High-pT tails in VH/VV for TGCs

Dibosons at the 'High Energy-Luminosity' frontier

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in collaboration with Banerjee, Englert, and Spannowsky

(arXiv: 1807.01796)

Higgs Precision Physics

- Measuring Higgs properties is the most concrete particle physics goal of our times.
- Indirect deviations can constrain scale much higher than direct searches.
- Eg. : The S,T parameters at LEP constrain certain kinds of new Physics to scales higher than a few TeV. Much higher than LEP energies.

SM as an EFT

- 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:

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\ \frac{g_* H}{\Lambda}\,,\ \frac{g_* f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

LEP vs LHC

- Can LHC compete with LEP ? Can LHC searches give us new information that LEP does not provide ?

- EFT techniques show that many anomalous Higgs interactions were already probed by LEP.

- One way to compete with LEP precision is by going to higher energies.

- We will show how this is possible with the concrete example of high energy diboson production at LHC (WW, WZ, Wh, Zh).

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

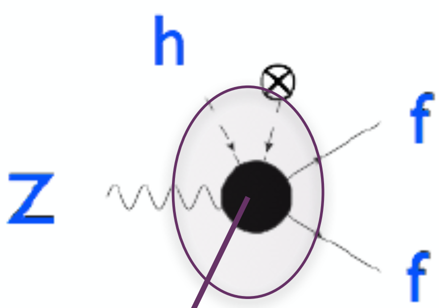
LEP vs LHC

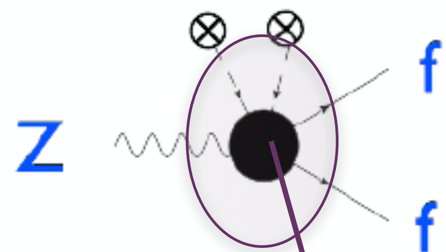
But Higgs was not directly produced at LEP.

So Higgs interactions to be measured for the first time at LHC ?

Not Really True within EFT framework!!

Vertices with or without Higgs





CAN BE ONLY SEEN
AT LHC

CAN BE MEASURED
MUCH MORE
PRECISELY AT LEP

+ Anomalous Higgs interactions at dimension-6 level

$$
\begin{aligned}
\mathcal{L}_h^{\text{primary}} &= g_{VV}^h\, h\left[W^{+\,\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2}Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g_{ff}^h\, \left(h\bar{f}_L f_R + h.c.\right) \\
&+ \kappa_{GG}\,\frac{h}{v}G^{A\,\mu\nu}G_{\mu\nu}^A + \kappa_{\gamma\gamma}\,\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,
\end{aligned}
$$

$$
\begin{aligned}
\Delta\mathcal{L}_h &= \delta g_{ZZ}^h\,\frac{v}{2c_{\theta_W}^2}hZ^\mu Z_\mu + g_{Zff}^h\,\frac{h}{2v}\left(Z_\mu J_N^\mu + h.c.\right) + g_{Wff'}^h\,\frac{h}{v}\left(W_\mu^+ J_C^\mu + h.c.\right) \\
&+ \kappa_{WW}\,\frac{h}{v}W^{+\,\mu\nu}W_{\mu\nu}^- + \kappa_{ZZ}\,\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,
\end{aligned}
$$

A. Pomarol (arxiv: 1412.4410)

Anomalous Higgs interactions at dimension-6 level

$$\mathcal{L}_h^{\rm primary} \;=\; g^h_{VV}\, h \left[W^{+\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu \right] + g_{3h}\, h^3 + g^h_{ff}\, \left(h \bar{f}_L f_R + h.c. \right)$$

Higgs interactions to be directly measured for the first time at LHC.

$$\Delta\mathcal{L}_h \;=\; \delta g^h_{ZZ}\, \frac{v}{2c^2_{\theta_W}} h Z^\mu Z_\mu + g^h_{Zff}\, \frac{h}{2v} \left(Z_\mu J^\mu_N + h.c. \right) + g^h_{Wff'}\, \frac{h}{v} \left(W^+_\mu J^\mu_C + h.c. \right)$$
$$+\;\; \kappa_{WW}\, \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ}\, \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}\,,$$

A. Pomarol (arxiv: 1412.4410)

Organizing principle: Effective Field Theory (EFT)

- Only 18 independent operators generate above vertices:

H^2-operators
$\mathcal{O}_r = \lvert H\rvert^2 \lvert D_\mu H\rvert^2$ $\mathcal{O}_6 = \lambda \lvert H\rvert^6$ $\mathcal{O}_y = \lvert H\rvert^2 \bar{F} H f$ $\mathcal{O}_f = iH^\dagger \overleftrightarrow{D}_\mu H \bar{f}\gamma^\mu f$ $\mathcal{O}_L = iH^\dagger \overleftrightarrow{D}_\mu H \bar{F}\gamma^\mu F$ $\mathcal{O}_L^{(3)} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F}\sigma^a\gamma^\mu F$ $\mathcal{O}_{W-B} = ig\left(H^\dagger \tau^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $-ig' Y_H \left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{WB'} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu} - 4ig' Y_H \left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$ $\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$
H^0-operators
$\mathcal{O}_{3W} = \frac{\epsilon_{abc}}{3!} W^{a\mu\nu} W^{b\mu\rho} W^{c\nu\rho}$

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

- EFT techniques imply many of these Higgs deformations not independent from electroweak precision/TGC deformations already constrained by LEP.

- Same operators give both Higgs and EW deformations

+ Correlations between observables

18 Operators → **50 Vertices /pseudo-observables**

H^2-operators
$\mathcal{O}_r = \lvert H\rvert^2 \lvert D_\mu H\rvert^2$
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$
$\mathcal{O}_y = \lvert H\rvert^2 \bar{F} H f$
$\mathcal{O}_f = i H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\mu f$
$\mathcal{O}_L = i H^\dagger \overleftrightarrow{D}_\mu H \bar{F} \gamma^\mu F$
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H^0-operators
$\mathcal{O}_{3W} = \frac{\epsilon_{abc}}{3!} W^{a\mu\nu} W^{b}{}_{\mu\rho} W^{c\nu\rho}$

Z-pole+Higgs observ.

+Triple Gauge Couplings+…

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)
Grojean and RSG, in preparation

+ Correlations between observables

18 Operators

50 Vertices /pseudo-observables

serv.

lings+…

$\mathcal{O}_{WB'} = gg'$

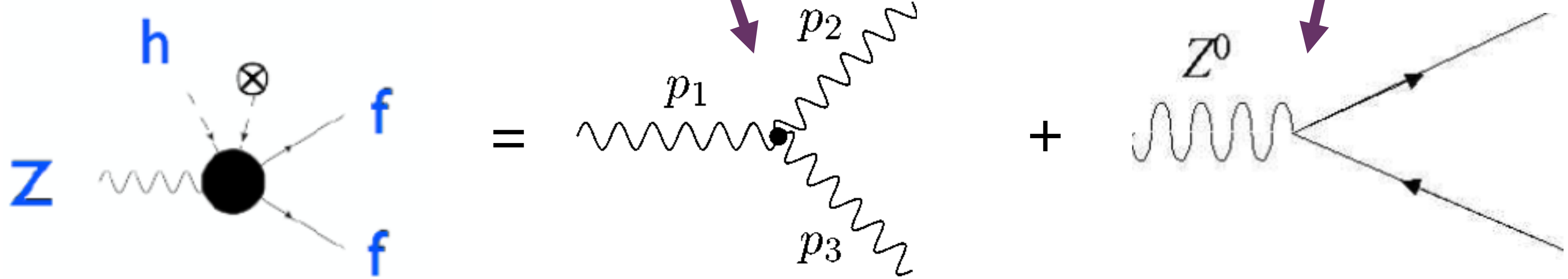
At any given order
Number of contributing operators << Number of vertices/pseudo-observables

Correlations between different vertices/observables

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)
Grojean and RSG, in preparation

Correlation Example

hVff = Triple Gauge Coupling +Z decay modifications



Can only be seen at LHC

Constrained already by LEP !

