MOTIVATION

- Why do a SMEFT fit?
- Experimentally, the LHC results are very good now

based on Ellis, CM, Sanz, You: 1803.03252
Differential Information

- More constraining than total cross section alone
- This has been known for some time

Isidori, Manohar, Trott: 1305.0663
Grinstein, CM, Pirtshhalava: 1305.6938

The differential information helps in constraining the couplings more than the total cross section alone.

Limits on contact-interaction decay terms
- Terms modifying the contact-interaction between the Higgs and left- and right-handed leptons
  - Lepton universality assumed
- Double-differential cross section in the $m_{12}, m_{34}$ plane used to extract limits in the pseudo-observables framework [Eur. Phys. J. C (2015) 75: 128]
EFFECTIVE FIELD THEORY

- Most useful when UV and IR scales are well-separated

\[ \mathcal{L}_{EFT} = \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^n} O_i^{(n)}(x) \]

- EFT is a full-fledged QFT provided one works to finite order in \( \Lambda \)

- No reference to or input from UV physics needed

- Advantages over ad-hoc BSM parameterization
STANDARD MODEL EFFECTIVE FIELD THEORY

- Given SM particle content, write down all terms allowed by SM symmetries...

- ...including (non-redundant) higher-dimensional operators

\[ \mathcal{L}_{SM} = \mathcal{L}_m + \mathcal{L}_g + \mathcal{L}_h + \mathcal{L}_Y, \]

\[ \mathcal{L}_m = \bar{Q}_L \gamma^\mu D^\mu Q_L + \bar{q}_R \gamma^\mu D^\mu q_R + \bar{L}_L \gamma^\mu D^\mu L_L + \bar{l}_R \gamma^\mu D^\mu l_R \]

\[ \mathcal{L}_g = -\frac{1}{4} B_{\mu \nu} B^{\mu \nu} - \frac{1}{4} W_{\mu \nu} W^{\mu \nu} \]

\[ \mathcal{L}_h = (D^\mu \phi) (D^\nu \phi) - V(\phi) \]

\[ \mathcal{L}_Y = y_d \bar{Q}_L \phi q_R^d + y_u \bar{Q}_L \phi q_R^u + y_l \bar{L}_L \phi l_R + \text{h.c.} \]

\[ \mathcal{L}_{SM}^{\text{dim-6}} = \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i \]
MOTIVATION PART 2

- Fits previously assumed:
  - EWPD $\gg$ diboson $\gg$ Higgs
- Theoretically unsatisfactory, no longer justified
ANALYSIS FRAMEWORK

- Focus on leading dimension-6 operators

\[ \mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2_i} \mathcal{O}_i \]

- Work to linear order in Wilson coefficients

- Use \( \alpha_{\text{EM}}, G_F, M_Z \), as input parameters
ANALYSIS FRAMEWORK

- Assume $U(3)^5$ flavor symmetry in SMEFT, helps reduce parameters to a manageable number
- Yukawa matrices promoted to spurions, formally preserve symmetry
20 COEFFICIENTS CONSIDERED

DIMENSION–6 OPERATORS IN WARSAW BASIS

\[ \mathcal{L}_{\text{SMEFT}} \supset \frac{C_{H\ell}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{l}\tau^I \gamma^\mu l) + \frac{C_{Hd}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{d}\gamma^\mu d) + \frac{C_{H\ell u}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{u}\gamma^\mu u) + \frac{C_{H\ell d}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{d}\gamma^\mu d)
\]

\[ + \frac{C_{H\ell q}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{q}\tau^I \gamma^\mu q) + \frac{C_{Hd h}}{v^2} (H^\dagger i \bar{D}^{I}_{\mu} H)(\bar{d}\gamma^\mu d) + \frac{C_{W}}{v^2} \epsilon^{IJK} W_{\mu}^{I} W_{\nu}^{J} W_{\rho}^{K} W_{\rho}^{\mu} \]

\[ \bar{C} \equiv \frac{v^2}{\Lambda^2} C \]

results of EMSY 1803.03252 expressed in both SILH and Warsaw bases
FIT SETUP AND RESULTS
### Precision Electroweak Measurements Used in SMEFT Fit

- **12 Z-pole measurements**
- **74 LEP 2 $W^+W^-$ measurements**
- **New $M_W$ measurement from ATLAS**
- **Probes 11 SMEFT directions**

