The equivalent EDM in SMEFT

Nicola Valori
IFIC (University of Valencia-CSIC)

SMEFT meets ChEFT
Vancouver 29/09/2025

Based on M. Ardu, N. Valori: arXiv 2503.21920

CSIC
Consejo Superior de Investigaciones Científicas
Vniversitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa

Outline of the talk

- Introduction to dipole moments
  - Definition
  - SMEFT interpretation
- The equivalent EDM in SMEFT
  - EDM: Overview
  - EDM: Theory and Exp.
  - Equivalent EDM in SMEFT
- Conclusions

Dipole moments*

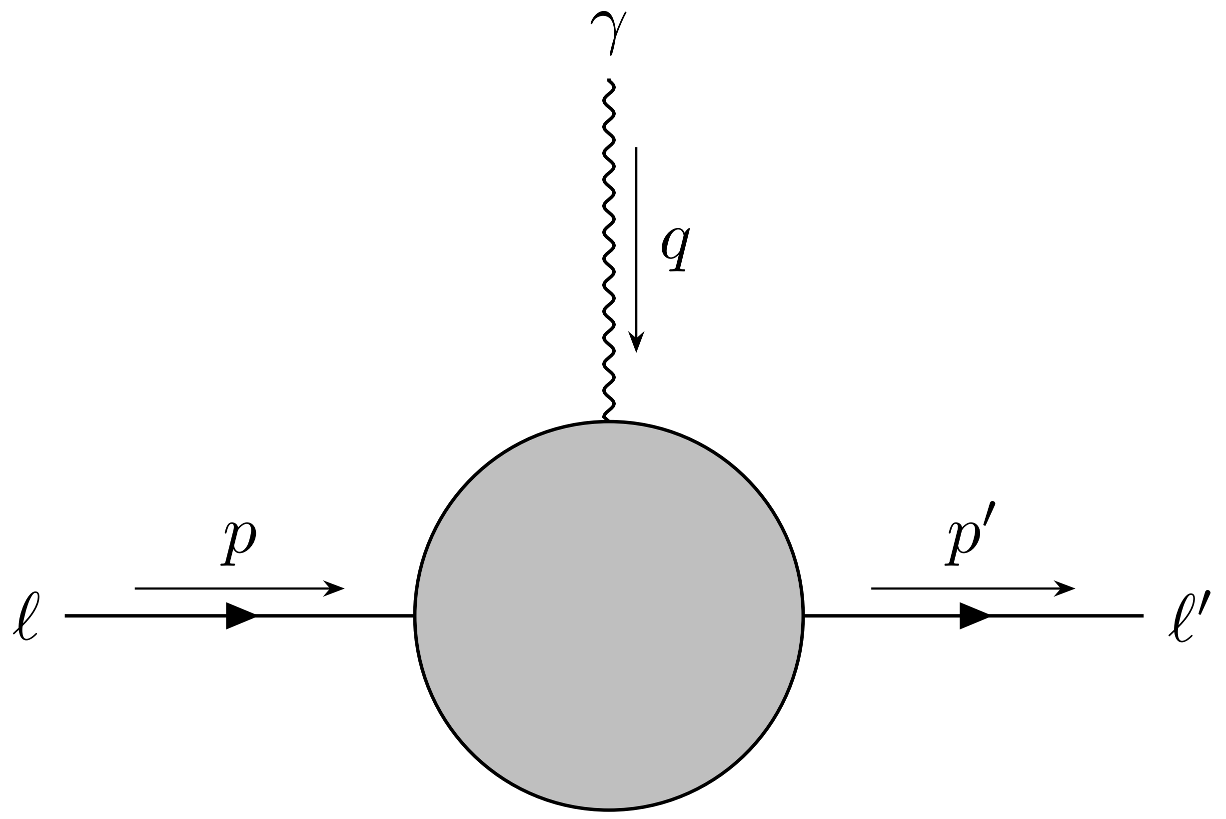
Based on N.Valori, O.Vives: arXiv ***2505.06345***

** Only leptons*

Dipole moments: definition

Dipole moments: definition

Loop-level interaction between a photon and fermions

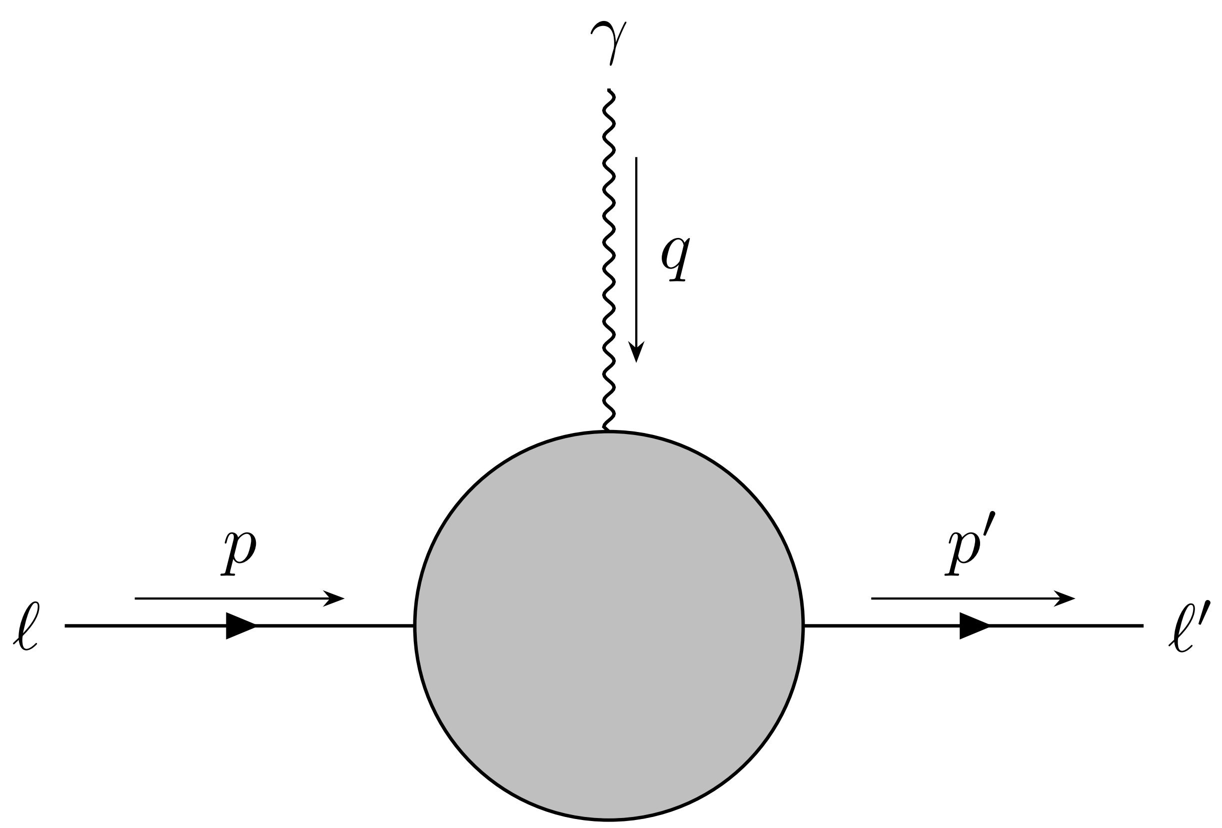


$$= -i\, e\, Q_\ell\, A_\mu(q)\, \bar{u}_l(p')\, \Gamma^\mu(q^2)\, u_l(p)$$

$$\Gamma^\mu = F_1(q^2)\,\gamma^\mu + F_2(q^2)\,\frac{i\,\sigma^{\mu\nu} q_\nu}{2m_\ell} - F_3(q^2)\,\gamma_5\,\sigma^{\mu\nu} q_\nu$$

Dipole moments: definition

Loop-level interaction between a photon and fermions



$$= -i\, e\, Q_\ell\, A_\mu(q)\, \bar{u}_l(p')\, \Gamma^\mu(q^2)\, u_l(p) \qquad \Gamma^\mu = F_1(q^2)\,\gamma^\mu + F_2(q^2)\,\frac{i\,\sigma^{\mu\nu} q_\nu}{2m_\ell} - F_3(q^2)\,\gamma_5\,\sigma^{\mu\nu} q_\nu$$

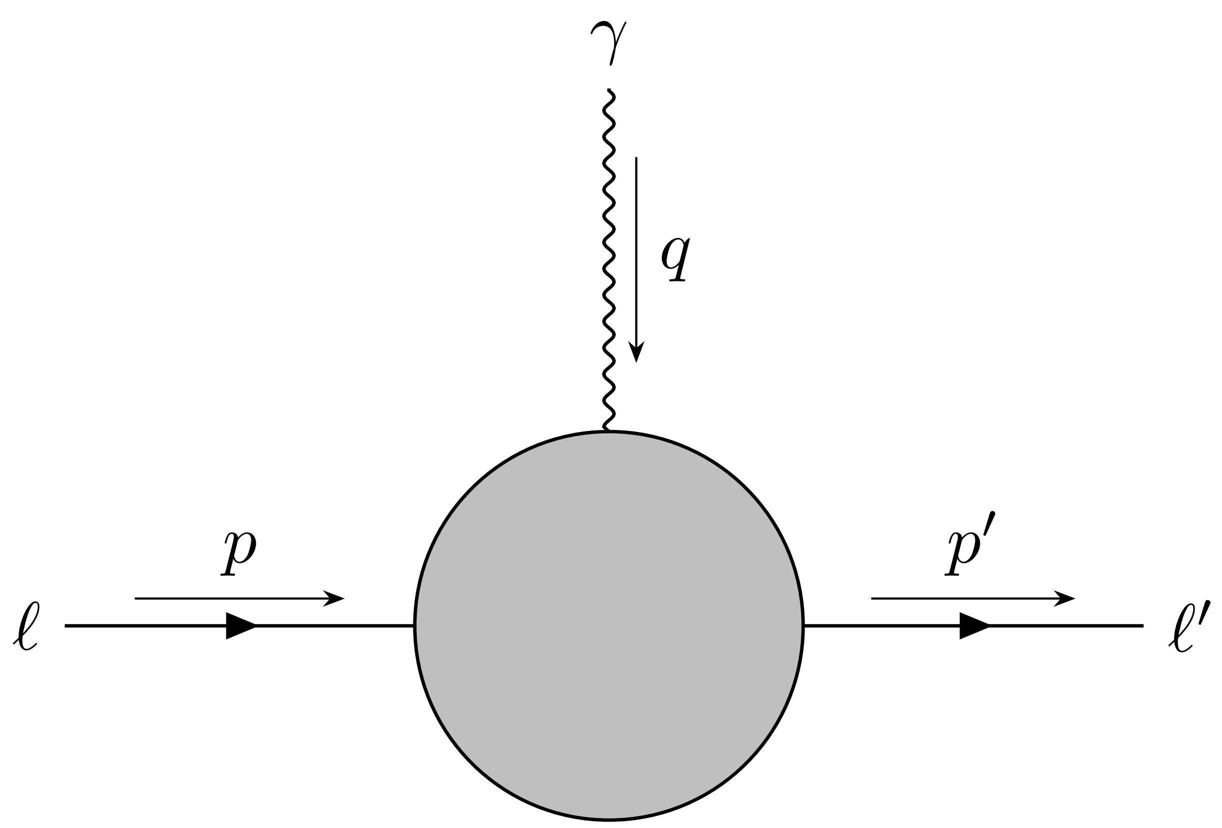
Observables:

$$\ell = \ell'$$

Anomalous magnetic moment	*Electric dipole moment*
CP-even	*CP-odd*
$a_\ell = F_2(0)$	$d_\ell/(Q_\ell e) = F_3(0)$

Dipole moments: definition

Loop-level interaction between a photon and fermions



$$= -i\, e\, Q_\ell\, A_\mu(q)\, \bar{u}_l(p')\, \Gamma^\mu(q^2)\, u_l(p)$$

$$\Gamma^\mu = F_1(q^2)\,\gamma^\mu + F_2(q^2)\,\frac{i\,\sigma^{\mu\nu} q_\nu}{2m_\ell} - F_3(q^2)\,\gamma_5\,\sigma^{\mu\nu} q_\nu$$

Observables:

$$\ell = \ell'$$

$$\ell \neq \ell'$$

Anomalous magnetic moment	Electric dipole moment	Lepton Flavor Violation
CP-even	CP-odd	
$a_\ell = F_2(0)$	$d_\ell/(Q_\ell e) = F_3(0)$	$\ell \to \ell' \gamma$

Dipole moments: definition

Dipole moments: definition

Three classes of observables, one effective operator

$$\mathcal{L} \supset \frac{e}{8\,\pi^2} C_{ij} \left(\bar{\ell}_i \sigma_{\mu\nu} P_R \ell_j\right) F^{\mu\nu} + \text{h.c.}$$

Dipole moments: definition

Three classes of observables, one effective operator

$$\mathcal{L} \supset \frac{e}{8\,\pi^2} C_{ij} \left(\bar{\ell}_i \sigma_{\mu\nu} P_R \ell_j\right) F^{\mu\nu} + \text{h.c.}$$

Anomalous magnetic moment

$$\Delta a_{\ell_i} = -\frac{m_{\ell_i}}{2\pi^2 Q_\ell} \text{Re}(C_{ii})$$

Measured and computed with extraordinary accuracy

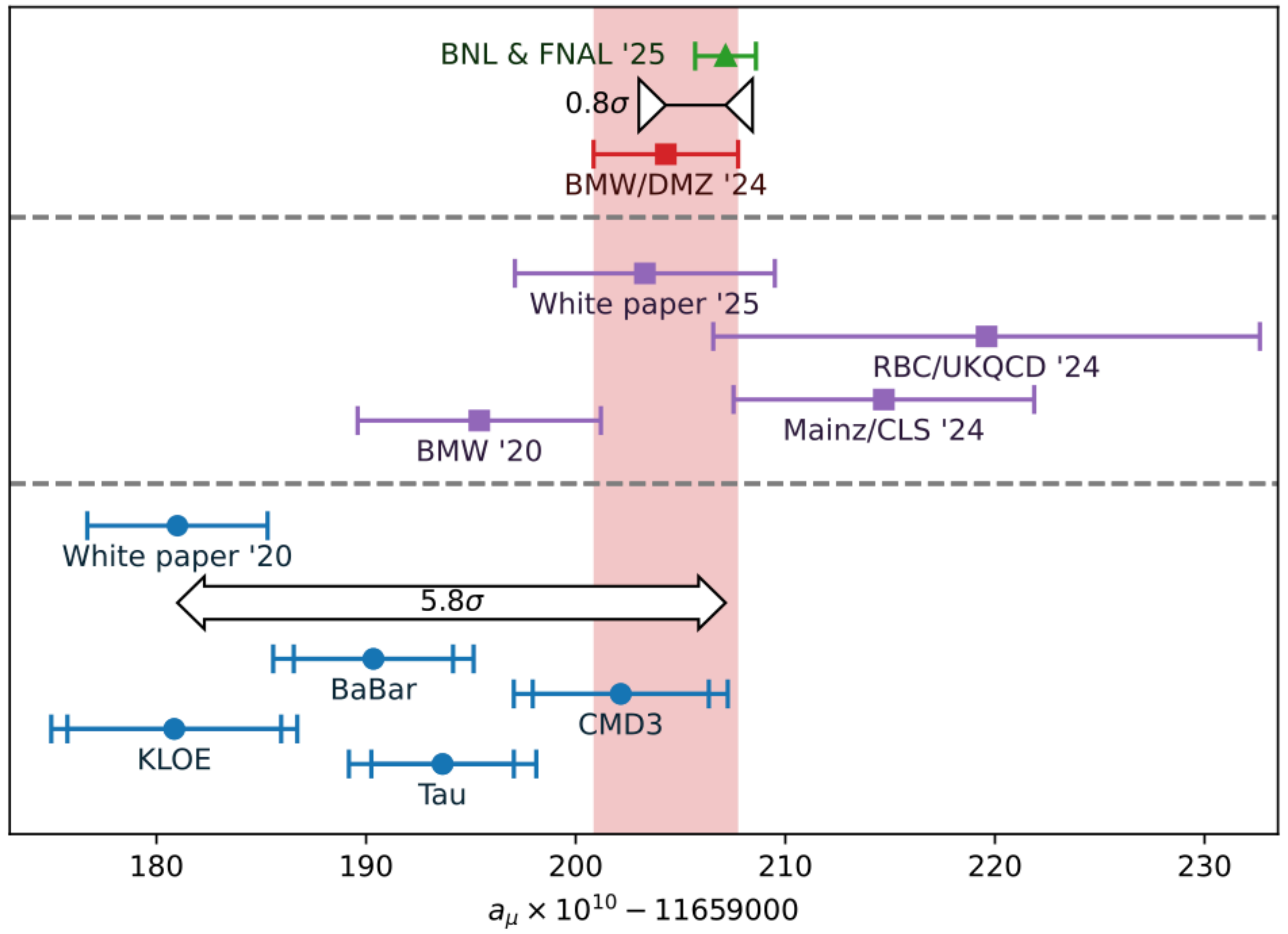
SM at work?

