Multi-Boson interactions 2019
Summary Talk

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MBI 2019, Thessaloniki, Greece
Outline

1 Theory
   - Standard Model
   - Understanding Cross Sections
     - Diboson Production
     - VBF and VBS
     - Polarization
   - Beyond the SM
     - EFTs
     - Other BSM strategies?

2 Experimental Searches
   - Diboson Production
   - VBF and VBS
   - Polarization

3 Constraints on aTGCs

4 Constraints on aQGCs

5 Future sensitivity

6 Epilogue
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A. Dedes (University of Ioannina)

MBI 2019 Summary Talk

August 28, 2019
Personal view of the current SM state...
Multi-boson interactions probe the non-abelian local symmetry of the gauge sector.

In the SM there are two triple, $W^+W^-\gamma$, $W^+W^-Z$

and four quartic, $W^+W^-\gamma\gamma$, $W^+W^-Z\gamma$, $W^+W^-ZZ$, $W^+W^-W^+W^-$

gauge boson vertices. No pure “neutral particle” vertices exist at tree level.

$D \leq 4$ and Gauge Invariance $\rightarrow$ 2 SM Parameters: $\{g', g\}$ OR $\{e, \sin \theta_W\}$
Anomalous Triple Gauge Couplings (aTGCs)

Historically\(^1\), aTGCs parametrized by a general Lorentz invariant Lagrangian

\[
\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1 V \left( W^\dagger_{\mu\nu} W^{\mu\nu} - W^{\dagger\mu} V_\nu W^{\mu\nu} \right) + i \kappa V W^\dagger_\mu W_\nu V^{\mu\nu} \\
+ \frac{i \lambda V}{m_W^2} W^\dagger_{\rho\mu} W^{\mu\nu} V^{\nu\rho} - g_4 V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
+ g_5 V \epsilon^{\mu\nu\rho\sigma} \left( W^\dagger_{\mu} \overleftrightarrow{\partial}_{\rho} W_\nu \right) V_\sigma + i \tilde{\kappa} V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\
+ \frac{i \tilde{\lambda} V}{m_W^2} W^\dagger_{\rho\mu} W^{\mu\nu} \tilde{V}^{\nu\rho}
\]

Historically, aTGCs parametrized by a general Lorentz invariant Lagrangian

\[
\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left( W_{\mu\nu} W^\mu V^\nu - W^\mu V_\nu W^{\mu\nu} \right) + i \kappa V W^{\mu\nu} W_\mu W_\nu V_{\mu\nu}
\]

\[+ \frac{i \lambda V}{m_W^2} W_{\rho\mu} W_{\nu} V^{\nu\rho} - g_4^V W^\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu)
\]

\[+ g_5^V \epsilon^{\mu\nu\rho\sigma} (W^\mu \overleftarrow{\partial}_\rho W_\nu) V_\sigma + i \tilde{\kappa} V W^{\mu\nu} W_\mu W_\nu \tilde{V}^{\mu\nu}
\]

\[+ \frac{i \tilde{\lambda} V}{m_W^2} W_{\rho\mu} W_{\nu} \tilde{V}^{\nu\rho}
\]

where

\[ V = V^\dagger = Z, \gamma, V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu, \tilde{V}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} V^{\rho\sigma}. W^\mu \equiv W_\mu - \text{ and}
\]

\[ W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu \]

\[ \lambda_V, \tilde{\lambda}_V \text{ are dimension-6 operator couplings}
\]

\[ 2 \times 7 = 14 \text{ parameters} \]
Anomalous Triple Gauge Couplings (aTGCs)

