Effective-Field-Theory Approach of the anomalous Triple Gauge Couplings at the LHC

Minho Son
KAIST

Greljo, Gonzalez-Alonso, Falkowski, Marzoca, SON in progress
Lesson from Run 1, part of Run 2

\[ \Lambda_{\text{LHC}} > \mathcal{O}(\text{TeV}) \]

: cut-off scale
extracted from data
Higgs Effective Field Theory

Widely separated two scales, or seemingly un-natural hierarchy offers a remarkable bonus

\[ \mathcal{L} = \mathcal{L}_{\text{pheno.}} + \text{Higgs} = \mathcal{L}_{(d \leq 4)} + \frac{1}{\Lambda_{\text{LHC}}} \mathcal{L}_{(5)} + \frac{1}{\Lambda_{\text{LHC}}^2} \mathcal{L}_{(6)} + \cdots \]

Stole text from the talk by Rattazzi
Structural picture of EFT

\[ M_\text{cut} = \frac{M_\text{cut}}{g^*_\text{Interaction scale}} \]

Racco, Wulzer, Zwirner 15’
Contino, Falkowski, Goertz, Grojean, Riva 16’
Structural picture of EFT

Typical interaction in EFT is controlled by the effective coupling,

\[ g(E) = \frac{E}{M_*} \leq \frac{M_{\text{cut}}}{M_*} = g_* \]

Interaction scale: the only scale accessible to a low-E observer

**Structural picture of EFT**

Typical interaction in EFT is controlled by the effective coupling,

\[ g(E) = \frac{E}{M_*} \leq \frac{M_{\text{cut}}}{M_*} = g_* \]

\[ g(E) = \frac{g_w}{m_w} E \]

\[ m \rightarrow m_\psi \]

Interaction scale: the only scale accessible to a low-E observer

\[ g_* \rightarrow g_w \]

\[ M_* = \frac{M_{\text{cut}}}{g_*} \]

New particle? New force? unknown new physics

Racco, Wulzer, Zwirner 15'
Contino, Falkowski, Goertz, Grojean, Riva 16'
Structural picture of EFT

Typical interaction in EFT is controlled by the effective coupling,

\[ g(E) = \frac{E}{M_*} \leq \frac{M_{\text{cut}}}{M_*} = g_* \]

Racco, Wulzer, Zwirner 15’
Contino, Falkowski, Goertz, Grojean, Riva 16’

Interaction scale
This picture fits to Higgs physics well
& also to aTGC

Unknown New Physics
Unitarity violation in EFT

$M_\text{cut} = \frac{M_\text{cut}}{g_*}$

Early new physics hint in EFT approach relies on the E-growing feature due to decent $S/\sqrt{B}$. However, this benefit should cut off at a certain energy scale, $E < M_\text{cut}$.
Constraining HEFT via VV processes

We will parameterize BSM in the Higgs basis

\[ \mathcal{L}_{\text{phenom. EFT}} = \mathcal{L}_{\text{SM}} + \Delta \mathcal{L} \]

- shift of the coupling strength away from SM predictions
- new tensor structures of interaction absent in SM

\[ \mathcal{L}_{\text{HEFT}} = \mathcal{L}_{\text{SM}} + \sum \overline{c}_i \frac{\mathcal{O}^{\text{dim}=6}}{v^2} \]

Warsaw, SILH bases etc with SU(2) doublet Higgs H

\[ g^2(E) \sim O \left( g_{\text{SM}}^2 \frac{E^2}{m_W^2} \bar{c} \right) \]
Constraining HEFT via VV processes

\[ \mathcal{L}_{TGC} = ie[(W_{\mu\nu}^+ W_{\mu}^- - W_{\mu\nu}^- W_{\mu}^+)] A_{\nu} + (1 + \delta \kappa_{\gamma}) A_{\mu\nu} W_{\mu}^+ W_{\nu}^- \]

