Exploring the SM EFT with diboson production

Marc Montull
(postdoc at DESY)

Based on:
1810.05149 with C. Grojean and M. Riembau
190x.xxxxx with G. Durieux and M. Riembau
190x.xxxxx with F. Bishara, P. Englert, C. Grojean, G. Panico, A. Rossia

The 27th International Workshop on Weak Interactions and Neutrinos
As we know, the LHC discovered the **first scalar** and **elementary** (?) particle consistent with the SM Higgs boson

With this discovery, the SM is complete!!

Are we done?
No! There are still many things to be understood … for instance

DM, Neutrinos, Inflation, Baryon asymmetry, Gravity
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Even more, the LHC will keep running until 2037!

New discoveries or New constrains
No! There are still **many** things to be understood … for instance

Even more the LHC will keep running until 2037!

In any case clues on:

- All the above +
- Hierarchy problem
- Strong CP problem
- Flavour structure

New discoveries or
New constrains

For instance:

- DM
- Neutrinos
- Inflation
- Baryon asymmetry
- Gravity
So far the LHC has not found any new physics yet...

Hence, if there is NP around the EW scale it is either:
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- **Light (but weakly coupled)**
- **Limited by systematics**
  (large at LHC)
So far the LHC has not found any new physics yet… Hence, if there is NP around the EW scale it is either:

- **Light** (but weakly coupled)
  - **Limited by systematics** (large at LHC)

- **Heavy** (effects suppressed)
  - Effects can be enhanced at high energy

What does this mean??
If new physics is heavy it can be studied with the SM EFT

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots \]
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The BSM cross section can be parametrized as

\[
\sigma_{BSM} = \sigma_{SM} + \delta\sigma
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If the BSM part grows faster with the CM Energy than the SM one

\[ \frac{\delta \sigma}{\sigma_{\text{SM}}} \sim c_i \left( \frac{E}{m_W} \right)^\beta \]

In this case the sensitivity to the BSM coefficients is increased with the CM Energy
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\[ \chi^2 \sim \left( \frac{\delta \sigma}{\sigma_{SM}} \right)^2 \left( \frac{1}{\Delta} \right)^2 \ll 1 \]

(error in %) \[ \Delta \equiv \sqrt{\Delta_{sys}^2 + \Delta_{stat}^2} \]
If new physics is heavy it can be studied with the SM EFT

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

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\[ \chi^2 \sim \left( \frac{\delta\sigma}{\sigma_{\text{SM}}} \right)^2 \left( \frac{1}{\Delta} \right)^2 \lesssim 1 \]

Bound becomes stronger at large E

(error in %) \[ \Delta \equiv \sqrt{\Delta^2_{\text{sys}} + \Delta^2_{\text{stat}}} \]
Diboson production at the LHC is specially interesting

In particular, the processes modified by dimension 6 operators, which are:

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} \]

1) \( pp \to WW \), 2) \( pp \to WZ \), 3) \( pp \to Zh \), 4) \( pp \to Wh \)

Why are they interesting?

1) Sensitive to BSM physics addressing the hierarchy problem

*for instance:* Composite Higgs models, extra dimensions, Little Higgs
Why are they interesting?

2) The BSM contributions grow faster than the SM one

For example: \( pp \rightarrow WW \)

\[
\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_t = -i \frac{e^2 \sin \theta}{2m_W^2} s \left( Q_q + \frac{1}{s_W^2} \left( T_q^3 - s_W^2 Q_q \right) - \frac{T_q^3}{s_W^2} \right) + \ldots
\]

- In the SM each diagram grows with CM Energy but sum \textit{cancels}
Why are they interesting?

2) The BSM contributions grow faster than the SM one for example:

\[
p p \rightarrow W W \quad \text{for example:} \quad g_{SM} (1 + \delta g)
\]

\[
M_{\gamma} + M_{Z} + M_{t} = -i \frac{e^2 \sin \theta}{2m_W^2} \mathcal{S} \left( Q_q + \frac{1}{s_W^2} \left( T_q^3 - s_W^2 Q_q \right) - \frac{T_q^3}{s_W^2} \right) + \ldots
\]

- In the SM each diagram grows with CM Energy but sum cancels

- In the SMEFT vertices are modified, cancellation is spoiled (at dimension 6)

Enhanced sensitivity!
Why are they interesting?