Historically, aTGCs parametrized by a general Lorentz invariant Lagrangian

\[
\frac{L_{WWV}}{g_{WWV}} = i g_1^V \left( W_{\mu\nu}^\dagger W_{\mu}^\nu V_{\nu}^\mu - W_{\mu}^\dagger V_{\nu}^\mu W_{\mu\nu}^\dagger \right) + i \kappa V W_{\mu}^\dagger W_{\nu} V^{\mu\nu} \\
+ \frac{i \lambda V}{m_W^2} W_{\mu\nu}^\dagger W_{\mu} W^{\nu\rho} - g_4^V W_{\mu}^\dagger W_{\nu} V^{\mu} (\partial_{\mu} V_{\nu}^\dagger + \partial_{\nu} V_{\mu}^\dagger) \\
+ g_5^V \epsilon_{\mu\nu\rho\sigma} (W_{\mu}^\dagger \bar{\partial}_{\rho} W_{\nu}) V_{\sigma} + i \tilde{\kappa} V W_{\mu}^\dagger W_{\nu} V^{\mu\nu} \\
+ \frac{i \tilde{\lambda} V}{m_W^2} W_{\mu\nu}^\dagger W_{\nu} V^{\mu\rho}
\]

Some terms in this parametrization explicitly break gauge invariance that we know it is valid from LEP.
Anomalous Triple Gauge Couplings (aTGCs)

Historically, aTGCs parametrized by a general Lorentz invariant Lagrangian

\[
\frac{\mathcal{L}_{WWV}}{g_{WWV}} = \frac{i g_1^V}{g_{WWV}} \left( W_{\mu\nu}^\dagger W^\mu W^\nu - W_{\mu}^\dagger V_{\nu} W_{\mu\nu} \right) + \frac{i \kappa_V}{g_{WWV}} W_{\mu}^\dagger W_{\nu} V_{\mu\nu} \\
+ \frac{i \lambda_V}{m_W^2} W_{\mu\nu}^\dagger W_{\nu\rho} \nu V_{\mu\rho} - g_4^V W_{\mu}^\dagger W_{\nu} \left( \partial^\mu V^\nu + \partial^\nu V^\mu \right) \\
+ g_5^V \epsilon_{\mu\nu\rho\sigma} \left( W_{\mu\nu}^\dagger \partial^\rho W_{\nu} \right) V_{\sigma} + i \tilde{\kappa}_V W_{\mu}^\dagger W_{\nu} \tilde{V}_{\mu\nu} \\
+ \frac{i \tilde{\lambda}_V}{m_W^2} W_{\mu\nu}^\dagger W_{\nu\rho} \tilde{V}_{\mu\rho}
\]

Better formulated as deviations from SM TGCs

**SM tree level:** \( g_1^V = \kappa_V = 1 \), \( \lambda_V = \tilde{\lambda}_V = g_4^V = g_5^V = \tilde{\kappa}_V = 0 \)

\( g_{WW\gamma} = e \), \( g_{WWZ} = e \cot \theta_W \)
Goldstone Boson Equivalence Theorem (GBET)\textsuperscript{1}

At High Energies (HE) relative to the $W$-mass, massive gauge bosons $W^\pm, Z$ can be replaced by the corresponding Goldstone Bosons $G^\pm, G^0$ in scattering processes.

\[ S[W_L^\pm, \text{physical}] = i^n \times S[G^\pm, \text{physical}] \]

Dynamics of $V_L$s is directly linked to GBET and $SU(2)_L \times U(1)_Y$ invariance restoration at HE.

GBET and Unitarity

Tree Level Unitarity\(^1\)

"the N-particle S-matrix elements in the tree approximation must grow no more rapidly than \(E^{4-N}\) in the limit of HE, at fixed non-zero angles"

In the SM all multi Goldstone Boson interactions do not contain momenta and therefore leading \(s\)-behaviour cancels against \(s\), \(t\) and \(u\) exchanges of vector and Higgs-boson mediated amplitudes.

Processes

**Diboson Production**

**Vector Boson Fusion (VBF)**

**Vector Boson Scattering (VBS)**
Understanding Cross Sections

Diboson Production

- Experimental uncertainties have been surpassed the 10% uncertainty so we have to go to few present theoretically.
- All NNLO QCD corrections have been completed! They are included in a code (MATRIX+OneLoops)\(^2\)
- Excellent agreement between NNLO and data
- NNLO QCD + NLO EW corrections\(^3\) giant K-factors in observables for \(ZZ, WW, WZ\)
- At HE, NLO EW/LO = -40% - 50%.
- One must set jet-veto at high-\(s\) since the process is driven away from aTGC searches

\(^2\)Review talk by Marius Wiesemann
\(^3\)Review talk by Jonas Lindert
**VBF and VBS**

