HKIAS HEP Conference 2016

Probing the Higgs with Angular Observables at Future e+e− Colliders

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Talk based on work w N. Craig, J. Gu and K. Wang, arXiv:1512.06877

- Precision Higgs physics could directly probe new physics
- New physics can easily couples to Higgs, linking to hierarchy problem, electroweak Baryogenesis, Naturalness, Dark Matter, etc.
- Next generation colliders “Higgs factory” are to chase this opportunity.

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Future Circular Collider (FCC-ee) by CERN
Circular Electron-Positron Collider (CEPC) in China,
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General purpose collider experiments require ~twenty years planning ahead.

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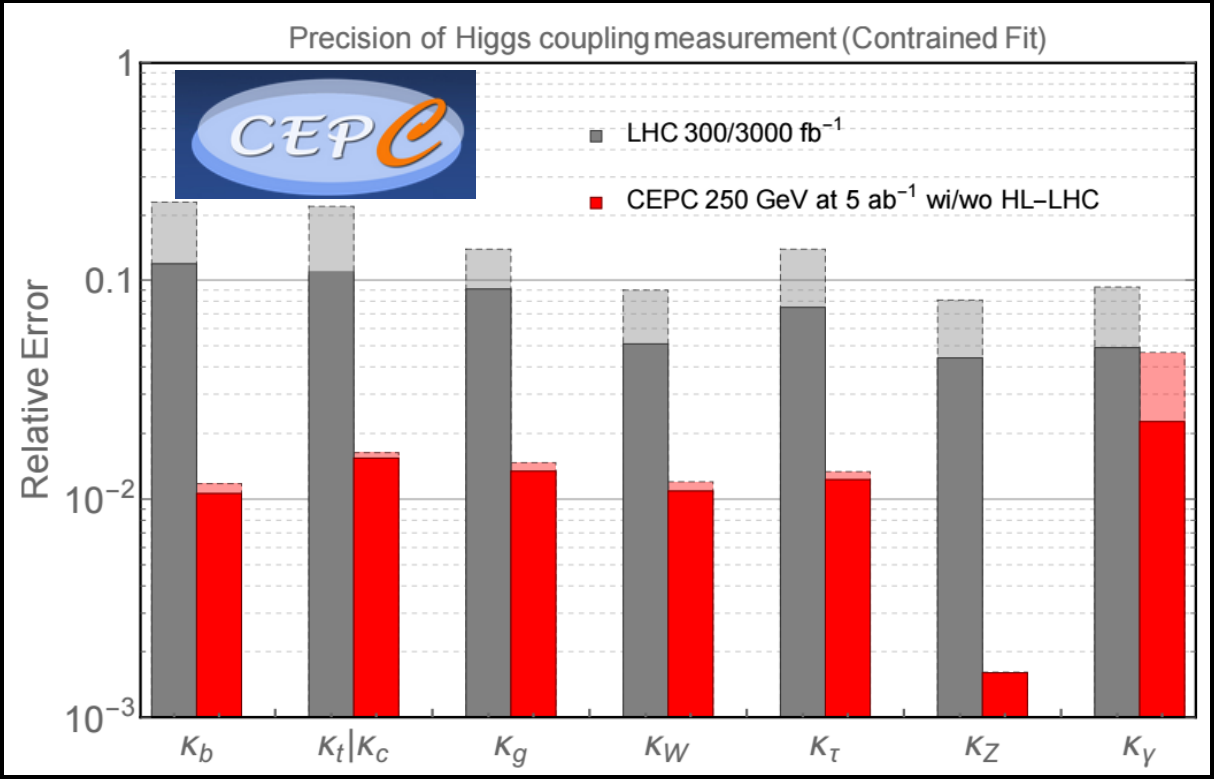

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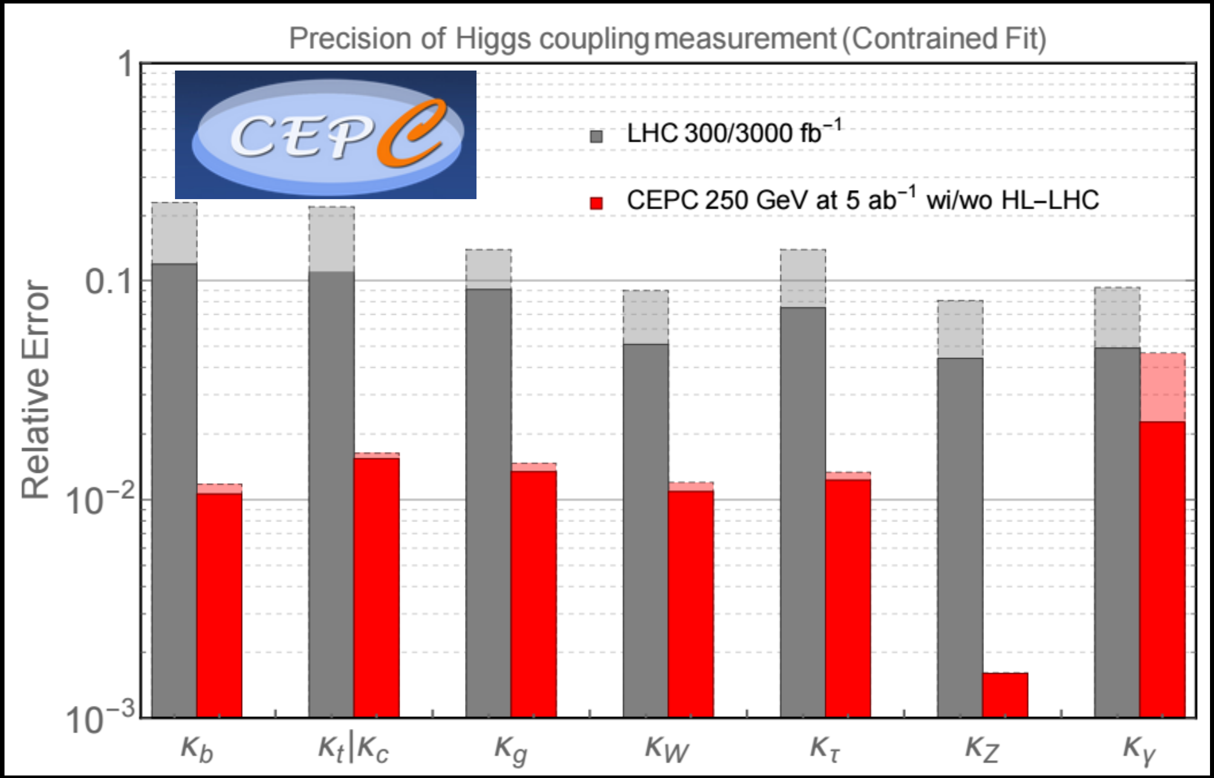

Comparing to HL-LHC

- Nearly one order of magnitude better precision, to (sub) percent level.
- Combining with the HL-LHC does improve, e.g. Higgs photon couplings (see more discussion for the case of the ILC, e.g., T. Han, ZL, J. Sayre, **arXiv: 1311.7155**).
- Similar plots exist for FCC-ee, ILC, etc.
- Lepton collider Higgs factories also enable “model-independent” fits (not shown here.)

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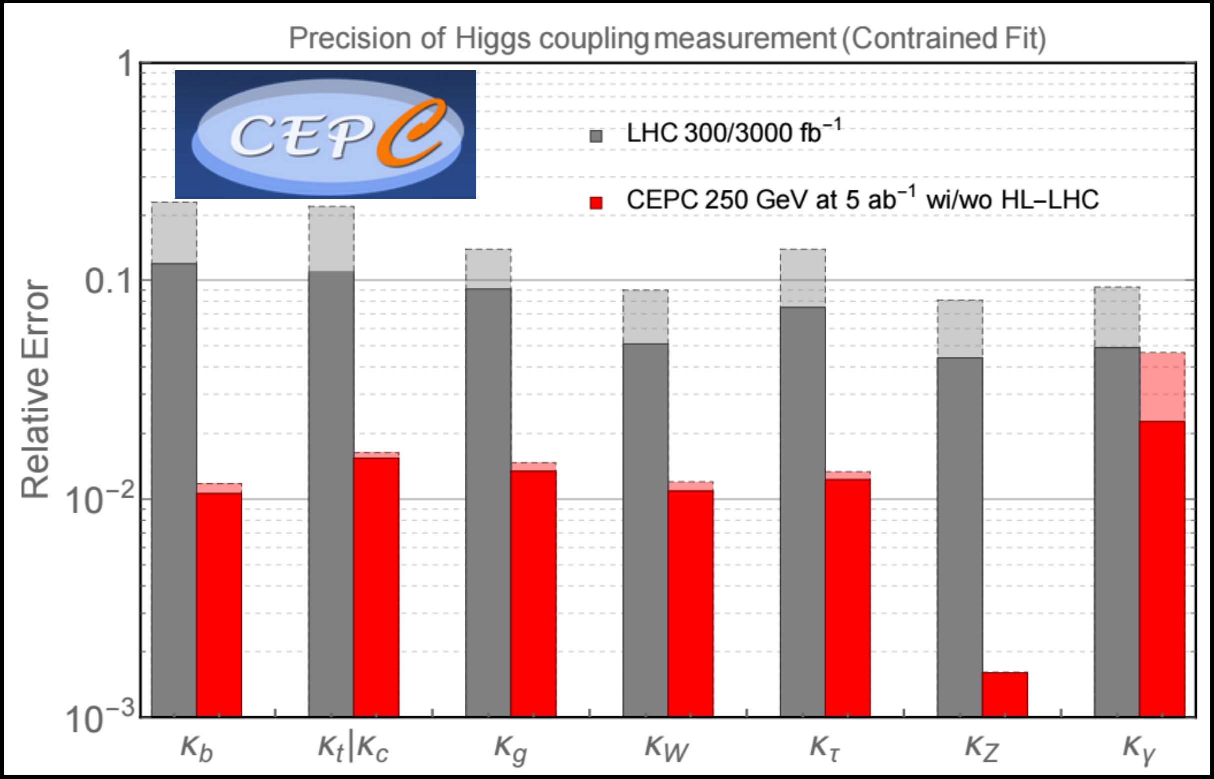

CEPC-circular electron-positron collider, preCDR (link) public. A future collider proposal in China, with a possible upgrade to hadron-collider (named SPPC) at 50-100 TeV.
These Higgs projection results are one of my main contributions to CEPC at this stage. (open to discussion about results/improvements, etc.)
A Higgs whitepaper out soon describing the details.

