QCD Corrections to effective field theories at the Large Hadron Collider

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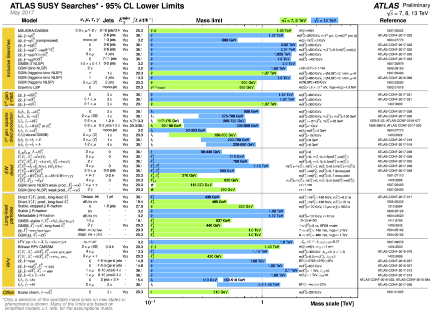
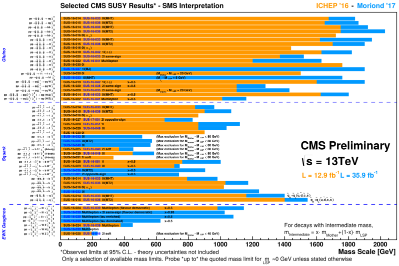
Goal: Find New BSM Physics

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

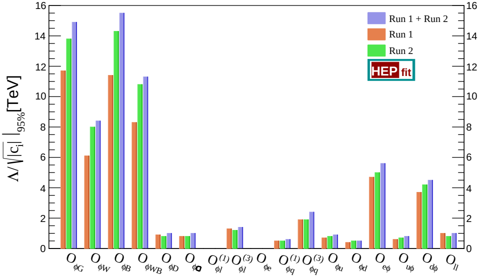
"Model Independent" Parameterization

- SM effective field theory (EFT):

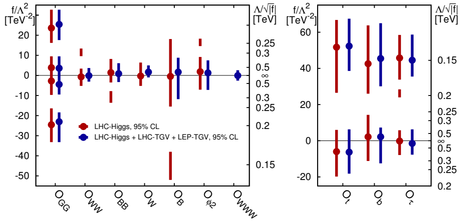
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_k \frac{c_{n,k}}{\Lambda^n} O_{n,k}$$

- 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.

Fits to LHC Data

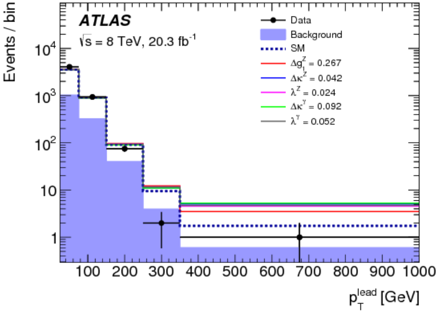


de Blas, *et al* arXiv:1710.05402



Butter *et al* JHEP 1607 (2016) 152

Process-by-Process and NLO QCD



- If new physics not directly produced at the LHC, need to precision measurements and precision calculations to find limits on new physics scales.
  - Especially true for legacy measurements.
- Other interesting things about process-by-process is that we can really understand the physics of that process, and understand which observables are most sensitive. In contrast to the global fit approach, where we apply current experimental searches.

NLO QCD EFT

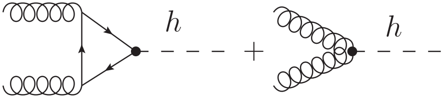
- Much recent work on doing NLO QCD calculation for SM EFT (incomplete):
  - VV: Dixon, Kunszt, Signer, PRD60 (1999) 114037
  - Top pair production: Franzosi, Zhang, PRD91 (2015) 114010
  - Single top: Zhang, PRL 116 (2016) 162002
  - ttZ/γ: Bylund, Maltoni, Tsinikos, Vryonidou, Zhang, JHEP 1605 (2016) 052
  - ttH: Maltoni, Vryonidou, Zhang, JHEP 1610 (2016) 123, Demartin, Mawatari, Page, Zaro EPJ C74 (2014) 3065
  - tH Demartin, Maltoni, Mawatari, Zaro EPJ C75 (2015) 267
  - Top FCNC: Degrande, Maltoni, Wang, Zhang PRD91 (2015) 034024; Durieux, Maltoni, Zhang PRD91 (2015) 074017
  - Higgs Characterization: Artoisenet JHEP 1311 (2013) 043
  - VBF, VH: Maltoni, Mawatari, Zaro EPJ C74 (2014) 2710; Degrande, Fuks, Mawatari, Mimasu, Sanz EPJ C77 (2017) 262
  - ggH: Deutschmann, Duhr, Maltoni, Vryonidou JHEP 2712 (2017) 063
  - Di-Higgs: Grober, Muhlleitner, Spira, Streicher JHEP 1509 (2015) 092; Grober, Muhlleitner, Spira NPB925 (2017) 1
- Will focus on a few calculations Dawson, **IL** Zeng, PRD90 (2014) 093007; Dawson, **IL**, Zeng PRD91 (2015) 074012; Baglio, Dawson, **IL** PRD96 (2017) 073003

