Precision diboson measurements

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06/02/2020
New Physics on the Low-Energy Precision Frontier
CERN
Testing SM interactions in diboson production

- New interactions can modify $\psi\psi V$, $VVV$ vertices
- EFT presents a perfect framework for parametrizing deviations from the SM
Anomalous TGC

- In SM interactions of the vector bosons are fixed by the gauge symmetry
  \[ ig \, W^+_{\mu\nu} \, W^-_{\nu} + ig \, W^3_{\mu\nu} \, W^+_{\mu} \, W^-_{\nu} \]

- Three possible deformations are allowed at the level of dimension six operators:
  \[ igc_0 \delta g_{1, Z} \, Z_{\nu} \, W^+_{\mu\nu} \, W^-_{\mu} + h.c. + ig \left( c_0 \, \delta \kappa \, Z_{\mu\nu} + s_0 \, \delta \kappa \gamma \, A_{\mu\nu} \right) \, W^+_{\mu} \, W^-_{\nu} \]
  and
  \[ \lambda_Z \, \frac{ig}{m_W^2} \, W^+_{\mu_1} \, W^-_{\mu_2} \, W^3_{\mu_3} \, W^3_{\mu_1} \]

These interactions are bounded at LEP-2 at % level
\[ \lambda_Z \in [-0.059, 0.017], \, \delta g_{1, Z} \in [-0.054, 0.021], \, \delta \kappa Z \in [-0.074, 0.051] \]
At LHC these couplings are constrained mainly from the $qq \rightarrow VV$ process.

We want to exploit large collision energy of LHC to put stricter bounds.
We can use the Goldstone equivalence theorem to easily predict the leading energy growth of the amplitudes.

\[ W_L^+ = G^+ \times \left(1 + O(m_W^2/E^2)\right) \]

\[ \text{tr} W_{\mu\nu} W^{\mu\nu} \supset \partial V_T V_T V_T, \quad (D_\mu H)^\dagger D^\mu H \supset \partial V_L V_T V_L + v V_T V_T V_L \]

\[ \Downarrow \]

\[ M \left(q\bar{q} \rightarrow V_T W_T^+ \right) \sim E^0, \quad M \left(q\bar{q} \rightarrow V_L W_L^+ \right) \sim E^0 \]

\[ M \left(q\bar{q} \rightarrow V_T W_L^+/V_L W_T^+ \right) \sim \frac{v}{E} \]
Anomalous TGC energy scaling

- It is useful to think about TGC in terms of the EFT operators before EWSB.

\[ O_{HB} = ig'(D^\mu H)^\dagger D^\nu HB_{\mu\nu}, \quad O_{HW} = ig(D^\mu H)^\dagger \sigma^a D^\nu HW^a_{\mu\nu} \]
\[ O_{3W} = \frac{g}{3!} \epsilon_{abc} W^a_{\mu\nu} W^b_\nu W^c_\rho W^{c,\mu}_\rho \]

\[ \lambda_Z = \frac{m_W^2}{\Lambda^2} c_{3W}, \quad \delta g_{1,Z} = \frac{m_Z^2}{\Lambda^2} c_{HW}, \quad \delta \kappa_Z = \frac{m_W^2}{\Lambda^2} (c_{HW} - \tan^2 \theta c_{HB}) \]

(not a unique map)

- We can use the Goldstone boson equivalence theorem to estimate the leading energy scaling of the new contributions.
Energy growth of the BSM amplitudes

We start with dimension six operators

\[ O_{HB} = ig'(D^\mu H)\dagger D^\nu HB_{\mu\nu}, \quad O_{HW} = ig(D^\mu H)\dagger \sigma^a D^\nu HW^a_{\mu\nu} \]

\[ O_{3W} = \frac{g}{3!} \epsilon_{abc} W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\mu\rho} \]

Goldstone equivalence theorem relates \( H \Rightarrow W_L, Z_L \)

\[ O_{HB} \supset \partial W_L \partial Z_T \partial W_L + 2 W_T \partial Z_T \partial V_T + \ldots \\
O_{HW} \supset \partial V_L \partial V_T \partial V_L + 2 V_T \partial V_T \partial V_T + \ldots \\
O_{3W} \supset \partial V_T \partial V_T \partial V_T + \ldots \]

