High-pT tails in VH/VV for TGCs

Dibosons at the ‘High Energy-Luminosity’ frontier

Rick Sandeepan Gupta (IPPP Durham), MBI 2019

in collaboration with Banerjee, Englert, and Spannowsky
(arXiv: 1807.01796)
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:

\[
\mathcal{L}_{\text{eff}} = \frac{\Lambda^4}{g^2_*} \mathcal{L} \left( \frac{D_\mu}{\Lambda}, \frac{g_* H}{\Lambda}, \frac{g_* f_{L,R}}{\Lambda^{3/2}}, \frac{g F_{\mu\nu}}{\Lambda^2} \right) \sim \mathcal{L}_4 + \mathcal{L}_6 + \ldots
\]
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)
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 and can be measured much more precisely at LEP.
Anomalous Higgs interactions at dimension-6 level

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

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

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

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

A. Pomarol (arxiv: 1412.4410)
Anomalous Higgs interactions at dimension-6 level

Higgs interactions to be directly measured for the first time at LHC.
Organizing principle: Effective Field Theory (EFT)

- Only 18 independent operators generate above vertices:

<table>
<thead>
<tr>
<th>$H^2$-operators</th>
<th>$H^0$-operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{O}_r =</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}_6 = \lambda</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}_y =</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}<em>f = i H^\dagger \bar{D}</em>\mu H \bar{f} \gamma^\mu f$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}<em>L = i H^\dagger \bar{D}</em>\mu H \bar{F} \gamma^\mu F$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}<em>L^{(3)} = i H^\dagger \sigma^a \bar{D}</em>\mu H \bar{F} \sigma^a \gamma^\mu F$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}<em>{W-B} = i g \left( H^\dagger \tau^a \bar{D}</em>\mu H \right) D^\nu W^a_{\mu\nu}$</td>
<td></td>
</tr>
<tr>
<td>$-i g' Y_H \left( H^\dagger \bar{D}<em>\mu H \right) \partial^\nu B</em>{\mu\nu}$</td>
<td></td>
</tr>
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<td>$\mathcal{O}_{BB} = g'^2</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}<em>{WB'} = g g' H^\dagger \sigma^a HW^a</em>{\mu\nu} B^{\mu\nu} - 4 i g' Y_H \left( H^\dagger \bar{D}<em>\mu H \right) \partial^\nu B</em>{\mu\nu}$</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{O}_{WW} = g^2</td>
<td>H</td>
</tr>
<tr>
<td>$\mathcal{O}_{GG} = g^2_s</td>
<td>H</td>
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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**

### $H^2$-operators

- $O_e = |H|^2 |D_\mu H|^2$
- $O_6 = \lambda |H|^6$
- $O_y = |H|^2 \bar{F} HF$
- $O_f = i H^\dagger \bar{D}_\mu H f \gamma^\mu f$
- $O_L = i H^\dagger \bar{D}_\mu H \bar{F} \gamma^\mu F$
- $O_L^{(3)} = i H^\dagger \sigma^a \bar{D}_\mu H F \sigma^a \gamma^\mu F$

### $O_{W-B}$

$$O_{W-B} = ig \left( H^\dagger \tau^a \bar{D}_\mu H \right) \partial^\nu W^a_{\mu\nu}$$

$$- ig' Y_H \left( H^\dagger \bar{D}_\mu H \right) \partial^\nu B^\mu_{\mu\nu}$$

### $O_{BB}$

$$O_{BB} = g'^2 |H|^2 \bar{B}_{\mu\nu} B^{\mu\nu}$$

### $O_{WW}$

$$O_{WW} = g'^2 |H|^2 W^a_{\mu\nu} W^{a^\mu\nu}$$

### $O_{GG}$

$$O_{GG} = g'^2 |H|^2 G^a_{\mu\nu} G^{a^\mu\nu}$$

**50 Vertices**

/pseudo-observables

- 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

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

Correlations between different
vertices/observables

Grojean and RSG, in preparation
Correlation Example

$h_{Vff} = \text{Triple Gauge Coupling + } Z \text{ decay modifications}$

Constrained already by LEP!