\[ + i g_L \cos \theta [(1 + \delta g_{1,z})(W_{\mu\nu}^+ W_{\mu}^- - W_{\mu\nu}^- W_{\mu}^+)] Z_{\nu} + (1 + \delta \kappa_{z}) Z_{\mu\nu} W_{\mu}^+ W_{\nu}^- \]

\[ + i e \frac{\lambda_{\gamma}}{m_W^2} W_{\mu\nu}^+ W_{\nu\rho} A_{\rho\mu} + i g_L \cos \theta \frac{\lambda_{z}}{m_W^2} W_{\mu\nu}^+ W_{\nu\rho} Z_{\rho\mu} \]

\[ \delta \kappa_{z} = \delta g_{1,z} - \frac{g_{\gamma}^2}{g_{L}^2} \delta \kappa_{\gamma} \quad \lambda_{z} = \lambda_{\gamma} \]

\[ \rightarrow \text{Three variables for } VV \]
\[ \{ \lambda_{z}, \delta g_{1,z}, \delta \kappa_{\gamma} \} \]

A difficulty of EFT approach:

Many parameters lead to a degeneracy
Decay vs 2-to-2 scattering process

\[
\frac{\delta c}{c_{SM}} \sim \left( \frac{g_*}{g_{SM}} \right)^2 \frac{m_h^2}{M_{cut}^2}
\]

Main focus of Run 1

\[
\frac{\delta \sigma_{2\to2}}{\sigma_{SM}} \sim \frac{g^2(E)}{g_{SM}^2} \sim \left( \frac{g_*}{g_{SM}} \right)^2 \frac{E^2}{M_{cut}^2}
\]

Important item of Run 2

Parameters in HEFT are $\theta, \sqrt{s}$ -dependent

\[
\frac{d\sigma}{d\sqrt{s}}, \quad \frac{d\sigma}{d\cos\theta}, \quad \frac{(d\sigma}{d\sqrt{s})_{13\text{TeV}}}{(d\sigma}{d\sqrt{s})_{8\text{TeV}}}
\]

Can see more microscopic structure of BSM
**Decay vs 2-to-2 scattering process**

$$\delta c \sim \frac{(g_*)^2}{g_{SM}} \frac{m_h^2}{M_{cut}}$$

**Main focus of Run 1**

$$\frac{\delta \sigma_{2\to 2}}{\sigma_{SM}} \sim \frac{g^2(E)}{g_{SM}^2} \sim \left( \frac{g_*}{g_{SM}} \right)^2 \frac{E^2}{M_{cut}^2}$$

**Important item of Run 2**

**Parameters in HEFT are $\theta, \sqrt{s}$ -dependent**

What we want to know vs. What we currently measure

$$\sqrt{s} = m_{WW}, m_{WZ}$$

Not exactly matches

$$m_{ll}, m_{WWZ}^T, p_T \text{ etc}$$
Accessing to the truth-level $\sqrt{S}$ is non-trivial

What we want to know

What we want to know

What is measured

What is measured
Pollution from the wrong events

Theory

\[
\frac{d\sigma}{dm_{WW}} \quad \text{EFT works} \quad \text{EFT breaks down}
\]

Events beyond EFT regime

Data

\[
\frac{d\sigma}{dm_{ll}} \quad \text{Wrong events go into the analysis!}
\]

\[m_{ll} < M_{\text{cut}}\]

\[m_{WW} < m_{WW}^{\text{max}}\]

not suitable to take into account the validity of EFT
Removal of the healthy events

Theory

\[ \frac{d\sigma}{dm_{WW}} \]

EFT works

EFT breaks down

Events beyond EFT regime

Data

\[ \frac{d\sigma}{dm_{ll}} \]

Healthy events are removed from the analysis!

not suitable to take into account the validity of EFT
You wrongly kill healthy events

