Precision Higgs @ FCC-ee

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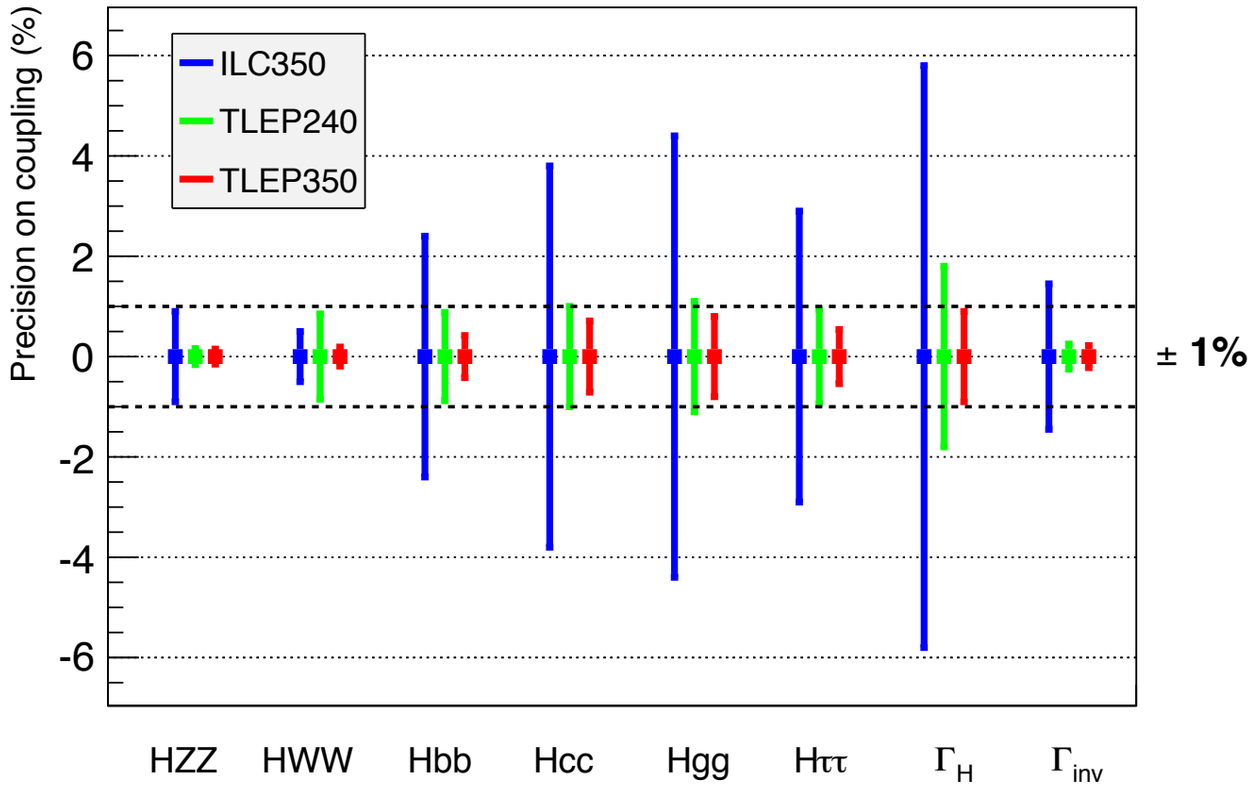
Based primarily on **NC**, J. Gu, Z. Liu, K. Wang arXiv:1512.06877

LHC, FCC-ee, FCC-hh Interplay, 11.25.16

The Higgs Precision Frontier

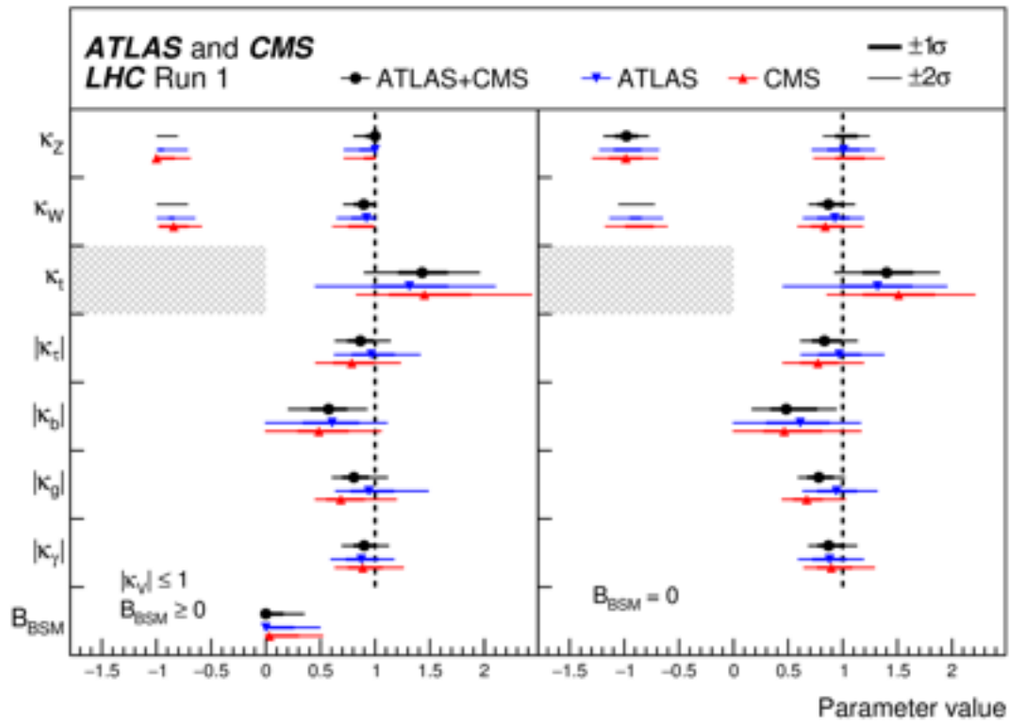


Natural from rate measurements, but misses the variety of possible Lorentz structures arising in general Higgs EFT, leaves many flat directions.

E.g. $|H|^2 W_\mu W^\mu$ vs. $|H|^2 W_{\mu\nu} W^{\mu\nu}$

Astonishing Higgs precision possible at FCC-ee.
How do we use it?

Higgs precision measurements @ LHC & projections for future colliders couched in terms of "κ framework" (deviations in SM-like couplings)

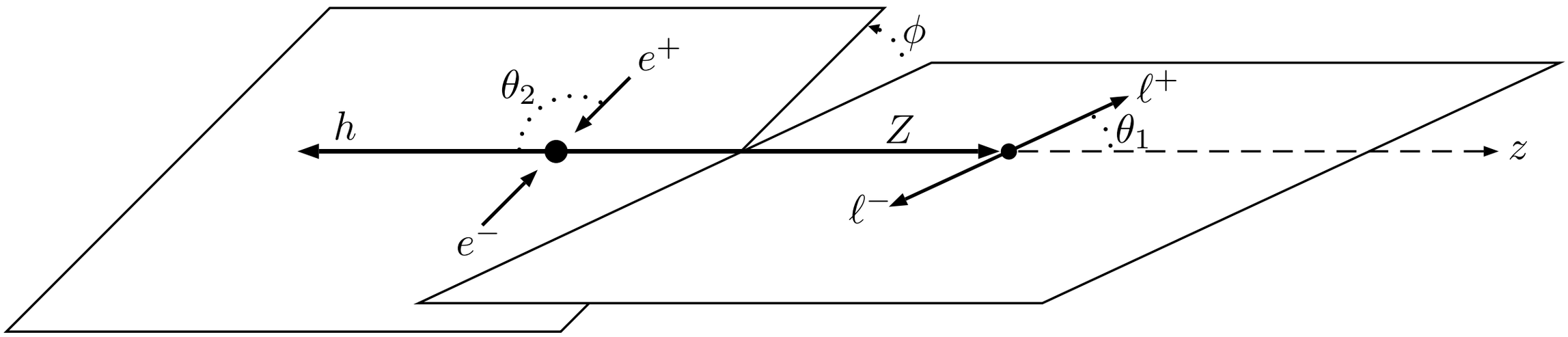


Higgs angular observables

[M. Beneke, D. Boito, Y-M Wang '14; **NC**, J. Gu, Z. Liu, K. Wang '15]

Let's squeeze all the blood from this proverbial stone!

Make use of all angular information available in $e^+e^- \to Zh \to \ell^+\ell^- h$



Six form factors in the amplitude, **six** independent angular observables

Angular observables provide additional sensitivity on top of rate measurements, disambiguate various EFT coefficients.