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- Similar plots exist for FCC-ee, ILC, etc.
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- Thus far, most works on Higgs physics focus on the simple kappa-scheme, where BSM effects are captured by a scaling parameter,

$$\kappa = \frac{g_{BSM}}{g_{SM}}$$

In terms of higher-dimensional operators, these only capture the operators of type

$$O_{dim6} = (H^+H)O_{SM}^h$$

There are vast majority of other dim-6 operators, see, e.g. from Review of Particle Physics (Higgs section).

Operators involving bosons only
$\mathcal{O}_H = 1/(2v^2)\left(\partial^\mu\left(\Phi^\dagger\Phi\right)\right)^2$
$\mathcal{O}_T = 1/(2v^2)\left(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right)^2$
$\mathcal{O}_6 = -\lambda/(v^2)\left(\Phi^\dagger\Phi\right)^3$
$\mathcal{O}_B = (ig')/(2m_W^2)\left(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi\right)\left(\partial^\nu B_{\mu\nu}\right)$
$\mathcal{O}_W = (ig)/(2m_W^2)\left(\Phi^\dagger \sigma^i \overleftrightarrow{D}^\mu \Phi\right)\left(D^\nu W_{\mu\nu}\right)^i$
$\mathcal{O}_{HB} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)B_{\mu\nu}$
$\mathcal{O}_{HW} = (ig)/m_W^2\,(D^\mu\Phi)^\dagger\sigma^i(D^\nu\Phi)W^i_{\mu\nu}$
$\mathcal{O}_{BB} = g'^2/m_W^2\,\Phi^\dagger\Phi\,B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{GG} = g_S^2/m_W^2\,\Phi^\dagger\Phi\,G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{H\tilde{B}} = (ig')/m_W^2\,(D^\mu\Phi)^\dagger(D^\nu\Phi)\tilde{B}_{\mu\nu}$
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Ops. involving bosons and fermions
$\mathcal{O}_t = y_t/v^2\,(\Phi^\dagger\Phi)\,(\bar{q}_L\Phi^c t_R)$
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$\mathcal{O}_{Hq} = i/v^2\,\left(\bar{q}_L\gamma^\mu q_L\right)\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)$
$\mathcal{O}^{(3)}_{Hq} = i/v^2\,\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(\Phi^\dagger\sigma^i\overleftrightarrow{D}_\mu\Phi\right)$
$\mathcal{O}_{Hu} = i/v^2\,\left(\bar{u}_R\gamma^\mu u_R\right)\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)$
$\mathcal{O}_{Hd} = i/v^2\,\left(\bar{d}_R\gamma^\mu d_R\right)\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)$
$\mathcal{O}_{Hud} = i\,y_u y_d/v^2\,\left(\bar{u}_R\gamma^\mu d_R\right)\left(\Phi^{c\,\dagger}\overleftrightarrow{D}_\mu\Phi\right)$
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$\mathcal{O}_{Hl}$

Ops. involving bosons and fermions

$$\mathcal{O}_{uB} = (g'\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}u_R)\,B_{\mu\nu}$$
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$$\mathcal{O}_{uG} = (g_S\,y_u)/m_W^2\,(\bar{q}_L\Phi^c\sigma^{\mu\nu}t^A u_R)\,G^A_{\mu\nu}R$$
$$\mathcal{O}_{dB} = (g'\,y_d)/m_W^2\,(\bar{q}_L\Phi\sigma^{\mu\nu}d_R)\,B_{\mu\nu}$$
$$\mathcal{O}_{dW} = (g\,y_d)/m_W^2\,(\bar{q}_L\sigma^i\Phi\sigma^{\mu\nu}d_R)\,W^i_{\mu\nu}$$
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$$\mathcal{O}_{lB} = (g'\,y_l)/m_W^2\,(\bar{L}_L\Phi\sigma^{\mu\nu}l_R)\,B_{\mu\nu}$$
$$\mathcal{O}_{lW} = (g\,y_l)/m_W^2\,(\bar{L}_L\sigma^i\Phi\sigma^{\mu\nu}l_R)\,W^i_{\mu\nu}$$

Some efforts trying to capture the Higgs physics with different Lorentz structure (comparing to SM), includes,

Off-shell, Higgs plus X (jet, W, Z) as function of scale parameter such as pT, etc, measurements.

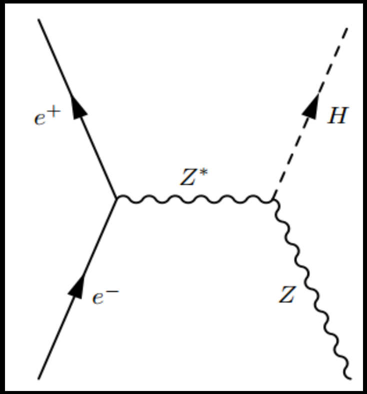
R. Harlander, T. Neumann, arXiv:1308.2225; A. Banf, A. Martin, V. Sanz, arXiv:1308.4771; A. Azatov, A. Paul, arXiv:1309.5273; G. Grojean, E. Salvioni, M. Schlaffer, A. Weiler, arXiv:1312.3317; M. Buschmann, C. Englert, D. Goncalves, T. Plehn, M. Spannowsky, arXiv:1405.7651; S. Dawson, I. Lewis, M. Zeng **arXiv:1501.04103**, **arXiv:1409.6299**; and more

(Top, Tau, VV) CP (beyond scaling)

R.Harnik, A. Martin, T. Okui, R. Primula, F. Yu, **arXiv:1308.1094**; F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J. Shu and J. Zupan, **arXiv:1312.2955**; Y. Chen, R. Harnik, R. Vega-Morales, **arXiv:1503.05855**; N.Belyaev, R. Konoplich, L. Pedersen, K. Prokofiev, **arXiv:1502.03045**; S. Berge, W. Bernreuther, S. Kirchner, **arXiv:1408.0798**; M. Dolan, P. Harris, M. Jankowiak, M. Spannowsky, **arXiv:1406.3322**; Y. Chen, A. Falkowski, I. Low, R. Vega-Morales, **arXiv:1405.6723**; Y. Chen, E. Di Marco, J. Lykken, M. Spiropulu, R. Vega-Morales, S. Xie, **arXiv:1401.2077**; Y. Chen, D. Stolarski, R. Vega-Morales, arXiv:1505.01168; G. Li, H.-R. Wang, S.-H. Zhu arXiv:1506.06453; C. Shen, S.-H. Zhu, arXiv:1504.05626; and more.

Or some other inclusive measurements, such as total rates.

INCLUSIVE MEASUREMENT



N. Craig, M. Farina, M. McCullough and M. Perelstein **arXiv:1411.0676**

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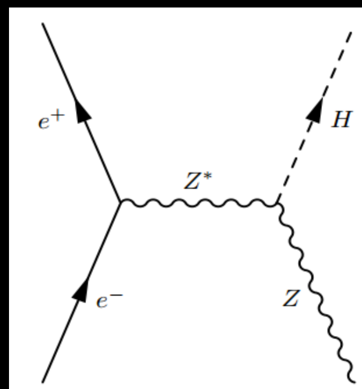

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$$
\begin{aligned}
\mathcal{O}_{WW} &= g^2|H|^2 W^a_{\mu\nu}W^{a,\mu\nu} \\
\mathcal{O}_{BB} &= g'^2|H|^2 B_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}_{WB} &= gg' H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}_{H} &= \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \\
\mathcal{O}_{T} &= \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
\mathcal{O}^{(3)\ell}_{L} &= \left(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right)\left(\bar{L}_L\gamma^\mu\sigma^a L_L\right) \\
\mathcal{O}^{(3)\ell}_{LL} &= \left(\bar{L}_L\gamma_\mu\sigma^a L_L\right)\left(\bar{L}_L\gamma^\mu\sigma^a L_L\right) \\
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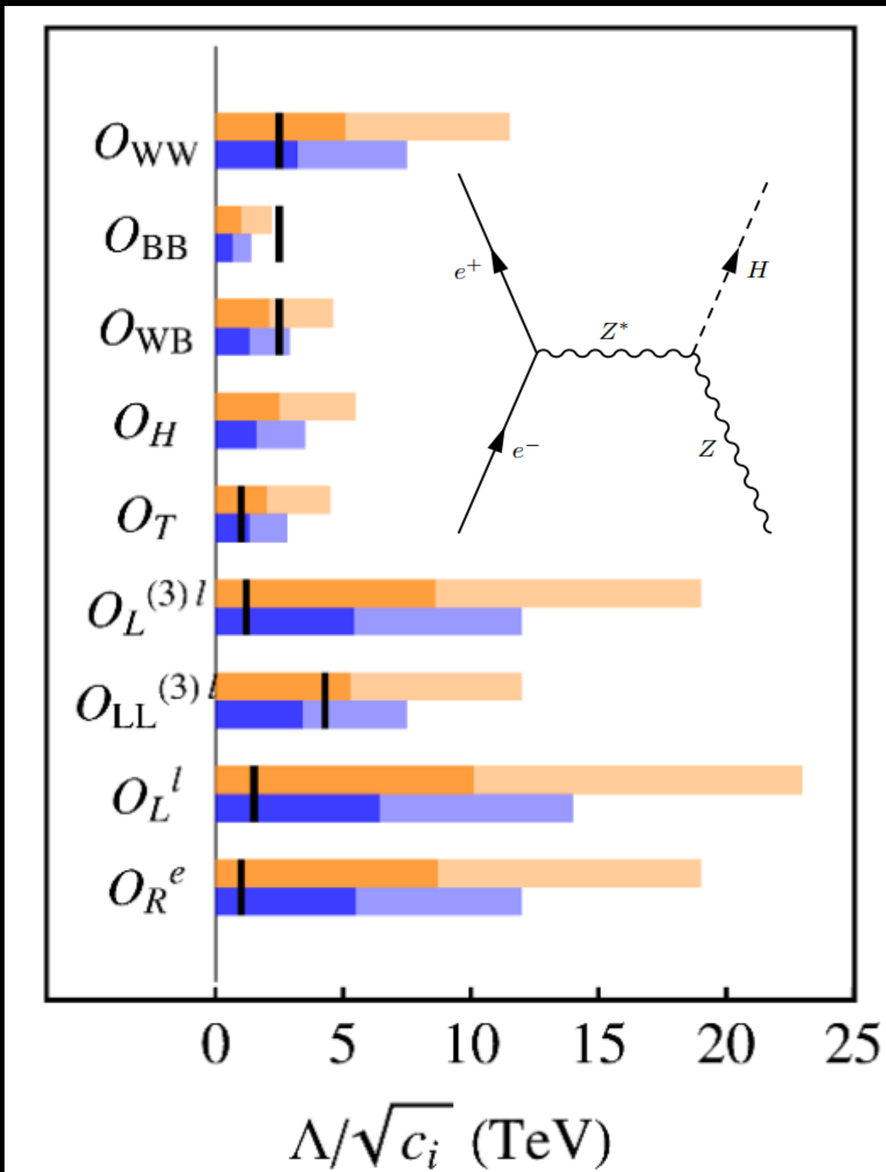

