Removing Flat Directions in SMEFT Fits: Complementing the LHC with polarized EIC data

Daniel Wiegand
Northwestern University/Argonne National Lab
@Snowmass Community Planning Meeting 2020

Based on:
Boughezal/Petriello/DW - (arXiv: 2004.00748)
The Why, the What and the How

- **the Why**
  - No smoking gun(s) at LHC
  - Standard Model Effective Theory (SMEFT) is a systematic way to combine and analyze data and look for New Physics in a model-independent way

- **the What**
  - Four-Fermi Operators are a large class of SMEFT operators
  - **Flat directions** are a prevalent problem resolve for **global fit**

- **the How**
  - Future **Electron-Ion** Collider (EIC) :
    - Lift flat directions by combining polarized observables
  - Combine with LHC data for strongest bounds (here: **Drell-Yan**)

© Ilaria Brivio 05/18
The Warsaw Basis

Write down all possible operators that new physics could induce
- Stay consistent with SM symmetries!
- Build from SM field content!

Many equivalent bases to parametrize new physics
⇒ go for least number of derivatives

\[ \mathcal{L}_{SMEFT} \supset \mathcal{L}_{SM} + \frac{C_5}{\Lambda^5} \mathcal{O}_5 + \frac{C_6}{\Lambda^2} \mathcal{O}_6^i + \frac{C_7}{\Lambda^3} \mathcal{O}_7^i + \cdots \]

We focus at 1-loop/Dim-6 Semi-hadronic 4-Fermi Operators
(Potential Z-coupling shifts are better probed with Z-Pole observables)

Warsaw Basis: 59 Operators (\(\delta B = 0, \delta L = 0\))
Overview: Previous Constraints

Previous constraints mostly from low-energy and EW precision data \textit{Falkowski et al (1706.03783)}

**Below the Z pole:**

DIS $e^-/\mu^-$ scattering

$\beta, \pi, n^0$ decay

Atomic Parity Violation

Weak charge $Q_W(Z, N)$ (PVDIS @6GeV, SPS data,...)

**Above the Z pole:**

Low-energy di-Jet Production (LEP2 data, also KEKB)

Combined observables are only sensitive to certain \textbf{combinations of Wilson coefficients}:

\[
\begin{array}{c|c|c|c|c|c}
\hat{C}_{qe} & \hat{C}_{lq}^{(3)} & \hat{C}_{lu} & \hat{C}_{ld} & \hat{C}_{eu} & \hat{C}_{ed} \\
\hline
< 2.8 & < 0.05 & < 0.16 & < 0.28 & < 0.11 & < 0.25 \\
\end{array}
\]

Bounds on the absolute values of the linear combinations of Wilson Coefficients (from 1706.03783) ($\Lambda = 1$TeV)

\[
\begin{align*}
\hat{C}_{qe} &= C_{qe} + C_{lq}^{(1)} \\
\hat{C}_{lu} &= C_{lu} + C_{lq}^{(1)} - C_{qe} \\
\hat{C}_{ld} &= C_{ld} + C_{lq}^{(1)} - C_{qe} \\
\hat{C}_{ed} &= C_{ed} - C_{lq}^{(1)} \\
\end{align*}
\]
Flat Directions: Drell-Yan

What’s a flat direction (more generally)?

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

Alte/König/Shepherd (1812.07575)
What’s a flat direction (more generally)?

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

Resolving different rapidity bins leads to no new information near the high-energy flat direction

The flat directions limit how far the bounds can be pushed, even with significantly more data (e.g. HL-LHC) or when measuring different differential distributions
Drell-Yan SMEFT deviation greatest for high $m_{ll}$

**BUT** More Wilson Coefficients than kinematic variables
Drell-Yan SMEFT deviation greatest for high $m_{ll}$

**BUT** More Wilson Coefficients than kinematic variables

The SMEFT contribution to $\sigma_{DY}$ depends at $s \gg m_{ll}$ **only** on

$$\Delta\sigma_{SMEFT} \sim \begin{cases} 
- \frac{4\alpha\pi}{9c_w^2} (C_{qe} + 2C_{lu}) \\
- \frac{2\alpha\pi}{9c_w^2 s_w^2} \left[ \left( C_{lq}^{(1)} - C_{lq}^{(3)} \right) (3 - 2s_w^2) + 8s_w^2 C_{eu} \right] \end{cases}$$
Drell-Yan SMEFT deviation greatest for high $m_{ll}$

