Probing Electroweak Precision Physics via Boosted Higgsstrahlung at the LHC

Rick Sandeepan Gupta (IPPP Durham)

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in collaboration with Banerjee, Englert, and Spannowsky

LEP vs LHC

- 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.

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.

Anomalous Higgs interactions at dimension-6 level

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

$$\Delta\mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} h Z^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} \left(Z_\mu J_N^\mu + h.c. \right) + g_{Wff'}^h \frac{h}{v} \left(W_\mu^+ J_C^\mu + h.c. \right)$$
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A. Pomarol (arxiv: 1412.4410)

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

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- 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

EW and Higgs Pseudo-observables

(1) Higgs observables (20):

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

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

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

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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

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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.

Organizing principle: Effective Field Theory (EFT)

- Only 18 independent operators generate above vertices:

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$

$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$

Correlations between observables

18 Operators

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$
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$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
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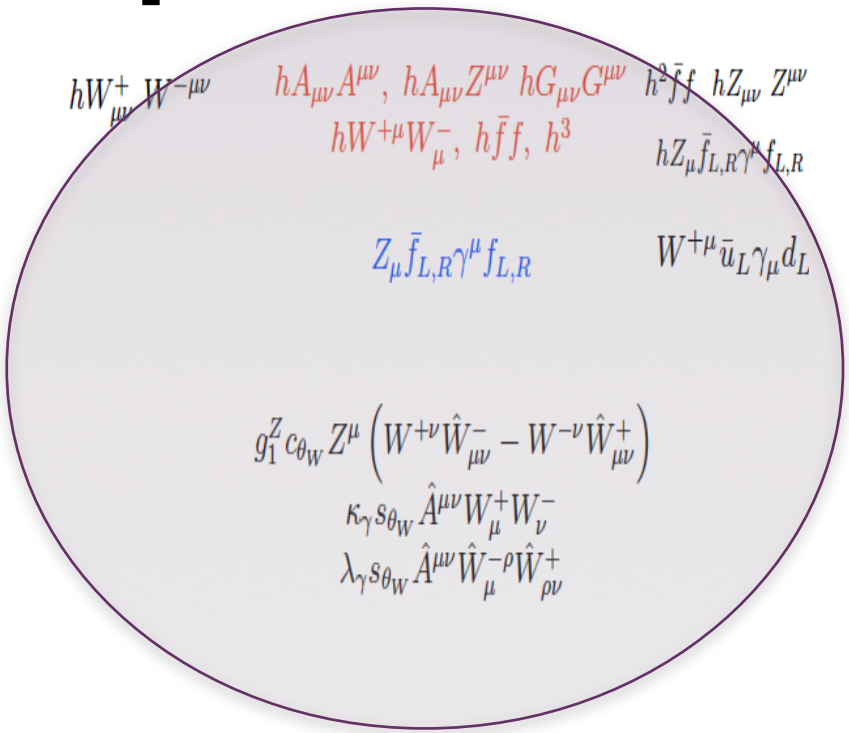
Many Vertices /pseudo-observables



# of contributing operators << # of vertices/pseudo-observables

18 EW and Higgs Operators

18 Operators

Many Vertices/pseudo-observables

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$

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$\mathcal{O}_6 = \lambda |H|^6$

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right)$

$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\mu$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$

$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$

$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$

$\mathcal{O}_L^{(3)q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$

$h^2 \bar{f} f \quad h Z_{\mu\nu} Z^{\mu\nu}$

$h Z_\mu \bar{f}_{L,R} \gamma^\mu f_{L,R}$

$W^{+\mu} \bar{u}_L \gamma_\mu d_L$

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

↓

Correlations between different vertices/observables

Anomalous Higgs interactions not constrained by LEP

8 operators cannot be constrained by LEP at all !

$\hat{h} = v + h$

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

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

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

$Y_f(\hat{h})$

8 operators

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

Redefining 8 parameters in the vacuum

$|H|^6$

$|H|^2 f_L H f_R + h.c.$

+ Anomalous Higgs interactions not constrained by LEP

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

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

Anomalous Higgs interactions
already constrained by LEP

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Anomalous Higgs interactions already constrained by LEP

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

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

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

$$g^h_{Wff'} = 2\delta g^W_{ff'} - 2\delta g^Z_1 g^W_f c^2_{\theta_W}\,,$$

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

$$\kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

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

Anomalous Higgs interactions already constrained by LEP

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

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

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

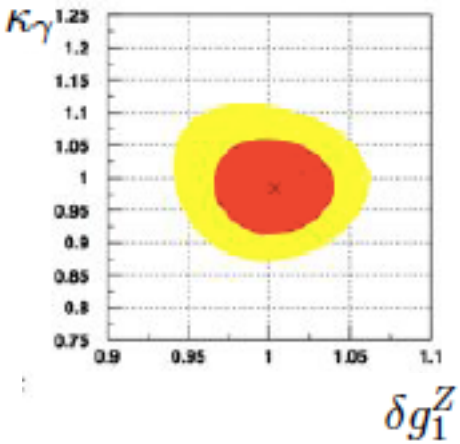
RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

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

(1)h not part of a doublet.

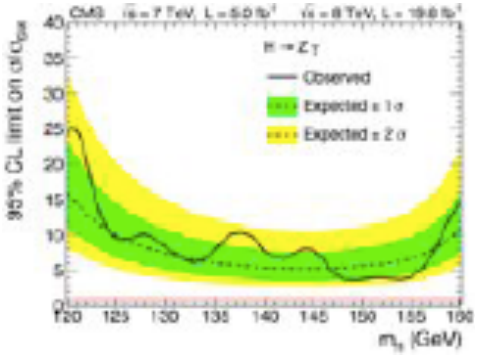
(2) Scale of new physics not very high and dimension 8 operators cannot be ignored

Example: *h* ->*Zff*

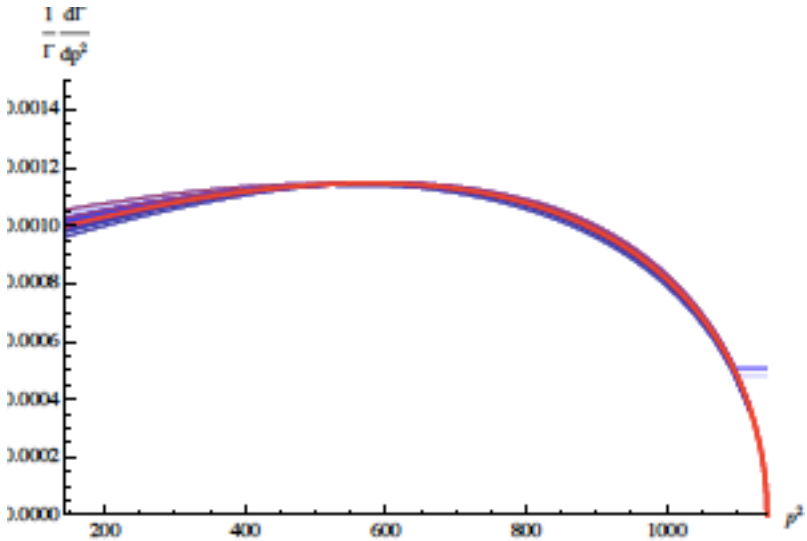


+

$h \to \gamma Z$



Already constrained !