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IN THE MODEL SPACE…

	$\Phi(\mathbf{1},\mathbf{3},0)$	$\Phi(\mathbf{1},\mathbf{2},-\frac{1}{2})$	$\Phi(\mathbf{1},\mathbf{1},0)$	$A^\mu_{U(1)}$	$A^\mu_{SU(2)}$
$\mathcal{O}_{\Phi W}$	✓	✓	-	-	-
$\mathcal{O}_{\Phi B}$	-	✓	-	-	-
$\mathcal{O}_{\Phi WB}$	-	✓	-	-	-
$\mathcal{O}_H$	✓	✓	✓	-	✓
$\mathcal{O}_T$	✓	✓	-	✓	-
$\mathcal{O}^{(3)}_{\Phi\ell}$	✓	✓	-	-	✓
$\mathcal{O}^{prst}_{4L}$	✓	✓	-	-	✓
$\mathcal{O}^{(1)}_{\Phi\ell}$	-	✓	-	✓	-
$\mathcal{O}_{\Phi e}$	-	✓	-	✓	-

Black/Gray: Tree-/loop-level

- Corrections in terms of higher dimensional operators usually coexist.
- The relative sizes depend on the dynamics, overall sizes depend on new physics scale.
- Thus, difficult to extract new physics scale nor distinguish (needs extra information on) different models.

B. Henning, X. Lu, H. Murayama, arXiv:1412.1837; table summarized by N. Craig.

DIM-6 OPERATORS AFFECTING EE->ZH

$$
\begin{array}{ll}
\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi) & \mathcal{O}_{\Phi W} = (\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\mu\nu} \\
\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi) & \mathcal{O}_{\Phi B} = (\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}^{(1)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar\ell\gamma^\mu\ell) & \mathcal{O}_{\Phi WB} = (\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}^{(3)}_{\Phi\ell} = (\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar\ell\gamma^\mu\tau^I\ell) & \mathcal{O}_{\Phi\widetilde{W}} = (\Phi^\dagger\Phi)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu} \\
\mathcal{O}_{\Phi e} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar e\gamma^\mu e) & \mathcal{O}_{\Phi\widetilde{B}} = (\Phi^\dagger\Phi)\widetilde{B}_{\mu\nu}B^{\mu\nu} \\
\mathcal{O}_{4L} = (\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell) & \mathcal{O}_{\Phi\widetilde{W}B} = (\Phi^\dagger\tau^I\Phi)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}
\end{array}
$$

Operator basis

$$
\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ}\, hZ_\mu Z^\mu + c^{(2)}_{ZZ} h\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\widetilde{Z}} h\, Z_{\mu\nu}\widetilde{Z}^{\mu\nu} + c_{AZ} h\, Z_{\mu\nu}A^{\mu\nu} + c_{A\widetilde{Z}} hZ_{\mu
$$
$$
+ hZ_\mu\bar\ell\gamma^\mu\left(c_V + c_A\gamma_5\right)\ell + Z_\mu\bar\ell\gamma^\mu(g_V - g_A\gamma_5)\ell - g_{\rm em}Q_\ell A_\mu\bar\ell\gamma^\mu\ell,
$$

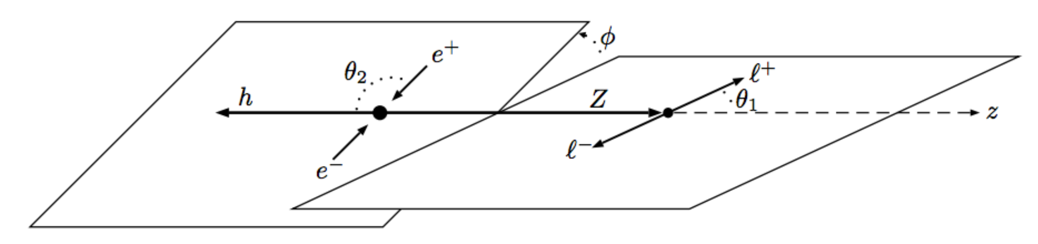
$$
\mathcal{M}^\mu_{HZ\ell\ell} = \frac{1}{m_H}\,\bar u(p_3,s_3)\left[\gamma^\mu\left(H_{1,V} + H_{1,A}\,\gamma_5\right) + \frac{q^\mu \not p}{m_H^2}\left(H_{2,V} + H_{2,A}\,\gamma_5\right) + \frac{\epsilon^{\mu\nu\sigma\rho}p_\nu q_\sigma}{m_H^2}\,\gamma_\rho\,\left(H_{3,V} + H_{3,A}\,\gamma_5\right)\right]v(p_4,s_4),
$$

Interaction basis

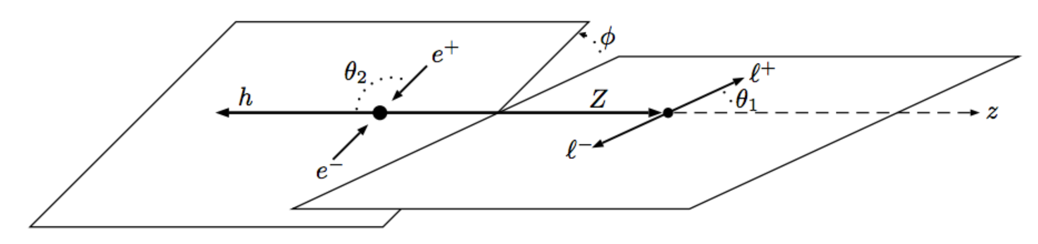
$$
\begin{aligned}
\mathcal{J}(q^2,\theta_1,\theta_2,\phi) = {} & J_1(1 + \cos^2\theta_1\cos^2\theta_2 + \cos^2\theta_1 + \cos^2\theta_2) \\
& + J_2\sin^2\theta_1\sin^2\theta_2 + J_3\cos\theta_1\cos\theta_2 \\
& + (J_4\sin\theta_1\sin\theta_2 + J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi \\
& + (J_6\sin\theta_1\sin\theta_2 + J_7\sin 2\theta_1\sin 2\theta_2)\cos\phi \\
& + J_8\sin^2\theta_1\,\sin^2\theta_2\,\sin 2\phi + J_9\sin^2\theta_1\,\sin^2\theta_2\,\cos 2\phi.
\end{aligned}
$$

Matrix Element

BEYOND RATE-- ASYMMETRIES



$$\mathcal{M}^{\mu}_{HZ\ell\ell} = \frac{1}{m_H}\,\bar{u}(p_3,s_3)\Big[\gamma^{\mu}\left(H_{1,V}+H_{1,A}\,\gamma_5\right)+\frac{q^{\mu}\not{p}}{m_H^2}\left(H_{2,V}+H_{2,A}\,\gamma_5\right) + \frac{\epsilon^{\mu\nu\sigma\rho}p_{\nu}q_{\sigma}}{m_H^2}\,\gamma_{\rho}\left(H_{3,V}+H_{3,A}\,\gamma_5\right)\Big]v(p_4,s_4),$$



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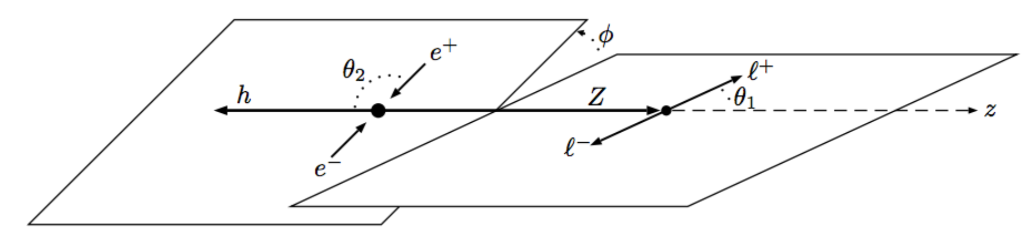
Many operators (twelve) contribute.
Amplitude decomposed into six different currents.
Expanding over dim-6 operators in LO (interfering with SM), only six matrix elements are independent.
Construct six asymmetry observable.