Dipole moments: definition

Three classes of observables, one effective operator

$$\mathcal{L} \supset \frac{e}{8\,\pi^2} C_{ij} \left(\bar{\ell}_i \sigma_{\mu\nu} P_R \ell_j\right) F^{\mu\nu} + \text{h.c.}$$

Anomalous magnetic moment



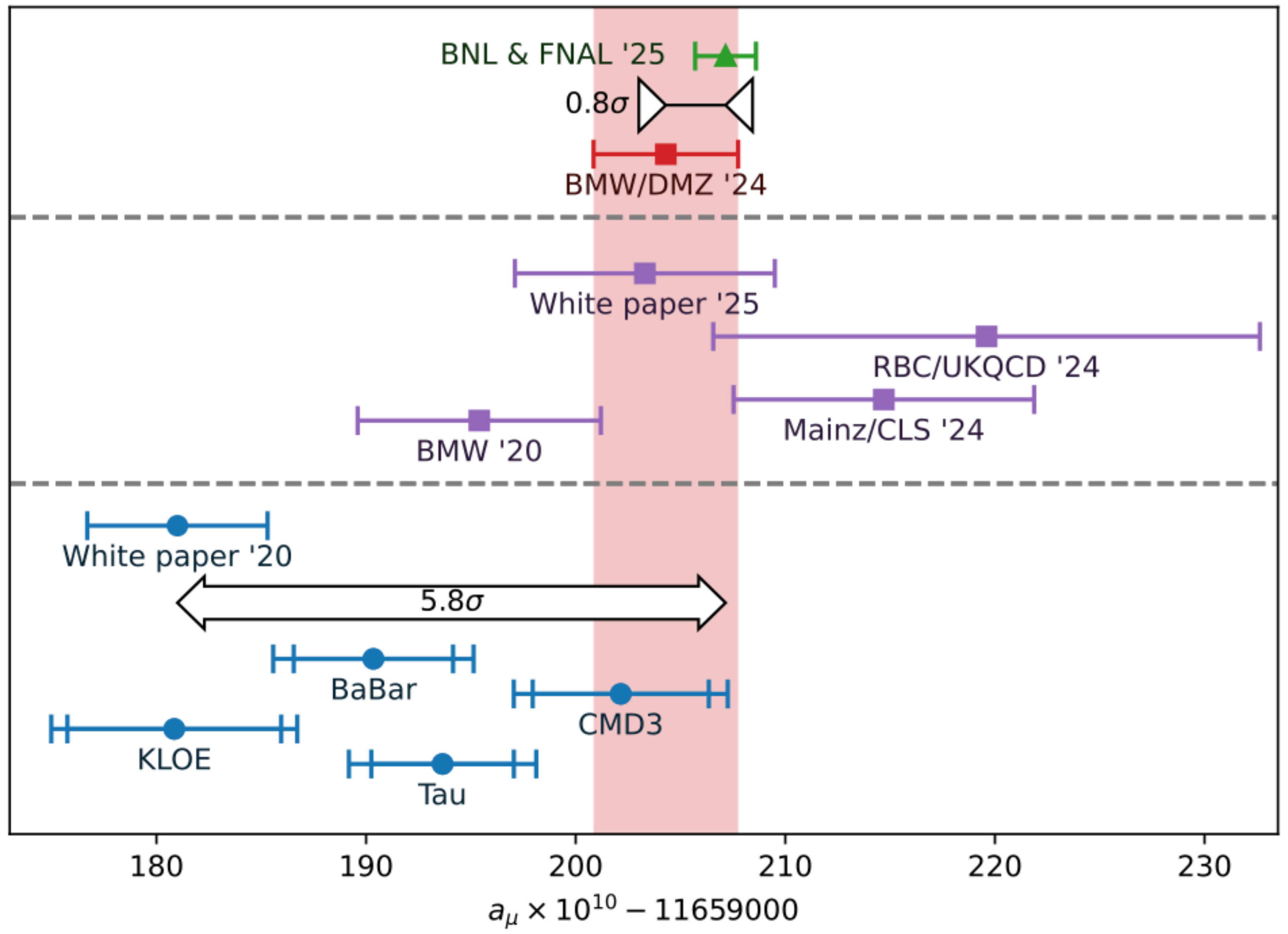
[BMW, 2025]

Dipole moments: definition

Three classes of observables, one effective operator

$$\mathcal{L} \supset \frac{e}{8\,\pi^2} C_{ij} \left(\bar{\ell}_i \sigma_{\mu\nu} P_R \ell_j\right) F^{\mu\nu} + \text{h.c.}$$

Anomalous magnetic moment



[BMW, 2025]

Electric dipole moment

$$d_{\ell_i} = -\frac{e}{4\pi^2}\text{Im}(C_{ii})$$

SM prediction very far from
The experimental sensitivity

↓

Window to NP?

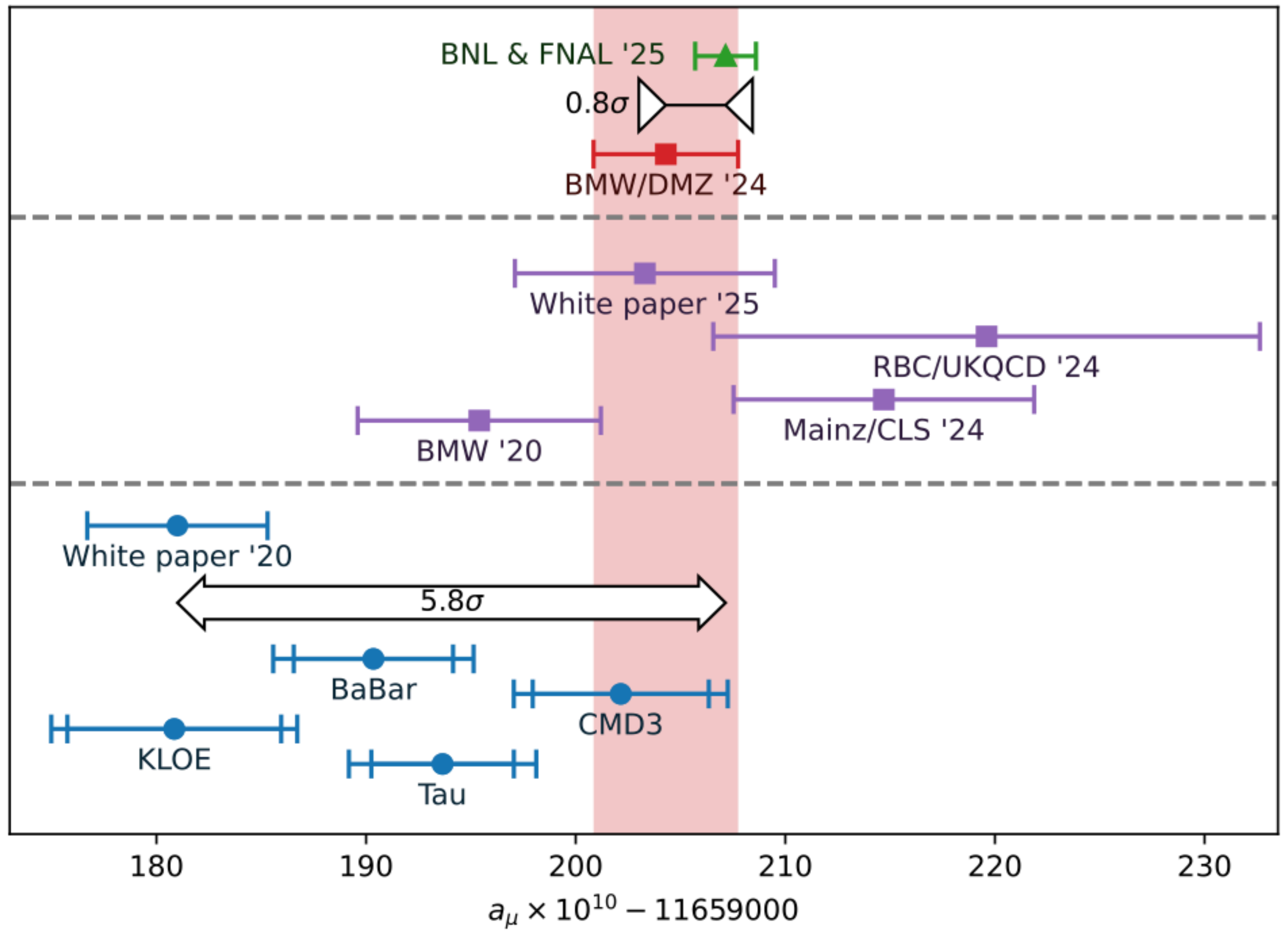
*More on that later

Dipole moments: definition

Three classes of observables, one effective operator

$$\mathcal{L} \supset \frac{e}{8\,\pi^2} C_{ij} \left(\bar{\ell}_i \sigma_{\mu\nu} P_R \ell_j\right) F^{\mu\nu} + \text{h.c.}$$

Anomalous magnetic moment



[BMW, 2025]

Electric dipole moment

$$d_{\ell_i} = -\frac{e}{4\pi^2}\text{Im}(C_{ii})$$

SM prediction very far from The experimental sensitivity

Window to NP?

*More on that later

Lepton Flavor Violation

$$\text{BR}(\ell_j \to \ell_i \gamma) = \frac{3\,\alpha_{\text{em}}}{\pi\, G_F^2\, m_{\ell_j}^2} \left(|C_{ji}|^2 + |C_{ij}|^2\right)$$

Motivated by neutrino oscillations

Insight into ν masses?

Dipole moments: current status

Observable	Experiment	SM Prediction
a_e	$115\,965\,218.059(13) \times 10^{-11}$ [14]	$115\,965\,218.0252(95) \times 10^{-11}$ [α(Rb)] [18] $115\,965\,218.161(23) \times 10^{-11}$ [α(Cs)] [19]
a_μ	$116\,592\,059(22) \times 10^{-11}$ [15]	$116\,591\,810(43) \times 10^{-11}$ (e^+e^-) [16] $116\,592\,019(38) \times 10^{-11}$ (BMW) [17]
$\|d_e\|$	$< 4.1 \times 10^{-30}$ e cm [22]	$\sim 1 \times 10^{-39}$ e cm [21]
$\|d_\mu\|$	$< 1.8 \times 10^{-19}$ e cm [23]	$\sim 1 \times 10^{-38}$ e cm [21]
$\|d_\tau\|$	$\lesssim 1 \times 10^{-17}$ e cm [24]	$\sim 1 \times 10^{-37}$ e cm [21]
BR($\mu \to e\gamma$)	$< 3.1 \times 10^{-13}$ [25]	$\sim 10^{-55} \div 10^{-54}$
BR($\tau \to e\gamma$)	$< 3.3 \times 10^{-8}$ [26]	$\sim 10^{-55} \div 10^{-54}$
BR($\tau \to \mu\gamma$)	$< 4.4 \times 10^{-8}$ [26]	$\sim 10^{-55} \div 10^{-54}$

[NV, O. Vives, 2505.06345 [hep-ph]]

Sensitivity to heavy NP?

Dipole moments: SMEFT interpretation

Dipole moments: SMEFT interpretation

$$O_{eB}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}e_R^j H B^{\mu\nu}$$

$$O_{eW}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}\tau^a e_R^j H W_a^{\mu\nu}$$

$$\xrightarrow{\textit{Matching at the EW scale}}$$

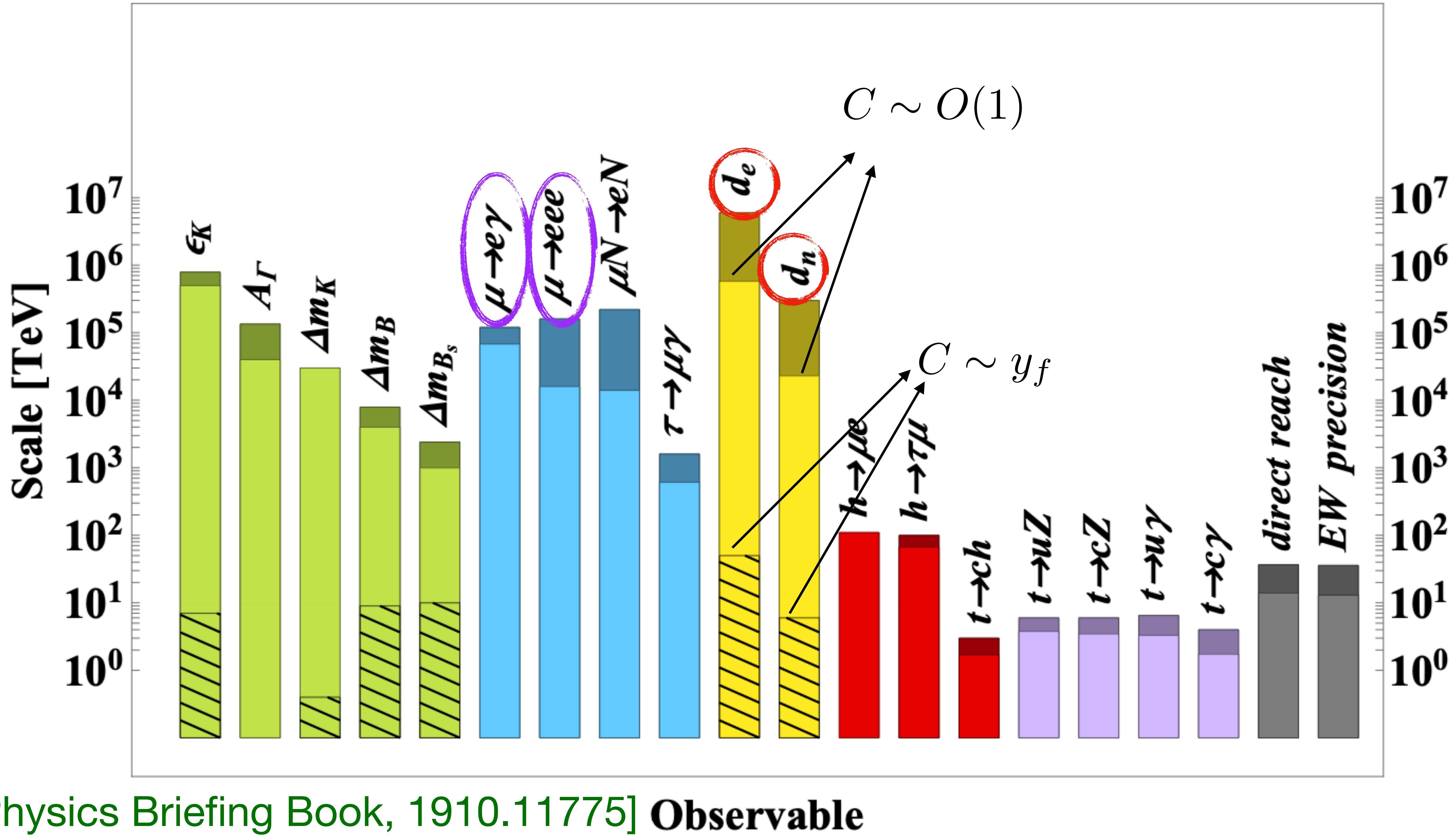
$$C_{ij} = \frac{8\pi^2}{e}\frac{v}{\sqrt{2}\Lambda^2}(\cos\theta_W C_{eB}^{ij} - \sin\theta_W C_{eW}^{ij})$$

