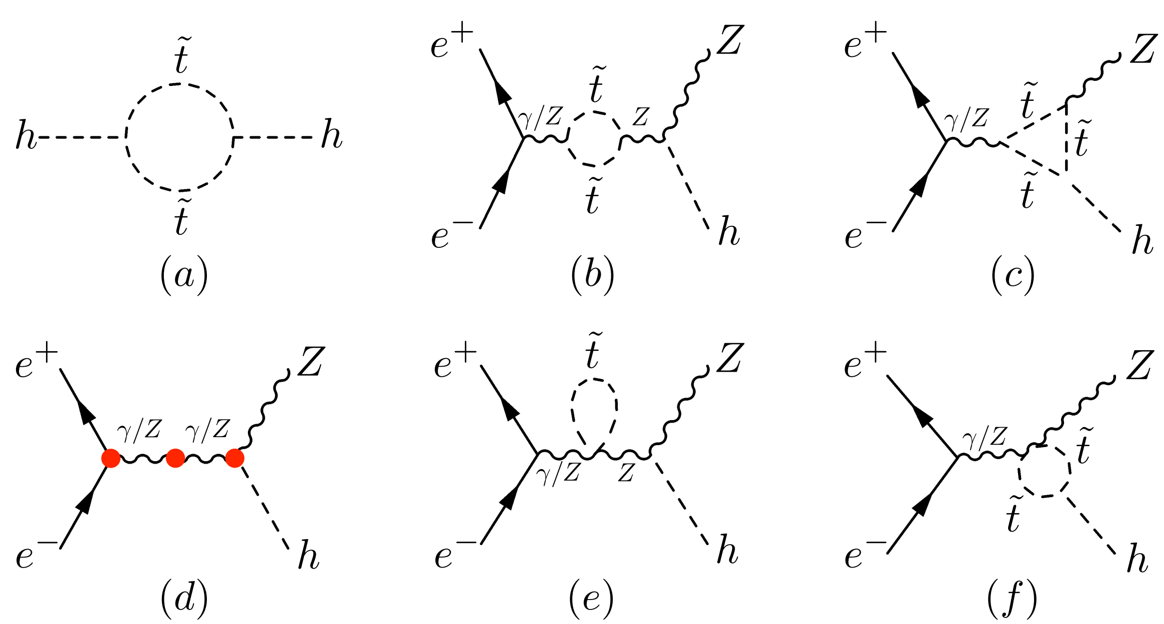


Explicit NP Example

- Now, let's compute the same $\Delta\sigma$ in an explicit BSM model - choose "natural SUSY" with 3rd-gen. squarks at the weak scale, everything else heavy

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Kin,\tilde{t}} - \widetilde{m}_L^2|\widetilde{Q}_3|^2 - \widetilde{m}_R^2|\widetilde{T}_R|^2 - A_t(\widetilde{T}_R H\cdot\widetilde{Q}_3 + h.c.) \\
-\lambda_t^2|H|^2(|\widetilde{Q}_3|^2 + |\widetilde{T}_R|^2) - \frac{g'^2}{2}\left(\frac{2}{3}|\widetilde{T}_R|^2 2 - \frac{1}{6}|\widetilde{Q}_3|^2 - \frac{1}{2}|H|^2\right)^2 \\
-\frac{g^2}{2}\sum_a\left(\widetilde{Q}_3^\dagger\cdot\tau^a\cdot\widetilde{Q}_3 + H^\dagger\cdot\tau^a\cdot H\right)^2,
\end{aligned}
$$

- Compute full NLO correction, not assuming $m_{\tilde{t}} \gg \sqrt{s}$



EFT/Full-NLO Comparison

- In the limit $m_{\tilde{t}} \gg \sqrt{s}$, stop-loop contribution to the cross section can be described in the EFT language
- Henning, Lu, Murayama (HLM) computed the Wilson coefficients for our model, with $\tilde{m}_L = \tilde{m}_R$ and any A_t
- Operator basis used by HLM is slightly different from ours (and slightly redundant), easy to translate using e.o.m. and field redefinitions
- Our NLO calculation used on-mass-shell renormalization scheme (used in FeynArts/FormCalc/LoopTools)
- This corresponds to (m_Z, m_W, α) input basis - crucial to achieve agreement between EFT and NLO!

