Double Gauge Boson Production in the SM EFT

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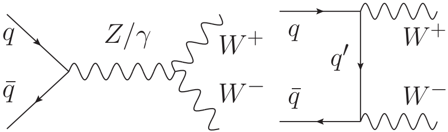
"Model Independent" Parameterization

- In the absence of direct evidence, useful to have a model independent formulation of new physics.
- Philosophy:
  - We know the SM is there at the EW scale with a very SM-like Higgs boson.
  - Treat $SU(2) \times U(1)_Y$ as a good symmetry.
- SM effective field theory (EFT) Buchmuller, Wyler NPB268 (1986) 621; Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 1010 (2010) 085; Giudice, Grojean, Pomarol, Rattazzi JHEP 0706 (2007 045; Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993) 2182; Brivio, Trott arXiv:1706.08945

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{k} \frac{c_{n,k}}{\Lambda^n} O_{n,k}$$

  - $O_{n,k}$: $SU(3) \times SU(2)_L \times U(1)_Y$ gauge invariant $4+n$ dimensional higher order operators.
  - Λ: scale of new physics.
  - Allows for a systematic parameterization of deviations from SM predictions without doing too much damage to lower energy measurements.

W^+W^- production



- Informative to focus on one process.
  - Of particular interest is the electroweak sector.
  - Focus on W^+W^- production at the LHC.
  - Sensitive to anomalous trilinear gauge boson couplings (ATGCs)

W^+W^- production

- Another language, anomalous couplings Hagiwara, Peccei, Zeppenfeld, Hikasa NPB482 (1987):

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

  - $V = Z, \gamma$
  - $g_{WWZ} = g\cos\theta_w, \quad g_{WW\gamma} = e$
- Parameterize deviations from SM:

$$g_1^Z = 1 + \delta g_1^Z \qquad g_1^\gamma = 1 + \delta g_1^\gamma \qquad \kappa^Z = 1 + \delta\kappa^Z \qquad \kappa^\gamma = 1 + \delta\kappa^\gamma$$

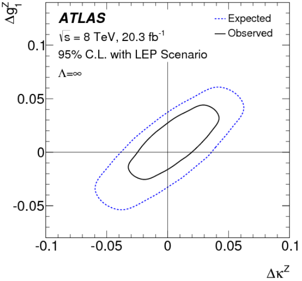
- $\lambda^Z = 0$ and $\lambda^\gamma = 0$ in SM.
- $SU(2)_L$ implies:

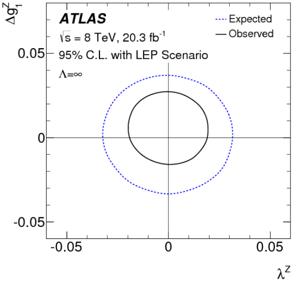
$$\delta g_1^\gamma = 0 \qquad \lambda^\gamma = \lambda^Z \qquad \delta\kappa^\gamma = \frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\delta g_1^Z - \delta\kappa^Z\right)$$

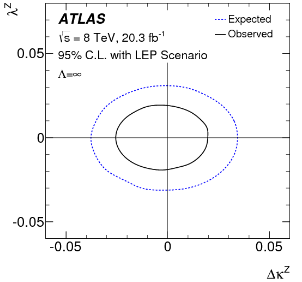
- Three independent parameters: λ^Z, δg_1^Z, $\delta\kappa^Z$

Experimental results

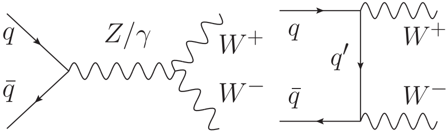
- ATGCs actively being searched for in W^+W^- production by both ATLAS JHEP 1609 (2016) 029 and CMS Phys.Lett. B772 (2017) 21







Missing Terms



- Have not included anomalous quark gauge boson couplings.
  - Highly constrained by LEP.
  - But SM contains cancellations to unitarize amplitudes: growth with energy cancels.
  - Anomalous quark couplings can spoil cancellation and have growth with energy.
  - This was recently pointed out Zhang PRL118 (2017) 011803

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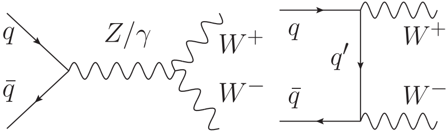

