WW Scattering

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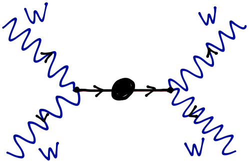
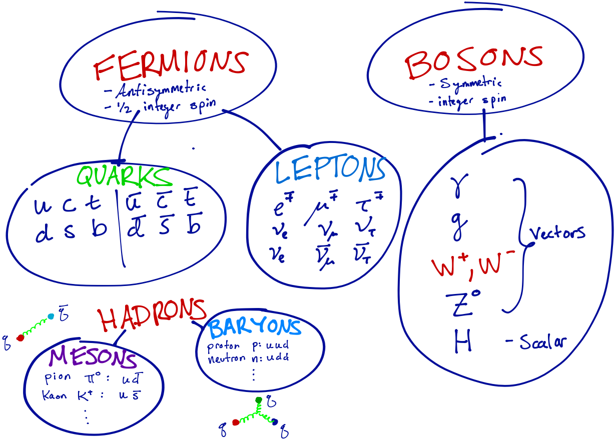


Outline

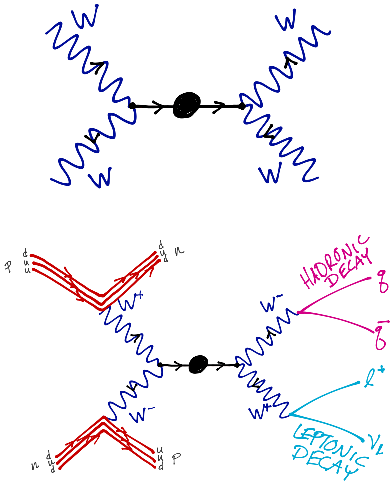
Zoology

Hierarchy in the Standard Model



WW Scattering

The Feynman Diagram of Choice



Higgs Mechanism
Longitudinal WW Scattering

- W's can have 3 polarizations due to being massive
- 1 W_L (longitudinal) and 2 W_T (transverse)
- W_L's dominate at high energy
- W_L's are Goldstone bosons
- They are the result of couplings to the Higgs

Electroweak Symmetry Breaking

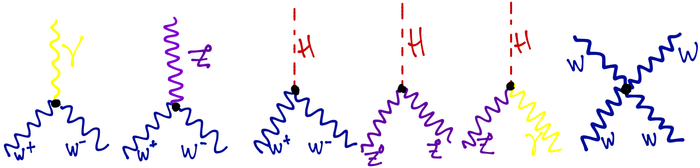
Z boson $$Z_\mu = \cos\theta_W W^3_\mu - \sin\theta_W B^0_\mu$$
Photon $$A_\mu = \sin\theta_W W^3_\mu + \cos\theta_W B^0_\mu$$
W bosons

$$W^\pm_\mu = \frac{W^1_\mu \pm i W^2_\mu}{\sqrt{2}}$$

- Compare to coupling of $\vec{L}$ and $\vec{S}$ into $\vec{L} + \vec{S} = \vec{J}$
- $W^\pm$, Z, and γ linear combinations of W^1_μ, W^2_μ, W^3_μ and B^0_μ fields
- The Weinberg (weak mixing angle) $\theta_W \simeq 30^\circ$

Effects of New Physics

- New particles, extra dimensions, effects of fields decoupling
- New Vertices with anomalous couplings (new physics)



Lagrangians in Particle Physics

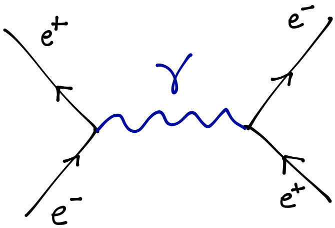
- Much more complicated workflow than Euler-Lagrange
- $\mathcal{H} = \sum_i \dot{q}_i p_i - \mathcal{L}$
- $e^{i\frac{\mathcal{H}}{\hbar}t} \rightarrow e^{i\mathcal{S}t} \rightarrow$ Feynman Path Integrals $\rightarrow$ Real Quantities
- Wavefunctions ψ are promoted to operators (creation/annihilation)
- Objects are scalars, vectors, and tensors in Minkowski space

Example

Quantum Electrodynamics (QED) Diagram

Electron-Positron pair creation/annihilation

$$\mathcal{L}_{QED} = \underbrace{\overline{\psi}(i\gamma^{\mu} D_{\mu} - m)\psi}_{\text{Electron Lagrangian}} - \underbrace{\frac{1}{4} F^{\mu\nu} F_{\mu\nu}}_{\text{Photon Lagrangian}}$$



SM Lagrangian

memorize *this!*

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w M A_\mu (W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu\phi^- +
\end{gathered}
$$

Effective Field Theory

Electroweak Dimension-6

Ansatz

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

- Λ is the energy scale of the new physics in eV
- Each operator contributes to the signal of new vertices with anomalous couplings.

