Looking at *New Physic* through the *LOW-ENERGY HIGH-PRECISION* physics window

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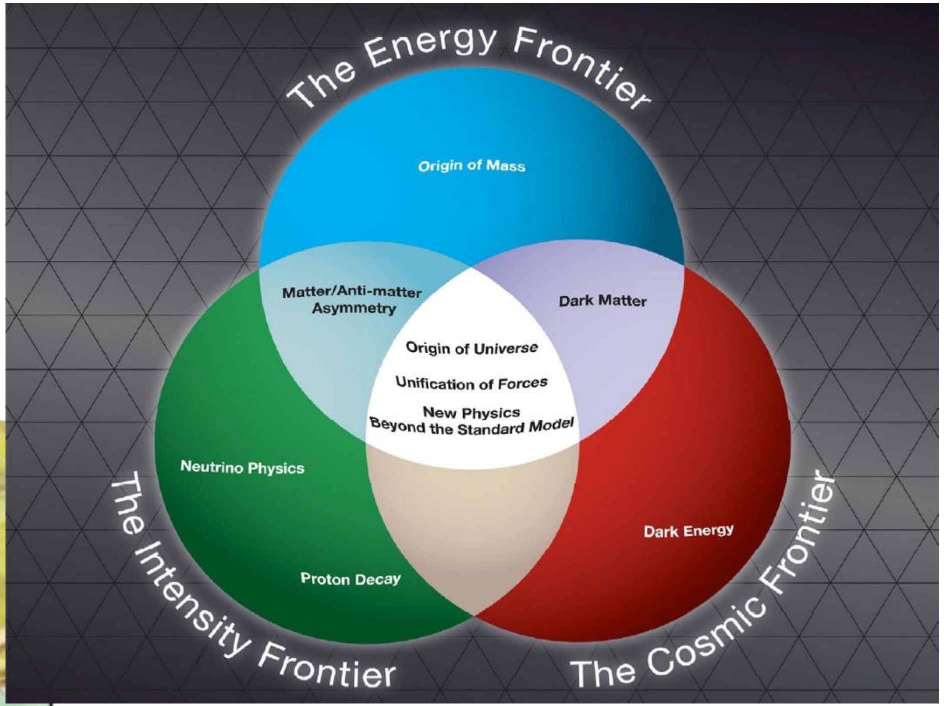
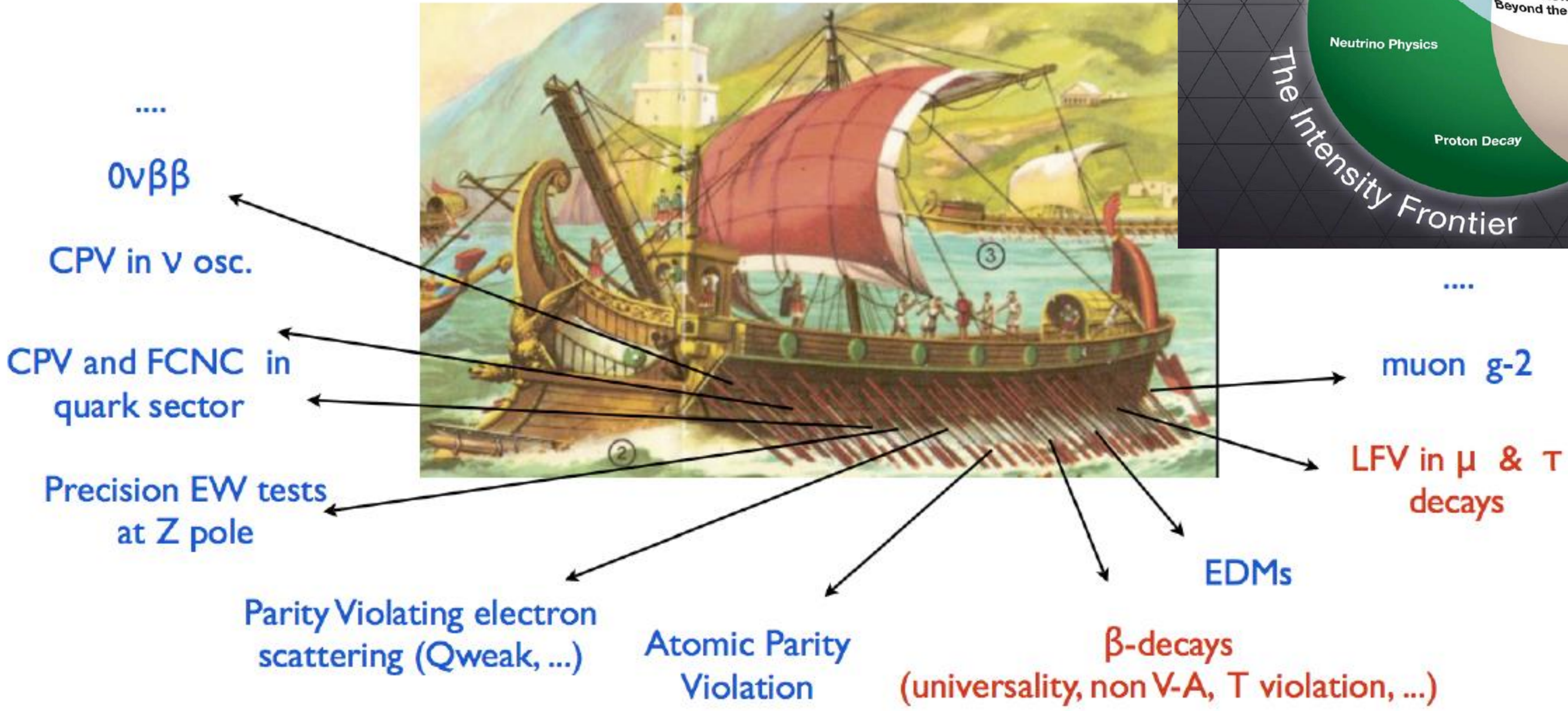
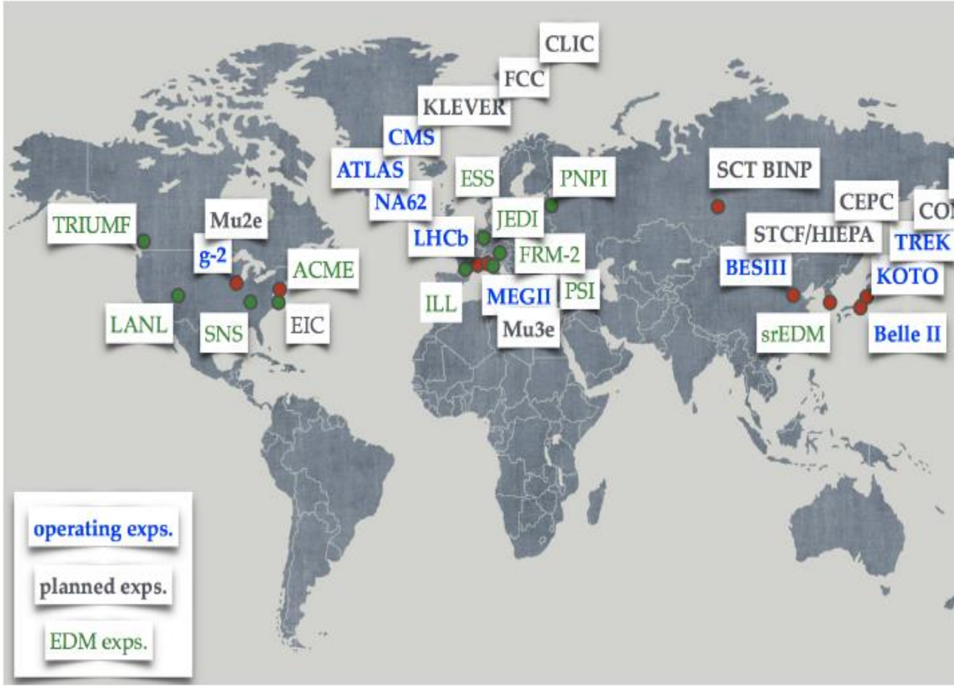