Slide Courtesy: F. Riva

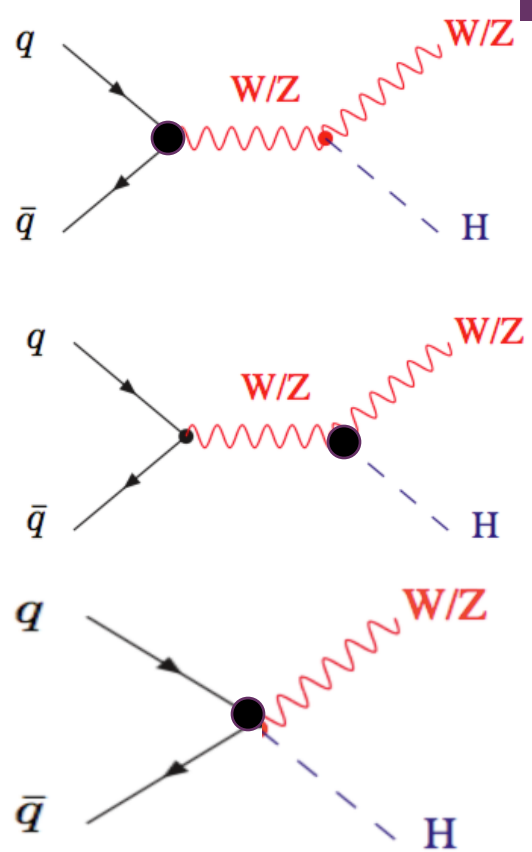
- Only way to compete with LEP is to go to high energies.

- 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 (work in progress)

Zh production at LHC

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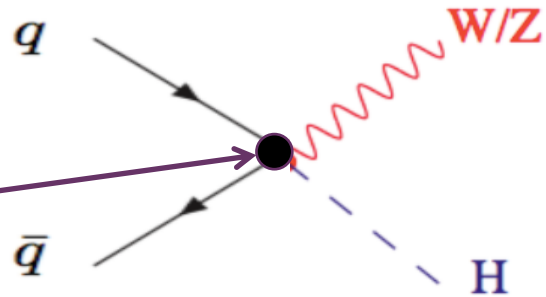
$$



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

Zh production at LHC

- The following vertices in the unitary gauge contribute:

$$\Delta\mathcal{L}_6 \supset \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$
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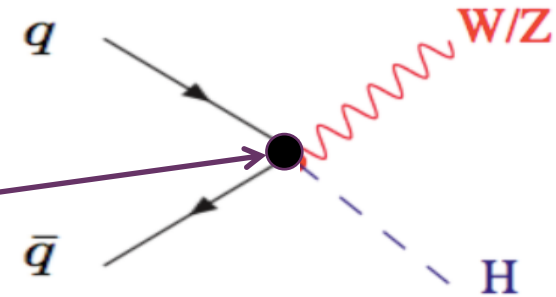
$$+ \sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{Wud}^h \frac{h}{v} (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$



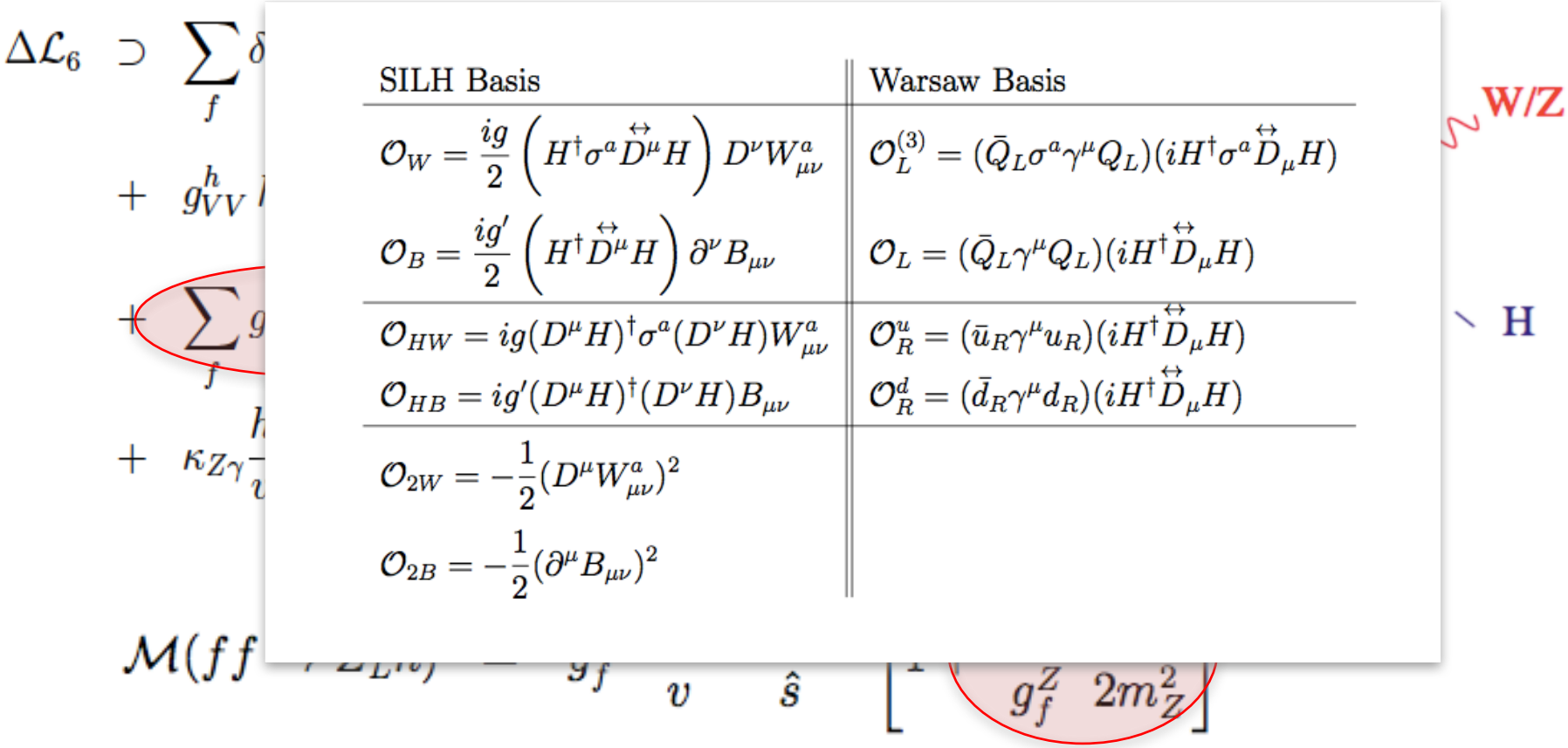
Leading effect from contact interaction at high energies.
Energy growth as there is no propagator.

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

Zh production at LHC

- The following vertices in the unitary gauge contribute:

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.

