Interpreting eEDM searches in paramagnetic systems within SMEFT

Based on MA, N. Valori, Phys. Rev. D 113, 015035

Marco Ardu
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EDMs2026 : WE-Heraeus
2/03/2026

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Electric dipole moments in SMEFT

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Dipole moments in QFT

- A particle with spin $\vec{S}$ can have a **magnetic** and an **electric** dipole moment

$$H = -(\mu\,\vec{S}\cdot\overrightarrow{B} + d\,\vec{S}\cdot\overrightarrow{E})/S$$

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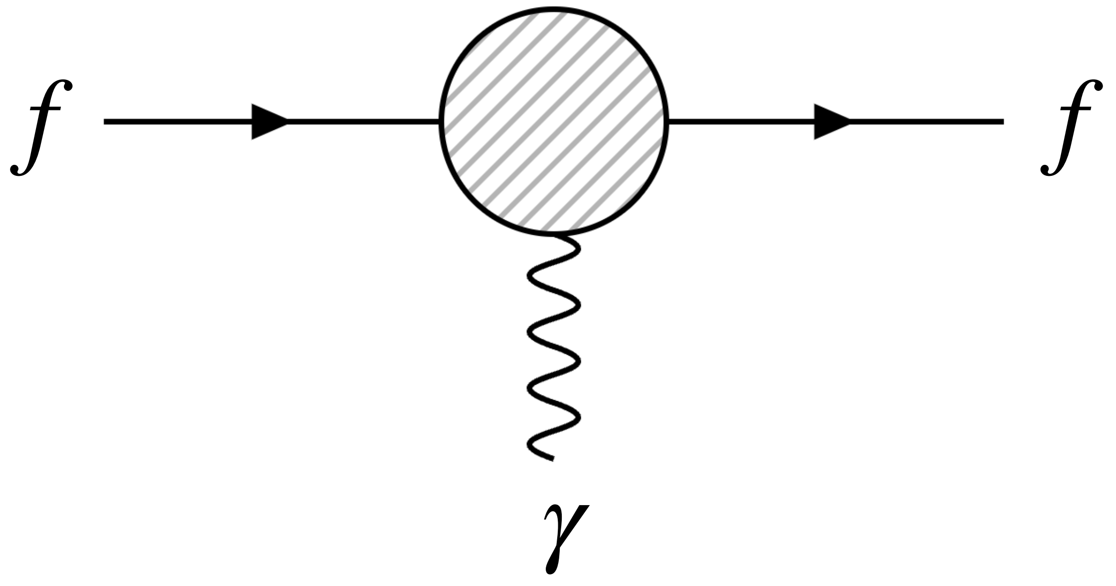
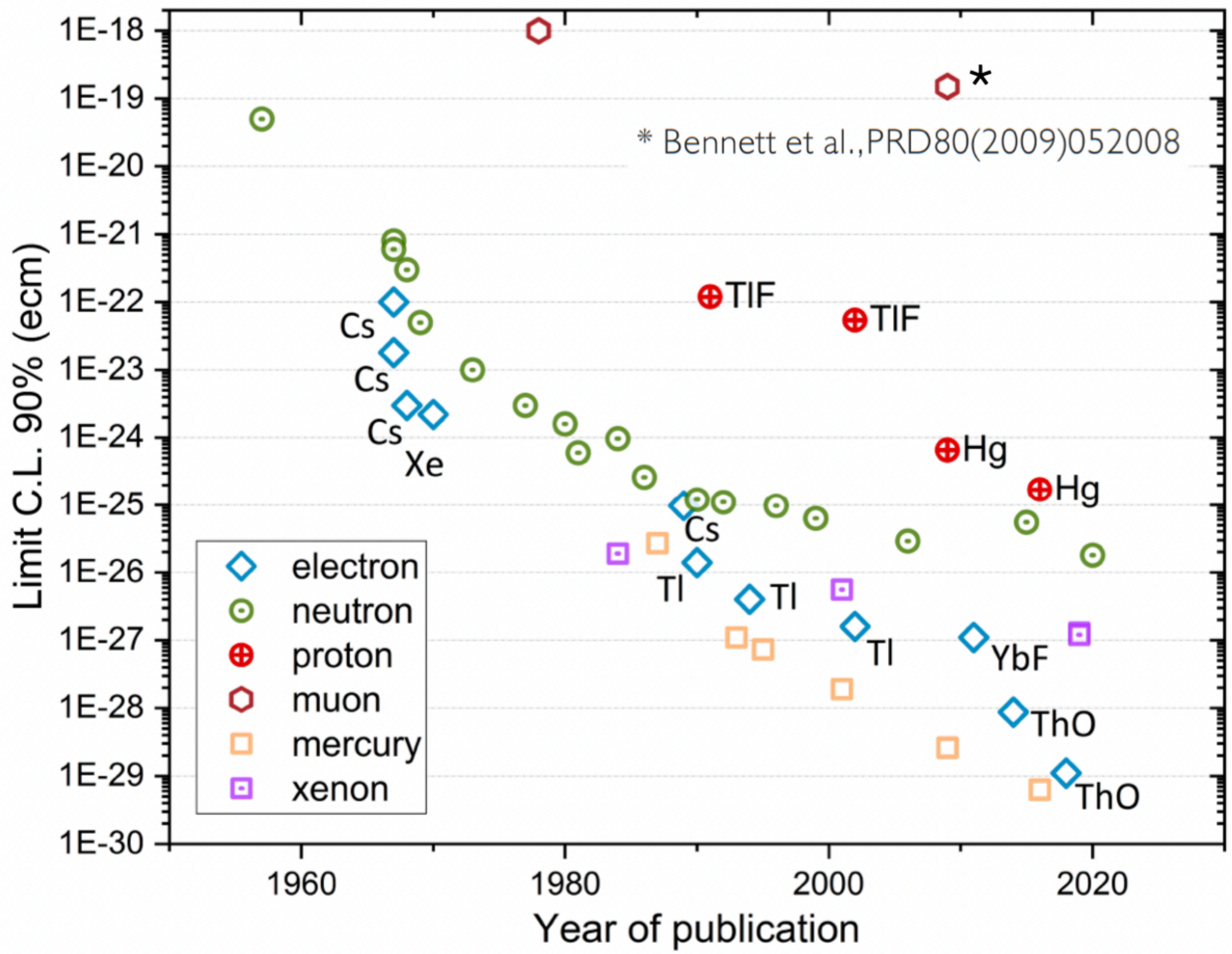
- In a relativistic quantum field theory, the dipole moments of a fermion are given by the effective Lagrangian

$$\delta\mathscr{L}_{\text{dip}} = -\frac{1}{2}\,\bar{\psi}_f\sigma_{\mu\nu}(\mu_f + i\gamma_5 d_f)\psi_f\,F^{\mu\nu}$$



$$[\psi] = 3/2,\ [F_{\mu\nu}] = 2,\ [\mathscr{L}] = 4 \ \Rightarrow \ \begin{matrix}[d_f] = -1 \\ [\mu_f] = -1\end{matrix}$$

EDMs: experimental bounds



d_e

Experiment	Current bound/Upcoming sensitivity
JILA eEDM	$< 4.1 \times 10^{-30}$ e cm
ACME III	$\sim 1 \times 10^{-30}$ e cm
YBF	$\sim 1 \times 10^{-31}$ e cm
BaF	$\sim 1 \times 10^{-33}$ e cm

[psi.ch/en/nedm/edms-world-wide]

$d_\mu < 1.8 \times 10^{-19}\, e \cdot \mathrm{cm} \rightarrow 6 \times 10^{-23}\, e \cdot \mathrm{cm}$

[muEDM, 2201.06561]

$d_\tau < 10^{-18}\, e \cdot \mathrm{cm} \rightarrow 10^{-19}\, e \cdot \mathrm{cm}$

[Snowmass BelleII, 2207.06307]

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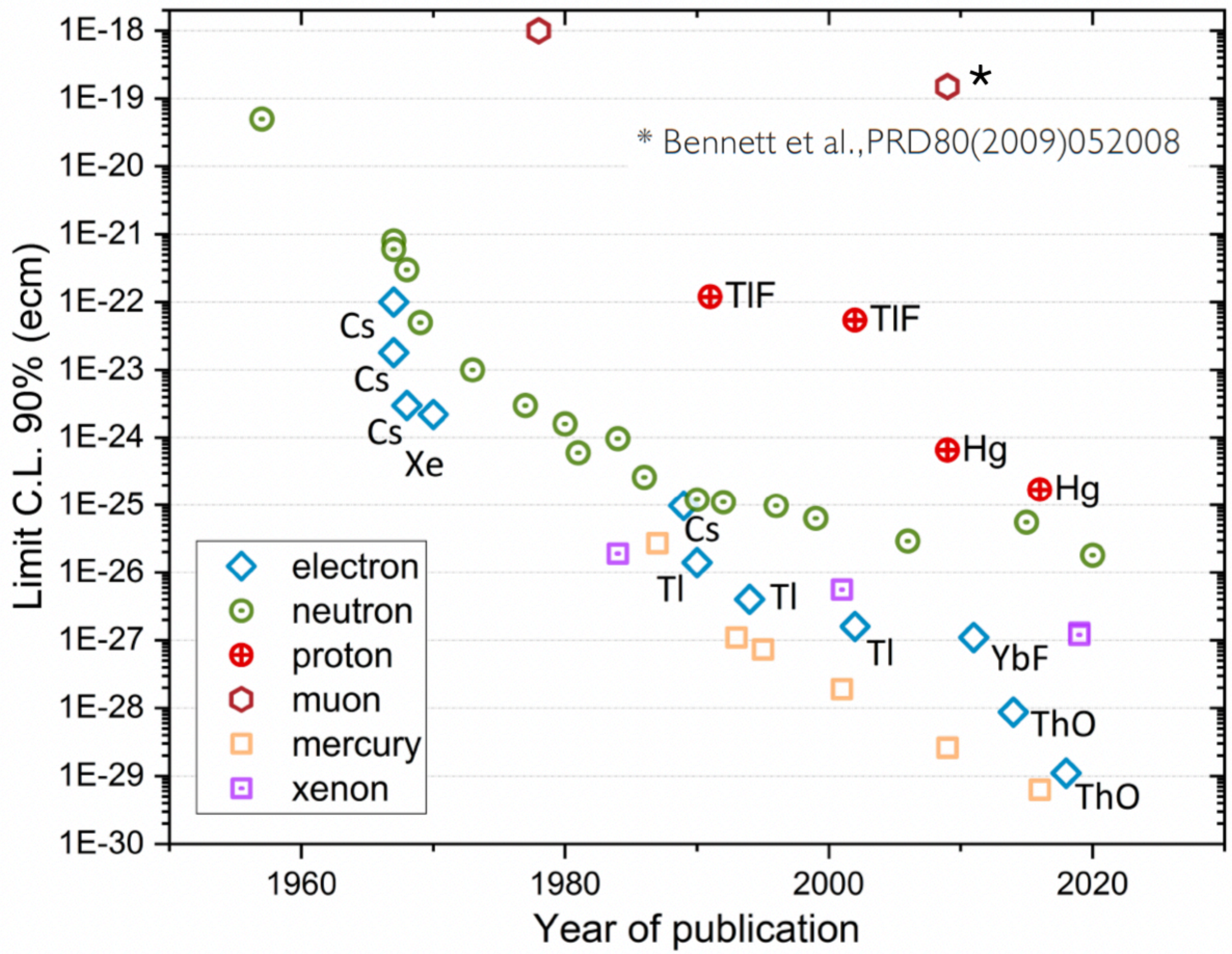

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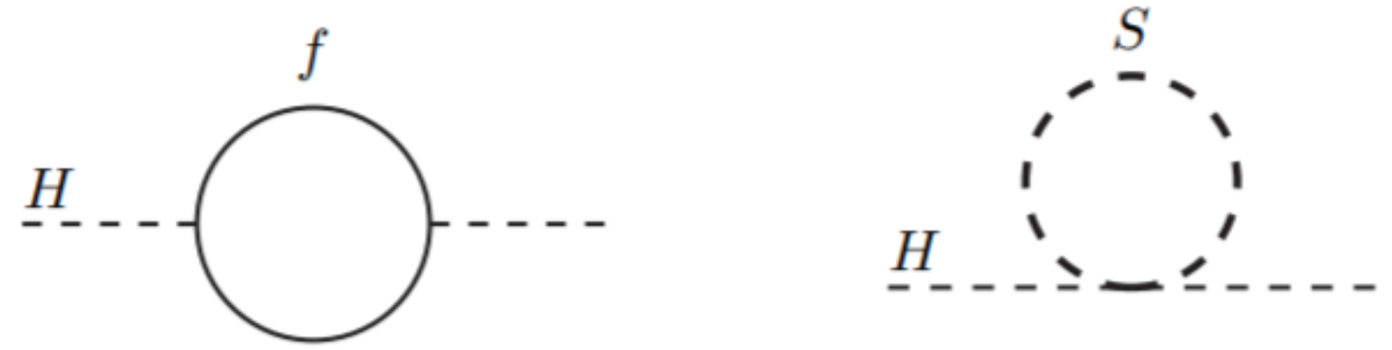
[Snowmass BelleII, 2207.06307]

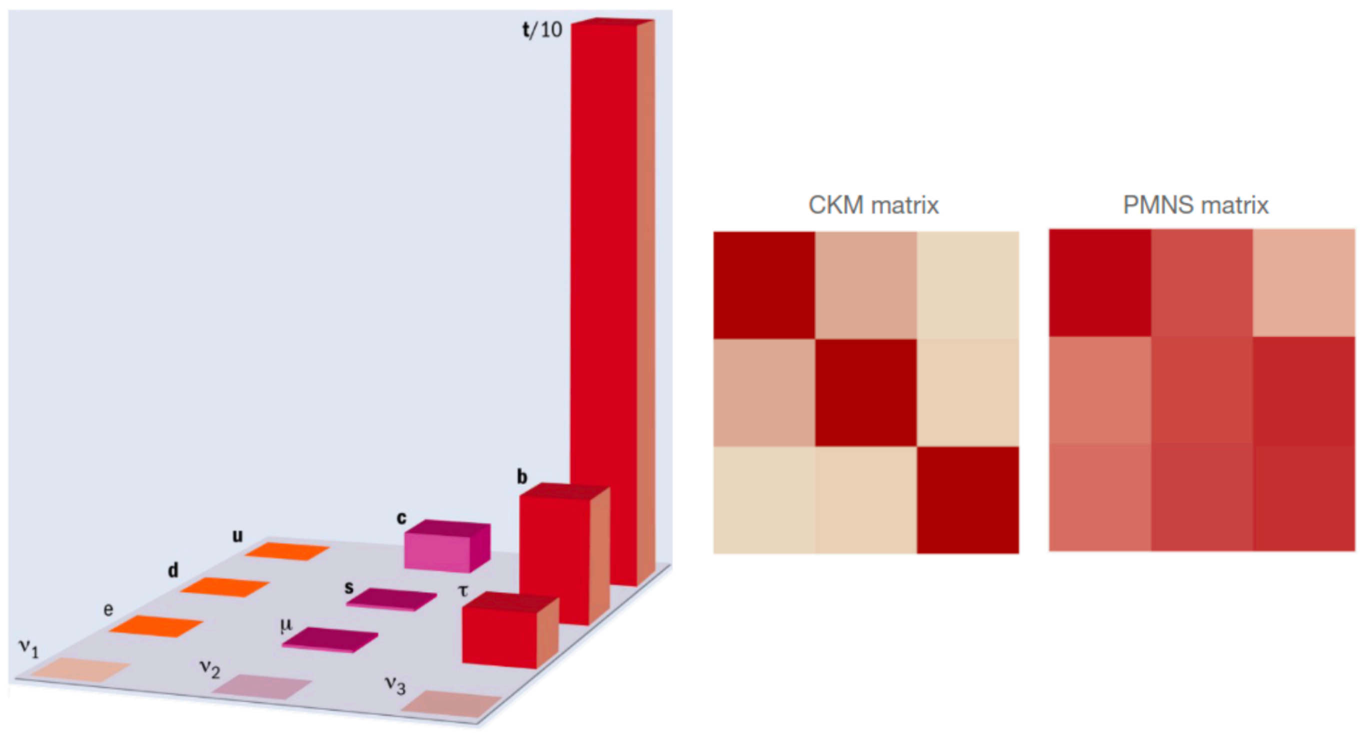
- Experiments sensitive to much larger values than SM prediction

