Double Gauge Boson Production in the SM EFT

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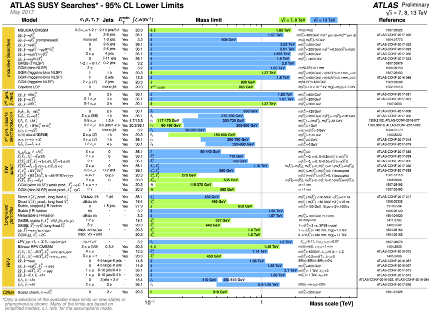
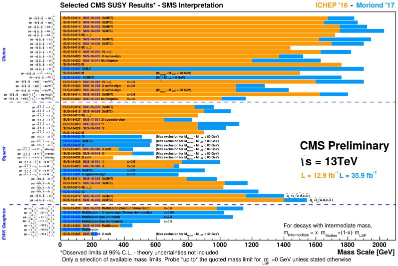
Goal: Find New BSM Physics

- LHC very successful so far: Discovered Higgs boson and obtained huge amount of date.
- However, have only confirmed the SM.
- Good reasons to expect beyond-the-SM physics.





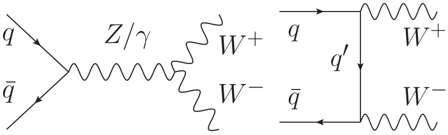
“Model Independent" Parameterization

- In the absence of direct evidence, useful to have a model independent formulation of new physics.
- SM effective field theory (EFT):

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

  - $\mathcal{O}_{n,k}$: $SU(3) \times SU(2)_L \times U(1)_Y$ gauge invariant $4+n$ dimensional higher order operators.
  - Λ: scale of new physics.
- Typically restrict to flavor universal and baryon number conserving operators:
  - $n=1$: neutrino mass Weinberg PRL43 (1979)
  - $n=2$: 59 independent operators Buchmüller, Wyler, NPB 268 (1986); Grzadowski, Iskrzynski, Misiak, Rosiek, JHEP1010; Giudice, Grojean, Pomaral, Rattazi JHEP0706; Contino, Ghezzi, Grojean, Muhlleitner, Spira JHEP1307
- Philosophy:
  - We know the SM is there at the EW scale.
  - Do not assume what new physics appears at Λ and allow $c_{n,k}$ to be independent.

W^+W^- production



- Of particular interest is the electroweak sector: focus on W^+W^- production.
- Sensitive to anomalous trilinear gauge boson couplings (ATGCs).
- In operator language, have three (CP-conserving) operators that give rise to ATGCs Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993):

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

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

$$\delta\mathcal{L} = -ig_{WWV}\left(g_V^1(W^+_{\mu\nu}W^{-\mu}V^\nu - W^-_{\mu\nu}W^{+\mu}V^\nu) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^+_{\rho\mu}W^{-\mu}{}_\nu V^{\nu\rho}\right)$$

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

ATGCs

- In operator language, have three (CP-conserving) operators that give ATGCs Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993):

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

- Another language: anomalous couplings:

$$\delta \mathcal{L} = -i g_{WWV} \left(g_V^1 (W^+_{\mu\nu} W^{-\mu} V^\nu - W^-_{\mu\nu} W^{+\mu} V^\nu) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^+_{\rho\mu} W^{-\mu}{}_\nu V^{\nu\rho} \right)$$

- Matching the two descriptions:

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

$$\kappa_Z = 1 + \delta\kappa_Z = 1 + (c_W - c_B \tan^2\theta_W) \frac{M_W^2}{2\Lambda^2} \qquad \kappa_\gamma = 1 + \delta\kappa_\gamma = 1 + (c_W + c_B) \frac{M_W^2}{2\Lambda^2}$$

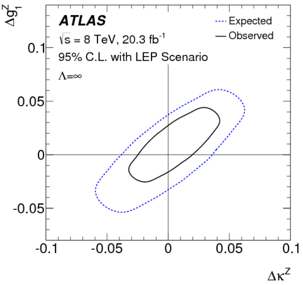
$$\lambda_Z = \lambda_\gamma = c_{WWW} \frac{3 g^2 M_W^2}{2\Lambda^2}$$

