WW Production and Anomalous Gauge Couplings

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Based on J. Baglio, S. Dawson, **IL** Phys. Rev. D96 (2017) 073003

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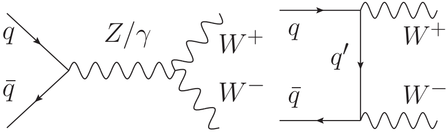
HL/HE-LHC Electroweak Physics Meeting
CERN

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

- Anomalous couplings language 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:

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

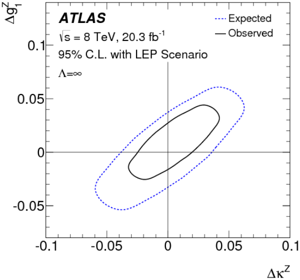
- $\lambda^Z = 0$ and $\lambda^\gamma = 0$ in SM.
- $SU(2)_L$ implies:

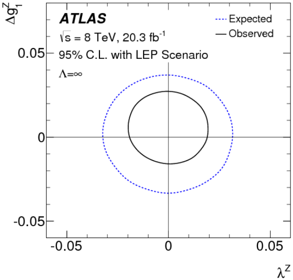
$$\delta g_1^\gamma = 0 \qquad \lambda^\gamma = \lambda^Z \qquad \delta\kappa^\gamma = \frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\delta g_1^Z - \delta\kappa^Z\right)$$

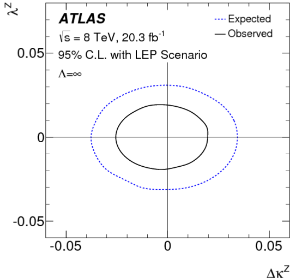
- Three independent parameters: λ^Z, δg_1^Z, $\delta\kappa^Z$

Experimental results

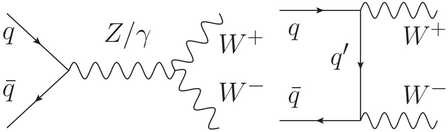
- ATGCs actively being searched for in W^+W^- production by both ATLAS JHEP 1609 (2016) 029 and CMS Phys.Lett. B772 (2017) 21







Missing Terms



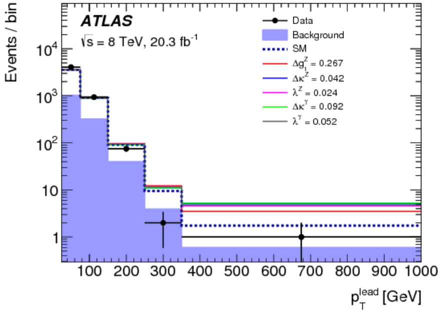
- Have not included anomalous quark gauge boson couplings.
  - Highly constrained by LEP.
  - But SM contains cancellations to unitarize amplitudes: growth with energy cancels.
  - Anomalous quark couplings can spoil cancellation and have growth with energy.
  - Garnered more attention recently Zhang PRL118 (2017) 011803; J. Baglio, S. Dawson **I.M. Lewis**, Phys. Rev. D96 (2017) 073003; Eboli Phenomelogoy Symposium 2018
- Parameterize via anomalous couplings:

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

- $SU(2)$ 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 $\sigma(p_T^{W^+} > 500\text{ GeV})$.
  - Have verified we can reconstruct ATLAS 2-D and 1-D fits limits on ATGCs.

Refit

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

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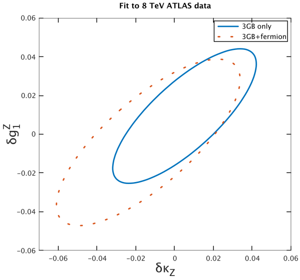
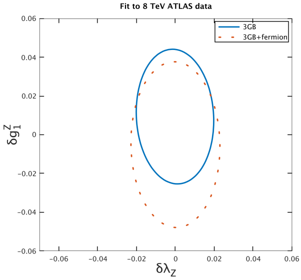
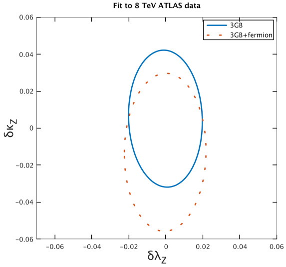






