Introduction to EFT

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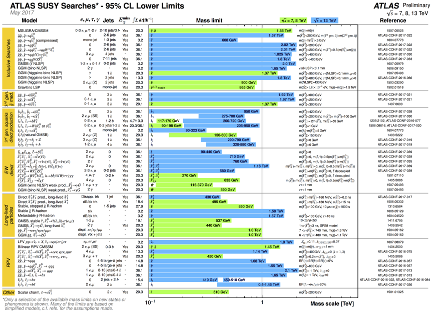
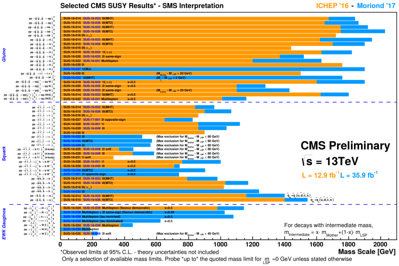
Probing Physics Beyond the Standard Model with Precision
MITP

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:





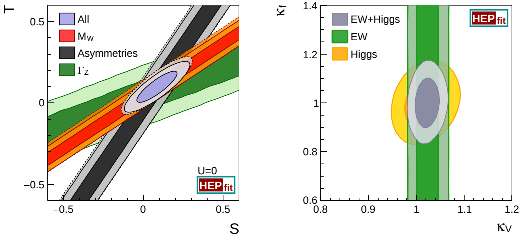
“Model Independent” Parameterization

- 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) 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.

Electroweak Precision

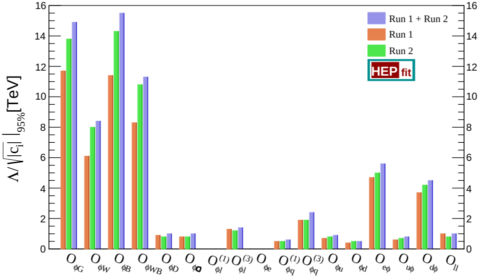


de Blas, *et al* arXiv:1710.05402

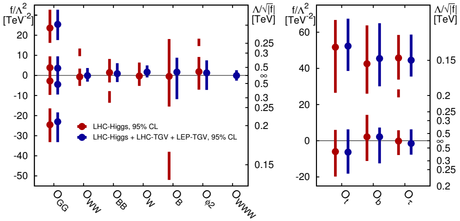
- LEP constraints on anomalous quark couplings Falkowski, Riva JHEP 1502:

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

Fits to LHC Data

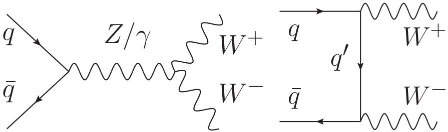


de Blas, *et al* arXiv:1710.05402



Butter *et al* JHEP 1607 (2016) 152

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:

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

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

W^+W^- production

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

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

  - $V = Z, \gamma$
  - $g_{WWZ} = g\cos\theta_w, \quad g_{WW\gamma} = e$
- Parameterize deviations from SM:

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

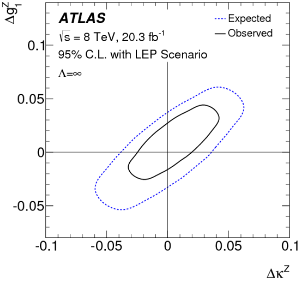
- $\lambda^Z = 0$ and $\lambda^\gamma = 0$ in SM.
- $SU(2)_L$ implies:

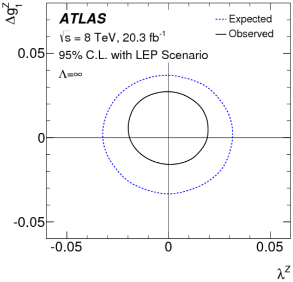
$$\delta g_1^\gamma = 0 \qquad \lambda^\gamma = \lambda^Z \qquad \delta\kappa^\gamma = \frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\delta g_1^Z - \delta\kappa^Z\right)$$

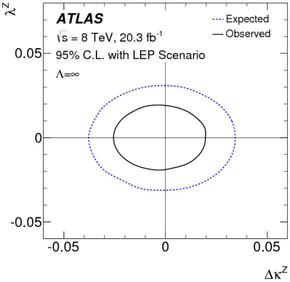
- Three independent parameters: λ^Z, δg_1^Z, $\delta\kappa^Z$

Experimental results

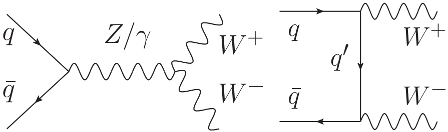
- ATGCs actively being searched for in W^+W^- production by both ATLAS JHEP 1609 (2016) 029 and CMS Phys.Lett. B772 (2017) 21







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.
  - This was recently pointed out Zhang PRL118 (2017) 011803