$\Rightarrow$ **There is ample room for CP violating New Physics**

The need for Beyond SM physics

- Strong CP Problem
- Hierarchy Problem
- Flavour puzzle
- …

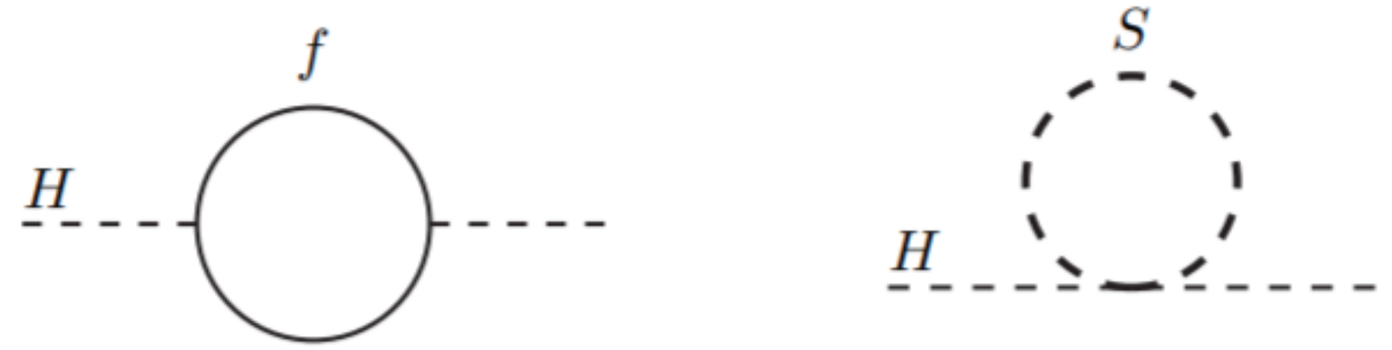


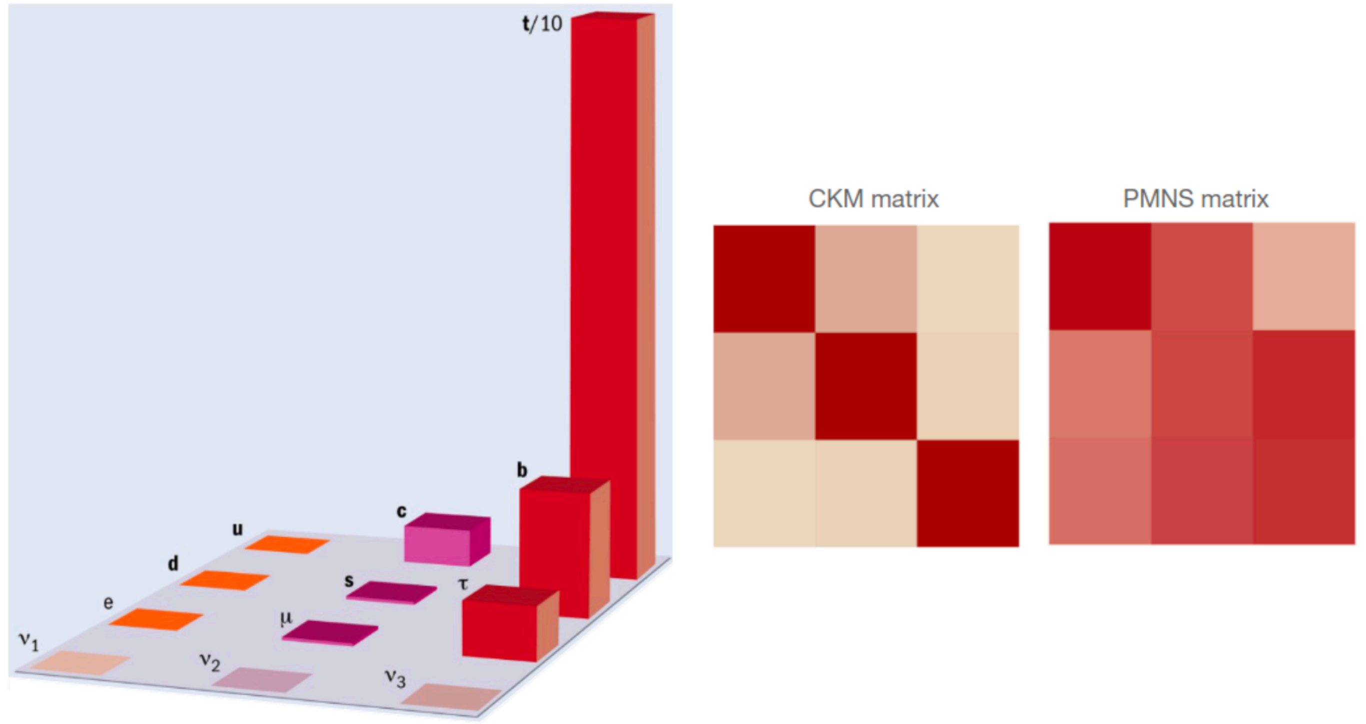


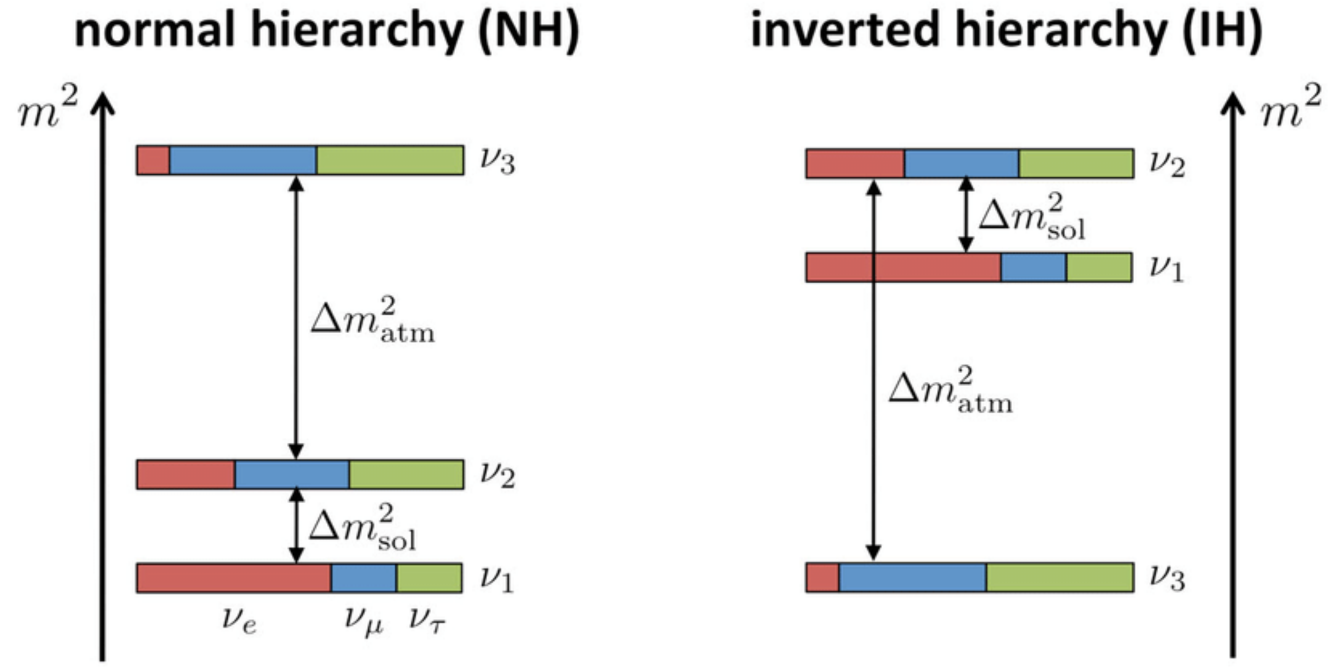
The need for Beyond SM physics

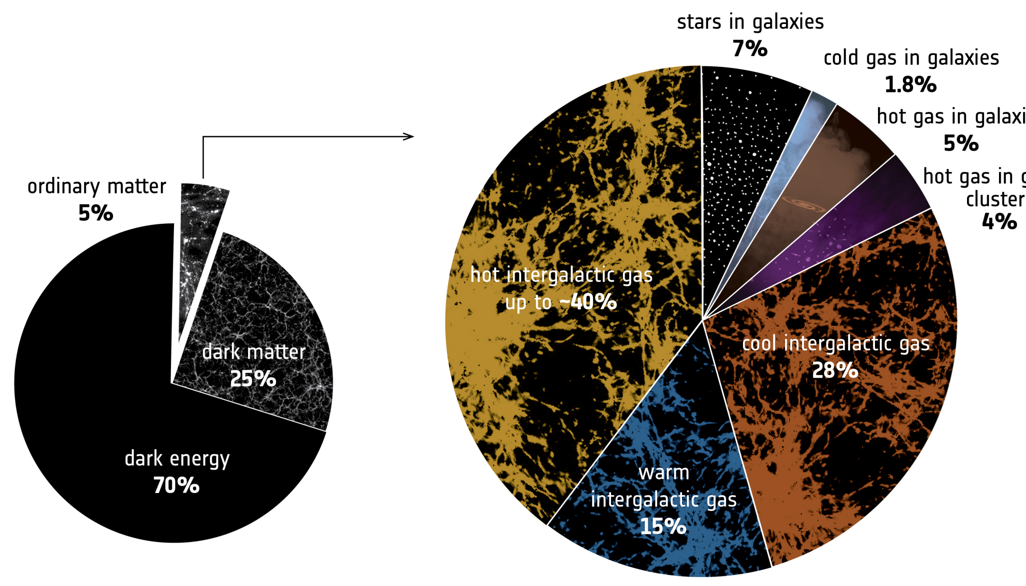
- Strong CP Problem
- Hierarchy Problem
- Flavour puzzle
- …

- Neutrino masses
- Dark matter
- Baryon asymmetry of the Universe









$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Heavy New Physics

- There many good reasons to expect CP-odd New physics (**baryogenesis**, origin of flavour…)

- But there is also a huge number of NP models in the market

- What if the NP is heavy?

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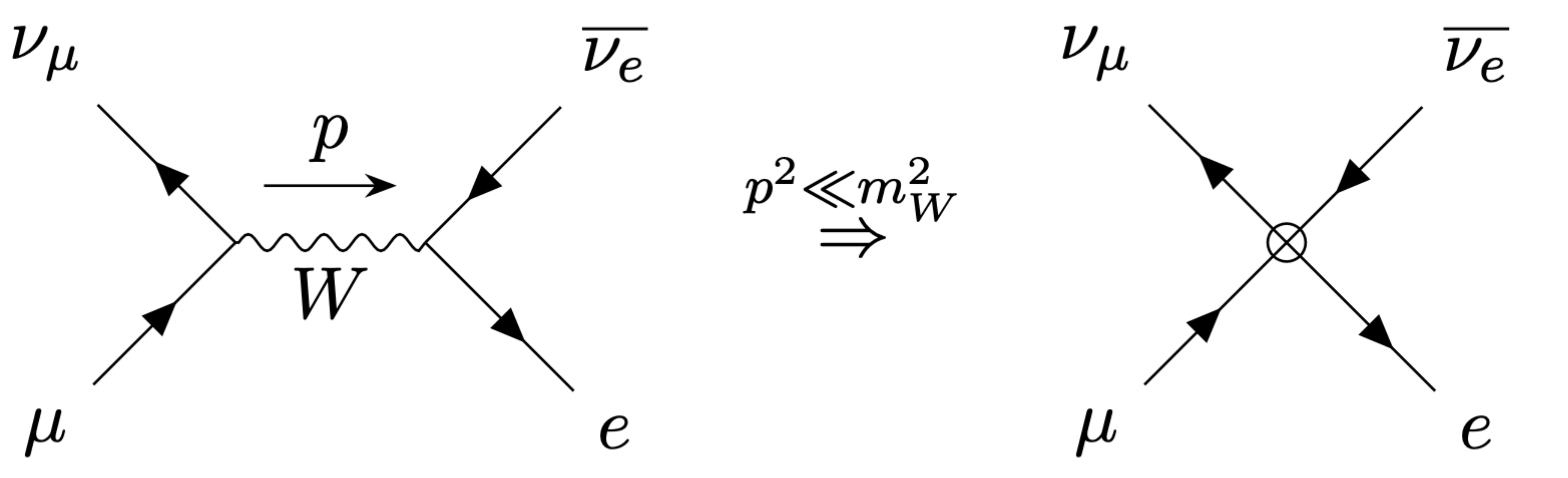
Muon decay and Fermi theory



At energies relevant for the muon decay ($E \ll M_W$), it is well described by a four-fermion contact interaction

$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

$$-2\sqrt{2}G_F\left(\overline{\nu_\mu}\gamma_\alpha P_L \mu\right)\left(\bar{e}\gamma^\alpha P_L \nu_e\right)$$

Short-distance heavy physics

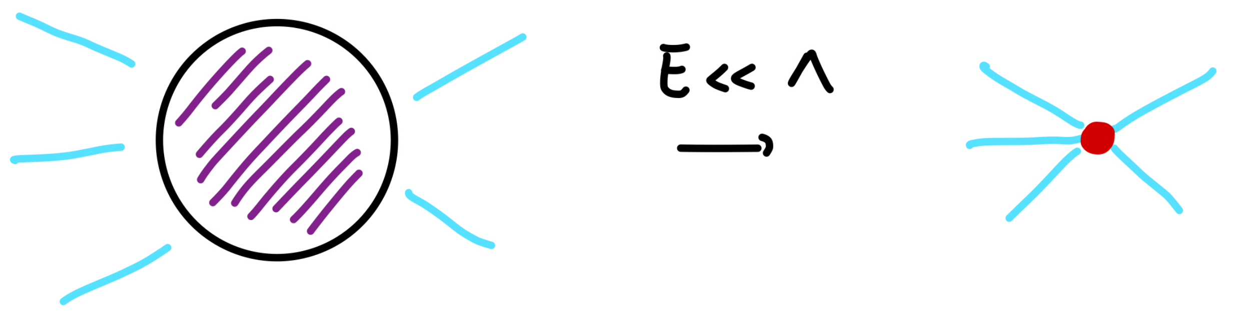
Contact interactions among light fields

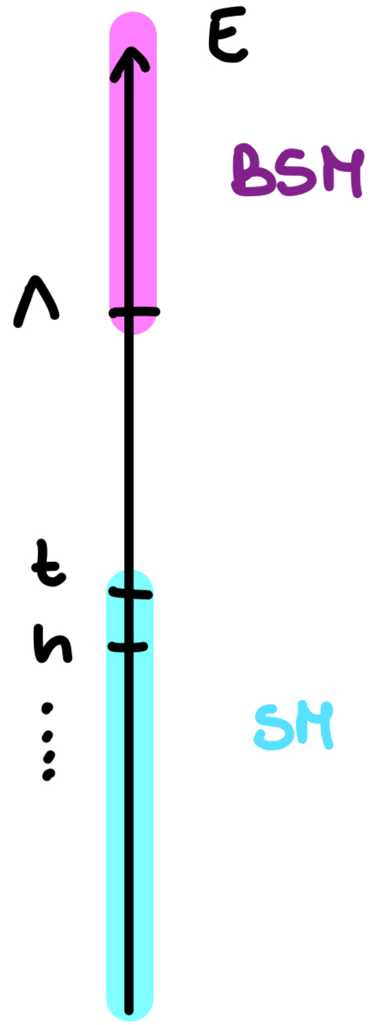
Effective Field Theories (EFTs)