Comment on Calculating Cross Sections

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

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

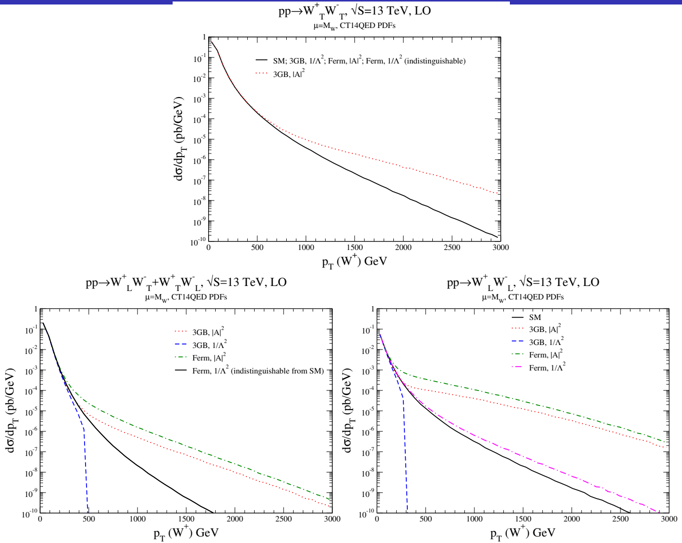
- Same order as dimension-8 contributions:

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

Future Directions

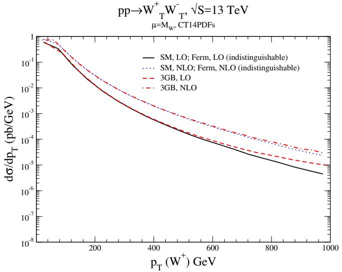
- Fully incorporate W leptonic decays at LO and NLO in QCD.
- Perform realistic collider study at NLO and fit to relevant distributions for HL and HE LHC studies.
- Perform study of importance of differnet $1/\Lambda^{2n}$ terms in the total cross section.
  - Relevant for transversely polarized gauge bosons. Different polarizations may be more sensitive Panico, Riva, Wulzer Phys.Lett. B776 (2018) 473; Azatov, Elias-Miro, Reyimuaji, Venturini JHEP 1710 (2017) 027
  - Relevant for on-shell gauge bosons. Off-shell effects can be relevant for interference between SM and EFT Helset, Trott JHEP 1804 (2018) 038.

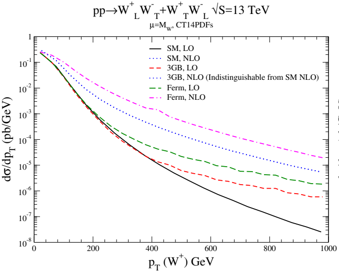
Differential Distributions by Helicity

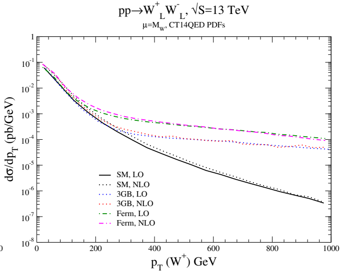


3GB: ATGCs only, Ferm: Anomalous fermion couplings only Baglio, Dawson, **IL** PRD96 (2017) 073003

NLO QCD by Helicity including all EFT terms







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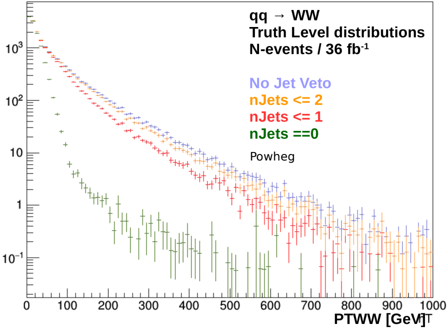
Projections for pT-WW



Truth level distribution can be used to extract expected "unfolded" cross section for 3000 fb^{-1}

- Allow large statistical uncertainties in highest pT bin: → >10 events (on reco level)
- Other bins: balance out statistics, detector systematics and backgrounds
- NJets==0 with very low acceptance for high pTWW → detector uncertainties ~10%