Leading energy scaling can be estimated by noting that the light quarks couple mostly to transverse gauge bosons:

\[
\mathcal{M} \left( q\bar{q} \rightarrow W_L^- W_L^+ \right) \sim E^2/\Lambda^2 c_{HB} + E^2/\Lambda^2 c_{HW} \sim E^2/m_W^2 \delta g_{1,Z} + E^2/m_W^2 \delta \kappa_Z \\
\mathcal{M} \left( q\bar{q} \rightarrow Z_L W_L^+ \right) \sim E^2/\Lambda^2 c_{HW} = E^2/m_Z^2 \delta g_{1,Z} \\
\mathcal{M} \left( q\bar{q} \rightarrow V_T W_T^+ \right) \sim E^2/\Lambda^2 c_{3W} = E^2/m_W^2 \lambda_Z
\]

We have an additional \( E^2 \) compared to the SM amplitudes, as expected from dimensional analysis.
Current constraints from LHC

Baglio et al 1909.11576

**LEP-2 % bounds**

\[ \lambda_Z \in [-0.059, 0.017], \quad \delta g_{1Z} \in [-0.054, 0.021], \quad \delta \kappa_Z \in [-0.074, 0.051] \]
SM and BSM amplitudes with more details

\[ M \left( q \bar{q} \rightarrow W^-_L W^+_L \right) \sim E^2 / \Lambda^2 \ c_{HB} + E^2 / \Lambda^2 \ c_{HW} \sim E^2 / m_W^2 \ \delta g_{1,Z} + E^2 / m_W^2 \ \delta \kappa_{Z} \]

\[ M \left( q \bar{q} \rightarrow Z_L W^+_L \right) \sim E^2 / \Lambda^2 \ c_{HW} = E^2 / m_Z^2 \ \delta g_{1,Z}, \]

\[ M \left( q \bar{q} \rightarrow V_T W^+_T \right) \sim E^2 / \Lambda^2 \ c_{3W} = E^2 / m_W^2 \ \lambda_{Z} \] does not interfere with SM!

\[ \epsilon_{abc} W^{a \nu}_\mu W^{b \rho}_\nu W^{c, \mu}_\rho \]

External vectors have the same polarizations
SM and BSM amplitudes with more details

\[ \mathcal{M} \left( q \bar{q} \rightarrow W^- L^+ \right) \sim E^2/\Lambda^2 \ c_{HB} + E^2/\Lambda^2 \ c_{HW} \sim E^2/m_W^2 \ \delta g_{1,Z} + E^2/m_W^2 \ \delta \kappa_Z \]
\[ \mathcal{M} \left( q \bar{q} \rightarrow Z L^+ \right) \sim E^2/\Lambda^2 \ c_{HW} = E^2/m_Z^2 \ \delta g_{1,Z} , \]
\[ \mathcal{M} \left( q \bar{q} \rightarrow V^*_T W^T_T \right) \sim E^2/\Lambda^2 \ c_{3W} = E^2/m_W^2 \ \lambda_Z \] does not interfere with SM!

Helicity selection rule for \( O_{3W} \)

Lorentz symmetry and the dimensional analysis fixes three point amplitudes to satisfy:

\[ \sum h = 1 - [g] = 3 \]

for dimension 6 operators (Cachazo, Benincasa) \( \Rightarrow \) fields coming from \( W_{\mu\nu} W_{\nu\lambda} W_{\lambda\mu} \) have always the same helicity.

in SM the vectors will have opposite helicities

![Graph showing the ratio of \( \sigma_{int}/\sigma_{SM} \) against \( m_{VV} [GeV] \). The graph includes several curves representing different helicity contributions.](image-url)
In high energy limit we can treat all the SM particles as massless, the spinor-helicity formalism becomes very useful!

In SM all the amplitudes for $2 \rightarrow 2$ processes follow the helicity selection rule:

$$A(V^+ V^+ V^+ V^+) = A(V^+ V^+ V^+ V^-) = A(V^+ V^+ \psi^+ \psi^-)$$
$$= A(V^+ V^+ \phi \phi) = A(V^+ \psi^+ \psi^+ \phi) = 0.$$  

The total helicity is always zero, except for the four fermion amplitudes mediated by the Higgs exchange.

