GLOBAL SMEFT FITS
FOR VBS

RAQUEL GOMEZ AMBROSIO
SM@LHC 2019, ZÜRICH
Dim-6 EFT and VV processes

- Outline:
  - Introduction and motivation
  - TGCs and QGCs in Dim-8 and Dim-6
  - The global Dim-6 picture: Differential distributions and fitting tools
  - Backgrounds
  - Future colliders

- Goals:
  - Focus on the less understood and/or controversial points
  - Introduce open questions on the topic:
    - Open questions and backup
  - Disclaimer: Won’t cover ALL related topics (apologies!)
Vector Boson Scattering

• Family of processes of the type: \( q_1 \bar{q}_2 \rightarrow VV q_3 \bar{q}_4 \)

• Fundamental for tests of the EWSB mechanism

• Only way to access Quartic Gauge Couplings (QGC) at LHC

Why are TGC/QGC so attractive?

The VBS amplitudes violate unitarity at high energies.
What makes VBS & the Gauge sector so interesting?

\[ W_L W_L \rightarrow W_L W_L \]

At high energies, the longitudinal modes are dominating.
What makes VBS & the Gauge sector so interesting?

\[ W_L W_L \rightarrow W_L W_L \]

Need very precise cancellations …

1. TGC/QGC
2. Higgs
SM Effective Field Theory (SMEFT)

- Effective field theory: Decoupling heavy states from the light energy regime

\[
\sim \frac{1}{p^2 + M^2} \to M^2 \gg p^2 \to \frac{1}{M^2} \left( 1 - \frac{p}{M} + \frac{1}{2} \left( \frac{p}{M^2} \right)^2 + \ldots \right)
\]

- Assuming linear representation for the Higgs, no new light particles, and SM symmetries:

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

- The most general basis in dim-6 has 2499 Operators, 59 if we assume some flavour symmetries: Here we will use the so-called Warsaw Basis

Compatible with NLO corrections! (unlike kappa/anomalous approach)
Higher DIM operators in TGC and QGC

The higher dimensional effects can be parametrised as:

\[ Z_\mu W_\nu W_\rho \sim g^{\mu\nu} p^\rho + \ldots + \frac{1}{\Lambda^2} p^\mu p^\nu p^\rho + \ldots + \frac{M^2}{\Lambda^2} p^\mu p^\nu p^\rho + \ldots + \ldots \]

\[ \sim \underbrace{\frac{1}{\Lambda^2} p^\mu p^\nu + \ldots + \frac{1}{\Lambda^2} p^\mu p^\nu p^\rho p^\sigma + \ldots + \ldots}_{\text{dim-8}} \]

Grows very fast with energy:

Unitarity constraints on EFT
TRADITIONAL VBS INTERPRETATION: DIM 8

- VBS has traditionally been associated with Quartic Gauge Couplings, and the former have traditionally been described in terms of dim-8 operators only.
- QGC can be parametrised in terms of “non-TGC EFT operators”

