Anomalous Fermion Couplings in Double Gauge Boson Production

Ian Lewis
University of Kansas

J. Baglio, S. Dawson, **I. Lewis**, PRD99 (2019) 035029 and PRD96 (2017) 073003

July 12, 2019
Workshop on Standard Model Effective Theory
Universität Heidelberg

Effective Field Theory

- Useful to have a "model independent" formulation of deviations from the Standard Model.
- Philosophy:
  - We know the Standard Model is there at the 100 GeV-1 TeV scale with a very Standard Model-like Higgs boson.
  - Treat $SU(2) \times U(1)_Y$ as a good symmetry.

Effective Field Theory

- Useful to have a "model independent" formulation of deviations from the Standard Model.
- Philosophy:
  - We know the Standard Model is there at the 100 GeV-1 TeV scale with a very Standard Model-like Higgs boson.
  - Treat $SU(2)\times U(1)_Y$ as a good symmetry.
- Standard Model 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 Phys.Rept. 793 (2019)

$$\mathcal{L}=\mathcal{L}_{SM}+\sum_k\frac{c_{1,k}}{\Lambda}O_{1,k}+\sum_k\frac{c_{2,k}}{\Lambda^2}O_{2,k}+\cdots$$

  - $O_{n,k}$: $SU(3)\times SU(2)_L\times U(1)_Y$ gauge invariant $4+n$ dimensional higher order operators.
  - Λ: scale of new physics.

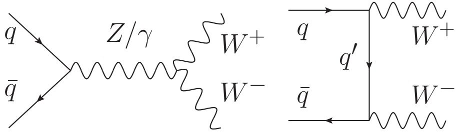
Effective Field Theory

- Useful to have a "model independent" formulation of deviations from the Standard Model.
- Philosophy:
  - We know the Standard Model is there at the 100 GeV-1 TeV scale with a very Standard Model-like Higgs boson.
  - Treat $SU(2)\times U(1)_Y$ as a good symmetry.
- Standard Model 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 Phys.Rept. 793 (2019)

$$\mathcal{L}=\mathcal{L}_{SM}+\sum_k \frac{c_{1,k}}{\Lambda}\mathcal{O}_{1,k}+\sum_k \frac{c_{2,k}}{\Lambda^2}\mathcal{O}_{2,k}+\cdots$$

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

W^+W^- production



- Informative to focus on one process.
  - Focusing on a single process allows us to learn the most about that process.
  - Of particular interest is the electroweak sector.
  - Focus on W^+W^- production at the LHC. Baglio, Dawson, **I. Lewis** PRD96 (2017) 073003; Baglio, Dawson **I. Lewis**, PRD99 (2019) 035029
  - Sensitive to anomalous trilinear gauge boson couplings (ATGCs)

W^+W^- production

- Anomalous coupling language Hagiwara, Peccei, Zeppenfeld, Hikasa NPB482 (1987):

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

  - $V = Z, \gamma$
  - $g_{WWZ} = g\cos\theta_w, \quad g_{WW\gamma} = e$

W^+W^- production

- Anomalous coupling 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 Standard Model:

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

- $\lambda^Z = 0$ and $\lambda^\gamma = 0$ in Standard Model.

W^+W^- production

- Anomalous coupling 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 Standard Model:

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

- $\lambda^Z = 0$ and $\lambda^\gamma = 0$ in Standard Model.
- $SU(2)_L$ invariance 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: $\lambda^Z, \delta g_1^Z, \delta\kappa^Z$

W^+W^- production

- Five operators affecting ATGCs in Warsaw basis:

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

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

W^+W^- production

- Five operators affecting ATGCs in Warsaw basis:

$$O_{3W} = \varepsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu} \qquad O_{HD} = |\Phi^\dagger D_\mu \Phi|^2 \qquad O_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu}$$
$$O_{H\ell}^{(3)} = i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \sigma^a \Phi\right) \bar{\ell}_L \gamma^\mu \sigma^a \ell_L \qquad O_{ll} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L)$$

- 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

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

Matching ATGCs

- Operators affecting ATGCs:

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

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

- Anomalous Couplings Framework:

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

Matching ATGCs

- Operators affecting ATGCs:

$$\begin{aligned} O_{3W} &= \epsilon^{abc} W^{a\nu}_{\mu} W^{b\rho}_{\nu} W^{c\mu}_{\rho} \qquad O_{HD} = |\Phi^\dagger D_\mu \Phi|^2 \qquad O_{HWB} = \Phi^\dagger \sigma^a \Phi W^a_{\mu\nu} B^{\mu\nu} \\ O^{(3)}_{H\ell} &= i\left(\Phi^\dagger \overleftrightarrow{D}_\mu \sigma^a \Phi\right) \bar{\ell}_L \gamma^\mu \sigma^a \ell_L \qquad O_{ll} = (\bar{\ell}_L \gamma^\mu \ell_L)(\bar{\ell}_L \gamma_\mu \ell_L) \end{aligned}$$

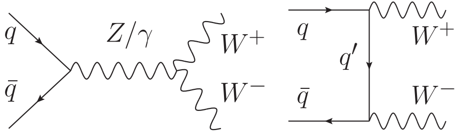
- Anomalous Couplings Framework:

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

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

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

Missing Terms



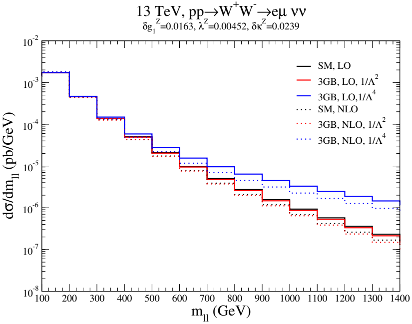
- Have not included anomalous quark gauge boson couplings:

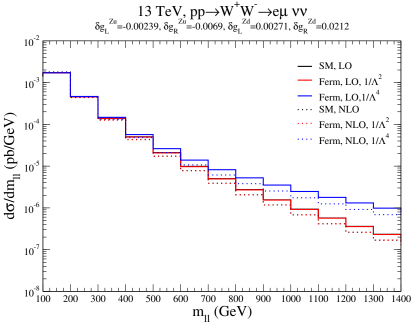
$$\mathcal{L} = g_V V^\mu \left((g_L^{Vq} + \delta g_L^{Vq}) \bar{q}_L \gamma_\mu q_L + (g_R^{Vq} + \delta g_R^{Vq}) \bar{q}_R \gamma_\mu q_R \right)$$

$$\delta g_L^W = \delta g_L^{Zu} - \delta g_L^{Zd}$$

  - Highly constrained by LEP.
  - Each diagram individually violates unitarity and grow uncontrollably with energy.
    - Will eventually get probabilities greater than one.
    - Standard Model contains cancellations to unitarize amplitudes and growth with energy cancels.
  - Anomalous quark couplings can spoil cancellation and have growth with energy.
  - This was recently pointed out Zhang PRL118 (2017) 011803. See also Grojean, Montull, Riembau JHEP 1903 (2019) 020; Alves, Rosa-Agostinho, Éboli, Gonzalez-Garcia, PRD 98 (2018) 013006; Almeida, Rosa-Agostinho, Éboli, Gonzalez-Garcia arXiv:1905.05187

Differential Distributions





Baglio, Dawson, **I. Lewis** PRD96 (2017) 073003

- $1/\Lambda^4$ 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.

Anomalous quark couplings

- The anomalous quark couplings have been highly constrained by LEP Falkowski, Riva JHEP 1502:

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

- However, when looking at W^+W^- production, find that the anomalous quark couplings receive a longitudinal enhancement and can be important at high energies:

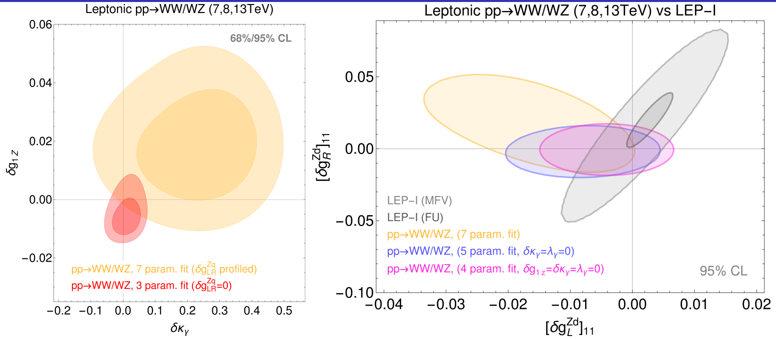
$$\begin{aligned}\mathcal{A}_{+-00} &\sim \frac{g^2 s}{2M_W^2}\left\{\delta\kappa^Z\left(s_W^2 Q_q - T_3\right) - s_W^2\, Q_q \delta\kappa^\gamma - \delta g_L^{Zq} + 2\,T_3\,\delta g_L^W\right\} + O(s^0)\\ \mathcal{A}_{-+00} &\sim \frac{g^2 s}{2M_W^2}\left\{s_W^2\, Q_q\left(\delta\kappa^\gamma - \delta\kappa^Z\right) + \delta g_R^{Zq}\right\} + O(s^0)\end{aligned}$$

For transversely polarized Ws:

$$\begin{aligned}\mathcal{A}_{+-\pm\pm} &\sim -g^2\lambda^Z T_3\,\frac{s}{2\,M_W^2} + O_{EFT}(s^0) + O_{SM}(s^{-1})\\ \mathcal{A}_{+-\pm\mp} &\sim \frac{g^2}{\sqrt{2}}\,\frac{(1+\delta g_L^W)^2}{1-2\,T_3\,\cos\theta} + O(s^{-1})\end{aligned}$$

- Notation: $\mathcal{A}_{\bar{q}q'W^+W^-}$

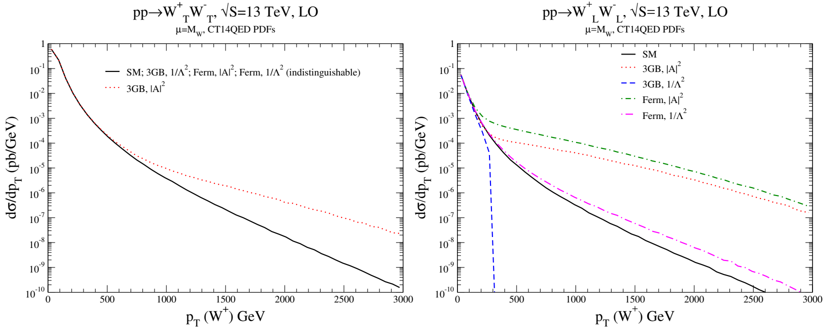
Importance at 8 and 13 TeV



Grojean, Montull, Riembau JHEP 1903 (2019) 020

- 7,8, 13 TeV diboson data.
- Yellow: Includes all operators.
- Red: Only anomalous trilinear gauge boson couplings.
- Pink: Only anomalous quark-gauge boson couplings.
- Anomalous quark couplings make impact on anomalous trilinear gauge boson coupling.
- Bounds on down-type quark coupling comparable to LEP (LEP bounds on up-type quarks still more stringent.)
- See also Baglio, **Lewis**, Dawson PRD96 (2017) 073003; Alves, Rosa-Agostinho, Éboli, Gonzalez-Garcia, PRD98 (2018) 013006