What is measured

You cut here on $m_{ll}$

$\mathcal{M}_{WW}$

You fail to remove these wrong events

What controls EFT validity

$$\int_{0}^{m_{WW}^{\text{max}}} dm_{VV} \frac{d\sigma}{dm_{VV}} \neq \int_{0}^{M_{\text{cut}}} dm_{\text{vis}} \frac{d\sigma}{dm_{\text{vis}}}$$

Cutting on $m_{ll}$ is not justified. What do we do?
In principle, if we can access to \( m_{VV} \equiv \sqrt{s} \)

\[
(\sigma_{SM} + \sigma_{BSM})(m_{VV} < m_{VV}^{\text{max}}) \quad \sigma_{obs} (m_{VV} < m_{VV}^{\text{max}})
\]

In mass situations, we do not have access to \( m_{VV} \equiv \sqrt{s} \)
We only hope to set a conservative bound

\[(\sigma_{\text{obs}} - \sigma_{\text{SM}}) - \Delta \sigma \leq \sigma_{\text{BSM}} \leq (\sigma_{\text{obs}} - \sigma_{\text{SM}}) + \Delta \sigma\]

\[\sigma_{\text{BSM}} = \sigma_{m_{VV}^{\text{max}}} + \sigma_{m_{VV}^{\text{max}}} \]

Inspired by Racco, Wulzer, Zwirner 15’
For general discussion for Validity of EFT
Biekötter, Krämer, Liu, Riva 15’
Contino, Falkowski, Goertz, Grojean, Riva 16’
setting a conservative bound

\[(\sigma_{obs} - \sigma_{SM}) - \Delta \sigma \leq \sigma_{BSM} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta \sigma \]

\[\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq \sigma_{BSM}^{m_{VV}>m_{VV}^{max}}\]

If \(\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} > 0 \) \&\& \(\sigma_{BSM}^{m_{VV}>m_{VV}^{max}} > 0 \) \&\& No excess

\[(\sigma_{obs} - \sigma_{SM}) - \Delta \sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta \sigma \]

Inspired by Racco, Wulzer, Zwirner 15’

For general discussion for Validity of EFT
Biektter, Krämer, Liu, Riva 15’
Contino, Falkowski, Goertz, Grojean, Riva 16’
setting a conservative bound

\[
(\sigma_{obs} - \sigma_{SM}) - \Delta \sigma \leq \sigma_{BSM} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta \sigma
\]

\[
\sigma_{BSM}^{m_{VV}<m_{VV}^{max}} + \sigma_{BSM}^{m_{VV}>m_{VV}^{max}}
\]

If \( \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} > 0 \) \&\& \( \sigma_{BSM}^{m_{VV}>m_{VV}^{max}} > 0 \) \&\& No excess

\[
(\sigma_{obs} - \sigma_{SM}) - \Delta \sigma \leq \sigma_{BSM}^{m_{VV}<m_{VV}^{max}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta \sigma
\]

✓ In the absence of the interference between SM and BSM
✓ In the presence of the interference
  • Incomplete justification
    \[
    \sigma_{BSM} \propto (\mathcal{A}_{SM}^* \mathcal{A}_{BSM} + h.c.) + |\mathcal{A}_{BSM}|^2
    \]
    \[
    \frac{|\mathcal{A}_{BSM}|}{\mathcal{A}_{SM}} \sim \left( \frac{g_*}{g_{SM}} \right)^2 \left( \frac{E}{m_{VV}^{max}} \right)^2 > 1 \quad \text{for } E > m_{VV}^{max}
    \]
    If a theory is strongly coupled, \( g_* \gg g_{SM} \)
  • Suppression of interference by hidden selection rules
    \[
    \sigma_{BSM} \propto (\mathcal{A}_{SM}^* \mathcal{A}_{BSM} + h.c.) + |\mathcal{A}_{BSM}|^2 \sim |\mathcal{A}_{BSM}|^2
    \]

Inspired by Racco, Wulzer, Zwirner 15’
For general discussion for Validity of EFT
Biekötter, Krämer, Liu, Riva 15’
Contino, Falkowski, Goertz, Grojean, Riva 16’