- $pp \to e^+ \nu_e \mu^+ \mu^- jj$ at NLO EW/QCD corrections for $W^+Z$ scattering at the LHC: corrections of order $O(\alpha_s\alpha^6)$ and $O(\alpha^7)$ the latter being large $\sim -17.5\%$ especially at high $p_T j$ (Sudakov enhancement)$^4$

- Progress in QCD effects in borderline between perturbative and non-perturbative regime dictated by the factorization theorem discussed$^5$

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$^4$Talk by Christopher Schwan

$^5$Talk by Simon Plaetzer
Polarization

- Important to provide accurate theory predictions for polarized VBS for LHC analyses
- A nice formula but assumes no lepton cuts so interference effects vanish

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6 Talk by Giovanni Pelliccioli

A. Dedes (University of Ioannina)
Systematic deviations from the SM can be studied effectively within EFT as long as the scale of New Physics, $\Lambda$, is $\Lambda^2 \gg M_W^2$ and $s = (p_1 + p_2)^2$. A particularly interesting EFT scenario is SMEFT.

**SMEFT:** Assuming there is nothing but the SM below, say $\Lambda \sim 1$ TeV, and the Higgs field belongs to the SU(2)-doublet, SM is augmented with high dimensional gauge invariant operators.

“Warsaw basis”\(^7\) is a non-redundant basis. The complete set of Feynman Rules have been completed for $d \leq 6$ operators in Unitary and $R_\xi$-gauges.\(^8\) **SmeftFR code**\(^9\) generates FRs and interfaces them to UFO and FeynArts for various event generator and symbolic calculations.

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\(^7\)B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, arXiv:1008.4884

\(^8\)AD, W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, arXiv:1704.03888

Beyond the SM

$\gamma W^+ W^- \text{ in SMEFT with } d \leq 6 \text{ operators}$
“Triboson” parameters in EFT with \( d \leq 6 \) operators:
CP-invariant parameters : 5 new - 2 constraints = 3
CP-violating parameters = 2

One should be very careful with EFTs!

- \( s, M_W^2 << \Lambda^2 \) – otherwise using EFT is nonsense!
- Bounds on Wilson coefficients are given in particular operator basis (e.g. Warsaw, SILH, etc)
- Bounds on Wilson coefficients should be given in a particular input scheme e.g. one has to trade \( \bar{g}, \bar{g}', \nu \) with measurable quantities like for example\(^{10}\)
  - \( \{\alpha_{em}, m_Z, G_F, m_h, m_t, \ldots\}\)-scheme
  - \( \{m_W, m_Z, G_F, m_h, m_t, \ldots\}\)-scheme
  - ....

\(^{10}\)I. Brivio and M. Trott, arXiv:1701.06424
Beyond the SM

SMEFT@NLO

- The S-matrix must be renormalization scale independent (up to a fixed order in loop and EFT expansion).
- In SMEFT one has to include running from all operators so that the result is gauge invariant.
- Overview of NLO calculations in SMEFT\textsuperscript{11}. Several observable studies fully at 1-loop in SMEFT.
- A first step towards SMEFT@NLO QCD has been done. NLO EW fully automated?

\textsuperscript{11}Review talk by Cen Zhang

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Non-linear EFT

- Non Linear EFT$^{12}$: the Higgs field does not reside in the $SU(2)_L$ doublet
- EFT is now more involved. $d = 8$ operators are promoted to $d = 6$ operators that reach easily unitarity bound, $|a_J(s)| = 1.$, because for example VBS amplitudes grow with $A \sim s^2$
- There must be a cut-off at scales much before the typical $\Lambda^2$: there are unitarization suggestions

My opinion: a prototype model (if it exists) could be used as a benchmark to be used in experimental studies

$^{12}$Talk by Rafael Lopez Delgado
**Positivity constraints:** In every QFT based on analyticity, unitarity, Lorentz invariance there are certain bounds on certain linear combinations of $d = 8$ operators in SMEFT\(^{13}\)

\[
\sum_i C_i^{(8)} x_i \geq 0
\]
BSM Models and EFTs

- SMEFT at HE: there are 4 parameters that grow with $\sigma \sim s$ in diboson processes. Observables are $WW$, $WZ$, $HW$, $HZ$. Possible to probe "weak coupling regime" where $g^2/M^2$ with $g^* \sim g \lesssim 0.1\%$.

