Double Gauge Boson Production in the SM EFT

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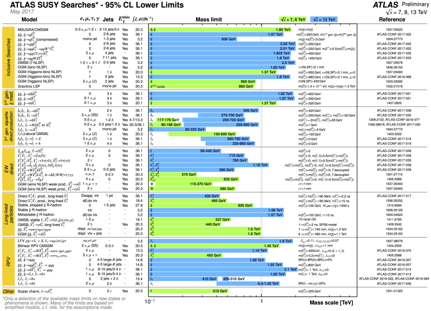
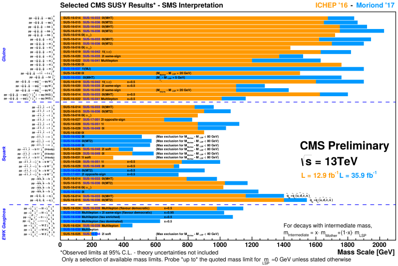
Goal: Find New BSM Physics

- LHC very successful so far: Discovered Higgs boson and obtained huge amount of data.
- However, have only confirmed the SM.
- $O(1\text{ TeV})$ lower bounds on new physics:





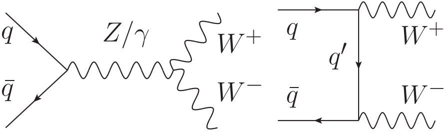
“Model Independent” Parameterization

- 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):

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

  - $O_{n,k}$: $SU(3)\times SU(2)_L\times U(1)_Y$ 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)
- Operators affecting ATGCs:

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

W^+W^- production

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

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

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

Matching ATGCs in two prescriptions

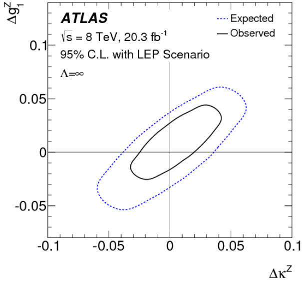
- Had 5 dimension-6 operators, only three independent combinations.
- In Warsaw basis:

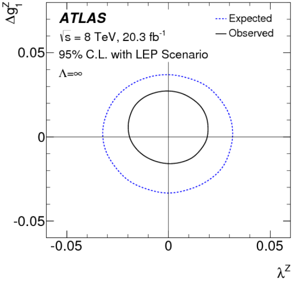
$$\begin{aligned}
\delta g_1^Z &= \frac{v^2}{\Lambda^2}\frac{1}{\cos^2\theta_W-\sin^2\theta_W}\left(\frac{\sin\theta_W}{\cos\theta_W}C_{HWB}+\frac{1}{4}C_{HD}+\delta v\right)\\
\delta\kappa^Z &= \frac{v^2}{\Lambda^2}\frac{1}{\cos^2\theta_W-\sin^2\theta_W}\left(2\sin\theta_W\cos\theta_W C_{HWB}+\frac{1}{4}C_{HD}+\delta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

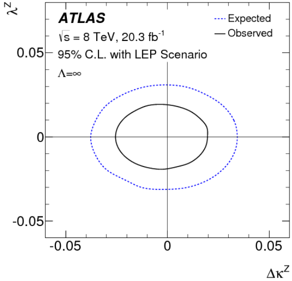
- Anomalous coupling language generic enough that any basis can be matched onto it.

Experimental results

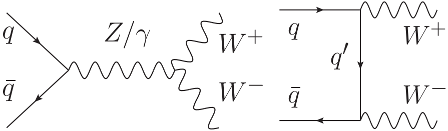
- ATGCs actively being searched for in W^+W^- production by both ATLAS JHEP 1609 (2016) 029 and CMS Phys.Lett. B772 (2017) 21







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

Missing Terms

- Anomalous quark-gauge boson couplings occur from the operators

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

- Parameterize via anomalous couplings:

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

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

Refit Experimental Results

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

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

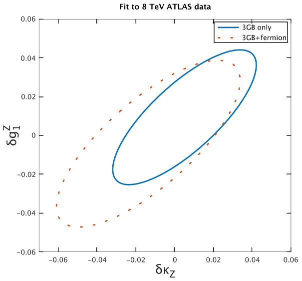
- Now scan over all parameters and determine allowed regions taking into consideration LEP constraints on anomalous quark couplings Falkowski, Riva JHEP 1502:

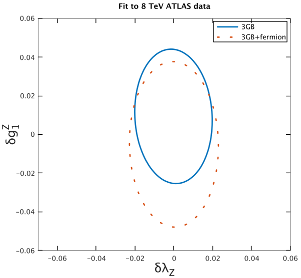
$$\begin{aligned} \delta g_L^{Zd} &= (2.3 \pm 1) \times 10^{-3} \\ \delta g_L^{Zu} &= (-2.6 \pm 1.6) \times 10^{-3} \\ \delta g_R^{Zd} &= (16.0 \pm 5.2) \times 10^{-3} \\ \delta g_R^{Zu} &= (-3.6 \pm 3.5) \times 10^{-3} \end{aligned}$$

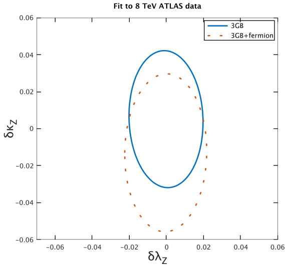
  - Accept points that fall within allowed region of $\sigma(p_T^{W^+} > 500\text{ GeV})$.