\[
\begin{align*}
O_{T,0} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right], \\
O_{T,1} &= \text{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right] \times \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right], \\
O_{T,2} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \text{Tr} \left[ \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} \right], \\
O_{T,5} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \hat{B}_{\alpha\beta} \hat{B}^{\alpha\beta}, \\
O_{T,6} &= \text{Tr} \left[ \hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right] \times \hat{B}_{\mu\nu} \hat{B}^{\mu\nu}, \\
O_{T,7} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \hat{B}_{\beta\nu} \hat{B}^{\beta\nu}, \\
O_{T,8} &= \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \hat{B}_{\alpha\beta} \hat{B}^{\alpha\beta}, \\
O_{T,9} &= \hat{B}_{\alpha\beta} \hat{B}^{\alpha\beta} \hat{B}_{\beta\nu} \hat{B}^{\beta\nu}, \\
O_{S,0} &= \left( D_\mu \Phi \right)^\dagger D_\nu \Phi \times \left( D^\mu \Phi \right)^\dagger D^\nu \Phi, \\
O_{S,1} &= \left( D_\mu \Phi \right)^\dagger D^\mu \Phi \times \left( D_\nu \Phi \right)^\dagger D^\nu \Phi, \\
O_{S,2} &= \left( D_\mu \Phi \right)^\dagger D_\nu \Phi \times \left( D^\nu \Phi \right)^\dagger D^\mu \Phi, \\
O_{M,0} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left( D_\beta \Phi \right)^\dagger D^\beta \Phi, \\
O_{M,1} &= \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left( D_\beta \Phi \right)^\dagger D^\mu \Phi, \\
O_{M,2} &= \left[ \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \right] \times \left( D_\beta \Phi \right)^\dagger D^\beta \Phi, \\
O_{M,3} &= \left[ \hat{B}_{\mu\nu} \hat{B}^{\nu\beta} \right] \times \left( D_\beta \Phi \right)^\dagger D^\mu \Phi, \\
O_{M,4} &= \left( D_\mu \Phi \right)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \hat{B}^{\beta\nu}, \\
O_{M,5} &= \left( D_\mu \Phi \right)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \hat{B}^{\beta\mu}, \\
O_{M,7} &= \left( D_\mu \Phi \right)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi.
\end{align*}
\]

Approach adopted by ATLAS and CMS

- Basis from Eboli et al., Phys. Rev. D74, 073005 (2006),
- Complete Dim-8 basis in: (Henning et al. 2015)
  “2, 84, 30, 993, 560, 15456, 11962, 261485, ...: Higher dimension operators in the SM EFT”
TRADITIONAL APPROACH: DIM-8

“Same-sign WW scattering at the LHC: can we discover BSM effects before discovering new states?” (Kalinowski et al. 2018)

Apply BSM significance + Unitarity considerations to find the optimal search region

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>Lower limit (TeV⁻¹)</th>
<th>Upper limit (TeV⁻¹)</th>
<th>Coeff.</th>
<th>Lower limit (TeV⁻¹)</th>
<th>Upper limit (TeV⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{S0}$</td>
<td>1.3</td>
<td>2.0</td>
<td>$-f_{S0}$</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>$f_{S1}$</td>
<td>8.0</td>
<td>6.5</td>
<td>$-f_{S1}$</td>
<td>5.5</td>
<td>6.0</td>
</tr>
<tr>
<td>$f_{T0}$</td>
<td>0.08</td>
<td>0.13</td>
<td>$-f_{T0}$</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>$f_{T1}$</td>
<td>0.03</td>
<td>0.06</td>
<td>$-f_{T1}$</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>$f_{T2}$</td>
<td>0.20</td>
<td>0.25</td>
<td>$-f_{T2}$</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>$f_{M0}$</td>
<td>1.0</td>
<td>1.2</td>
<td>$-f_{M0}$</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>$f_{M1}$</td>
<td>1.0</td>
<td>1.9</td>
<td>$-f_{M1}$</td>
<td>0.9</td>
<td>1.8</td>
</tr>
<tr>
<td>$f_{M6}$</td>
<td>2.0</td>
<td>2.4</td>
<td>$-f_{M6}$</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>$f_{M7}$</td>
<td>1.1</td>
<td>2.8</td>
<td>$-f_{M7}$</td>
<td>1.3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 1: Estimated lower limits for BSM signal significance and upper limits for EFT consistency for each dimension-8 operator (positive and negative $f$ values), for the case when $\Lambda$ is equal to the unitarity bound, in the $W^+W^+$ scattering process at the LHC with 3 ab⁻¹.
DIM 6: TGC AND QGC IN THE WARSAW BASIS

For the previous reasons, a description in terms of Dim-6 is more general and consistent. In terms of dim-6 operators, QGCs and TGCs can be written as:

\[ Z_\mu Z_\nu W_\rho^+ W_\sigma^- \]