Can only be seen at LHC

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

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

$$+ \kappa_{GG}^{h} g_{A}^{A\mu\nu} G_{\mu\nu}^{A} + \kappa_{\gamma\gamma}^{h} g_{\gamma}^{A\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma t_{W}}^{h} g_{\gamma}^{A\mu\nu} Z_{\mu\nu} ,$$

$$\Delta \mathcal{L}_{h} = \delta g_{ZZ}^{h} \frac{v}{2 c_{\theta_{W}}^{2}} h Z^{\mu} Z_{\mu} + g_{Zff}^{h} \frac{h}{2 v} (Z_{\mu} J_{N}^{\mu} + h.c.) + g_{Wff}^{h} \frac{h}{v} (W^{+}_{\mu} J_{C}^{\mu} + h.c.)$$

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

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

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

\[ g_{Zff}^h = 2\delta g_{ff}^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ_f s_{2\theta_W}) + 2\delta \kappa_{\gamma} Y_f \frac{e s_{\theta_W}}{c_{\theta_W}^3}, \]

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

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

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

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

**Right Hand Side: Z-pole obs. + TGCs**

\[
\begin{align*}
\delta g^h_{ZZ} &= \delta g^Z_1 e^2 - \delta \kappa_\gamma \frac{e^2}{c^2_{\theta_W}}, \\
g^h_{Zff} &= 2 \delta g^Z_{ff} - 2 \delta g^Z_1 (g_f^Z c_{2\theta_W} + e Q_f s_{2\theta_W}) + 2 \delta \kappa_\gamma Y_f \frac{e s_{\theta_W}}{c^3_{\theta_W}}, \\
\kappa_{ZZ} &= \frac{1}{2 c^2_{\theta_W}} (\delta \kappa_\gamma + \kappa_{Z\gamma} c_{2\theta_W} + 2 \kappa_{\gamma\gamma} c^2_{\theta_W}), \\
g^h_{Wff'} &= 2 \delta g^W_{ff'} - 2 \delta g^Z_1 g_f^Z c_{\theta_W}^2, \\
\kappa_{WW} &= \delta \kappa_\gamma + \kappa_{Z\gamma} + 2 \kappa_{\gamma\gamma},
\end{align*}
\]

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: $h \rightarrow Zf\bar{f}$

Already constrained!
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:

\[ \Delta \mathcal{L}_6 \supset \sum_f \delta g_f Z \bar{f} \gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u} L \gamma^\mu d_L + h.c.) + g_{VV}^h h \left[ W_\mu^+ W_\mu^- + \frac{1}{2 c_w^2} Z_\mu^+ Z_\mu^- \right] + \delta g_{ZZ}^h h \frac{Z_\mu^+ Z_\mu^-}{2 c_w^2} + \sum_f g_{Zff}^h \frac{h}{u} Z_\mu \bar{f} \gamma^\mu f + g_{Wud}^h \frac{h}{u} (W_\mu^+ \bar{u} L \gamma^\mu d_L + h.c.) + \kappa_Z \gamma^\mu A_\mu^Z Z_\mu^\nu + \kappa_{WW} \frac{h}{u} W_\mu^+ W_\mu^- + \kappa_{ZZ} \frac{h}{2 u} Z_\mu^\nu Z_\mu^\rho . \]

Banerjee, Englert, RSG and Spannowsky (arXiv: 1807.01796)
The following vertices in the unitary gauge contribute:

\[ \Delta \mathcal{L}_6 \supset \sum_f \delta g_f^Z Z_\mu \bar{f} \gamma^\mu f + \delta g_{ud}^W (W^+_\mu \bar{u}_L \gamma^\mu d_L + \text{h.c.}) \]