The vast domains of the **PRECISION FRONTIER** physics

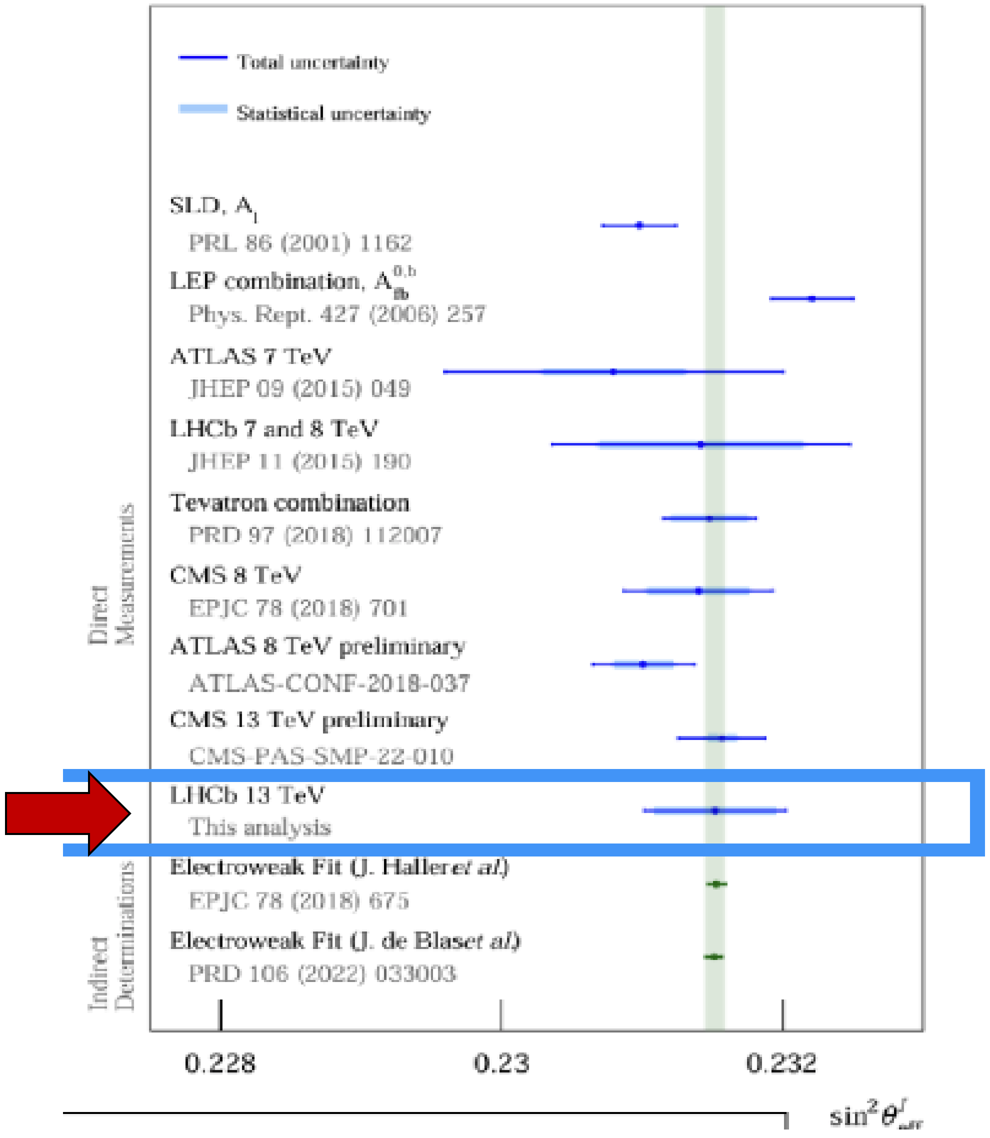
- Precision physics at **HIGH ENERGY** (Higgs physics, top physics, precision electrowek physics, etc.)
- **Hadronic flavour physics** (K, D, B mesons, …)
- Electric Dipole Moments (**EDMs**)
- **Leptonic Magnetic Dipole Moments**
- Charged Lepton Flavor Violations (**CLFV**)
- **Violations of Lorentz symmetries and precision tests of gravity**

LOW-ENERGY HIGH-PRECISION PHYSICS

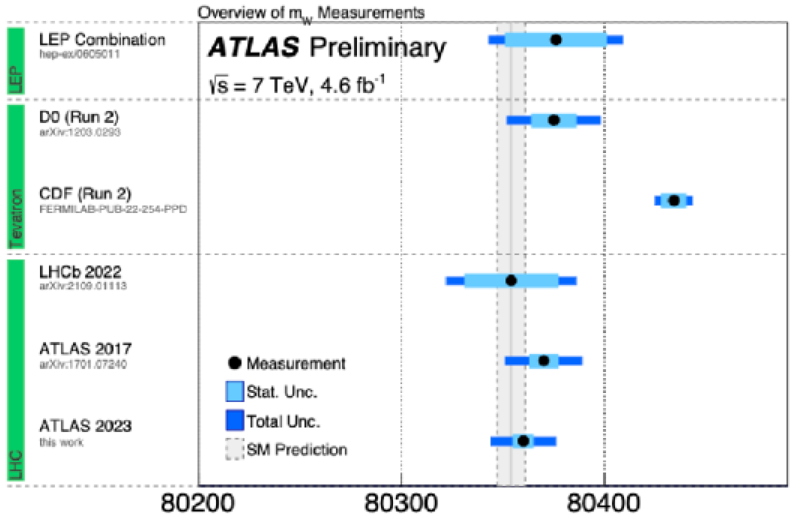


Testing the GAUGE part of the SM

LHC: from **DISCOVERY** to **PRECISION** physics

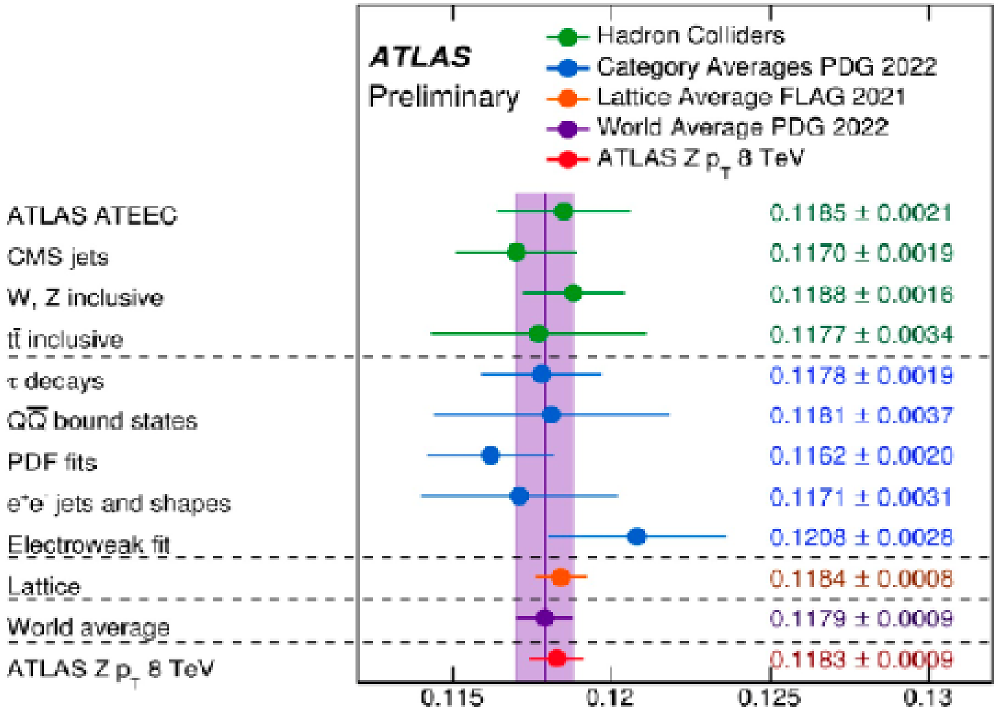


$$\sin^2\theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$



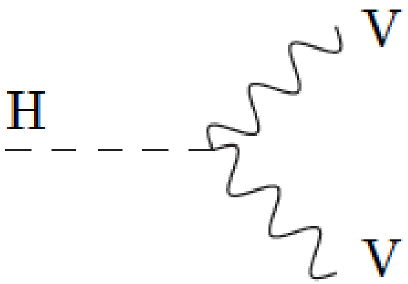
m_W (MeV)

$$m_W = 80360 \pm 5_{(stat.)} \pm 15_{(syst.)} = 80360 \pm 16 \text{ MeV}$$



$\alpha_S(m_Z)$

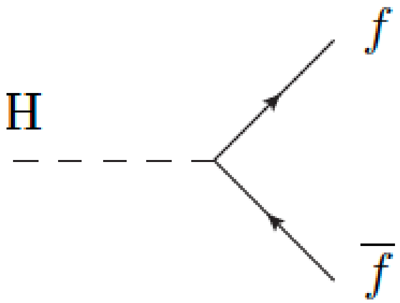
Testing the **HIGGS part** of the SM: present and future



$$\frac{2m_V^2}{v}$$

$$|D_\mu \phi|^2$$

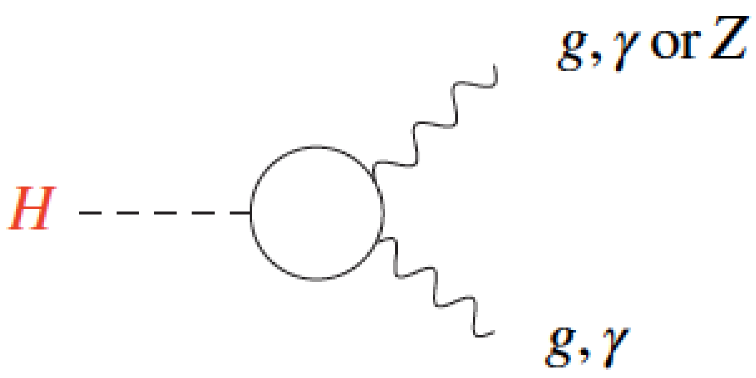
	Current	HL-LHC	FCC (ee)
$\kappa_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

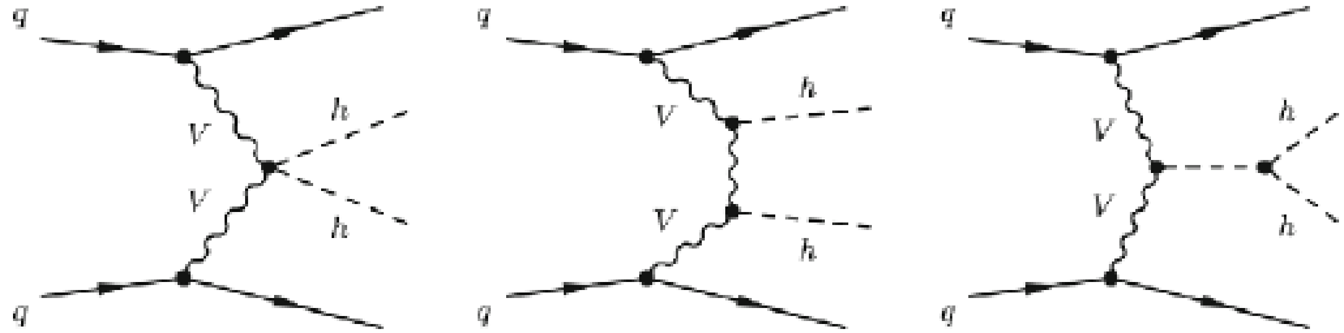


$$\frac{m_f}{v}$$

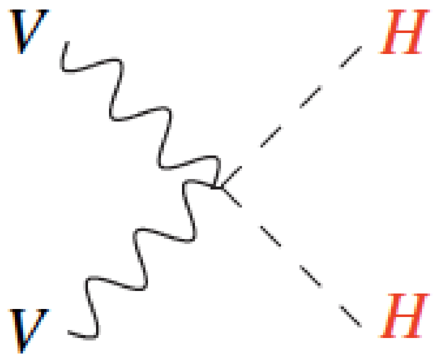
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

