Flat Directions in the SMEFT: LHC and PVES

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Based on:
Boughezal/Petriello/DW - (arXiv: 2104.03979)
No smoking gun(s) at LHC
- Indirect searches might tell us where New Physics lies
- Standard Model Effective Field Theory (SMEFT) is a systematic way to combine and analyze data and constrain New Physics in a model-independent way

Flat directions are a prevalent problem
- Important to know which measurements to combine

Future Measurements & Experiments:
- Extract best bounds from available data (e.g.: Drell-Yan)
- Disentangle dim-6/dim-8

Low-energy SoLID/P2 data
Many **dim-8 extensions** of Four-Fermi operators. Focus on **derivatives**:

\[ \mathcal{L}_{SMEFT} \supset \mathcal{L}_{SM} + \frac{C_6}{\Lambda^2} O_6^i + \frac{C_8}{\Lambda^4} O_8^i + \ldots \]

\[
\begin{align*}
\mathcal{O}^{(1)}_{uq} & \quad (\bar{l} \gamma^\mu l) (\bar{q} \gamma_\mu q) \\
\mathcal{O}^{(2)}_{uq} & \quad (\bar{l} \gamma^\mu l) D_\nu (\bar{q} \gamma_\mu q) \\
\mathcal{O}^{(3)}_{e_q} & \quad (\bar{l} \gamma^\mu \tau l) (\bar{q} \gamma_\mu \tau q) \\
\mathcal{O}^{(4)}_{e_q} & \quad (\bar{l} \gamma^\mu \tau l) D_\nu (\bar{q} \gamma_\mu \tau q) \\
\mathcal{O}^{(5)}_{e_u} & \quad (\bar{e} \gamma^\mu e) (\bar{u} \gamma_\mu u) \\
\mathcal{O}^{(6)}_{e_d} & \quad (\bar{e} \gamma^\mu e) (\bar{d} \gamma_\mu d) \\
\mathcal{O}^{(7)}_{b_u} & \quad (\bar{l} \gamma^\mu l) (\bar{u} \gamma_\mu u) \\
\mathcal{O}^{(8)}_{b_d} & \quad (\bar{l} \gamma^\mu l) (\bar{d} \gamma_\mu d) \\
\mathcal{O}^{(9)}_{q_e} & \quad (\bar{q} \gamma^\mu q) (\bar{e} \gamma_\mu e) \\
\mathcal{O}^{(10)}_{q_e} & \quad (\bar{q} \gamma^\mu q) D_\nu (\bar{e} \gamma_\mu e)
\end{align*}
\]

*Semi-leptonic dimension-8 derivative operators*
SMEFT @ Dim-8

Many dim-8 extensions of Four-Fermi operators. Focus on derivatives:

$$\mathcal{L}_{SMEFT} \supset \mathcal{L}_{SM} + \frac{C_6^i}{\Lambda^2} \mathcal{O}_i^6 + \frac{C_8^i}{\Lambda^4} \mathcal{O}_i^8 + \ldots$$

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<thead>
<tr>
<th>Dimension 6</th>
<th>Dimension 8</th>
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<tbody>
<tr>
<td>$\mathcal{O}_{1q}^{(1)}$</td>
<td>$(\bar{t}\gamma^\mu t)(\bar{q}\gamma_\mu q)$</td>
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<tr>
<td>$\mathcal{O}_{1q}^{(2)}$</td>
<td>$(\bar{t}\gamma^\mu \bar{D}<em>\mu ^3 t)(\bar{q}</em>\mu \gamma_\mu)$</td>
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<tr>
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<tr>
<td>$\mathcal{O}_{1q}^{(4)}$</td>
<td>$(\bar{t}\gamma^\mu D_\mu ^2 \tau^i t)(\bar{q}<em>\mu \gamma</em>\mu \tau^i q)$</td>
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<tr>
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<td>$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$</td>
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<tr>
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<tr>
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Semi-leptonic dimension-8 derivative operators

Angular distributions cannot distinguish $C_6 \rightarrow C_6 - \frac{\delta}{\Lambda^2} C_8^{(1)}$

Distinguish $C_6$ and $C_8^{(2)}$ with angular observables

$$\frac{C_6}{\Lambda^2} (\bar{\psi}_\mu \gamma_\mu \psi) (\bar{\psi}_\mu \gamma_\mu \psi)$$

$$\frac{C_8^{(1)}}{\Lambda^4} D^\nu (\bar{\psi}_\mu \gamma_\mu \psi) D_\nu (\bar{\psi}_\mu \gamma_\mu \psi)$$

$$\frac{C_8^{(2)}}{\Lambda^4} (\bar{\psi}_\mu \gamma_\mu \bar{D}_\nu \psi) (\bar{\psi}_\mu \gamma_\mu \bar{D}_\nu \psi)$$
\[ \mathcal{L}_{\text{SMEFT}} \supset \mathcal{L}_{\text{SM}} + \frac{C_6^i}{\Lambda^2} \mathcal{O}_i^6 + \frac{C_8^i}{\Lambda^4} \mathcal{O}_i^8 + \ldots \]