Effective Field Theories are QFTs that are the **low-energy limit** of an ultraviolet theory and contain only the accessible light degrees of freedom

C_n **: Wilson Coefficients = short-distance heavy physics**

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{n>4} \frac{C_n \mathcal{O}_n}{\Lambda^{n-4}}$$





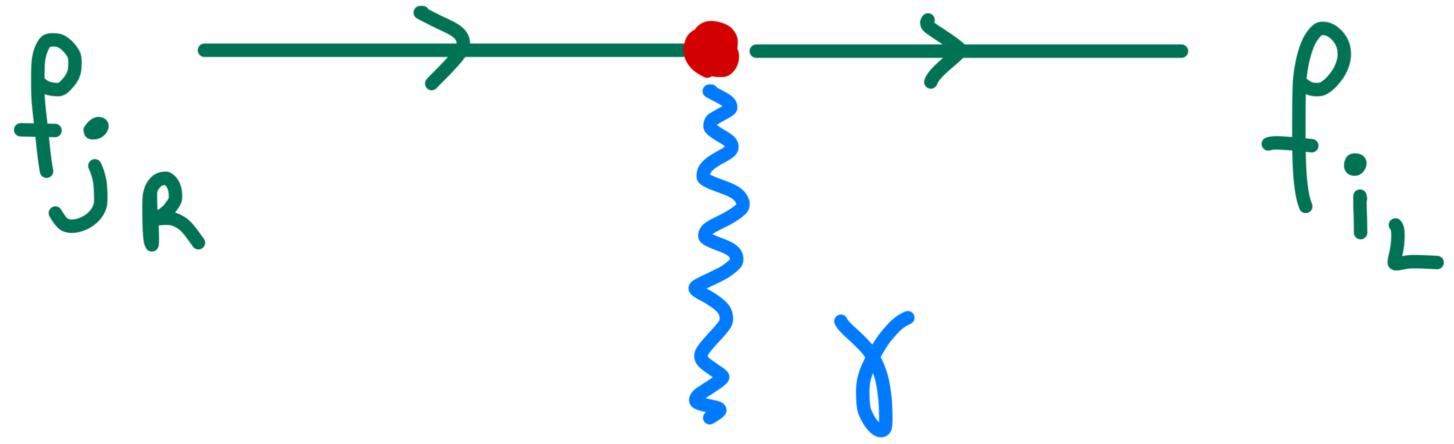
$\mathcal{O}_n$ **: Contact interactions among light fields**

n : operator dimension

They provide the most general description of NP at energies lower than the heavy states masses

The dipole operator (low-energy)

Remember: $\delta\mathscr{L}_{\text{dip}} = -\frac{1}{2}\,\bar\psi_f\sigma_{\mu\nu}(\mu_f + i\gamma_5 d_f)\psi_f\,F^{\mu\nu}$ ⟶ $H = -(\mu_f\vec S\cdot\vec B + d_f\vec S\cdot\vec E)/S$



$$C_D^{f_if_j}\,(\bar f_i\sigma_{\mu\nu}P_R f_j)\,F^{\mu\nu} + \text{h.c.}$$

→ $-2\,\text{Im}(C_D^{ff}) = d_f$

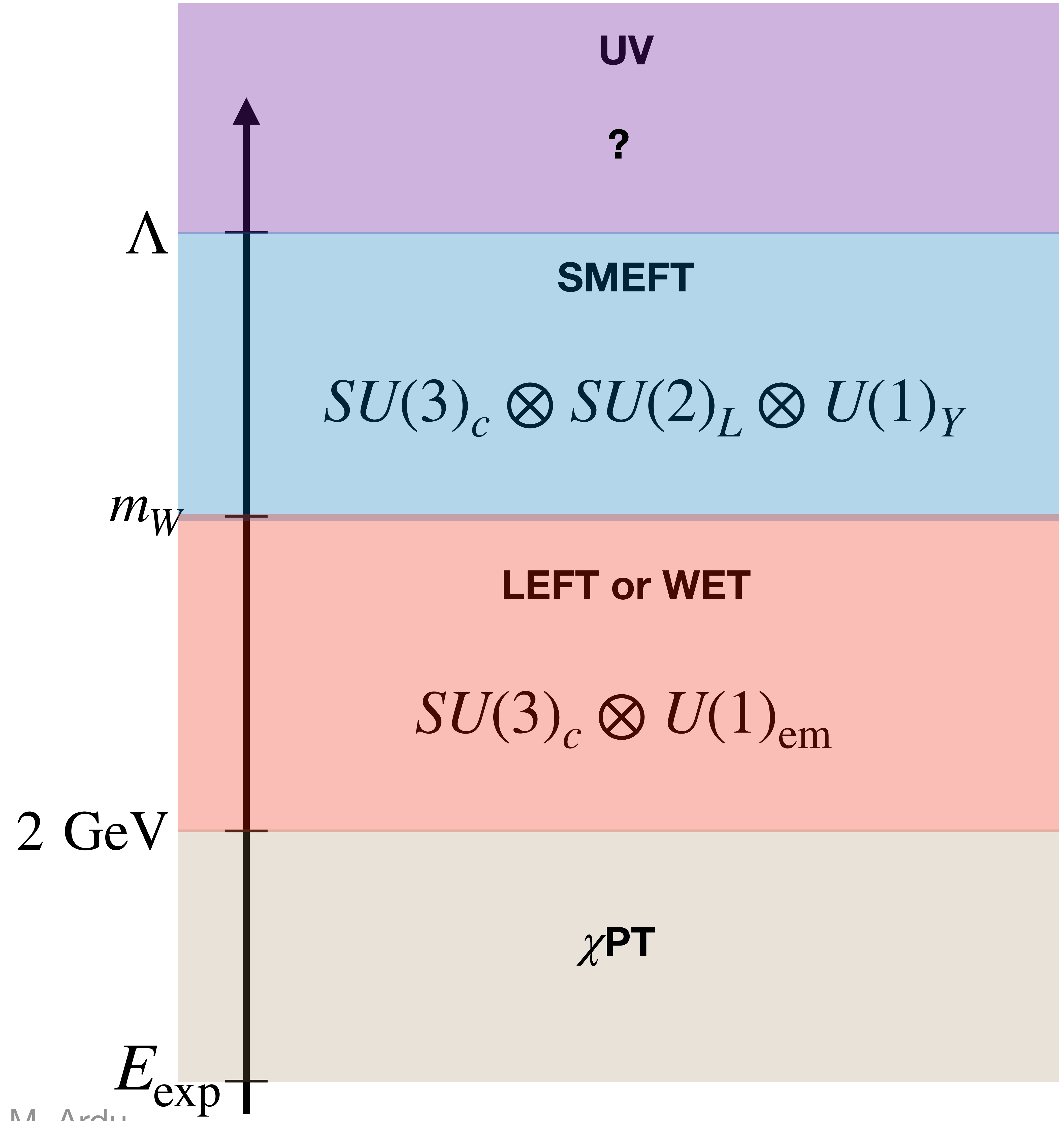
→ $-2\,\text{Re}(C_D^{ff}) = \mu_f$

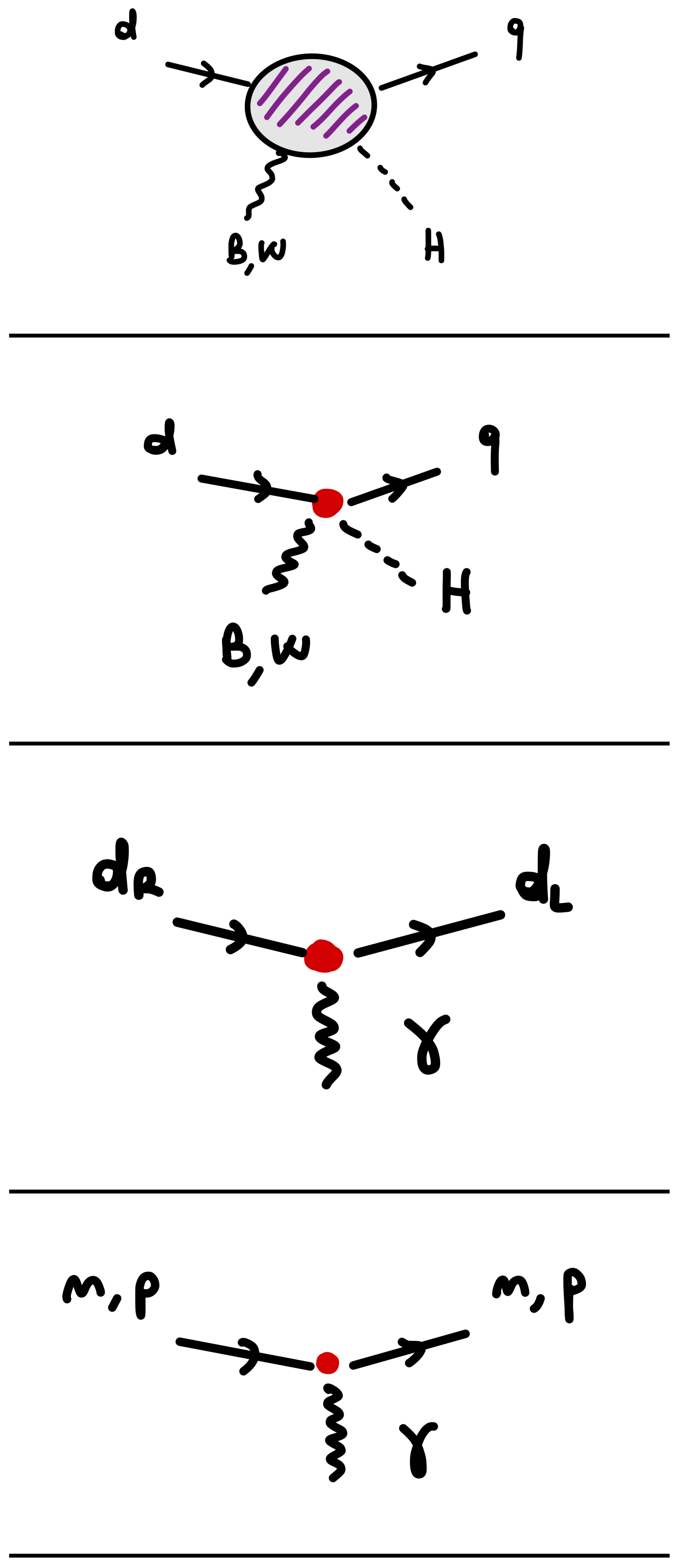
→ $C_D^{f_if_j} \neq 0,\ f_i \neq f_j \qquad f_j \to f_i\,\gamma$

*Tensor currents are chiral (connect right-handed and left-handed fields)

Tower of EFTs

The appropriate EFT to use depends on the energy of the process we want to describe





Heavy states are integrated out = Matched onto the EFT

dim=6 $(\bar{q}\sigma_{\mu\nu}Hd)B^{\mu\nu}, (\bar{q}\sigma_{\mu\nu}H\tau^a d)W_a^{\mu\nu} + \mathrm{h.c}$

$\langle H \rangle = v$ t, h, Z, W Integrated out

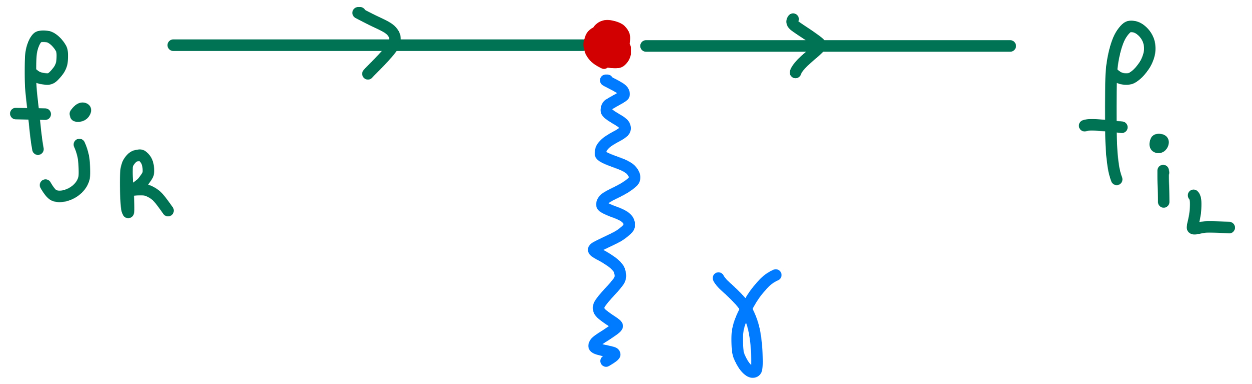
dim=5 $(\overline{d_L}\sigma_{\mu\nu}d_R)F^{\mu\nu} + \mathrm{h.c}$

Strong interactions are strong = quarks combine in bound states

dim=5 $(\bar{n}\sigma_{\mu\nu}n)F^{\mu\nu}, (\bar{n}\sigma_{\mu\nu}\gamma_5 n)F^{\mu\nu}$

