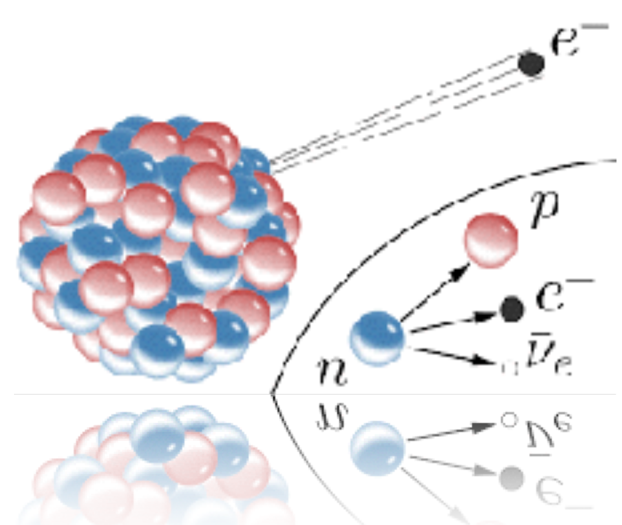
Adam Falkowski

CP violation and D parameter: EFT side

Jyväskylä, 03 May 2022



based on work to appear with Antonio Rodriguez-Sanchez, arXiv 2205.xxxx

Plan

1. **Ladder of effective field theories (EFTs) from high energies to the nuclear scale**

2. **D parameter in the language of EFT**

3. **Scenarios for the D parameter from the EFT perspective**

wait for Antonio's talk for concrete examples of leptoquark UV completions of the EFT

Ladder of EFTs: from high energies to the nuclear scale

EFT Ladder

Connecting high-energy physics to nuclear physics via a series of effective theories

"Fundamental" BSM model

? TeV

EFT for SM particles

100 GeV

EFT for Light Quarks

2 GeV

EFT for Hadrons

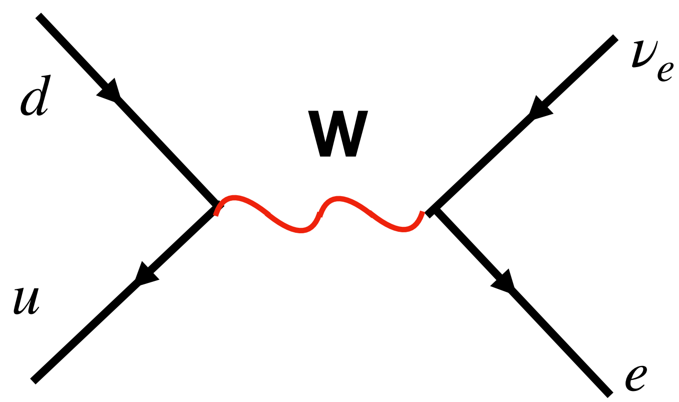
1 GeV

NR EFT for beta decay

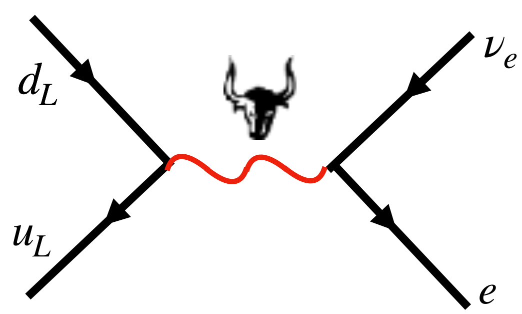
1 MeV

“Fundamental” models

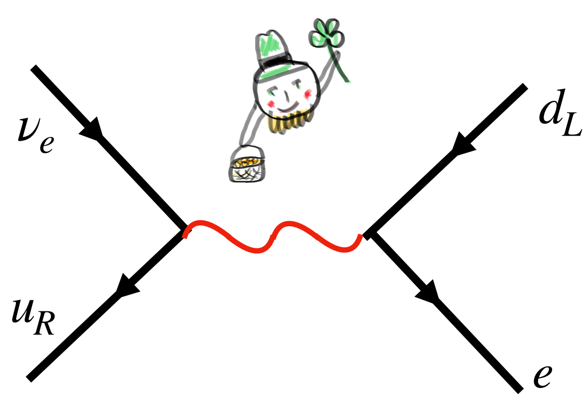
In the SM beta decay is mediated by the W boson



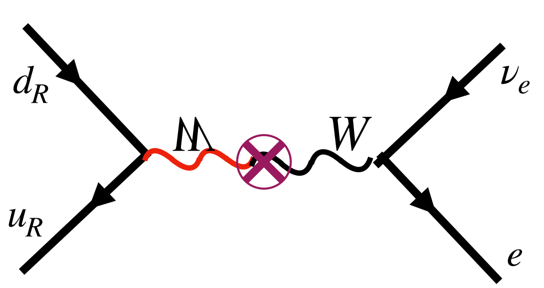
Several high-energy effects may contribute to beta decay



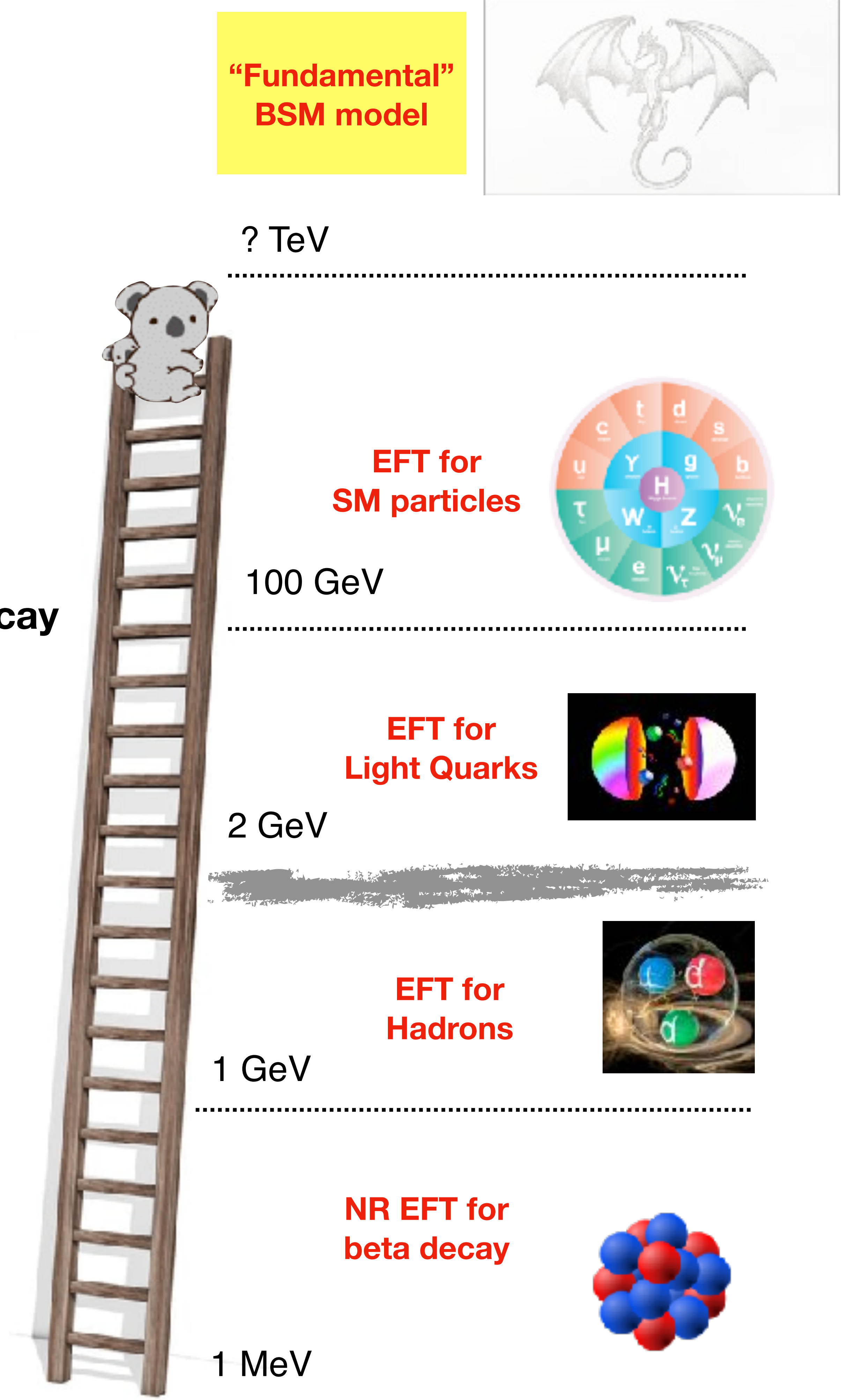
W’



Leptoquark



W_L-W_R mixing



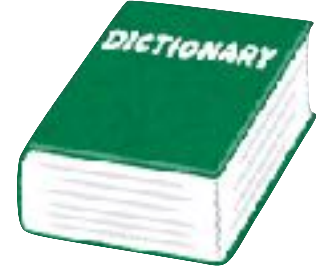
EFT at electroweak scale

$$\mathscr{L}_{\rm EFT} \supset iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c)$$
$$+ C^{(3)}_{lequ} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)$$
$$+ C^{(1)}_{lequ} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$$
$$+ C_{ledq} (\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q)$$
$$+ C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$$
$$+ \text{hc}$$

Above the electroweak scale ~100 GeV, interactions must be invariant under the full SM gauge group SU(3)xSU(2)xU(1)

Literally thousands of different interaction terms possible. Above, I'm only displaying a small subset most relevant for the D parameter

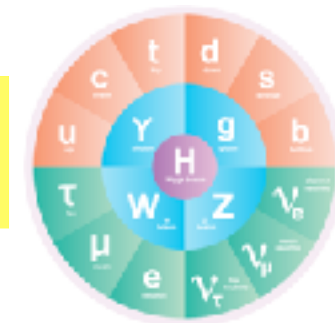
For any "fundamental" model, the Wilson coefficients C_i can be calculated in terms of masses and couplings of new particles at the high-scale