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

Anomalous Higgs interactions already constrained by LEP

$$\mathcal{L}_h^{\text{primary}} = g^h_{VV}\, h\left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}}Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g^h_{ff}\,\left(h\bar{f}_L f_R + h.c.\right)$$
$$+ \quad \kappa_{GG}\,\frac{h}{v}G^{A\,\mu\nu}G^A_{\mu\nu} + \kappa_{\gamma\gamma}\,\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,$$

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\,\frac{v}{2c^2_{\theta_W}}hZ^\mu Z_\mu + g^h_{Zff}\,\frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\,\frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)$$
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RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

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$$+\ \kappa_{WW}\,\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,$$

$$\delta g^h_{ZZ} = \delta g^Z_1 e^2 - \delta\kappa_\gamma \frac{e^2}{c^2_{\theta_W}}\,,$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1\left(g^Z_f c_{2\theta_W} + eQ_f s_{2\theta_W}\right) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}\,, \qquad g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}\,,$$

$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c^2_{\theta_W}\right), \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

+ # Anomalous Higgs interactions already constrained by LEP

$$\Delta\mathcal{L}_h = \delta g^h_{ZZ}\,\frac{v}{2c^2_{\theta_W}}hZ^\mu Z_\mu + g^h_{Zff}\,\frac{h}{2v}\left(Z_\mu J^\mu_N + h.c.\right) + g^h_{Wff'}\,\frac{h}{v}\left(W^+_\mu J^\mu_C + h.c.\right)$$
$$+ \kappa_{WW}\,\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\,\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,$$

Right Hand Side: Z-pole obs. +TGCs

$$\delta g^h_{ZZ} = \delta g^Z_1 e^2 - \delta\kappa_\gamma\frac{e^2}{c^2_{\theta_W}}\,,$$

$$g^h_{Zff} = 2\delta g^Z_{ff} - 2\delta g^Z_1\left(g^Z_f c_{2\theta_W} + eQ_f s_{2\theta_W}\right) + 2\delta\kappa_\gamma Y_f\frac{e s_{\theta_W}}{c^3_{\theta_W}}\,, \qquad g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}\,,$$

$$\kappa_{ZZ} = \frac{1}{2c^2_{\theta_W}}\left(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c^2_{\theta_W}\right)\,, \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

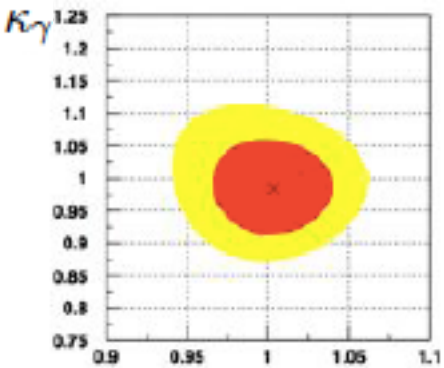
RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

If these predictions are not confirmed, one of our assumptions must have been wrong:

(1) *h* not part of a doublet.

(2) Scale of new physics not very high and dimension 8 operators cannot be ignored

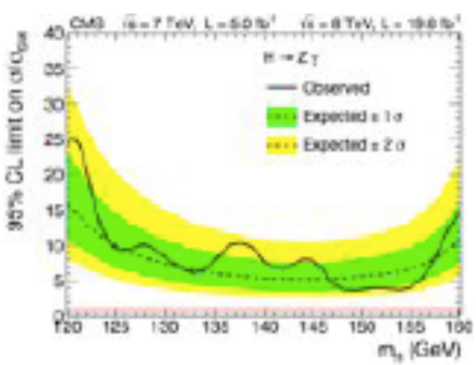
+ Example: *h ->Zff*



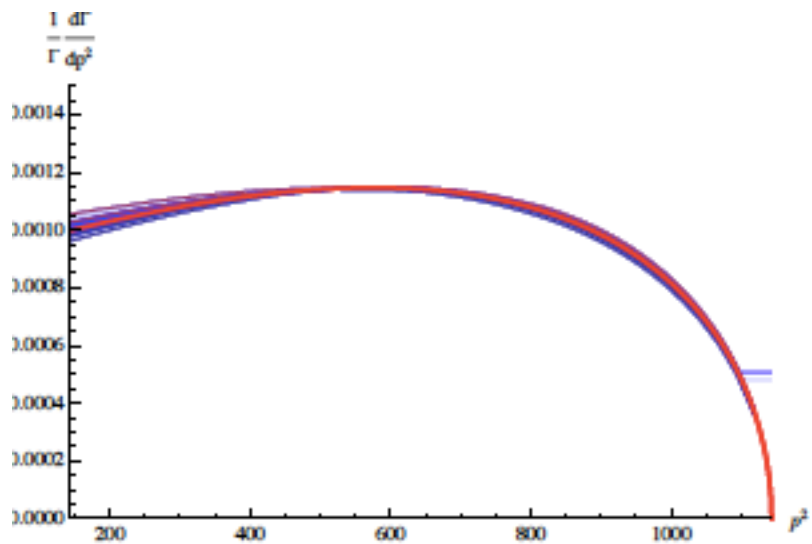
δg_1^Z

+

$h \to \gamma Z$



Already constrained !



Slide Courtesy: F. Riva

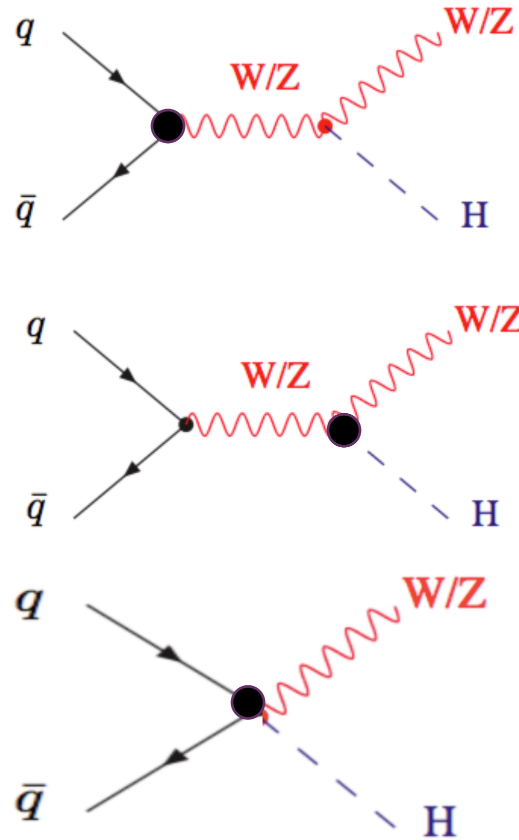
+ Anomalous Higgs interactions already constrained by LEP

- Only way to compete with LEP is to go to high energies.
- Rest of the talk: Zh production at high energies

Zh production at LHC

- The following vertices in the unitary gauge contribute:

$$\begin{aligned}
\Delta\mathcal{L}_6 \;\supset\; & \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
& + \; g_{VV}^h \, h \left[W^{+\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu \right] + \delta g_{ZZ}^h \, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} \\
& + \; \sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{Wud}^h \frac{h}{v} (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
& + \; \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W_{\mu\nu}^- + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} \,.
\end{aligned}$$



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

+ Zh production at LHC

- The following vertices in the unitary gauge contribute:

$$
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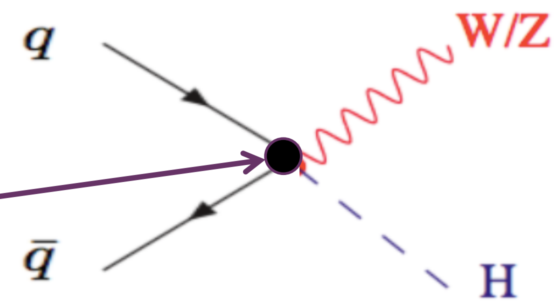
\Delta\mathcal{L}_6 \;\supset\; & \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
+ \; & g_{VV}^h\, h \left[W^{+\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu \right] + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} \\
+ \; & \sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{Wud}^h \frac{h}{v} (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
+ \; & \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} \,.
\end{aligned}
$$