Note: Same info as in $h \to ZZ^* \to 4\ell$, but larger $\sigma \cdot \mathrm{Br}$ at circular e^+e^-, cleaner measurement, and q^2/m_h^2 enhancement of corrections

Dim-6 EFT

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

Choose your favorite basis; the above is a complete basis for $e^+e^-\to Zh$

After EWSB, gives us an effective Lagrangian w/ 9 relevant coeffs:

$$(\mathcal{L}_{\rm eff} - \mathcal{L}_{\rm SM,tree}) \supset m_Z^2(\sqrt{2}G_F)^{1/2}\widehat{\alpha}^{(1)}_{ZZ}hZ_\mu Z^\mu + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{ZZ}hZ_{\mu\nu}Z^{\mu\nu} + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{Z\tilde{Z}}hZ_{\mu\nu}\widetilde{Z}^{\mu\nu}$$
$$+(\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{AZ}hZ_{\mu\nu}A^{\mu\nu} + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{A\tilde{Z}}hZ_{\mu\nu}\widetilde{A}^{\mu\nu}$$
$$+\sqrt{2}G_F m_Z hZ_\mu\bar{\ell}\gamma^\mu\left(\widehat{\alpha}^V_{\Phi\ell} + \widehat{\alpha}^A_{\Phi\ell}\gamma_5\right)\ell + \frac{1}{2}m_Z(\sqrt{2}G_F)^{1/2}Z_\mu\bar{\ell}\gamma^\mu(\delta g_V - \delta g_A\gamma_5)\ell$$

Fun exercise: map dim-6 operator coefficients to Lagrangian

$$\begin{aligned}
\alpha^{(1)}_{ZZ} &= \alpha_{\Phi\Box} - \frac{1}{2}\delta'_{G_F} + \frac{1}{4}\alpha_{\Phi D},\\
\alpha_{ZZ} &= c_W^2\alpha_{\Phi W} + s_W^2\alpha_{\Phi B} + s_W c_W\alpha_{\Phi WB},\\
\alpha_{Z\tilde{Z}} &= c_W^2\alpha_{\Phi\widetilde{W}} + s_W^2\alpha_{\Phi\widetilde{B}} + s_W c_W\alpha_{\Phi\widetilde{W}B},\\
\alpha_{AZ} &= 2s_W c_W(\alpha_{\Phi W} - \alpha_{\Phi B}) + (s_W^2 - c_W^2)\alpha_{\Phi WB},\\
\alpha_{A\tilde{Z}} &= 2s_W c_W(\alpha_{\Phi\widetilde{W}} - \alpha_{\Phi\widetilde{B}}) + (s_W^2 - c_W^2)\alpha_{\Phi\widetilde{W}B},
\end{aligned}$$

$$\begin{aligned}
\widehat{\alpha}^V_{\Phi\ell} &= \widehat{\alpha}_{\Phi e} + \left(\widehat{\alpha}^{(1)}_{\Phi\ell} + \widehat{\alpha}^{(3)}_{\Phi\ell}\right)\\
\widehat{\alpha}^A_{\Phi\ell} &= \widehat{\alpha}_{\Phi e} - \left(\widehat{\alpha}^{(1)}_{\Phi\ell} + \widehat{\alpha}^{(3)}_{\Phi\ell}\right)\\
\delta g_V &= -\widehat{\alpha}^V_{\Phi\ell} + \frac{\widehat{\alpha}_{\Phi D}}{4} + \frac{\delta_{G_F}}{2} + \frac{4s_W^2}{c_{2W}}\left[\frac{\widehat{\alpha}_{\Phi D}}{4} + \frac{c_W}{s_W}\widehat{\alpha}_{\Phi WB} + \frac{\delta_{G_F}}{2}\right]\\
\delta g_A &= -\widehat{\alpha}^A_{\Phi\ell} - \frac{\widehat{\alpha}_{\Phi D}}{4} - \frac{\delta_{G_F}}{2}
\end{aligned}$$

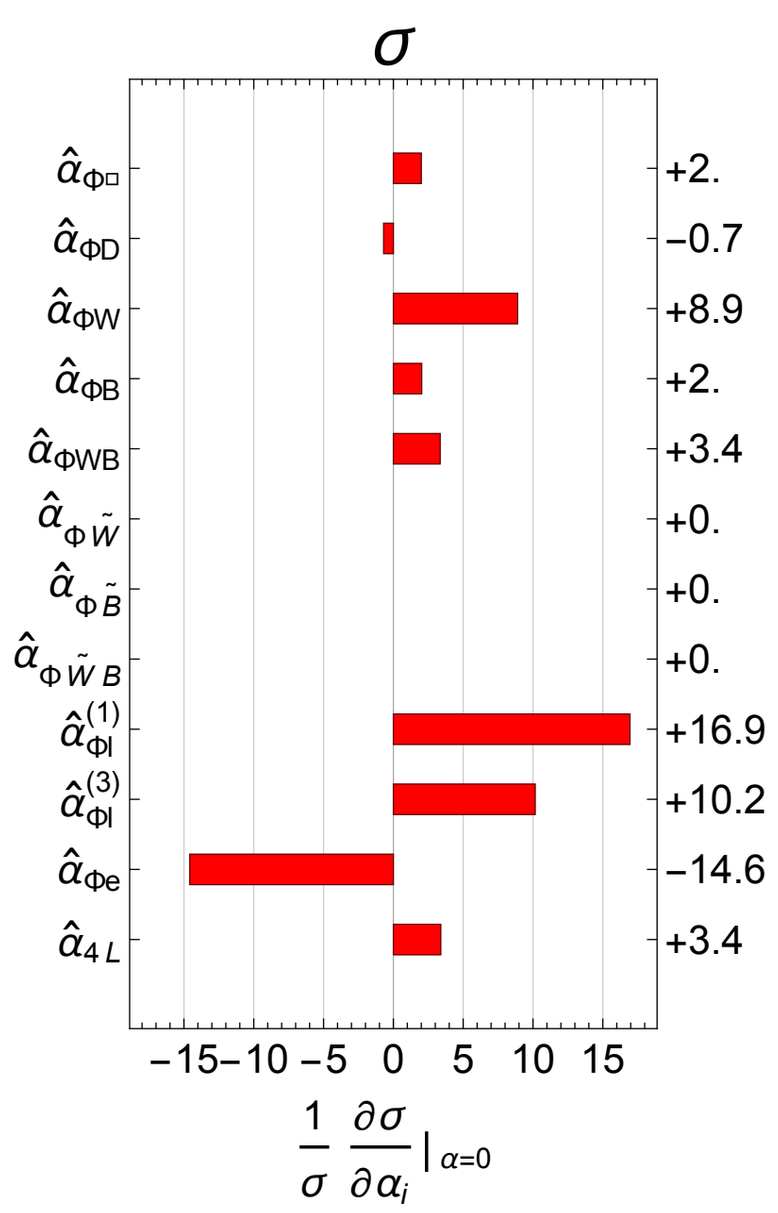
Here $\widehat{\alpha}_i = \alpha_i v^2/\Lambda^2$