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Ref.</th>
<th>SM Prediction</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>[41]</td>
<td>$2.4943 \pm 0.0005$</td>
<td>[40]</td>
</tr>
<tr>
<td>$\sigma_0^{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>[41]</td>
<td>$41.488 \pm 0.006$</td>
<td>[40]</td>
</tr>
<tr>
<td>$R_\ell^0$</td>
<td>$20.767 \pm 0.025$</td>
<td>[41]</td>
<td>$20.752 \pm 0.005$</td>
<td>[40]</td>
</tr>
<tr>
<td>$A_{\text{FB}}^{0,\ell}$</td>
<td>$0.0171 \pm 0.0010$</td>
<td>[41]</td>
<td>$0.01622 \pm 0.00009$</td>
<td>[118]</td>
</tr>
<tr>
<td>$A_{\ell} (P_\tau)$</td>
<td>$0.1465 \pm 0.0033$</td>
<td>[41]</td>
<td>$0.1470 \pm 0.0004$</td>
<td>[118]</td>
</tr>
<tr>
<td>$A_{\ell} (\text{SLD})$</td>
<td>$0.1513 \pm 0.0021$</td>
<td>[41]</td>
<td>$0.1470 \pm 0.0004$</td>
<td>[118]</td>
</tr>
<tr>
<td>$R_b^0$</td>
<td>$0.021629 \pm 0.000066$</td>
<td>[41]</td>
<td>$0.2158 \pm 0.00015$</td>
<td>[40]</td>
</tr>
<tr>
<td>$R_c^0$</td>
<td>$0.1721 \pm 0.0030$</td>
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<td>$0.17223 \pm 0.00005$</td>
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<td>$A_{\text{FB}}^{0,b}$</td>
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<td>$0.1031 \pm 0.0003$</td>
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<tr>
<td>$A_{\text{FB}}^{0,c}$</td>
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<td>$0.0736 \pm 0.0002$</td>
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<td>$A_b$</td>
<td>$0.923 \pm 0.020$</td>
<td>[41]</td>
<td>$0.9347$</td>
<td>[118]</td>
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<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$</td>
<td>[41]</td>
<td>$0.6678 \pm 0.0002$</td>
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<tr>
<td>$M_W$ [GeV]</td>
<td>$80.387 \pm 0.016$</td>
<td>[42]</td>
<td>$80.361 \pm 0.006$</td>
<td>[118]</td>
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<tr>
<td>$M_W$ [GeV]</td>
<td>$80.370 \pm 0.019$</td>
<td>[98]</td>
<td>$80.361 \pm 0.006$</td>
<td>[118]</td>
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## ATLAS+CMS Higgs Data from Run 1

