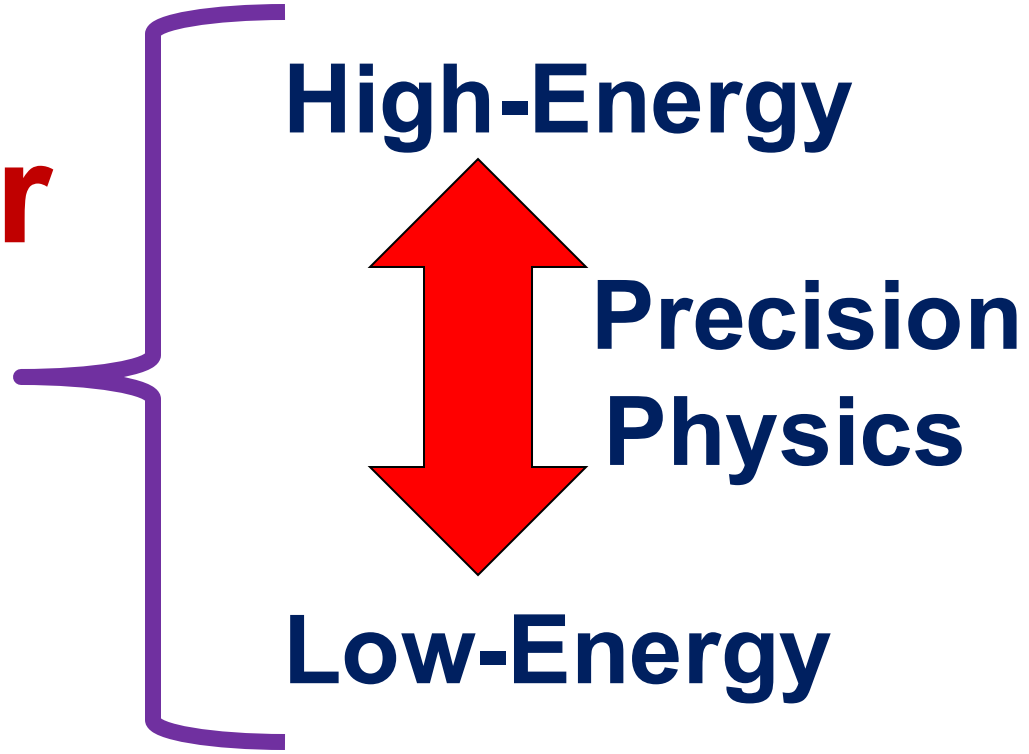
The Precision frontier of particle physics in 2025



Antonio Masiero
Univ. of Padova and INFN, Padova

4th Liverpool Workshop on Muon Precision Physics 2025 (MPP2025)

Liverpool, Nov. 11 – 13, 2025

LIGHT and HEAVY New Physics extensions of the SM

$$\mathcal{L}_{\rm EFT} = m_H^2 H^\dagger H + \mathcal{L}_{\rm SM,\,dim\,4}(A,\psi,H) + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathcal{O}^{(n)}_{\rm SM,\,dim\,n}(A,\psi,H)$$

$$+ \mathcal{L}_{\rm portals}(\psi, A, H; \varphi_{\rm DS}) + \mathcal{L}_{DS}(\varphi_{\rm DS}).$$

HEAVY NP

LIGHT NP

HEAVY BSM physics

$$\sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} \mathcal{O}^{(n)}_{\rm SM,\,dim\,n}(A,\psi,H)$$

Effective **dim>4 operators** generated integrating out the heavy BSM physics at a new

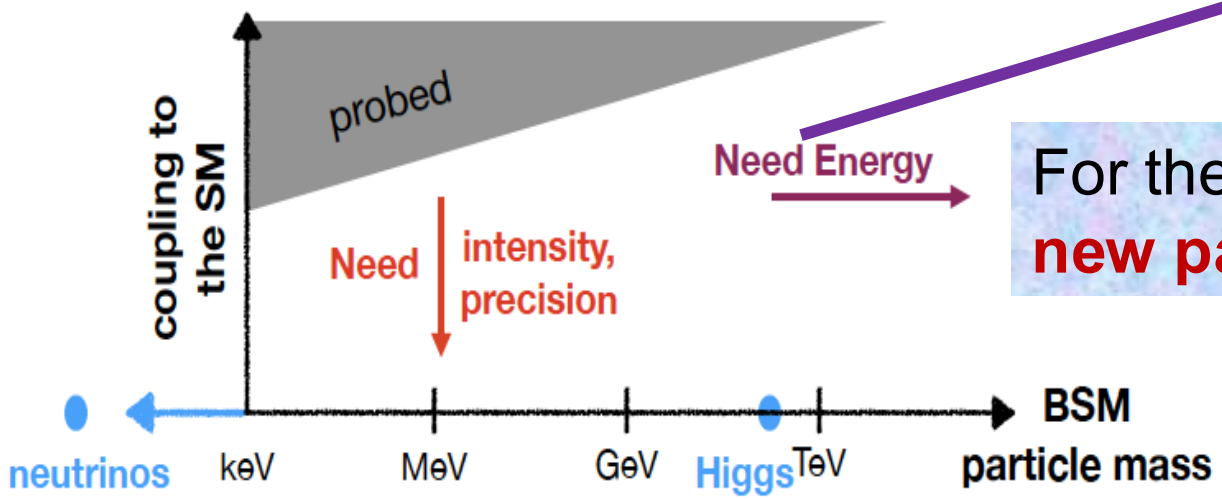
Λ >> electroweak scale ~ M_W

LIGHT BSM physics

$$\mathcal{L}_{\rm portals}(\psi, A, H; \varphi_{\rm DS}) + \mathcal{L}_{DS}(\varphi_{\rm DS})$$

Light << M_W "Dark Sector" (DS) **weakly coupling** to the SM fields through the so-called **portal couplings**

The quest for new physics



Need **intensity, precision** for the production of **VIRTUAL** **new HEAVY PARTICLES** **with masses >> M_W**

For the production of **real (physical) new particles with masses >> M_W**

We do not know what will be the next New Physics (NP) scale.

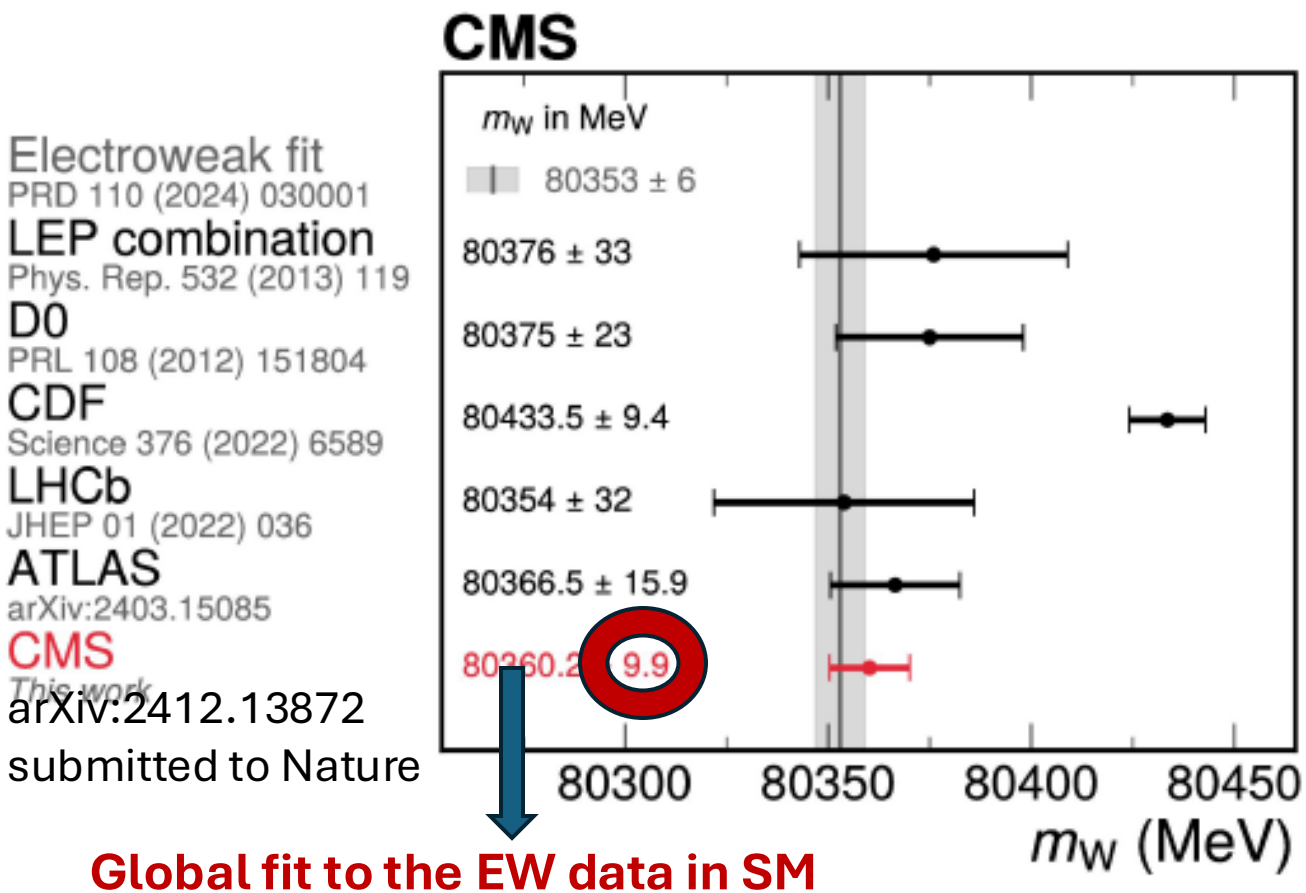
LOW-ENERGY high-precision physics at small- or mid-scale size experiments

Search for NEW LIGHT PARTICLES FEEBLY coupled to the SM

Search for NEW HEAVY PARTICLES – through their VIRTUAL effects → use of SM EFFECTIVE THEORY (SMEFT) techniques

PRECISION HIGH-ENERGY PHYSICS

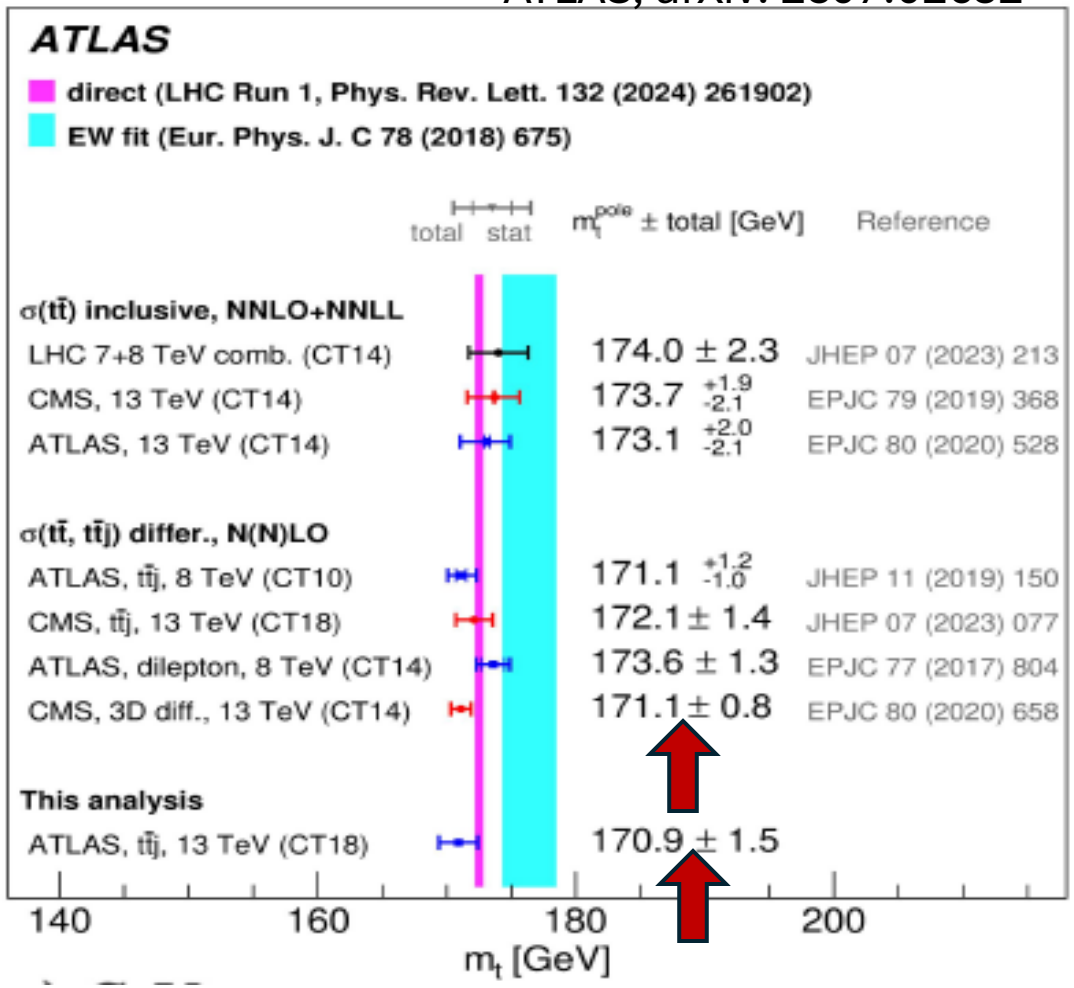
LHC: from (purely) discovery → precision physics machine



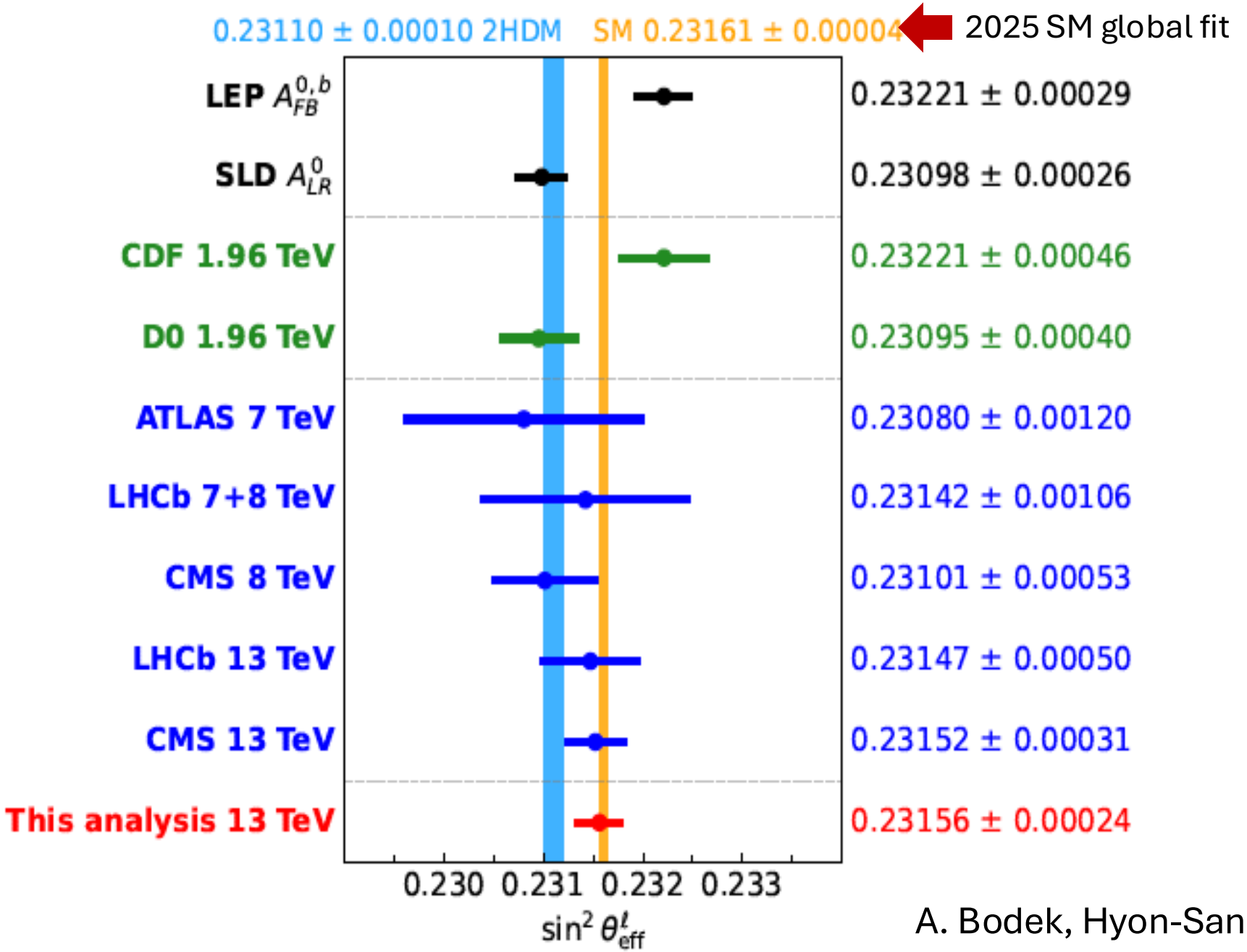
arXiv:2412.13872
submitted to Nature

Global fit to the EW data in SM
→ M_W determination with
6 MeV uncertainty

ATLAS, arXiv: 2507.02632



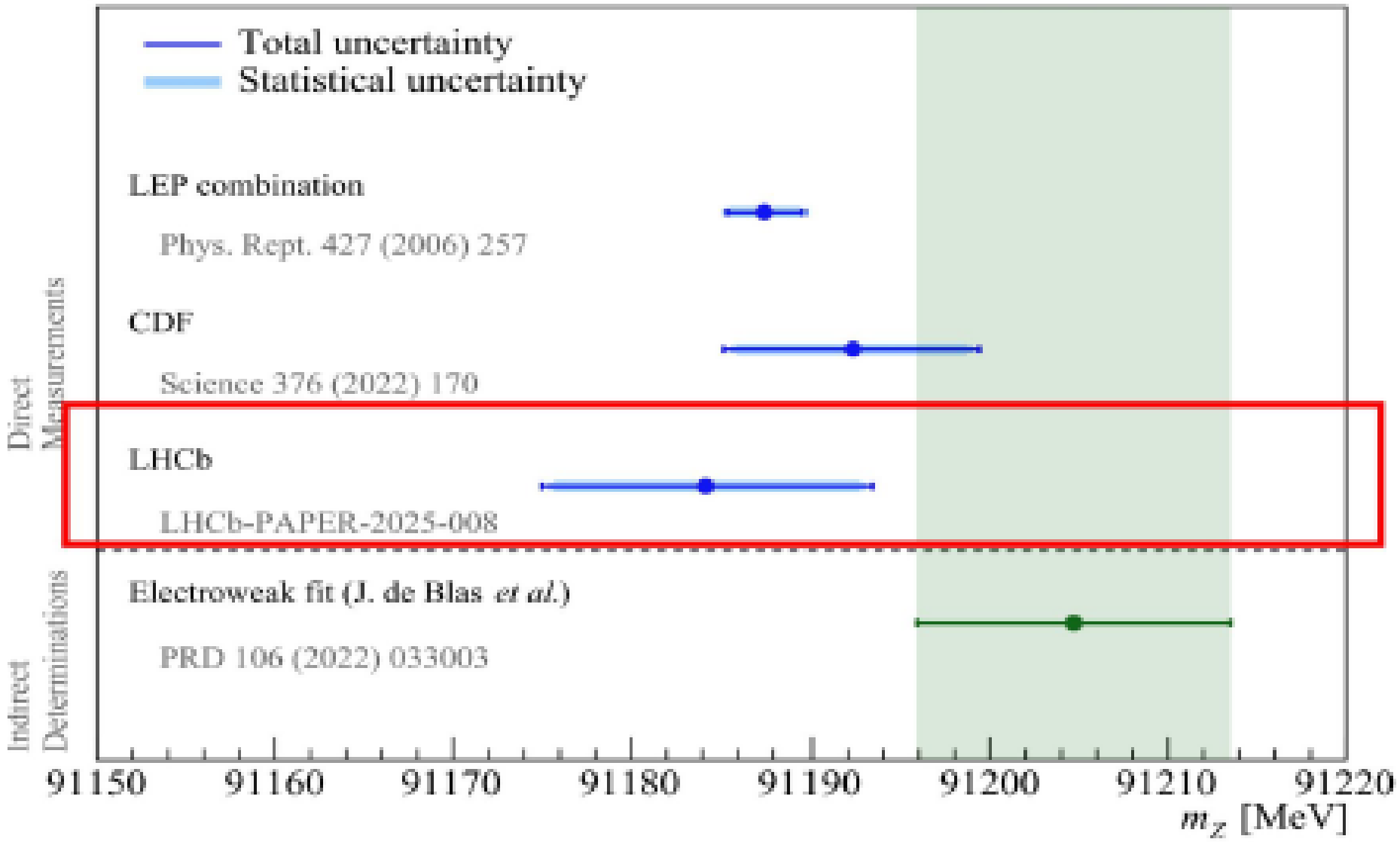
J. Bendavid, EPS-HEP 2025



A. Bodek, Hyon-San Seo, Un-Ki Yang,
PLB 866 (2025) 139526

CMS coll.

even for the **direct determination of M_Z** LHC starts getting a competitive precision



LHCb, arXiv:2505.15582

LHC → High Luminosity LHC

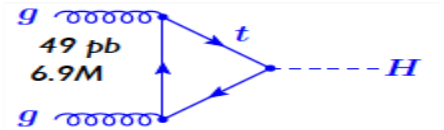
H couplings to:	**O(5-10)%**
H self-coupling to:	**O(50)%**

(or better)

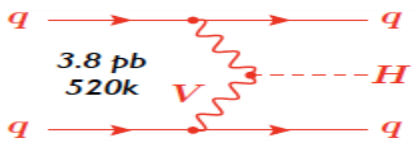
New physics expectation: $\delta\kappa \sim O(v^2/\Lambda^2) \sim \frac{6\%}{(\Lambda/\mathrm{TeV})^2}$

thus the reach Λ ~ O(a few TeV).

