High energy lepton colliders as the ultimate Higgs microscopes

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XXXVI RADPyC

September 09, 2022

JHEP02(2022)176 [arXiv:2109.14634]

In collaboration with

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Overview

1. Motivation
2. SMEFT: anomalous couplings, leptonic high-energy primaries…
3. *Zh* and *ZBF* at e^+e^- colliders
4. Projected sensitivities to EFT couplings
5. Summary and conclusions

Motivation: Where are we standing?

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\
& + i\bar{\psi}\not{D}\psi + h.c. \\
& + \bar{\psi}\mathcal{Y}_{ij}\psi_j\phi + h.c. \\
& + |D_\mu\phi|^2 - V(\phi)
\end{aligned}
$$

SM 10 years ago: gauge and matter fields

SM today: gauge, matter, and Higgs fields

2012 boson: SM-like Higgs

Motivation: Where are we standing?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}\mathcal{Y}_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

SM 10 years ago: gauge and matter fields

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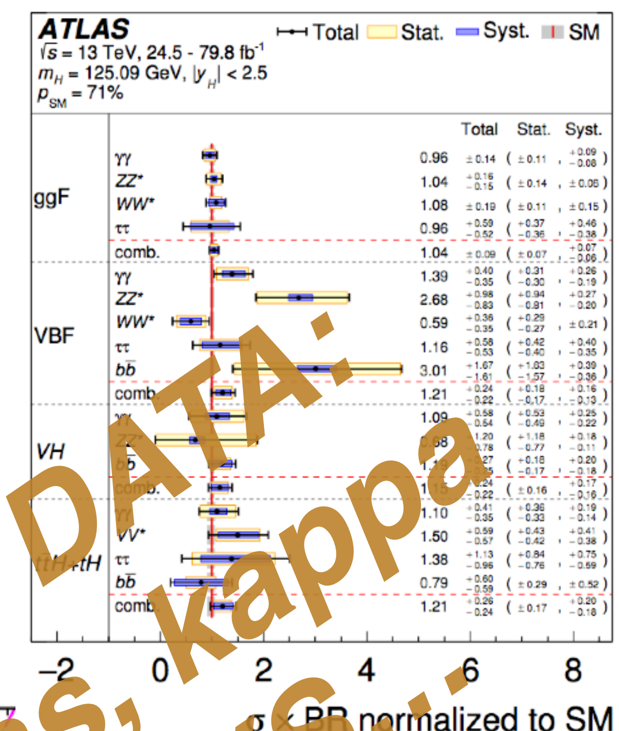
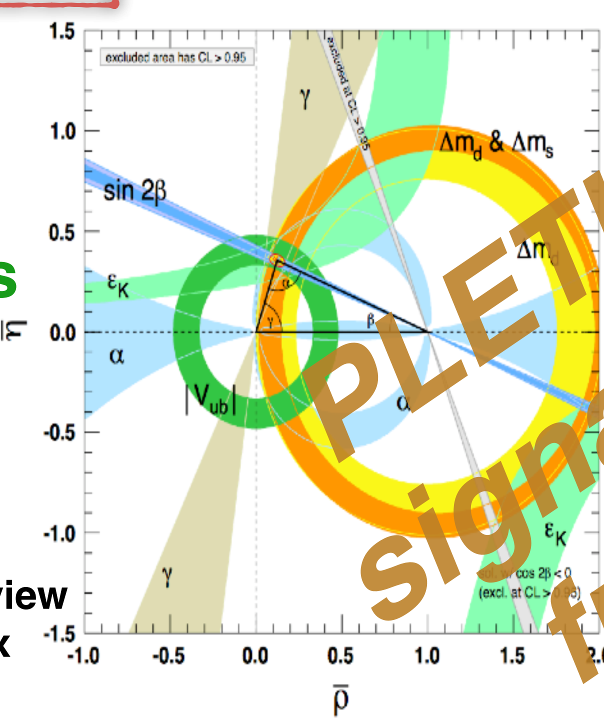
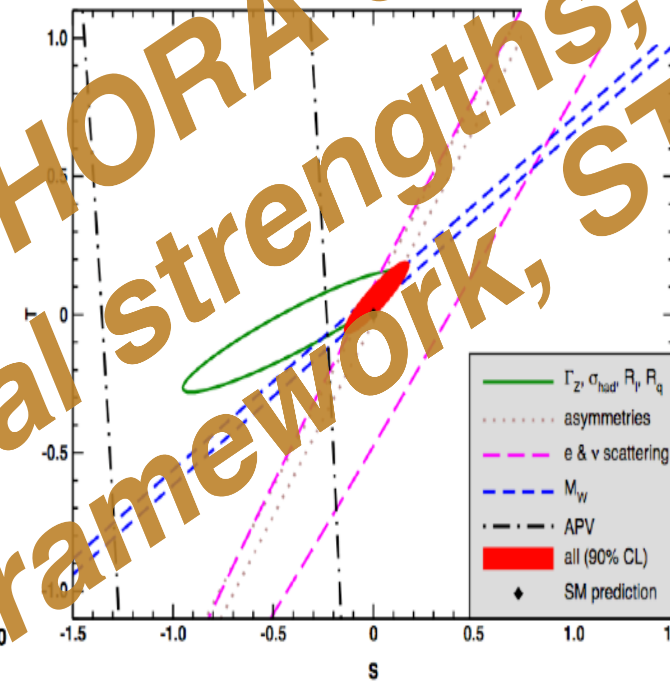


Phys. Rev. D 101, 012002 (2020)



PDG 2019 Review CKM Matrix



PDG 2019 Review Electroweak Model and Constraints on New Physics

PLETHORA OF DATA: signal strengths, kappa framework, STXS…

Motivation: What can be done?

Absence at the LHC of new physics BSM ⁉

Reconstruct TeV-scale Lagrangian with current data?

Rates are not enough. Include differential information?

What observables are best to anticipate to incoming data?

Motivation: What can be done?

EFT: PARAMETERISE NEW PHYSICS IN A "MODEL-INDEPENDENT" WAY 💪😎

Wilson coefficients (c_i, d_j)

Higher-dimensional operators ($\mathcal{O}_i^{(6)}$, $\mathcal{O}_j^{(8)}$)

- **Respect SM gauge symmetry (SU(2) x U(1))**
- **Include only SM fields**

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \ldots$$

Mass scale of new physics (should be large) (Λ)

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SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \dots$$

- SM here is a low-energy effective theory *valid below a cut-off scale* $\boldsymbol{\Lambda}$, superseded by a bigger theory above such scale.

- Appelquist-Carazzone theorem: at the perturbative level, all heavy ($> \boldsymbol{\Lambda}$) DOF are decoupled from the low-energy theory.

SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \ldots$$

d = 5: Majorana mass term to neutrinos

Leading BSM effects (59 independent B-conserving operators)

d = 7: Breaks B, L

Neutral TGC interactions

Many deformations from a single operator: correlated interactions

(Nucl. Phys. B 268 (1986) 621-653; Phys.Rev.D 48 (1993) 2182-2203; JHEP10(2010)085; …)

15 boson + 19 single fermion + 25 four fermion. Lowest dimension, after d=4, inducing hXY, hXYZ, charged TGCs

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SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \dots$$

New vertices ensuing from EFT can produce novel/enhanced effects in certain PS regions

Observables to study the effects of certain operators/processes?

In the Higgs sector, precisely measure their couplings to gauge bosons and fermions

Indirect constraints (S, T), precision physics at LEP, correlations… Need more and better measurements to improve current bounds

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SMEFT: HD operators, choice of basis, …

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \boxed{\frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2}} + \sum_j \frac{d_j \mathcal{O}_j^{(8)}}{\Lambda^4} + \ldots$$

- SM here is a low-energy effective theory *valid below a cutoff scale* Λ, superseded by a bigger theory above such scale.

★ **Bottom-up approach: find set of independent new interactions that can arise and are the experimentally best tested ones.**

- Appelquist-Carazzone theorem: at the perturbative level, all heavy ($> \Lambda$) DOF are decoupled from the low-energy theory.

★ **Use BSM primary effects to constrain new physics (broken phase).**

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Anomalous Higgs Couplings

Interactions *constrained by LEP*:

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{v}{2c^2_{\theta_W}} h Z^\mu Z_\mu + g^h_{Zff}\frac{h}{2v}(Z_\mu J^\mu_N + h.c.) + g^h_{Wff'}\frac{h}{v}(W^+_\mu J^\mu_C + h.c.)$$
$$+ \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}$$

Terms *not constrained by LEP*. First time probed at the LHC:

$$\mathcal{L}^{\text{primary}}_h = g^h_{VV} h\left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}}Z^\mu Z_\mu\right] + g_{3h}h^3 + g^h_{ff}(h\bar{f}_L f_R + h.c.)$$
$$+ \kappa_{GG}\frac{h}{v}G^{A\mu\nu}G^A_{\mu\nu} + \kappa_{\gamma\gamma}\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}$$

(Phys. Rev. D 91, 035001)

Anomalous Higgs Couplings

Interactions *constrained by LEP*:

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{v}{2c^2_{\theta_W}}hZ^\mu Z_\mu + g^h_{Zff}\frac{h}{2v}(Z_\mu J^\mu_N + h.c.) + g^h_{Wff'}\frac{h}{v}(W^+_\mu J^\mu_C + h.c.)$$

$$+\kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}$$

$$\delta g^h_{ZZ} = \delta g^Z_1 e^2 - \delta\kappa_\gamma\frac{e^2}{c^2_{\theta_W}}$$

$$g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1\left(g^Z_f c_{2\theta_W} + eQ_f s_{2\theta_W}\right) + 2\delta\kappa_\gamma Y_f\frac{e s_{\theta_W}}{c^3_{\theta_W}}$$

$$\kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}$$

$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c^2_{\theta_W}\right)$$

(1412.4410) **(Phys. Rev. D 91, 035001)**

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Anomalous Higgs Couplings

- Correlations between LEP and LHC measurements can be exploited.
- Only 8 Higgs BSM primary effects (1 family), while all other Higgs interactions are related to BSM primaries.

