UNITARISATION
OF ANOMALOUS COUPLINGS
IN VECTOR BOSON SCATTERING

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Hope for interesting features to show up in the near future:  

➡️ LHC Run 2
INTRODUCTION

- Interactions among vector bosons predicted in the SM
- Coupling structure determined by the Glashow-Weinberg-Salam model of weak interactions
- Measurement has only begun recently
  - Room for new physics

\[
\mathcal{L}_{\text{gauge}} = -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}
\]

\[
W^a_{\mu\nu} = ig \left( \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\epsilon_{abc} W^b_\mu W^c_\nu \right)
\]

\[
B_{\mu\nu} = ig \left( \partial_\mu B_\nu - \partial_\nu B_\mu \right)
\]
VECTOR BOSON SCATTERING

First results for electroweak production of same sign $W$-pairs from ATLAS

$\rightarrow$ Vector Boson Scattering

$\begin{align*}
\text{arXiv:} & \quad 1405.6241 \text{ [hep-ex]} \\
\end{align*}$
NEW PHYSICS

At least two ways to describe new physics effects:

- Propose specific new physics model like SUSY
  - new particles
  - new symmetries
- Problem: relatively long way from physics model to explicitly modeling e.g. deviations in vector boson couplings

- Use model independent approach: effective field theory (EFT) or anomalous couplings
  - SM particle content with modified couplings
• **Lagrangian approach** (a little outdated): constructed to contain all possible Lorentz-structures

\[
\mathcal{L}^{V V V' V'} = c_0^{WW} W^+\mu W^-\mu W^+\nu W^-\nu + c_1^{WW} W^+\mu W^+\mu W^-\nu W^-\nu
+ c_0^{WZ} W^+\mu Z^-\nu Z^\nu + c_1^{WZ} W^+\mu W^-\mu Z^-\nu Z^\nu
+ c_Z Z (Z^\mu Z^\mu)^2 .
\]

⇒ Not necessarily gauge invariant
⇒ Could add arbitrary number of terms with derivatives accompanied by factor \( m_V^{-1} \)

• Standard Model values:

\[
c_{0,SM}^{WW} = -c_{1,SM}^{WW} = \frac{2}{\cos^2 \theta_W} c_{0,SM}^{WZ} = - \frac{2}{\cos^2 \theta_W} c_{0,SM}^{WZ} = g^2 , \quad c_{SM}^{ZZ} = 0 ,
\]
EFFECTIVE FIELD THEORY

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{f_i}{\Lambda^2} \mathcal{O}_{i}^{(6)} + \sum_{k} \frac{f_k}{\Lambda^4} \mathcal{O}_{k}^{(8)} \]

- Use model independent approach: effective field theory (EFT) or anomalous couplings
  - SM particle content with modified couplings
- Extend SM by adding higher dimensional operators
- Capture any physics beyond SM in accessible energy range
- Balance energy dimension by inserting appropriate mass scale \( \Lambda \) (scale of New Physics)
- Dim. 8 operators as tools to model potential deviations of quartic gauge couplings from their SM values
DIM. 8 OPERATORS

- 3 classes of dim. 8 operators:
  \[ \mathcal{O}_{S,0} = [(D_\mu \Phi)^\dagger (D_\nu \Phi)] \times [(D^\mu \Phi)^\dagger (D^\nu \Phi)] \]
  \[ \mathcal{O}_{M,0} = \text{Tr}[W_{\mu\nu} W^{\mu\nu}] \times [(D_\beta \Phi)^\dagger (D^\beta \Phi)] \]
  \[ \mathcal{O}_{T,0} = \text{Tr}[W_{\mu\nu} W^{\mu\nu}] \times \text{Tr}[W_{\alpha\beta} W^{\alpha\beta}] \]

- 18 dim. 8 operators in total

- All are effecting vector boson 4-vertices in different ways

- Problem: Different combinations of polarizations lead to unphysically large cross sections

\[ \epsilon_L^\mu (k) = \frac{k_\mu}{m} + \mathcal{O} \left( \frac{m}{E} \right) \]
• Want to study deviations from the SM in an accessible energy range, e.g. at the LHC
• All effective operators break tree-level unitarity for high c.o.m. energy
  ‣ Unphysically large cross-sections
  ‣ When comparing predictions to data, all couplings would need to be zero
UNITARISATION

Is this a reasonable procedure?