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>Signal Strength</th>
<th>Production</th>
<th>Decay</th>
<th>Signal Strength</th>
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</thead>
<tbody>
<tr>
<td>$ggF$</td>
<td>$\gamma\gamma$</td>
<td>$1.10^{+0.23}_{-0.22}$</td>
<td>$Wh$</td>
<td>$\tau\tau$</td>
<td>$-1.4 \pm 1.4$</td>
</tr>
<tr>
<td>$ggF$</td>
<td>$ZZ$</td>
<td>$1.13^{+0.34}_{-0.31}$</td>
<td>$Wh$</td>
<td>$bb$</td>
<td>$1.0 \pm 0.5$</td>
</tr>
<tr>
<td>$ggF$</td>
<td>$WW$</td>
<td>$0.84 \pm 0.17$</td>
<td>$Zh$</td>
<td>$\gamma\gamma$</td>
<td>$0.5^{+3.0}_{-2.5}$</td>
</tr>
<tr>
<td>$ggF$</td>
<td>$\tau\tau$</td>
<td>$1.0 \pm 0.6$</td>
<td>$Zh$</td>
<td>$WW$</td>
<td>$5.9^{+2.6}_{-2.2}$</td>
</tr>
<tr>
<td>VBF</td>
<td>$\gamma\gamma$</td>
<td>$1.3 \pm 0.5$</td>
<td>$Zh$</td>
<td>$\tau\tau$</td>
<td>$2.2^{+2.2}_{-1.8}$</td>
</tr>
<tr>
<td>VBF</td>
<td>$ZZ$</td>
<td>$0.1^{+1.1}_{-0.6}$</td>
<td>$Zh$</td>
<td>$bb$</td>
<td>$0.4 \pm 0.4$</td>
</tr>
<tr>
<td>VBF</td>
<td>$WW$</td>
<td>$1.2 \pm 0.4$</td>
<td>$tt\theta$</td>
<td>$\gamma\gamma$</td>
<td>$2.2^{+1.6}_{-1.3}$</td>
</tr>
<tr>
<td>VBF</td>
<td>$\tau\tau$</td>
<td>$1.3 \pm 0.4$</td>
<td>$tt\theta$</td>
<td>$WW$</td>
<td>$5.0^{+1.8}_{-1.7}$</td>
</tr>
<tr>
<td>$Wh$</td>
<td>$\gamma\gamma$</td>
<td>$0.5^{+1.3}_{-1.2}$</td>
<td>$tt\theta$</td>
<td>$\tau\tau$</td>
<td>$-1.9^{+3.7}_{-3.3}$</td>
</tr>
<tr>
<td>$Wh$</td>
<td>$WW$</td>
<td>$1.6^{+1.2}_{-1.0}$</td>
<td>$tt\theta$</td>
<td>$bb$</td>
<td>$1.1 \pm 1.0$</td>
</tr>
<tr>
<td>$pp$</td>
<td>$Z\gamma$</td>
<td>$2.7^{+4.6}_{-4.5}$</td>
<td>$pp$</td>
<td>$\mu\mu$</td>
<td>$0.1 \pm 2.5$</td>
</tr>
</tbody>
</table>
RUN 2 HIGGS MEASUREMENTS USED IN SMEFT FIT

- Include all available kinematical information
- Include 1 $W^+W^-$ measurement at high $p_T$
- Probe 13 SMEFT directions

New: Moriond EW ’18

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>1-jet, $p_T &gt; 450$</td>
<td>$bb$</td>
<td>2.3$^{+1.8}_{-1.6}$</td>
</tr>
<tr>
<td>103</td>
<td>$Zh$</td>
<td>$bb$</td>
<td>0.9 $\pm$ 0.5</td>
</tr>
<tr>
<td>103</td>
<td>$W\ell$</td>
<td>$bb$</td>
<td>1.7 $\pm$ 0.7</td>
</tr>
<tr>
<td>104</td>
<td>$t\ell_h, \geq 1\ell$</td>
<td>$bb$</td>
<td>0.72 $\pm$ 0.45</td>
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<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$\ell + 2\tau_h$</td>
<td>$-1.52^{+1.76}_{-1.72}$</td>
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<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$2\ell_{ss} + 1\tau_h$</td>
<td>0.94$^{+0.80}_{-0.67}$</td>
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<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$3\ell + 1\tau_h$</td>
<td>1.34$^{+1.42}_{-1.07}$</td>
</tr>
<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$2\ell_{ss}$</td>
<td>1.61$^{+0.58}_{-0.51}$</td>
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<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$3\ell$</td>
<td>0.82$^{+0.77}_{-0.71}$</td>
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<tr>
<td>105</td>
<td>$t\ell_h$</td>
<td>$4\ell$</td>
<td>0.9$^{+0.7}_{-0.6}$</td>
</tr>
<tr>
<td>106</td>
<td>0-jet DF</td>
<td>$WW$</td>
<td>1.30$^{+0.24}_{-0.23}$</td>
</tr>
<tr>
<td>106</td>
<td>1-jet DF</td>
<td>$WW$</td>
<td>1.29$^{+0.42}_{-0.27}$</td>
</tr>
<tr>
<td>106</td>
<td>2-jet DF</td>
<td>$WW$</td>
<td>0.82$^{+0.54}_{-0.50}$</td>
</tr>
<tr>
<td>106</td>
<td>VBF 2-jet</td>
<td>$WW$</td>
<td>0.72$^{+0.44}_{-0.41}$</td>
</tr>
<tr>
<td>106</td>
<td>Vh 2-jet</td>
<td>$WW$</td>
<td>3.92$^{+1.32}_{-1.17}$</td>
</tr>
<tr>
<td>106</td>
<td>Wh 3-jet</td>
<td>$WW$</td>
<td>2.23$^{+1.53}_{-1.53}$</td>
</tr>
<tr>
<td>107</td>
<td>$ggF$</td>
<td>$\gamma\gamma$</td>
<td>1.10$^{+0.20}_{-0.18}$</td>
</tr>
<tr>
<td>107</td>
<td>VBF</td>
<td>$\gamma\gamma$</td>
<td>0.8$^{+0.5}_{-0.5}$</td>
</tr>
<tr>
<td>107</td>
<td>$t\ell_h$</td>
<td>$\gamma\gamma$</td>
<td>2.2$^{+0.9}_{-0.8}$</td>
</tr>
<tr>
<td>107</td>
<td>$Vh$</td>
<td>$\gamma\gamma$</td>
<td>2.4$^{+1.6}_{-1.0}$</td>
</tr>
<tr>
<td>108</td>
<td>$ggF$</td>
<td>$4\ell$</td>
<td>1.20$^{+0.22}_{-0.21}$</td>
</tr>
<tr>
<td>109</td>
<td>0-jet</td>
<td>$\tau\tau$</td>
<td>0.84 $\pm$ 0.89</td>
</tr>
<tr>
<td>109</td>
<td>boosted</td>
<td>$\tau\tau$</td>
<td>1.17$^{+0.47}_{-0.40}$</td>
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<td>109</td>
<td>VBF</td>
<td>$\tau\tau$</td>
<td>1.11$^{+0.34}_{-0.35}$</td>
</tr>
<tr>
<td>106</td>
<td>Zh 4-lep</td>
<td>$WW$</td>
<td>0.77$^{+1.49}_{-1.80}$</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