Tao Han LP2025

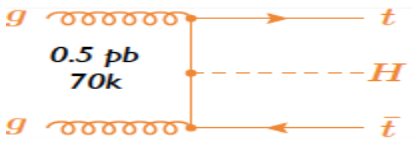


gluon fusion
ggH: 86%

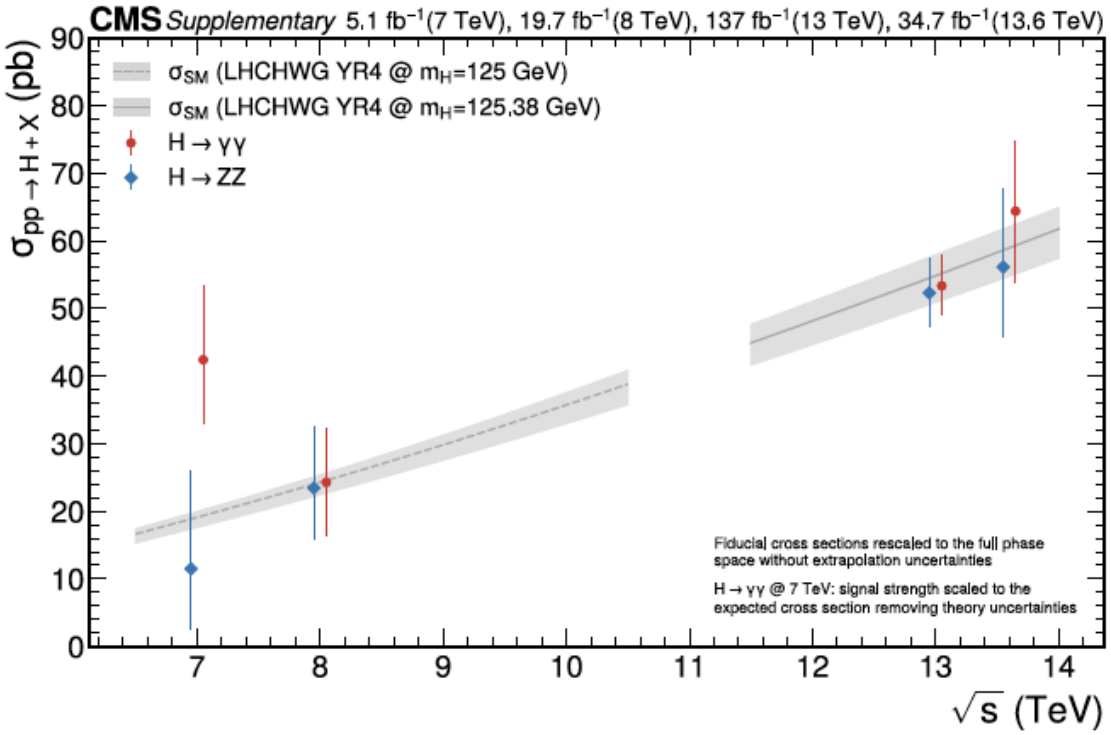


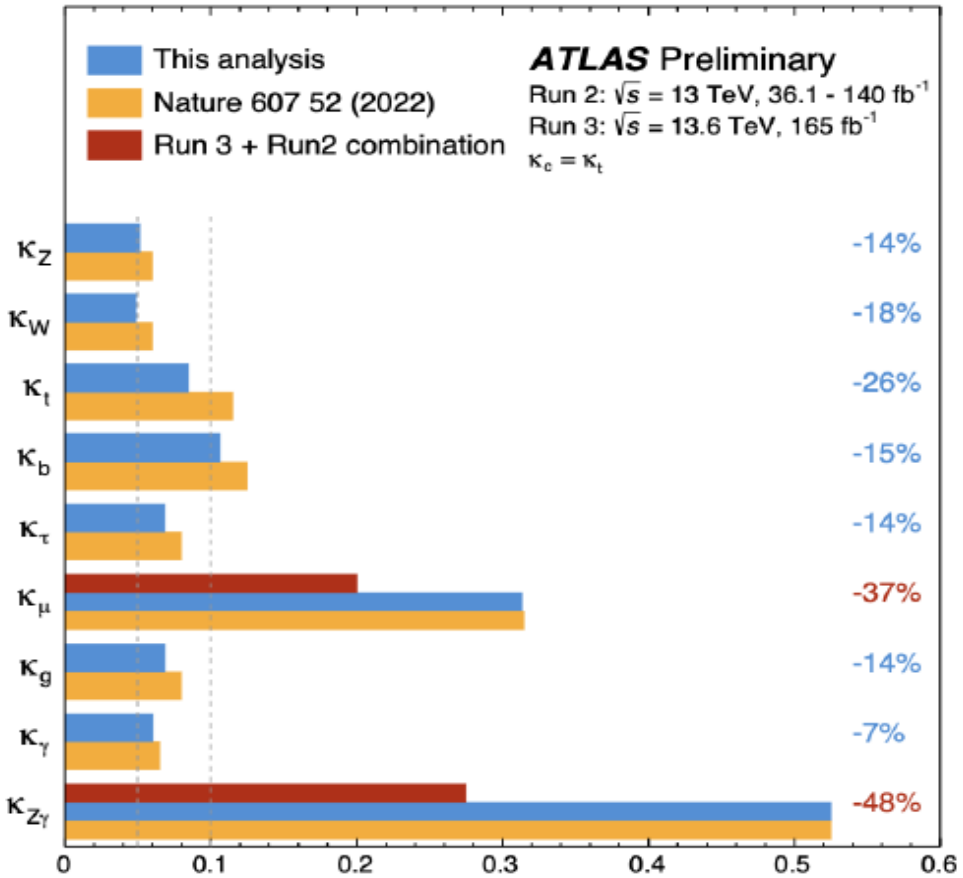
vector boson fusion (**VBF**): **6.5%**

W,Z associated production
WH/ZH: 4%



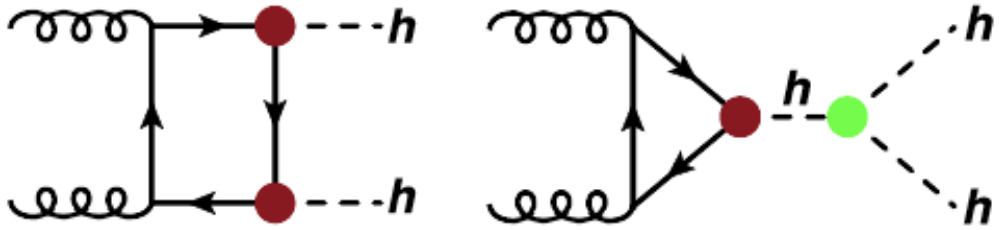
$t\bar{t}H$ associated production: **1%**





SM Higgs boson pair production at the LHC

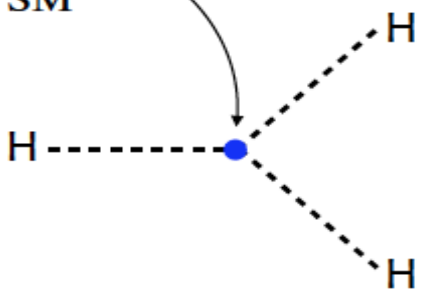
SM Higgs boson pair production (gluon-gluon fusion - ggF):



Higgs-fermion Yukawa coupling

Higgs boson self-coupling

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

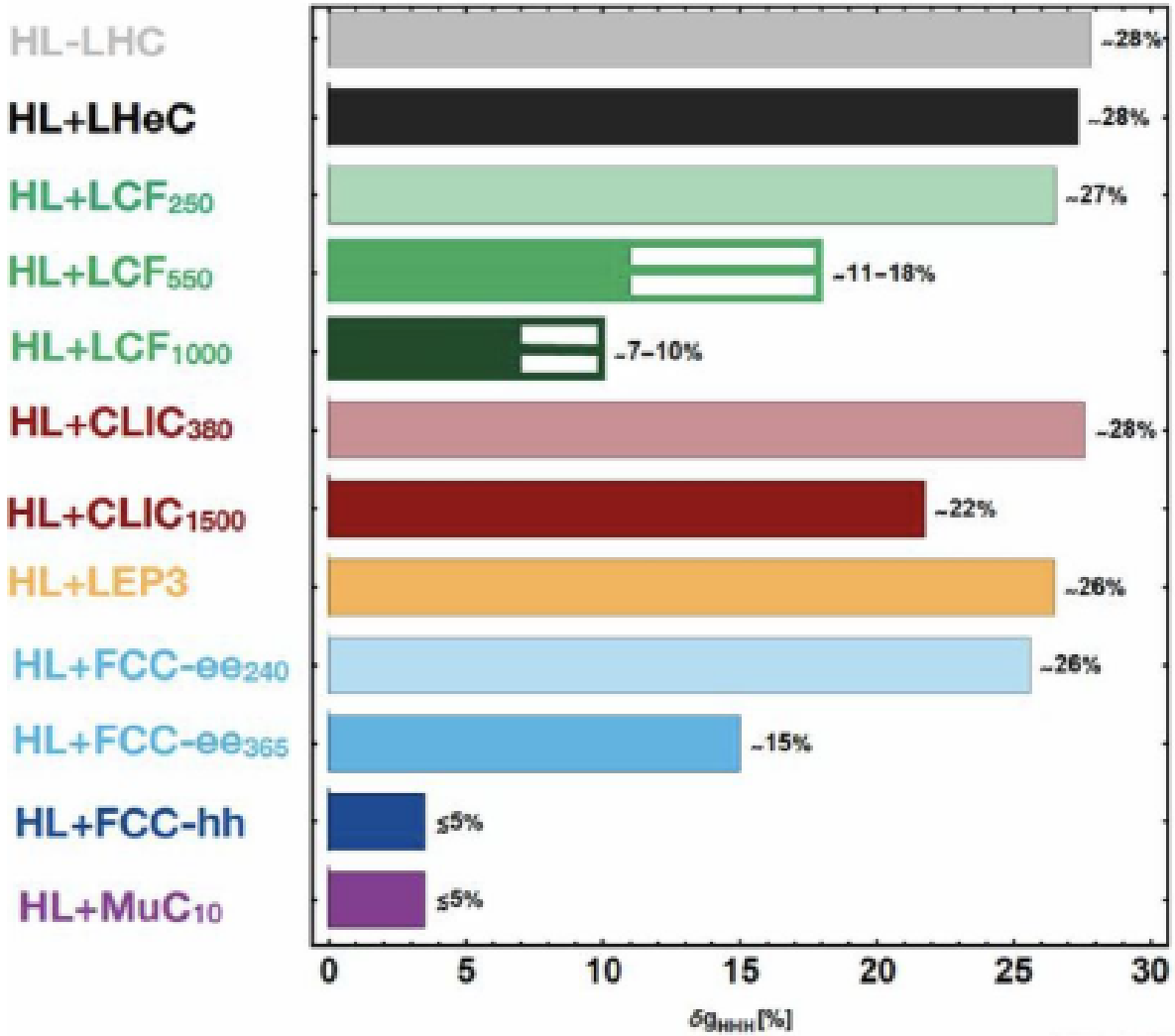


most stringent 95% CLs on Higgs boson self-coupling from HH:

$$-1.2 < \kappa_\lambda < 7.2 \text{ (ATLAS)}$$
$$-1.39 < \kappa_\lambda < 7.02 \text{ (CMS)}$$

CMS-PAS-HIG-20-011

ATLAS: PRL 133 (2024) 101801



Higgs self-coupling and ELW BARYOGENESIS

λ_{hhh} dictate EW phase transition & impact on early universe cosmology:

$\lambda_{SM} \sim 0.13$ implies a cross-over change.

CKM Triangle – present and future

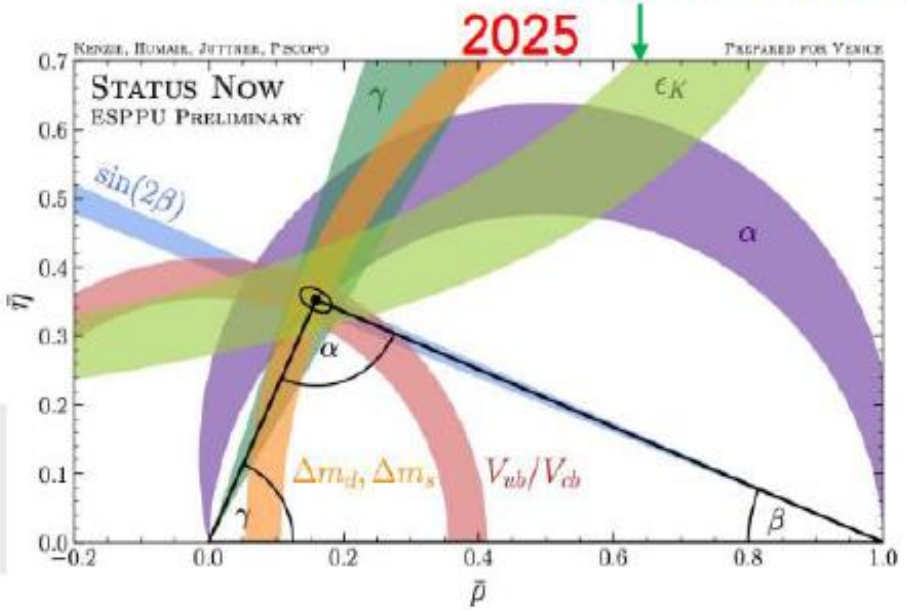
- Update from the European Strategy for Particle Physics, June 2025, Venice meeting
  - Measured uncertainties on selected key observables (arXiv:2503.24346v2)

Experiment Assumed data sample	ATLAS 20.3-99.7 fb^{-1}	CMS 116-140 fb^{-1}	LHCb 2-9 fb^{-1}	Belle II 364-1075 fb^{-1}
CKM angles				
β	—	—	0.57° [15]	1.2° [16]
α	—	—	—	6.6° [17]
γ	—	—	2.8° [18]	13° [17]
ϕ_s [mrad]	42 [19]	23 [20]	20 [21]	—

WA: HFLAV, August 2025

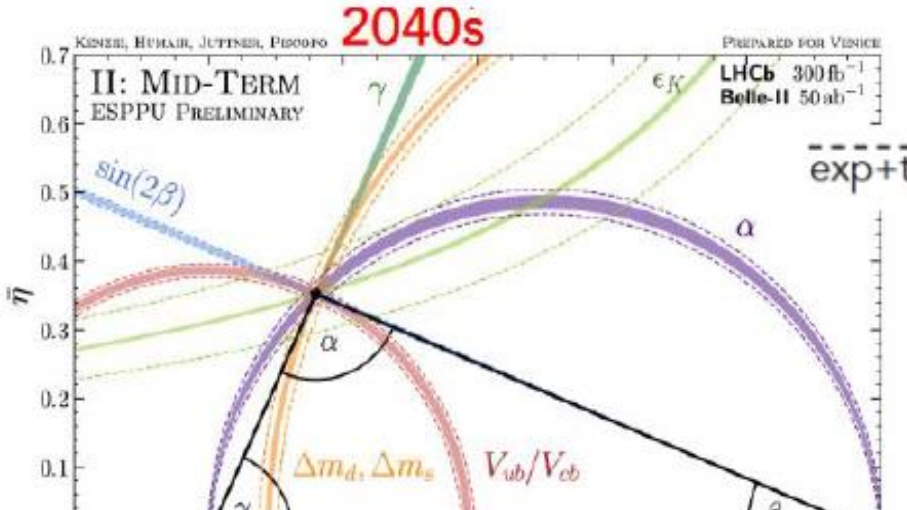
Parameters: $(\bar{\rho}, \bar{\eta})$ apex of Unitarity Triangle
$\bar{\rho} = 0.139 \pm 0.014$
$\bar{\eta} = 0.360 \pm 0.008$

Talk by M-H Schune



  - Sensitivity to selected key observables (arXiv:2503.24346v2)

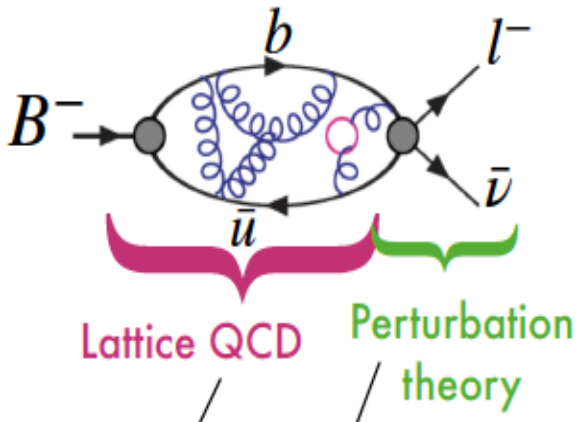
Experiment Assumed data sample	ATLAS 3000 fb^{-1}	CMS 3000 fb^{-1}	LHCb 300 fb^{-1}	Belle II 50 ab^{-1}
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	$(4-9)$	3	3	—



- A lot of additional work in the experiments beyond the ESPPU document

Great progress of the precision achieved in LATTICE QCD computations of non-perturbative QCD contributions for the hadronic inputs in flavour measurements

EXAMPLE: leptonic B decay

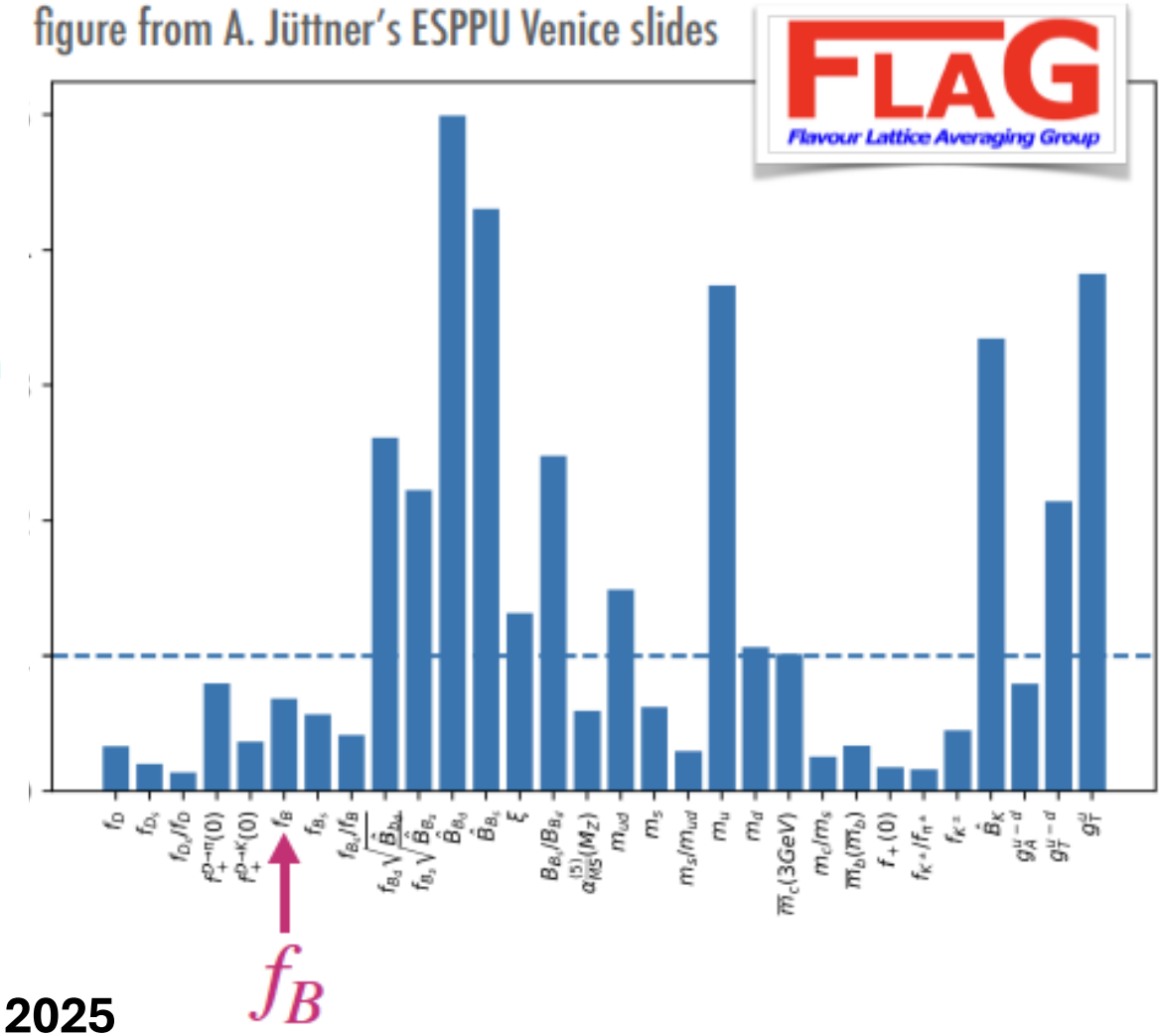


kinematics

$$\Gamma(B^- \to l^- \bar{\nu}) = \frac{m_B}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 \; |V_{ub}|^2 G_F^2$$

Under the assumption that this is dominated by SM, can then compare with measured decay rate to extract V_{ub}

figure from A. Jüttner's ESPPU Venice slides



S. Renner, EPS-HEP 2025

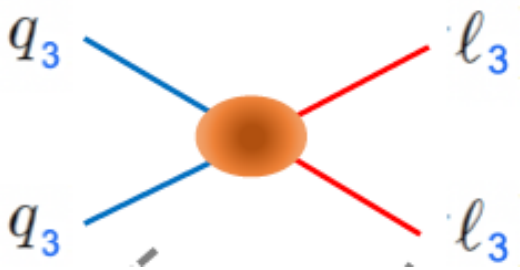
Hints of **LEPTON FLAVOR NON-UNIVERSAL** New Physics

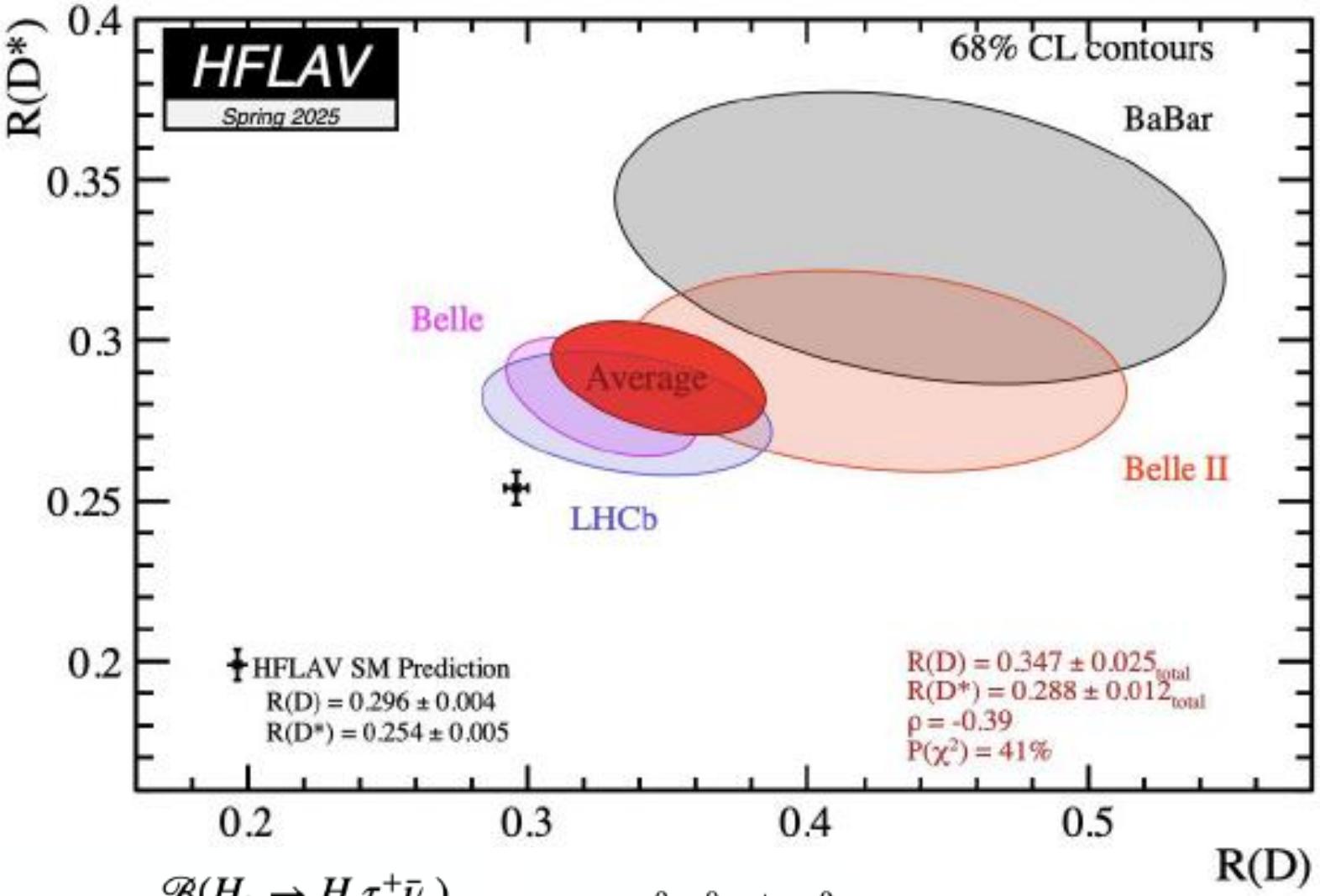
M. Calvi, A. Juttner, ESPPU2026 Symposium, Venice 2025

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$

Is the fermionic 3rd generation somewhat "special"? →

Due to HEAVY New Physics coupled only or mostly to 3rd generation





But getting R(D) and R(D*) from **different B and D decay modes** globally exceeds the SM prediction by about 3.8 σ

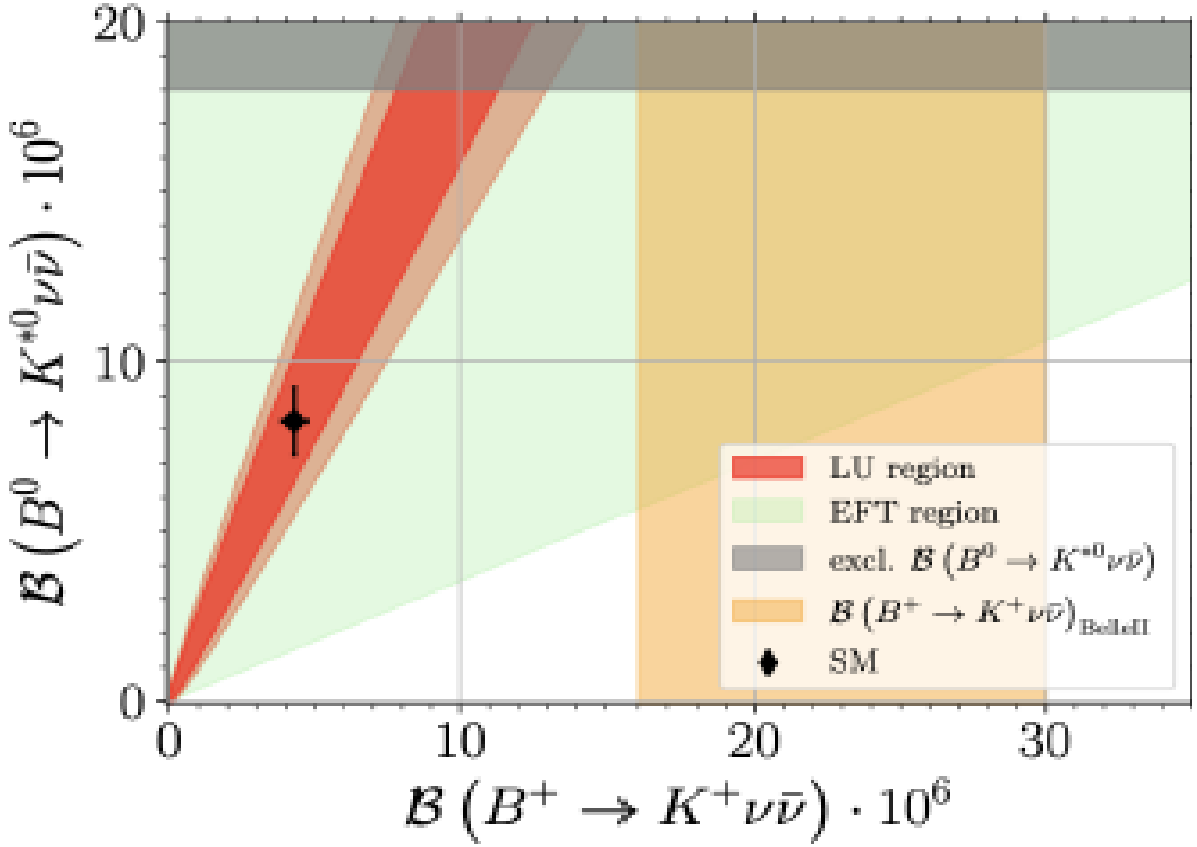
$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau^+\bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\mu^+\bar{\nu}_\mu)}$$