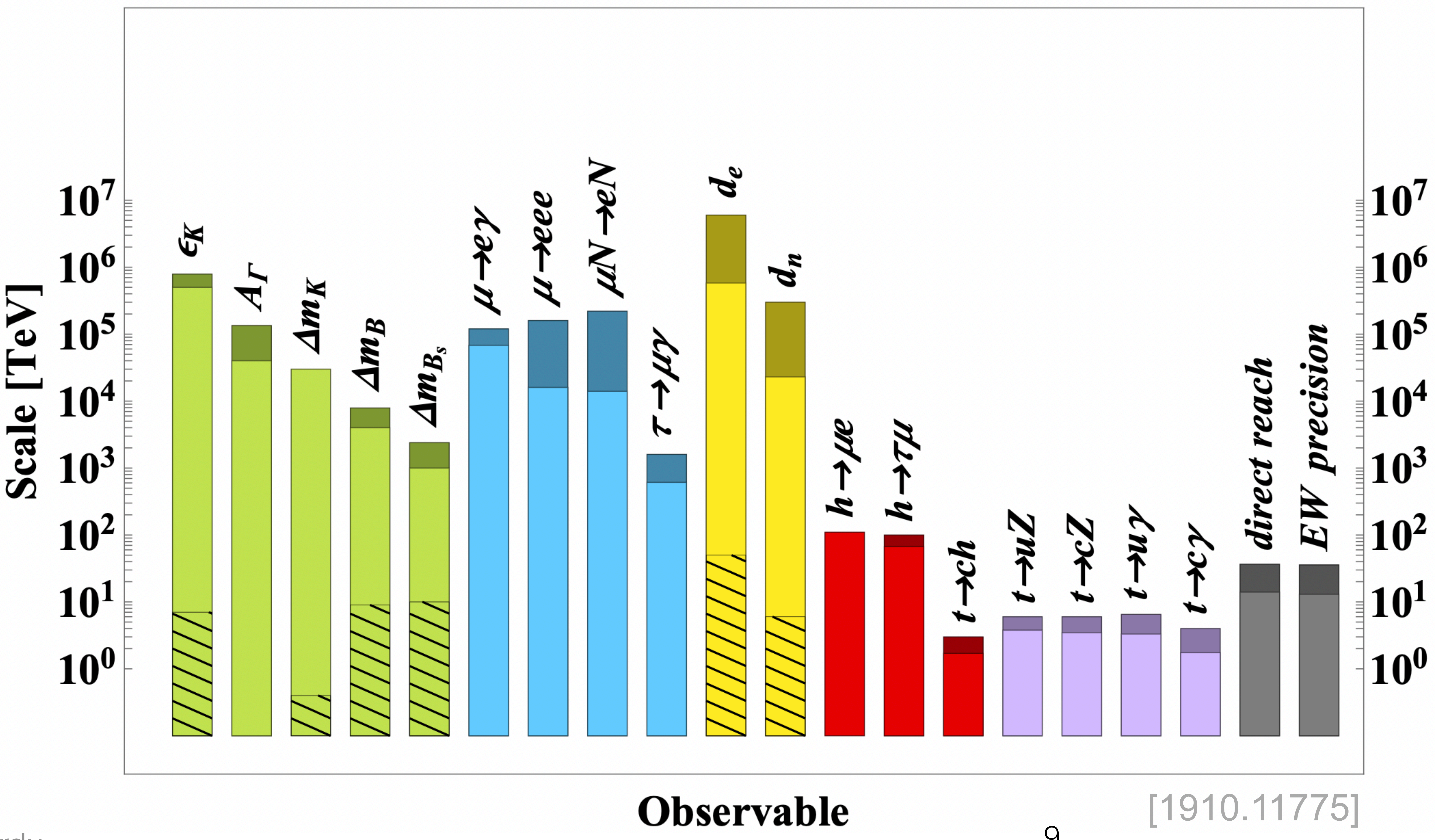
d_n, d_p

The dipole operator



$$C_D^{f_i f_j}(\bar{f}_i \sigma_{\mu\nu} P_R f_j) F^{\mu\nu} + \mathrm{h.c.} \qquad C_D = \frac{v}{\Lambda^2}\tilde{C}_D$$

The dipole operator at low energy must arise from a dimension six SMEFT operator and must be proportional to the Higgs VEV $\langle H \rangle = v$



Solid bars assuming $\mathrm{Im}(\tilde{C}_D) \sim 1$

Hatched bars assuming $\mathrm{Im}(\tilde{C}_D^{ff}) \sim y_f$

[1910.11775]

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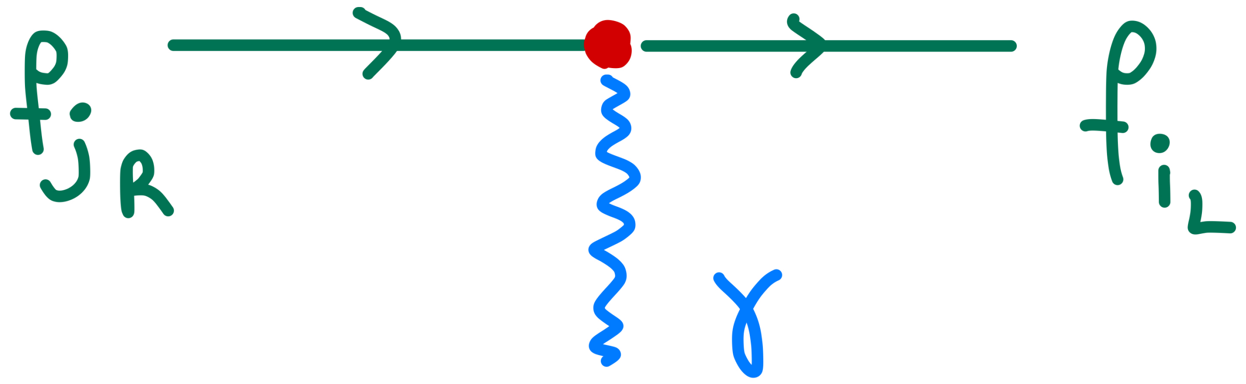
The dipole operator



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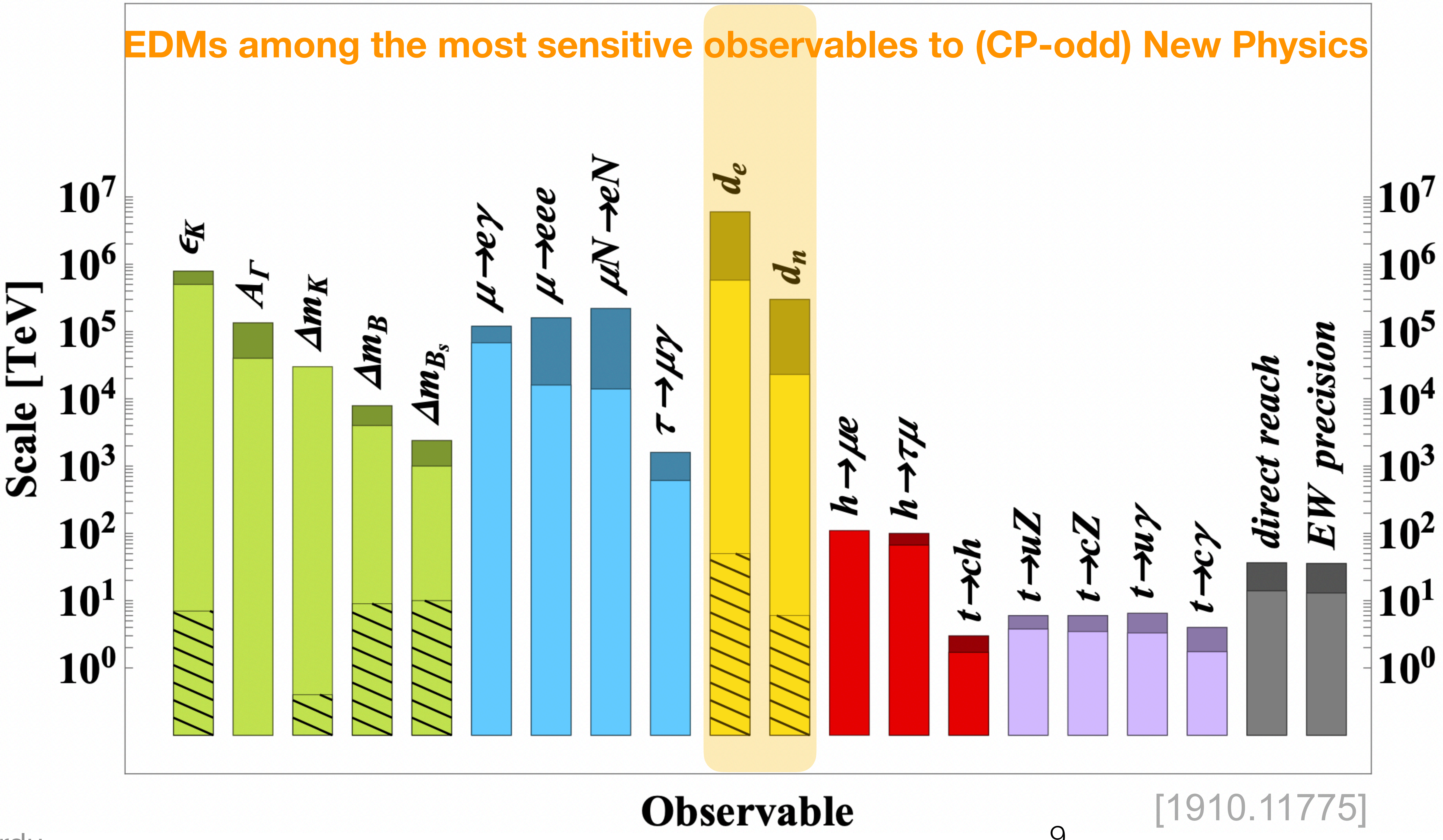

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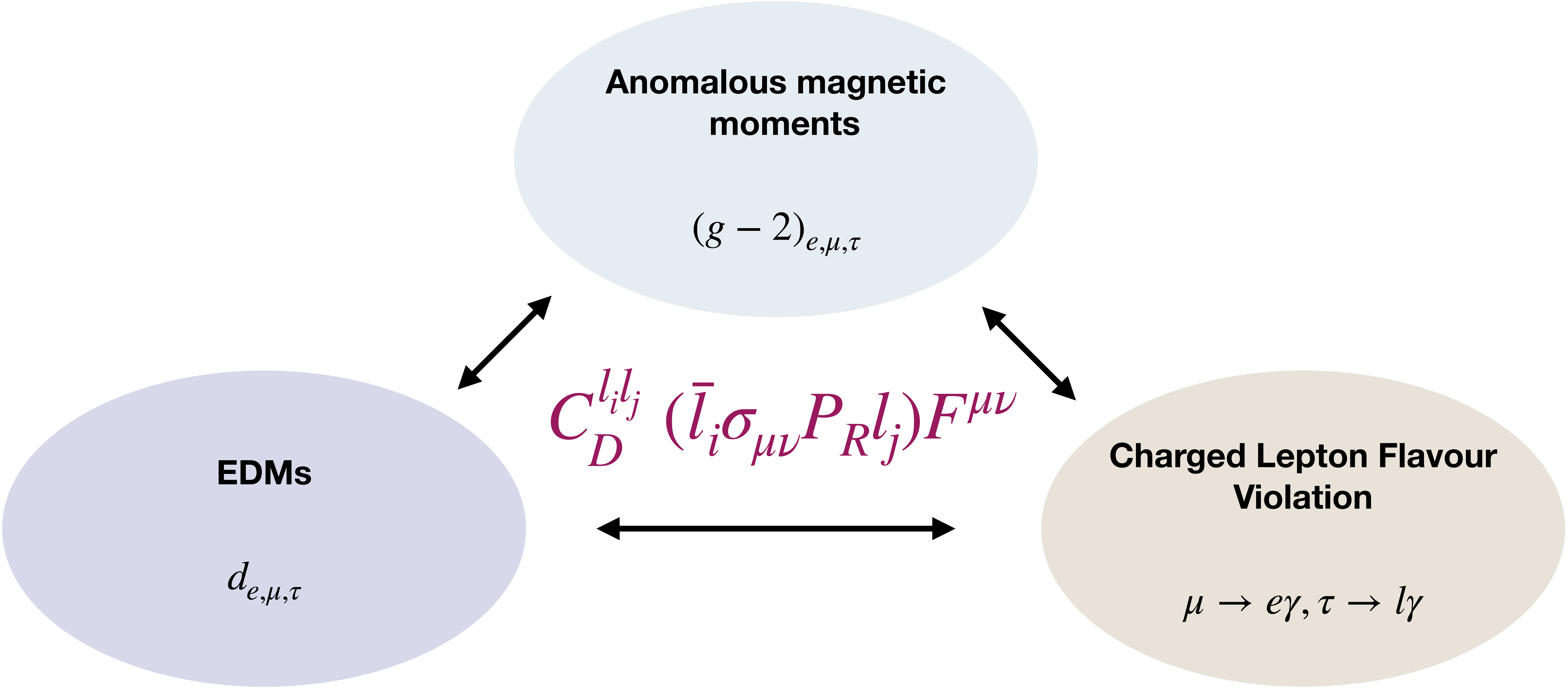
Dipoles in the lepton sector

$l = e, \mu, \tau$



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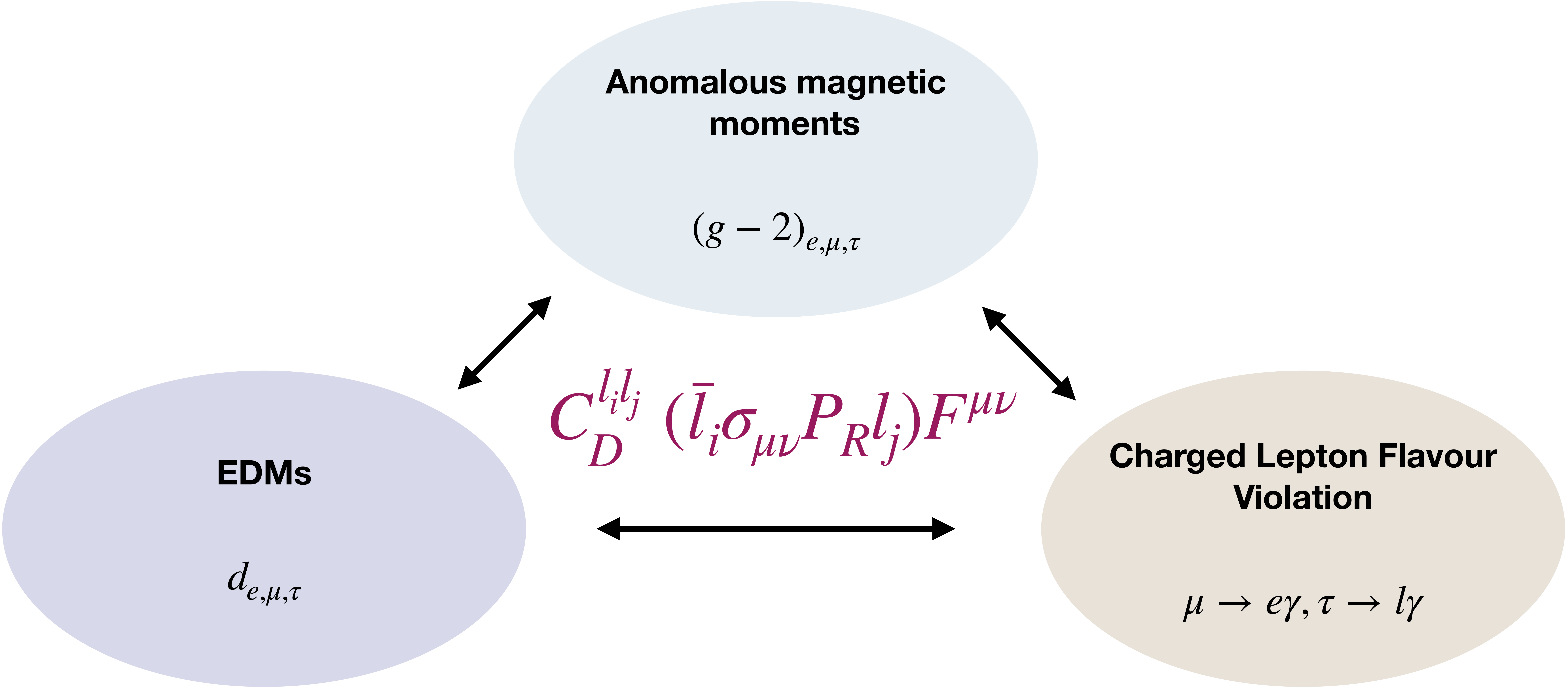

