EFT bounds from VV production

at hadron colliders

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based on an ongoing project with De Curtis, Delgado, Panico, Redi

with material from Panico’s slides
Precision at Hadron Colliders

Can we perform “precision measurements” at the hadron colliders?

- Obvious answer: 
  yes, for previously untested observables

for example:

- Higgs couplings at the LHC (can reach a precision better than 10%)
- Higgs trilinear coupling at the FCC (can reach ~5% precision)

- Are there other precision observables that we can access at the hadron colliders?

- Can we take advantage of the high energy to improve EW precision measurements?
Energy and accuracy

If new physics is heavy, low-energy effects are well described in the EFT framework:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

with the leading corrections arising from the dimension-6 operators.
Energy and accuracy

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with the leading corrections arising from the dimension-6 operators

- The deviations from the SM predictions typically grow with the energy

\[ \frac{A_{\text{SM+BSM}}}{A_{\text{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2} \]

- Hadronic machines can match lepton collider accuracies by exploiting the high energy reach

  - e.g. LEP vs LHC

  \[ 0.1 \% \text{ at } 100 \text{ GeV} \quad \rightarrow \quad 10 \% \text{ at } 1 \text{ TeV} \]
A comment on the EFT validity

Corrections can not be arbitrarily large

\[
\frac{A_{\text{SM+BSM}}}{A_{\text{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}
\]

Restrictions:

* consistency condition: \( E \lesssim \Lambda \)
* typically (for weakly coupled models)  \( \# < 1 \) \( \Rightarrow \frac{\delta A}{A_{\text{SM}}} \lesssim 1 \)

* leading effects are linear in BSM from the interference with the SM

* a reliable bound can be extracted only if the accuracy is better than the SM
  (\textit{need for clean channels with low systematic and statistical uncertainties})

* the cut-off restricts the analysis only to acceptable kinematic regions
Channels for EW precision tests

- large cross sections (low statistical uncertainties)
- small background and good theoretical control (low systematic uncertainties)
- good sensitivity to new physics effects (corrections growing with energy)

2 → 2 scattering processes are the natural candidates
Classes of $2 \rightarrow 2$ channels

* large cross sections
* background is ok
* large NP effects

* cross section is ok (pay BRs)
* background is ok (especially in leptonic channels)

* cross sections are small
* channels are dirtier

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 2017]
[Alioli, Farina, Pappadopulo, Ruderman, 2017]
[Franceschini, Panico, Pomarol, Riva, Wulzer, 2018]
[Panico, Riva, Wulzer, 2018]
[Banerjee, Englert, Gupta, Spannowsky, 2018]
[Azatov, Barducci, Venturini, 2019]
[......]
**Drell-Yan**

Drell-Yan production (neutral or charged)

\[ \overline{q} \rightarrow W/Z/\gamma \rightarrow q \ell \]

- Large cross section and interference at leading order with the SM

---

*direct searches for new resonances*
Drell-Yan production (neutral or charged)

\[ \overline{q} \rightarrow W/Z/\gamma \ell \]

\[ q \rightarrow W/Z/\gamma \overline{\ell} \]

Large cross section and interference at leading order with the SM

\[ \text{NP is too heavy:} \]

indirect searches for deformations from the SM
**Drell-Yan**

Drell-Yan production (neutral or charged)

\[ \bar{q} \rightarrow W/Z/\gamma \ell \]

- Large cross section and interference at leading order with the SM

- NP effects can be parameterised by oblique parameters

\[
\begin{align*}
\frac{gg' \hat{S}}{16m_w^2} (H^\dagger \sigma^a H) W_{\mu \nu}^a B^{\mu \nu} & \quad - \frac{g^2 T}{2m_w^2} |H^\dagger D_\mu H|^2 \\
- \frac{W}{4m_w^2} (D_\rho W_{\mu \nu}^a)^2 & \quad - \frac{Y}{4m_w^2} (\partial_\rho B_{\mu \nu})^2
\end{align*}
\]