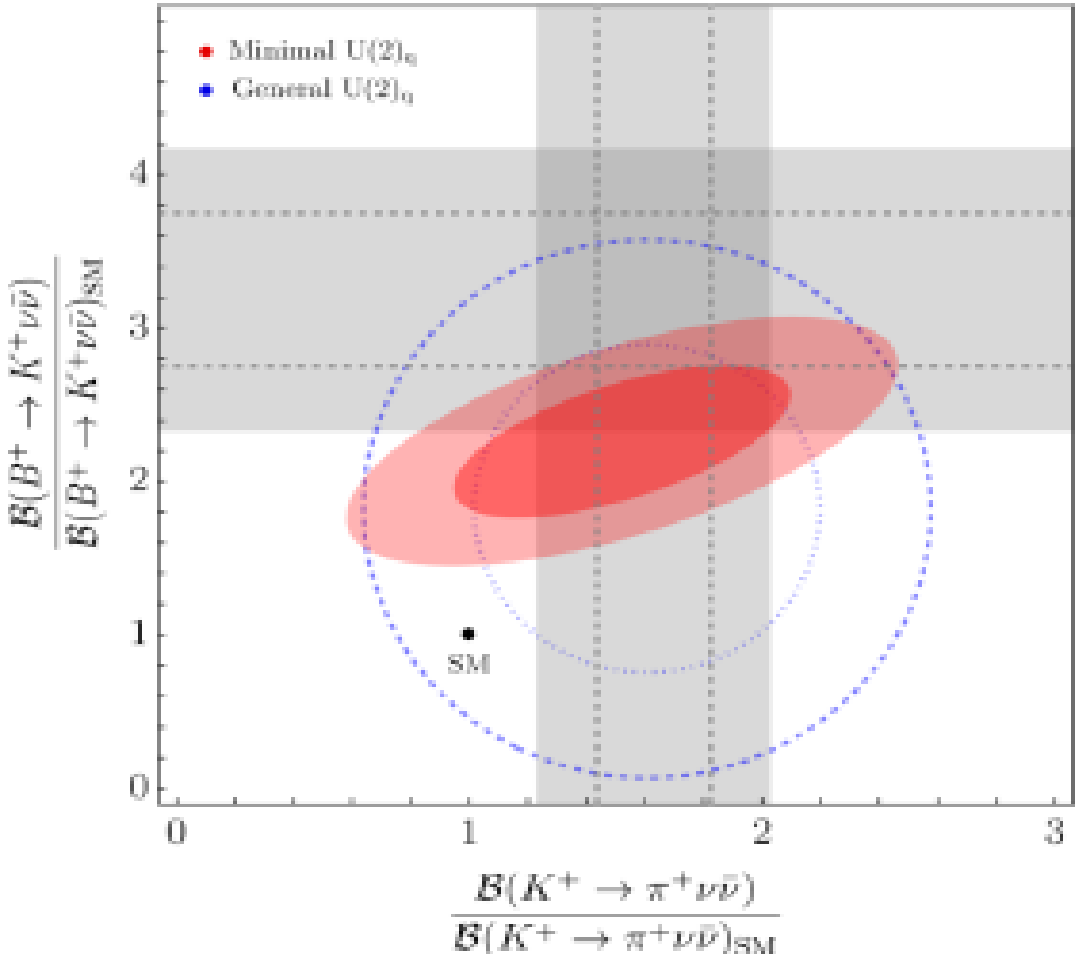
$$H_b = B^0, B_s^0, B_{(c)}^+, \Lambda_b^0$$

$$H_c = D^*, D^0, D^+, D_s^+, J/\psi, \Lambda$$

$\mathrm{Br}(B^+ \to K^+\bar{\nu}\nu) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$ 2.7σ above SM prediction Belle II 2311.14647

$\mathrm{Br}(K^+ \to \pi^+\bar{\nu}\nu) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$ 1.7σ above SM prediction NA62 2412.121015



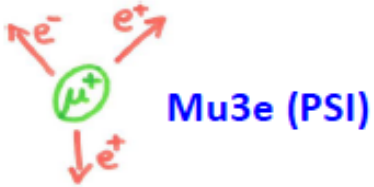


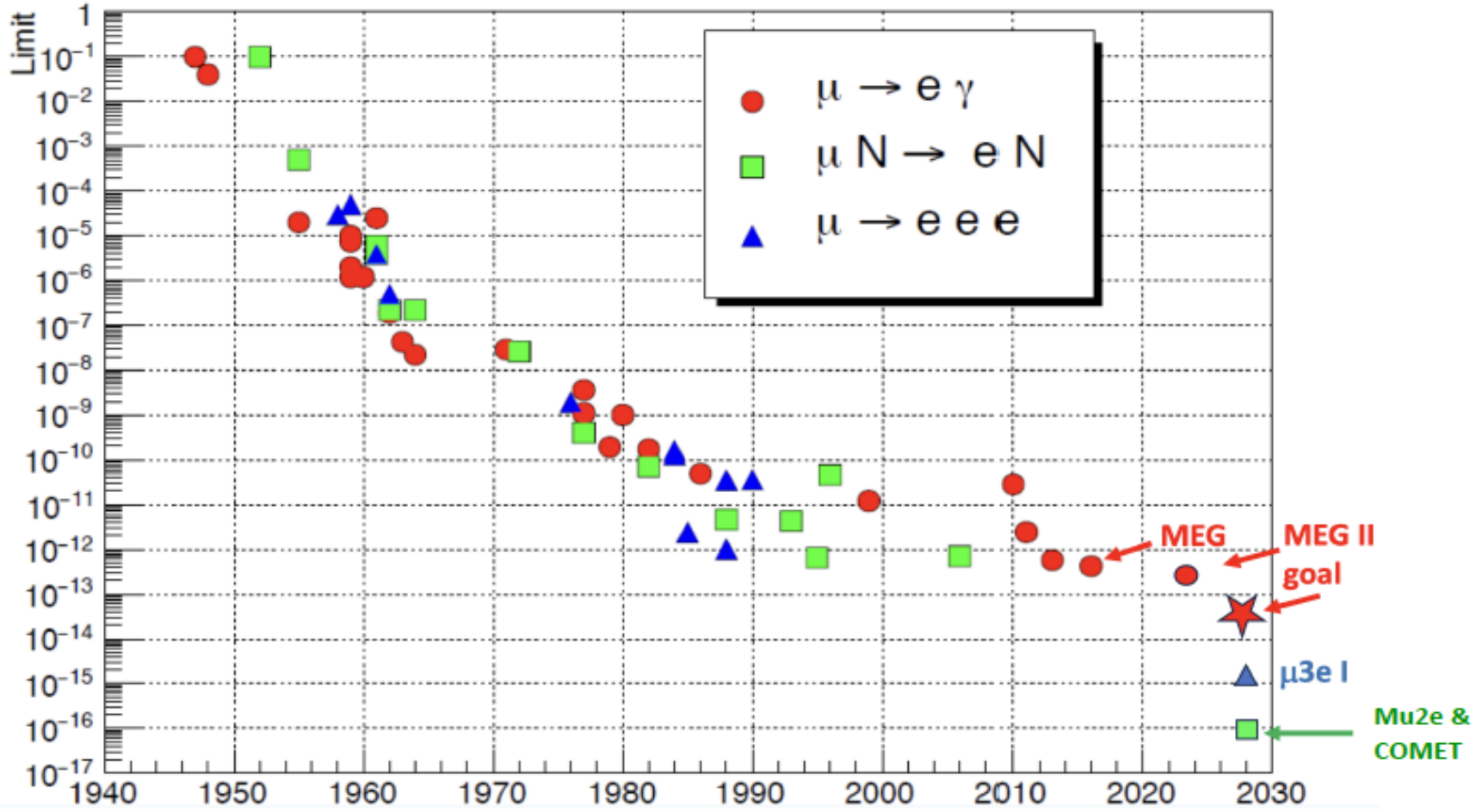
R.Bause, H.Gisbert, G.Hiller PRD 109 (2024) 1, 015006

L.Allwicher, M.Bordone, G.Isidori, G. Piazza, A. Stanzione, PLB 861 (2025) 139295

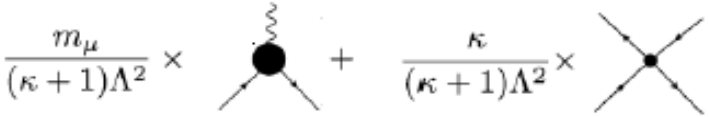
Prospects for cLFV searches

A. Papa, cLFV, ESPPU2026 Symposium

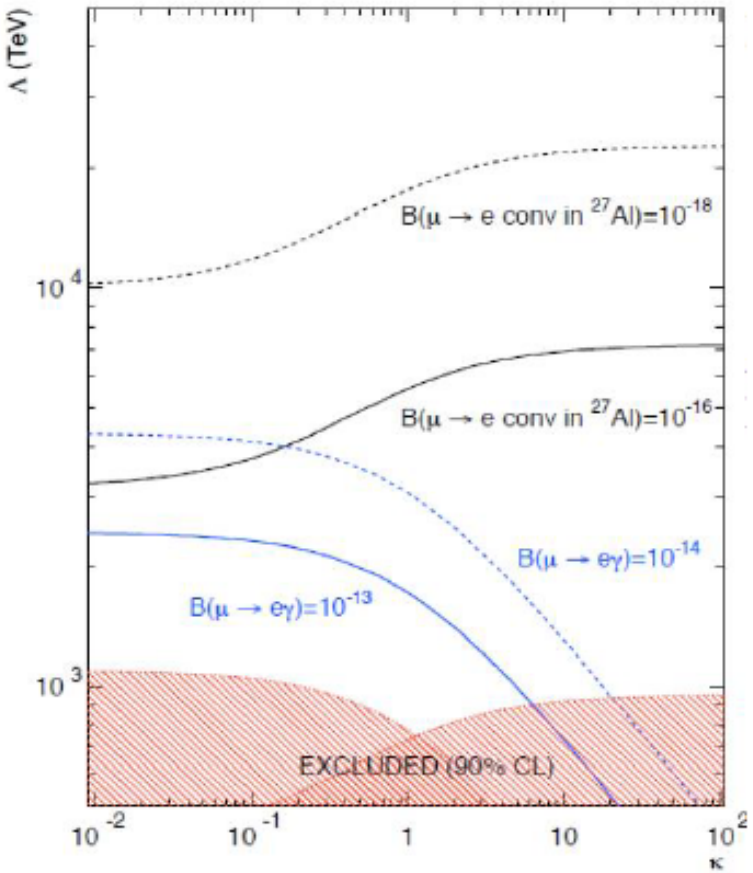




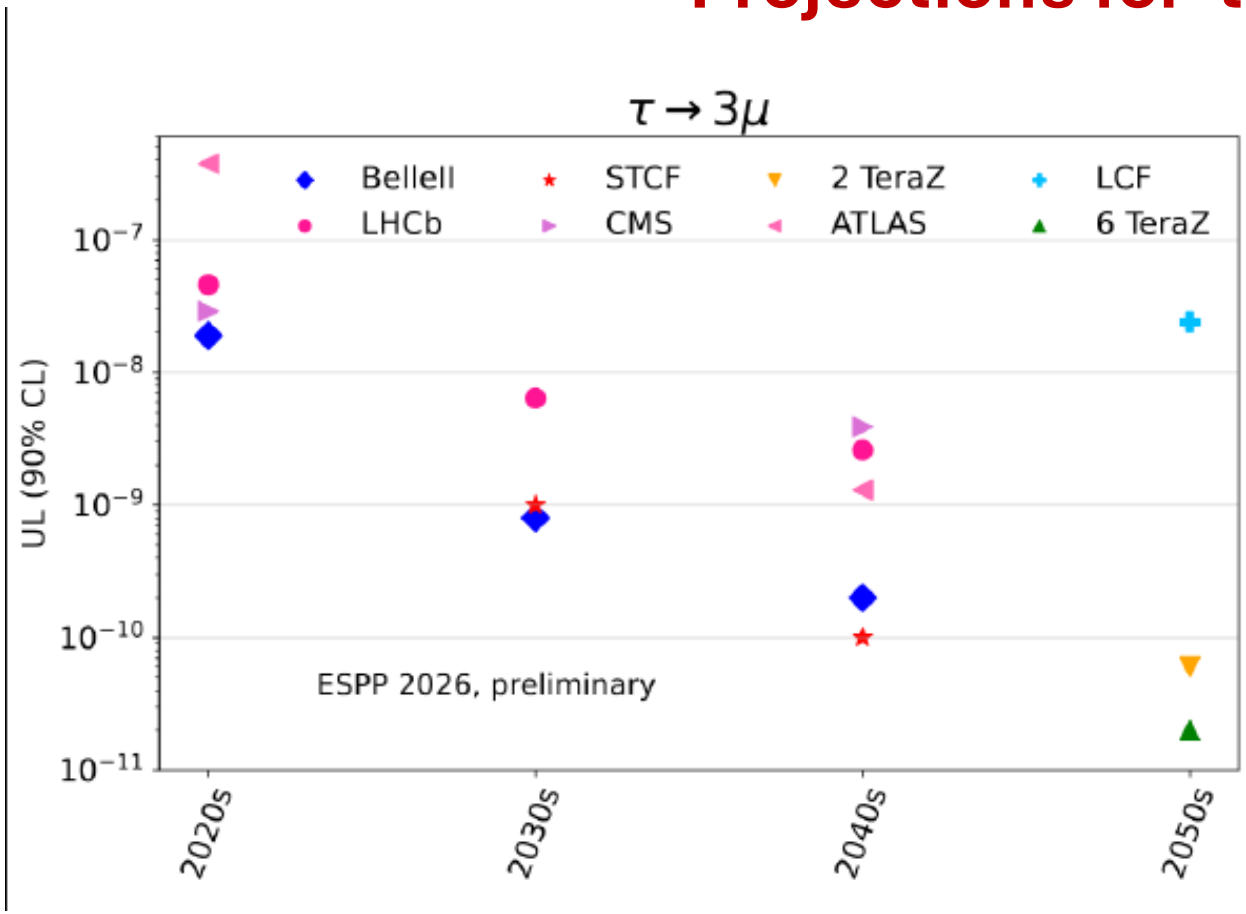
Complementarity of the 3 channels:
They probe different operators

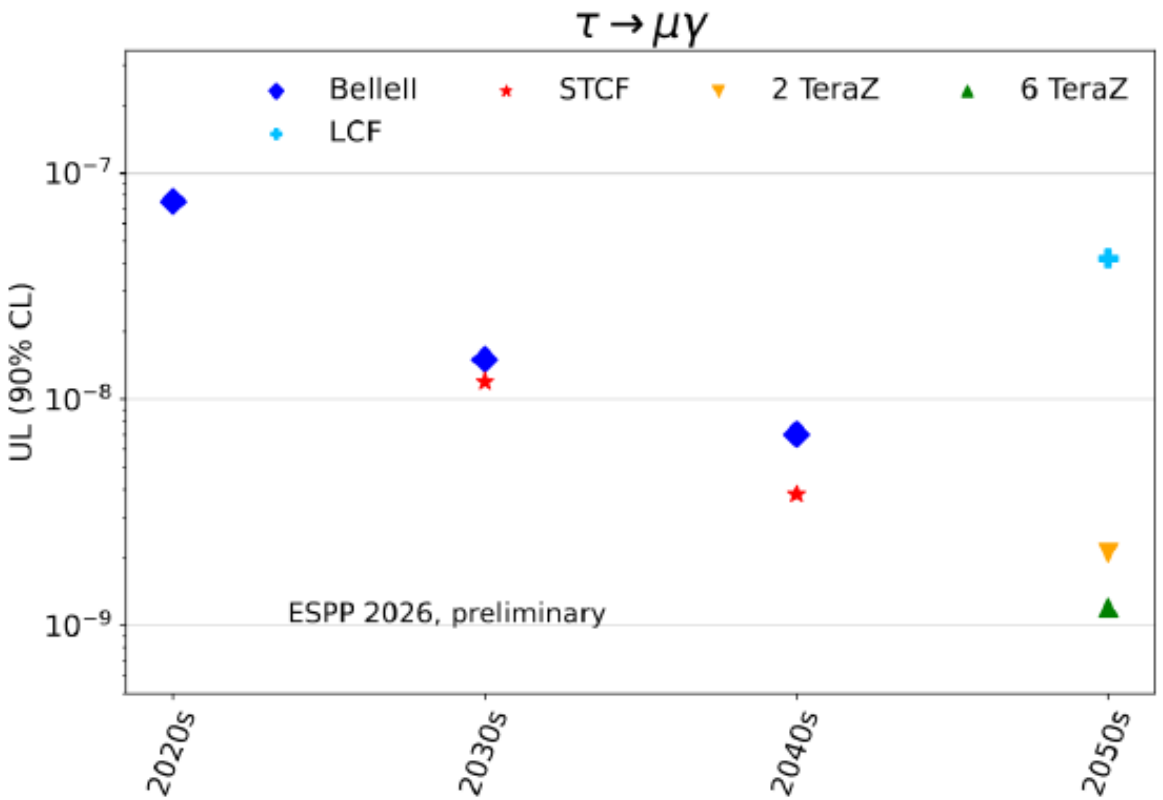


$\mu \to e\gamma$ $\mu \to eee$ $\mu N \to eN$



Projections for tau LFV decays





mode	Belle II 10 ab-1	LHCb 50 fb-1	Belle II 50 ab-1	LHCb 300 fb-1	ATLAS 3 ab-1	CMS 3 ab-1	6 TeraZ	2 TeraZ	STFC 1 (10)ab-1	LCF
BR(τ→ 3μ) x10^9	0.8	6.4	0.2-1.7	2.6	1.3-6.4	3.9	0.02	0.06	1 (0.1)	24
BR(τ→μγ) x10^9	15	-	7	-	-	-	1.2	2.1	12 (3.8)[1]	42

J. Serrano, M. Calvi
ESPPU2026 Symposium, Venice 2025

Relativistic generalization of EDMs and MDMs

Interaction of a fermion f with the photon field A_μ, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

T violation

$$-d_f \frac{\vec{S}}{|S|} \cdot \vec{E} \quad \rightarrow \quad d_f \frac{i}{2} (\bar{f} \sigma_{\mu\nu} \gamma_5 f) F^{\mu\nu}$$

Salpeter (1958)

P violation

$$-\mu_f \frac{\vec{S}}{|S|} \cdot \vec{B} \quad \rightarrow \quad e(\bar{f} \gamma_\mu f) A^\mu + a_f \frac{e}{4m_f} (\bar{f} \sigma_{\mu\nu} f) F^{\mu\nu}$$

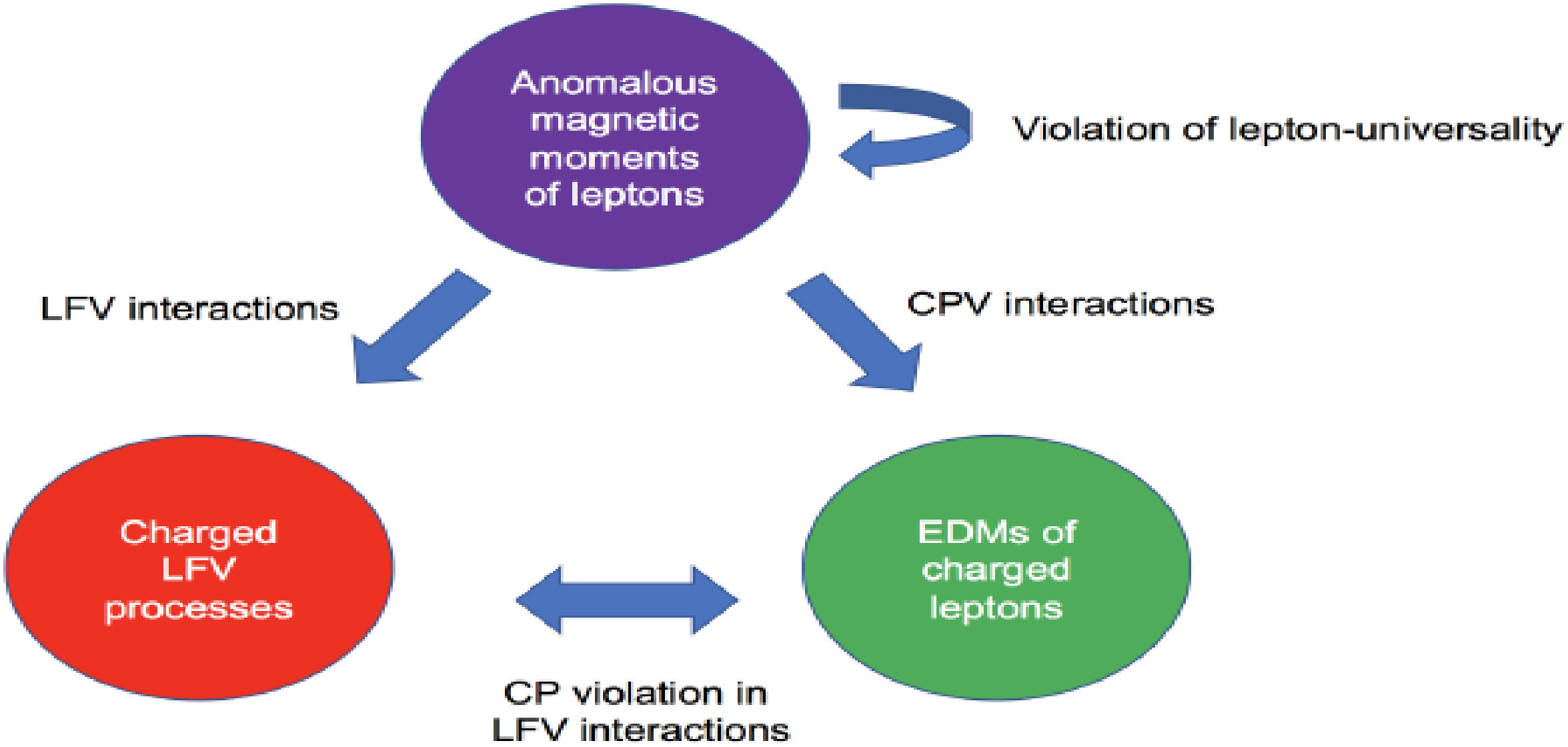
the usual minimal coupling of fermions with the photon give rise to a magnetic moment with gyromagnetic factor $g = 2$

the dimension 5 operators induce an electric dipole moment d_f and an anomalous magnetic moment a_f

$$\mu_f = g_f \frac{e}{2m_f} \quad , \qquad (g_f - 2) = 2a_f$$

d_f and a_f are described by non-renormalizable interactions of fermions with the photon. They are absent for elementary fermions at the classical level, but can be induced by loop corrections.

Probing NP in the leptonic sector



LFV, $(g-2)_{lept}$ and $(EDM)_{lept}$ correlations in Effective Theories

Giudice, Paradisi and Passera JHEP 2012

- $\mathrm{BR}(\ell_i \to \ell_j \gamma)$ vs. $(g-2)_\mu$

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

$$\mathrm{BR}(\tau \to \mu\gamma) \approx 4 \times 10^{-8} \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{\mu\tau}}{10^{-2}}\right)^2$$

- EDMs vs. $(g-2)_\mu$

$$d_e \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 10^{-29} \left(\frac{\phi_e^{CPV}}{10^{-5}}\right) \; e\,\mathrm{cm}\,,$$

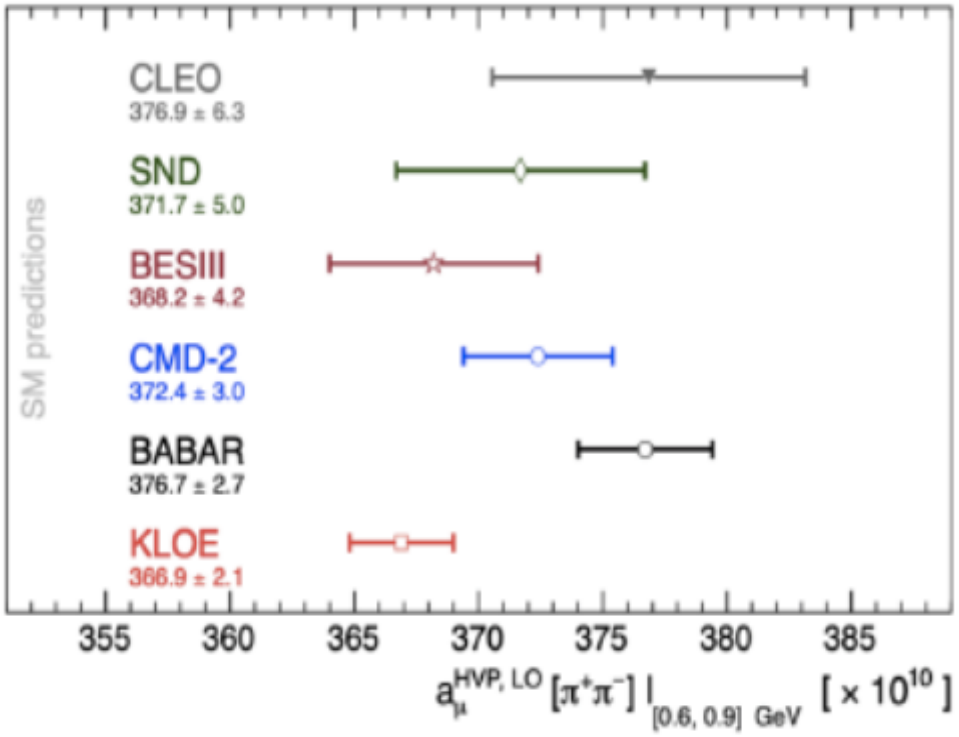
$$d_\mu \simeq \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 2 \times 10^{-22}\, \phi_\mu^{CPV} \; e\,\mathrm{cm}\,,$$

- Main messages:
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ requires a nearly flavor and CP conserving NP
  - Large effects in the muon EDM $d_\mu \sim 10^{-22}\, e\,\mathrm{cm}$ are still allowed!