	Current	HL-LHC	FCC (ee)	FCC (hh)
κ_t	11%	3.4%	-	1%
κ_b	11%	3.7%	0.7%	-
κ_τ	8%	1.9%	0.7%	-
κ_μ	20%	4.3%	8.9%*	





	Current	HL-LHC	FCC (ee)
κ_γ	6%	1.8%	3.9%
κ_g	7%	2.5%	1%
$\kappa_{Z\gamma}$	30%	9.8%	

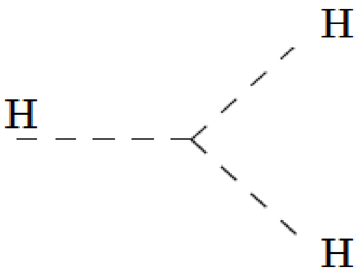


$$g_{HHVV} \sim \frac{2M_V^2}{v^2}$$

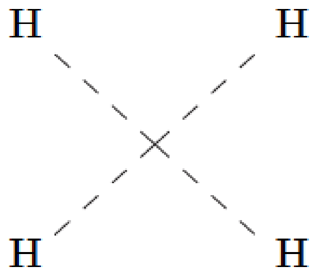
$$\kappa_{2V} \in [0.67, 1.38]$$

CMS result (ATLAS similar)

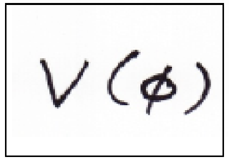
Higgs self-interactions



$$\frac{3m_H^2}{v}$$



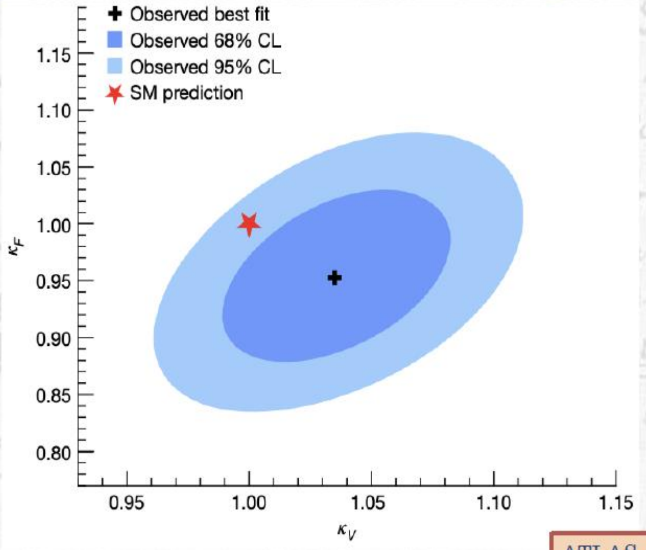
$$\frac{3m_H^2}{v^2}$$



Large trilinear deviations are possible while deviations of the Higgs to Z coupling remain small

Status of Higgs Couplings

What are experimental limits on modifications of couplings relative to Standard Model prediction?



ATLAS, Nature, 2022

Higgs physics is still in its nascence. Pions were discovered in the early 1940's. Their fundamental origin, QCD, was developed theoretically in the early 1970's and only experimentally established in the late 1970's.

Twelve years since discovery of the Higgs boson.

As it stands, we don't know how it interacts with itself, or if it is composite; with far-reaching implications.

Precision Hadronic Flavour Physics: Mixings and CP Violation in the SM Quark sector

The Unitarity Triangle Analysis

- Flavor-changing processes and CP violation in the SM ruled by 4 parameters in the 3x3 CKM (unitary) matrix

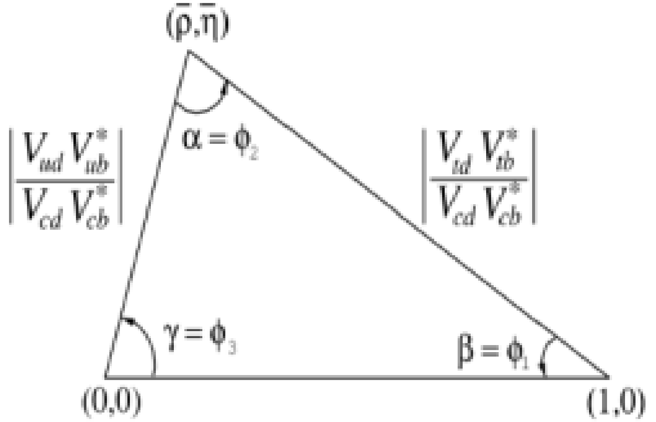
$$V_{\rm CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- $A, \lambda, \bar\rho$ and $\bar\eta$

$$\bar\rho = \rho(1-\lambda^2/2+\ldots) \quad \bar\eta = \eta(1-\lambda^2/2+\ldots)$$

- Small value sin of Cabibbo angle (λ) makes the CKM matrix close to diagonal

- Unitarity implies relations between elements, that can be represented as a triangle in a plane



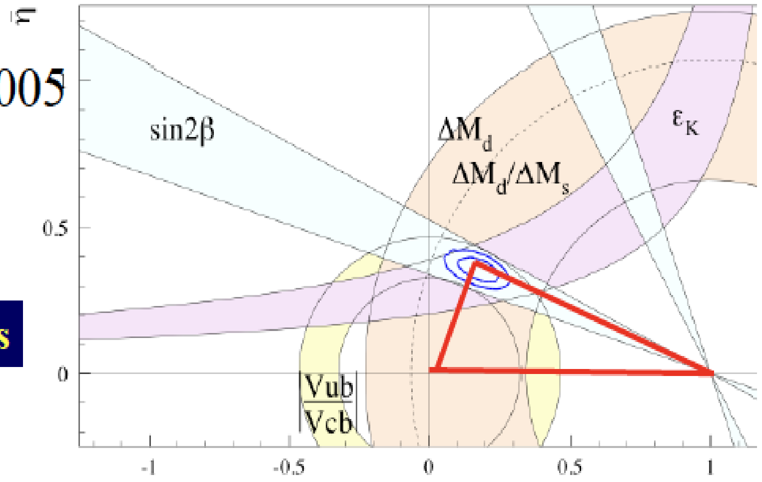
- By determining th[...] CKM matrix

$\text{Sin}\,\theta_{12} = \lambda$
$\text{Sin}\,\theta_{23} = A\,\lambda^2$
$\text{Sin}\,\theta_{13} = A\,\lambda^3(\rho - i\,\eta)$

$$\delta_{13} = \gamma = \phi_3$$

UTfit

Unitary Triangle SM



semileptonic decays

Experimental cor

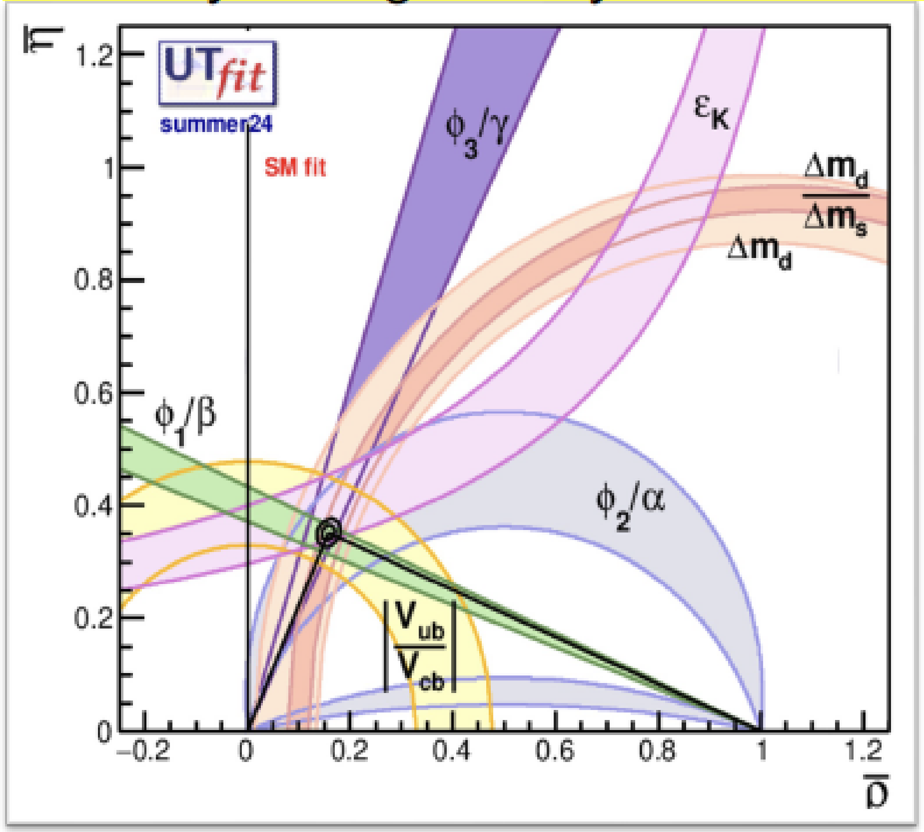
Meas.	$V_{CKM}\times$other	$(\bar\rho,\bar\eta)$
$\frac{b\to u}{b\to c}$	$\lvert V_{ub}/V_{cb}\rvert^2$	$\bar\rho^2+\bar\eta^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d}$	$(1-\bar\rho)^2+\bar\eta^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert^2 \xi^2$	$(1-\bar\rho)^2+\bar\eta^2$
ϵ_K	$f(A,\bar\eta,\bar\rho,B_K)$	$\propto \bar\eta(1-\bar\rho)$
$A(J/\psi K^0)$	$sin2\beta$	$\frac{2\bar\eta(1-\bar\rho)}{\sqrt{\bar\eta^2+(1-\bar\rho)^2}}$

