SMEFT at high energies

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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.

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

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

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\end{aligned}$$

- 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

+ Anomalous Higgs interactions not constrained by LEP

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Anomalous Higgs interactions already constrained by LEP

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EW and Higgs Pseudo-observables

(1) Higgs observables (20):

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

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

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

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(2) Electorweak precision observables (9):

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

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

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

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

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

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

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

Organizing principle: Effective Field Theory (EFT)

- Only 18 independent operators generate above vertices:

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

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

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

Correlations between observables

18 Operators

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Many Vertices /pseudo-observables

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

$hW^{+\mu}W^-_\mu$, $h\bar{f}f$, h^3

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

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$$g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu}\right)$$
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# of contributing operators << # of vertices/pseudo-observables

18 EW and Higgs Operators

18 Operators

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

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

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

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

Correlations between different vertices/observables

More observables than operators !

When expanded one operator gives rise to many deformations/vertices/observables.

TGCs

$\delta\kappa_\gamma$ $\delta\kappa_Z$

$$(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \longrightarrow \hat{h}^2\left[\hat{W}^3_{\mu\nu}B^{\mu\nu} + 2igc_{\theta_W}W^-_\mu W^+_\nu(A^{\mu\nu} - t_{\theta_W}Z^{\mu\nu})\right]$$

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

Higgs Physics

$$hA_{\mu\nu}A^{\mu\nu} \; hA_{\mu\nu}Z^{\mu\nu} \; hZ_{\mu\nu}Z^{\mu\nu} \; hW_{\mu\nu}W^{\mu\nu}$$

$$\hat{W}^3_{\mu\nu}B^{\mu\nu}$$

S-parameter

1 Operator but 7 observables

+ Anomalous Higgs interactions already constrained by LEP

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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)

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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

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Dim-6 correlation violations can be mapped to dim-8 Wilson coefficients

Bertuzzo, RSG and C. Grojean (in progress)

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Higgs Physics

$$hA_{\mu\nu}A^{\mu\nu} \quad hA_{\mu\nu}Z^{\mu\nu} \quad hZ_{\mu\nu}Z^{\mu\nu} \quad hW_{\mu\nu}W^{\mu\nu}$$

$$\hat{W}^3_{\mu\nu}B^{\mu\nu}$$

S-parameter

1 Operator but 7 observables

Anomalous Higgs interactions not constrained by LEP

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

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

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

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

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

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

$$|H|^6$$

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

8 operators

Redefining 8 parameters in the vacuum

Anomalous Higgs interactions not constrained by LEP

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

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

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!

Anomalous Higgs interactions already constrained by LEP

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

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

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

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

Anomalous Higgs interactions already constrained by LEP

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

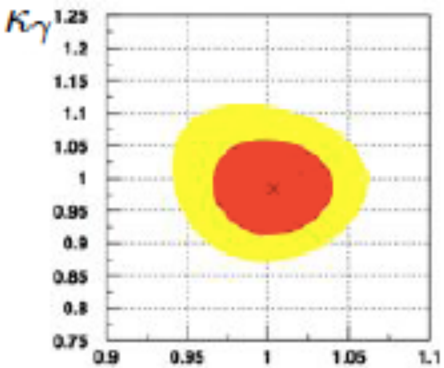
$$\delta g^h_{ZZ} = \delta g^Z_1 e^2 - \delta\kappa_\gamma \frac{e^2}{c^2_{\theta_W}}\,,$$

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

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

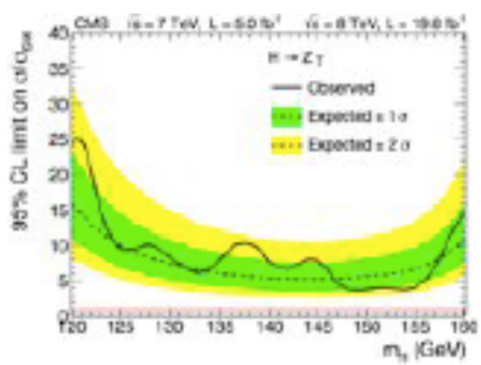
Example: *h ->Zff*

Already constrained !