Missing Terms

- Anomalous quark-gauge boson couplings occur from the operators

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

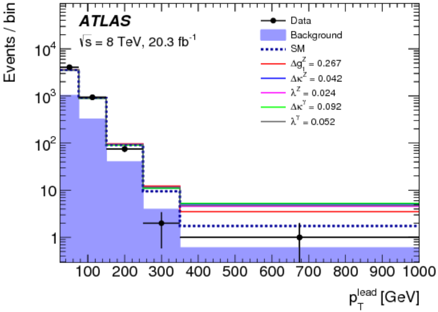
- Parameterize via anomalous couplings:

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

- $SU(2)$ 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:

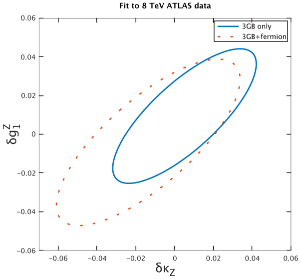
$$\begin{aligned} \delta g_L^{Zd} &= (2.3 \pm 1) \times 10^{-3} \\ \delta g_L^{Zu} &= (-2.6 \pm 1.6) \times 10^{-3} \\ \delta g_R^{Zd} &= (16.0 \pm 5.2) \times 10^{-3} \\ \delta g_R^{Zu} &= (-3.6 \pm 3.5) \times 10^{-3} \end{aligned}$$

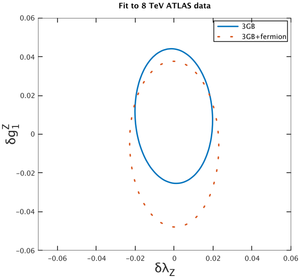
  - Accept points that fall within allowed region of $\sigma(p_T^{W^+} > 500\text{ GeV})$.

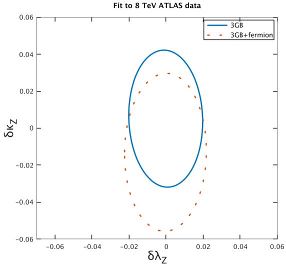
Refit

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

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







Comment on Calculating Cross Sections

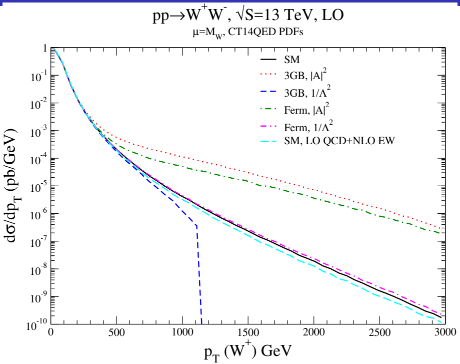
- Previous bounds found using full amplitude squared.
- Includes terms that go as Λ^{-4}.:

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

- Same order as dimension-8 contributions:

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

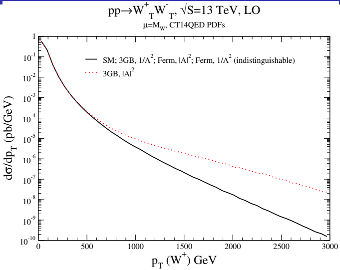
Differential Distributions

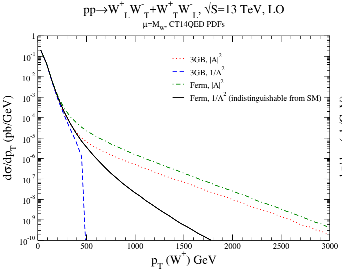


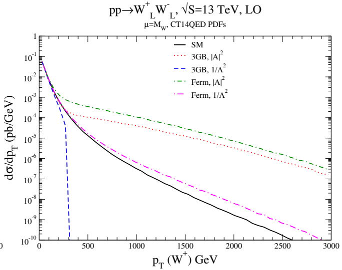
Baglio, Dawson, **IL** PRD96 (2017) 073003

