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Resolving the tensor structure

of the Higgs coupling to Z-bosons via Higgs-strahlung

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Based on work with S Banerjee, R S Gupta & M Spannowsky

IPPP, Durham

In a nutshell...

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What have we attempted to do?

- Constrain the $hZZ^*/hZ\bar{f}f$ vertex

Why is this a challenge?

- Leading contributions vanish

What is our solution?

- Resurrect using analytical knowledge

Based on [1905.02728]

Motivation

The trajectory of particle physics:

- Going to higher *E* and *L*
- Time to move from total rates
- More sophisticated observables available

$$\sigma \quad \rightarrow \quad \frac{d\sigma}{dEd\varphi d\Theta d\theta}$$

Roadmap

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SMEFT operators in Warsaw basis
$$\mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

→

hZZ*/hZff corrections
$$\delta\hat{g}^h_{ZZ},\ g^h_{Zf},\ \kappa_{ZZ},\ \tilde{\kappa}_{ZZ}$$

→

Amplitude
$$\mathcal{A}_h(\hat{s},\Theta,\theta,\varphi)$$

→

Angular observables
$$\frac{a^2_{LL}}{4}C_\varphi S_{2\theta}S_{2\Theta}$$

SMEFT

EFT framework for parameterising effects of higher-energy resonances

- Mostly model-independent
- Mass-dimension 6 operators
- Warsaw basis [1008.4844]

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^{(6)} + \ldots \qquad \mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)}$$

The $hZZ^*/hZ\bar{f}f$ vertex

We have 4 tensor structures of interest:

- $h Z^\mu Z_\mu$
- $h Z_\mu (\bar{f}\gamma^\mu f)$ [equiv. $h Z_\mu \partial_\nu Z^{\mu\nu}$]
- $h Z^{\mu\nu} Z_{\mu\nu}$
- $h Z^{\mu\nu} \tilde{Z}_{\mu\nu}$

The $hZZ^*/hZ\bar{f}f$ vertex

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In the parameterisation of [1405.0181],

$$\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset \delta\hat{g}^h_{ZZ}\,\frac{2m_Z^2}{v}h\frac{Z^\mu Z_\mu}{2} + \sum_f g^h_{Zf}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$

$$+\,\kappa_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\,\frac{h}{2v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

The vertex in SMEFT

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Which Warsaw basis SMEFT operators contribute to this vertex?

12 CP-even and 3 CP-odd (pre EWSB)

See [1008.4844] for operator notation.

$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{HL}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{L}\sigma^a\gamma^\mu L$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	$\mathcal{O}_{HB} = \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hu} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{HWB} = H^\dagger\sigma^a H W^a_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{Hd} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{d}_R\gamma^\mu d_R$	$\mathcal{O}_{HW} = \lvert H\rvert^2 W_{\mu\nu}W^{\mu\nu}$
$\mathcal{O}_{He} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{e}_R\gamma^\mu e_R$	$\mathcal{O}_{H\tilde{B}} = \lvert H\rvert^2 B_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{Q}\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}B} = H^\dagger\sigma^a H W^a_{\mu\nu}\tilde{B}^{\mu\nu}$
$\mathcal{O}_{HQ}^{(3)} = iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{Q}\sigma^a\gamma^\mu Q$	$\mathcal{O}_{H\tilde{W}} = \lvert H\rvert^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$
$\mathcal{O}_{HL}^{(1)} = iH^\dagger \overleftrightarrow{D}_\mu H\bar{L}\gamma^\mu L$	

The $hZZ^*/hZ\bar{f}f$ vertex

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These contribute to the earlier parameters:

$$\delta\hat{g}^h_{ZZ} = \frac{v^2}{\Lambda^2}\left(c_{H\Box} + \frac{3c_{HD}}{4}\right)$$

$$g^h_{Zf} = -\frac{2g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(|T^f_3|c^{(1)}_{HF} - T^f_3 c^{(3)}_{HF} + (1/2 - |T^f_3|)c_{Hf})$$

$$\kappa_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{HW} + s^2_{\theta_W}c_{HB} + s_{\theta_W}c_{\theta_W}c_{HWB})$$

$$\tilde{\kappa}_{ZZ} = \frac{2v^2}{\Lambda^2}(c^2_{\theta_W}c_{H\tilde{W}} + s^2_{\theta_W}c_{H\tilde{B}} + s_{\theta_W}c_{\theta_W}c_{H\tilde{W}B})$$

The analytic amplitude

How do we extract information about these corrections?