Input params: $m_Z, G_F, \alpha_{em}(q^2=0)$

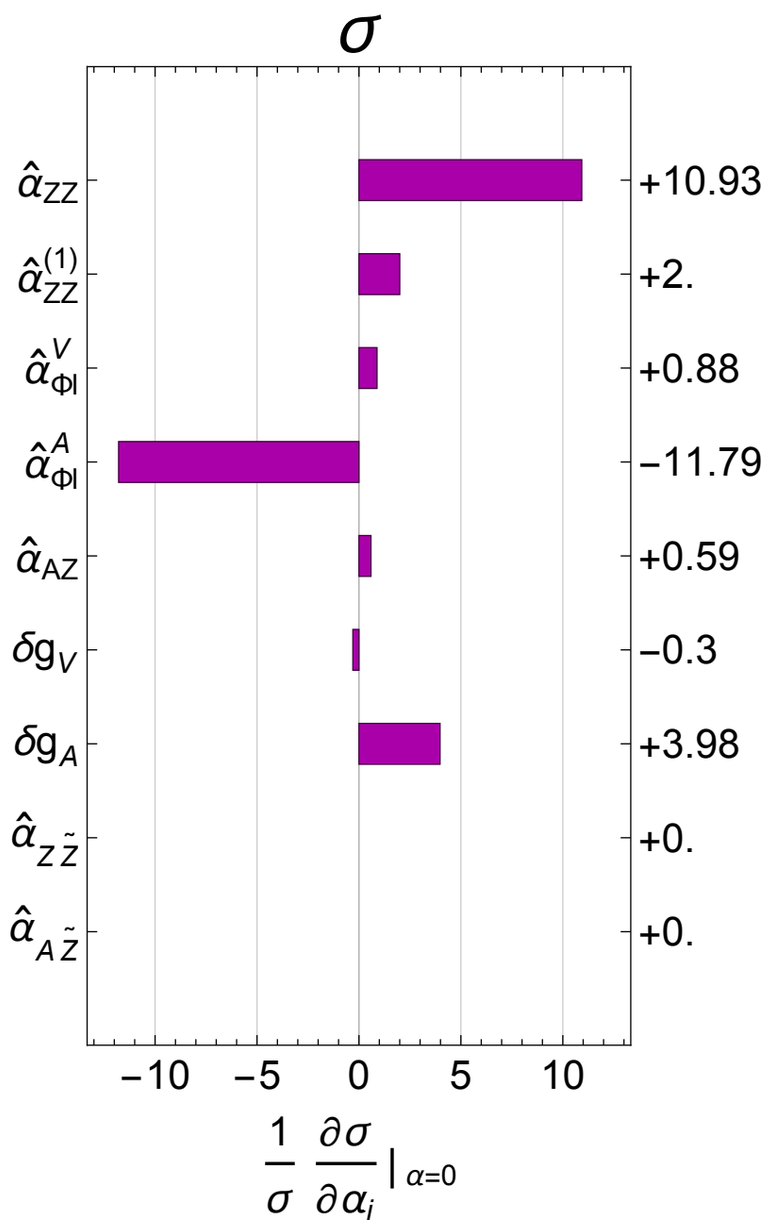
Rates at $\sqrt{s} = 240$ GeV

By-now familiar result: cross section strongly sensitive to shifts in hZZ coupling…plus other operators.

$$\hat{\alpha}_i = \alpha_i \frac{v^2}{\Lambda^2}$$

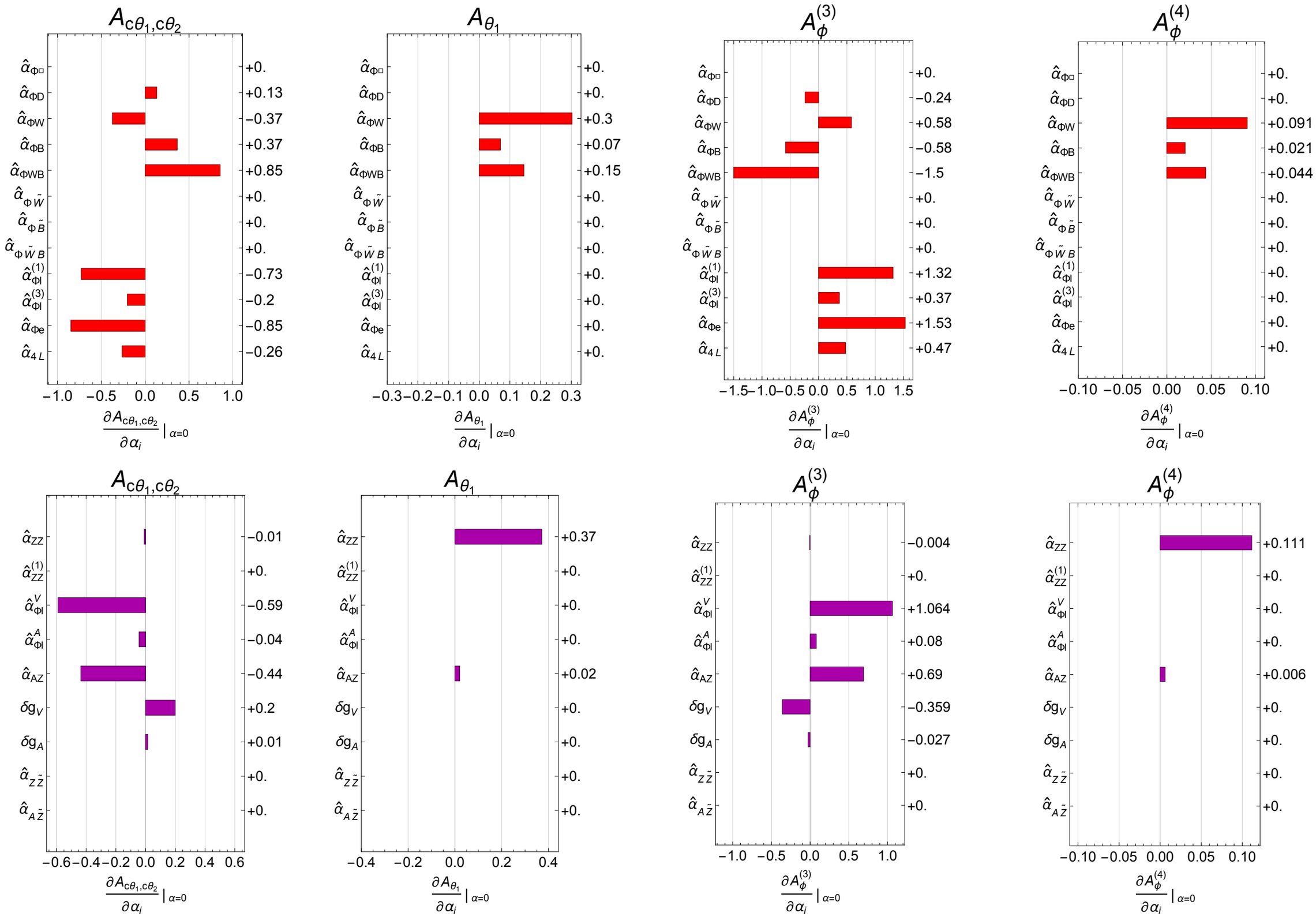


In terms of dim-6 coefficients…

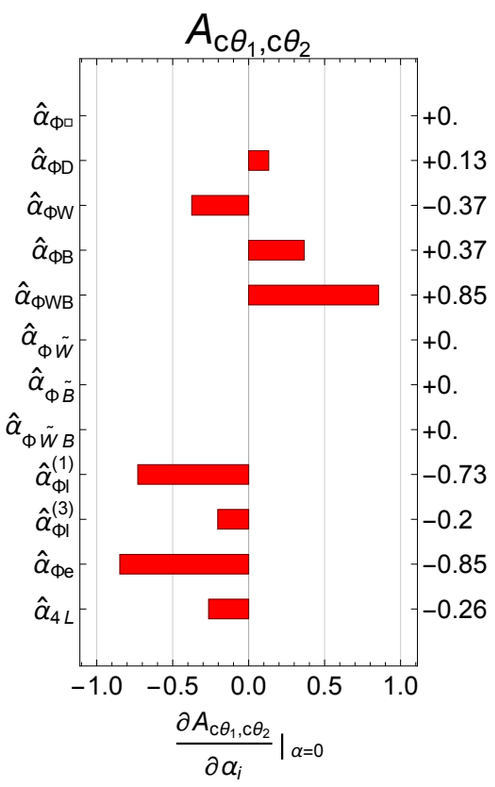


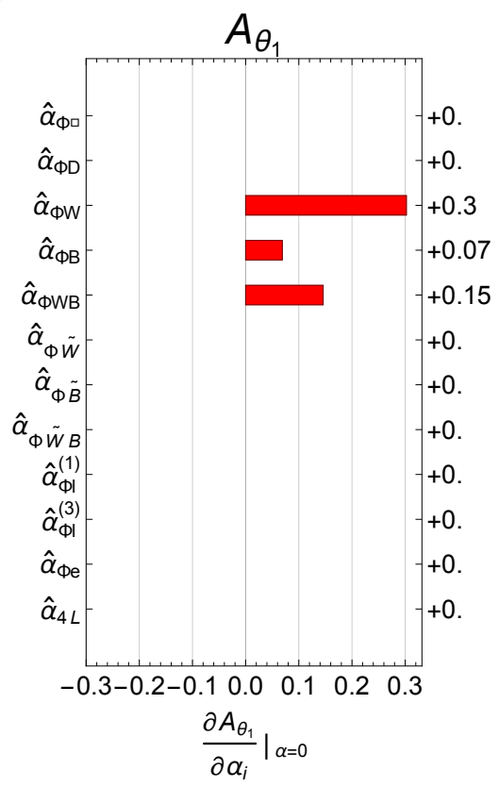
…and broken-phase coefficients

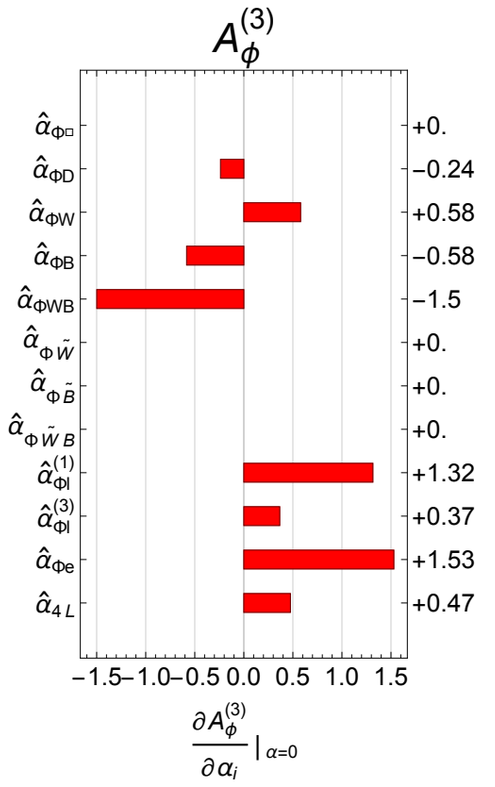
Everything else (CP-even)

