Looking Beyond the Standard Model with the SMEFT

“...the direct method may be used...but indirect methods will be needed in order to secure victory....”

“The direct and the indirect lead on to each other in turn. It is like moving in a circle....”

Who can exhaust the possibilities of their combination?”

Sun Tzu, The Art of War
Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

<table>
<thead>
<tr>
<th>$L_L$</th>
<th>$(\nu_e, e^-)<em>L$, $(\nu</em>\mu, \mu^-)<em>L$, $(\nu</em>\tau, \tau^-)_L$</th>
<th>$(1,2,-1)$, $(1,1,-2)$</th>
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<tbody>
<tr>
<td>$E_R$</td>
<td>$e_R^-, \mu_R^-, \tau_R^-$</td>
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<table>
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<th>$Q_L$</th>
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<tr>
<td>$D_R$</td>
<td>$d_R, s_R, b_R$</td>
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- Lagrangian:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i \bar{\psi} \not\!D \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Where are we?

- Tested < 0.1% before LHC
- Testing now in progress
LHC Measurements

Agree with the Standard Model

Higgs production

All results at: http://cern.ch/go/pNj7
The Particle Higgsaw Puzzle

Has LHC found the missing piece?
Is it the right shape?
Is it the right size?
It Walks and Quacks like a Higgs

• Do couplings scale ~ mass? With scale = $v$?

$\lambda_f = \sqrt{2} \left( \frac{m_f}{M} \right)^{1+\epsilon}$, $g_V$

Red line = SM, dashed line = best fit

Global fit

CMS Preliminary
$m_H = 125.38$ GeV
p-value = 44%

35.9-137 fb$^{-1}$ (13 TeV)

Force carriers
Leptons and neutrinos
Quarks
Higgs boson

Ratio to SM

particle mass (GeV)

$e$, $\mu$, $\tau$, $\nu_e$, $\nu_\mu$, $\nu_\tau$, $u$, $c$, $t$, $d$, $s$, $b$, $\gamma$, $g$, $W$, $Z$, $H$
… to make an end is to make a beginning. The end is where we start from.

T.S. Eliot
Everything about Higgs is Puzzling

\[ \mathcal{L} = yH \bar{\psi} \psi + \mu^2 |H|^2 - \lambda |H|^4 - V_0 + \ldots \]

- Pattern of Yukawa couplings \( y \):
  - Flavour problem
- Magnitude of mass term \( \mu \):
  - Naturalness/hierarchy problem
- Magnitude of quartic coupling \( \lambda \):
  - Stability of electroweak vacuum
- Cosmological constant term \( V_0 \):
  - Dark energy

Higher-dimensional interactions?
Effective Field Theories (EFTs) 
a long and glorious History

• 1930’s: “Standard Model” of QED had d=4

• **Fermi’s four-fermion theory of the weak force**

• Dimension-6 operators: form = S, P, V, A, T?
  – Due to exchanges of massive particles?

• V-A ➔ massive vector bosons ➔ gauge theory

• Yukawa’s meson theory of the strong N-N force
  – Due to exchanges of mesons? ➔ pions

• Chiral dynamics of pions: \((\partial \pi \partial \pi)\pi\pi\) clue ➔ QCD
Standard Model Effective Field Theory
a more powerful way to analyze the data

• Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
• Look for additional interactions between SM particles
• Analyze Higgs data together with electroweak precision data and top data
• Most efficient way to extract largest amount of information from LHC and other data
• Model-independent way to look for physics beyond the Standard Model (BSM)
Summarize Analysis Framework

- Include all leading dimension-6 operators?

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} O_i \]

- Simplify by assuming SU(3)^5 or SU(2)^2 \times SU(3)^3 symmetry for fermions

- Work to linear order in operator coefficients

- Use \( G_F \), \( M_Z \), \( \alpha \) as input parameters
### Dimension-6 Operators in Detail

- **Including 2- and 4-fermion operators**
- **Various colours for different data sectors**
- **Grey cells violate SU(3)^5 symmetry**
- **Important when including top observables**

Operators included in Global Fit

- Operators in flavour-universal SU(3)$^5$ fit

EWPO: $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$, $\mathcal{O}_{ll}$, $\mathcal{O}_{Hl}$, $\mathcal{O}_{Hl}^{(3)}$, $\mathcal{O}_{He}$, $\mathcal{O}_{Hq}$, $\mathcal{O}_{Hq}^{(3)}$, $\mathcal{O}_{Hq}^{(1)}$, $\mathcal{O}_{Hd}$, $\mathcal{O}_{Hu}$,

Bosonic: $\mathcal{O}_{H\Box}$, $\mathcal{O}_{HG}$, $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$, $\mathcal{O}_{W}$, $\mathcal{O}_{G}$,

Yukawa: $\mathcal{O}_{\tau H}$, $\mathcal{O}_{\mu H}$, $\mathcal{O}_{bH}$, $\mathcal{O}_{tH}$.

