The TeraZ mirage: new physics lost in blind directions

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→ M. Chala, JCC, M. Spannowsky [2504.16558]

TeraZ

Production of 10^{12} Z bosons at CEPC or FCC-ee

$\hookrightarrow$ High-precision measurement of EWPOs

$\hookrightarrow$ Deviations from the SM parametrized by SMEFT

$$\mathrm{EWPO} = \Big\{ \Gamma_W, \Gamma_W^{e\nu,\mu\nu,\tau\nu}, \Gamma_W^{\mathrm{had}}, \sigma_{\mathrm{had}}, \Gamma_Z, A_{\mathrm{FB}}^{e,\mu,\tau}, A_{\mathrm{FB}}^{s,c,b}, A_{e,\mu,\tau}, A_{s,c,b}, R_{e,\mu,\tau}, R_{s,c,b}, \alpha \Big\}.$$

SMEFT and EWPOs

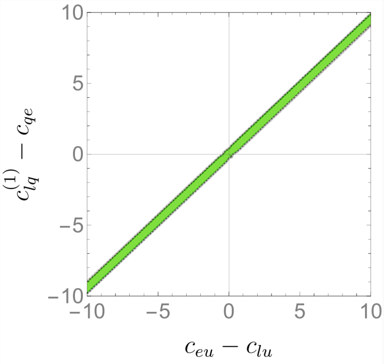
- There are $\sim$ 3000 dimension-6 operators in the SMEFT
- Ignoring flavor, there are $\sim$ 100 of them.
- Only 10 contribute to EWPOs at tree level.
- Including RGE, there are 31 operators with contributions to EWPOs.

To be compared with **26 EWPOs**.

Blind directions

Some combinations of operators have vanishing or negligible contributions to EWPOs.

$\hookrightarrow$ Even within the set of 31 operators that contribute to them individually.



Are blind directions generated in realistic UV completions?

Tree-level UV completions

de Blas, JCC, Perez-Victoria, Santiago [1711.10391]:

$$\text{Any UV model} \xrightarrow{\text{tree-level}} \text{dimension-6 SMEFT}$$

`MatchingDB` [gitlab.com/jccriado/matchingdb]:

```python
from matchingdb import JsonDB

db = JsonDB.load("smeft_dim6_tree.json")
```

```python
# Select the terms of the coefficient of the uG Warsaw operator
db.select_terms(coefficient="uG", output_format="pandas")
```

Type to search

	coefficient	fields	couplings
0	uG	[U]	[f, lambdaTildeGU, lambdaU]
1	uG	[Q1]	[f, lambdaTildeGQ1, lambdauQ1]

Classification of BSM particles

Scalars:

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

$\hookrightarrow$ Similar tables for fermions and vectors.

UV models with EWP effects

Study contributions to EWPOs from single-particle extensions:

Allwicher, McCullough, Renner [2408.03992]

Gargalionis, Quevillon, Hoa Vuong, You [2412.01759]

Maura, Stefanek, You [2412.14241]

$\hookrightarrow$ Strong constraints on most models

Potential blind directions in UV models

However:

- Some particles do generate a single unconstrained operator.
- SM extensions with two particles or more can generate operators that individually would have sizable effects in EWPOs, but combined go along a blind direction.

Finding some blind directions in the SMEFT

- Consider the set of all 4-fermion operators in the Warsaw basis.
- Exclude flavor-violating ones: $c^{(1)}_{quqd}$, $c^{(8)}_{quqd}$, c_{ledq}, $c^{(1)}_{lequ}$ and $c^{(3)}_{lequ}$.
- Include third-generation fermions only (since we assume NP couples to those).
- Compute observables at tree-level + RGE from 1 TeV

The following operators do not contribute (or do so negligibly) to EWPOs:

$$c_{dd},\ c^{(8)}_{qu},\ c^{(8)}_{qd},\ c^{(8)}_{ud},\ c_{le},\ c_{ll},\ c_{ed},\ c_{ld}.$$