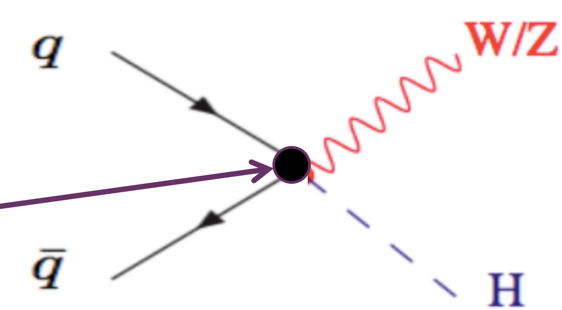


$$
\mathcal{M}(ff \to Z_L h) \;=\; g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right]
$$

Zh production at LHC

- The following vertices in the unitary gauge contribute:

$$\Delta\mathcal{L}_6 \supset \sum_f \delta g_f^Z Z_\mu \bar f \gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar u_L \gamma^\mu d_L + h.c.)$$
$$+ \quad g_{VV}^h\, h \left[W^{+\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2}$$
$$+ \sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar f \gamma^\mu f + g_{Wud}^h \frac{h}{v}(W_\mu^+ \bar u_L \gamma^\mu d_L + h.c.)$$



Leading effect from contact interaction at high energies.
Energy growth as there is no propagator.

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

Zh production at LHC

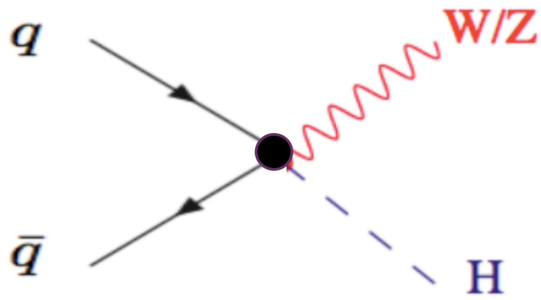
- The following vertices in the unitary gauge contribute:

SILH Basis	Warsaw Basis
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_L = (\bar{Q}_L \gamma^\mu Q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	

Zh production: High energy primaries

- At high energies four directions in EFT space are isolated by high energy ZH production.

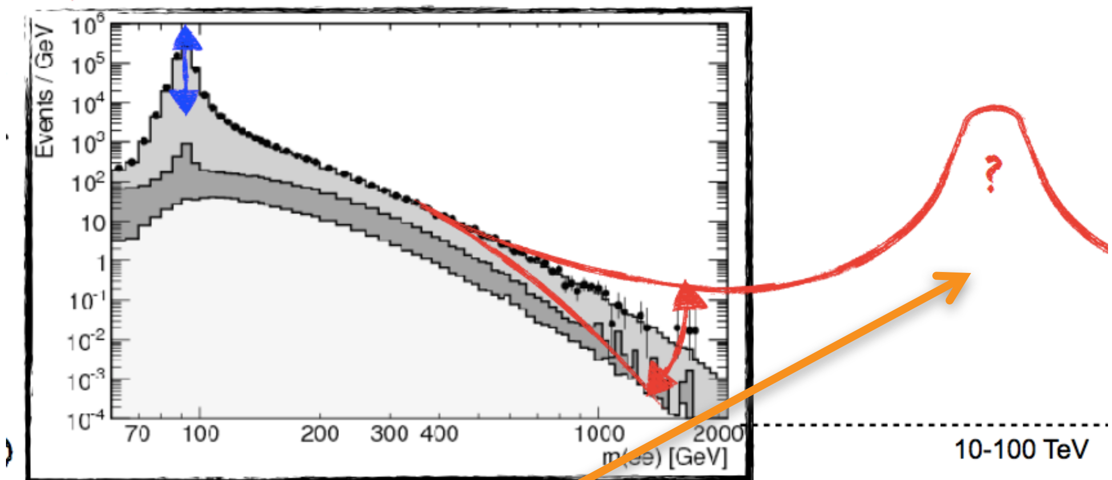
$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L - c^3_L) \\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}(c^1_L + c^3_L) \\
g^h_{Zu_Ru_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^u_R \\
g^h_{Zd_Rd_R} &= -\frac{g}{c_{\theta_W}}\frac{v^2}{\Lambda^2}c^d_R
\end{aligned}
$$



WARSAW BASIS

The hVff term

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



Resonance

hVff term

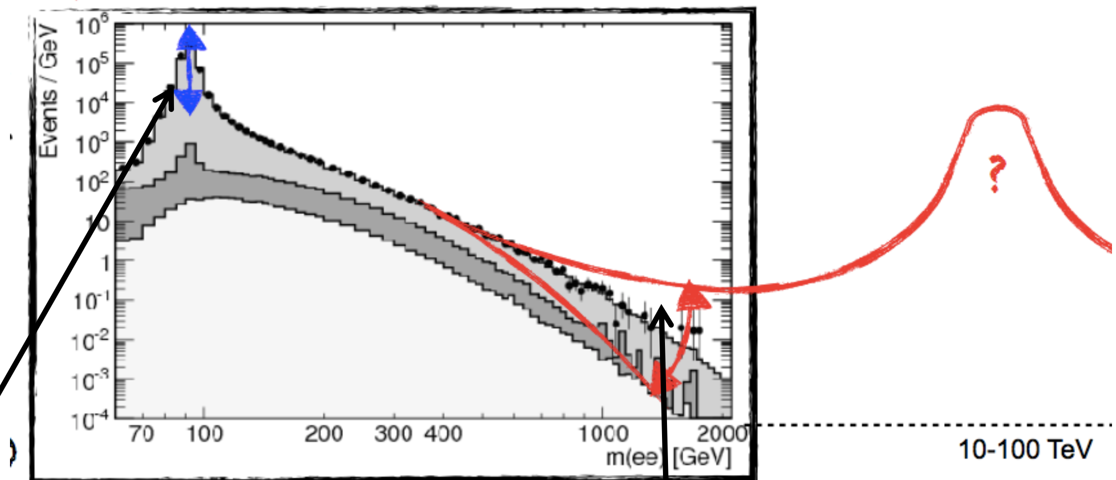
$\bar{f}\gamma^\mu f$

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

Picture Courtesy: F Riva

LEP vs LHC

- High precision vs High energies



Small deviation. Need LEP precision

Larger deviation. Energy Growth. Only LHC can see

Picture Courtesy: F Riva

Zh production: LHC vs LEP

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

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

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

- 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

Zh production: LHC vs LEP

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

Factor of 30

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

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

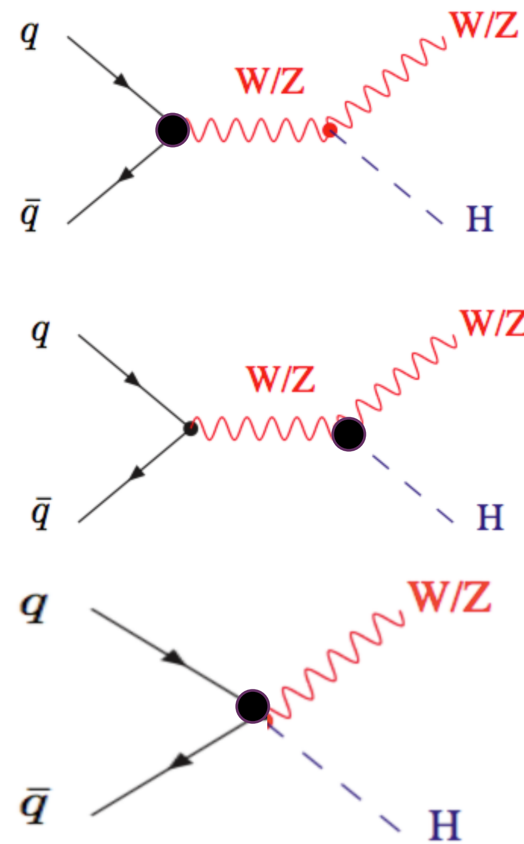
Per mille - % level constraint possible ?