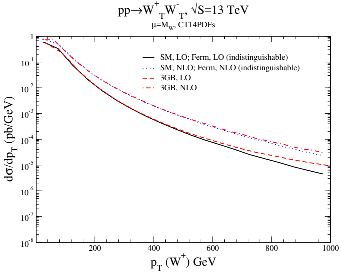
Leading Order Differential Distributions by Helicity

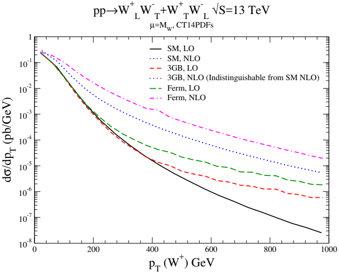


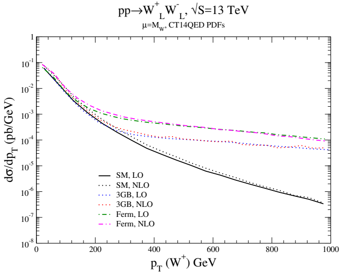
Baglio, Dawson, **I. Lewis** PRD96 (2017) 073003

- Negligible interference between SM and ATGCs for fully transversely polarized Ws. Hagiwara, Peccei, Zeppenfeld, Hikasa NPB282 (1987); Azatov, Contino, Machado, Riva, PRD95 (2017)
- Effects of EFT depend on polarization of gauge bosons.
- Λ^{-2}: SM amplitude squared+interference with EFT.
- $|A|^2$: full amplitude squared.

NLO QCD Differential Distributions by Helicity up to $1/\Lambda^4$



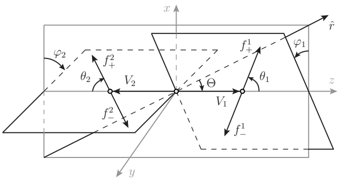


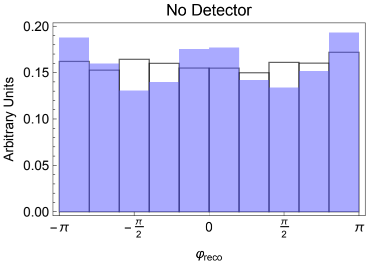


Baglio, Dawson, **I. Lewis** PRD96 (2017) 073003

Importance of Decays

- Have clear indication that different vector boson polarizations depend on anomalous couplings differently.
- Observables sensitive to the polarizations can be more sensitive to the EFT, and maybe "resurrect" the interference between the SM and EFT.
- Additionally, once the vector bosons are not in the final state, different polarizations of the internal vector bosons can interfere with each other.
  - In particular, the angles between the two bosons decay planes or decay and production planes can be sensitive the interference between the SM and EFT Panico, Riva, Wulzer PLB776 (2018) 473; Azatov, Elias-Miro, Reyimuaji, Venturini, JHEP 1710 (2017) 027; Azatov, Barducci, Venturini JHEP 1904 (2019) 075





Panico, Riva, Wulzer PLB776 (2018) 473

How important are quark couplings at HL-LHC and HE-LHC?

- Only consider the last bin.
  - Define last bin where $\delta_{statistical} \sim \delta_{systematic} \sim 16\%$ ATLAS, JHEP 1609 (2016) 029
  - 14 TeV HL-LHC (3 ab^{-1}):

$$p^{\ell}_{T,lead} > 750 \text{ GeV}.$$

  - 27 TeV HE-LHC (15 ab^{-1}):

$$p^{\ell}_{T,lead} > 1350 \text{ GeV}.$$

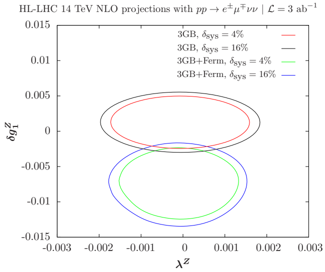
- Scan over the allowed LEP ranges Falkowski, Riva JHEP 1502:

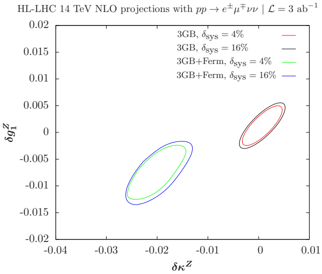
$$\begin{aligned}
\delta g_L^{Zd} &= (2.3 \pm 1) \times 10^{-3} \\
\delta g_L^{Zu} &= (-2.6 \pm 1.6) \times 10^{-3} \\
\delta g_R^{Zd} &= (16.0 \pm 5.2) \times 10^{-3} \\
\delta g_R^{Zu} &= (-3.6 \pm 3.5) \times 10^{-3}
\end{aligned}$$

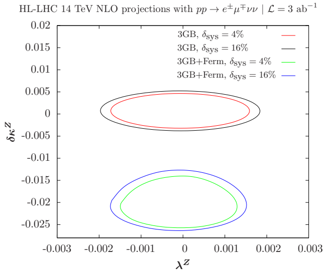
- Note: δg_R^{Zd} is not centered around zero.
  - Need non-zero anomalous trilinear gauge boson couplings to compensate for non-zero δg_R^{Zd} and get expected rate from the SM.