The interplay between these observables could shed light on the flavour and CP structure of New Physics

Dipole observables in the lepton sector

$$C_D^{l_i l_j}\,(\bar{l}_i \sigma_{\mu\nu} P_R l_j) F^{\mu\nu}$$

$$\Delta a_l = \frac{4m_l}{e}\mathrm{Re}(C_D^{ll})$$

$$d_l = -2\mathrm{Im}(C_D^{ll})$$

$$2\Delta a_l = (g-2)_l$$

- EDMs vs anomalous magnetic moments

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[Giudice, Paradisi, Passera 1208.6583]

$$d_e \simeq \left(\frac{\Delta a_e}{7\times 10^{-14}}\right) 10^{-29} \left(\frac{\phi_e^{\mathrm{CPV}}}{10^{-5}}\right) e\,\mathrm{cm}$$

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$$\mathrm{BR}(\mu \to e\gamma) \simeq 3 \times 10^{-13} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{10^{-5}}\right)^2$$

Flavour UV alignment

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Flavour UV alignment

- Ratios with different flavors probe to the NP flavour structure

$$\frac{d_l}{d_{l'}} = ?$$ **Often** $= m_l/m_{l'}$

$$\frac{\Delta a_l}{\Delta a_{l'}} = ?$$ **Often** $= m_l^2/m_{l'}^2$

Lepton flavour violation and EDMs

[MA, S. Davidson, N. Valori, 2507.19421]

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In this class of models EDMs arise at least at two-loop $$d_i \sim \frac{1}{(16\pi^2)^2}\frac{m_i}{\Lambda_{NP}^2}{\rm Im}\left\{\Pi_{ii}\right\}$$

While lepton flavour violation can arise already at one-loop: $$C_D^{ij} \sim \frac{1}{(16\pi^2)}\frac{m_j}{\Lambda_{NP}^2}$$

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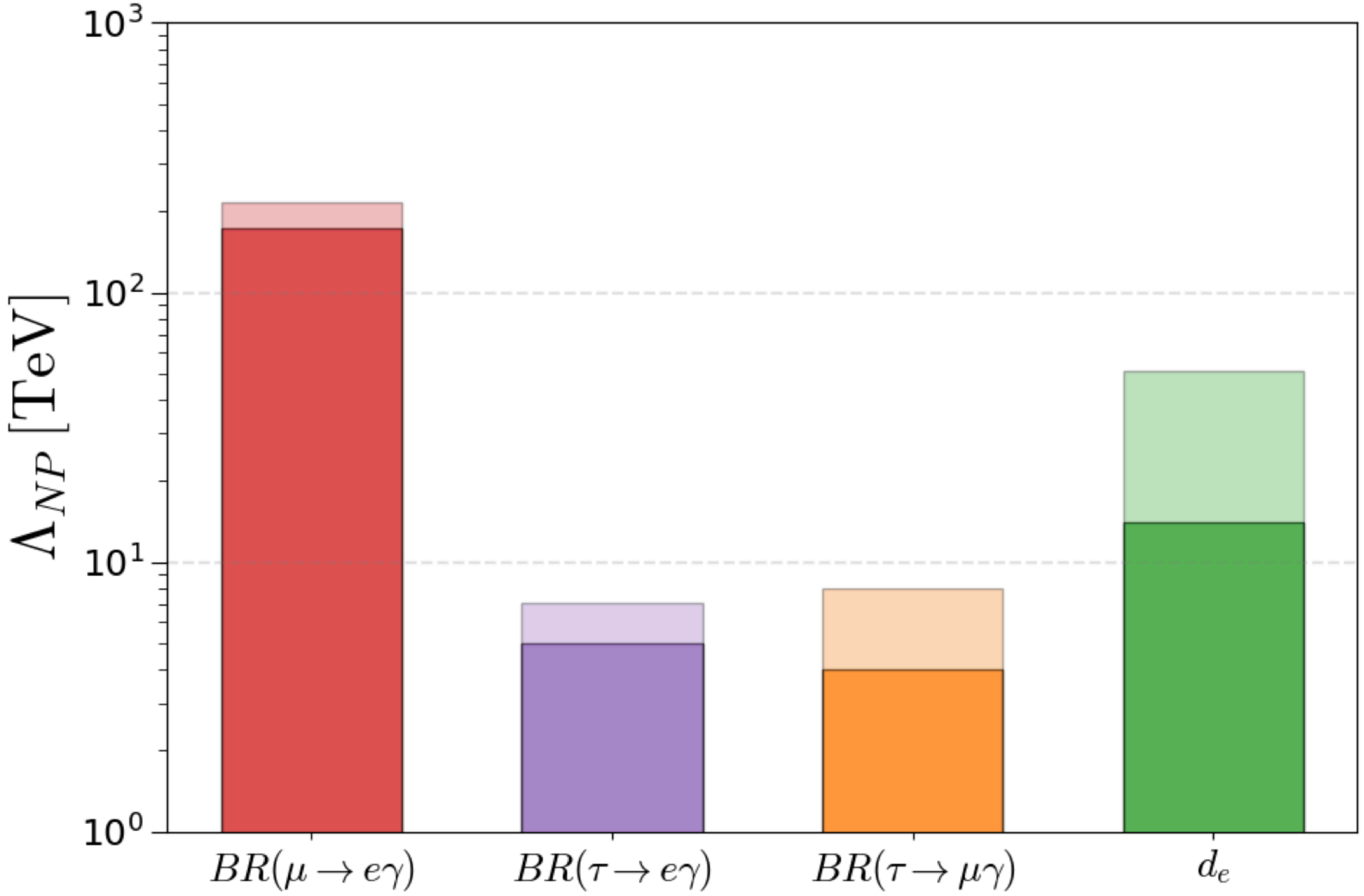

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Including loops in the EFT

Effective field theories at fixed dimension (= fixed accuracy in E/Λ) **are** as **renormalizable** as any QFT

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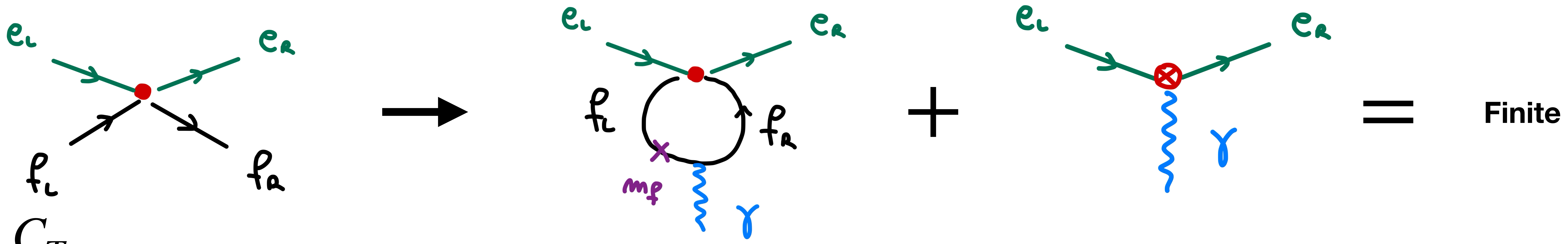

$$\frac{C_T}{\Lambda^2}(\overline{e_R}\sigma_{\mu\nu}e_L)(\overline{f_R}\sigma^{\mu\nu}f_L)$$

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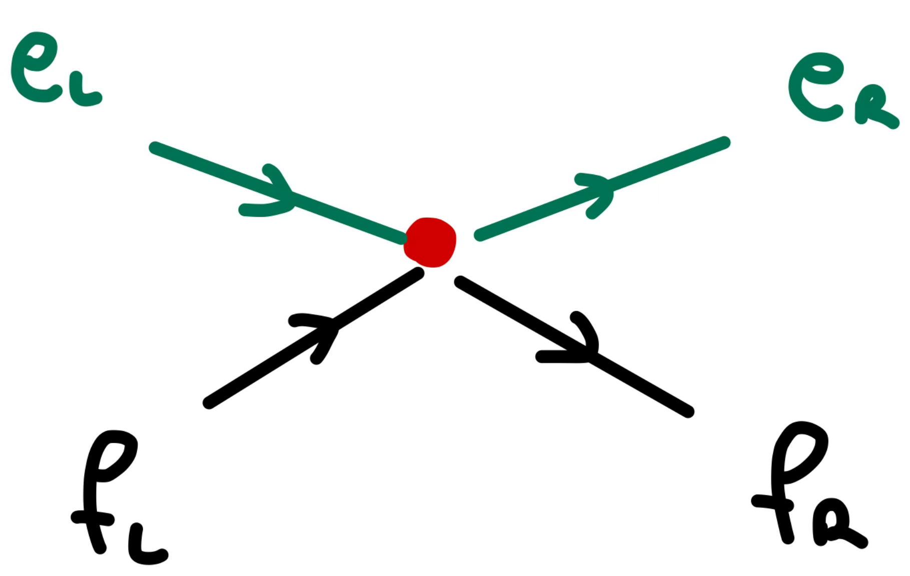

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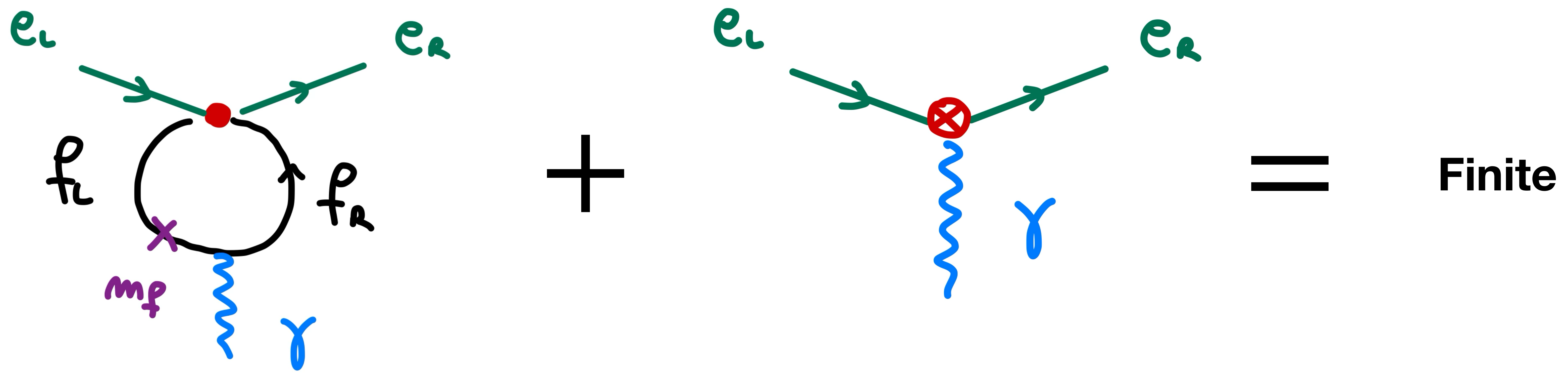

At the loop level, **operators** acquire a dependence on the energy (renormalization) scale μ and **mix with each other**

Renormalization Group Equations (RGEs):

$$\frac{d}{d\log\mu}[C(\mu_f)]_k = [C(\mu_i)]_j U_{jk}(\mu_f,\mu_i)$$

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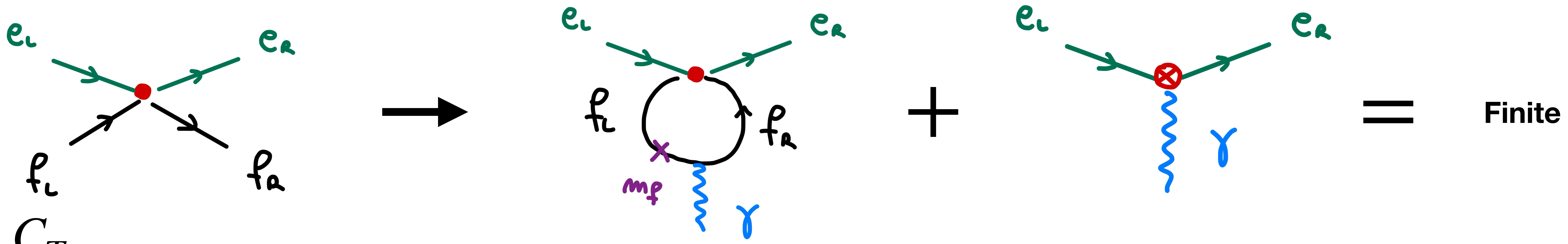

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Renormalization Group Equations (RGEs):

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Solution in our example:

$$C_D(\mu_f) \sim C_T(\mu_i) \times \frac{e m_f}{16\pi^2\Lambda^2}\log\left(\frac{\mu_f}{\mu_i}\right) + \cdots$$

Running up & down the ETFs tower

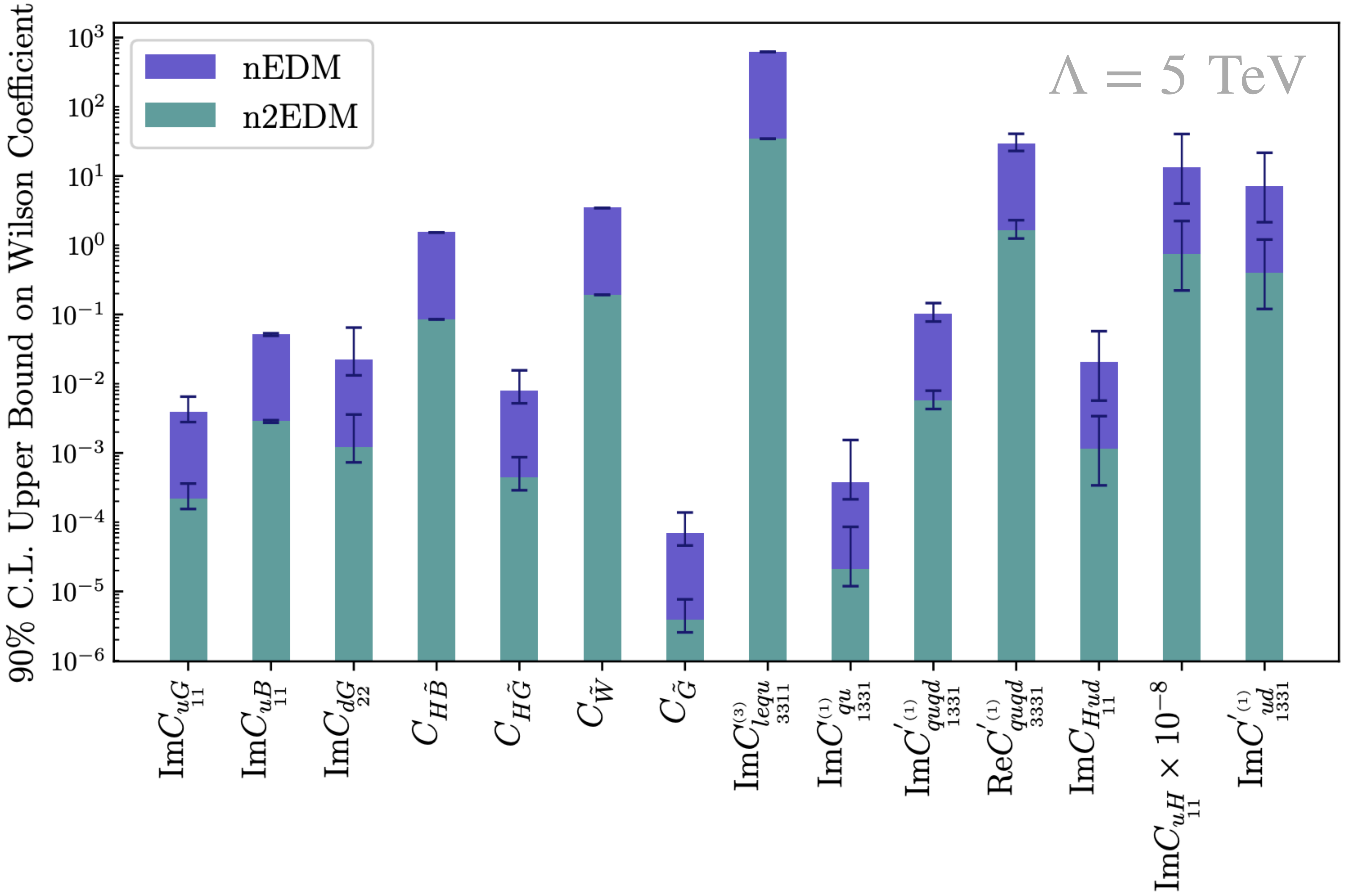
SMEFT analysis of EDMs

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{n=6} \frac{C_n \mathcal{O}_n}{\Lambda^2}$$

