Probing Electroweak Precision Physics via Boosted Higgsstrahlung at the LHC

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in collaboration with Banerjee, Englert, and Spannowsky
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

\[ \mathcal{L}_h^{\text{primary}} = g_{VV}^h h \left[ W^{+\mu} W^-_{\mu} + \frac{1}{2c_{\theta_W}^2} Z^{\mu} Z_{\mu} \right] + g_3 h^3 + g_f^h (h \bar{f} L f_R + h.c.) \]

\[ + \ k_G \ G^{A \mu \nu} G_{\mu \nu}^A + k_{\gamma \gamma} \ A^{\mu \nu} A_{\mu \nu} + k_Z t_{\theta_W} \ A^{\mu \nu} Z_{\mu \nu}, \]

\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} h Z^{\mu} Z_{\mu} + g_{Zff}^h \frac{h}{2v} (Z_{\mu} J^\mu_N + h.c.) + g_{Wff'}^h \frac{h}{v} (W^+_{\mu} J^\mu_C + h.c.) \]

\[ + \ k_{WW} \ W^{+ \mu \nu} W^-_{\mu \nu} + k_{ZZ} \ Z^{\mu \nu} Z_{\mu \nu}, \]
Anomalous Higgs interactions at dimension-6 level

\[ \mathcal{L}_{h}^{\text{primary}} = g_{VV}^{h} h \left[ W^{+\mu} W_{\mu}^{-} + \frac{1}{2 c_{\theta W}^{2}} Z^{\mu} Z_{\mu} \right] + g_{3h} h^{3} + g_{f f}^{h} \left( h \bar{f}_{L} f_{R} + h.c. \right) \]

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

\[ \Delta \mathcal{L}_{h} = \delta g_{ZZ}^{h} \frac{v}{2 c_{\theta W}^{2}} h Z^{\mu} Z_{\mu} + g_{Z f f}^{h} \frac{h}{2 v} \left( Z_{\mu} J_{N}^{\mu} + h.c. \right) + g_{W f f}^{h} \frac{h}{v} \left( W_{\mu}^{+} J_{C}^{\mu} + h.c. \right) + \kappa_{WW} \frac{h}{v} W^{+\mu \nu} W_{\mu \nu}^{\nu} + \kappa_{Z Z} \frac{h}{v} Z^{\mu \nu} Z_{\mu \nu} , \]

A. Pomarol (arxiv: 1412.4410)
• 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):

\[ hW^+_{\mu\nu} W^{-\mu\nu}, \quad hA_{\mu\nu} A^{\mu\nu}, \quad hA_{\mu\nu} Z^{\mu\nu}, \quad hG_{\mu\nu} G^{\mu\nu}, \quad hW^{+\mu} W^{-\mu}, \quad h\bar{f}f, \quad h^3, \quad h^2 \bar{f}f, \quad hZ_{\mu\nu} Z^{\mu\nu}, \quad hZ_{\mu} \bar{f}_{L,R} \gamma^\mu f_{L,R} \]

These contain the physical Higgs probed for the first time at LHC in Higgs Production/decay
EW and Higgs Pseudo-observables

(1) Higgs observables (20):

\[ hW^{+}_{\mu\nu}W^{-\mu\nu}, hA_{\mu\nu}A^{\mu\nu}, hA_{\mu\nu}Z^{\mu\nu}, hG_{\mu\nu}G^{\mu\nu}, hW^{+\mu}W^{-\mu}, h\bar{f}f, h^3, h^2\bar{f}f, hZ_{\mu\nu}Z^{\mu\nu}, hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R} \]

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

(2) Electroweak precision observables (9):

\[ Z_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}, W^{+\mu}\bar{u}_{L}\gamma_{\mu}d_{L} \]

These were measured very precisely at the W/Z-pole in W/Z decays.
EW and Higgs Pseudo-observables