14 TeV HL-LHC, 3 ab^{-1}

- Black, red: ATGCs only
- Blue, green: ATGCs+anomalous quark couplings.
- Black, blue: $\delta_{sys} = 16\%$
- Red, green: $\delta_{sys} = 4\%$
- Areas inside contours allowed.
- Non-overlapping contours.

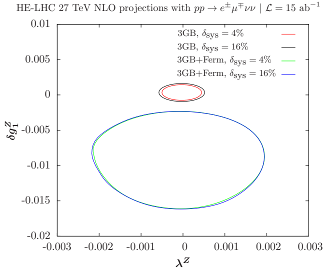


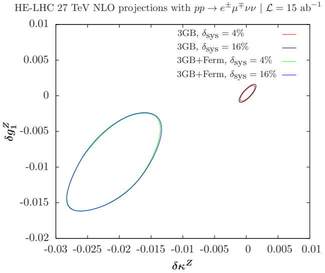


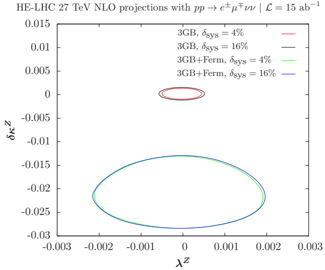


27 TeV HE-LHC, 15 ab^{-1}

- Black, red: ATGCs only
- Blue, green: ATGCs+anomalous quark couplings.
- Black, blue: $\delta_{sys} = 16\%$
- Red, green: $\delta_{sys} = 4\%$
- Areas inside contours allowed.
- Non-overlapping contours.







Non-overlapping allowed regions

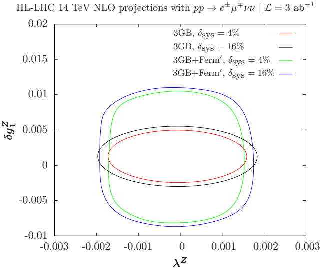
- LEP bounds on anomalous quark-gauge boson couplings are not centered about zero Falkowski, Riva JHEP 1502:

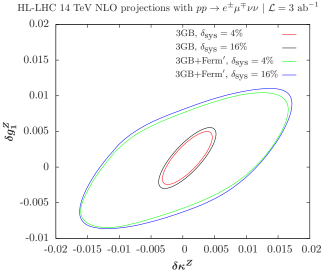
$$
\begin{aligned}
\delta g_L^{Zd} &= (2.3\pm 1)\times 10^{-3} \\
\delta g_L^{Zu} &= (-2.6\pm 1.6)\times 10^{-3} \\
\delta g_R^{Zd} &= (16.0\pm 5.2)\times 10^{-3} \\
\delta g_R^{Zu} &= (-3.6\pm 3.5)\times 10^{-3}
\end{aligned}
$$

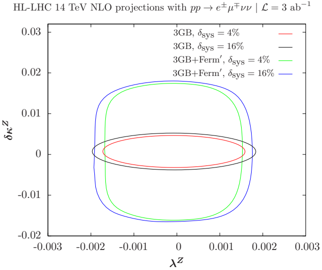
- The "last bin" was determined using the Standard Model cross section.
  - At high luminosity, to obtain Standard Model cross section need non-zero anomalous trilinear gauge boson couplings to cancel non-zero anomalous quark-gauge boson couplings.
  - Hence, the contours including anomalous quark-gauge boson couplings are centered off zero and do not overlap with those including only anomalous trilinear gauge boson couplings.
- Now, center anomalous quark gauge boson couplings at zero and keep same uncertainties.

14 TeV HL-LHC, 3 ab^{-1}, LEP bounds centered at zero

- Black, red: ATGCs only
- Blue, green: ATGCs+anomalous quark couplings.
- Black, blue: $\delta_{sys} = 16\%$
- Red, green: $\delta_{sys} = 4\%$
- Areas inside contours allowed.

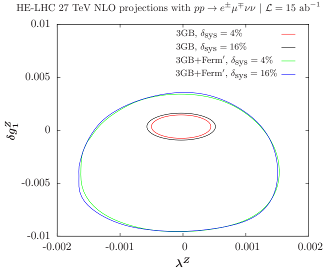


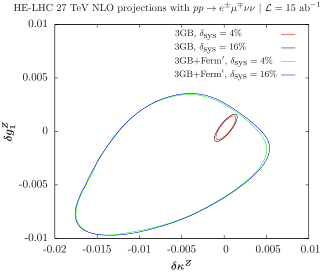


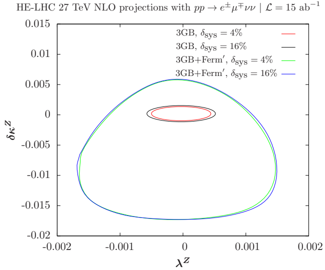


27 TeV HE-LHC, 15 ab^{-1}, LEP bounds centered at zero

- Black, red: ATGCs only
- Blue, green: ATGCs+anomalous quark couplings.
- Black, blue: $\delta_{sys} = 16\%$
- Red, green: $\delta_{sys} = 4\%$
- Areas inside contours allowed.







