The Operator-Observable Map

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in collaboration with S. Banerjee, C. Englert, F. Krauss,
J. Reiness, M. Spannowsky, O. Valeriano

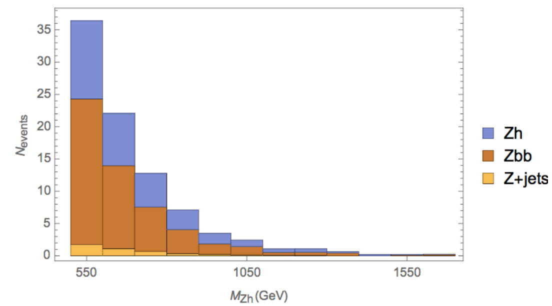
EFT as an organising principle

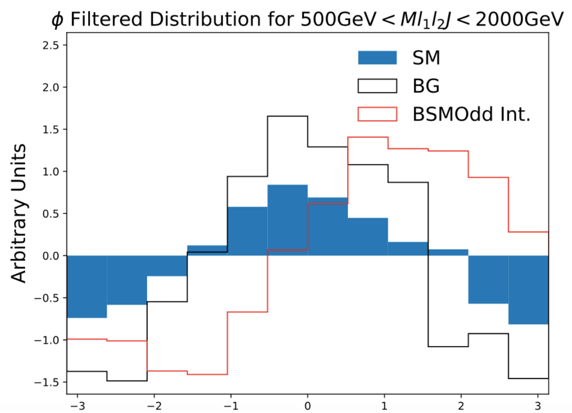
- The absence at the LHC of new states beyond the SM (BSM) suggests that the new-physics scale must be heavier than the electroweak (EW) scale and we can write:

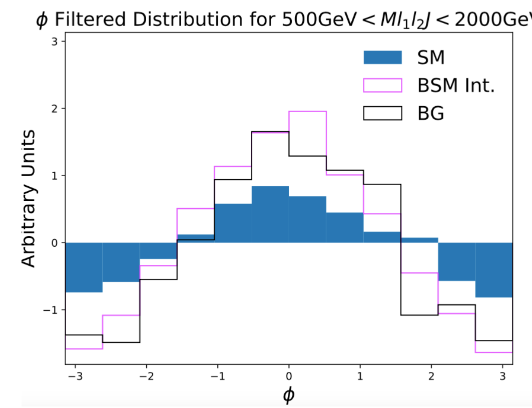
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_i \frac{c_i}{\Lambda^4}\mathcal{O}_i^8 \cdots$$

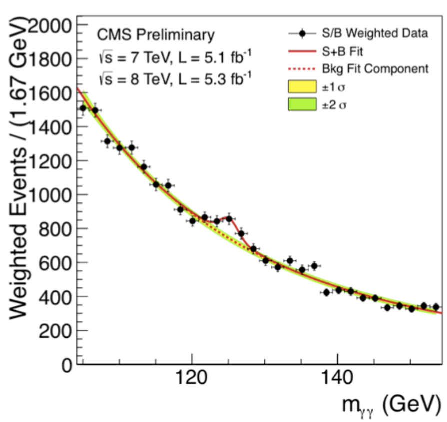
- This gives a model independent parametrization
- LHC probing Lagrangian at the TeV scale ($10^{-19} m$) for the first time.

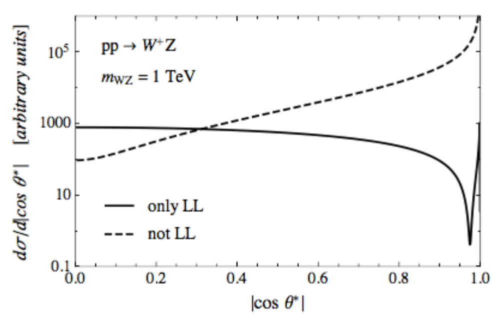
Plethora of data at LHC

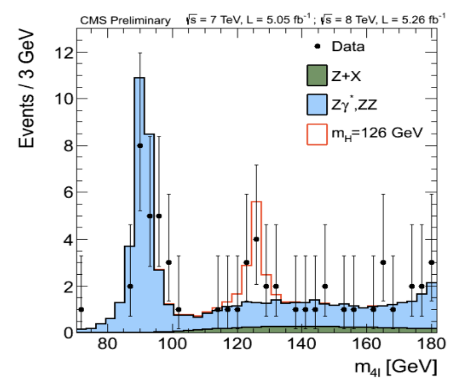






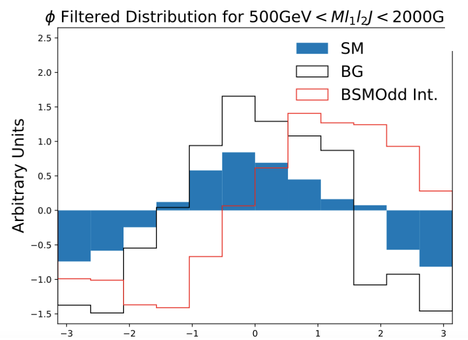


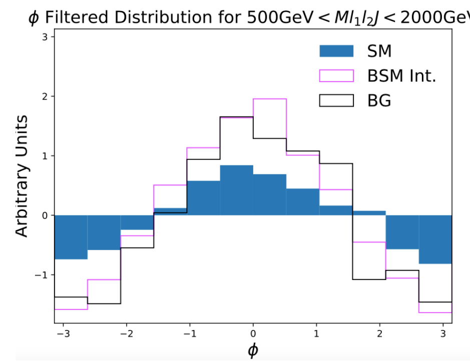


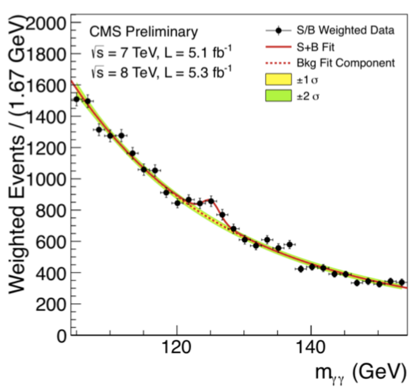


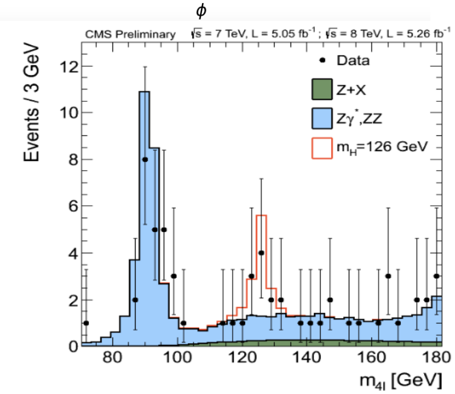
The operator-observable map to reconstuct TeV scale *L*

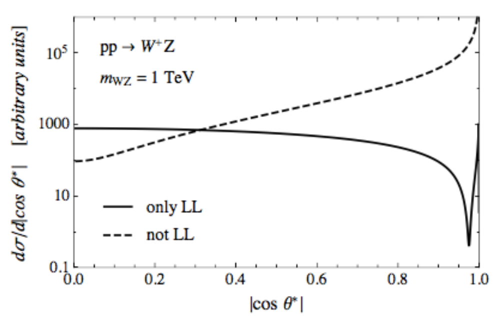
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^6 + \sum_i \frac{c_i}{\Lambda^4}\mathcal{O}_i^8 \cdots$$

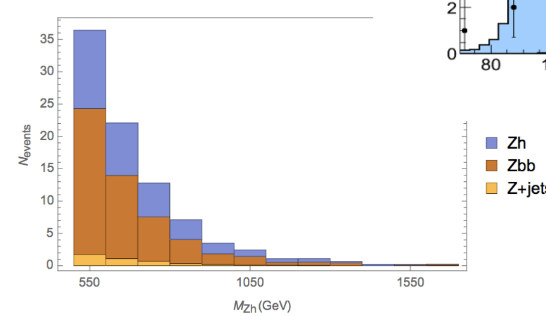












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Main theme in this talk

- We are entering era of high luminosities/energies. Time to move from total rates to differential distributions more sophisticated experimental observables.