Dipole moments: SMEFT interpretation

$$O_{eB}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}e_R^j H B^{\mu\nu}$$
$$O_{eW}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}\tau^a e_R^j H W_a^{\mu\nu}$$

Matching at the EW scale

$$C_{ij} = \frac{8\pi^2}{e}\frac{v}{\sqrt{2}\Lambda^2}(\cos\theta_W C_{eB}^{ij} - \sin\theta_W C_{eW}^{ij})$$



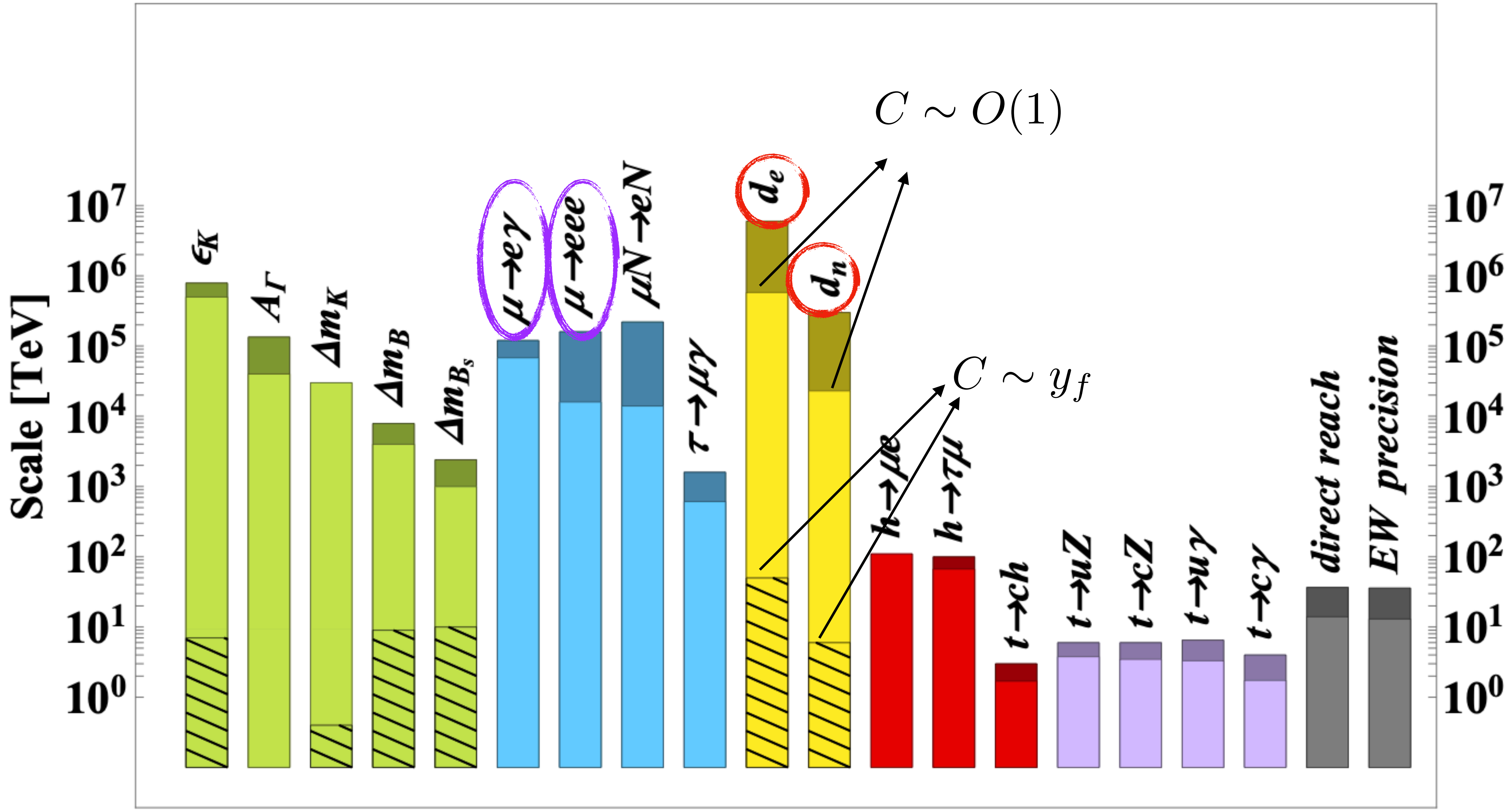
[Physics Briefing Book, 1910.11775]

Dipole moments: SMEFT interpretation

$$O_{eB}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}e_R^j H B^{\mu\nu}$$
$$O_{eW}^{ij} = \overline{l_L^i}\sigma_{\mu\nu}\tau^a e_R^j H W_a^{\mu\nu}$$

Matching at the EW scale

$$C_{ij} = \frac{8\pi^2}{e}\frac{v}{\sqrt{2}\Lambda^2}(\cos\theta_W C_{eB}^{ij} - \sin\theta_W C_{eW}^{ij})$$



[Physics Briefing Book, 1910.11775]

Dipole-related observables able to probe the highest scale

Ideal candidate to Search for New Physics!

The equivalent EDM in SMEFT

Based on M. Ardu, N. Valori: arXiv <u>2503.21920</u>

Why do we need New Physics?

Why do we need New Physics?

Evidence-based

- *Neutrino masses*
- *Dark Matter*
- *Baryon Asymmetry*

Fine-tuning

- *Hierarchy Problem*
- *Strong CP problem*
- *Flavor puzzle*

Why do we need New Physics?

Evidence-based

- *Neutrino masses*
- *Dark Matter*
- *Baryon Asymmetry*

Fine-tuning

- *Hierarchy Problem*
- *Strong CP problem*
- *Flavor puzzle*

Why do we need New Physics?

Evidence-based

- *Neutrino masses*
- *Dark Matter*
- *Baryon Asymmetry*

Fine-tuning

- *Hierarchy Problem*
- *Strong CP problem*
- *Flavor puzzle*

Baryogenesis

Sakharov conditions

- *Out of Equilibrium*
- *Baryon number violation*
- *CP-violation*

$\delta_{CKM}, \quad \theta_{QCD}$

BUT

SM CP-violation is not Enough!

[Gavela et al.,hep-ph/9312215]
[Huet Sather, hep-ph/9404302]
[Kuzmin et a., PhysRevD.45.466]

EDMs: ideal candidates to look for CPV

General features

A particle with spin can interact with an electric field according to:

QM

EDM

$$H = -d\vec{E} \cdot \frac{\vec{S}}{S}$$

P(CP)-odd interaction

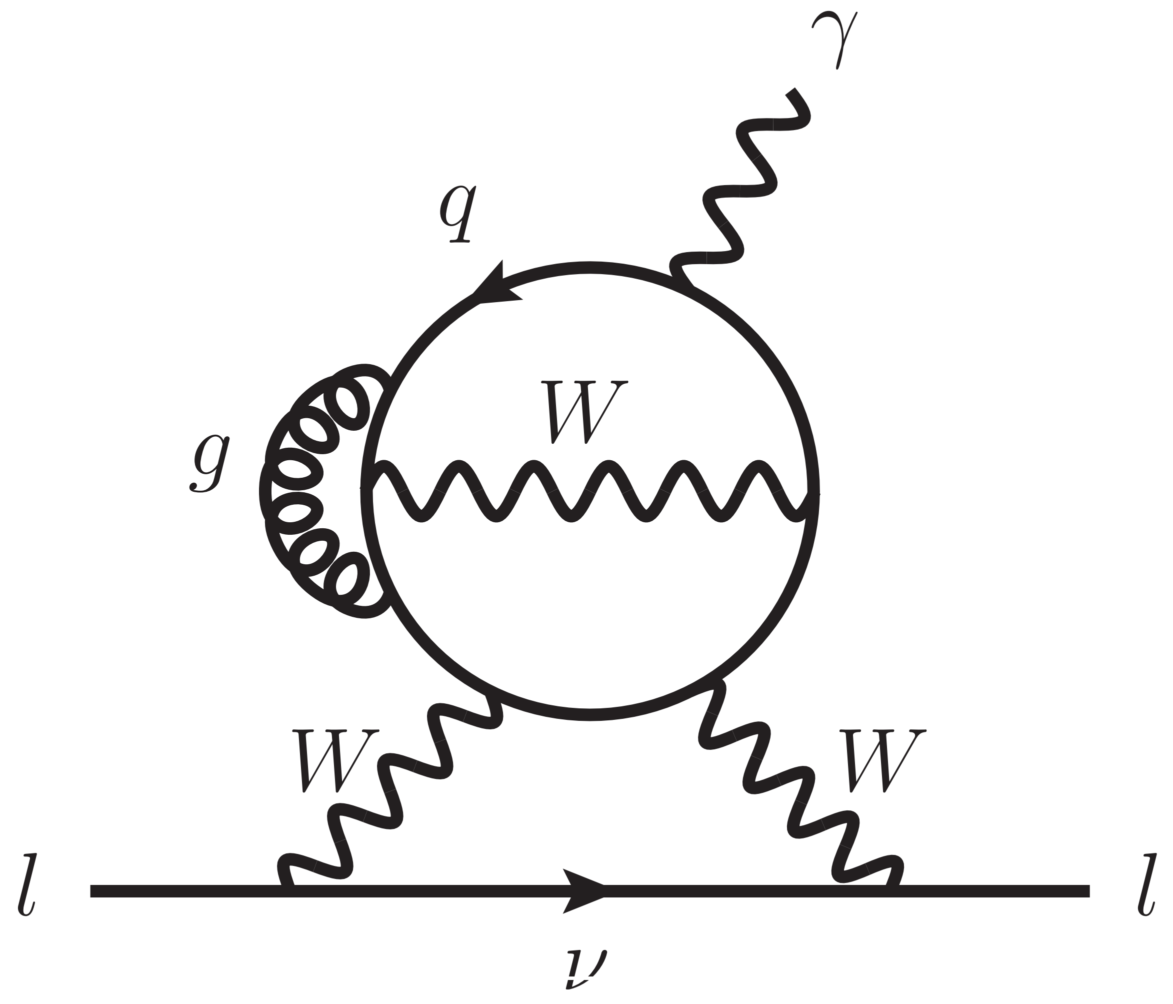
Vector x Pseudo-vector

What is the SM prediction?

EDM: SM Theory

SM perturbation theory (quark-gluon level)

- *SM CP-violation from* δ_{CKM}
- *Encoded in Jarlskog invariant ($\mathcal{J}$)*
- *First non-vanishing contribution at 4 loops*



NDA estimate

$$d_\ell \sim e\mathcal{J}\frac{m_\ell m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3\alpha_s}{(4\pi)^4}$$

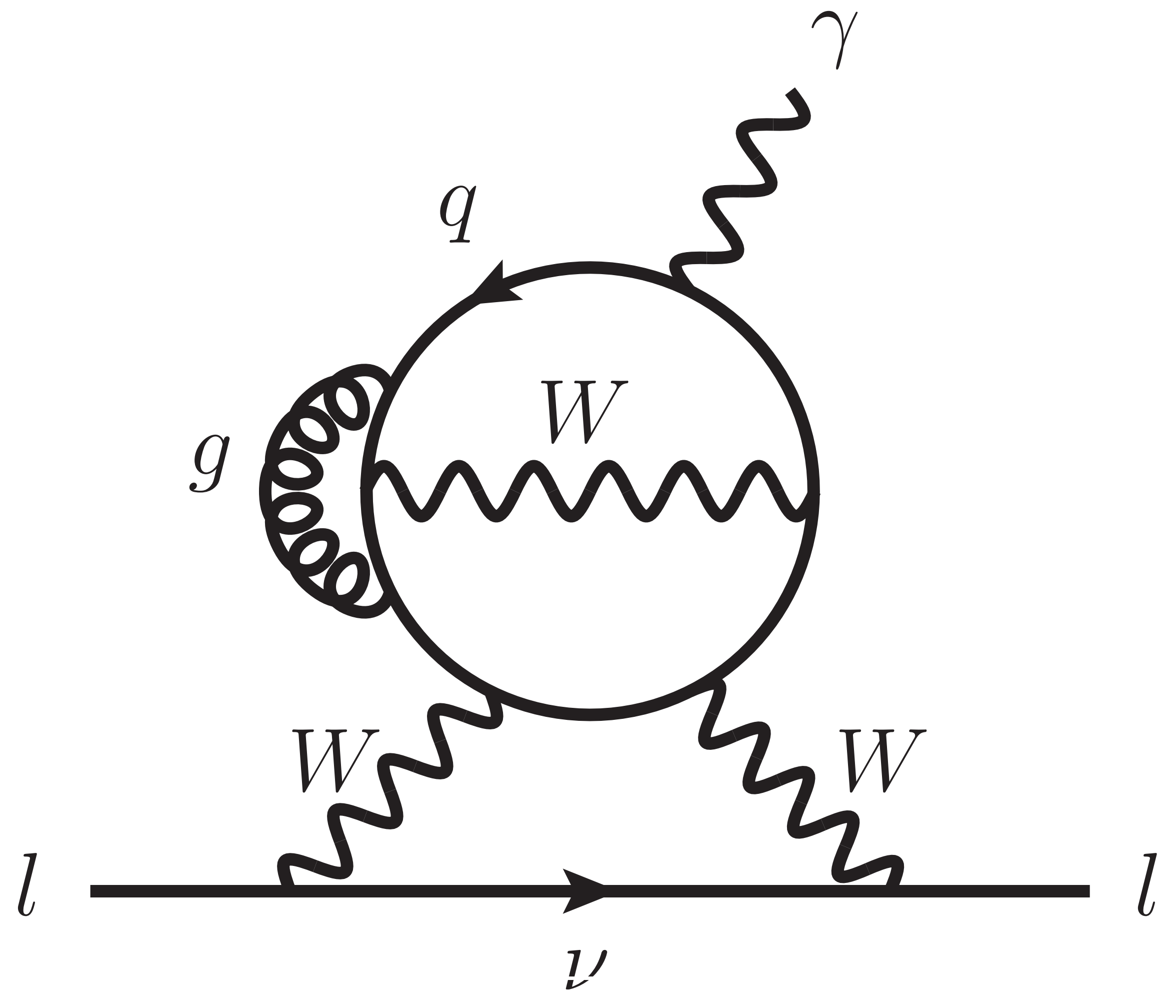
$$\boxed{d_e \sim O(10^{-44})\, e\cdot cm}$$

[Pospelov, Ritz, 2014]

EDM: SM Theory

SM perturbation theory (quark-gluon level)

- *SM CP-violation from* δ_{CKM}
- *Encoded in Jarlskog invariant ($\mathcal{J}$)*
- *First non-vanishing contribution at 4 loops*



NDA estimate

$$d_\ell \sim e\mathcal{J}\frac{m_\ell m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3\alpha_s}{(4\pi)^4}$$