K^0 - $\bar{K}^0$ mixing

B_d

$B^0_{d,s}$ - $\bar{B}^0_{d,s}$ mixing

Unitarity Triangle analysis in the SM:



levels @ 95% Prob

$\rho = 0.158 \pm 0.009$
$\eta = 0.352 \pm 0.010$

$\lambda = 0.2250 \pm 0.0007$

$A = 0.826 \pm 0.009$

At the present level of accuracy, i.e. ~ %, all measurements are consistent and intersect at the apex of the UT → no hints for BSM New Physics, however lessons from the past (CP violation!) that % accuracy may not be enough …

Conceivable progress in the "mid-term" of flavour

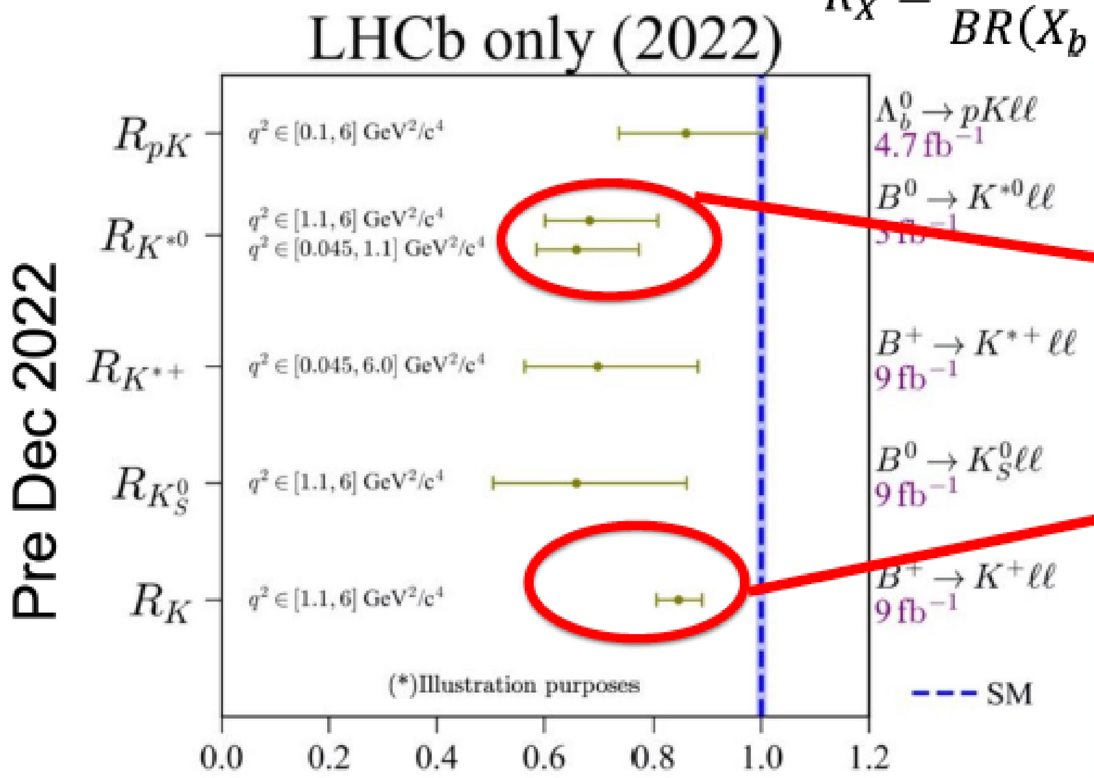
Input	Reference	Measurement	UTfit Prediction	Pull	current	mid-term
$\sin 2\beta$	[22], UTfit	0.688(20)	0.736(28)	−1.4	4%th/exp	0.6%
γ	[22]	66.1(3.5)	64.9(1.4)	+0.29	5%exp	0.8%
α	UTfit	94.9(4.7)	92.2(1.6)	+0.6	5%exp	0.4%
$\varepsilon \cdot 10^3$	[38]	2.228(1)	2.00(15)	+1.56	8%th	
$\|V_{ud}\|$	UTfit	0.97433(19)	0.9738(11)	+0.03	0.1%th	
$\|V_{ub}\| \cdot 10^3$ •	UTfit	3.77(24)	3.70(11)	+0.25	8%exp/th	1%
$\|V_{ub}\| \cdot 10^3$ (excl)	[39]	3.74(17)				
$\|V_{ub}\| \cdot 10^3$ (incl)	[22]	4.32(29)				
$\|V_{cb}\| \cdot 10^3$ •	UTfit	41.25(95)	42.22(51)	−0.59	2%exp/th	0.5%
$\|V_{cb}\| \cdot 10^3$ (excl)	UTfit	39.44(63)				
$\|V_{cb}\| \cdot 10^3$ (incl)	[40]	42.16(50)				
$\|V_{ub}\|/\|V_{cb}\|$	[39]	0.0844(56)				
$\Delta M_d \times 10^{12}\,\mathrm{s}^{-1}$	[38]	0.5065(19)	0.519(23)	−0.49	5%th/exp	2%
$\Delta M_s \times 10^{12}\,\mathrm{s}^{-1}$	[38]	17.741(20)	17.94(69)	−0.30	4%th	1.5%
$\mathrm{BR}(B_s \to \mu\mu) \times 10^9$	[38]	3.41(29)	3.47(14)	−0.14	9%exp	4%
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	[38]	1.06(19)	0.869(47)	+0.96	20%exp	4%
$\mathrm{Re}\,(\varepsilon'/\varepsilon) \times 10^4$	[38]	16.6(3.3)	15.2(4.7)	+0.27	30%th	
$(\|q/p\|_D - 1) \times 10^2$		0.05(2.50)	0.8(4.0)	−0,15	100%th*	30%*
$BR(B^+ \to K^+\nu\nu)10^6$		23(7)	5.58(37)	+2.5	35%exp	10%
$BR(K^+ \to \pi^+\nu\nu)10^{11}$		10.6(4.0)	9.31(76)	+0,3	40%exp	20%
R_D		0.344(26)	0.298(4)	+1.7	8%exp	3%
R_{D^*}		0.285(12)	0.254(5)	+2.3	4%exp	2%

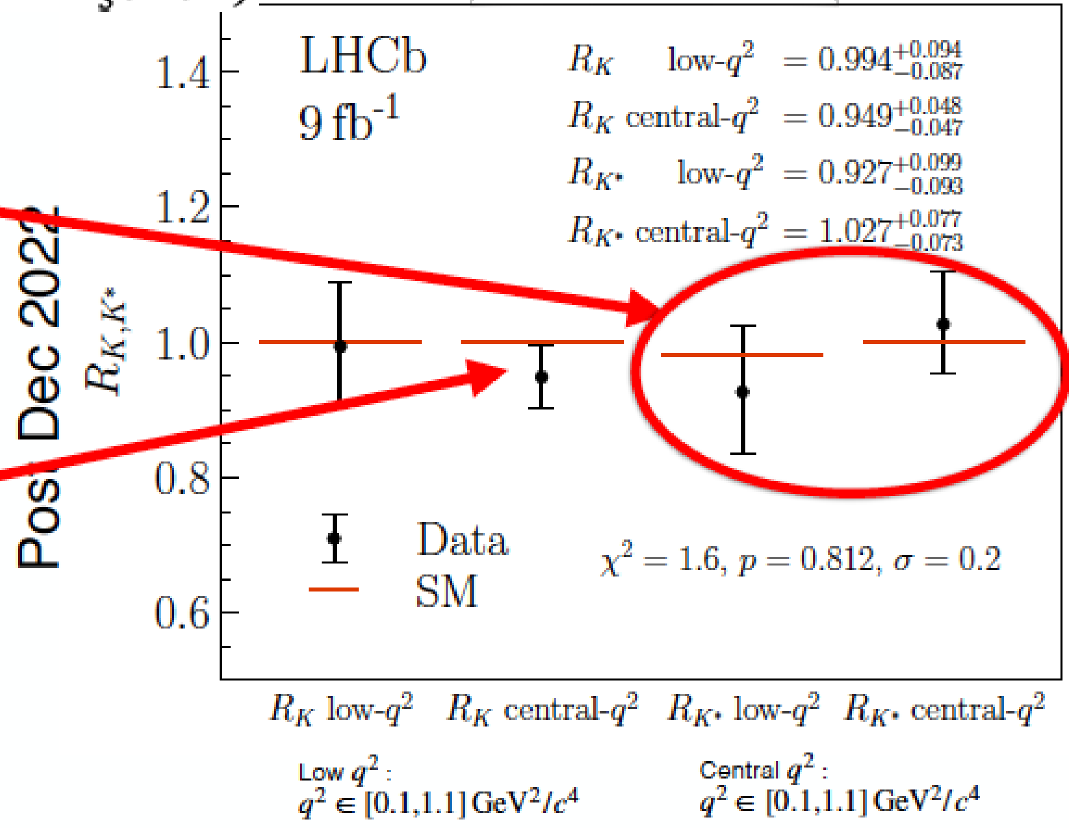
with strong correlations!

Tests of Lepton Flavour Universality

$$R_X = \frac{BR(X_b \to X_s \mu^+ \mu^-)}{BR(X_b \to X_s e^+ e^-)}$$

arXiv:2212.09152
arXiv:2212.09153





A remaining flavor puzzle in B physics?