M. Benekea, D. Boitoa, and Y.-M. Wang, arXiv:1406.1361



BEYOND RATE-- ASYMMETRIES

$$\mathcal{M}^{\mu}_{HZ\ell\ell} = \frac{1}{m_H}\,\bar{u}(p_3,s_3)\Big[\gamma^{\mu}\left(H_{1,V}+H_{1,A}\,\gamma_5\right)+\frac{q^{\mu}\not{p}}{m_H^2}\left(H_{2,V}+H_{2,A}\,\gamma_5\right)$$
$$+\frac{\epsilon^{\mu\nu\sigma\rho}p_{\nu}q_{\sigma}}{m_H^2}\,\gamma_{\rho}\left(H_{3,V}+H_{3,A}\,\gamma_5\right)\Big]v(p_4,s_4),$$

$$\mathcal{A}_{\theta_1} = \frac{1}{d\Gamma/dq^2}\int_{-1}^{1} d\cos\theta_1\ \mathrm{sgn}(\cos(2\theta_1))\,\frac{d^2\Gamma}{dq^2 d\cos\theta_1}$$

$$\mathcal{A}^{(1)}_{\phi} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\sin\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{9\,\pi}{32}\,\frac{J_4}{4J_1+J_2},$$

$$\mathcal{A}^{(2)}_{\phi} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\sin(2\phi))\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{2}{\pi}\,\frac{J_8}{4J_1+J_2},$$

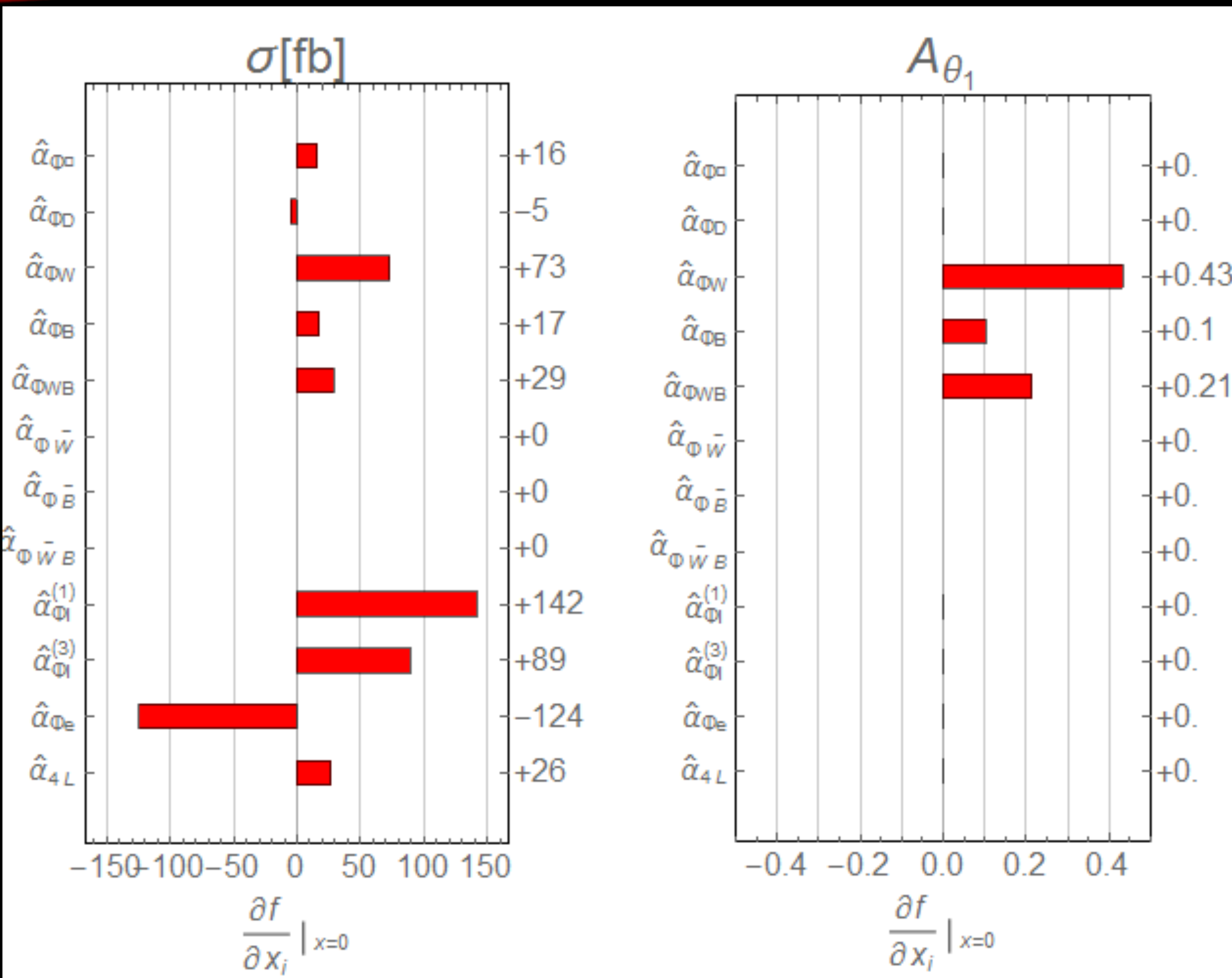
$$\mathcal{A}^{(3)}_{\phi} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\cos\phi)\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{9\,\pi}{32}\,\frac{J_6}{4J_1+J_2},$$

$$\mathcal{A}^{(4)}_{\phi} = \frac{1}{d\Gamma/dq^2}\int_{0}^{2\pi} d\phi\ \mathrm{sgn}(\cos(2\phi))\,\frac{d^2\Gamma}{dq^2 d\phi} = \frac{2}{\pi}\,\frac{J_9}{4J_1+J_2}.$$

$$\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{d\Gamma/dq^2}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\,\frac{d^3\Gamma}{dq^2 d\cos\theta_1 d\cos\theta_2}$$

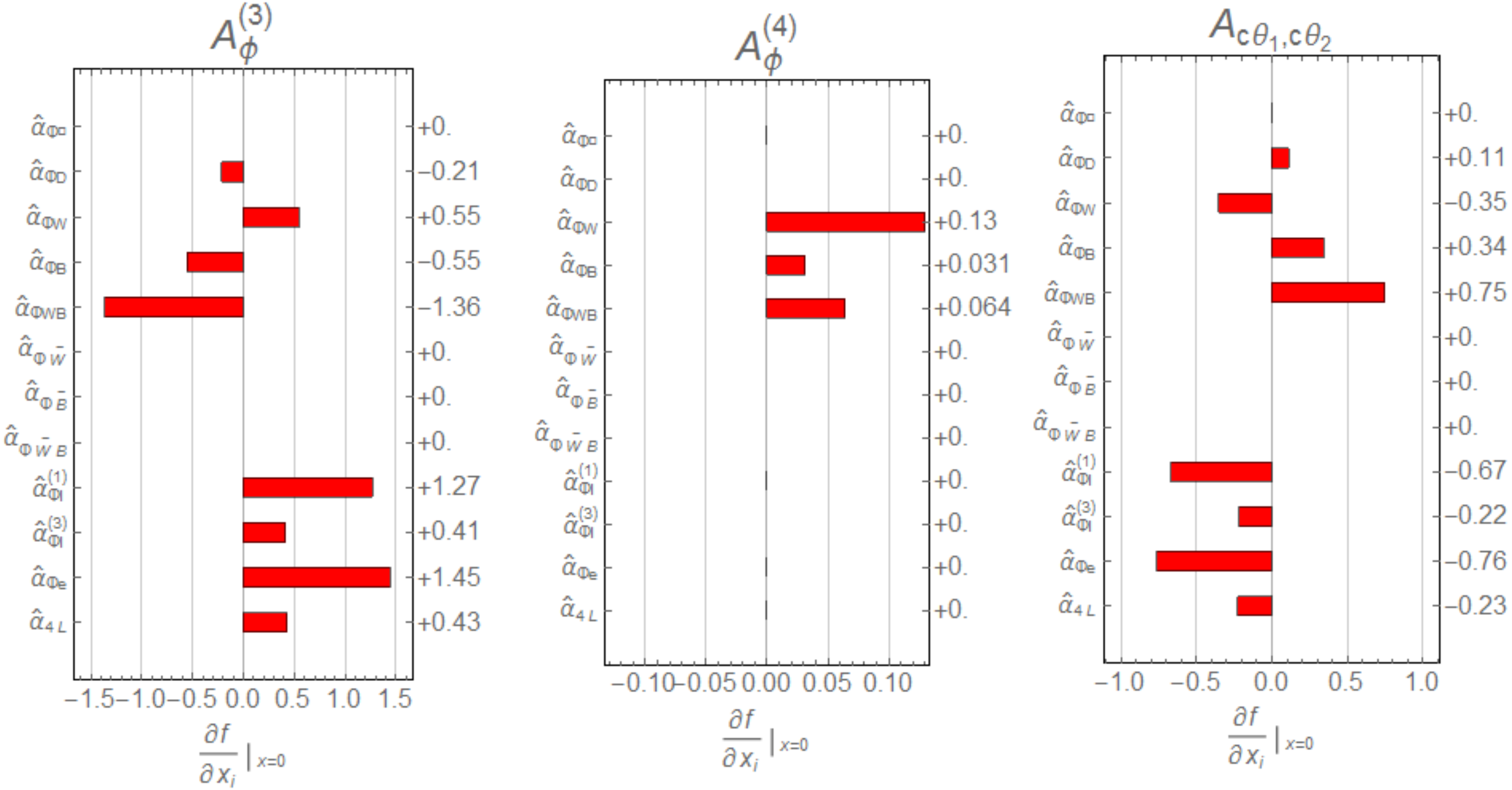
Many operators (twelve) contribute.
Amplitude decomposed into six different currents.
Expanding over dim-6 operators in LO (interfering with SM), only six matrix elements are independent.
Construct six asymmetry observable.