"Fundamental" BSM model

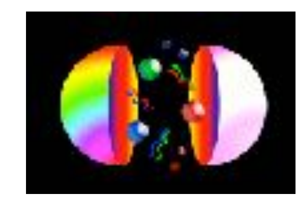
? TeV

EFT for SM particles



100 GeV

EFT for Light Quarks

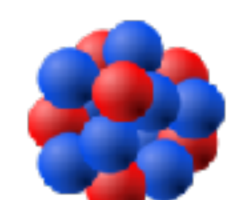


2 GeV

EFT for Hadrons

1 GeV

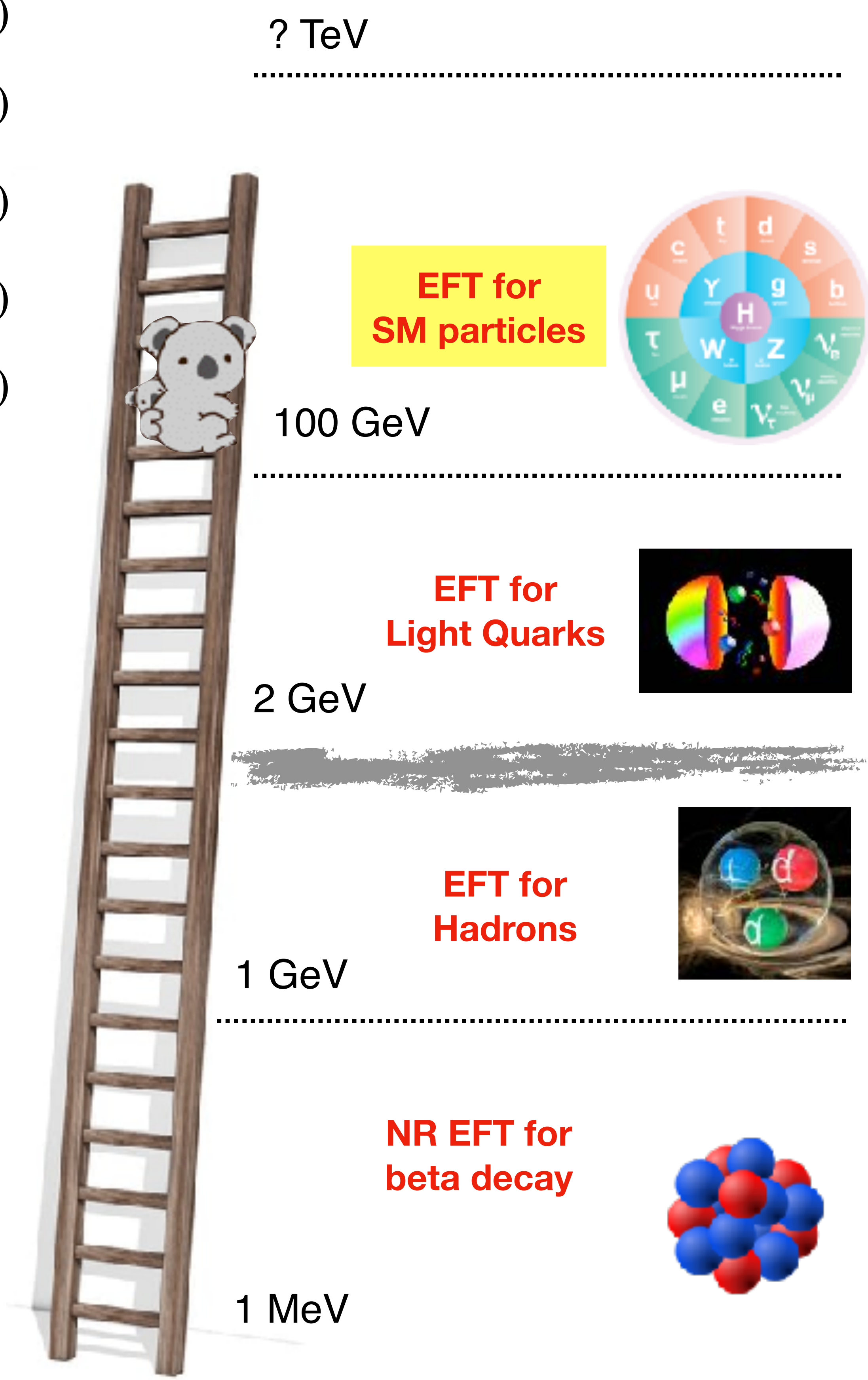
NR EFT for beta decay



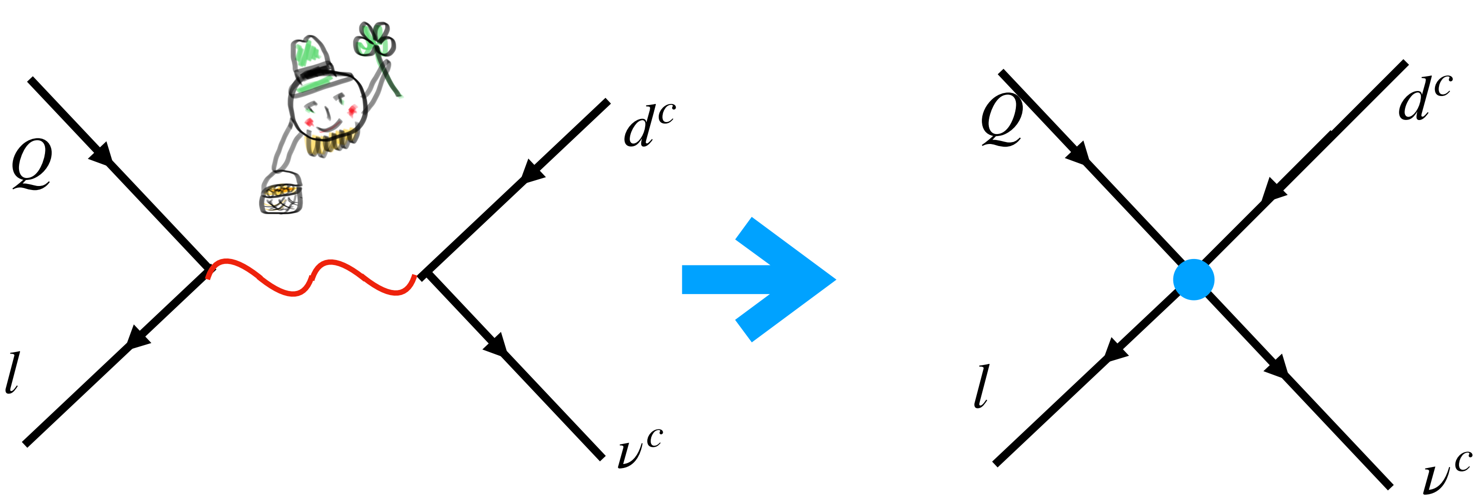
1 MeV

EFT at electroweak scale

$$\mathscr{L}_{\rm EFT} \supset iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c)$$
$$+ C^{(3)}_{lequ} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)$$
$$+ C^{(1)}_{lequ} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$$
$$+ C_{ledq} (\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q)$$
$$+ C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$$
$$+ \text{hc}$$



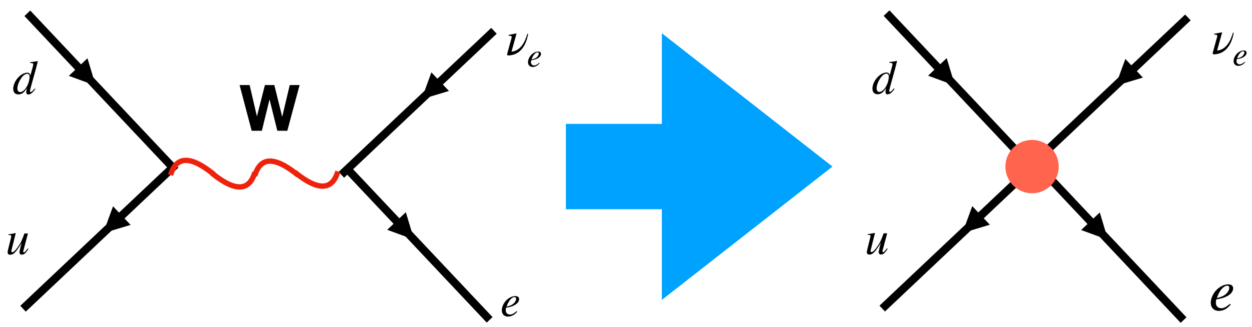
$$\mathscr{L} \supset y_L S_1 (Ql) + y_\nu S_1 (\bar{d}^c \bar{\nu}^c) + \text{hc}$$



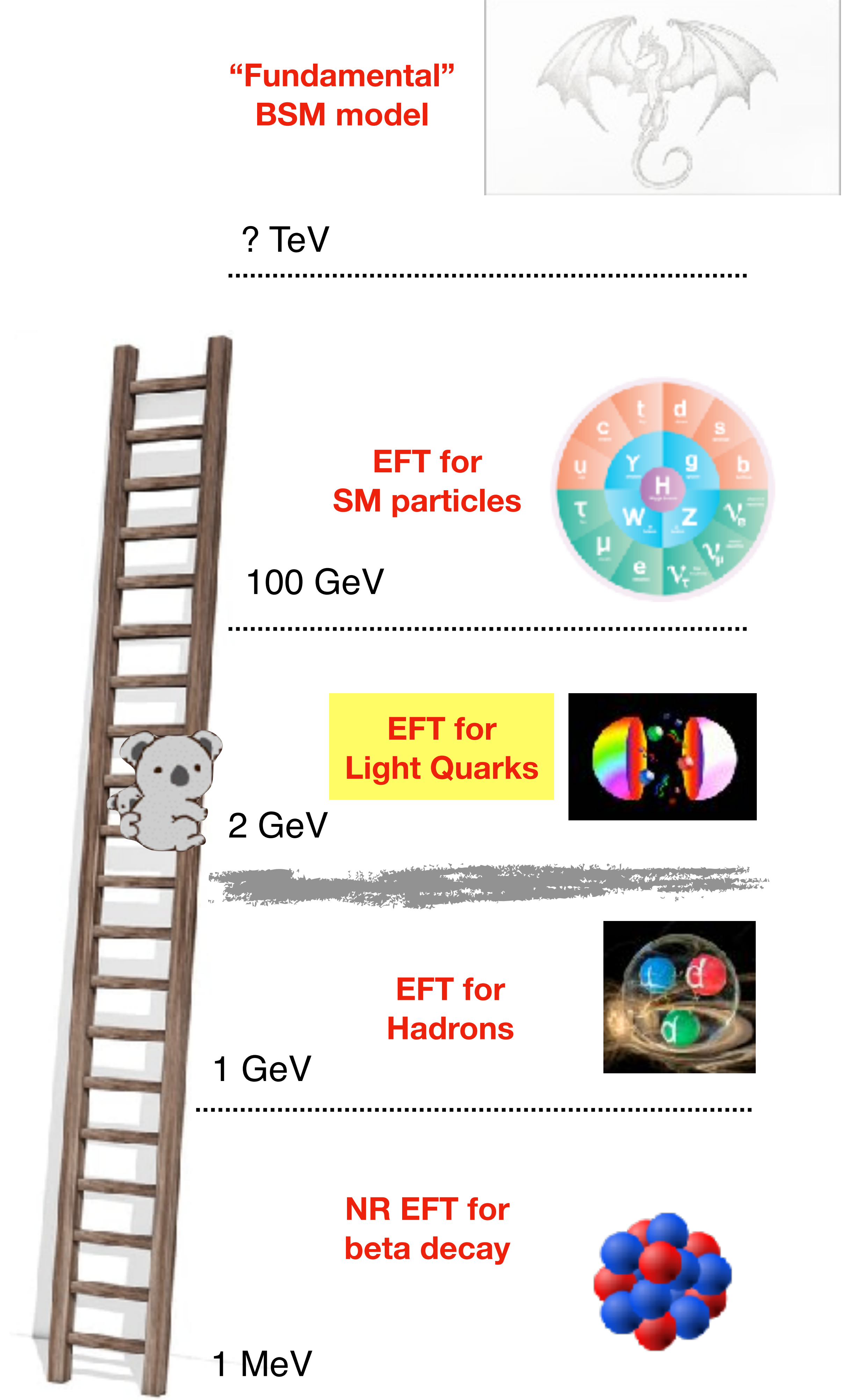
$$C^{(1)}_{l\nu qd}, C^{(3)}_{l\nu qd} \sim \frac{y_L y_\nu}{M^2_{LQ}}$$

EFT below electroweak scale

Below the electroweak scale, there is no W, thus all leading effects relevant for beta decays are described contact 4-fermion interactions, whether in SM or beyond the SM



Much simplified description, only 10 (in principle complex) parameters at leading order



Quark level effective Lagrangian

Effective Lagrangian defined at a low scale μ ~ 2 GeV

	Left-handed neutrino	Right-handed neutrino	
$\mathcal{L} \supset -\frac{2V_{ud}}{\mathrm{v}^2}\Big\{$	$(1+\epsilon_L)\ \bar{e}\bar{\sigma}_\mu\nu \cdot \bar{u}\bar{\sigma}^\mu d$	$+\ \tilde{\epsilon}_L\, e^c\sigma_\mu\bar{\nu}^c \cdot \bar{u}\bar{\sigma}^\mu d$	V-A
	$+\epsilon_R\, \bar{e}\bar{\sigma}_\mu\nu \cdot u^c\sigma^\mu\bar{d}^c$	$+\ \tilde{\epsilon}_R\, e^c\sigma_\mu\bar{\nu}^c u^c\sigma^\mu\bar{d}^c$	V+A
	$+\epsilon_T\frac{1}{4}e^c\sigma_{\mu\nu}\nu \cdot u^c\sigma^{\mu\nu}d$	$+\ \tilde{\epsilon}_T\frac{1}{4}\bar{e}^c\bar{\sigma}_{\mu\nu}\bar{\nu}^c \cdot \bar{u}\bar{\sigma}^{\mu\nu}\bar{d}^c$	Tensor
	$+\epsilon_S\frac{1}{2}e^c\nu \cdot (u^c d + \bar{u}\bar{d}^c)$	$+\ \tilde{\epsilon}_S\frac{1}{2}\bar{e}\bar{\nu}^c \cdot (u^c d + \bar{u}\bar{d}^c)$	Scalar
Pseudo-scalar	$+\epsilon_P\frac{1}{2}e^c\nu \cdot (u^c d - \bar{u}\bar{d}^c)$	$-\ \tilde{\epsilon}_P\frac{1}{2}\bar{e}\bar{\nu}^c \cdot (u^c d - \bar{u}\bar{d}^c)\Big\} + \mathrm{h.c.}$	

CKM element → V_{ud}

Normalization scale, set by Fermi constant → v^2

$$\mathrm{v} = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246\ \mathrm{GeV}$$

The Wilson coefficients of this EFT can be connected, to the Wilson coefficients above the electroweak scale, and consequently to masses and couplings of new heavy particles at the scale M :

$$\epsilon_X, \tilde{\epsilon}_X \sim \mathrm{v}^2 c_i \sim g_*^2\frac{\mathrm{v}^2}{M^2}$$

Translation from low-to-high energy EFT

Assuming lack of right-handed neutrinos, the EFT below the weak scale can be matched to the EFT above the weak scale