(JHEP11(2013)066; JHEP01(2014)151)

Measurements at colliders

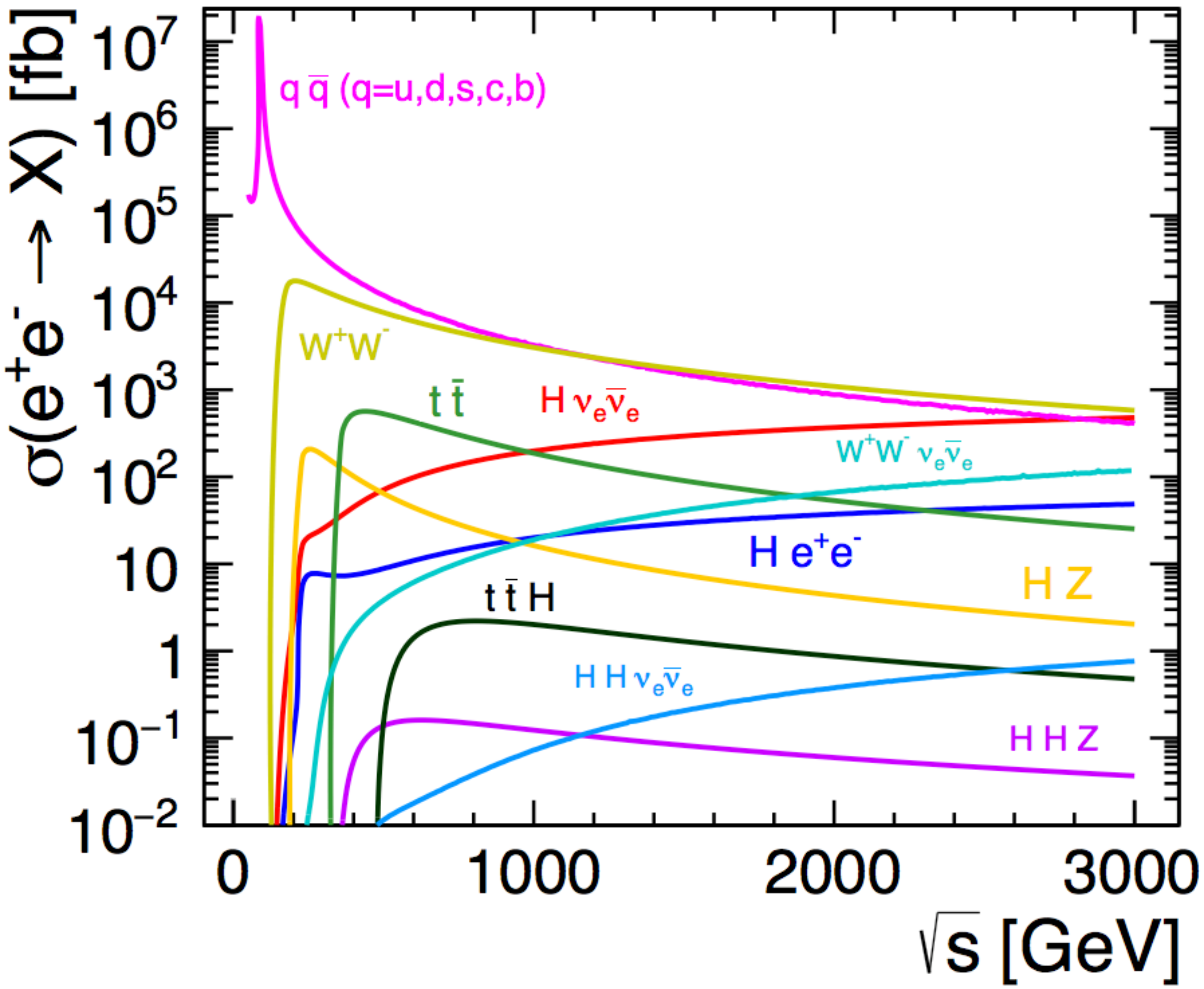
- ***h* → *Zγ*, *h* → μ⁺μ⁻, λ*hhh* ...** 😰   NEED PRECISION!

- Potential of constraining several couplings for processes that grow with energy at per-mille level.

$$\mathcal{O}(30\%) \longleftarrow \frac{\delta\sigma(\hat{s})}{\sigma_{\rm SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2}, \qquad \hat{s} \longrightarrow 1\ \text{TeV}^2$$

- Exploit technical capabilities of future colliders (ILC, CLIC, …): luminosity, resolution, beam polarisation.

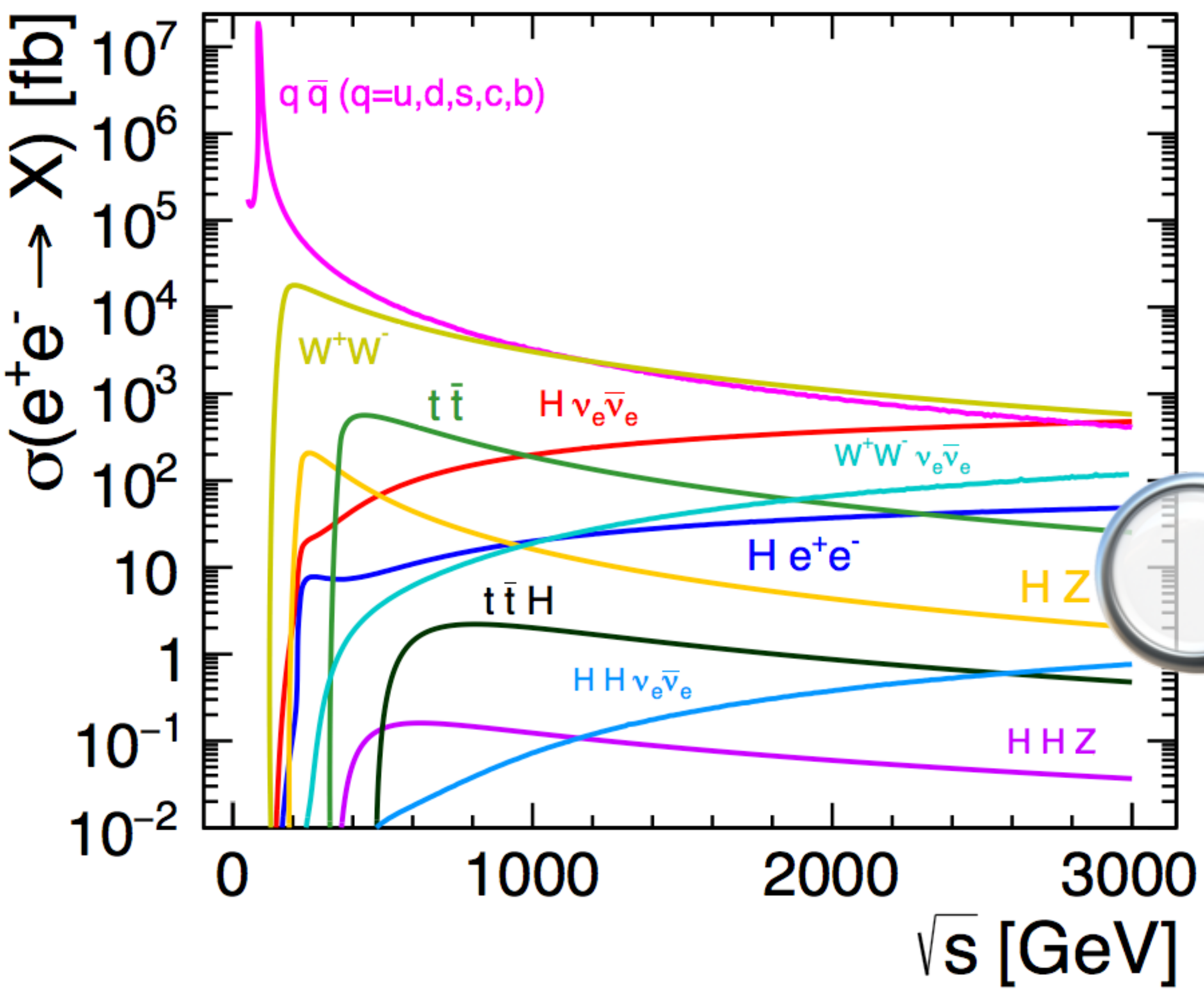
Future e^+e^- colliders:
Cross-sections overview



LO cross-section for important Standard Model processes in *e^+e^-* collisions (CYRM-2018-003)

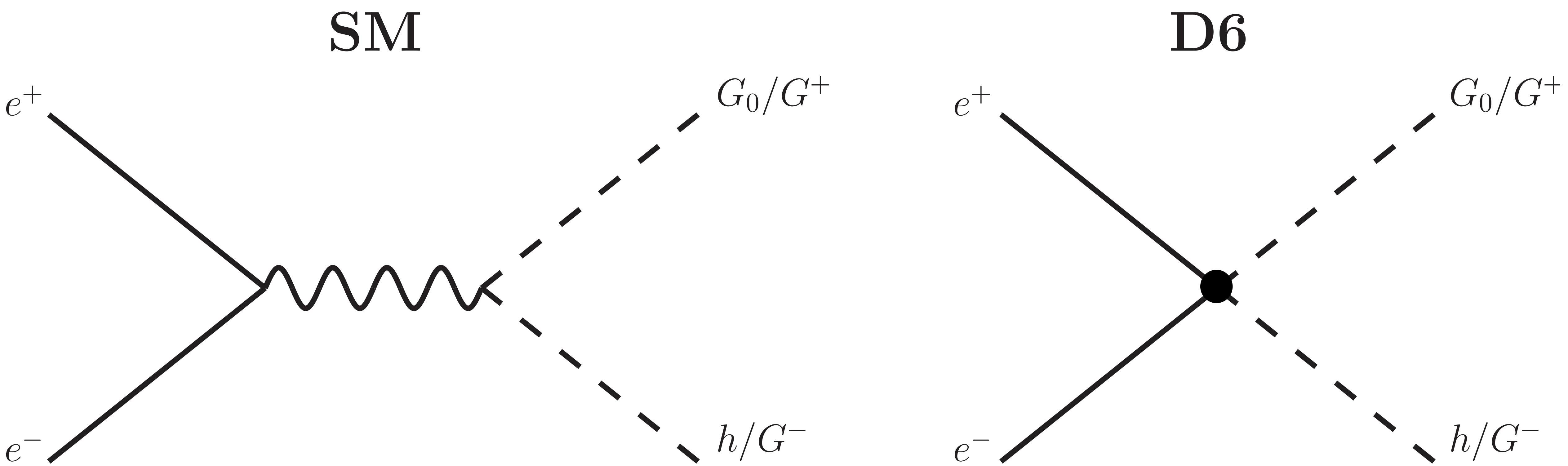
Future e^+e^- colliders:

Cross-sections overview



LO cross-section for important Standard Model processes in *e^+e^-* collisions (CYRM-2018-003)

Zh and *W^+W^-* at high energy *e^+e^-* colliders



Leading high energy contribution to *e^+e^-* > *Zh*, *W^+W^-* amplitudes in the SM (left), and D6 SMEFT (right) using the Goldstone Boson Equivalence Theorem.