3) Diboson errors are small enough to set strong bounds thanks to \( E \) enhancement.
Why are they interesting?

3) Diboson errors are small enough to set strong bounds thanks to E enhancement.

Since the BSM XS grows with E faster than the SM XS

\[ c_i \lesssim \Delta \left( \frac{m_W}{E} \right)^\beta \]

\[ \Delta \sim 10\%, \ E \sim 1 \ TeV \]

\[ \beta = 2 \]

\[ c_i \lesssim 0.1\% \]

Naively we expect a permille bound!!
Schematically diboson production ($WW, WZ$):

Equivalent to study modifications to $Zqq$ and $aTGC$

$Z$ couplings to quarks

anomalous TGC
Schematically diboson production \((WW, WZ)\):

\[ q \rightarrow W, \quad \bar{q} \rightarrow W \]

Equivalent to study modifications to \(Zqq\) and \(a\text{TGC}\)

\[ g_{SM} (1 + \delta g) \]

\(Z\) couplings to quarks

Anomalous TGC

At \(\text{dim}=6\): (Flavour Universality)

\[ \delta g_{Zu}, \delta g_{Zd}, \delta g_{Ru}, \delta g_{Rd}, \delta \kappa_{\gamma}, \delta g_{1z}, \lambda_{\gamma} \]

\[ 4 + 3 = 7 \text{ param} \]
Schematically diboson production (WW, WZ):

Equivalent to study modifications to Zqq and aTGC

\[ q \rightarrow W \]

\[ \bar{q} \rightarrow W \]

\[ q \rightarrow Z/\gamma \]

\[ \bar{q} \rightarrow W \]

Z couplings to quarks (LEP-1 @ Z-pole)

\[ \delta g \lesssim 0.1\% - 1\% \]

\[ g_{SM} (1 + \delta g) \]

Anomalous TGC (LEP-2)

\[ \delta g \lesssim 1\% - 10\% \]
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Equivalent to study modifications to \(Zqq\) and \(aTGC\)

\[ g_{SM} (1 + \delta g) \]

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\(\text{Z couplings to quarks (LEP-1 @ Z-pole)}\)
Summary of our work on diboson:

1) 1810.05149 with C. Grojean and M. Riembau

1.1) Is it justified to neglect Zqq couplings @ LHC?

1.2) Can the LHC improve the bounds on the Zqq w.r.t LEP?

2) 190x.xxxxx with G. Durieux and M. Riembau
   (ongoing)

   2.1) Improving the sensitivity and range with VBF

3) 190x.xxxxx with F. Bishara, P. Englert, C. Grojean, G. Panico, A. Rossia
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   3.1) Detailed study of the Wh channel
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Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **anomalous Triple Gauge Couplings**

![Graph showing leptonic pp → WW/WZ (7, 8, 13 TeV) and LEP-1 with 95% CL regions for different coupling scenarios.](image-url)

- **solid**: pp → WW/WZ, δg_{LR}^{Zq} = 0 (3 param. fit)
- **dashed**: pp → WW/WZ + LEP(MFV) (7 param. fit)
- **dotted**: pp → WW/WZ + LEP(FU) (7 param. fit)

(LHC only)

Zqq = 0
1.1) Is it justified to neglect Zqq couplings @ LHC?

Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **anomalalouts Triple Gauge Couplings**

![Diagram showing 95% CL contour for dglz and dka parameters with Zqq=0 fit and other fits with LHC and LEP data.](image)
- Difference between considering $Zqq$ non-zero or zero is of order 20%

(+ global fit w/ LEP)
- Difference > 100% @ HL-LHC: **Not Justified to Neglect Zqq!**

**LHC**

**NOW**

**Zqq ≠ 0**

**Zqq = 0**

**HL-LHC**

3 ab$^{-1}$
At high energies WW, WZ only test 5 directions

<table>
<thead>
<tr>
<th>Process</th>
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<th>Warsaw basis</th>
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<td>$d_R u_L \rightarrow W_L^+ Z_L$</td>
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but depend on **7 parameters:** 4 Zqq couplings and 3 aTGC

![LHC bounds](image)
At high energies WW, WZ only test 5 directions but depend on 7 parameters: 4 Zqq couplings and 3 aTGC

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At high energies $WW, WZ$ only test 5 directions but depend on 7 parameters: 4 $Zqq$ couplings and 3 aTGC

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LEP I bounds

Zqq=0

Zqq \neq 0 + LEP

LHC bounds
1.2) Can the LHC improve the bounds on the Zqq w.r.t LEP?
1.2) Can the LHC improve the bounds on the $Zqq$ w.r.t LEP?

Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **$Zqq$ vertex corrections**

**$Z$ to down type q**
1.2) Can the LHC improve the bounds on the Zqq w.r.t LEP?

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Fit to **Zqq vertex corrections**

Z to **down** type q

- **LHC 7 param**
- **LHC 5 param** \( \lambda_\gamma = 0 \)

**LHC 4 param**

\( \delta \kappa_\gamma, \delta g_{1z}, \lambda_\gamma = 0 \)
1.2) Can the LHC improve the bounds on the $Zqq$ w.r.t LEP?

Combine current **leptonic data for WW, WZ** from CMS & ATLAS

Fit to **$Zqq$ vertex corrections**

- **Current data is competitive with LEP** setting bounds to $Zqq$ down type $q$!
- For the up type corrections, the LHC is still not competitive with LEP
WV @ HL-LHC may improve the bounds on all the Zqq vertices w.r.t LEP!

- Z to down type q
- Z to up type q
Interpreting the bounds

Our LHC bounds on the BSM parameters are only valid for large BSM masses. In our case this means that we can only constrain theories where $g_\star > g_{SM}$.
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We would like to:

1) Increase the Sensitivity (constrain weakly coupled theories)
2) Lower the cutoff (increase range of the bounds)
Many work done on diboson to improve the bounds, e.g.

Falkowski et al. (1609.06312)
Azatov et. al (1707.08060)
Panico et al. (1708.07823)
Franceschini et al. (1712.01310)
Bellazzini et al. (1806.09640)
Azatov et. al (1901.04821)
Banerjee et. al (1905.02728)
+ …

(ongoing work with G. Durieux and M. Riembau)

2.1) Improving the sensitivity and range with VBF?
Why study VBF?

1) Analytic simplification is possible via Equivalent EW bosons

The process factorises into a:

- soft scale (radiated $W$)
- hard scale (2->2 scattering)

Rattazzi et al. 1202.1904
Why study VBF?

1) Analytic simplification is possible via Equivalent EW bosons

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- hard scale (2->2 scattering)

2) VBF is sensitive to the same operators as diboson

Diboson has the same diagrams as the 2->2 channel rotated 90 degrees
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Diboson has the same diagrams as the 2->2 channel rotated 90 degrees

3) It is possible to completely reconstruct final state

Implement cuts on CM Energy + cuts to increase sensitivity (angular distr)
First naive attempt: Separating of soft vs hard processes

We can define a jet imbalance variable given by:

\[ I_{pT,jj} = \frac{|p_{T,j1} - p_{T,j2}|}{p_{T,j1} + p_{T,j2}} \]

which we checked has a good discriminating power between signal and bkg
Comparing to other works with cuts that increase sensitivity

CMS VBF analysis adding CM E cuts only

1712.01310 (WZ with run1 data)

Wilson coefficient in the Warsaw basis
Comparing to other works with cuts that increase sensitivity

- Simple analysis already very powerful
  Increased sensitivity and range to lower scales
- Possibility to further improve it with angular distributions, BDT
Conclusions

1) CMS and ATLAS aTGC fits will need to include Zqq corrections soon
   - At least under the MFV or FU assumptions

2) Diboson @ LHC can improve the LEP bounds on the Zqq corrections
   - Need of further study with other channels and more sensitive cuts
   - Would be interesting if CMS and ATLAS would try to do it

3) New possibilities to test diboson operators with VBF
   - Results hopefully coming soon
Thanks
We studied WW, WZ channels using the same cuts as CMS/ATLAS. Possible to improve bounds with other cuts/channels.