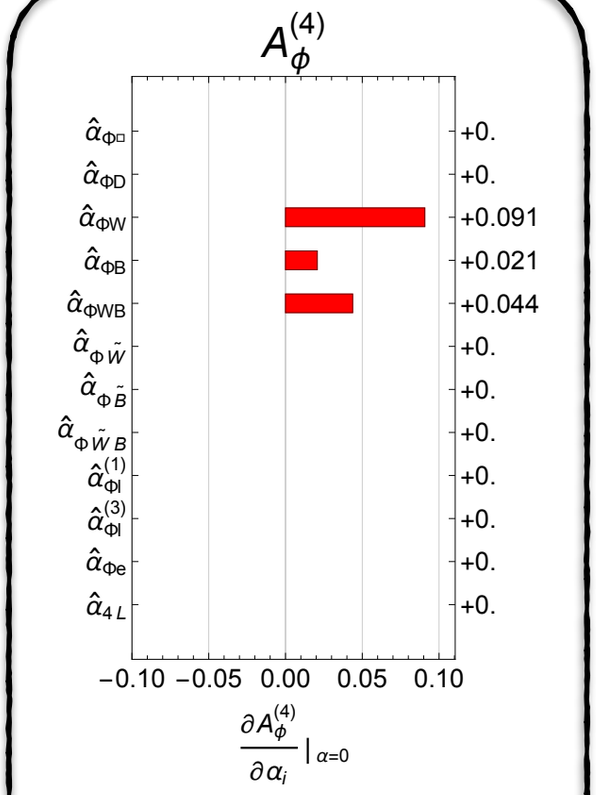


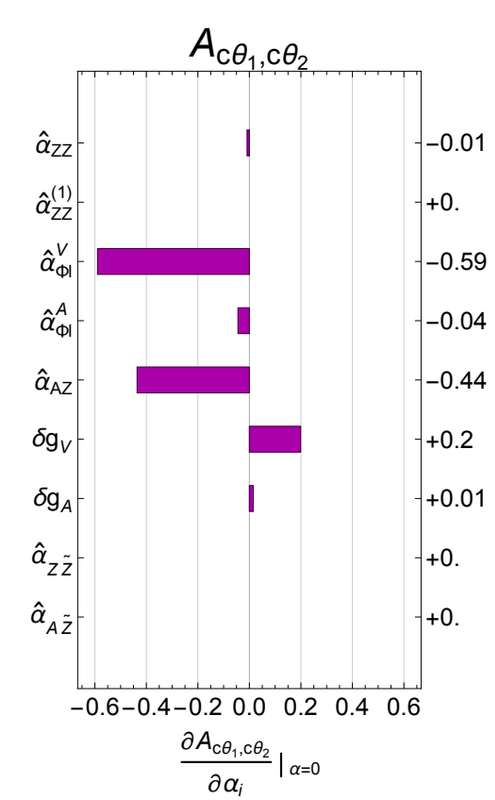
Same operators as constrained by h → γ γ (linearly independent)