Field and parameter shifts

\[ \mathcal{O}_{HD} = \left( H^\dagger D_\mu H \right)^* \left( H^\dagger D_\mu H \right) \]
\[ \mathcal{O}_{H\ell^{(3)}} = \left( H^\dagger iD_\mu H \right) \left( \bar{\ell}_p \gamma_\mu \ell_r \right) \]
\[ \mathcal{O}_\ell^\prime \ell = \left( \bar{\ell}_p \gamma_\mu \ell_r \right) \left( \bar{\ell}_s \gamma^\mu \ell_t \right) \]

Vertex

\[ \mathcal{O}_{HW} = ( H^\dagger H ) W^I_{\mu\nu} W^{\mu\nu I} \]
\[ \mathcal{O}_W = \epsilon_{IJK} W^I_{\mu\nu} W^J_{\nu\rho} W^K_{\rho\mu} \]
\[ \mathcal{O}_{HWB} = ( H^\dagger \tau^I H ) W^I_{\mu\nu} B^{\mu\nu} \]
Grzadkowski et al. (basis), Alonso et al. (representation)
EXAMPLE: ZZ VBS AND WZ

- Evidence/Measured at Run-2

\[
\frac{\sigma_{EFT,\text{bosonic}}}{\sigma_{SM}} \approx 1 + 0.047 \, \hat{c}_{HB} - 0.053 \, \hat{c}_{H\Box} - 0.0021 \, \hat{c}_{HB} + 0.010 \, \hat{c}_{Hd} - 1.84 \, \hat{c}_{HD} \\
- 3.86 \, \hat{c}_{H(3)}^{(1)} - 0.017 \, \hat{c}_{Hq(1)} + 5.61 \, \hat{c}_{Hq(3)} - 0.033 \, \hat{c}_{Hu} + 0.59 \, \hat{c}_{HW} \\
- 0.0041 \, \hat{c}_{HW} - 0.69 \, \hat{c}_{HWB} - 0.022 \, \hat{c}_{HWB} + 0.23 \, \hat{c}_{W} - 0.086 \, \hat{c}_{W}.
\]

\[
\frac{\sigma_{EFT,\text{fermionic}}}{\sigma_{SM}} \approx 1 - 3.23 \cdot 10^{-6} \, \hat{c}_{dd} - 2.89 \cdot 10^{-6} \, \hat{c}_{dd}^{(1)} - 3.86 \, \hat{c}_{\ell \ell}^{(1)} + 0.0010 \, \hat{c}_{qd}^{(1)} \\
+ 1.80 \cdot 10^{-20} \, \hat{c}_{qd}^{(8)} - 1.93 \, \hat{c}_{qq}^{(1)} - 2.57 \, \hat{c}_{qq}^{(11)} - 14.3 \, \hat{c}_{qq}^{(3)} - 10.3 \, \hat{c}_{qq}^{(31)} \\
- 0.0049 \, \hat{c}_{qu}^{(1)} - 2.51 \cdot 10^{-20} \, \hat{c}_{qu}^{(8)} + 0.00020 \, \hat{c}_{ud}^{(1)} \\
+ 1.62 \cdot 10^{-21} \, \hat{c}_{ud}^{(8)} - 0.0010 \, \hat{c}_{uu} - 0.00099 \, \hat{c}_{uu}^{(1)}.
\]

\[
\frac{\sigma_{EFT,bkg}}{\sigma_{SM,bkg}} \approx 1 - 0.00073 \, \hat{c}_{HD} - 0.0036 \, \hat{c}_{HD} + 0.044 \, \hat{c}_{HG} - 0.00016 \, \hat{c}_{HG} \\
- 0.077 \, \hat{c}_{H(3)}^{(3)} + 0.018 \, \hat{c}_{Hq(1)} + 0.17 \, \hat{c}_{Hq}^{(3)} \\
+ 0.0065 \, \hat{c}_{Hu} + 0.035 \, \hat{c}_{HWB} - 0.077 \, \hat{c}_{\ell \ell}^{(1)}
\]
Not only total cross-sections... Differential observables shed light on the EFT effects