Finding some blind directions in the SMEFT

Allowing for 2 non-vanishing coefficients at a time:

$$\begin{pmatrix} \Gamma_Z \\ A_b \\ R_{e,\mu,\tau} \end{pmatrix} \sim \begin{pmatrix} -0.0009 & 0.0008 \\ -0.004 & 0.004 \\ -0.01 & 0.009 \end{pmatrix} \begin{pmatrix} c_{ud}^{(1)} \\ c_{qd}^{(1)} \end{pmatrix} \longrightarrow c_{ud}^{(1)} \sim c_{qd}^{(1)}$$

$$\left.\begin{array}{l} \begin{pmatrix} A_\tau \\ R_\tau \end{pmatrix} \sim \begin{pmatrix} -0.01 & 0.01 \\ -0.19 & 0.20 \end{pmatrix} \begin{pmatrix} c_{eu} \\ c_{qe} \end{pmatrix} \quad \longrightarrow \quad c_{eu} \sim c_{qe} \\ \begin{pmatrix} A_\tau \\ R_\tau \end{pmatrix} \sim \begin{pmatrix} 0.01 & -0.01 \\ -0.24 & 0.23 \end{pmatrix} \begin{pmatrix} c_{lq}^{(1)} \\ c_{lu} \end{pmatrix} \quad \longrightarrow \quad c_{lq}^{(1)} \sim c_{lu} \end{array}\right\} \begin{array}{l} \text{become more robust when} \\ c_{eu} \sim c_{qe} \sim \pm c_{lq}^{(1)} \sim \pm c_{lu} \end{array}$$

SM extensions that generate simple blind directions

Blind direction	Extensions
$\mathcal{O}_{ll}$	$\{\Xi_1\}\quad\{\mathcal{B}\}\quad\{\mathcal{W}\}$
$\mathcal{O}_{le}$	$\{\varphi\}\quad\{\mathcal{L}_3\}$
$\mathcal{O}_{dd}$	$\{\Omega_2\}\quad\{\mathcal{G}\}$
$\mathcal{O}_{ed}$	$\{\omega_4\}\quad\{\mathcal{U}_2\}$
$\mathcal{O}_{ld}$	$\{\Pi_1\}\quad\{\mathcal{L}_3\}$
$\mathcal{O}_{ud}^{(1)}+\mathcal{O}_{qd}^{(1)}$	$\{\varphi,\mathcal{B}_1\}\quad\{\varphi,\mathcal{G}_1\}\quad\{\omega_1,\mathcal{Q}_1\}\quad\{\omega_1,\mathcal{Y}_1\}$ $\{\Omega_1,\mathcal{Q}_1\}\quad\{\Omega_1,\mathcal{Y}_1\}\quad\{\Phi,\mathcal{B}_1\}\quad\{\Phi,\mathcal{G}_1\}$
$\mathcal{O}_{eu}+\mathcal{O}_{qe}$ $+\mathcal{O}_{lu}+\mathcal{O}_{lq}^{(1)}$	$\{\omega_1,\mathcal{Q}_5,\mathcal{Q}_1,\omega_1,\zeta\}\quad\{\omega_1,\mathcal{Q}_5,\mathcal{Q}_1,\zeta,\mathcal{U}_2\}$ $\{\mathcal{U}_5,\Pi_7,\Pi_7,\omega_1,\mathcal{X}\}\quad\{\mathcal{U}_5,\Pi_7,\Pi_7,\mathcal{U}_2,\mathcal{X}\}$
$\mathcal{O}_{eu}+\mathcal{O}_{qe}$ $-\mathcal{O}_{lu}-\mathcal{O}_{lq}^{(1)}$	$\{\omega_1,\mathcal{Q}_5,\Pi_7,\omega_1,\mathcal{X}\}\quad\{\omega_1,\mathcal{Q}_5,\Pi_7,\mathcal{U}_2,\mathcal{X}\}$ $\{\mathcal{U}_5,\Pi_7,\mathcal{Q}_1,\omega_1,\zeta\}\quad\{\mathcal{U}_5,\Pi_7,\mathcal{Q}_1,\zeta,\mathcal{U}_2\}$

(assuming a single coupling to the SM for each new particle)