M. Benekea, D. Boitoa, and Y.-M. Wang, arXiv:1406.1361

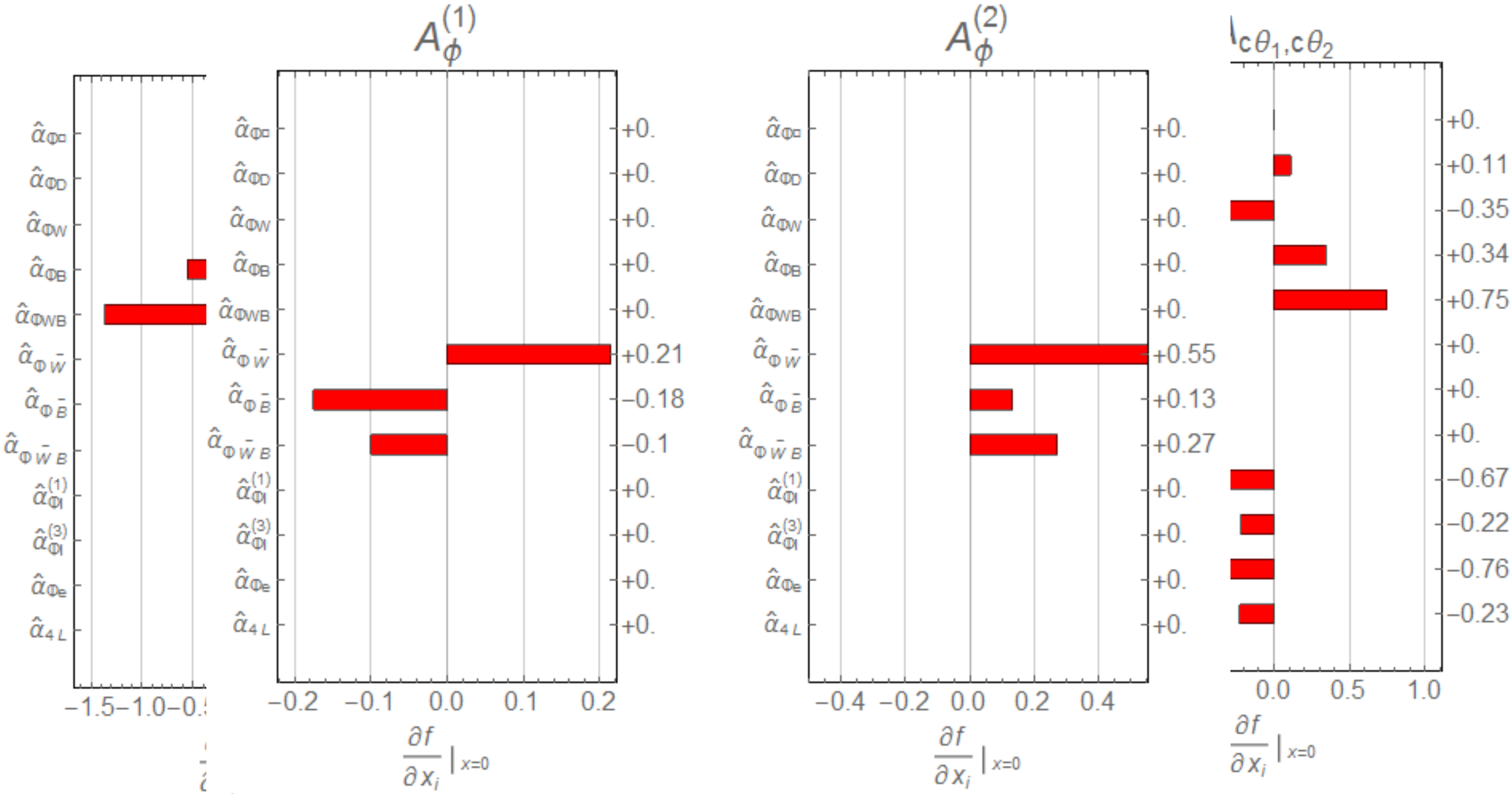


Response function—how much the observable would change as a function of the coefficients of relevant operators.

Total rate sees most operators, CP-odd ones at quadratic level, while different asymmetries pick up corresponding "modes".



$A_\phi^{(3)}$
$A_\phi^{(4)}$
$A_{c\theta_1, c\theta_2}$
$\hat{\alpha}_{\Phi\Box}$
$\hat{\alpha}_{\Phi D}$
$\hat{\alpha}_{\Phi W}$
$\hat{\alpha}_{\Phi B}$
$\hat{\alpha}_{\Phi WB}$
$\hat{\alpha}_{\Phi \tilde{W}}$
$\hat{\alpha}_{\Phi \tilde{B}}$
$\hat{\alpha}_{\Phi \tilde{W} B}$
$\hat{\alpha}_{\Phi l}^{(1)}$
$\hat{\alpha}_{\Phi l}^{(3)}$
$\hat{\alpha}_{\Phi e}$
$\hat{\alpha}_{4L}$
+0. −0.21 +0.55 −0.55 −1.36 +0. +0. +0. +1.27 +0.41 +1.45 +0.43
+0. +0. +0.13 +0.031 +0.064 +0. +0. +0. +0. +0. +0. +0.
+0. +0.11 −0.35 +0.34 +0.75 +0. +0. +0. −0.67 −0.22 −0.76 −0.23
−1.5 −1.0 −0.5 0.0 0.5 1.0 1.5
−0.10 −0.05 0.00 0.05 0.10
−1.0 −0.5 0.0 0.5 1.0
$\frac{\partial f}{\partial x_i}|_{x=0}$


$A_\phi^{(1)}$
$A_\phi^{(2)}$
$c\theta_1, c\theta_2$
$\hat{\alpha}_{\Phi\Box}$
$\hat{\alpha}_{\Phi D}$
$\hat{\alpha}_{\Phi W}$
$\hat{\alpha}_{\Phi B}$
$\hat{\alpha}_{\Phi WB}$
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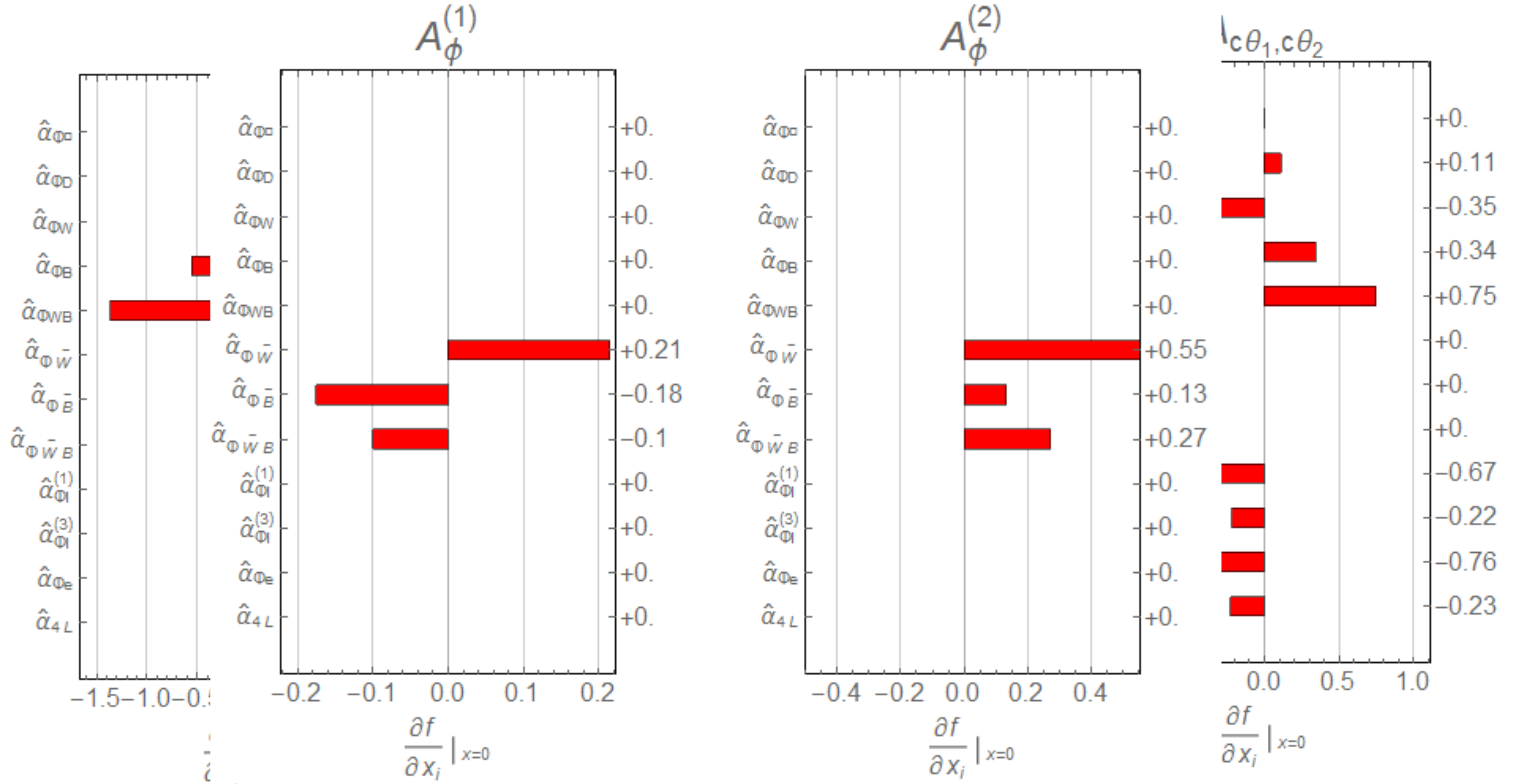
−0.4 −0.2 0.0 0.2 0.4
0.0 0.5 1.0
$\frac{\partial f}{\partial x_i}|_{x=0}$