Refit

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







Comment on Calculating Cross Sections

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

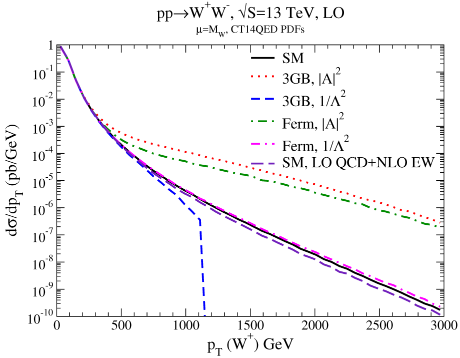
$$|\mathcal{A}|^2 \sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2}|^2 \sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4}$$

- Same order as dimension-8 contributions:

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

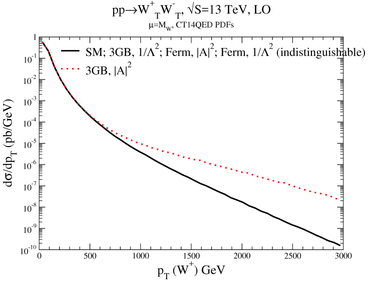
- If new sector is strongly interacting $c \gg g_{SM}$ then square of dimension 6 operators dominate.

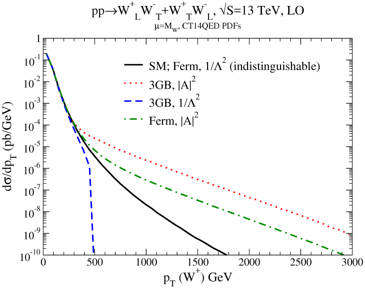
Differential Distributions

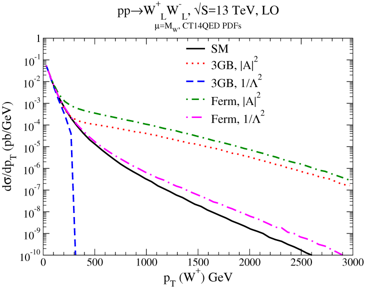


- $1/\Lambda^4$ terms dominate in tails and the bounds on anomalous couplings. Falkowski, Gonzalez-Alonso, Greijo, Marzocca, Son JHEP 1702 (2017) 115
- Ferm: ATGCs set to zero.
- 3GB: Anomalous fermion couplings set to zero.
- Assuming $C_i \lesssim 1$, anomalous couplings correspond to $\Lambda \gtrsim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