Important to understand TH and EXP correlations across observables, in order to choose wisely!
**Overview of Physics Models**

- The default behavior in `combine` is to have a single POI, the "signal strength", which is applied to all of the signal processes.
- "Physics Models" can be used to make more complicated interpretations with the data.
- They are essentially python modules which add variables, functions, and RooStats expressions to the model which define the set of POI's and how they effect the signal processes.
- Common (HIG related) models are stored in the package, e.g. Multiple Signals, $\kappa$ framework, floating Higgs mass, etc.
- Users can also easily write their own Physics Models.
- Many measurements in HIG use custom Physics Models written by analysts, e.g. Anomalous Couplings, Fiducial Cross Sections, Higgs Width/Lifetime, etc.
- Some examples from HIG will be shown, can be used as an example on how to construct a physics model suitable for other analyses.
VBS ZZ BACKGROUND

- QCD induced VV:

Figure 10: Some of the Feynman diagrams contributing to the VBS(ZZ) dominant background process in $\text{dim} = 6$ EFT. The blobs represent the dimension-six insertions.

Figure 11: Effect of the B1 scenario in the background process. The effect is in principle very small, however it is important to remark that the number of background events is about one order of magnitude larger per bin, than that for the signal.

EFT effect for ZZ VBS background

<table>
<thead>
<tr>
<th>Sensitivity %</th>
<th>Positive interference</th>
<th>Negative interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>cG</td>
<td>cHbox</td>
</tr>
<tr>
<td>100</td>
<td>cHDD</td>
<td>cHD</td>
</tr>
<tr>
<td>100</td>
<td>cHG</td>
<td>cHDD</td>
</tr>
<tr>
<td>100</td>
<td>cHW</td>
<td>cHB</td>
</tr>
<tr>
<td>100</td>
<td>cHq1</td>
<td>cHq3</td>
</tr>
<tr>
<td>100</td>
<td>cHq3</td>
<td>cHq3</td>
</tr>
<tr>
<td>100</td>
<td>cHung</td>
<td>cHd</td>
</tr>
<tr>
<td>100</td>
<td>cl11</td>
<td>cqq3</td>
</tr>
<tr>
<td>100</td>
<td>cqq31</td>
<td>cqq3</td>
</tr>
</tbody>
</table>

Keep calm and don't forget the background.
STATE OF THE ART: FUTURE COLLIDERS

Longitudinal Vector Boson Scattering in $e^+ e^-$

$e^+ e^- \rightarrow \bar{\nu} \nu ZZ$

CLIC 3 TeV

$\frac{d\sigma}{dM} \ [\text{fb}/\text{GeV}]$

$0 \ \ \ 10^{-1} \ \ \ 10^{-2} \ \ \ 10^{-3} \ \ \ 10^{-4}$

$p_{\perp (ZZ)} \ [\text{GeV}]$

$0 \ \ 100 \ \ 200 \ \ 300 \ \ 400 \ \ 500$

- SM
- EFT $F_{S,0} = 25 \ \text{TeV}^{-4}$
- EFT $F_{S,1} = 25 \ \text{TeV}^{-4}$
- Bkg. $W^+ W^- e^+ e^-$
- Bkg. $W^\pm Z e^{\mp} \nu$

(see refs. in the backup slides)
OPEN QUESTIONS

1. Is it enough to fit signal strengths as we do in f.ex Higgs physics?
   
   A. First problem: jet smearing

2. Why do the collaborations look for these “anomalous Dim-8” operators? Is there hope for Dim-6 in the current analyses?

3. Optimal observables for the fit (cover most of the NP space/avoid flat directions & correlations)?

4. .... ?
TRADITIONAL VBS INTERPRETATION: DIM 8

- One has to think which UV completion is compatible with this behaviour: only generating QGC and not TGC, predicting ZZZZ interactions….

If we assume the Higgs is a Doublet in a linear representation, we are implicitly assuming EWSB, where TGC and QGC are generated simultaneously.