**BUT** More Wilson Coefficients than kinematic variables

The SMEFT contribution to $\sigma_{DY}$ depends at $s \gg m_{ll}$ only on

$$\Delta \sigma_{SMEFT} \sim \begin{cases} -\frac{4\alpha\pi}{9c_W^2} \left(C_{qe} + 2C_{lu}\right) \\ -\frac{2\alpha\pi}{9c_W^2s_W^2} \left[(C_{lq}^{(1)} - C_{lq}^{(3)}) (3 - 2s_W^2) + 8s_W^2C_{eu}\right] \end{cases}$$

When fitting e.g. $C_{lq}^{(1)}$ and $C_{eu}$, for $C_{lq}^{(1)} = -\frac{8s_W^2}{3-2s_W^2}C_{eu} \approx -0.69C_{eu}$, $\Delta \sigma_{SMEFT} = 0$, marking a flat direction

---

Boughezal/Petriello/DW (2004.00748)
Technical Specifications:
- CoM Energy up to $\sqrt{S} = 140\text{GeV}$
- Polarized Electron and pol/unpol Proton Beam (70%)
- Projected Luminosity $\mathcal{L} \sim 10\text{ fb}^{-1}$ (100 fb$^{-1}$?)
- Assume angular variable $0.1 < \gamma < 0.9$ and momentum fraction $x < 0.2$

https://www.bnl.gov/eic/

Aschenauer et al (1309.5327, 1705.08831)
Technical Specifications:
- CoM Energy up to $\sqrt{S} = 140\text{GeV}$
- Polarized Electron and pol/unpol Proton Beam (70%)
- Projected Luminosity $\mathcal{L} \sim 10 \text{ fb}^{-1}$ (100 fb$^{-1}$?)
- Assume angular variable $0.1 < y < 0.9$ and momentum fraction $x < 0.2$

Expected size of SMEFT effect in DIS (including PDF error, $\Lambda = 1\text{TeV}$)

https://www.bnl.gov/eic/

Aschenauer et al (1309.5327, 1705.08831)

Also Interesting: Charged Current (not as clean but only sensitive to $C_{ij}^{(3)}$)
Probing SMEFT at EIC

General Idea:
- Use different polarization combinations to lift flat directions
- Polarized/Unpolarized Protons vs 2 Electron Polarizations
- Ultimately: Global fit of PDFs and Wilson Coefficients

Different Wilson coefficients contribute for different Electron polarizations
Probing SMEFT at EIC

Different Wilson coefficients contribute for different Electron polarizations

General Idea:
- Use different polarization combinations to lift flat directions
- Polarized/Unpolarized Protons vs 2 Electron Polarizations
- Ultimately: Global fit of PDFs and Wilson Coefficients

Bounds with and without polarized proton beam data
Fitting Methodology (68% CL): 

For EIC/DIS: 
- Integrate over \((x, Q^2)\) bins 
- Assume uncorrelated errors 
- \(\Delta \sigma_{SMFT}\) measures deviation from SM

For LHC/DY: 
- Integrate over \(m_{ll}\) bins 
- Error Correlation from ATLAS 
- Data deviation from SM

ATLAS Collab. (1606.01736)

Define \(\chi^2\) test statistic (DIS case):

\[
\chi^2 = \sum_{\text{Bins}} \sum_{\text{Pol}/\pm} \left( \frac{\Delta \sigma_{SMFT}}{\Delta \sigma_{Err}} \right)^2
\]
Fitting Methodology (68% CL):

For EIC/DIS:
- Integrate over \((x, Q^2)\) bins
- Assume uncorrelated errors
- \(\Delta \sigma_{SMFT}\) measures deviation from SM

For LHC/DY:
- Integrate over \(m_{ll}\) bins
- Error Correlation from ATLAS
- Data deviation from SM

Define \(\chi^2\) test statistic (DIS case):
\[
\chi^2 = \sum_{\text{Bins Pol/\pm}} \left( \frac{\Delta \sigma_{SMFT}}{\Delta \sigma_{Err}} \right)^2
\]

ATLAS Collab. (1606.01736)
SMEFT is a practical framework to constrain new physics!

SMEFT suffers from a large number of flat directions

- Requires additional observables before global fit
- We presented a strategy to lift 4-Fermi flat directions

The future EIC will complement LHC data

- Combine EIC observables with different polarizations additionally to LHC measurements
- Interplay of different measurements improve bounds significantly

Thanks!