Zh and *W⁺W⁻* at high energy *e⁺e⁻* colliders

$s \gg m_Z^2,$

$$\frac{\delta\mathcal{A}_{e_R e_R \to WW}}{\mathcal{A}^{SM}_{e_R e_R \to WW}} = \frac{\delta\mathcal{A}_{e_R e_R \to Zh}}{\mathcal{A}^{SM}_{e_R e_R \to Zh}} = \frac{1}{2q^Z_{e_R}} \frac{s}{m_Z^2} \alpha_{e_R}$$

$$\frac{\delta\mathcal{A}_{e_L e_L \to Zh}}{\mathcal{A}^{SM}_{e_L e_L \to Zh}} = \frac{1}{2q^Z_{e_L}} \frac{s}{m_Z^2} (\alpha_{L1} + \alpha_{L3})$$

$$\frac{\delta\mathcal{A}_{e_L e_L \to WW}}{\mathcal{A}^{SM}_{e_L e_L \to WW}} = \frac{1}{2q^Z_{e_L}} \frac{s}{m_Z^2} (\alpha_{L1} - \alpha_{L3}),$$

$$q^Z_f = (T_{3f} - Q_f s^2_{\theta_W})$$

Leptonic high-energy primaries

(1712.01310)

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Leptonic high energy primaries

Warsaw Basis
$\mathcal{O}_L^{l,(3)} = (\bar{L}\sigma^a\gamma^\mu L)(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)$ $\longrightarrow$ $\alpha_{L3} = -\frac{c_L^{l,(3)} v^2}{\Lambda^2}$
$\mathcal{O}_L^{l,(1)} = (\bar{L}\gamma^\mu L)(iH^\dagger \overleftrightarrow{D}_\mu H)$ $\longrightarrow$ $\alpha_{L1} = -\frac{c_L^{l,(1)} v^2}{\Lambda^2}$
$\mathcal{O}_R^e = (\bar{e}_R\gamma^\mu e_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$ $\longrightarrow$ $\alpha_{e_R} = -\frac{c_R^e v^2}{\Lambda^2}$

(1008.4884)

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Leptonic high energy primaries

How well can we test the following correlations?

$$\alpha_{L1} = \frac{c_{\theta_W}}{g}(\delta g^Z_{e_L} + \delta g^Z_{\nu_L}) + s^2_{\theta_W}\delta g^Z_1 - t^2_{\theta_W}\delta\kappa_\gamma,$$

$$\alpha_{L3} = \frac{c_{\theta_W}}{g}(\delta g^Z_{e_L} - \delta g^Z_{\nu_L}) + c^2_{\theta_W}\delta g^Z_1,$$

$$\alpha_{e_R} = \frac{2c_{\theta_W}}{g}\delta g^Z_{e_R} + 2s^2_{\theta_W}\delta g^Z_1 - 2t^2_{\theta_W}\delta\kappa_\gamma.$$

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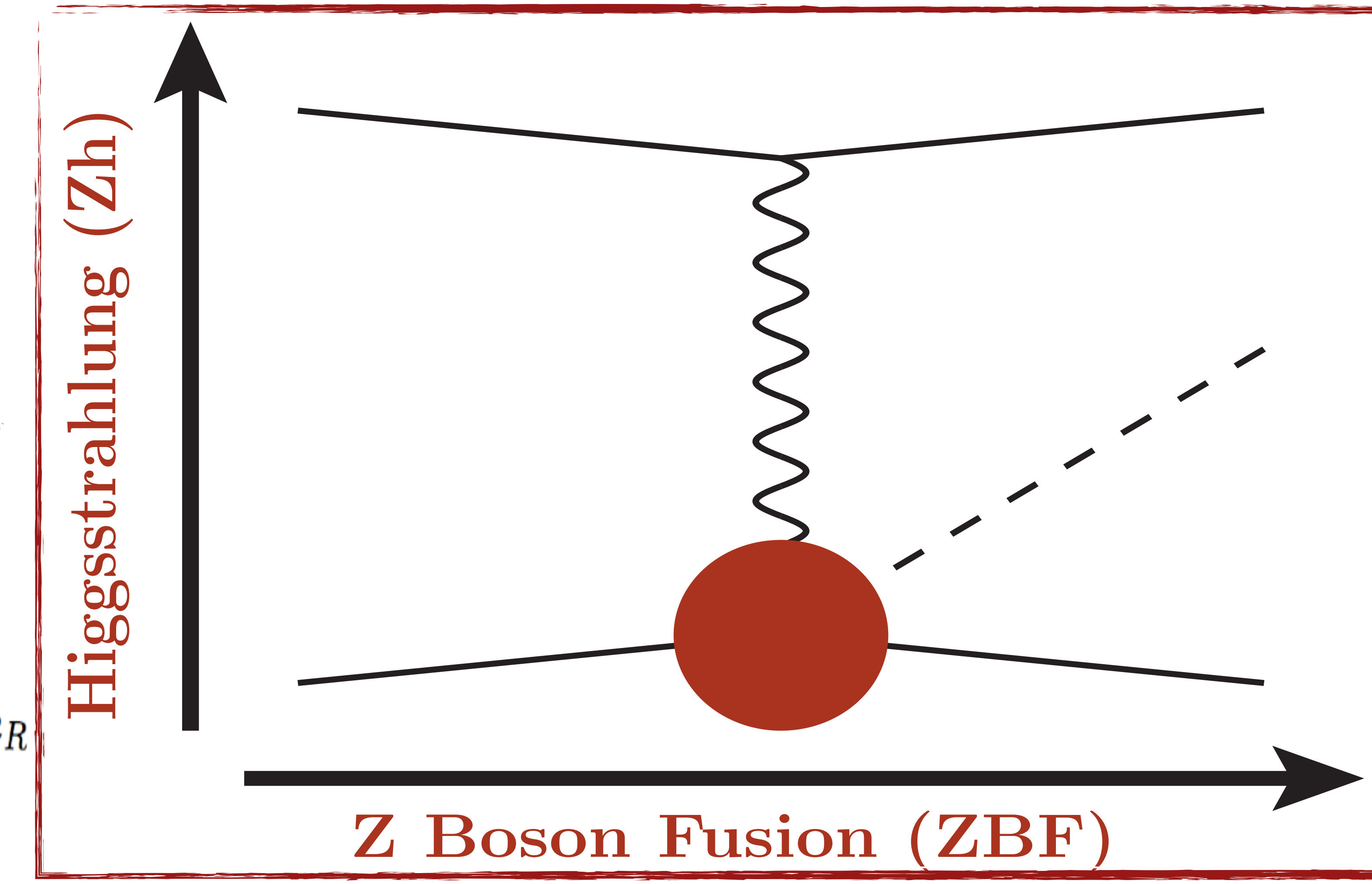
Future e^+e^- colliders:

Higgs and Z boson

Same amplitude, up to an exchange of $s \leftrightarrow t$



$$\frac{\delta \mathcal{A}_{e_R Z \to e_R h}}{\mathcal{A}^{SM}_{e_R Z \to e_R h}} = \frac{\delta \mathcal{A}_{e_R e_R \to Zh}}{\mathcal{A}^{SM}_{e_R e_R \to Zh}}(s \to t) = \frac{t}{m_Z^2}\alpha_{e_R}$$

$$\frac{\delta \mathcal{A}_{e_L Z \to e_L h}}{\mathcal{A}^{SM}_{e_L Z \to e_L h}} = \frac{\delta \mathcal{A}_{e_L e_L \to Zh}}{\mathcal{A}^{SM}_{e_L e_L \to Zh}}(s \to t) = \frac{t}{m_Z^2}(\alpha_{L1} + \alpha_{L3})$$