Primitive Cross Sections

- "Primitive cross sections" and NLO:

$$\begin{aligned} d\sigma^2(\vec{C}) &= d\sigma_{SM}(1 - \sum_{i=1}^{m} C_i) + \sum_{i=1}^{m} C_i\, d\sigma(1; \vec{R}_i) + \sum_{i=1}^{m} C_i^2 \left(d\sigma(2; \vec{R}_i) - d\sigma(1; \vec{R}_i) \right) \\ &+ \sum_{i>j=1}^{m} C_i C_j \left[d\sigma(2; \vec{M}_{ij}) - d\sigma(2; \vec{R}_i) - d\sigma(2; \vec{R}_j) + d\sigma_{SM} \right] \end{aligned}$$

  - C_i are Wilson coefficients.
  - Primitive cross sections $d\sigma(n, \vec{R}_i)$ and $d\sigma(n, \vec{M}_{ij})$ defined by setting one or two Wilson coefficients to one and all others to zero.
    - For a given basis, they are independent of the Wilson coefficients.
  - Primitive cross sections in Warsaw and HISZ bases are included in supplemental data in arXiv submission 1812.00214.
    - Realistic collider cuts.
    - Several distributions available.
    - We provide the method to take our primitive cross sections and recast into your own favorite basis.
  - Can download yourself and test operator-by-operator or perform your own fits.

Comment on Calculating Cross Sections

- Amplitude has terms up to Λ^{-2}.
- Amplitude squared includes terms that go as Λ^{-4}.:

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

  - g_{SM} is a generic Standard Model coupling.

Comment on Calculating Cross Sections

- Amplitude has terms up to Λ^{-2}.
- Amplitude squared includes terms that go as Λ^{-4}.:

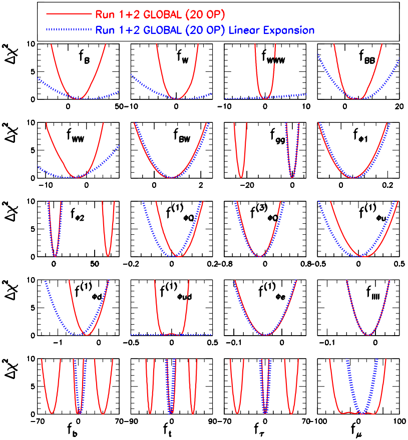
$$|\mathcal{A}|^2 \sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2}|^2 \sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4}$$

  - g_{SM} is a generic Standard Model coupling.
- Same order as dimension-8 contributions:

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

- Validity of keeping dimension-6 squared without dimension-8:
  - Strongly interacting theory: $c \gg g_{SM}$ so that $c_{dim-6}^2 \gg c_{dim-8} \times g_{SM}$.
  - Or the UV completion suppresses the dimension-8 terms.

Linear vs. Quadratic terms



Almeida, Alves, Agostinho, Éboli, Gonzalez-Garcia, PRD99 (2019) 033001

- Red: including quadratic contributions, Blue: Linear terms only.
- Quadratic terms dominate for operators with non-interference.
- Little difference between fits with quadratic or linear when operator limited by precision Higgs or EW data, not di-boson distributions.

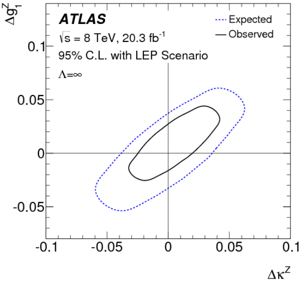
Conclusions

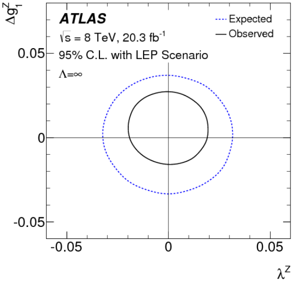
- We showed a case study of W^+W^- production.
  - Important effects from anomalous quark couplings have been neglected thus far.
  - LHC constraints on anomalous quark couplings can be comparable to LEP already.
  - Can be very significant at 3 ab^{-1} and a proposed 27 TeV machine.
  - We have incorporated anomalous trilinear gauge boson couplings and quark couplings into POWHEG at NLO (publicly available)
  - Have provided sufficient supplemental material so you can perform your own scans using your favorite operator basis.

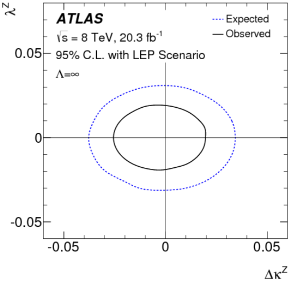
Thank You

Experimental results

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







Anomalous Quark-Gauge Boson Couplings

- Anomalous quark-gauge boson couplings occur from the operators

$$\begin{aligned} O^{(3)}_{HF,ij} &= i\left(\Phi^\dagger\sigma^a D_\mu\Phi-(D_\mu\Phi)^\dagger\sigma^a\Phi\right)\bar{Q}_{Li}\gamma^\mu\sigma^a Q_{Lj} \\ O^{(1)}_{HF,ij} &= i\left(\Phi^\dagger D_\mu\Phi-(D_\mu\Phi)^\dagger\Phi\right)\bar{Q}_{Li}\gamma^\mu Q_{Lj} \\ O_{Hf,ij} &= i\left(\Phi^\dagger D_\mu\Phi-(D_\mu\Phi)^\dagger\Phi\right)\bar{q}_{Ri}\gamma^\mu q_{Rj} \end{aligned}$$

Anomalous Quark-Gauge Boson Couplings

- Anomalous quark-gauge boson couplings occur from the operators

$$\begin{aligned} O^{(3)}_{HF,ij} &= i\left(\Phi^\dagger\sigma^a D_\mu\Phi-(D_\mu\Phi)^\dagger\sigma^a\Phi\right)\bar{Q}_{Li}\gamma^\mu\sigma^a Q_{Lj} \\ O^{(1)}_{HF,ij} &= i\left(\Phi^\dagger D_\mu\Phi-(D_\mu\Phi)^\dagger\Phi\right)\bar{Q}_{Li}\gamma^\mu Q_{Lj} \\ O_{Hf,ij} &= i\left(\Phi^\dagger D_\mu\Phi-(D_\mu\Phi)^\dagger\Phi\right)\bar{q}_{Ri}\gamma^\mu q_{Rj} \end{aligned}$$