Calculate the contribution to d_e for each SMEFT operator (at dimension six) to EDMs accounting for loop effects (solving the RGEs)

d_n

[Kley et al, 2109.15085]



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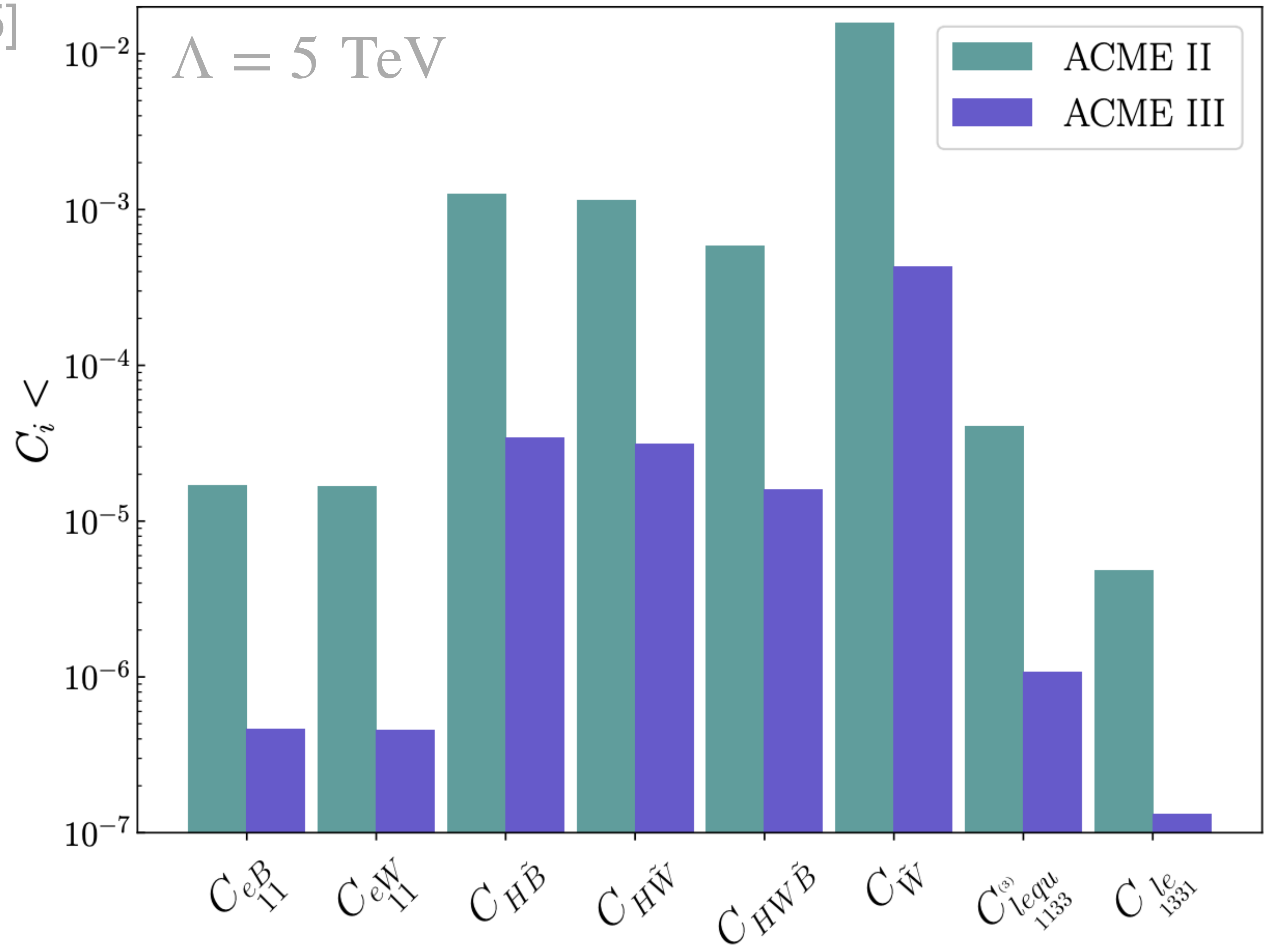

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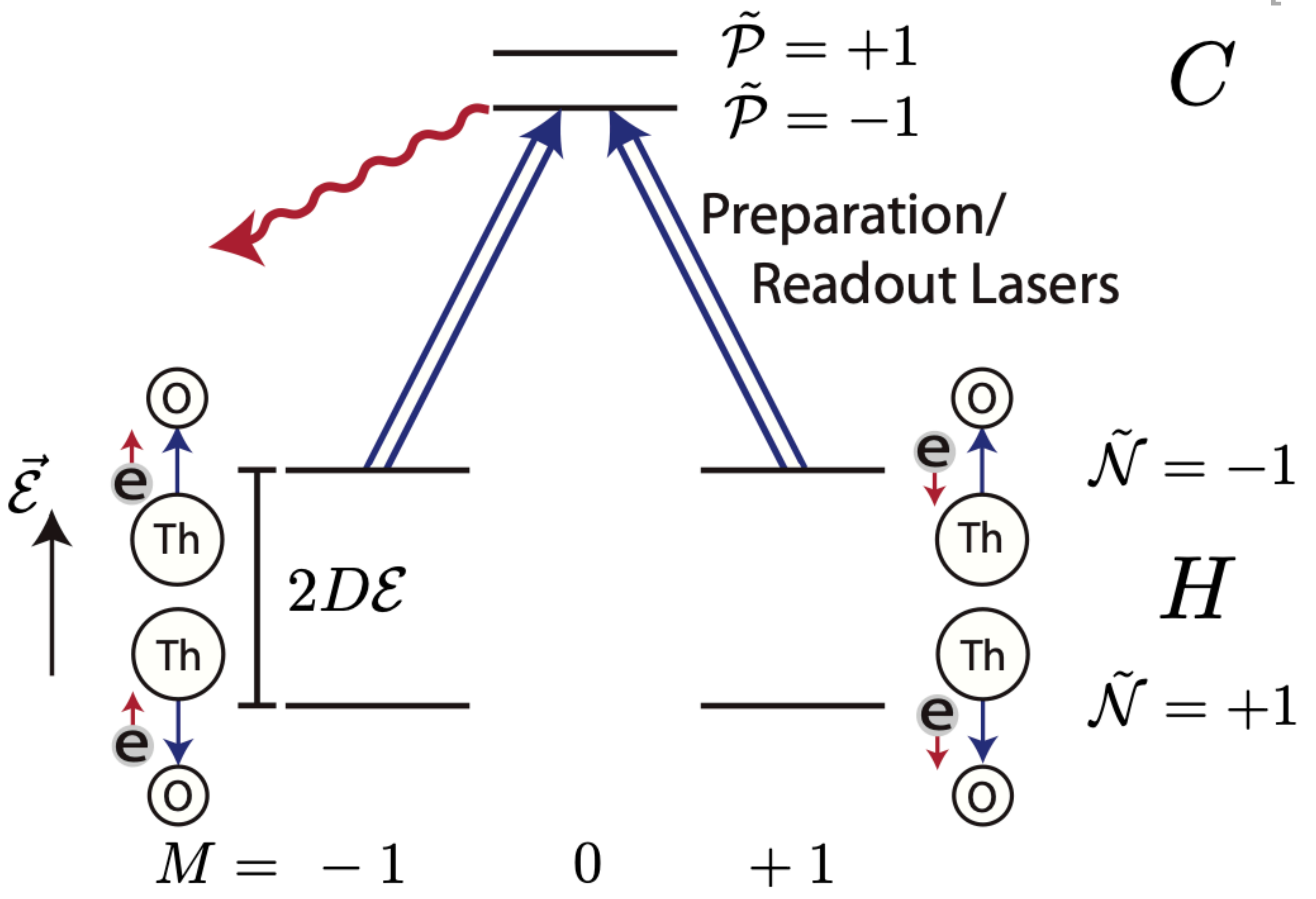
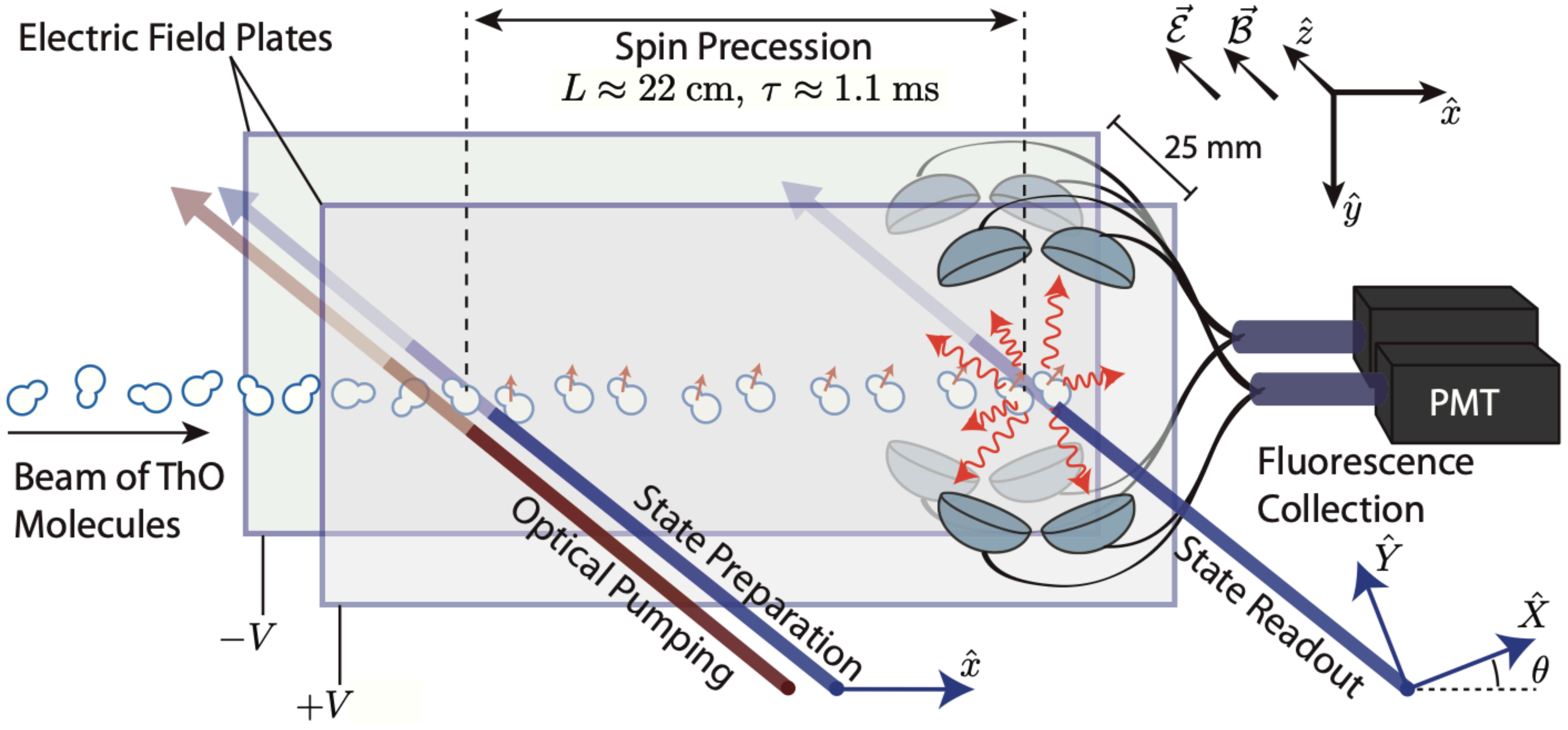
Paramagnetic molecules (ThO, HfF+,…) have an unpaired electron and can have very large internal electric field due to relativistic effects.

In the presence of the electron EDM there is a P, T-odd energy shift between two states with flipped “orientation”

[ACME, 1310.7534]





$$H^{\text{eff}}_{P,T} = -\tilde{\mathcal{N}}(d_e E_{eff} + \dots)$$

Paramagnetic eEDM searches

But other CP odd interactions between the electron and the nucleus can mimic this energy shift

$$\frac{G_F}{\sqrt{2}} C_S i(\bar{e}\gamma_5 e)(\bar{N}N) \longrightarrow H_S = i\frac{G_F}{\sqrt{2}} C_S \sum_i \rho_N(\mathbf{r}_i)\,\gamma_i^0\gamma_i^5$$

Can also contribute to the energy shift as the electron EDM

$$H_{P,T}^{\mathrm{eff}} = -\tilde{\mathcal{N}}(d_e E_{eff} + W_S C_S + \ldots) \qquad W_S \equiv \frac{1}{\tilde{\mathcal{N}}}\left\langle \Psi_{\tilde{\mathcal{N}}} \left| i\frac{G_F}{\sqrt{2}} \sum_i \rho_N(\mathbf{r}_i)\gamma_i^0\gamma_i^5 \right| \Psi_{\tilde{\mathcal{N}}} \right\rangle$$

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[Skripnov, 1704.07318]

$$X = E_{\text{eff}}, W_S$$

$$\begin{aligned}
X(\text{TOTAL}) = {} & X(\text{52e-4c-CCSD(T), QZ}) \\
& + X(\text{80e-4c-CCSD(T), DZ}) - X(\text{52e-4c-CCSD(T), DZ}) \\
& + X(\text{4c-Dirac-Fock-Gaunt, QZ}) - X(\text{4c-Dirac-Fock, QZ}) \\
& + X(\text{two-step-2c-20e-CCSDT(Q),CBas}) - X(\text{two-step-2c-20e-CCSD(T),CBas}) \\
& + X(\text{two-step-1c-52e-CCSD(T),LBasExt}) - X(\text{two-step-1c-52e-CCSD(T),LBas})
\end{aligned} \qquad (7)$$

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Which leads to an **equivalent EDM** as the measurable observable:

[Chupp et al, 1710.02504]

$$d^{\text{equiv.}} = d_e + \# \times C_S \; e \cdot \text{cm}$$

$$\text{ThO} \simeq 1.5 \times 10^{-20}$$

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$$d^{\text{equiv.}}(\text{exp}) \sim 10^{-29} - 10^{-30}\; e \cdot \text{cm} \gg d^{\text{equiv.}}_{\text{ThO}}(\text{SM}) \sim 10^{-35}\; e \cdot \text{cm} \gg d_e$$

[Ema et al, 2202.10524]

Interpreting paramagnetic searches in SMEFT

Heavy CP-odd New Physics can contribute both to d_e and C_S at low-energy

$$\mathscr{L} = -i\,\frac{d_e}{2}\,\bar{e}\,\sigma_{\mu\nu}\gamma_5\,e\,F^{\mu\nu} + \frac{G_F}{\sqrt{2}}\,C_S\,\bar{e}\,i\,\gamma_5\,e\,\bar{N}N + \ldots$$

Low-energy EFT

which enter in the experimental observable as

$$d^{\text{equiv.}}_{\text{HfF}^+} = d_e + 0.9 \times 10^{-20}\; C_S\; e \cdot \text{cm}$$

$$d^{\text{equiv.}}_{\text{HfF}^+} \leq 4.1 \times 10^{-30}\; e \cdot \text{cm}$$

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- What is the (correct) sensitivities of paramagnetic eEDM searches to SMEFT operators?