New: Moriond EW ’18

EMSY 1803.03252
SMEFT PREDICTIONS

- pre-LHC: Berthier, Bjorn, Trott 1606.06693; Brivio, Trott 1706.08945
- LHC: Brivio, Jiang, Trott SMEFTsim 1709.06492
- Our SMEFT predictions and $\chi^2$ are available online:
FIT TO EACH OPERATOR INDIVIDUALLY

Note: different scaling factors

EMSY 1803.03252
FIT TO ALL OPERATORS SIMULTANEOUSLY

Note: different scaling factors

EMSY 1803.03252
CORRELATION MATRIX
CORRELATIONS GENERALLY REDUCED

CORRELATION MATRIX

Fit to all measurements

Fit to Z-pole, W-mass, & LEP2 WW measurements

EMSY 1803.03252

EMSY unpublished
FUTURE PROJECTIONS
PROJECTION STRATEGY

- Leave all pre-LHC, and LHC Run-1 measurements unchanged

- For each LHC Run-2 measurement used in the fit of 1803.03252...

“It’s difficult to make predictions, especially about the future” - Yogi Berra
PROJECTION STRATEGY

- For each LHC Run-2 measurement used in the fit of 1803.03252
  - Set central value to SM prediction
  - Scale all uncertainties for the $i^{th}$ measurement by:
  - **HL-LHC:** $\sqrt{\frac{36/\text{fb}}{3/\text{ab}}} \sqrt{\frac{\sigma_{13,i}}{\sigma_{27,i}}} \frac{36/\text{fb}}{15/\text{ab}}$
  - **HE-LHC:**
  - Leave experimental correlations unchanged
PROJECTION: ONE COEFFICIENT AT A TIME

Note: different scaling factors

CM: in progress, this plot supersedes the one presented at Fermilab on 05/04/18
PROJECTION: ALL COEFFICIENTS SIMULTANEOUSLY

Note: different scaling factors

CM: in progress, this plot supersedes the one presented at Fermilab on 05/04/18
NEW CORRELATIONS APPEAR IN PROJECTION

Current correlations

HE-LHC

Preliminary

EMSY 1803.03252

CM: in progress
CORRELATIONS APPEAR IN PROJECTION

- A challenge (re)appears for theorists doing SMEFT fits
- Correlations tamed by:
  - using a finer binning for Higgs measurements (via STXS)
  - including more info for LHC diboson measurements
  - (a future linear collider would also help)
SUMMARY

- EMSY 1803.03252 was the first combined global analysis within the SMEFT of electroweak, diboson, and Higgs data
  - Higgs/LHC measurements currently compete w/ EWPD
  - HE-LHC better option for constraining SMEFT Wilson coefficients
  - but this is a win-win situation, either HL- or HE-LHC will improve existing bounds