Dimension-6 EW Operators

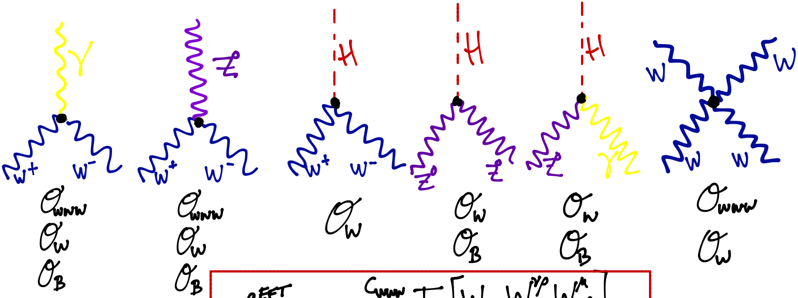
$$\mathcal{O}_{WWW} = Tr[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}]$$
$$\mathcal{O}_{W} = (D_{\mu}\Phi)^{\dagger} W^{\mu\nu} (D_{\nu}\Phi)$$
$$\mathcal{O}_{B} = (D_{\mu}\Phi)^{\dagger} B^{\mu\nu} (D_{\nu}\Phi)$$

- We add on the terms to the SM Lagrangian, e.g.,

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{c_W}{\Lambda^2}\mathcal{O}_W + \frac{c_B}{\Lambda^2}\mathcal{O}_B$$

- Compare pure SM signal to SM + EFT Signal

EW Dim-6 Operators and Anomalous Couplings

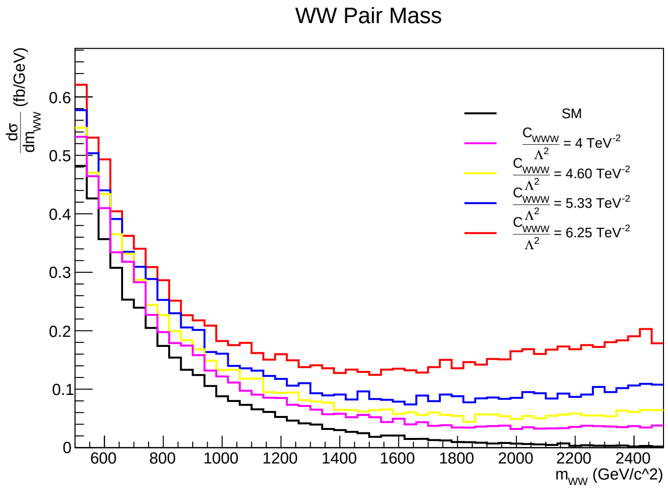


$$\mathcal{L}^{EFT}_{\mathcal{O}_{WWW}} = \frac{c_{WWW}}{\Lambda^2} \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\rho} W^{\mu}{}_{\rho}\right]$$

$$\mathcal{L}^{EFT}_{\mathcal{O}_{W}} = \frac{c_{W}}{\Lambda^2} (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{L}^{EFT}_{\mathcal{O}_{B}} = \frac{c_{B}}{\Lambda^2} (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

SM versus EWdim6



What's the point?

- Put lower and upper bounds on the energy scale Λ

$$\Lambda_{low} < \text{New Physics} < \Lambda_{high}$$

- Tells us where the heck to look for new physics!

Thank you!
Jason Nielson - Research Professor
Howard Haber - Advising
Niklas Garner, for the plots - Research Colleague
Friends

Sojourn into Software

Software Chain for Particle Simulation and Analysis

- Madgraph/Madevent - particle event creation
- Pythia - Jet level event creation
- Delphes - Detector level simulation
- ROOT - Data Analysis


```
</event>
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       21   -1    0    0  506  504  0.00000000000E+00  0.00000000000E+00 -0.10413594328E+04  0.10413594328E+04  0.00000000000E+00 0.   1.
        6    2    1    2  501    0  0.16104685515E+03  0.25898901465E+02  0.53822131039E+02  0.24280463870E+03  0.17161127042E+03 0.   0.
       24    2    3    3    0    0  0.38826556124E+02  0.29224953535E+01 -0.31713929099E+02  0.91793962541E+02  0.76839545942E+02 0.   0.
       -6    2    1    2    0  503 -0.10973725976E+03  0.51308580258E+02  0.47059705864E+02  0.21732016625E+03  0.17417979835E+03 0.   0.
      -24    2    5    5    0    0 -0.26069177835E+02  0.64798130791E+02  0.71102663586E+02  0.12910185907E+03  0.82056696619E+02 0.   0.
      -11    1    4    4    0    0  0.59432562994E+02  0.13143866476E+02 -0.32047385424E+02  0.68789720762E+02  0.00000000000E+00 0.   1.
       12    1    4    4    0    0 -0.20606006870E+02 -0.10221371122E+02  0.33345632463E+00  0.23004241780E+02  0.00000000000E+00 0.  -1.
        5    1    3    3  501    0  0.12222029902E+03  0.22976406111E+02  0.85536060138E+02  0.15101067616E+03  0.46999998093E+01 0.  -1.
        3    1    6    6  502    0  0.28854932552E+01  0.39176156614E+02 -0.88719601583E+01  0.40271689751E+02  0.00000000000E+00 0.  -1.
       -4    1    6    6    0  502 -0.28954671090E+02  0.25621974177E+02  0.79974623745E+02  0.88830169322E+02  0.00000000000E+00 0.   1.
       -5    1    5    5    0  503 -0.83668081928E+02 -0.13489550532E+02 -0.24042957722E+02  0.88218307178E+02  0.46999998093E+01 0.   1.
       21    1    1    2  505  504 -0.91324246638E+02 -0.74734913649E+02 -0.12377263575E+03  0.17101196070E+03  0.00000000000E+00 0.   1.
       21    1    1    2  506  501  0.40014651253E+02 -0.24725680741E+01 -0.71378314770E+03  0.71490815344E+03  0.00000000000E+00 0.   1.
</event>
```


Px Py Pz ENERGY MASS

EWdim6 operators in Madgraph

```
###################################
## INFORMATION FOR DIM6
###################################
Block dim6
    1 6.250000e-2 # CWWWL2
    2 0.000000e+00 # CWL2
    3 0.000000e+00 # CBL2
    4 0.000000e+00 # CPWWWL2
    5 0.000000e+00 # CPWL2
```