In BSM for the processes we never get total helicity zero if there is at least one transverse vector boson. arXiv:1607.05236 AA R.Contino, C.Machado, F.Riva

No interference between SM and BSM in the presence of the transverse vector bosons!
\[ pp \rightarrow V_L V_L \]
Longitudinal vector boson production

- At the level of dimension six there are also contact operators between fermions contributing to the same process

\[ \bar{\psi} \gamma^\mu \psi (H^\dagger \leftrightarrow D_\mu H) \]

- If are looking at the \(qq \to VV\) process all of the amplitudes (in high energy limit) can be parametrized in terms of only 4 parameters

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>High-energy primaries</th>
<th>Low-energy primaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{u}_L d_L \to W_L Z_L, W_L h)</td>
<td>(\sqrt{2}a_q^{(3)})</td>
<td>(\sqrt{2} \frac{g^2}{m_W^2} [c_{\phi W}(\delta g_{uL}^{Z} - \delta g_{dL}^{Z})/g - c_{\phi W}^{2} \delta g_{1}^{Z}])</td>
</tr>
<tr>
<td>(\bar{u}_L u_L \to W_L W_L)</td>
<td>(a_q^{(1)} + a_q^{(3)})</td>
<td>(- \frac{2g^2}{m_W^2} [Y_{L} t_{\phi W}^{2} \delta \kappa_{\gamma} + T_{Z}^{dL} \delta g_{1}^{Z} + c_{\phi W} \delta g_{1}^{Z}]/g)</td>
</tr>
<tr>
<td>(\bar{d}_L d_L \to Z_L h)</td>
<td>(a_q^{(1)} - a_q^{(3)})</td>
<td>(- \frac{2g^2}{m_W^2} [Y_{L} t_{\phi W}^{2} \delta \kappa_{\gamma} + T_{Z}^{dL} \delta g_{1}^{Z} + c_{\phi W} \delta g_{1}^{Z}]/g)</td>
</tr>
<tr>
<td>(\bar{u}_L u_L \to Z_L h)</td>
<td>(a_f)</td>
<td>(- \frac{2g^2}{m_W^2} [Y_{fR} t_{\phi W}^{2} \delta \kappa_{\gamma} + T_{Z}^{fR} \delta g_{1}^{Z} + c_{\phi W} \delta g_{1}^{Z}]/g)</td>
</tr>
</tbody>
</table>

1609.06312, Falkowski et al; 1712.01310, Franceschini et al
Improving the LHC reach

- SM contribution is dominated by the transverse modes $\gtrsim 93\%$
- Luckily the transverse contribution can be suppressed by cutting away $W$ bosons at small angles

1712.01310, Franceschini et al
Results for $pp \rightarrow V_L V_L$
Results for $pp \to V_L V_L$

1810.05149 Grojean et al; 1807.01796 Banerjee et al
LHC vs Z pole observables at LEP-1

\[ \bar{\psi} \gamma^\mu \psi (H^\dagger \leftrightarrow D_\mu H) \] will effect the Z pole observables strongly constrained by LEP-1

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1810.05149 Grojean et al
\[ pp \rightarrow V_T V_T \]

\[ W_{\mu\nu} W^{\nu\lambda} W^\mu_\lambda, \quad \tilde{W}_{\mu\nu} W^{\nu\lambda} W^\mu_\lambda \] a TGC give a contribution growing as \( E^2 \) but not interfering with SM

\[
\begin{align*}
SM : \, qq & \rightarrow V^\pm V^\mp \\
BSM : \, qq & \rightarrow V^\pm V^\pm
\end{align*}
\]
Why the interference term is important?

- Generically in the presence of new physics
  \[ \mathcal{L} = \mathcal{L}^{SM} + \mathcal{L}^6 + \mathcal{L}^8 + \cdots, \quad \mathcal{L}^D = \sum_i c_i^{(D)} \mathcal{O}_i^{(D)}, \quad c_i^{(D)} \sim \frac{1}{\Lambda^{D-4}} \]

\[ \sigma \sim SM^2 + \frac{SM \times BSM_6}{\Lambda^2} + \frac{BSM_6^2}{\Lambda^4} + \frac{SM \times BSM_8}{\Lambda^4} + \cdots \]

- Leading term in $\frac{1}{\Lambda^2}$ comes from the interference between SM and BSM
- Both $|BSM_8|$ and $|BSM_6|^2$ are suppressed by the $\Lambda^4$ scale. Is it consistent to truncate the expansion at the dimension six level?