Banerjee, Englert, RSG & Spannowsky (arXiv: 1807.01796), Banerjee, RSG, Reiness & Spannowsky (to appear), Banerjee, RSG, Krauss, Spannowsky & Valeriano(to appear), Banerjee, RSG, Reiness & Seth (to appear)

$hVV/hVff$ anomalous couplings

- 4 tensor structures for dimension 6 vertices

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{2m_W^2 h}{v}\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

equivalent to $g^h_{Z\partial Z}\frac{h}{v}Z_\mu \partial_\nu Z_{\mu\nu}$,

- Can we determine all these four structures in Zh production?

Banerjee, RSG, Reiness & Spannowsky (to appear)

hVV/hVff anomalous couplings

- 4 tensor structures for dimension 6 vertices

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{2m_W^2 h}{v}\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

equivalent to $g^h_{Z\partial Z}\frac{h}{v}Z_\mu \partial_\nu Z_{\mu\nu},$

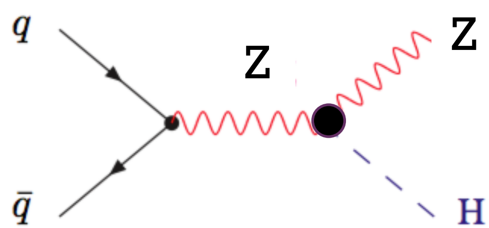
- Can we determine all these four structures ?

Now we are entering the era of high energies and luminosities so such questions can be answered!

Banerjee, RSG, Reiness & Spannowsky (to appear)

$hVV/hVff$ anomalous couplings

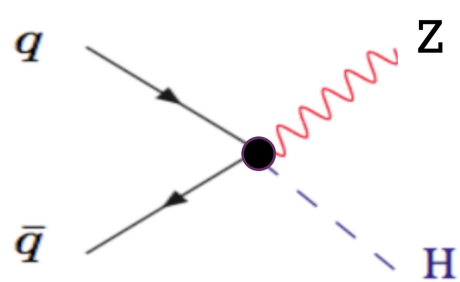
$$\delta g^h_{ZZ}\,\frac{2m_W^2}{v}\,h\,\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$



$$\delta g^h_{ZZ}\,\mathcal{A}_{\rm SM}$$

(just rescales rate,
no differential signature)

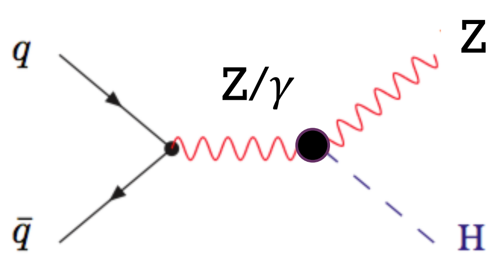
$$g^h_{Z\partial Z}\,\frac{h}{v}Z_\mu\partial_\nu Z_{\mu\nu}/g^h_{Zff}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$



$$\frac{\hat{s}-m_Z^2}{m_Z^2}\,\mathcal{A}_{\rm SM}$$

(only differential signature:
energy growth,
angular dist. unchanged)

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

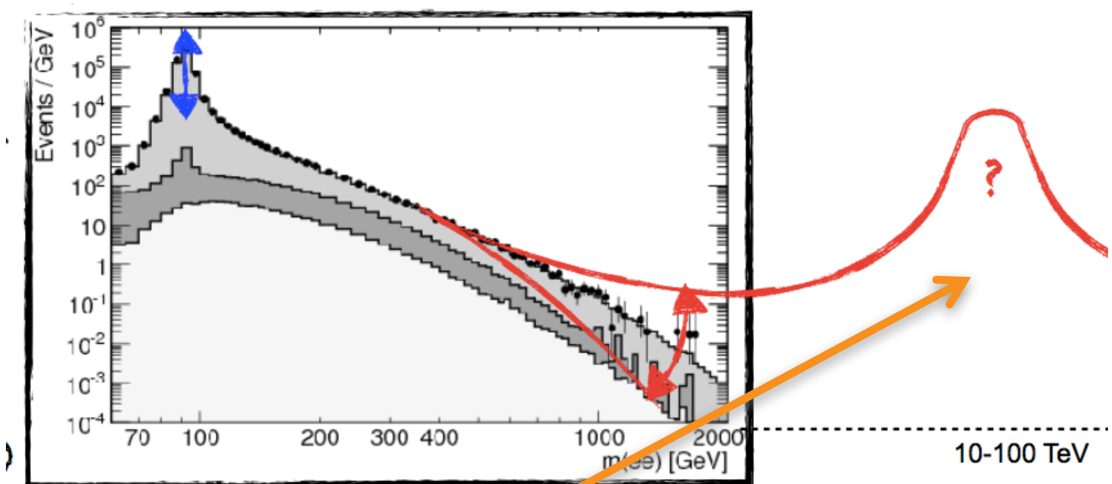


Angular correlations
+energy growth

Banerjee, RSG, Reiness &
Spannowsky (to appear)

The hVff term

- High energy deviations in ff ->Zh production dominated by hVff contact term:



Resonance

hVff term

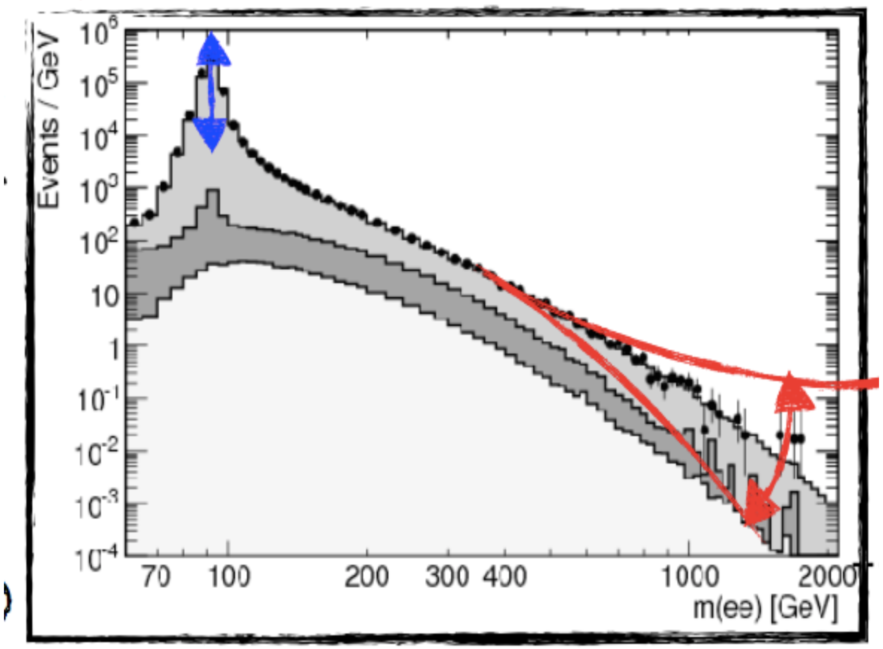
$\bar{f}\gamma^\mu f$

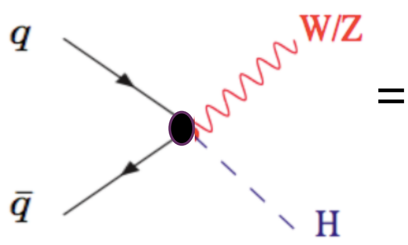
$$iH^\dagger \overleftrightarrow{D}_\mu H \longrightarrow iH^\dagger \overleftrightarrow{D}_\mu H \, \bar{f}\gamma^\mu f$$

Banerjee, Englert, RSG & Spannowsky (arXiv: 1807.01796)