A puzzling result
in tree-level $b \to c$ transitions

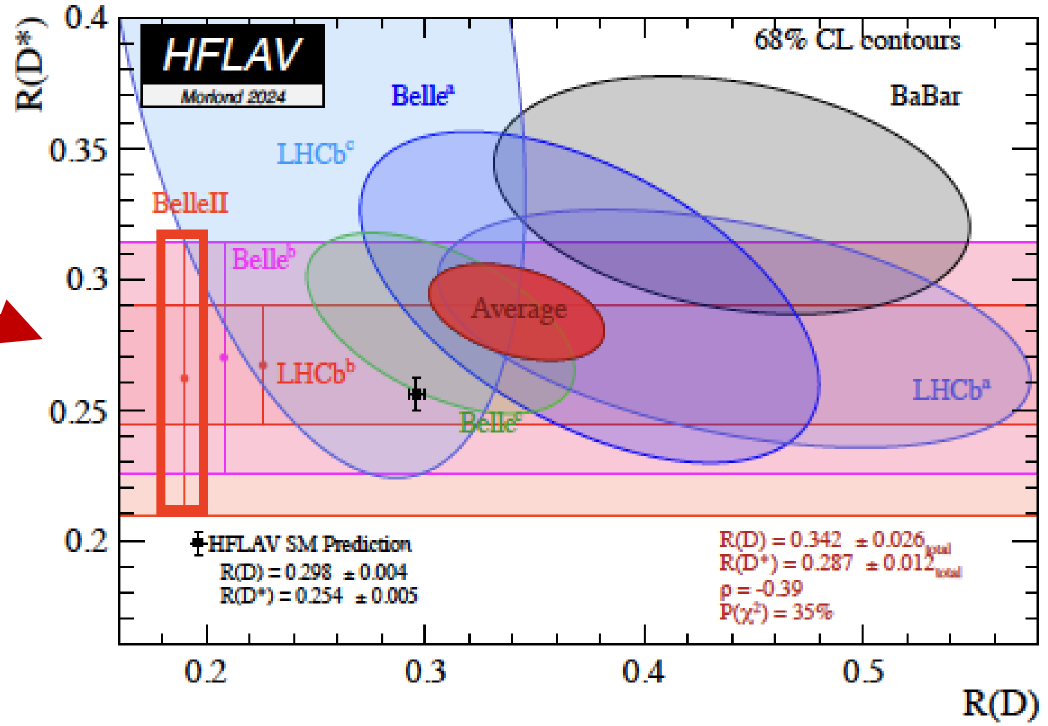
~3σ tension

In conclusion, **NO firm hints for any discrepancy between SM expectations and experimental results in the many and accurate tests in FLAVOR PHYSICS** (FCNC, lepton flavor universality in K,D, B semileptonic decays, etc.)

First Belle II RD* measurement!

Both TH and EXP clean!

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{\mathcal{B}\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$

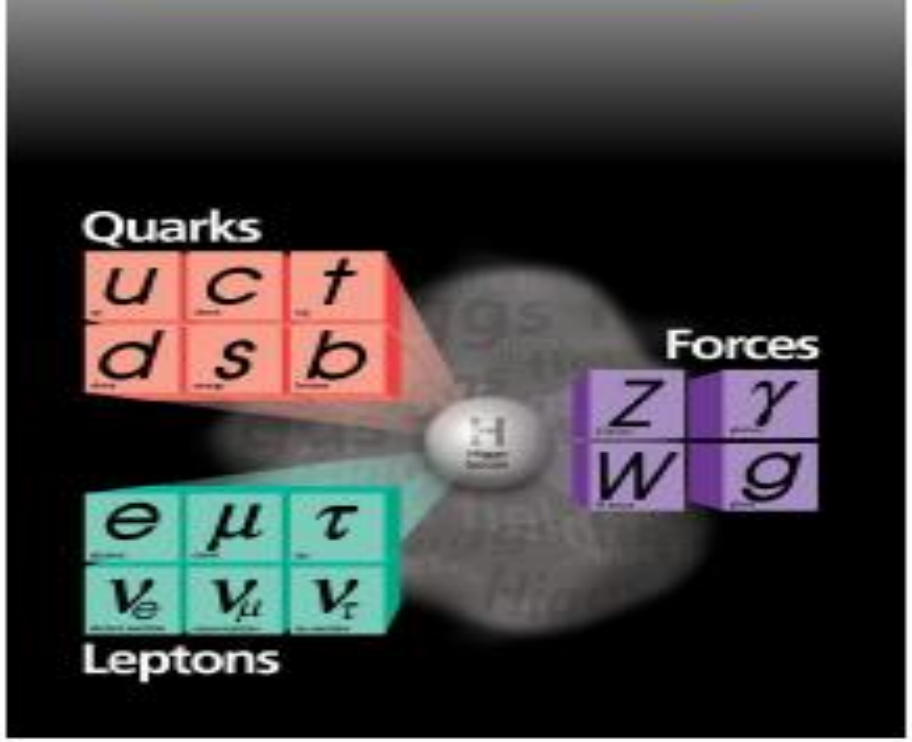


$$R_D^* = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

UV Theory

↓

SM (EFT)



The flavor structure of the SM-EFT

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

U(3)^5 flavor symmetry

Flavor-degeneracy broken by the Yukawa interaction

Three identical replica of the basic fermion family [$\psi = Q_L, u_R, d_R, L_L, e_R$]

↓

U(3)^5 symmetry

Breaking structure which is

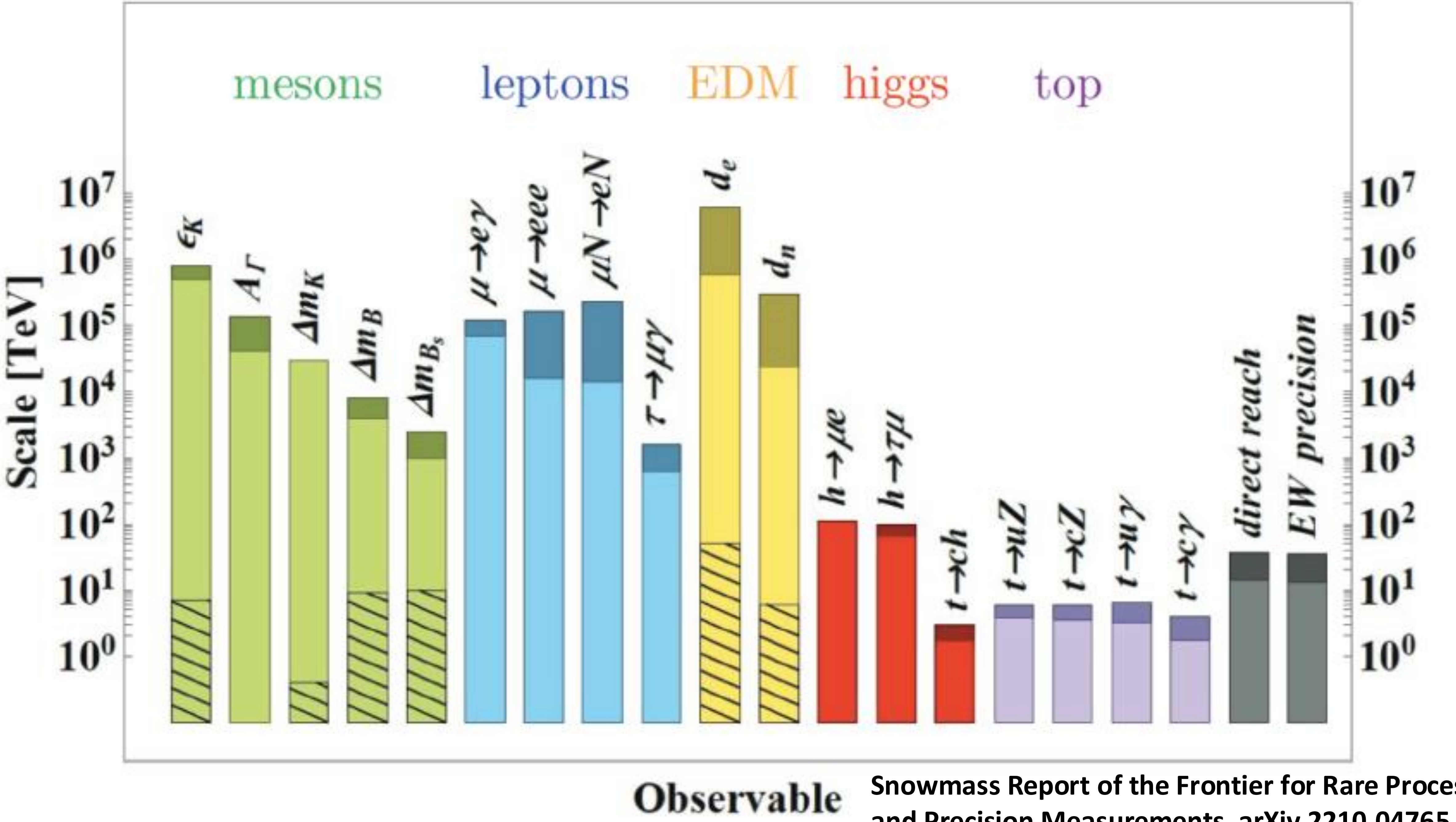
- confined to LR terms (by EW symm + d=4)
- *Highly non-generic*

Eg

$$Y_U \sim \begin{pmatrix} \sim 10^{-5} & \sim 10^{-4} & 0.003 \\ & 0.005 & 0.04 \\ & & \boxed{1} \end{pmatrix}$$

$$\mathcal{L}_Y = \bar{Q}_L Y_U U_R H + \ldots$$

Y_U in the basis where Y_D is diagonal



Snowmass Report of the Frontier for Rare Processes and Precision Measurements arXiv 2210.04765

The flavor structure of the SM-EFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

Flavor-degeneracy: $U(3)^5$ symmetry

Yukawa couplings: $U(3)^5 \rightarrow \sim U(2)^n$
peculiar breaking of the flavor symm.

