Exploring constraints on νSMEFT coefficients in the presence of an extra $\mathrm{U}'(1)$

Nicola Losacco

Dipartimento Interateneo di Fisica "M. Merlin", Università e Politecnico di Bari,
Istituto Nazionale di Fisica Nucleare, Sezione di Bari

2-6 December 2024

DISCRETE 2024 in Ljubljana

Based on: Constraining vSMEFT coefficients: The case of the extra U(1)′, Phys. Rev. D 110 (2024), no. 3 035007,
P. Colangelo, F. De Fazio, F. Loparco, and N. L.

Motivations to physics beyond the SM

The Standard Model

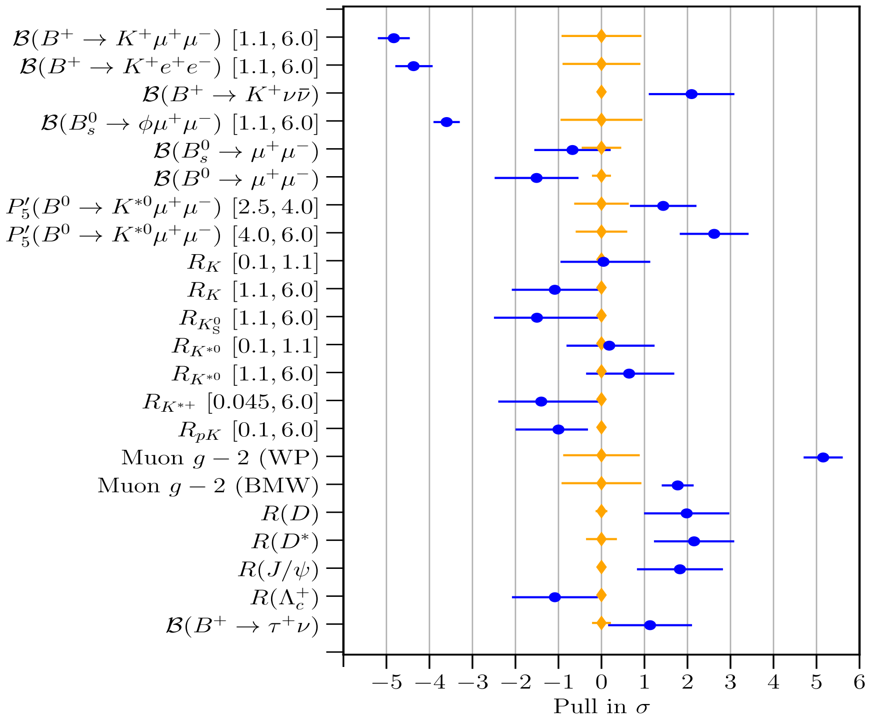
Successes

- All predicted particles have been discovered
- The features of fundamental interactions correctly described

Unsolved issues

- Gravity not included
- No dark matter explanation
- Neutrino masses
- CP asymmetry not sufficient to explain the observed universe
- Instability of the Higgs mass under radiative correction
- Hierarchy among the fermion masses