- The analysis is consistent if only
  \[ \text{Max} \left[ \frac{SM \times BSM_6}{\Lambda^2}, \frac{BSM_6^2}{\Lambda^4} \right] \gg \frac{SM \times BSM_8}{\Lambda^4} \]
Importance of interference \((qq \rightarrow V_T V_T)\)

\[
\sigma_6 \sim g_{SM}^4 \frac{E^2}{E^2} \left[ 1 + c_3W \frac{m_V^2}{\Lambda^2} + c_3W \frac{E^4}{\Lambda^4} \right], \quad \sigma_8 \sim g_{SM}^4 \left[ c_8 \frac{E^4}{\Lambda^4} + c_8 \frac{E^8}{\Lambda^8} \right]
\]

Then the dimension six truncation is valid if only

\[
\max \left( c_3W \frac{m_V^2}{\Lambda^2}, c_3W \frac{E^4}{\Lambda^4} \right) > \max \left( c_8 \frac{E^4}{\Lambda^4}, c_8 \frac{E^8}{\Lambda^8} \right)
\]

If we will be able to overcome the interference suppression the condition relaxes to

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\]

is this important?
Importance of interference \((qq \rightarrow V_T V_T)\)

\[
\sigma_6 \sim \frac{g_{SM}^4}{E^2} \left[1 + c_3 W \frac{m_V^2}{\Lambda^2} + c_3 W \frac{E^4}{\Lambda^4}\right], \quad \sigma_8 \sim \frac{g_{SM}^4}{E^2} \left[c_8 \frac{E^4}{\Lambda^4} + c_8^2 \frac{E^8}{\Lambda^8}\right]
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\]

is this important?

Depends on power-counting i.e. types of UV completions we are studying.
Importance of interference, breaking the flat directions

\[ \sigma = \sigma_0 + \sigma^{\text{int}} c_3 W + \tilde{\sigma}^{\text{int}} \tilde{c}_3 W + \sigma^{\text{BSM}_1} c_3^2 W + \sigma^{\text{BSM}_2} \tilde{c}_3^2 W + \sigma^{\text{BSM}_3} c_3 W \tilde{c}_3 W. \]

Only interference can distinguish the contributions of the \( O_{3W}, O_{3\tilde{W}} \) operators.

The only way to measure the sign of the Wilson coefficients!
Overcoming the non-interference obstruction: 1st method

Dixon, Shadmi 94

- The non-interference selection rule applies only for the $2 \rightarrow 2$ processes at tree level. There are violations at NLO!

- $(W)^3$ vertex always emits same helicity $W$ bosons, however the helicity of the gluon is not restricted!

- For SM amplitudes gluons are carrying away the needed opposite helicity.

- at one loop level helicity selection rules are not valid any more.

We can use a tag for jet to suppress the background as well, no need to pay $\frac{\alpha_s}{4\pi}$ for the signal to background ratio.
No Jet
Jet with $p_j^T > 100\text{GeV}$
Jet with $p_j^T > m_{wz}/10$
Jet with $p_j^T > m_{wz}/5$

$m_{wz}$ [GeV]

$\sigma_{int}/\sigma_{SM}$

1707.08060
Overcoming the interference obstruction: 2nd method

- Non-interference result is obtained for the $2 \rightarrow 2$ processes, in reality we are looking at $2 \rightarrow 4$ process since both $W,Z$ decay.