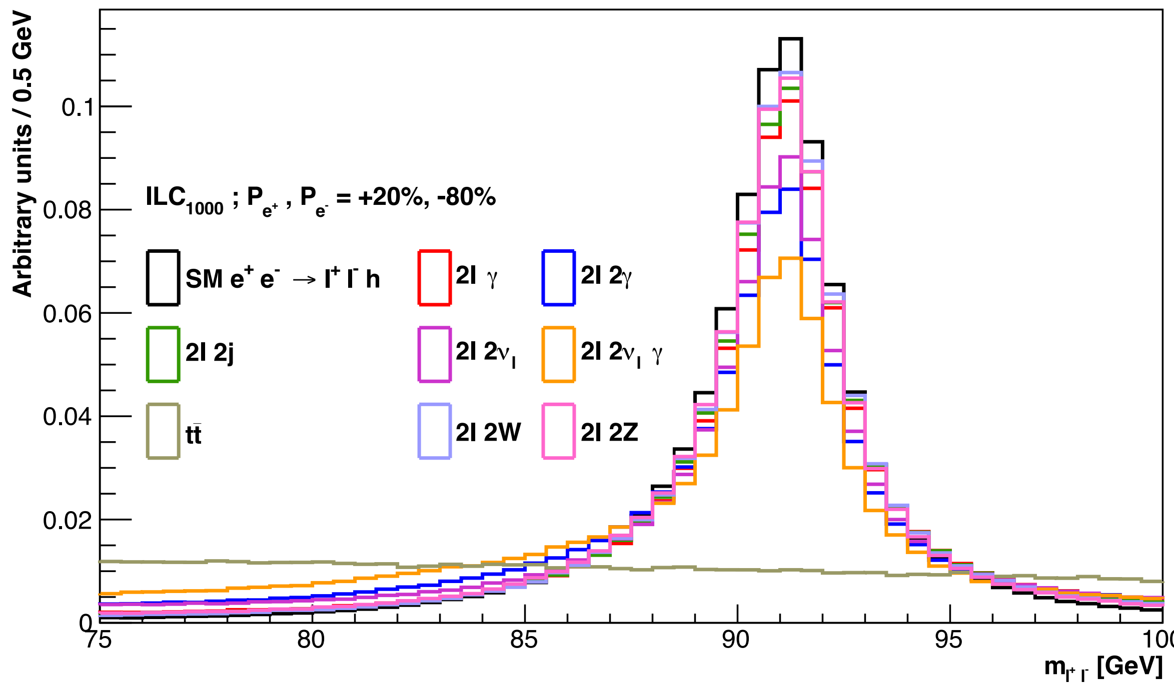
Zh and *ZBF* at *e⁺e⁻* colliders

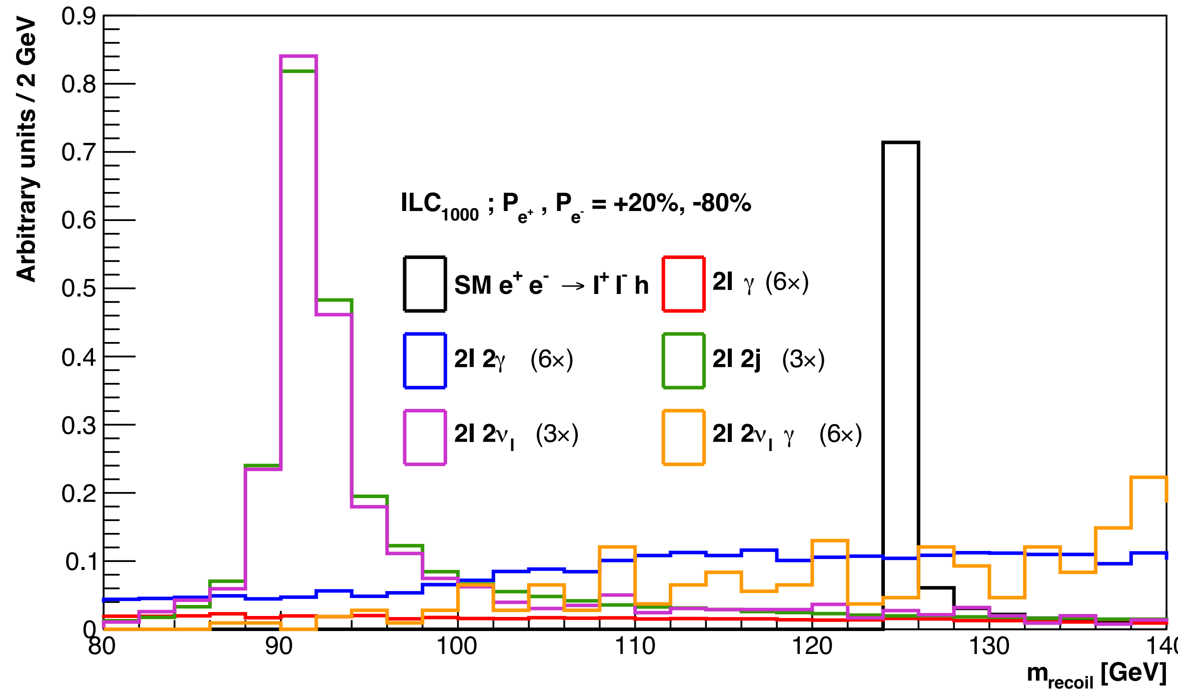
$$p_h = p_{e^+e^-} - p_{\ell^+\ell^-}$$

$$\downarrow$$

$$m^2_{\text{recoil}} \equiv s - 2\sqrt{s}E_{\ell^+\ell^-} + m^2_{\ell^+\ell^-}$$

Zh and *ZBF* at e^+e^- colliders





Some plots of the ILC_{1000} *Zh* selection.
Left: Invariant mass of the FS 2-lepton system.
Right: Recoil mass distribution.

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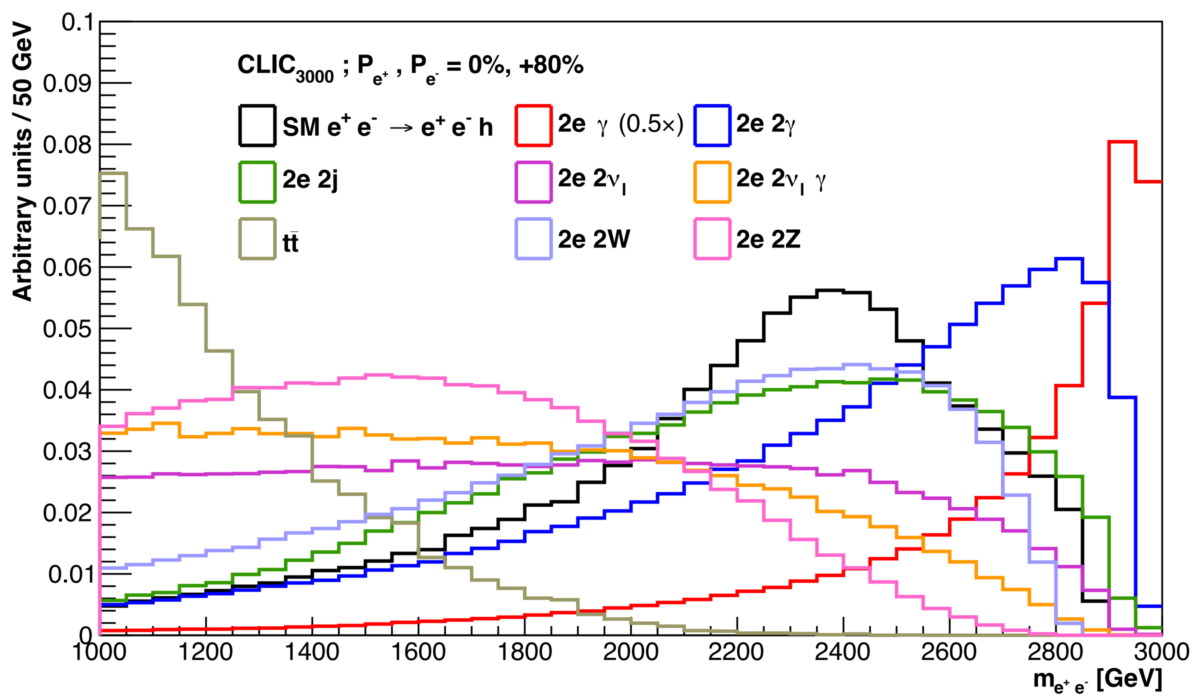
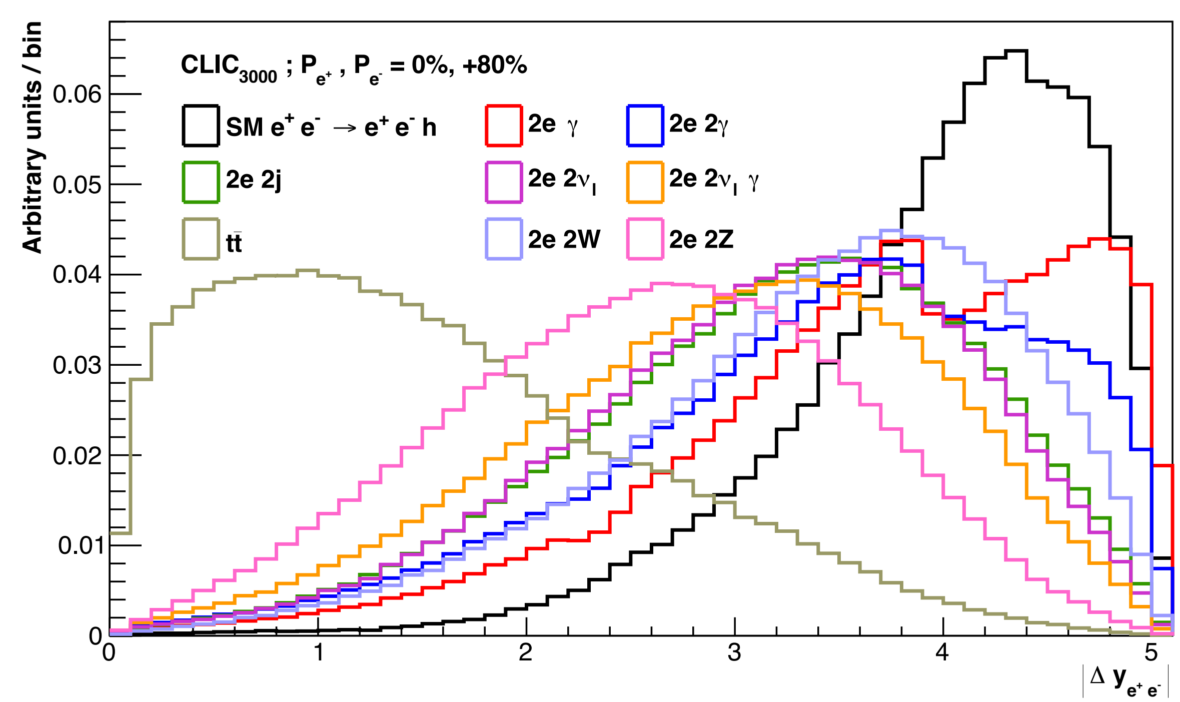
Zh and *ZBF* at e^+e^- colliders





Some plots of the CLIC$_{3000}$ *ZBF* selection.
Left: Invariant mass of the FS e^+e^- system.
Right: Rapidity gap between the FS electron-positron pair.