- $1/\Lambda^4$ 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

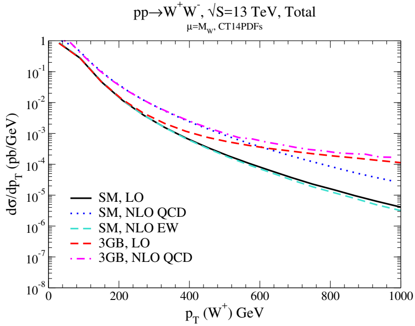


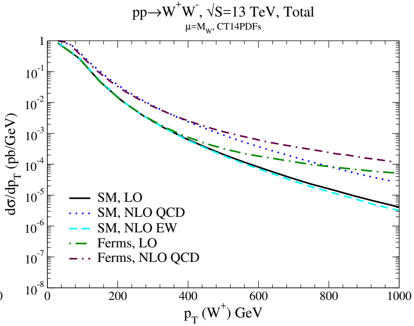




Baglio, Dawson, **IL** PRD96 (2017) 073003

NLO SM Corrections

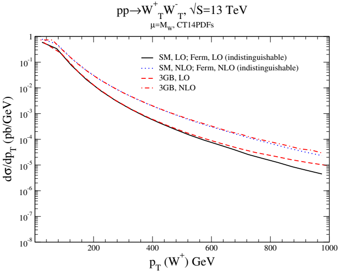


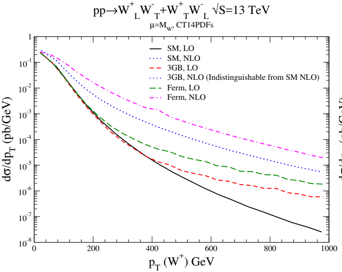


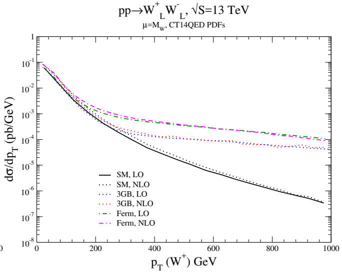
Known up to NNLO in QCD and NLO in EW Frixione NPB410; Ohnemus PRD44; Dixon, Kunszt, Signer NPB531; Dicus, Kao, Repko PRD36; Glover, van der Bij PLB219; Binoth, Ciccolini, Kauer, Kramer JHEP 0612, JHEP 0503; Baglio, Ninh, Weber PRD94; Bierweiler, Kasprzik, Kuhn, Uccirati JHEP 1211; Bierweiler, Kasprzik, 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 Distributions by Helicity for $|A|^2$

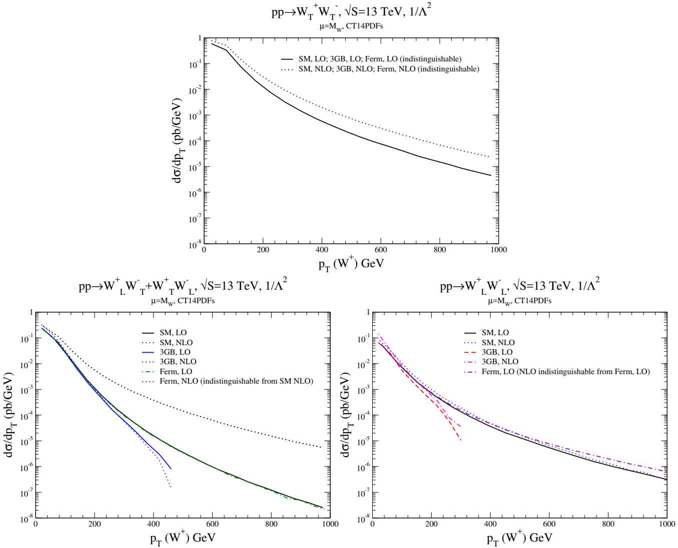






Baglio, Dawson, **IL** PRD96 (2017) 073003

NLO QCD by Helicity for Interference



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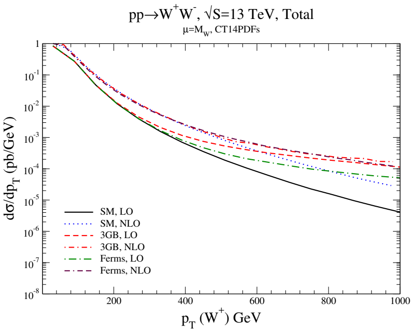
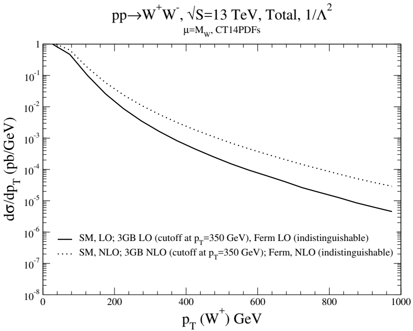
NLO QCD Corrections



Full Amplitude Squared



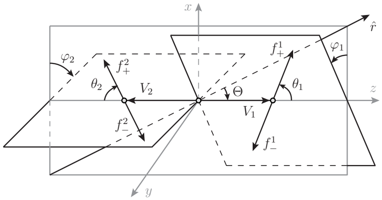
SM+$1/\Lambda^2$

- "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.

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

Interference Resurrection

- We have considered on-shell production of W^+W^-, and have not considered their decays.
- In such cases, the interference between the SM and EFT for transversely polarized Ws is negligible at high energy Azatov, Contino, Machado PRD 95 (2017) 065014
- However, when gauge boson decays, sum over polarizations occurs at amplitude level and not amplitudes squared.



  - Observables sensitive to interference of different gauge boson polarizations, such as angles between the gauge boson decay planes, can resurrect the interference. Azatov, Elias-Miro, Reyimuaji, Venturini JHEP 1710 (2017) 027; Panico, Riva, Wulzer Phys. Lett. B776 (2018) 473
- If the gauge bosons are off-shell, interference is also non-negligible. Helset, Trott arXiv:1711.07954

Higgs Physics

Higgs effective Field Theory

- Higgs precision measurements can constrain effective operators.
- Several operators only rescale SM couplings. For example Corbett, Eboli, Goncalves, Gonzalez-Fraile,Plehn, Rauch, JHEP 1508 (2015) 156

$$(\Phi^\dagger\Phi)\overline{Q}_3\widetilde{\Phi}t_R, \quad \frac{1}{2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)$$