- **Wh** hasn’t been studied in detail yet.
- Preliminary results seem competitive **(ongoing work)**.
Used MadGraph5_aMC@NLO to get BSM cross section and fit

- BSMC package Fuks et al

We did a simple analysis

- Leading order
- No Pythia (we checked didn’t affect much)
- No correlation between bins

Cross check with CMS and ATLAS is OK, e.g.
Interpreting the bounds

In these fits, the quadratic pieces are non-negligible

\[ |\mathcal{M}|^2 \sim |\mathcal{M}_{SM}|^2 + \mathcal{M}_{SM} \mathcal{M}_6 + |\mathcal{M}_6|^2 \]

so they are of the same order as dim 8

\[ |\mathcal{M}_6|^2 \sim \frac{1}{\Lambda^4} \sim \mathcal{M}_{SM} \mathcal{M}_8 \]

Need of power counting to ensure:

1) dimension 8 are negligible

2) physical mass larger than Energy events

![Graph showing LEP, LHC, and LHC & LEP regions with EFT OK and EFT not-OK zones.]
At dimension six

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C^{(6)}_i}{\Lambda^2} \mathcal{O}^{(6)}_i \]

59 operators (Flavour Universality)

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<th>2: ( H^6 )</th>
<th>3: ( H^4D^2 )</th>
<th>5: ( \psi^2H^3 + \text{h.c.} )</th>
<th>4: ( X^2H^2 )</th>
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<td>( (\tilde{q}<em>u\sigma^{\mu\nu}e_r)^\dagger H B^{\mu}</em>{\nu} )</td>
<td>( Q_{vt} )</td>
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<td>( H^1H G^{\mu}<em>{\nu}G^{\nu}</em>{\rho}G^{\rho}_{\mu} )</td>
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8: \( \langle LL \rangle \langle LL \rangle + \text{h.c.} \) 8: \( \langle RR \rangle \langle RR \rangle + \text{h.c.} \)
Toy Model to get more intuition

A simple toy model: $SU(2)_R$ triplet so that respects custodial.

Figure 9: 95% CL exclusion regions in the $(\gamma_H, \gamma_Q)$ plane for various values of the resonance masses. In blue, the projected constraints from diboson data at HL-LHC, using our projections (dark shade) or the refined analysis strategy of Ref. 12. The other constraints come from a recast of the studies in Refs. 21, 60, 63 and are commented in detail in the text.
Sensitivity enhancement already used to expand previous LEP bounds

1) Drell-Yan
   Farina et al 1609.08157
   Improving LEP bounds on Universal Parameters $W, Y$

2) Diboson production
   Butter et al 1604.03105
   Azatov et al 1707.08060
   Improving LEP-2 bounds on anomalous Triple Gauge Couplings
Bounds on Zff anomalous couplings (from LEP)

**Flavour Universality**

\[
[\delta g_{Zu}^{\mu}]_{ij} = A \delta_{ij}
\]

- \(\delta g_{L}^{Zu} = -0.0017 \pm 0.002\)
- \(\delta g_{R}^{Zu} = -0.0023 \pm 0.005\)
- \(\delta g_{L}^{Zd} = 0.0028 \pm 0.0015\)
- \(\delta g_{R}^{Zd} = 0.019 \pm 0.008\)

**MFV**

\[
[\delta g_{Zu}^{\mu}]_{ij} = \left( A + B \frac{m_i}{m_3} \right) \delta_{ij}
\]

- \(\delta g_{L}^{Zu} = -0.002 \pm 0.003\)
- \(\delta g_{R}^{Zu} = -0.003 \pm 0.005\)
- \(\delta g_{L}^{Zd} = 0.002 \pm 0.005\)
- \(\delta g_{R}^{Zd} = 0.016 \pm 0.027\)

Falkowski et al. 1503.07872

**Bounds on aTGC**

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<td>68 % CL</td>
<td>Correlations</td>
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<td>Correlations</td>
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<td>(\Delta g_I^Z)</td>
<td>0.010 ± 0.008</td>
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<td>(\Delta \kappa_\gamma)</td>
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<td>(\lambda)</td>
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<td>-0.06</td>
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Butter, et al. 1604.03105
1) Data used

We chose the most significant **leptonic** channels

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<th>Detector</th>
<th>$\mathcal{L}[^{\text{fb}^{-1}}]$</th>
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