High-energy fit

- *Zh*: total rate.

$$\chi^2_{Zh} = \frac{\left(N^{\rm exp}_{Zh} - N^{\rm obs}_{Zh}\right)^2}{\sigma^2_{Zh}},$$

$$\sigma_{Zh} = \sqrt{N^{\rm exp}_{Zh} + (\Delta_{\rm sys} N^{\rm exp}_{Zh})^2}\ ; \Delta_{\rm sys} = 0.03$$

- *ZBF*: p_T^h differential distribution.

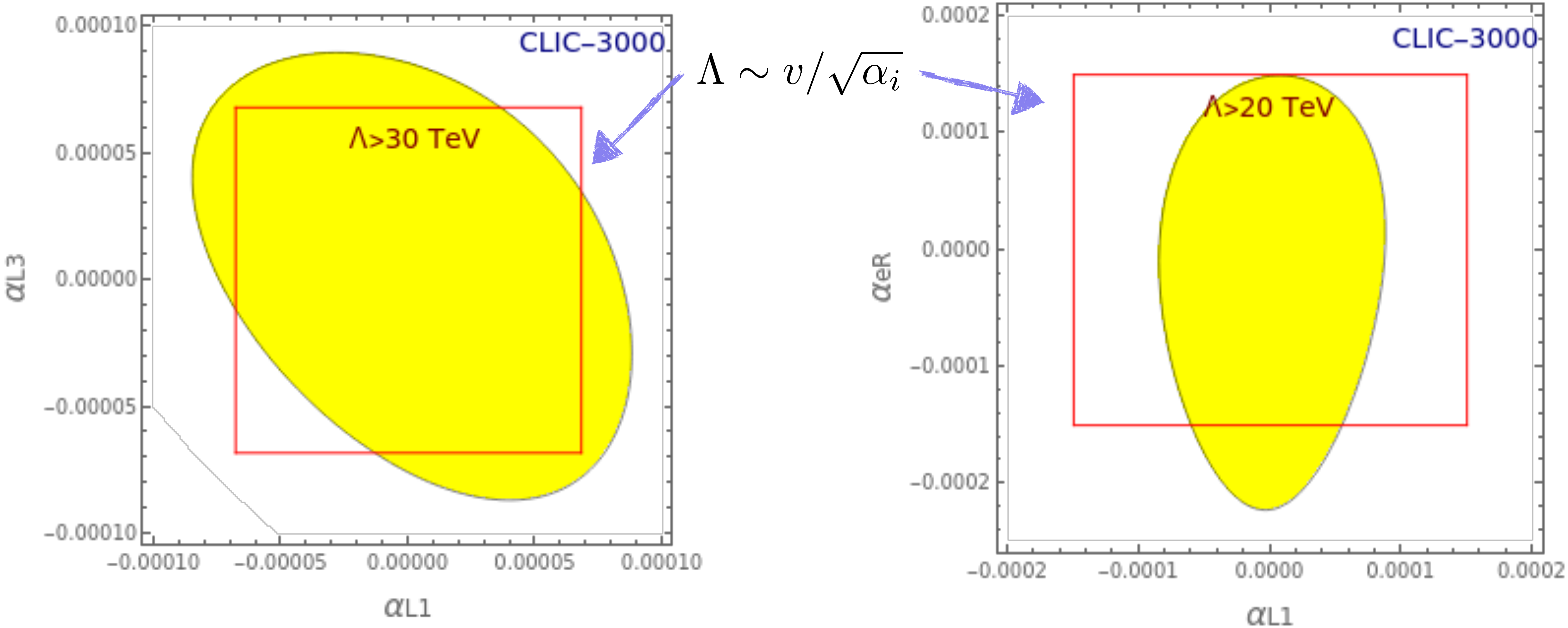
$$\chi^2_{ZBF} = \sum_i^N \frac{\left(N^{\rm exp}_i - N^{\rm obs}_i\right)^2}{\sigma^2_i}$$

$$\sigma_i = \sqrt{N^{\rm exp}_i + (\Delta_{\rm sys} N^{\rm exp}_i)^2}$$

- W^+W^-: inferred from (1812.02093).

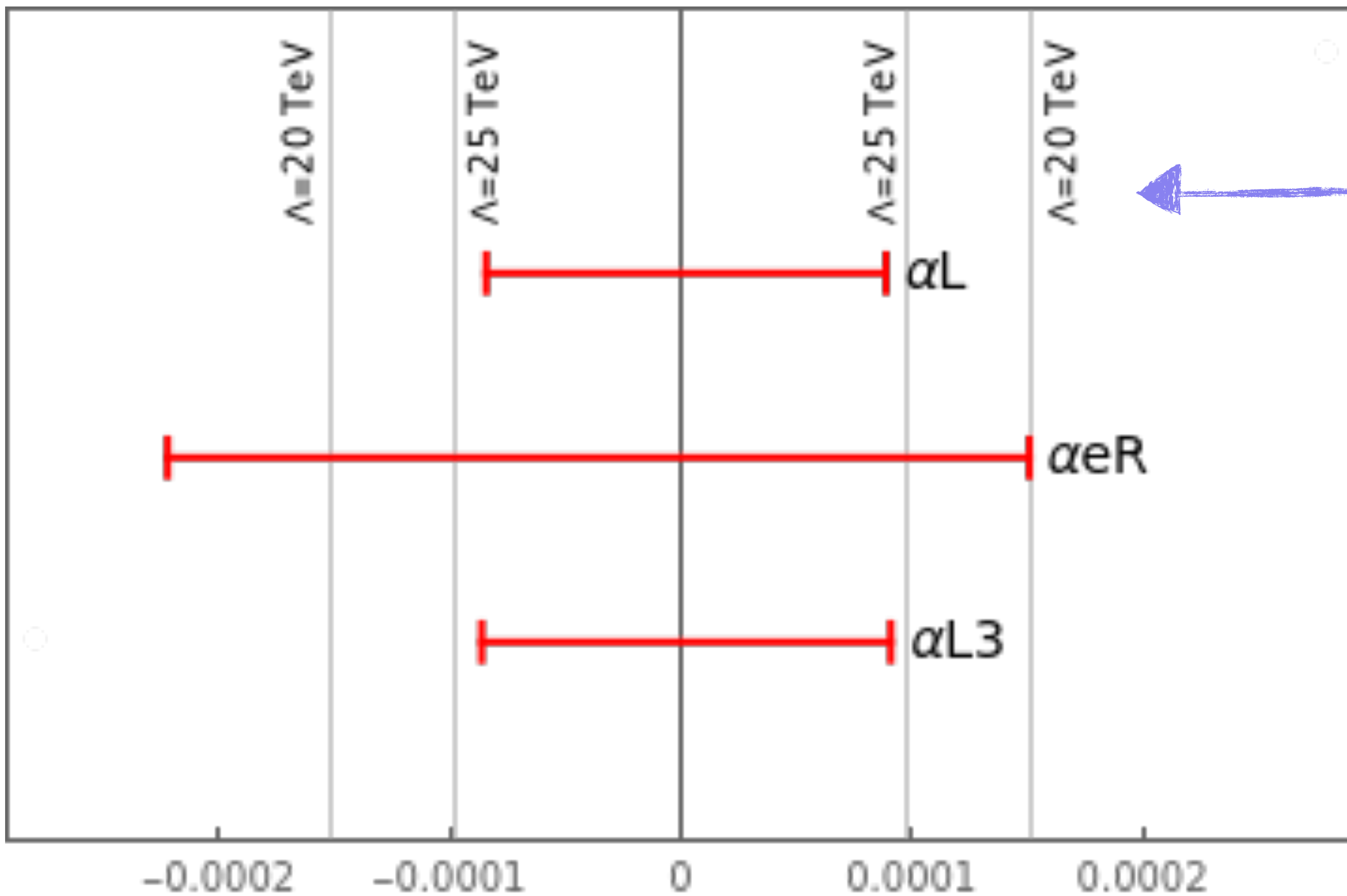
$$\chi^2_{\rm total} = \sum_{\rm pols} \chi^2_{Zh} + \sum_{\rm pols} \chi^2_{ZBF} + \sum_{\rm pols} \chi^2_{W^+W^-}$$

Projected sensitivities to EFT couplings



Projected sensitivities for the leptonic high-energy primaries at $CLIC_{3000}$ in two-dimensional planes, where the third parameter has been marginalised over.

Projected sensitivities to EFT couplings



$\Lambda \sim v/\sqrt{\alpha_i}$

Projected sensitivities on the individual leptonic high-energy primaries at CLIC_{3000} where the other two parameters have been marginalised over.

Projected sensitivities to EFT couplings

Remember the correlations we're testing?

$$\alpha_{L1} = \frac{c_{\theta_W}}{g}(\delta g^Z_{e_L} + \delta g^Z_{\nu_L}) + s^2_{\theta_W}\delta g^Z_1 - t^2_{\theta_W}\delta\kappa_\gamma,$$

$$\alpha_{L3} = \frac{c_{\theta_W}}{g}(\delta g^Z_{e_L} - \delta g^Z_{\nu_L}) + c^2_{\theta_W}\delta g^Z_1,$$

$$\alpha_{e_R} = \frac{2c_{\theta_W}}{g}\delta g^Z_{e_R} + 2s^2_{\theta_W}\delta g^Z_1 - 2t^2_{\theta_W}\delta\kappa_\gamma.$$

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Projected sensitivities to EFT couplings

95% CL bounds on each of the three couplings after marginalising over the other two

$$\alpha_{L1} \in [-8.5, 8.8] \times 10^{-5}$$
$$\alpha_{L3} \in [-9, 9] \times 10^{-4}$$
$$\alpha_{e_R} \in [-2.2, 1.5] \times 10^{-5}$$

LEP bounds (*Z*-pole)

$$\delta g^Z_{e_L} \in [-1, 9] \times 10^{-4}$$
$$\delta g^Z_{e_R} \in [-4, 2] \times 10^{-4}$$

(1411.0669)

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Summary and Conclusions

- High-energy e^+e^- colliders can i) compete with LEP, and ii) improve constraints.