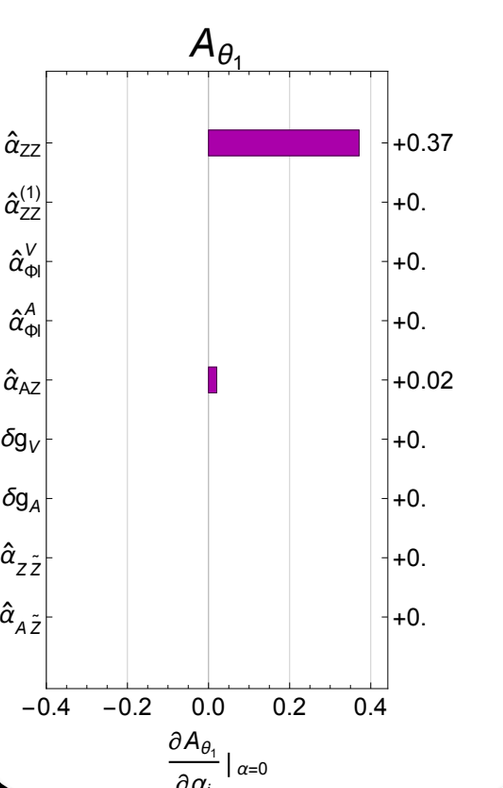


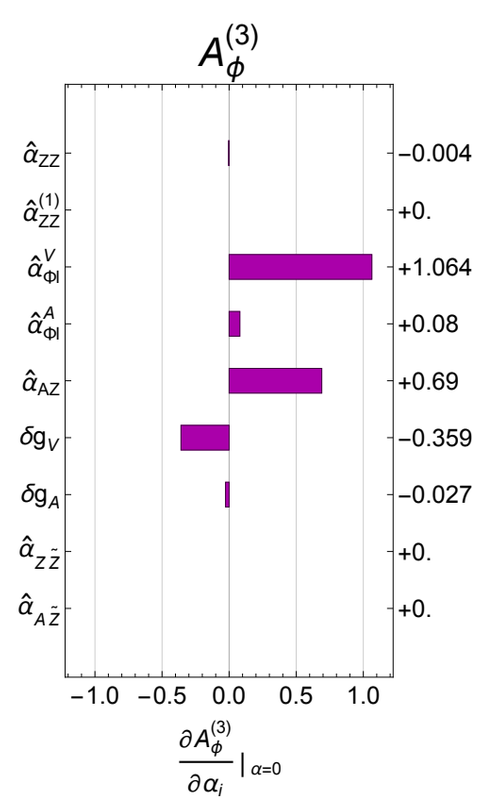


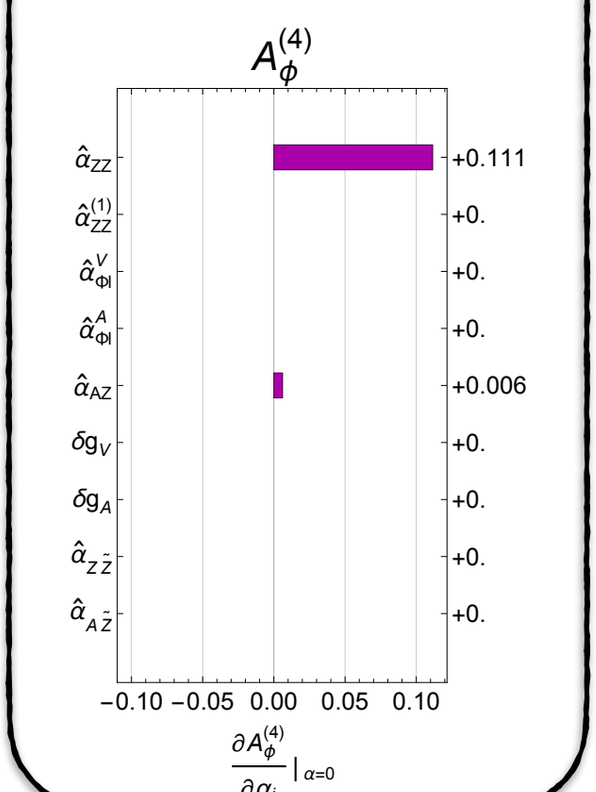




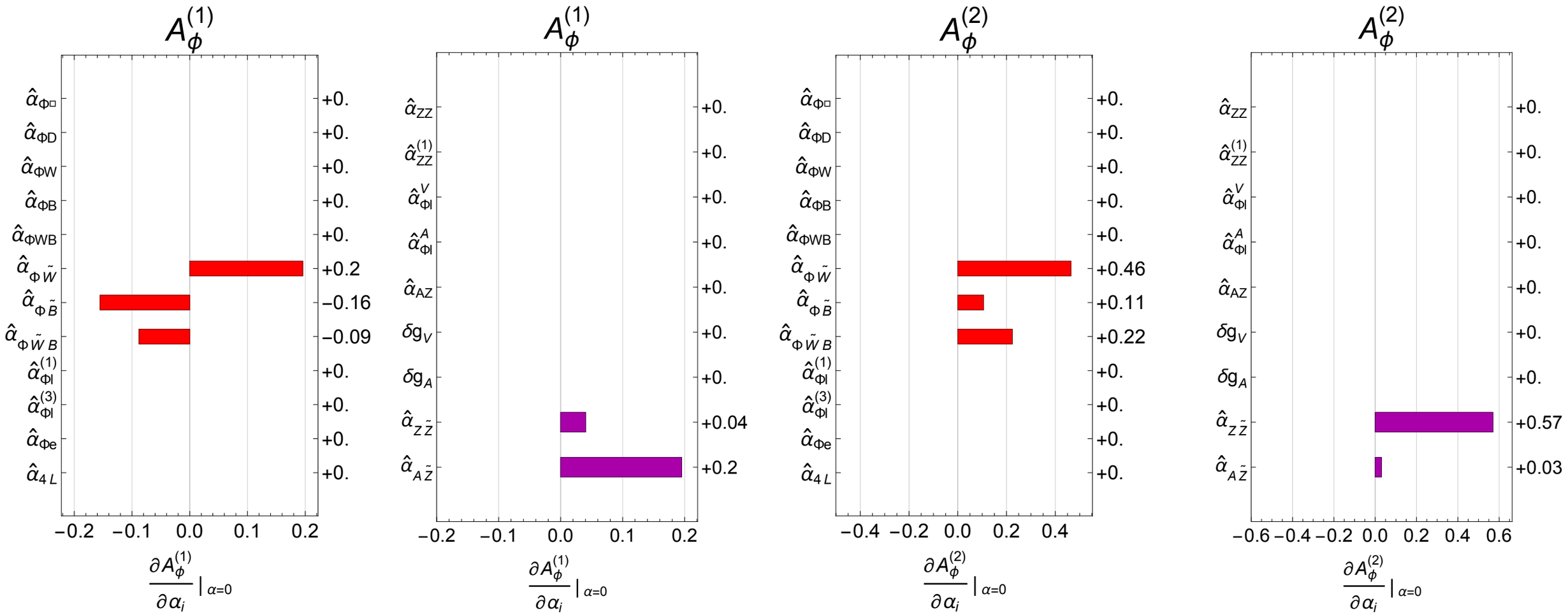








Everything else (CP-odd)



Note: for completeness only; these operators induce Barr-Zee diagrams constrained by electron EDM

ACME limit: $\alpha_{\Phi\tilde{B}} < 1.4 \times 10^{-4}$, $\alpha_{\Phi\tilde{W}} < 3.6 \times 10^{-5}$, and $\alpha_{\Phi\tilde{W}B} < 6.7 \times 10^{-5}$ for Λ = 1 TeV

Predicted precision

observable	SM expectation	Precision σ_A		
		$5\,\mathrm{ab}^{-1}$	$30\,\mathrm{ab}^{-1}$	Full Stat.
		CEPC	FCC-ee	
$\mathcal{A}_{\theta_1}$	-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

Using $Z \to \ell^+\ell^-$ and $h \to b\bar{b}$

Rate (after basic cuts) from CEPC Pre-CDR, scaled to FCC-ee

“Full Stat.”: Not overly magical thinking (including all visible decays of Z boson)

Making the measurement

Impact of selection cuts on asymmetry observables:

Sim: Madgraph 5 w/ dim-6 EFT in FeynRules

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

Modest shifts in fiducial asymmetries, no show-stoppers

Also checked: impact of ISR (changes reconstruction of scattering plane) using Pre-CDR event samples (Whizard); *negligible effect*.

Not accounted for: *theory uncertainties.*

Constraining coefficients

$$(\mathcal{L}_{\rm eff} - \mathcal{L}_{\rm SM,tree}) \supset \begin{aligned} & m_Z^2(\sqrt{2}G_F)^{1/2}\widehat{\alpha}^{(1)}_{ZZ} h Z_\mu Z^\mu + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{ZZ} h Z_{\mu\nu} Z^{\mu\nu} + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{Z\widetilde{Z}} h Z_{\mu\nu}\widetilde{Z}^{\mu\nu} \\ & + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{AZ} h Z_{\mu\nu} A^{\mu\nu} + (\sqrt{2}G_F)^{1/2}\widehat{\alpha}_{A\widetilde{Z}} h Z_{\mu\nu}\widetilde{A}^{\mu\nu} \\ & + \sqrt{2}G_F m_Z h Z_\mu \bar{\ell}\gamma^\mu \left(\widehat{\alpha}^V_{\Phi\ell} + \widehat{\alpha}^A_{\Phi\ell}\gamma_5\right)\ell + \frac{1}{2} m_Z (\sqrt{2}G_F)^{1/2} Z_\mu \bar{\ell}\gamma^\mu(\delta g_V - \delta g_A \gamma_5)\ell \end{aligned}$$

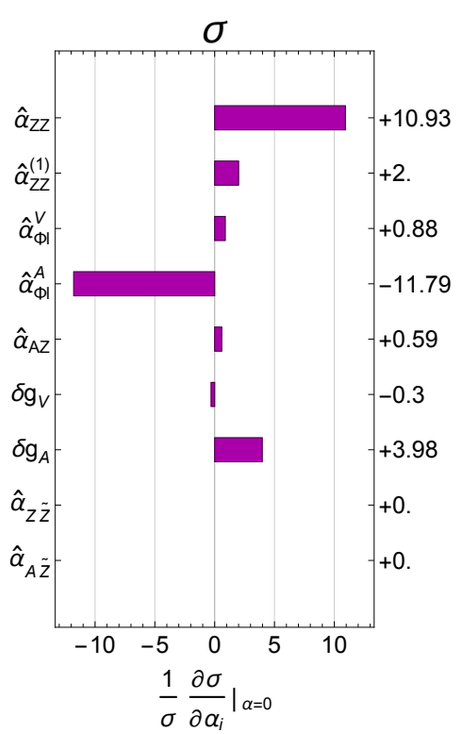
Considering operators singly (using CEPC statistics):

	$\widehat{\alpha}_{ZZ}$	$\widehat{\alpha}^{(1)}_{ZZ}$	$\widehat{\alpha}^V_{\Phi\ell}$	$\widehat{\alpha}^A_{\Phi\ell}$	$\widehat{\alpha}_{AZ}$	δg_V	δg_A	$\widehat{\alpha}_{Z\widetilde{Z}}$	$\widehat{\alpha}_{A\widetilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	∞	∞
angles	0.016	∞	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	0.0047	0.00059	0.0070	0.014	0.0018	0.012	0.036

Adds little for: $hZ_{\mu\nu}Z^{\mu\nu}$ $hZ_\mu\bar{\ell}\gamma^\mu\gamma_5\ell$ $Z_\mu\bar{\ell}\gamma^\mu\gamma_5\ell$

Powerful for: $hZ_{\mu\nu}A^{\mu\nu}$ $hZ_\mu\bar{\ell}\gamma^\mu\ell$ $Z_\mu\bar{\ell}\gamma^\mu\ell$

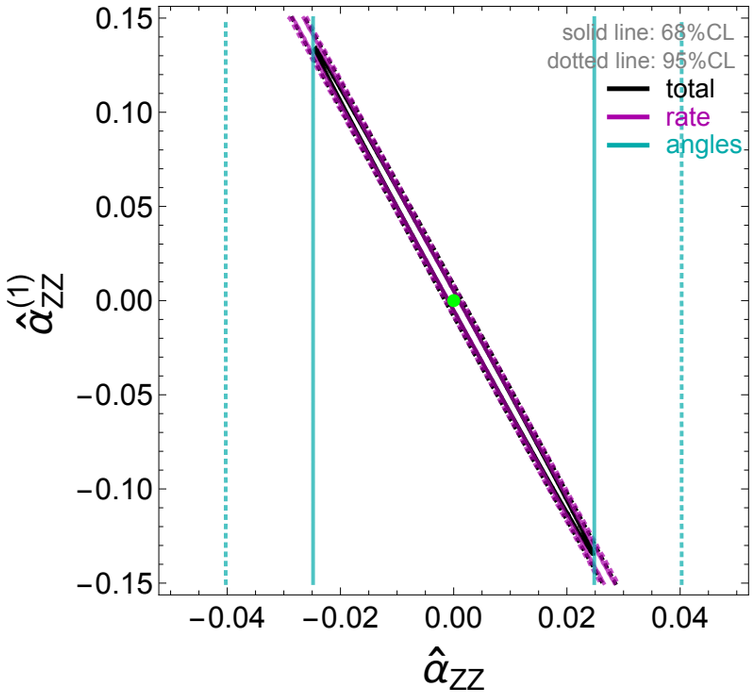
(and very useful for CP-odd terms, if we didn't have EDM measurements)