Higgs Plus Jet

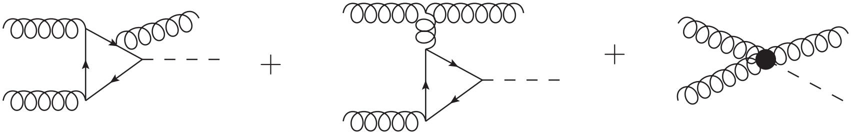
Higgs Plus Jet EFT

$$\mathcal{L} = -\kappa_t \left(\frac{m_t}{v}\right) \bar{t}th + \kappa_g \left(\frac{\alpha_s}{12\pi v}\right) G^{A,\mu\nu} G^A_{\mu\nu} h$$

- Assume simple deviations from SM predictions.



- Simple to keep single Higgs rate SM-like: $\kappa_t + \kappa_g = 1$.



- In Higgs+jet, κ_t and κ_g scale differently with energy.

Validity of EFT

- Assuming relatively large deviations from SM. How stable is EFT?
- Lowest order operator contribution to Higgs+jet Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, Eur.Phys.J C74 (2014) 10, 3120; Azatov, Paul JHEP 1401 (2014) 014; Grojean, Salvioni, Schlaffer, Weiler, JHEP 1405 (2014) 022; Langenegger, Spira, Strebel arxiv:1507.01373; Maltoni, Vryonidou, Zhang JHEP 1610 (2016) 123; Grazzini, Ilnicka, Spira, Wiesemann JHEP 1703 (2017) 115:

$$O_1 = h\, G^a_{\mu\nu} G^{a,\mu\nu}$$

- Can have contributions from higher order operators (for on-shell Higgs): Neill arXiv:0908.1573; Harlander, Neumann PRD88 (2013) 074015; Dawson, **IL** Zeng, PRD90 (2014) 093007; Dawson, **IL**, Zeng PRD91 (2015) 074012:

$$\begin{aligned} O_3 &= h\, f_{abc} G^{a,\mu}_{\nu} G^{b,\nu}_{\sigma} G^{c,\sigma}_{\mu} \\ O_4 &= g_s^2\, h \sum_{i,j} \overline{\psi}_i \gamma_\mu T^a \psi_i \overline{\psi}_j \gamma^\mu T^a \psi_j \\ O_5 &= g_s\, h \sum_i G^a_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i \end{aligned}$$

Operator Mixing

- Multiple choices in basis:

$$\mathcal{O}_3 = h\, f_{abc} G_\nu^{a,\mu} G_\sigma^{b,\nu} G_\mu^{c,\sigma} \quad \mathcal{O}_4 = g_s^2\, h \sum_{i,j} \overline{\psi}_i \gamma_\mu T^a \psi_i \overline{\psi}_j \gamma^\mu T^a \psi_j$$
$$\mathcal{O}_5 = g_s\, h \sum_i G^a_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i$$

- Apply SM equations of motion to $\mathcal{O}_4$ and $\mathcal{O}_5$:

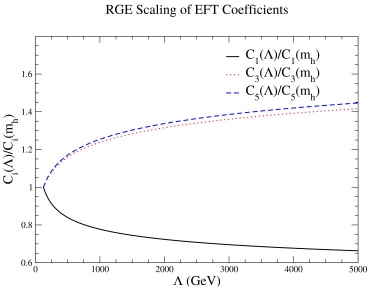
$$\mathcal{O}_3 = h\, f_{abc} G_\nu^{a,\mu} G_\sigma^{b,\nu} G_\mu^{c,\sigma} \quad \mathcal{O}_4' = h D^\sigma G^A_{\sigma\nu} D_\rho G^{A,\rho\nu}$$
$$\mathcal{O}_5' = h\, G^A_{\sigma\nu} D^\nu D^\rho G_\rho^{A,\sigma}$$