Stringent bounds on additional symmetry breaking terms

3 classes of "interpretations"

- ~~"Simplicity": the scale of NP is high (> 10^5 TeV) → no way to test the origin of the Y's~~
- "High-scale flavor dynamics" & MFV: the scale of NP is low, but $U(3)^5$ is broken @ high scales
- "Flavor deconstruction": the scale of NP is low & $U(2)^n$ emerges as accidental symm. from flavor non-universal gauge interactions @ nearby scales

No "QFT solution" to EW hierarchy problem

"decoupling" of flavor & EW problems

"interplay" of flavor & EW problems

FLAVOUR DECONSTRUCTION

Barbieri, Isidori, 2024

Going beyond the EFT approach, a consistent way to construct a multi-scale theory with flavor non-universal interactions is via the "*flavor deconstruction*" of the SM gauge symmetries:

Arkani-Hamed, Cohen, Georgi '01
Craig, Green, Katz, '11
...

⋆ Basic idea:

$$G^{[1]} \times G^{[2]} \longrightarrow G^{[12]}$$

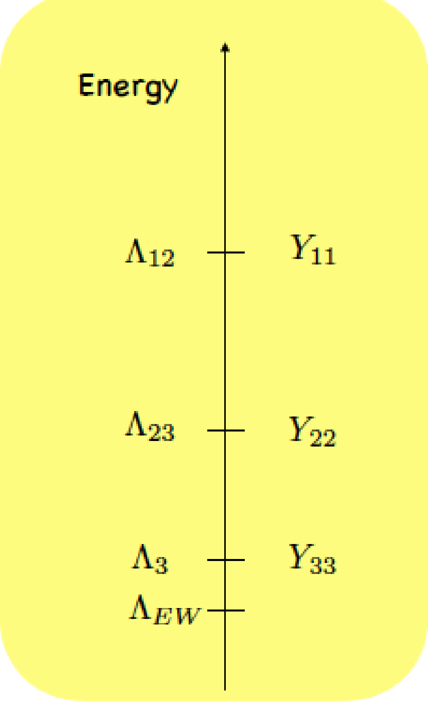
flavor non-univ. groups acting on single families

flavor univ. group acting on both families

1. The $SU(3) \times SU(2) \times U(1)$ gauge interactions are (fully or in part) flavour non-universal

Unlike $SU(3) \times SU(2) \times U(1) \times G^{[i]}$ gauged, global, discrete, etc

2. The flavour universal gauge interactions (observed so far) are a low energy manifestation of the step-wise breaking of the gauge group at different scales, responsible for the hierarchical structure of the Yukawa couplings

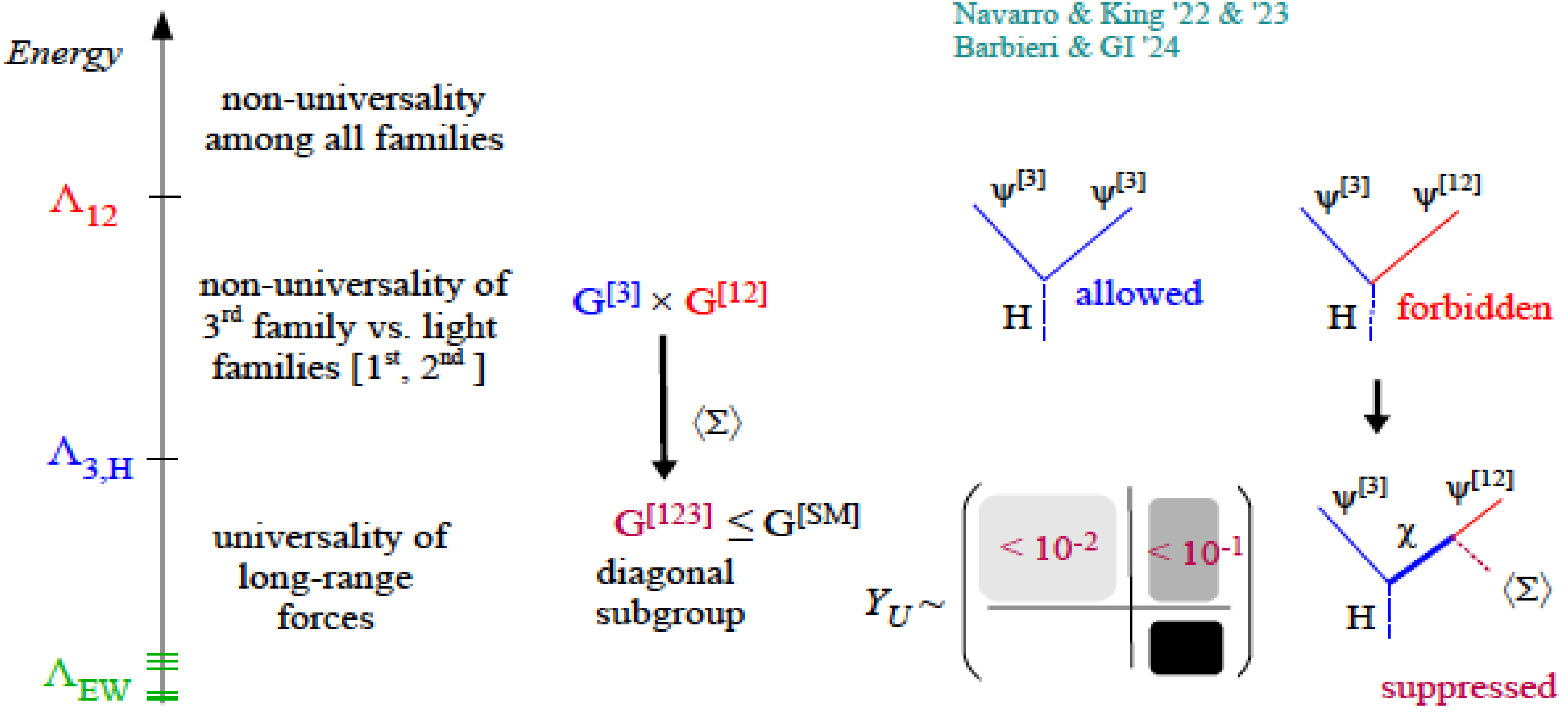


Davighi, Isidori, 2023; Davighi et al., 2023
Fernando-Navarro, King, 2023;