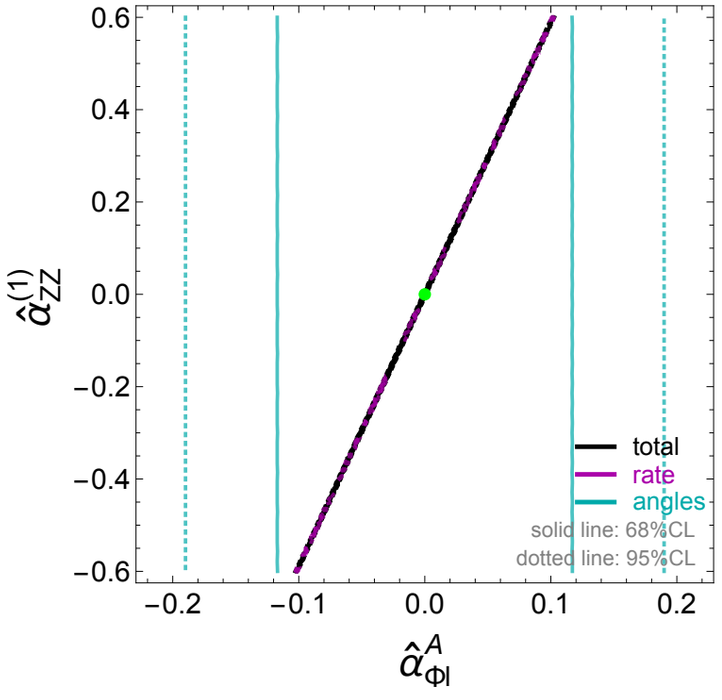
~~Degeneracy~~

For sake of illustration: consider coefficients two at a time; compare different operators to $hZ_\mu Z^\mu$

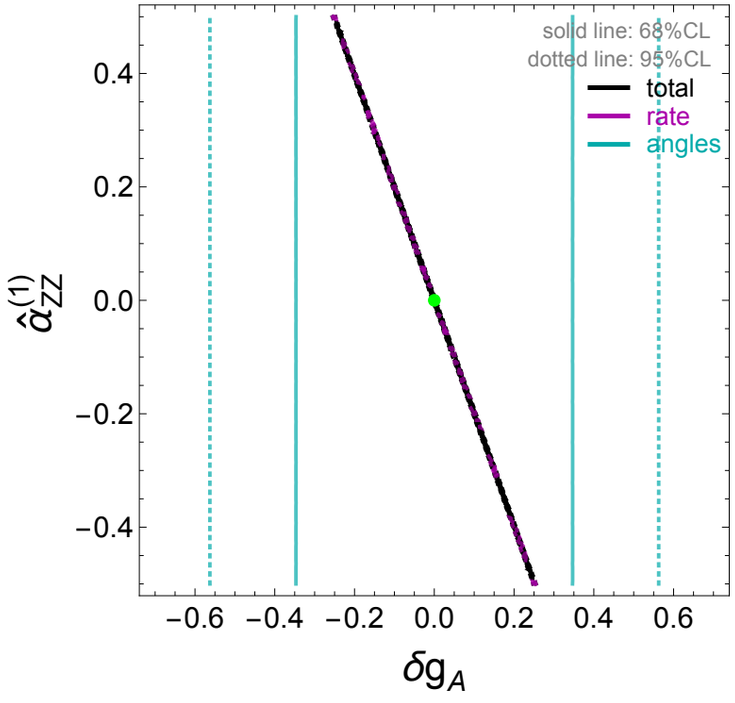
In some cases, angular observables have little impact but break rate degeneracies:



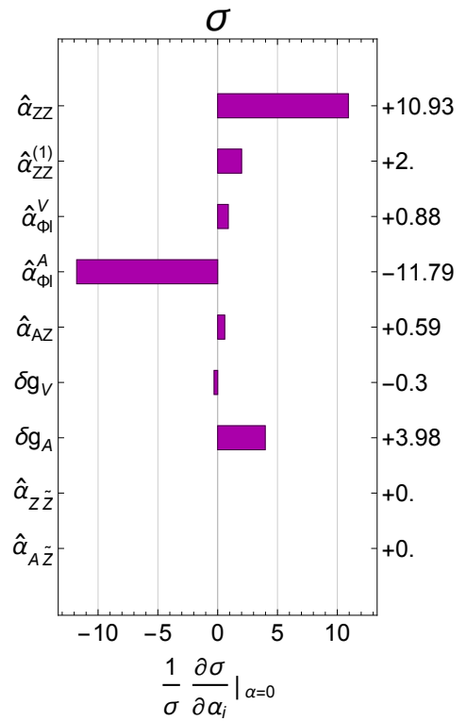
$hZ_{\mu\nu}Z^{\mu\nu}$



$hZ_\mu \bar{\ell}\gamma^\mu\gamma_5\ell$

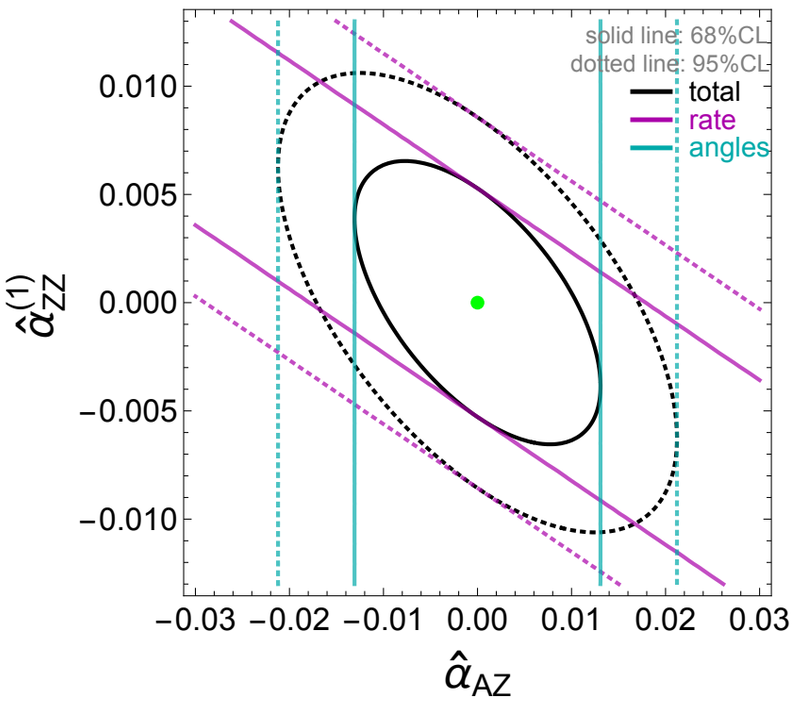


$Z_\mu \bar{\ell}\gamma^\mu\gamma_5\ell$

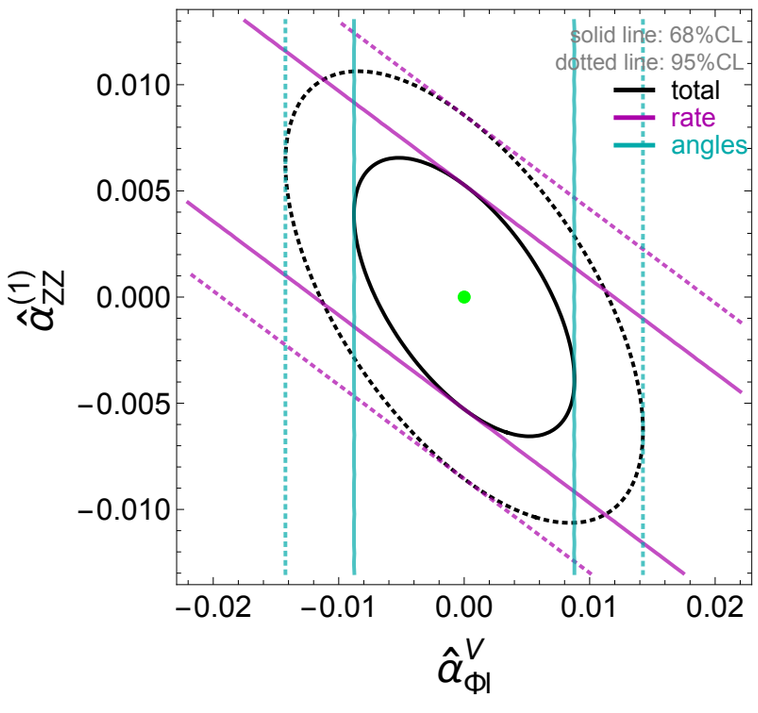


~~Degeneracy~~

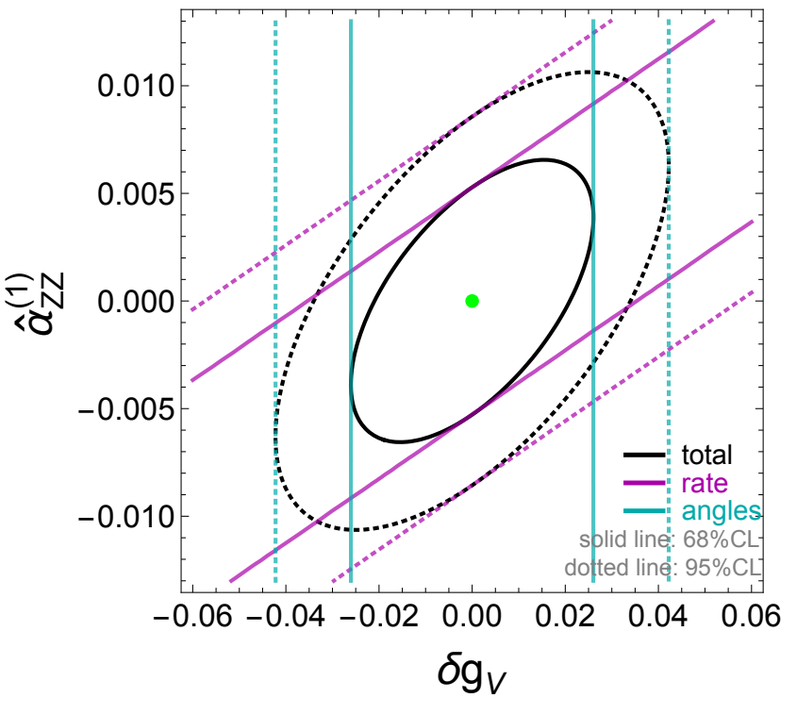
In others, angular observables have significant impact:



$hZ_{\mu\nu}A^{\mu\nu}$



$hZ_{\mu}\bar{\ell}\gamma^{\mu}\ell$

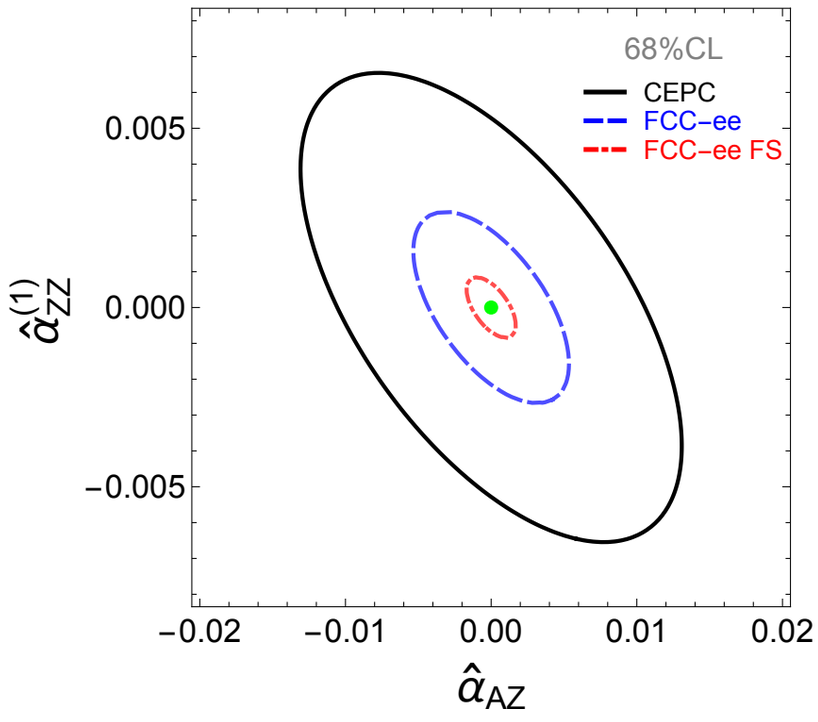


$Z_{\mu}\bar{\ell}\gamma^{\mu}\ell$

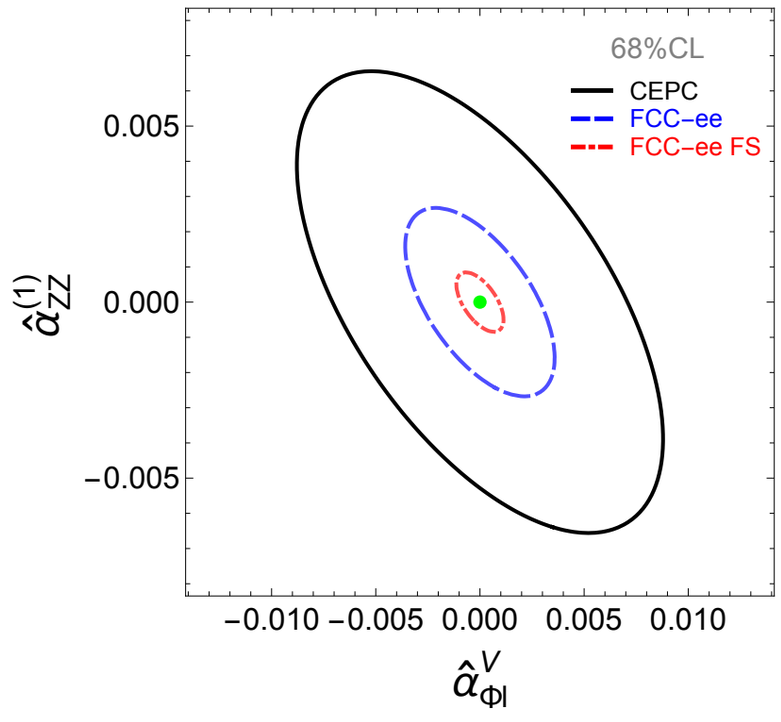
Note: hZγ measurement via asymmetry comparable to direct $e^+e^- \to h\gamma$