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

\[ + \sum_f g_{Zff}^h \eta_{\nu} Z_\mu \bar{f} \gamma^\mu f + g_{Wud}^h \eta_{\nu} (W^+_\mu \bar{u}_L \gamma^\mu d_L + \text{h.c.}) \]

\[ + \kappa_{Z\gamma}^h \frac{h}{\nu} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW}^h \frac{h}{\nu} W^{\mu\nu} W_{\mu\nu} + \kappa_{Z\gamma}^h \frac{h}{2 \nu} Z^{\mu\nu} Z_{\mu\nu}. \]

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

- The following vertices in the unitary gauge contribute:

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

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

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

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

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

- The following vertices in the unitary gauge contribute:

<table>
<thead>
<tr>
<th>SILH Basis</th>
<th>Warsaw Basis</th>
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<tr>
<td>$O_W = \frac{ig}{2} \left( H^\dagger \sigma^a D^\mu H \right) D^\nu W^a_{\mu\nu}$</td>
<td>$O_L^{(3)} = (\bar{Q}<em>L \sigma^\mu Q_L)(iH^\dagger \sigma^a \hat{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$O_B = \frac{ig'}{2} \left( H^\dagger \hat{D^\mu} H \right) \partial^\nu B_{\mu\nu}$</td>
<td>$O_L = (\bar{Q}<em>L \gamma^\mu Q_L)(iH^\dagger \hat{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$O_{HW} = ig(D^\mu H)^\dagger \sigma^a(D^\nu H)W^a_{\mu\nu}$</td>
<td>$O_R^u = (\bar{u}<em>R \gamma^\mu u_R)(iH^\dagger \hat{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$O_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$</td>
<td>$O_R^d = (\bar{d}<em>R \gamma^\mu d_R)(iH^\dagger \hat{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$O_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$</td>
<td>$O_{2R}^u = (\bar{u}<em>R \gamma^\mu u_R)(iH^\dagger \hat{D}</em>\mu H)$</td>
</tr>
<tr>
<td>$O_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$</td>
<td></td>
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</tbody>
</table>

$\Delta L_6 \supset \sum_f \delta L_6^{(f)}$
Zh production: High energy primaries

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

\[
\begin{align*}
g_{ZuL}^{h}u_{L} & = -\frac{g}{c_{\theta W}} \frac{v^{2}}{\Lambda^{2}}(c_{L}^{1} - c_{L}^{3}) \\
g_{ZdL}^{h}d_{L} & = -\frac{g}{c_{\theta W}} \frac{v^{2}}{\Lambda^{2}}(c_{L}^{1} + c_{L}^{3}) \\
g_{ZuR}^{h}u_{R} & = -\frac{g}{c_{\theta W}} \frac{v^{2}}{\Lambda^{2}}c_{R}^{u} \\
g_{ZdR}^{h}d_{R} & = -\frac{g}{c_{\theta W}} \frac{v^{2}}{\Lambda^{2}}c_{R}^{d}
\end{align*}
\]
The hVff term

- High energy deviations in $ff \rightarrow Zh$ production dominated by hVff contact term:

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:

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

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

- 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:

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

\[ g_{ZuLuL} = -\frac{g}{c_{\theta_W}} \left( (c_{\theta_W}^2 + \frac{s_{\theta_W}^2}{3}) \delta g_{1^Z}^Z + W - \frac{t_{\theta_W}^2}{3} (\hat{s} - \delta \kappa - Y) \right) \]

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

Factor of 30
Per mille - % level constraint possible?
HIGH ENERGIES ESSENTIAL!