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

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

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

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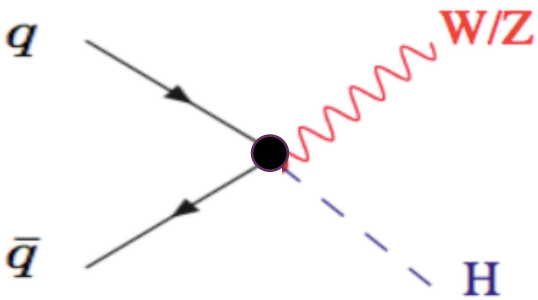
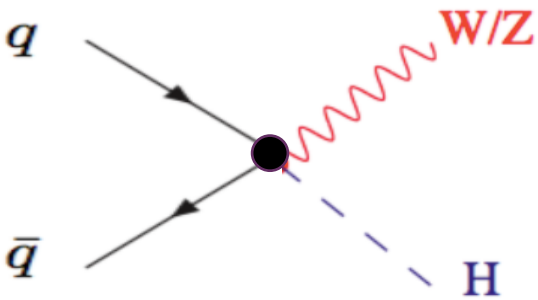


WARSAW BASIS

Zh production: High energy primaries

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

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= 2\delta g^Z_{Zu_Lu_L} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zd_Ld_L} &= 2\delta g^Z_{Zd_Ld_L} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zu_Ru_R} &= 2\delta g^Z_{Zu_Ru_R} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{Zd_Rd_R} &= 2\delta g^Z_{Zd_Rd_R} - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c^2_{\theta_W}}
\end{aligned}
$$



CORRELATIONS (BSM PRIMARIES)

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

Zh production: High energy primaries

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

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= \frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right) \\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right) \\
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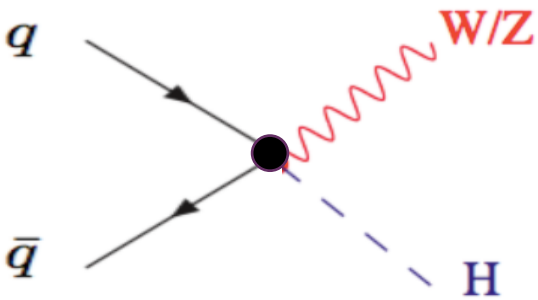
\end{aligned}
$$



SILH BASIS (UNIVERSAL MODELS)

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$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}+\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W + \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zd_Ld_L} &= \frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}-\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W - \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
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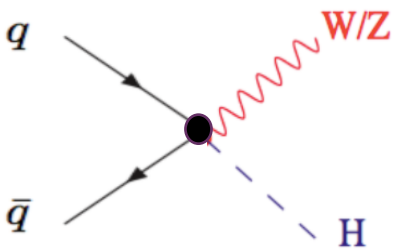
\end{aligned}
$$



CORRELATIONS (UNIVERSAL MODELS)

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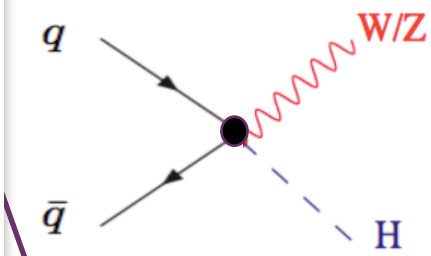
\end{aligned}
$$



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

CORRELATIONS (UNIVERSAL MODELS)

Zh production: LHC vs LEP

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

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

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

- 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

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

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

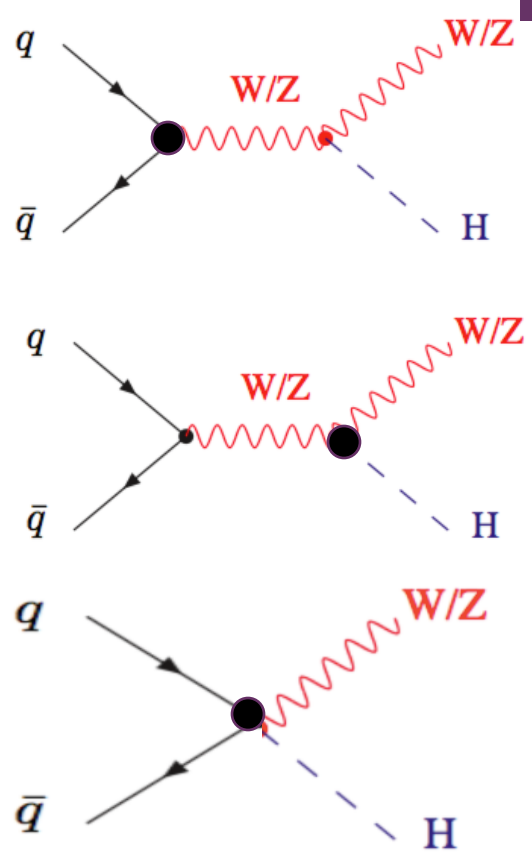
$$c_i \frac{\hat{s}}{\Lambda^2}$$

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

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

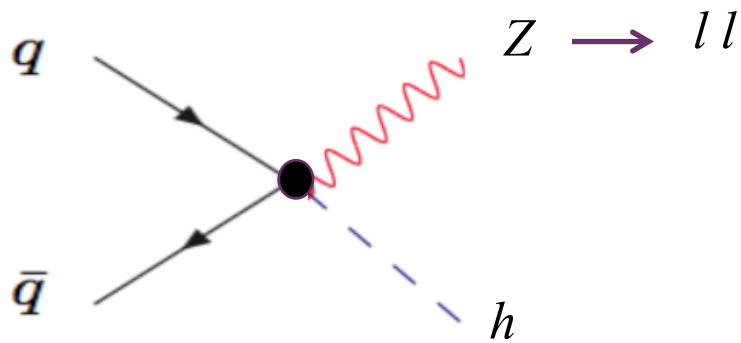
Zh production at LHC

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



Banerjee, Englert, RSG and Spannowsky
(work in progress)

Search Strategy



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

↓

Cross Section: 5.6 fb

↓

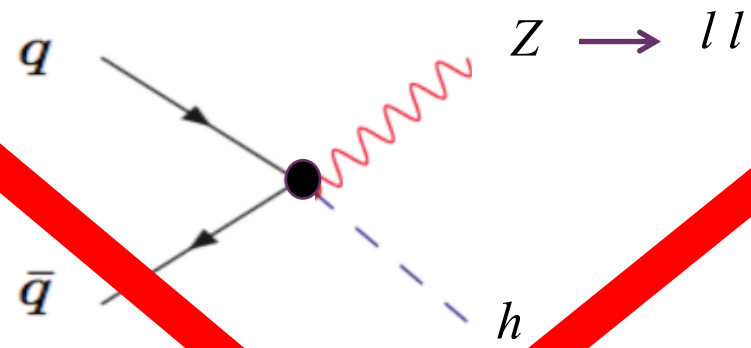
$$pp \to Z(ll)h(\gamma\gamma)$$

↓

Less than 4 SM events at 300 ifb

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

Search Strategy



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

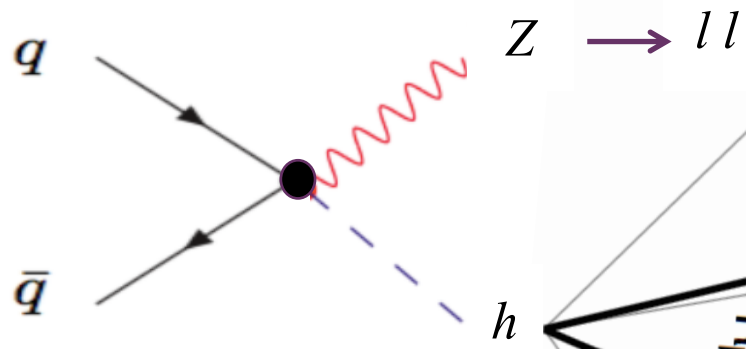
Cross Section: 5.6 [illegible]