“When you come to the fork in the road, take it” - Yogi Berra
SILH BASIS

\[ \mathcal{L}_{\text{SILH}}^{\text{SMEFT}} \supset \frac{\bar{c}_W}{m_W^2} \frac{ig}{2} \left( H^\dagger \sigma^a \tilde{D}^\mu H \right) D^\nu W^a_{\mu \nu} + \frac{\bar{c}_B}{m_B^2} \frac{ig'}{2} \left( H^\dagger \tilde{D}^\mu H \right) \partial^\nu B_{\mu \nu} + \frac{\bar{c}_T}{v^2} \frac{1}{2} \left( H^\dagger \tilde{D}^\mu H \right)^2 \\
+ \frac{\bar{c}_{\ell}}{v^2} (\bar{L} \gamma^\mu L) (\bar{L} \gamma^\mu L) + \frac{\bar{c}_{H^e}}{v^2} (i H^\dagger \tilde{D}^\mu H)(\bar{e}_R \gamma^\mu e_R) + \frac{\bar{c}_{H^u}}{v^2} (i H^\dagger \tilde{D}^\mu H)(\bar{u}_R \gamma^\mu u_R) \\
+ \frac{\bar{c}_{H^d}}{v^2} (i H^\dagger \tilde{D}^\mu H)(\bar{d}_R \gamma^\mu d_R) + \frac{\bar{c}_{H^q}}{v^2} (i H^\dagger \sigma^a \tilde{D}^\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L) \\
+ \frac{\bar{c}_{H^w}}{v^2} (i H^\dagger \tilde{D}^\mu H)(\bar{Q}_L \gamma^\mu Q_L) + \frac{\bar{c}_{H^h}}{m_W^2} i g (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu \nu} + \frac{\bar{c}_{H^b}}{m_W^2} i g' (D^\mu H)^\dagger (D^\nu H) B_{\mu \nu} \\
+ \frac{\bar{c}_{3W}}{m_W^2} g^3 \epsilon_{abc} W^a_{\mu \nu} W^b_{\nu \rho} W^c_{\rho \mu} + \frac{\bar{c}_g}{m_W^2} g_s^2 |H|^2 G^A_{\mu \nu} G^{A \mu \nu} + \frac{\bar{c}_\gamma}{m_W^2} g'^2 |H|^2 B_{\mu \nu} B^{\mu \nu} \\
+ \frac{\bar{c}_H}{v^2} \frac{1}{2} (\partial^\mu |H|^2)^2 + \sum_{f=e,u,d} \frac{\bar{c}_f}{v^2} y_f |H|^2 \bar{F}_L H^{(c)} f_R \\
+ \frac{\bar{c}_{3G}}{m_W^2} g_s^3 f_{ABC} G^A_{\mu \nu} G^B_{\nu \rho} G^C_{\rho \mu} + \frac{\bar{c}_{uG}}{m_W^2} g_s y_u \bar{Q}_L H^{(c)} \sigma^{\mu \nu} \lambda_A u_R G^A_{\mu \nu}.
\]
ONE COEFFICIENT AT A TIME

GLOBAL FITS IN THE SILH BASIS

- 95% CL interval
- previous work by JE, VS, TY
GLOBAL FITS IN THE SILH BASIS

Marginalised

95% CL interval

previous work by JE, VS, TY

ALL COEFFICIENTS SIMULTANEously

1803.03252
familiar pre-LHC bounds on $S$ and $T$
pre-LHC
LHC Higgs Run-1
combination: small improvement
pre-LHC
LHC Run-2: picks complementary direction
combination: comparable precision

\[ \tilde{C}_{HD} \propto \Delta T \]

\[ \tilde{C}_{HWB} \propto \Delta S \]
LHC Run-2 + Higgs Run-1
combination: slight improvement
let's go back to just Higgs Run-1...

\[ \tilde{C}_{HD} \propto \Delta T \]

\[ \tilde{C}_{HWB} \propto \Delta S \]
...and add in the ATLAS $M_W$ measurement

Shape changes dramatically

Based on Ellis, CM, Sanz, You: 1803.03252
based on Ellis, CM, Sanz, You: 1803.03252
SIMPLIFIED TEMPLATE CROSS SECTIONS

