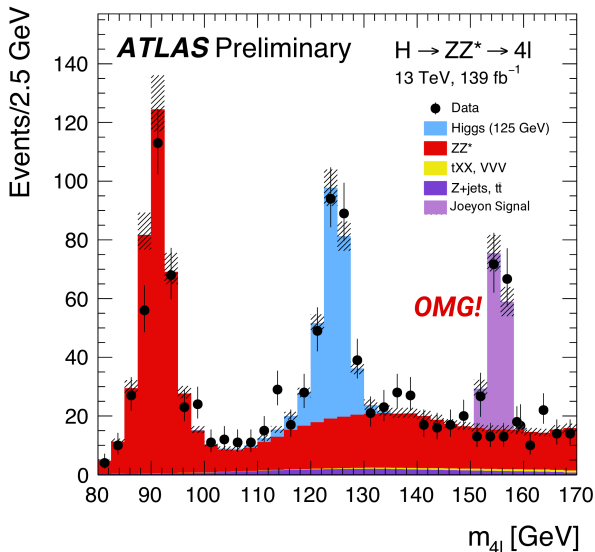


Resolving the tensor structure of the Higgs coupling to Z-bosons via Higgs-strahlung

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

New signal at LHC!!! (if only)



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

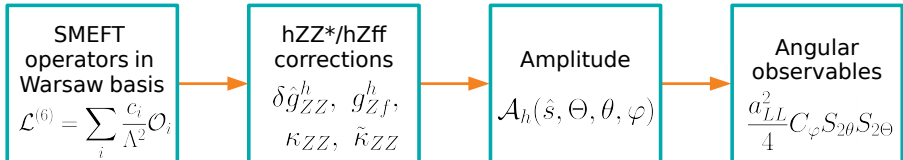
Based on [1905.02728]

The trajectory of particle physics:

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

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

"It's the tails, stupid"

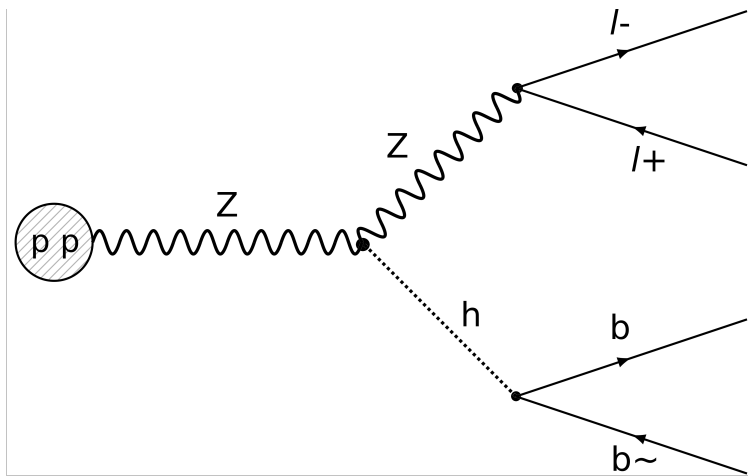




EFT framework for parameterising effects of higher-energy resonances

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

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



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

In the parameterisation of [1405.0181],

$$\begin{aligned}\Delta\mathcal{L}_6^{hZ\bar{f}f} \supset & \delta\hat{g}_{ZZ}^h \frac{2m_Z^2}{v} h \frac{Z^\mu Z_\mu}{2} + \sum_f g_{Zf}^h \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f \\ & + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}\end{aligned}$$

The vertex in SMEFT

Which Warsaw basis SMEFT operators contribute to this vertex?

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

See [1008.4844] for operator notation.

$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$$

$$\mathcal{O}_{Hu} = iH^\dagger \overset{\leftrightarrow}{D}_\mu H \bar{u}_R \gamma^\mu u_R$$

$$\mathcal{O}_{Hd} = iH^\dagger \overset{\leftrightarrow}{D}_\mu H \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}_{He} = iH^\dagger \overset{\leftrightarrow}{D}_\mu H \bar{e}_R \gamma^\mu e_R$$

$$\mathcal{O}_{HQ}^{(1)} = iH^\dagger \overset{\leftrightarrow}{D}_\mu H \bar{Q} \gamma^\mu Q$$

$$\mathcal{O}_{HQ}^{(3)} = iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H \bar{Q} \sigma^a \gamma^\mu Q$$

$$\mathcal{O}_{HL}^{(1)} = iH^\dagger \overset{\leftrightarrow}{D}_\mu H \bar{L} \gamma^\mu L$$

$$\mathcal{O}_{HL}^{(3)} = iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H \bar{L} \sigma^a \gamma^\mu L$$

$$\mathcal{O}_{HB} = |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}$$

$$\mathcal{O}_{HW} = |H|^2 W_{\mu\nu} W^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{B}} = |H|^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{W}B} = H^\dagger \sigma^a H W_{\mu\nu}^a \tilde{B}^{\mu\nu}$$

$$\mathcal{O}_{H\tilde{W}} = |H|^2 W_{\mu\nu}^a \tilde{W}^{a\mu\nu}$$

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

These contribute to the earlier parameters:

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

$$g_{Zf}^h = -\frac{2g}{c_{\theta_W}} \frac{v^2}{\Lambda^2} (|\mathcal{T}_3^f| c_{HF}^{(1)} - \mathcal{T}_3^f c_{HF}^{(3)} + (1/2 - |\mathcal{T}_3^f|) c_{Hf})$$

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

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

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

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

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

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...

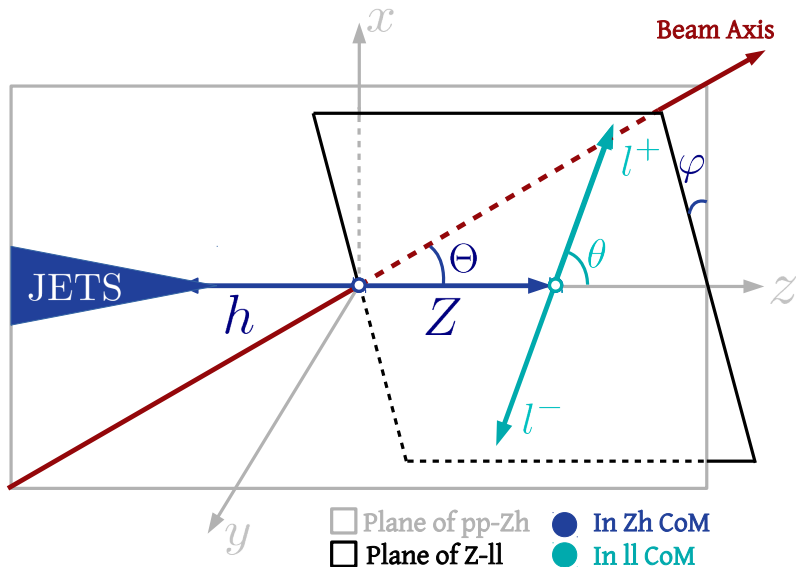
The analytic amplitude

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

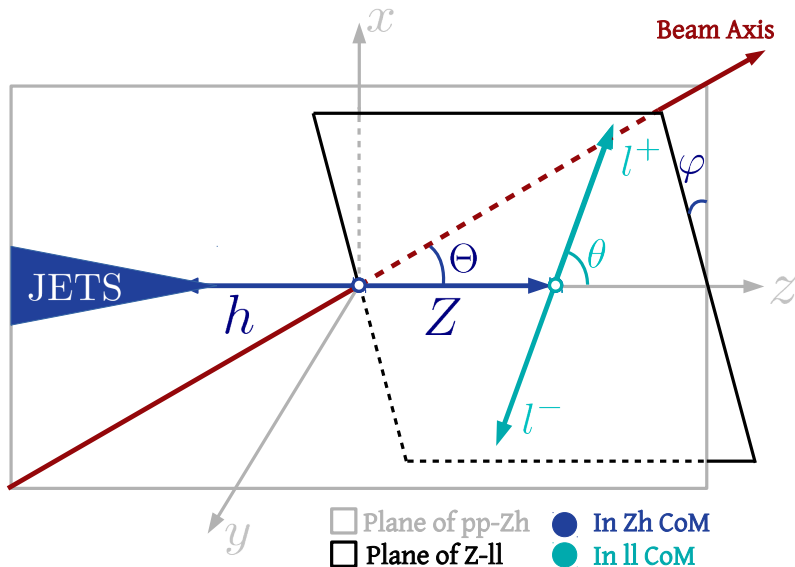


The 3 angles



**WHY DO YOU HAVE TO GO AND MAKE
THINGS SO COMPLICATED? (YEAH, YEAH)**

The 3 angles



The analytic amplitude

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

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

The analytic amplitude

We collect into 9 angular structures:

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

and thus 9 angular observables.