$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ (1+\epsilon_L)\; \bar e \bar\sigma_\mu \nu \cdot \bar u \bar\sigma^\mu d \;+\; \tilde\epsilon_L\, e^c \sigma_\mu \bar\nu^c \cdot \bar u \bar\sigma^\mu d$$
$$+\epsilon_R\, \bar e\bar\sigma_\mu\nu\cdot u^c\sigma^\mu \bar d^c \;+\; \tilde\epsilon_R\, e^c\sigma_\mu\bar\nu^c u^c\sigma^\mu\bar d^c$$
$$+\epsilon_T \frac{1}{4} e^c\sigma_{\mu\nu}\nu\cdot u^c\sigma^{\mu\nu} d \;+\; \tilde\epsilon_T \frac{1}{4} \bar e^c\bar\sigma_{\mu\nu}\bar\nu^c\cdot\bar u\bar\sigma^{\mu\nu}\bar d^c$$
$$+\epsilon_S\frac{1}{2} e^c\nu\cdot(u^c d+\bar u\bar d^c) \;+\; \tilde\epsilon_S \frac{1}{2} \bar e\bar\nu^c\cdot(u^c d+\bar u\bar d^c)$$
$$+\epsilon_P\frac{1}{2} e^c\nu\cdot(u^c d-\bar u\bar d^c) \;-\; \tilde\epsilon_P\frac{1}{2}\bar e\bar\nu^c\cdot(u^c d-\bar u\bar d^c)\Big\} + \mathrm{h.c.}$$

$$\mathcal{L}_{\rm EFT} \supset iC_{\phi ud} H D_\mu H (u^c\sigma^\mu\bar d^c) \;+\; iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c\sigma^\mu\bar\nu^c)$$
$$+C^{(3)}_{lequ}(\bar l\bar\sigma_{\mu\nu}\bar e^c)(\bar q\bar\sigma^{\mu\nu}\bar u^c) \;+\; C^{(3)}_{l\nu qd}(\bar l\bar\sigma^{\mu\nu}\bar\nu^c)(\bar q\bar\sigma_{\mu\nu}\bar d^c)$$
$$+C^{(1)}_{lequ}(\bar l\bar e^c)(\bar q\bar u^c) \;+\; C^{(1)}_{l\nu qd}(\bar l\bar\nu^c)(\bar q\bar d^c)$$
$$+C_{ledq}(\bar l\bar e^c)(d^c q) \;+\; C_{l\nu uq}(\bar l\bar\nu^c)(u^c q)$$
$$+C_{e\nu ud}(e^c\sigma^\mu\bar\nu^c)(u^c\sigma_\mu\bar d^c)$$
$$+\mathrm{hc}$$

At the scale mW, Wilson coefficients ϵ_X in one EFT can be mapped onto Wilson coefficients C_X in the other EFT

$$\epsilon_R = \frac{v^2}{2V_{ud}} C_{\phi ud} + \frac{v^4}{4V_{ud}} C_8$$

$$\epsilon_S = -\frac{v^2}{2V_{ud}}\left(C^{(1)*}_{lequ} + V_{ud} C^*_{ledq}\right)$$

$$\epsilon_P = -\frac{v^2}{2V_{ud}}\left(C^{(1)*}_{lequ} - V_{ud} C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2v^2}{V_{ud}} C^{(3)*}_{lequ}$$

$$\tilde\epsilon_L = -\frac{v^2}{2} C_{\phi e\nu}$$

$$\tilde\epsilon_R = -\frac{v^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde\epsilon_S = \frac{v^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd} V_{ud} - C_{l\nu uq}\right]$$

$$\tilde\epsilon_P = -\frac{v^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd} V_{ud} + C_{l\nu uq}\right]$$

$$\tilde\epsilon_T = 2v^2 C^{(3)}_{l\nu qd}$$

Known RG running equations can translate it to Wilson coefficients ϵ_X and $\tilde\epsilon_X$ at a low scale μ ~ 2 GeV

NR EFT for nucleons

Below the QCD scale there is no quarks.
The relevant degrees of freedom are instead nucleons

In beta decay, the momentum transfer is much smaller than the nucleon mass, due to approximate isospin symmetry leading to small mass splittings

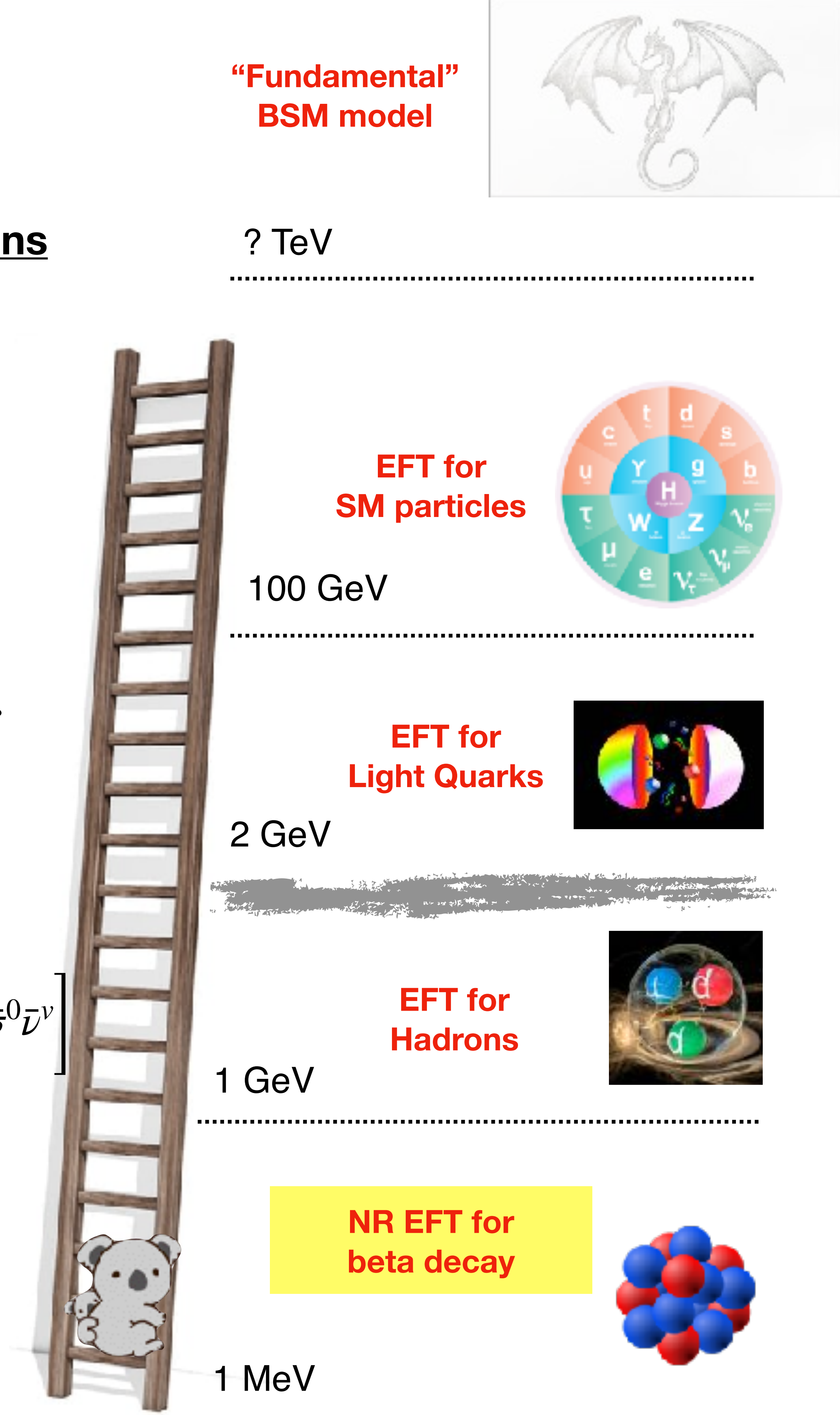
Appropriate EFT is non-relativistic!

$$\mathcal{L}_{\rm EFT} = \mathcal{L}^{(0)} + \mathcal{L}^{(1)} + \mathcal{O}(\nabla^2/m_N^2) + {\rm h.c.}$$

Leading order EFT described by the Lagrangian

$$\mathcal{L}^{(0)} = -(\psi_p^\dagger \psi_n)\Big[C_V^+ \bar{e}\bar{\sigma}^0\nu + C_V^- e^c \sigma^0 \bar{\nu}^c + C_S^+ e^c \nu + C_S^- \bar{e}\bar{\nu}^c\Big] + \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\Big[C_A^+ \bar{e}\bar{\sigma}^k\nu + C_A^+ e^c\sigma^k\bar{\nu}^c + C_T^+ e^c\sigma^0\bar{\sigma}^k\nu + C_T^- \bar{e}\bar{\sigma}^k\bar{\sigma}^0\bar{\nu}^c\Big]$$

Now 8 complex parameters at leading order to describe physics of beta decay



Translation from nuclear to particle physics

$$C_V^+ = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\left(1+\epsilon_L+\epsilon_R\right) \qquad C_V^- = \frac{V_{ud}}{v^2} g_V \sqrt{1+\Delta_R^V}\left(\tilde{\epsilon}_L+\tilde{\epsilon}_R\right)$$

$$C_A^+ = -\frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}\left(1+\epsilon_L-\epsilon_R\right) \qquad C_A^- = \frac{V_{ud}}{v^2} g_A \sqrt{1+\Delta_R^A}\left(\tilde{\epsilon}_L-\tilde{\epsilon}_R\right)$$

Non-zero in the SM (pointing to C_V^+ and C_A^+)

$$C_T^+ = \frac{V_{ud}}{v^2} g_T \epsilon_T \qquad C_T^- = \frac{V_{ud}}{v^2} g_T \tilde{\epsilon}_T$$

$$C_S^+ = \frac{V_{ud}}{v^2} g_S \epsilon_S \qquad C_S^- = \frac{V_{ud}}{v^2} g_S \tilde{\epsilon}_S$$

Note that pseudoscalar interactions do not enter at the leading order

Lattice + theory fix with good accuracy the non-perturbative parameters in the matching

$$g_V \approx 1, \qquad g_A = 1.246 \pm 0.028, \qquad g_S = 1.02 \pm 0.10, \qquad g_T = 0.989 \pm 0.034$$

Ademolo, Gatto (1964) — **Flag'21 N_f=2+1+1 value** — Gupta et al 1806.09006

Matching includes short-distance (inner) radiative corrections

$$\Delta_R^V = 0.02467(22)$$

Seng et al 1807.10197

$$\Delta_R^A - \Delta_R^V = 0.036(8)$$

Cirigliano et al 2202.10439

Summary of the language

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}\bar{\sigma}^0\nu + C_V^- e^c \sigma^0 \bar{\nu}^c + C_S^+ e^c \nu + C_S^- \bar{e}\bar{\nu}^c\right]$$

$$+\sum_{k=1}^{3}(\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}\bar{\sigma}^k\nu + C_A^+ e^c \sigma^k \bar{\nu}^c + C_T^+ e^c \sigma^0 \bar{\sigma}^k \nu + C_T^- \bar{e}\bar{\sigma}^k \bar{\sigma}^0 \bar{\nu}^\nu\right]$$

See the talk of Martin Gonzalez-Alonso for the constraints on the real parts of these Wilson coefficients from CP conserving observables

- Using this low-energy non-relativistic EFT Lagrangian one can calculate differential distributions in nuclear beta transitions, in particular the D parameter

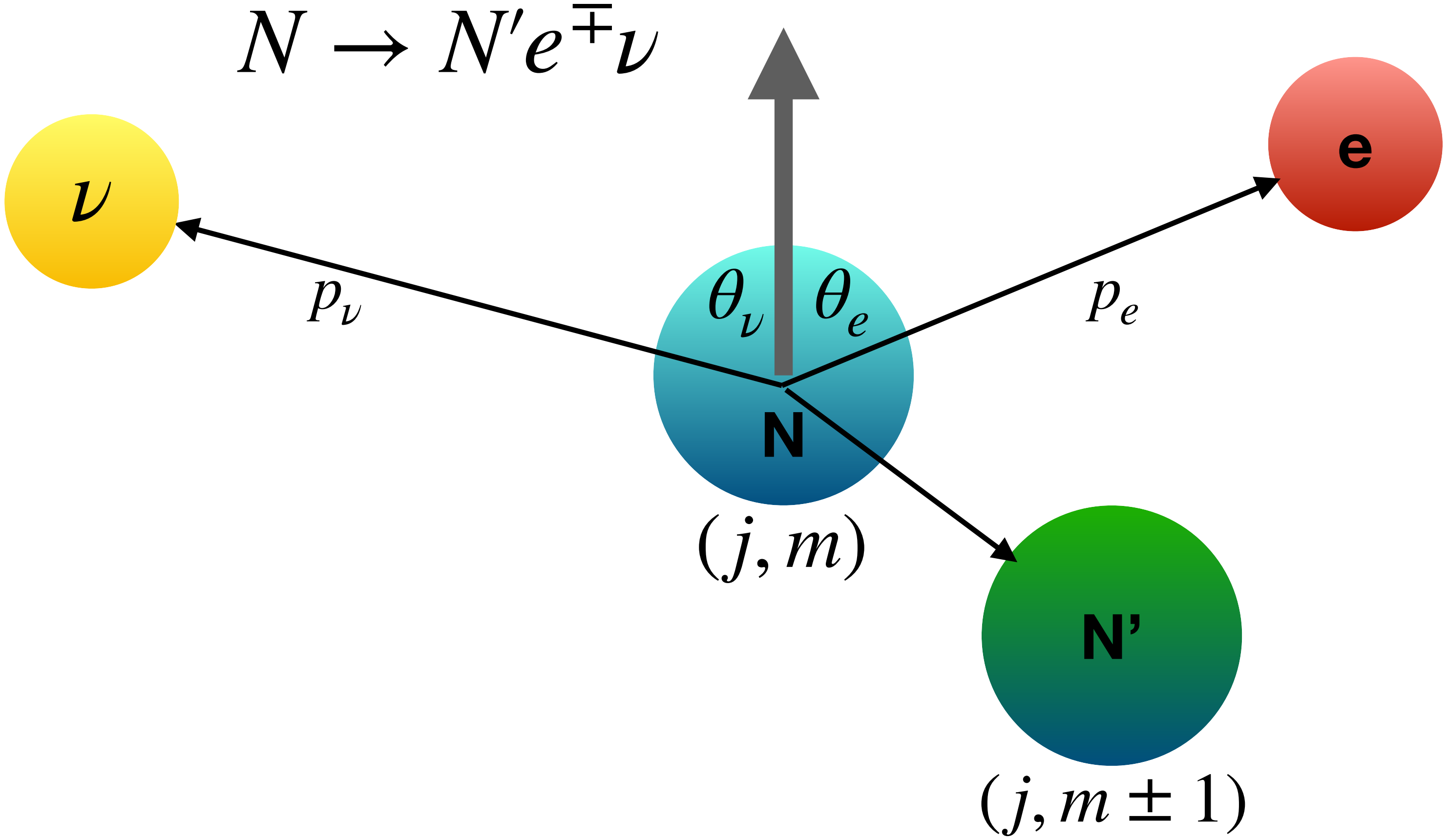
- Using the dictionaries above one can express the D parameter in terms of Wilson coefficients of the relativistic EFTs below and above the electroweak scale