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Many dim-8 extensions of Four-Fermi operators. Focus on derivatives:

\[ \frac{C_6}{\Lambda^2} (\bar{\psi} \gamma_\mu \psi)(\bar{\psi} \gamma_\mu \psi) \]
\[ \frac{C_8}{\Lambda^4} (\bar{\psi} \gamma_\mu D^\mu \psi)(\bar{\psi} \gamma_\mu \gamma_\lambda \gamma_\nu D^\mu \psi) \]

\[ C_6 \rightarrow C_6 - \frac{\hat{s}}{\Lambda^2} C_6^{(1)} \]
\[ C_6 \rightarrow C_6 - \frac{\hat{t} - \hat{u}}{\Lambda^2} C_8^{(2)} \]

Angular distributions cannot distinguish

Distinguish \( C_6 \) and \( C_8^{(t)} \) with angular observables

Need different approach to distinguish dim-6 and dim-8 contributions!

Combine Low-Energy precision experiments \( \left( \frac{\hat{s}}{\Lambda^2} \right. \) is suppressed! \)
with High-Energy data to disentangle dim-6 and dim-8
What’s a flat direction?

- More Wilson coefficients than observables
- Either exact or approximate (in a certain regime)
- Severely limits possible bounds on individual coefficients
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- More Wilson coefficients than observables
- Either exact or approximate (in a certain regime)
- Severely limits possible bounds on individual coefficients

Example: Drell-Yan observables are only sensitive to a few combinations of Coefficients

Too many Wilson Coefficients: kinematic variable distributions show flat directions (e.g.: Rapidity, Lepton $m_{ll}$, ...)

Alte/König/Shepherd (1812.07575)

Boughezal/Petriello/DW (2004.00748)
Parity-Violating Deep Inelastic Scattering (PVDIS)

Asymmetry Parameter: 
\[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\left( \frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \right) \left[ Q_w - F(E, Q^2) \right] \]

Technical Details (P2):
- Fixed \( H \) and \( ^{12}C \) targets for measuring \( Q_w \sim s_W^2 \)
- Complement QWEAK, atomic PV, DIS, E158(SLAC)

Technical Details (SoLID):
- Fixed \( p^+ \) target for measuring \( \frac{d(x)}{u(x)} \) ratio
- Fixed \( D^+ \) target for BSM searches
PVES at Low Energies

To illustrate the difference between P2 and SoLID:

Use historic Four-Fermi PV Lagrangian, in terms of \textbf{axial/vector} couplings instead of $\gamma^\mu P_{L,R}$ (and fix $\Lambda$ to Higgs vev)

\[\rightarrow\text{ Linear transformation to SMEFT basis}\]
PVES at Low Energies

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Use historic Four-Fermi PV Lagrangian, in terms of axial/vector couplings instead of $\gamma^\mu P_{L,R}$ (and fix $\Lambda$ to Higgs vev)

- Linear transformation to SMEFT basis

**Elastic Scattering (P2)**

$$\frac{C_{1q}}{v^2} \left( \bar{e} \gamma^\mu \gamma_5 e \right) \left( \bar{q} \gamma_\mu q \right)$$

contributes via $\gamma$-interference

**Deep Inelastic Scattering (SoLID)**

Mostly

$$\frac{C_{2q}}{v^2} \left( \bar{e} \gamma^\mu \gamma_5 e \right) \left( \bar{q} \gamma_\mu \gamma_5 q \right)$$

contributes
Dim8 Extension: \( \frac{C_{1q}^8}{\nu^4} D^\nu (\bar{e} \gamma^\mu \gamma_5 e) D_\nu (\bar{q} \gamma_\mu q) \)
Dimension-8 PV Operators

\[ \frac{C_{1q}^8}{v^4} D^\nu (\bar{e} \gamma^\mu \gamma_5 e) D_\nu (\bar{q} \gamma_\mu q) \]

Translate bounds into SMEFT basis

\[ C_{1u}^6 \rightarrow \frac{v^2}{2\Lambda^2} \left\{ - \left( C_{lq}^{(1)} - C_{lq}^{(3)} \right) + \ldots \right\}, \ldots \]

Example SMEFT fit dim-6/dim-8

(Normalized to \( \Lambda = 3\text{TeV} \))
Dimension-8 PV Operators

Translate bounds into SMEFT basis

$$C_{1u}^6 \rightarrow \frac{v^2}{2\Lambda^2} \left\{ -\left( C_{lq}^{(1)} - C_{lq}^{(3)} \right) + \ldots \right\}, \ldots$$

- LHC Drell-Yan measurements only poorly differentiate dim-6/dim-8 SMEFT combinations
- Low-Energy $A_{PV}$ measurements lift the degeneracy and allow for tighter bounds

Example SMEFT fit dim-6/dim-8 (Normalized to $\Lambda = 3$ TeV)
SMEFT is a practical framework to constrain new physics!

SMEFT suffers from a large number of flat directions

- Combine different observables to optimize fit
- We presented a strategy to lift 4-Fermi flat directions at dim-6 and dim-8

The future Low-Energy experiments will take data soon

- Energy suppression can be used to disentangle dim-6 and dim-8
- Correct interplay of different measurements improve bounds significantly!

Thanks!