- They alter the amplitudes:

$$\begin{aligned} \widetilde{\mathcal{A}}_{-+\lambda\lambda'} &= g_Z^2\cos^2\theta_W\left(g_R^{Zq}+\delta g_R^{Zq}\right)\beta_W\frac{E_{CM}^2}{E_{CM}^2-M_Z^2}A^Z_{\lambda\lambda'}+e^2Q_q\beta_W A^\gamma_{\lambda\lambda'} \\ \widetilde{\mathcal{A}}_{+-\lambda\lambda'} &= g_Z^2\cos^2\theta_W\left(g_L^{Zq}+\delta g_L^{Zq}\right)\beta_W\frac{E_{CM}^2}{E_{CM}^2-M_Z^2}A^Z_{\lambda\lambda'}+e^2Q_q\beta_W A^\gamma_{\lambda\lambda'}+2T_3\frac{g^2}{\beta_W}(1+\delta g_W)^2A^W_{\lambda\lambda'}, \end{aligned}$$

  - We assume flavor diagonal ($i=j$) and universal.
- From $SU(2)_L$ invariance we have

$$\delta g_W=\delta g_L^{Zu}-\delta g_L^{Zd}$$

- 4 free anomalous quark couplings.

Anomalous Quark-Gauge Boson Couplings

- Anomalous quark-gauge boson couplings occur from the operators

$$
\begin{aligned}
O^{(3)}_{HF,ij} &= i\left(\Phi^\dagger \sigma^a D_\mu \Phi - (D_\mu \Phi)^\dagger \sigma^a \Phi\right) \bar{Q}_{Li} \gamma^\mu \sigma^a Q_{Lj} \\
O^{(1)}_{HF,ij} &= i\left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi\right) \bar{Q}_{Li} \gamma^\mu Q_{Lj} \\
O_{Hf,ij} &= i\left(\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi\right) \bar{q}_{Ri} \gamma^\mu q_{Rj}
\end{aligned}
$$

Anomalous Quark-Gauge Boson Couplings

- Anomalous quark-gauge boson couplings occur from the operators

$$O^{(3)}_{HF,ij} = i\left(\Phi^\dagger\sigma^a D_\mu\Phi - (D_\mu\Phi)^\dagger\sigma^a\Phi\right)\bar{Q}_{Li}\gamma^\mu\sigma^a Q_{Lj}$$

$$O^{(1)}_{HF,ij} = i\left(\Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi\right)\bar{Q}_{Li}\gamma^\mu Q_{Lj}$$

$$O_{Hf,ij} = i\left(\Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi\right)\bar{q}_{Ri}\gamma^\mu q_{Rj}$$

- They alter the amplitudes:

$$\widetilde{\mathcal{A}}_{-+\lambda\lambda'} = g_Z^2\cos^2\theta_W\left(g_R^{Zq} + \delta g_R^{Zq}\right)\beta_W\frac{s}{s-M_Z^2}A^Z_{\lambda\lambda'} + e^2 Q_q\beta_W A^\gamma_{\lambda\lambda'}$$

$$\widetilde{\mathcal{A}}_{+-\lambda\lambda'} = g_Z^2\cos^2\theta_W\left(g_L^{Zq} + \delta g_L^{Zq}\right)\beta_W\frac{s}{s-M_Z^2}A^Z_{\lambda\lambda'} + e^2 Q_q\beta_W A^\gamma_{\lambda\lambda'} + 2\,T_3\frac{g^2}{\beta_W}\left(1+\delta g_W\right)^2 A^W_{\lambda\lambda'},$$

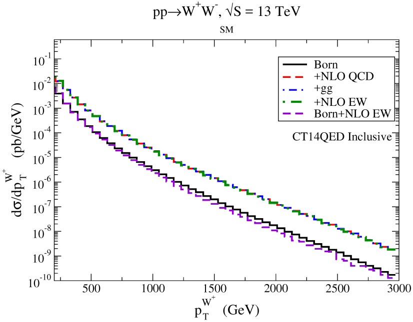
  - where, assuming flavor diagonal ($i=j$) and universal,

$$\delta g_L^{Zu} = -\frac{v^2}{2\Lambda^2}\left(C^{(1)}_{HF} - C^{(3)}_{HF}\right) \qquad \delta g_L^{Zd} = -\frac{v^2}{2\Lambda^2}\left(C^{(1)}_{HF} + C^{(3)}_{HF}\right)$$

$$\delta g_R^{Zu} = -\frac{v^2}{2\Lambda^2}C_{Hu} \qquad \delta g_R^{Zd} = -\frac{v^2}{2\Lambda^2}C_{Hd}$$

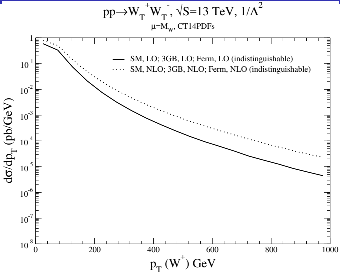
$$\delta g_W = \delta g_L^{Zu} - \delta g_L^{Zd}$$