- Via this ladder of EFTs, one can connect the D parameter to parameters of fundamental UV models, e.g. to leptoquarks masses and their CP violating couplings to matter

D parameter in EFT

Observables in beta decay

$N \to N' e^{\mp} \nu$



Electron energy/momentum

$$E_e = \sqrt{p_e^2 + m_e^2}$$

Neutrino energy

$$E_\nu = p_\nu \approx m_N - m_{N'} - E_e$$

Information about the Wilson coefficients can be accessed by measuring (differential) decay width:

Control lifetime — **Routinely measured correlations** — **Main focus here**

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = F(E_e)\left\{ 1 + b\frac{m_e}{E_e} + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu}{E_e E_\nu} + A\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_e}{J E_e} + B\frac{\langle \boldsymbol{J} \rangle \cdot \boldsymbol{p}_\nu}{J E_\nu} \right.$$
$$\left. + c\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\nu - 3(\boldsymbol{p}_e \cdot \boldsymbol{j})(\boldsymbol{p}_\nu \cdot \boldsymbol{j})}{3E_e E_\nu}\left[\frac{J(J+1) - 3(\langle \boldsymbol{J} \rangle \cdot \boldsymbol{j})^2}{J(2J-1)}\right] + D\frac{\langle \boldsymbol{J} \rangle \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)}{J E_e E_\nu} \right\}$$

No-one talks about it

D parameter

Jackson Treiman Wyld (1957)

$$\mathscr{L}^{(0)} = -(\psi_p^\dagger \psi_n)\left[C_V^+ \bar{e}\bar{\sigma}^0\nu + C_V^- e^c\sigma^0\bar{\nu}^c + C_S^+ e^c\nu + C_S^- \bar{e}\bar{\nu}^c\right]$$
$$+ \sum_{k=1}^{3} (\psi_p^\dagger \sigma^k \psi_n)\left[C_A^+ \bar{e}\bar{\sigma}^k\nu + C_A^+ e^c\sigma^k\bar{\nu}^c + C_T^+ e^c\sigma^0\bar{\sigma}^k\nu + C_T^- \bar{e}\bar{\sigma}^k\bar{\sigma}^0\bar{\nu}^\nu\right]$$

For same spin (J'=J) mixed allowed beta transitions:

$$D = -2r\sqrt{\frac{J}{J+1}}\frac{\mathrm{Im}\left\{C_V^+\bar{C}_A^+ - C_S^+\bar{C}_T^+ + C_V^-\bar{C}_A^- - C_S^-\bar{C}_T^-\right\}}{|C_V^+|^2 + |C_S^+|^2 + |C_V^-|^2 + |C_S^-|^2 + r^2\left[|C_A^+|^2 + |C_T^+|^2 + |C_A^-|^2 + |C_T^-|^2\right]}$$

Ratio of GT and Fermi matrix elements measured by experiment

$$r \approx -\rho/g_A$$

So-called mixing parameter

For D parameter to be non-zero:

- **Beta decay has to neither pure Fermi nor pure GT**
- **At least two distinct Wilson coefficients have to be non-zero**
- **There has to be a relative phase difference between these two parameters**

D parameter

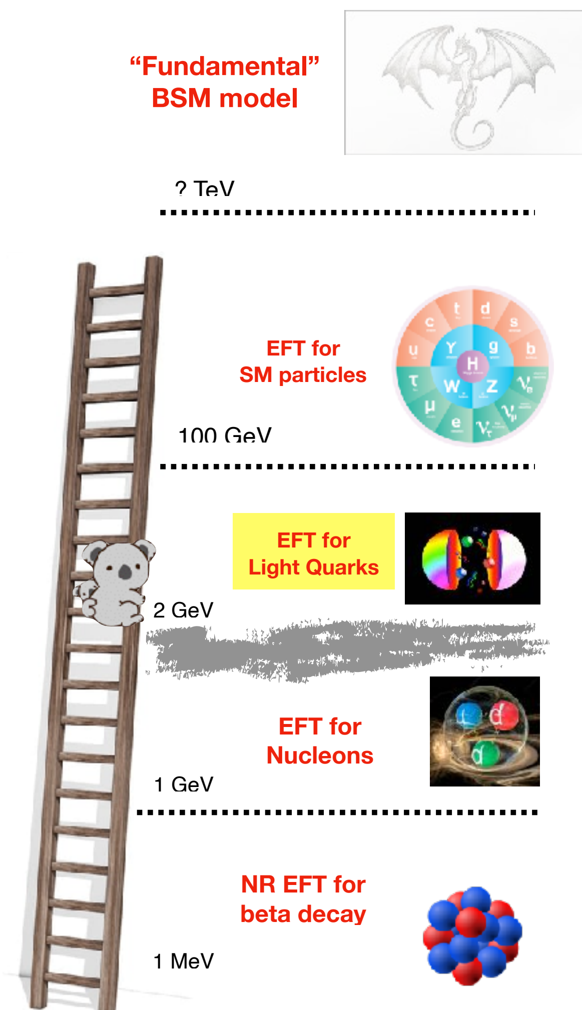
Translation to the quark-level Wilson coefficients below the electroweak scale:

$$
\begin{aligned}
\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ & (1+\epsilon_L)\ \bar{e}\bar{\sigma}_\mu \nu \cdot \bar{u}\bar{\sigma}^\mu d && + \tilde{\epsilon}_L\, e^c\sigma_\mu \bar{\nu}^c \cdot \bar{u}\bar{\sigma}^\mu d \\
& + \epsilon_R\, \bar{e}\bar{\sigma}_\mu \nu \cdot u^c\sigma^\mu \bar{d}^c && + \tilde{\epsilon}_R\, e^c\sigma_\mu \bar{\nu}^c u^c\sigma^\mu \bar{d}^c \\
& + \epsilon_T \frac{1}{4} e^c\sigma_{\mu\nu}\nu \cdot u^c\sigma^{\mu\nu} d && + \tilde{\epsilon}_T \frac{1}{4} \bar{e}^c\bar{\sigma}_{\mu\nu}\bar{\nu}^c \cdot \bar{u}\bar{\sigma}^{\mu\nu}\bar{d}^c \\
& + \epsilon_S \frac{1}{2} e^c\nu \cdot (u^c d + \bar{u}\bar{d}^c) && + \tilde{\epsilon}_S \frac{1}{2} \bar{e}\bar{\nu}^c \cdot (u^c d + \bar{u}\bar{d}^c) \\
& + \epsilon_P \frac{1}{2} e^c\nu \cdot (u^c d - \bar{u}\bar{d}^c) && - \tilde{\epsilon}_P \frac{1}{2} \bar{e}\bar{\nu}^c \cdot (u^c d - \bar{u}\bar{d}^c) \Big\} + \mathrm{h.c.}
\end{aligned}
$$

$$
D = \frac{4 r g_V g_A}{g_V^2 + r^2 g_A^2}\sqrt{\frac{J}{J+1}}\,\mathrm{Im}\left[\epsilon_R(1+\epsilon_L^*) + \frac{g_S g_T}{2 g_V g_A}(\epsilon_S \epsilon_T^* + \tilde{\epsilon}_S \tilde{\epsilon}_T^*) - \tilde{\epsilon}_R \tilde{\epsilon}_L^*\right]
$$

At the linear level in Wilson coefficients, D parameter measures the imaginary part of non-standard right-handed currents involving the left-handed neutrino

At the quadratic level, sensitivity to imaginary parts of scalar and tensor current and to interactions of right-handed neutrino



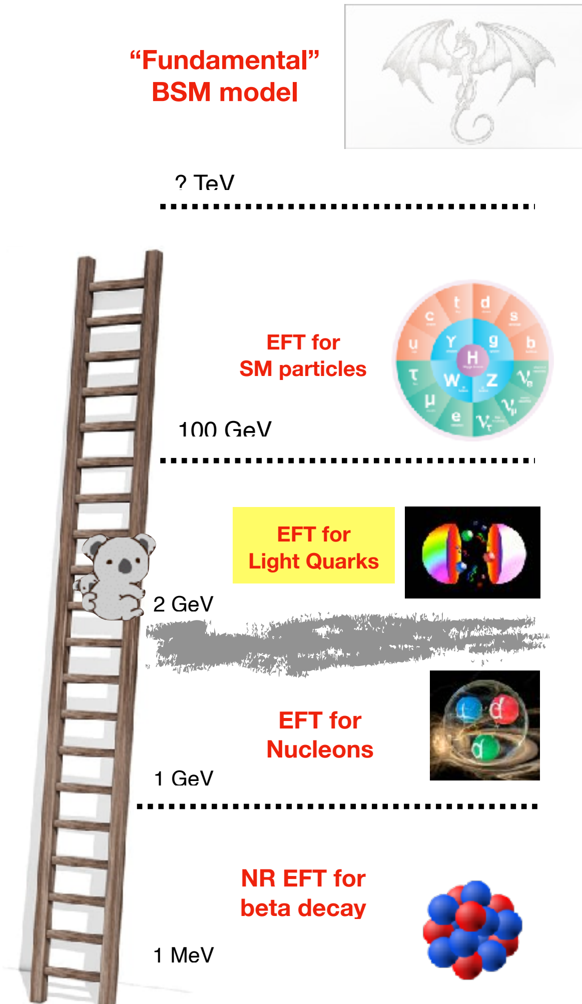
D parameter

Translation to the quark-level Wilson coefficients:

$$\mathscr{L} \supset -\frac{2V_{ud}}{v^2}\Big\{ (1+\epsilon_L)\ \bar{e}\bar{\sigma}_\mu\nu\cdot\bar{u}\bar{\sigma}^\mu d \quad + \tilde{\epsilon}_L\, e^c\sigma_\mu\bar{\nu}^c\cdot\bar{u}\bar{\sigma}^\mu d$$
$$+\epsilon_R\,\bar{e}\bar{\sigma}_\mu\nu\cdot u^c\sigma^\mu\bar{d}^c \quad + \tilde{\epsilon}_R\, e^c\sigma_\mu\bar{\nu}^c u^c\sigma^\mu\bar{d}^c$$
$$+\epsilon_T\frac{1}{4}e^c\sigma_{\mu\nu}\nu\cdot u^c\sigma^{\mu\nu}d \quad + \tilde{\epsilon}_T\frac{1}{4}\bar{e}^c\bar{\sigma}_{\mu\nu}\bar{\nu}^c\cdot\bar{u}\bar{\sigma}^{\mu\nu}\bar{d}^c$$
$$+\epsilon_S\frac{1}{2}e^c\nu\cdot(u^c d+\bar{u}\bar{d}^c) \quad + \tilde{\epsilon}_S\frac{1}{2}\bar{e}\bar{\nu}^c\cdot(u^c d+\bar{u}\bar{d}^c)$$
$$+\epsilon_P\frac{1}{2}e^c\nu\cdot(u^c d-\bar{u}\bar{d}^c) \quad - \tilde{\epsilon}_P\frac{1}{2}\bar{e}\bar{\nu}^c\cdot(u^c d-\bar{u}\bar{d}^c)\Big\} + \mathrm{h.c.}$$

$$D \approx \kappa_D\,\mathrm{Im}\big[\epsilon_R(1+\epsilon_L^*) + 0.4(\epsilon_S\epsilon_T^* + \tilde{\epsilon}_S\tilde{\epsilon}_T^*) - \tilde{\epsilon}_R\tilde{\epsilon}_L^*\big] \qquad \kappa_D \equiv \frac{4rg_Vg_A}{g_V^2+r^2g_A^2}\sqrt{\frac{J}{J+1}}$$

Parent	J	r	κ_D	$D_{\rm exp}$	$\Delta D_{\rm future}$
n	$1/2$	$\sqrt{3}$	0.88	$-1.2(2.0)\times 10^{-4}$ [12]	?
^{19}Ne	$1/2$	-1.26	-1.04	0.0001(6)	?
^{23}Mg	$3/2$	-0.44	-1.30	-	$< 10^{-4}$ [13]
^{39}Ca	$3/2$	0.52	1.42	-	?