EFT/Full-NLO Comparison

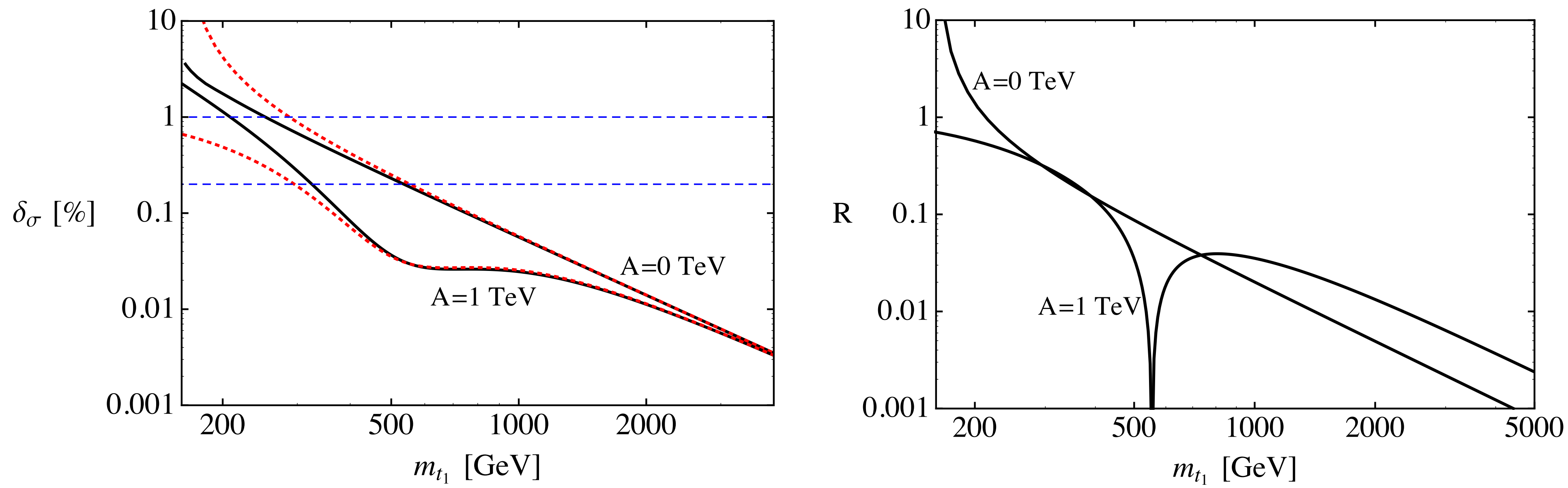
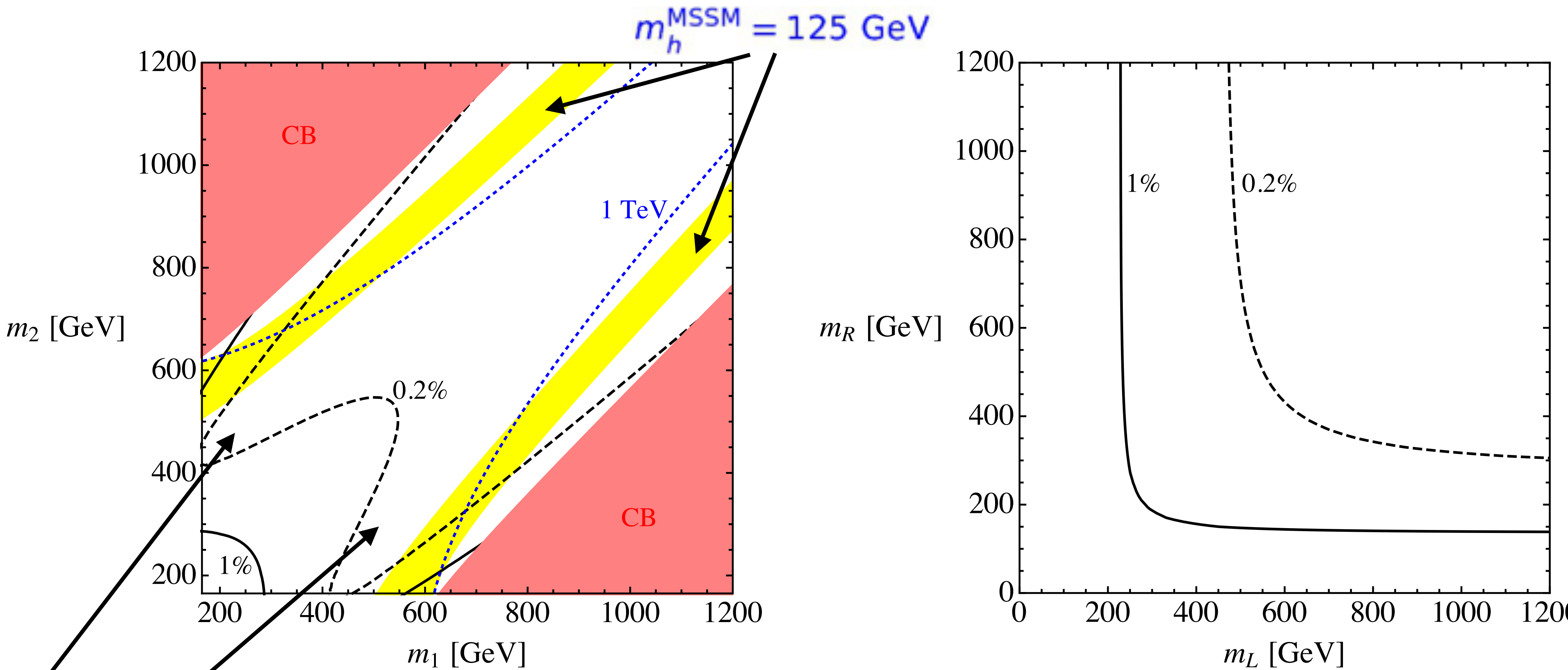