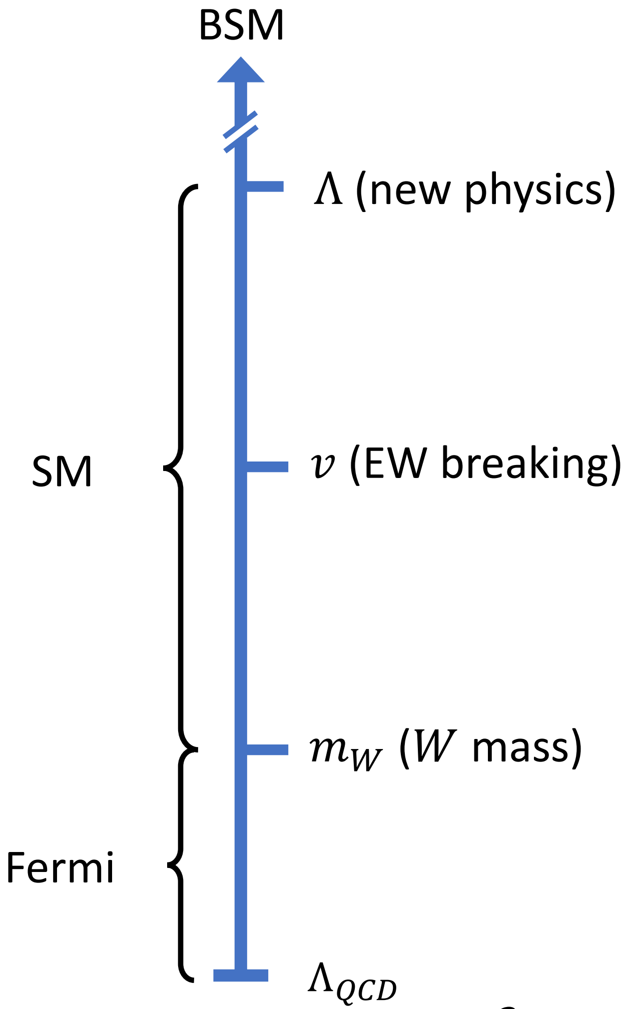
Flavour anomalies



Furthermore, several anomalies in the flavour sector

No results from direct searches at colliders → Effective field theories help explore virtual effects

Standard Model as an Effective Field Theory



SM as low energy theory of a more fundamental one

Unknown BSM theory

Extention of the SM Lagrangian with higher dimensional operators weighted by Λ^{-n}

Dimensionless Wilson Coefficients

For $\mu \ll \Lambda$

$$\mathcal{L}_{\nu SMEFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Invariant under $\mathcal{G}_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$

d dimension operators only SM fields

A simple extension: $U(1)'$

$$\mathcal{G}_{BSM} = \mathcal{G}_{SM} \times U(1)'$$

Z' New gauge field
g_Z Gauge coupling
z_ψ, z_H z-hypercharges of fermions and Higgs

For $\mu \sim \Lambda$

UV Lagrangian involving Z': $\mathcal{L}^{Z'} = \mathcal{L}^{Z'}_{\text{free}} + \mathcal{L}^{Z'}_{\text{int,fermions}} + \mathcal{L}^{Z'}_{\varphi}$

Free term $$\mathcal{L}^{Z'}_{\text{free}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu \qquad Z'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$$

$M_{Z'}$: mass of the Z' after SSB

Fermion interaction

$$\mathcal{L}^{Z'}_{\text{int,fermions}} = \sum_\psi g_Z\, z_\psi\, \bar\psi \gamma^\mu \psi\, Z'_\mu = \sum_\psi \left[\left(\Delta^\psi_L\right)^{ij} \bar\psi^i_L \gamma^\mu \psi^j_L + \left(\Delta^\psi_R\right)^{ij} \bar\psi^i_R \gamma^\mu \psi^j_R \right] Z'_\mu$$

$$\left(\Delta^\psi_{L,R}\right)^{ij} = g_Z\, z_\psi\, \delta^{ij}$$

Higgs interaction

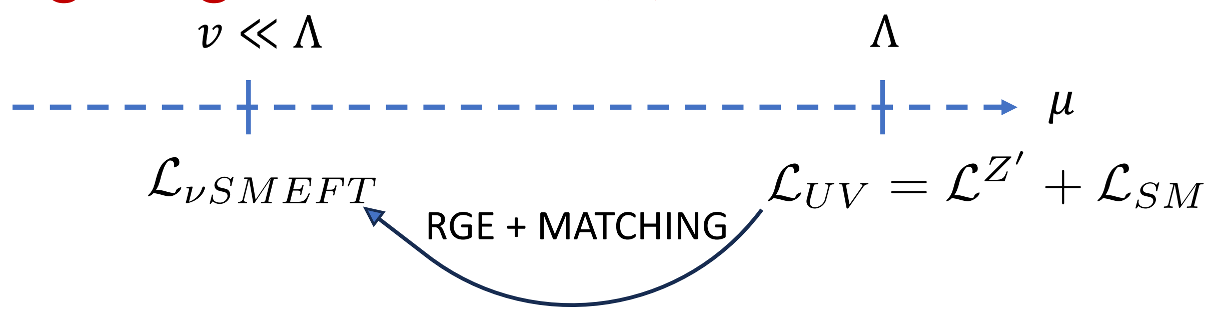
$$\mathcal{L}^{Z'}_{\varphi} = g_H \left(\varphi^\dagger\, i \overleftrightarrow{D}_\mu\, \varphi \right) Z'^\mu$$

$$g_H = g_Z\, z_H$$

D_μ is the SM covariant derivative

$$\varphi^\dagger\, i \overleftrightarrow{D}_\mu\, \varphi = \varphi^\dagger \left(i\, D_\mu\, \varphi\right) - \left(i\, D_\mu\, \varphi^\dagger\right) \varphi$$

