CP violation and precise D-measurement

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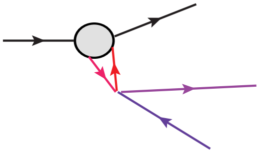
$D_{\rm BSM}$ in EFT

Effective Field Theory (EFT): Heavy dynamics in $\epsilon \sim \frac{M_W^2}{M_{\rm BSM}}$



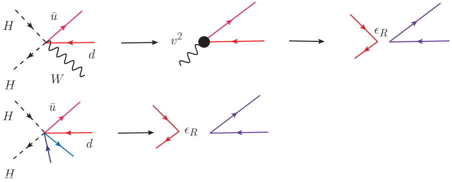
$$\mathcal{L}_{\rm WEFT} \supset -\frac{V_{ud}}{v^2}\Big\{ (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \epsilon_R\, \bar{e}\gamma_\mu\nu_L \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \frac{1}{2}\epsilon_T\ \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}d + \epsilon_S\, \bar{e}\nu_L \cdot \bar{u}d - \epsilon_P\, \bar{e}\nu_L \cdot \bar{u}\gamma_5 d \Big\} + \text{h.c.}$$

$$D \approx \kappa_D\, \mathrm{Im}\Big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\Big]$$

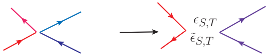
D_{BSM} in EFT

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

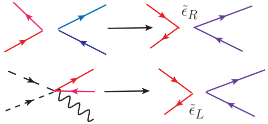
Scenario I



Scenario II,III



Scenario IV



Leptoquarks

- SM: no vertices with both quarks and leptons
- Leptoquark: BSM boson with quark-lepton vertices
- Taking into account symmetries, limited possibilities

Name	Representation	Name	Representation	SM	Representation
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$	U_1	$(\mathbf{3}, \mathbf{1}, \mathbf{2/3})$	q	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6})$
$\bar{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3})$	$\bar{U}_1$	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$	u	$(\mathbf{3}, \mathbf{1}, \mathbf{2/3})$
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{4/3})$	$\tilde{U}_1$	$(\mathbf{3}, \mathbf{1}, \mathbf{5/3})$	d	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$
R_2	$(\mathbf{3}, \mathbf{2}, \mathbf{7/6})$	V_2	$(\bar{\mathbf{3}}, \mathbf{2}, \mathbf{5/6})$	l	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2})$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6})$	$\tilde{V}_2$	$(\bar{\mathbf{3}}, \mathbf{2}, -\mathbf{1/6})$	e	$(\mathbf{1}, \mathbf{1}, -\mathbf{1})$
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1/3})$	U_3	$(\mathbf{3}, \mathbf{3}, \mathbf{2/3})$	H	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2})$

For example see Phys.Rept. 641 (2016) 1-68

Scalar Leptoquarks

Name	Spin	Representation	Currents
S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$	$ql,\ \bar{u}^c\bar{e}^c,\ \bar{d}^c\bar{\nu}^c$
$\bar{S}_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3})$	$\bar{u}^c\bar{\nu}^c$
$\tilde{S}_1$	0	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{4/3})$	$\bar{d}^c\bar{e}^c$
R_2	0	$(\mathbf{3}, \mathbf{2}, \mathbf{7/6})$	$u^c l,\ \bar{q}\bar{e}^c$
$\tilde{R}_2$	0	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6})$	$d^c l,\ \bar{q}\bar{\nu}^c$

Some can mix after symmetry breaking

$$\Delta\mathcal{L}_{\text{leptoquark}} = \lambda_{RR}(R_2^\dagger H)(\tilde{H}^\dagger \tilde{R}_2)$$

Vector Leptoquarks

Name	Spin	Representation	Currents
U_1	1	$(\mathbf{3}, \mathbf{1}, \mathbf{2/3})$	$\bar{q}\bar{\sigma}^\mu l$, $d^c\sigma^\mu\bar{e}^c$, $u^c\sigma^\mu\bar{\nu}^c$
$\bar{U}_1$	1	$(\mathbf{3}, \mathbf{1}, \mathbf{-1/3})$	$d^c\sigma^\mu\bar{\nu}^c$
$\tilde{U}_1$	1	$(\mathbf{3}, \mathbf{1}, \mathbf{5/3})$	$u^c\sigma^\mu\bar{e}^c$
V_2	1	$(\bar{\mathbf{3}}, \mathbf{2}, \mathbf{5/6})$	$l\sigma^\mu\bar{d}^c$, $q\sigma^\mu\bar{e}^c$
$\tilde{V}_2$	1	$(\bar{\mathbf{3}}, \mathbf{2}, \mathbf{-1/6})$	$l\sigma^\mu\bar{u}^c$, $q\sigma^\mu\bar{\nu}^c$
U_3	1	$(\mathbf{3}, \mathbf{3}, \mathbf{2/3})$	$\bar{q}\sigma^k\bar{\sigma}^\mu l$