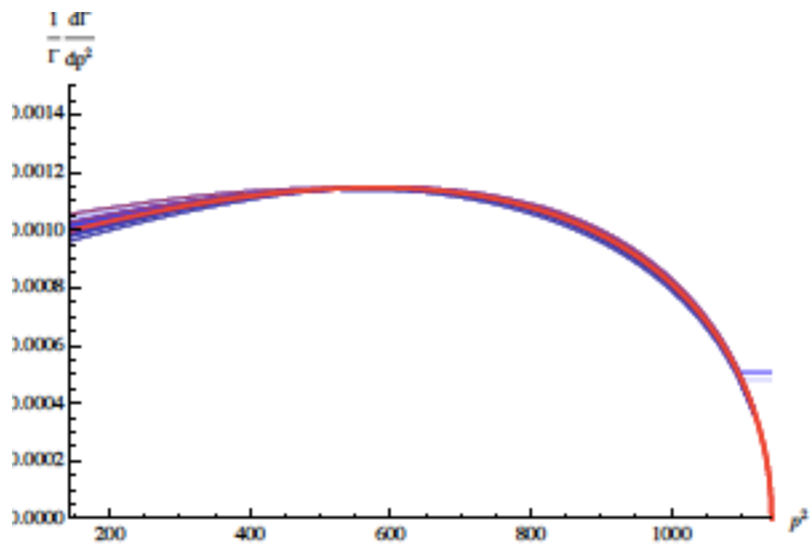


δg_1^Z

+



$h \to \gamma Z$



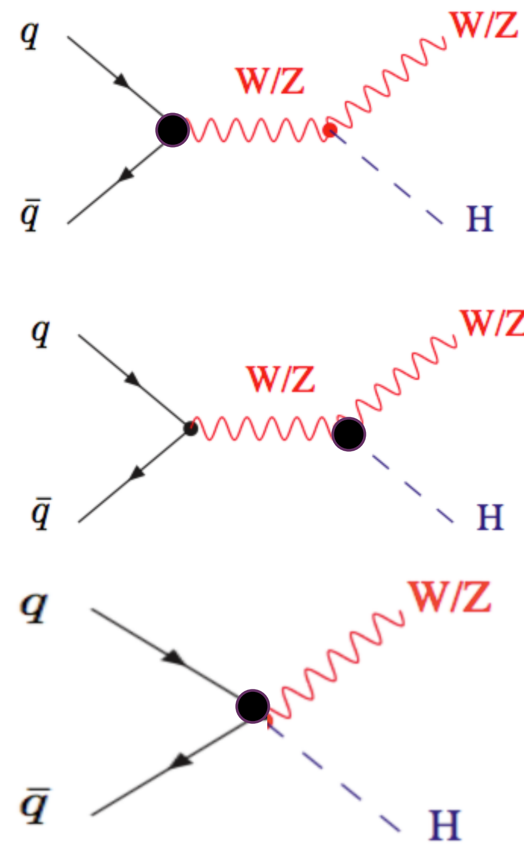
- Only way to compete with LEP is to go to high energies.

- Rest of the talk: ZH production at high energies

+ ZH production at LHC

- The following vertices in the unitary gauge contribute:

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

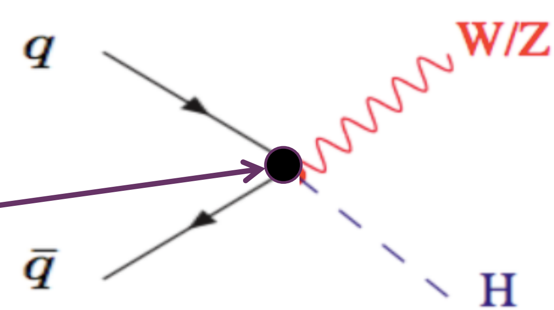


Banerjee, Englert, RSG and Spannowsky (work in progress)

ZH production at LHC

- The following vertices in the unitary gauge contribute:

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

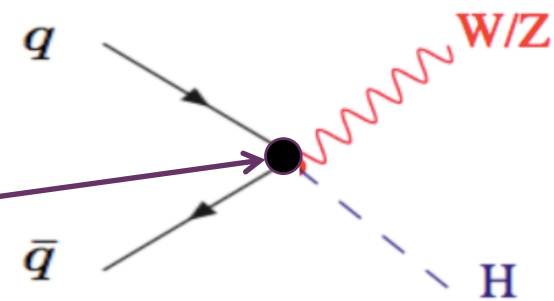


$$
\mathcal{M}(ff \to Z_L h) = g^Z_f \frac{q\cdot J_f}{v}\frac{2m_Z}{\hat{s}}\left[1 + \frac{g^h_{Zff}}{g^Z_f}\frac{\hat{s}}{2m_Z^2}\right]
$$

ZH production at LHC

- The following vertices in the unitary gauge contribute:

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



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:

$\Delta\mathcal{L}_6 \supset \sum_f \delta$

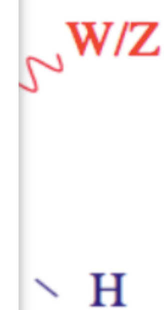
$+ \; g^h_{VV}$

$+ \sum_f g$

$+ \; \kappa_{Z\gamma} \frac{h}{v}$

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

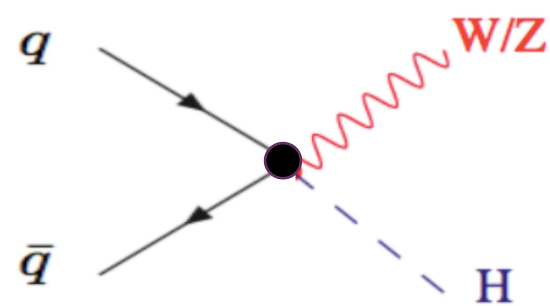
$\mathcal{M}(f f \ldots \; g_f \; v \; \hat{s} \; \Big[\ldots \; g_f^Z \; 2m_Z^2 \Big]$



ZH production: High energy primaries

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

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

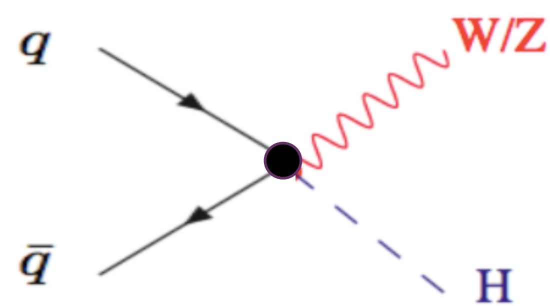


WARSAW BASIS

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)

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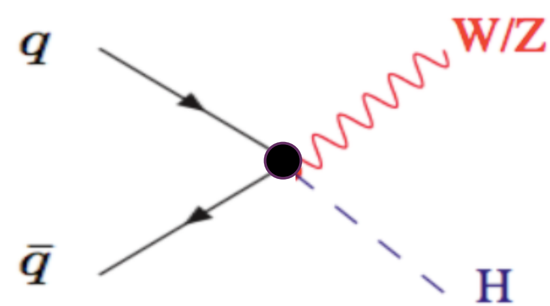
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} - \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right)\\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\frac{m_W^2}{\Lambda^2}\left(c_W + c_{HW} - c_{2W} + \frac{t^2_{\theta_W}}{3}(c_B + c_{HB} - c_{2B})\right)\\
g^h_{Zu_Ru_R} &= \frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})\\
g^h_{Zd_Rd_R} &= -\frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}\frac{m_W^2}{\Lambda^2}(c_B + c_{HB} - c_{2B})
\end{aligned}
$$

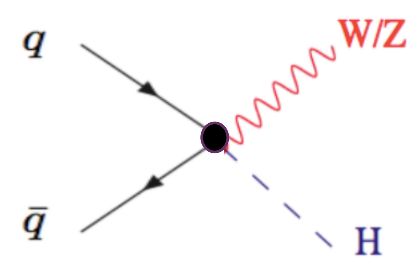


SILH BASIS (UNIVERSAL MODELS)