CEPC to FCC-ee

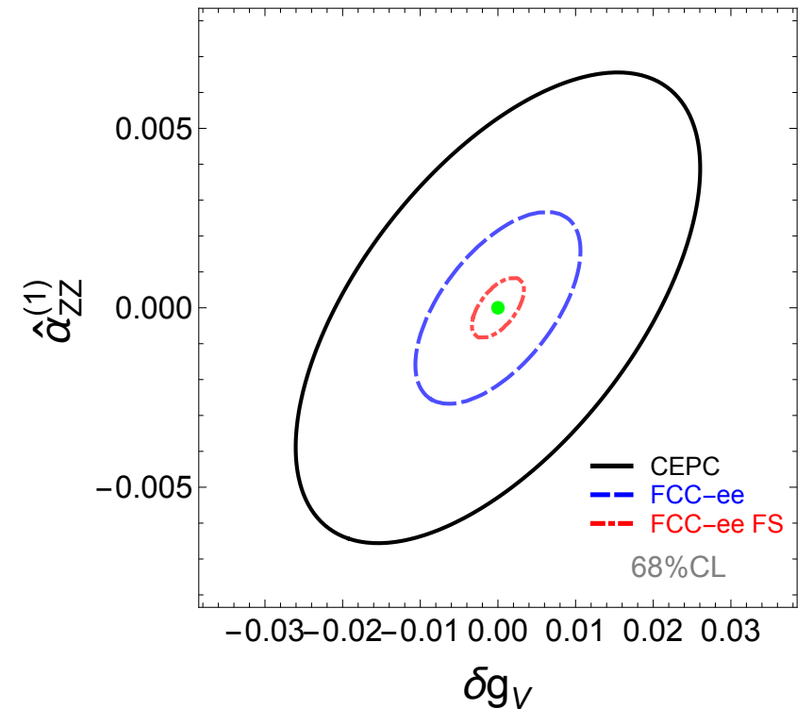
$hZ_{\mu\nu}A^{\mu\nu}$



$hZ_{\mu}\bar{\ell}\gamma^{\mu}\ell$



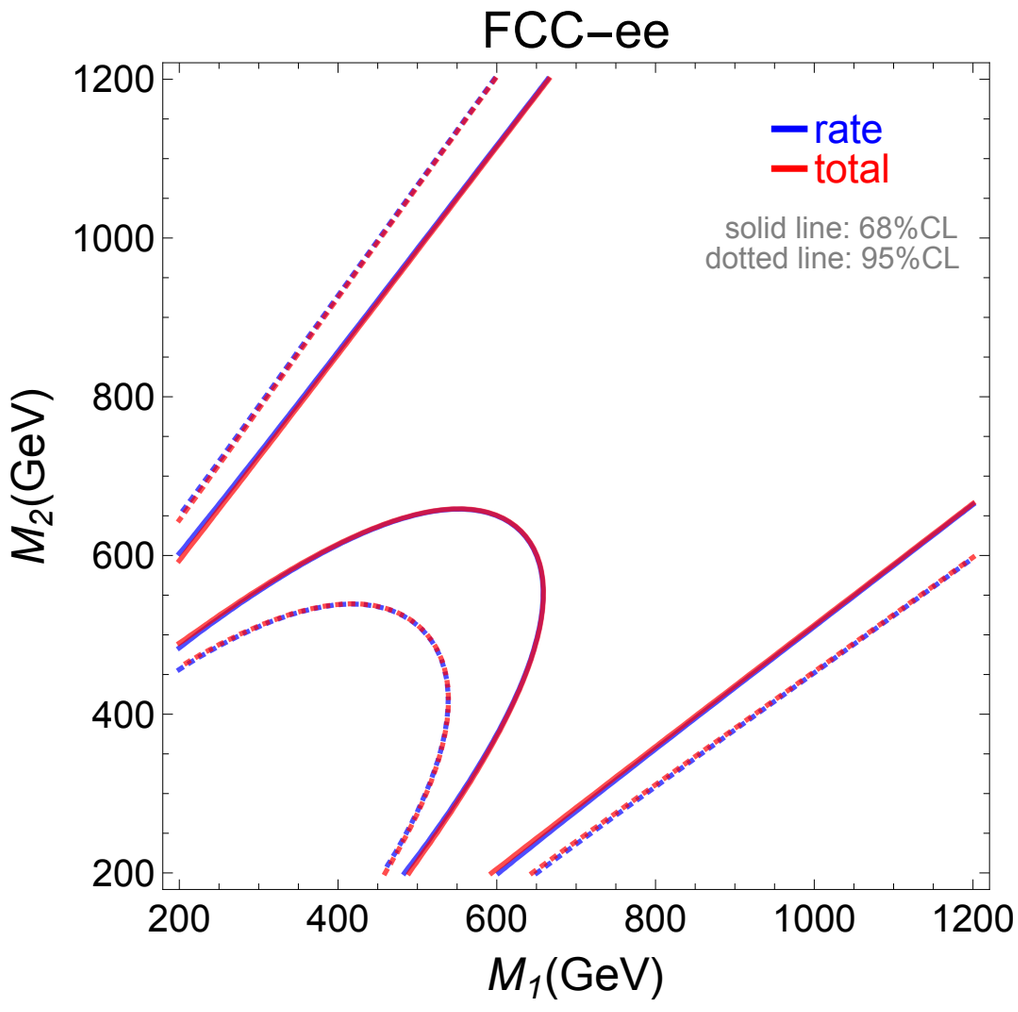
$Z_{\mu}\bar{\ell}\gamma^{\mu}\ell$

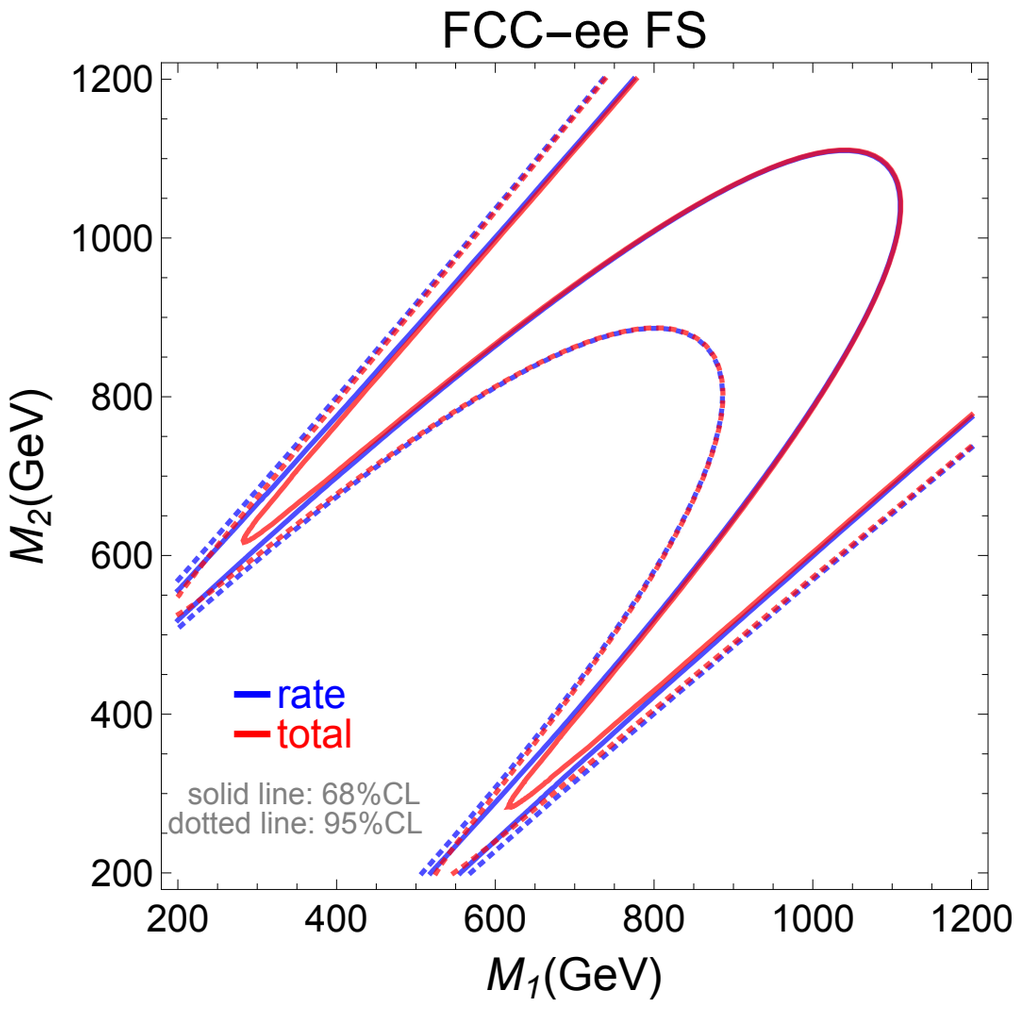


Constraining stops

Everyone's favorite test case

Zh rate only: [NC, M. Farina, M. McCullough, M. Perelstein '14]





Unsurprisingly, rate wins. **But** added information breaks blind spot.

Some closing thoughts

- Astonishing precision in Higgs couplings: time to move beyond kappa framework for FCC-ee Higgs studies.
- Angular observables stable against ISR, analysis cuts, detector effects.
- Clear opportunities: breaks degeneracies, places competitive constraints on some operators.
- Some surprises thus far: hZγ measurement, closing the blind spot.

To do:

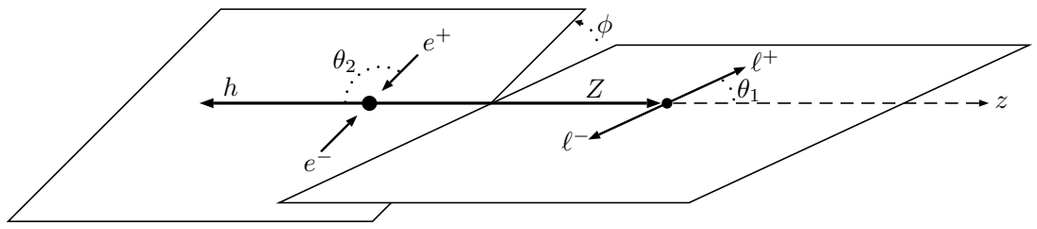
- Think seriously about theory systematics and target precision.
- Optimize choice of angular observables.
- Look beyond $e^+e^- \to Zh \to \ell^+\ell^- b\bar{b}$ (e.g. contribution from additional modes)
- Place in the context of complete fits from LEP, LHC, etc.
- Just scratching the surface of models, applications, etc…

Thank you!

Backup

Angular observables

$$
\begin{aligned}
\mathcal{A}_{\theta_1} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos(2\theta_1))\,\frac{d\sigma}{d\cos\theta_1} \\
&= 1-\frac{5}{2\sqrt{2}}+\frac{3J_1}{\sqrt{2}(4J_1+J_2)} \\
\mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\,\mathrm{sgn}(\sin\phi)\,\frac{d\sigma}{d\phi} = \frac{9\pi}{32}\,\frac{J_4}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\,\mathrm{sgn}(\sin(2\phi))\,\frac{d\sigma}{d\phi} = \frac{2}{\pi}\,\frac{J_8}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\,\mathrm{sgn}(\cos\phi)\,\frac{d\sigma}{d\phi} = \frac{9\pi}{32}\,\frac{J_6}{4J_1+J_2} \\
\mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi\,\mathrm{sgn}(\cos(2\phi))\,\frac{d\sigma}{d\phi} = \frac{2}{\pi}\,\frac{J_9}{4J_1+J_2} \\
\mathcal{A}_{c\theta_1,c\theta_2} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1\,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2\,\mathrm{sgn}(\cos\theta_2)\,\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} \\
&= \frac{9}{16}\,\frac{J_3}{4J_1+J_2}.
\end{aligned}
$$



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