- Both sets of equations are equivalent under unphysical field redefinitions
- However, with first choice, solve for RGE and find there is no operator mixing Dawson, **IL**, Zeng, PRD90 (2014) 093007; PRD92 (2015) 094023:

$$\frac{d}{d\ln\mu_R} \ln\left(\frac{C_1(\mu_R)}{g_s^2(\mu_R)}\right) = \mathcal{O}(\alpha_s^2(\mu_R)), \quad \frac{d}{d\ln\mu_R} \ln\left(\frac{C_3(\mu_R)}{g_s^3(\mu_R)}\right) = \frac{\alpha_s(\mu_R)}{\pi} 3C_A,$$
$$\frac{d}{d\ln\mu_R} \ln\left(\frac{C_5(\mu_R)}{g_s^2(\mu_R)}\right) = \frac{\alpha_s(\mu_R)}{\pi}\left(\frac{11}{6}C_A + \frac{4}{3}C_F\right)$$

- For much more on operator mixing in SMEFT see Jenkins, Manohar, Trott, JHEP 1310 (2013) 087, JHEP 1401 (2014) 035; Alonso, Jenkins, Manohar, Trott, JHEP 1404 (2014) 159je

RGE Running



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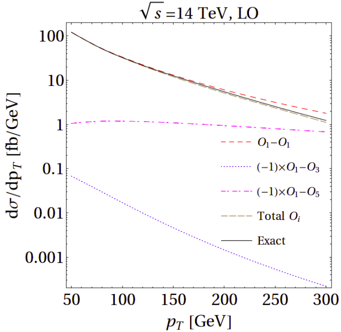
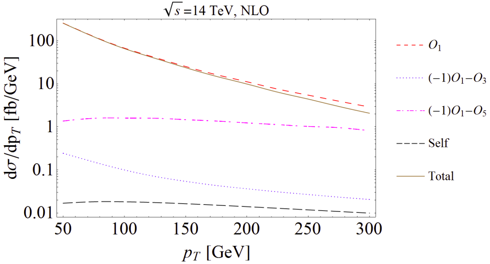
- See also Englert, Spannowsky PLB740 (2014)

Validity of EFT





Dawson, **IL**, Zeng, PRD90 (2014) 093007; PRD92 (2015) 094023

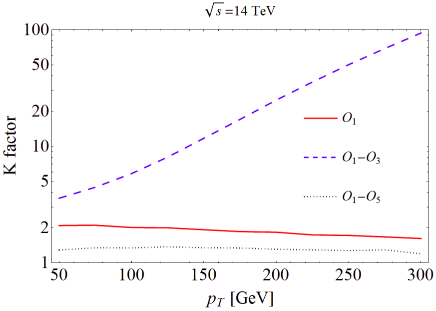
- Using SM values of Wilson coefficients. NLO changes story

$$O_3 = h f_{abc} G_\nu^{a,\mu} G_\sigma^{b,\nu} G_\mu^{c,\sigma}$$

$$O_4 = g_s^2 h \sum_{i,j} \overline{\psi}_i \gamma_\mu T^a \psi_i \overline{\psi}_j \gamma^\mu T^a \psi_j$$

$$O_5 = g_s h \sum_i G_{\mu\nu}^a D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i$$

Validity of EFT

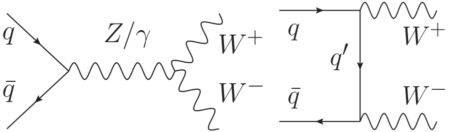


Dawson, **IL**, Zeng, PRD90 (2014) 093007; PRD92 (2015) 094023

- Depending on what operators are important for a given BSM scenario, get very different QCD corrections.
- K-factor = $d\sigma_{NLO}/d\sigma_{LO}$