ZH production: High energy primaries

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

$$
\begin{aligned}
g^h_{Zu_Lu_L} &= -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}+\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W - \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zd_Ld_L} &= -\frac{g}{c_{\theta_W}}\left((c^2_{\theta_W}-\frac{s^2_{\theta_W}}{3})\delta g^Z_1 + W + \frac{t^2_{\theta_W}}{3}(\hat{S}-\delta\kappa_\gamma - Y)\right)\\
g^h_{Zu_Ru_R} &= \frac{4gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)\\
g^h_{Zd_Rd_R} &= -\frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g^Z_1 - Y)
\end{aligned}
$$



CORRELATIONS (UNIVERSAL MODELS)

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g^h_{Zd_Ld_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)\\
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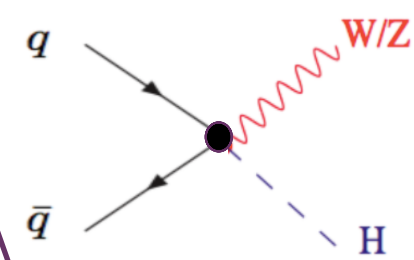
g^h_{Zd_Rd_R} &= -\frac{2gs^2_{\theta_W}}{3c^3_{\theta_W}}(\hat{S}-\delta\kappa_\gamma + c^2_{\theta_W}\delta g_1^Z - Y)
\end{aligned}
$$



CORRELATIONS (UNIVERSAL MODELS)

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

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

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

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

1 % level constraint possible ?

- LEP constraint: 5-10% 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

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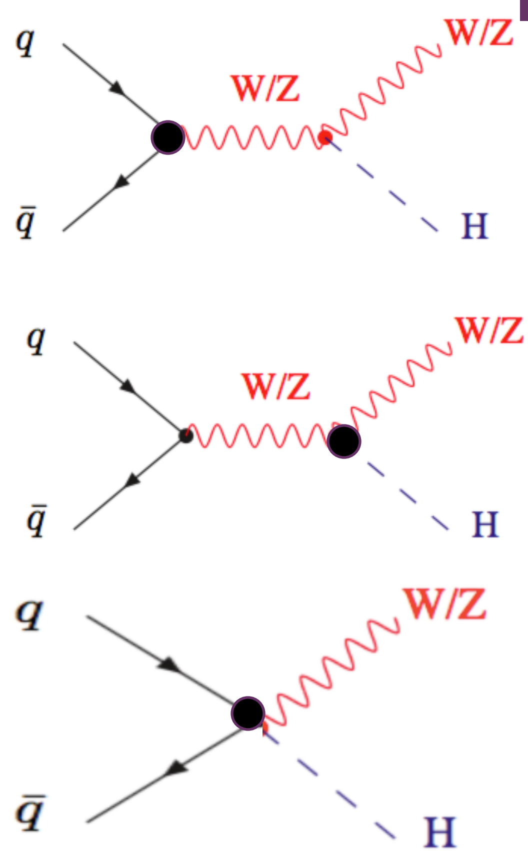
1 % level constraint possible ?

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

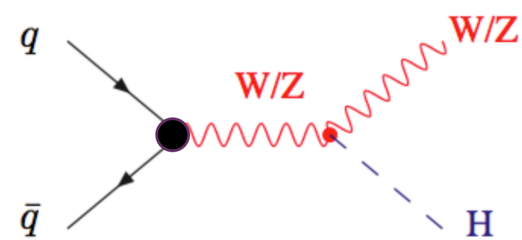
ZH production at LHC



- Can 30 % accuracy be achieved in high energy bins for this process ?
- Use of subjet techniques for boosted *h->bb* required to remove 100 times larger Zbb background.