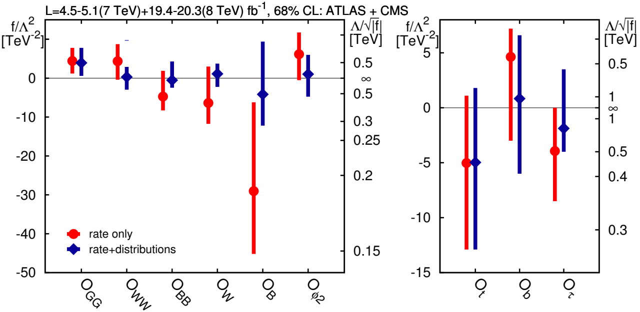
  - Operators such as these only rescale SM rates.
- Other operators introduce new Lorentz structures:

$$\Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi, \quad \Phi^\dagger B_{\mu\nu}B^{\mu\nu}\Phi, \quad (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi), \quad (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

  - Rate measurements essentially at one scale, measurements of distributions or off-shell Higgs can disentangle new structures from EFT.
- Or, operators can scale differently with energy than the SM contribution:

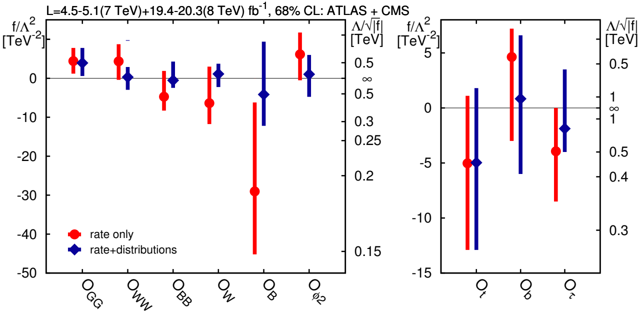
$$\Phi^\dagger\Phi G^a_{\mu\nu}G^{a,\mu\nu}$$

Rate vs. Distribution and Off-Shell

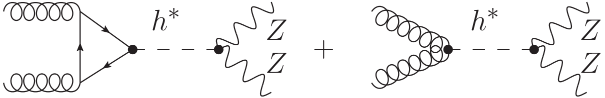


Corbett, Eboli, Goncalves, Gonzalez-Fraile,Plehn, Rauch, JHEP 1508 (2015) 156

Rate vs. Distribution and Off-Shell



Corbett, Eboli, Goncalves, Gonzalez-Fraile,Plehn, Rauch, JHEP 1508 (2015) 156

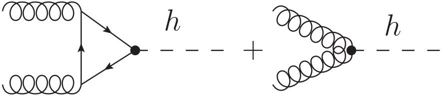


Gainer, Lykken, Matchev, Mrenna, Park PRD91 (2015) 035011; Englert, Soreq, Spannowsky, JHEP 05 (2015) 145; Azatov, Grojean, Paul, Salvioni J.Exp.Theor.Phys 120 (2015)

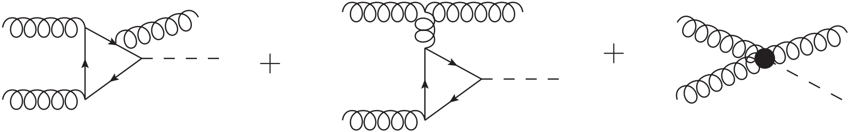
Higgs Plus Jet EFT

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

- Assume simple deviations from SM predictions.

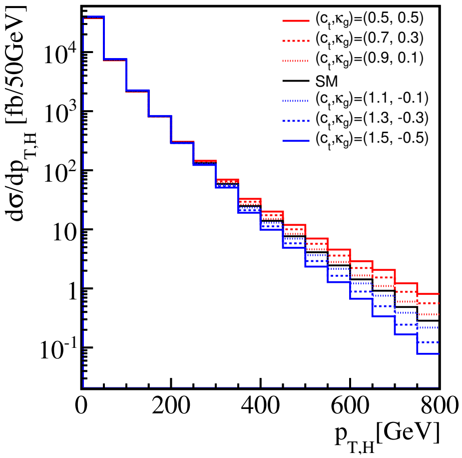


- Simple to keep single Higgs rate SM-like: $\kappa_t + \kappa_g = 1$.



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

Higgs Plus Jet EFT



Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, Eur.Phys.J C74 (2014) 10, 3120

- Impose $\kappa_t + \kappa_g = 1$.
- Can see some deviation in tail.
- Direction of deviation determines direction that relevant couplings change relative to the Standard Model.