By using knowledge of the amplitude's analytic structure...

The analytic amplitude

Begin with $2 \to 2$ process $f(\sigma)\bar{f}(-\sigma) \to Z(\lambda)h$ in the helicity amplitude formalism:

$$\mathcal{M}_{\sigma}^{\lambda=\pm} = \sigma \frac{1+\sigma\lambda\cos\Theta}{2\sqrt{2}} \frac{g g_f^Z}{c_{\theta_W}} \gamma^{-1} \left[1 + 2\gamma^2 \left(\frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} - i\lambda\tilde{\kappa}_{ZZ} \right) \right]$$

$$\mathcal{M}_{\sigma}^{\lambda=0} = -\sin\Theta \frac{g g_f^Z}{2 c_{\theta_W}} \left[1 + \delta\hat{g}_{ZZ}^h + 2\kappa_{ZZ} + \frac{g_{Zf}^h}{g_f^Z} \left(-\frac{1}{2} + 2\gamma^2 \right) \right]$$

Neglect terms subdominant* in $\gamma = \sqrt{\hat{s}}/(2m_Z)$

The analytic amplitude

Leading SM is **longitudinal** $(\lambda = 0)$

Leading effect of κ_{ZZ} and $\tilde{\kappa}_{ZZ}$ is in **transverse** $(\lambda = \pm 1)$

The LT interference term vanishes if we're not careful...

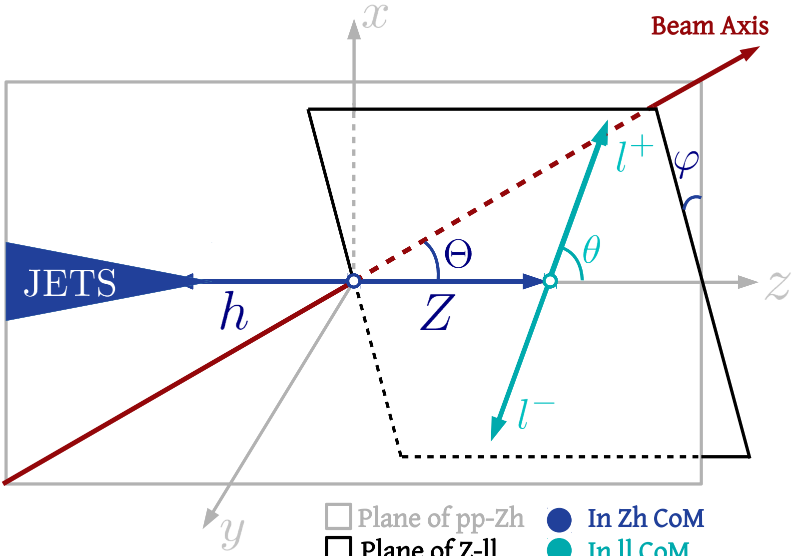
The analytic amplitude

Full amplitude can be written as:

$$\mathcal{A}_h(\hat{s}, \Theta, \hat{\theta}, \hat{\varphi}) = \frac{-i\sqrt{2}g_\ell^Z}{\Gamma_Z} \sum_\lambda \mathcal{M}_\sigma^\lambda(\hat{s}, \Theta) d_{\lambda,1}^{J=1}(\hat{\theta}) e^{i\lambda\hat{\varphi}}$$

Wigner functions $d_{\lambda,1}^{J=1}(\hat{\theta})$, hats indicate positive helicity leptons rather than positive charge [1708.07823].