- Correlated anomalous couplings => Higgs couplings were already indirectly constrained by LEP.

- Full tensor structures can be disentangled by combining **total rates + differential information + beam polarisation** (*ZBF* + *Zh*).

High energy lepton colliders as the ultimate Higgs microscopes

👏🙌

Questions/Comments/Suggestions?

Backup slides

Deformations and correlated interactions

Operator $(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$

Expanding, get terms like: $\hat{h}^2 \left[\hat{W}^3_{\mu\nu} B^{\mu\nu} + 2igc_{\theta_W} W^-_\mu W^+_\nu (A^{\mu\nu} - t_{\theta_W}) Z^{\mu\nu} \right]$

Considering $\hat{h} = v + h$ and expanding further:

$hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}Z^{\mu\nu}, hW^+_{\mu\nu}W^{-,\mu\nu}$ $\rightarrow$ Higgs deformations

$2igc_{\theta_W} W^-_\mu W^+_\nu (A^{\mu\nu} - t_{\theta_W} Z^{\mu\nu})$ $\rightarrow$ $\delta\kappa_\gamma, \delta\kappa_Z$ (TGCs)

$\hat{W}_{\mu\nu} B^{\mu\nu}$ $\rightarrow$ S-parameter

7 deformations from a single operator

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Anomalous Higgs Couplings

Assuming flavour universality, some anomalous Higgs couplings first probed at the LHC are:

$hW^{+}_{\mu\nu}W^{-,\mu\nu}$

$hZ_{\mu\nu}Z^{\mu\nu}, hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hG_{\mu\nu}G^{\mu\nu}$

$hf\bar{f}, h^2 f\bar{f}$

$hW^{+}_{\mu}W^{-,\mu}$

h^3

$hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$

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EW Anomalous Couplings:
9 EW Precision Observables

Z/W-pole measurements:

$Z_\mu \bar{f}_{L,R} \gamma^\mu f_{L,R}$

$W_\mu^+ \bar{u}_L \gamma^\mu d_R$

3 TGCs measured at LEP by the $e^+e^- \to W^+W^-$ channel:

$g_1^Z c_{\theta_W} Z^\mu \left(W^{+,\nu} \hat{W}_{\mu\nu}^- - W^{-,\nu} \hat{W}_{\mu\nu}^+ \right)$

$\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W_\mu^+ W_\nu^-$

$\lambda_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W_\mu^{-,\rho} W_{\rho\nu}^+$

$QGCs$:

$Z^\mu Z^\nu W_\mu^- W_\nu^+$

$W^{-,\mu} W^{+,\nu} W_\mu^- W_\nu^+$

Processes entering the high-energy fit

Process	ILC_{1000}	CLIC_{3000}
$e^+e^- \to Z\,(\ell^+\ell^-)\,h(\text{all})$	✓	✓
$e^+e^- \to e^+e^-h(\text{all})$	✓	✓
$e^+e^- \to W(2j)W(2j)$	×	✓
$e^+e^- \to W(2j)W(\ell\nu_\ell)$	×	✓

This work

(1812.02093)

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Collider parameters

- UFO > FeynRules.
- MadGraph5: LO MC events > Pythia 8.2.
- DELPHES 3: ILD Tune (ILC_{250}, ILC_{1000}); CLICdet Stage3 Tune ($CLIC_{3000}$).

Collider	$\sqrt{s}$ [GeV]	P_{e^+}, P_{e^-} [%]	$\mathcal{L}$ [fb^{-1}]
ILC_{250}	250	$\pm 30, \mp 80$	2000
ILC_{1000}	1000	$\pm 20, \mp 80$	8000
$CLIC_{3000}$	3000	$0, \mp 80$	5000

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Zh event selection

$\sigma^{\text{stage}}_{\sqrt{s}}$ [fb]	SM	$2\ell\gamma$	$2\ell2\gamma$	$2\ell2\nu_\ell$	$2\ell2\nu_\ell\gamma$	$2\ell2j$
σ^{in}_{250}	29.85/26.26	5107.28/4735.02	316.95/287.56	651.88/101.26	68.75/8.21	264.22/181.23
$\sigma^{\text{out}}_{250}$	6.99/6.14	$< 10^{-6}$	0.40/0.32	1.02/0.12	0.13/0.04	0.22/0.08
$\sigma^{\text{in}}_{1000}$	1.45/1.45	105.60/87.80	19.46/16.48	318.14/37.86	39.18/4.91	28.24/17.80
$\sigma^{\text{out}}_{1000}$	0.33/0.31	0.017/0.013	0.0064/0.0053	0.0046/0.0024	$3/2\ (\times 10^{-4})$	0.0140/0.0072
$\sigma^{\text{in}}_{3000}$	0.17/0.17	6.17/5.09	1.65/1.37	376.87/43.02	61.51/7.18	2.29/1.31
$\sigma^{\text{out}}_{3000}$	0.026/0.025	$12/9\ (\times 10^{-4})$	$9.64/6.09\ (\times 10^{-5})$	$3.8/1.9\ (\times 10^{-4})$	$61.5/3.6\ (\times 10^{-6})$	$8.3/4.9\ (\times 10^{-4})$

Table 4. Cross-sections, σ, in fb, for the *Zh*-like SM-driven signal $e^+e^- \to \ell^+\ell^- h$ and its dominant backgrounds before (*in*) and after (*out*) event selection at $\sqrt{s} = \{250, 1000, 3000\}$ GeV. We consider the *left* and *right* beam polarisations P_{e^+}, P_{e^-} for each $\sqrt{s}$, reported as *left*/*right* (see text for details). For the $t\bar{t}$, $\ell^+\ell^- W^+W^-$, and $\ell^+\ell^- ZZ$ channels, σ^{in} (in fb) $\sim$ 3.47/0.62, 4.44/0.41, and 0.22/0.12, respectively at 1 TeV. At 3 TeV, the respective numbers are 0.08/0.01, 1.77/0.21, and 0.06/0.03. For all cases, $\sigma^{\text{out}} < 10^{-6}$ fb. For $\sqrt{s} = 250$ GeV, the kinematic phase space is not open for any of these three channels.

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ZBF event selection

$\sigma^{\text{stage}}_{\sqrt{s}}$ [fb]	SM	$2e\gamma$	$2e2\gamma$	$2e2\nu_\ell$	$2e2\nu_\ell\gamma$	$2e2j$
σ^{in}_{250}	0.88/0.66	47354.7/46966	628.53/620.28	1348.33/99.46	59.79/4.29	125.27/115.97
$\sigma^{\text{out}}_{250}$	0.26/0.19	$< 10^{-4}$	0.37/0.34	1.57/0.13	0.11/0.01	0.033/0.024
$\sigma^{\text{in}}_{1000}$	14.02/10.54	9651.21/9221.23	394.58/376.18	430.13/59.66	36.89/5.04	93.29/76.42
$\sigma^{\text{out}}_{1000}$	2.52/1.92	$< 10^{-4}$	0.034/0.030	0.099/0.016	0.0045/0.0017	0.024/0.012
$\sigma^{\text{in}}_{3000}$	4.11/3.08	1754.91/1631	115.66/107.46	154.04/29.84	17.45/3.56	42.19/33.55
$\sigma^{\text{out}}_{3000}$	0.22/0.15	$< 10^{-4}$	0.0052/0.0054	0.0084/0.0022	$8.4/4.7\ (\times 10^{-4})$	0.0033/0.0018

Table 5. Cross-sections, σ, in fb, for the *ZBF*-like SM-driven signal $e^+e^- \to e^+e^-h$ and its dominant backgrounds before (*in*) and after (*out*) event selection at $\sqrt{s} = \{250, 1000, 3000\}$ GeV. We consider the *left* and *right* beam polarisations P_{e^+},P_{e^-} for each $\sqrt{s}$, reported as *left/right* (see text for details). For the $t\bar{t}$, $e^+e^-W^+W^-$, and e^+e^-ZZ channels, σ^{in} (in fb) $\sim$ 1.52/2.38, 15.03/2.69, and 0.04/0.02, respectively at 1 TeV. At 3 TeV, the respective numbers are 0.12/0.21, 29.84/3.88, and 0.08/0.05. For all cases, $\sigma^{\text{out}} < 10^{-4}$ fb. For $\sqrt{s} = 250$ GeV, the kinematic phase space is not open for any of these three channels.