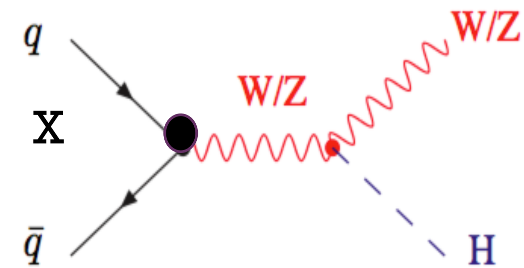
The hVff term

- High energy deviations in ff ->Zh production dominated by hVff contact term:





$$\frac{\hat{s} - m_Z^2}{m_Z^2}$$ X



Banerjee, Englert, RSG & Spannowsky (arXiv: 1807.01796)

Zh production: LHC vs LEP

- These vertices can be thus measured in this process. For eg. At high energies:

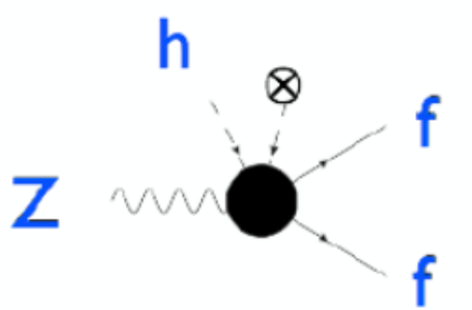
$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g^h_{Zff}}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right]$$

$$g^h_{Zu_L u_L} = -\frac{g}{c_{\theta_W}} \left((c^2_{\theta_W} + \frac{s^2_{\theta_W}}{3}) \delta g_1^Z + W - \frac{t^2_{\theta_W}}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$

- LEP constraint: 5-10 % level, 0.2% level.
- To be as sensitive as LEP, LHC needs to measure this process at 30 % level because of energy enhancement

Dim-6 level Correlation

hVff = Triple Gauge Coupling +Z decay modifications



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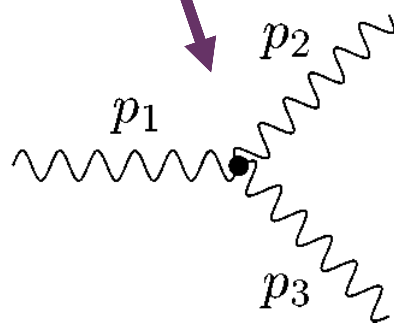

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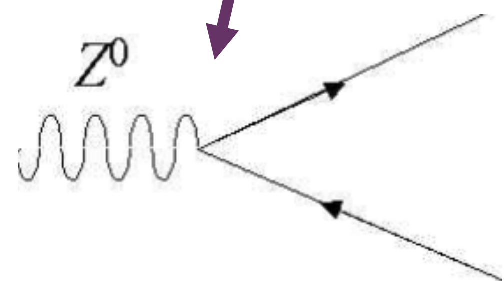


Can only be seen at LHC

Constrained already by LEP !

Zh production: LHC vs LEP

- These vertices can be thus measured in this process. For eg. At high energies:

Factor of 30

$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g^h_{Zff}}{g_f^Z} \frac{\hat{s}}{2m_Z^2}\right]$$

$$g^h_{Zu_Lu_L} = -\frac{g}{c_{\theta_W}} \left((c^2_{\theta_W} + \frac{s^2_{\theta_W}}{3}) \delta g_1^Z + W - \frac{t^2_{\theta_W}}{3} (\hat{S} - \delta\kappa_\gamma - Y) \right)$$

Per mille- % level constraint possible ?

- LEP constraint: 5-10% level
- To compete with LEP, LHC needs to measure this process at 30 % level because of energy enhancement

HIGH ENERGIES ESSENTIAL !

Greater sensitivity expected at higher energies such the HE-LHC at 27 TeV.

Cross section deviations and EFT Validity

$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right]$$

$$c_i \frac{\hat{s}}{\Lambda^2}$$

EFT validity: $\hat{s} \ll \Lambda^2$

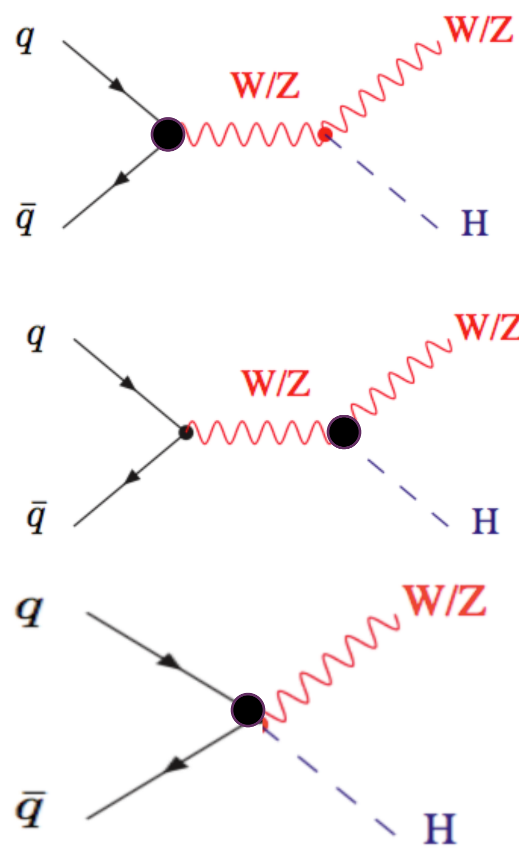
Fractional Deviations >>1 signal a breakdown of EFT expansion unless UV completion is strongly coupled

HIGH LUMINOSITIES ESSENTIAL !

To get sensitivity to such small deviations

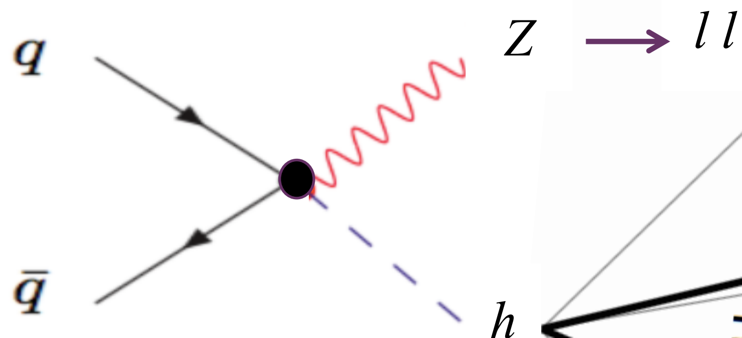
Zh production at LHC

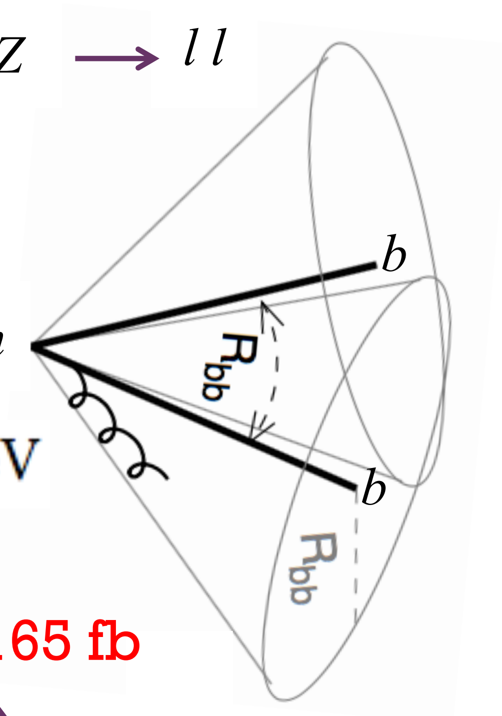
- Can sensitivity to 30 % deviation be achieved in high energy bins for this process ?