Validity of EFT

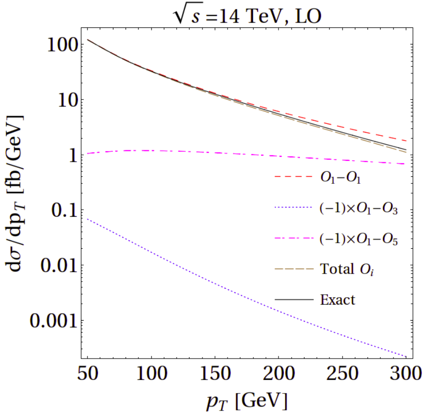
- Assuming relatively large deviations from SM. How stable is EFT?
- Lowest order operator contribution to Higgs+jet Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant, Eur.Phys.J C74 (2014) 10, 3120; Azatov, Paul JHEP 1401 (2014) 014; Grojean, Salvioni, Schlaffer, Weiler, JHEP 1405 (2014) 022; Langenegger, 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:

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

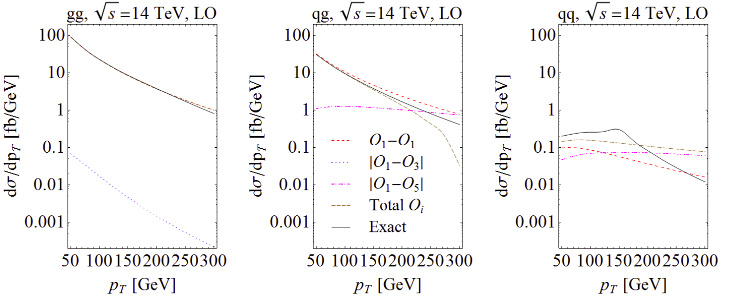
Validity of EFT at LO in QCD



Dawson, **IL**, Zeng, PRD90 (2014) 093007

- Using SM values of Wilson coefficients.
- $O_5 = g_s h \sum_i G^a_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i$, becomes increasingly important at high p_T

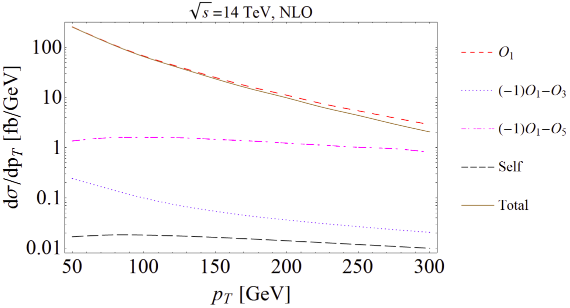
Validity of EFT at LO in QCD



Dawson, **IL**, Zeng, PRD90 (2014) 093007

- $O_5 = g_s h \sum_i G^a_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i$ important for qg channel.
- qg channel increasingly important at high p_T.
- Large cancellation between O_1 and O_5 in qg channel.

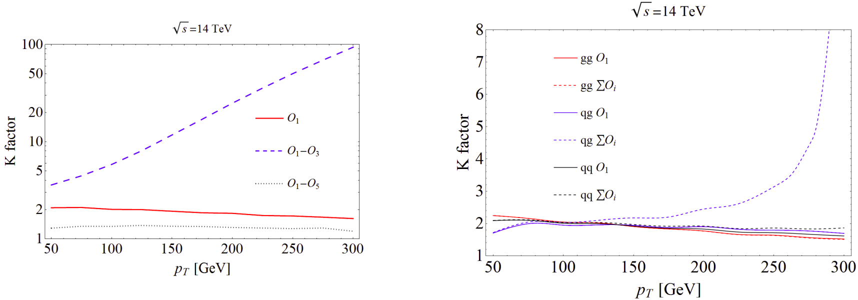
Validity of EFT at NLO in QCD



Dawson, **IL**, Zeng, PRD90 (2014) 093007

- At NLO $O_3 = h\, f_{abc} G_\nu^{a,\mu} G_\sigma^{b,\nu} G_\mu^{c,\sigma}$ no longer plunging at high p_T.

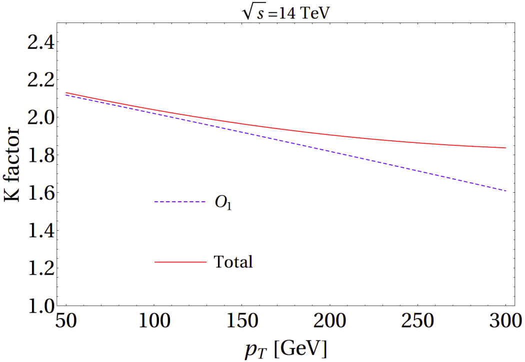
Validity of EFT at NLO in QCD



Dawson, **IL**, Zeng, PRD90 (2014) 093007

- K-factor for $O_3 = h\, f_{abc} G_\nu^{a,\mu} G_\sigma^{b,\nu} G_\mu^{c,\sigma}$ is gigantic.
  - LO contribution exceptionally small.
  - Still small contribution.
- *qg* K-factor blows up.
  - Cancellation between O_1 and $O_5 = g_s\, h \sum_i G^a_{\mu\nu} D^\mu \overline{\psi}_i \gamma^\nu T^a \psi_i$ at LO.
  - O_1 and O_5 receive different K-factors, spoil cancellation.