-> This is what’s happening in a TGC
No excess scenario

Theory

<table>
<thead>
<tr>
<th>dσ</th>
<th>dm_{WW}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Valid EFT regime

EFT breaks down

m_{WW} < m^\text{max}_{WW}

What we propose

1. Assume possible cut-off scale
2. Remove events from \( m_{VV} > m^\text{max}_{VV} \) in your simulation
3. Recast data in entire \( m_{ll} \) distribution
4. Repeat 1-3 for different choice of cut-off scales

Data

<table>
<thead>
<tr>
<th>dσ</th>
<th>dm_{ll}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( m_{WW} \)

\( m_{ll} \)

\( \sigma_{obs} - \sigma_{SM} - \Delta \sigma \leq \sigma_{BSM}^{m_{VV} < m^\text{max}_{VV}} \leq (\sigma_{obs} - \sigma_{SM}) + \Delta \sigma \)
Complication in Resonance scenario

EFT assumes no resonance

\[ m_{WW} < m_{\text{max}}^{WW} \]

Data includes whole events

Unavoidable pollution from the resonance

Unphysical Fit

\[
(s_{\text{obs}} - s_{\text{SM}}) - \Delta s \leq s_{\text{BSM}}^{m_{WW}} < s_{\text{BSM}}^{\text{max}} \leq (s_{\text{obs}} - s_{\text{SM}}) + \Delta s
\]

will be overestimated

* Can be fixed if we recover full \( \sqrt{s} = m_{WW} \)

\[ \checkmark \quad \text{In this case, we might just switch to resonance search than relying on EFT} \]
aTGC Amplitude
**aTGC in WW**

Anomalous Triple Gauge couplings

\[ \mathcal{A} \sim \sin \theta \]

\[ \mathcal{A} \sim \cos \theta \]

Perfect cancellation of E-growing pieces

**S-channel**

\[ \mathcal{A}_{0,0}^S \sim \frac{\sin \theta}{2} \left[ \left( T_3 u - s^2 \theta Q_u \right) g^2 + e^2 Q_u \right] \frac{s}{m_w^2} = 0 \]

**T**

Imperfect cancellation picks up E-growing behavior

\[ \mathcal{A}_{0,0} \sim \frac{\sin \theta}{2} \left[ g^2 ( T_3 u - s^2 \theta Q_u ) \delta \kappa_z + e^2 Q_u \delta \kappa_y \right] \frac{s}{m_w^2} \]

\[ \mathcal{A}_{L/R,0} \sim \frac{1 - \cos \theta}{2 \sqrt{2}} \left[ g^2 ( T_3 u - s^2 \theta Q_u ) ( \delta g_{1z} + \delta \kappa_z + \lambda_z ) + e^2 Q_u ( \delta \kappa_y + \lambda_y ) \right] \frac{\sqrt{s}}{m_w} \]
**aTGC in WZ**

Anomalous Triple Gauge couplings

Perfect cancellation of E-growing pieces

\[ \mathcal{A}_{0,0}^{SM} \sim \sin \theta \frac{g^2}{2\sqrt{2}c_{\theta_w}} [c_{\theta_w}^2 + (T_d^3 - s_{\theta_w}^2 Q_d) - (T_u^3 - s_{\theta_w}^2 Q_u)] \frac{s}{m_W m_Z} = 0 \]

Imperfect cancellation picks up E-growing behavior

\[ \mathcal{A}_{0,0} \sim \sin \theta \frac{g^2}{2\sqrt{2}c_{\theta_w}} [c_{\theta_w}^2 \delta g_{1,z}] \frac{s}{m_W m_Z} \]

\[ \mathcal{A}_{L/R,U/L} \sim -\sin \theta \frac{c_{\theta_w} g^2}{2\sqrt{2} \lambda_z} \frac{s}{m_W^2} \]

\[ \mathcal{A}_{L/R,0} \sim (\pm 1 + \cos \theta) \frac{g^2}{4c_{\theta_w}} [2 c_{\theta_w}^2 \delta g_{1,z} + \lambda_z] \frac{\sqrt{s}}{m_Z} \]

\[ \mathcal{T, U} \text{ channels participate in} \]