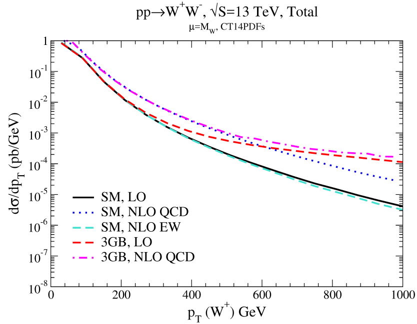
Differential Distrbutions by Helicity

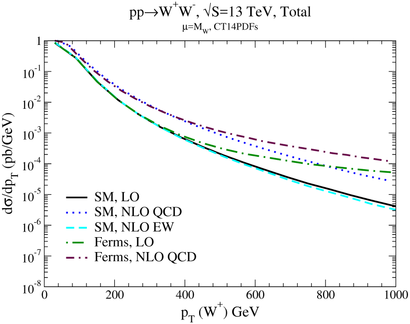






NLO SM Corrections

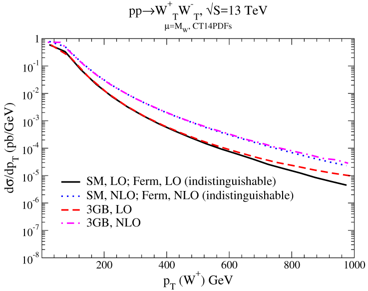


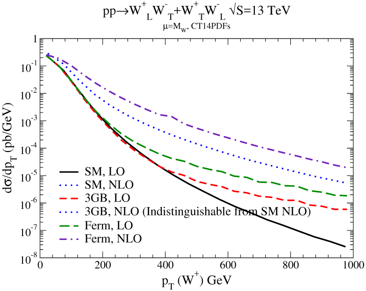


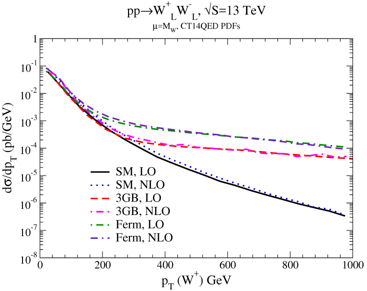
Known up to NNLO in QCD and NLO in EW Frixione NPB410; Ohnemus PRD44; Dixon, Kunszt, Signer NPB531; Dicus, Kao, Repko PRD36; Glover, van der Bij PLB219; Binoth, Ciccolini, Kauer, Kramer JHEP 0612, JHEP 0503; Baglio, Ninh, Weber PRD94; Bierweiler, Kasprzik, Kuhn, Uccirati JHEP 1211; Bierweiler, Kasprzik,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

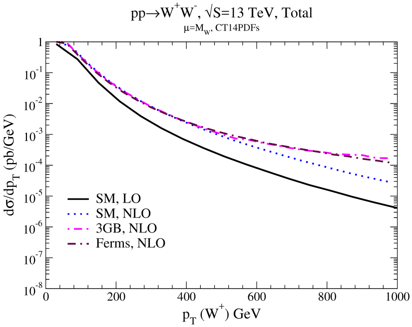
NLO QCD Differential Distrbutions by Helicity for $|A|^2$



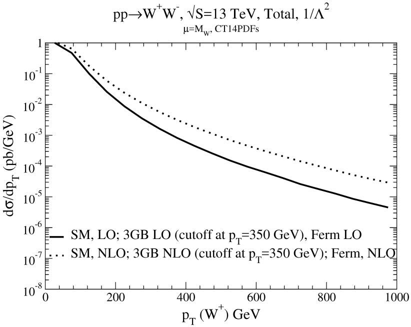




NLO QCD Corrections



Full Amplitude Squared



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.

Conclusions

- Investigated the effects of anomalous couplings on W^+W^- production.
  - At LHC the experiments have only so far considered ATGCs.
  - Although strongly constrained at LEP, anomalous quark-gauge boson couplings significantly change fits to anomalous couplings.
  - Effect of quark-gauge boson anomalous couplings strongly depends on if the full amplitude squared is considered or just the $1/\Lambda^2$ terms are kept and W^+W^- polarizations.
  - Terms quadratic in dimension-6 operators dominate in tails.
- Public code available: WWEFT@NLO

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

  - NLO QCD corrections for W^+W^- production with anomalous couplings.
  - SM NLO EW corrections.
  - Can separate NLO QCD corrections by W^+W^- helicity configurations.

Thank You

EXTRA SLIDES

W^+W^- production

- Operators affecting ATGCs:

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

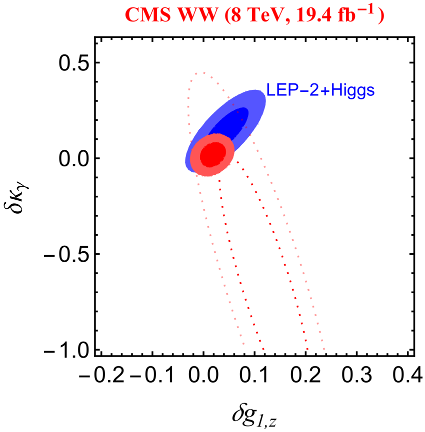
- In the EW sector have to choose input parameters: G_F, M_W, M_Z
- EFT alters relationships between other parameters and input parameters:

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

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

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

Amplitude Squared vs. Linear Pieces



Falkowski *et al* JHEP 1702

- Red filled: Full Amplitude Squared.
- Red dashed: only linear pieces

“Model Independent” Parameterization

- SM effective field theory (EFT):

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

- 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
- There are global analyses of SMEFT Corbett, Eboli, Goncalves, Gonzalez-Fraille, Plehn, Rauch JHEP 1508; Butler, Eboli, Gonzalez-Fraille, Gonzalez-Garcia, Plehn, Rauch JHEP 1607; Berthier, Trott JHEP 1505; Falkowski, Riva JHEP 1502; Brivio, Trott arXiv: 1706.08945 [hep-ph]etc.
- Choices have to be made. Examples of sets of operators:
  - SILH: “Strongly interacting light Higgs” Giudice, Grojean, Pomaral, Rattazzi JHEP 0706 (2007) 045
  - HISZ Hagiwara, Ishihara, Szalapski, Zeppenfeld PRD48 (1993) 2182
  - “Warsaw Basis” Grzadkowski, Iskrzynski, Misiak, Rosiek JHEP 1010 (2010) 085
- Choice of operators different among bases, but complete bases are equivalent.