W^+W^- Production

EFT W^+W^- productions

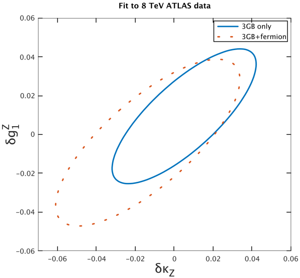


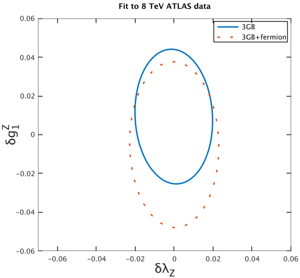
- Important because sensitive to anomalous trilinear gauge couplings.
- Most/many analyses did not consider anomalous
  - Highly constrained by LEP, sub-percent level deviations from SM values Falkowski, Riva JHEP 1502
  - But SM contains cancellations to unitarize amplitudes: growth with energy cancels.
  - Anomalous quark couplings can spoil cancellation and have growth with energy.
  - This was recently pointed out Zhang PRL118 (2017) 011803

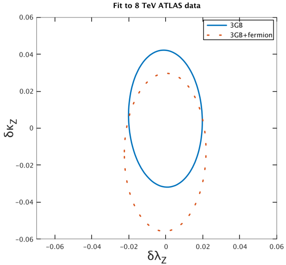
Refit

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

  Baglio, Dawson, **IL** PRD96 (2017) 073003
- See also: Alves, Rosa-Agostinho, Éboli, Gonzalez-Garcia, arXiv:1805.11108







Comment on Calculating Cross Sections

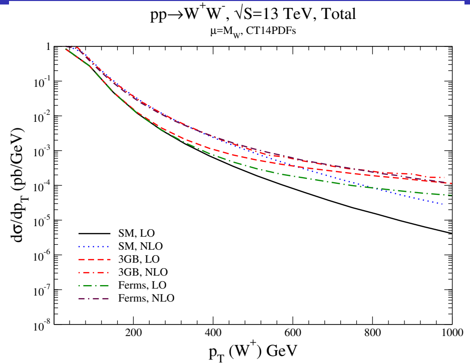
- Previous bounds found using full amplitude squared.
- Includes terms that go as Λ^{-4}.:

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

- Same order as dimension-8 contributions:

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

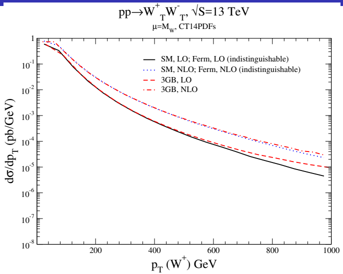
LO vs. NLO Differential Distributions at $1/\Lambda^4$

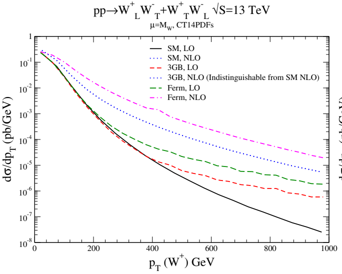


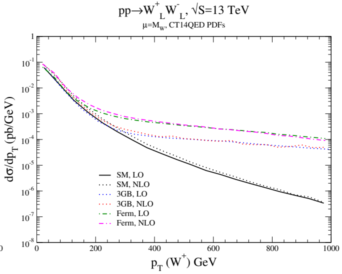
Baglio, Dawson, **IL** PRD96 (2017) 073003

- $1/\Lambda^4$ 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.

Differential Distributions by Helicity at $1/\Lambda^4$







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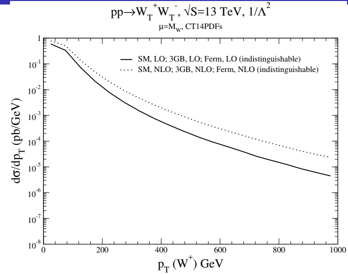
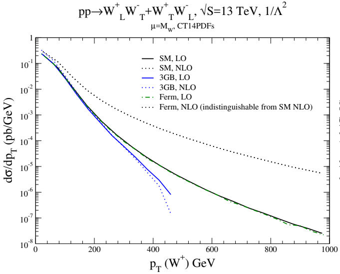
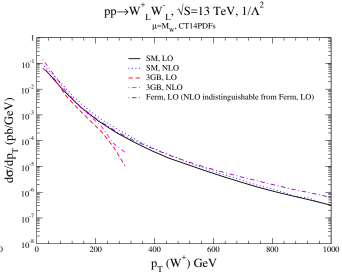
Differential Distributions by Helicity at $1/\Lambda^2$