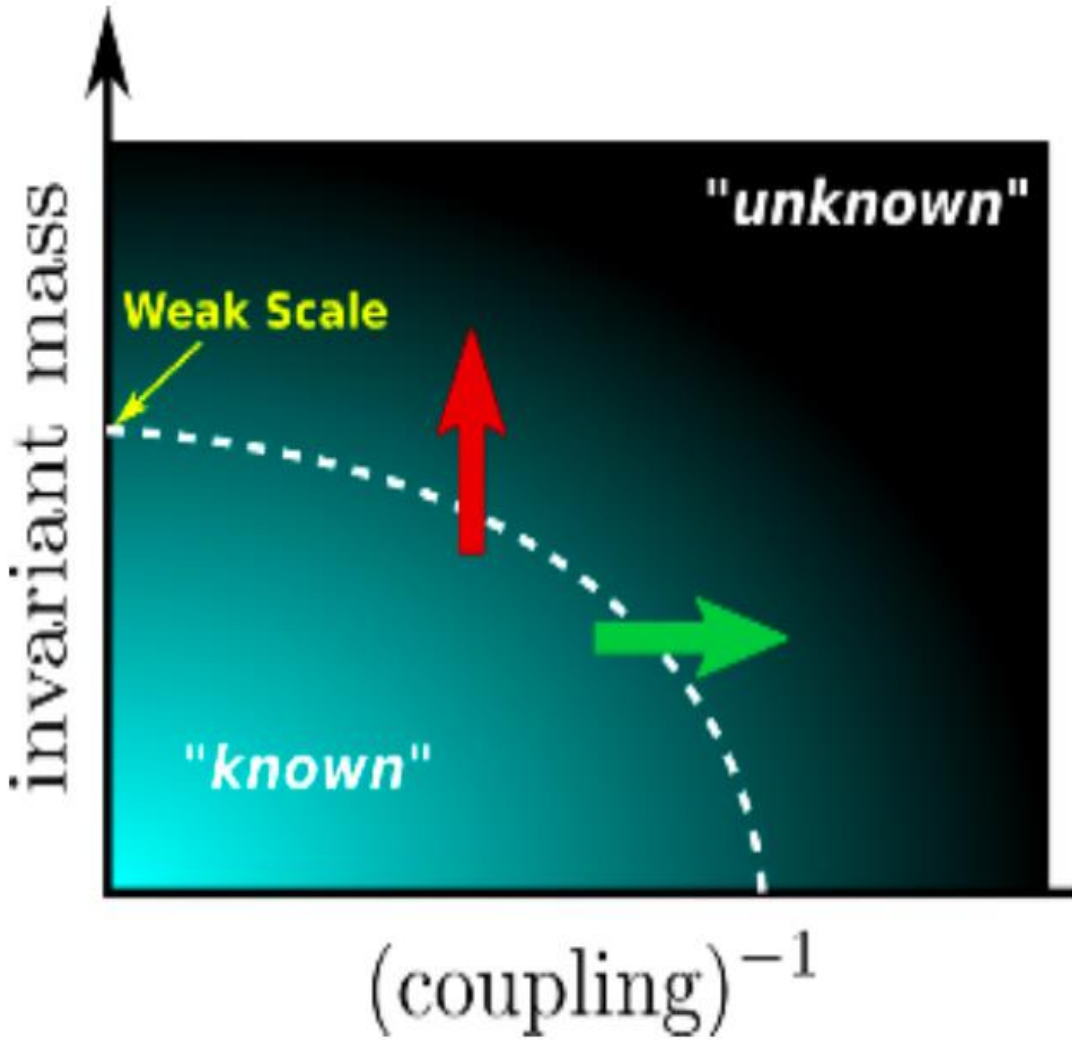
▶ *Flavor deconstruction*

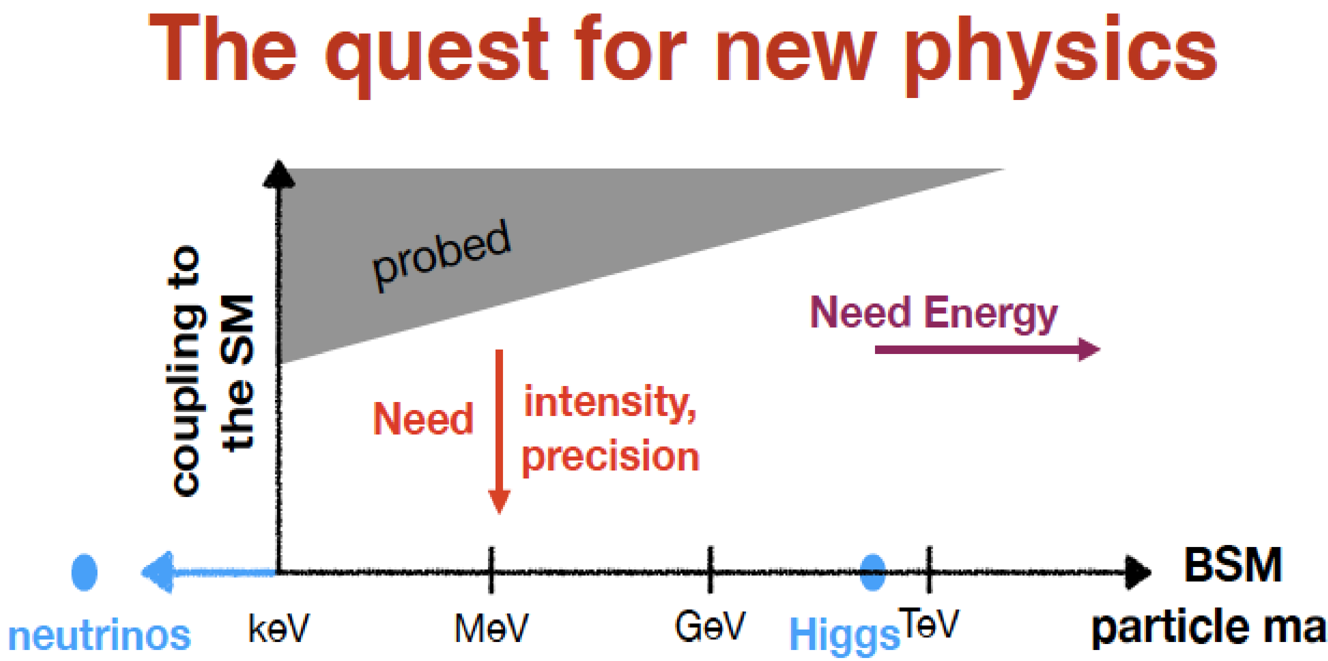
Going beyond the EFT approach, a consistent way to construct a multi-scale theory with flavor non-universal interactions is via the "*flavor deconstruction*" of the SM gauge symmetries:

Bordone *et al.* '17, Allwicher *et al.* '20
Davighi & GI '23, Davighi & Stefanek '23
Navarro & King '22 & '23
Barbieri & GI '24



How to approach the "Unknown"

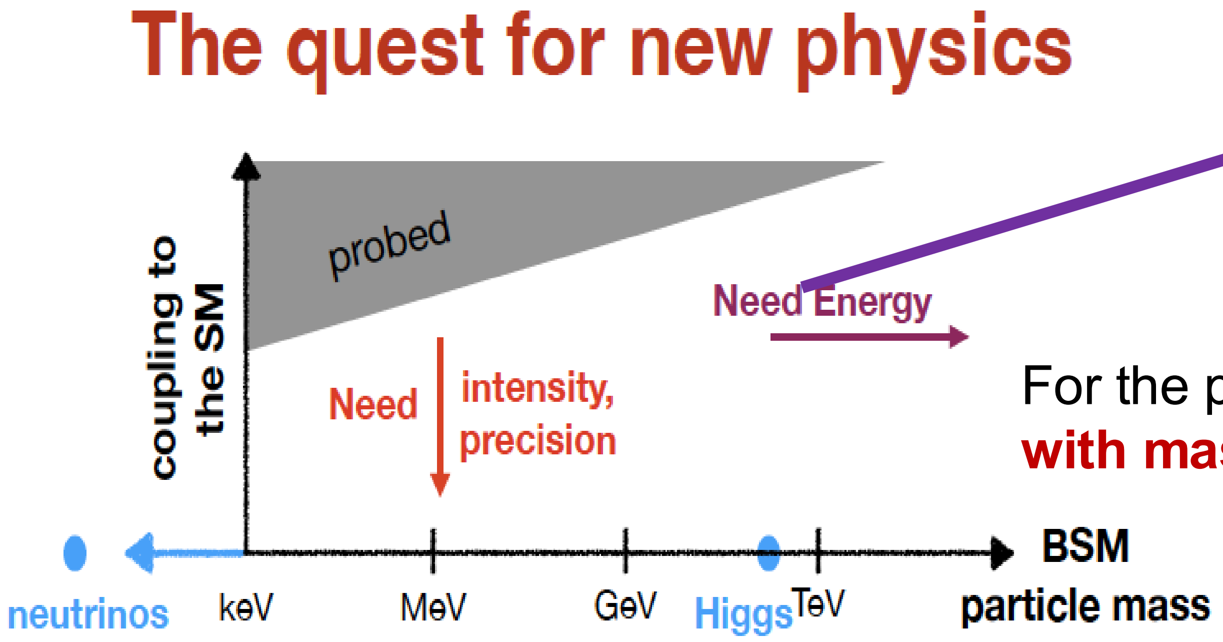




We do not know what will be the next New Physics (NP) scale.

Gori, ICHEP 2024

The twofold role of the Frontier for Rare Processes and Precision Measurements



Need **intensity, precision** for the production of **virtual new particles with masses >> M_W**

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

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

Complementary (*not* ALTERNATIVE!) approach → HIGH-PRECISION SMALL/MID-SCALE EXPS.

Low-energy high-precision exps. can exploit :

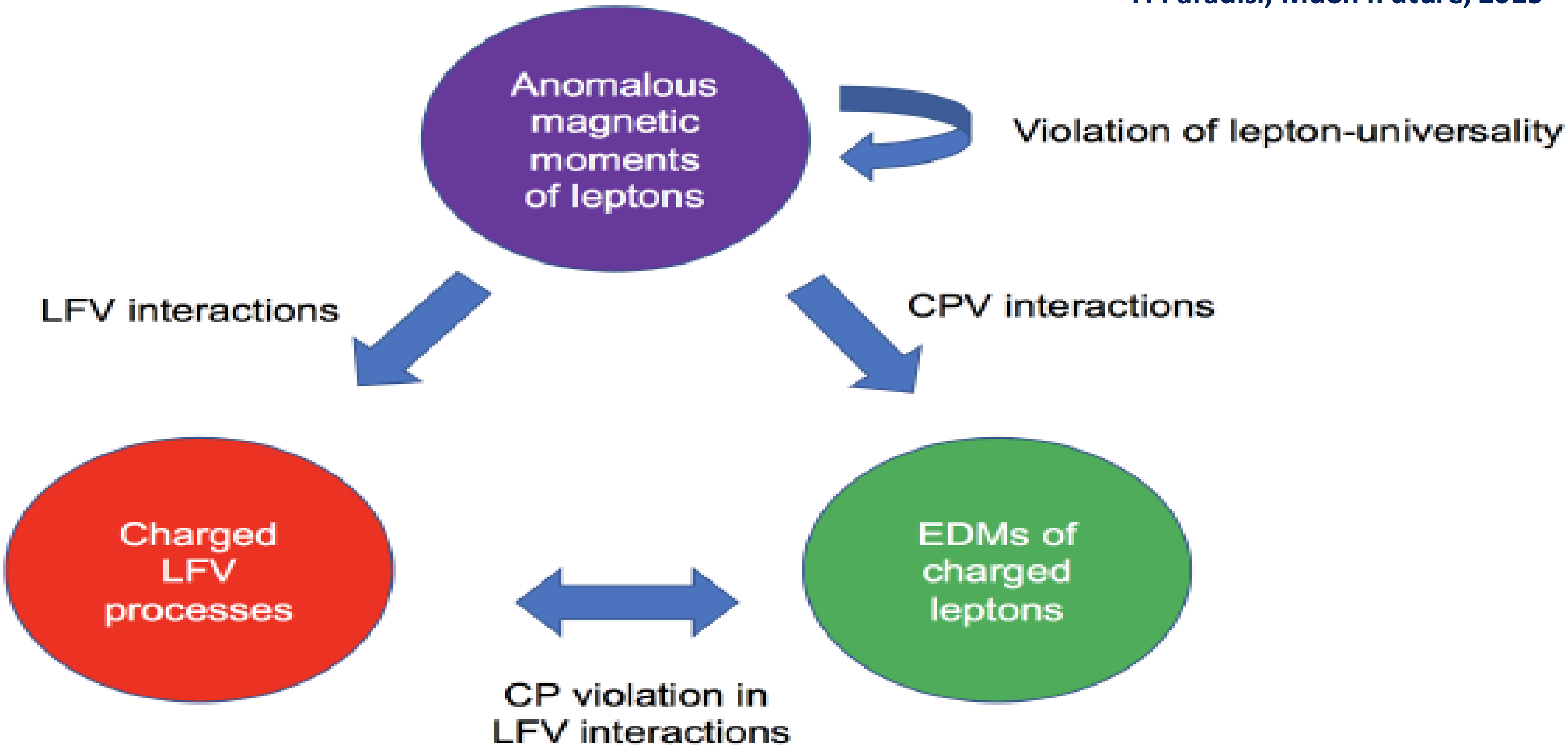
- many recent ***advances in experimental techniques and technologies*** + **(experimental as well as theoretical)** ***synergies*** with adjacent areas of particle physics (atomic, molecular, optical, nuclear, particle physics)
- the relevant impact of ***quantum mechanical virtual effects*** on physical phenomena → access to the exploration of BSM new physics areas (large energy scales, very feebly coupled new particles, hidden sectors, etc.) difficult to be probed by traditional HE particle physics