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  - Anomalous quark couplings can spoil cancellation and have growth with energy.
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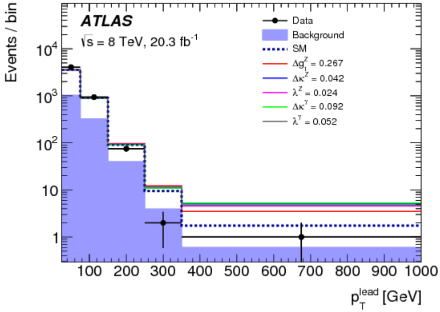
- Parameterize via anomalous couplings:

$$\begin{aligned}\mathcal{L} &= g_Z Z_\mu \bar{q}\gamma^\mu \left\{\left[T_3 - \sin^2_W Q_q + \delta g_L^{Zq}\right] P_L + \left[-\sin^2_W Q_q + \delta g_R^{Zq}\right] P_R\right\} q \\ &+ \frac{g}{\sqrt{2}}\left\{W_\mu^+ (1+\delta g_L^W)\bar{u}\gamma^\mu P_L d + \text{hc.}\right\}\end{aligned}$$

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

Refit Experimental results

- ATGCs limits from ATLAS JHEP 1609.
- In practice want to take differential distributions from experimental collaborations, extract constraints on anomalous couplings.
- We do not decay the W^+.



Refit Experimental Results

- Assume strongest constraint comes from last bin.
- Scan over allowed ATGCs and determine allowed

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

- Now scan over all parameters and determine allowed regions taking into consideration LEP constraints on anomalous quark couplings Falkowski, Riva JHEP 1502:

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

  - Accept points that fall within allowed region of $\sigma(p_T^{W^+} > 500 \text{ GeV})$.

Refit

- Blue: Including only ATGCs.
- Red dots: adding in anomalous quark couplings
- Inner regions allowed

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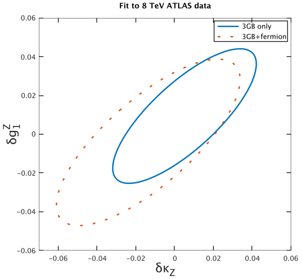
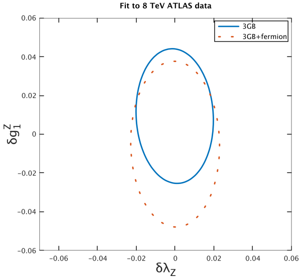
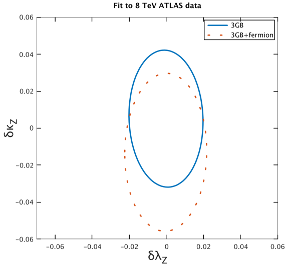






Comment on Calculating Cross Sections

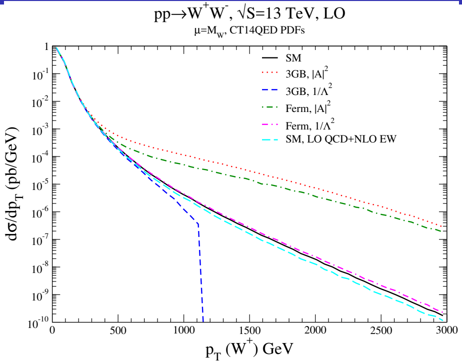
- Previous bounds found using full amplitude squared.
- Includes terms that go as Λ^{-4}.:

$$|\mathcal{A}|^2 \sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2}|^2 \sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4}$$

- Same order as dimension-8 contributions:

$$\begin{aligned} |\mathcal{A}|^2 &\sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-8}}{\Lambda^4}|^2 \\ &\sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4} + g_{SM} \times \frac{c_{dim-8}}{\Lambda^4} + O(\Lambda^{-6}) \end{aligned}$$

Differential Distributions



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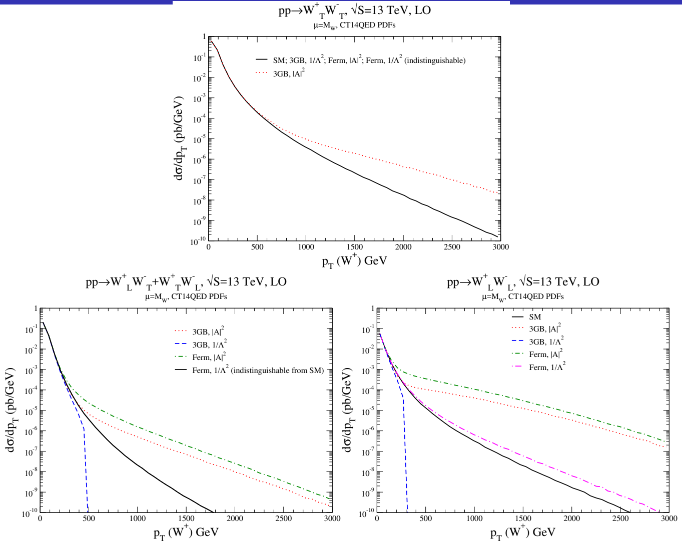
- $1/\Lambda^4$ terms dominate in tails and the bounds on anomalous couplings. Falkowski, Gonzalez-Alonso, Greijo, Marzocca, Son JHEP 1702 (2017) 115
- Ferm: ATGCs set to zero.
- 3GB: Anomalous fermion couplings set to zero.
- Assuming $C_i \lesssim 1$, anomalous couplings correspond to $\Lambda \gtrsim 2.8$ TeV.