νSMEFT Lagrangian from $U(1)'$ extension



νSMEFT operators of $d = 6$ dimension after Z' integration

B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, JHEP 1010, 085 (2010) Y. Liao and X.-D. Ma, Phys. Rev. D 96, 015012 (2017)

$$
\begin{aligned}
\mathcal{L}^{(6)}_{Z'} \;=\;& C_{\ell\ell}\,\mathcal{O}_{\ell\ell} + C^{(1)}_{qq}\,\mathcal{O}^{(1)}_{qq} + C_{ee}\,\mathcal{O}_{ee} + C_{uu}\,\mathcal{O}_{uu} + C_{dd}\,\mathcal{O}_{dd} + C^{(6)}_{\nu\nu}\,\mathcal{O}^{(6)}_{\nu\nu} \\
&+ C^{(1)}_{\ell q}\,\mathcal{O}^{(1)}_{\ell q} + C^{(1)}_{ud}\,\mathcal{O}^{(1)}_{ud} + C_{eu}\,\mathcal{O}_{eu} + C_{ed}\,\mathcal{O}_{ed} + C_{\ell e}\,\mathcal{O}_{\ell e} + C_{\ell u}\,\mathcal{O}_{\ell u} \\
&+ C_{\ell d}\,\mathcal{O}_{\ell d} + C_{qe}\,\mathcal{O}_{qe} + C^{(1)}_{qu}\,\mathcal{O}^{(1)}_{qu} + C^{(1)}_{qd}\,\mathcal{O}^{(1)}_{qd} + C_{\nu e}\,\mathcal{O}_{\nu e} + C_{\nu u}\,\mathcal{O}_{\nu u} \\
&+ C_{\nu d}\,\mathcal{O}_{\nu d} + C_{\ell\nu}\,\mathcal{O}_{\ell\nu} + C_{q\nu}\,\mathcal{O}_{q\nu} + C_{\varphi\Box}\,\mathcal{O}_{\varphi\Box} + C_{\varphi D}\,\mathcal{O}_{\varphi D} + C_{e\varphi}\,\mathcal{O}_{e\varphi} \\
&+ C_{u\varphi}\,\mathcal{O}_{u\varphi} + C_{d\varphi}\,\mathcal{O}_{d\varphi} + C_{\nu\varphi}\,\mathcal{O}_{\nu\varphi} + C^{(1)}_{\varphi\ell}\,\mathcal{O}^{(1)}_{\varphi\ell} + C_{\varphi e}\,\mathcal{O}_{\varphi e} + C^{(1)}_{\varphi q}\,\mathcal{O}^{(1)}_{\varphi q} \\
&+ C_{\varphi u}\,\mathcal{O}_{\varphi u} + C_{\varphi d}\,\mathcal{O}_{\varphi d} + C_{\varphi\nu}\,\mathcal{O}_{\varphi\nu} + \text{h.c.}\,.
\end{aligned}
$$

Wilson coefficients depend on the parameter of the UV theory: g_Z, z_ψ, z_H and Z' mass

Blue terms are 0 for this extension

Relations from the gauge group structure

Few parameters to express all Wilson coefficients → Relations among them

Generation indices

$$\left[C_{\psi_1\psi_2}\right]_{ijkp} = \pm 2\sqrt{\left[C_{\psi_1\psi_1}\right]_{ijij}\left[C_{\psi_2\psi_2}\right]_{kpkp}}$$

$$\left[C_{\psi\psi}\right]_{ijkp} = \frac{\left[C_{\varphi\psi}\right]_{ij}\left[C_{\varphi\psi}\right]_{kp}}{C_{\varphi D}}$$

$$\left[C_{\psi_1\psi_2}\right]_{ijkp} = 2\,\frac{\left[C_{\varphi\psi_1}\right]_{ij}\left[C_{\varphi\psi_2}\right]_{kp}}{C_{\varphi D}}$$