The 3 angles



x
Beam Axis
l^+
φ
Θ
θ
JETS
h
Z
z
l^-
y
Plane of pp-Zh
Plane of Z-ll
In Zh CoM
In ll CoM

The analytic amplitude

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Squared amplitude can be written as:

$$\sum_{L,R} |\mathcal{A}(\hat{s}, \Theta, \theta, \varphi)|^2 = \alpha_L |\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)|^2 + \alpha_R |\mathcal{A}_h(\hat{s}, \Theta, \pi - \theta, \pi + \varphi)|^2$$

with $\alpha_{L,R} = (g^Z_{l_{L,R}})^2 / [(g^Z_{l_L})^2 + (g^Z_{l_R})^2]$

Also define $\epsilon_{LR} = \alpha_L - \alpha_R \approx 0.16$

The analytic amplitude

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We collect into 9 angular structures:

$$
\begin{aligned}
= \;& a_{LL} \sin^2\Theta \sin^2\theta \\
&+ a^1_{TT} \cos\Theta \cos\theta \\
&+ a^2_{TT} (1+\cos^2\Theta)(1+\cos^2\theta) \\
&+ \cos\varphi \sin\Theta \sin\theta (a^1_{LT} + a^2_{LT} \cos\theta \cos\Theta) \\
&+ \sin\varphi \sin\Theta \sin\theta (\tilde{a}^1_{LT} + \tilde{a}^2_{LT} \cos\theta \cos\Theta) \\
&+ a_{TT'} \cos 2\varphi \sin^2\Theta \sin^2\theta \\
&+ \tilde{a}_{TT'} \sin 2\varphi \sin^2\Theta \sin^2\theta
\end{aligned}
$$

and thus 9 angular observables.

a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1+2\delta\hat{g}^h_{ZZ}+4\kappa_{ZZ}+\frac{g^h_{Zf}}{g^Z_f}(-1+4\gamma^2)\right]$
a^1_{TT}	$\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^2_{TT}	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^1_{LT}	$-\frac{\mathcal{G}^2\sigma\epsilon_{LR}}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
a^2_{LT}	$-\frac{\mathcal{G}^2}{2\gamma}\left[1+2\left(\frac{2g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}^1_{LT}$	$-\mathcal{G}^2\sigma\epsilon_{LR}\tilde{\kappa}_{ZZ}\gamma$
$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{ZZ}\gamma$
$a_{TT'}$	$\frac{\mathcal{G}^2}{8\gamma^2}\left[1+4\left(\frac{g^h_{Zf}}{g^Z_f}+\kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}_{TT'}$	$\frac{\mathcal{G}^2}{2}\tilde{\kappa}_{ZZ}$

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a_{LL}	$\frac{\mathcal{G}^2}{4}\left[1 + 2\delta\hat{g}^h_{ZZ} + 4\kappa_{ZZ} + \frac{g^h_{Zf}}{g^Z_f}(-1 + 4\gamma^2)\right]$
a^2_{LT}	$-\frac{\mathcal{G}^2}{2\gamma}\left[1 + 2\left(\frac{2g^h_{Zf}}{g^Z_f} + \kappa_{ZZ}\right)\gamma^2\right]$
$\tilde{a}^2_{LT}$	$-\mathcal{G}^2\tilde{\kappa}_{ZZ}\gamma$

The analytic amplitude

LT interference term dominated by:

$$\sim \frac{a_{LT}^2}{4} \cos\varphi \sin 2\theta \sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4} \sin\varphi \sin 2\theta \sin 2\Theta$$

NB: these terms vanish on integration of ANY angle!

We will constrain a_{LL} and thus g_f^Z via LL at high E
See [1807.01796]

Allows us to separate κ_{ZZ} contribution to a_{LT}^2

Other contributions

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Operators that rescale the $hb\bar{b}$ and $Z\bar{f}f$ contribute:

$$\kappa_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{Z\gamma}\,\frac{h}{v}A^{\mu\nu}\tilde{Z}_{\mu\nu}$$

For $\hat{s} \gg m_Z^2$ just shifts parameters:

$$\kappa_{ZZ} \to \kappa_{ZZ} + 0.3\;\kappa_{Z\gamma} \qquad \tilde{\kappa}_{ZZ} \to \tilde{\kappa}_{ZZ} + 0.3\;\tilde{\kappa}_{Z\gamma}$$