- 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.

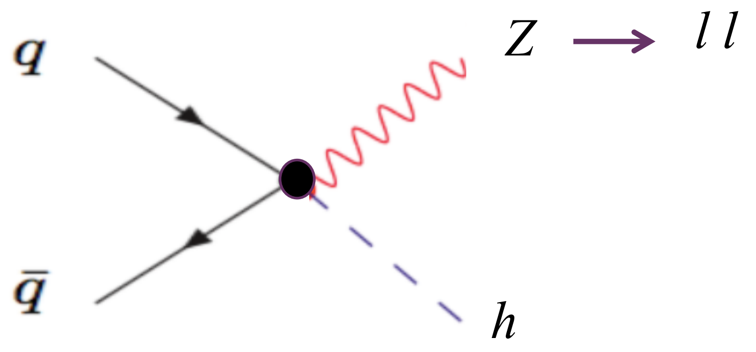
+ Zh production at LHC



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

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

Search Strategy



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

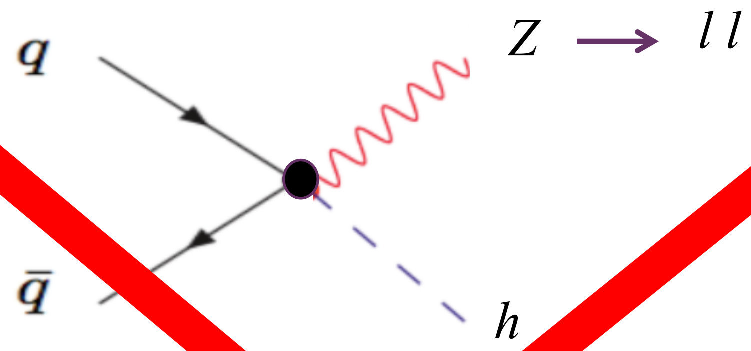
Cross Section: 5.6 fb

$$pp \to Z(ll)h(\gamma\gamma)$$

Less than 4 SM events at 300 ifb

BSM (EFT) events can only be a fraction of this

Search Strategy



$$p_T^{l_1} + p_T^{l_2} > \text{[illegible] GeV}$$

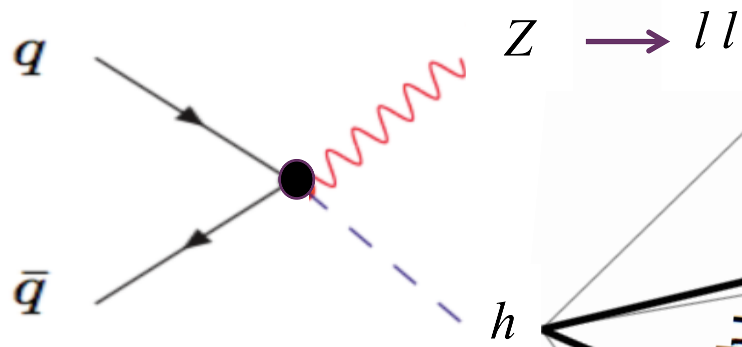
Cross Section: 5.6 [illegible]