Unitarity restoration in SM

Accessing to the polarizations could give us further discriminating power.
Quadratic vs Linear fit

\[
\frac{\sigma}{\sigma_{SM}} = 1 + B_{a}\kappa_{a} + C_{ab}\kappa_{a}\kappa_{b}
\]

\[
\kappa_{a} = \{\lambda_{z}, \delta g_{1,z}, \delta \kappa_{y}\}
\]

Linear: \(\text{dim-6*SM} \sim \mathcal{O}(\Lambda^{-2})\)

Quadratic: \(\text{dim-6*dim-6} \sim \mathcal{O}(\Lambda^{-4})\)

[ \text{dim-8*SM} \sim \mathcal{O}(\Lambda^{-4}) ]

Inclusive cross sections
Varying one aTGC at a time (no cross-term included)

---

**Interference terms appear to be suppressed**

Deeper insight comes from Helicity Amplitude

**Structural difference between WW and WZ**
Helicity Amplitude

Deeper insight into the suppressed interference

Azatov, Contino, Machado, Riva 16’
Cheung, Shen 15’

In the massless limit

$$p_{ab} = - |p|_a \langle p \rangle_b, \quad p^{\hat{a} b} = - |p^{\hat{a}}| [p]_b$$

I. Gluing amplitudes to get n-pt amplitude

$$h(A_n) = h(A_m) + h(A_{m'})$$

II. 3-pt amplitude

Little Group scaling uniquely fixes the 3-point amplitudes

$$A_3(1^{h_1} 2^{h_2} 3^{h_3}) = g \begin{cases} (12)^{h_3-h_1-h_2} (13)^{h_2-h_1-h_3} (23)^{h_1-h_2-h_3} & \text{for } \Sigma h_i < 0 \\ [12]^{h_1+h_2-h_3} [13]^{h_1+h_3-h_2} [23]^{h_2+h_3-h_1} & \text{for } \Sigma h_i > 0 \end{cases}$$

Little group + NDA

$$\rightarrow |\Sigma h_i| = |h| = 1 - [g]$$

E.g.

$$\mathcal{O}_{3W} = \text{tr}(W^3) \quad |h(A_{3SM}^\mathcal{O})| = 1 - [c_{3W}] = 3$$

III. Some of SM 4-pt amplitude with $|h(A_{4SM}^\mathcal{O})| = 2$ vanish

$$A_4(V^+V^+V^-) = A_4(V^+V^+\psi^+\psi^-) = A_4(V^+V^+\phi\phi) = A_4(V^+\psi^+\psi^-\phi) = 0$$
Illustrative example

Helicity selection rule: total helicity should match

\[ h(A_{4}^{SM}) = 0 \]

\[ h(A_{4}^{BSM}) = 2 \]

How to interfere? Flip the helicity via VEV insertion (finite mass effect)

\[ h(A_{6}^{SM}) = 2 \]

\[ \propto \left( \frac{m_{W}}{E} \right)^{2} \]
# EFT interpretation of LHC data