Banerjee, Englert, RSG and Spannowsky
(arXiv: 1807.01796)

Search Strategy





$$p_T^{l_1} + p_T^{l_2} > 160 \text{ GeV}$$

Zh (bb) =4.6 fb   Zbb= 165 fb

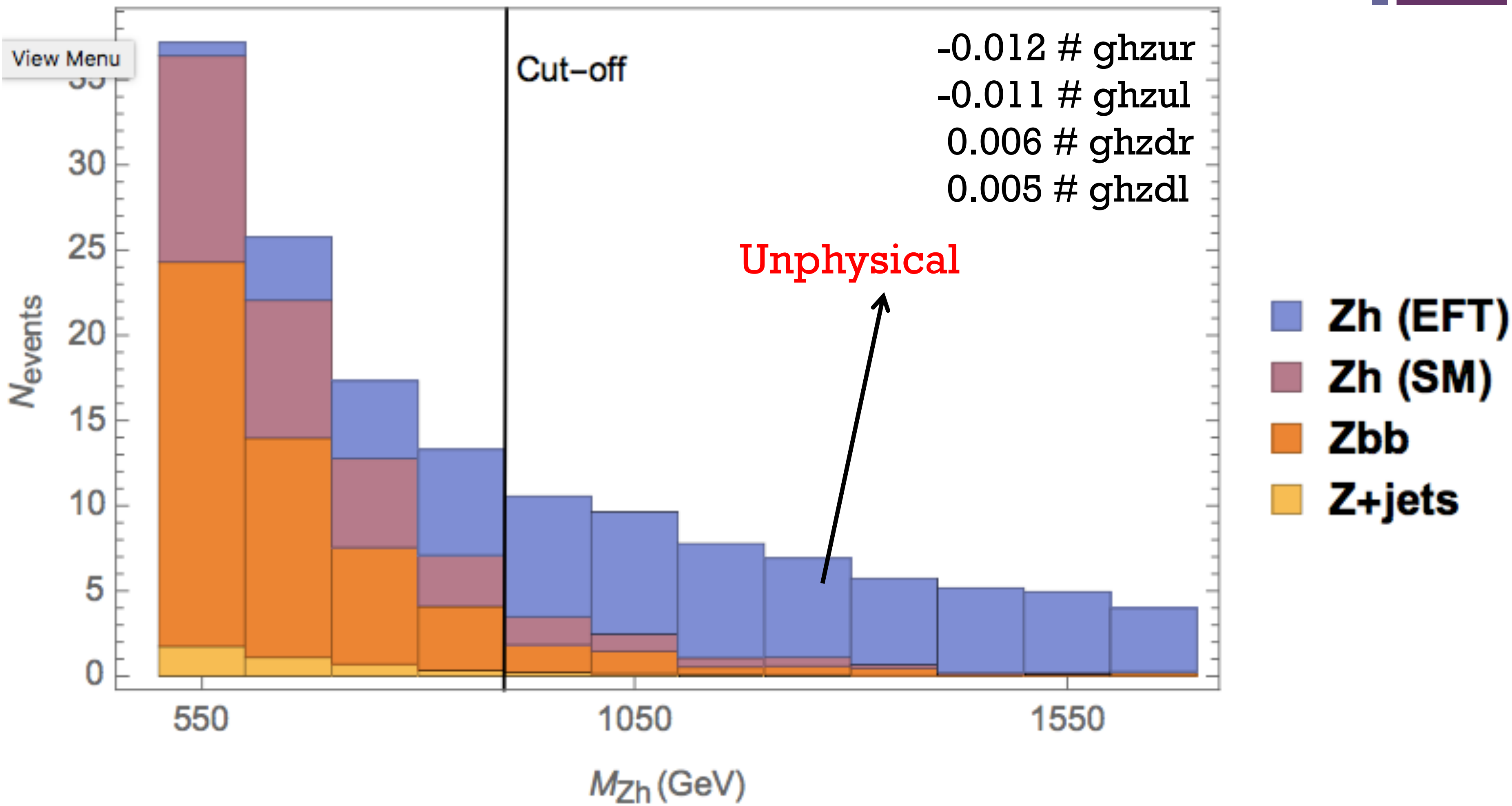
BDT optimisation

Zh (bb) =0.12 fb   Zbb= 0.22 fb

Cut-based Analysis

Zh (bb) =0.11 fb   Zbb= 0.35 fb

SM background vs EFT Signal



Results

- As initial parton polarisation cannot be controlled and up type and down type initial states cannot be disentangled at the LHC, it probes only a linear combination of the 4 couplings above:

$$g^Z_{\mathbf{p}} = g^h_{Zu_L} - 0.76\, g^h_{Zd_L} - 0.45\, g^h_{Zu_R} + 0.14\, g^h_{Zd_R}$$

- We get a bound much stronger than LEP (10 % level) at 300 (3000) ifb,

$$\begin{aligned} g^h_{Z\mathbf{p}} &\in [-0.004, 0.004] \quad (300\ \mathrm{fb}^{-1}) \\ g^h_{Z\mathbf{p}} &\in [-0.001, 0.001] \quad (3000\ \mathrm{fb}^{-1}). \end{aligned}$$

Banerjee, Englert, RSG and Spannowsky (arXiv: 1807.01796)

Results

- As initial parton polarisation cannot be controlled and up type and down type initial states cannot be disentangled at the LHC, it probes only a linear combination of the 4 couplings ... l_R

- We get a l...) at 300 (3000) ifb ...

	Our Projection	LEP Bound
$\delta g^Z_{u_L}$	± 0.002 (± 0.0007)	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	± 0.003 (± 0.001)	0.0023 ± 0.001
$\delta g^Z_{u_R}$	± 0.005 (± 0.001)	-0.0036 ± 0.0035
$\delta g^Z_{d_R}$	± 0.016 (± 0.005)	0.016 ± 0.0052
δg^Z_1	± 0.005 (± 0.001)	$0.009^{+0.043}_{-0.042}$
$\delta \kappa_\gamma$	± 0.032 (± 0.009)	$0.016^{+0.085}_{-0.096}$
$\hat{S}$	± 0.032 (± 0.009)	0.0004 ± 0.0007
W	± 0.003 (± 0.001)	0.0000 ± 0.0006
Y	± 0.032 (± 0.009)	0.0003 ± 0.0006

Couplings turned on one by one.
Can improve bound on Zqq couplings & TGC wrt LEP

Banerjee, Englert, RSG and Spannowsky (arXiv: 1807.01796)