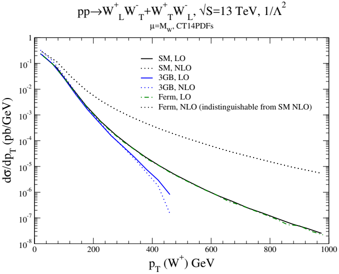
Higher Order QCD Corrections

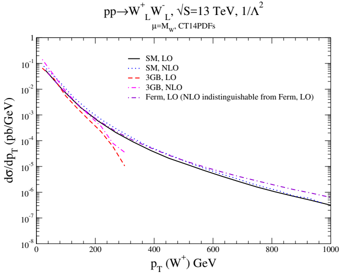


Known up to NNLO in QCD and NLO in electroweak Frixione NPB410; Ohnemus PRD44; Dixon, Kunszt, Signer NPB531; Dicus, Kao, Repko PRD36; Glover, van der Bij PLB219; Binoth, Ciccolini, Kauer, Kramer JHEP 0612, JHEP 0503; Baglio, Ninh, Weber PRD94; Bierweiler, Kasprzik, Kuhn, Uccirati JHEP 1211; Bierweiler, 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

Differential Distributions at NLO by Helicity up to $1/\Lambda^2$







Baglio, Dawson, **I. Lewis** PRD96 (2017) 073003

Choice of Basis

- Have worked in the anomalous coupling framework, however as seen can match the EFT onto these.
- The operators listed before are in a certain basis, the "Warsaw Basis" Grzadkowski, Iskrzynski, Misiak, Rosiek JHEP 10 (2010) 085

$$
\begin{aligned}
O_{3W} &= \varepsilon^{abc} W_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{c\mu} \qquad O_{HD} = |\Phi^{\dagger} D_{\mu}\Phi|^2 \qquad O_{HWB} = \Phi^{\dagger}\sigma^a \Phi W_{\mu\nu}^a B^{\mu\nu} \\
O_{H\ell}^{(3)} &= i\left(\Phi^{\dagger} \overleftrightarrow{D}_{\mu}\sigma^a \Phi\right) \bar{\ell}_L \gamma^{\mu}\sigma^a \ell_L \qquad O_{\ell\ell} = (\bar{\ell}_L\gamma^{\mu}\ell_L)(\bar{\ell}_L\gamma_{\mu}\ell_L)
\end{aligned}
$$

- There is another set of operators in the so-called HISZ basis Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993) 2182:

$$
\begin{aligned}
O_{3W} &= \varepsilon^{abc} W_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{c\mu}, \quad O_{DW} = i\,\frac{g}{2}(D_{\mu}\Phi)^{\dagger}\sigma^a W^{a,\mu\nu} D_{\nu}\Phi \\
O_{DB} &= i\,\frac{g'}{2}(D_{\mu}\Phi)^{\dagger} B^{\mu\nu} D_{\nu}\Phi
\end{aligned}
$$

- Many other bases, such as SILH (Strongly Interacting Light Higgs).
- One set of operators can be related to another via the SM equations of motion.
  - Hence, to dimension-6, all these complete sets of operators are equivalent.
  - It's a choice which basis we work in.

Matching ATGCs-HISZ basis

- HISZ operators effecting ATGCs
  Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993):

$$O_{WWW} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho{}^\mu], \quad O_W = (D_\mu\Phi)^\dagger W^{\mu\nu}D_\nu\Phi, \quad O_B = (D_\mu\Phi)^\dagger B^{\mu\nu}D_\nu\Phi$$

- Anomalous couplings:

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

- Matching the two descriptions:

$$\delta g_1^Z = c_W\frac{M_Z^2}{2\Lambda^2} \qquad \delta g_\gamma^1 = 0$$

$$\delta\kappa_Z = (c_W - c_B\tan^2\theta_W)\frac{M_W^2}{2\Lambda^2} \qquad \delta\kappa_\gamma = (c_W + c_B)\frac{M_W^2}{2\Lambda^2}$$

$$\lambda_Z = \lambda_\gamma = c_{WWW}\frac{3g^2M_W^2}{2\Lambda^2}$$

Primitive Cross Sections

- Specialize to a basis with a set of Wilson coefficients

$$\overrightarrow{C} = (C_1, C_2, \ldots, C_m),$$

  where $C_i \sim \Lambda^{-2}$
- Typically, the amplitude will be linear in C_i and hence the cross section will be quadratic in C_i.
- Keeping only linear terms

$$d\sigma^1(\overrightarrow{C}) = d\sigma_{SM}(1 - \sum_{i=1}^{m} C_i) + \sum_{i=1}^{m} C_i \, d\sigma(1; \overrightarrow{R}_i)$$

  - $\overrightarrow{R}_i = (0, 0, \ldots, 1, \ldots, 0)$ the Wilson coefficient vector with the i'th Wilson coefficient set to one.
  - Hence, $d\sigma(1; \overrightarrow{R}_i)$ is the cross section linear in Wilson coefficients with the i'th Wilson coefficient set to one.
  - $d\sigma(1; \overrightarrow{R}_i)$ is a "primitive cross section" and is just a number at this point and independent of the Wilson coefficients.