- Currently we are probing the strong coupling regime $g^* \sim (4\pi)$ in diboson searches.

- A composite model related to TGCs presented.

- One way to compete with LEP precision is by going to HE and study ZH production. Due to GBET we have a contact term that dominates the amplitude far from resonances.\(^{15}\)

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\(^{14}\) Review talk by Marc Montull
\(^{15}\) Talk by Sandeepan Gupta
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A. Dedes (University of Ioannina)  MBI 2019 Summary Talk  August 28, 2019
CMS $\mathcal{L} = 137 \text{fb}^{-1}$ (partly Run-II data included) total and differential cross sections. Report on $WW$, $WZ$, $ZZ$ leptonic final states as well as on

Precision of 5% reached.

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Talk by Alicia Calderon
ATLAS fiducial and diff Xsections Reports on WW and ZZ$^{16}$

$^{16}$Talk by Valerie Lang
Measurement of Diboson production in semileptonic decay modes and anomalous Couplings\textsuperscript{17}

\textbf{Semileptonic:}

Diboson final state with one V decay to quarks (→ jets), and other V decay to final state with lepton (e, μ)

\textsuperscript{17}Review talk of ATLAS and CMS results by Robin Cameron Aggleton
Measurement of Diboson production in **semileptonic** decay modes and anomalous Couplings\(^{17}\)

Direct Searches for NP in diboson searches: limits on KK gravitons, \(V'\) and \(W'\) masses \(\geq 1.5\) TeV.\(^{18}\)

\(^{17}\)Review talk of ATLAS and CMS results by Robin Cameron Aggleton

\(^{18}\)Talk by Antonis Agapitos
- $ssWWjj$, $WZjj$ and $ZZjj$ at $\sqrt{s} = 13$ TeV seem to have been observed at ATLAS
- Also photons in the final state\(^1\): $Z\gamma jj$ (strong evidence for both ATLAS and CMS) or $\gamma\gamma jj$ (observation in heavy ions by ATLAS)
- Higgs VBF and Z/W VBF presented\(^2\). The former agrees with the SM while the latter are dominated by systematics.
- Jet-veto technics based on event-by-event selection may help in VBF/VBS signal/background in SM and BSM searches\(^3\)

\(^1\)Talk by Narei Lorenzo Martinez
\(^2\)Talk by Dag Gillberg
\(^3\)Talk by Richard Ruiz
Polarization

Probing GBET directly. ATLAS search for $WZ$ channel$^{22}$

- $F_0$ is measured different from 0 at more than 3 sigma and in agreement with predictions
- $F_L - F_R$ at 2 sigma from predictions in $W^+$

$^{22}$Talk by Corinne Goy
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Dibosons

CMS at 13 TeV (1D and 2D limits). Semileptonic final state. Big improvements w.r.t 8 TeV results

<table>
<thead>
<tr>
<th>Parametrization</th>
<th>aTGC</th>
<th>Expected limit</th>
<th>Observed limit</th>
<th>Observed best-fit</th>
<th>CMS 8TeV observed limit</th>
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<tr>
<td>EFT</td>
<td>$c_{WWW}/\Lambda^2$ (TeV$^{-2}$)</td>
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<td>$c_W/\Lambda^2$ (TeV$^{-2}$)</td>
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<td>[-2.00, 2.65]</td>
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<td>$c_B/\Lambda^2$ (TeV$^{-2}$)</td>
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<tr>
<td>LEP</td>
<td>$\lambda^Z$</td>
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<td>[-0.0065, 0.0066]</td>
<td>-0.0010</td>
<td>[-0.011, 0.011]</td>
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<tr>
<td></td>
<td>$\Delta g_1^Z$</td>
<td>[-0.0070, 0.0061]</td>
<td>[-0.0061, 0.0074]</td>
<td>0.0027</td>
<td>[-0.009, 0.024]</td>
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<tr>
<td></td>
<td>$\Delta \kappa_Z$</td>
<td>[-0.0074, 0.0078]</td>
<td>[-0.0079, 0.0082]</td>
<td>-0.0010</td>
<td>[-0.018, 0.013]</td>
</tr>
</tbody>
</table>