(1) Higgs observables (20):

\[ hW_{\mu\nu}^+ W_{-\mu\nu}^-, hA_{\mu\nu} A^{\mu\nu}, hA_{\mu\nu} Z^{\mu\nu}, hG_{\mu\nu} G^{\mu\nu}, hW^{+\mu} W^-_{\mu}, h\bar{f} f, h^3, hZ_{\mu\nu} Z^{\mu\nu}, hZ_\mu \bar{f}_{L,R} \gamma^\mu f_{L,R} \]

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

(2) Electroweak precision observables (9):

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

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

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

\[ g_1^Z c_{\theta_W} Z^\mu \left( W^{+\nu} \hat{W}_{\mu\nu}^- - W^{-\nu} \hat{W}_{\mu\nu}^+ \right), \kappa_{\gamma} s_{\theta_W} A^{\mu\nu} W_{\mu}^+ W_{\nu}^- \]

These were measured in ee->WW process at LEP.
Organizing principle: Effective Field Theory (EFT)

- Only 18 independent operators generate above vertices:

\[
\begin{align*}
\mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\
\mathcal{O}_T &= \frac{1}{2} \left( H^{\dagger} \tilde{D}_\mu H \right)^2 \\
\mathcal{O}_6 &= \lambda |H|^6 \\
\mathcal{O}_W &= \frac{i g}{2} \left( H^{\dagger} \sigma^a \tilde{D}_\mu H \right) D^\nu W^a_{\mu \nu} \\
\mathcal{O}_B &= \frac{i g^f}{2} \left( H^{\dagger} \tilde{D}_\mu H \right) \partial^\nu B_{\mu \nu}
\end{align*}
\]

\[
\begin{align*}
\mathcal{O}_{BB} &= g^B |H|^2 B_{\mu \nu} B^{\mu \nu} \\
\mathcal{O}_{GG} &= g^G_s |H|^2 G_{\mu \nu}^A G^{A \mu \nu} \\
\mathcal{O}_{HW} &= ig (D^\mu H)^{\dagger} \sigma^a (D^\nu H) W^a_{\mu \nu} \\
\mathcal{O}_{HB} &= ig' (D^\mu H)^{\dagger} (D^\nu H) B_{\mu \nu} \\
\mathcal{O}_{3W} &= \frac{1}{3!} g \epsilon_{abc} W^a_{\mu \nu} W^b_{\nu \rho} W^c_{\rho \mu}
\end{align*}
\]
Correlations between observables

18 Operators

Many Vertices /pseudo-observables

# of contributing operators $\ll$ # of vertices/pseudo-observables
18 Operators and Higgs Operators

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!
Anomalous Higgs interactions not constrained by LEP
Anomalous Higgs interactions already constrained by LEP

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

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

\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2 c^2_{\theta_W}} h Z^{\mu \nu} Z_{\mu \nu} + g_{Zff}^h \frac{h}{2v} (Z_{\mu} J^\mu_N + \text{h.c.}) + g_{Wff'}^h \frac{h}{v} (W^+_{\mu} J^\mu_C + \text{h.c.}) \]

\[ + \kappa_{WW} \frac{h}{v} W^{+ \mu \nu} W^-_{\mu \nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu \nu} Z_{\mu \nu} , \]
Anomalous Higgs interactions already constrained by LEP

\[
\Delta L_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} h Z^\mu Z_\mu + g_{Zf}^h \frac{c_{\theta_W}}{2v} (Z_\mu J_N^\mu + h.c.) + g_{Wf}^h \frac{h}{v} (W_\mu J_C^\mu + h.c.) \\
+ \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^{-\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu},
\]

\[
\delta g_{ZZ}^h = \delta g_1^Z e^2 - \delta \kappa_\gamma \frac{e^2}{c_{\theta_W}^2},
\]

\[
g_{Zf}^h = 2\delta g_{Zf}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ_f s_{2\theta_W}) + 2\delta \kappa_\gamma Y_f \frac{e s_{\theta_W}}{c_{\theta_W}^2},
\]

\[
g_{Wf}^h = 2\delta g_{f}^W - 2\delta g_1^Z g_f^W c_{\theta_W}^2,
\]