## Available analyses

<table>
<thead>
<tr>
<th>Channel</th>
<th>Distribution</th>
<th># bins</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW \rightarrow \ell^+\ell^- + \mathbb{E}_T (0j)$</td>
<td>Leading lepton $p_T$</td>
<td>4</td>
<td>ATLAS 8 TeV, 20.3 fb$^{-1}$</td>
</tr>
<tr>
<td>$WW \rightarrow \ell^+\ell^-\ell^{(i)} + \mathbb{E}_T (0j)$</td>
<td>$m_{\ell\ell^{(i)}}$</td>
<td>8</td>
<td>CMS 8 TeV, 19.4 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell^+\ell^-\ell^{(i)}\pm$</td>
<td>$m_T^{WZ}$</td>
<td>6</td>
<td>ATLAS 8 TeV, 20.3 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell^+\ell^-\ell^{(i)}\pm + \mathbb{E}_T$</td>
<td>Z candidate $p_T^{\ell\ell}$</td>
<td>10</td>
<td>CMS 8 TeV, 19.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WV \rightarrow \ell^{\pm}jj + \mathbb{E}_T$</td>
<td>V candidate $p_T^{jj}$</td>
<td>12</td>
<td>ATLAS 7 TeV, 4.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WV \rightarrow \ell^{\pm}jj + \mathbb{E}_T$</td>
<td>V candidate $p_T^{jj}$</td>
<td>10</td>
<td>CMS 7 TeV, 5.0 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell^+\ell^-\ell^{(i)}\pm + \mathbb{E}_T$</td>
<td>Z candidate $p_T^{\ell\ell}$</td>
<td>7</td>
<td>ATLAS 7 TeV, 4.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \rightarrow \ell^+\ell^-\ell^{(i)}\pm + \mathbb{E}_T$</td>
<td>Z candidate $p_T^{\ell\ell}$</td>
<td>8</td>
<td>CMS 7 TeV, 4.9 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Butter et al. 16'
**EFT interpretation of LHC data**

### Available analyses

<table>
<thead>
<tr>
<th>Channel</th>
<th>Distribution</th>
<th># bins</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WW \to \ell^+\ell^- + \not E_T (0j)$</td>
<td>Leading lepton $p_T$</td>
<td>4</td>
<td>ATLAS 8 TeV, 20.3 fb$^{-1}$</td>
</tr>
<tr>
<td>$WW \to \ell^+\ell^0 + \not E_T (0j)$</td>
<td>$m_{\ell\ell}$</td>
<td>8</td>
<td>CMS 8 TeV, 19.4 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \to \ell^+\ell^- \ell^0$</td>
<td>$m_T^{WZ}$</td>
<td>6</td>
<td>ATLAS 8 TeV, 20.3 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \to \ell^+\ell^- \ell^0 + \not E_T$</td>
<td>$Z$ candidate $p_T^{\ell\ell}$</td>
<td>10</td>
<td>CMS 8 TeV, 19.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WV \to \ell^\pm jj + \not E_T$</td>
<td>$V$ candidate $p_T^{jj}$</td>
<td>12</td>
<td>ATLAS 7 TeV, 4.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WV \to \ell^\pm jj + \not E_T$</td>
<td>$V$ candidate $p_T^{jj}$</td>
<td>10</td>
<td>CMS 7 TeV, 5.0 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \to \ell^+\ell^- \ell^0 + \not E_T$</td>
<td>$Z$ candidate $p_T^{\ell\ell}$</td>
<td>7</td>
<td>ATLAS 7 TeV, 4.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$WZ \to \ell^+\ell^- \ell^0 + \not E_T$</td>
<td>$Z$ candidate $p_T^{\ell\ell}$</td>
<td>8</td>
<td>CMS 7 TeV, 4.9 fb$^{-1}$</td>
</tr>
</tbody>
</table>

Butter et al. 16'

---

We choose these to make our point, e.g. for illustrative purpose.
Recasting WW-lvlv
CMS analysis at 8TeV

CMS-SMP-14-016

- Weak correlation among aTGC
- $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}$(TeV). Weakening is pronounced for $m_{VV} < \mathcal{O}$(sub-TeV)
Recasting WW-lvlv
CMS analysis at 8TeV

CMS-SMP-14-016

This is what you normally see
Fluctuation can be this big

✓ Weak correlation among aTGC
✓ $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}(\text{TeV})$. Weakening is pronounced for $m_{VV} < \mathcal{O}(\text{sub-TeV})$
Recasting WZ-lvlI
ATLAS analysis at 8TeV