Wilson coefficient $\neq 0$ only if $i = j$ and $k = p$

Relations from the gauge group structure

Defining $\underline{i} = ii$

Coefficients structure synthetized

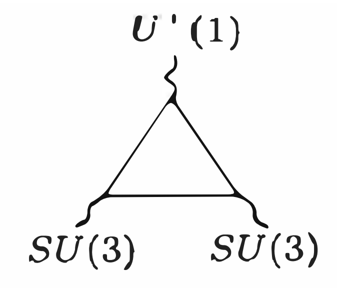
$$C_{\varphi\psi} = \begin{pmatrix} [C_{\varphi\psi}]_{\underline{1}} & [C_{\varphi\psi}]_{\underline{2}} & [C_{\varphi\psi}]_{\underline{3}} \end{pmatrix}$$

$$C_{\psi\psi} = \frac{1}{C_{\varphi D}} \begin{pmatrix} \left([C_{\varphi\psi}]_{\underline{1}}\right)^2 & [C_{\varphi\psi}]_{\underline{1}} [C_{\varphi\psi}]_{\underline{2}} & [C_{\varphi\psi}]_{\underline{1}} [C_{\varphi\psi}]_{\underline{3}} \\ [C_{\varphi\psi}]_{\underline{2}} [C_{\varphi\psi}]_{\underline{1}} & \left([C_{\varphi\psi}]_{\underline{2}}\right)^2 & [C_{\varphi\psi}]_{\underline{2}} [C_{\varphi\psi}]_{\underline{3}} \\ [C_{\varphi\psi}]_{\underline{3}} [C_{\varphi\psi}]_{\underline{1}} & [C_{\varphi\psi}]_{\underline{3}} [C_{\varphi\psi}]_{\underline{2}} & \left([C_{\varphi\psi}]_{\underline{3}}\right)^2 \end{pmatrix}$$

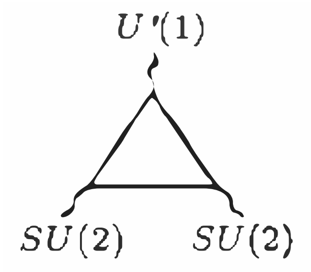
$$C_{\psi_1\psi_2} = \frac{2}{C_{\varphi D}} \begin{pmatrix} [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{1}} [C_{\varphi\psi_2}]_{\underline{3}} \\ [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{2}} [C_{\varphi\psi_2}]_{\underline{3}} \\ [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{1}} & [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{2}} & [C_{\varphi\psi_1}]_{\underline{3}} [C_{\varphi\psi_2}]_{\underline{3}} \end{pmatrix}$$

Constraints from Anomaly Cancellation Equations (ACE)

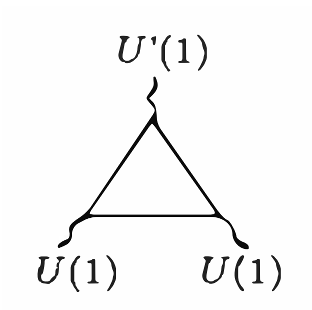
$$z_\psi^{(n)} = \sum_{i=1}^{3} z_{\psi_i}^{n}$$



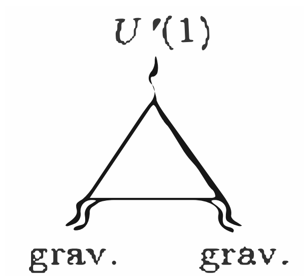
$$A_{33z} = 2\, z_q^{(1)} - z_u^{(1)} - z_d^{(1)} = 0$$



$$A_{22z} = 3\, z_q^{(1)} + z_\ell^{(1)} = 0$$

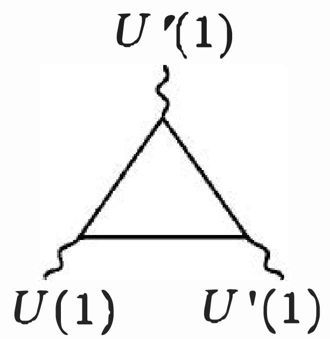


$$A_{11z} = \frac{1}{6}\, z_q^{(1)} - \frac{4}{3}\, z_u^{(1)} - \frac{1}{3}\, z_d^{(1)} + \frac{1}{2}\, z_\ell^{(1)} - z_e^{(1)} = 0$$