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

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)
Anomalous Higgs interactions already constrained by LEP

\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_{\theta_W}^2} hZ^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} (Z_\mu J_N^\mu + h.c.) + g_{Wff}^h \frac{h}{v} (W_\mu^+ J_C^\mu + h.c.) \]

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

\[ \delta g_{ZZ}^h = \delta g_1^Z e^2 - \delta \kappa_\gamma \frac{e^2}{c_{\theta_W}^2} , \]

\[ g_{Zff}^h = 2 \delta g_{ff}^Z - 2 \delta g_1^Z (g_f c_{2\theta_W} + e Q_f s_{2\theta_W}) + 2 \delta \kappa_\gamma Y_f \frac{e s_{\theta_W}}{c_{\theta_W}^2} , \]

\[ g_{Wff}^h = 2 \delta g_{ff}^W - 2 \delta g_1^W g_f c_{\theta_W}^2 , \]

\[ \kappa_{ZZ} = \frac{1}{2c_{\theta_W}^2} (\delta \kappa_\gamma + \kappa_{Z\gamma} c_{2\theta_W} + 2 \kappa_{\gamma\gamma} c_{\theta_W}^2) , \]

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

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: $h \rightarrow Zff$

Already constrained!
• 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:

$$\Delta L_6 \supset \sum_f \delta g^Z f Z_\mu \bar{f} \gamma^\mu f + \delta g^W_{ud} (W^+ u_L \gamma^\mu d_L + h.c.)$$

$$+ \ g^h_{VV} h \left[ W^+ \mu W^- \mu + \frac{1}{2 c^2_{\theta_W}} Z^\mu Z_\mu \right] + \delta g^h_{ZZ} h \frac{Z^\mu Z_\mu}{2 c^2_{\theta_W}}$$

$$\sum_f \ g^h_{Zff} \frac{h}{v} Z_\mu \bar{f} \gamma^\mu f + g^h_{Wud} \frac{h}{v} (W^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$

$$+ \ k_{Z} \frac{h}{v} A^{\mu \nu} Z_{\mu \nu} + k_{WW} \frac{h}{v} W^{+ \mu \nu} W^{\mu \nu}_- + k_{ZZ} \frac{h}{2 v} Z^{\mu \nu} Z_{\mu \nu}.$$
Zh production at LHC

- The following vertices in the unitary gauge contribute:

\[ \Delta L_6 \supset \sum_f \delta g^Z_f Z_{\mu} \bar{f} \gamma^\mu f + \delta g^W_{ud} (W^+_{\mu} \bar{u}_L \gamma^\mu d_L + h.c.) \]

\[ + g^h_{VV} h \left[ W^+_{\mu} W^-_{\mu} + \frac{1}{2 c_{\theta_W}^2} Z^\mu Z_{\mu} \right] + \delta g^h_{ZZ} h \frac{Z^\mu Z_{\mu}}{2 c_{\theta_W}^2} \]

\[ + \sum_f g^h_{Zff} \frac{h}{v} Z_{\mu} \bar{f} \gamma^\mu f + g^h_{Wud} \frac{h}{v} (W^+_{\mu} \bar{u}_L \gamma^\mu d_L + h.c.) \]

\[ + \kappa_{Z\gamma} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW} h_v W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{2 v} Z^{\mu\nu} Z_{\mu\nu} . \]

\[ \mathcal{M}(ff \to ZLh) = g^Z_f \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[ 1 + \frac{g^Z_{Zff}}{g^Z_f} \frac{\hat{s}}{2m_Z^2} \right] \]
Zh production at LHC

- The following vertices in the unitary gauge contribute:

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

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:

<table>
<thead>
<tr>
<th>SILH Basis</th>
<th>Warsaw Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}<em>W = \frac{ig}{2} \left( H^\dagger \sigma^a D^\mu H \right) D^\nu W</em>{\mu\nu}^a$</td>
<td>$\mathcal{O}_{L}^{(3)} = (\bar{Q}<em>L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a D</em>\mu H)$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>B = \frac{ig'}{2} \left( H^\dagger \tilde{D}^\mu H \right) \partial^\nu B</em>{\mu\nu}$</td>
<td>$\mathcal{O}_L = (\bar{Q}<em>L \gamma^\mu Q_L)(iH^\dagger \tilde{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{HW} = ig(D^\mu H)^{\dagger} \sigma^a(D^\nu H) W</em>{\mu\nu}^a$</td>
<td>$\mathcal{O}_R^{u} = (\bar{u}<em>R \gamma^\mu u_R)(iH^\dagger \tilde{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{HB} = ig'(D^\mu H)^{\dagger}(D^\nu H) B</em>{\mu\nu}$</td>
<td>$\mathcal{O}_R^{d} = (\bar{d}<em>R \gamma^\mu d_R)(iH^\dagger \tilde{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{2W} = -\frac{1}{2}(D^\mu W</em>{\mu\nu}^a)^2$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}<em>{2B} = -\frac{1}{2}(\partial^\mu B</em>{\mu\nu})^2$</td>
<td></td>
</tr>
</tbody>
</table>
Zh production: High energy primaries

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

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

**WARSAW BASIS**
Zh production: High energy primaries

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

\[
g_{Z^{u_L}u_L}^h = 2\delta g_{Z^{u_L}u_L}^Z - 2\delta g_1^Z (g_j^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}}
\]

\[
g_{Z^{d_L}d_L}^h = 2\delta g_{Z^{d_L}d_L}^Z - 2\delta g_1^Z (g_j^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}}
\]

\[
g_{Z^{u_R}u_R}^h = 2\delta g_{Z^{u_R}u_R}^Z - 2\delta g_1^Z (g_j^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}}
\]

\[
g_{Z^{d_R}d_R}^h = 2\delta g_{Z^{d_R}d_R}^Z - 2\delta g_1^Z (g_j^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta \kappa_\gamma g' Y_h \frac{s_{\theta_W}}{c_{\theta_W}}
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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.

\[
\begin{align*}
    g^{h}_{Zu_{LL}} & = \frac{g}{c_{\theta_{W}}} \frac{m_{W}^{2}}{\Lambda^{2}} (c_{W} + c_{H_{W}} - c_{2W} - \frac{t_{\theta_{W}}^{2}}{3} (c_{B} + c_{H_{B}} - c_{2B})) \\
    g^{h}_{Zd_{LL}} & = -\frac{g}{c_{\theta_{W}}} \frac{m_{W}^{2}}{\Lambda^{2}} (c_{W} + c_{H_{W}} - c_{2W} + \frac{t_{\theta_{W}}^{2}}{3} (c_{B} + c_{H_{B}} - c_{2B})) \\
    g^{h}_{Zu_{RR}} & = -\frac{4g s_{\theta_{W}}^{2}}{3 c_{\theta_{W}}^{3}} \frac{m_{W}^{2}}{\Lambda^{2}} (c_{B} + c_{H_{B}} - c_{2B}) \\
    g^{h}_{Zd_{RR}} & = -\frac{2g s_{\theta_{W}}^{2}}{3 c_{\theta_{W}}^{3}} \frac{m_{W}^{2}}{\Lambda^{2}} (c_{B} + c_{H_{B}} - c_{2B})
\end{align*}
\]
Zh production: High energy primaries