D parameter

Translation to Wilson coefficients of EFT above electroweak scale

$$\mathscr{L}_{\rm EFT} \supset iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c)$$
$$+ C^{(3)}_{lequ} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)$$
$$+ C^{(1)}_{lequ} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$$
$$+ C_{ledq} (\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q)$$
$$+ C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c)$$
$$+ \mathrm{hc}$$

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C^{(1)*}_{lequ} + V_{ud} c^*_{ledq}\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C^{(1)*}_{lequ} - V_{ud} C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C^{(3)*}_{lequ}$$

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2} C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}} \left[C^{(1)}_{l\nu qd} V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}} \left[C^{(1)}_{l\nu qd} V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

EFT scenarios for D parameter

D parameter scenarios

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

Scenario #1 **Scenario #2** **Scenario #3** **Scenario #4**

Scenario	νWEFT	νSMEFT	max $\|D\|$
I	ϵ_R	$HD_\mu H u^c \sigma^\mu \bar{d}^c$ $[(\bar{l}H\bar{\sigma}_\mu H l)(u^c\sigma^\mu\bar{d}^c)]$	
II	ϵ_S, ϵ_T	$(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c)$, $(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c)$, $(\bar{l}\bar{e}^c)(d^c q)$	
III	$\tilde{\epsilon}_S$, $\tilde{\epsilon}_T$	$(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)$, $(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$, $(\bar{l}\bar{\nu}^c)(u^c q)$	
IV	$\tilde{\epsilon}_L$, $\tilde{\epsilon}_R$	$H^\dagger D_\mu H^\dagger e^c \sigma^\mu \bar{\nu}^c$ $[e^c\sigma^\mu\bar{\nu}^c\bar{q}H^\dagger\sigma_\mu H^\dagger q]$, $(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)$	

D parameter scenario #1

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}}C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud}c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud}C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}}C_{lequ}^{(3)*}$$

$$\mathscr{L}_{\mathrm{EFT}} \supset iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) + C_{lequ}^{(3)}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C_{lequ}^{(1)}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C_{ledq}(\bar{l}\bar{e}^c)(d^cq)$$

$$+ iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c) + C_{l\nu qd}^{(3)}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) + C_{l\nu qd}^{(1)}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^cq) + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)$$

$$+\mathrm{hc}$$

One can generate imaginary right-handed currents from a dimension-6 or a dimension-8 operator

D parameter scenario #1a

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} + V_{ud} c^*_{ledq}\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C^{(1)*}_{lequ} - V_{ud} C^*_{ledq}\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C^{(3)*}_{lequ}$$

$$\begin{aligned}\mathscr{L}_{\rm EFT} \supset\; & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar d^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar\nu^c) \\ & + C^{(3)}_{lequ} (\bar l \bar\sigma_{\mu\nu} \bar e^c)(\bar q \bar\sigma^{\mu\nu} \bar u^c) && + C^{(3)}_{l\nu qd} (\bar l \bar\sigma^{\mu\nu} \bar\nu^c)(\bar q \bar\sigma_{\mu\nu} \bar d^c) \\ & + C^{(1)}_{lequ} (\bar l \bar e^c)(\bar q \bar u^c) && + C^{(1)}_{l\nu qd} (\bar l \bar\nu^c)(\bar q \bar d^c) \\ & + C_{ledq} (\bar l \bar e^c)(d^c q) && + C_{l\nu uq} (\bar l \bar\nu^c)(u^c q) \\ & && + C_{e\nu ud} (e^c \sigma^\mu \bar\nu^c)(u^c \sigma_\mu \bar d^c) \\ & + \mathrm{hc} \end{aligned}$$

Dimension-6 is naively a better option, because then $D \sim \frac{\mathrm{v}^2}{\Lambda^2}$

where v=246 GeV is the electroweak scale, and Λ **is the mass scale of new BSM particles**

Moreover, the Wilson coefficients $C_{\phi ud}$ **is generated by many motivated BSM models, for example by the left-right symmetric models**

However, there are strong model-independent constraints from EDMs...

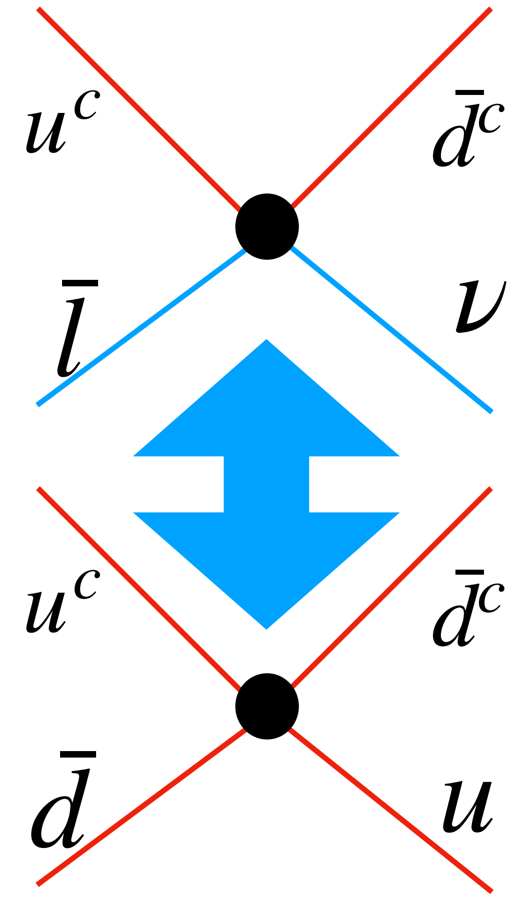
D parameter scenario #1a

$$\mathscr{L}_{\nu\text{SMEFT}} \supset \frac{g_L}{\sqrt{2}} W_\mu^+ \left[\bar{\nu}\bar{\sigma}^\mu e + V_{ud}\bar{u}\bar{\sigma}^\mu d + \frac{\mathrm{v}^2}{2} C_{\phi ud} u^c \sigma^\mu \bar{d}^c \right]$$

Integrating out the W boson

$$\mathscr{L}_{\nu\text{WEFT}} \supset -C_{\phi ud}(\bar{e}\bar{\sigma}_\mu \nu)(\bar{u}^c \sigma^\mu \bar{d}^c) - V_{ud} C_{\phi ud}(\bar{d}\bar{\sigma}_\mu u)(u^c \sigma^\mu \bar{d}^c) + \mathrm{h.c.}$$

Contributes to D **Contributes to EDM**



$C_{\phi ud}$ **contributes not only to the D parameter, but also to a 4-quark operator contributing to nuclear EDM, with both contribution being governed by the same parameter**

EDM constraints dominated by 199Hg

$$\mathrm{v}^2 |\mathrm{Im}[C_{\phi ud}]| \lesssim 3 \times 10^{-6}$$

It follows that assuming absence of fine-tuning

$$|D| \approx \frac{|\kappa_D|}{2} \mathrm{v}^2 |\mathrm{Im}[C_{\phi ud}]| \lesssim 2 \times 10^{-6}$$

$\mathrm{v}^2 |\mathrm{Im} C_{\phi ud}| \lesssim 1 \times 10^{-5}$

if only neutron EDM contraints used

$|D| \lesssim 5 \times 10^{-6}$

See Ramsey-Musolf & Vasquez [arXiv:2012.02799] for a more general discussion allowing fine-tuning EDM against θ_{QCD}

D parameter scenario #1b

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud} + \frac{\mathrm{v}^4}{4V_{ud}} C_8$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}} \left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\begin{aligned}
\mathscr{L}_{\mathrm{EFT}} \supset\; & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) \\
& + C_{lequ}^{(3)} (\bar{l} \bar{\sigma}_{\mu\nu} \bar{e}^c)(\bar{q} \bar{\sigma}^{\mu\nu} \bar{u}^c) && + C_{l\nu qd}^{(3)} (\bar{l} \bar{\sigma}^{\mu\nu} \bar{\nu}^c)(\bar{q} \bar{\sigma}_{\mu\nu} \bar{d}^c) \\
& + C_{lequ}^{(1)} (\bar{l} \bar{e}^c)(\bar{q} \bar{u}^c) && + C_{l\nu qd}^{(1)} (\bar{l} \bar{\nu}^c)(\bar{q} \bar{d}^c) \\
& + C_{ledq} (\bar{l} \bar{e}^c)(d^c q) && + C_{l\nu uq} (\bar{l} \bar{\nu}^c)(u^c q) \\
& + C_8 (\bar{l} H \bar{\sigma}_\mu H l)(u^c \sigma^\mu \bar{d}^c) && + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c) \\
& + \mathrm{hc}
\end{aligned}$$

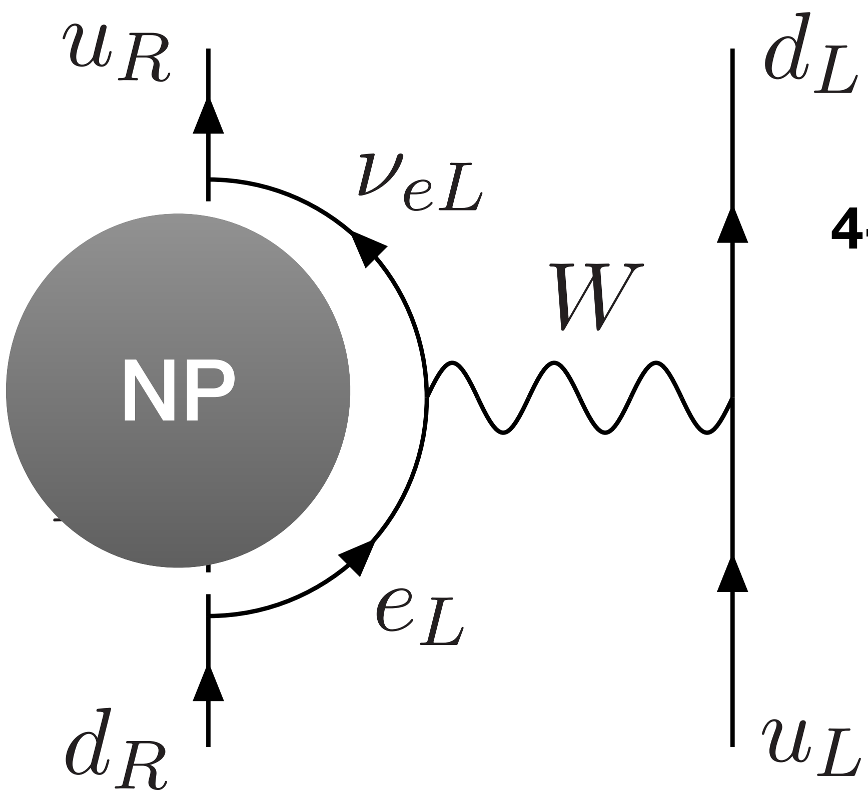
Generating D parameter via a dimension-8 operator means that D is more suppressed: $D \sim \frac{\mathrm{v}^4}{\Lambda^4}$

where v=246 GeV is the electroweak scale, and Λ is the mass scale of new BSM particles
This dimension-8 operator can be generated at tree level in certain leptoquark models

Ng Tulin
arXiv:1111.0649

Constraints from EDMs are now weaker and model dependent...

D parameter scenario #1b



As soon as 4-fermion vertex leading to non-zero ϵ_R appears, 4-quark operators leading to EDM is generated at 1 loop in EFT although its coefficient is not calculable in EFT

$$\mathscr{L}_{\nu\text{WEFT}} \supset -C_{1LR}(\bar{d}\bar{\sigma}_\mu u)(u^c \sigma^\mu \bar{d}^c) + \text{h.c.}$$

$$C_{1LR} \sim \frac{C_8 \Lambda^2}{16\pi^2} \Rightarrow \text{v}^2\Lambda^2 \text{Im}C_8 \lesssim 3 \times 10^{-4}$$

$$|D| \sim \frac{\text{v}^4 \text{Im} C_8}{4} \lesssim 10^{-4} \frac{\text{v}^2}{\Lambda^2}$$

In the scenario 1b the D parameter can be large only when new physics is at the EW scale, which is difficult to achieve in realistic models.

As soon as new physics is at 3 TeV, we are back to the severe constraint $|D| \lesssim 10^{-6}$

Mind that these are just rough estimates, a quantitative limit can only be obtained in specific UV models where the quadratic divergence is resolved

D parameter scenario 1c

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud} + \frac{\mathrm{v}^4}{4V_{ud}} C_8$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud} HD_\mu H(u^c\sigma^\mu \bar{d}^c) && +iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c)\\ & +C_{lequ}^{(3)}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && +C_{l\nu qd}^{(3)}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & +C_{lequ}^{(1)}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && +C_{l\nu qd}^{(1)}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & +C_{ledq}(\bar{l}\bar{e}^c)(d^c q) && +C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & +C_8(\bar{l}H\bar{\sigma}_\mu H l)(u^c\sigma^\mu \bar{d}^c) && +C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu \bar{d}^c)\\ & +\mathrm{hc}\end{aligned}$$

One more possible option is that operators contributing to ϵ_R are real, and the imaginary part is contained in ϵ_L.