$$a_{LL} \quad \frac{\mathcal{G}^2}{4} \left[1 + 2\delta\hat{g}_{ZZ}^h + 4\kappa_{ZZ} + \frac{g_{Zf}^h}{g_f^Z} (-1 + 4\gamma^2) \right]$$

$$a_{TT}^1 \quad \frac{\mathcal{G}^2 \sigma_{\text{ELR}}}{2\gamma^2} \left[1 + 4 \left(\frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$a_{TT}^2 \quad \frac{\mathcal{G}^2}{8\gamma^2} \left[1 + 4 \left(\frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$a_{LT}^1 \quad -\frac{\mathcal{G}^2 \sigma_{\text{ELR}}}{2\gamma} \left[1 + 2 \left(\frac{2g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$a_{LT}^2 \quad -\frac{\mathcal{G}^2}{2\gamma} \left[1 + 2 \left(\frac{2g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$\tilde{a}_{LT}^1 \quad -\mathcal{G}^2 \sigma_{\text{ELR}} \tilde{\kappa}_{ZZ} \gamma$$

$$\tilde{a}_{LT}^2 \quad -\mathcal{G}^2 \tilde{\kappa}_{ZZ} \gamma$$

$$a_{TT'} \quad \frac{\mathcal{G}^2}{8\gamma^2} \left[1 + 4 \left(\frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$\tilde{a}_{TT'} \quad \frac{\mathcal{G}^2}{2} \tilde{\kappa}_{ZZ}$$

$$a_{LL} \quad \frac{\mathcal{G}^2}{4} \left[1 + 2\delta\hat{g}_{ZZ}^h + 4\kappa_{ZZ} + \frac{g_{Zf}^h}{g_f^Z} (-1 + 4\gamma^2) \right]$$

$$a_{LT}^2 \quad -\frac{\mathcal{G}^2}{2\gamma} \left[1 + 2 \left(\frac{2g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} \right) \gamma^2 \right]$$

$$\tilde{a}_{LT}^2 \quad -\mathcal{G}^2 \tilde{\kappa}_{ZZ} \gamma$$

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

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:

$$\kappa_{ZZ} \rightarrow \kappa_{ZZ} + 0.3 \kappa_{Z\gamma} \quad \tilde{\kappa}_{ZZ} \rightarrow \tilde{\kappa}_{ZZ} + 0.3 \tilde{\kappa}_{Z\gamma}$$

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

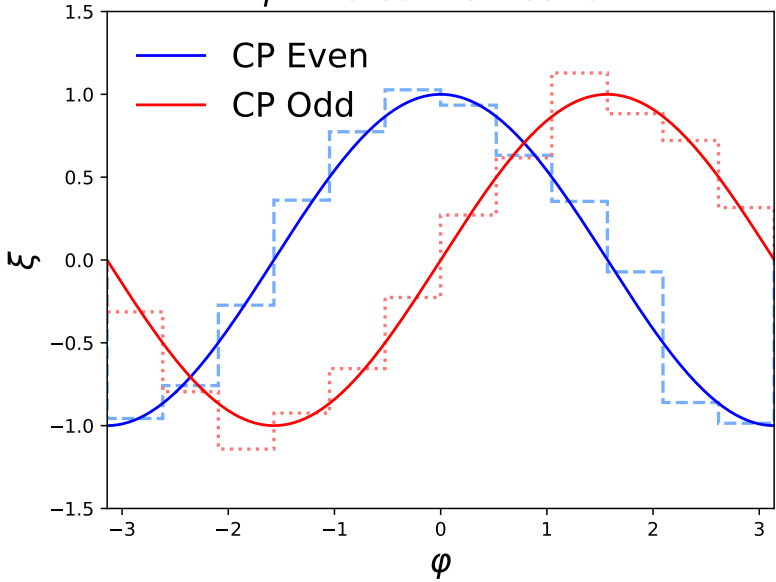
Flip signs in regions to maintain positive
 $\sin 2\theta \sin 2\Theta$

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

→ expect $\cos \varphi$ distribution for CP even

→ expect $\sin \varphi$ distribution for CP odd

φ Filtered Distribution



Perform χ^2 tests:

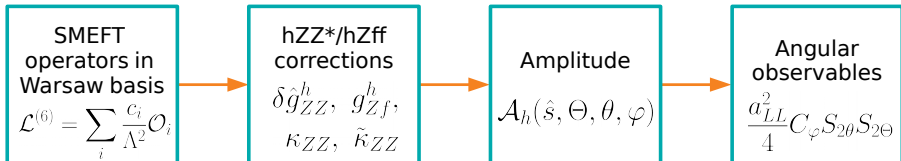
- Look at high M_{Zh} range to constrain g_{Zf}^h
- Look at low M_{Zh} range to constrain $\delta\hat{g}_{ZZ}^h$
- Split into bins across all three angles $(\varphi, \theta, \Theta)$ to resurrect interference term

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

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

$$-0.01 < \kappa_{ZZ} < 0.01$$

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



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

For more, see [1905.02728]