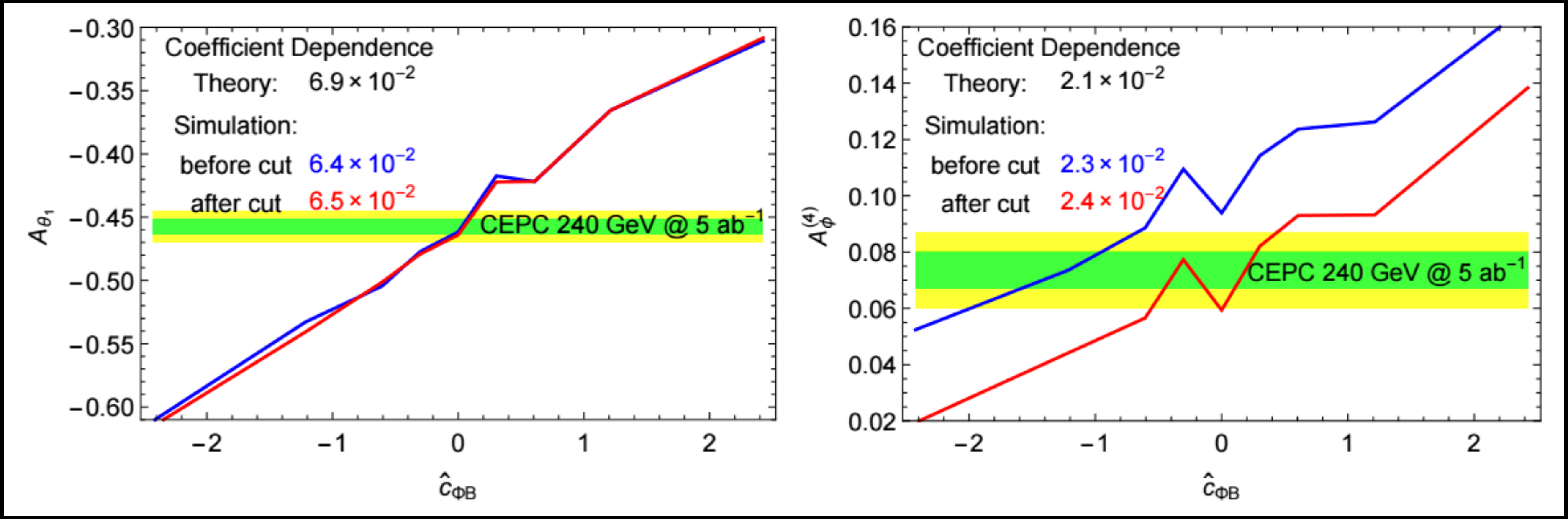
When studying all these asymmetries simultaneously, we are to see the relative sizes of the operators, and get much better sense of possible underlying new physics.

PHENOMENOLOGY

For simplicity and without much lose of generality, we study the "background-free" channel of ee->ZH, Z->ll, H->bb at lepton colliders.

~few million of events will be selected, we impose selection cuts on these channels following the detailed studies done for CEPC preCDR.

Study includes various collider effects including beamstrhlung, collider cuts, input parameter dependence, and their relative contribution to uncertainty.



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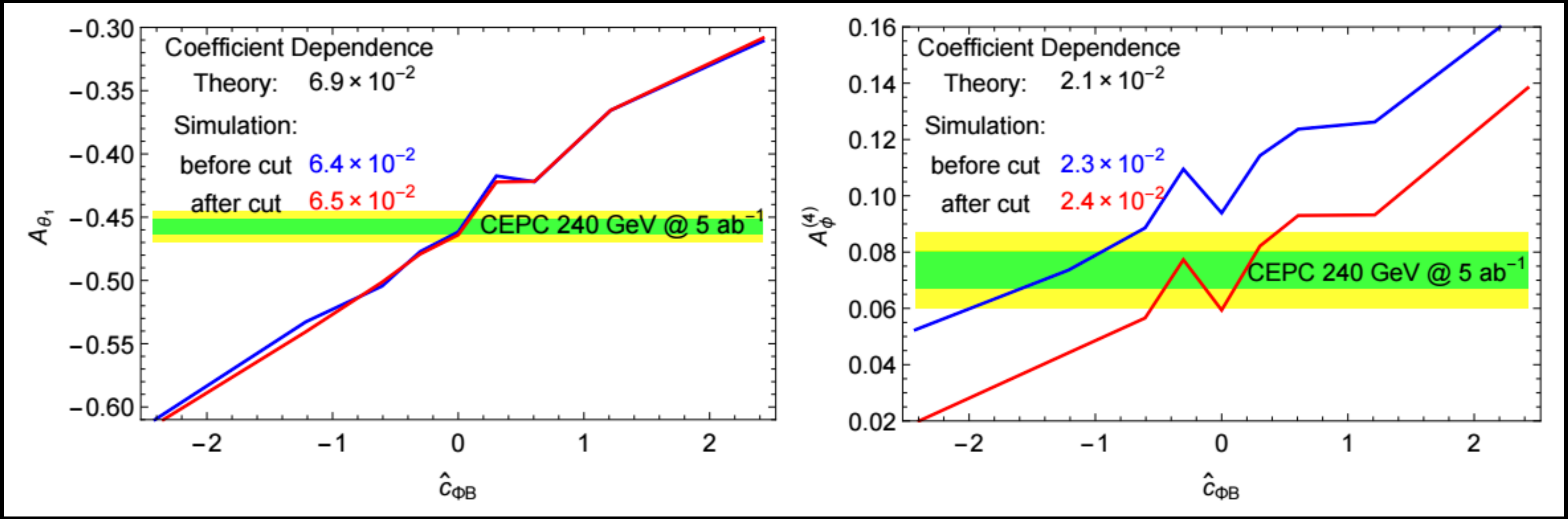


E.g, how the parton level simulation on the asymmetries (which agrees well with our analytic calculation) change under collider environment.

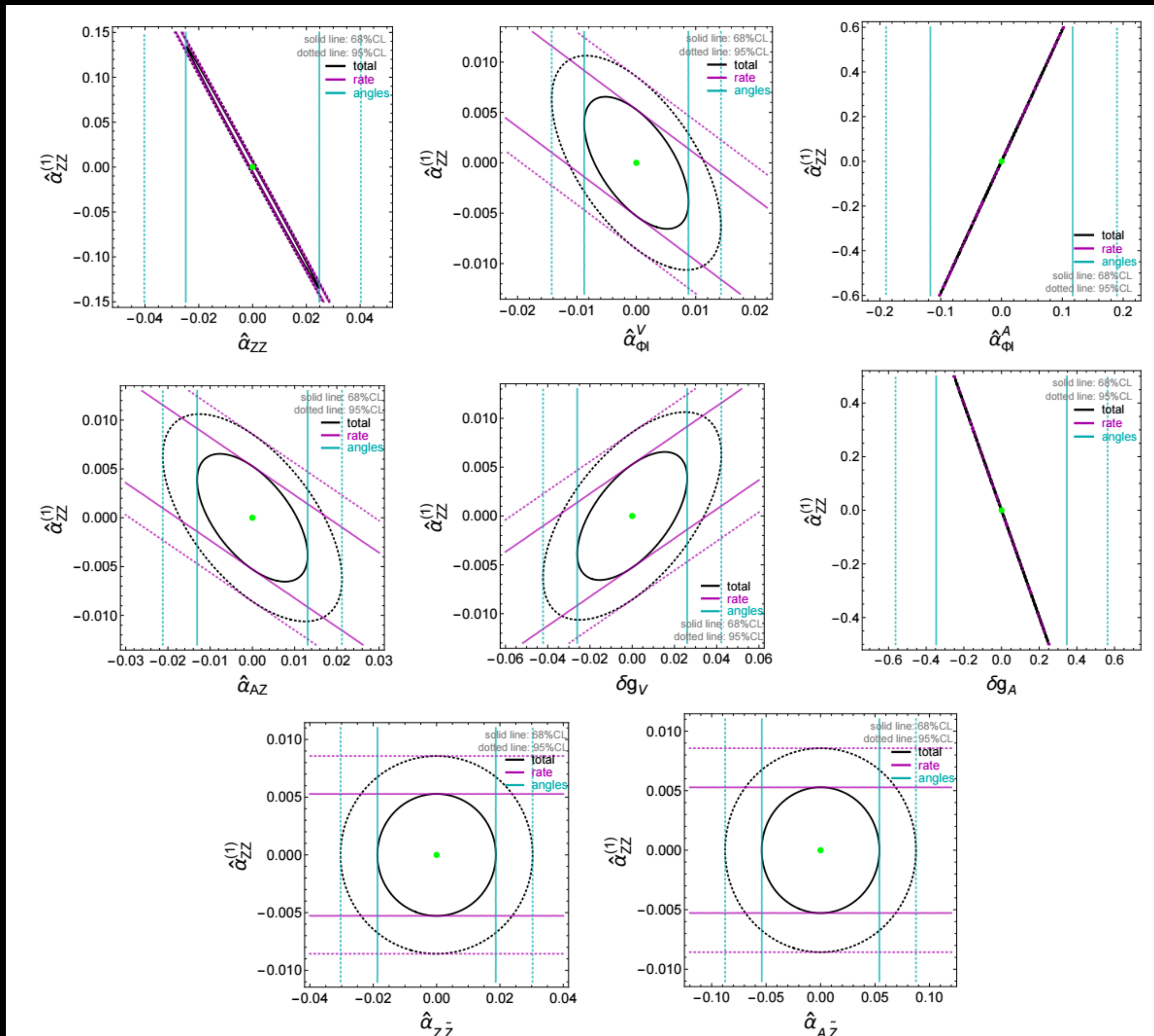
Blue/red before/after cuts.