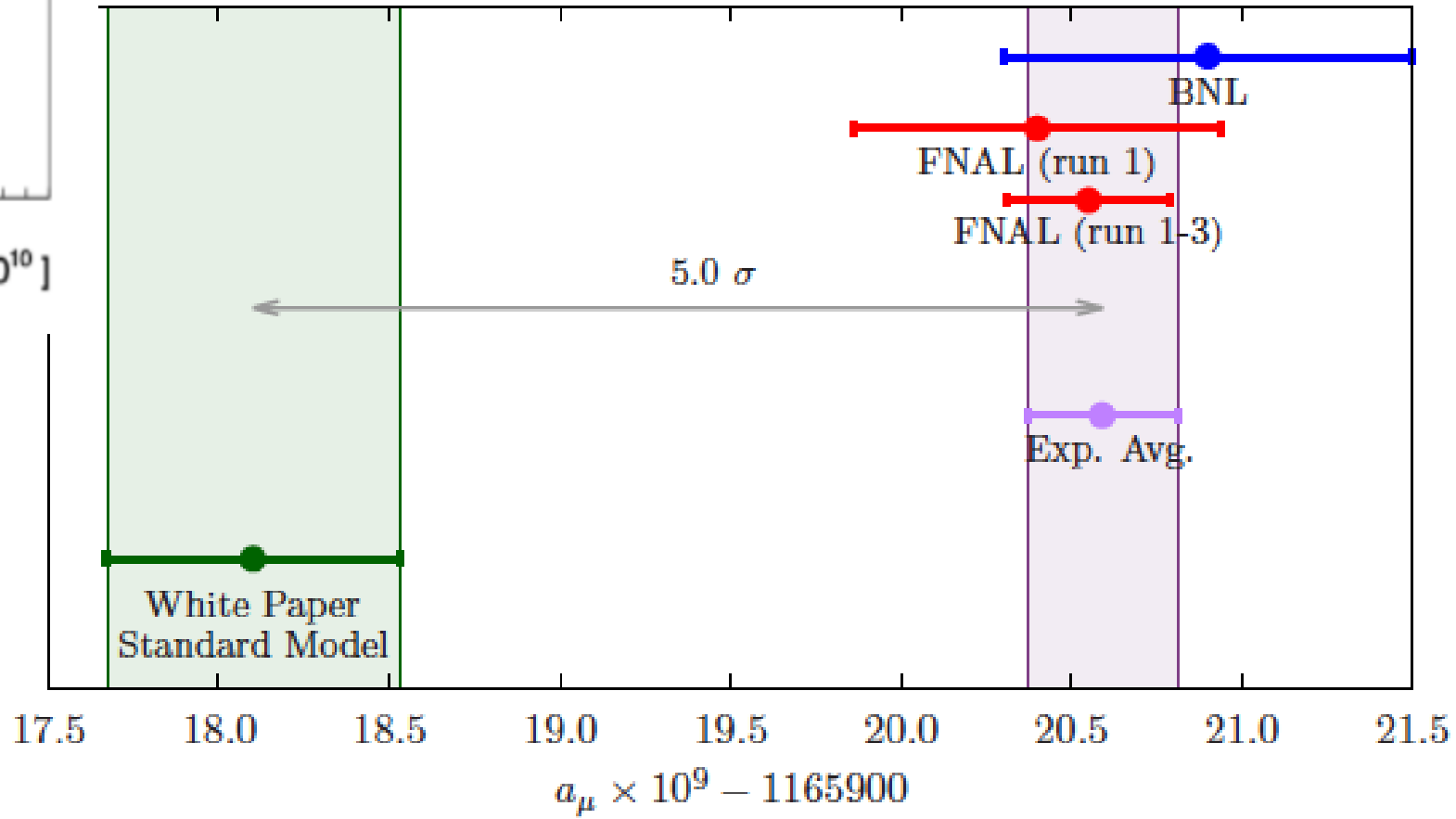
Paradisi, muEDM Workshop Pisa, 2022

$$\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} \quad \Longleftrightarrow \quad \Delta a_e = \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right) 0.7 \times 10^{-13}$$

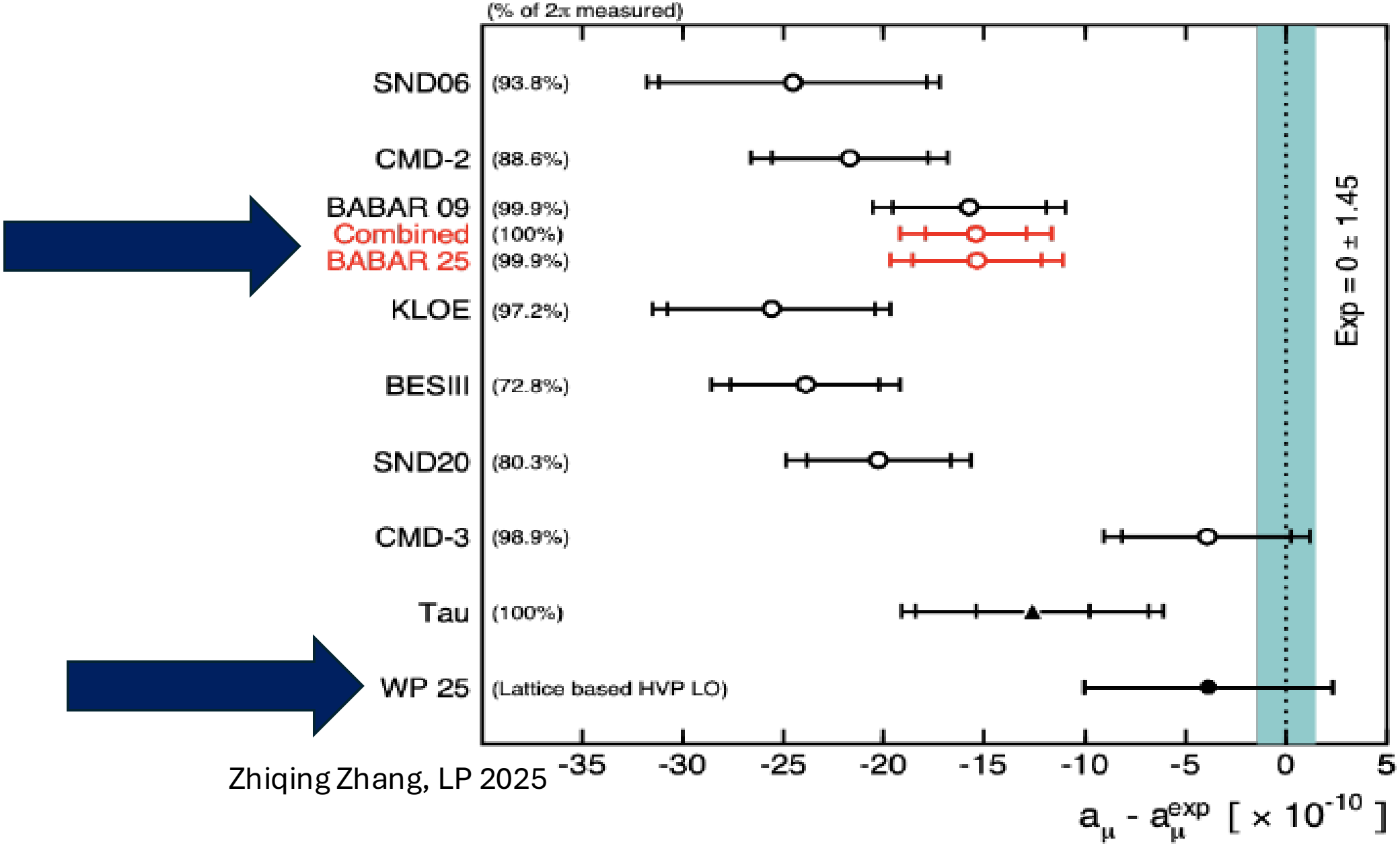
[WP20, 2006.04822]



The "old" (2020) muon g-2 problem



The "NEW" (2025) muon g-2 problem



Zhiqing Zhang, LP 2025

Model independent tests of the HVP contribution to the muon g-2

$$(a_\mu^{\rm HVP})_{e^+e^-} = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} {\rm d}s\, K_\mu(s)\,\sigma_{\rm had}(s) \qquad K_\mu(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2}$$

at large energy, $s>m_l \rightarrow K_l \sim m_l^2$

The KNT19 data replaced by the CDM3 data only in its available energy range

compilation by the KNT coll. in 2019 without the CMD-3 data

$$\delta a_\mu^{\rm CMD3} \equiv (a_\mu^{\rm HVP})_{e^+e^-}^{\rm CMD3} - (a_\mu^{\rm HVP})_{e^+e^-}^{\rm KNT19} = (21.7 \pm 3.6)\times 10^{-10}$$

6.1σ tension

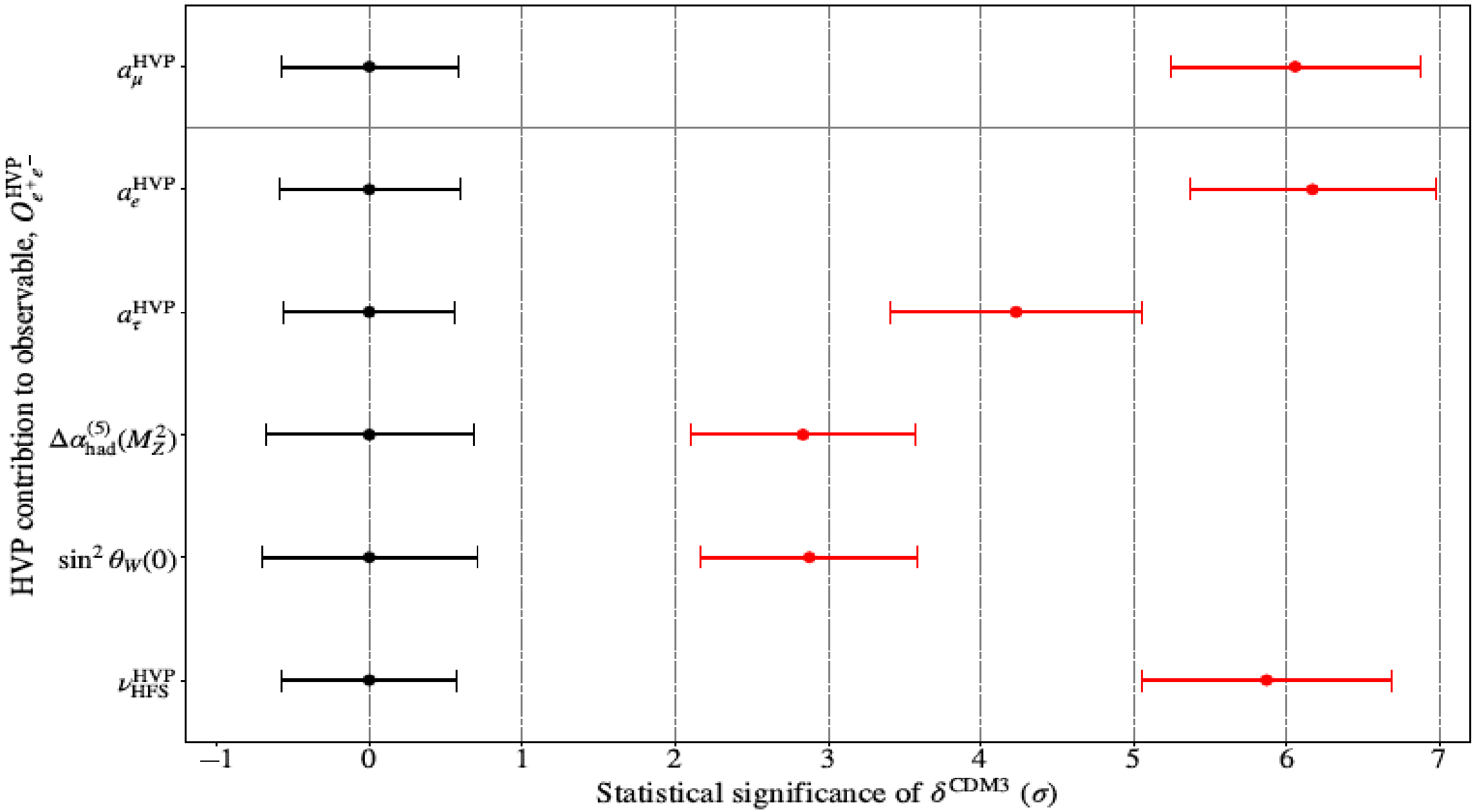
$$\delta O^{\rm CMD3} \equiv (O_{e^+e^-}^{\rm HVP})^{\rm CMD3} - (O_{e^+e^-}^{\rm HVP})^{\rm KNT19}$$

Di Luzio, Keshavarzi, A.M. , Paradisi PRL 134 (2025) 1

Observables to consider

- **the Electron g-2 (a_e)**
- **the Muonium HyperFine Splitting (HFS)**
- **the Tau g-2 (a_τ)**
- **the low-energy weak mixing angle $\sin^2\theta_W(0)$**
- **the running of α_{em}**

Model independent tests of the HVP contribution to the muon g-2



Di Luzio, Keshavarzi, A.M. , Paradisi PRL 134 (2025) 1

$O^{\rm HVP}_{e^+e^-}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, $\delta O^{\rm CMD3}$	Significance (σ)
$a_\mu^{\rm HVP} \times 10^{10}$	692.8 ± 2.4	714.5 ± 3.4	0.280	21.7 ± 3.6	6.1
$a_e^{\rm HVP} \times 10^{14}$	186.1 ± 0.7	192.0 ± 0.0	0.257	6.0 ± 1.0	6.2
$a_\tau^{\rm HVP} \times 10^{8}$	332.8 ± 1.4	340.2 ± 2.1	0.546	7.4 ± 1.8	4.2
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) \times 10^4$	276.1 ± 1.1	277.5 ± 1.2	0.908	1.4 ± 0.5	2.8
$\sin^2\theta_W(0) \times 10^4$	2386.0 ± 1.4	2386.4 ± 1.5	0.996	0.4 ± 0.1	2.9
$\nu^{\rm HVP}_{\rm HFS}$ (Hz)	540.5 ± 1.9	557.0 ± 2.7	0.297	16.5 ± 2.8	5.9

Muonium HFS one of the most sensitive probes of $\delta a_\mu^{\rm CMD3}$ → to be sensitive to this shift **needs a precision of O(1) Hz**

Current measurement $\nu_{\rm HFS}^{\rm exp} = (4\,463\,302\,776 \pm 51)\ Hz$

MuSEUM at J-PARC plans to reduce the uncertainties by ~ one order of magnitude, hence going well below the shift (Strasser et al. Hyperfine Interact. 2016)

Other sources of uncertainty:

i) uncertainty on ν_F fully dominated by **m_e / m_μ** → induced error on ν_F ~ **4×10^3 Hz**

Mu-MASS at PSI to improve the precision on the measurement of ν_{1S-2S} (from which m_e / m_μ is extracted) by **3 orders of magnitude** (P. Crivelli Hyperfine Interact. 2018);

ii) **Theory uncertainty** in $\nu_{\rm HFS}$ from unknown **3-loop QED** contributions to $\delta_{\rm HFS}^{\rm QED}$ amounting to **~ 70 Hz** → **need for a complete 3-loop QED calculation** (Eides and Shelyuto Int. J. Mod. Phys A 2016; Eides PLB 2019)

Electron g-2

relating $a_\mu^{\rm HVP}$ and $a_e^{\rm HVP}$ → $\delta a_e^{\rm CMD3} \approx \delta a_\mu^{\rm CMD3} \left(\frac{m_e}{m_\mu}\right)^2 \approx (5 \pm 1) \times 10^{-14}$

in good agreement with the numerical results

$O^{\rm HVP}_{e^+e^-}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, $\delta O^{\rm CMD3}$	Significance (σ)
$a_\mu^{\rm HVP} \times 10^{10}$	692.8 ± 2.4	714.5 ± 3.4	0.280	21.7 ± 3.6	6.1
$a_e^{\rm HVP} \times 10^{14}$	186.1 ± 0.7	192.0 ± 0.0	0.257	6.0 ± 1.0	6.2

Δa_e error source	Value	% of Δa_e error
Five-loop QED, $\delta a_e^{\rm QED5}$	6×10^{-14}	5% (Cs)/13% (Rb)
Hadronic, $\delta a_e^{\rm HAD}$	1×10^{-14}	$< 1\%$
α(Cs), $\delta a_e^{\alpha({\rm Cs})}$	22×10^{-14}	70%
α(Rb), $\delta a_e^{\alpha({\rm Rb})}$	9×10^{-14}	28%
Experiment, $\delta a_e^{\rm exp}$	13×10^{-14}	24% (Cs)/59% (Rb)

If the **experimental resolution on α_{em} and a_e^{exp} improve by ~ one order of magnitude** → uncertainties on **Δa_e ~ O(10^{-14})** → sensitivity to the increase of a_μ^{HVP} due to CMD-3 (and BMWc)

Why EDMs are a good probe of BSM physics

- EDMs → **AMPLITUDE-level** observables → enhanced sensitivity to BSM physics w.r.t. **CROSS-SECTIONS**

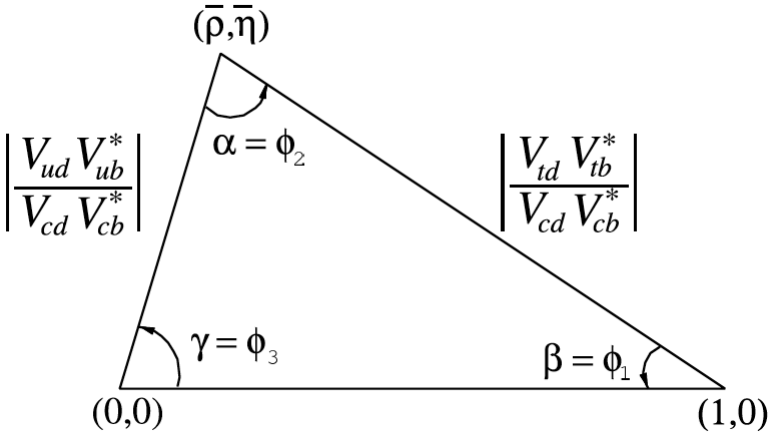
- EDM searches → **absence** of a significant **SM (CKM) background** (like, e.g., in the case of proton-decay searches or cLFV processes)

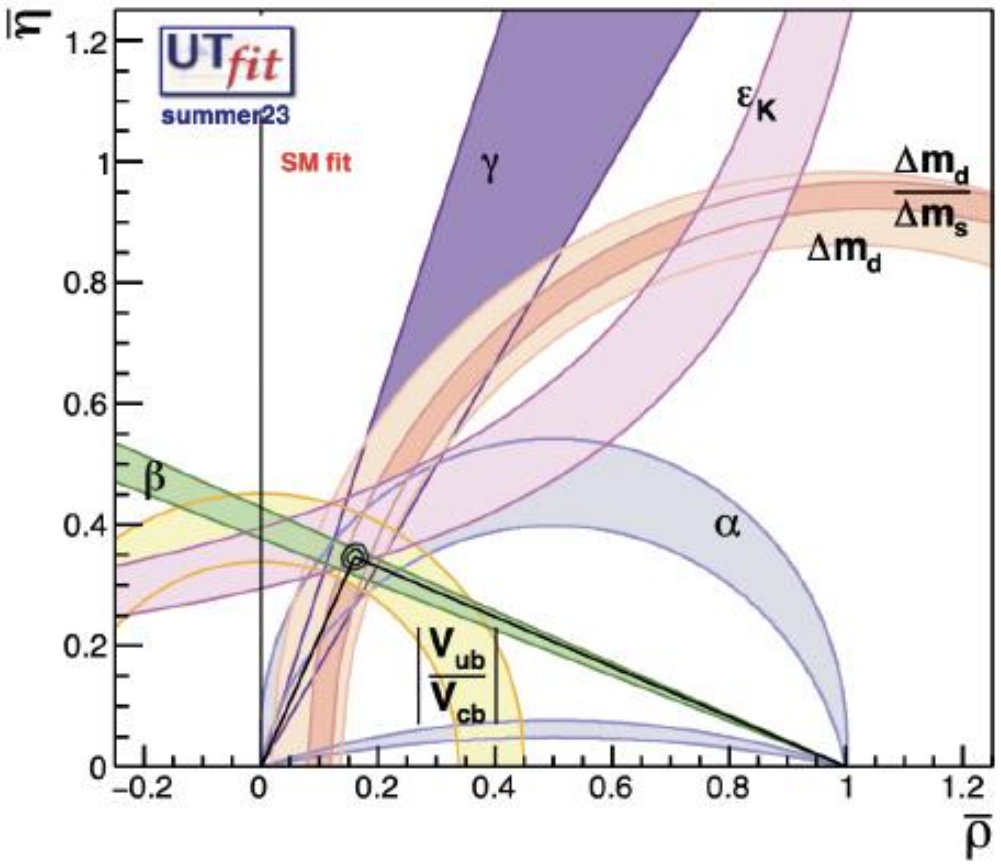
- EDM searches in **atomic and molecular systems** → **enhanced sensitivity through macroscopic effects magnifying the internal electric field and possibility of an extended coherence time** → **NONLINEAR response** of such systems to external parameters such as the electric field

M. Pospelov and A. Ritz, EDMs and New Physics, arXiv:2509.2353

CP Violation in the SM : 1. the CKM phase

$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$





CP violation observed in K and B physics.
parametrized by the

Jarlskog invariant $J = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta$

$$\mathrm{Im}\left[V_{ij}V_{kl}V_{i\ell}^*V_{kj}^*\right] = J\sum_{mn}\epsilon_{ikm}\epsilon_{j\ell n}$$

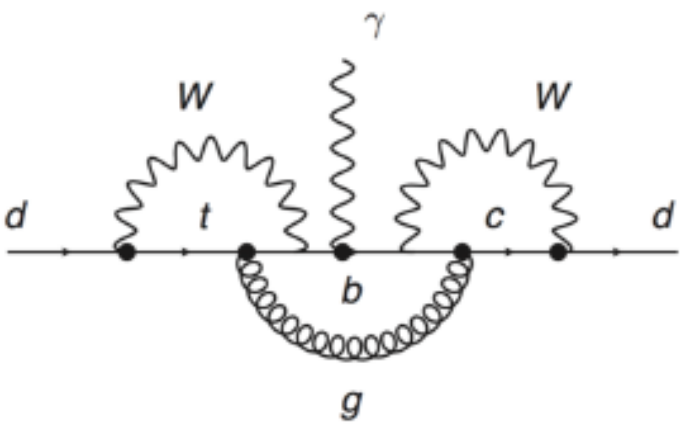
$= (3.08^{+0.15}_{-0.13}) \times 10^{-5}$ ➡ **O(5%) accuracy**

CKM induced EDMs in the SM

- quark EDM (for nucleon EDM see later)

$$d_d^{(\mathrm{est})}(\mathcal{J}) \sim e\mathcal{J}\frac{\alpha_s\alpha_W^2}{(4\pi)^3}\frac{m_d}{m_W^2}\frac{m_c^2}{m_W^2} < 10^{-34}\mathrm{ecm}.$$

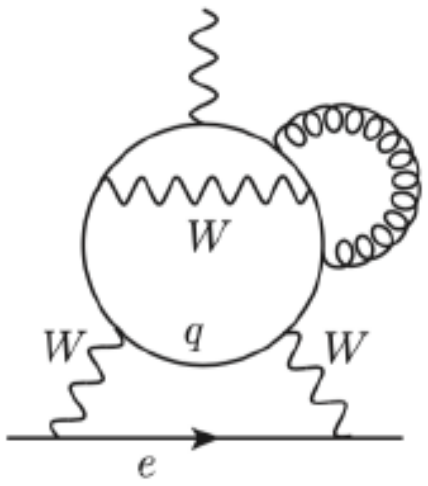
[Khriplovich, Phys. Lett. B 173, 193 (1986)
Czarnecki, Krause, Phys. Rev. Lett. 78 (1997)]