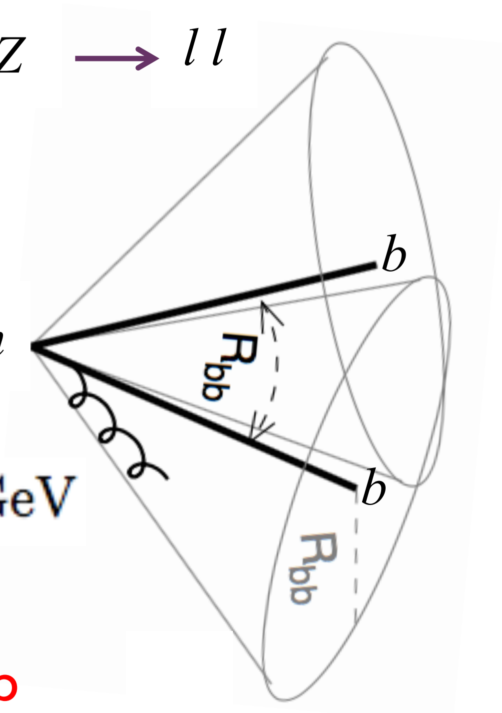
$$pp \to Z(ll)h(\gamma\gamma)$$

Less than 4 SM events at 300 ifb

BSM (EFT) events can only be a fraction of this

Search Strategy





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

$$\downarrow$$

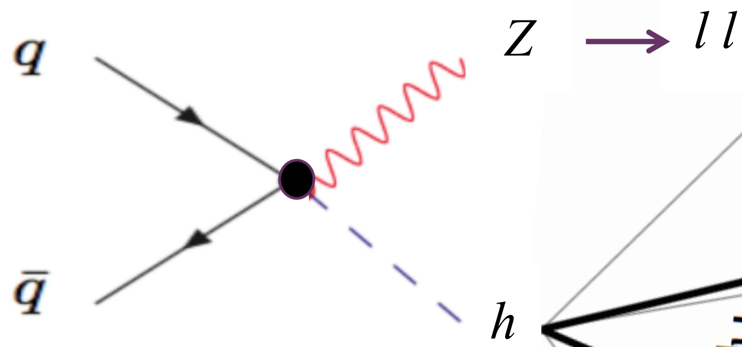
$$pp \to Z(ll)h(bb)$$

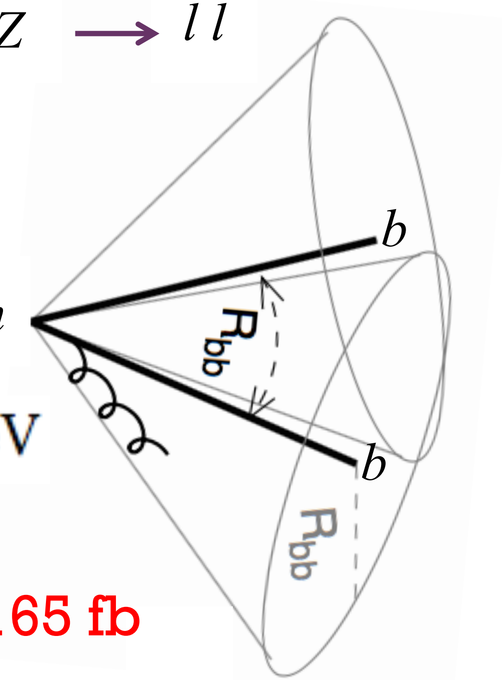
Cross Section: 4.6 fb

Much larger rate than diphoton channel

But 40 times larger Zbb background= 165 fb

Search Strategy





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

↓

Zh (bb) =4.6 fb   Zbb= 165 fb

↙ ↘

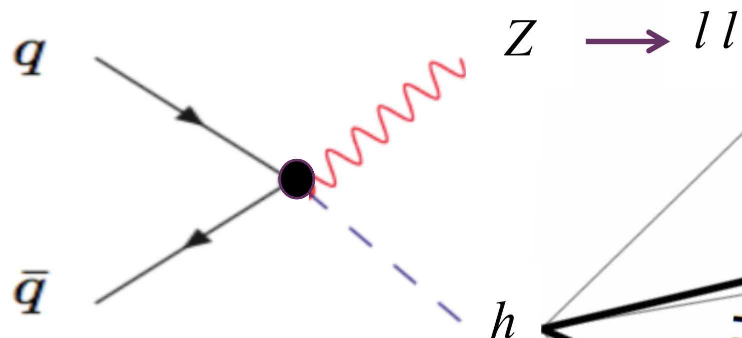
BDT optimisation | Cut-based Analysis

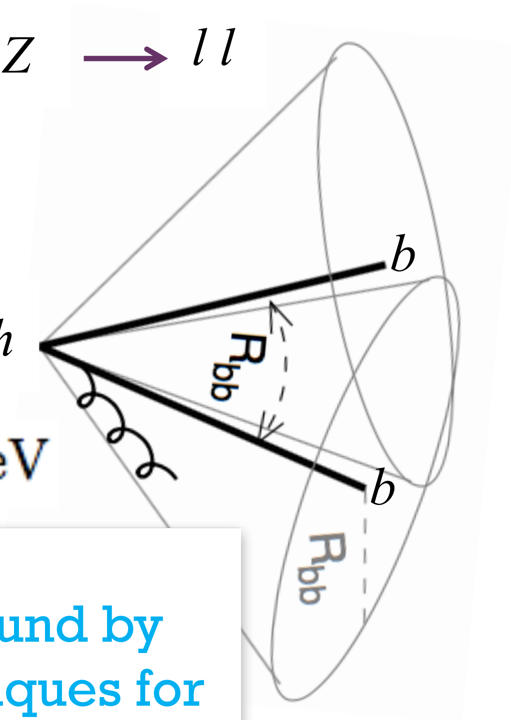
↓ ↓

Zh (bb) =0.12 fb   Zbb= 0.22 fb

Zh (bb) =0.11 fb   Zbb= 0.35 fb

Search Strategy





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

Zh (b

Remove Background by using subjet techniques for boosted Higgs (BDRS)

BDT optimisation

Cut-based Analysis

Zh (bb) =0.12 fb   Zbb= 0.22 fb

Zh (bb) =0.11 fb   Zbb= 0.35 fb

Butterworth et al, arXiv:0802.2470

For both cut based and BDT analyses:

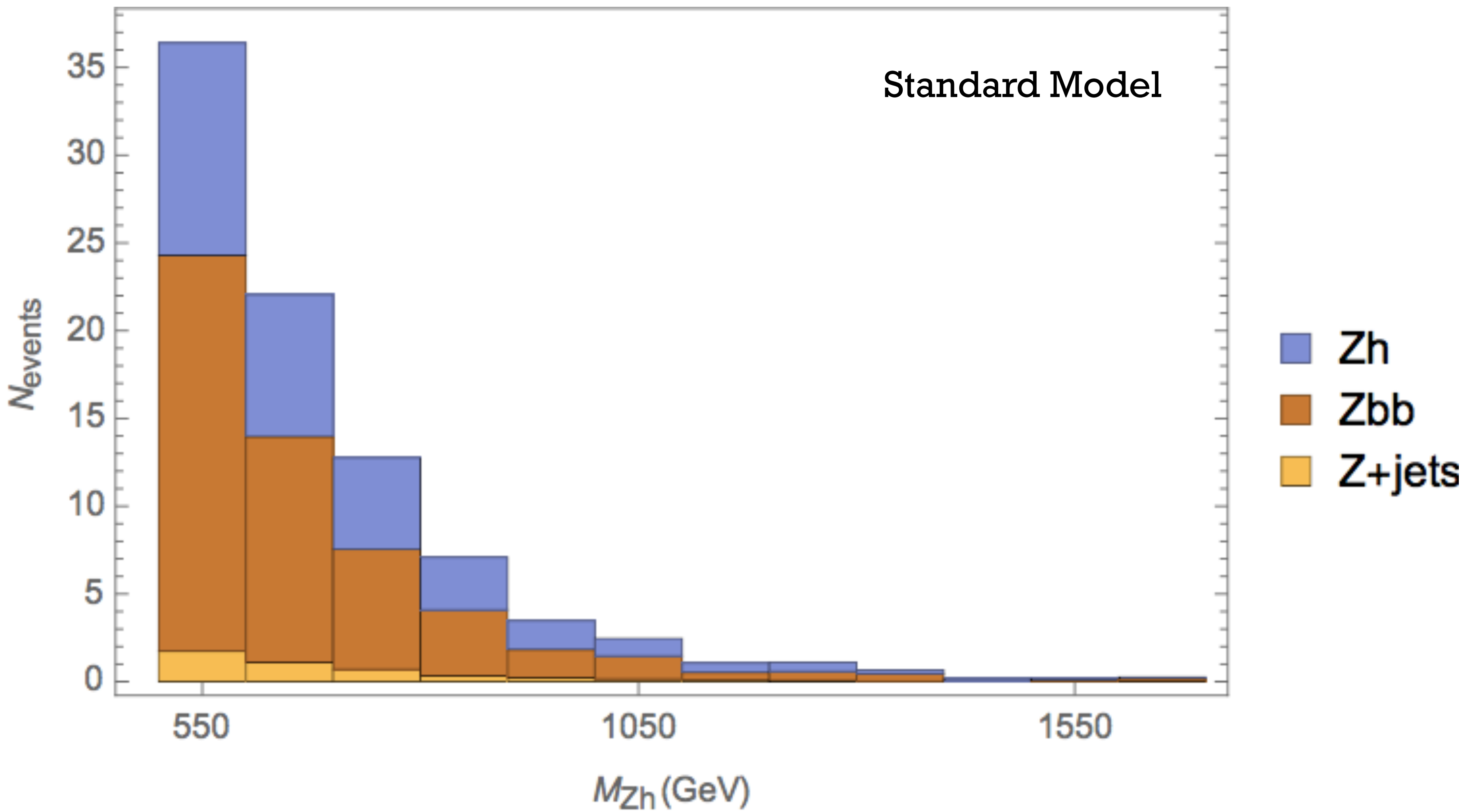
1. About 35 SM Zh(bb) events left at 300 ifb.