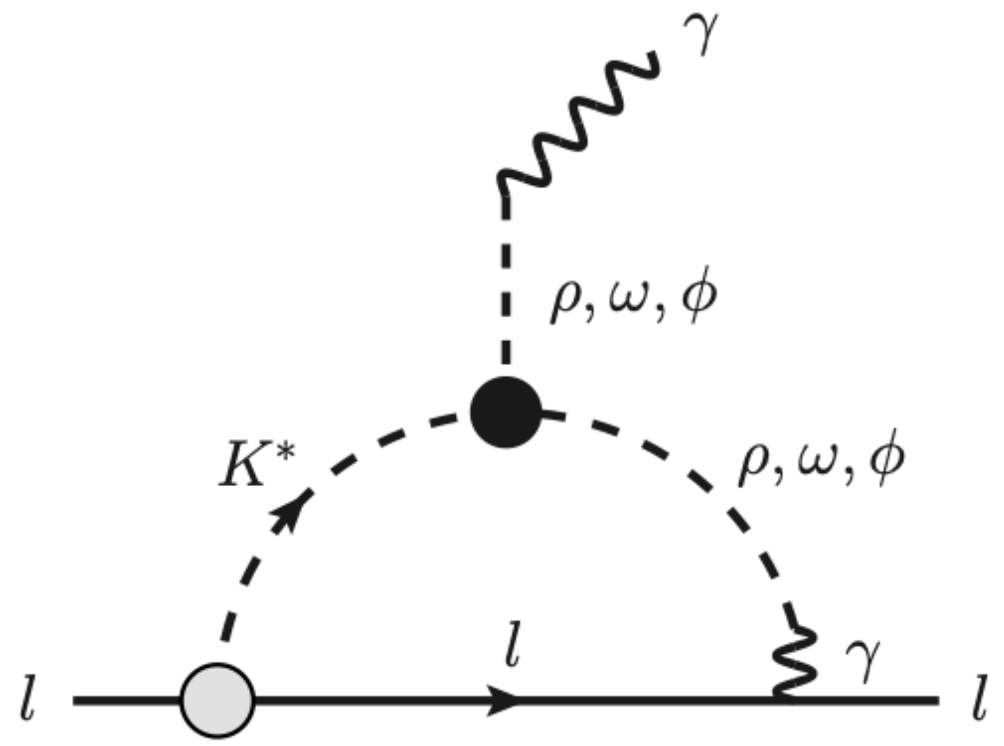
$$\boxed{d_e \sim O(10^{-44})\, e\cdot cm}$$

[Pospelov, Ritz, 2014]

Long distance effects

See [Yamaguchi, Yamanaka,2020]
[Yamaguchi, Yamanaka,2021]

- *Computed in ChiPt*
- *Dominant contribution to EDMs*

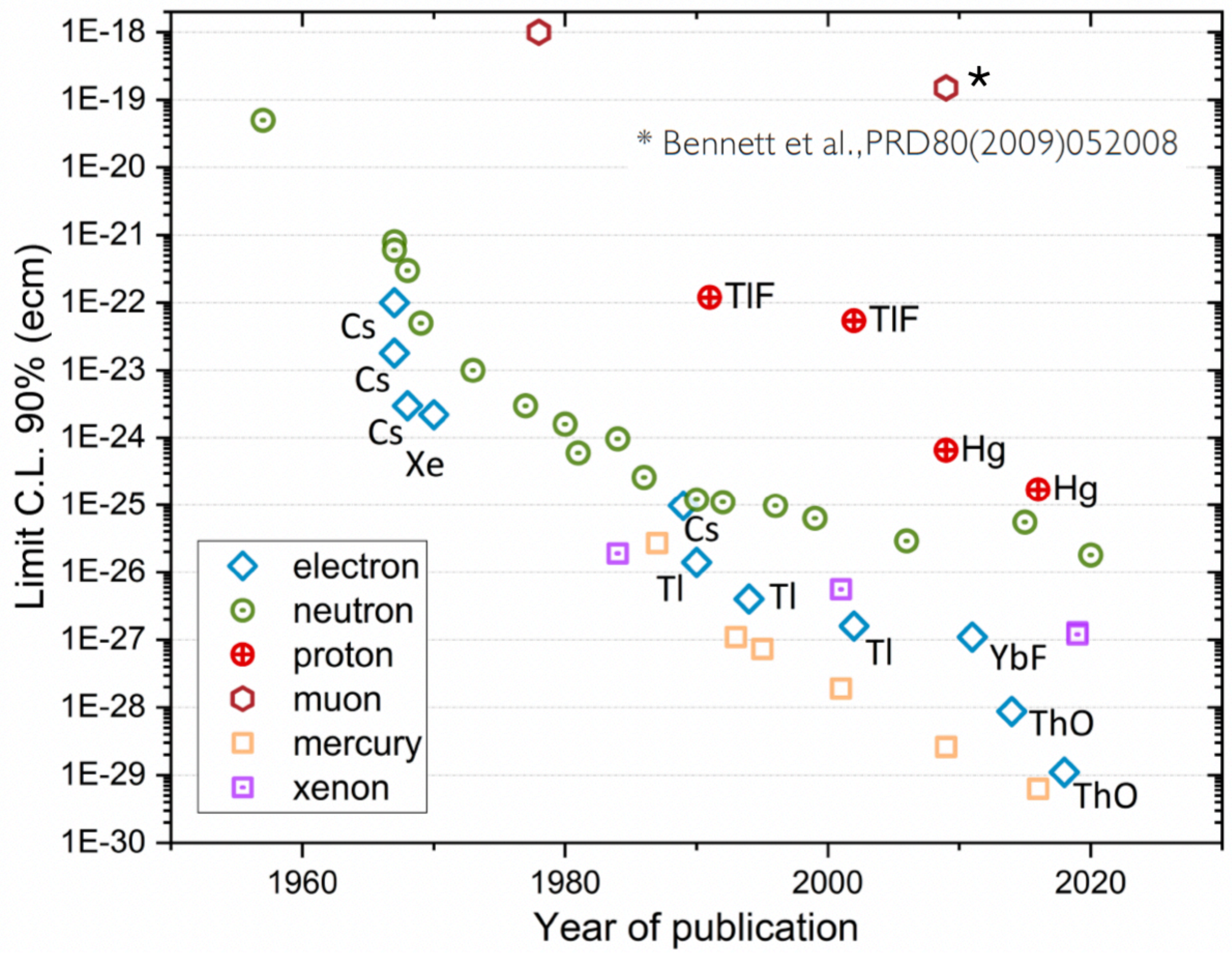


(a)

$$|d_e^{SM}| = 5.80\ \times 10^{-40}\mathrm{e\cdot cm}$$
$$|d_\mu^{SM}| = 1.38\ \times 10^{-38}\mathrm{e\cdot cm}$$
$$|d_\tau^{SM}| = 7.32\ \times 10^{-38}\mathrm{e\cdot cm}$$

EDM: Exp. bounds

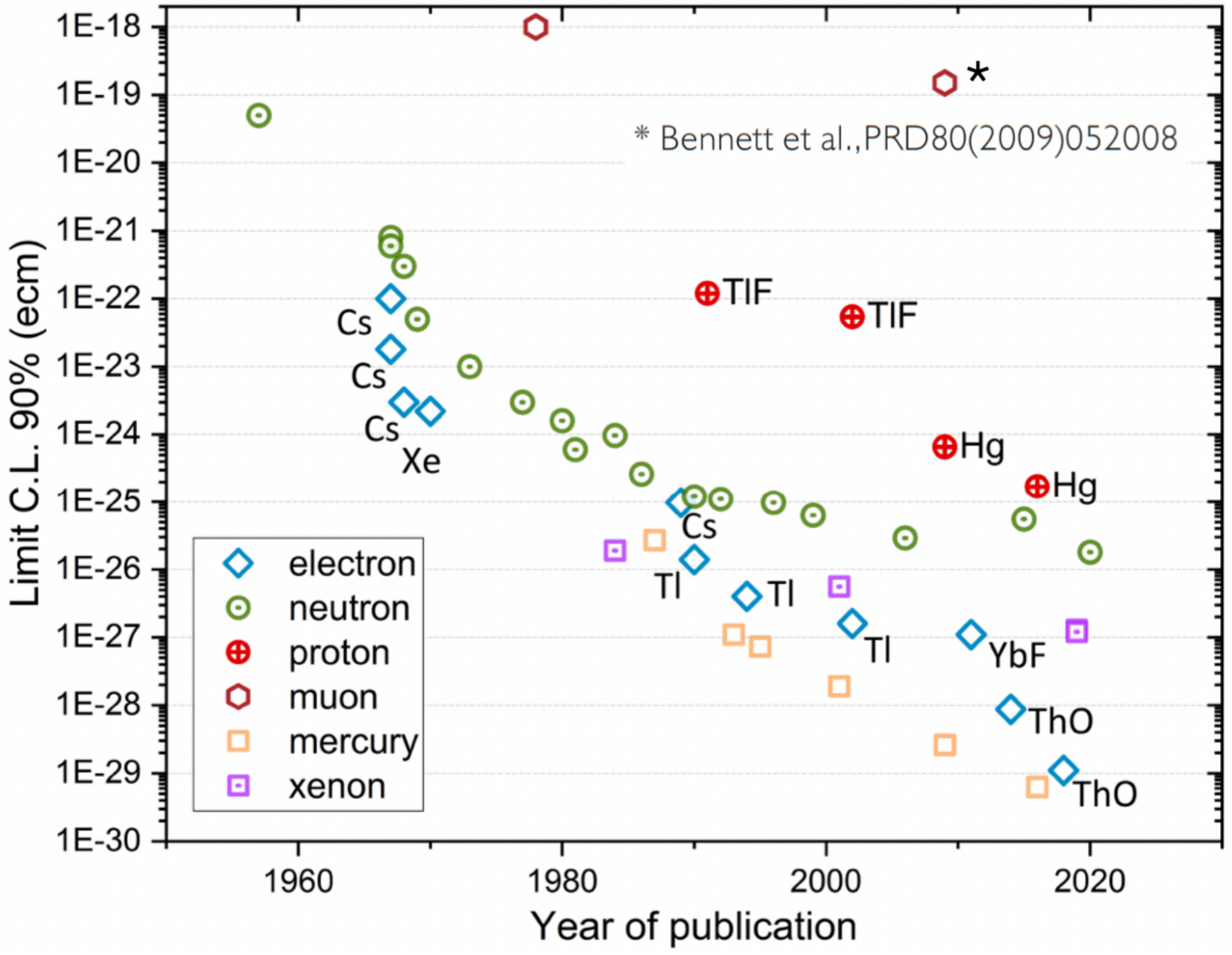
EDM: Exp. bounds



EDM: Exp. bounds

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

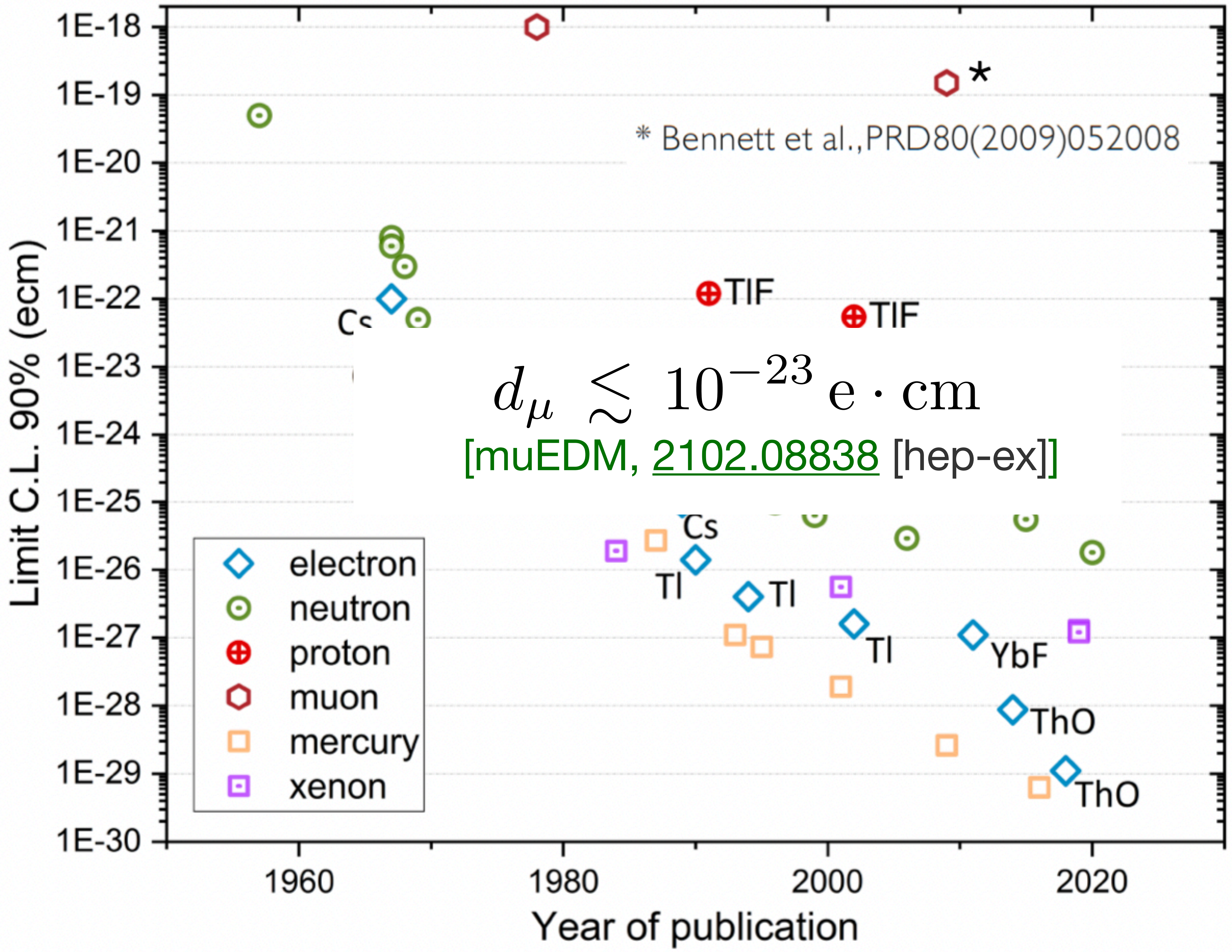
[psi.ch/en/nedm/edms-world-wide]



EDM: Exp. bounds

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]



