W^+W^- PAIR PRODUCTION AND ANOMALOUS COUPLINGS

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HE/HL Study

Based on work with Julien Baglio and Ian Lewis,
PRD96 (2017) 073003
W^+W^- Production

- Sensitive to variations of Zff and Z(γ)WW couplings

- Old story: Individual contributions grow with energy
- Cancellations keep amplitude from growing at high energy

Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB482 (1987)
Delicate Cancellations

\[ A^Z_{+LL} = g^2(T_3^q - Q_q s^2_W) \beta \frac{s}{s - M_Z^2} \left( 1 + \frac{s}{2M_W^2} \right) \]
\[ \rightarrow g^2(T_3^q - Q_q s^2_W) \frac{s}{2M_W^2} \]

\[ A^\gamma_{+LL} = e^2 Q_q \beta \left( 1 + \frac{s}{2M_W^2} \right) \]
\[ \rightarrow e^2 Q_q \frac{s}{2M_W^2} \]

\[ A^W_{+LL} = 2T_3^q \frac{g^2}{\beta} \left[ -\frac{s}{4M_W^2} + \frac{4M_W^2}{s(1 + \beta^2 - 4T_3^q \cos \theta)} \right] \]
\[ \rightarrow -g^2 T_3^q \frac{s}{2M_W^2} \]

No growth with energy in SM

Changing gauge or fermion couplings spoils cancellation
Anomalous Couplings Language

- $V=Z, \gamma$

$$L = -g_{WWV} \left( g_1^V (W_{\mu\nu}^+ W^{-\mu} V^\nu - W_{\mu\nu}^- W^{+\mu} V^\nu) + \kappa^V W_{\mu}^+ W_{\nu}^- V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W_{\mu}^+ W^{-\mu\nu} V^{\nu\rho} \right)$$

- Deviations from SM:

  - $g_1^Z = 1 + \delta g_1^Z, \quad g_1^\gamma = 1 + \delta g_1^\gamma, \quad \kappa^Z = 1 + \delta \kappa^Z, \quad \kappa^\gamma = 1 + \delta \kappa^\gamma$

  - $\text{SU}(2)_L$ invariance implies $\delta g_1^\gamma = 0, \quad \lambda^\gamma = \lambda^Z, \quad \delta \kappa^\gamma = \cot^2 \theta_W (\delta g_1^Z - \delta \kappa^Z)$

- 3 independent parameters
Anomalous quark-Z couplings

- Lore is that anomalous quark couplings highly constrained by LEP
- Yes, but …. SM cancellations preventing growth with energy spoiled even with small anomalous quark-Z couplings

\[
L = g_Z Z_\mu \bar{q} \gamma^\mu \left[ T_3 - s_W^2 Q_q + \delta g_L^{Zq} \right] P_L + \left[ -s_W^2 Q_q + \delta g_R^{Zq} \right] P_R \bigg\} q + \frac{g}{\sqrt{2}} \left\{ \left( 1 + \delta g_L^W \right) \bar{u} \gamma^\mu P_L d + h.c. \right\}
\]

- SU(2) invariance implies \( \delta g_L^W = \delta g_L^{Zu} - \delta g_L^{Zd} \)

\[
\begin{align*}
\delta g_L^{Zu} &= (-2.6 \pm 1.6) \times 10^{-3} \\
\delta g_L^{Zd} &= (2.3 \pm 1) \times 10^{-3} \\
\delta g_R^{Zu} &= (-3.6 \pm 3.5) \times 10^{-3} \\
\delta g_R^{Zd} &= (16.0 \pm 5.2) \times 10^{-3}
\end{align*}
\]

Zhang, \textbf{PRL118} (2017) 011803

Falkowski, Riva, \textbf{JHEP} 1502 (2015)
Fit to Experimental Results

- Assume strongest constraint comes from last bin
- Scan over anomalous couplings and determine allowed

\[
\sigma(p_T^{W+} > 500\,\text{GeV}) = \int_{500\,\text{GeV}}^{\infty} dp_T^{W+} \frac{d\sigma}{dp_T^{W+}}
\]

- Scan over anomalous couplings and accept points that fall within allowed region of \(\sigma(p_T^{W+} > 500)\) GeV
- Computation includes full NLO QCD corrections, and SM EW corrections
- Procedure reproduces ATLAS/CMS limits on anomalous 3 gauge boson couplings