2. Zh(bb)/Zbb increases from 1/40 to an O(1) number.

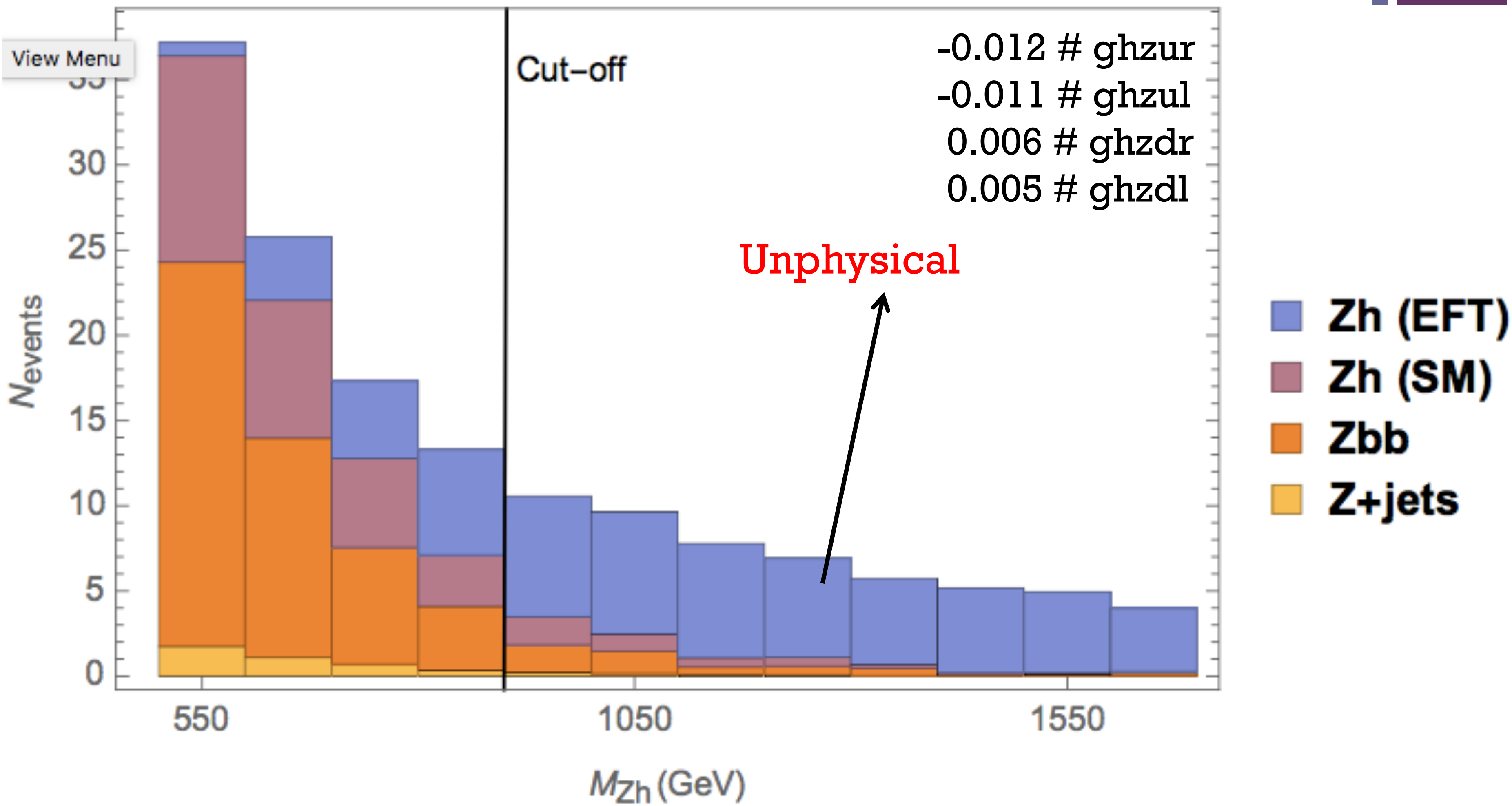
HIGH LUMINOSITIES ESSENTIAL !

SM background vs EFT Signal

To discriminate between SM and EFT we look at Zh invariant mass distribution (300 ifb):



+ SM background vs EFT Signal



+

Cross section deviations and EFT Validity

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

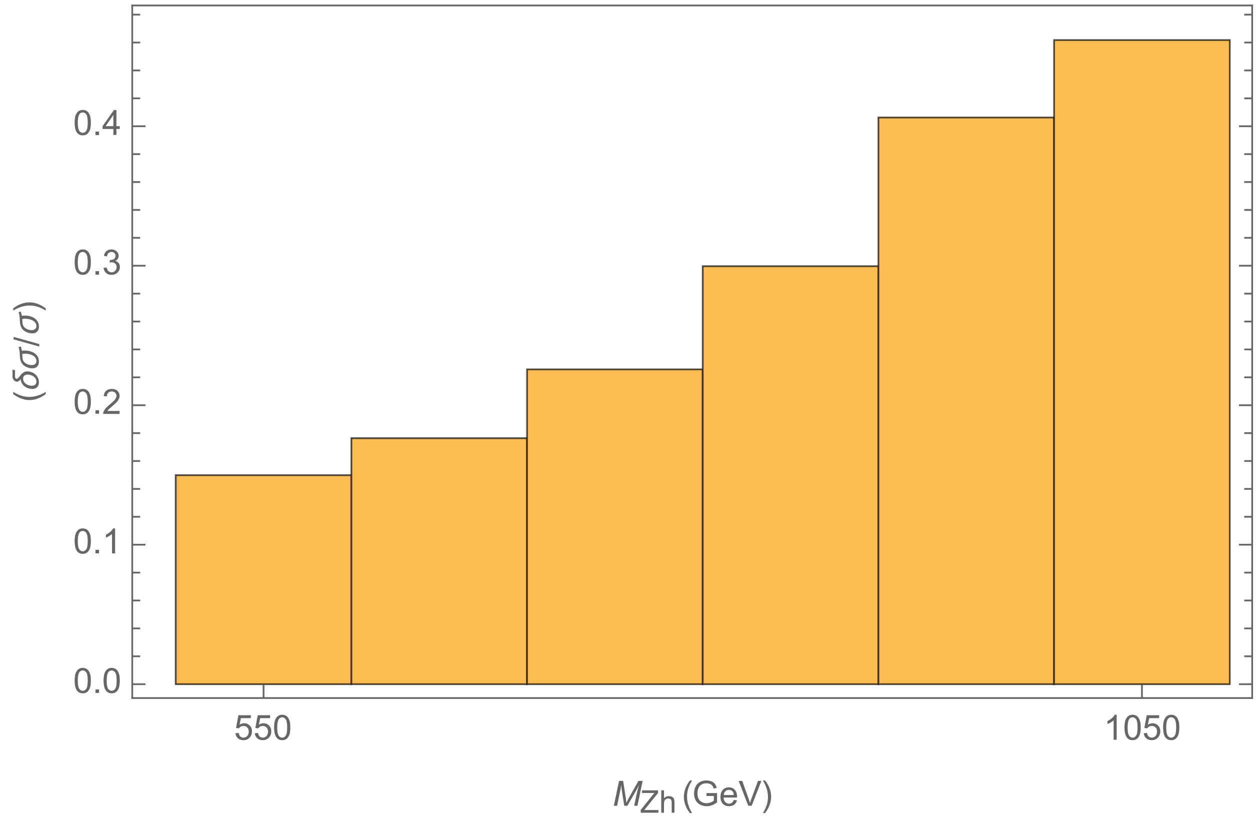
$$c_i \frac{\hat{s}}{\Lambda^2}$$

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

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

Sensitivity

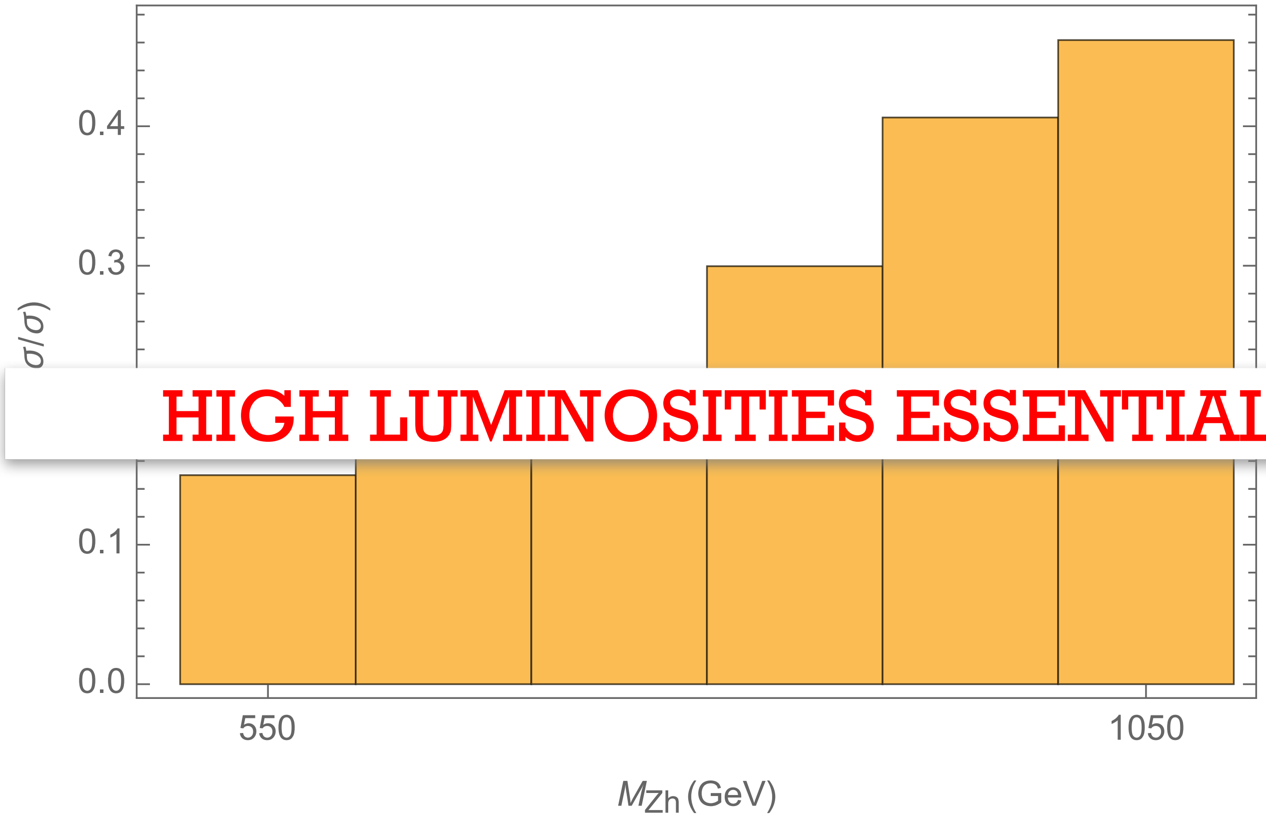
We can find the sensitivity to % cross-section deviation given the SM background assuming 5% syst. uncertainity (300 ifb):