- Let us consider for simplicity $2 \rightarrow 3$ process in the narrow width approximation, then the interference with of the amplitudes with opposite intermediate $Z$ helicities will be:

$$
\frac{\pi}{2s} \frac{\delta(s-m_Z^2)}{\Gamma_Z m_Z} M^{SM}_{q\bar{q} \rightarrow W_T^+ Z_{T-}} \left( M^{BSM}_{q\bar{q} \rightarrow W_T^+ Z_{T-}} \right)^* M_{Z_{T-} \rightarrow l^- \bar{l}^+} M^*_{Z_{T+} \rightarrow l^- \bar{l}^+} \Rightarrow \\
\frac{d\sigma_{\text{int}}(q\bar{q} \rightarrow W_+ l^- \bar{l}^+)}{d\phi_Z} \propto M_{Z_{T-} \rightarrow l^- \bar{l}^+} M^*_{Z_{T+} \rightarrow l^- \bar{l}^+} \propto \cos(2\phi_Z)
$$
Overcoming the interference obstruction: 2nd method

Duncan, Kane, Repko 85

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\frac{\pi}{2s} \frac{\delta(s-m_Z^2)}{\Gamma_Z m_Z} M_{q\bar{q} \rightarrow W_{T^+} Z_{T^-}} \left( \mathcal{M}_{q\bar{q} \rightarrow W_{T^+} Z_{T^+}}^{\text{BSM}} \right)^* M_{Z_{T^-} \rightarrow l^- \bar{l}^+} M_{Z_{T^+} \rightarrow l^- \bar{l}^+}^* \Rightarrow \\
d\sigma_{\text{int}}(q\bar{q} \rightarrow W_{T^+} l^- \bar{l}^+) \propto M_{Z_{T^-} \rightarrow l^- \bar{l}^+} M_{Z_{T^+} \rightarrow l^- \bar{l}^+}^* \propto \cos(2\phi_Z)
\]

1707.08060
Azimuthal angle modulation

\[ \frac{d\sigma_{\text{int}}(q\bar{q} \rightarrow WZ \rightarrow 4\psi)}{d\phi_Z d\phi_W} \propto \cos(2\phi_Z) + \cos(2\phi_W) \]

- The modulation in azimuthal angles will always happen if there are virtual states with the different polarizations.
- for the $\lambda_Z$ deformation, no need to bin in both angles, we can just look at the decays of one gauge boson.
Azimuthal angle modulation

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- The modulation in azimuthal angles will always happen if there are virtual states with the different polarizations.
- for the \( \lambda_Z \) deformation, no need to bin in both angles, we can just look at the decays of one gauge boson.
Can repeat a similar argument for the CP odd operator

\[ O_{3\tilde{W}} = -\frac{1}{\Lambda^2} \frac{g}{3!} \epsilon_{abc} \tilde{W}^{a,\mu\nu} W^{b}_{\nu\lambda} W^{c\lambda}_{\mu} \]

we are getting the interference scales as

\[ \frac{d\sigma_{\text{int}}^{3\tilde{W}}(q\bar{q} \to WZ \to 4\psi)}{d\phi_{Z} d\phi_{W}} \propto \sin(2\phi_{Z}) + \sin(2\phi_{W}) \]
In experiment we measure only the charges of the leptons, not their helicities.

Angular modulation is fixed by the helicities of the decay products, so we have an ambiguity in determining the plane of the $Z$ decay $\phi_Z$.

$$\phi_Z \rightarrow \phi_Z + \pi \mod 2\pi$$

irrelevant for the $O_{3W}$, $O_{3\tilde{W}}$ operators since the modulation is

$$\propto \cos 2\phi_Z, \sin 2\phi_Z$$
So far we have focused only on the Z decay plane, what about W decay plane? We need to reconstruct the neutrino momentum. Two-fold ambiguity leads to the degeneracy

\[ \phi_W \rightarrow \pi - \phi_W \mod 2\pi \]

\[ O_{3W} \propto \cos 2\phi \quad \text{OK} \]
\[ O_{3\bar{W}} \propto \sin 2\phi \quad \text{NO} \]
\[ \phi_W \rightarrow \pi - \phi_W \mod 2\pi \quad \phi_Z \rightarrow \phi_Z + \pi \mod 2\pi \]

Both \( O_{3W} \) and \( \tilde{O}_{3W} \) can be measured in spite of these ambiguities:

\[
\frac{g}{3!} \epsilon_{abc} W^a_{\mu \nu} W^b_{\nu \rho} W^c_{\rho \mu} \propto \cos 2\phi_Z + \cos 2\phi_W,
\]

\[
\frac{g}{3!} \epsilon^{abc} \tilde{W}^a_{\mu \nu} W^b_{\nu \rho} W^c_{\rho \mu} \propto \sin 2\phi_Z + \sin 2\phi_W.
\]
Higher order QCD effects are known to be important (1703.09065, Grazzini et al)