- Operators in top-specific SU(2)$^2 \times$ SU(3)$^3$ fit

EWPO: $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$, $\mathcal{O}_{ll}$, $\mathcal{O}_{Hl}$, $\mathcal{O}_{Hl}^{(3)}$, $\mathcal{O}_{He}$, $\mathcal{O}_{Hq}$, $\mathcal{O}_{Hq}^{(3)}$, $\mathcal{O}_{Hq}^{(1)}$, $\mathcal{O}_{Hd}$, $\mathcal{O}_{Hu}$,

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Yukawa: $\mathcal{O}_{\tau H}$, $\mathcal{O}_{\mu H}$, $\mathcal{O}_{bH}$, $\mathcal{O}_{tH}$,

Top 2F: $\mathcal{O}_{HQ}^{(3)}$, $\mathcal{O}_{Hq}^{(1)}$, $\mathcal{O}_{Ht}$, $\mathcal{O}_{tG}$, $\mathcal{O}_{tW}$, $\mathcal{O}_{tB}$,

Top 4F: $\mathcal{O}_{Qq}^{3,1}$, $\mathcal{O}_{Qq}^{3,8}$, $\mathcal{O}_{Qq}^{1,8}$, $\mathcal{O}_{Qu}^{8}$, $\mathcal{O}_{Qd}^{8}$, $\mathcal{O}_{tQ}^{8}$, $\mathcal{O}_{tu}^{8}$, $\mathcal{O}_{td}^{8}$.

Indicating which sectors constrain which operators
Global SMEFT Fit to Top, Higgs, Diboson, Electroweak Data

- Global fit to dimension-6 operators using precision electroweak data, $W^+W^-$ at LEP, top, Higgs and diboson data from LHC Runs 1 and 2
- Constraints on BSM
  - At tree level
  - At loop level
### Data included in Global Fit

- **EW precision observables**
- **LHC Run 2 Higgs**
  - ATLAS combination of measurements including ratios of branching fractions
  - Signal strengths coarses
  - CMS LHC combination
  - Production: ggF, VBF, ZH, WH & ttH
  - Decays: $\gamma \gamma$, ZZ, WW, $W^+ W^-$
  - CMS stage 1.0 STXS
    - 13 parameter fit | 7 parameters
  - CMS stage 1.0 STXS
  - CMS stage 1.1 STXS
  - CMS differential cross section in the $WW^*$ channel
  - ATLAS $H \to Z\gamma$ signal
  - ATLAS $H \to \mu^+ \mu^-$ signal

- **Tevatron & Run 1 top**
  - ATLAS combination of differential $t\bar{t}$ forward-backward asymmetry, $A_{FB}(m_{t\bar{t}})$
  - CMS $t\bar{t}$ differential distributions in the dilepton channel.
  - ATLAS measurement of differential $t\bar{t}$ charge asymmetry, $A_C(m_{t\bar{t}})$
  - CMS measurements of $t\bar{t}$ and $ttZ$ cross section measurements
  - ATLAS measurements of $t\bar{t}$ and $ttZ$ cross section measurements
  - ATLAS measurement of differential $t\bar{t}$ and $ttZ$ cross section measurements

### LHC Run 1 Higgs
- ATLAS and CMS LHC Run 1 combination of Higgs signal strengths
  - Production: ggF, VBF, ZH, WH & ttH
  - Decays: $\gamma \gamma$, ZZ, WW, $W^+ W^-$, $\tau^+ \tau^-$ & $b\bar{b}$
  - ATLAS inclusive $Z\gamma$ signal strength measurement

### Table

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**328 measurements included in global analysis**
Dimension-6 Constraints with Flavour-Universal SU(3)$^5$ Symmetry

- Individual operator coefficients
- Marginalised over all other operator coefficients

Impacts of Measurements

\[ \frac{X}{X_{SM}} = 1 + \sum_{i} \frac{a_{i}^{X} C_{i}}{\Lambda^{2}} + O \left( \frac{1}{\Lambda^{4}} \right) \]
Dimension-6 Constraints with Top-Specific $SU(2)^2 \times SU(3)^3$

- Individual operator coefficients
- Marginalised over all other operator coefficients