- Bounds from LEP are at \( \sim 0.1\% \) level
**Drell-Yan**

Drell-Yan production (neutral or charged)

\[
\begin{array}{c}
\bar{q} \\
W/Z/\gamma \\
q \\
\ell \\
\ell
\end{array}
\]

\[P_N = \left[ \frac{1}{q^2} - \frac{t_w^2 W + Y}{m_z^2} \times \frac{t_w((Y + \hat{T})c_w^2 + s_w^2 W - \hat{S})}{(c_w^2 - s_w^2)(q^2 - m_z^2)} + \frac{t_w(Y - W)}{m_z^2} \right]
\]

\[P_C = \frac{1 + ((\hat{T} - W - t_w^2 Y) - 2t_w^2(\hat{S} - W - Y))(1 - t_w^2)}{q^2 - m_w^2} - \frac{W}{m_w^2}
\]

* \(\hat{S}\) and \(\hat{T}\) only affect the total cross section through a modification of the residue of the poles in the propagators (*not competitive with LEP*)

* \(W\) and \(Y\) introduce constant terms and thus induce an enhancement at high energy
** 13 TeV measurements much better than LEP

** FCC-hh more than one order of magnitude better than HL-LHC
We are interested in processes that fulfil two conditions:

* BSM effects growing with $E^2$ at leading order (in $d=6$ EFT)

* SM amplitudes constant and sizeable at high $E$

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>BSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{L,R} \bar{q}_{L,R} \rightarrow V_L V_L(h)$</td>
<td>$\sim 1$</td>
<td>$\sim E^2/M^2$</td>
</tr>
<tr>
<td>$q_{L,R} \bar{q}<em>{L,R} \rightarrow V</em>{\pm} V_L(h)$</td>
<td>$\sim m_W/E$</td>
<td>$\sim m_W E/M^2$</td>
</tr>
<tr>
<td>$q_{L,R} \bar{q}<em>{L,R} \rightarrow V</em>{\pm} V_{\pm}$</td>
<td>$\sim m_W^2/E^2$</td>
<td>$\sim E^2/M^2$</td>
</tr>
<tr>
<td>$q_{L,R} \bar{q}<em>{L,R} \rightarrow V</em>{\pm} V_{\mp}$</td>
<td>$\sim 1$</td>
<td>$\sim 1$</td>
</tr>
</tbody>
</table>

opposite chirality $q, \bar{q}$ initial states are suppressed by Yukawa couplings in the SM

$V_L V_L$ and $V_L h$ are the only processes that display quadratic energy growth at the interference level
Growing with the energy

All \( d = 6 \) operators induce an energy growth but not in all channels

Example: the \( WZ \) channel

**the triplet operator**

\[
\mathcal{O}_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L) (i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)
\]

- corrections to \( W \) and \( Z \) vertices
- growth with \( E^2 \)

**the singlet operator**

\[
\mathcal{O}_L = (\bar{q}_L \gamma^\mu q_L) (i H^\dagger \overleftrightarrow{D}_\mu H)
\]

- corrections to \( Z \) vertices
- no growth
Growing with the energy

very easy to understand by exploiting the equivalence theorem

\[ W^\pm, Z \rightarrow \phi^\pm, \phi^0 \] at high energy

the triplet operator

\[ O_L^3 = (\bar{q}_L \sigma^a \gamma^\mu q_L)(iH^\dagger \sigma^a \bar{D}_\mu H) \]

\[ u_L \rightarrow \phi^+ \]

\[ d_L \rightarrow \phi^0 \]

contributes to \( W_LZ_L \)

the singlet operator

\[ O_L = (\bar{q}_L \gamma^\mu q_L)(iH^\dagger \bar{D}_\mu H) \]

\[ u_L, d_L \rightarrow \phi^\pm, \phi^0 \]

\[ u_L, d_L \rightarrow \phi^\mp, \phi^0 \]

does not contribute to \( W_LZ_L \) (but to \( W_LW_L \) and \( Z_Lh \))

probing di-boson at high-energy is a way to test the Higgs dynamics
The relevant operators