Green/yellow band, projected 1-/2- sigma sensitivity on individual observable.

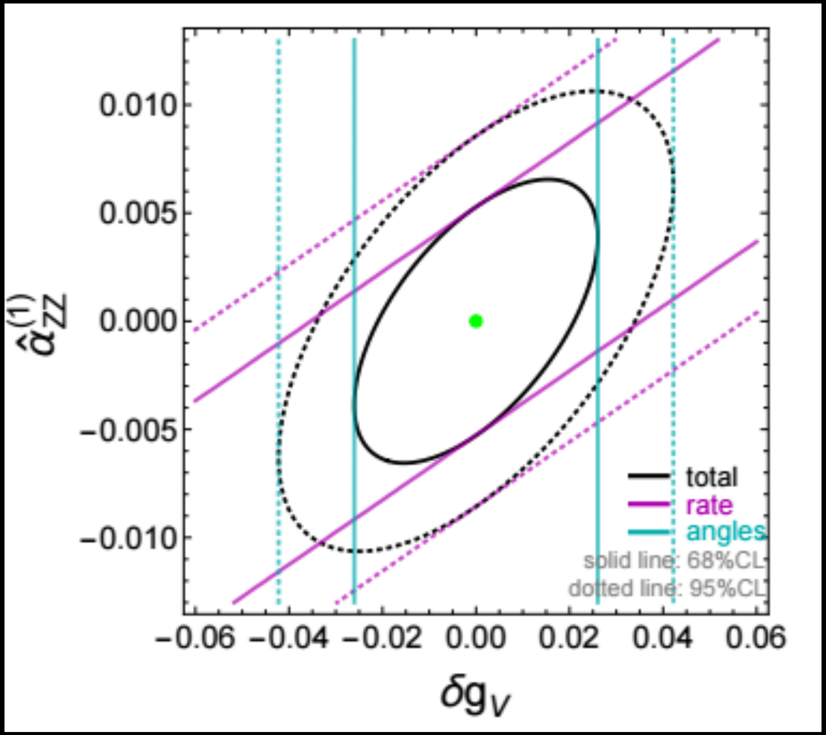
Selection	$\mathcal{A}_{\theta_1}$	$\mathcal{A}_{\phi}^{(1)}$	$\mathcal{A}_{\phi}^{(2)}$	$\mathcal{A}_{\phi}^{(3)}$	$\mathcal{A}_{\phi}^{(4)}$	$\mathcal{A}_{c\theta_1,c\theta_2}$
Initial	-0.46	0.0013	0.00076	0.013	0.093	-0.0054
$10^\circ < \theta_\mu < 170^\circ$	-0.46	0.0013	0.00063	0.012	0.057	-0.0053
$10\ \text{GeV} < p_T(\mu^+\mu^-) < 90\ \text{GeV}$	-0.46	0.0011	0.00070	0.012	0.058	-0.0054
$81\ \text{GeV} < m_{\mu^+\mu^-} < 101\ \text{GeV}$	-0.46	0.0009	0.00055	0.012	0.058	-0.0056
$120\ \text{GeV} < m_{\text{recoil}} < 150\ \text{GeV}$	-0.46	0.0009	0.00055	0.012	0.058	-0.0056

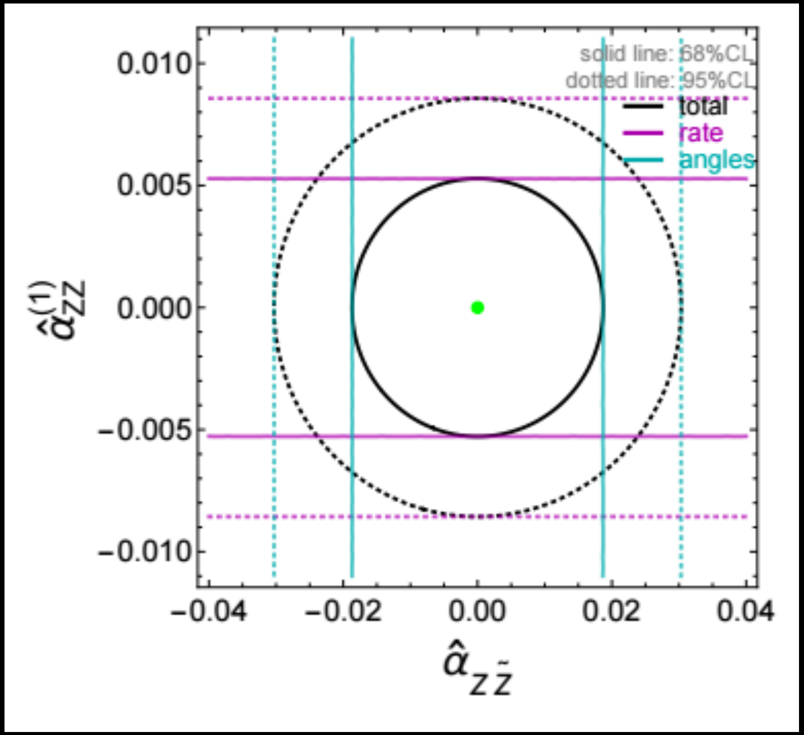
observable	SM expectation	Precision σ_A		
		$5\,\text{ab}^{-1}$ CEPC	$30\,\text{ab}^{-1}$ FCC-ee	Full Stat.
$\mathcal{A}_{\theta_1}$	-0.448	0.0060	0.0025	0.00078
$\mathcal{A}_{\phi}^{(1)}$	0	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(2)}$	0	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(3)}$	0.0136	0.0067	0.0027	0.00087
$\mathcal{A}_{\phi}^{(4)}$	0.0959	0.0067	0.0027	0.00086
$\mathcal{A}_{c\theta_1,c\theta_2}$	-0.0075	0.0067	0.0027	0.00087

THE DIAGNOSTIC POWER



THE DIAGNOSTIC POWER



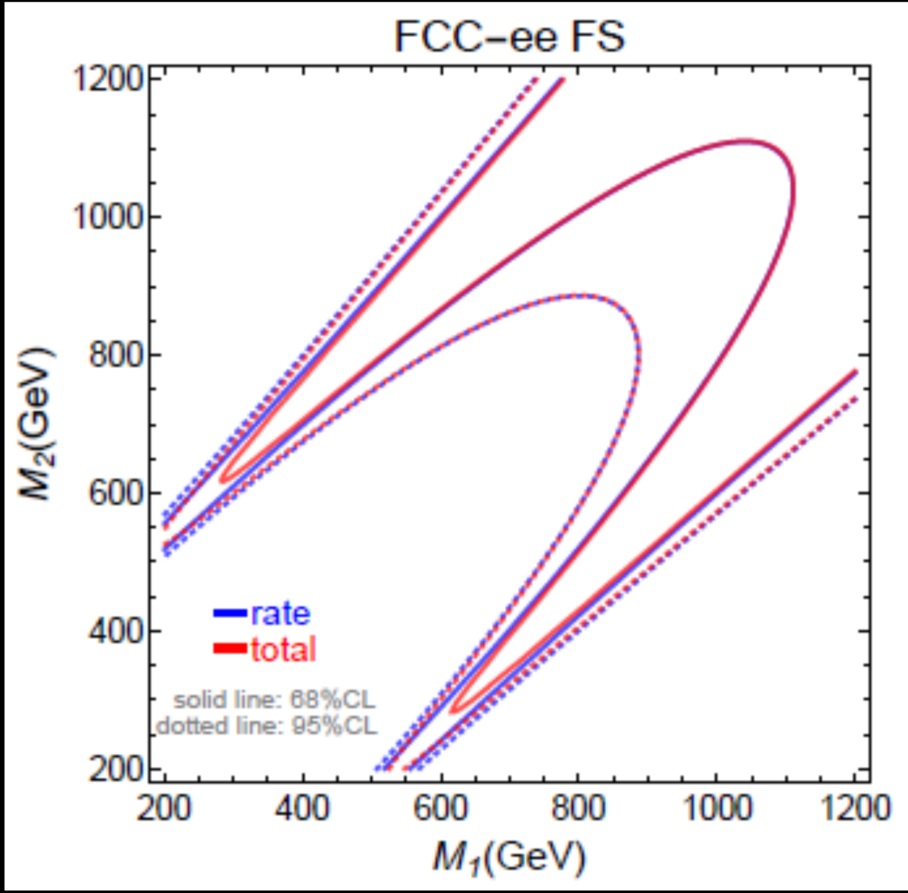


Asymmetry breaks the flat direction of inclusive rate measurement, and provides novel information about the underlying operator structures.

Many plots of similar types are obtained by our studies.

We are to demonstrate these diagnostic power in model space as well.

DIAGNOSTIC POWER: CASE OF TOP SQUARK



Blue: cross section alone
Red: with asymmetries

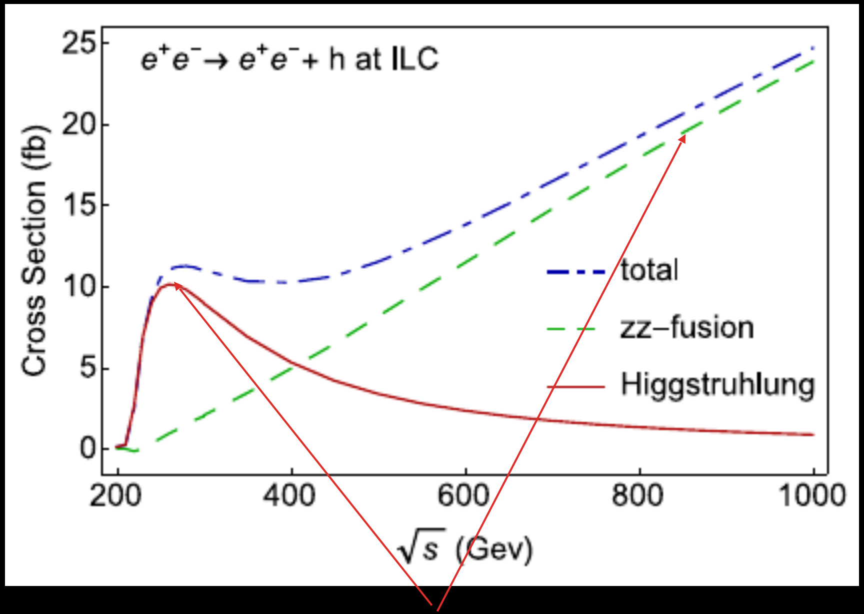
Asymmetries could cover the region where stop contribution to rates being zero, shining lights on the “blind spot”.