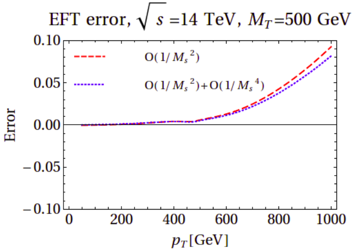
Validity of EFT at NLO in QCD



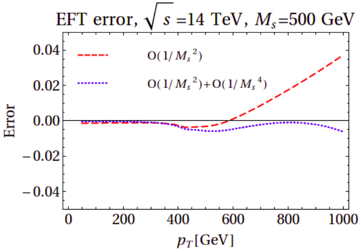
Dawson, **IL**, Zeng, PRD90 (2014) 093007

- Even with K-factors blowing up by operator or channel, overall behavior is mild.

Validity of EFT for New Physics



Top Partner



Scalar Triplet

Dawson, **IL**, Zeng, Phy.Rev. D91 (2015) 074012

- Comparing higher order EFT to exact result.
- Lowest order EFT valid within a few percent.
- Convergence depends on UV completion.

Simplified Models and EFTs

Scalar Singlet

- Add a real gauge singlet, scalar singlet S to SM:

$$V(\Phi,S) = V_\Phi(\Phi) + V_{\Phi S}(\Phi,S) + V_S(S)$$

- Higgs potential:

$$V_\Phi(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

- Scalar singlet potential:

$$V_S(S) = b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

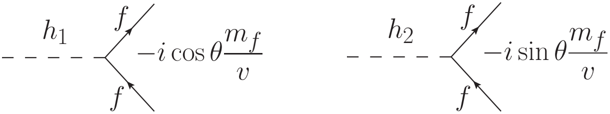
- Mixing terms:

$$V_{\Phi S}(\Phi,S) = \frac{a_1}{2}\Phi^\dagger\Phi S + \frac{a_2}{2}\Phi^\dagger\Phi S^2$$

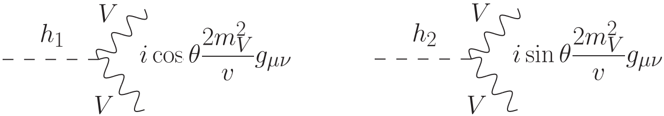
- After electroweak symmetry breaking, have two mass eigenstates:
  - h_1 with mass $m_1 = 125$ GeV.
  - h_2 with mass $m_2 > m_1$.

Relevant Feynman Diagrams

- Couplings to fermions:

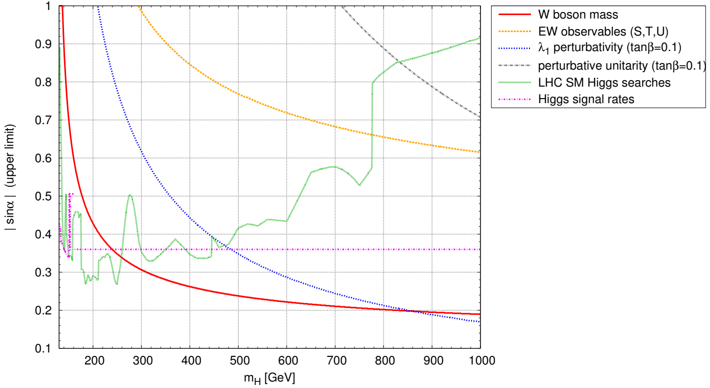


- Couplings to gauge bosons:



- Higgs rates only depend on $\cos^2\theta$.
  - Branching ratios unchanged.
  - Production rate suppressed by $\cos^2\theta$.
  - Simple interpretation of Higgs results.
- Since h_2 couplings to fermions and gauge bosons proportional to SM coupling, it is produced through same mechanisms as SM Higgs boson.

Current Limits



Robens, Stefaniak EPJ C76 (2016) 268

- See also Falkowski, Gross, Lebedev JHEP 1505 (2015) 057; Buttazzo, Sala, Tesi JHEP 1511 (2015) 158

Stability of Simplified Models

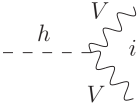
- In singlet model, Higgs precision measurements simply bound the mixing angle.
- Perturb the model with an EFT:

$$\mathcal{L} = g_s^2 \frac{c_{gg}}{\Lambda} S G^{\mu\nu,a} G^a_{\mu\nu} + \frac{c_{BB}}{\Lambda} g'^2 S B^{\mu\nu} B_{\mu\nu} + \frac{c_{WW}}{\Lambda} g^2 S W^{\mu\nu,a} W^a_{\mu\nu} .$$

- After scalar mixing, these operators introduce new interactions between the gauge bosons and the Higgs.

WW and ZZ Couplings

- New terms in Feynman Rules of observed Higgs boson:



$$i\cos\theta\frac{2m_V^2}{v}g_{\mu_1\mu_2}+16i\sin\theta\frac{m_V^2}{\Lambda v^2}c_{VV}\left(p_{1,\mu_2}p_{2,\mu_1}-g_{\mu_1\mu_2}p_1\cdot p_2\right)$$

  - $c_{ZZ}=c_{WW}\cos^4\theta_W+c_{BB}\sin^4\theta_W$

- Since original term is large, expect new EFT terms to make a small difference.