Note that the real part ϵ_R can be at percent level, as constraints are relatively weak

[arXiv:2010.13797] with Martin Gonzalez-Alonso, Oscar Naviliat-Cuncic

D parameter scenario 1c

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

One more possible option is that operators contributing to ϵ_R are real, and the imaginary part is contained in ϵ_L

This is not a very attractive scenario for BSM, because dimension-6 operators lead to a real ϵ_L , thus D would be at least of order $\frac{\mathrm{v}^6}{\Lambda^6}$

However, ϵ_L effectively acquires a complex part due to SM loop effect, because of a photon going on-shell in the loop
Thus, in the scenario 1c the D parameter may be a sensitive probe of CP conserving new physics contribution to $\epsilon_R \sim \frac{\mathrm{v}^2}{\Lambda^2}$, as long as the SM contribution can be reliably calculated

D parameter scenario #2

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

$$\epsilon_R = \frac{\mathrm{v}^2}{2V_{ud}} C_{\phi ud}$$

$$\epsilon_S = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} + V_{ud} c_{ledq}^*\right)$$

$$\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left(C_{lequ}^{(1)*} - V_{ud} C_{ledq}^*\right)$$

$$\epsilon_T = -\frac{2\mathrm{v}^2}{V_{ud}} C_{lequ}^{(3)*}$$

$$\begin{aligned}\mathscr{L}_{\rm EFT} \supset\ & iC_{\phi ud} H D_\mu H (u^c \sigma^\mu \bar{d}^c) && + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c \sigma^\mu \bar{\nu}^c) \\ & + C_{lequ}^{(3)} (\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && + C_{l\nu qd}^{(3)} (\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) \\ & + C_{lequ}^{(1)} (\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && + C_{l\nu qd}^{(1)} (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) \\ & + C_{ledq} (\bar{l}\bar{e}^c)(d^c q) && + C_{l\nu uq} (\bar{l}\bar{\nu}^c)(u^c q) \\ & && + C_{e\nu ud} (e^c \sigma^\mu \bar{\nu}^c)(u^c \sigma_\mu \bar{d}^c) \\ & + \mathrm{hc} \end{aligned}$$

This scenario is doomed from the start, because EDM constraints on the imaginary parts of $C_{lequ}^{(1,3)}$, C_{ledq} are prohibitive

$$\mathrm{v}^2 |\mathrm{Im} C_{lequ}^{(1)}| \lesssim 3\times 10^{-11} \qquad \mathrm{v}^2 |\mathrm{Im} C_{lequ}^{(3)}| \lesssim 1\times 10^{-11} \qquad \mathrm{v}^2 |\mathrm{Im} C_{ledq}| \lesssim 3\times 10^{-11}$$

de Vries et al arXiv:1809.09114
Dekens et al arXiv: 1810.05675

D parameter scenario #3

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

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\; & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) + iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c)\\ & + C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & + C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & + C_{ledq}(\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & + \mathrm{hc}\end{aligned}$$

This scenario does not have the EDM problem, because the neutral curent from the scalar and tensor operators with RH neutrinos do not generate $\bar{e}e\bar{q}q$ terms. Moreover, constraints on $\tilde{\epsilon}_{S,T}$ from beta decay are less stringent, at the percent level, because of the lack of interference with SM amplitudes

However it has the pion decay problem ...

D parameter scenario #3

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

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2} C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}} C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd} V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd} V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\; & iC_{\phi ud} H D_\mu H (u^c\sigma^\mu \bar{d}^c) + iC_{\phi e\nu} H^\dagger D_\mu H^\dagger (e^c\sigma^\mu\bar{\nu}^c) \\ & + C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) + C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c) \\ & + C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) + C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c) \\ & + C_{ledq}(\bar{l}\bar{e}^c)(d^c q) + C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q) \\ & + C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c) \\ & + \mathrm{hc}\end{aligned}$$

The problem here is that this scenario generically predicts $\tilde{\epsilon}_S \sim \tilde{\epsilon}_P$
and from measure $\mathrm{Br}(\pi \to e\nu)$ **one has** $|\tilde{\epsilon}_P| \lesssim 10^{-5}$

$$D \sim 10^{-6}\kappa_D \mathrm{Im}\left[\left(\frac{\tilde{\epsilon}_T}{10^{-1}}\right)\left(\frac{\tilde{\epsilon}_S}{10^{-5}}\right)\right] \Rightarrow |D| \lesssim 10^{-6}$$

D parameter scenario #3

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

$$\tilde{\epsilon}_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde{\epsilon}_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde{\epsilon}_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\right]$$

$$\tilde{\epsilon}_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar{d}^c) && +iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar{\nu}^c)\\ & +C^{(3)}_{lequ}(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c) && +C^{(3)}_{l\nu qd}(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)\\ & +C^{(1)}_{lequ}(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c) && +C^{(1)}_{l\nu qd}(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)\\ & +C_{ledq}(\bar{l}\bar{e}^c)(d^c q) && +C_{l\nu uq}(\bar{l}\bar{\nu}^c)(u^c q)\\ & && +C_{e\nu ud}(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)\\ & +\mathrm{hc} &&\end{aligned}$$

Additional constraint is provided by the fact that the gauge invariant operators, contribute to the neutrino masses and neutrino magnetic moment, which requires fine-tuning unless $\mathrm{v}^2|C_{l\nu qd,l\nu uq}| \lesssim 10^{-3}$

D parameter scenario #4

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

$$\tilde\epsilon_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde\epsilon_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde\epsilon_S = \frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\right]$$

$$\tilde\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\left[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\right]$$

$$\tilde\epsilon_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}\mathscr{L}_{\mathrm{EFT}} \supset\ & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar d^c) && + iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar\nu^c)\\ & + C^{(3)}_{lequ}(\bar l\bar\sigma_{\mu\nu}\bar e^c)(\bar q\bar\sigma^{\mu\nu}\bar u^c) && + C^{(3)}_{l\nu qd}(\bar l\bar\sigma^{\mu\nu}\bar\nu^c)(\bar q\bar\sigma_{\mu\nu}\bar d^c)\\ & + C^{(1)}_{lequ}(\bar l\bar e^c)(\bar q\bar u^c) && + C^{(1)}_{l\nu qd}(\bar l\bar\nu^c)(\bar q\bar d^c)\\ & + C_{ledq}(\bar l\bar e^c)(d^c q) && + C_{l\nu uq}(\bar l\bar\nu^c)(u^c q)\\ & && + C_{e\nu ud}(e^c\sigma^\mu\bar\nu^c)(u^c\sigma_\mu\bar d^c)\\ & + \mathrm{hc} && \end{aligned}$$

From the EFT point of view, scenario 4 looks promising, because model-independent constraints on the highlighted operators are relatively mild.

In particular, from $\mathrm{Br}(W\to e\nu)$ **one gets** $\mathrm{v}^2|C_{\phi e\nu}| \lesssim 0.3$

while $pp\to e\nu$ **at the LHC leads to** $\mathrm{v}^2|C_{e\nu ud}| \lesssim \mathcal{O}(0.01)$

At loop level, there is a quadratic in $C_{e\nu ud}$ **contribution to the 4-quark EDM operator, but in this case we gain the loop and quadratic suppressions**

D parameter scenario #4

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

$$\tilde\epsilon_L = -\frac{\mathrm{v}^2}{2}C_{\phi e\nu}$$

$$\tilde\epsilon_R = -\frac{\mathrm{v}^2}{2V_{ud}}C_{e\nu ud}$$

$$\tilde\epsilon_S = \frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} - C_{l\nu uq}\Big]$$

$$\tilde\epsilon_P = -\frac{\mathrm{v}^2}{2V_{ud}}\Big[C^{(1)}_{l\nu qd}V_{ud} + C_{l\nu uq}\Big]$$

$$\tilde\epsilon_T = 2\mathrm{v}^2 C^{(3)}_{l\nu qd}$$

$$\begin{aligned}
\mathscr{L}_{\rm EFT} \supset\; & iC_{\phi ud}HD_\mu H(u^c\sigma^\mu\bar d^c) && +iC_{\phi e\nu}H^\dagger D_\mu H^\dagger(e^c\sigma^\mu\bar\nu^c) \\
& +C^{(3)}_{lequ}(\bar l\bar\sigma_{\mu\nu}\bar e^c)(\bar q\bar\sigma^{\mu\nu}\bar u^c) && +C^{(3)}_{l\nu qd}(\bar l\bar\sigma^{\mu\nu}\bar\nu^c)(\bar q\bar\sigma_{\mu\nu}\bar d^c) \\
& +C^{(1)}_{lequ}(\bar l\bar e^c)(\bar q\bar u^c) && +C^{(1)}_{l\nu qd}(\bar l\bar\nu^c)(\bar q\bar d^c) \\
& +C_{ledq}(\bar l\bar e^c)(d^c q) && +C_{l\nu uq}(\bar l\bar\nu^c)(u^c q) \\
& && +C_{e\nu ud}(e^c\sigma^\mu\bar\nu^c)(u^c\sigma_\mu\bar d^c) \\
& && +\tilde C_8(e^c\sigma^\mu\bar\nu^c)(\bar q H^\dagger\sigma_\mu H^\dagger q) \\
& +\mathrm{hc}
\end{aligned}$$

Much as in scenario 1, one can trade one dimension-6 operators for a dimension-8 one leading to the same interaction below the electroweak scale.
The advantage is that the latter can be generated in lepoquark models,
the disadvantage is that $D \sim \frac{\mathrm{v}^6}{\Lambda^6}$ so new physics has to be very light

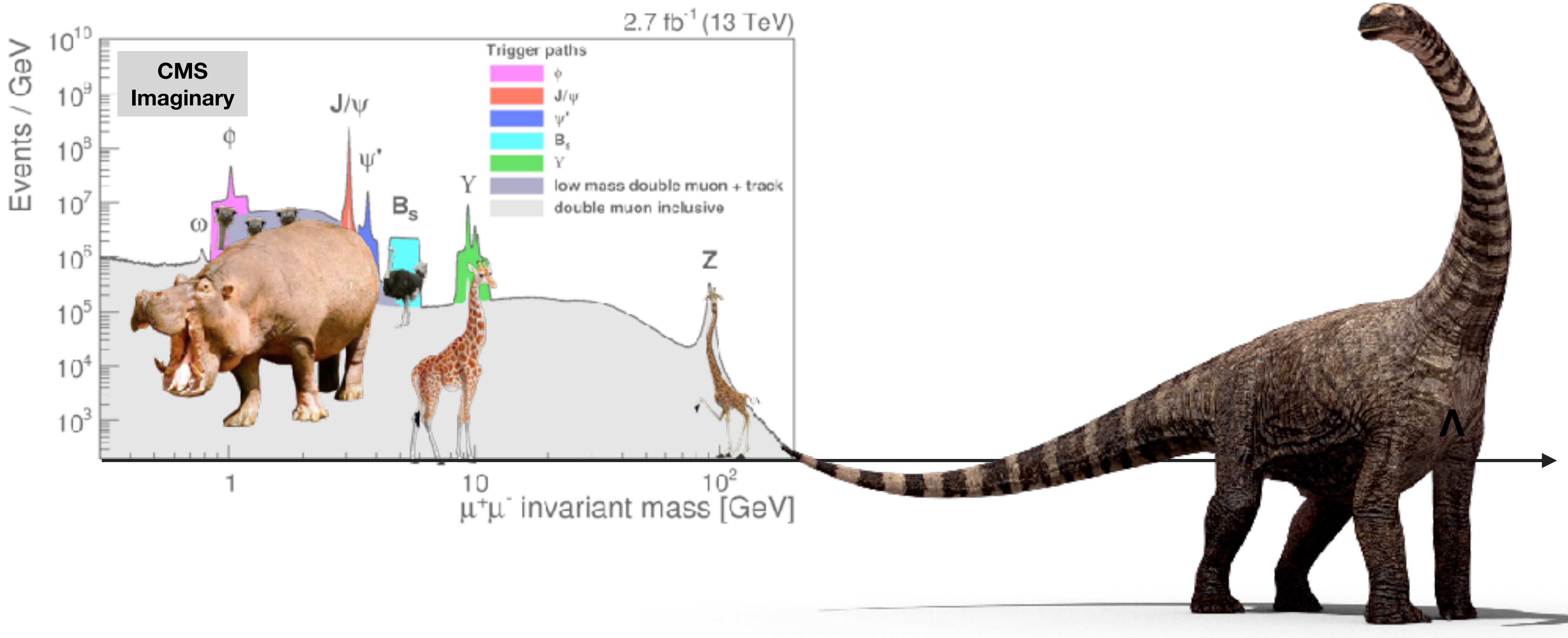
D parameter scenarios

Scenario	νWEFT	νSMEFT	max $\lvert D \rvert$
I	ϵ_R	$HD_\mu H u^c \sigma^\mu \bar{d}^c$ $[(\bar{l}H\bar{\sigma}_\mu H l)(u^c\sigma^\mu \bar{d}^c)]$	$\mathcal{O}(10^{-6})$
II	ϵ_S, ϵ_T	$(\bar{l}\bar{\sigma}_{\mu\nu}\bar{e}^c)(\bar{q}\bar{\sigma}^{\mu\nu}\bar{u}^c)$, $(\bar{l}\bar{e}^c)(\bar{q}\bar{u}^c)$, $(\bar{l}\bar{e}^c)(d^c q)$	$\mathcal{O}(10^{-14})$
III	$\tilde{\epsilon}_S$, $\tilde{\epsilon}_T$	$(\bar{l}\bar{\sigma}^{\mu\nu}\bar{\nu}^c)(\bar{q}\bar{\sigma}_{\mu\nu}\bar{d}^c)$, $(\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$, $(\bar{l}\bar{\nu}^c)(u^c q)$	$\mathcal{O}(10^{-6})$
IV	$\tilde{\epsilon}_L$, $\tilde{\epsilon}_R$	$H^\dagger D_\mu H^\dagger e^c \sigma^\mu \bar{\nu}^c$ $[e^c\sigma^\mu\bar{\nu}^c\bar{q}H^\dagger\sigma_\mu H^\dagger q]$, $(e^c\sigma^\mu\bar{\nu}^c)(u^c\sigma_\mu\bar{d}^c)$	$\mathcal{O}(10^{-4})$