Refit Experimental Results

- Define χ^2:

$$\Delta\chi^2 = y^T C^{-1} y$$

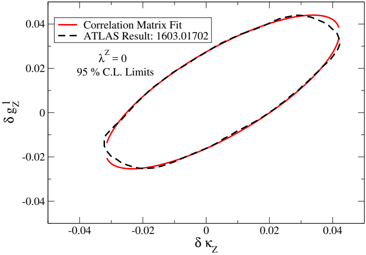
where

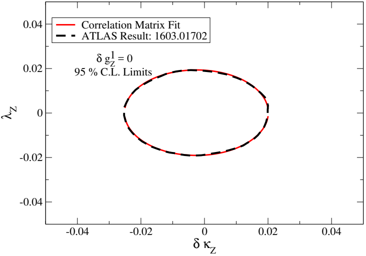
$$y^T = (\delta g_1^Z - \mu_{g_1^Z}, \delta\kappa^Z - \mu_{\kappa^Z}, \lambda^Z - \mu_{\lambda^Z})$$

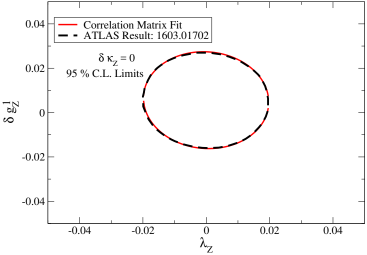
- With 3-parameter fit require that $\Delta\chi^2 < 7.815$.
- Fit to the 2D plots and find means and covariant matrix:

$$\begin{aligned} \mu_{g_1^Z} &= 0.00935, \quad \mu_{\kappa^Z} = 0.00518, \quad \mu_{\lambda^Z} = -0.000185 \\ C &= \begin{pmatrix} 1.55 & 1.28 & -0.0563 \\ 1.28 & 1.76 & -0.0455 \\ -0.0563 & -0.0455 & 0.511 \end{pmatrix} \times 10^{-4} \end{aligned}$$

Refit Experimental Results

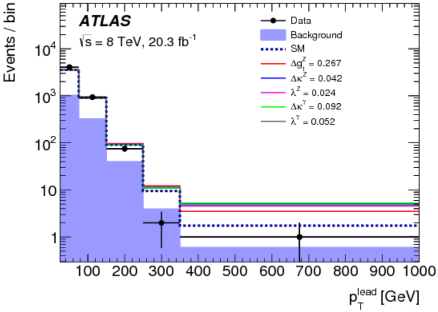






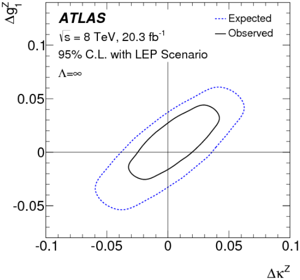
Refit Experimental results

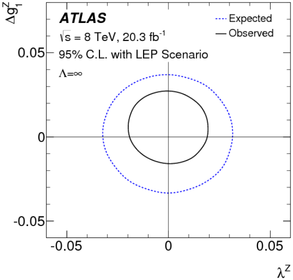
- ATGCs limits from ATLAS JHEP 1609.
- In practice want to take differential distributions from experimental collaborations, extract constraints on anomalous couplings.
- Problem: we do not decay the W^+.

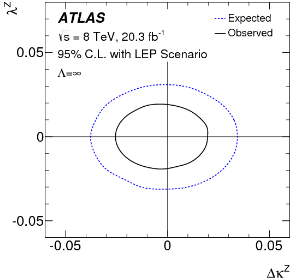


Refit Experimental results

- Solution: repurpose ATLAS ATGC 95% C.L. JHEP 1609.
- Each 2D plot set 3rd parameter to zero.
- Can fit ellipsoid.





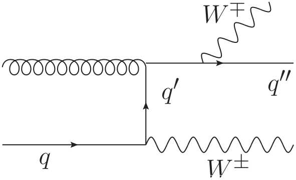


Refit Experimental Results

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

	95% C.L. limit Using Previous Number	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]

Large Sudakov Logarithms



- LO Story:
  - SM calculation is unitary and growth with energy cancels.
  - Anomalous quark couplings spoil cancellation and allow for non-unitary behavior.
  - Even though small, the effects grow with energy.
- NLO story:
  - SM K-factor huge due to large Sudakov logarithms, grows with energy.
  - No cancellations for anomalous quark couplings to spoil.
  - Anomalous quark couplings not as enhanced relative to SM as energy grows.

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