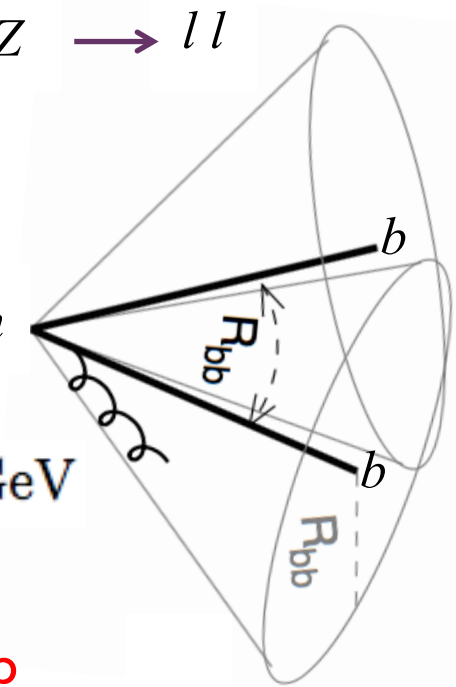
$pp \to Z(ll)h(\gamma\gamma)$

Less than 4 SM events at 300 ifb

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

Search Strategy





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

$$\downarrow$$

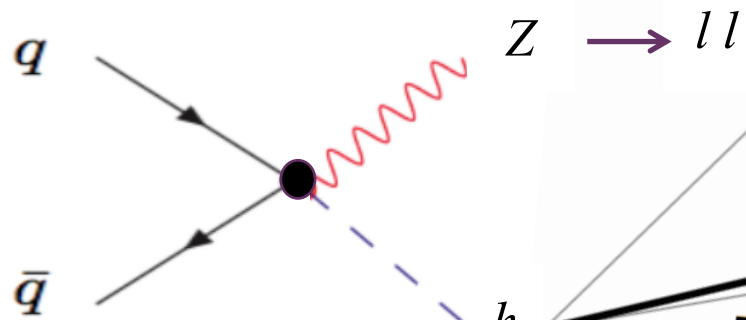
$$pp \to Z(ll)h(bb)$$

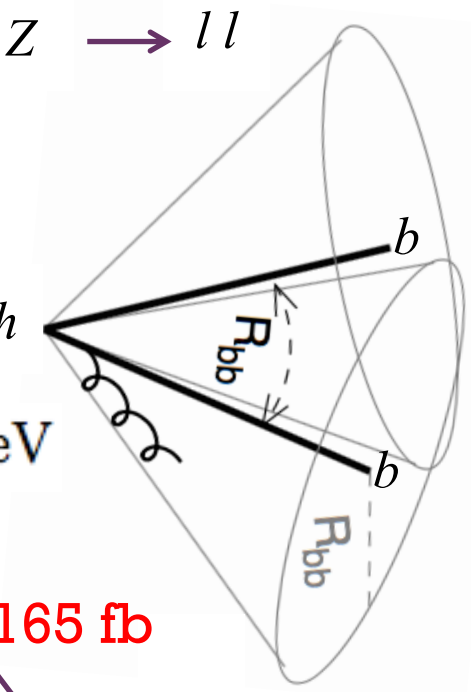
Cross Section: 4.6 fb

Much larger rate than diphoton channel

But 40 times larger Zbb background= 165 fb

Search Strategy





$p_T^{l_1} + p_T^{l_2} > 160$ 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

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) =0.12 fb

Zbb= 0.22 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) =0.11 fb

Zbb= 0.35 fb

For both cut based and BDT analyses:

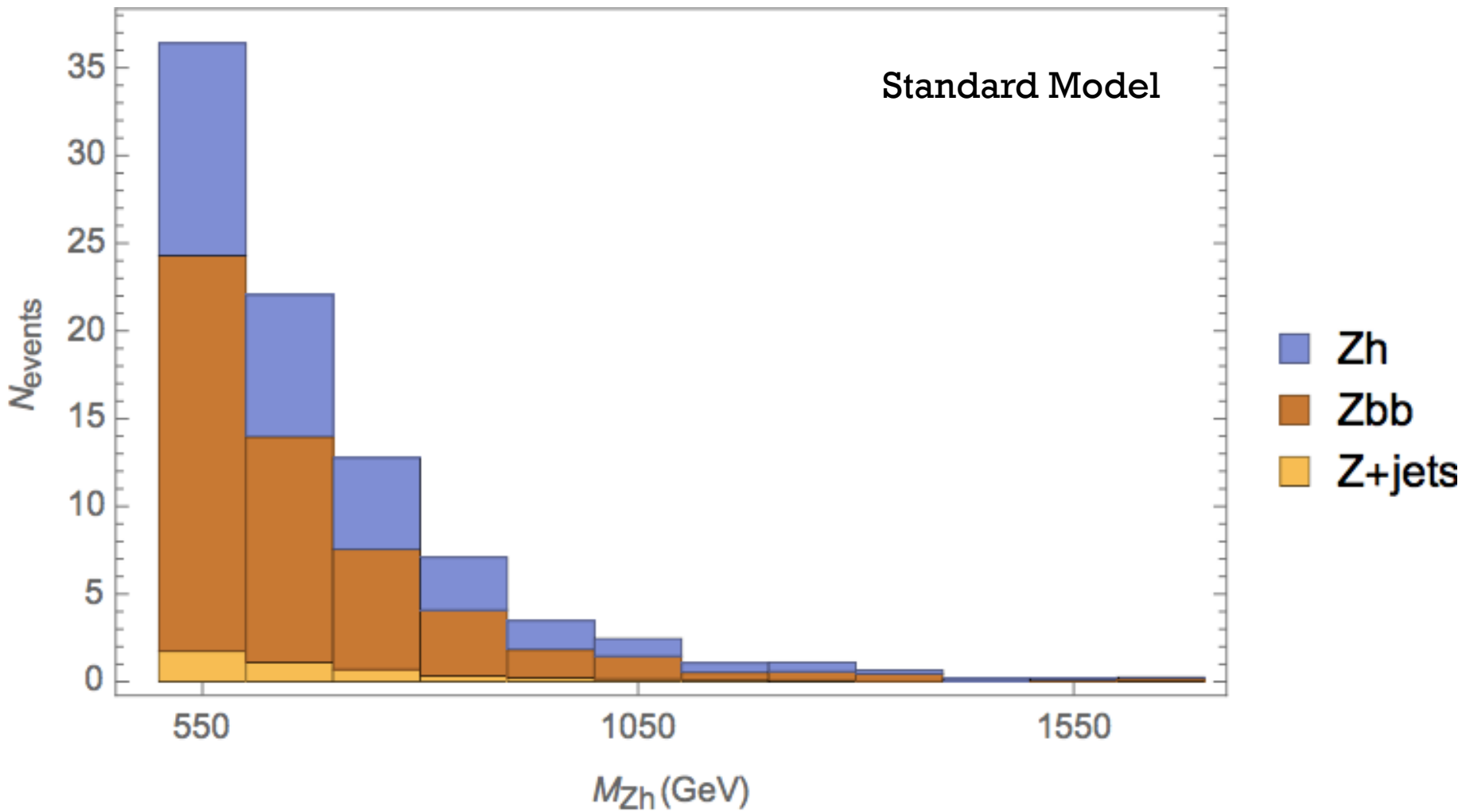
1. About 35 SM Zh(bb) events left at 300 ifb.