Correlation Analysis

- EWPO and boson sectors correlated
- Also within top sector
- Weaker correlations between sectors
Example of Interplay between Data Sets

- **Higgs data**
- Include $t\bar{t}H$
- Include top data
- Global analysis

Principal Component Analysis

- Diagonalise correlation matrix
- Analyze eigenvectors and eigenvalues
- Scales from 20 TeV to 100 GeV
- Strongest constraints from Electroweak, H

# Single-Field Extensions of the Standard Model

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<th>SU(2)</th>
<th>U(1)</th>
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**Spin zero**

**Vector**

## Contributions to SMEFT Coefficients

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Constraints on Single-Field BSM Scenarios

- No significant pulls away from SM
- Any single-field extension of SM must have mass scale > 400 GeV if coupling = 1

Scalar could weigh 800 GeV

Vector must weigh > 1.5 TeV
SMEFT Constraints on Light Stops

From quantum loop corrections:

\[ C_{HG} = \frac{g_s^2}{12} \frac{h_t^2}{(4\pi)^2} \left[ (1 + \frac{1}{12} \frac{c_{2\beta} g'^2}{h_t^2}) - \frac{1}{2} \frac{X_t^2}{m_t^2} \right], \]

\[ C_{HB} = \frac{17 g'^2}{144} \frac{h_t^2}{(4\pi)^2} \left[ (1 + \frac{31}{102} \frac{c_{2\beta} g'^2}{h_t^2}) - \frac{38}{85} \frac{X_t^2}{m_t^2} \right], \]

\[ C_{HW} = \frac{g^2}{16} \frac{h_t^2}{(4\pi)^2} \left[ (1 - \frac{1}{6} \frac{c_{2\beta} g'^2}{h_t^2}) - \frac{2}{5} \frac{X_t^2}{m_t^2} \right], \]

\[ C_{HWB} = -\frac{g g'}{24} \frac{h_t^2}{(4\pi)^2} \left[ (1 + \frac{1}{2} \frac{c_{2\beta} g'^2}{h_t^2}) - \frac{4}{5} \frac{X_t^2}{m_t^2} \right]. \]

(ALmost) model-independent lower limit on stop squark mass

Direct Search Constraints on Light Stops

- Patchwork of many model-dependent searches
- Indirect constraint excludes low-mass region (almost) model-independently
Model-Independent BSM Survey

- Top-less sector fits SM very well
- Top sector does not fit so well
- Overall, pulls not excessive
- No hint of BSM
Comparison of Linear and Quadratic Fits

- Quadratic fit does not include EWPOs
- Tighter constraints in general
- What about dimension 8?
- Fitting process slower, difficult to make broad BSM survey

Ethier et al., arXiv:2105.00006
How about Dimension 8?

Some windows of opportunity:
Light-by-light scattering
$gg \rightarrow \gamma\gamma$
Neutral triple-gauge couplings
First Measurement of Light-by-Light Scattering

- Peripheral heavy-ion collisions at the LHC: $\gamma\gamma \rightarrow \gamma\gamma$

![Diagram of heavy-ion collisions](image)

- Expected in ordinary QED from fermion loops
- ATLAS measurement agrees with QED
- Can be used to constrain nonlinearities in Born-Infeld

Heisenberg & Euler 1936

Light-by-Light Scattering in QED

- Electron (charged particle) loops induce light-by-light scattering: γ

- First calculations:

\[
\Omega = \frac{1}{2} (C^2 - B^2) + \frac{e^2}{\hbar c} \int_0^\infty e^{-\eta} \frac{d\eta}{\eta^3} \left\{ i \eta^2 (CB) \cdot \frac{\cos \left( \frac{\eta}{|E_k|} \sqrt{C^2 - B^2 + 2i(CB)} \right) + \text{konj}}{\cos \left( \frac{\eta}{|E_k|} \sqrt{C^2 - B^2 + 2i(CB)} \right) - \text{konj}} \right\} + |E_k|^2 + \frac{\eta^2}{3} (B^2 - C^2)
\]
• Original Born-Infeld modification of QED:

\[ L = b^2 \left( \sqrt{1 + \frac{1}{b^2} (H^2 - E^2)} - 1 \right) \]

• Based on “unitarian” idea of maximum electromagnetic field, cf, velocity of light