ATLAS arXiv:1603.02151

✓ Strong correlation among aTGC

✓ $m_{VV} < \infty$ is roughly similar to $m_{VV} < \mathcal{O}(\text{TeV})$. Weakening is pronounced for $m_{VV} < \mathcal{O}(\text{sub-TeV})$
\(\delta \kappa_\gamma\) is strongly constrained by WW, not by WZ
'First' recasting of 13 TeV data on aTGC

WZ ATLAS analysis

arXiv:1606.04017

No dramatic improvement. More or less similar to 8 TeV case.
Combine all (8TeV CMS + ATLAS and 13TeV ATLAS)

Profiled 95% CL bounds on the each aTGC from our combined fit with diff. mVV cut

<table>
<thead>
<tr>
<th>$m_{VV}^\text{max}$ [GeV]</th>
<th>$\infty$</th>
<th>1400</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{1,z}$ (%)</td>
<td>$[-1.2, 2.0]$</td>
<td>$[-1.2, 2.2]$</td>
<td>$[-1.3, 2.4]$</td>
</tr>
<tr>
<td>$\delta \kappa_\gamma$ (%)</td>
<td>$[-7.8, 9.9]$</td>
<td>$[-8.3, 10]$</td>
<td>$[-8.4, 11]$</td>
</tr>
<tr>
<td>$\lambda_z$ (%)</td>
<td>$[-1.3, 1.3]$</td>
<td>$[-1.5, 1.7]$</td>
<td>$[-1.8, 1.8]$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{VV}^\text{cut}$ [GeV]</th>
<th>1000</th>
<th>800</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{1,z}$ (%)</td>
<td>$[-1.4, 2.5]$</td>
<td>$[-1.7, 3.2]$</td>
<td>$[-2.1, 5.4]$</td>
</tr>
<tr>
<td>$\delta \kappa_\gamma$ (%)</td>
<td>$[-9.0, 11]$</td>
<td>$[-10, 15]$</td>
<td>$[-15, 21]$</td>
</tr>
<tr>
<td>$\lambda_z$ (%)</td>
<td>$[-2.1, 2.1]$</td>
<td>$[-2.9, 3.0]$</td>
<td>$[-4.2, 4.8]$</td>
</tr>
</tbody>
</table>
Combine all (8TeV CMS + ATLAS and 13TeV ATLAS)

Profiled 95% CL bounds on the each aTGC from our combined fit with diff. mVV cut

<table>
<thead>
<tr>
<th>$m_{VV}^{max}$ [GeV]</th>
<th>$\infty$</th>
<th>1400</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_{1,z}$ (%)</td>
<td>$[-1.2, 2.0]$</td>
<td>$[-1.2, 2.2]$</td>
<td>$[-1.3, 2.4]$</td>
</tr>
<tr>
<td>$\delta \kappa_\gamma$ (%)</td>
<td>$[-7.8, 9.9]$</td>
<td>$[-8.3, 10]$</td>
<td>$[-8.4, 11]$</td>
</tr>
<tr>
<td>$\lambda_z$ (%)</td>
<td>$[-1.3, 1.3]$</td>
<td>$[-1.5, 1.7]$</td>
<td>$[-1.8, 1.8]$</td>
</tr>
</tbody>
</table>

*What is usually reported in literature*

Can be widely different
\[ \mathcal{L}_{\text{int}} = V^a_{\mu} \left( \frac{i}{2} g \kappa'_H J^a_H + \frac{g}{2} \kappa'_{fJ} J^a_f \right) + V^0_{\mu} \left( - \frac{i}{2} g \kappa_H J^\mu_H + \frac{g}{2} \kappa_{fJ} J^\mu_f \right) \]