Summary

- The most convenient language to discuss low-energy precision measurement is that of EFTs
- D-parameter measurements are essential to constrain the parameter space of the ladder of EFTs from the electroweak scale down to nuclear scales
- The EFT approach leads, in a transparent way, to correlations between the D-parameter and other CP-violating and CP-conserving observables (EDMs, pion decays, etc)
- Certain directions are already severely disfavored in a model independent way
- For other scenarios, studies of explicit UV completions is necessary, see the next talk for leptoquark UV completions

Fantastic Beasts and Where To Find Them



THANK YOU

Back up

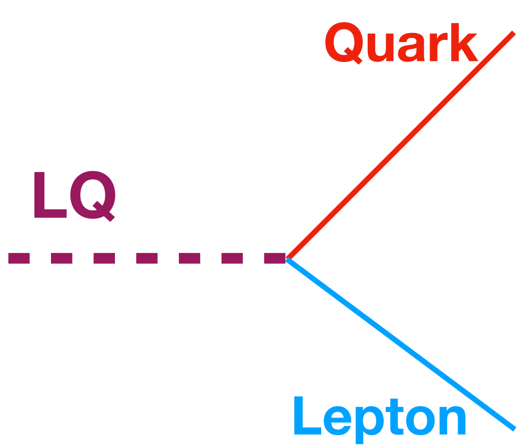
Leptoquarks

Leptoquarks are particles carrying both lepton and baryon quantum numbers

Two main families

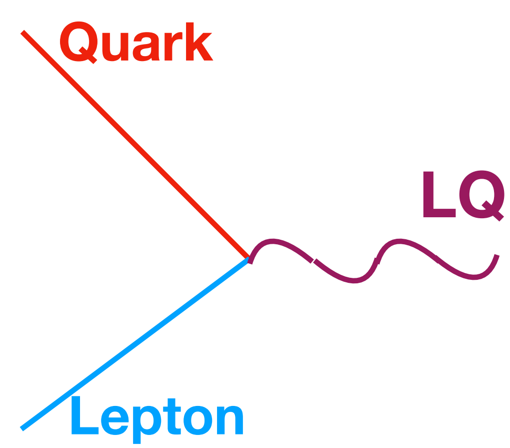
Scalar

Spin 0
UV complete models



Vector

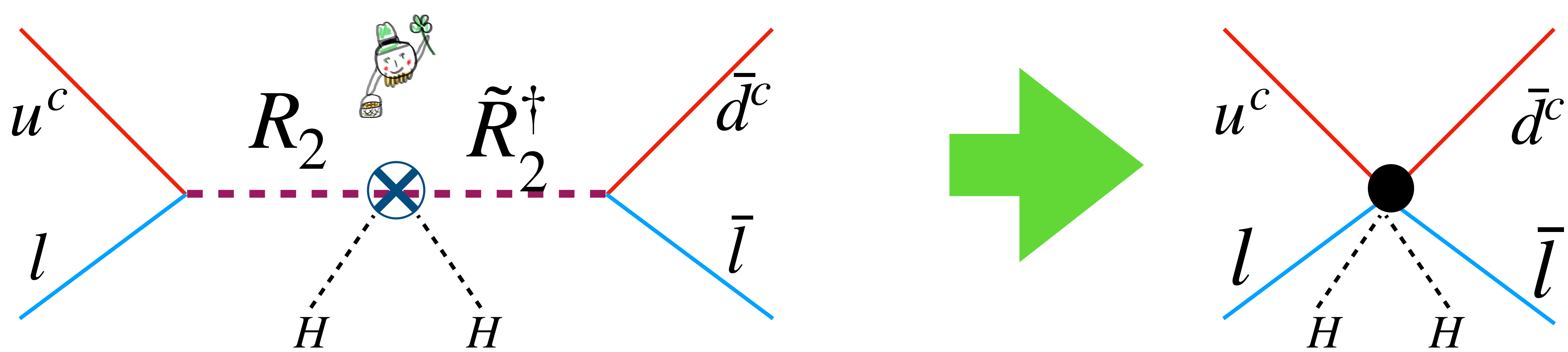
Spin 1
Effective theories



In both cases, leptoquarks can be classified according to quantum numbers under the SM SU(3)xSU(2)xU(1) gauge group, see e.g. Dorsner et al arXiv:1603.04993

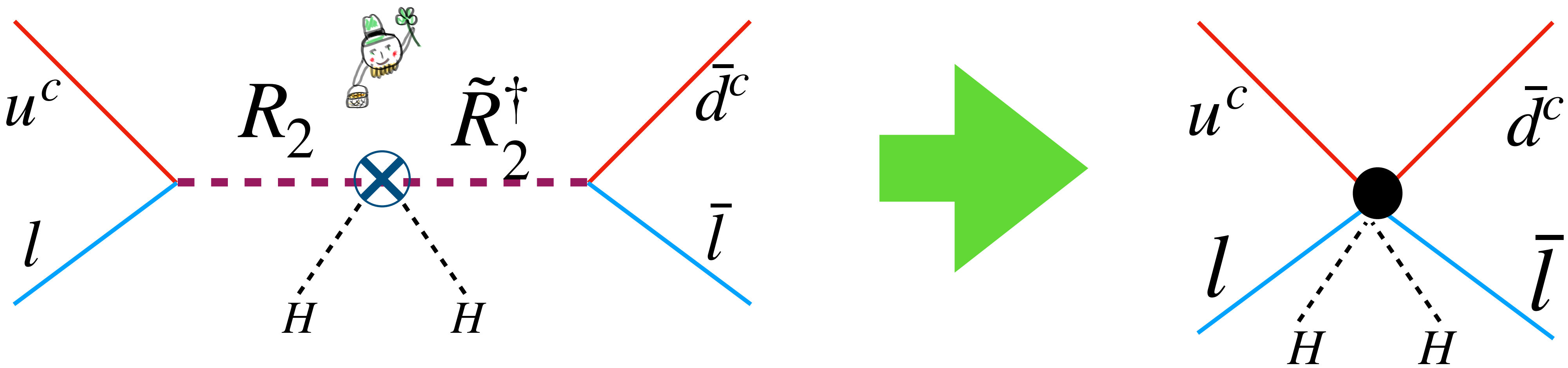
Leptoquarks for D-parameter

Name	Quantum numbers	Yukawa couplings
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$	$ql,\ \bar{u}^c\bar{e}^c,\ \bar{d}^c\bar{\nu}^c$
$\bar{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3})$	$\bar{u}^c\bar{\nu}^c$
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{4/3})$	$\bar{d}^c\bar{e}^c$
R_2	$(\mathbf{3}, \mathbf{2}, \mathbf{7/6})$	$u^c l,\ \bar{q}\bar{e}^c$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6})$	$d^c l,\ \bar{q}\bar{\nu}^c$
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1/3})$	$q\sigma^k l$



$(\bar{l}H\bar{\sigma}_\mu\tilde{H}l)(u^c\sigma^\mu\bar{d}^c)$

Leptoquarks for D-parameter



Ng Tulin
arXiv:1111.0649

Mass mixing

$$\mathscr{L} \supset -M_R^2|R_2|^2 - M_{\tilde{R}}^2|\tilde{R}_2|^2 + \left[\lambda(R_2^\dagger H)(\tilde{R}_2 H) + y_R R_2 u^c l + y_{\tilde{R}} \tilde{R}_2 d^c l + \mathrm{hc}\right]$$

Mass terms **Yukawa coupling**

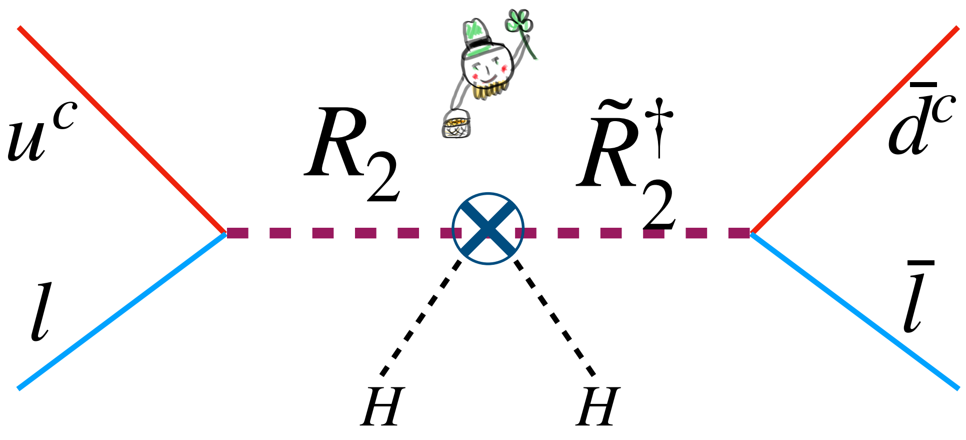
After integrating out the leptoquarks one gets the operators

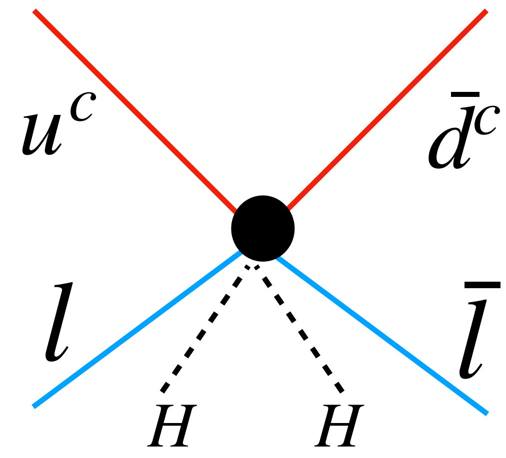
$$\mathscr{L}_{\mathrm{eff}} \supset -\frac{|y_R|^2}{2M_R^2}(\bar{l}\bar{\sigma}_\mu l)(u^c\sigma^\mu \bar{u}^c) - \frac{|y_{\tilde{R}}|^2}{2M_{\tilde{R}}^2}(\bar{l}\bar{\sigma}_\mu l)(d^c\sigma^\mu \bar{d}^c) - \left[\frac{\lambda y_R \bar{y}_{\tilde{R}}}{2M_R^2 M_{\tilde{R}}^2}\boxed{(\bar{l}H\bar{\sigma}_\mu H l)(u^c\sigma_\mu \bar{d}^c)} + \mathrm{hc}\right]$$

The last one contributes to the D parameter as

$$D = -\kappa \frac{\mathrm{v}^4}{8V_{ud}M_R^2 M_{\tilde{R}}^2}\mathrm{Im}[\lambda y_R \bar{y}_{\tilde{R}}]$$

Leptoquarks for D-parameter





Ng Tulin
arXiv:1111.0649

Mass mixing

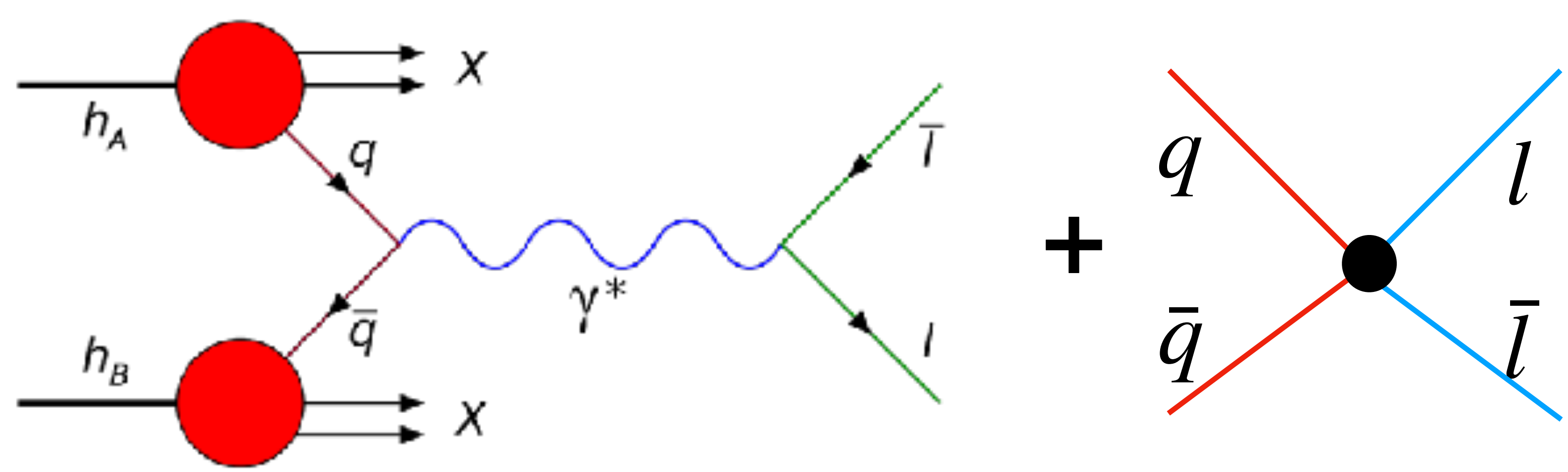
$$\mathscr{L} \supset -M_R^2|R|^2 - M_{\tilde R}^2|\tilde R|^2 + \left[\lambda(R^\dagger H)(\tilde R H) + y_R R_2 u^c l + y_{\tilde R}\tilde R_2 d^c l + \text{hc}\right]$$