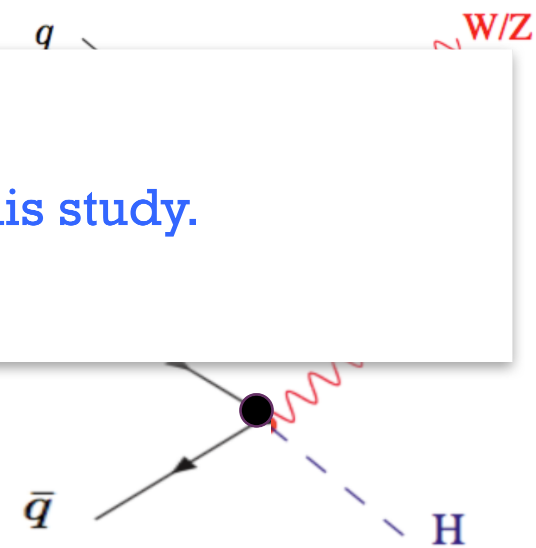
Banerjee, Englert, RSG and Spannowsky
(work in progress)

ZH production at LHC



- Can 30 % accuracy be achieved in high energy bins for this process ?

See Shankha's talk for details of this study.



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

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

Diboson production at LHC

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

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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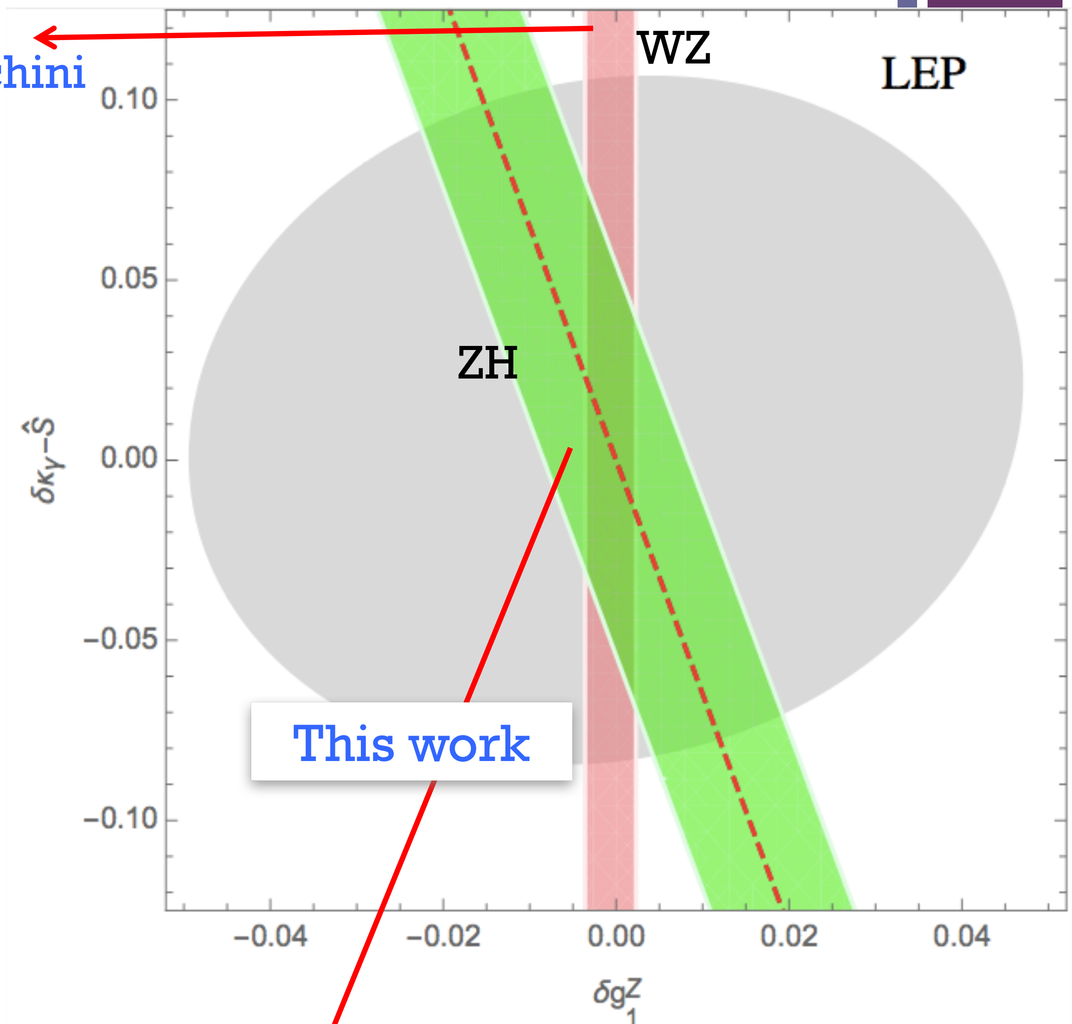
Franceschini et al