- Crucial question: how will knowledge of detector performance evolve at the HL-LHC with regards to background?
- Dominant uncertainties expected to be: MET and Jet scales as well as Pileup

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissPublicResults#PubPlotsHLLHC

Contributors: Valerie Lang, Elias Ruettinger, Kristin Lohwasser

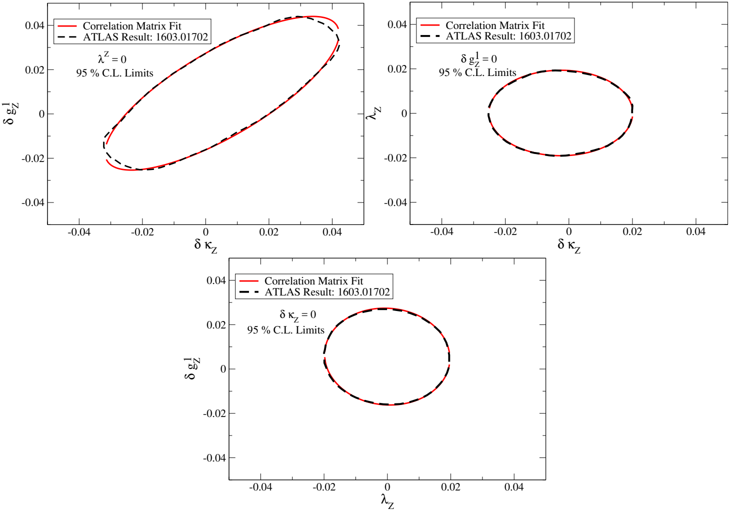
Conclusions

- 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

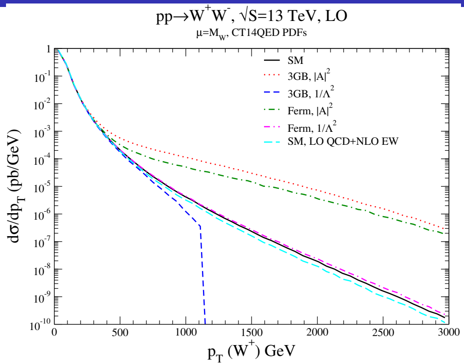
Verification



Refit Experimental Results

- Check by comparing to 1D results: set two of the ATGCs to zero:

	95% C.L. limit	ATLAS 95% C.L. limit JHEP 1609
δg_1^Z	[-0.0162,0.0274]	[-0.016,0.027]
$\delta\kappa^Z$	[-0.0252,0.0201]	[-0.025,0.020]
λ^Z	[-0.0189,0.0192]	[-0.019,-0.019]



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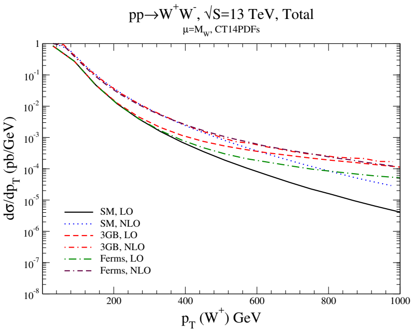
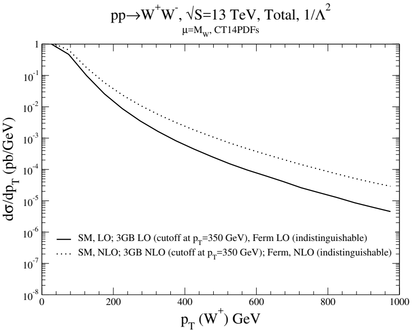
- $1/\Lambda^4$ terms dominate in tails and the bounds on anomalous couplings. Falkowski, Gonzalez-Alonso, Greijo, Marzocca, Son JHEP 1702 (2017) 115
- Ferm: ATGCs set to zero.
- 3GB: Anomalous fermion couplings set to zero.
- Assuming $C_i \lesssim 1$, anomalous couplings correspond to $\Lambda \gtrsim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