In our case we know that NLO QCD effects can change qualitatively interference effects

MadGraph5 aMCNLO using (HELatNLOUFO model) + PYTHIA8

NLO+j events with Fx Fx merging are simulated to understand the importance of the NNLO effects

We have checked the results for the SM signal and we are able to reproduce identically the NLO results known in the literature

The analysis is done for the $WZ \rightarrow lll\nu$ and $W\gamma \rightarrow l\nu\gamma$ final state following very closely experimental studies (ATLAS-CONF-2018-034 (2018), CMS Collaboration, Phys. Rev. D89 (2014)).
So far we have been completely ignoring the kinematic acceptance cuts needed to suppress the background.

In order to suppress the background without genuine missing $E_T$ cut on $M_W^{T}$ variable is used

$$(M_W^{T})^2 = (p_T^e + \vec{p}_T)^2 - (\vec{p}_T^e + \vec{p}_T)^2$$

There is correlation between $M_W^{T}$ cut and $\phi_W$
Modulation from cuts

\[ M_T^W = 0 \Rightarrow \vec{p}_T^e || \vec{p}_T^W \Rightarrow \phi_W = 0, \pi \]

\[ M_T^W = M_W \Rightarrow \frac{|\vec{p}_T^e|}{|\vec{p}_T^\nu|} = -\frac{p_z^e}{p_z^\nu}, \text{ if } p_T^W \gg p_z^W \Rightarrow \text{ then we will have} \]
\[ p_T^{e,\nu} \gg p_z^{e,\nu} \text{ so that the angles are roughly } \pi/2 . \]

**Figure:** Left- no cuts, Right- \( p_T^\gamma > 100 \text{ GeV} \)

Strong correlation between \( M_T \) and azimuthal angles, especially for the boosted particles. Strong cut on \( M_T \) selects the bin \( \phi \in [\pi/4, 3\pi/4] \) (\( \sim \cos 2\phi \) modulation).
NLO effects

\[ \phi_Z = [\pi/4, 3\pi/4] \]

\[ \text{Ratio of } \sigma_{\text{int}}^{\text{NLO}} / \sigma_{\text{LO}} \]

\[ \text{NLO}/\text{LO} \]
\[ \text{NLO}_j/\text{LO} \]
\[ \text{NLO}_j/\text{NLO} \]

\[ m_{WZ}^T [\text{GeV}] \]
**Results: WZ analysis @ 14 TeV**

The sensitivity on $O_{3W}$ is comparable to the bounds from neutron EDM's.
Results: WA analysis @ 14 TeV

\[ pp \to W\gamma \text{ LHC 14 TeV } L = 3 \text{ ab}^{-1} \]

\[ C_3^W \quad \tilde{C}_3^W \]

\[ m_{W\gamma}^{max} [\text{GeV}] \]

\[ C_3^W \text{ or } \tilde{C}_3^W [1/\text{TeV}^2] \]

The modulation from cuts mimics the binning in \( \phi_W \)
Results: WZ analysis @ 27 TeV
Results: WA analysis @ 27 TeV
### Summary of the bounds

<table>
<thead>
<tr>
<th>Channel</th>
<th>Energy</th>
<th>Luminosity</th>
<th>$\lambda_Z \times 10^{-3}$</th>
<th>$\tilde{\lambda}_Z \times 10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>68%</td>
<td>95%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>68%</td>
<td>95%</td>
</tr>
<tr>
<td>$WZ$</td>
<td>14 TeV</td>
<td>3 ab$^{-1}$</td>
<td>[-2.1, 1.2]</td>
<td>[-2.9, 1.7]</td>
</tr>
<tr>
<td></td>
<td>27 TeV</td>
<td>3 ab$^{-1}$</td>
<td>[-1.4, 0.7]</td>
<td>[-2.2, 1.2]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 ab$^{-1}$</td>
<td>[-0.7, 0.4]</td>
<td>[-1.2, 0.6]</td>
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<td>$W\gamma$</td>
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<tr>
<td></td>
<td>27 TeV</td>
<td>3 ab$^{-1}$</td>
<td>[-0.7, 0.4]</td>
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<tr>
<td></td>
<td></td>
<td>15 ab$^{-1}$</td>
<td>[-0.4, 0.2]</td>
<td>[-0.6, 0.3]</td>
</tr>
</tbody>
</table>

**Table 2:** Summary of the results for the various channels in terms of the CP-even and CP-odd anomalous triple gauge couplings. Only events with $m_{WZ,W\gamma}^T < 1.5$ TeV are used.
$pp \rightarrow vH$ with dimension 6 operators

In SM the process is dominated by the final state with the longitudinal vector boson in the final state.