Future e^+e^- colliders:
Beam polarisation and Higgs + leptons

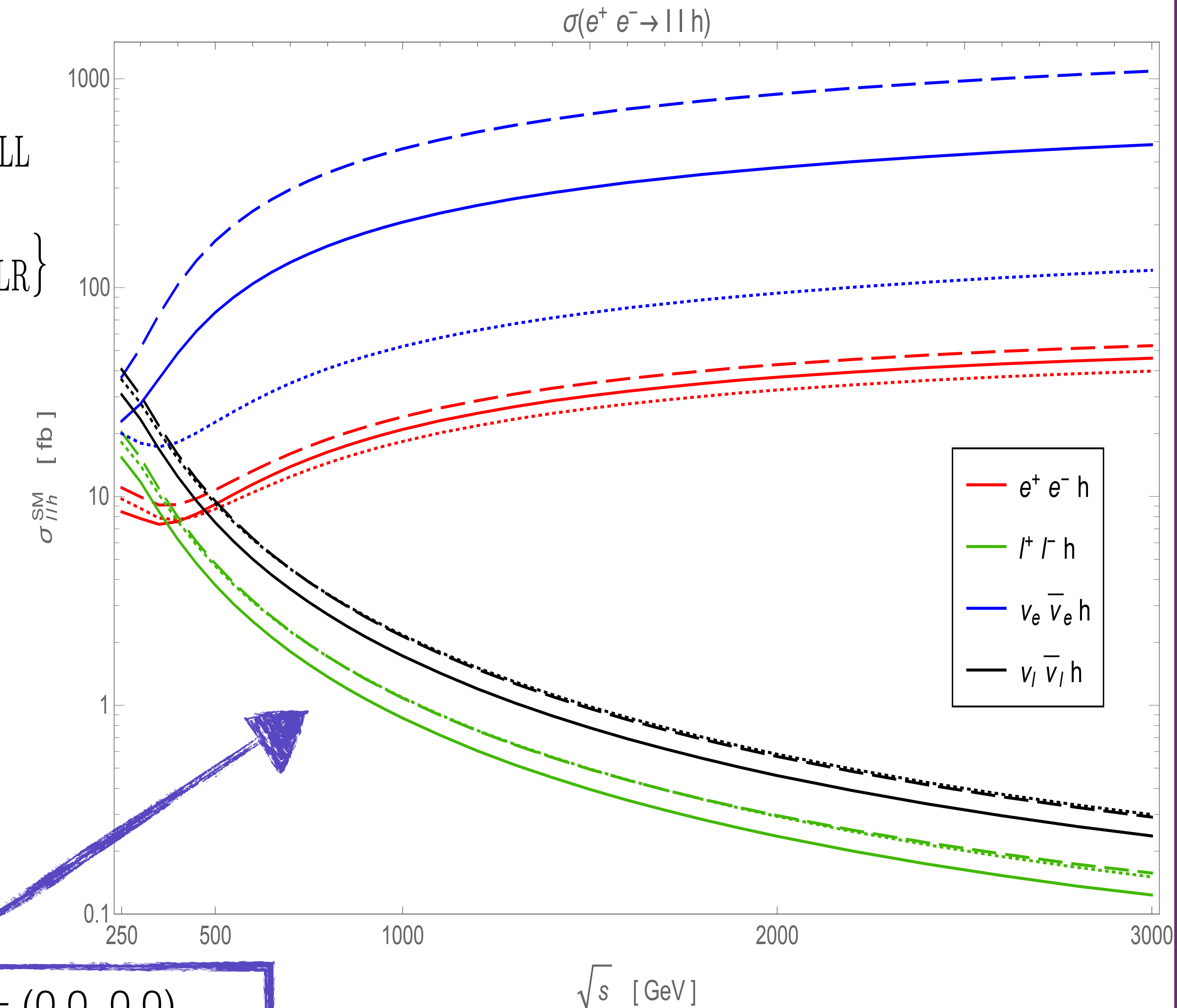
$$\sigma(\mathcal{P}_{e^-},\mathcal{P}_{e^+}) = \frac{1}{4}\{(1+\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm RR} + (1-\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm LL} + (1+\mathcal{P}_{e^-})(1-\mathcal{P}_{e^+})\sigma_{\rm RL} + (1-\mathcal{P}_{e^-})(1+\mathcal{P}_{e^+})\sigma_{\rm LR}\}$$

$$A_{\rm LR} = \frac{(\sigma_{\rm LR} - \sigma_{\rm RL})}{(\sigma_{\rm LR} + \sigma_{\rm RL})}$$

$$\mathcal{L}_{\rm eff} = \frac{1}{2}(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})\mathcal{L}$$

$$\mathcal{P}_{\rm eff} = \frac{\mathcal{P}_{e^-} - \mathcal{P}_{e^+}}{1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+}}$$

(1801.02840)



P(e⁺, e⁻) = (0.0, 0.0)
P(e⁺, e⁻) = (+0.5, -0.5)
P(e⁺, e⁻) = (-0.5, +0.5)

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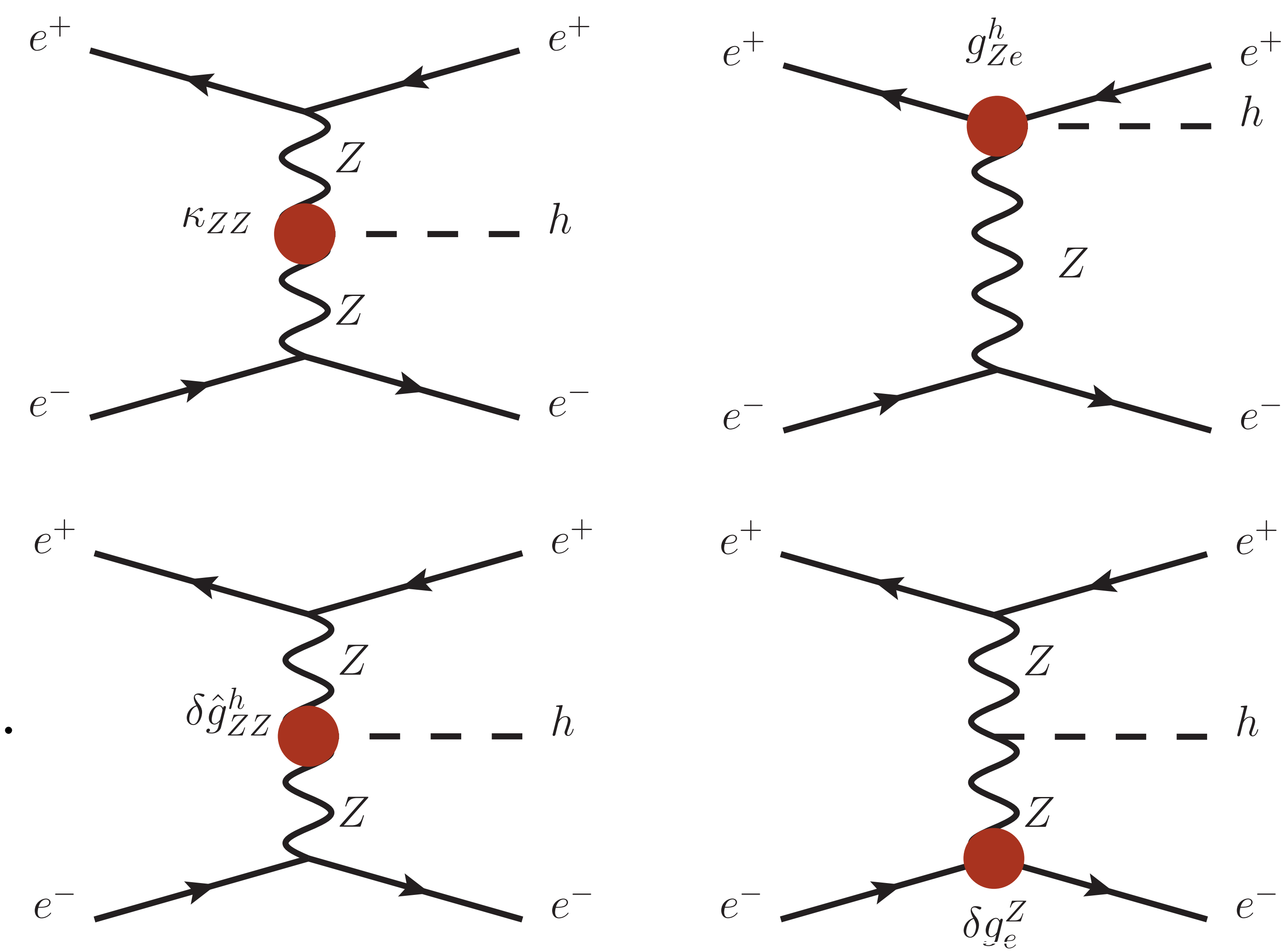
Future e^+e^- colliders:

ZBF

$$\Delta\mathcal{L}_6 \supset \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \sum_{f=e_L,e_R} g^h_{Zf}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f + \delta\hat{g}^h_{ZZ}\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_{f=e_L,e_R}\delta g^Z_f Z_\mu\bar{f}\gamma^\mu f + \ldots$$



Future e^+e^- colliders: *ZBF*

$$g^h_{Zf} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T^f_3|c^{l,(1)}_L - T^f_3 c^{l,(3)}_L + (1/2 - |T^f_3|)c^e_R)$$

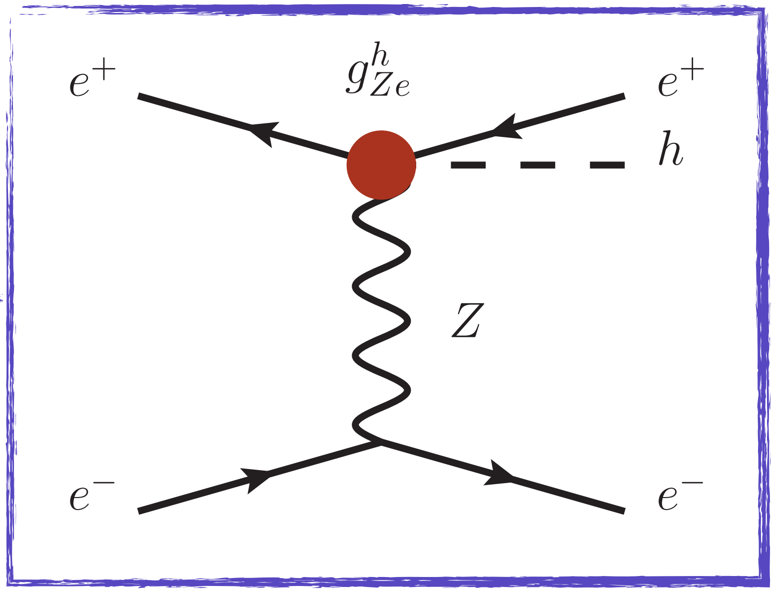
$$\Delta\mathcal{L}_6 \supset \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}$$