- Historic example: Fermi’s 4-point interaction (1933):
  - effective 4-vertex leads to rise of the amplitude with \( s \)
  - Insertion of \( W^- \) propagator unitarizes the amplitude and gives correct low energy behavior

\[
\begin{align*}
N & \rightarrow P^+ \\
\bar{\nu}_e & \rightarrow e^- \\
N & \rightarrow W^- \\
W^- & \rightarrow e^- \\
N & \rightarrow P^+ \\
\end{align*}
\]
FORM FACTORS

- Multiply amplitudes by factor resembling a propagator:
  \[ \mathcal{A} \rightarrow \mathcal{A} \times \frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n} \]

- Choice of form factor lacks strong physical motivation

- One has to deal with two input-parameters depending on the operator structure and coupling strength
UNITARITY CONSIDERATIONS

- Unitarity of Scattering operator $S$ leads to condition for eigenvalues of transition operator $T$:

$$SS^\dagger = I$$

$$\Leftrightarrow (I + 2iT)(I + 2iT)^\dagger = I$$

- Argand-circle condition: $|t_j - \frac{i}{2}| = \frac{1}{2}$

- $T$ can be expressed in terms of the so called K-matrix:

$$T = \frac{K}{I - iK}$$

- Perturbatively, $K$ can be expressed in terms of partial wave amplitudes

$$A_{\lambda \mu}^J(s) = \int d(\cos \theta) \ A_{V_1V_2 \rightarrow V_3V_4}(s, \theta) \ d_{\lambda \mu}^J(\theta)$$

- Unitarized partial wave amplitudes:

$$\hat{A}_{\lambda \mu}^J = \frac{A_{\lambda \mu}^J}{1 - iA_{\lambda \mu}^J/32\pi}$$
K-MATRIX-UNITARISATION

- Partial waves include dependence on couplings
  - Dynamic unitarisation for any size of coupling
- Saturation at high energies while keeping original low energy behavior
- Worked out for the operators $\mathcal{L}_{S,i}$
VBFNLO

- Parton level Monte Carlo program for NLO QCD simulation of
  - Vector boson fusion
  - Double and triple vector boson production in hadronic collisions
  - Double vector boson production in association with a hadronic jet
- Includes Higgs and vector boson decays with full spin correlations and all off-shell effects.
- Anomalous Couplings available for most processes
- Efficient by reusing electroweak part of diagrams in terms of leptonic tensors

https://www.itp.kit.edu/~vbfnloweb

VBFNLO / WHIZARD COMPARISON

- K-Matrix unitarisation implemented in **VBFNLO** (Parton level Monte Carlo program @ NLO QCD) for $\mathcal{L}_{S,i}$

- Comparable to implementation in WHIZARD
  - Qualitative agreement found for invariant mass distributions
  - Agreement at per mill level for total cross sections

\[
\frac{f_{S,0}}{A^4} = \frac{f_{S,1}}{A^4} = 100 \text{ TeV}^{-4}
\]
Need different treatment for the other operators

- No diagonalizing basis for S-matrix available
- More than one important contribution in helicity space
- Translation to off-shell implementation difficult

→ Use K-matrix-like form factors:

\[ \mathcal{F}_K(s) = \frac{\hat{A}^J_{\lambda\mu}}{A^J_{\lambda\mu}} = \frac{1}{1 - i A^J_{\lambda\mu}} = \frac{1}{1 - i \frac{s^2}{\Lambda_K^4}}. \]
Framework for calculating analytic expressions of partial wave amplitudes:

- Start from an arbitrary operator set, i.e. Lagrangian
- Generate analytic expressions for amplitudes by inserting explicit momenta and helicity eigenvectors
- Get partial waves for all of the 9x9 possible helicity configurations
- Determine leading contributions and use them for unitarisation

$$J = 0: \begin{pmatrix} 0 & -\frac{m_W^2}{2v^2} \bar{f}_{M,1}s^2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

$$J = 1: \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

$$J = 2: \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{m_W^2}{5\sqrt{6}v^2} \bar{f}_{M,1}s^2 & 0 & 0 \end{pmatrix},$$
CONCLUSION

• Use a model independent way to describe New Physics: Effective Field Theory

• Need unitarisation scheme to suppress unphysical behavior for high c.o.m. energy

• K-matrix unitarisation implemented in VBFNLO for $\mathcal{L}_{S,i}$ and form factors for other operators

• Proposition of K-matrix-like form factors for other operators

• Development of Mathematica framework for calculating partial wave amplitudes of arbitrary dim. 8 operator set

• Simulation in VBFNLO including NLO QCD corrections

• New features available in VBFNLO 3.0beta: https://www.itp.kit.edu/~vfnloweb
ONE-LOOP FERMION MASS CORRECTIONS AND FLAVOR SYMMETRIES

Maximilian Löschner
Advisor: Walter Grimus
INTRODUCTION

• Measurement of $\nu$-oscillations:
  
  ‣ $\nu$’s are massive and have non-vanishing mass differences

• Possibly far reaching implications of mass generating mechanisms:
  
  ‣ Lepton number violation, leptogenesis, baryon asymmetry
  
  ‣ Composition and origin of dark matter
SOME OPEN QUESTIONS

Experiment

1. Value of the CP-violating phase in the mixing matrix
2. Normal or inverted mass hierarchy
3. Absolute mass scale of the lightest neutrinos
4. Dirac or Majorana nature

Theory

1. Smallness of $\nu$ masses
2. Strong hierarchy in mass spectra of charged leptons
3. Mild hierarchy in $\nu$ spectrum
4. One small and two large mixing angles in lepton mixing matrix
MASS MECHANISMS

- In order to add mass terms to SM Lagrangian, necessarily need to introduce new particles
  - At least three right-handed $\nu$'s for gauge invariant Yukawa mass terms
- $\nu$ masses are at least $10^6$ times smaller than electron mass
  - $y \lesssim 10^{-11}$
  - seems unnaturally small

$$\mathcal{L}_{\text{Yuk},\nu} = y(\bar{\nu}_L \phi^0 - \bar{l}_L \phi^-) \nu_R$$
Example: **Scotogenic Model**

[arXiv:1408.4785]

- Extend SM by three right-handed $\nu$’s and second scalar doublet

- Impose exact $Z_2$ -symmetry: all SM particles even, new particles odd

  - $y (\nu \phi^0 - l \phi^+) N$ forbidden
  - $y (\nu \eta^0 - l \eta^+) N$ allowed

- Vanishing VEV of second scalar doublet
  - No tree level Dirac mass
  - Radiative Majorana mass

- Possible dark matter candidate
OUTLOOK

- Determine one-loop mass corrections in general framework, investigate stability of tree level masses and influence of (discrete) flavor symmetries

\[ \mathcal{L}_{\text{toy}} = i \bar{\chi}_{L} \gamma_{\mu} \partial^{\mu} \chi_{L} + \left( \frac{1}{2} y \chi_{L}^{T} C^{-1} \chi_{L} \phi + \text{h.c.} \right) + \frac{1}{2} (\partial_{\mu} \phi)(\partial^{\mu} \phi) - V(\phi) \]

- First step: Generalization of a simple toy model with arbitrary \# of fermion and scalar fields imposing \( Z_2 \) symmetry

- In the end: apply to specific models like the scotogenic model and produce numerical results for corrections to masses and mixing angles
„There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.“
- Lord Kelvin, 1900

THANKS!
Backup Slides
### DIM. 6 VS. DIM. 8

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Polarizations

Each operator has its „fingerprint“ of which polarization states are the most important.