Some can mix after symmetry breaking

$$\Delta\mathcal{L}_{\text{leptoquark}} = \lambda_{VV}(V_2^\dagger H)(\tilde{H}^\dagger \tilde{V}_2)$$

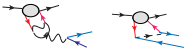
Motivations for leptoquarks

Original motivations. Elegance, simplicity.

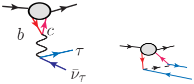
- Grand unification
- Supersymmetry
- Technicolor

Modern motivations: Flavor anomalies

- $B \to K l^+ l^-$



- $B \to D \tau \bar{\nu}$



Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

Phys.Rev.D 104 (2021) 5, 055017

- Muon g-2 JHEP 06 (2020) 089

Leptoquarks for D

Models that explain flavor anomalies are related to different families

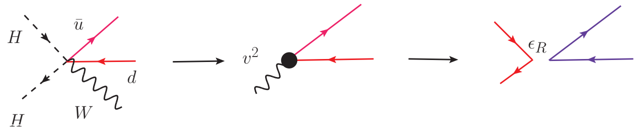
$$\text{Scalars: } \{S_1, \bar{S}_1, \tilde{S}_1, R_2, \tilde{R}_2, S_3\}$$
$$\text{Vectors: } \{U_1, \bar{U}_1, \tilde{U}_1, V_2, \tilde{V}_2, V_3\}$$

Only blue leptoquarks can generate (CP-violating) D

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

Scenario Ia

✗ →

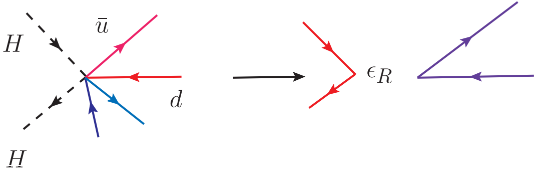


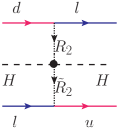
Not generated from leptoquarks at tree level

Leptoquarks contributing to D

$$D \approx \kappa_D \,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

Scenario Ib: Imϵ_R from $D = 8$ SMEFT





$$C_8 = -\frac{\lambda_{RR}\, y_{Rul}\, \bar{y}_{Rdl}}{2M_{R_2}^2 M_{\tilde{R}_2}^2}$$

$$D \approx \frac{\kappa_D}{4}\,\mathrm{Im}\left[v^4 C_8\right]$$

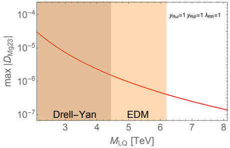
Similar result for V_2-$\tilde{V}_2$

Prog. Part. Nucl. Phys. 46, 413

Limited by

- EDM 
- LHC

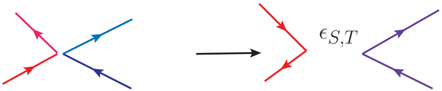
Phys.Rev.D 85 (2012) 033001



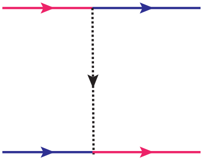
Leptoquarks contributing to D

$$D \approx \kappa_D \,\mathrm{Im}\big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\big]$$

Scenario II



Simple mechanism, many models



S_1-R_2, U_1-S_1, U_1-R_2, V_2-S_1, V_2-R_2. Example

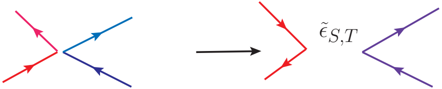
$$D \approx 0.1\kappa_D \frac{v^4}{M_{S_1^2} M_{R_2}^2} \mathrm{Im}\left[y_{Sue}\bar{y}_{Sql}y_{Rqe}\bar{y}_{Rul}\right]$$

But EDM sets $D < |10|^{-14}$ for any JHEP 01 (2019) 069, JHEP 07 (2021) 107

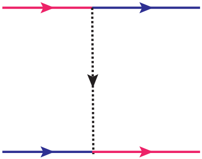
Leptoquarks contributing to D

$$D \approx \kappa_D \, \mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\right]$$