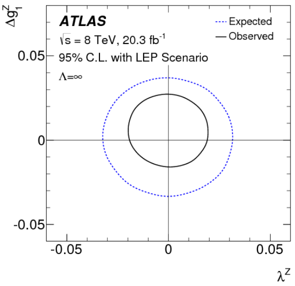
- Have relationships following from $SU(2)_L$ gauge invariance:

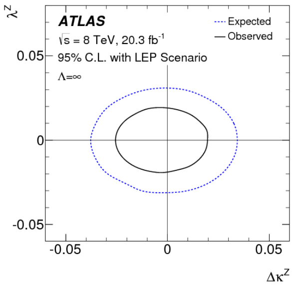
$$\lambda_\gamma = \lambda_Z \qquad \delta\kappa_\gamma = \frac{\cos^2\theta_W}{\sin^2\theta_W} \left(\delta g_Z^1 - \delta\kappa_Z \right)$$

Experimental results

- ATGCs actively being searched for in W^+W^- production by both ATLAS JHEP 1609 and CMS 1703.06095







Missing Terms

- Haven't included anomalous quark gauge boson couplings.
  - Highly constrained by LEP.
- There are arguments for why interference between SM and NP couplings is suppressed at high energies Hagiwara, Peccei, Zeppenfeld, Hikasa NPB282 (1987); Azatov, Contino, Machado, Rive, PRD95 (2017)
- Amplitudes for $\bar{q}_s q_{s'} \to W^+_\lambda W^-_{\lambda'}$ Hagiwara, Peccei, Zeppenfeld, Hikasa NPB282 (1987):

$$\begin{aligned}
\mathcal{A}_{ss'\lambda\lambda'} &= \sqrt{2}\widetilde{\mathcal{A}}_{ss'\lambda\lambda'}\tilde{d}_{ss'\lambda\lambda'}(-1)^{\Delta\lambda} \\
\widetilde{\mathcal{A}}_{-+\lambda\lambda'} &= g_Z^2\cos^2\theta_W g_R^{Zq}\beta_W \frac{s}{s-M_Z^2}A^Z_{\lambda\lambda'} + e^2 Q_q \beta_W A^\gamma_{\lambda\lambda'} \\
\widetilde{\mathcal{A}}_{+-\lambda\lambda'} &= g_Z^2\cos^2\theta_W g_L^{Zq}\beta_W \frac{s}{s-M_Z^2}A^Z_{\lambda\lambda'} + e^2 Q_q \beta_W A^\gamma_{\lambda\lambda'} + 2T_3\frac{g^2}{\beta_W}A^W_{\lambda\lambda'},
\end{aligned}$$

  - $g_Z = e/(\sin\theta_W\cos\theta_W)$, $g_R^{Zq} = -\sin^2\theta_W Q_q$, $g_L^{Zq} = T_3 - \sin^2\theta_W Q_q$
  - $\beta_W = \sqrt{1-4M_W^2/s}$

$W_T^+ W_T^+$ production

- For $\lambda\lambda' = ++$ or $\lambda\lambda' = --$:

$$A^Z_{\pm\pm} = 1 + \delta g^1_Z + \frac{s}{2M_W^2}\lambda_Z \qquad A^\gamma_{\pm\pm} = 1 + \frac{s}{2M_W^2}\lambda_Z$$

$$A^W_{\pm\pm} = -\frac{1}{2} + \frac{2M_W^2}{s}\frac{1}{1+\beta_W^2 - 4\,T_3\,\beta_W\cos\theta}$$

  - Taking high energy expansion $s \gg M_Z^2$:

$$\widetilde{\mathcal{A}}_{-+\pm\pm} = -e^2 Q_q\left(\delta g^1_Z + \frac{M_Z^2}{2M_W^2}\lambda_Z\right) + \mathcal{O}(s^{-1})$$