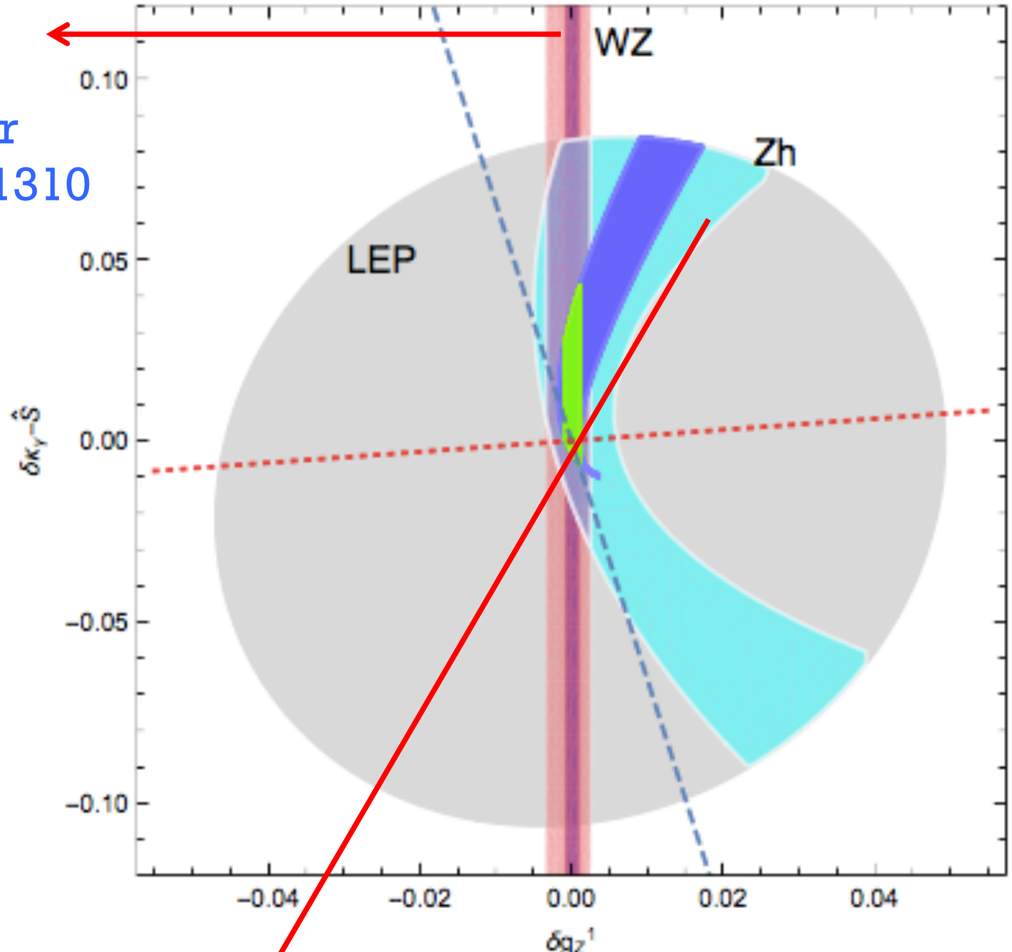
Combined bound with WZ production

Four channels:

- ZH $\longrightarrow$ G^0 H
- WH $\longrightarrow$ G^+H
- WW $\longrightarrow$ G^+ G^-
- WZ $\longrightarrow$ G^+G^0

Franceschini, Panico, Pomarol, Riva & Wulzer arxiv:1712.01310

Light (Dark) Blue: 300 (3000) ifb

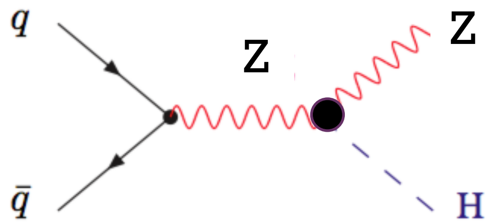


Banerjee, Englert, RSG and Spannowsky

(hV and *VV* processes amplitude connected by symmetry. They constrain the same set of observables at high energies)

Other anomalous Higgs couplings?

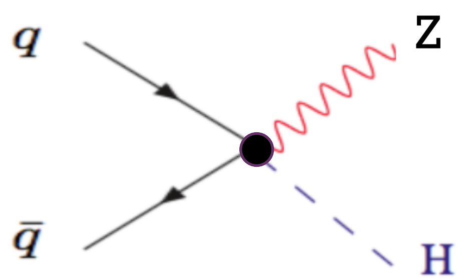
$$\delta g^h_{ZZ}\,\frac{2m_W^2}{v}\,h\,\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$$



$\delta g^h_{ZZ}\mathcal{A}_{\rm SM}$

(just rescales rate, no differential signature)

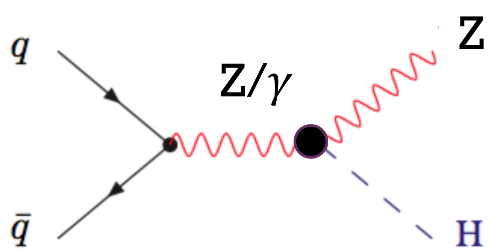
$$g^h_{Z\partial Z}\,\frac{h}{v}Z_\mu\partial_\nu Z_{\mu\nu}/g^h_{Zff}\,\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$$



$$\frac{\hat{s}-m_Z^2}{m_Z^2}\mathcal{A}_{\rm SM}$$

(only differential signature: energy growth, angular dist. unchanged)

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



Angular correlations +energy growth

Banerjee, RSG, Reiness & Spannowsky (to appear)

ZH amplitude

$$\hat{\kappa}_{ZZ} = \kappa_{ZZ} + \alpha\kappa_{Z\gamma}$$

- *Zh* amplitude at high energies:

$$Z_T h: \; g_f^Z \frac{\epsilon^* \cdot J_f}{v} \frac{2m_Z^2}{\hat{s}} \left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \hat{\kappa}_{ZZ}\right) \frac{\hat{s}}{2m_Z^2}\right]$$

$$Z_L h: \; g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2}\right],$$

Dominant contribution only to transverse mode

- Squared Amplitude:

$$|\mathcal{M}(p_h, p_Z)|^2 \sim \frac{(a_{\rm SM}^L)^2 m_Z^2}{E^2} \left(1 + c_{LL'} g_{Zff}^h \frac{E^2}{m_Z^2} + c_{TT'} \hat{\kappa}_{ZZ} \cdots\right)$$

LL LL' TT'

+

ZH amplitude

$$\hat{\kappa}_{ZZ} = \kappa_{ZZ} + \alpha\kappa_{Z\gamma}$$

- *Zh* amplitude at high energies:

$$Z_T h:\; g_f^Z \frac{\epsilon^* \cdot J_f}{v}\frac{2m_Z^2}{\hat{s}}\left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \hat{\kappa}_{ZZ}\right)\frac{\hat{s}}{2m_Z^2}\right]$$

$$Z_L h:\; g_f^Z \frac{q \cdot J_f}{v}\frac{2m_Z}{\hat{s}}\left[1 + \frac{g_{Zff}^h}{g_f^Z}\frac{\hat{s}}{2m_Z^2}\right],$$

Dominant contribution only to transverse mode

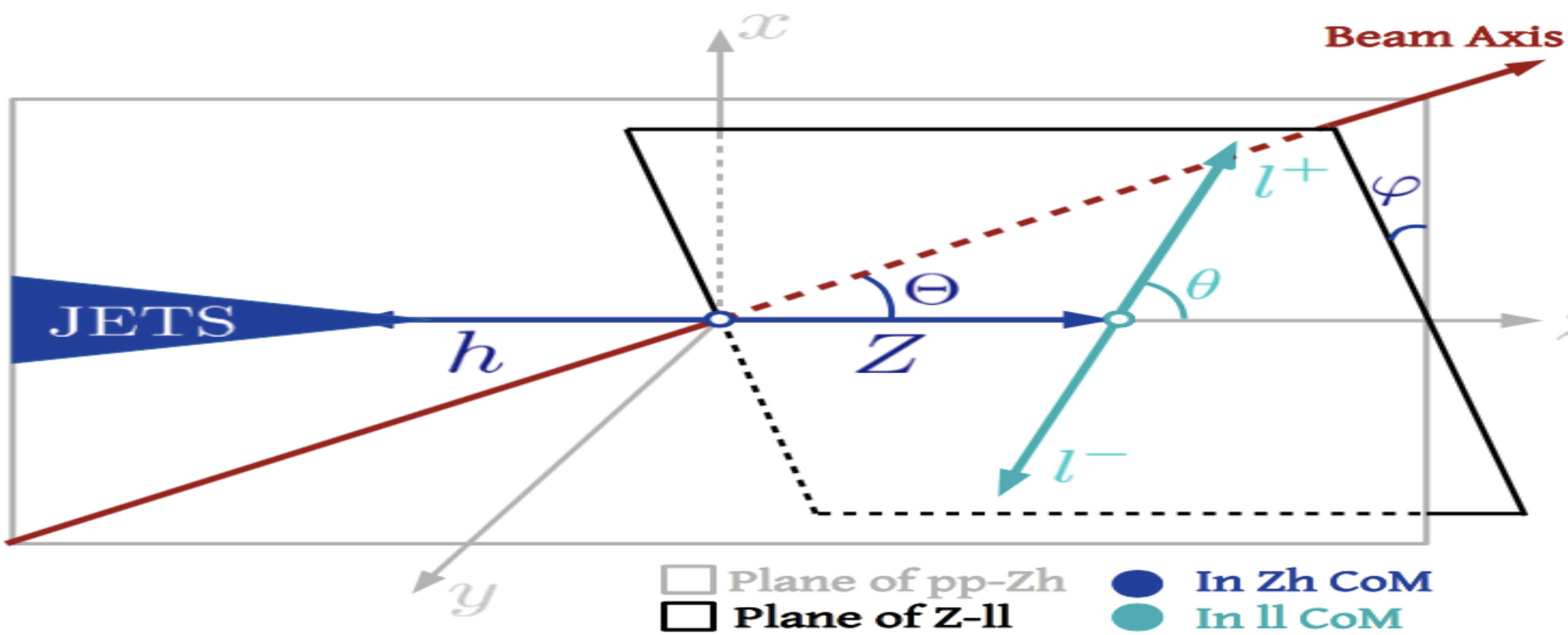
- Squared Amplitude:

subdominant

$$|\mathcal{M}(p_h, p_Z)|^2 \sim \frac{(a_{\rm SM}^L)^2 m_Z^2}{E^2}\left(1 + c_{LL'} g_{Zff}^h \frac{E^2}{m_Z^2} + c_{TT'}\hat{\kappa}_{ZZ} \cdots\right)$$

LL LL' TT'

Interference at the level of decay products



If we do not look at full phase space of decay products we do not know if intermediate Z was longitudinal or transverse. QM says we must add both possibilities: LT' interference possible !