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

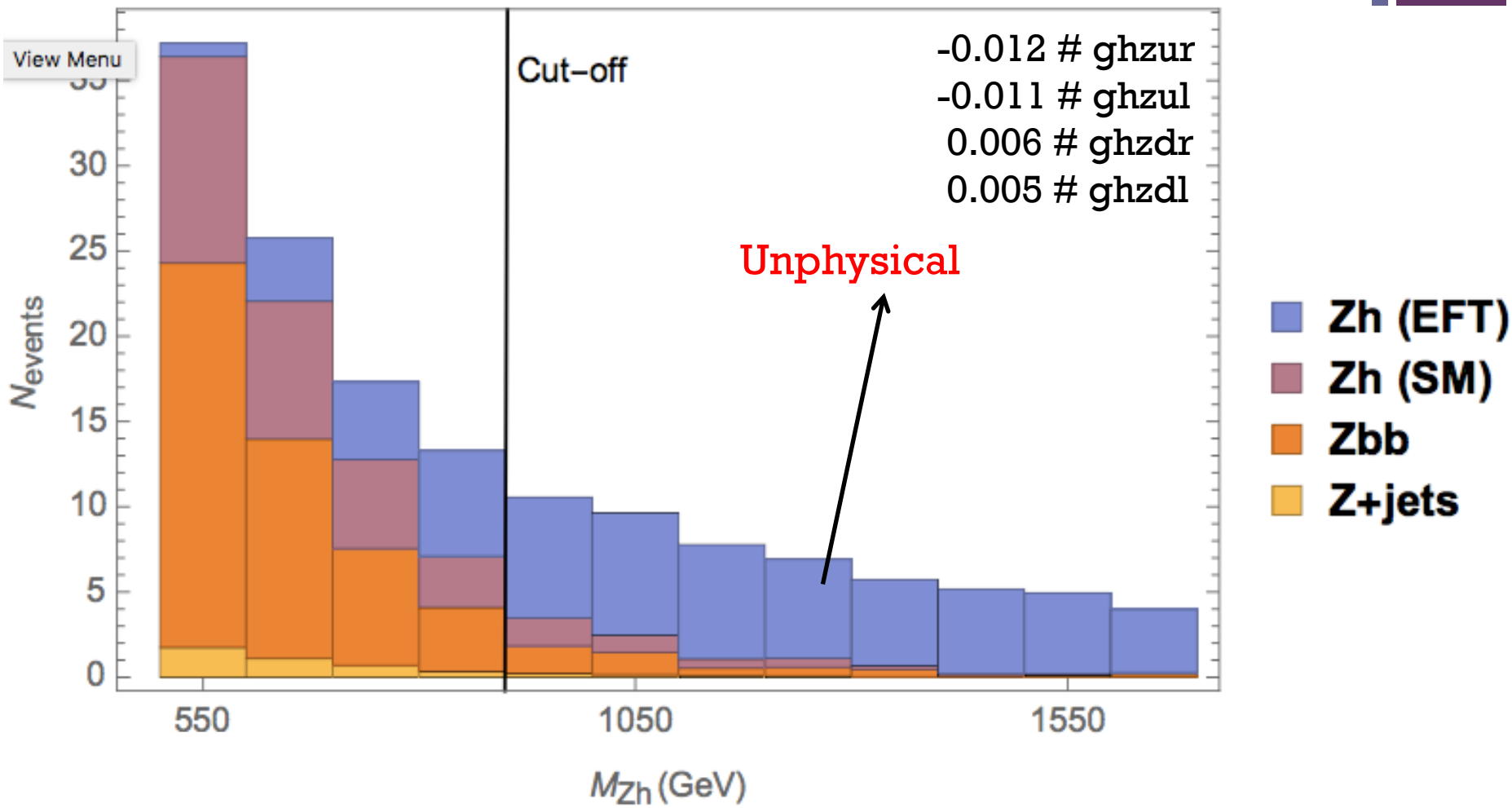
HIGH LUMINOSITIES ESSENTIAL !