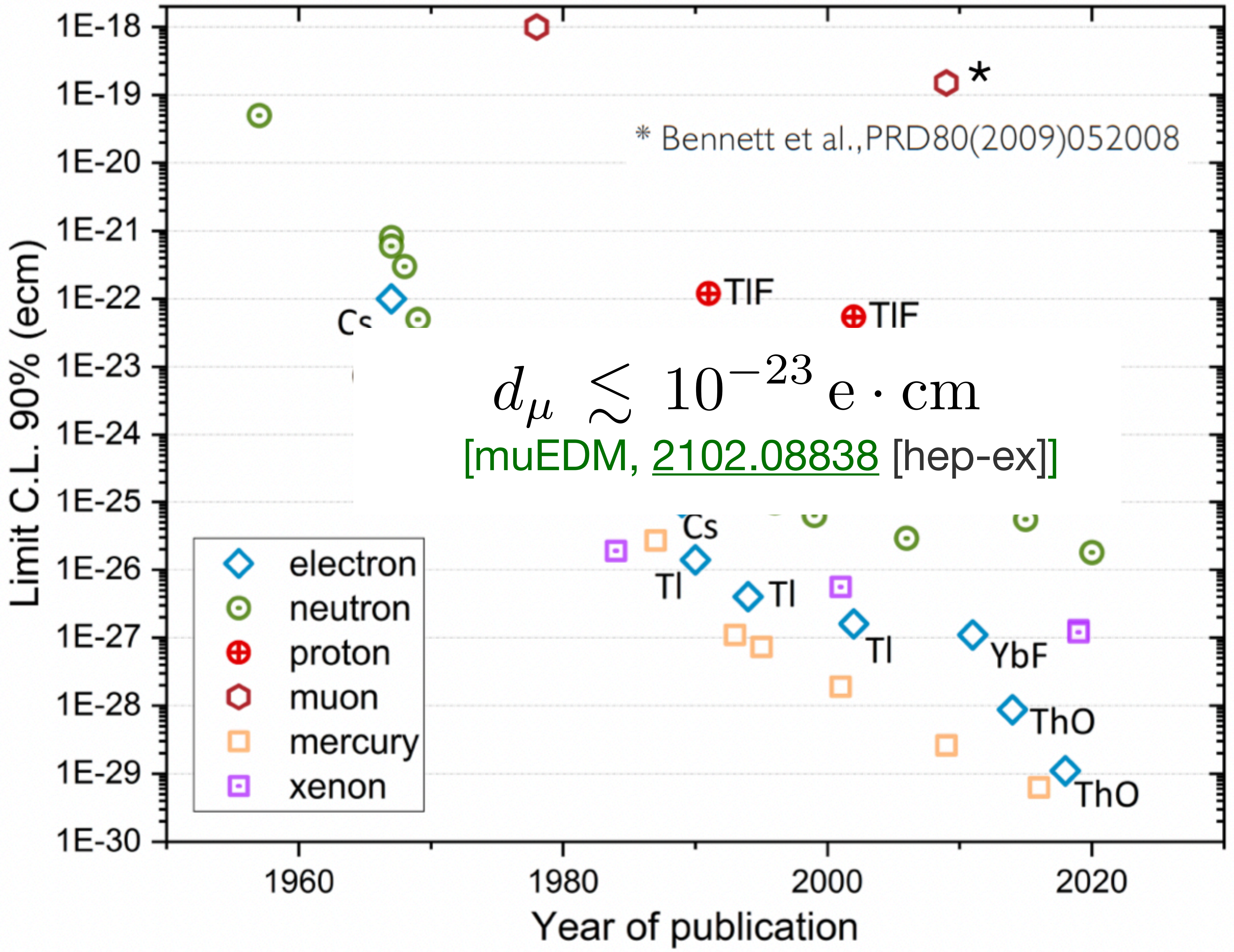
$$d_\mu \lesssim 10^{-23}\ \mathrm{e \cdot cm}$$

[muEDM, 2102.08838 [hep-ex]]

EDM: Exp. bounds

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]



$$d_\mu \lesssim 10^{-23}\,\mathrm{e \cdot cm}$$

[muEDM, 2102.08838 [hep-ex]]

eEDM sensitivity 10 OoM better than the muon + *Naive scaling* $d_\mu \sim \frac{m_\mu}{m_e} d_e$ → *eEDM probes scales 4 OoM higher*

+

Exp. Sensitivity still far from SM prediction ! → *eEDM is particularly well suited for the search of NP*

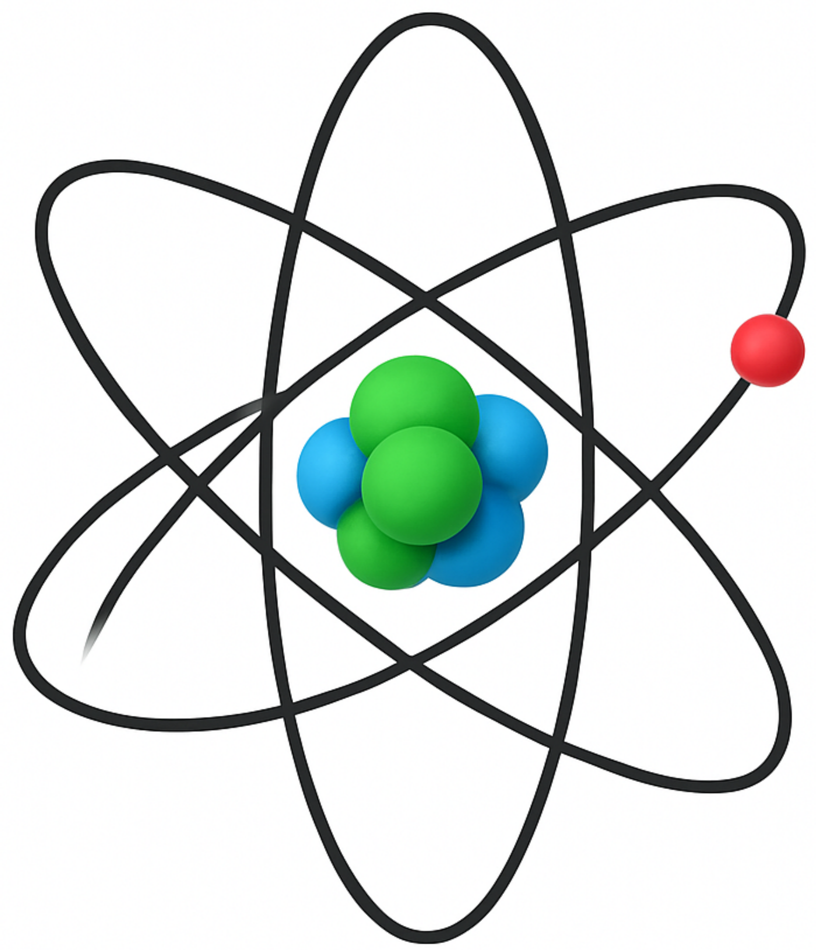
Theory vs Experiments

Theory vs Experiments

eEDM is typically investigated in paramagnetic atoms or molecules (n,p,e)

Theory vs Experiments

eEDM is typically investigated in paramagnetic atoms or molecules (n,p,e)

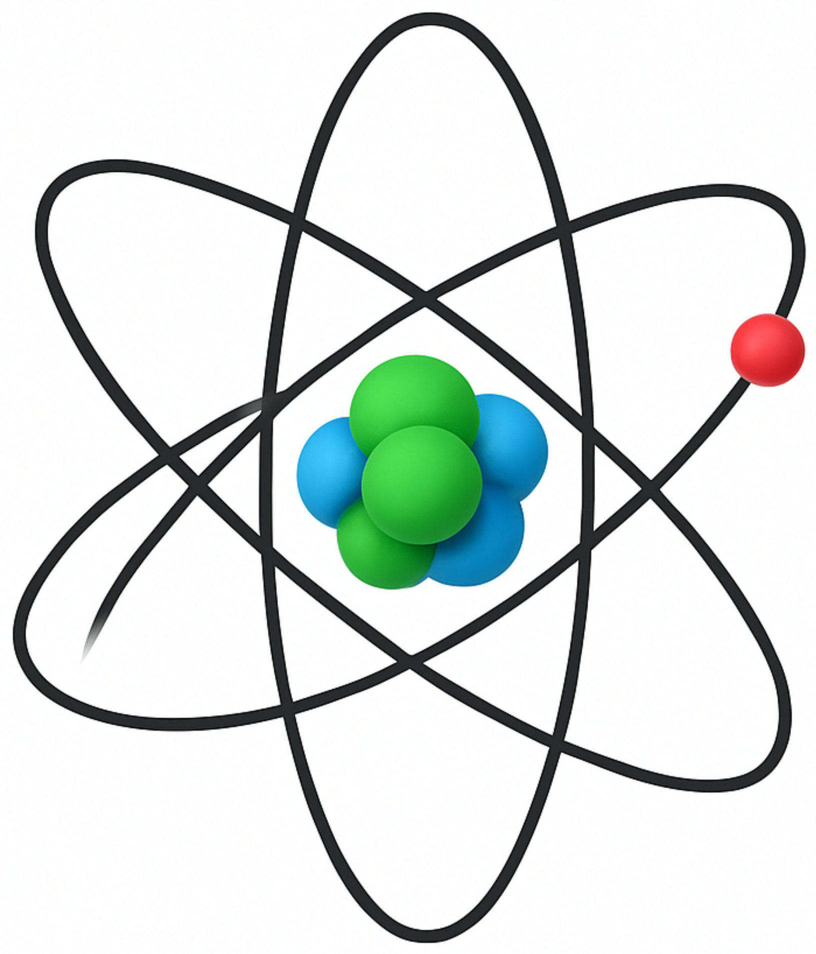


Oh, bother!
I'm all alone

- Sensitivity to the EDM of unpaired electron
- Look for energy shift under parity
- Molecules overpower atoms

Theory vs Experiments

eEDM is typically investigated in paramagnetic atoms or molecules (n,p,e)



Oh, bother!
I'm all alone

- Sensitivity to the EDM of unpaired electron
- Look for energy shift under parity
- Molecules overpower atoms

However, also neutrons and protons are present!

CP-odd interaction other than EDM?

Heavy Baryon ChPt

[Jenkins, Manhoar, 1991]

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

Heavy Baryon ChPt

[Jenkins, Manhoar, 1991]

EFT below Λ_χ where nucleons are treated as non relativistic

Relevant CP-odd interaction:

$$\boxed{\begin{array}{c} \bar{N}N\,\bar{e}\gamma^5 e \\ \bar{N}\gamma^5 N\,\bar{e}e \\ \bar{N}\sigma^{\mu\nu}\gamma^5 N\,\bar{e}\sigma^{\alpha\beta}e \end{array}} \xrightarrow{\text{Non rel. limit}} \boxed{\begin{array}{ccc} \bar{N}N\,\bar{e}\gamma^5 e & \longrightarrow & \textit{Nucleons add coherently} \\ 0 & & \\ v_\nu \bar{N}S_\mu N\,\bar{e}\sigma^{\mu\nu}e & \longrightarrow & \textit{Average over spin} \end{array}}$$

Heavy Baryon ChPt

[Jenkins, Manhoar, 1991]

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

$$\bar{N}N\,\bar{e}\gamma^5 e \quad \longrightarrow \quad \textit{Nucleons add coherently}$$
$$0$$
$$v_\nu \bar{N}S_\mu N\,\bar{e}\sigma^{\mu\nu}e \quad \longrightarrow \quad \textit{Average over spin}$$

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

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

Z+N

Z-N

The equivalent EDM

The equivalent EDM

Effective Lagrangian at the Exp. Scale:

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

The equivalent EDM

Effective Lagrangian at the Exp. Scale:

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

Observable:

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

Depend on the system

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

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

The equivalent EDM

Effective Lagrangian at the Exp. Scale:

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

Observable:

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

Depend on the system

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

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

How the scenario changes:

used in our analysis

Experiments

$d_{\rm HfF+}^{\rm equiv.} < 4.1\times 10^{-30}\; e\cdot cm$

$d_{\rm ThO}^{\rm equiv.} < 1.1\times 10^{-29}\; e\cdot cm$

$\downarrow$

upper bounds on

d_e if $C_S = 0$

SM prediction

$d_{\rm ThO}^{\rm equiv.} \simeq 1.0\times 10^{-35}\; e\cdot cm$

[Ema et al.,hep-ph/2202.10524]

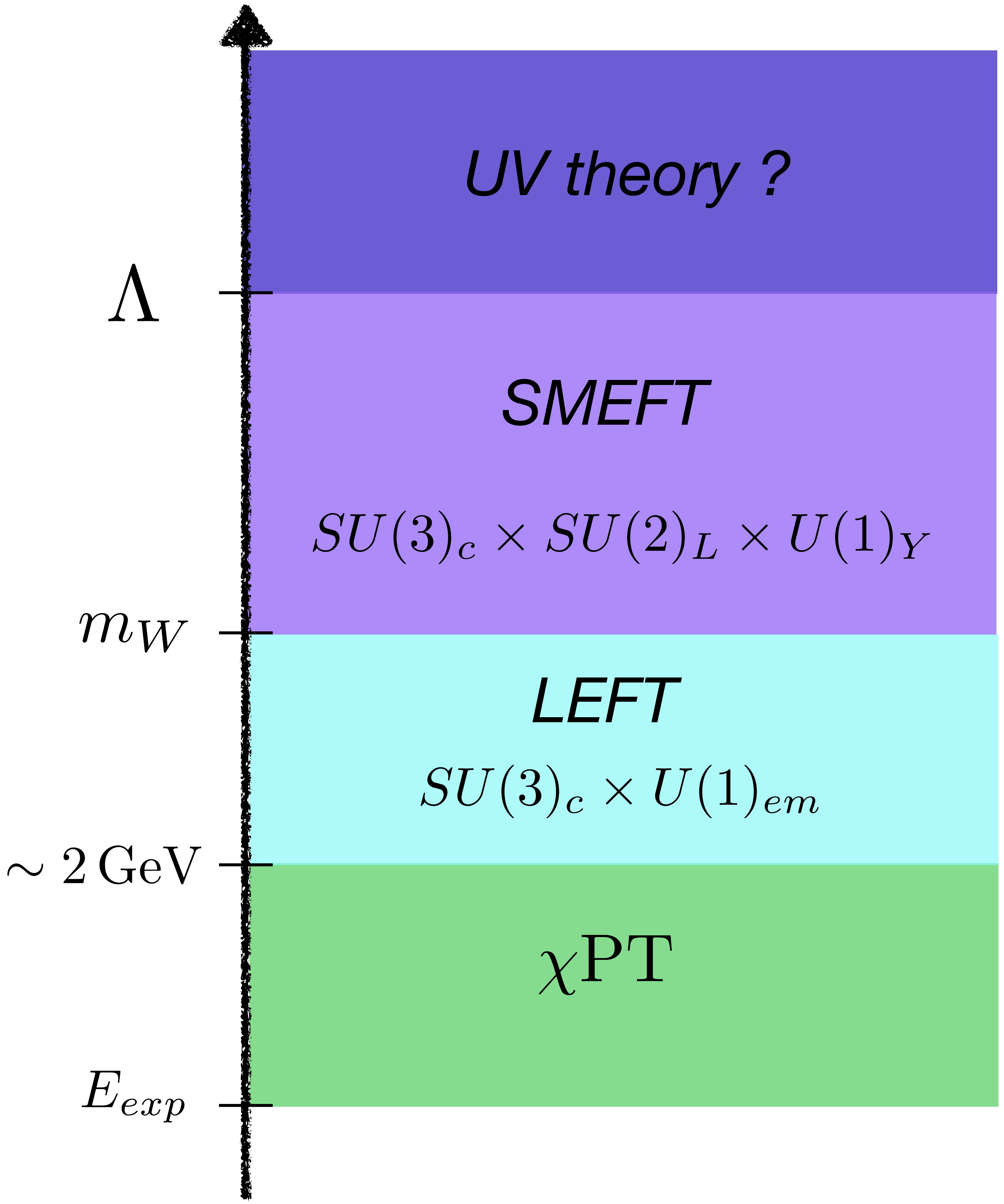
Dominated by semileptonic interaction

Previous EFT analysis:

[Kley et al., 2109.15085]
[Panico et al., 1810.09413]

C_S ?