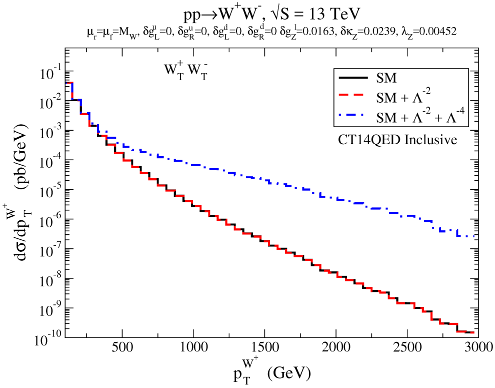
$$\widetilde{\mathcal{A}}_{+-\pm\pm} = \frac{e^2}{\sin^2\theta_W}\left(\frac{s}{2M_W^2}T_3\lambda_Z + g_L^{Zq}\delta g^1_Z + \frac{1}{2\cos^2\theta_W}\left(g_L^{Zq} - 2\cos^2\theta_W T_3\right)\lambda_Z\right) + \mathcal{O}(s^{-1})$$

  - SM contributions suppressed by s^{-1}
- For $\lambda\lambda' = \pm\mp$ no NP contribution:

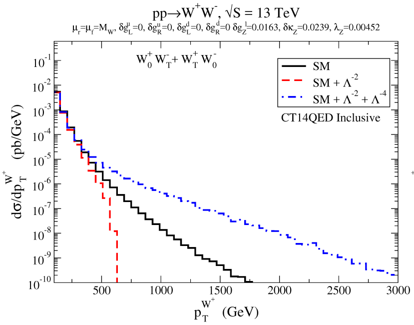
$$A^Z_{\pm\mp} = A^\gamma_{\pm\mp} = 0 \quad A^W_{\pm\mp} = 2\sqrt{2}T_3\beta_W\frac{1}{1+\beta_W^2 - 4\,T_3\,\beta_W\cos\theta}$$

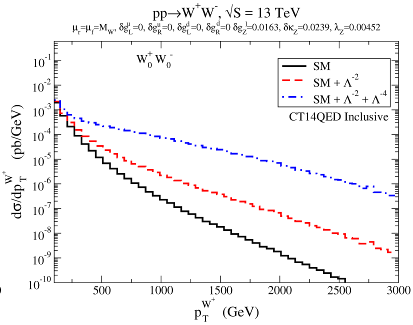
Polarized W^+W^- production

- Negligible interference between SM and ATGCs for fully transversely polarized Ws.
- SM+Λ^{-2}: SM amplitude squared+interference with EFT.
- SM+Λ^{-2}+Λ^{-4}: full amplitude squared.
- Assumed SM fermion-gauge boson couplings.



Longitudinal Ws





- If at least one W is longitudinal interference with SM occurs.
- Assumed SM fermion-gauge boson couplings.

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:

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

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

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

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

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

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

Anomalous quark couplings

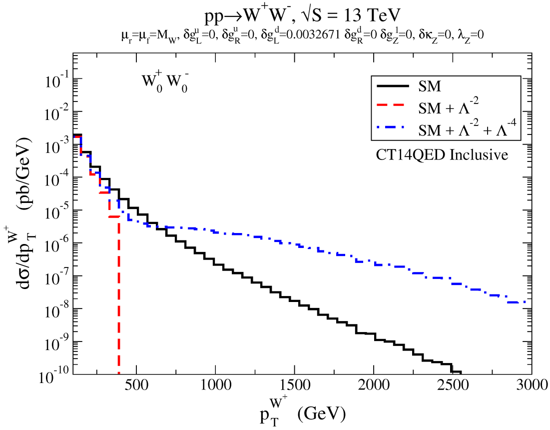
- The anomalous quark couplings have been highly constrained by LEP Falkowski, Riva JHEP 1502:

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

- However, when looking at W^+W^- production, find that the anomalous quark couplings receive a longitudinal enhancement and can be important at high energies Zhang PRL118 (2017) (neglecting ATGCs):