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

Diboson production at LHC

Four channels:

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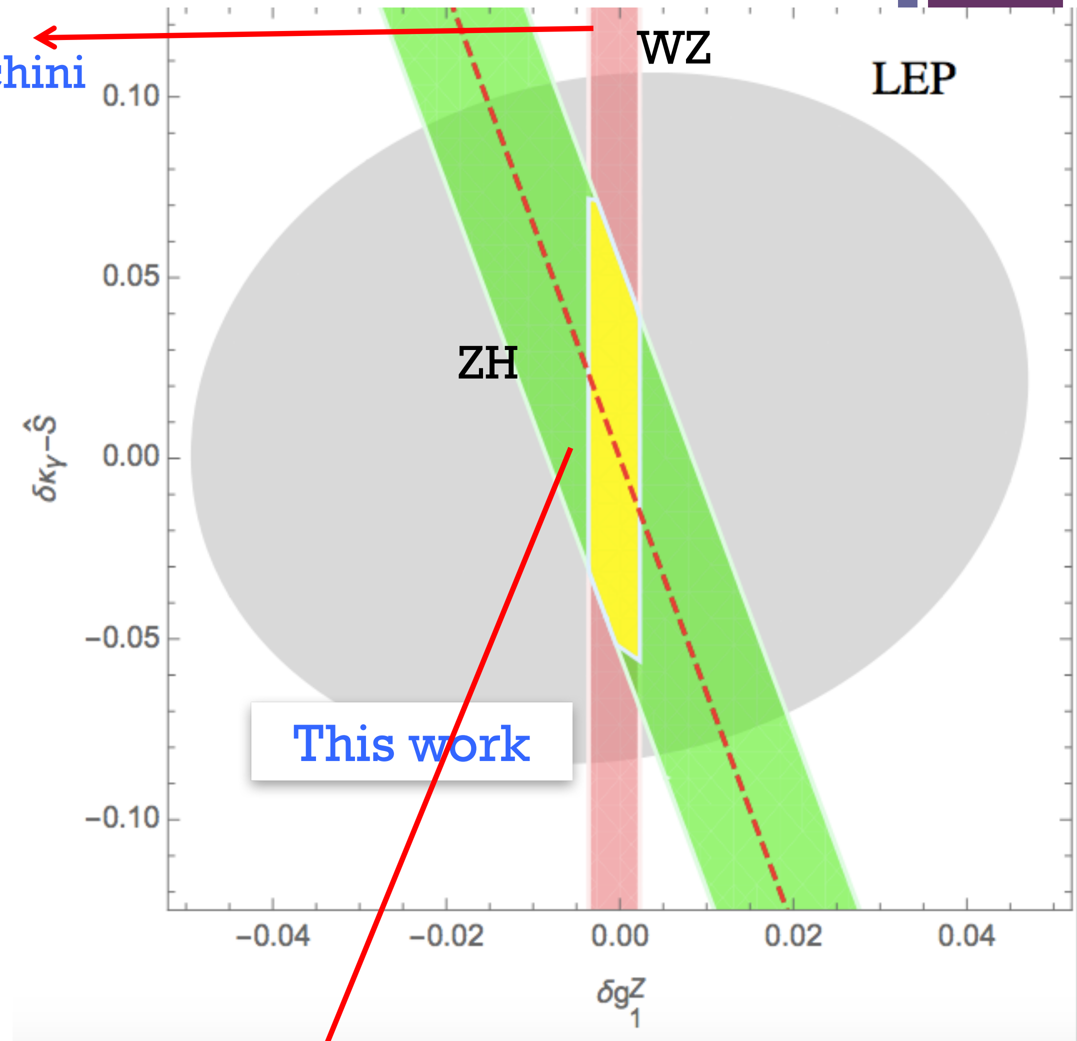
Franceschini et al



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

Diboson production at LHC

Four channels:

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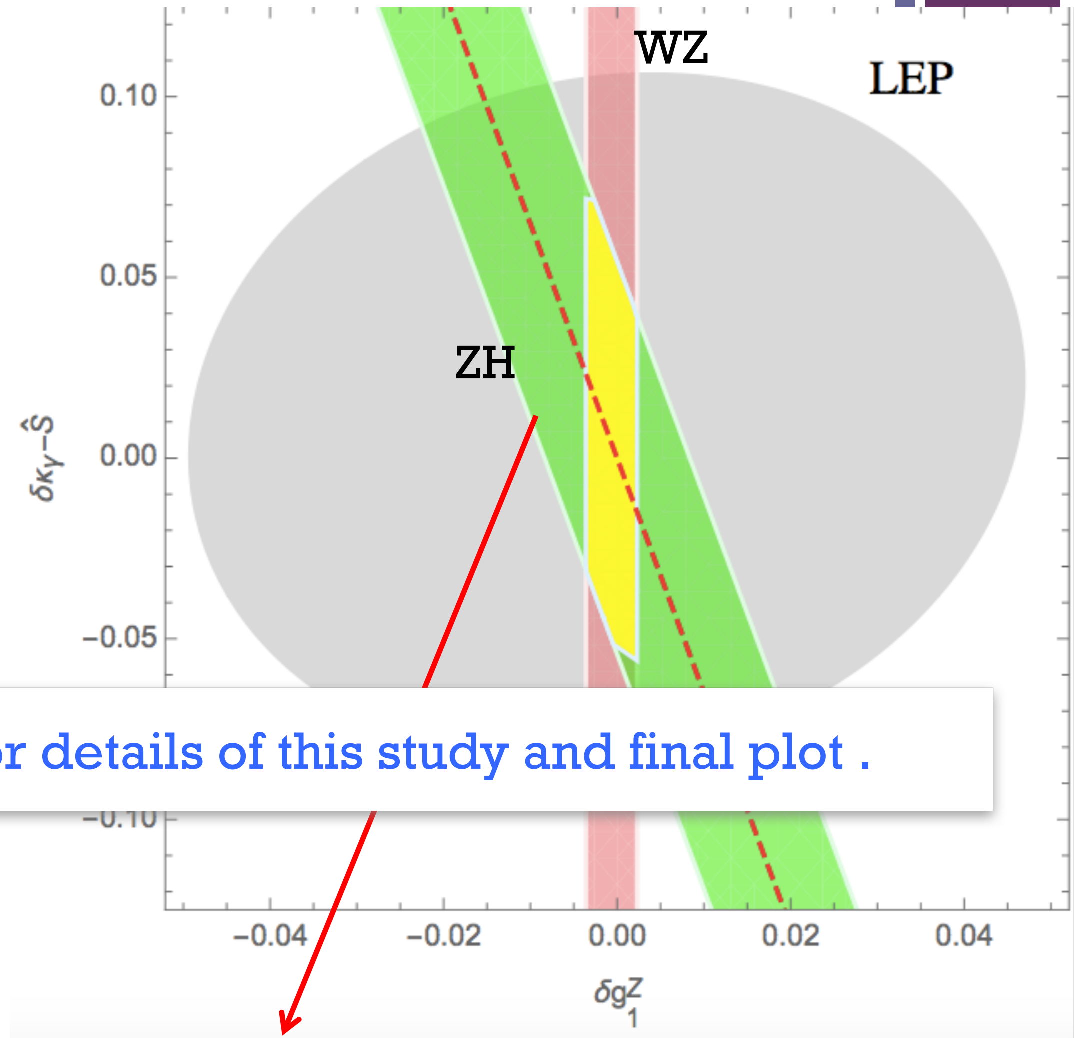
- WW $\longrightarrow$ G^+ G^-
- WZ $\longrightarrow$ G^+G^0



HV an... amplitude connected by symmetry. They constrain the same set of observables at high energies

See Shankha's talk for details of this study and final plot .

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.
- ZH production promising example channel. We perform collider analysis for Z(ll)H(bb) final state using subjet techniques.
- ZH, WH, WZ, WW intimately related by symmetry. Probe same plane in EFT space at high energies.