SM background vs EFT Signal

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

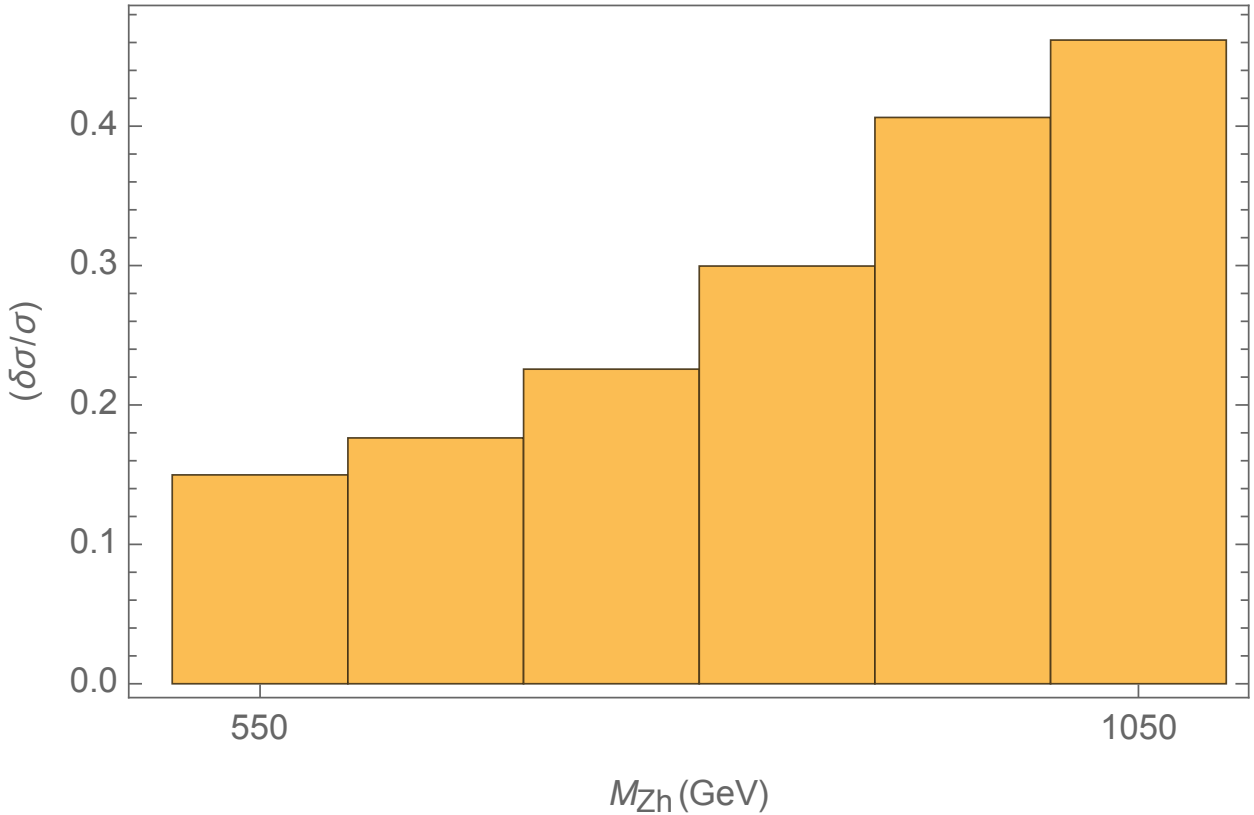


SM background vs EFT Signal



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

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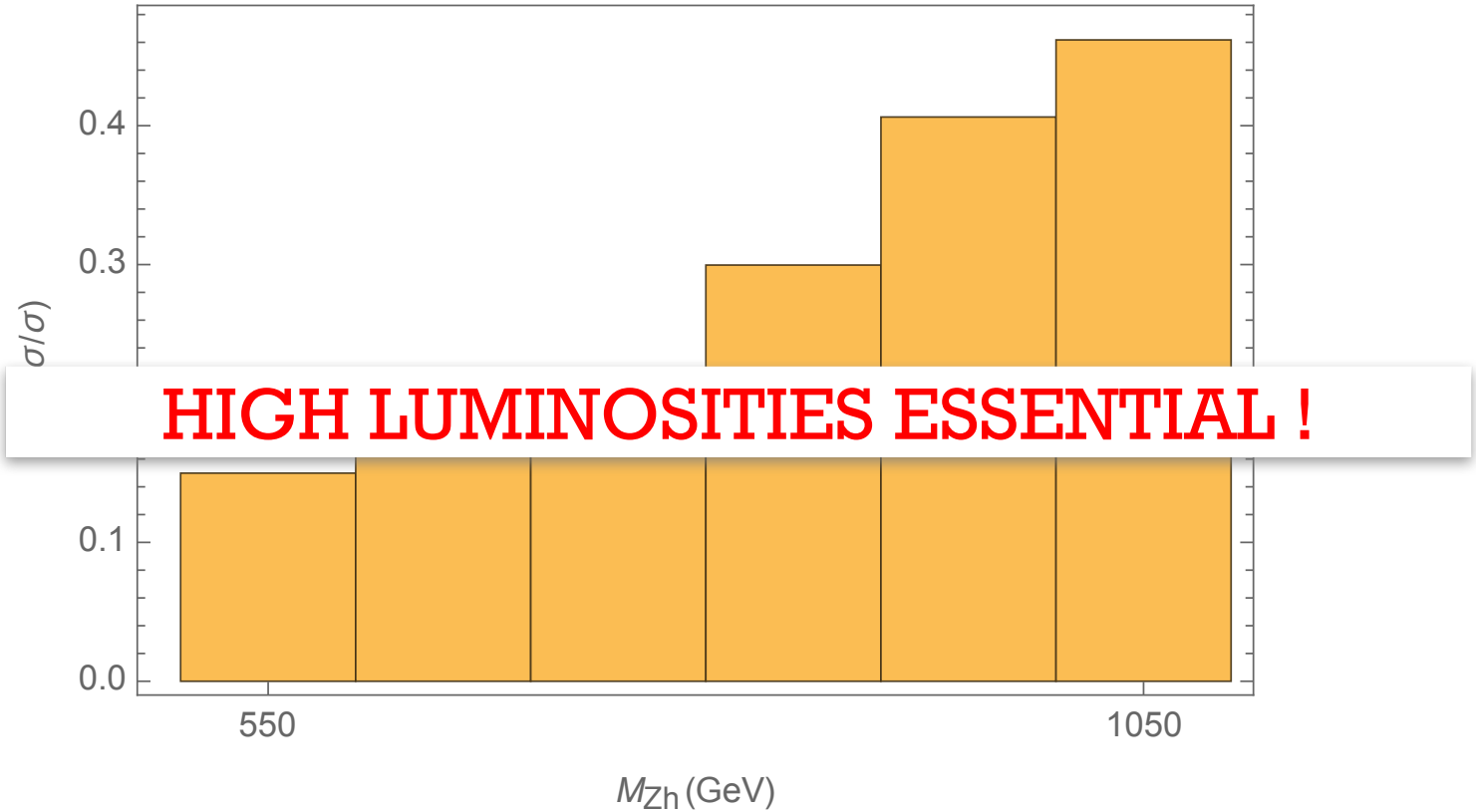

Sensitive to 20-40 % cross-section deviations

ZH production: LHC vs LEP

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Per mille- % level constraint possible ?

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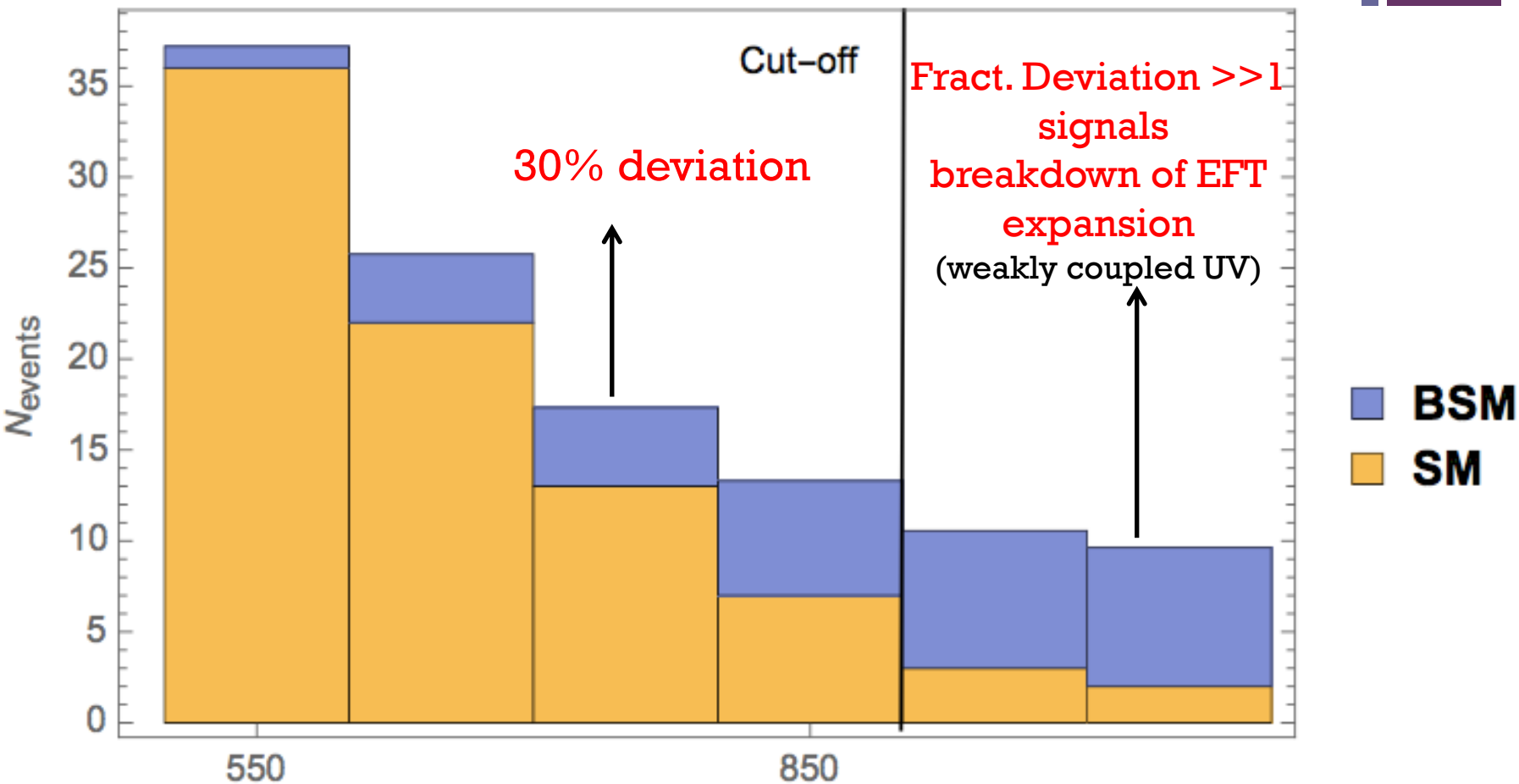
EFT Signal