Baglio, Dawson, **IL** PRD96 (2017) 073003

Conclusions

- As the LHC searches for directly produced particles push the mass scale higher and higher, SM EFT increasingly important.
- Higher order corrections are important to fully understand the limits on the scale of new physics. Especially important for legacy measurements.
- For both Higgs+jet and W^+W^- production, NLO QCD corrections were different for different operators.
  - For a given UV completion, some operators may be more important than others.
  - QCD corrections may be very important.
- For W^+W^- production saw NLO QCD corrections were highly dependent on W polarizations.
  - Strongly dependent on the operators.
  - Important experimentally, if we can tag polarizations or have observables sensitive to them. Azatov, Elias-Miro, Reyimuaji, Venturini JHEP 1710 (2017) 027; Panico, Riva, Wulzer Phys. Lett. B776 (2018) 473
  - Were able to test some non-interference theorems Azatov, Contino, Machado PRD 95 (2017) 065014 for transverse-transverse W^+W^- production at NLO.
- Public code available: WWEFT@NLO

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

Thank You

Missing Terms

- Anomalous quark-gauge boson couplings occur from the operators

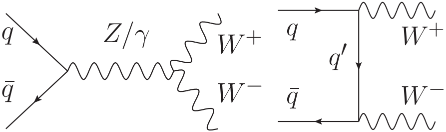
$$
\begin{aligned}
O^{(3)}_{HQ,ij} &= i\left(\Phi^\dagger\sigma^a D_\mu\Phi - (D_\mu\Phi)^\dagger\sigma^a\Phi\right)\bar{Q}_{Li}\gamma^\mu\sigma^a Q_{Lj} \\
O^{(1)}_{HQ,ij} &= i\left(\Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi\right)\bar{Q}_{Li}\gamma^\mu Q_{Lj} \\
O_{Hq,ij} &= i\left(\Phi^\dagger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

- Parameterize via anomalous couplings:

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

- $SU(2)$ invariance implies $\delta g^W_L = \delta g^{Zu}_L - \delta g^{Zd}_L$.

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:

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

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

W^+W^- production

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

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

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

W^+W^- production

- Operators affecting ATGCs:

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

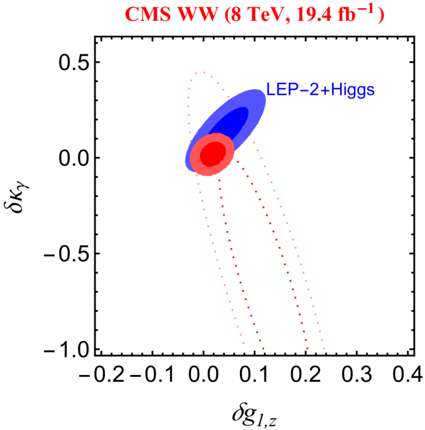
- In the EW sector have to choose input parameters: G_F, M_W, M_Z
- EFT alters relationships between other parameters and input parameters:

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

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

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

Amplitude Squared vs. Linear Pieces

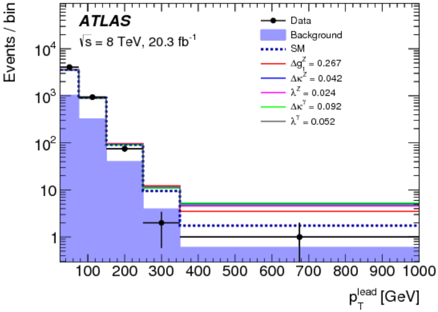


Falkowski *et al* JHEP 1702

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

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:

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

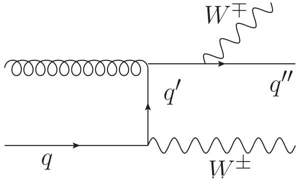
  - Accept points that fall within allowed region of $\sigma(p_T^{W^+} > 500\text{ GeV})$.

Refit 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.