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[Kley et al, 2109.15085] [Panico et al,1810.09413] [Aebischer et al, 2102.08954]

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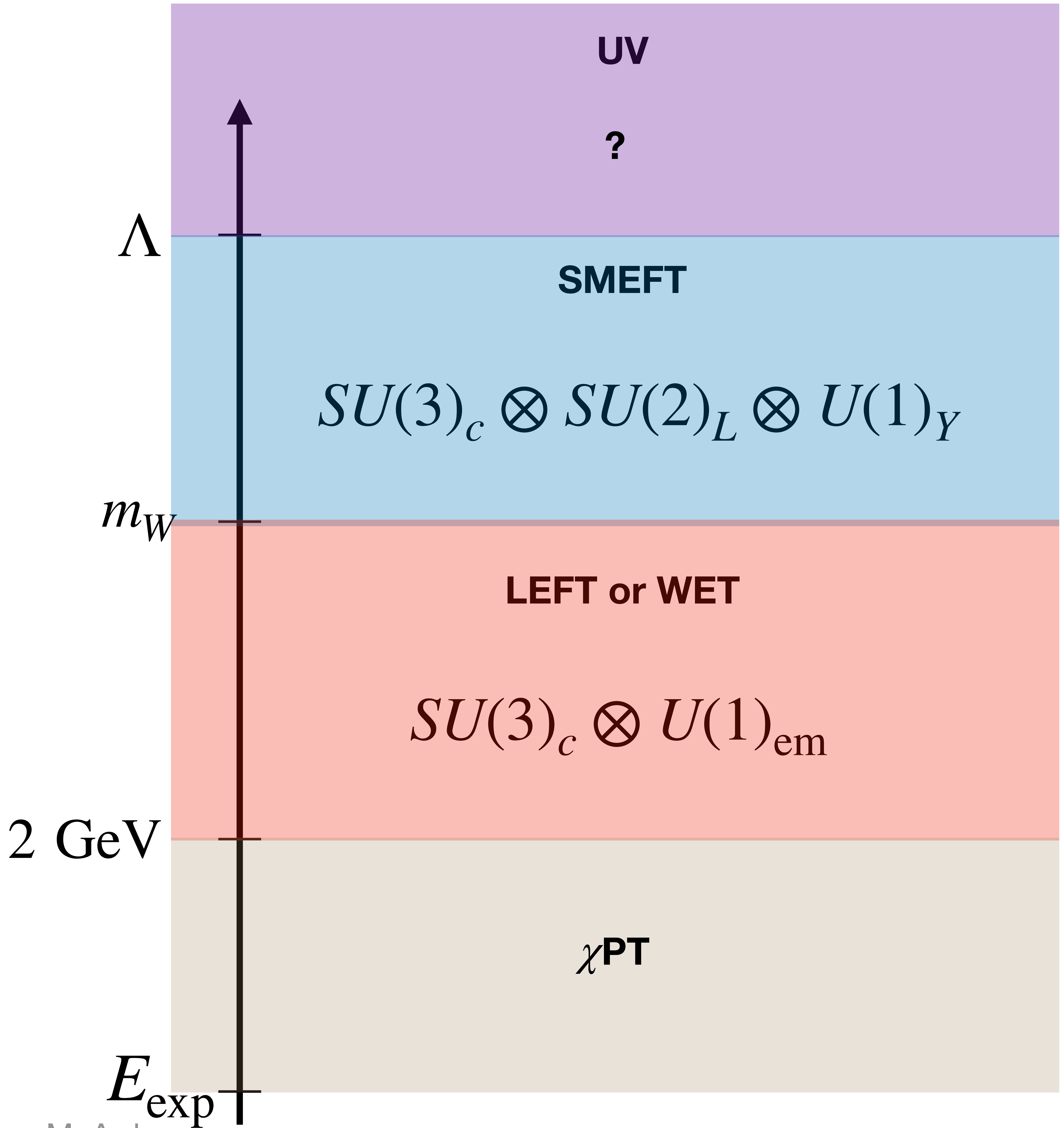
Calculating $d^{\text{equiv.}}$ in SMEFT



Start from $C_i(\mu)$ at $\mu = \Lambda$

↓ **Run in SMEFT** ✓

Match the $C_j(\mu = m_W)$ to LEFT operators

↓ **Run in LEFT** ✓

Match the LEFT operators to χPT interactions with nucleons

↓ **Run in χPT** ✗

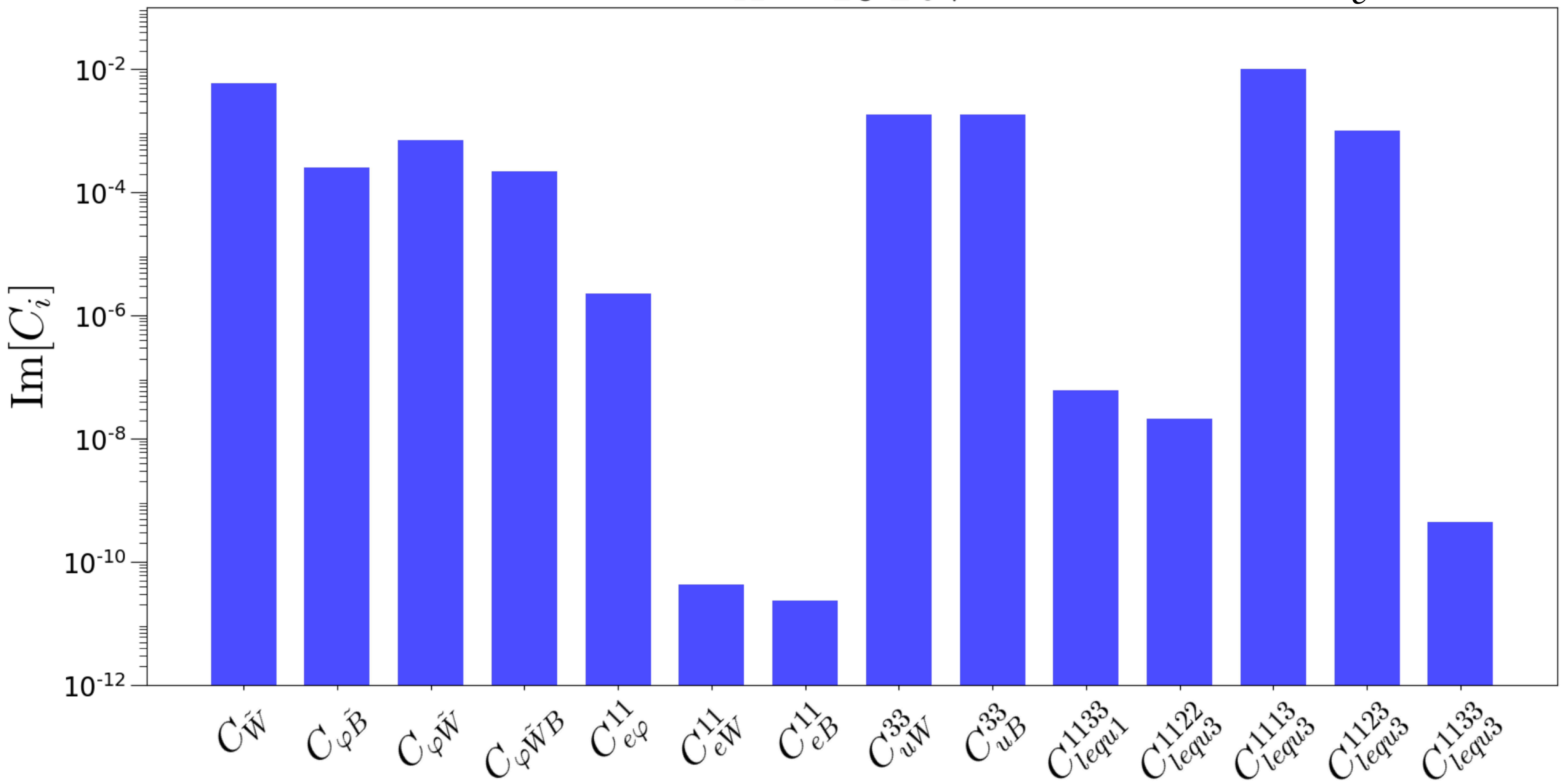
Compute $$d^{\text{equiv.}}_{\text{HfF+}} = d_e + 0.9 \times 10^{-20}\, C_S\, e \cdot \text{cm}$$

Results

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{n=6} \frac{C_n \mathcal{O}_n}{\Lambda^2}$$

One-loop RGEs + some two-loop effects

$\Lambda = 10\,\text{TeV}$ $\qquad d_e \sim d^{\text{equiv.}}$



M. Ardu

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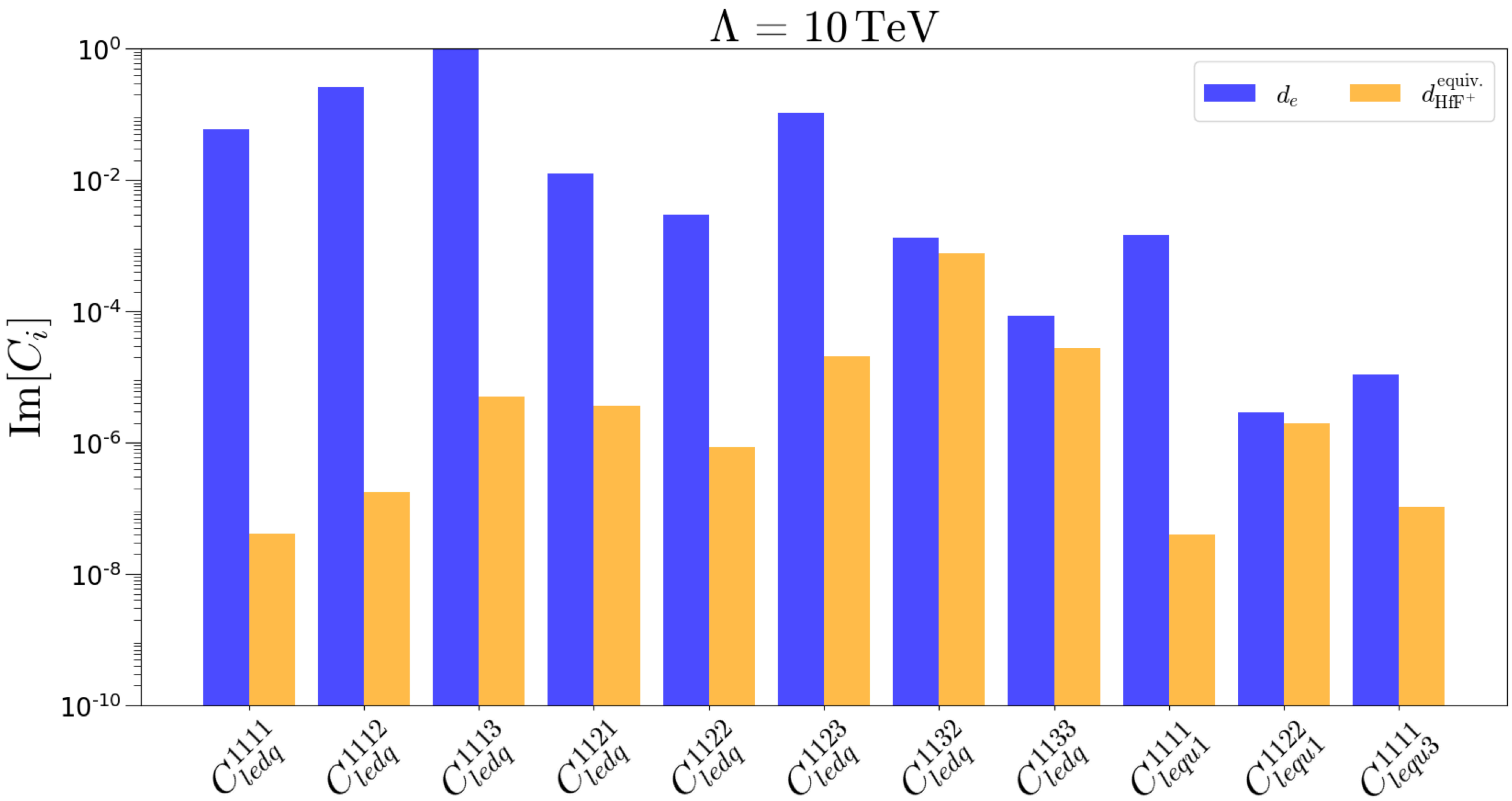


Conclusions

- Electric dipole moments are among the most sensitive observables for new physics.
- More broadly, dipole observables and their interplay provide uniquely powerful probes of beyond Standard Model scenarios
- In an effective field theory framework, heavy ultraviolet dynamics can be captured model-independently through higher-dimensional operators, enabling a systematic charting of the (heavy) BSM space
- Previous EFT studies focused on the SMEFT contribution to the electron EDM, but used paramagnetic-system sensitivities, i.e. to an “equivalent EDM” that also includes CP-odd semileptonic interactions
- We showed that electron-EDM searches in paramagnetic molecules probe a wider class of EFT operators than previously recognized