Scenario III



Simple mechanism, many models



S_1-$\tilde{R}_2$ U_1-S_1, U_1-$\tilde{R}_2$, $\tilde{V}_2$-S_1, or $\tilde{V}_2$-$\tilde{R}_2$. Example

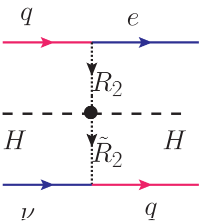
$$D \approx 0.1\kappa_D \frac{v^4}{M_{S_1}^2 M_{\tilde{R}_2}^2} \mathrm{Im}\left[y_{Sd\nu}\bar{y}_{Sql}\bar{y}_{Rq\nu}y_{Rdl}\right]$$

But again $D < |10|^{-7}$ (pion decay)

Leptoquarks contributing to D

Scenario IV: $\mathrm{Im}[\tilde{\epsilon}_R \tilde{\epsilon}_L^*]$

- $\tilde{\epsilon}_R$ induced by e.g. S or U
- $\tilde{\epsilon}_L = 0$ in tree-level leptoquarks at $D = 6$ SMEFT level.
- Yet induced by $R_2 - \tilde{R}_2$ and as in Scenario Ib.



Limited by

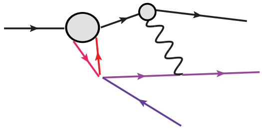
- EDM
- LHC

Phys.Rev.D 85 (2012) 033001 Yet suppressed by $1/M_{LQ}^6$

$|D| < 10^{-5}$

CP conserving $D_{\rm BSM}$: EFT

- Extra contributions to D arise from Coulomb re-scattering



- Couplings receive phase shift $C_X^\pm \to C_X^\pm e^{i\Delta_{\mathcal{N}'}\delta_X^\pm}$
- $\Delta_{\mathcal{N}'} = \frac{Z_{\mathcal{N}'}\alpha m_e}{2p_e}$ is not very small for $Z = 11$
- $D_{\rm SM} = 0$ yet at this level (extra recoil suppression)
- But $D \neq 0$ if nonstandard currents are there Treiman '57

$$D \approx \mp \frac{Z_{\mathcal{N}'}\kappa_D \alpha}{2}\frac{m_e}{p_e}\left[g_S\epsilon_S + \frac{g_T}{g_A}\epsilon_T + g_S\tilde{\epsilon}_S(\tilde{\epsilon}_R - \tilde{\epsilon}_L) + \frac{g_T}{g_A}(\tilde{\epsilon}_R + \tilde{\epsilon}_L)\tilde{\epsilon}_T\right]$$

- $\Delta D \sim 10^{-5}$ could test ϵ_S and ϵ_T at the level of the most precise CP conserving probes

CP conserving D_{BSM}: from EFT to leptoquarks

- $\Delta D \sim 10^{-5}$ could test ϵ_S and ϵ_T at the level of the most precise CP conserving β probes
- In practice bound in ϵ_T more interesting
- Similar bounds from LHC, slightly worse from electron $g-2$
- A minimal leptoquark model inducing it could contain S_1-R_2

$$\mathcal{L} = y_1 \left(S_1 q \pm R_2 u^c\right) \tilde{l} + y_2 \left(S_1 u \mp R_2 \bar{q}\right) \bar{e}^c + \mathrm{h.c.}\,,$$

so that $\epsilon_T = \frac{y_1 y_2}{2V_{ud}} \frac{v^2}{M^2}$. Leptoquark with masses of $\sim 10\,\mathrm{TeV}$ would be tested

Conclusions

- Systematic study of T-odd $D_{\rm BSM}$ from EFT to leptoquarks
- Many possible ways of generating D with leptoquarks
- But realistic leptoquark models always predict $|D| < 10^{-5}$
- On the other hand there are recoil-enhanced CP-even contributions for BSM interactions
  $D_{\text{CP-even}} \approx \mp \frac{Z_{\mathcal{N}'} \kappa_D \alpha}{2} \frac{m_e}{p_e} \left[g_S \epsilon_S + \frac{g_T}{g_A} \epsilon_T + g_S \tilde{\epsilon}_S (\tilde{\epsilon}_R - \tilde{\epsilon}_L) + \frac{g_T}{g_A} (\tilde{\epsilon}_R + \tilde{\epsilon}_L) \tilde{\epsilon}_T \right]$
- $D_{\rm Mg} \sim 10^{-5}$ may be competitive to test $\epsilon_{S,T} \sim 10^{-3}$