- electron EDM (for paramagnetic EDM see later)

$$d_e(\mathcal{J}) \sim e\mathcal{J}\frac{m_e m_c^2 m_s^2}{m_W^6}\frac{\alpha_W^3\alpha_s}{(4\pi)^4} \sim O(10^{-44})\ \mathrm{ecm}$$

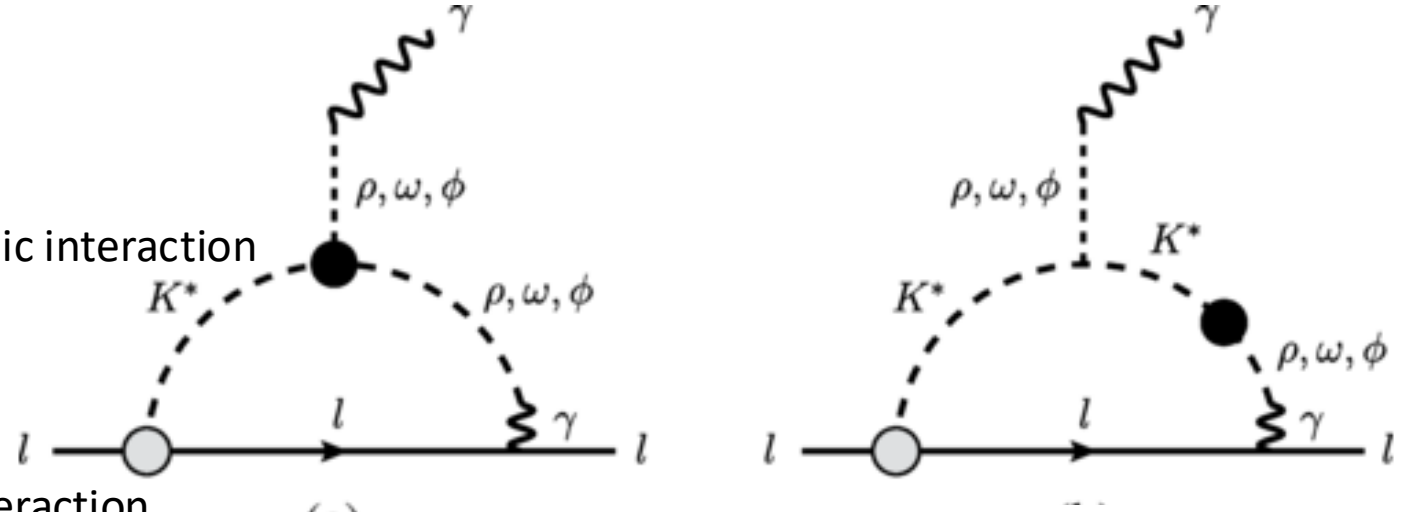
[Pospelov, Khriplovich, Sov. J. Nucl. Phys. 53 (1991),
Pospelov, Ritz, Phys. Rev. D89 no. 5 (2014)]



SM LONG-DISTANCE contribution to the CHARGED LEPTON EDMs

ΔS = 1 hadronic interaction

ΔS = 1 semileptonic interaction

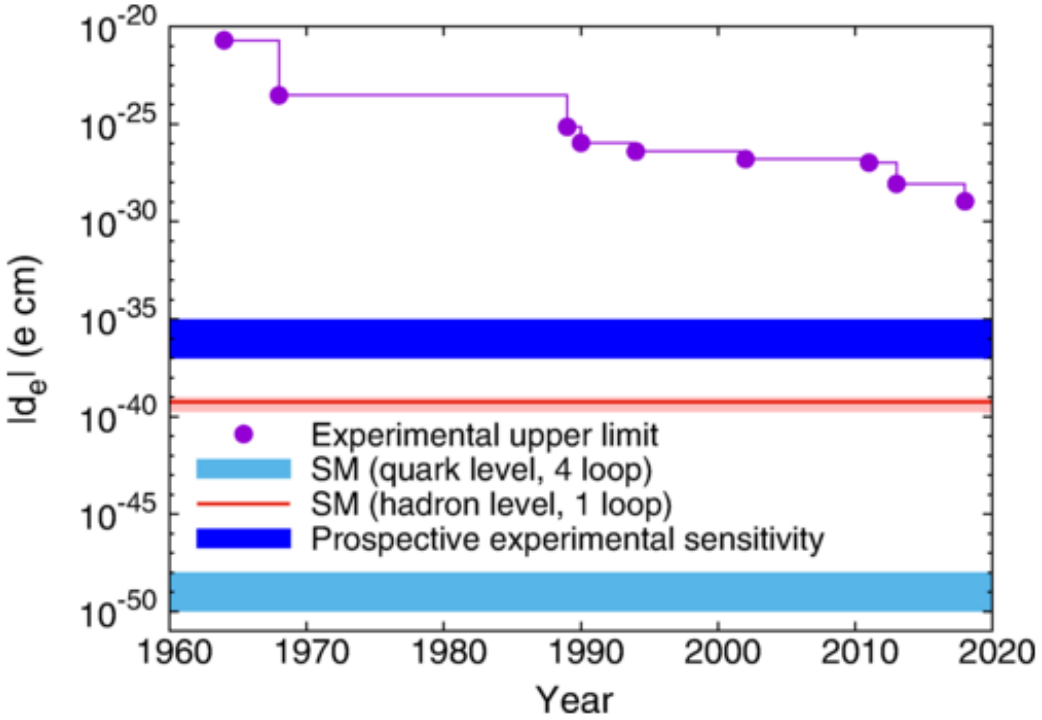


(a)

$$d_e^{(\mathrm{SM})} = 5.8 \times 10^{-40}\ e\ \mathrm{cm},$$

$$d_\mu^{(\mathrm{SM})} = 1.4 \times 10^{-38}\ e\ \mathrm{cm},$$

$$d_\tau^{(\mathrm{SM})} = -7.3 \times 10^{-38}\ e\ \mathrm{cm}.$$



Yamaguchi and Yamanaka, Phys. Rev. Lett. 125, 241802 (2020)

PARAMAGNETIC EDMs

- Paramagnetic atoms and molecules (e.g. ThO) have **UNPAIRED electrons** → sensitive to the **electron EDM** and to the **electron-nucleus scalar and pseudo-scalar interaction**

Semi-leptonic CP-odd operators

$$\mathcal{L}_{CP} = -\frac{i}{2} d_e \bar{e} F \sigma \gamma_5 e - \frac{G_F}{\sqrt{2}} C_{SP} \bar{N} N \bar{e} i \gamma_5 e$$

Coherently enhanced by the number of nucleons

- shift of atomic/molecular energy levels (under external E field)

$$\frac{\Delta E}{\mathcal{E}_{\text{ext}}} = f_d (d_e + r C_{SP})$$

- $f_d \simeq \frac{10\, Z^3 \alpha_{\text{em}}}{J(J+1/2)(J+1)^2} \sim O(10^{2\div3})$ enhancement factor due to relativistic violation of Schiff th.

- r : ratio of atomic matrix elements of C_{SP} and d_e operators ($r_{\text{ThO}} = 1.33 \times 10^{-20}\,\text{ecm}$)

- Equivalent EDM : $d_e^{\text{equiv}} \equiv r C_{SP}$

CKM-induced C_{SP} contribution dominates w.r.t. the direct contribution d_e

$$d_e^{\rm equiv}(\mathcal{J}) \sim 10^{-38} e\,{\rm cm}$$

[Pospelov, Ritz, Phys. Rev. D89 no. 5 (2014)]

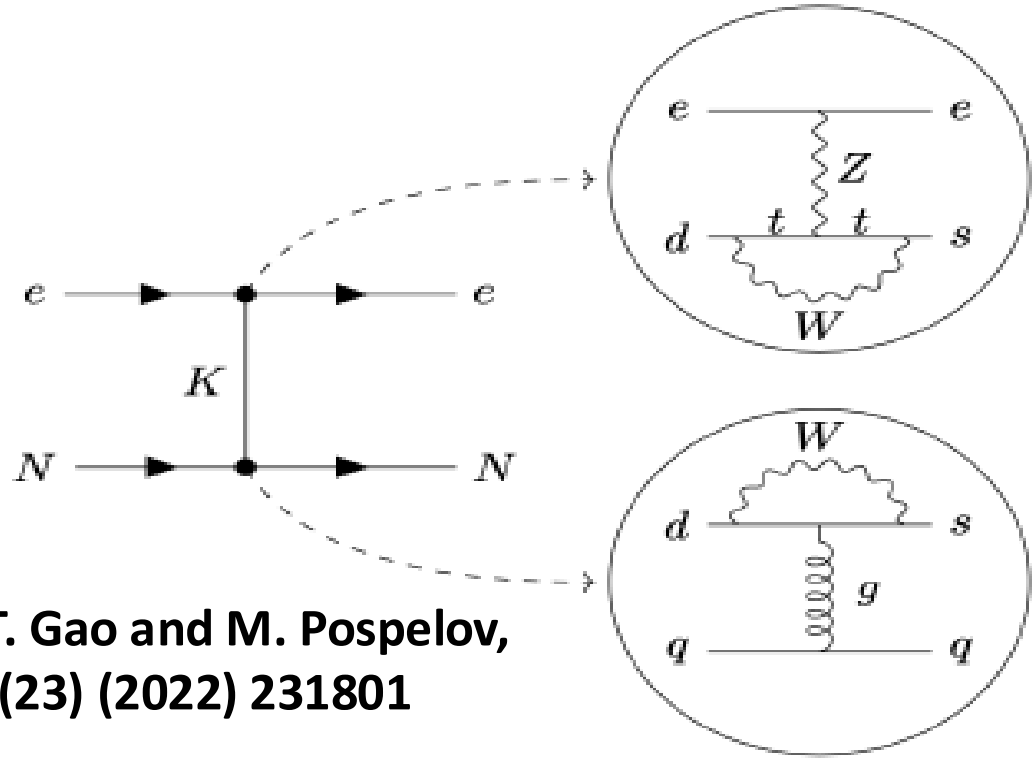
to be compared with $d_e \sim 6 \times 10^{-40}\, e\, cm$

[Yamaguchi, Yamanaka, Phys. Rev. Lett. 125 (2020)]

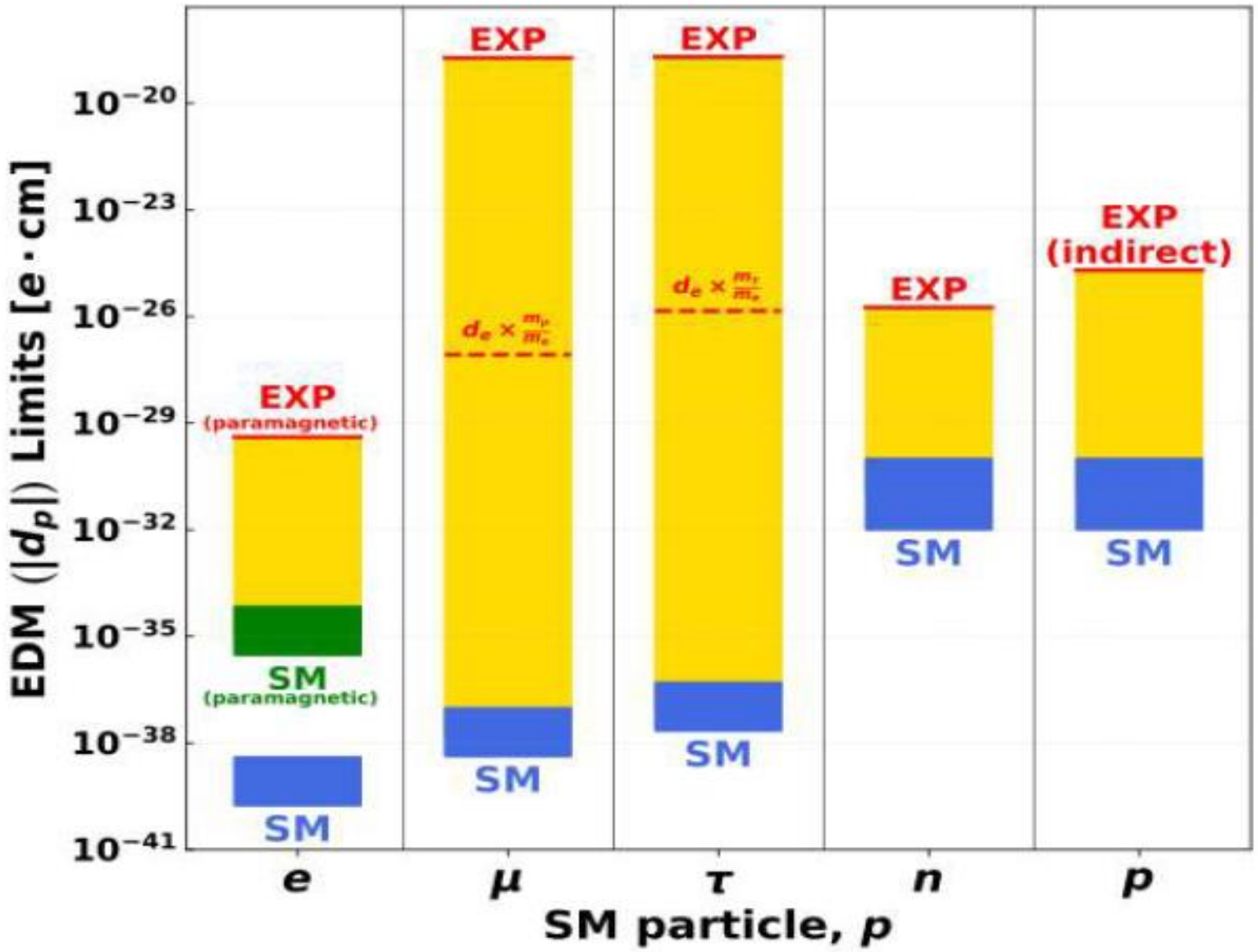
In 2022 Ema, Gao and Pospelov showed that $d_e^{\rm equiv}$ is enhaced by

~ 3 orders of magnitude (!)

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



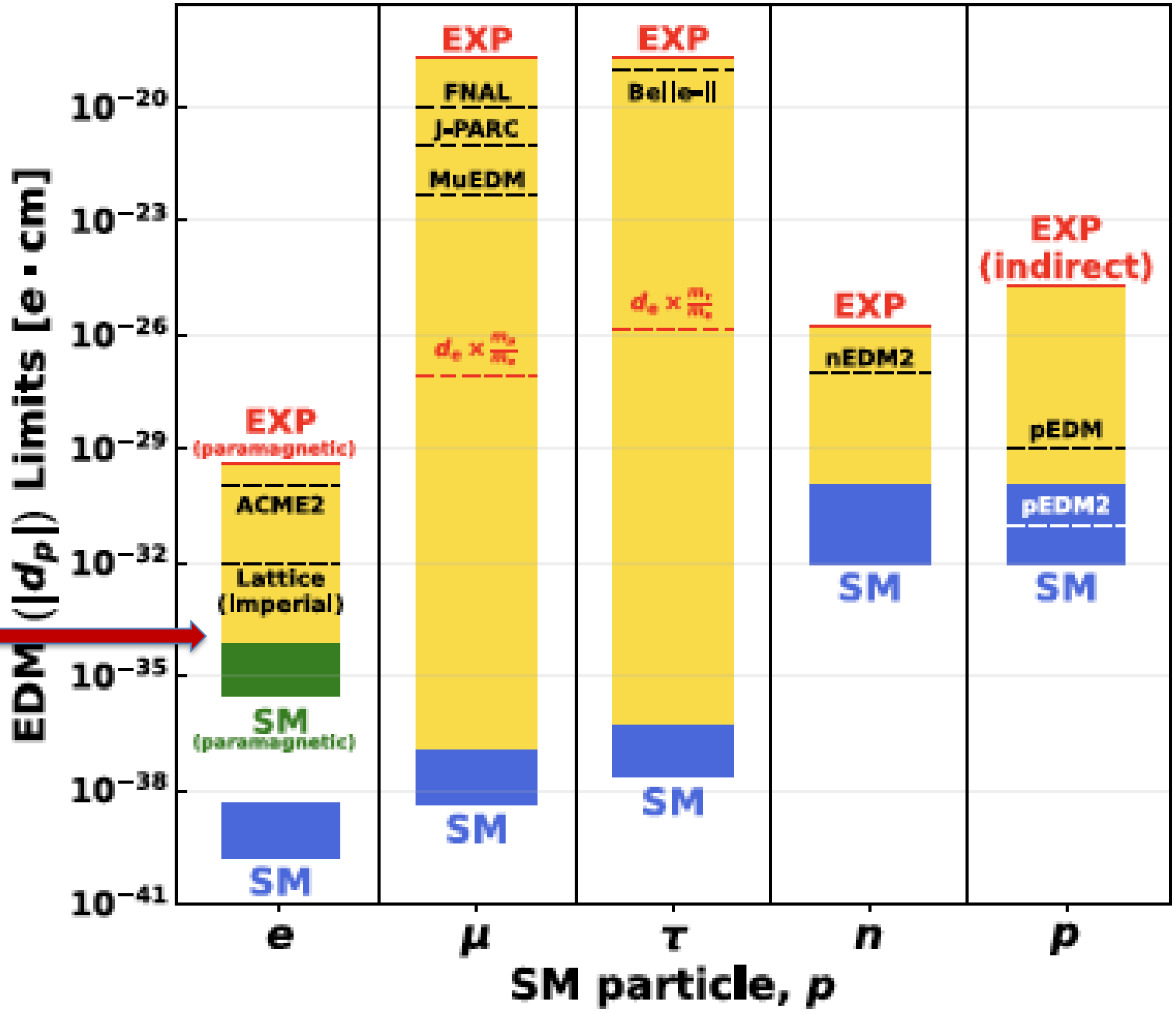
Y.Ema, T. Gao and M. Pospelov, PRL 129(23) (2022) 231801

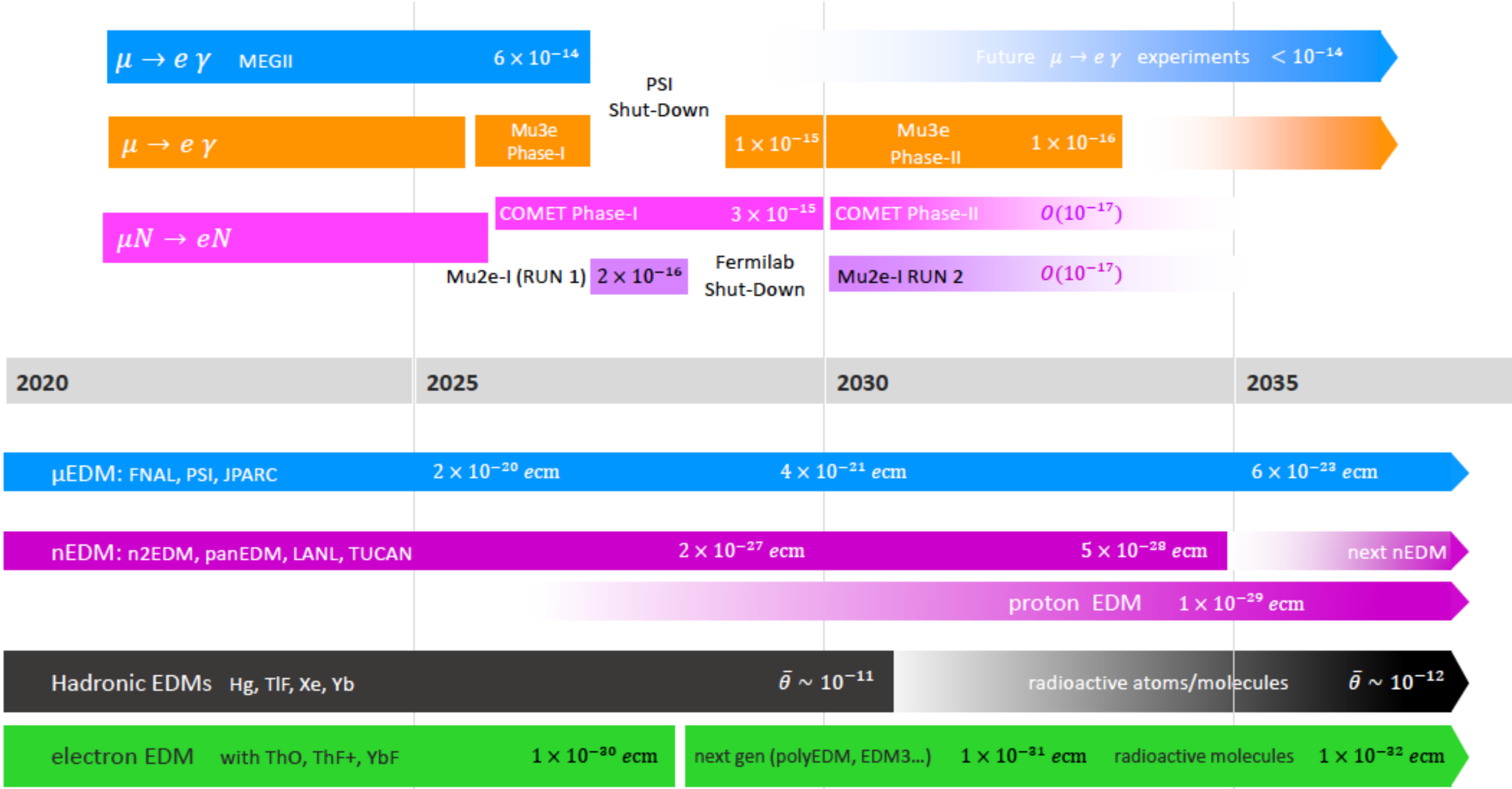


Fundamental Physics in Small Experiments, Communiyy Planning Exercise : Snowmass 2021, contribution to the 2023 P5 Report, Blum and Winter, 2209.08041

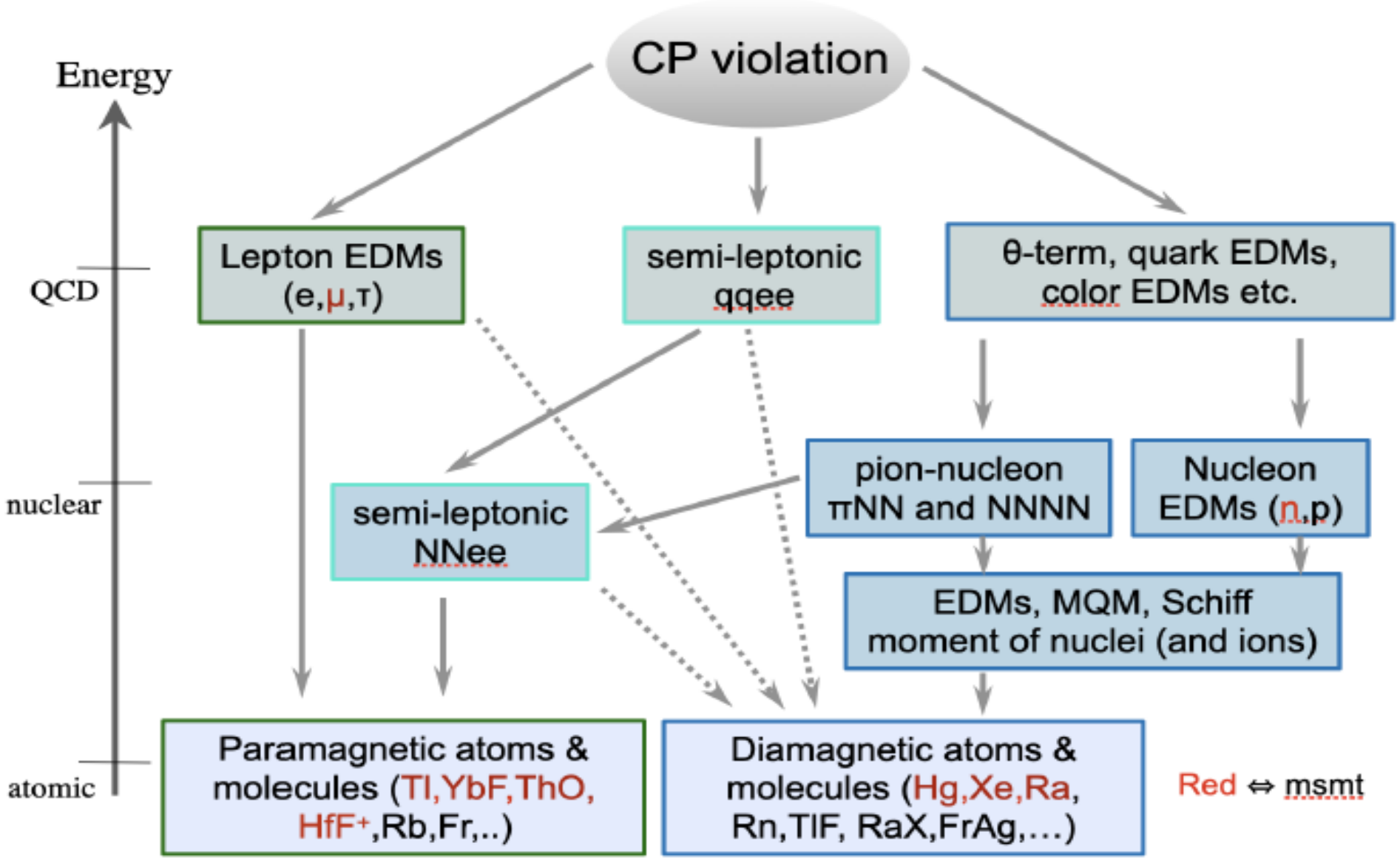
[Courtesy of A. Keshavarzi]