Back-up

SMEFT dimension six Basis-I

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

SMEFT dimension six Basis-II

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

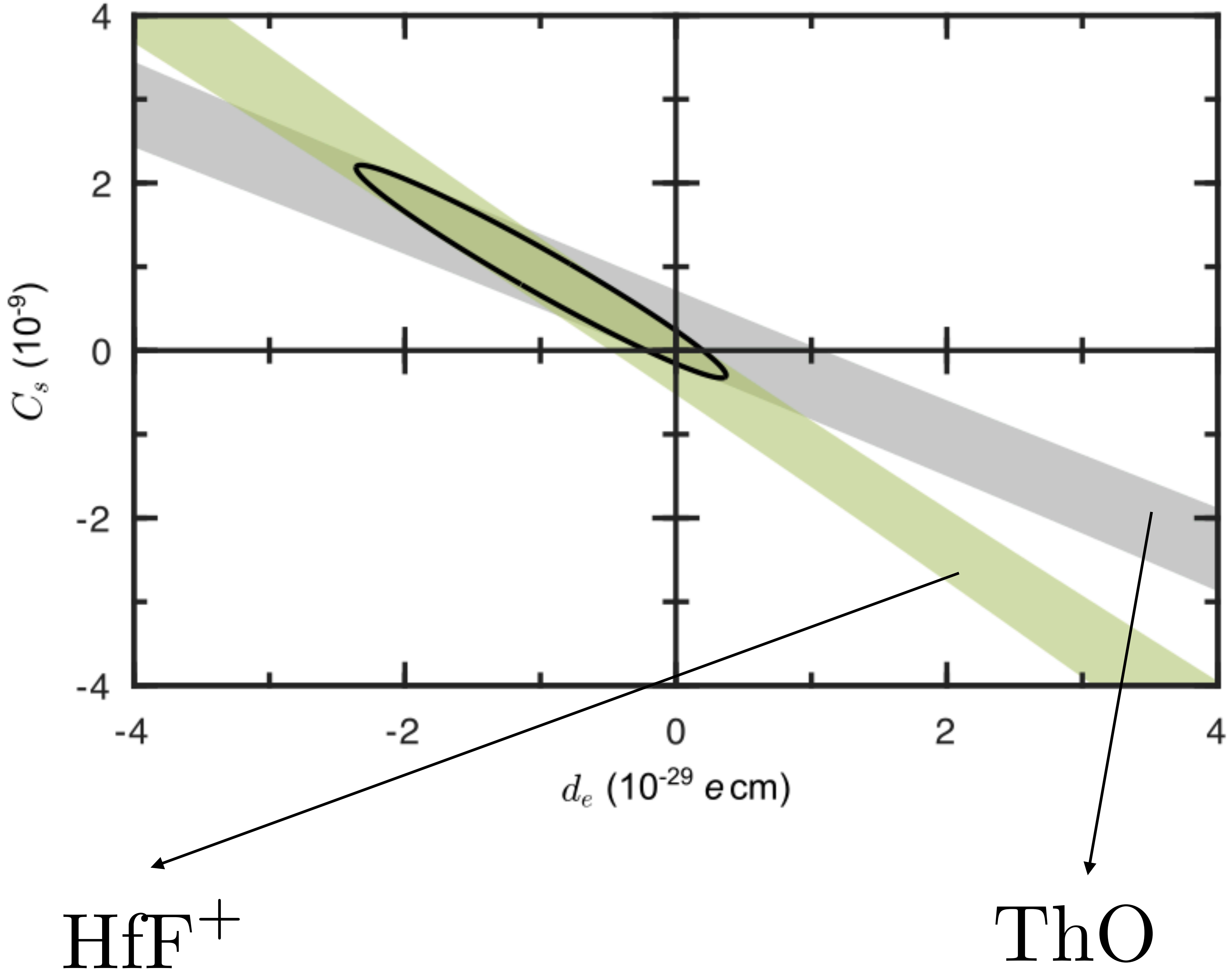
$8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

What if we have 2 or more Exps?

[Courtesy of Nicola Valori, SMEFT meets ChiPT 2025]

Roussy et al.,hep-ph/2212.11841



$$d_{sys}^{equiv.} = d_e + \# C_S \, e \cdot cm$$

Two experiments with different #
Can disentangle eEDM and Cs.

$$ThO \sim 1.5 \times 10^{-20}$$

$$HfF^+ \sim 0.9 \times 10^{-20}$$

Combined fit

$$|d_e| < 2.1 \times 10^{-29} \text{ e cm}$$

$$|C_S| < 1.9 \times 10^{-9}$$

Heavy Baryon ChPt

[Jenkins, Manhoar, 1991] [Courtesy of Nicola Valori, SMEFT meets ChiPT 2025]

EFT below Λ_χ *where nucleons are treated as non relativistic*

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EFT below Λ_χ *where nucleons are treated as non relativistic*

Relevant CP-odd interaction:

$$\bar{N}N\,\bar{e}\gamma^5 e$$
$$\bar{N}\gamma^5 N\,\bar{e}e$$
$$\bar{N}\sigma^{\mu\nu}\gamma^5 N\,\bar{e}\sigma^{\alpha\beta}e$$

Non rel. limit →

$$\bar{N}N\,\bar{e}\gamma^5 e$$ → *Nucleons add coherently*

$$0$$

$$v_\nu \bar{N}S_\mu N\,\bar{e}\sigma^{\mu\nu}e$$ → *Average over spin*

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$$C_n\,\bar{n}n\,\bar{e}\gamma^5 e + C_p\,\bar{p}p\,\bar{e}\gamma^5 e \longrightarrow \bar{N}(C_S + C'_S\tau_3)N\,\bar{e}\gamma^5 e$$

$$N = \begin{pmatrix} p \\ n \end{pmatrix}$$

C_S → *Z+N*; $C'_S\tau_3$ → *Z-N*

[Courtesy of Nicola Valori, SMEFT meets ChiPT 2025]

Matching at the nucleon scale

[Courtesy of Nicola Valori, SMEFT meets ChiPT 2025]

Matching at the nucleon scale

Non-perturbative matching at the confinement scale: connecting quark and gluons to nucleons

Relevant LEFT operators: $O^{eq}_{XY} = (\bar{e}P_X e)\,(\bar{q}P_Y q) \longrightarrow \frac{i}{2}\,\mathrm{Im}\,[C^{eq}_{RL} + C^{eq}_{RR}]\,(\bar{e}\gamma_5 e)(\bar{q}q) \equiv C^q_s(\bar{e}i\gamma_5 e)(\bar{q}q)$

[Courtesy of Nicola Valori, SMEFT meets ChiPT 2025]

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Light quarks contribution:

$$\langle\, N\,|\bar{q}q|\, N\,\rangle \sim G_S^{N,q}\langle\, N\,|\bar{N}N|\, N\,\rangle$$

	$q=u$	$q=d$	$q=s$
$G_S^{p,q}$	9	8.2	0.42
$G_S^{n,q}$	8.1	9	0.42

[Hoferichter et al., 2015]
[Alarcon et al., 2012]
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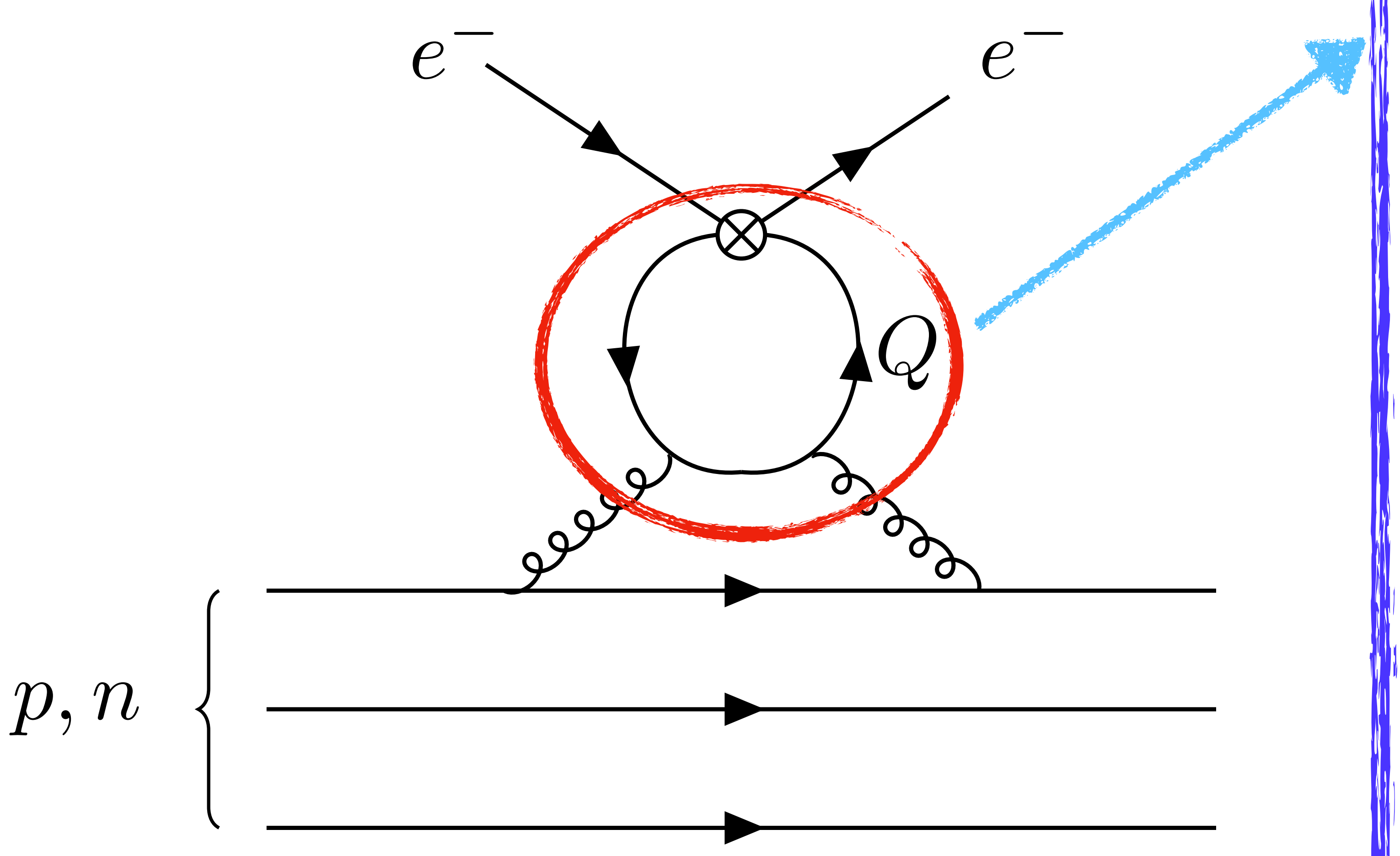

Heavy quarks contribution:

1-loop match to $O_{eG} = (\bar{e}i\gamma_5 e)(G^a_{\mu\nu}G^{\mu\nu}_a)$

$$C_{eG} = -\frac{\alpha_s(m_Q)}{12\pi^2 m_Q}C^Q_s(m_Q)$$

$$\downarrow$$

$$\langle N|G^a_{\mu\nu}G^{\mu\nu}_a|N\rangle = -\frac{8\pi m_N}{9\alpha_s(\mu)}\langle N|\bar{N}N|N\rangle$$

[Shifman et al., 1978]

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$G^{p,q}_S$	9	8.2	0.42
$G^{n,q}_S$	8.1	9	0.42

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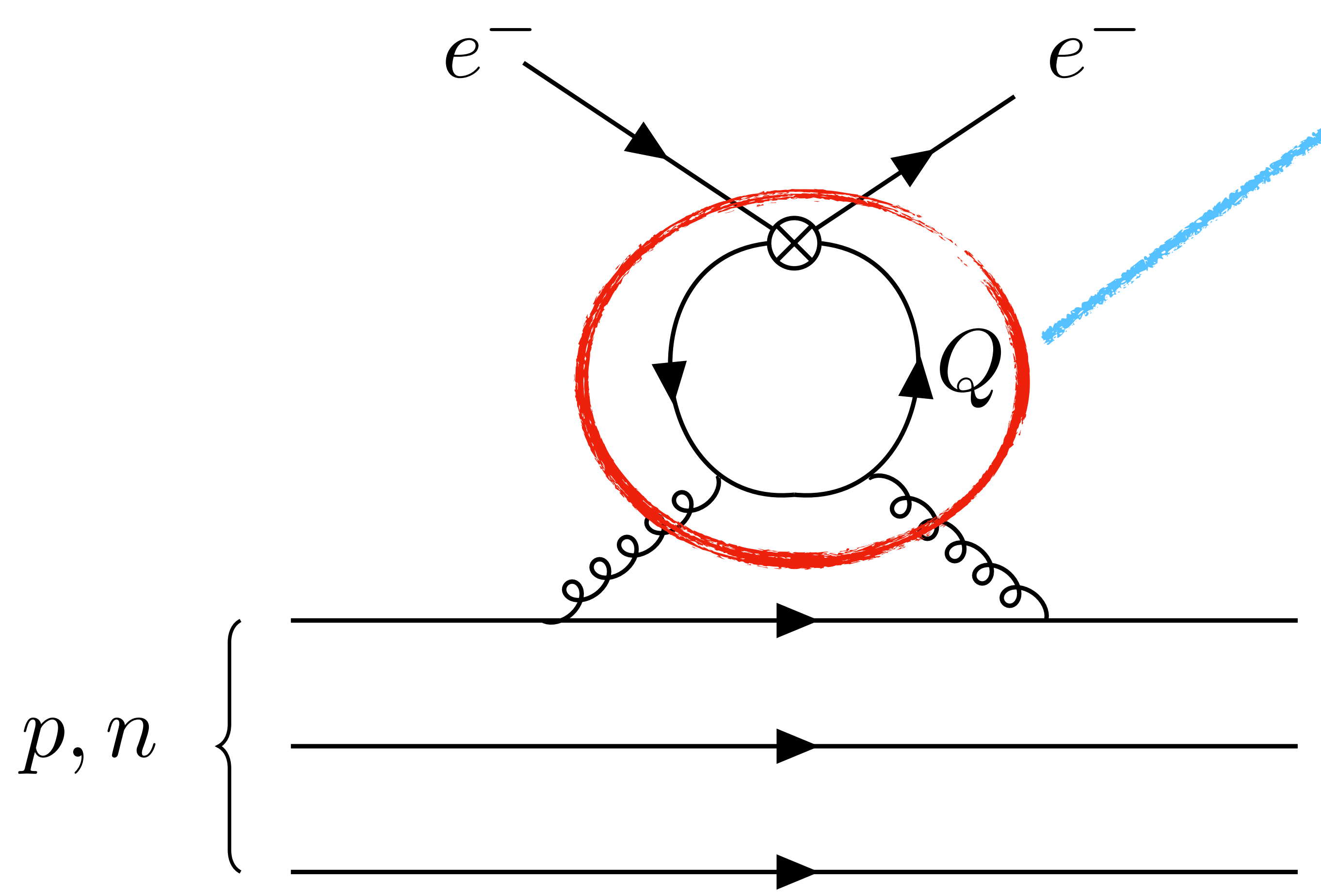
[Alarcon et al., 2012]
[Junarkar et al, 2013]



Heavy quarks contribution:

1-loop match to $O_{eG} = (\bar{e}i\gamma_5 e)(G^a_{\mu\nu}G^{\mu\nu}_a)$

$$C_{eG} = -\frac{\alpha_s(m_Q)}{12\pi^2 m_Q} C^Q_s(m_Q)$$

$$\langle N|G^a_{\mu\nu}G^{\mu\nu}_a|N\rangle = -\frac{8\pi m_N}{9\alpha_s(\mu)}\langle N|\bar{N}N|N\rangle$$

[Shifman et al., 1978]

Matching at the nucleon scale:

$$\frac{\Lambda^2 G_F}{\sqrt{2}} C_S(\mu) = \sum_{q=u,d,s} G^{N,q}_s C^q_s(\mu) + \sum_{Q=c,b,t} \frac{2m_N}{27 m_Q} C^Q_s(m_Q)$$