Sensitive to 20-40 % cross-section deviations

Sensitivity

We can find the sensitivity to % cross-section deviation given the SM background assuming 5% syst. uncertainity (300 ifb):



HIGH LUMINOSITIES ESSENTIAL !

Sensitive to 20-40 % cross-section deviations

- We will present final projections together with WZ projections.

Diboson production at LHC

Four channels:

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

$$\Phi = \begin{pmatrix} G^+ \\ \frac{(v+H)+iG^0}{\sqrt{2}} \end{pmatrix}$$

- These different final states are connected by more than nomenclature.
- At high energies longitudinal W/Z production dominates.
- Using goldstone boson equivalence theorem one can compute amplitudes for various components of Higgs doublet in the unbroken phase.
- Full SU(2) symmetry manifest

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

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

Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}a_q^{(3)}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f

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

Franceschini, Panico,Pomarol, Riva & Wulzer
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Diboson production at LHC

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- WW $\longrightarrow$ G^+ G^-
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Amplitude	High-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\boxed{\frac{g^h_{Zd_Ld_L} - g^h_{Zu_Lu_L}}{\sqrt{2}}}$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$\boxed{g^h_{Zd_Ld_L}}$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$\boxed{g^h_{Zu_Lu_L}}$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	$\boxed{g^h_{Zf_Rf_R}}$

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

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Diboson production at LHC

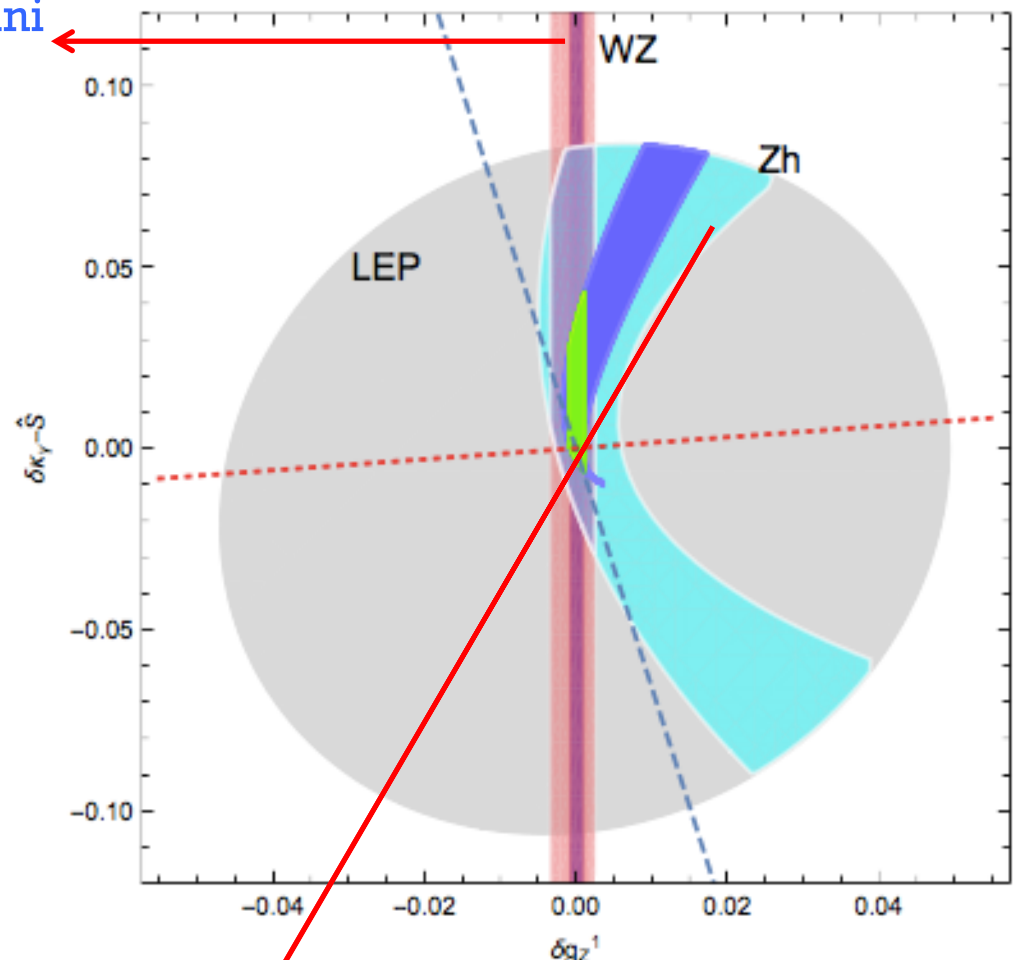
Four channels:

- ZH ⟶ G^0 H
- WH ⟶ G^+H
- WW ⟶ G^+ G^-
- WZ ⟶ G^+G^0

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

Light (Dark) Blue: 300 (3000) ifb

Franceschini et al



Banerjee, Englert, RSG and Spannowsky

+ LHC Projectiion vs existing LEP bound

	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

300 ifb (3000 ifb)

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

LHC Projectiion vs existing LEP bound

	Our Projection	LEP Bound
$\delta g^Z_{u_L}$	$\pm 0.002\ (\pm 0.0007)$	-0.0026 ± 0.0016
$\delta g^Z_{d_L}$	$\pm 0.003\ (\pm 0.001)$	0.0023 ± 0.001
$\hat{S}$	$\pm 0.032\ (\pm 0.009)$	0.0004 ± 0.0007
W	$\pm 0.003\ (\pm 0.001)$	0.0000 ± 0.0006
Y	$\pm 0.032\ (\pm 0.009)$	0.0003 ± 0.0006

- Improvement over LEP possible for Z-quark couplings and TGCs

300 ifb (3000 ifb)

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

Conclusions

- Can LHC compete with LEP ? Can LHC searches give us new information that LEP does not provide ?
- EFT techniques show that many anomalous Higgs interactions were already probed by LEP.
- Only way to compete with LEP precision is by going to higher energies and luminosities.
- Zh production promising example channel. We perform collider analysis for Z(ll)H(bb) final state using subjet techniques. Order of Magnitude improvement over LEP.
- Both High energies and luminosities essential