Merged STXS Stage-1 regions enclosed by red boxes
FIT METHODOLOGY

- Method of least squares

\[ \chi^2 (c) = (y - \mu (c))^T V^{-1} (y - \mu (c)) \]

- Working to linear order in Wilson coefficients

\[ \mu = \mu_{SM} + H \cdot c \]

- Analytic solution

\[ \hat{c} = (H^T V^{-1} H)^{-1} H^T V^{-1} (y - \mu_{SM}) \]

\[ U = (H^T V^{-1} H)^{-1} \]
TTH PRODUCTION

- Probes many coefficients not otherwise constrained by our dataset

\[ C'_{uG} \rightarrow C_{uG} + 0.006C'_{uW} + 0.002C'_{uB} - 0.13C'^{(8)}_{qu} + \text{additional } \psi^4 \text{ operators} \]

- Include only \( C_{uG} \) as it has the largest contribution

- Alternatively:
  - one could regularize the fit...
  - add in top-quark measurements
REGULARIZED LEAST SQUARES

- Augment standard chi-squared function w/ positive definite regulation term

\[
\chi^2(c) = (y - \mu(c))^\top V^{-1} (y - \mu(c)) + c^\top \kappa c
\]

take
\[
\kappa_{ij} = \kappa \delta_{ij}
\]

\[
\hat{c} = (H^\top V^{-1} H + \kappa I)^{-1} H^\top V^{-1} y
\]

\[
U = (H^\top V^{-1} H + \kappa I)^{-1}
\]
REGULARIZED LEAST SQUARES

- Fit an arbitrary number of coefficients

\[ \chi^2(c) = (y - \mu(c))^T V^{-1} (y - \mu(c)) + c^T \kappa c \]

\[ \kappa_{ij} = \kappa \delta_{ij} \]

\[ \hat{c} = \left( H^T V^{-1} H + \kappa I \right)^{-1} H^T V^{-1} y \]

\[ U = \left( H^T V^{-1} H + \kappa I \right)^{-1} \]

CM: 1710.02008

Henning, Lu, Melia, Murayama: 1512.03433
GLOBAL FIT RESULTS

*assumes SMEFT is UV-completed by a renormalizable, weakly-coupled theory

EMSY 1803.03252

<table>
<thead>
<tr>
<th>Theory</th>
<th>$\chi^2$</th>
<th>$\chi^2/n_d$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
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GLOBAL FITS IN THE WARSAW BASIS

LHC competing w/ LEP
GLOBAL FITS IN THE WARSAW BASIS

Marginalised

- \(10^{-1} \tilde{C}_{dH} \)
- \(10^{-1} \tilde{C}_{eH} \)
- \(10^{-1} \tilde{C}_{HB} \)
- \(10^{-1} \tilde{C}_{HD} \)
- \(10^{-1} \tilde{C}_{He} \)
- \(10 \tilde{C}_{HG} \)
- \(10 \tilde{C}_{HH} \)
- \(10 \tilde{C}_{H(1)} \)
- \(10 \tilde{C}_{H(2)} \)
- \(10 \tilde{C}_{H(3)} \)
- \(10 \tilde{C}_{Hb} \)
- \(10 \tilde{C}_{Hw} \)
- \(10 \tilde{C}_{HWB} \)
- \(10^{-2} \tilde{C}_{uG} \)
- \(10^{-1} \tilde{C}_{uH} \)
- \(10^{-1} \tilde{C}_{w} \)
FIT SUMMARY

95% CL limits LEP + LHC Run 1+2

$\Lambda/\sqrt{c}$ [TeV]

- Individual
- Marginalised

EMSY 1803.03252
WHAT DO WE LEARN FROM THE FIT?

\[ C_{dH} = C_{eH} = C_{uH} = C_f \]

\[ C_H = -2 \bar{C}_H \]

- **real singlet**
- **real triplet**
- **complex triplet**
### EXTENSIONS OF THE SM

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<th>$SU(2)$</th>
<th>$U(1)$</th>
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Table from EMSY 1803.03252

Full dictionary: de Blas, Criado, Perez-Victoria, Santiago: 1711.10391
## NUMERICAL CONSTRAINTS ON EXTENSIONS

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<tr>
<th>Model</th>
<th>$\chi^2$</th>
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**2HDM**