Azatov, Elias-Miro, Reyimuaji & Venturini(2017)
Panico. Riva & Wulzer (2017)
Banerjee, RSG, Reiness & Spannowsky (to appear)

Interference at the level of decay products

LT' interf. present differentially

- Squared amplitude again:

$$|\mathcal{M}(p_h, p_{l1,l2})|^2 \sim \frac{(a^L_{\rm SM})^2 m_Z^2}{E^2}\left(1 + c_{LL'} g^h_{Zff}\frac{E^2}{m_Z^2} + c_{LT'}\hat{\kappa}_{ZZ}\frac{E}{m_Z} + \tilde{c}_{LT'}\hat{\tilde{\kappa}}_{ZZ}\frac{E}{m_Z}\cdots\right)$$

Energy growth, even CP odd

$$\frac{d\sigma}{d\Theta d\theta d\varphi} \sim \hat{\kappa}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\cos\varphi$$

$$\frac{d\sigma}{d\Theta d\theta d\varphi} \sim \hat{\tilde{\kappa}}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\sin\varphi$$

Banerjee, RSG, Reiness & Spannowsky (to appear)

Interference at the level of decay products

LT' interf.
present

- Squ

$|\mathcal{M}(p$

These distributions can be derived in a few lines using helicity amplitudes.
Completely determined by symmetries (angular momentum conservation)

Energy growth, even CP odd

$$\frac{d\sigma}{d\Theta d\theta d\varphi} \sim \hat{\kappa}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\cos\varphi$$

$$\frac{d\sigma}{d\Theta d\theta d\varphi} \sim \hat{\tilde{\kappa}}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\sin\varphi$$

Banerjee, RSG, Reiness & Spannowsky (to appear)

Interference at the level of decay products

LT' interference vanishes upon integration

- Squared amplitude again:

$$\int |\mathcal{M}(p_h, p_{l1}, p_{l2})|^2 \sim \frac{(a^L_{\rm SM})^2 m_Z^2}{E^2}\left(1 + c_{LL'} g^h_{Zff}\frac{E^2}{m_Z^2} + c_{TT'}\hat{\kappa}_{ZZ}.\cdots\right)$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\Theta \sim \int \hat{\kappa}_{ZZ}\frac{m_Z}{\sqrt{s}} \cos\Theta\cos\theta\cos\varphi d\Theta = 0$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\Theta \sim \int \hat{\tilde{\kappa}}_{ZZ}\frac{m_Z}{\sqrt{s}} \cos\Theta\cos\theta\sin\varphi d\Theta = 0$$

Banerjee, RSG, Reiness & Spannowsky (to appear)

Interference at the level of decay products

LT' interference vanishes upon integration

- Squared amplitude again:

$$\int |\mathcal{M}(p_h, p_{l1}, p_{l2})|^2 \sim \frac{(a^L_{\rm SM})^2 m_Z^2}{E^2}\left(1 + c_{LL'} g^h_{Zff}\frac{E^2}{m_Z^2} + c_{TT'}\hat{\kappa}_{ZZ}\cdots\right)$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\theta \sim \int \hat{\kappa}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\cos\varphi d\theta = 0$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\theta \sim \int \hat{\tilde{\kappa}}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\sin\varphi d\theta = 0$$

Banerjee, RSG, Reiness & Spannowsky (to appear)

Interference at the level of decay products

LT' interference vanishes upon integration

- Squared amplitude again:

$$\int |\mathcal{M}(p_h, p_{l1}, p_{l2})|^2 \sim \frac{(a^L_{\rm SM})^2 m_Z^2}{E^2}\left(1 + c_{LL'} g^h_{Zff}\frac{E^2}{m_Z^2} + c_{TT'}\hat{\kappa}_{ZZ}.\cdots\right)$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\varphi \sim \int \hat{\kappa}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\cos\varphi d\varphi = 0$$

$$\int \frac{d\sigma}{d\Theta d\theta d\varphi} d\varphi \sim \int \hat{\tilde{\kappa}}_{ZZ}\frac{m_Z}{\sqrt{s}}\cos\Theta\cos\theta\sin\varphi d\varphi = 0$$

Banerjee, RSG, Reiness & Spannowsky (to appear)

Asymmetry variable

$$\frac{d\sigma}{d\Theta d\theta d\varphi} \sim \hat{\kappa}_{ZZ} \frac{m_Z}{\sqrt{s}} \cos\Theta \cos\theta \cos\varphi$$

- This term vanishes if we integrate inclusively over any of the three angles.
- To obtain this term we can reverse weight of the event whenever any of the above cosines becomes –ve and do a weighted integral.
- This is equivalent to evaluating the asymmetry variable:

$$\xi = N_1 - N_2 - N_3 + N_4 - N_5 + N_6 + N_7 - N_8.$$

where we have split phase space into 8 octants depending on whether each cosine is +ve or –ve.

Banerjee, RSG, Reiness & Spannowsky (to appear)

Asymmetry variable

$$\frac{d\ldots}{d\Theta\ldots} \ldots \ldots\text{os}\,\theta \cos\varphi$$

1.	n_1	$+++$
2.	n_2	$++-$
3.	n_3	$+-+$
4.	n_4	$+--$
5.	n_5	$-++$
6.	n_6	$-+-$
7.	n_7	$--+$
8.	n_8	$---$