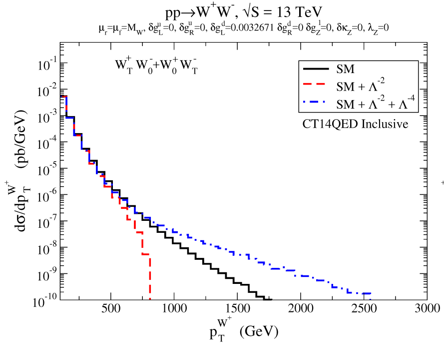
$$\begin{aligned}\widetilde{\mathcal{A}}_{-+00} &= \frac{g_Z^2}{2}\left(g_R^{Zq}+\delta g_R^{Zq}\left(1+\frac{s}{M_Z^2}\right)\right)+O(s^{-1})\\ \widetilde{\mathcal{A}}_{+-00} &= \frac{g_Z^2}{2}\left[g_L^{Zq}+\delta g_L^{Zq}\left(1+\frac{s}{M_Z^2}\right)\right]-g^2T_3\left[1+2\delta g_W\left(1+\frac{\delta g_W}{2}\right)\left(1+\frac{s}{2M_W^2}\right)\right]+O(s^{-1})\end{aligned}$$

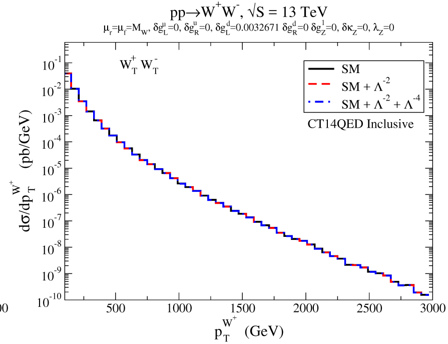
Anomalous quark couplings



- Longitudinal enhancements.
- One non-zero anomalous quark coupling near maximum allowed value from LEP.
- Can become important at high energies. Increasingly important at future HL-LHC.

Anomalous quark couplings-Transverse Ws





- Smaller effect with transverse Ws.

Refit

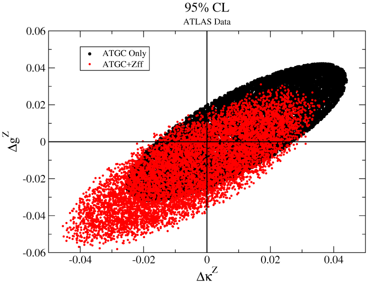
- Anomalous quark couplings are important and need to be included in fits.
- In practice want to take differential distributions from experimental collaborations, extract constraints on anomalous couplings.
- Problem: we do not decay the W^+.
- Solution: Take allowed ranges for ATGCs and determined the upper and lower limit on

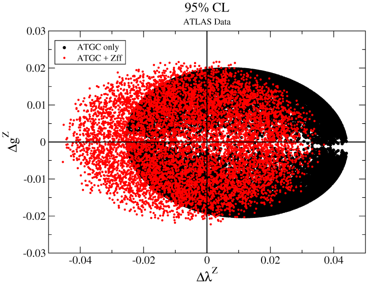
$$\sigma(p_T^{W^+} > 500\text{ GeV}) = \int_{500\text{ GeV}}^{\infty} dp_T^{W^+} \frac{d\sigma}{dp_T^{W^+}}$$

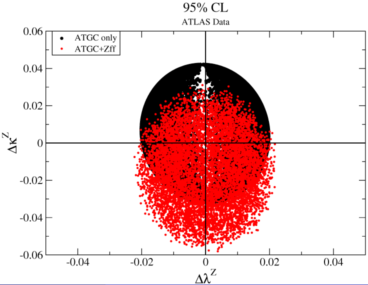
- Now scan over all parameters and determine allowed regions taking into consideration LEP constraints on anomalous quark couplings.

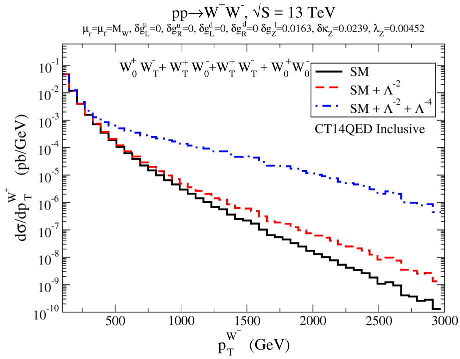
Refit

- Black dots: Including only ATGCs.
- Red dots: adding in anomalous quark couplings