$^{23}$Talk by Robin Cameron Aggleton
Dibosons

CMS at 13 TeV (1D and 2D limits). Semileptonic final state. Big improvements w.r.t 8 TeV results

Talk by Robin Cameron Aggleton
VH and HH

\( V(\ell\ell)H(\bar{b}b) \) has been observed\(^{24} \). HH is currently being searched for. At High \( p_T \) is an interesting probe for NP (see theory talks on EFTs)


\(^{24}\)Talk by Stephane Cooperstein
V(ℓℓ)H(¯bb) has been observed\textsuperscript{24}. HH is currently being searched for.

At High $p_T$ is an interesting probe for NP (see theory talks on EFTs)

\textsuperscript{24}Talk by Stephane Cooperstein
Triboson Production

There is evidence for triboson production at ATLAS\textsuperscript{25}.

\[ \text{ATLAS, } \sqrt{s} = 13 \text{ TeV, } 79.8 \text{ fb}^{-1} \]

Triboson searches are under investigation also at CMS.\textsuperscript{26}

\textsuperscript{25} Talk by Andrea Sciandra
\textsuperscript{26} Talk by Miaoyuan Liu
Effects on VBS Xsection from SMEFT parameters (Warsaw basis) in WZ production\textsuperscript{27}

\textsuperscript{27}Talk by Despoina Sampsonidou
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Limits on $d = 8$ Wilson coefficients in VBS (CMS, EWK VV production, semileptonic mode)$^{28}$

<table>
<thead>
<tr>
<th></th>
<th>Obs Low</th>
<th>Obs High</th>
<th>Exp Low</th>
<th>Exp High</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{S,0}$</td>
<td>-2.7</td>
<td>2.7</td>
<td>-4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>$F_{S,1}$</td>
<td>-3.4</td>
<td>3.4</td>
<td>-5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>$F_{M,0}$</td>
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<td>0.70</td>
<td>-1.0</td>
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</tr>
<tr>
<td>$F_{M,1}$</td>
<td>-2.0</td>
<td>-2.1</td>
<td>-3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$F_{M,6}$</td>
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<td>1.3</td>
<td>-1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>$F_{M,7}$</td>
<td>-3.4</td>
<td>3.4</td>
<td>-5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>$F_{T,0}$</td>
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<td>0.11</td>
<td>-0.17</td>
<td>0.16</td>
</tr>
<tr>
<td>$F_{T,1}$</td>
<td>-0.12</td>
<td>0.13</td>
<td>-0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>$F_{T,2}$</td>
<td>-0.28</td>
<td>0.28</td>
<td>-0.41</td>
<td>0.41</td>
</tr>
</tbody>
</table>

$F/\Lambda^4$ are in TeV$^{-4}$ units. These are the best limits so far.

$^{28}$Talk by Andrew Levin

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The plot created most discussions!\textsuperscript{29}

\textsuperscript{29}Talk by Hannes Mildner
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A. Dedes (University of Ioannina)  MBI 2019 Summary Talk  August 28, 2019
Polarization in VBS at HL-LHC: projective evidence for LL at few $\sigma$s per experiment but for the $VV \rightarrow V_L V_L$

But, using machine learning techniques ATLAS+CMS at $3000 fb^{-1}$ each may reach $5\sigma$ for ssWW and VBS ZZ scattering\textsuperscript{30}

HH prospects ...........\textsuperscript{31}

\textsuperscript{30}Talk by Meng Lu
\textsuperscript{31}Talk by Stephane Cooperstein
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Epilogue

- We had a constructive and focused meeting, a “real” gathering of both experimenters and theorists
- We learnt about cutting edge techniques and results in multi-boson interactions
We had a constructive and focused meeting, a “real” gathering of both experimenters and theorists.

We learnt about cutting edge techniques and results in multi-boson interactions.

Many thanks to the organizers, Chara, Spyros, Dimos and Kostas!!