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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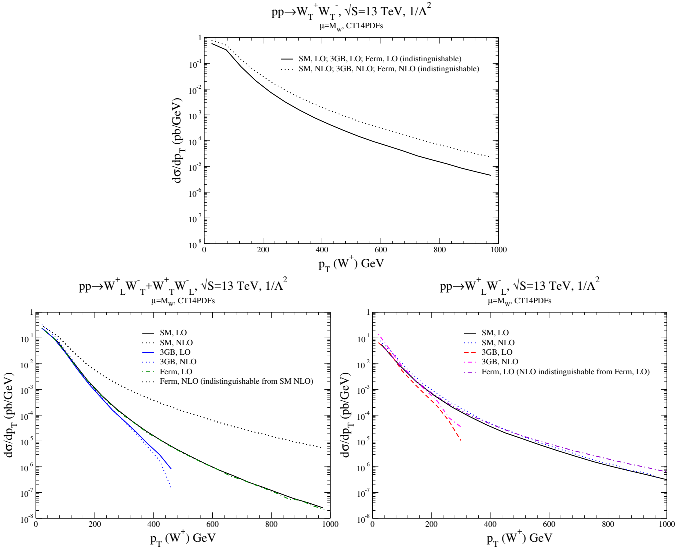
NLO QCD by Helicity truncating at $1/\Lambda^2$



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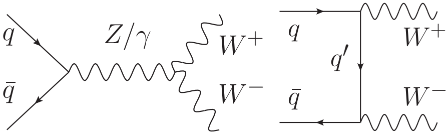
W^+W^- production



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  - Focus on W^+W^- production at the LHC.
  - Sensitive to anomalous trilinear gauge boson couplings (ATGCs)
- Operators affecting ATGCs:

$$O_{3W} = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu} \qquad O_{HD} = |\Phi^\dagger D_\mu \Phi|^2 \qquad O_{HWB} = \Phi^\dagger \sigma^a \Phi W_{\mu\nu}^a B^{\mu\nu}$$

$$O_{H\ell}^{(3)} = i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \sigma^a \Phi\right) \bar{\ell}_L \gamma^\mu \sigma^a \ell_L \qquad O_{ll} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$$

Matching ATGCs in two prescriptions

- Had 5 dimension-6 operators, only three independent combinations.
- In Warsaw basis:

$$\begin{aligned}
\delta g_1^Z &= \frac{v^2}{\Lambda^2}\frac{1}{\cos^2\theta_W-\sin^2\theta_W}\left(\frac{\sin\theta_W}{\cos\theta_W}C_{HWB}+\frac{1}{4}C_{HD}+\delta v\right)\\
\delta\kappa^Z &= \frac{v^2}{\Lambda^2}\frac{1}{\cos^2\theta_W-\sin^2\theta_W}\left(2\sin\theta_W\cos\theta_W C_{HWB}+\frac{1}{4}C_{HD}+\delta v\right)\\
\delta\lambda^Z &= \frac{v}{\Lambda^2}3M_W C_{3W}
\end{aligned}$$

- Anomalous coupling language generic enough that any basis can be matched onto it.

W^+W^- production

- Operators affecting ATGCs:

$$
\begin{aligned}
O_{3W} &= \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu} \qquad O_{HD} = |\Phi^\dagger D_\mu \Phi|^2 \qquad O_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu} \\
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\end{aligned}
$$

- In the EW sector have to choose input parameters: G_F, M_W, M_Z
- EFT alters relationships between other parameters and input parameters:

$$
g_Z \to g_Z + \delta g_Z \qquad v \to v(1+\delta v) \qquad s_W^2 \to s_W^2 + \delta s_W^2,
$$

where $s_W = \sin\theta_W$, $c_W = \cos\theta_W$ and

$$
\begin{aligned}
g_Z &= \frac{g}{\cos\theta_W} \quad s_W^2 = 1 - \frac{M_W^2}{M_Z^2} \quad G_F = \frac{1}{\sqrt{2} v^2} \\
\delta v &= C_{H\ell}^{(3)} - \frac{1}{2} C_{\ell\ell} \qquad \delta \sin^2_W = -\frac{v^2}{\Lambda^2} \frac{s_W c_W}{c_W^2 - s_W^2} \left[2 s_W c_W \left(\delta v + \frac{1}{4} C_{HD} \right) + C_{HWB} \right] \\
\delta g_Z &= -\frac{v^2}{\Lambda^2} \left(\delta v + \frac{1}{4} C_{HD} \right)
\end{aligned}
$$