**EMSY 1803.03252**
CONSTRAINTS ON SM EXTENSIONS

Complex Scalar Triplet

VLQ w/ quantum #s of SM $Q_L$
CONSTRAINTS ON SM EXTENSIONS

Z prime

Spin-One Triplet

(c) $B$, no $\psi^4$ operators

(d) $W$, no $\psi^4$ operators
NON-RENORMALIZABLE MODELS

- Subset of models: explanations of muon $g-2$

\[ E^{(5)}: \quad C^{(1)}_{H\ell} = C^{(3)}_{H\ell}, \quad \chi^2 = 157, \quad \chi^2 / n_d = 0.999. \]

\[
\begin{pmatrix}
\bar{C}_{eH} \\
\bar{C}^{(3)}_{H\ell}
\end{pmatrix}
= \begin{pmatrix}
(-0.8 \pm 8.9) \cdot 10^{-2} \\
(-0.3 \pm 1.5) \cdot 10^{-4}
\end{pmatrix}
\]

\[ \Delta^{(5)}_{1,3}: \quad \chi^2 = 156, \quad \chi^2 / n_d = 0.996. \]

\[
\begin{pmatrix}
\bar{C}_{eH} \\
\bar{C}_{He}
\end{pmatrix}
= \begin{pmatrix}
(-0.8 \pm 8.9) \cdot 10^{-2} \\
(-2.3 \pm 3.3) \cdot 10^{-4}
\end{pmatrix}
\]

\[ \Sigma^{(5)}_1: \quad C^{(1)}_{H\ell} = -3C^{(3)}_{H\ell}, \quad \chi^2 = 155, \quad \chi^2 / n_d = 0.988. \]

\[
\begin{pmatrix}
\bar{C}_{eH} \\
\bar{C}^{(3)}_{H\ell}
\end{pmatrix}
= \begin{pmatrix}
(-0.8 \pm 8.9) \cdot 10^{-2} \\
(-1.2 \pm 0.9) \cdot 10^{-4}
\end{pmatrix}
\]
NON-RENORMALIZABLE MODELS

- Heavy scalar singlet

\[ S^{(5)}: \chi^2 = 153, \chi^2/n_d = 1.00. \]

\[
\begin{pmatrix}
0.54\tilde{C}_{H\Box} - 0.05\tilde{C}_{HW} + 0.01\tilde{C}_{HB} + 0.08\tilde{C}_{eH} + 0.84\tilde{C}_{uH} + 0.03\tilde{C}_{dH} \\
-0.16\tilde{C}_{H\Box} + 0.75\tilde{C}_{eH} + 0.64\tilde{C}_{dH} \\
0.50\tilde{C}_{H\Box} - 0.04\tilde{C}_{HW} + 0.01\tilde{C}_{HB} + 0.57\tilde{C}_{eH} - 0.36\tilde{C}_{uH} - 0.54\tilde{C}_{dH} \\
0.65\tilde{C}_{H\Box} - 0.06\tilde{C}_{HW} + 0.02\tilde{C}_{HB} - 0.32\tilde{C}_{eH} - 0.42\tilde{C}_{uH} + 0.54\tilde{C}_{dH} \\
0.09\tilde{C}_{H\Box} + 0.95\tilde{C}_{HW} - 0.29\tilde{C}_{HB} \\
0.91\tilde{C}_{HG} + 0.12\tilde{C}_{HW} + 0.39\tilde{C}_{HB} \\
-0.39\tilde{C}_{HG} + 0.27\tilde{C}_{HW} + 0.88\tilde{C}_{HB}
\end{pmatrix}
= 
\begin{pmatrix}
-0.03 \pm 0.18 \\
0.11 \pm 0.11 \\
(-4.1 \pm 7.9) \cdot 10^{-2} \\
(8.0 \pm 6.0) \cdot 10^{-2} \\
(1.8 \pm 9.6) \cdot 10^{-3} \\
(1.7 \pm 1.4) \cdot 10^{-4} \\
(2.0 \pm 8.4) \cdot 10^{-5}
\end{pmatrix}
\]
## Fisher Information per Measurement

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<th>Wilson Coefficient</th>
<th>Z-pole + W-mass</th>
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<th>Higgs LHC Run 1</th>
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<th>LHC WW Scattering pt&gt;120</th>
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LHC diboson measurements more powerful than LEP2

Ellis, CM, Sanz, You: unpublished