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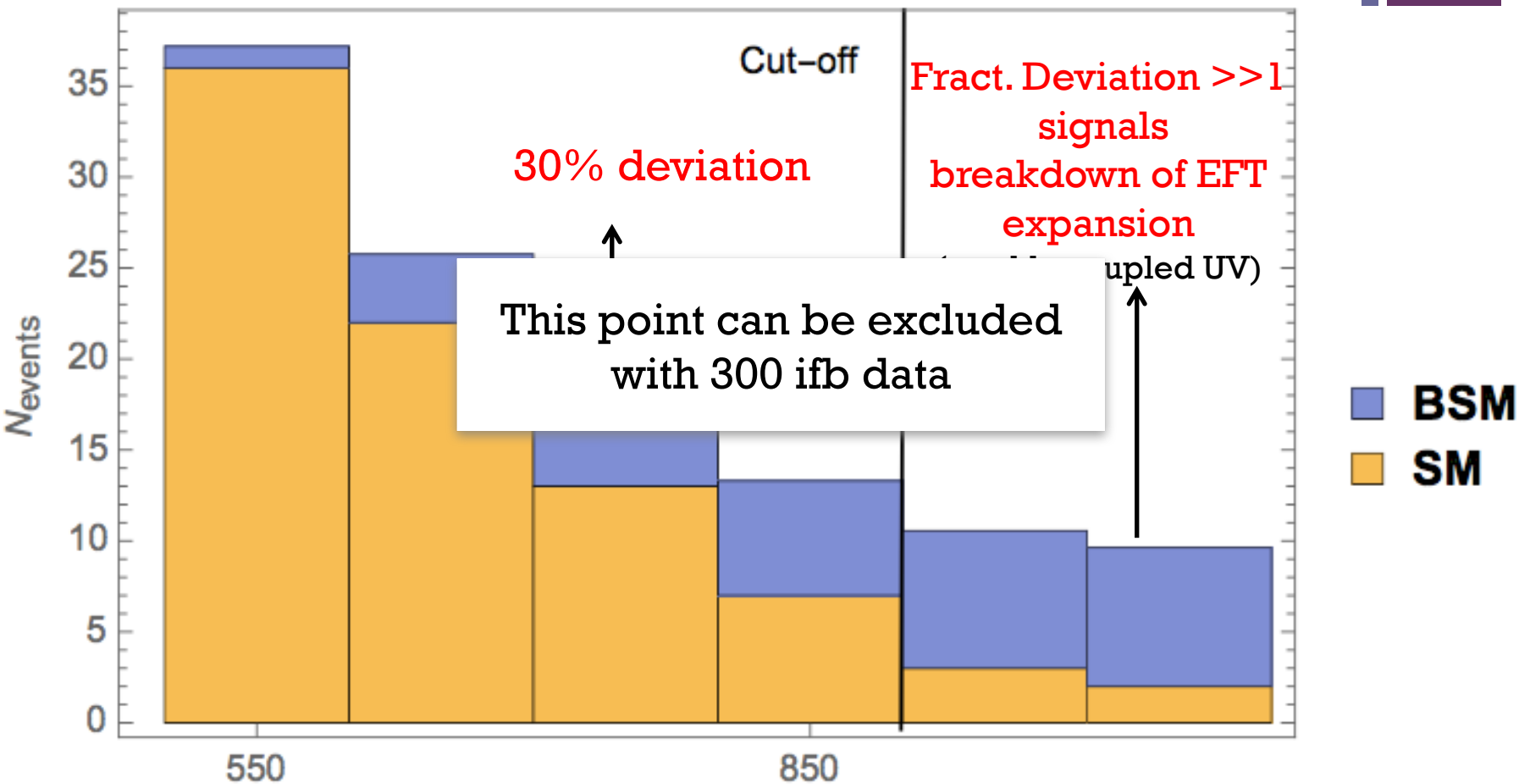
EFT Signal



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

- 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
arxiv:1712.01310

Diboson production at LHC

Four channels:

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

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

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Franceschini, Panico,Pomarol, Riva & Wulzer
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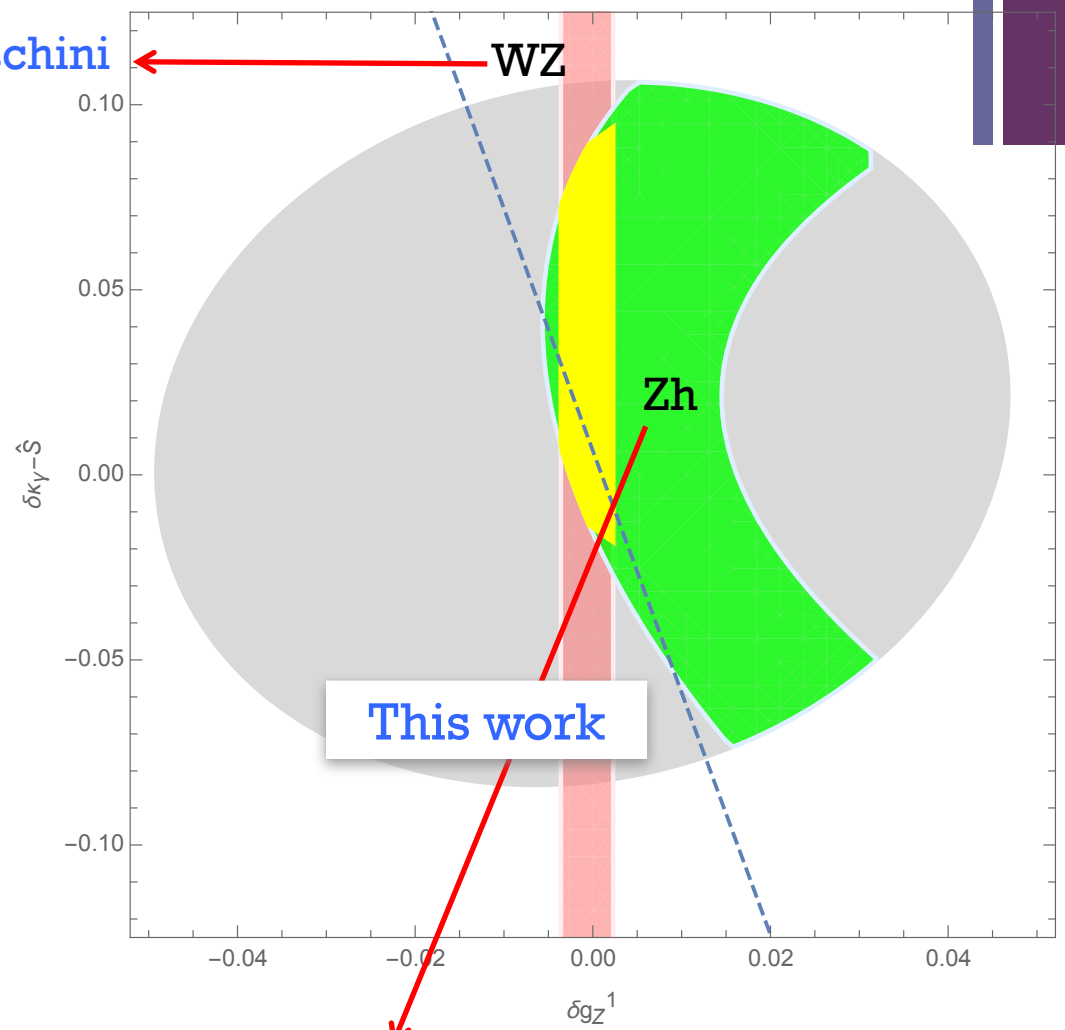
HV and *VV* processes amplitude connected by symmetry. They constrain the same set of observables at high energies

Franceschini et al



Banerjee, Englert, RSG and Spannowsky (work in progress)

Diboson production at LHC

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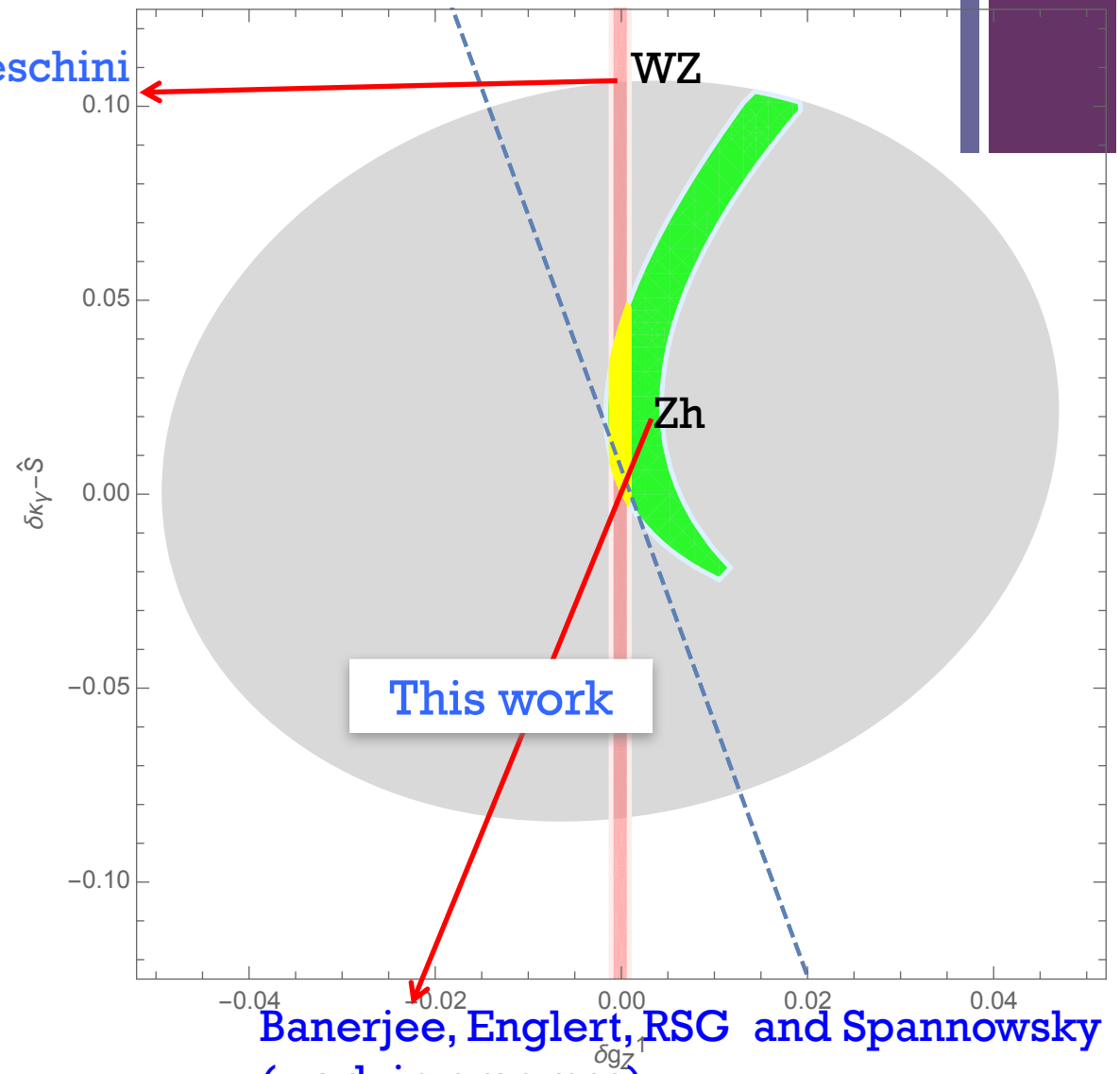
Franceschini et al



Banerjee, Englert, RSG and Spannowsky (work in progress)

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

+ Anomalous Higgs interactions not constrained by LEP

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

$$\Delta\mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} h Z^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} \left(Z_\mu J_N^\mu + h.c. \right) + g_{Wff'}^h \frac{h}{v} \left(W_\mu^+ J_C^\mu + h.c. \right)$$
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Anomalous Higgs interactions already constrained by LEP

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

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

$H^\dagger H \mathcal{O}_{SM}$ →

8 operators

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

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

$\overline{|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}}$

$\overline{|H|^2 |D_\mu H|^2}$

$\overline{|H|^6}$

$\overline{|H|^2 f_L H f_R + h.c.}$

→ $e(\hat{h}),\ s_{\theta_W}(\hat{h}),\ g_s(\hat{h}),\ \lambda_h(\hat{h}),\ Z_h(\hat{h})$

$Y_f(\hat{h})$

Redefining 8 parameters in the vacuum

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!