• Limit on Coulomb potential
Born-Infeld & String Theory

• Original Born-Infeld modification of QED:

\[ \mathcal{L}_{\text{QED}} = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} \rightarrow \mathcal{L}_{\text{BI}} = \beta^2 \left( 1 - \sqrt{1 + \frac{1}{2\beta^2} F_{\mu \nu} F^{\mu \nu} - \frac{1}{16\beta^4} (F_{\mu \nu} F^{\mu \nu})^2} \right) \]

• Derived from string theory:

\[ \int d^D y \left[ \det \left( \delta_{\mu \nu} + 2\pi \alpha' F_{\mu \nu} \right) \right]^{1/2} \]

4 dimensions: \[ \left[ \det (\delta_{\mu \nu} + F_{\mu \nu}) \right]^{1/2} = [1 + \frac{1}{2} F_{\mu \nu}^2 + \frac{1}{16} (F_{\mu \nu} F_{\mu \nu})^2]^{1/2} \]

• Limiting gauge field \( \leftrightarrow \) brane velocity = light

\[ \mathcal{L}_{\text{BI}} \propto \sqrt{1 - (2\pi \alpha' eE)^2} \leftrightarrow \mathcal{L}_{\text{particle}} \propto \sqrt{1 - v^j v_j} \]

• Mass scale \( M = \sqrt{\beta} \)

\( \leftrightarrow \) 1/distance between branes, \( \geq \) TeV?
Constraint on Born-Infeld Scale

- ATLAS constraint on $\sigma(\gamma\gamma \rightarrow \gamma\gamma)$ constrains $M = \sqrt{\beta}$

- All events with $m_{\gamma\gamma} \leq M$: limit $M \approx 100, 210$ GeV
- Assume $\sigma = 1/m_{\gamma\gamma}^2$ at higher masses: $M \approx 190, 330$ GeV
- Entering range of low-scale brane models
Production of Isolated $\gamma\gamma$ at LHC

- Data agree with SM
- Can be used to constrain dimension-8 $gg\gamma\gamma$ operators

Constraints from Collider Data

- **ATLAS**: 95% CL lower limits in TeV range

- Prospective sensitivities of future colliders in multi-TeV range

- **Unique window on dimension-8 physics**
Summary

• **Remember Sun Tzu:** search for new physics indirectly as well as directly

• SMEFT is an effective, model-independent tool for probing indirectly possible physics beyond the SM

• It can be used to analyze jointly precision electroweak, diboson and top quark data from LHC and elsewhere

• Our current analysis indicates that the scale of new physics is probably > TeV

• Useful for assessing sensitivities of proposed future accelerators
Precision Electroweak Measurements with FCC-ee

Blondel et al, arXiv:1809.01830
Future EFT Constraints from Higgs and Electroweak Measurements

Dark colours include theoretical errors
Beyond Dimension 6

- Neutral triple gauge couplings have no dimension-4, -6 contributions
- Appear first at dimension-8:

\[
g_{G^+} = \tilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} + D_\nu D_\lambda W^{a\rho}),
\]

\[
g_{G^-} = \tilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} - D_\nu D_\lambda W^{a\rho}).
\]

\[
\mathcal{O}_{BW} = i H^+ \tilde{B}_{\mu\nu} W^{a\mu\rho} \{D_\rho, D_\nu\} H
\]

\[
\mathcal{O}_{C^+} = \tilde{B}_{\mu\nu} W^{a\mu\rho} [D_\rho (\bar{\psi}_L T^a \gamma_\rho \psi_L) + D_\nu (\bar{\psi}_L T^a \gamma_\rho \psi_L)].
\]

- Probe in $e^+e^- \rightarrow Z\gamma$, using hadronic Z decays:

<table>
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<tr>
<th>(\sqrt{s})</th>
<th>(\Lambda_{G^+}^{2\sigma})</th>
<th>(\Lambda_{G^+}^{5\sigma})</th>
<th>(\Lambda_{G^-}^{2\sigma})</th>
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<td>(4.5, 4.7)</td>
<td>(5.7, 6.8)</td>
<td>(4.5, 5.5)</td>
</tr>
</tbody>
</table>

- **Unpolarized** beams: \(\Lambda >> E_{CM}\)


(JE, Ge, He & Xiao, arXiv:1902.06632)
Dimension-8 Operators in nTGCs

- Angular distributions in SM and with dim-8
- Easy to distinguish dimension-8

(JE, Ge, He & Xiao, arXiv:1902.06612)
Sensitivity to Dimension-8

- New physics scale $\Lambda$ vs centre-of-mass energy

- Solid: 2-$\sigma$ exclusion, dashed: 5-$\sigma$ discovery

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(arXiv:1902.00612)
Dimension 4

SMEFT
dimensions > 4

Standard Model