Figure 4: Left: Fractional corrections to the Higgsstrahlung cross section as a function of the physical mass $\widetilde{m}_1$ of the lightest stop squark, for equal soft masses $\widetilde{m}_L = \widetilde{m}_R$ and two values of the A-term. NLO results are shown in solid black and EFT results in dashed red. For comparison the conservative and optimistic estimates of the 2σ reach of a Higgs factory are shown in dashed blue. Right: The ratio of EFT to NLO results $R = \delta_\sigma^{EFT}/\delta_\sigma^{NLO} - 1$ for the same parameters.

Perfect agreement in the $m_{\tilde{t}} \gg \sqrt{s}$ limit provides a highly non-trivial check on our EFT and NLO calculations as well as HLM matching calculation!

Sensitivity to Stops



$\tilde{m}_L = \tilde{m}_R$

$A_t = 0$

"blind spots":

$$\mathcal{L}_{eff} = y_t^2 \left(1 - \frac{X_t^2}{m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2}\right) |H|^2 |\tilde{t}_1|. \rightarrow 0$$

Can probe stops up to 300-500 GeV, with optimistic luminosity assumptions. Not super-impressive. But completely independent of stop decays.

Conclusions

- Precision Higgsstrahlung cross section measurement at e+e- Higgs factories will give a powerful tool to search for new physics
- Presented a complete calculation of the d=6 HEFT correction
- Both direct and indirect (true vs. reference coupling) contributions need to be taken into account to compute deviation of cross section from the SM
- Once they are, excellent agreement between HEFT and full-NLO calculations in the $m_{\tilde{t}} \gg \sqrt{s}$ limit is seen in the case of stops