Integrate out Triplet and Singlet and match to EFT coefficients

\[
\begin{align*}
&c_{WB} = 0 \quad c_T = \frac{\kappa^2_H m^2_W}{2 m_v^2} \quad c_H = \frac{3 \kappa'_H m^2_W}{2 m_v^2} \quad c_6 = -4 \lambda \kappa'^2_H \frac{m^2_W}{m_v^2} \quad c_{\psi} = \kappa'^2_H \frac{m^2_W}{m_v^2} \\
\end{align*}
\]

\[
\delta g_{1z} = \frac{g^2 + g'^2}{g^2 - g'^2} (c_T - \delta v)
\]

\[
\delta v = \frac{1}{2} ([c'_{Hl}]_{11} + [c'_{Hl}]_{22}) - \frac{1}{4} [c_{ll}]_{1221} = -\kappa'_H \kappa'_l \frac{m^2_W}{m_v^2}
\]

\[
[c'_{Hl}]_{11} = [c'_{Hl}]_{22} = -\kappa'_H \kappa'_l \frac{m^2_W}{m_v^2}
\]

\[
[c_{ll}]_{1221} = -2 \kappa'^2_l \frac{m^2_W}{m_v^2} + \Delta = 0
\]

\[
\delta m = \frac{1}{g^2 - g'^2} \left( g^2 c_T - g'^2 \delta v \right) = 0 \quad \rightarrow \quad \kappa'_H \kappa'_f = -\frac{g^2}{2 g'^2} \kappa'^2_H
\]

Both triplet and singlet are required to have \( \Delta m = 0 \)

\[
\delta g_{1z} = -\kappa^2_H \frac{g^2 + g'^2}{2 g'^2} \frac{m^2_W}{m_v^2}
\]

\[
\delta \kappa'_H = \lambda_Z = 0
\]
**EFT vs UV model (strongly vs weakly)**

$SU(2)_L$ triplet + singlet

\[ \mathcal{L}_{\text{int}} = V_\mu^a \left( \frac{i}{2} g \kappa_H J_H^{a \mu} + \frac{g'}{2} \kappa_{J} J_J^{a \mu} \right) + V_\mu^0 \left( -\frac{i}{2} g \kappa_H J_H^{\mu} + \frac{g'}{2} \kappa_{J} J_J^{\mu} \right) \]

\[ \delta g_{1z} = -\kappa_H^2 \frac{g^2 + g'^2 m_W^2}{2 g'^2 m_V^2} \propto -\frac{\kappa_H^2}{m_V^2} \]

\[ \delta g_{1z} = -0.009 \quad \leftrightarrow \quad \frac{\kappa_H}{m_V} = \frac{0.75}{1 \text{ TeV}} = \frac{1.5}{2 \text{ TeV}} = \frac{4.5}{6 \text{ TeV}} \]

**Weakly coupled**  
**Strongly coupled**

EFT works better for a strong coupling

---

Similar exercise for Wh appeared in Contino, Falkowski, Goertz, Grojean, Riva 16’
**Illustration of EFT vs Direct**

$SU(2)_L$ triplet + singlet

\[ \mathcal{L}_{int} = V_\mu^a \left( \frac{i}{2} g' \kappa_H J^{a \mu}_H + \frac{g}{2} \kappa^a f J^{a \mu}_f \right) + V_\mu^0 \left( -\frac{i}{2} g \kappa_H J^{\mu}_H + \frac{g}{2} \kappa_f J^{\mu}_f \right) \]

\[ \delta g_{1Z} = -\kappa_H^2 \frac{g^2 + g'^2 m_W^2}{2 g'^2 m_W^2} m_V \propto -\frac{\kappa_H^2}{m_V} : \text{EFT constrains } \frac{\kappa_H}{m_V} \]

---

**WZ-lvll @8TeV**

- Will become more conservative with cuts
- Exclusion via EFT
- No mwz cut applied
- Direct exclusion for $\kappa_H \geq 3 \kappa H$

---

Similar exercise for Wh appeared in Contino, Falkowski, Goertz, Grojean, Riva 16'