Method

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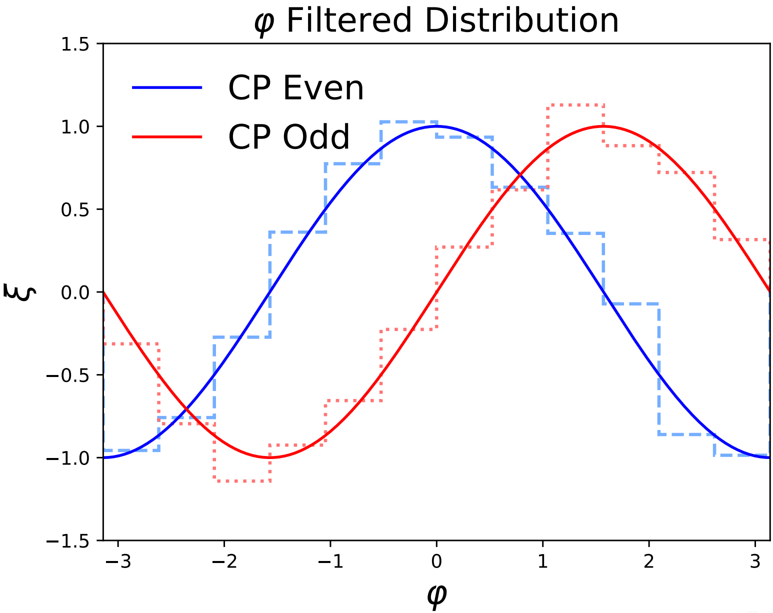
How to probe κ_{ZZ} and $\tilde{\kappa}_{ZZ}$?

Flip signs in regions to maintain positive $\sin 2\theta \sin 2\Theta$

$$\sim \frac{a_{LT}^2}{4} \cos\varphi \sin 2\theta \sin 2\Theta + \frac{\tilde{a}_{LT}^2}{4} \sin\varphi \sin 2\theta \sin 2\Theta$$

$\rightarrow$ expect $\cos\varphi$ distribution for CP even
$\rightarrow$ expect $\sin\varphi$ distribution for CP odd



φ Filtered Distribution
CP Even
CP Odd
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
ξ
−3
−2
−1
0
1
2
3
φ

Method

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Perform χ^2 tests:

- Look at high M_{Zh} range to constrain g^h_{Zf}
- Look at low M_{Zh} range to constrain $\delta\hat{g}^h_{ZZ}$
- Split into bins across all three angles $(\varphi, \theta, \Theta)$ to resurrect interference term

Use above knowledge of g^h_{Zf}, $\delta\hat{g}^h_{ZZ}$ and angular split to instruct constraint on κ_{ZZ}, $\tilde{\kappa}_{ZZ}$

Results

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For an integrated luminoisty of 3ab^{-1}:

$$-0.01 < \kappa_{ZZ} < 0.01$$
$$-0.04 < \tilde{\kappa}_{ZZ} < 0.04$$

Summary

SMEFT operators in Warsaw basis

$$\mathcal{L}^{(6)} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

→

hZZ*/hZff corrections

$$\delta\hat{g}^h_{ZZ},\ g^h_{Zf},\ \kappa_{ZZ},\ \tilde{\kappa}_{ZZ}$$

→

Amplitude

$$\mathcal{A}_h(\hat{s}, \Theta, \theta, \varphi)$$

→

Angular observables

$$\frac{a^2_{LL}}{4} C_\varphi S_{2\theta} S_{2\Theta}$$

Conclusions

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- Move to more sophisticated observables
- Resurrect elusive effects of κ_{ZZ}, $\tilde{\kappa}_{ZZ}$ by analytic knowledge of amplitude
- Split across all three angles $(\varphi, \theta, \Theta)$ to resurrect interference term
- Get percent-level bounds
- Future work could use more observables $\rightarrow$ stronger bounds

For more, see [1905.02728]