Baglio, Dawson and Lewis, PRD96 (2017) 073003
Fits with anomalous quark-Z and WWV couplings

- Blue: only anomalous WWZ and WWg couplings
- Red: allow also anomalous qqZ couplings

\[
\begin{align*}
\delta g_1 Z & \\
\delta \kappa Z & \\
\delta \lambda Z & 
\end{align*}
\]
Significant Effect on fit from QCD

- Effects of QCD NLO significant at high $p_T$
  - Which is where the limits come from
- 3GB curve has:
  $$\delta g_1^Z = 0.0163, \quad \delta \kappa^Z = 0.0239, \quad \lambda^Z = 0.00452$$
- Ferms curve has:
  $$\delta g_L^{Zu} = -0.00239, \quad \delta g_R^{Zu} = -0.0069, \quad \delta g_L^{Zd} = 0.00271, \quad \delta g_R^{Zd} = 0.0212$$
Details

- Can map effective coupling language to EFT language
  - Consistent expansion in higher dimension operators
    \[ L = L_{SM} + \sum \frac{c_i}{\Lambda^2} O_{i}^{d=6} + \sum \frac{c_i}{\Lambda^4} O_{i}^{d=8} + \ldots \]

- Previous bounds found using \((amplitude)^2\)
  \[ |A|^2 \sim \left| g_{SM} + \frac{c_6}{\Lambda^2} \right|^2 \sim g_{SM}^2 + g_{SM} \frac{c_6}{\Lambda^2} + \frac{c_6^2}{\Lambda^4} \]

- Includes terms that go as \(\Lambda^{-4}\)
  - Formally same size as dimension-8 operators
Calculation in EFT Language

- Operators that contribute to VVV vertices and Higgs-VV vertices*

\[
O_W = (D_\mu H) \dagger W^{\mu\nu} (D_\nu H)
\]
\[
O_B = (D_\mu H) \dagger B^{\mu\nu} (D_\nu H)
\]
\[
O_{WWW} = Tr(W_{\mu\nu} W^{\nu\rho} W_{\rho}^\mu)
\]

\[
L \sim \frac{f_B}{\Lambda^2} O_B + \frac{f_W}{\Lambda^2} O_W + \frac{f_{WWW}}{\Lambda^2} O_{WWW}
\]

* Assuming CP conservation
Calculation in EFT Language

- Include fermion operators, work at LO QCD, fit to $W^+W^-$, WZ data
- Largest effect of fermion operators is on $C_B$, almost no effect on $C_{WWW}$

Alves, Rosa-Agostinho, Eboli, Gonzalez-Garcia, [1805.11106](https://arxiv.org/abs/1805.11106)
Lessons from 8 TeV Fit

- Need to fit more than just anomalous gauge couplings
- Fit affected by inclusion of NLO QCD corrections
- IN PROGRESS: SAME FIT for high luminosity and for 27 TeV
- Progress to date: NLO QCD EFT contributions for WWZ, WWγ, and qqZ anomalous quark and gauge couplings implemented in POWHEG
- Previous POWHEG implementation of $W^+W^-$ anomalous couplings had only WWZ and WWγ anomalous couplings
- Estimates of systematic uncertainties at high $p_T$ from rescaling 8 TeV experimental results

Melia, Nason, Rontsch, Zanderighi, JHEP 1111(2011) 078
Projections for $p_T(WW)$

- Truth level distribution used to extract expected "unfolded" cross section for 3 ab$^{-1}$
- Allow large statistical uncertainties in highest $p_T$ bin
- Other bins: balance statistics, detector systematics and backgrounds

$n_{Jets} == 0$ has very low acceptance at high $p_T$
Results at LO with anomalous fermion, WWV couplings

Above $p_T \sim 300$ GeV, the EFT expansion at $O(1/\Lambda^2)$ fails at both 13 and 27 TeV

Baglio, Dawson, Lewis in progress
Outlook (Soon...)

- Projections for fits to anomalous couplings from $W^+W^-$ production at 27 TeV
- Using background/detector systematics estimates from rescaling 8 TeV fits
  - Need to do fits using anomalous gauge and fermion couplings
  - Need to do fits using NLO QCD