Mass terms **Yukawa coupling**

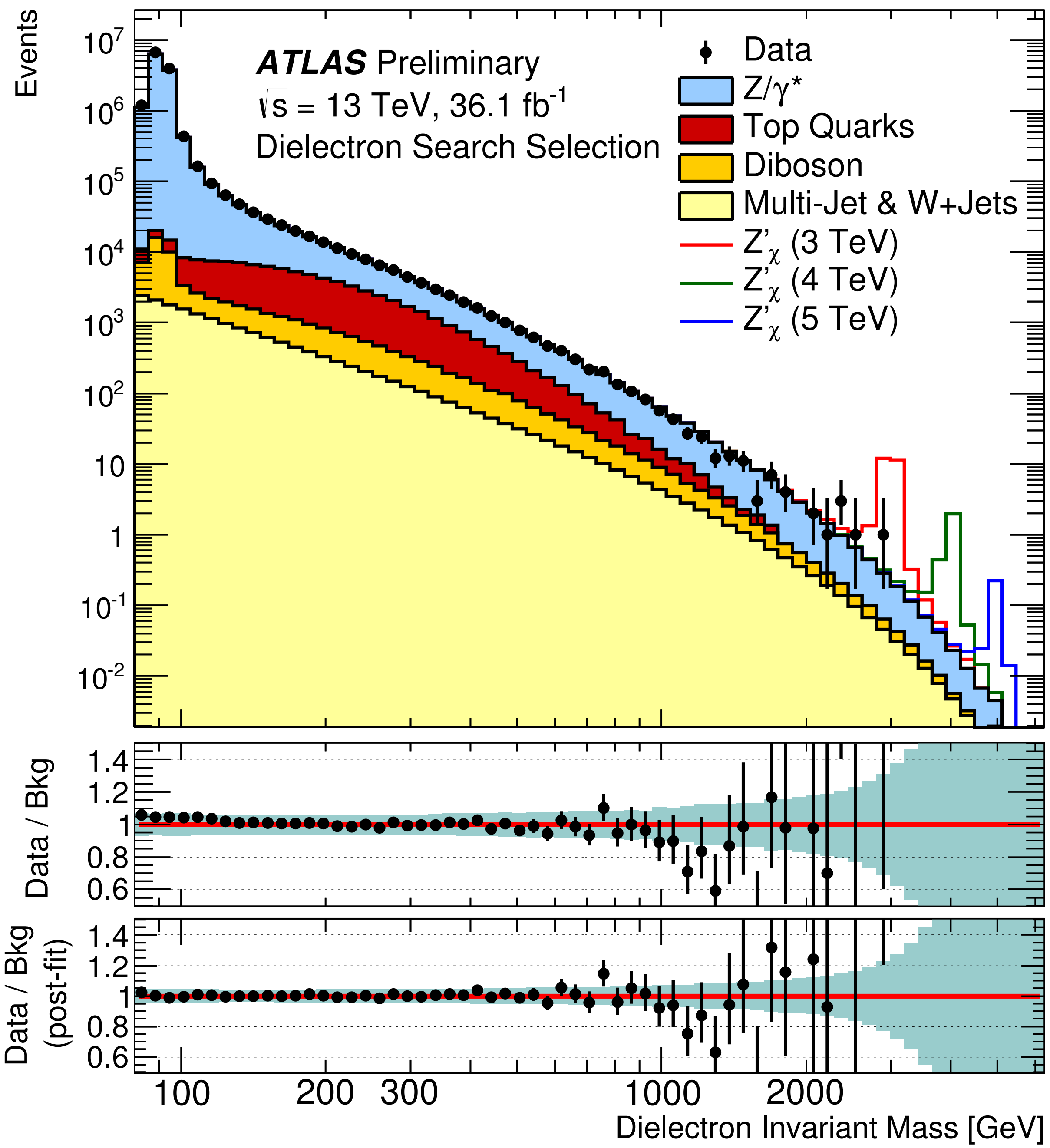
After integrating out the leptoquarks one gets the operators

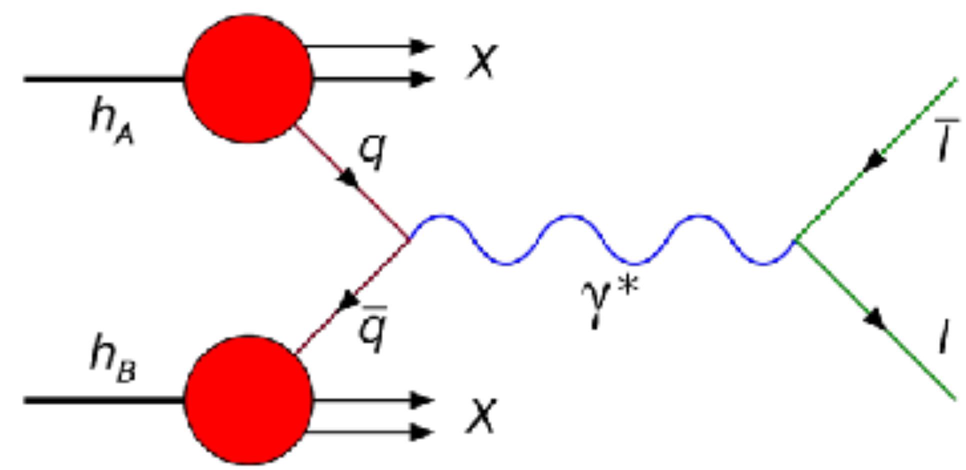
$$\mathscr{L}_{\text{eff}} \supset -\frac{|y_R|^2}{2M_R^2}(\bar l\bar\sigma_\mu l)(u^c\sigma^\mu\bar u^c) - \frac{|y_{\tilde R}|^2}{2M_{\tilde R}^2}(\bar l \bar\sigma_\mu l)(d^c\sigma^\mu \bar d^c) - \left[\frac{\lambda y_R \bar y_{\tilde R}}{2M_R^2M_{\tilde R}^2}(\bar l H\bar\sigma_\mu H l)(u^c\sigma_\mu \bar d^c)+\text{hc}\right]$$

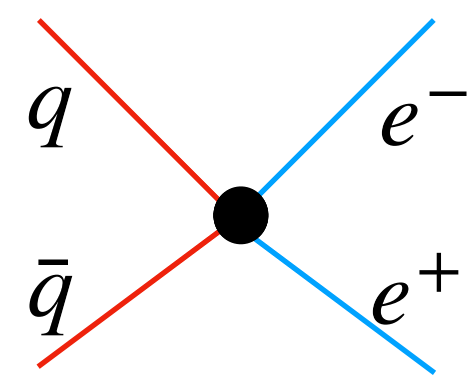
The first two contribute to Drell-Yan production at the LHC and are strongly constrained!



LHC Drell Yan



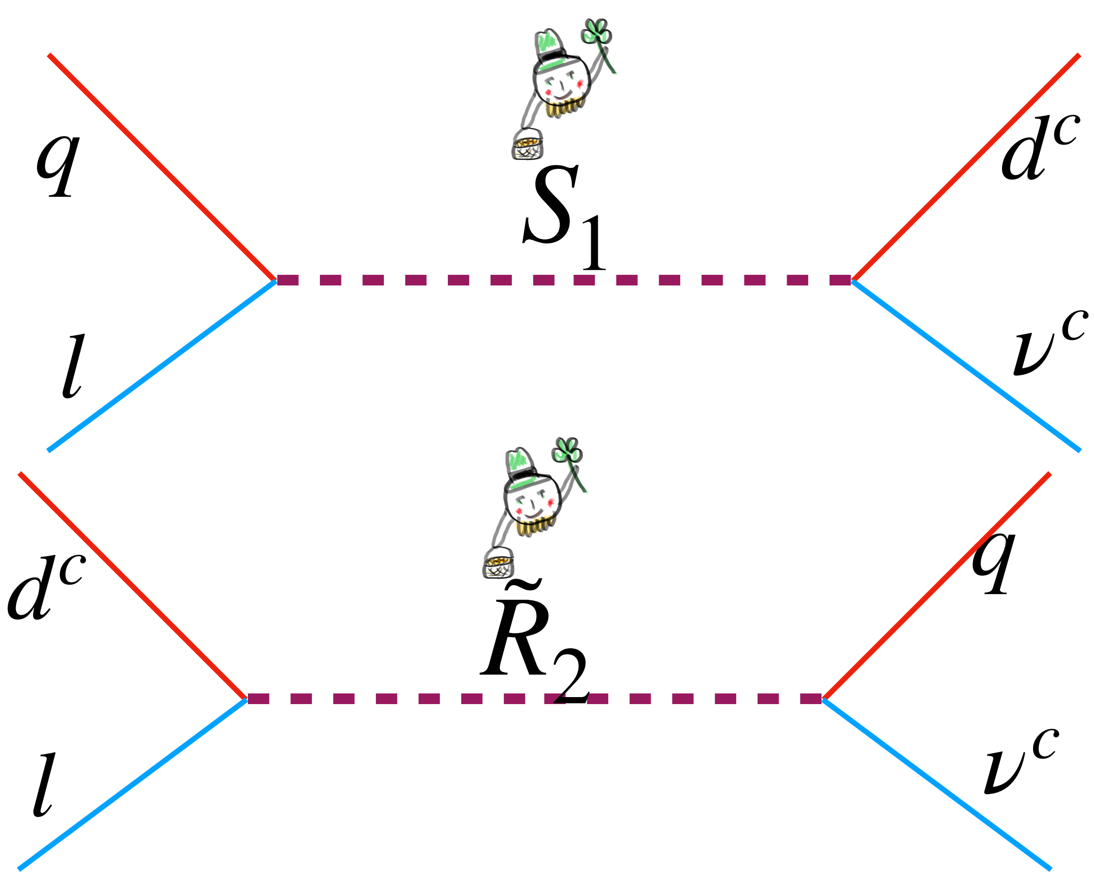


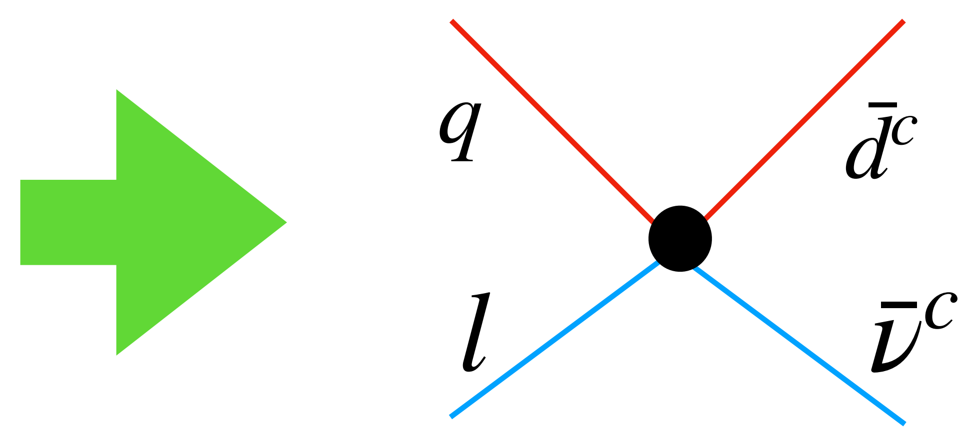


Effective quark-lepton interactions would show up as an excess of events at the high invariant mass tail of the distribution

Leptoquarks for D-parameter

Name	Quantum numbers	Yukawa couplings
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$	ql, $\bar{u}^c\bar{e}^c$, $\bar{d}^c\bar{\nu}^c$
$\bar{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, -\mathbf{2/3})$	$\bar{u}^c\bar{\nu}^c$
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{4/3})$	$\bar{d}^c\bar{e}^c$
R_2	$(\mathbf{3}, \mathbf{2}, \mathbf{7/6})$	$u^c l$, $\bar{q}\bar{e}^c$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, \mathbf{1/6})$	$d^c l$, $\bar{q}\bar{\nu}^c$
S_3	$(\bar{\mathbf{3}}, \mathbf{3}, \mathbf{1/3})$	$q\sigma^k l$





$(\bar{l}\bar{q})(\bar{\nu}^c\bar{d}^c), (\bar{l}\bar{d}^c)(\bar{\nu}^c\bar{q}) \rightarrow (\bar{l}\bar{\nu}^c)(\bar{q}\bar{d}^c)$