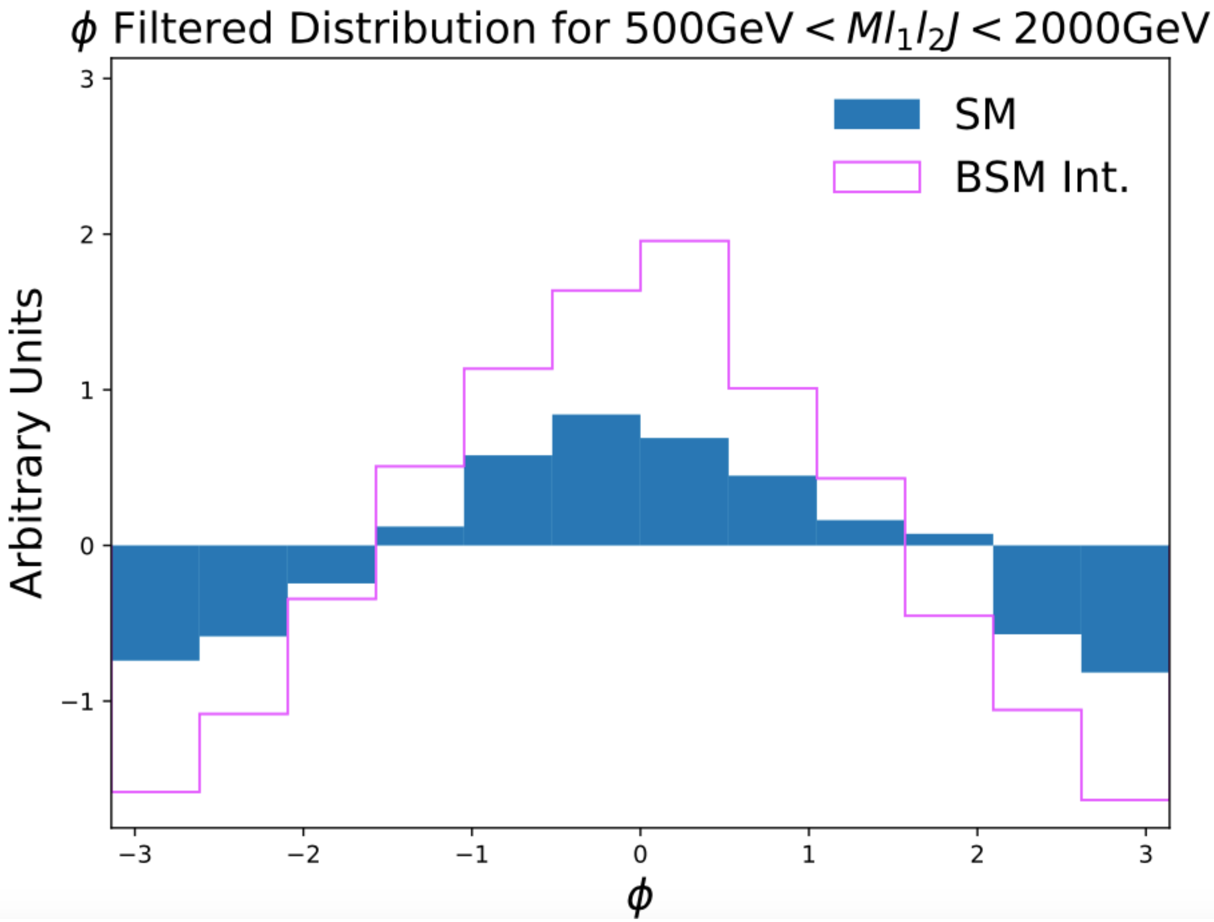
- This term **vanis**… **over any of the three angles.**
- To obtain this t… **the event whenever any of the abov**… o a weighted integral.
- This is equival… **ry variable:**

$$\xi = N \ldots N_7 - N_8.$$

where we have s… depending on whether each cosine is +ve or –ve.

Banerjee, RSG, Reiness & Spannowsky (to appear)

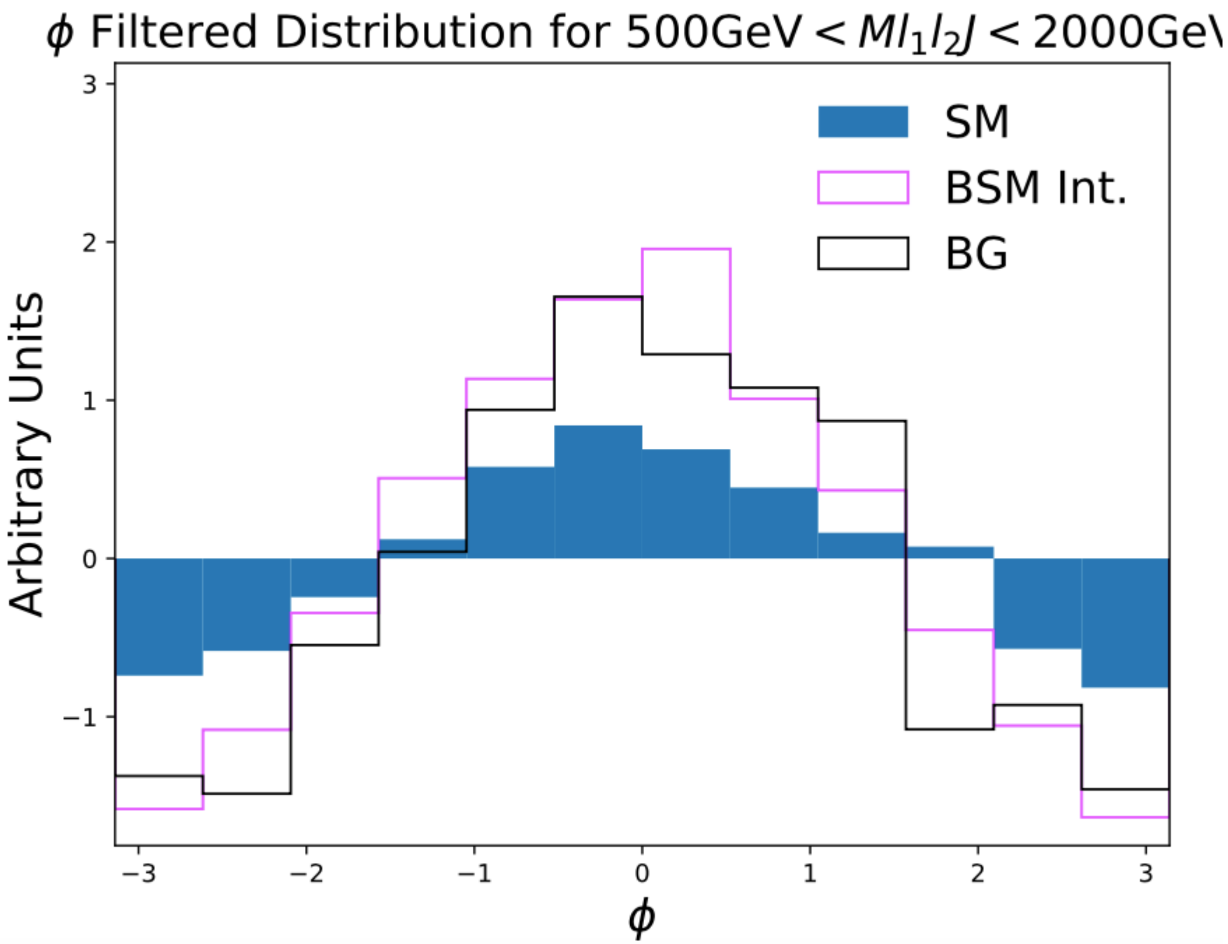
Distributions



$\cos\Theta\cos\theta$ sign flipped when negative

Banerjee, RSG, Reiness & Spannowsky (to appear)