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

\[
\begin{align*}
    g_{Zu_Lu_L}^h &= -\frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W + \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_{\gamma} - Y) \right) \\
    g_{Zd_Ld_L}^h &= \frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_{\gamma} - Y) \right) \\
    g_{Zu_Ru_R}^h &= -\frac{4gs_{\theta_W}^2}{3c_{\theta_W}^3} (\hat{S} - \delta \kappa_{\gamma} + c_{\theta_W}^2 \delta g_1^Z - Y) \\
    g_{Zd_Rd_R}^h &= \frac{2gs_{\theta_W}^2}{3c_{\theta_W}^3} (\hat{S} - \delta \kappa_{\gamma} + c_{\theta_W}^2 \delta g_1^Z - Y)
\end{align*}
\]
Zh production: High energy primaries

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

\[
\begin{align*}
  g_{ZuLdL}^h &= -\frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W + \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_\gamma - Y) \right) \\
  g_{ZdLdL}^h &= \frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 - \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{S} - \delta \kappa_\gamma - Y) \right) \\
  g_{ZuRuR}^h &= -\frac{4gs_{\theta_W}^2}{3c_{\theta_W}^3} (\hat{S} - \delta \kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y) \\
  g_{ZdRdR}^h &= \frac{2gs_{\theta_W}^2}{3c_{\theta_W}^3} (\hat{S} - \delta \kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y)
\end{align*}
\]

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:

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

\[
g_{Zu_L u_L}^h = -\frac{g}{c_{\theta_W}} \left( c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3} \right) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} \left( \hat{S} - \delta \kappa_{\gamma} - Y \right)
\]

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

\[ \mathcal{M}(f f \rightarrow Z_L h) = g_f^Z q \cdot J_f \frac{2m_Z}{u} \left[ 1 + \frac{g_{Zf}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right] \]

\[
g_{Zu_Lu_L}^h = -\frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_1^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{s} - \delta \kappa_{\gamma} - Y) \right)
\]

\text{Factor of 30}

\text{Per mille- % level constraint possible?}

\text{LEP constraint: 5-10% level}

\text{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 as the HE-LHC at 27 TeV.
Cross section deviations and EFT Validity

\[ \mathcal{M}(f f \rightarrow Z_{L} h) = g_{f}^{Z} q \cdot J_{f} \frac{2m_{Z}}{\hat{s}} \left[ 1 + \frac{g_{Z ff}^{n}}{g_{f}^{Z}} \frac{\hat{s}}{2m_{Z}^{2}} \right] \]

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

Fractional Deviations \( \gg 1 \) signal a breakdown of EFT expansion unless UV completion is strongly coupled
Can sensitivity to 30 % deviation be achieved in high energy bins for this process?

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

\[ q + \bar{q} \rightarrow Z \rightarrow ll \]

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

Cross Section: 5.6 fb

\[ pp \rightarrow Z(ll)h(\gamma\gamma) \]

Less than 4 SM events at 300 fb

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

Cross Section: 5.6 fb

Less than 4 SM events at 300 fb

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

Cross Section: $4.6 \text{ fb}$

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

$pp \rightarrow Z(ll)h(\bar{b}b)$

Much larger rate than diphoton channel

But 40 times larger $Z(\bar{b}b)$ background = $165 \text{ fb}$
Search Strategy

$\mathcal{Z} h (b b) = 4.6 \text{ fb} \quad \mathcal{Z} b b = 165 \text{ fb}$

$\mathcal{Z} h (b b) = 0.12 \text{ fb} \quad \mathcal{Z} b b = 0.22 \text{ fb}$

$\mathcal{Z} h (b b) = 0.11 \text{ fb} \quad \mathcal{Z} b b = 0.35 \text{ fb}$

$\mathcal{P}_{T1} + \mathcal{P}_{T2} > 160 \text{ GeV}$

BDT optimisation

Cut-based Analysis
### Cut-flow

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

\[
\begin{align*}
\text{Zh (bb)} &= 4.6 \text{ fb} \\
\text{Zbb} &= 165 \text{ fb}
\end{align*}
\]