+ Cut-flow

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

Zh (bb) =4.6 fb Zbb= 165 fb

R=1.2

Cuts	Zbb	Zh (SM)
1. At least 1 fat jet with 2 B-mesons with pT > 15 GeV	0.157	0.411
2. 2 OSSF isolated leptons	0.407	0.501
3. 80 GeV < M_l1l2 < 100 GeV, pT_l1l2 > 160 GeV, dR_l1l2 > 0.2	0.846	0.887
4. At least 1 fat jet, at least 1 fat jet with 2 B-meson tracks with pT > 110 GeV	0.952	0.980
5. 2 Mass drop subjets and >= 2 filtered subjets	0.857	0.923
6. Exactly 2 b-tagged jets	0.383	0.409
7. 115 GeV < M_fatjet < 135 GeV	0.254	0.505
8. Delta R(l_i, b_j) > 0.4, MET < 30 GeV, lY_fatjetl < 2.5, pT_fatjet > 200 GeV and pT_l1l2 > 200 GeV	0.490	0.693
Total	0.002	0.024

Butterworth et al, arXiv:0802.2470

Zh (bb) =0.11 fb

Zbb= 0.35 fb

Cut-flow

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

Zh (bb) =4.6 fb   Zbb= 165 fb

R=1.2

Cuts	Zbb	Zh (SM)
1. At least 1 fat jet with 2 B-mesons with pT > 15 GeV	**0.157**	**0.411**
2. 2 OSSF isolated leptons	0.407	0.501
3. Combined (please see last mail)	0.145	0.217
4. BDT cut	0.148	0.593
Total	0.0014	0.026

Zh (bb) =0.12 fb

Zbb= 0.22 fb

+ Anomalous Higgs interactions not constrained by LEP

$$\mathcal{L}_h^{\text{primary}} = g_{VV}^h \, h \left[W^{+\,\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu \right] + g_{3h} \, h^3 + g_{ff}^h \, \left(h \bar{f}_L f_R + h.c. \right)$$
$$+ \kappa_{GG} \, \frac{h}{v} G^{A\,\mu\nu} G_{\mu\nu}^A + \kappa_{\gamma\gamma} \, \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} t_{\theta_W} \, \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} \, ,$$

$$\Delta\mathcal{L}_h = \delta g_{ZZ}^h \, \frac{v}{2c_{\theta_W}^2} h Z^\mu Z_\mu + g_{Zff}^h \, \frac{h}{2v} \left(Z_\mu J_N^\mu + h.c. \right) + g_{Wff'}^h \, \frac{h}{v} \left(W_\mu^+ J_C^\mu + h.c. \right)$$
$$+ \kappa_{WW} \, \frac{h}{v} W^{+\,\mu\nu} W_{\mu\nu}^- + \kappa_{ZZ} \, \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu} \, ,$$

+ Anomalous Higgs interactions not constrained by LEP

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$$+ \quad \kappa_{GG}\,\frac{h}{v}G^{A\,\mu\nu}G_{\mu\nu}^A + \kappa_{\gamma\gamma}\,\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\,\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,$$

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$$+ \quad \kappa_{WW}\,\frac{h}{v}W^{+\mu\nu}W_{\mu\nu}^- + \kappa_{ZZ}\,\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,$$

Anomalous Higgs interactions already constrained by LEP

$$\begin{aligned}\mathcal{L}_h^{\text{primary}} &= g_{VV}^h\, h \left[W^{+\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g_{ff}^h\, \left(h \bar{f}_L f_R + h.c.\right) \\ &+ \kappa_{GG}\, \frac{h}{v} G^{A\,\mu\nu} G_{\mu\nu}^A + \kappa_{\gamma\gamma}\, \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} t_{\theta_W} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}\,,\end{aligned}$$

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Anomalous Higgs interactions already constrained by LEP

$$\begin{aligned}\mathcal{L}_h^{\text{primary}} &= g^h_{VV}\, h\left[W^{+\,\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g^h_{ff}\, \left(h\bar{f}_L f_R + h.c.\right) \\ &+ \kappa_{GG}\, \frac{h}{v} G^{A\,\mu\nu} G^A_{\mu\nu} + \kappa_{\gamma\gamma}\, \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} t_{\theta_W} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}\,,\end{aligned}$$

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+ Anomalous Higgs interactions not constrained by LEP

$$\Delta\mathcal{L}_{h^2SM} = c_V g^2 \hat{h}^4 (W^2 + Z^2/2c_{\theta_W}^2) + c_6 \hat{h}^6 + \frac{\hat{h}^2}{\Lambda^2}\left[c_{WW} g^2 W^a_{\mu\nu} W^{\mu\nu\, a} + c_{BB} g'^2 B_{\mu\nu} B^{\mu\nu}\right]$$
$$+ \; c_{y_f} y_f (\hat{h}^3 \bar{f}_L f_R + h.c)\,,$$

$$\hat{h} = v + h$$

$$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

$$|H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$H^\dagger H \mathcal{O}_{SM} \longrightarrow |H|^2 W^a_{\mu\nu} W^{\mu\nu\, a} \longrightarrow e(\hat{h}),\ s_{\theta_W}(\hat{h}),\ g_s(\hat{h}),\ \lambda_h(\hat{h}),\ Z_h(\hat{h})$$

$$Y_f(\hat{h})$$

8 operators

$$|H|^2 |D_\mu H|^2$$

$$|H|^6$$

$$|H|^2 \bar{f}_L H f_R + h.c.$$

Redefining 8 parameters in the vacuum

EW and Higgs Pseudo-observables

(1) Higgs observables (20):

$hW^+_{\mu\nu}\, W^{-\mu\nu}$ $hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $h^2\bar{f}f\ \ hZ_{\mu\nu}\ Z^{\mu\nu}$

$hW^{+\mu}W^-_\mu,\ h\bar{f}f,\ h^3$ $hZ_\mu\bar{f}_{L,R}\gamma^\mu f_{L,R}$

These contain the physical Higgs probed for the first time at LHC in Higgs Production/decay

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$hW^{+}_{\mu\nu}\, W^{-\mu\nu}$ $\quad hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $\quad h^2\bar{f}f\ \ hZ_{\mu\nu}\, Z^{\mu\nu}$

$hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$ $\quad hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$

These contain the physical Higgs probed for the first time at LHC in Higgs Production/decay

(2) Electorweak precision observables (9):

$Z_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$ $\quad W^{+\mu}\bar{u}_L\gamma_{\mu}d_L$

These were measured very precisely at the W/Z-pole in W/Z decays.

EW and Higgs Pseudo-observables

(1) Higgs observables (20):

$hW^+_{\mu\nu}\, W^{-\mu\nu}$ $\quad hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $\quad h^2\bar{f}f\quad hZ_{\mu\nu}\, Z^{\mu\nu}$

$hW^{+\mu}W^-_\mu,\ h\bar{f}f,\ h^3$ $\quad hZ_\mu\bar{f}_{L,R}\gamma^\mu f_{L,R}$

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$Z_\mu\bar{f}_{L,R}\gamma^\mu f_{L,R}$ $\quad W^{+\mu}\bar{u}_L\gamma_\mu d_L$

These were measured very precisely at the W/Z-pole in W/Z decays.

(2) Triple and Quartic Gauge couplings (3+4):

$g_1^Z c_{\theta_W} Z^\mu\left(W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu}\right)$ $\quad Z^\mu Z^\nu W^-_\mu W^+_\nu$

$\kappa_\gamma s_{\theta_W}\hat{A}^{\mu\nu}W^+_\mu W^-_\nu$ $\quad W^{-\mu}W^{+\nu}W^-_\mu W^+_\nu$

$\lambda_\gamma s_{\theta_W}\hat{A}^{\mu\nu}\hat{W}^{-\rho}_\mu\hat{W}^+_{\rho\nu}$

These were measured in ee->WW process at LEP.

Anomalous Higgs interactions not constrained by LEP

8 operators → 8 Higgs Primaries

$$hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$$
$$hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$$

These operators could never have been probed at LEP as they only redefine 8 parameters in dim-4 Lagrangian in the vacuum.

Constrained for the first time by LHC!