A tower of EFTs



We fixed NP scale at 10 TeV

One operator at a time $O_i^{(n)}$

wilson → *Automated 1-loop running and tree level matching SMEFT-LEFT*

Matching EFT + LQCD →

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

[Hoferichter et al.,hep-ph/092301]

[P. M. Junnarkar et al.,hep-ph/114510]

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

Matching at the nucleon scale

Matching at the nucleon scale

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

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

Matching at the nucleon scale

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

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

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]
[Junarkar et al, 2013]

Matching at the nucleon scale

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

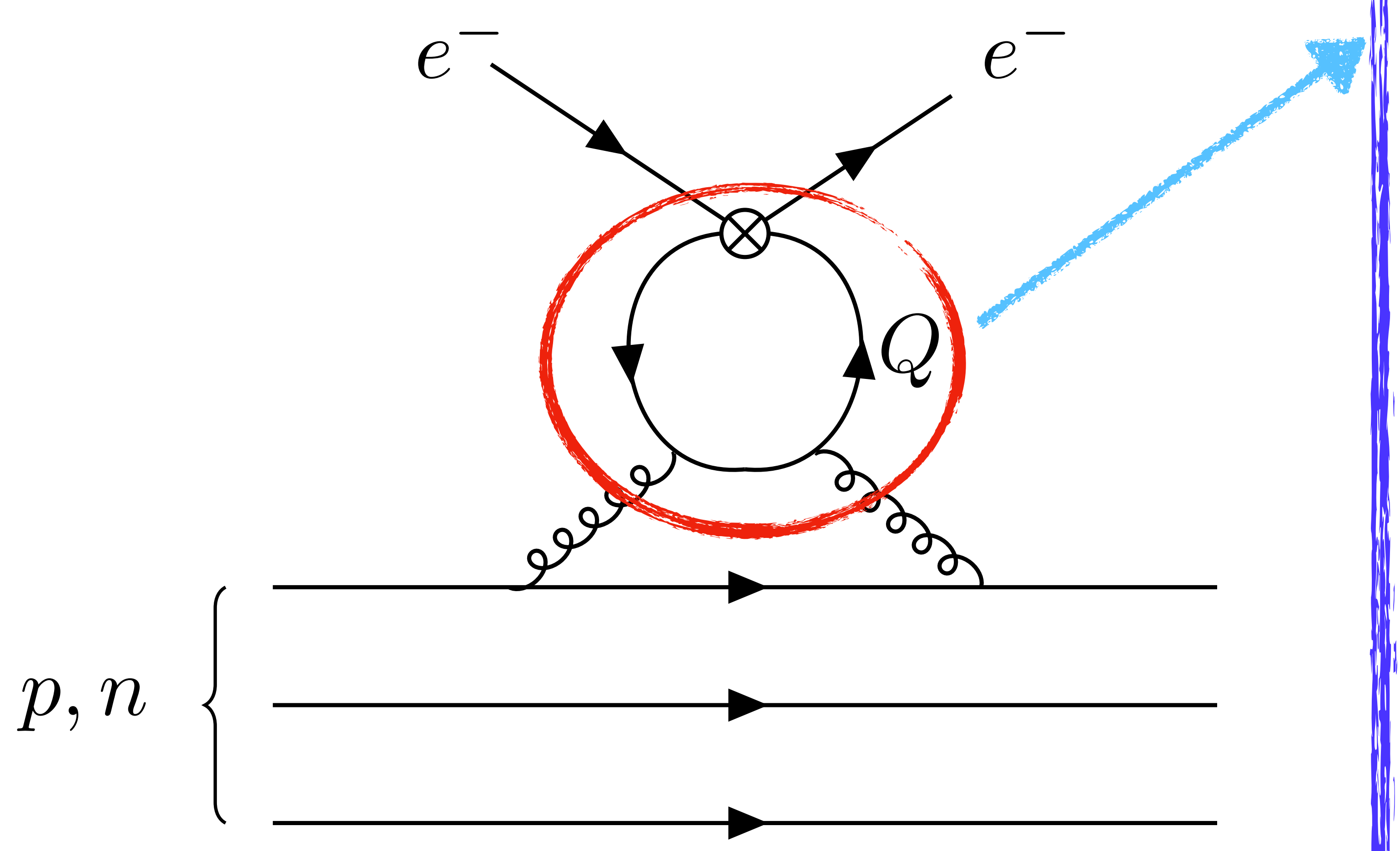
Relevant LEFT operators: $O^{eq}_{XY} = (\bar{e}P_X e)\,(\bar{q}P_Y q) \longrightarrow \frac{i}{2}\,\mathrm{Im}\,[C^{eq}_{RL} + C^{eq}_{RR}]\,(\bar{e}\gamma_5 e)(\bar{q}q) \equiv C^q_s(\bar{e}i\gamma_5 e)(\bar{q}q)$

Light quarks contribution:

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

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

[Hoferichter et al., 2015]
[Alarcon et al., 2012]
[Junarkar et al, 2013]



Heavy quarks contribution:

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

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

$$\downarrow$$

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

[Shifman et al., 1978]

Matching at the nucleon scale

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

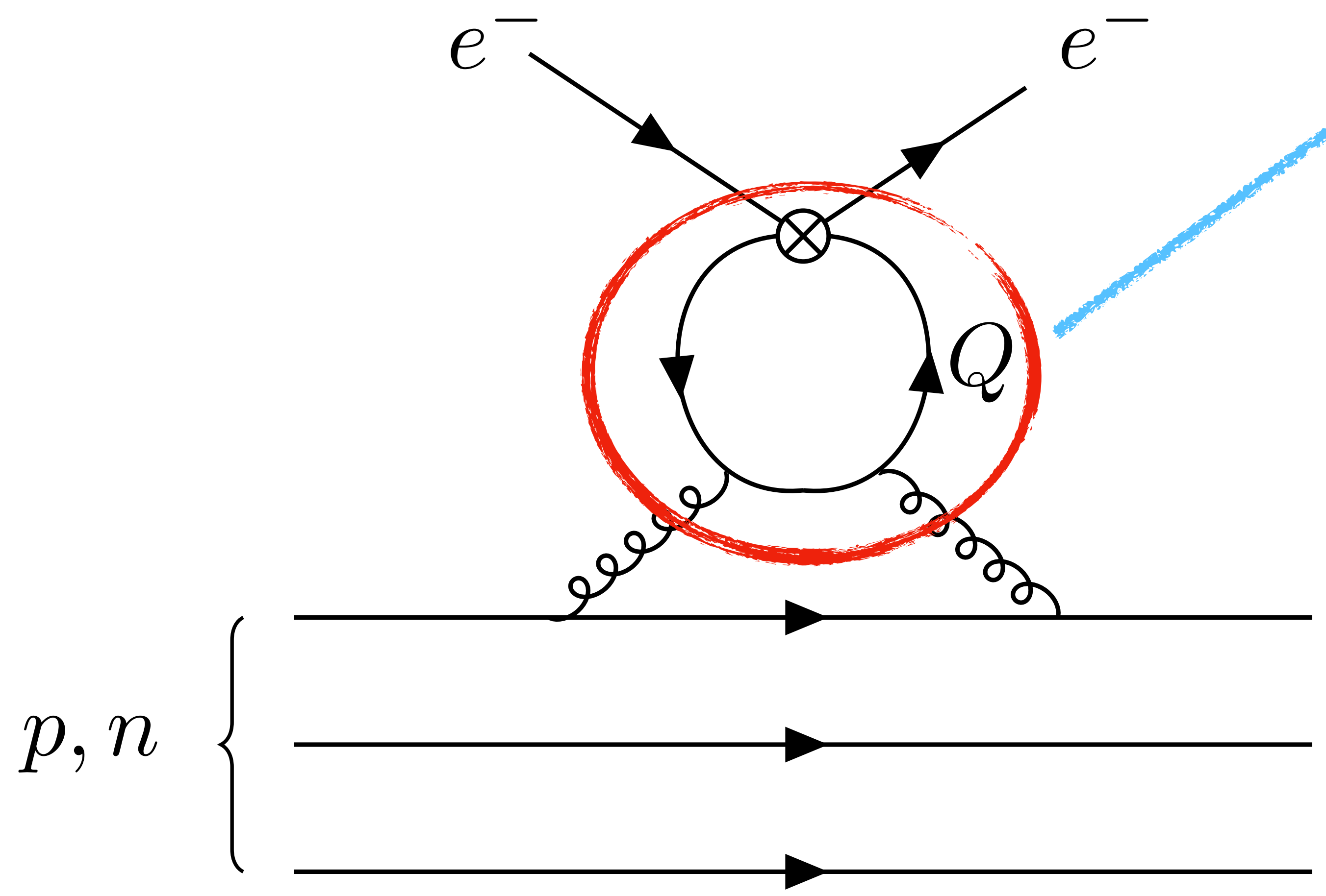
Relevant LEFT operators: $O_{XY}^{eq} = (\bar{e}P_X e)\,(\bar{q}P_Y q) \longrightarrow \frac{i}{2}\,\mathrm{Im}\,[C_{RL}^{eq} + C_{RR}^{eq}]\,(\bar{e}\gamma_5 e)(\bar{q}q) \equiv C_s^q(\bar{e}i\gamma_5 e)(\bar{q}q)$

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]
[Junarkar et al, 2013]



Heavy quarks contribution:

1-loop match to $O_{eG} = (\bar{e}i\gamma_5 e)(G_{\mu\nu}^a G_a^{\mu\nu})$

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

$$\downarrow$$

$$\langle\, N\,|G_{\mu\nu}^a G_a^{\mu\nu}|\,N\,\rangle = -\frac{8\pi m_N}{9\alpha_s(\mu)}\langle\, N\,|\bar{N}N|\,N\,\rangle$$

[Shifman et al., 1978]

Matching at the nucleon scale:

$$\boxed{\frac{\Lambda^2 G_F}{\sqrt{2}} C_S(\mu) = \sum_{q=u,d,s} G_s^{N,q} C_s^q(\mu) + \sum_{Q=c,b,t} \frac{2m_N}{27 m_Q} C_s^Q(m_Q)}$$

eEDM in SMEFT

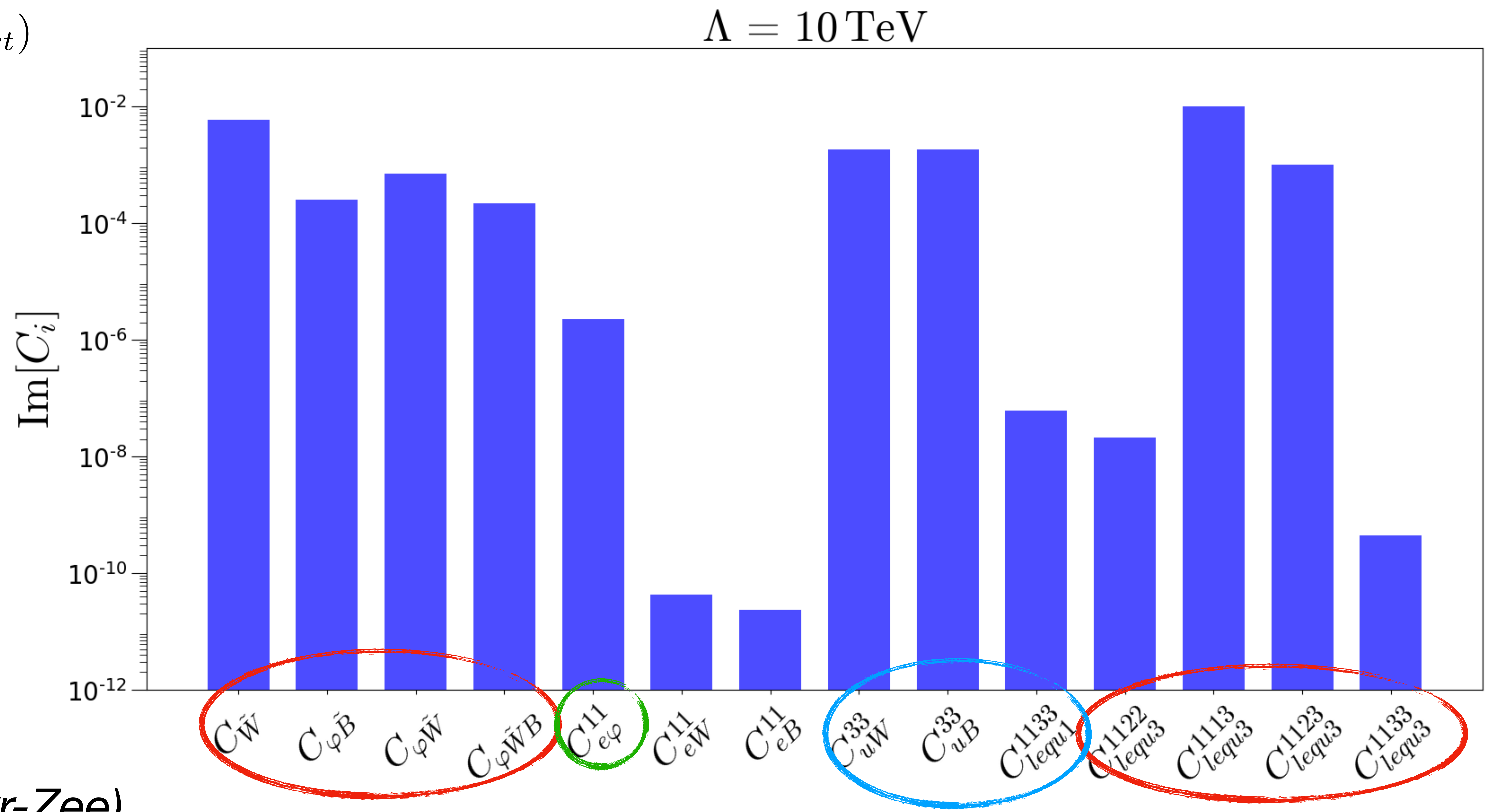
Large set of operators where $d^{\text{equiv.}} \sim d_e$

$$O_{lequ3}^{prst} = (\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$$

$$O_{f\varphi}^{pr} = (\varphi^\dagger \varphi)(\bar{F}_p f_r \varphi)$$

$$O_{\varphi\tilde{V}(X)} = (\varphi^\dagger \varphi)\tilde{V}_{\mu\nu} X^{\mu\nu}$$

$$O_{lequ1}^{prst} = (\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$$



1-loop RGE LL

1-loop RGE NLL

Mod. of Yukawa (Barr-Zee)

**No assumptions on MFV or loop order*

1-loop LL

EDM

$$16\pi^2 \frac{dC_{eW}^{ij}}{d\ln\mu} = -2g_2 N_c C_{lequ(3)}^{ijlm} [Y_u]_{ml} - [Y_e^\dagger]_{ij} \left(g_2 (C_{HW} + iC_{H\widetilde{W}}) + g_1 (y_l + y_e)(C_{HWB} + iC_{H\widetilde{W}B}) \right)$$

$$16\pi^2 \frac{dC_{eB}^{ij}}{d\ln\mu} = 4g_1 N_c (y_u + y_q) C_{lequ(3)}^{ijlm} [Y_u]_{ml} - [Y_e^\dagger]_{ij} \left(2g_1 (y_l + y_e)(C_{HB} + iC_{H\widetilde{B}}) + \frac{3}{2} g_2 (C_{HWB} + iC_{H\widetilde{W}B}) \right)$$

Electron Yukawa Supressed

Proportional to quark yukawas

Semileptonic

$$\dot{C}_{lequ(1)}^{prst} = -\left(24(y_q + y_u)(2y_e - y_q + y_u) g_1^2 - 18 g_2^2\right) C_{lequ(3)}^{prst}$$

	t	c	u
d_e	Yukawa enhanced	Yukawa enhanced	Yukawa suppressed
C_S	Suppressed in matching	Suppressed in matching	Unsuppressed in matching

1-loop NLL

Most relevant effect from operators mixing with O_{lequ3}^{prst} LL:

$$\boxed{\dot{C}^{(3)}_{\substack{lequ\\prst}} = +\frac{1}{8}\left(-4\left(\mathsf{y}_q+\mathsf{y}_u\right)\left(2\mathsf{y}_e-\mathsf{y}_q+\mathsf{y}_u\right)g_1^2+3g_2^2\right)C^{(1)}_{\substack{lequ\\prst}}}$$

	t	c	u
d_e	Yukawa enhanced	Same order as C_S	Yukawa suppressed
C_S	Suppressed in matching	Same order as d_e	Unsuppressed in matching