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Zbb</th>
<th>Zh (SM)</th>
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<tr>
<td>1. At least 1 fat jet with 2 B-mesons with pT &gt; 15 GeV</td>
<td>0.157</td>
<td>0.411</td>
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<td>2. 2 OSSF isolated leptons</td>
<td>0.407</td>
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</tr>
<tr>
<td>3. 80 GeV &lt; M_{l1l2} &lt; 100 GeV, pT_{l1l2} &gt; 160 GeV, dR_{l1l2} &gt; 0.2</td>
<td>0.846</td>
<td>0.887</td>
</tr>
<tr>
<td>4. At least 1 fat jet, at least 1 fat jet with 2 B-meson tracks with pT &gt; 110 GeV</td>
<td>0.952</td>
<td>0.980</td>
</tr>
<tr>
<td>5. 2 Mass drop subjets and &gt;= 2 filtered subjets</td>
<td>0.857</td>
<td>0.923</td>
</tr>
<tr>
<td>6. Exactly 2 b-tagged jets</td>
<td>0.383</td>
<td>0.409</td>
</tr>
<tr>
<td>7. 115 GeV &lt; M_{fatjet} &lt; 135 GeV</td>
<td>0.254</td>
<td>0.505</td>
</tr>
<tr>
<td>8. Delta R(l_i, b_j) &gt; 0.4, MET &lt; 30 GeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.490</td>
<td>0.693</td>
</tr>
<tr>
<td>and pT_{l1l2} &gt; 200 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.002</td>
<td>0.024</td>
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Butterworth et al, arXiv:0802.2470

\[
\begin{align*}
\text{Zh (bb)} &= 0.12 \text{ fb} \\
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## Cut-flow

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

\[ \text{Zh (bb)} = 4.6 \text{ fb} \quad \text{Zbb} = 165 \text{ fb} \]

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<tr>
<td>3. Combined (please see last mail)</td>
<td>0.145</td>
<td>0.217</td>
</tr>
<tr>
<td>4. BDT cut</td>
<td>0.148</td>
<td>0.593</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.0014</strong></td>
<td><strong>0.026</strong></td>
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\[ \text{Zh (bb)} = 0.11 \text{ fb} \]

\[ \text{Zbb} = 0.35 \text{ fb} \]
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!
To discriminate between SM and EFT we look at $Zh$ invariant mass distribution (300 ifb):
SM background vs EFT Signal

Unphysical

-0.012 $\# gzur$
-0.011 $\# gzul$
0.006 $\# ghzdr$
0.005 $\# ghzdl$
We can find the sensitivity to % cross-section deviation given the SM background assuming 5% syst. uncertainty (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. uncertainty (300 ifb):

Sensitivity to 20-40 % cross-section deviations

HIGH LUMINOSITIES ESSENTIAL!
ZH production: LHC vs LEP

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

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

- LEP constraint: 5-10% level

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

- Per mille-% level constraint possible?

- Factor of 30
\[ \mathcal{M}(ff \rightarrow Z_L h) = g_f^Z q \cdot J_f \frac{2m_Z}{\hat{s}} \left[ 1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right] \]
This point can be excluded with 300 ifb data.

\[ M(\mathbf{f} \mathbf{f} \rightarrow Z_L h) = g_f^Z q \cdot J_f \frac{2m_Z}{v} \left( 1 + \frac{g_{Zff}^h}{g_f^Z} \frac{s}{2m_Z^2} \right) \]
• We will present final projections together with WZ projections.
Diboson production at LHC

Four channels:

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

- 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

$$\Phi = \left( \frac{G^+}{(v + H) + iG^0} \right) \sqrt{2}$$

Franceschini, Panico, Pomarol, Riva & Wulzer
arxiv:1712.01310
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<td>$\sqrt{2}a_q^{(3)}$</td>
</tr>
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<td>$a_q^{(1)} + a_q^{(3)}$</td>
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<td></td>
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<td>$a_q^{(1)} - a_q^{(3)}$</td>
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<td>$\bar{u}_L u_L \rightarrow Z_L h$</td>
<td></td>
</tr>
<tr>
<td>$f_R f_R \rightarrow W_L W_L, Z_L h$</td>
<td>$a_f$</td>
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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
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<td>$\frac{g^h_{Zd_Ld_L} - g^h_{Zu_Lu_L}}{\sqrt{2}}$</td>
</tr>
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<td>$g^h_{Zd_Ld_L}$</td>
</tr>
<tr>
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<td>$g^h_{Zf_Rf_R}$</td>
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*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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This work

Banerjee, Englert, RSG and Spannowsky (work in progress)
Diboson production at LHC

Four channels:
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$HV$ and $VV$ processes amplitude connected by symmetry. They constrain the same set of observables at high energies.

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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

\[ \mathcal{L}_h^{\text{primary}} = g_{VV}^h h \left[ W^{+\mu} W^-_{\mu} + \frac{1}{2c_w^2} Z^\mu Z_{\mu} \right] + g_{3h}^h h^3 + g_{ff}^h (h f_L f_R + h.c.) \]

\[ + \kappa_{GG} \frac{h}{v} G_A^{\mu\nu} G_{\mu\nu}^A + \kappa_{\gamma\gamma} \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma t_{\theta_w}} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu}, \]

\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c_w^2} h Z^\mu Z_{\mu} + g_{Zff}^h \frac{h}{2v} (Z_{\mu} J_N^\mu + h.c.) + g_{Wff}^h \frac{h}{v} (W^{+\mu} J_C^\mu + h.c.) \]

\[ + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}, \]
Anomalous Higgs interactions not constrained by LEP

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\[ \Delta L_h = \delta g_{ZZ}^h \frac{v}{2c_W^2} h Z^\mu Z_{\mu} + g_{Zff}^h \frac{h}{2v} (Z_{\mu} J_{N}^\mu + h.c.) + g_{Wff}^h \frac{h}{v} (W^{+}_\mu J_{C}^\mu + h.c.) + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}, \]
Anomalous Higgs interactions already constrained by LEP

\[ \mathcal{L}_{h}^{\text{primary}} = g_{VV}^{h} h \left[ W^{+\mu} W_{\mu}^{-} + \frac{1}{2c_{\theta W}^2} Z^{\mu} Z_{\mu} \right] + g_{3h} h^3 + g_{ff}^{h} (h \bar{f}_L f_R + h.c.) \]

\[ + \kappa_{GG} \frac{h}{v} G_{\mu\nu}^{A} G_{\mu\nu}^{A} + \kappa_{\gamma\gamma} \frac{h}{v} A_{\mu}^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma t_{\theta W}} \frac{h}{v} A_{\mu\nu} Z_{\mu\nu} , \]

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\[ + \kappa_{WW} \frac{h}{v} W_{\mu\nu}^{+} W_{\mu\nu}^{-} + \kappa_{ZZ} \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu} , \]
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\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2 c_w^2} h Z^{\mu} Z_{\mu} + g_{Zff}^h \frac{h}{2v} \left( Z_{\mu} J^\mu_N + \text{h.c.} \right) + g_{Wff'}^h \frac{h}{v} \left( W^+_{\mu} J^\mu_C + \text{h.c.} \right) + \kappa_{WW}^h \frac{h}{v} W^{+\mu\nu} W^-_{\mu\nu} + \kappa_{ZZ}^h \frac{h}{v} Z^{\mu\nu} Z_{\mu\nu}, \]
Anomalous Higgs interactions not constrained by LEP

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

\[ \hat{h} = v + h \]

\[ H^\dagger H \mathcal{O}_{\text{SM}} \]

8 operators

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!