WW and ZZ Couplings

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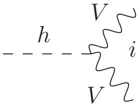

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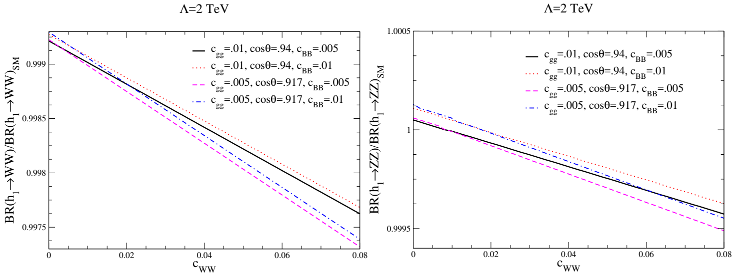
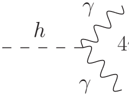


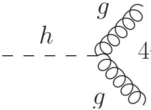
Dawson, **IL** PRD95 (2017) 015004

$\gamma\gamma$, $Z\gamma$, gg couplings

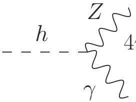
- Now have "tree-level" couplings to $\gamma\gamma$, $Z\gamma$, and gg:



$$4i\sin\theta e^2\frac{c_{BB}+c_{WW}}{\Lambda}\left(p_{1,\mu_2}p_{2,\mu_1}-g_{\mu_1\mu_2}p_1\cdot p_2\right)$$



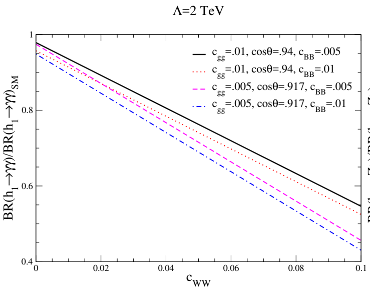
$$4i\sin\theta g_s^2\frac{c_{gg}}{\Lambda}\left(p_{1,\mu_2}p_{2,\mu_1}-g_{\mu_1\mu_2}p_1\cdot p_2\right)$$



$$4i\sin\theta e^2\frac{c_{WW}\cos^2\theta_W-c_{BB}\sin^2\theta_W}{\cos\theta_W\sin\theta_W\Lambda}\left(p_{1,\mu_2}p_{2,\mu_1}-g_{\mu_1\mu_2}p_1\cdot p_2\right)$$

- These were originally loop induced couplings.

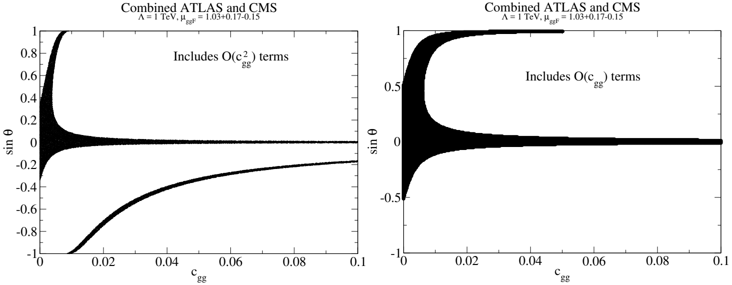
Branching ratios of Observed Higgs



Dawson, **IL** PRD95 (2017) 015004

- New interactions can significantly effect the $\gamma\gamma$ and $Z\gamma$ decays of the observed Higgs boson.

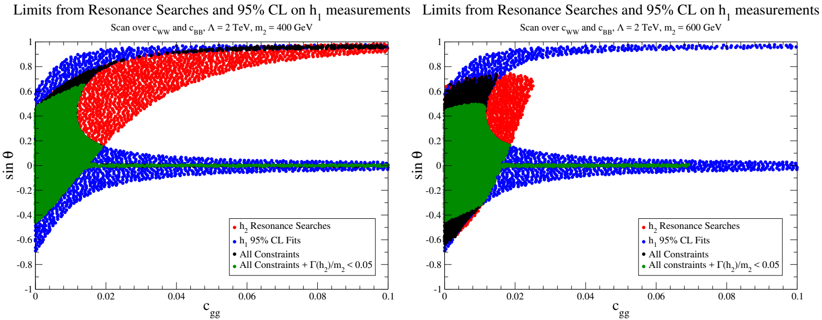
Additional EFT on overall signal strength



Dawson, **IL** PRD95 (2017) 015004

- Similarly new interaction with gg can significantly effect production rate.
- Fit to the combined gluon fusion signal strength at 7+8 TeV.
  - $\mu_{ggF} = \frac{\sigma_{ggF}}{(\sigma_{ggF})_{SM}}$
- Additional EFT coupling to the gluon field strength greatly changes fit.
  - At $c_{gg} = 0$ get usual limits on $\sin\theta$ from signal strength measurements.
  - Away from $c_{gg} = 0$, can get very different allowed values for $\sin\theta$
  - Also important to carefully count EFT.

All Constraints



Dawson, **IL** PRD95 (2017) 015004

- Constraints from Higgs measurements, scalar resonance searches, and narrow width requirement.
- Complementary information.