Sensitivity to CP violating NEW PHYSICS




$\mu \to e\,\gamma$ MEGII
6×10^{-14}
Future $\mu \to e\,\gamma$ experiments $< 10^{-14}$
PSI Shut-Down
$\mu \to e\,\gamma$
Mu3e Phase-I
1×10^{-15}
Mu3e Phase-II
1×10^{-16}
COMET Phase-I
3×10^{-15}
COMET Phase-II
$O(10^{-17})$
$\mu N \to eN$
Mu2e-I (RUN 1)
2×10^{-16}
Fermilab Shut-Down
Mu2e-I RUN 2
$O(10^{-17})$
2020
2025
2030
2035
μEDM: FNAL, PSI, JPARC
2×10^{-20} ecm
4×10^{-21} ecm
6×10^{-23} ecm
nEDM: n2EDM, panEDM, LANL, TUCAN
2×10^{-27} ecm
5×10^{-28} ecm
next nEDM
proton EDM
1×10^{-29} ecm
Hadronic EDMs Hg, TlF, Xe, Yb
$\bar{\theta} \sim 10^{-11}$
radioactive atoms/molecules
$\bar{\theta} \sim 10^{-12}$
electron EDM with ThO, ThF+, YbF
1×10^{-30} ecm
next gen (polyEDM, EDM3...)
1×10^{-31} ecm
radioactive molecules
1×10^{-32} ecm

Hierarchy of effective field theory operators linking CP-violating sources to observable EDMS



M. Pospelov and A. Ritz, arXiv:2509.23531

CP violating operators

- CP-odd Lagrangian at the GeV scale

$\frac{g_s^2}{32\pi^2}\bar{\theta} G^A_{\mu\nu}\tilde{G}^{\mu\nu,\,A}$	QCD theta term
$d_f \frac{i}{2}(\bar{f}\sigma_{\mu\nu}\gamma_5 f)F^{\mu\nu}$	EDMs of quarks and leptons
$d_q^c \frac{ig_s}{2}(\bar{q}_\alpha \sigma^{\mu\nu} T^A_{\alpha\beta}\gamma_5 q_\beta)G^A_{\mu\nu}$	chromo EDMs (CEDMs) of quarks
$\frac{w}{3} f^{ABC} G^A_{\mu\nu}\tilde{G}^{\nu\rho,\,B} G^{\mu,\,C}_{\rho}$	Weinberg three gluon operator
$C_{ij}(\bar{f}_i f_i)(\bar{f}_j i\gamma_5 f_j)$	CP violating 4 fermion operators

- terms at dimension 4, dimension 5, dimension 6

EDMs through non-CKM SOURCES OF CPV

STRONG CPV (theta term)

$$\delta\mathcal{L}_{\rm QCD} = \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$$

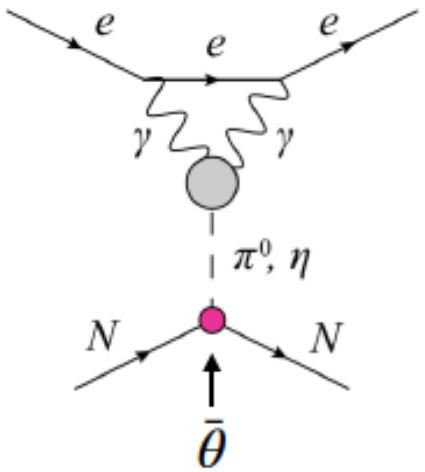
$$\bar{\theta} = \theta - \arg\det Y_U Y_D$$

$$|\bar{\theta}| \lesssim 10^{-10}$$

(bound from nEDM)

Bound on theta term from paramagnetic EDMs:

$$d_e^{\rm equiv} \sim 4 \times 10^{-22} \bar{\theta} \longrightarrow |\bar{\theta}|_{\rm ThO} \lesssim 3 \times 10^{-8}$$



[Flambaum, Pospelov, Ritz, Stadnik, Phys. Rev. D 102 (2020)]

Theta term in the SM

- In the SM, theta is a **FREE parameter**: even if one (**arbitrarily**) sets theta = 0 (when the theory is renormalized at some "relaxation" scale μ_0), since theta is the coefficient of a dim = 4 operator, the **renormalization of theta is expected to be infinite.**
- Indeed, an infinite renormalization (though, only log divergence!) of theta first occurs at $O(\alpha^7)$:

[Ellis, Gaillard NPB 150 (1979)
Khriplovich, Vainshtein NPB 414 (1994)]

$$\bar{\theta}_{\text{div.}} \sim \frac{1}{(4\pi)^{14}} g'^2 \left[Y^2(u_R) - Y^2(d_R)\right] J_{\text{CKM}} \log \Lambda_{\text{UV}} \sim 10^{-46} \log \Lambda_{\text{UV}} \ll 10^{-10}$$

$$\text{Im Det}\left[Y_U Y_U^\dagger, Y_D Y_D^\dagger\right] \approx 10^{-29}$$

In conclusion, **UNNATURALLY** assuming **$\theta = 0$**, the **SM θ-induced contribution to the EDMs turns out to be smaller than the (already small) SM CKM-induced contribution to the EDMs → hence, θ_{SM}** is **TECHNICALLY NATURAL**, i.e. **it remains small under radiative corrections**

Possible paths to get $\bar{\theta} \cong 0$ in a NATURAL way

- One of the light quark masses = 0 → excluded by several ChPT and lattice QCD results suggesting $m_u/m_d \sim 0.5$

- The fundamental **UV theory is P, CP conserving** → P, CP are **SPONTANEOUSLY broken** in such a way that **$\bar{\theta} \cong 0$, but the CKM phase is O(1)** → **technically possible, but very contrived models**

- **Imposing the Peccei-Quinn symmetry → the vacuum angle is promoted to a new dynamical field θ → a/f_a** driven to zero at its minimum energy.

NATURAL θ≅0 through the PQ path

- PQ symmetry → axion field a which does NOT completely relax to zero

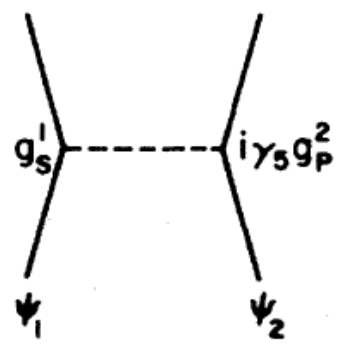
$$\theta_{\rm eff} = \frac{\langle a \rangle}{f_a} \sim G_F^2 f_\pi^4 j_{\rm CKM} \approx 10^{-18}$$

[Georgi, Randall, NPB276 (1986)]

$$d_n^{\rm axion} \sim 10^{-16}\, \theta_{\rm eff}\ e\,{\rm cm} \qquad d_n^{\rm SM} \simeq 10^{-32}\ e\,{\rm cm} \qquad |d_n^{\rm exp}| \lesssim 10^{-26}\ e\,{\rm cm}$$

- Possibility of testing the axion ground state via axion mediated forces arising from the CP-odd non-derivative axion-nucleon coupling

$$\mathscr{L} \supset g_s^N a \bar{N} N + g_p^N a \bar{N} i\gamma_5 N$$



(b)

monopole-dipole

New macroscopic forces
from
non-relativistic potentials

[Moody, Wilczek, Phys. Rev. D 30 (1984)
Barbieri, Romanino, Strumia, Phys. Lett. B 387 (1996)
Pospelov Phys. Rev. D 58 (1998)
Bertolini, Di Luzio, Nesti, Phys. Rev. Lett. 126 (2021)
Okawa, Pospelov, Ritz, Phys. Rev. D 105 (2022)
Dekens, de Vries, Shain, JHEP 07 (2022)]

ARIADNE, QUAX-gpgs, …

eEDM through CP violation the NEUTRINO sector

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i\rangle$$

1 Dirac phase + 2 Majorana phases

- $\delta_{\rm CP}$ from 3ν oscillations
- $\eta_{1,2}$ from $0\nu\beta\beta$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Typically too small and model-dependent

[Ng Ng, Mod. Phys. Lett. A 11 (1996)
Archambault, Czarnecki, Pospelov, Phys. Rev. D 70 (2004).
de Gouvea, Gopalakrishna Phys. Rev. D 72 (2005)]

- Pure Dirac neutrino contribution vanishes at 2-loops (as for qEDM)
- Pure Majorana contribution utterly small (as for $\mu \to e\gamma$)
- SMEFT expectation very small
- Type-I seesaw contribution also small (but model-dependent)

L. Di Luzio, The Low-Energy Frontier of Particle Physics, LNF, Febr. 2025

→ do not expect (generically) a measurable effect,
but not entirely ruled out in certain neutrino mass models

EDMs and electroweak baryogenesis

- **Sakharov's necessary conditions** to generate a **cosmic matter-antimatter ASYMMETRY** starting from a matter-antimatter symmetric universe:
- → **Baryon number violation** (in SM B+L violation through **sphalerons** at $T>M_W$)
- → **C and CP violation** (but in SM CP violation from CKM is **NOT** sufficient) *
- → **Departure from thermal equilibrium** (but in SM, being M_{higgs}> 60 GeV, the electroweak phase transition is **NOT** a first-order phase transition, rather it is just a **smooth crossover** → no departure from thermal equilibrium))

- To achieve baryogenesis at the electroweak phase transition → **new physics is required** **to i) enhance the strength of the transition and ii) provide new sources of CP violation**

- **New interactions responsible for an efficient electroweak baryogenesis generally induce observable EDMs**

amount of SM CKM CP violation

from Big Bang Nucleosynthesis and CMB data

$$\frac{\mathrm{Im\ Det}\,[M_U M_U^\dagger, M_D M_D^\dagger]}{(100\,\mathrm{GeV})^{12}} \simeq 10^{-20} \ll \eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

sphaleron B+L violation operative at T> O(100GeV)

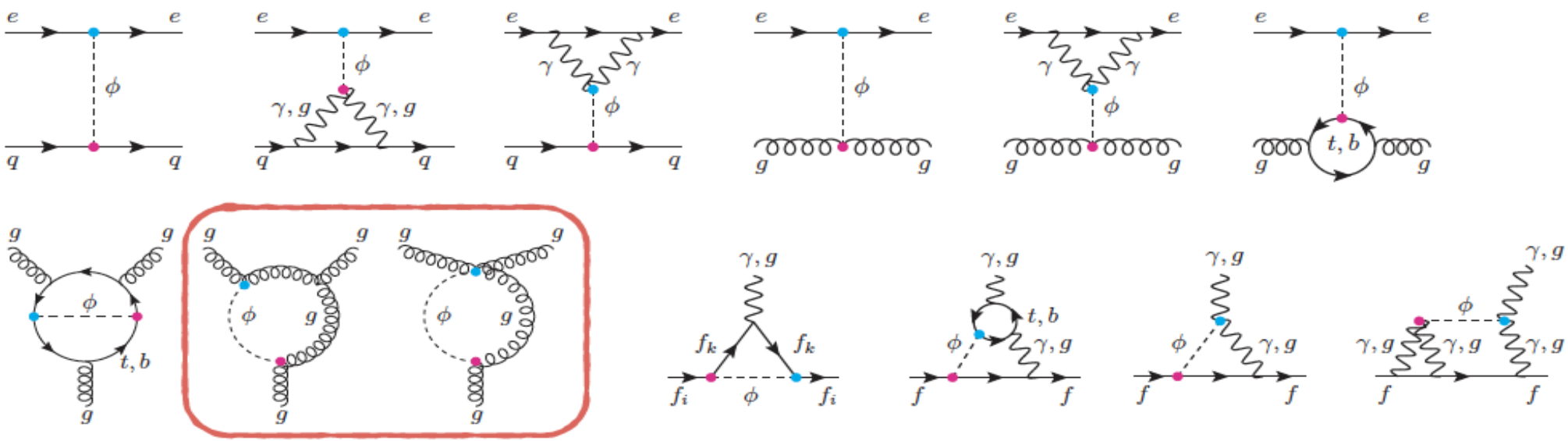
EDM sensitivity to light NP

- CP-violating axion-like particles (ALPs)

[Marciano, Masiero, Paradisi, Passera, Phys. Rev. D 94 (2016)
Di Luzio, Gröber, Paradisi, Phys. Rev. D 104 (2021)
Di Luzio, Levati, Paradisi, JHEP 02 (2024)]

$$\mathcal{L}_\phi = e^2 \frac{\tilde{C}_\gamma}{\Lambda} \phi F \tilde{F} + g_s^2 \frac{\tilde{C}_g}{\Lambda} \phi G \tilde{G} + i \frac{v}{\Lambda} y_P^{ij} \phi \bar{f}_i \gamma_5 f_j$$
$$+ e^2 \frac{C_\gamma}{\Lambda} \phi F F + g_s^2 \frac{C_g}{\Lambda} \phi G G + \frac{v}{\Lambda} y_S^{ij} \phi \bar{f}_i f_j$$

- different scaling/sensitivity w.r.t. heavy NP + new short-distance contributions to EDMs



some final thoughts …

The experimental and theoretical high-precision low-energy physics community has entered an era of unprecedented great potentialities:

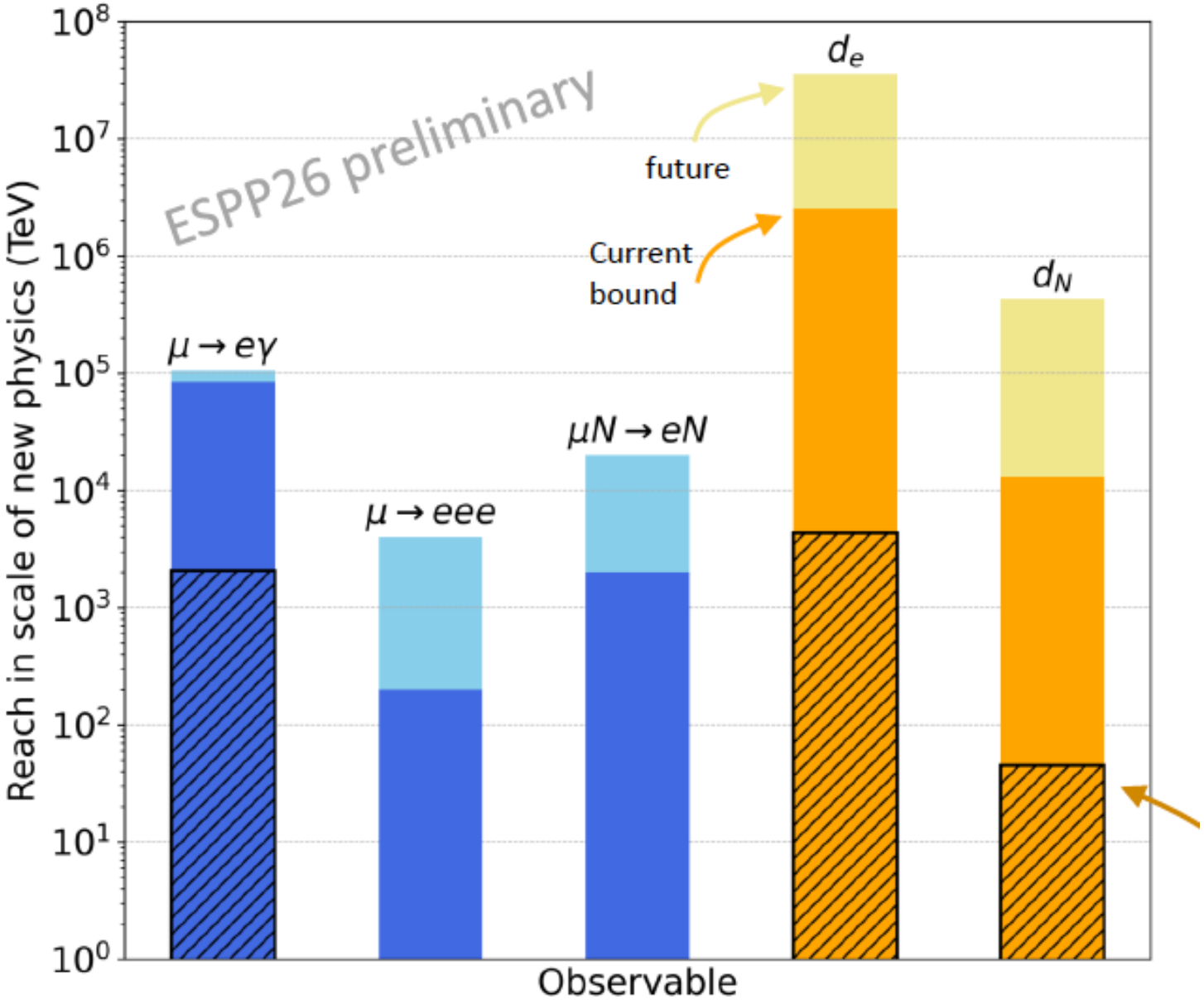
While relatively small in size and cost compared to their energy frontiers cousins, they are large in reach and discovery potential

Report of the 2023 P5 (Particle Physics Project Prioritization Panel)

i) SYNERGY between small/mid-scale (LOW-ENERGY) & large-scale (HIGH-ENERGY) experiments → casting a wider and tighter net for possible effects of BSM physics

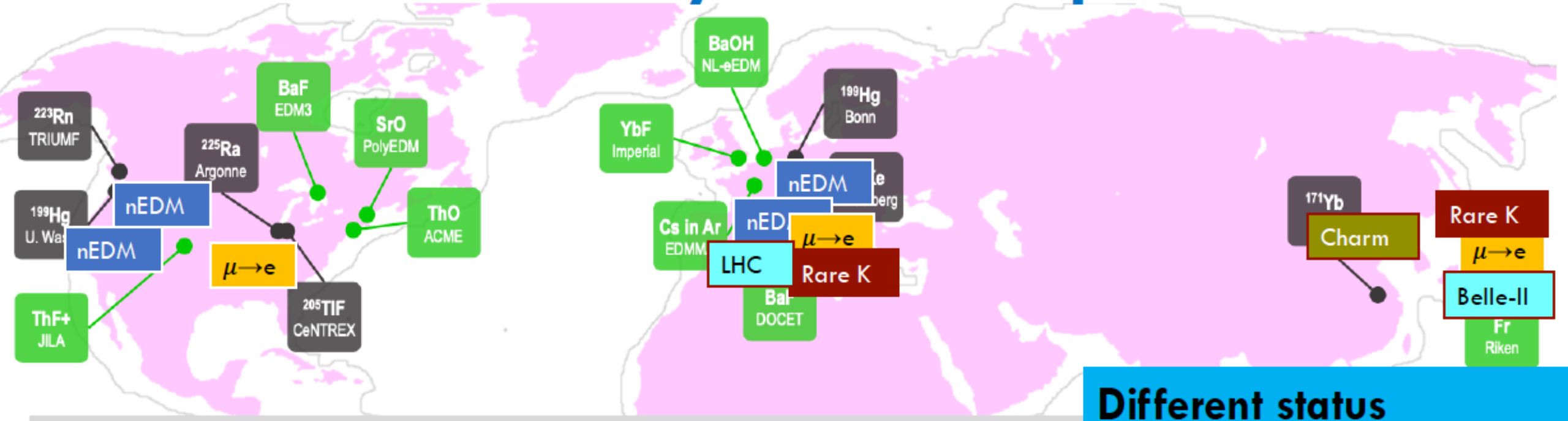
ii) SYNERGY among the **various communities** operating in **precision physics** in (very) **different experimental, technological and theoretical environments (particle physics, spin physics and polarimetry, modelling and simulation, magnetometry, surface physics, atomic laser spectroscopy, high-voltage techniques, vacuum techniques, …)**

BACKUP SLIDES



Current bound with chiral suppression

A diverse eco-system of experiments



Different sizes

Small size dedicated experiments (charged LFV, EDMs)

Medium size experiments focussing on a type of particle (K/π physics)

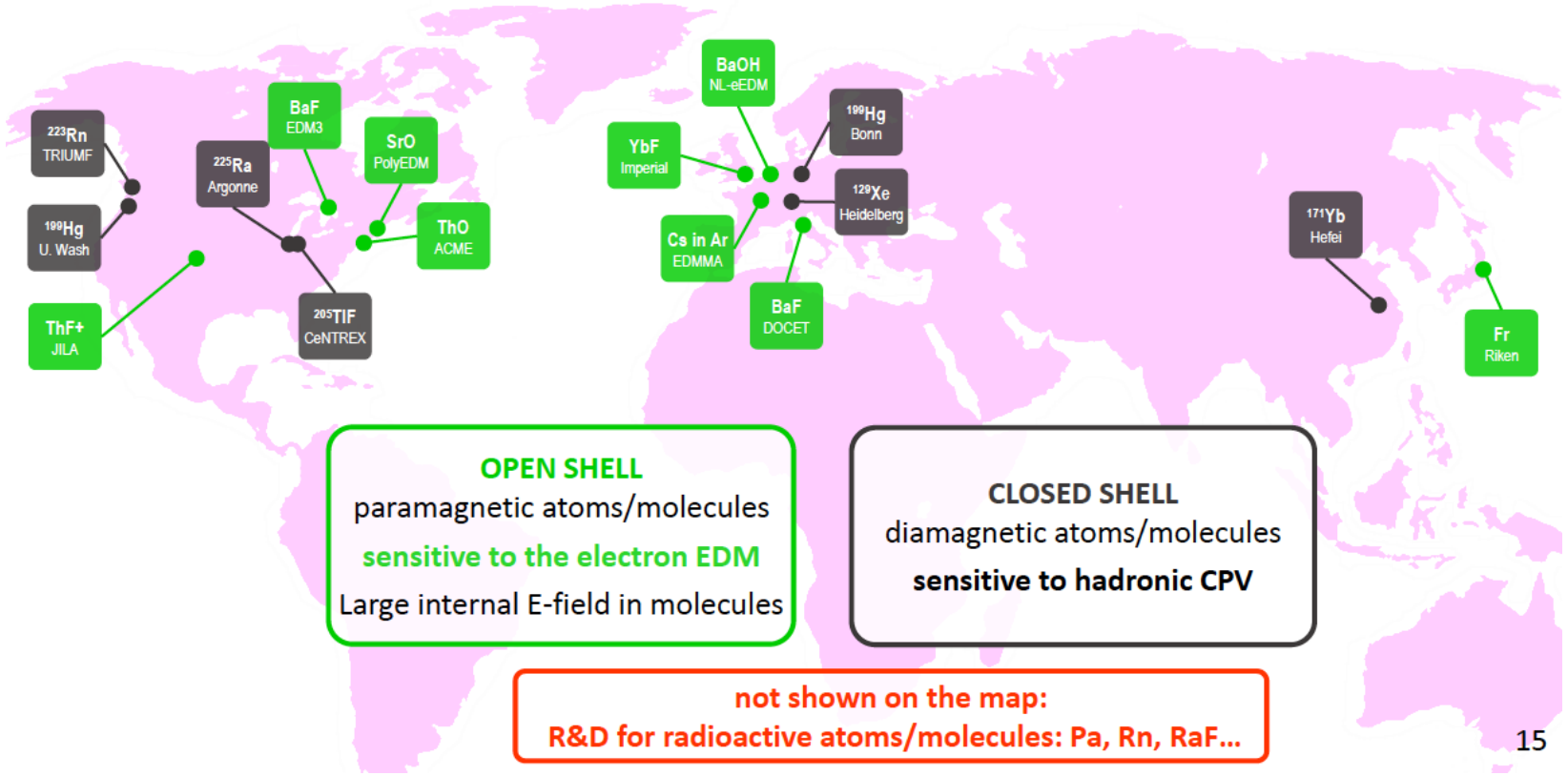
Large experiments 100% focussed (or not!) on Flavour physics

Different status

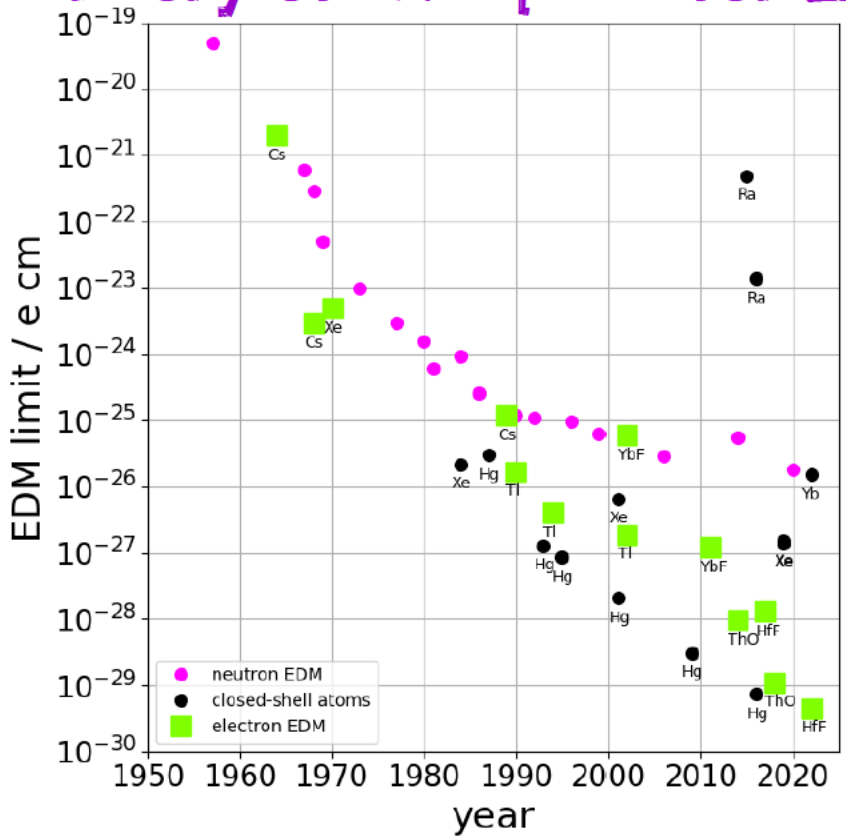
Running or approved

Proposed (not shown)