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

\[ pp \rightarrow Z(l\ell)h(\gamma\gamma) \]

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

$p_T^{l_1} + p_T^{l_2} > 60$ GeV

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

Less than 4 SM events at 300 fb

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

Cross Section: 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  \( \Rightarrow \)  Zh (bb) = 0.12 fb
- **Zbb** = 165 fb  \( \Rightarrow \)  Zbb = 0.22 fb
- **Zh (bb)** = 0.11 fb  \( \Rightarrow \)  Zh (bb) = 0.11 fb
- **Zbb** = 0.35 fb

**BDT optimisation**

**Cut-based Analysis**

- Zh (bb) = 0.12 fb  \( \Rightarrow \)  Zh (bb) = 0.12 fb
- Zbb = 0.22 fb  \( \Rightarrow \)  Zbb = 0.22 fb
- Zh (bb) = 0.11 fb  \( \Rightarrow \)  Zh (bb) = 0.11 fb
- Zbb = 0.35 fb  \( \Rightarrow \)  Zbb = 0.35 fb
Search Strategy

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

BDT optimisation

Cut-based Analysis

Butterworth et al, arXiv:0802.2470

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

Zh (bb) = 0.12 fb  Zbb = 0.22 fb

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!
To discriminate between SM and EFT we look at $Zh$ invariant mass distribution (300 ifb):
SM background vs EFT Signal

Unphysical

-0.012 # ghzur
-0.011 # ghzul
0.006 # ghzdr
0.005 # ghzdl
Cross section deviations and EFT Validity

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

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

Fractional Deviations \( \gg 1 \) signal a breakdown of EFT expansion unless UV completion is strongly coupled
Sensitivity

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):

Sensitive to 20-40 % cross-section deviations
• We will present final projections together with WZ projections.
Diboson production at LHC

Four channels:

- \( \text{ZH} \rightarrow G^0 H \)
- \( \text{WH} \rightarrow G^+ H \)
- \( \text{WW} \rightarrow G^+ G^- \)
- \( \text{WZ} \rightarrow G^+ G^0 \)

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

\[
\Phi = \left( \frac{G^+}{\sqrt{2}} \right) + i \frac{G^0}{\sqrt{2}} (v + H)
\]

Franceschini, Panico, Pomarol, Riva & Wulzer
arxiv:1712.01310
Diboson production at LHC

Four channels:

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- 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

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

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Four channels:

- **ZH** → $G^0 H$
- **WH** → $G^+ H$
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<td>$a_q^{(1)} + a_q^{(3)}$</td>
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<tr>
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<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

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<td>$\frac{g_{Zd_Ld_L}^h - g_{Zu_Lu_L}^h}{\sqrt{2}}$</td>
</tr>
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<td></td>
</tr>
<tr>
<td>$\bar{f}_R f_R \rightarrow W_L W_L, Z_L h$</td>
<td>$g_{Zf_Rf_R}^h$</td>
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Four channels:

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

$HV$ 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** → $G^0 H$
- **WH** → $G^+ H$
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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

Light (Dark) Blue: 300 (3000) ifb
LHC Projectiion vs existing LEP bound

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Projected Value</th>
<th>LEP Bound</th>
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<tbody>
<tr>
<td>$\delta g_{u_{L}^{Z}}$</td>
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</tr>
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<td>$-0.0036 \pm 0.0035$</td>
</tr>
<tr>
<td>$\delta g_{d_{R}^{Z}}$</td>
<td>$\pm 0.016 \ (\pm 0.005)$</td>
<td>$0.016 \pm 0.0052$</td>
</tr>
<tr>
<td>$\delta g_{1}$</td>
<td>$\pm 0.005 \ (\pm 0.001)$</td>
<td>$0.009_{-0.042}^{+0.043}$</td>
</tr>
<tr>
<td>$\delta \kappa_{\gamma}$</td>
<td>$\pm 0.032 \ (\pm 0.009)$</td>
<td>$0.016_{-0.096}^{+0.085}$</td>
</tr>
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<td>$\hat{S}$</td>
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300 ifb (3000 ifb)

Banerjee, Englert, RSG and Spannowsky (arxiv: 1807.01796)
**LHC Projection vs existing LEP bound**

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

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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(\ell\ell)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**