$$+ \sum_{f=e_L,e_R} g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f$$

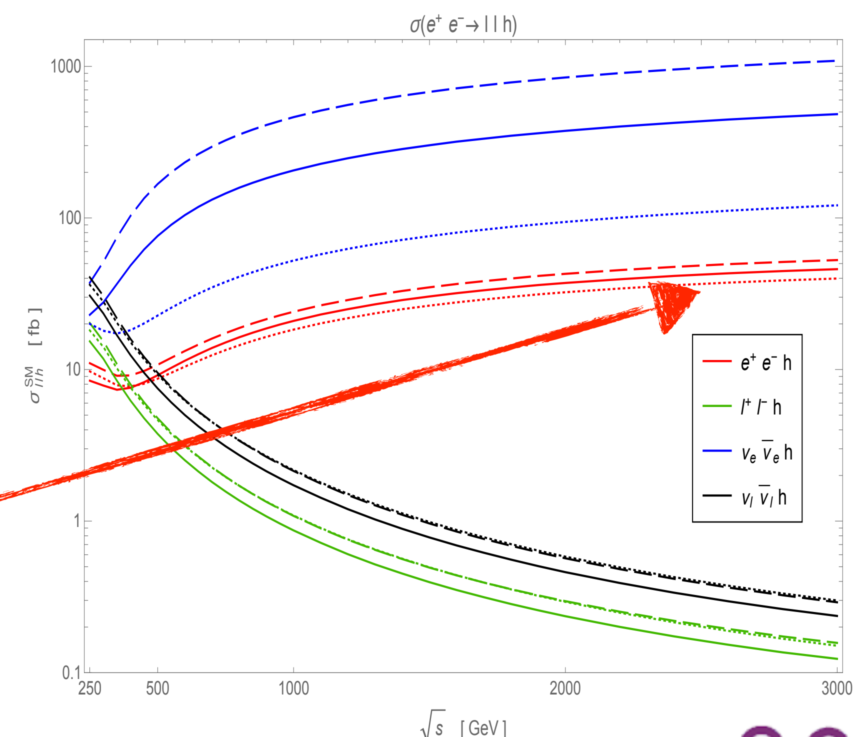
$$+ \delta\hat{g}^h_{ZZ}\frac{2m^2_Z}{v}h\frac{Z^\mu Z_\mu}{2}$$

$$+ \sum_{f=e_L,e_R} \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f + \ldots$$

Leading effect at high energies



Exploit beam polarisation!



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SILH basis

SILH Basis
$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \tau^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$
$\mathcal{O}_B = \left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$

$$\alpha_{L1} = \frac{\alpha_{e_R}}{2} = \frac{m_W^2 t_{\theta_W}^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})$$
$$\alpha_{L3} = -\frac{m_W^2}{\Lambda^2}(c_W + c_{HW} - c_{2W})\,.$$

$$\alpha_{L1} = \frac{\alpha_{e_R}}{2} = -t_{\theta_W}^2\left(\delta\kappa_\gamma - \hat{S} - \delta g_1^Z c_{\theta_W}^2 + Y\right)$$
$$\alpha_{L3} = \delta g_1^Z c_{\theta_W}^2 + W.$$

(hep-ph/0703164)

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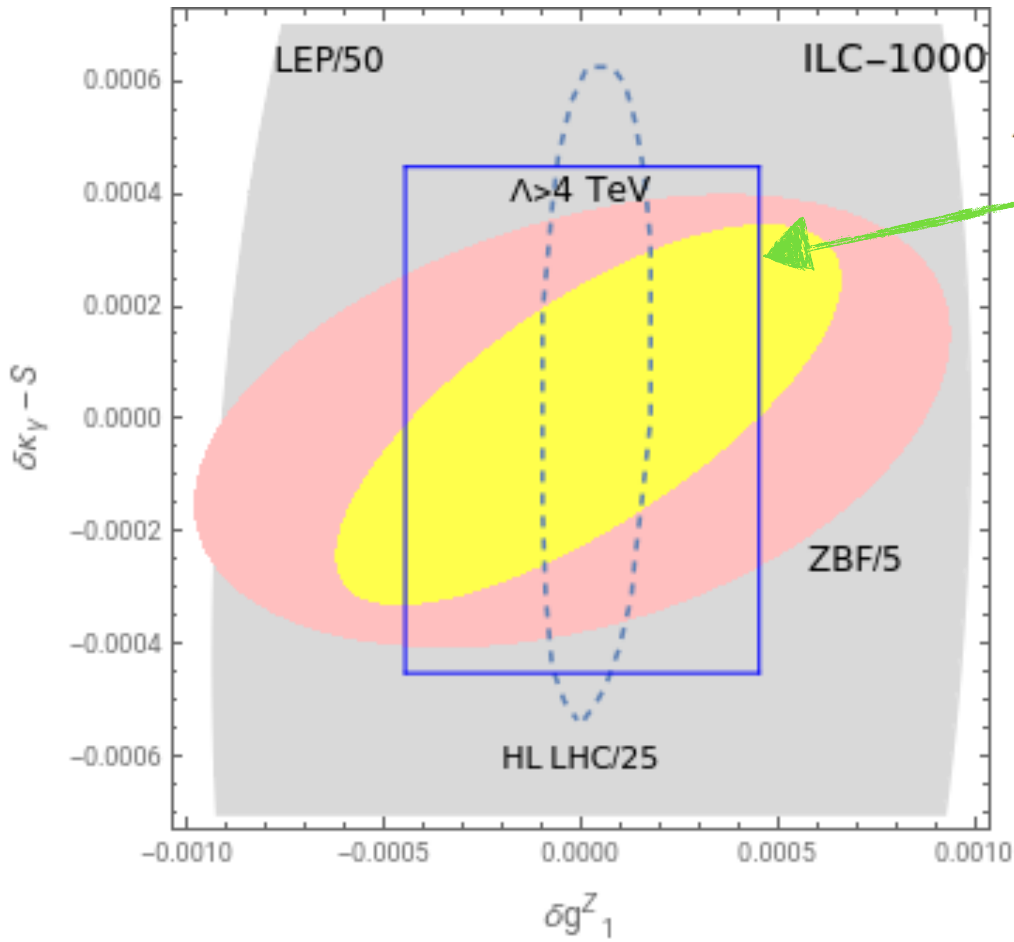
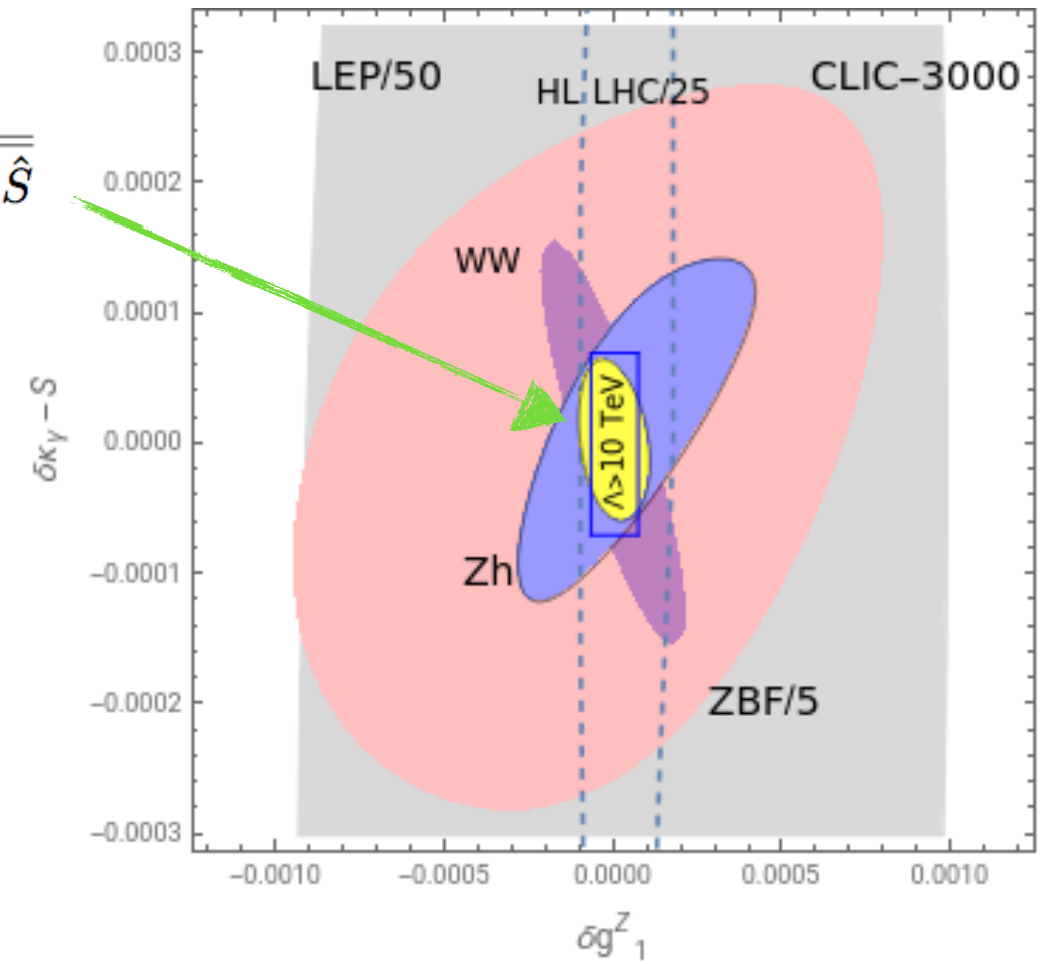
Projected sensitivities to EFT couplings (SILH)



$$\Lambda \sim \frac{m_W}{\sqrt{\delta g_1^Z c_{\theta_W}^2}}, \quad \frac{m_W}{\sqrt{\delta\kappa_\gamma - \hat{S}}}$$



Left: projected sensitivities for the case of universal new physics for ILC_{1000} and their comparison with LEP bounds (LEPEWWG-TGC-2003-01) and HL-LHC projections (1810.05149). Right: Projected sensitivities for the case of universal new physics for CLIC_{3000} and their comparison with LEP bounds and HL-LHC projections. We have assumed $W = Y = 0$.