In BSM we can have corrections both to $V_L$, $V_T$ final states

$$\Delta \mathcal{L}_{6}^{hZ \bar{f} f} \propto \delta \bar{g}_{Z}^{h} \frac{2m_{Z}^{2}}{v} h \frac{Z_{\mu}^{\gamma} Z_{\mu}}{2} + \sum_{f} g_{Z}^{h_{f}} h \frac{Z_{\mu} \bar{f} \gamma_{\mu} f}{v}$$

Sensitivity to $k_{zz}$, $\tilde{k}_{zz}$ is suppressed

1905.02728, 1912.07628 Banerjee et al
Amplitude becomes a function of $\Theta, \theta, \phi$

$$A_{\kappa_{zz}} \propto \frac{\sqrt{s}}{m_Z} \cos \phi \sin 2\theta \sin 2\Theta$$

$$A_{\tilde{\kappa}_{zz}} \propto \frac{\sqrt{s}}{m_Z} \sin \phi \sin 2\theta \sin 2\Theta$$

Need simultaneously to measure all three angles, otherwise the interference will be washed out due to the chirality ambiguity $(\theta, \phi) \rightarrow (\pi - \theta, \pi + \phi)$

$|\kappa, \tilde{\kappa}| < 0.07$ at 3 ab$^{-1}$

1905.02728, 1912.07628 Banerjee et al
Summary

HL-LHC precision surpasses the precision of LEP

Differential distributions improve the sensitivity to the New Physics: better EFT expansion, additional tool in differentiating the operators, sign measurements.

A lot of interesting physics within such simple measurements

- QCD NLO effects modify qualitatively the predictions
- Some acceptance cuts lead to the automatic selection of the azimuthal angles
- Bounds become comparable with neutron EDM constraints.
BACK UP
\[ \mathcal{L}_{\nu \bar{q}} = \sqrt{g^2 + g'^2} Z_\mu \left[ \sum_{f \in u,d} \bar{f}_L \gamma_\mu \left( T^3_f - s^2_W Q_f + \delta g_L^{Zf} \right) f_L + \sum_{f \in u,d} \bar{f}_R \gamma_\mu \left( -s^2_W Q_f + \delta g_R^{Zf} \right) f_R \right] \\
+ \frac{g}{\sqrt{2}} \left( W^+_\mu \bar{u}_L \gamma_\mu \left( I_3 + \delta g_L^{Wq} \right) d_L + \text{h.c.} \right). \]
aC summary plots at: http://cern.ch/go/BghC
\[
\frac{d\sigma}{dp_T} \left[ \text{fb/GeV} \right] \\
pp \to W^{+} Z @ 14 \text{ TeV} \\
\text{LO (11.2 fb)} \\
\text{NLO (26.7 fb)} \\
\text{NLO+j (29.6 fb)} \\
\text{NLO+j (42.8 fb)}
\]
\( \phi_{Z, W} \) binning
No \( \phi_{Z, W} \) binning
Dashed: 68\% CL
Solid: 95\% CL

\( pp \to WZ \to 3l\nu \)
LHC 27 TeV \( L = 15 \text{ ab}^{-1} \)
Linear Terms Only