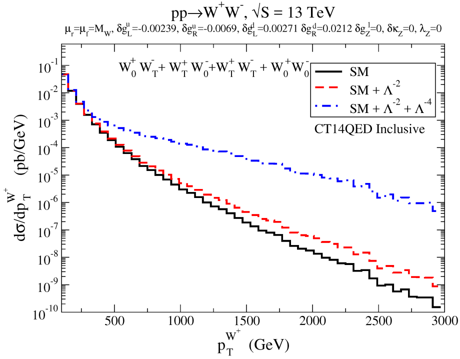






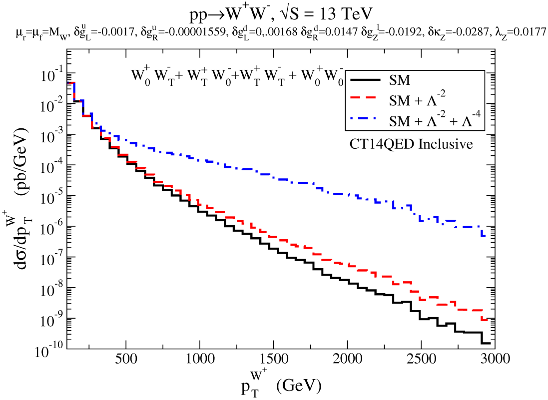


Anomalous quark couplings set to zero



ATGCs set to zero.

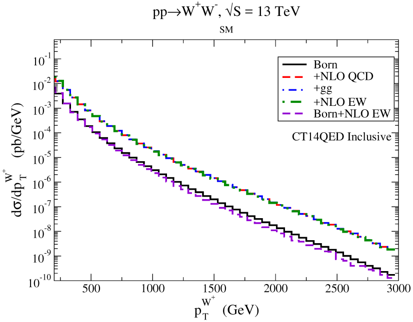
Maximizing Allowed Cross Sections



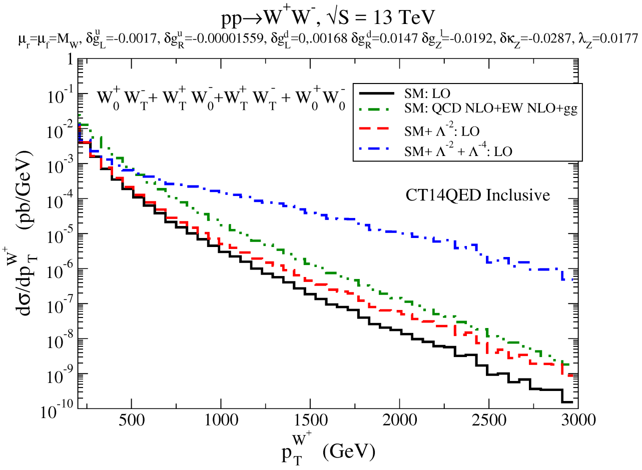
All couplings nonzero.

Adding NLO Corrections

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



pp→W+W-, √S = 13 TeV
μr=μf=MW, δgLu=-0.0017, δgRu=-0.00001559, δgLd=0,.00168 δgRd=0.0147 δgZ1=-0.0192, δκZ=-0.0287, λZ=0.0177
W0+ WT-+ WT+ W0-+WT+ WT- + W0+W0-
SM: LO
SM: QCD NLO+EW NLO+gg
SM+ Λ-2: LO
SM+ Λ-2 + Λ-4: LO
CT14QED Inclusive
dσ/dpTW+ (pb/GeV)
pTW+ (GeV)
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
500
1000
1500
2000
2500
3000

Conclusions

- Investigated the effects of anomalous couplings on W^+W^- production.
  - At LHC experiments have only so far considered ATGCs.
  - Although strongly constrained at LEP, anomalous quark-gauge boson couplings will become increasingly important due to longitudinal enhancements.
  - Found that including anomalous quark couplings changes the results of ATGC fits at the LHC.
- NLO corrections.
  - Corrections to the SM rate are substantial.
  - For ATGCs, NLO QCD corrections known for long time Dixon, Kunszt, Signer PRD60.