For a 2 to 2- process one has $3^4 = 81$ possible combinations.

- Number of independent amplitudes can be reduced using C-, P- and Bose symmetry.

\[
\begin{align*}
A_{S,1} &= 2m_W^2 m_Z^2 \frac{f_{S,1}}{\Lambda^4} \epsilon_1 \epsilon_2 \epsilon_3^* \epsilon_4^*, \\
A_{M,2} &= \frac{4m_W^2 m_Z^2 \sin^4 \theta_W}{v^2} \frac{f_{M,2}}{\Lambda^4} \epsilon_1 \epsilon_2 (k_3 \cdot k_4 \epsilon_3^* \epsilon_4^* - \epsilon_3^* k_4 \epsilon_4^* k_3), \\
A_{T,0} &= \frac{128m_W^2 m_Z^2 \cos^4 \theta_W}{v^4} \frac{f_{T,0}}{\Lambda^4} (k_1 \cdot k_2 \epsilon_1 \epsilon_2 - \epsilon_1 k_2 \epsilon_2 k_1) (k_3 \cdot k_4 \epsilon_3^* \epsilon_4^* - \epsilon_3^* k_4 \epsilon_4^* k_3)
\end{align*}
\]
Reduction of polarization matrix (for $WW$ to $ZZ$):

**W- interchange**

\[
\begin{bmatrix}
- - - - & - - - 0 & - - - + & - - 0 - & - - 0 0 & - - 0 + & - - + - & - - + 0 & - - + + \\
-0 - - & -0 - 0 & -0 - + & -0 0 - & -0 0 0 & -0 0 + & -0 + - & -0 + 0 & -0 + + \\
- + - - & - + - 0 & - + - + & - + 0 - & - + 0 0 & - + 0 + & - + + - & - + + 0 & - + + + \\
0 - - - & 0 - - 0 & 0 - - + & 0 - 0 - & 0 - 0 0 & 0 - 0 + & 0 - + - & 0 - + 0 & 0 - + + \\
00 - - & 00 - 0 & 00 - + & 00 0 - & 00 0 0 & 00 0 + & 00 + - & 00 + 0 & 00 + + \\
0 + - - & 0 + - 0 & 0 + - + & 0 + 0 - & 0 + 0 0 & 0 + 0 + & 0 + + - & 0 + + 0 & 0 + + + \\
+ - - - & + - - 0 & + - - + & + - 0 - & + - 0 0 & + - 0 + & + - + - & + - + 0 & + - + + \\
+ 0 - - & + 0 - 0 & + 0 - + & + 0 0 - & + 0 0 0 & + 0 0 + & + 0 + - & + 0 + 0 & + 0 + + \\
+ + - - & + + - 0 & + + - + & + + 0 - & + + 0 0 & + + 0 + & + + + - & + + + 0 & + + + + \\
\end{bmatrix}
\]

**Z- interchange**

**Parity**
Final polarization matrix for WW to ZZ:

\[
\begin{pmatrix}
+ & + & - & 0 & 0 & + & 0 & 0 & + & - & 0 & + & + & - & + \\
0 & 0 & - & 0 & 0 & 0 & 0 & 0 & - & 0 & 0 & - & 0 & - & + \\
- & 0 & - & - & 0 & 0 & 0 & 0 & - & 0 & - & 0 & - & + & + \\
0 & + & - & + & 0 & 0 & 0 & 0 & + & - & 0 & 0 & + & - & + \\
- & + & - & - & 0 & 0 & 0 & 0 & - & + & 0 & - & + & + & + \\
\end{pmatrix}
\]