\( \phi_{W} \) binning
No \( \phi_{W} \) binning
Dashed: 68\% CL
Solid: 95\% CL

\( pp \to W\gamma \to l\nu\gamma \)
LHC 27 TeV \( L = 15 \text{ ab}^{-1} \)
Linear Terms Only
$pp \rightarrow vH$ with dimension 6 operators

$$
\begin{align*}
\mathcal{O}_{H\Box} &= (H^\dagger H) \Box (H^\dagger H) \\
\mathcal{O}_{HD} &= (H^\dagger D_\mu H)^\dagger (H^\dagger D_\mu H) \\
\mathcal{O}_{Hu} &= iH^\dagger \bar{D}_\mu H \bar{u}_R \gamma^\mu u_R \\
\mathcal{O}_{Hd} &= iH^\dagger D_\mu H \bar{d}_R \gamma^\mu d_R \\
\mathcal{O}_{He} &= iH^\dagger \bar{D}_\mu H \bar{e}_R \gamma^\mu e_R \\
\mathcal{O}_{HQ}^{(1)} &= iH^\dagger \bar{D}_\mu H \bar{Q}_R \gamma^\mu Q \\
\mathcal{O}_{HQ}^{(3)} &= iH^\dagger \bar{Q}_R \bar{D}_\mu H \gamma^\mu Q \\
\mathcal{O}_{HL}^{(1)} &= iH^\dagger \bar{D}_\mu H \bar{L}_R \gamma^\mu L \\
\mathcal{O}_{HL}^{(3)} &= iH^\dagger \sigma^a \bar{D}_\mu H L \sigma^a \gamma^\mu L \\
\mathcal{O}_{HB} &= |H|^2 B_\mu B^{\mu
u} \\
\mathcal{O}_{H\tilde{W}B} &= H^\dagger \sigma^a \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu}\nu \\
\mathcal{O}_{H\tilde{W}W} &= |H|^2 W^a_{\mu\nu} \tilde{W}^{a\mu\nu} \\
\mathcal{O}_{H\tilde{W}B} &= H^\dagger \sigma^a \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu\nu} \\
\mathcal{O}_{H\tilde{W}W} &= |H|^2 W^a_{\mu\nu} \tilde{W}_a^{a\mu\nu} \\
\mathcal{O}_{\tilde{H}\tilde{W}B} &= H^{\dagger} \bar{\sigma}^a \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu\nu} \\
\mathcal{O}_{\tilde{H}\tilde{W}W} &= |H|^2 W^a_{\mu\nu} \tilde{W}_a^{a\mu\nu} \\
\mathcal{O}_{\tilde{H}\tilde{W}B} &= H^{\dagger} \bar{\sigma}^a \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu}\nu \\
\mathcal{O}_{\tilde{H}\tilde{W}W} &= |H|^2 W^a_{\mu\nu} \tilde{W}^{a\mu\nu} \\
\mathcal{O}_{\tilde{H}\tilde{W}B} &= H^{\dagger} \bar{\sigma}^a \tilde{W}^a_{\mu\nu} \tilde{B}^{\mu\nu} \\
\mathcal{O}_{\tilde{H}\tilde{W}W} &= |H|^2 W^a_{\mu\nu} \tilde{W}_a^{a\mu\nu}
\end{align*}
$$

$$
\Delta \mathcal{L}_6^{hZ\bar{f}f} \supset \delta g_{ZZ}^h \frac{2m_Z^2}{v} h \frac{Z_{\mu}Z_{\mu}}{2} + \sum_f g_{Zf}^h \frac{h}{v} Z_{\mu} \bar{f} \gamma^\mu f
$$

long

$$
+ \kappa_{ZZ} \frac{h}{2v} Z_{\mu\nu} Z_{\mu\nu} + \tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}
$$

transv.

$$
\begin{align*}
\mathcal{M}_{\sigma}^{\pm} &= \sigma \frac{1 + \sigma \lambda \cos \Theta}{\sqrt{2}} \frac{g_Z g_f^Z}{c_{\theta W}} m_Z \left[ 1 + \left( \frac{g_{Zf}^h}{g_f^Z} + \kappa_{ZZ} - i \lambda \tilde{\kappa}_{ZZ} \right) \frac{s}{2m_Z^2} \right] \\
\mathcal{M}_{\sigma}^{0} &= - \sin \Theta \frac{g_f^Z}{2c_{\theta W}} \left[ 1 + \delta g_{ZZ}^h + 2 \kappa_{ZZ} + \frac{g_{Zf}^h}{g_f^Z} \left( -\frac{1}{2} + \frac{s}{2m_Z^2} \right) \right],
\end{align*}
$$

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