Primitive Cross Sections

- Similar composition at quadratic order:

$$\begin{aligned} d\sigma^2(\overrightarrow{C}) &= d\sigma_{SM}(1-\sum_{i=1}^{m}C_i)+\sum_{i=1}^{m}C_i\, d\sigma(1;\overrightarrow{R}_i) \\ &+ \sum_{i=1}^{m}C_i^2\left(d\sigma(2;\overrightarrow{R}_i)-d\sigma(1;\overrightarrow{R}_i)\right) \\ &+ \sum_{i>j=1}^{m}C_iC_j\left[d\sigma(2;\overrightarrow{M}_{ij})-d\sigma(2;\overrightarrow{R}_i)-d\sigma(2;\overrightarrow{R}_j)+d\sigma_{SM}\right] \end{aligned}$$

  - $\overrightarrow{M}_i=(0,0,\ldots,1,\ldots,1,\ldots,0)$ the Wilson coefficient vector with *both* the i'th and j'th Wilson coefficients set to one.
  - $d\sigma(1;\overrightarrow{R}_i)$ is the primitive cross linear in Wilson coefficients with the i'th Wilson coefficient set to one.
  - $d\sigma(2;\overrightarrow{R}_i)$ is the primitive cross quadratic in Wilson coefficients with the i'th Wilson coefficient set to one.
  - $d\sigma(2;\overrightarrow{M}_i)$ is the primitive cross quadratic in Wilson coefficients with the i'th and j'th Wilson coefficient set to one.
  - All primitive cross sections are numbers independent of the Wilson coefficients.

Primitive Cross Sections

- Different operator basis, get different primitive cross sections (although total cross section does not change)

$$
\begin{aligned}
d\sigma^2(\vec{C}') &= d\sigma_{SM}(1-\sum_{i=1}^{m} C'_i) + \sum_{i=1}^{m} C'_i\, d\sigma'(1;\vec{R}_i) \\
&+ \sum_{i=1}^{m} C'^2_i \left(d\sigma'(2;\vec{R}_i) - d\sigma'(1;\vec{R}_i)\right) \\
&+ \sum_{i>j=1}^{m} C'_i C'_j \left[d\sigma'(2;\vec{M}_{ij}) - d\sigma'(2;\vec{R}_i) - d\sigma'(2;\vec{R}_j) + d\sigma_{SM}\right]
\end{aligned}
$$

  - If you know the relationship between $\vec{C}$ and $\vec{C}'$, can find relationship between the primitive cross sections $d\sigma$ and $d\sigma'$.
  - Master formulas can be found in Baglio, Dawson, **I. Lewis**, PRD99 (2019) 035029
  - In supplemental material of Baglio, Dawson, **I. Lewis**, PRD99 (2019) 035029 can find primitive cross sections for Warsaw and HISZ basis at LO and NLO for a variety of distributions.
  - Using master formula, can take these primitive cross sections and change to your favorite set of operators.

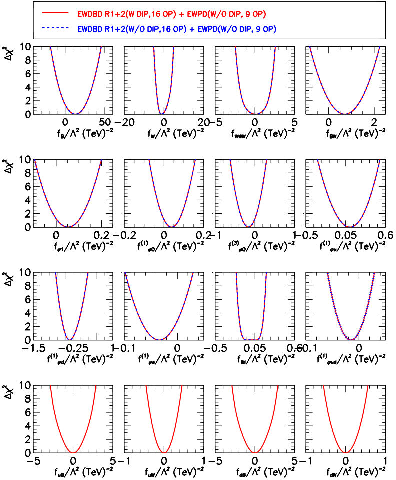
Dipole Operators

- Dipole operators of the form

$$O_{fW} = i\overline{F}_L \sigma^{\mu\nu} f_R \sigma^a \Phi W_{\mu\nu}, \quad O_{fB} = i\overline{F}_L \sigma^{\mu\nu} f_R \Phi B_{\mu\nu}$$

  - F_L is an $SU(2)_L$ doublet and f_R is an $SU(2)_L$ singlet.
  - Φ is SM Higgs doublet.
- Have new three-point and four-point quark-gauge boson couplings.
  - 3-point vertex is momentum dependent, important at high energies.
  - 4-point vertex will also grow quickly with energy.
- Note: dipoles couple left-chiral to right-chiral.
  - SM and other anomalous coupling contributions to WW/WZ considered so far couple left-left or right-right.
  - Since initial state fermions massless, there is no interference between dipole operators and other contributions.
  - Hence, only contribute at $(dimension-6)^2$.

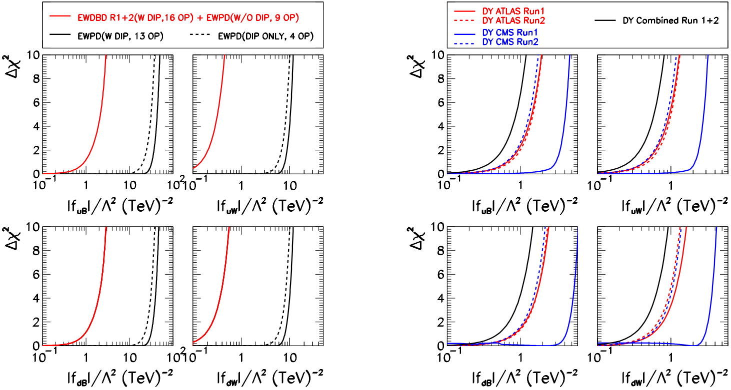
Dipole Operators



Almeida, Rosa-Agostinho, Éboli, Gonzalez-Garcia arXiv:1905.05187

- Red: With Dipoles, Blue: Without Dipoles
- No interference ⇒ Dipoles only add ⇒ no flat directions/cancellations with dipoles.

Dipole Operators



Almeida, Rosa-Agostinho, Éboli, Gonzalez-Garcia arXiv:1905.05187

- LHS: Electroweak diboson production
  - Red: electroweak diboson production, Black: electroweak precision data.
- RHS: Drell Yan
  - Red: ATLAS, Blue:CMS, Solid: Run 1, Dashed: Run 2, Black: All combined