The relevant BSM effects (d=6 EFT) can be parameterised by:

\[
\delta A(q'_\pm \bar{q}_\mp \rightarrow \Phi \Phi') = \frac{1}{4} A_{q'_\pm \bar{q}_\mp}^{\Phi \Phi'} E^2 \sin \theta^*
\]

the coefficients \( A_{q'_\pm \bar{q}_\mp}^{\Phi \Phi'} \) are subject to constrains:

* flavour universality in the light quark generations
* the coefficients can be taken real
* SM symmetry is restored in the high-energy limit

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>High-energy primaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{u}_L d_L \rightarrow W_L Z_L, W_L h )</td>
<td>( \sqrt{2}a_q^{(3)} )</td>
</tr>
<tr>
<td>( \bar{u}_L u_L \rightarrow W_L W_L ) ( \bar{d}_L d_L \rightarrow Z_L h )</td>
<td>( a_q^{(1)} + a_q^{(3)} )</td>
</tr>
<tr>
<td>( \bar{d}_L d_L \rightarrow W_L W_L ) ( \bar{u}_L u_L \rightarrow Z_L h )</td>
<td>( a_q^{(1)} - a_q^{(3)} )</td>
</tr>
<tr>
<td>( \bar{f}_R f_R \rightarrow W_L W_L, Z_L h )</td>
<td>( a_f )</td>
</tr>
</tbody>
</table>

[Franceschini, Panico, Pomarol, Riva, Wulzer, 2018]
The relevant operators

the fact that only 4 HEP parameters produce the sizeable effects is non-trivial since a generic d=6 EFT contributes to $V_LV_L$ with 6 anomalous couplings

$$\Delta \mathcal{L}_{BSM} = \delta g_{uL}^Z \left[ Z^\mu \bar{u}_L \gamma_\mu u_L + \frac{c_\theta W}{\sqrt{2}} (W^{+\mu} \bar{u}_L \gamma_\mu d_L + \text{h.c.}) + \cdots \right] + \delta g_{uR}^Z \left[ Z^\mu \bar{u}_R \gamma_\mu u_R + \cdots \right]$$

$$+ \delta g_{dL}^Z \left[ Z^\mu \bar{d}_L \gamma_\mu d_L - \frac{c_\theta W}{\sqrt{2}} (W^{+\mu} \bar{u}_L \gamma_\mu d_L + \text{h.c.}) + \cdots \right] + \delta g_{dR}^Z \left[ Z^\mu \bar{d}_R \gamma_\mu d_R + \cdots \right]$$

$$+ igc_\theta W \delta g_1^Z \left[ (Z^\mu (W^{+\nu} W_{\mu\nu} - \text{h.c.}) + Z^{\mu\nu} W^+_\mu W^-_{\nu} + \cdots \right]$$

$$+ ie \delta \kappa_\gamma \left[ (A_{\mu\nu} - t_{\theta W} Z_{\mu\nu}) W^{+\mu} W^{-\nu} + \cdots \right],$$

[Gupta, Pomarol, Riva, 2015]

the 4 high-energy primaries can be easily related to explicit operator basis

for instance, there is a 1-1 correspondence with operators in the Warsaw basis

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

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

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

$$\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \hat{D}_\mu H)$$

$$a_u = 4 \frac{c_{\theta R}}{M^2}, \ a_d = 4 \frac{c_{\theta R}}{M^2}, \ a_q^{(1)} = 4 \frac{c_{L}^{(1)}}{M^2}, \ a_q^{(3)} = 4 \frac{c_{L}^{(3)}}{M^2}$$
Reach at the LHC from WZ

Estimate of the bounds on $a_q^{(3)}$ from WZ (fully leptonic)

$$a \sim \frac{g_{BSM}^2}{M^2} \rightarrow \frac{A_{BSM}}{A_{SM}} \sim \left( \frac{g_{BSM}}{g} \right)^2 \left( \frac{E}{M} \right)^2$$

the departure from the SM can be larger than one even for $E \ll M$
Reach at the LHC from WZ

Estimate of the bounds on $a_q^{(3)}$ from WZ (fully leptonic)

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the departure from the SM is larger than one even for $E \ll M$

LEP2 measurements of the aTGC

- Fully Strong
- Strong TGC

Weak
- 10% syst.
- 5% syst.
- 1% syst.
- 1% syst.