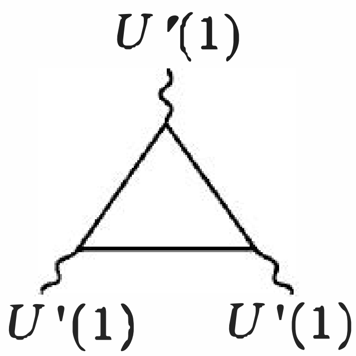


$$A_{GGz} = 2\, z_\ell^{(1)} - z_e^{(1)} - z_\nu^{(1)} = 0$$

Constraints from Anomaly Cancellation



$$A_{1zz} = [z_q^{(2)} - 2\, z_u^{(2)} + z_d^{(2)}] - [z_\ell^{(2)} - z_e^{(2)}] = 0$$



$$A_{zzz} = 3\,[2\, z_q^{(3)} - z_u^{(3)} - z_d^{(3)}] + [2\, z_\ell^{(3)} - z_\nu^{(3)} - z_e^{(3)}] = 0$$

Relations among coefficients

$$\tilde{C}^{(n)}_{\varphi\psi} = \sum_{\underline{i}=\underline{1}}^{3} \left(\left[C_{\varphi\psi}\right]_{\underline{i}}\right)^n \qquad \underline{i} = ii$$

z-hypercharge dependence

$$z_{\psi_i} = -\frac{M^2_{Z'}}{g_Z}\,\frac{1}{g_H}\left[C_{\varphi\psi}\right]_{\underline{i}} \quad \Rightarrow \quad z^{(n)}_{\psi} = \left(-\frac{M^2_{Z'}}{g_Z}\,\frac{1}{g_H}\right)^n \tilde{C}^{(n)}_{\varphi\psi}$$

$$A_{33z} \to 2\,\tilde{C}_{\varphi q} - \tilde{C}_{\varphi u} - \tilde{C}_{\varphi d} = 0$$

$$A_{22z} \to 3\,\tilde{C}_{\varphi q} + \tilde{C}_{\varphi \ell} = 0$$

$$A_{11z} \to \tilde{C}_{\varphi q} - 8\,\tilde{C}_{\varphi u} - 2\,\tilde{C}_{\varphi d} + 3\,\tilde{C}_{\varphi \ell} - 6\,\tilde{C}_{\varphi e} = 0$$

$$A_{GGz} \to 2\,\tilde{C}_{\varphi \ell} - \tilde{C}_{\varphi e} - \tilde{C}_{\varphi \nu} = 0$$

$$\tilde{C}_{\varphi q} = \frac{\tilde{C}_{\varphi u}+\tilde{C}_{\varphi d}}{2}$$

$$\tilde{C}_{\varphi \ell} = -3\,\tilde{C}_{\varphi q} = -3\,\frac{\tilde{C}_{\varphi u}+\tilde{C}_{\varphi d}}{2}$$

$$\tilde{C}_{\varphi e} = -2\,\tilde{C}_{\varphi u} - \tilde{C}_{\varphi d}$$

$$\tilde{C}_{\varphi \nu} = -\tilde{C}_{\varphi u} - 2\,\tilde{C}_{\varphi d}$$

$$A_{1zz} \to \tilde{C}^{(2)}_{\varphi q} - 2\,\tilde{C}^{(2)}_{\varphi u} + \tilde{C}^{(2)}_{\varphi d} - \tilde{C}^{(2)}_{\varphi \ell} + \tilde{C}^{(2)}_{\varphi e} = 0$$

$$A_{zzz} \to 3\,[2\,\tilde{C}^{(3)}_{\varphi q} - \tilde{C}^{(3)}_{\varphi u} - \tilde{C}^{(3)}_{\varphi d}] + [2\,\tilde{C}^{(3)}_{\varphi \ell} - \tilde{C}^{(3)}_{\varphi \nu} - \tilde{C}^{(3)}_{\varphi e}] = 0$$