EDMs of atoms & molecules



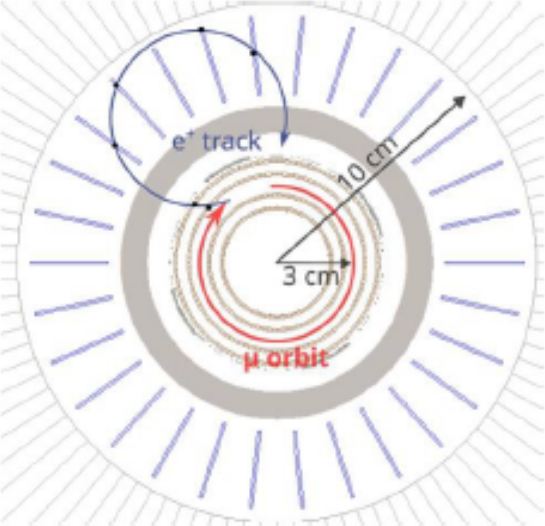
History of the quest for EDMs of various systems



Belle (2022) $d_\tau = (-0.6 \pm 0.6) \times 10^{-17}\ e\ \mathrm{cm}$	COLLIDER
Muon g-2 (2009) $d_\mu = (0.0 \pm 0.9) \times 10^{-19}\ e\ \mathrm{cm}$	STORAGE RING
PSI nEDM (2020) $d_n = (0.0 \pm 1.1) \times 10^{-26}\ e\ \mathrm{cm}$	ULTRACOLD NEUTRONS
Seattle ^{199}Hg (2016) $d_{\mathrm{Hg}} = (-2 \pm 3) \times 10^{-30}\ e\ \mathrm{cm}$	CLOSED-SHELL ATOMS
Boulder HfF$^+$ (2023) $d_e = (-1 \pm 2) \times 10^{-30}\ e\ \mathrm{cm}$	OPEN-SHELL MOLECULES

Prospects on muon EDM:

- With the g-2 experiments at FNAL and JPARC, sensitivity $\sim 10^{-21}\ e\ \mathrm{cm}$
- Dedicated μEDM project at PSI



Phase 1 – commissioning
$4 \times 10^{-21}\ e\ \mathrm{cm}$

Phase 2 – post 2030
$6 \times 10^{-23}\ e\ \mathrm{cm}$

Prospects on heavy flavour EDMs at colliders

- ALLADIN: a fixed-target experiment at LHC MDM and EDM of charmed baryons Λ_c^+ Ξ_c^+
- Super Tau-Charm Factory expects to improve on g EDM by factor ~10

Experimentally accessible EDMs

1. EDM of paramagnetic systems: atoms (Tl, Fr, …) and molecules (ThO, YbF, …)

2. EDM of diamagnetic atoms (Hg, Ra, Rn, …)

3. EDM of the neutron, proton, deuteron

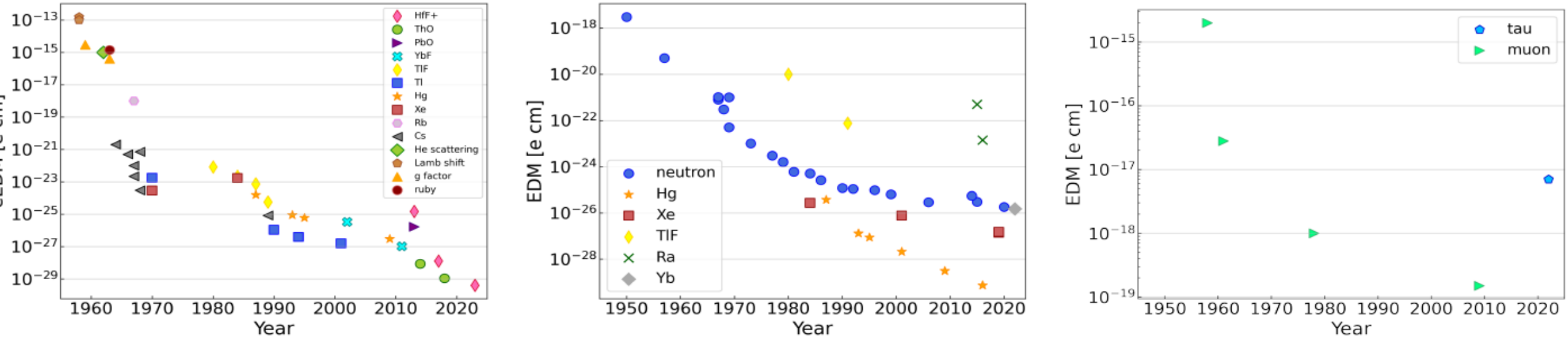
4. EDM of the muon/tau

L. Di Luzio, The Low-Energy Frontier of particle Physics, LNF, Febr. 2025

1. **PARAMAGNETIC** systems → EDM in atoms and molecules with uncompensated electron spins → sensitive to the **electron EDM**

2. **DIAMAGNETIC** systems → EDM in atoms and molecules with vlosed electron shells → testing the coupling of the electric field to the **NUCLEAR SPIN**

System	upper limit [$e$cm], 95% C.L.	Reference	Comment
n	2.2×10^{-26}	[9]	direct limit
μ	1.9×10^{-19}	[10]	direct limit
^{199}Hg	7.4×10^{-30}	[8]	best indirect (single-source) limit for proton: $\lvert d_p \rvert < 5.4 \times 10^{-25}$ $e$cm, 95% C.L.
HfF^+	4.8×10^{-30}	[5]	lowest EDM bound for any system; best indirect (single-source) limit for the electron: $\lvert d_e \rvert < 4.8 \times 10^{-30}$ $e$cm, 95% C.L.

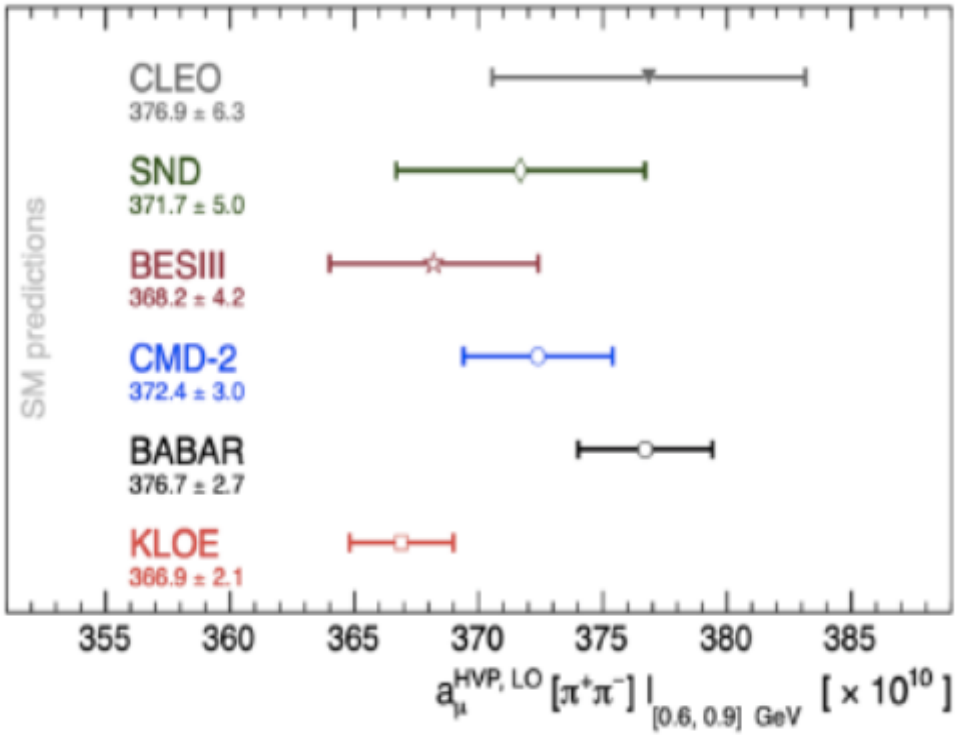


(a)

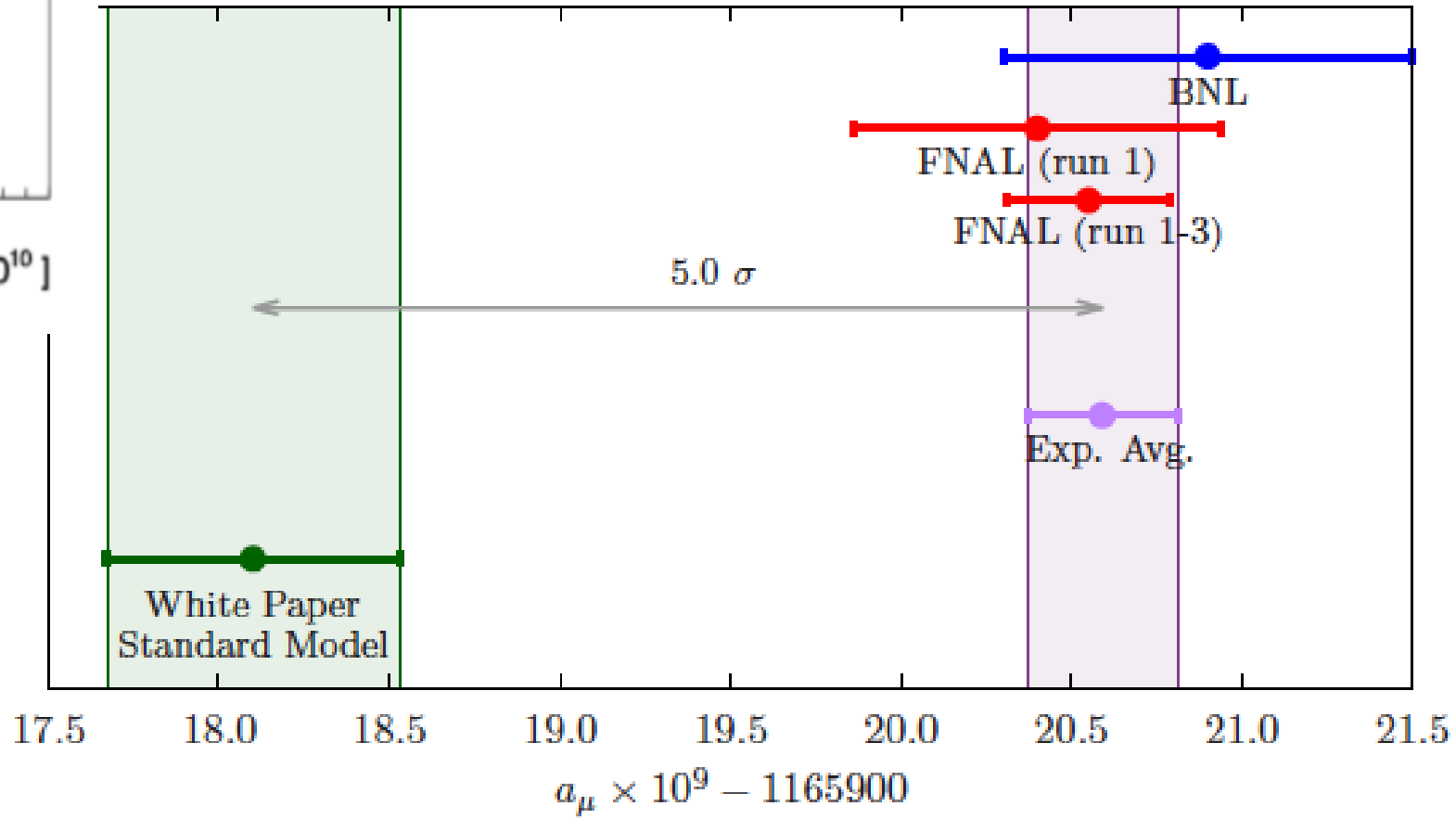
Community input to the European Strategy on particle physics: Searches for Permanent Electric Dipole Moments

arXiv:2505.22281c

[WP20, 2006.04822]



The "old" (2020) muon g-2 problem



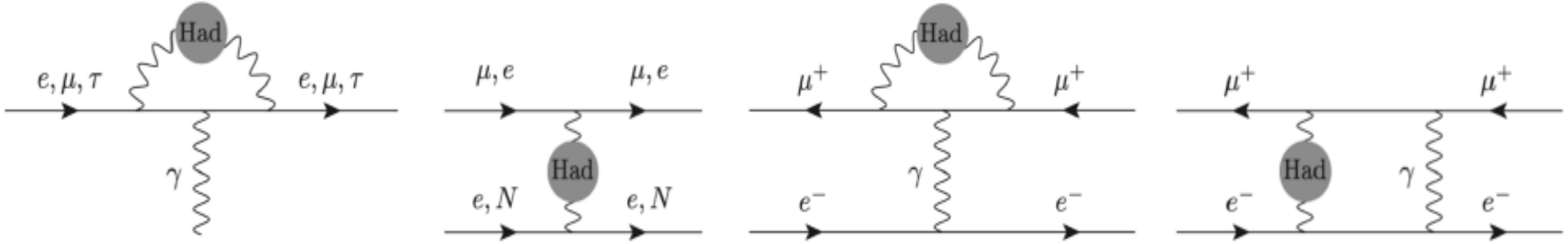
Sensitivity of other physical observables to

$$[\delta a_\mu^{HVP}]_{NP} = [a_\mu^{HVP}]_{LQCD,CDM3} - [a_\mu^{HVP}]_{DR,WP20}$$

which exp. and th. accuracy should be reached for the above observables to probe δa_μ^{HVP}

- **the Electron g-2 (a_e)**
- **the Muonium HyperFine Splitting (HFS)**
- **the Tau g-2 (a_τ)**
- **the low-energy weak mixing angle $\sin^2\theta_W(0)$**
- **the running of α_{em}**

Di Luzio, Keshavarzi, A.M. , Paradisi PRL 134 (2025) 1



(a) **Leptonic g-2**

(b) **$\sin^2\theta_W$ and running of α_{em}**

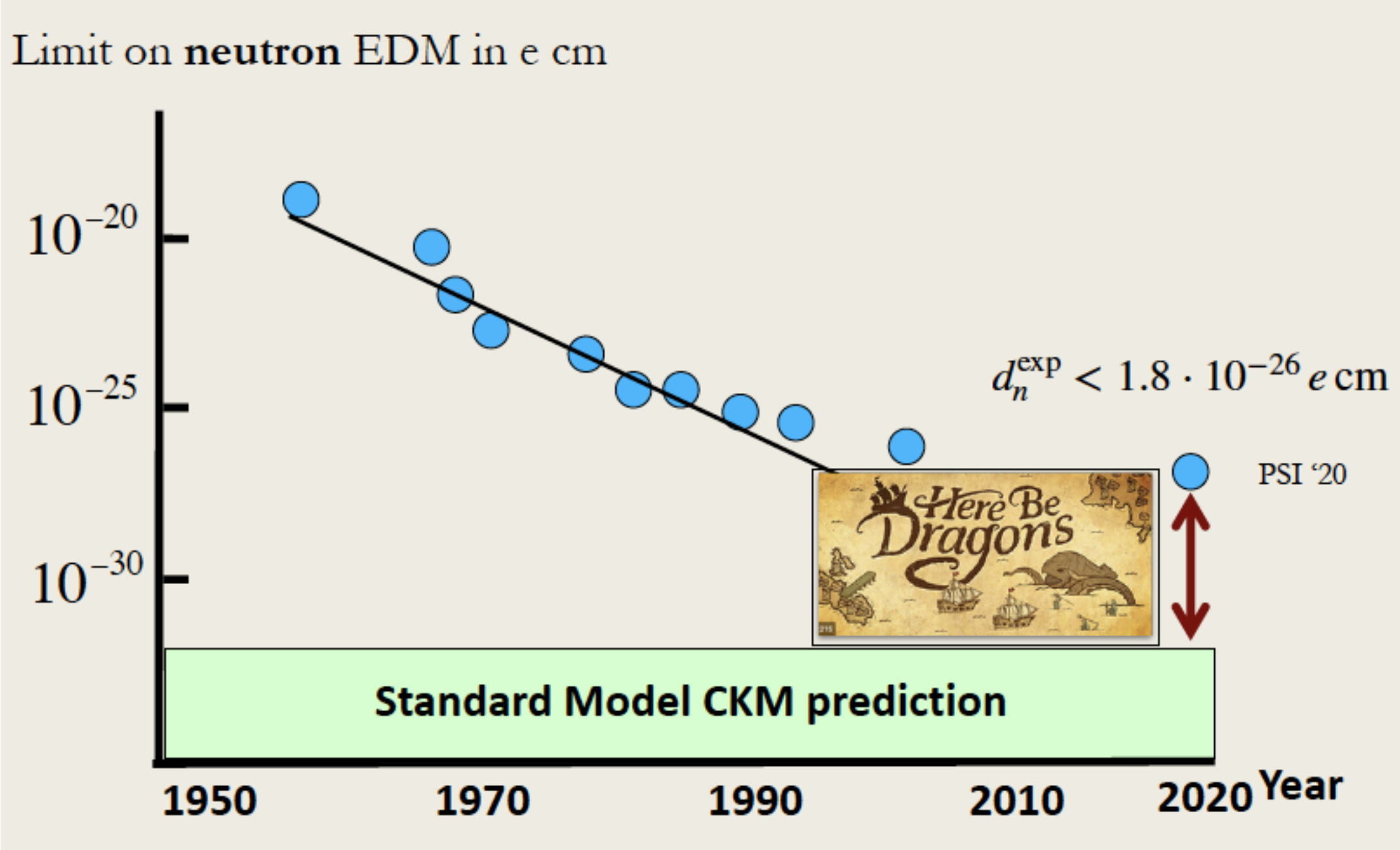
(c) **Muonium HFS**

Community input to the EU Strategy on particle physics: Searches for Permanent EDMs

arXiv:2505.22281c

Collaboration	Species	Method	Sensitivity (10^{-29} $e$cm)	Status	Duration (years)	Ref
PanEDM I	n	UCN	380	Commissioning	5	[43]
PanEDM II	n	UCN	79	Commissioning	8	[43]
Beam EDM	n	beam	500	proof-of-principle	?	[44]
n2EDM	n	UCN	110	Start data-taking	4	[45]
n2EDMagic	n	UCN	50	Construction	5	[45]
nEDMsf	n	UCN	20	Development	7	[42]
ACME III	ThO ($^3\Delta_1$)	Beam	0.1	Commissioning		[93]
JILA III	ThF^+ ($^3\Delta_1$)	Ion trap		Commissioning		[94]
Imperial II	YbF ($^2\Sigma$)	μK beam	0.1	Commissioning	3	[47]
Imperial III	YbF ($^2\Sigma$)	Lattice	0.01	Construction	6	[47]
NL-eEDM I	BaF ($^2\Sigma$)	Slow beam	0.5	Commissioning	3	[48]
NL-eEDM II	BaOH ($^2\Sigma$)	Lattice	0.1	Construction	6	[50]
PolyEDM	SrOH ($^2\Sigma$)	Lattice		Construction		[51]
EDM^3	BaF ($^2\Sigma$)	Matrix		Construction		[52]
DOCET	BaF ($^2\Sigma$)	Matrix		Construction	3	[53]
CeNTREX	^{205}TlF	Beam		Commissioning		[58]
HeXe	^{129}Xe	^{3}He-comagnetometer	10	Construction	4	[57]
quMercury	^{199}Hg	ultracold atoms	1	Construction	5	[61]
ALADDIN	Λ_c^+, Ξ_c^+	collider	1×10^{13}	Development	?+2	[64]
muEDM I	μ	frozen-spin	4×10^8	Commissioning	3	[67]
muEDM II	μ	frozen-spin	6×10^6	Conception	10	[67]
pEDM I	p	frozen-spin	1	Development	5	[69]
pEDM II	p	frozen-spin	0.01	Conception	5	[69]

TABLE II: Sensitivity goals of planned EDM measurements. All values are reported as transmitted in private communication or published in cited references

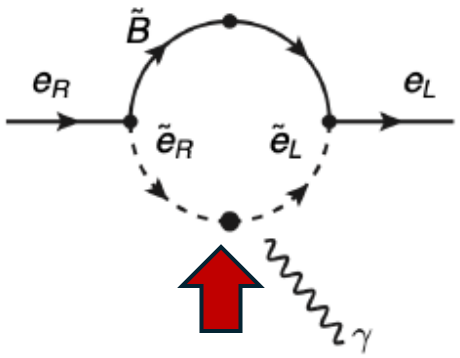


J. de Vries, CP2023, Les Houches

EDMs sensitivity to HEAVY New Physics

Since EDMs require a helicity flip → EDMs are actually dim=6 operators:

$$\frac{1}{\Lambda^2} H(\bar{f}_L \sigma_{\mu\nu} f_R) F^{\mu\nu} \quad \rightarrow \quad \frac{v}{\Lambda^2}(\bar{f}_L \sigma_{\mu\nu} f_R) F^{\mu\nu} \quad , \quad d_f \sim \frac{v}{\Lambda^2}$$



- typical NP contributions at 1- and 2-loops

$$\frac{|d_e|}{e} \sim \begin{cases} \dfrac{eg^2}{16\pi^2}\dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{50\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(1-loop)} \\[2ex] e\left(\dfrac{g^2}{16\pi^2}\right)^2 \dfrac{m_e}{\Lambda^2}\sin\phi_{\rm CPV} \sim 10^{-29}\, e\, cm \left(\dfrac{2.5\,\text{TeV}}{\Lambda}\right)^2 \sin\phi_{\rm CPV} & \text{(2-loops)} \end{cases}$$

EDMs of DIAMAGNETIC ATOMS

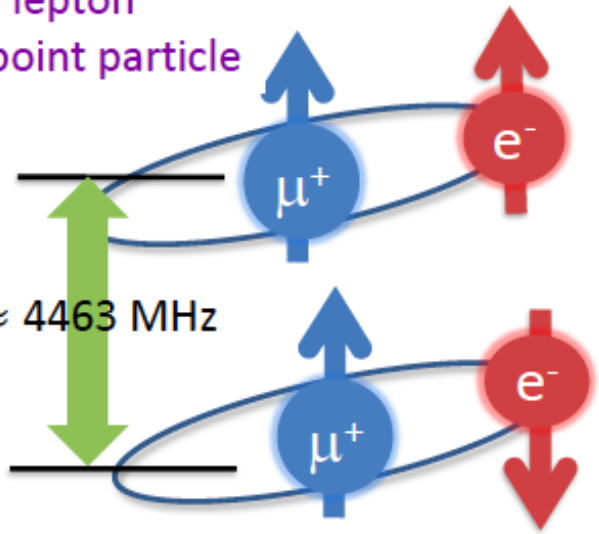
- Diamagnetic atoms (e.g., ^{199}Hg, ^{129}Xe) → **no unpaired electrons**
- the induced dipole moment due to an applied external field = 0 since electron spins cancel out → Diamagnetic atoms have **NO permanent electric dipole moment**
- Any measurable **EDM** must come from **NUCLEAR EFFECTS** (due to the nucleus finite size → not perfect electron shielding - evasion of the Schiff theorem)
- Atomic EDM is SUPPRESSED w.r.t. nucleus EDM by $\sim (R_{nucl}/R_{atom})^2 \sim O(10^{-3})$
- CKM contribution via CP-odd nucleon potential

$$\mathcal{L}_{\rm nuc} = \frac{1}{\sqrt{2}} G_F \eta_{np} \bar{N} N \bar{N} i \gamma_5 N \quad \Rightarrow \quad d_{\rm Hg}(\mathcal{J}) < 10^{-35} {\rm ecm}$$

The Muonium HyperFine Splitting (HFS)

Muonium: bound state of μ^+ and e^-

Pure lepton
= point particle



$\Delta\nu \approx 4463$ MHz

$\Delta\nu$: Muonium Hyperfine Structure

P. Strasser, Workshop of the Muon g-2 TI , Bern, Sept. 2023

Muonium HFS of the 1S ground state

$$\frac{\nu_{\rm HFS}}{\nu_F} = 1 + a_\mu + \Delta^{\rm QED}_{\rm HFS} + \Delta^{\rm weak}_{\rm HFS} + \Delta^{\rm HVP}_{\rm HFS}$$

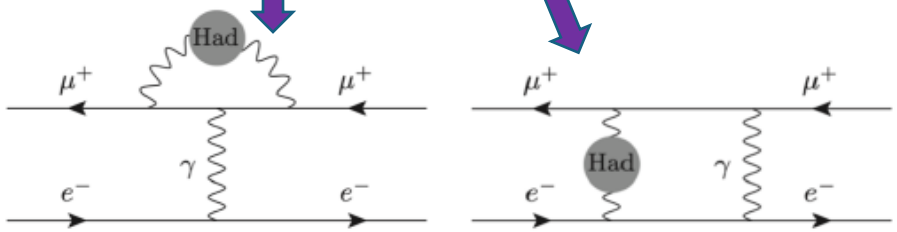
$$\Delta^{\rm HVP}_{\rm HFS} = \frac{1}{2\pi^3}\int_{m_\pi^2}^{\infty} ds\, K_{\rm Mu}(s)\,\sigma_{\rm had}(s) \qquad K_{\rm Mu}(s) \approx \frac{m_\mu^2}{s}\left(\frac{9}{2}\log\frac{s}{m_\mu^2} + \frac{15}{4}\right)\frac{m_e}{m_\mu}$$

for $s >> m_\mu^2$

$$\Delta^{\rm HVP}_{\rm HFS} \approx 6\,\frac{m_\rho^2}{m_\mu^2} K_{\rm Mu}(m_\rho^2)\,(a_\mu^{\rm HVP})_{e^+e^-}$$

$$\approx 0.63\,(a_\mu^{\rm HVP})_{e^+e^-}\,.$$

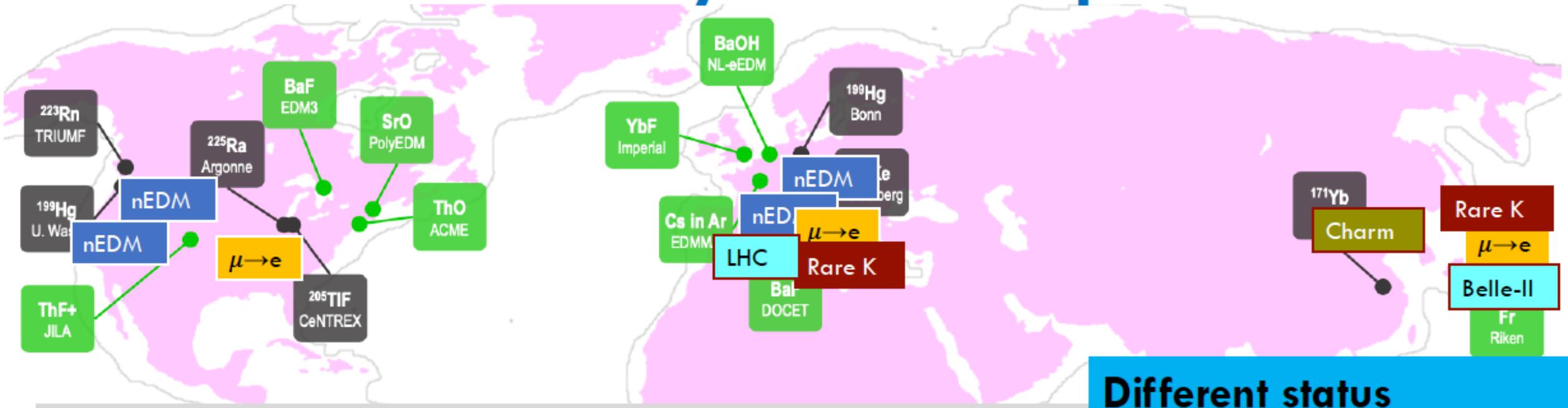
$$\nu^{\rm HVP}_{\rm HFS} = (a_\mu^{\rm HVP} + \Delta^{\rm HVP}_{\rm HFS})\,\nu_F \approx 1.63\,\nu_F\,a_\mu^{\rm HVP}$$



$$\delta\nu^{\rm CMD3}_{\rm HFS} \approx (16 \pm 3)\ {\rm Hz}$$

5.9σ discrepancy in the comparison!