1-loop NNLL

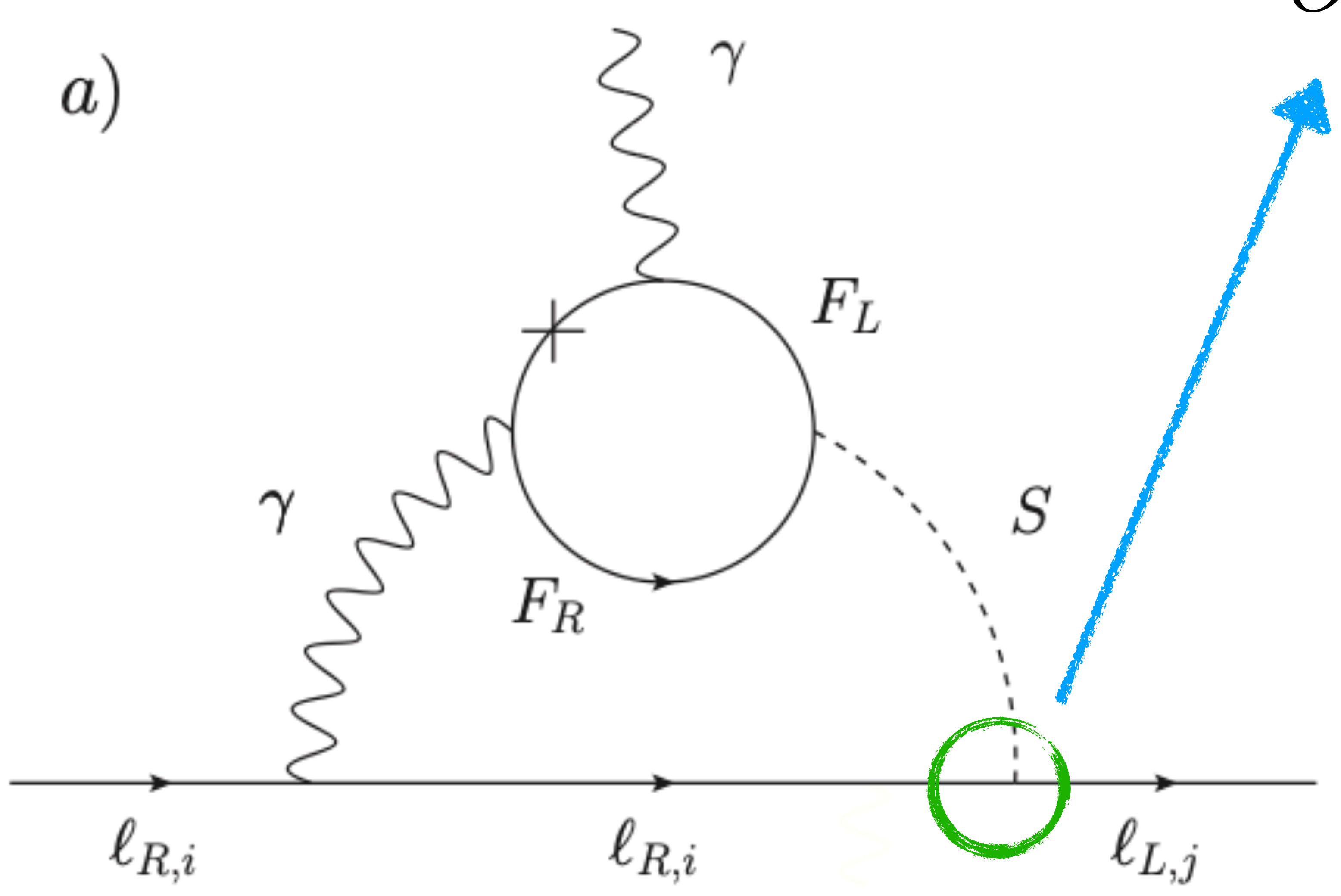
For some operators NNLL in one-loop RGE maybe sizeable

$$C_{ledq}^{eebb} \longrightarrow C_{lequ(1)}^{eett} \longrightarrow C_{lequ(3)}^{eett}$$

Still subdominant respect to the semileptonic direction!

Mod of Yukawa (Barr-Zee)

Dim.6 two loop effect at EW breaking scale



$O^{pr}_{f\varphi}$ *can induce a modification between Higgs-fermions coupling* → *Yukawa couplings not proportional to the mass matrix*

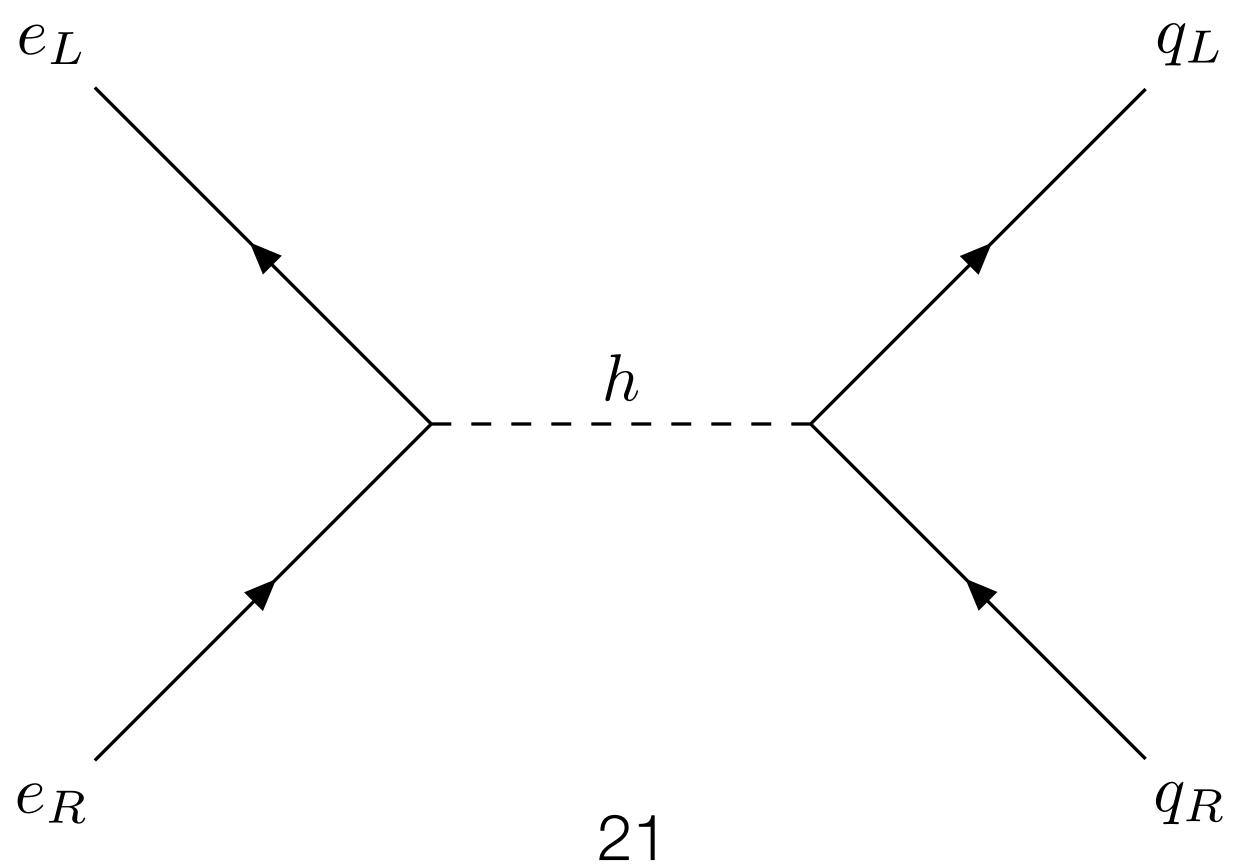
Most sizable contributions from top and W in the loop:

$$[\mathcal{Y}_\psi]_{rs} = \frac{1}{v_T}[M_\psi]_{rs}[1 + c_{H,\text{kin}}] - \frac{v^2}{\sqrt{2}} C^*_{\substack{\psi H \\ sr}}$$

$$d_e \sim \frac{e\alpha}{4\pi^2}\frac{v}{\Lambda^2}\text{Im}[C^{11}_{e\phi}]f(m_F/m_H)$$

Impact on C_S *?*

Same operator enters the semileptonic direction →



→ *Integrate out h*

Sub-dominant: Correction of a few % in the equivalent EDM

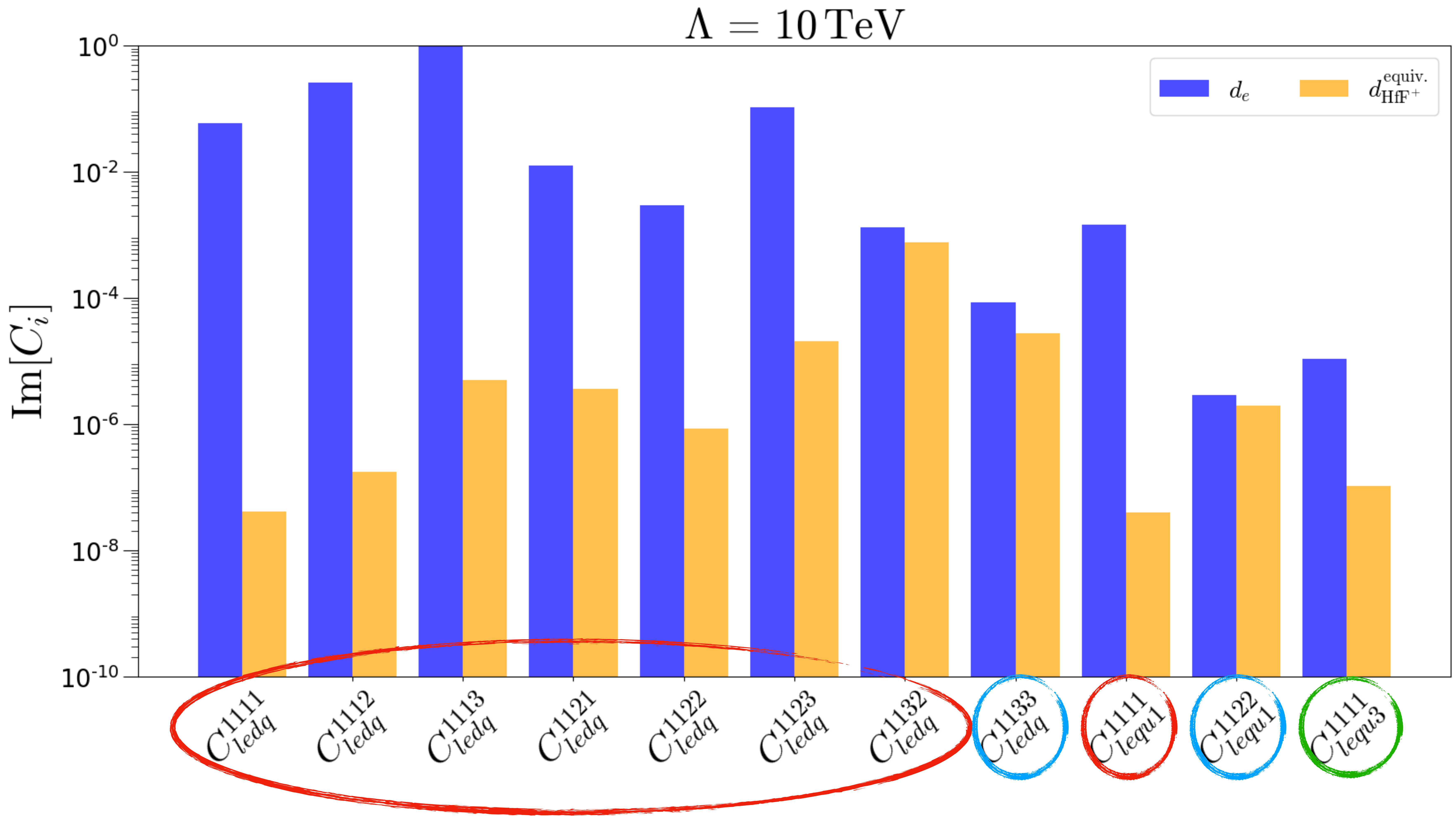
Looking at the full direction

equivalent EDM is more sensitive than eEDM to some semileptonic operators

Light quarks matching

Heavy quarks matching

1-loop RGE LL



Conclusions

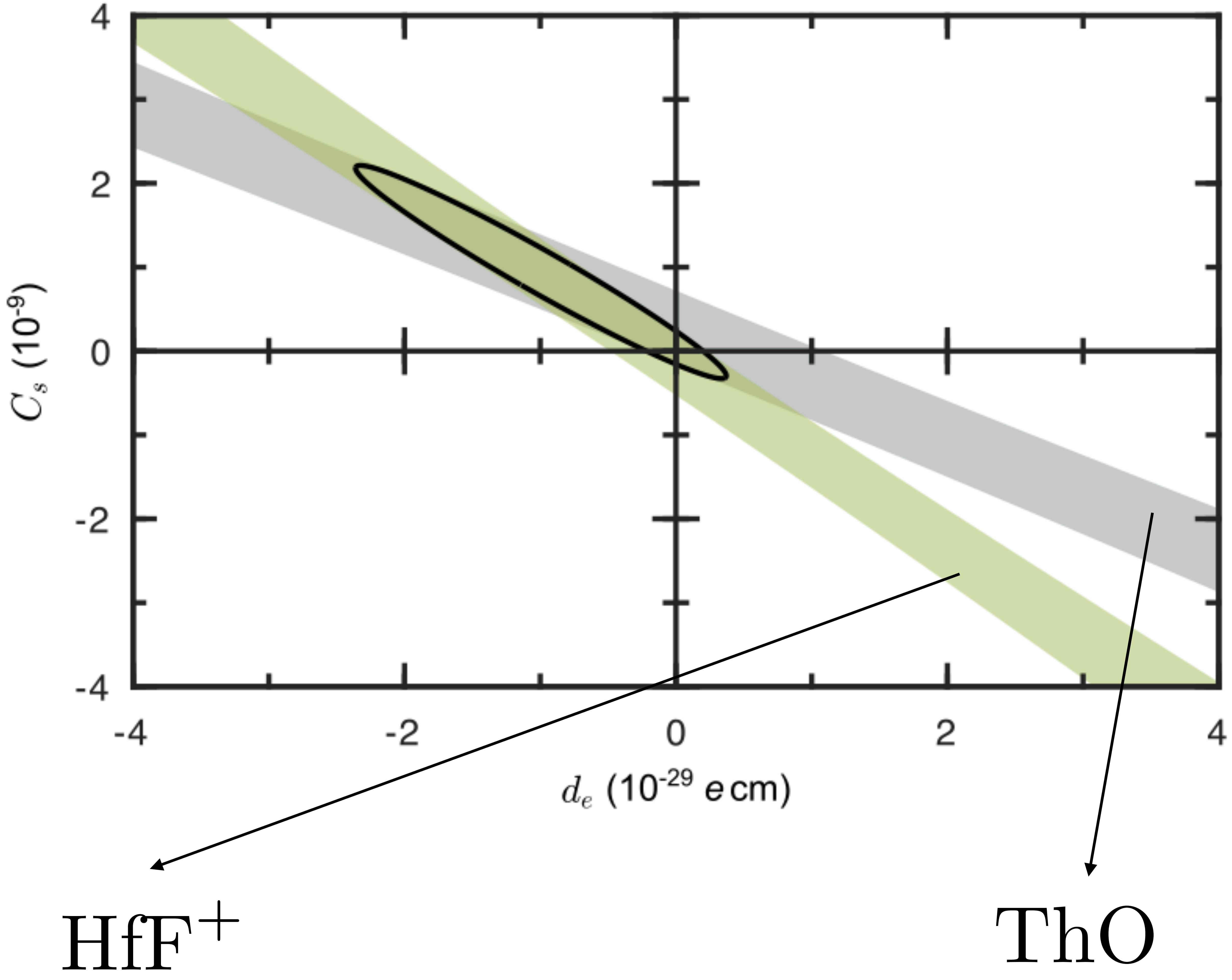
- Introduction to dipole moments
  - *Dipoles are the most sensitive observables to heavy NP*
- The equivalent EDM in SMEFT
  - *Paramagnetic system sensitive to eEDM and a semileptonic CP-odd int.*
  - *Previous works focused just on eEDM sensitivity to SMEFT operators*
  - *Extension of the analysis to explore the full direction probed by electron EDM exps.*
  - *Sensitivities of the eEDM experiments to a larger classes of operators than previously recognized*

BACK UP

What if we have 2 or more Exps?