<table>
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<tr>
<th>Cuts</th>
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<th>(Z_{h (SM)})</th>
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<tr>
<td>1. At least 1 fat jet with 2 B-mesons with (p_T &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>
<td>0.501</td>
</tr>
<tr>
<td>3. 80 GeV &lt; (M_{l1l2}) &lt; 100 GeV, (p_T_{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 (p_T &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_{\text{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>Y_{\text{fatjet}}</td>
<td>&lt; 2.5, p_T_{\text{fatjet}} &gt; 200) GeV</td>
</tr>
<tr>
<td>(\text{and } p_T_{l1l2} &gt; 200) GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total**  
| \(Z_{h (SM)}\) | 0.002 | 0.024 |

**Zh (bb) = 0.11 fb**  
**Zbb = 0.35 fb**

Butterworth et al, arXiv:0802.2470
### Cut-flow

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

\[ Z_h(bb) = 4.6 \text{ fb} \quad Z_{bb} = 165 \text{ fb} \]

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</tr>
<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>Total</td>
<td>0.0014</td>
<td>0.026</td>
</tr>
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</table>

\[ Z_h(bb) = 0.12 \text{ fb} \]

\[ Z_{bb} = 0.22 \text{ fb} \]
Anomalous Higgs interactions not constrained by LEP

\[ \mathcal{L}_h^{\text{primary}} = g_{VV}^h h \left[ W^{+\mu} W^-_{\mu} + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu \right] + g_3^h h^3 + g_{ff}^h (h \bar{f}_L f_R + h.c.) \\
+ \kappa_{GG} \frac{h}{v} G^A_{\mu \nu} G^A_{\mu \nu} + \kappa_{\gamma\gamma} \frac{h}{v} A^{\mu \nu} A_{\mu \nu} + \kappa_{ZZ} t_{\theta_W} \frac{h}{v} A^{\mu \nu} Z_{\mu \nu} , \]

\[ \Delta \mathcal{L}_h = \delta g_{ZZ}^h \frac{v}{2c^2_{\theta_W}} h Z^\mu Z_\mu + g_{Zff}^h \frac{h}{2v} (Z_\mu J_{N}^\mu + h.c.) + g_{Wff'}^h \frac{h}{v} (W^+_{\mu} J_{C}^\mu + h.c.) \\
+ \kappa_{WW} \frac{h}{v} W^{+\mu \nu} W^{-\mu \nu} + \kappa_{ZZ} \frac{h}{v} Z^{\mu \nu} Z_{\mu \nu} , \]
Anomalous Higgs interactions not constrained by LEP

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

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

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

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

\[ \mathcal{L}_{h}^{\text{primary}} = g_{VV}^h h \left[ W^{+\mu} W^-_\mu + \frac{1}{2 c_{\theta W}^2} Z^\mu Z_\mu \right] + g_{3h}^h h^3 + g_{f f}^h (h \bar{f}_L f_R + h.c.) \\
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+ \ k_{WW}^h \frac{h}{v} W^{+\mu \nu} W^-_{\mu \nu} + k_{ZZ}^h \frac{h}{v} Z^{\mu \nu} Z_{\mu \nu} , \]
Anomalous Higgs interactions already constrained by LEP

\[ \mathcal{L}^{\text{primary}}_h = g^h_{VV} h \left[ W^+ \mu W^-_\mu + \frac{1}{2 c^2_{\theta W}} Z^\mu Z_\mu \right] + g^h_3 h^3 + g^h_{ff} (h \bar{f}_L f_R + h.c.) + \kappa_{GG} \frac{h}{v} G^A_{\mu \nu} G^A_{\mu \nu} + \kappa_{\gamma \gamma} \frac{h}{v} A^{\mu \nu} A_{\mu \nu} + \kappa_Z \gamma_t \theta_W \frac{h}{v} A^{\mu \nu} Z_{\mu \nu} , \]

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

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

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

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

8 operators

Redefining 8 parameters in the vacuum
EW and Higgs Pseudo-observables

(1) Higgs observables (20):

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

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

(1) Higgs observables (20):

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

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

(2) Electroweak precision observables (9):

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

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

(1) Higgs observables (20):

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

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

(2) Electroweak precision observables (9):

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

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

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

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

These were measured in \text{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!