Distributions

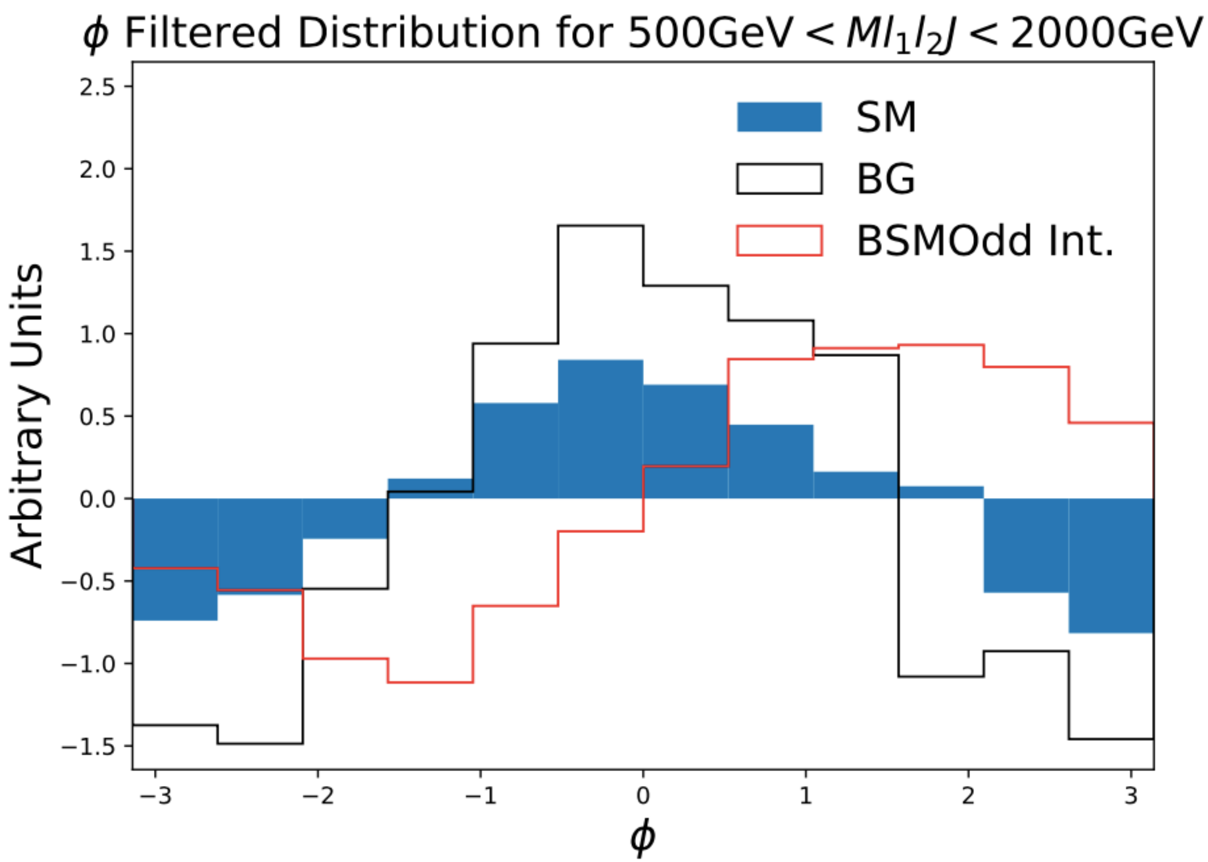


$\cos\Theta\cos\theta$ sign flipped when negative

Banerjee, RSG, Reiness & Spannowsky (to appear)

+

Distributions



$\cos\Theta\cos\theta$ sign flipped when negative

Banerjee, RSG, Reiness & Spannowsky (to appear)

Preliminary Bound

- With 3 iab data at LHC we can obtain,

$$\hat{\kappa}_{ZZ}, \hat{\tilde{\kappa}}_{ZZ} \lesssim 5\%$$

+ *hVV/hVff* anomalous couplings

- 4 tensor structures for dimension 6 vertices

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\frac{2m_W^2 h}{v}\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + \sum_f g^h_{Zf}\frac{h}{v}Z_\mu \bar{f}\gamma^\mu f + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu} + \tilde{\kappa}_{ZZ}\frac{h}{v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}$$

equivalent to $g^h_{Z\partial Z}\frac{h}{v}Z_\mu \partial_\nu Z_{\mu\nu}$,

- Can we determine all these four structures ?

Banerjee, RSG, Reiness & Spannowsky (to appear)

The Operator-Vertex-Observable Map

Vertex-Observable Map

VERTEX	OBSERVABLE	BOUND
$g^h_{Z\partial Z}\frac{h}{v}Z_\mu\partial_\nu Z_{\mu\nu}/g^h_{Zff}\frac{h}{v}Z_\mu\bar{f}\gamma^\mu f$	$\frac{d\sigma}{d\hat{s}}$	$g^h_{Z\mathrm{p}} \in [-0.004, 0.004]$ $(300\ \mathrm{fb}^{-1})$ $g^h_{Z\mathrm{p}} \in [-0.001, 0.001]$ $(3000\ \mathrm{fb}^{-1})$
$\kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}+\kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}$ $+\tilde{\kappa}_{ZZ}\frac{h}{v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}+\tilde{\kappa}_{Z\gamma}\frac{h}{v}Z^{\mu\nu}\tilde{Z}_{\mu\nu}\,.$	$\frac{d\sigma}{d\hat{s}d\Theta d\theta d\varphi}$	$\hat{\kappa}_{ZZ},\hat{\tilde{\kappa}}_{ZZ} \lesssim 5\%$ (3 iab)
$\delta g^h_{ZZ}\frac{2m^2_W}{v}h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$	$\mathrm{BR}(h\to ZZ^*\to 4l)$ $\sigma(pp\to Zh)$	$(2\delta g^h_{ZZ}-0.48\kappa_{ZZ}-2.2g^h_{Z\partial Z}) \lesssim 2\%$ (3 iab)

Banerjee, RSG, Reiness & Spannowsky (to appear)

Vertex-Observable Map

VERTEX	OBSERVABLE	BOUND
$g^h_{Z\partial Z}\frac{h}{v}$ …	$d\sigma$ …	$g^h_{Z\partial Z} \in [-0.004, 0.004]$ … $(300\ \mathrm{fb}^{-1})$ $(3000\ \mathrm{fb}^{-1})$
$\kappa_{ZZ}\frac{h}{2v}$ … $+\ \tilde{\kappa}_{ZZ}\frac{h}{v}$ …		…% (3 iab)
$\delta g^h_{ZZ}\frac{2m_W^2}{v}h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$	$\mathrm{BR}(h \to ZZ^* \to 4l)$ $\sigma(pp \to Zh)$	$(2\delta g^h_{ZZ} - 0.48\kappa_{ZZ} - 2.2 g^h_{Z\partial Z}) \lesssim 2\%$ (3 iab)

- Combining all these and h-> Z γ information, one can constrain all hVff couplings in CP even case.

Banerjee, RSG, Reiness & Spannowsky (to appear)

The Operator-Vertex-Observable Map

Operators ← Vertices/Anomalous Couplings/Pseudo-observables

Operator-Vertex Map

$$\delta g^h_{ZZ} = -\frac{g^4 v\xi}{4}(c_r + t^2_{\theta_W} c_{W-B})$$

$$\kappa_{Z\gamma} = gg'\left(2c^2_{\theta_W} c_{WW} - 2s^2_{\theta_W} c_{BB} - (c^2_{\theta_W} - s^2_{\theta_W})c_{WB'}\right)\xi$$

$$\kappa_{ZZ} = \frac{g^2}{c^2_{\theta_W}}\left(2c^4_{\theta_W} c_{WW} + 2s^4_{\theta_W} c_{BB} + 2s^2_{\theta_W} c^2_{\theta_W} c_{WB'}\right)\xi$$

$$\tilde{\kappa}_{Z\gamma} = gg'\left(2c^2_{\theta_W} \tilde{c}_{WW} - 2s^2_{\theta_W} \tilde{c}_{BB} - (c^2_{\theta_W} - s^2_{\theta_W})\tilde{c}_{WB'}\right)\xi$$

$$\tilde{\kappa}_{ZZ} = \frac{g^2}{c^2_{\theta_W}}\left(2c^4_{\theta_W} \tilde{c}_{WW} + 2s^4_{\theta_W} \tilde{c}_{BB} + 2s^2_{\theta_W} c^2_{\theta_W} \tilde{c}_{WB'}\right)\xi$$

$$g^h_{Zu_Lu_L} = -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L - c^3_L)$$

$$g^h_{Zd_Ld_L} = -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L + c^3_L)$$

$$g^h_{Zu_Ru_R} = -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^u_R$$

$$g^h_{Zd_Rd_R} = -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^d_R$$

This can be presented in one's favourite basis. Basis independent approach.

The Operator-Vertex-Observable Map

Operators ← Vertices/Anomalous Couplings/Pseudo-observables ← Observables

+ Still a lot LHC does not constrain!

- We do not know the shape of the Higgs potential

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \quad \text{OR} \quad V(H) = \mu^2 H^\dagger H + c_6 \frac{(H^\dagger H)^3}{\Lambda^2} \quad ?$$

- Resolving hVV/hVff tensor structure requires at least 10 times more data than we have.

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ} \frac{2m^2_W h}{v} \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} + \sum_f g^h_{Zf} \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \tilde{\kappa}_{ZZ} \frac{h}{v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

Conclusions

- We proposed observables that can resolve the full hVV/hVff tensor structure.
- Using differential information only beginning and will become more and more important with higher luminosities and energies. Important to carefully design observables.