Sensitivity is low because of all effects are loop-induced and operators are of similar strength. BSM models inducing different tensorial structure of interactions will be best application (for future work).

Asymmetry breaks the flat direction of inclusive rate measurement, and provides novel information about the underlying operator structures.

A side remark:

the case for lepton colliders with different operation energies have some extra handle.



To gain more from going to higher energies, we propose to study the ZZ-fusion channel for inclusive measurement.

T. Han, ZL, Z. Qian and J. Sayre, **arXiv: 1504.01399**.

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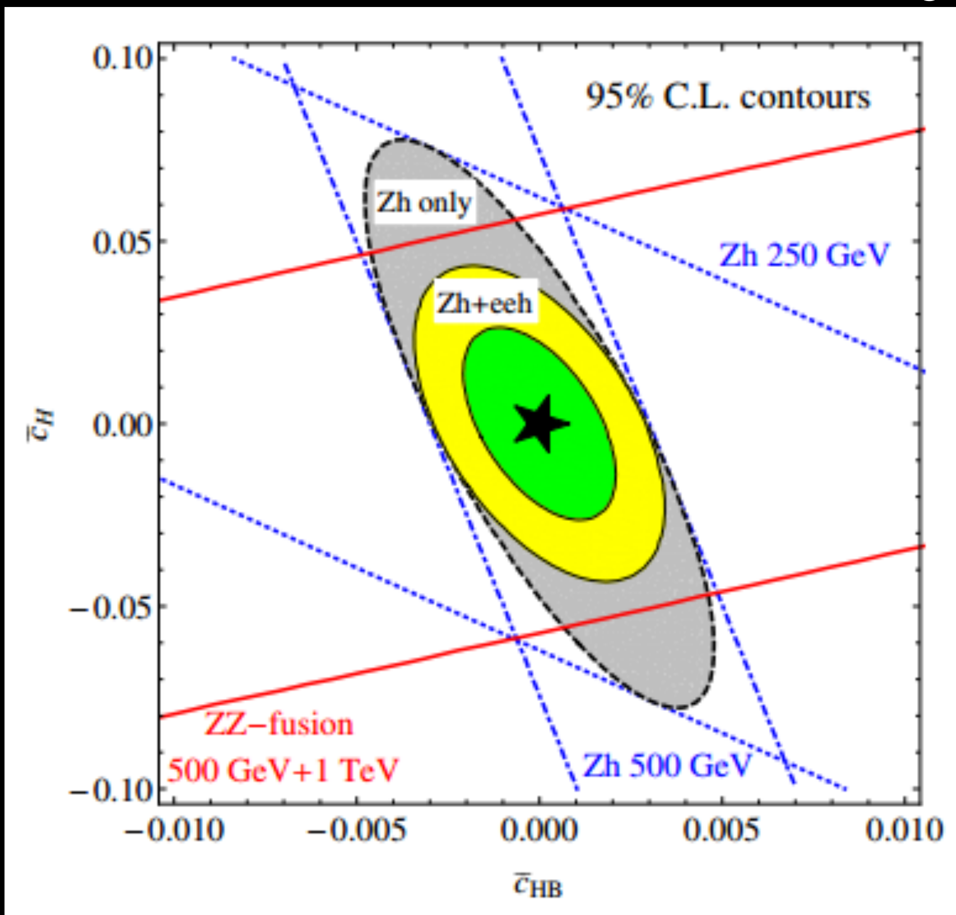

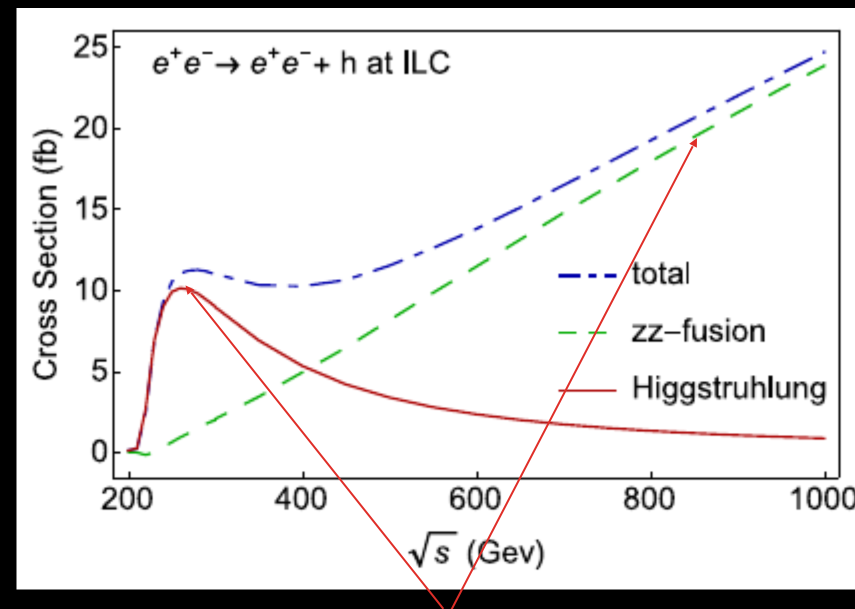

To gain more from going to higher energies, we propose to study the ZZ-fusion channel for inclusive measurement.

ZZ-fusion, break degeneracy and improve sensitivity.

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SUMMARY AND OUTLOOK

We explore lepton collider Higgs factory physics potential from asymmetry observable.

They provide novel information *not* captured in usual precision study.

Very important in improving sensitivities of precision measurement, distinguishing contributions from different new physics, and probing the underlying dynamics of new physics.

*high order corrections are important (not addressed here but in the paper)

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We explore lepton collider Higgs factory physics potential from asymmetry observable.

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Very important in improving sensitivities of precision measurement, distinguishing contributions from different new physics, and probing the underlying dynamics of new physics.

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Thank you !

BACKUP

$$
\begin{aligned}
\mathcal{J}(q^2, \theta_1, \theta_2, \phi) \;=\;& J_1(1 + \cos^2\theta_1 \cos^2\theta_2 + \cos^2\theta_1 + \cos^2\theta_2) \\
& + J_2 \sin^2\theta_1 \sin^2\theta_2 + J_3 \cos\theta_1 \cos\theta_2 \\
& + (J_4 \sin\theta_1 \sin\theta_2 + J_5 \sin 2\theta_1 \sin 2\theta_2) \sin\phi \\
& + (J_6 \sin\theta_1 \sin\theta_2 + J_7 \sin 2\theta_1 \sin 2\theta_2) \cos\phi \\
& + J_8 \sin^2\theta_1 \; \sin^2\theta_2 \; \sin 2\phi + J_9 \sin^2\theta_1 \; \sin^2\theta_2 \; \cos 2\phi .
\end{aligned}
$$

$$J_1 = 2\,r\,s\;\left(g_A^2 + g_V^2\right)\left(|H_{1,V}|^2 + |H_{1,A}|^2\right),$$

$$J_2 = \kappa\;\left(g_A^2 + g_V^2\right)\left[\kappa\;\left(|H_{1,V}|^2 + |H_{1,A}|^2\right) + \lambda\,\mathrm{Re}\left(H_{1,V}H_{2,V}^* + H_{1,A}H_{2,A}^*\right)\right],$$

$$J_3 = 32\,r\,s\,g_A\,g_V\,\mathrm{Re}\left(H_{1,V}\,H_{1,A}^*\right),$$

$$J_4 = 4\kappa\,\sqrt{r\,s\,\lambda}\,g_A\,g_V\,\mathrm{Re}\left(H_{1,V}H_{3,A}^* + H_{1,A}H_{3,V}^*\right),$$

$$J_5 = \frac{1}{2}\kappa\,\sqrt{r\,s\,\lambda}\;\left(g_A^2 + g_V^2\right)\mathrm{Re}\left(H_{1,V}H_{3,V}^* + H_{1,A}\,H_{3,A}^*\right),$$

$$J_6 = 4\sqrt{r\,s}\,g_A\,g_V\;\left[4\kappa\,\mathrm{Re}\left(H_{1,V}H_{1,A}^*\right) + \lambda\,\mathrm{Re}\left(H_{1,V}H_{2,A}^* + H_{1,A}H_{2,V}^*\right)\right],$$

$$J_7 = \frac{1}{2}\sqrt{r\,s}\left(g_A^2 + g_V^2\right)\left[2\kappa\;\left(|H_{1,V}|^2 + |H_{1,A}|^2\right) + \lambda\,\mathrm{Re}\left(H_{1,V}H_{2,V}^* + H_{1,A}H_{2,A}^*\right)\right]$$

$$J_8 = 2\,r\,s\,\sqrt{\lambda}\left(g_A^2 + g_V^2\right)\mathrm{Re}\left(H_{1,V}H_{3,V}^* + H_{1,A}H_{3,A}^*\right),$$

$$J_9 = 2\,r\,s\;\left(g_A^2 + g_V^2\right)\left(|H_{1,V}|^2 + |H_{1,A}|^2\right).$$