Corresponding helicity differences:

\[
\begin{pmatrix}
0 & 0 & 0 & 0 & 0 & -1 & 0 & -2 \\
0 & 0 & 0 & 0 & 0 & -1 & 0 & -2 \\
0 & 0 & 0 & 0 & 0 & -1 & 0 & -2 \\
-1 & 0 & -1 & 0 & -1 & -1 & 0 & -1 \\
-1 & 0 & -1 & 0 & -1 & -1 & 0 & -1 \\
-2 & 0 & -2 & 0 & -2 & -1 & 0 & -2 \\
\end{pmatrix}
\]
Result of this framework:
Partial waves that could be used as input for K-matrix like form factors

\[ J = 0 : \begin{pmatrix}
0 & 0 & -\frac{m_W^2}{2v^2} f_{M,1}s^2 & 0 & 0 \\
0 & 0 & -\frac{m_W^2}{2v^2} f_{M,1}s^2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}, \]

\[ J = 1 : \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}, \]

\[ J = 2 : \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & \frac{m_W^2}{5\sqrt{6}v^2} f_{M,1}s^2 & 0 & 0 & 0 \\
\end{pmatrix}, \]
Unitarity considerations lead to definition of inverse K-operator:

\[ K^{-1} \equiv T^{-1} + iI \]

Then \( T \) can be expressed as

\[ T = \frac{K}{I - iK} \]

If perturbative expansion of \( T \) exists then:

\[ K^{(1)} = T^{(1)} \]
• By expanding arbitrary set of EFT operators in terms of the fields, relations to anomalous couplings can easily be found:

\[ c_i^V V' = c_{i, SM}^V V' + g^2 \Delta c_i^V V'. \]
K-MATRIX VS. FORM FACTOR

\[ \frac{d\sigma}{d m_{ZZ}} \ [fb/GeV] \]

- SM
- non-unif.
- K-matrix
- FF, \( \Lambda_{FF} = 366 \) GeV
- FF, \( \Lambda_{FF} = 1000 \) GeV
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<td>VBFNLO</td>
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<td>(W^+W^+)</td>
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<td>1.311(1)</td>
<td>51.49(2)</td>
<td>51.54(4)</td>
<td>2.452(1)</td>
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<td>(W^+W^-)</td>
<td>0.9019(7)</td>
<td>0.902(2)</td>
<td>24.594(6)</td>
<td>21.52(4)</td>
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<td>(W^+Z)</td>
<td>0.1473(1)</td>
<td>0.1480(3)</td>
<td>2.633(1)</td>
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<td>(ZZ)</td>
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<td>0.0284(1)</td>
<td>3.141(2)</td>
<td>3.142(6)</td>
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Agreement in terms of total cross sections (surprisingly) very good, except for \(W^+W^-\):

- Differences in operator sets show up
- Can be cured by introducing new operator
UNITARITY AND HIGGS

Need to take care that cancellations between Higgs- and vector-boson-sector don’t get spoiled in BSM-Higgs-models

\[ \sim \frac{s}{v^2} + \mathcal{O}(1) \]

\[ \sim -\frac{s^2}{v^2(s - m_H^2)} + \mathcal{O}(1) \]
A CLOSER LOOK

\[ \mathcal{O}_{S,0} = [(D_\mu \Phi)^\dagger (D_\nu \Phi)] \times [(D^\mu \Phi)^\dagger (D^\nu \Phi)] \]

\[ \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \]

\[ D_\mu = \begin{pmatrix} \partial_\mu + \frac{i}{2} Z_\mu (g_{cW} + g's_W) + ieA_\mu & \frac{ig}{\sqrt{2}} W^+_\mu \\ \frac{ig}{\sqrt{2}} W^-_\mu & \partial_\mu + \frac{i}{2} Z_\mu \sqrt{g^2 + g'^2} \end{pmatrix} \]

\[ W_{\mu\nu} = \frac{ig}{2} \tau^i (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu) + g\epsilon_{ijk} W^j_\mu W^k_\nu \]

\[ \Rightarrow \mathcal{O}_{S,0} = m^4_W W^+ \cdot W^+ W^- \cdot W^- + m^2_W m^2_Z W^+ \cdot W^- Z \cdot Z + m^4_Z Z \cdot ZZ \cdot Z \]