In EDM experiments I want to measure the energy shift when s is aligned with E
Compare to when is anti-aligned

Roussy et al.,hep-ph/2212.11841



$$hf = -2d_e E_{eff} + 2W_S C_S$$

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

Two experiments with different #
Can disentangle eEDM and Cs.

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

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

$\downarrow$

Combined fit

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

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

A bit of dipoles

Crucial for this work are the dipole operators at dimension 6

Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$

Spontaneous symmetry breaking and gauge boson eigenstates:

$$\varphi \to \begin{pmatrix} 0 & \frac{v+h}{\sqrt{2}} \end{pmatrix}^T$$

$$B_\mu = \cos\theta_w A_\mu - \sin\theta_w Z_\mu$$
$$W^3_\mu = \sin\theta_w A_\mu + \cos\theta_w Z_\mu$$

Matching to our Effective lagrangian: $\boxed{\mathcal{L}_{EDM} = -\frac{i}{2} d\, \bar{f} \sigma_{\mu\nu}\, \gamma_5 f\, F^{\mu\nu}}$

$$d_e(\mu) = \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Im}\left[s_{\theta_W}\, C_{eW}(\mu) - c_{\theta_W}\, C_{eB}(\mu)\right]$$

But

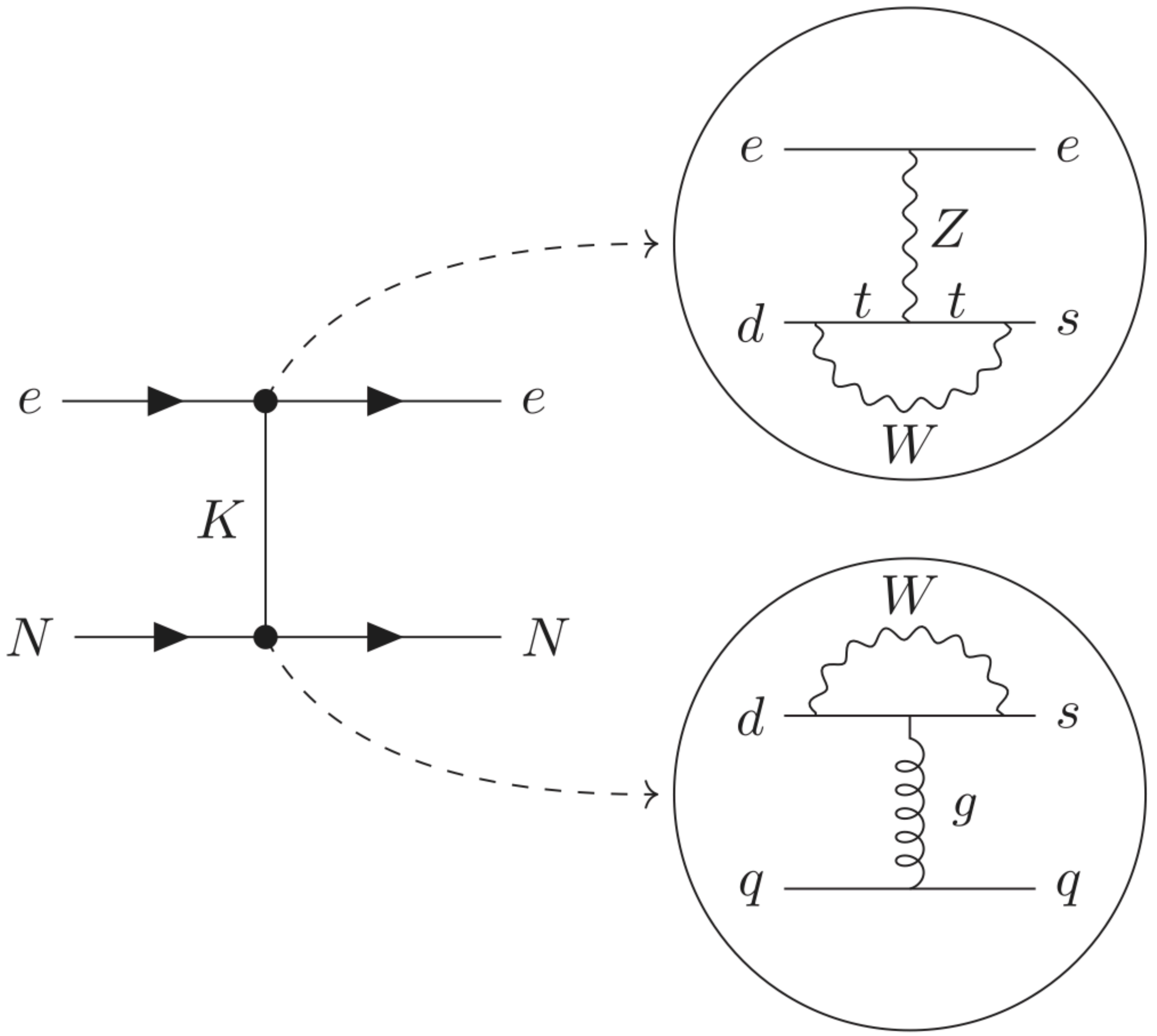
Solution of RGE (SMEFT or LEFT):

$$\vec{C}(\mu_f) = \vec{C}(\mu_i) U(\mu_f, \mu_i) \longrightarrow$$

Dipole operators at low energy can stem from the mixing under the RGE

A closer look at the SM contribution

Leading contribution given by kaons exchange



$$\boxed{\mathcal{L}_{Kee} = -2\sqrt{2} f_0 m_e \bar{e} i \gamma_5 e (K_S \times \mathrm{Im}\mathcal{P}_{\rm EW} + K_L \times \mathrm{Re}\mathcal{P}_{\rm EW})}$$

$$\mathcal{P}_{\rm EW} = \frac{G_F}{\sqrt{2}} \times V_{ts}^* V_{td} \times \frac{\alpha_{\rm EM}(m_Z)}{4\pi \sin^2\theta_W} I(x_t)$$

$$\boxed{\begin{aligned}\mathcal{L}_{KNN} \simeq & -\frac{\sqrt{2} G_F \times [m_{\pi^+}]^2 f_\pi}{|V_{ud} V_{us}| f_0} \times 2.84 (0.7 \bar{p} p + \bar{n} n) \\ & \times (\mathrm{Re}(V_{ud}^* V_{us}) K_S + \mathrm{Im}(V_{ud}^* V_{us}) K_L).\end{aligned}}$$

$$C_S \simeq \mathcal{J} \times \frac{N + 0.7 Z}{A} \times \frac{13 [m_{\pi^+}]^2 f_\pi m_e G_F}{m_K^2} \times \frac{\alpha_{\rm EM} I(x_t)}{\pi \sin\theta_W^2}$$

$$C_S(\mathrm{LO} + \mathrm{NLO}) \simeq 6.9 \times 10^{-16}$$

$$\Rightarrow d_e^{\rm equiv} \simeq 1.0 \times 10^{-35} \ e\,\mathrm{cm}.$$

$$\mathcal{J} = \mathrm{Im}(V_{ts}^* V_{td} V_{ud}^* V_{us}) \simeq 3.1 \times 10^{-5},$$

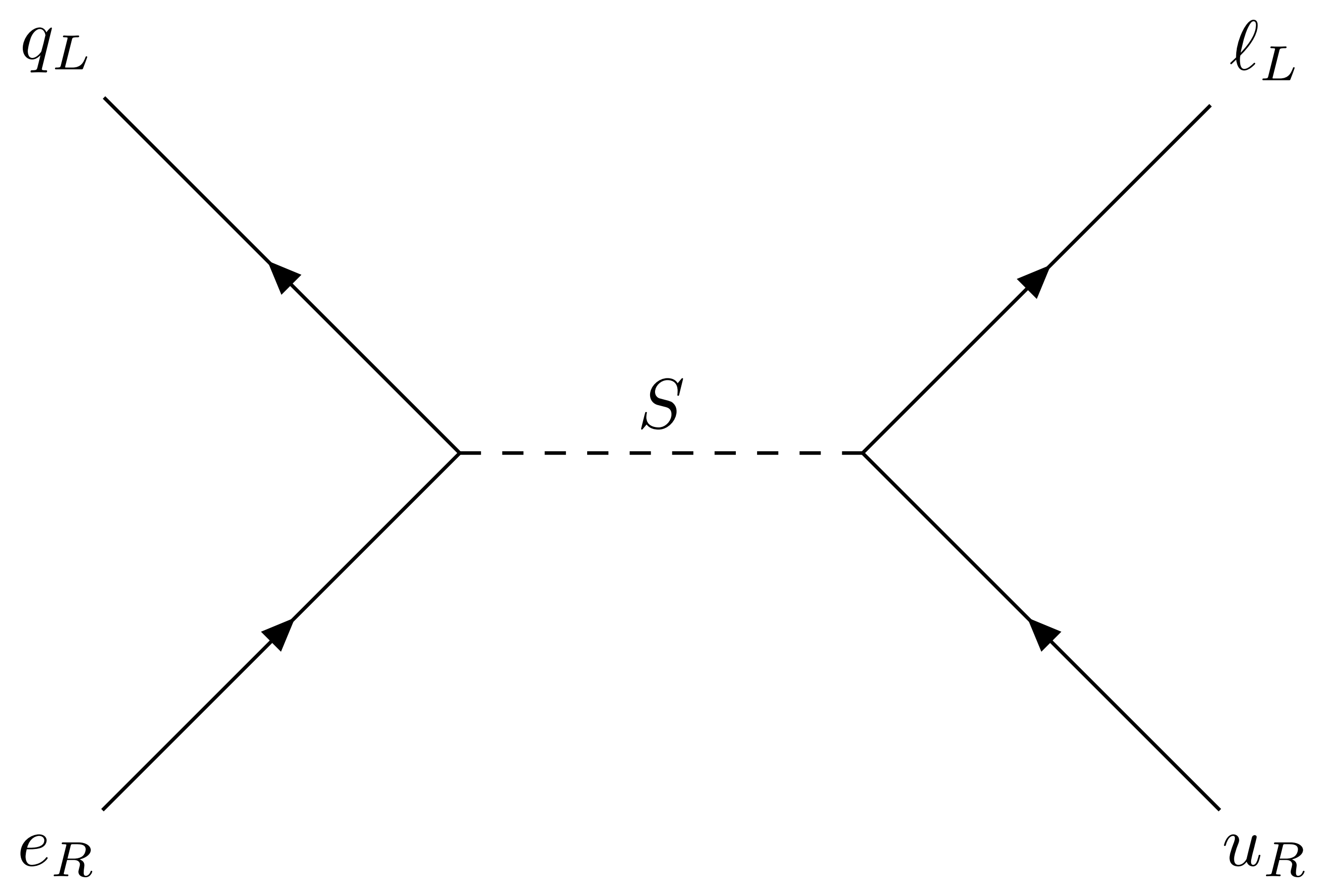
UV Completion?

EFT theories ask for UV completions

Scalar leptoquarks

$$S = (3, 2, 7/6)$$

$$\mathcal{L}_{\mathrm{Lq}} \supset -y^{qe}_{ij}\, S\, \bar{q}^i_L e^j_R - y^{lq}_{ij}\, \tilde{S}\, \bar{l}^l_L u^j_R \,+\, \text{H.c.}$$

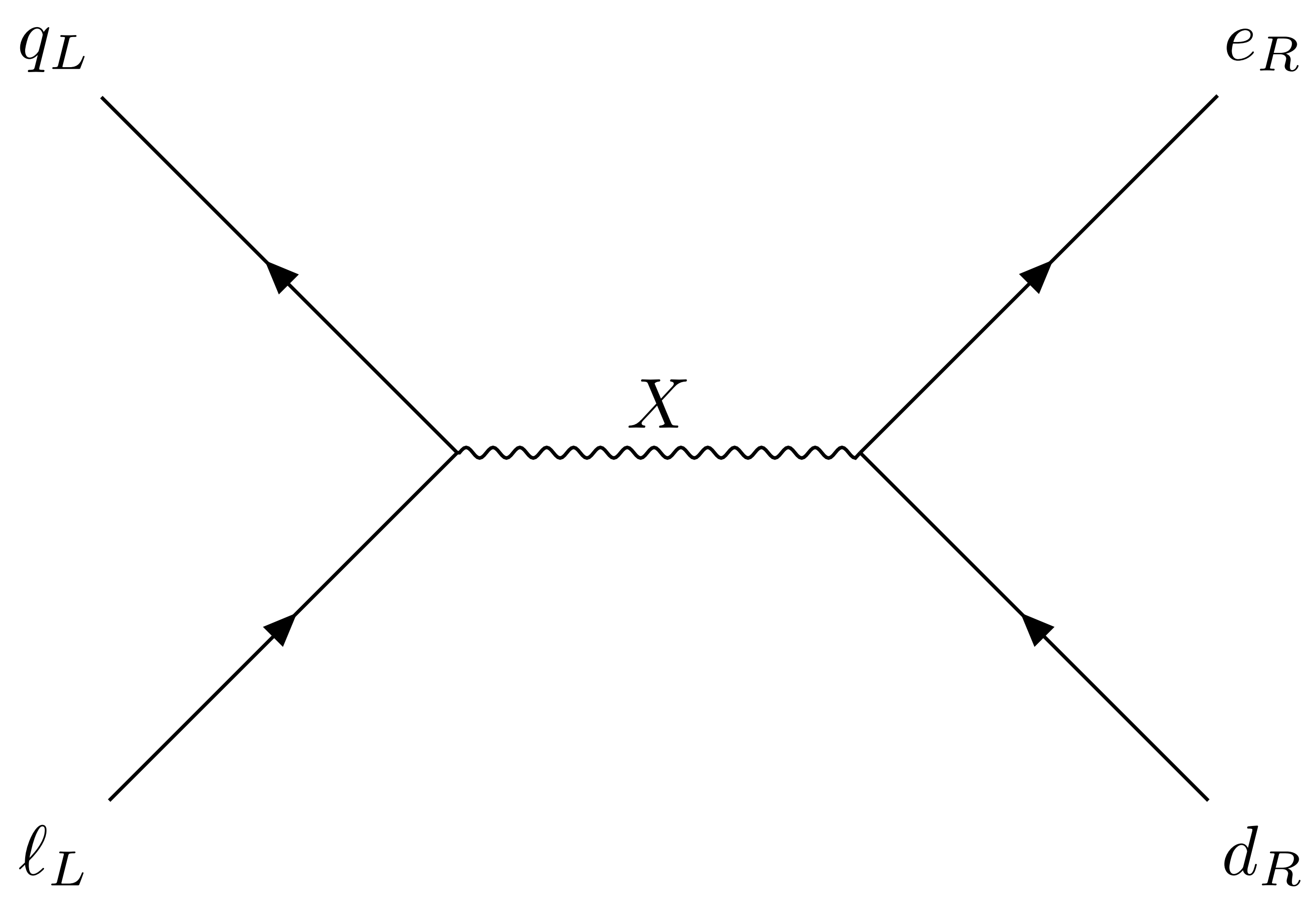


$C_{\ell equ(3)}$

Vector leptoquarks

$$X = (3, 1, 2/3)$$

$$\mathcal{L} = g_L X^\mu (\bar{d}^i_R \gamma^\mu e^j_R + \bar{q}^i_L \gamma^\mu \ell^j_L + \text{H.c.})$$



$C_{\ell edq}$