Differential Distributions by Helicity



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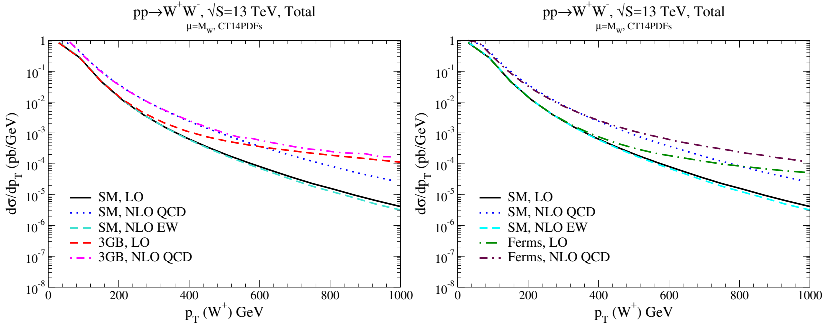
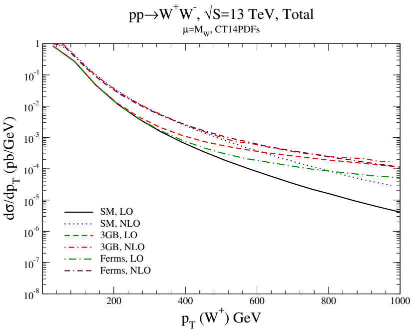
NLO SM Corrections



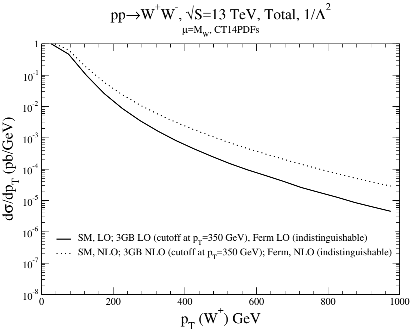
Known up to NNLO in QCD and NLO in EW Frixione NPB410; Ohnemus PRD44; Dixon, Kunszt, Signer NPB531; Dicus, Kao, Repko PRD36; Glover, van der Bij PLB219; Binoth, Ciccolini, Kauer, Kramer JHEP 0612, JHEP 0503; Baglio, Ninh, Weber PRD94; Bierweiler, Kasprzik, Kuhn, Uccirati JHEP 1211; Bierweiler, Kasprzik, Kuhn JHEP 1312; Billoni, Dittmaier, Jager, Speckner JHEP 1312; Biedermann, Billoni, Denner, Dittmaier, Hofer, Jager, Salfelder JHEP 1606; Gehrmann *et al.* PRL113; Grazzini *et al.* JHEP 1608; Biedermann *et al.* JHEP 1606

Known up to NLO in QCD for anomalous gauge couplings Dixon, Kunszt, Signer PRD60 (1999) 114037

NLO QCD Corrections



EFT Squared



$\mathrm{SM}+1/\Lambda^2$

- “Ferm”: Anomalous trilinear gauge boson couplings set to zero.
- “3GB”: Anomalous quark couplings set to zero.
- $1/\Lambda^4$ contributions from EFT still dominate in tails.

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Conclusions

- Investigated the effects of anomalous couplings on W^+W^- production.
  - Although strongly constrained at LEP, anomalous quark-gauge boson couplings significantly change fits to anomalous couplings.
  - LHC is at higher energy, new effects arise and assumptions have to be revisited.
  - Non-interference between SM and EFT is still in effect at NLO.
  - However, interference very dependent on polarizations of Ws.
  - Public code available: WWEFT@NLO

    `https://quark.phy.bnl.gov/Digital_Data_Archive/dawson/ww_2017/WWEFT_NLO.tar.gz`

Thank You