Possible UV completion.. not very model independent.
**SMEFT: LINEAR VS QUADRATIC**

- Assuming linear representation for the Higgs, no new light particles, SM symmetries, etc:

\[
\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} \mathcal{O}^{(5)} + \frac{1}{\Lambda^2} \sum_i c^{(6)}_i \mathcal{O}_i^{(6)} + \sum_j \sum_k \frac{1}{\Lambda^{2+k}} c^{(6+k)}_j \mathcal{O}_j^{(6+k)}
\]

\[
\mathcal{A}_{EFT} = \mathcal{A}_{SM} + \frac{g'}{\Lambda^2} \mathcal{A}_6 + \frac{g'^2}{\Lambda^4} \mathcal{A}_8 + \ldots
\]

\[
\sigma_{EFT} \sim |\mathcal{A}_{SM}|^2 + 2 \frac{g'}{\Lambda^2} \mathcal{A}_{SM} \mathcal{A}_6 + \frac{g'^2}{\Lambda^4} \left( 2 \mathcal{A}_{SM} \mathcal{A}_8 + |\mathcal{A}_6|^2 \right) + \ldots
\]
FUTURE PROSPECTS (HL-LHC)

- VBS(ZZ) with leptonic decays: very good prospects for the future runs
- LHC Run-2: $\mathcal{O}(10)$ events $\rightarrow$ HL-LHC: $\mathcal{O}(100)$ events

---

R. Covarelli, R. Gomez Ambrosio, for HL-HE-LHC yellow report
Overview Literatur: VBS in $e^+ e^- / e^- e^-$

- Gunion/Tofghi-Niaki, PRD36 (1987) 2671: full MEs for VBS (WW) and heavy Higgs production $[0.5, 1, 2 \text{ TeV}]$
- Gunion/Tofghi-Niaki, PRD38 (1988) 1433: same for ZZ final states $[0.5, 1, 2 \text{ TeV}]$
- Barger/Cheung/Han/Phillips, PRD52 (1995) 3815: measurements of WW/ZZ ratios $[1.5 – 2 \text{ TeV}]$
- Dominici, Riv.Nuo.Cim.20 (1997) 1: access to parameters of EW chiral Lagrangian in WW VBS $[1.5 \text{ TeV}]$
- Denner/Dittmaier/Hahn, PRD56 (1997) 117: EW corrections to $ZZ \to ZZ$
- Denner/Hahn, NPB525 (1998) 27: EW corrections to $WW \to WW$
- Han/He/Yuan, PLB422 (1998) 294: interplay of WW VBS and WWZ/ZZZ production $[0.5, 0.8, 1, 1.6 \text{ TeV}]$
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD57 (1998) 1553: EW chiral Lagrangian (strong EW) $[1.6 \text{ TeV}]$
- Boos/He/Kilian/Pukhov/Yuan/Zerwas, PRD61 (2000) 077901: strong EW: $ZZ/W^-W^-$ channels $[1.6 \text{ TeV}]$
- Chierici/Rosati/Kobel, LC-PHSM-2001-038: experimental study for strong EW $[0.18–0.8 \text{ TeV}]$
- Rosati, CERN-THESIS-2002-083: experimental study for strong EW $[0.18–0.8 \text{ TeV}]$
- Beyer/Kilian/Krstonošić/Mönig/JRR/Schmidt/Schröder, EPJC48 (2006) 353: $\alpha$ parameters, VBS+VVV $[1 \text{ TeV}]$
- Accomando/Denner/Pozzorini, JHEP 0703 (2007) 078: EW Sudakov logarithms in VBS $[3 \text{ TeV}]$
- Liebler/Moortgat-Pick/Weiglein, JHEP 1506 (2015) 093: on-shell Higgs effects in $ee \to vvVV$ $[0.25 – 1 \text{ TeV}]$
- Fleper/Kilian/JRR/Sekulla, EPJC77.2 (2017) 120: VBS for SMEFT with dim 8 / simplified models $[1, 1.4, 3 \text{ TeV}]$