Example I:

Z' universal and only coupled to the third generation

Universal coupling

$$z_{\psi_1} = z_{\psi_2} = z_{\psi_3} = z_\psi$$

$$[C_{\varphi\psi}]_{\underline{1}} = [C_{\varphi\psi}]_{\underline{2}} = $$
$$= [C_{\varphi\psi}]_{\underline{3}} = \bar{C}_{\varphi\psi}$$

$$\tilde{C}^{(n)}_{\varphi\psi} = 3\left(\bar{C}_{\varphi\psi}\right)^n$$

Only third generation coupling:

$$z_{\psi_3} = z_\psi$$
$$z_{\psi_1} = z_{\psi_2} = 0$$

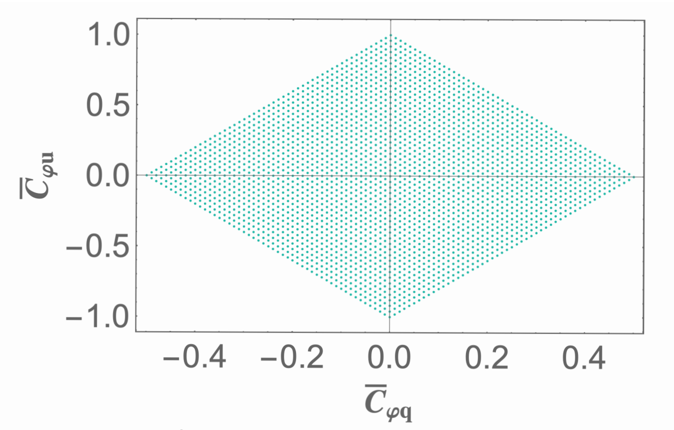
$$[C_{\varphi\psi}]_{\underline{1}} = [C_{\varphi\psi}]_{\underline{2}} = 0$$
$$[C_{\varphi\psi}]_{\underline{3}} = \bar{C}_{\varphi\psi}$$

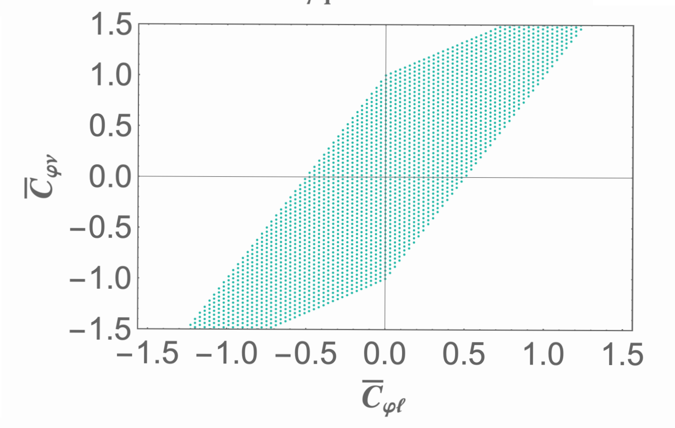
$$\tilde{C}^{(n)}_{\varphi\psi} = \left(\bar{C}_{\varphi\psi}\right)^n$$

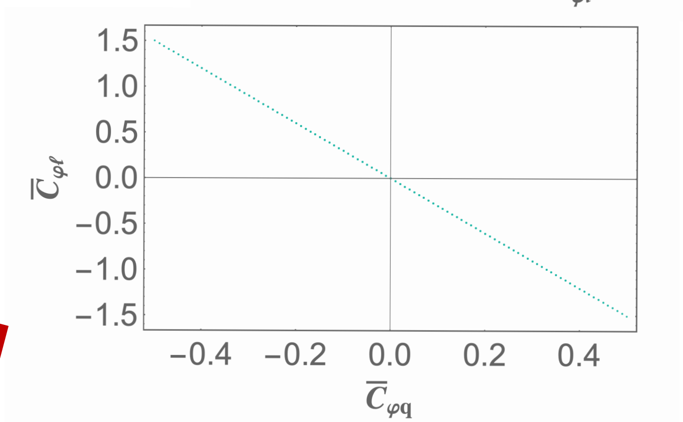
Same constraints from the linear ACE

6 coefficients and 4 linear relations

Correlation plots varying $\bar{C}_{\varphi d}, \bar{C}_{\varphi e} \in [-1, 1]$







Example II:

Z' only coupled to left-handed fermions

Only left-handed coupling

$z_{\ell_i} \neq 0 \qquad z_{q_i} \neq 0$ → 6 parameters

↓

2 constraints from linear ACE → $\tilde{C}_{\varphi q} = \tilde{C}_{\varphi \ell} = 0$

↓

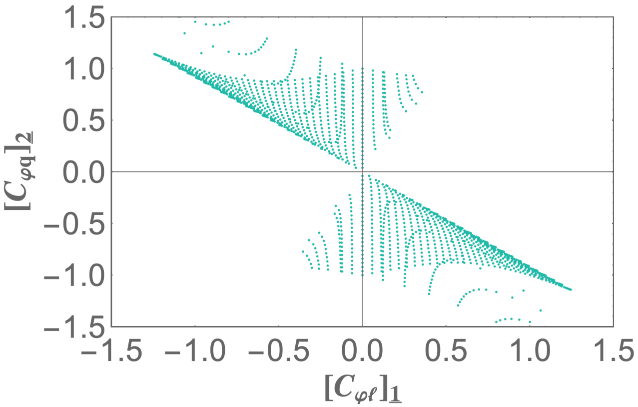
2 constraints from quadratic and cubic ACE

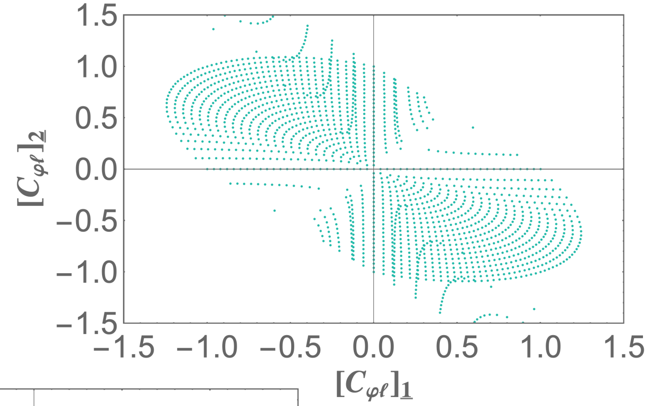
↓

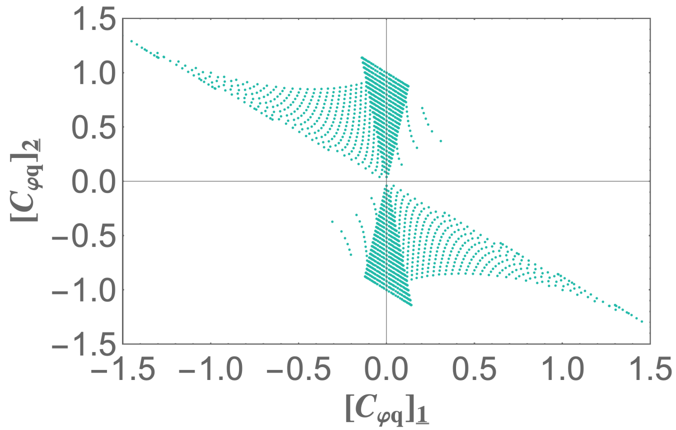
6 coefficients and 4 constraints

Correlation plots varying

$$[C_{\varphi q}]_{\underline{3}}\,, [C_{\varphi \ell}]_{\underline{3}} \in [-1, 1]$$







Correlations among coefficients produce correlations among observables

Conclusions and perspectives

SM might not be the ultimate theory

LO of an EFT ➡ SMEFT/νSMEFT

Effects of new physics
in its parameters

⬇

Constrained by experiments or
theoretical assumptions

Explored U(1)′ with νSMEFT :

- Gauge structure ➡ relations between coefficients
- Gauge anomaly cancellations significantly narrow down coefficients space

Results guide experimental searches and global fits

Future Work: Include experimental data to refine constraints.

THANKS

FOR YOUR

ATTENTION