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.
    - Public code available: WWEFT@NLO

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

- Higgs Physics:
    - Distributions and off-shell measurements important for constraining EFT.
    - Higgs+jet:
        - Informative to look beyond the dimension-6 EFT.
        - Interesting interplay between higher order operators and different production channels.
        - Different K-factors for different operators can change the LO QCD story.
        - Convergence of EFT depended on UV completion.

Conclusions

- Simplified models+EFT:
  - We hope that simplified models are a relatively good approximation of physics at LHC.
  - Perturbed the simplest of simplified models by an EFT.
  - The interpretation of Higgs physics changes dramatically in the presence of new operators.

Thank You

EXTRA SLIDES

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:

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

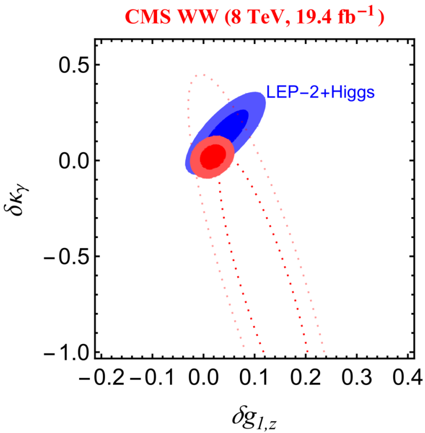
- In the EW sector have to choose input parameters: G_F, M_W, M_Z
- EFT alters relationships between other parameters and input parameters:

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

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

“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:

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

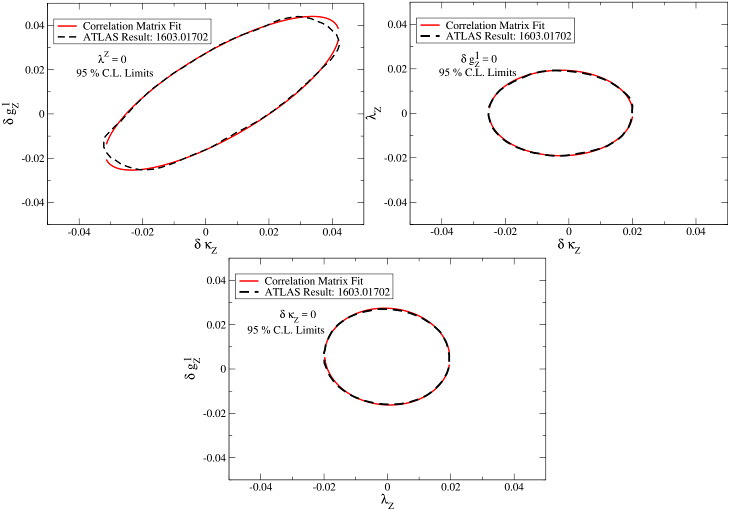
where

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

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

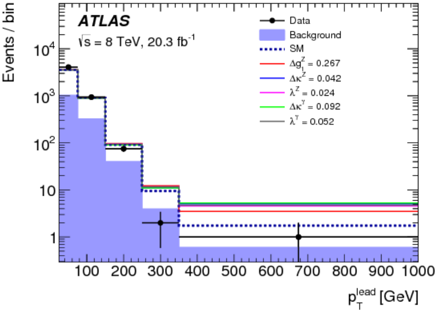
$$\begin{aligned} \mu_{g_1^Z} &= 0.00935, \quad \mu_{\kappa^Z} = 0.00518, \quad \mu_{\lambda^Z} = -0.000185 \\ C &= \begin{pmatrix} 1.55 & 1.28 & -0.0563 \\ 1.28 & 1.76 & -0.0455 \\ -0.0563 & -0.0455 & 0.511 \end{pmatrix} \times 10^{-4} \end{aligned}$$

Refit Experimental Results



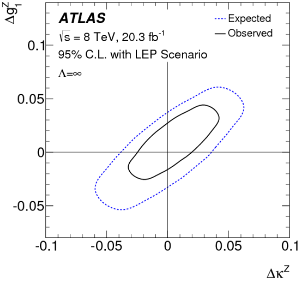
Refit Experimental results

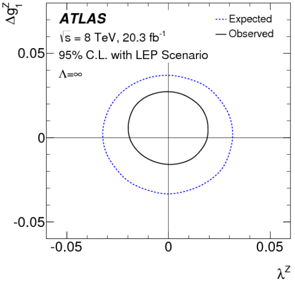
- ATGCs limits from ATLAS JHEP 1609.
- In practice want to take differential distributions from experimental collaborations, extract constraints on anomalous couplings.
- Problem: we do not decay the W^+.

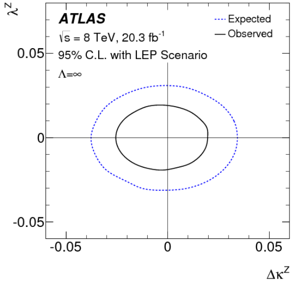


Refit Experimental results

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





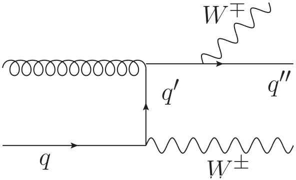


Refit Experimental Results

- 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.