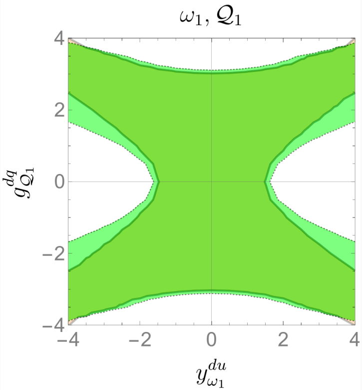
Example 1

- $\omega_1 \sim (3,1)_{-1/3}$ (a scalar leptoquark)
- $\mathcal{Q}_1 \sim (3,1)_{1/6}$ (a vector leptoquark)

$$\mathcal{L}_{UV} = g^{ud}_{\omega_1} \epsilon_{ABC} \omega_1^{A\dagger} \bar{d}^B_R u^{c\,C}_R + y^{dq}_{\mathcal{Q}_1} \epsilon_{ABC} \mathcal{Q}_1^{A\mu\dagger} \bar{d}^B_R \gamma_\mu i\sigma_2 q^{c\,C}_L + \text{h.c.}$$

$\hookrightarrow$ May arise in GUTs and models for flavor anomalies

Blind direction: $\boxed{\dfrac{|y^{du}_{\omega_1}|}{M_{\omega_1}} \simeq \sqrt{2}\dfrac{|g^{dq}_{\mathcal{Q}_1}|}{M_{\mathcal{Q}_1}}}$



(using current constraints)

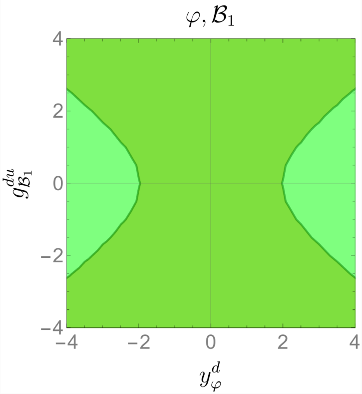
Example 2

- $\varphi \sim (1,2)_{1/2}$ (a second Higgs doublet)
- $\mathcal{B}_1 \sim (1,1)_1$ (a W')

$$\mathcal{L}_{UV} = y^d_\varphi \varphi^\dagger \bar{d}_R q_L + g^{du}_{\mathcal{B}_1} \mathcal{B}^\dagger_{1\,\mu} \bar{d}_R \gamma_\mu u_R + \text{h.c.}$$

$\hookrightarrow$ May arise in left-right SUSY models

Blind direction: $\boxed{\dfrac{|y^d_\varphi|}{M_\varphi} \simeq \sqrt{2}\dfrac{|g^{du}_{\mathcal{B}_1}|}{M_{\mathcal{B}_1}}}$



(using current constraints)

Example 3

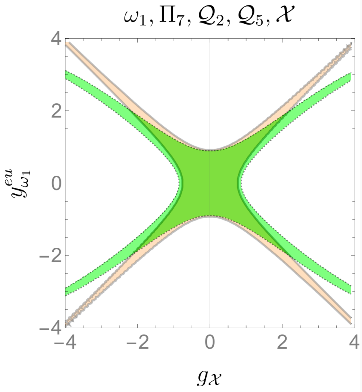
5 leptoquarks:

- Scalars: $\omega_1 \sim (3,1)_{-1/3}$ and $\Pi_7 \sim (3,2)_{7/6}$,
- Vectors: $\mathcal{U}_2 \sim (3,1)_{2/3}$, $\mathcal{Q}_5 \sim (3,2)_{-5/6}$ and $\mathcal{X} \sim (3,3)_{2/3}$

$\hookrightarrow$ May arise in GUTs

Blind direction:

$$\boxed{\frac{|y^{eu}_{\omega_1}|}{M_{\omega_1}} \sim \sqrt{2}\frac{|g^{eq}_{\mathcal{Q}_5}|}{M_{\mathcal{Q}_5}} \sim \frac{|y^{lu}_{\Pi_7}|}{M_{\Pi_7}} \sim 2\frac{|g^{lq}_{\mathcal{U}_2}|}{M_{\mathcal{U}_2}} \sim \frac{|g_{\mathcal{X}}|}{M_{\mathcal{X}}}.}$$



(using current constraints)

Summary

- SMEFT parameter space $\gg \#$ of EWPOs $\implies$ blind directions
- EWPOs are sensitive to many single-particle extensions
- However, other single-particle extensions only generate operators with negligible contributions to EWPO
- Additionally, multi-particle extensions may generate combinations of operators along blind directions
- Measurements at higher energies and different kinematic regimes are required to resolve these degeneracies