A diverse eco-system of experiments



Different sizes

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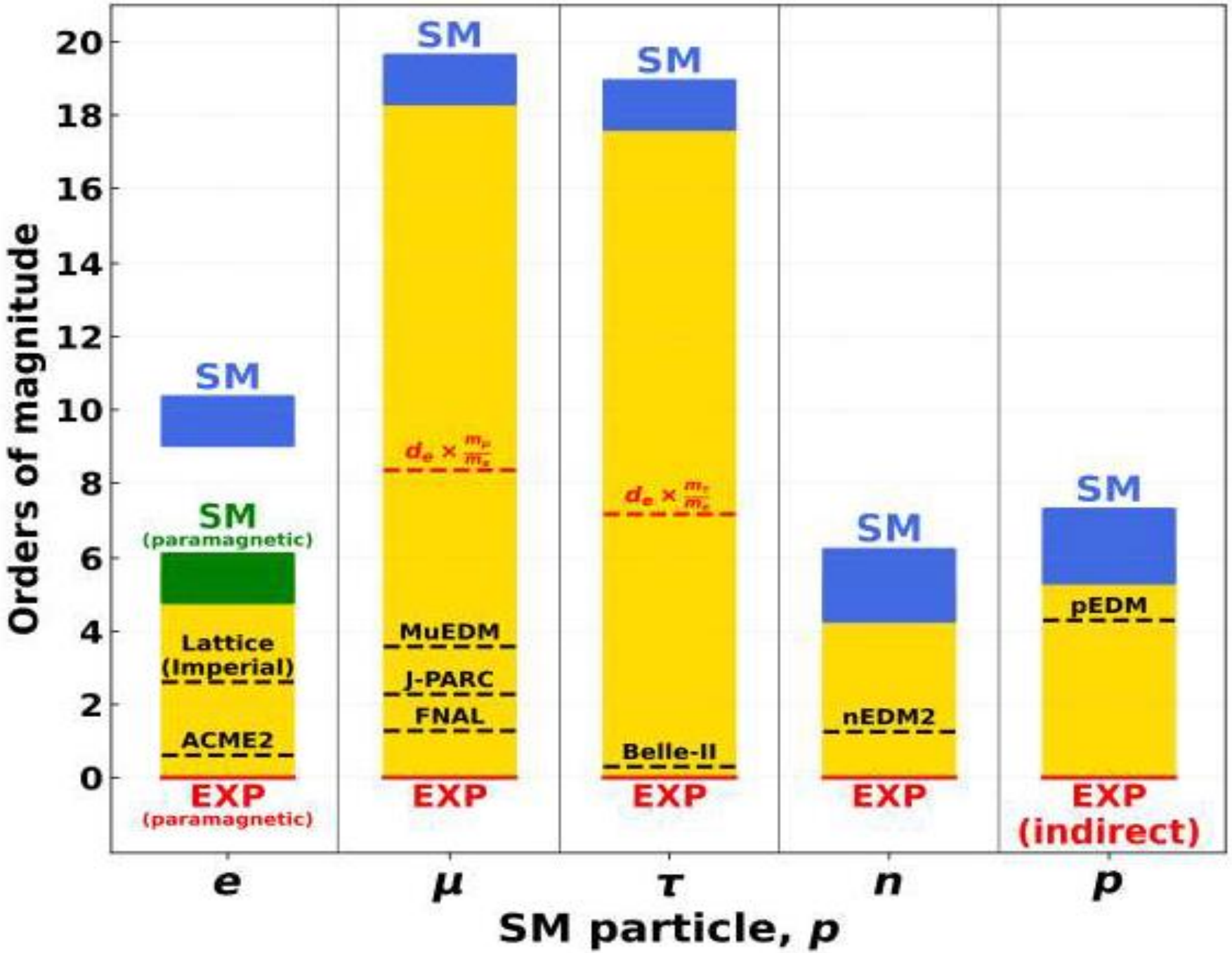
Large experiments 100% focussed (or not!) on Flavour physics

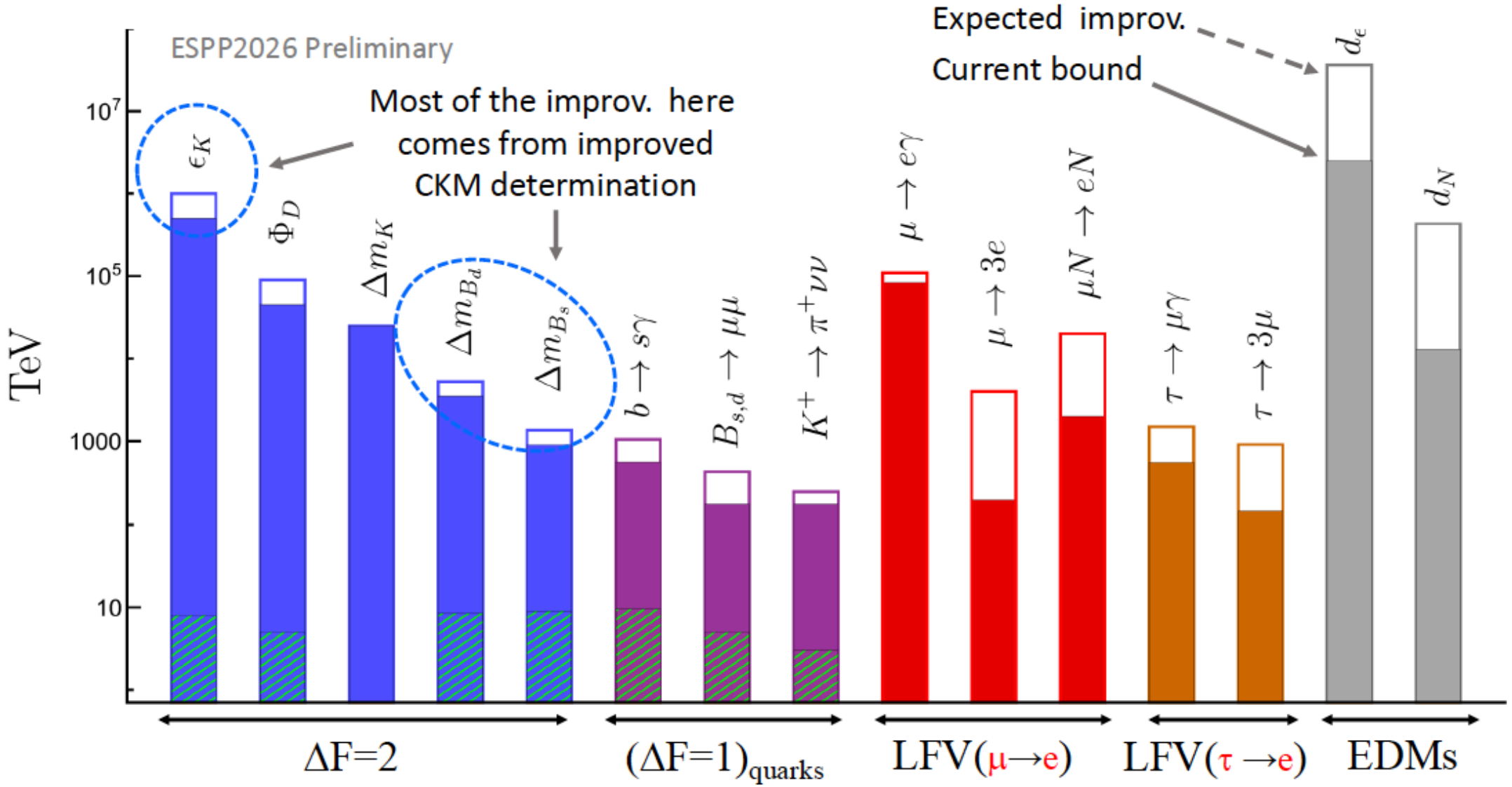
Different status

Running or approved

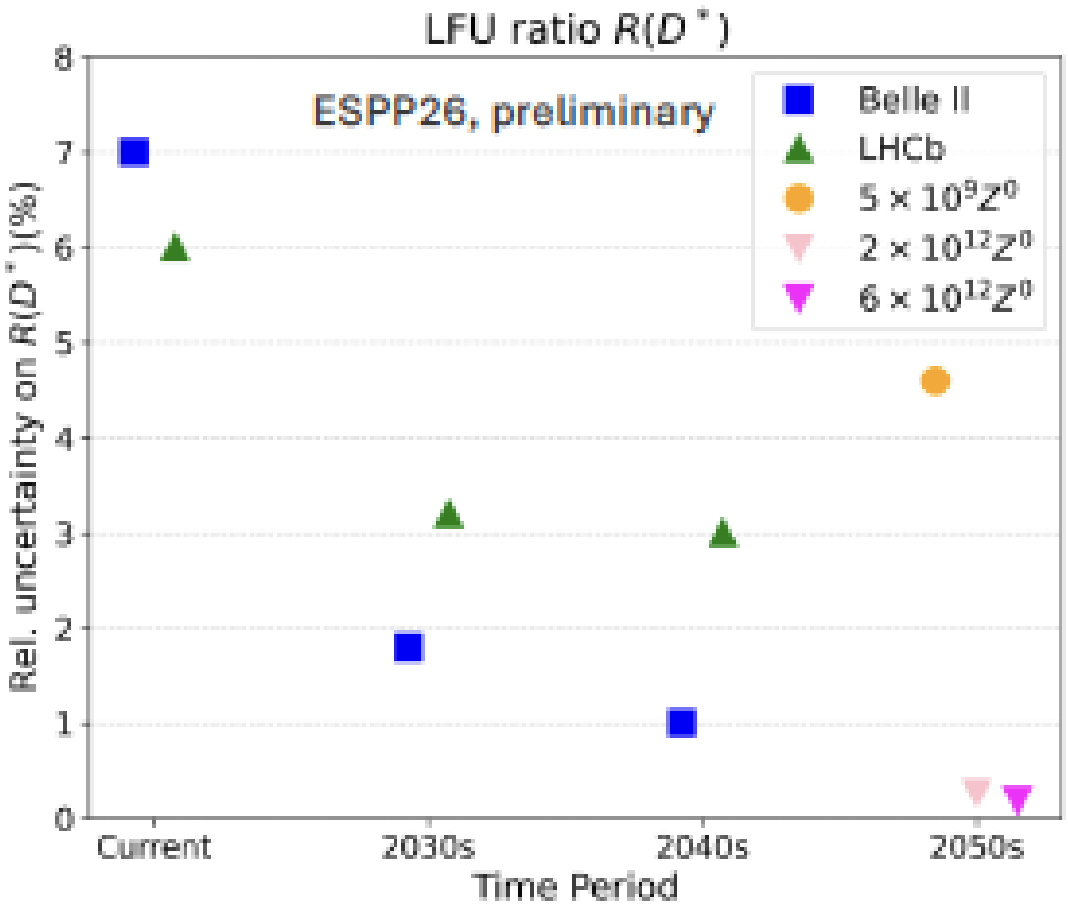
Proposed (not shown)

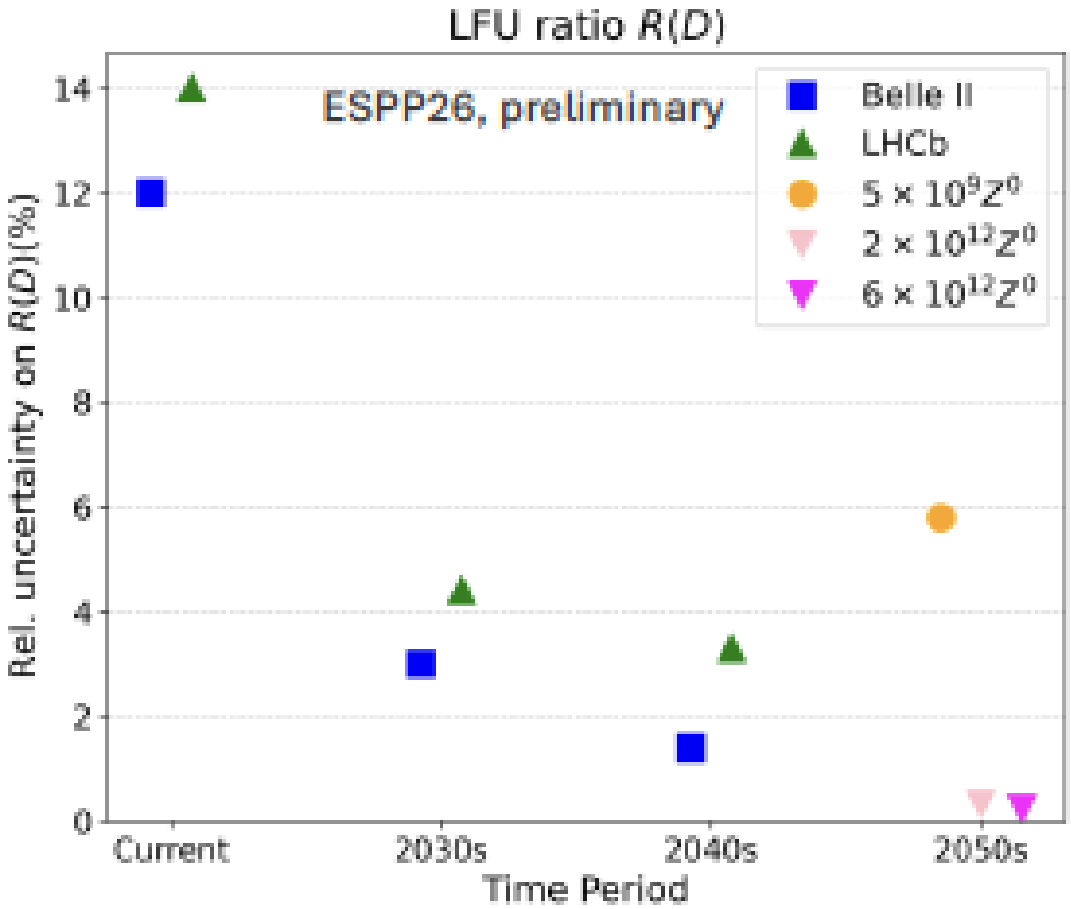

Orders of magnitude
20
18
16
14
12
10
8
6
4
2
0
SM
SM
(paramagnetic)
Lattice
(Imperial)
ACME2
EXP
(paramagnetic)
SM
$d_e \times \frac{m_\mu}{m_e}$
MuEDM
J-PARC
FNAL
EXP
SM
$d_e \times \frac{m_\tau}{m_e}$
Belle-II
EXP
SM
nEDM2
EXP
SM
pEDM
EXP
(indirect)
e
μ
τ
n
p
SM particle, p

I. Bounds on effective scales for generic (unit) couplings



Prospects to reduce the uncertainty on $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$





Nucleon EDMs from CKM

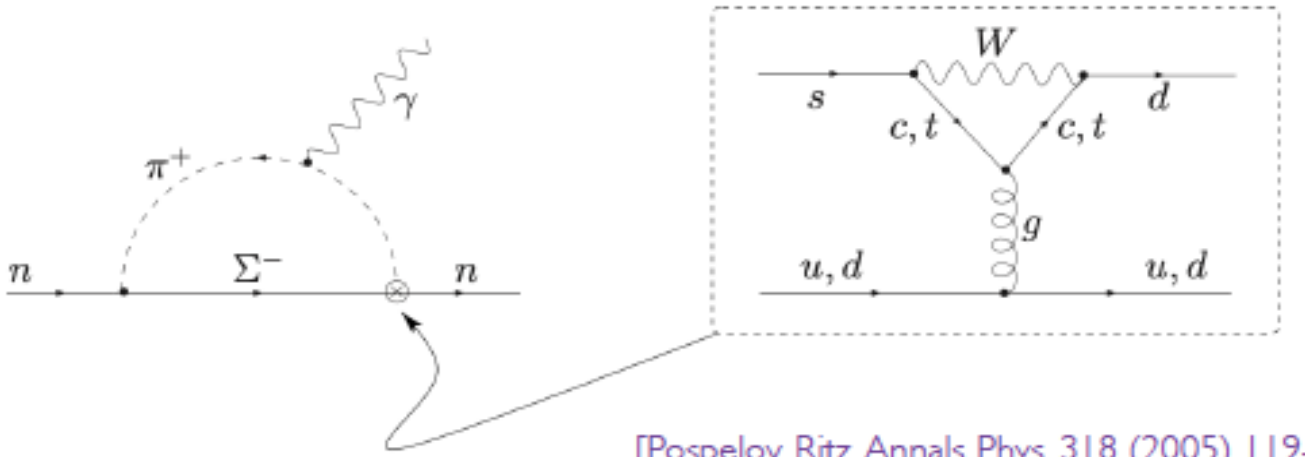
- qEDM is <u>not</u> the dominant source of the CKM-induced EDM of nucleons

  - 4-quark CP-odd operators + chirally enhanced contributions

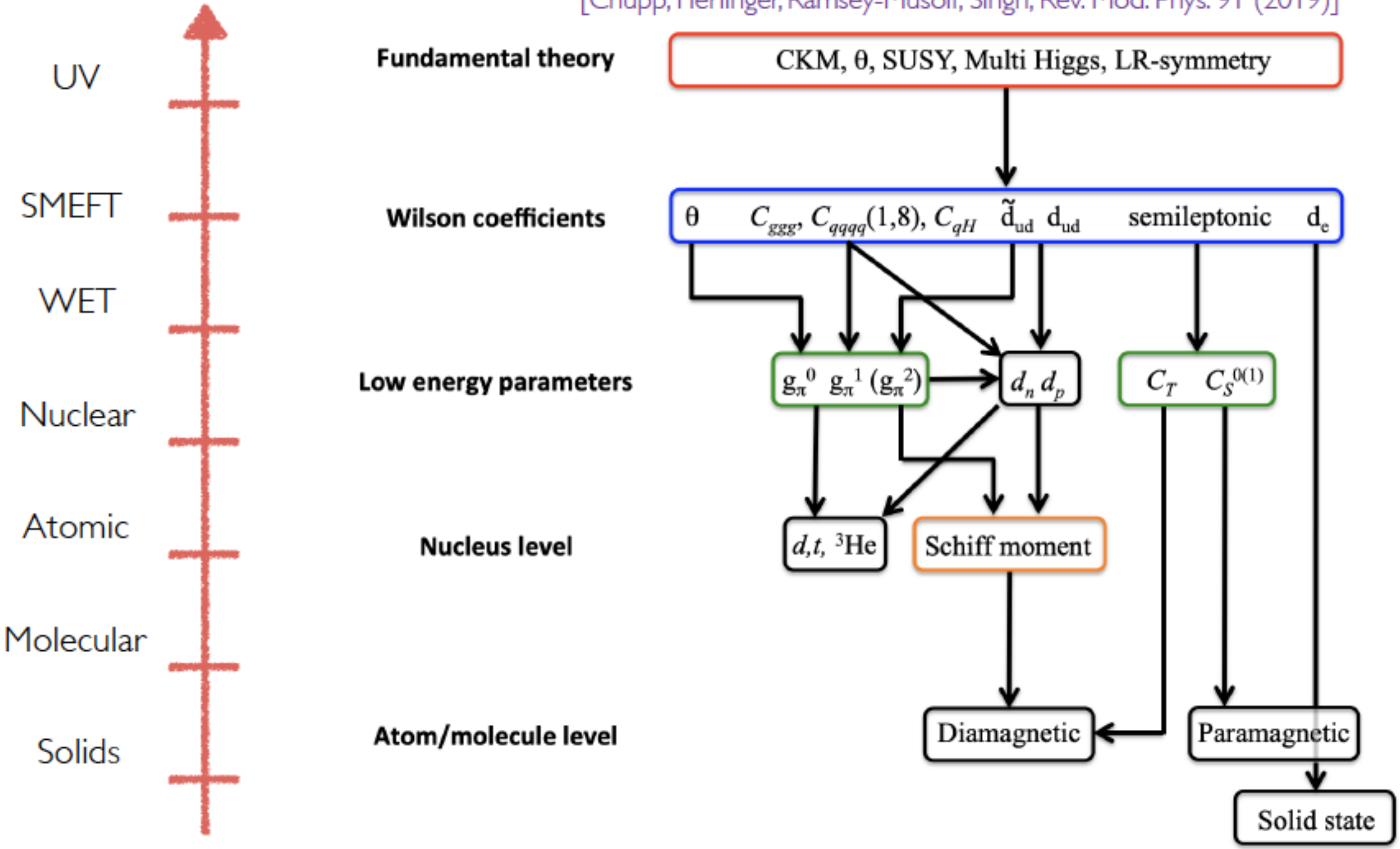
$$d_N^{(\mathrm{lim})}(\mathcal{J}) \sim e c_n \mathcal{J} G_F^2 m_{\mathrm{had}}^3$$
$$< 10^{-29} e\mathrm{cm} \times c_n \left(\frac{m_{\mathrm{had}}}{300\,\mathrm{MeV}}\right)^3$$

$\rightarrow$ $d_N \sim 10^{-(32\div31)}\, e\, cm$

[Khriplovich, Zhitnitsky, Phys. Lett. B 109 (1982)
Gavela, Le Yaouanc, Oliver, Pene, Raynal, Pham, Phys. Lett. B 109 (1982)
McKellar, Choudhury, He, Pakvasa, Phys. Lett. B 197 (1987)
Mannel, Uraltsev, Phys. Rev. D 85 (2012)]



[Pospelov, Ritz, Annals Phys. 318 (2005) 119-169]

Fig. 6. A leading contribution to the neutron EDM in the Standard Model, arising via a four-quark operator generated by a strong penguin, and then a subsequent enhancement via a chiral π^+ loop.

[Chupp, Fierlinger, Ramsey-Musolf, Singh, Rev. Mod. Phys. 91 (2019)]