14 TeV 300/ab
14 TeV 3/ab

supersymmetric models

models where both fermions and Higgs are strongly coupled

strongly coupled Higgs and transverse vectors

weakly-coupled models

excluded by perturbative unitarity
Reach at the LHC from WZ

Estimate of the bounds on $a_q^{(3)}$ from WZ (fully leptonic)

- big improvement with respect to LEP and LHC run1
- systematics play an important role in the precision reach
- wide range of weakly-coupled BSM is covered (but accuracy is important!)
Reach at future colliders from WZ

Estimate of the bounds on $a_q^{(3)}$ from WZ (fully leptonic)

![Graph showing expected 95% CL bounds from fully leptonic WZ on the high-energy primary parameter $a_q^{(3)}$ as a function of the new physics scale $M$. The plots report the results for the HL-LHC (orange lines), HE-LHC (green lines), and FCC-hh (brown lines) for different values of the systematic uncertainties.]

- *reach at the FCC-hh is more than one order of magnitude better than HL-LHC*
big improvement on $\delta g_1^Z$ with respect to LEP

hadron colliders are probing an independent direction
Reach at future colliders from $Zh$

Estimate of the bounds from $pp \rightarrow Zh$ on universal theories:

[Z leptonic, $h \rightarrow b\bar{b}$]

[Z leptonic, $h \rightarrow \gamma\gamma$]

[Fig. 2: We show in light blue (dark blue) the projection derived by turning on only the given parameter and putting all other parameters to zero.]

[Table IV: Comparison of the bounds obtained in this work for the allowed region with $300 \text{ fb}^{-1}$ for the pseudo-observables such as $\hat{f}$ obtained by varying each parameter one by one, as compared to the bounds obtained by varying all parameters to zero.]

[Banerjee, Englert, Gupta, Spannowsky, 2018]

* reach at the FCC-hh is more than one order of magnitude better than HL-LHC (the analysis is still very preliminary!)

[LEP, LHC, FCC-hh]

LEP bounds on the LEP observables in Eq. (23) and the bounds from Eq. (24) are shown. The bounds from Ref. [Banerjee, Englert, Gupta, Spannowsky, 2018] - $WZ$, $L = 3 \text{ ab}^{-1}$, $Zh$, $L = 300 \text{ fb}^{-1}$ - are shown. The purple (green) region shows the region that survived after our projection from Ref. [Banerjee, Englert, Gupta, Spannowsky, 2018] - $WZ$, $L = 3 \text{ ab}^{-1}$, $Zh$, $L = 300 \text{ fb}^{-1}$ - and the pink (dark pink) region corresponds to the projection from Ref. [Banerjee, Englert, Gupta, Spannowsky, 2018] - $WZ$, $L = 3 \text{ ab}^{-1}$, $Zh$, $L = 300 \text{ fb}^{-1}$ - with all other parameters to zero. The bound on the TGCs from Ref. [Banerjee, Englert, Gupta, Spannowsky, 2018] - $WZ$, $L = 3 \text{ ab}^{-1}$, $Zh$, $L = 300 \text{ fb}^{-1}$ - and the bound on the TGCs from Ref. [Banerjee, Englert, Gupta, Spannowsky, 2018] - $WZ$, $L = 3 \text{ ab}^{-1}$, $Zh$, $L = 300 \text{ fb}^{-1}$ - are shown. The bounds in the last column were derived in this work and are shown in light blue (dark blue).]
Conclusions

Hadron colliders can be used to perform **EW precision tests** exploiting:

- **energy growth** of new-physics effects and **accurate measurements**

Challenges:

- accessing the **high-energy** tails (*need for good statistics*)
- **accuracy** (*need for low systematics, eg. in leptonic final states*)

Hadron colliders can be competitive or even better than lepton ones

- di-lepton DY production
- di-boson production

FCC-hh can improve of (*more than*) one order of magnitude on HL-LHC

Outlook:

- study of other channels/signatures
- exploit full kinematic distributions