SYNERGY between small/mid-scale & large-scale experiments → casting a wider and tighter net for possible effects of BSM physics

Community Planning Exercise: Snowmass 2021 Blum, Winter et al. arXiv:2209.08041v2 → **2023 P5 (Particle Physics Project Prioritization Panel) Report**

Probing NP in the leptonic sector

P. Paradisi, Muon4Future, 2025



EFT approach to LFV

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

$\mu \to e\gamma$ $\mu \to 3e$ $\mu \to e$

Correlating LFV signals

- **LFV** operators **@ dim-6**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2_{\rm LFV}} \mathcal{O}^{\rm dim-6} + \ldots .$$

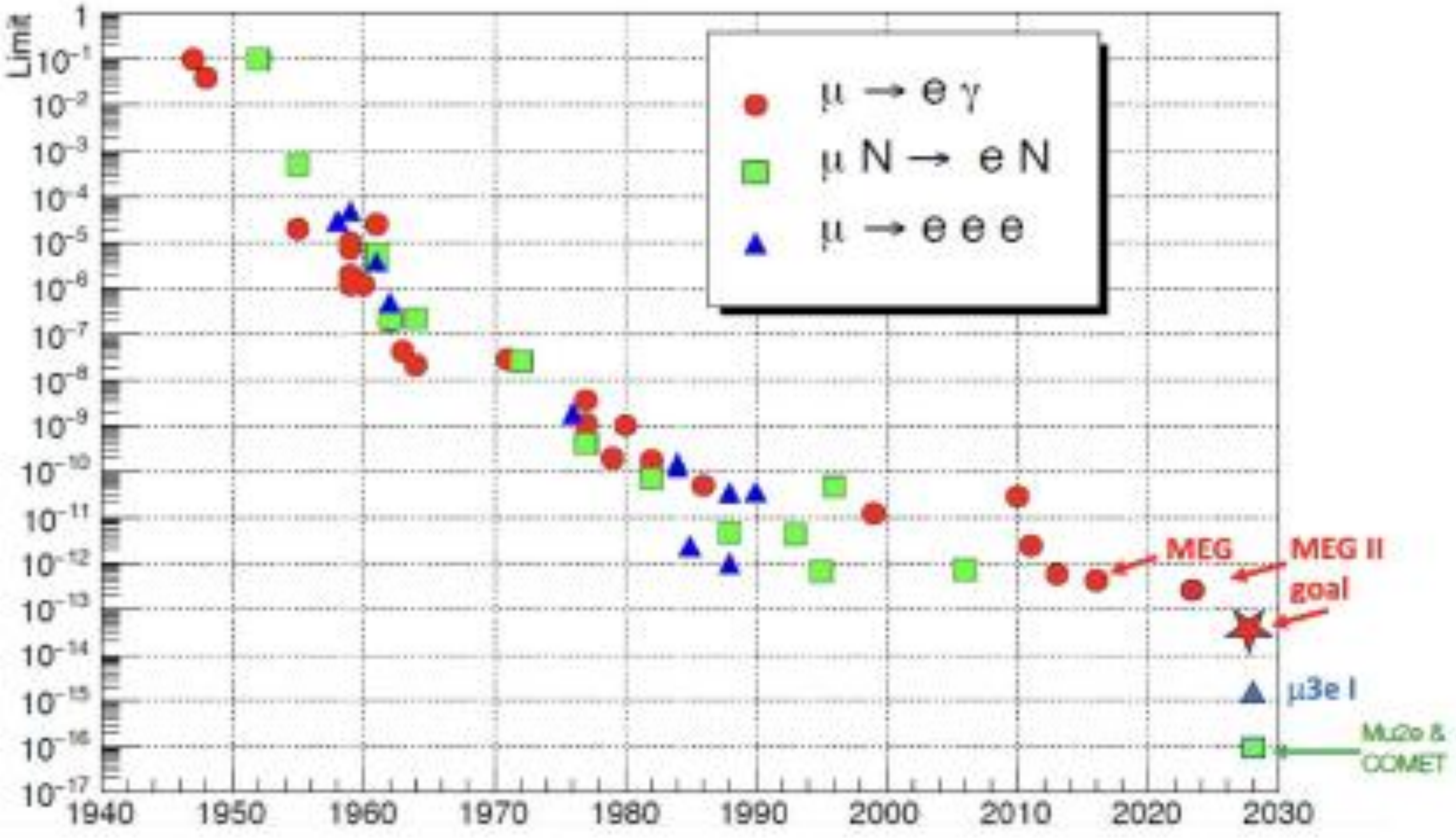
$$\mathcal{O}^{\rm dim-6} \ni \quad \bar{\mu}_R \, \sigma^{\mu\nu} \, H \, e_L \, F_{\mu\nu} \, , \quad (\bar{\mu}_L \gamma^\mu e_L) \left(\bar{f}_L \gamma^\mu f_L \right) \, , \quad (\bar{\mu}_R e_L) \left(\bar{f}_R f_L \right) \, , \; f = e, u, d$$

- $\ell \to \ell' \gamma$ probe ONLY the dipole-operator (at tree level)
- $\ell_i \to \ell_j \bar{\ell}_k \ell_k$ and $\mu \to e$ in Nuclei probe dipole and 4-fermion operators
- When the dipole-operator is dominant:

$$\mathrm{BR}(\ell_i \to \ell_j \ell_k \bar{\ell}_k) \approx \alpha \times \mathrm{BR}(\ell_i \to \ell_j \gamma)$$
$$\mathrm{CR}(\mu \to e \text{ in N}) \approx \alpha \times \mathrm{BR}(\mu \to e\gamma)$$

$$\frac{\mathrm{BR}(\mu \to 3e)}{3 \times 10^{-15}} \approx \frac{\mathrm{BR}(\mu \to e\gamma)}{5 \times 10^{-13}} \approx \frac{\mathrm{CR}(\mu \to e \text{ in N})}{3 \times 10^{-15}}$$

- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**



Limit
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
$\mu \to e\,\gamma$
$\mu N \to e N$
$\mu \to e e e$
MEG
MEG II
goal
μ3e I
Mu2e &
COMET

Experimental bounds

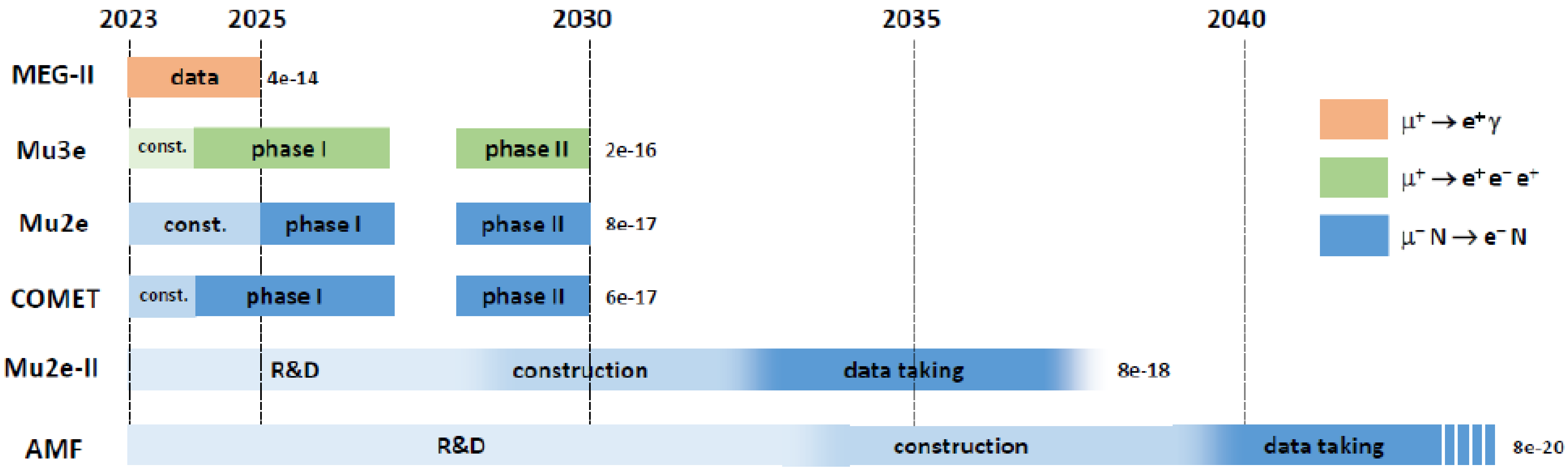
Process	Present	Experiment	Future	Experiment
$\mu \to e\gamma$	1.5×10^{-13}	MEG	$\approx 6 \times 10^{-14}$	MEG II
$\mu \to 3e$	1.0×10^{-12}	SINDRUM	$\approx 10^{-16}$	Mu3e
μ^- Au $\to e^-$ Au	7.0×10^{-13}	SINDRUM II	?	
μ^- Ti $\to e^-$ Ti	4.3×10^{-12}	SINDRUM II	?	
μ^- Al $\to e^-$ Al	–		$\approx 10^{-16}$	COMET, MU2e
$\tau \to e\gamma$	3.3×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to \mu\gamma$	4.4×10^{-8}	Belle & BaBar	$\sim 10^{-9}$	Belle II
$\tau \to 3e$	2.7×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$\tau \to 3\mu$	2.1×10^{-8}	Belle & BaBar	$\sim 10^{-10}$	Belle II
$d_e(\mathrm{e\ cm})$	1.1×10^{-29}	ACME	$\sim 3 \times 10^{-31}$	ACME III
$d_\mu(\mathrm{e\ cm})$	1.8×10^{-19}	Muon (g-2)	$\sim 10^{-22}$	PSI

Table: Present and future experimental sensitivities for relevant low-energy observables.

- So far, only upper bounds. Still excellent prospects for exp. improvements.
- We can expect a NP signal in all above observables below the current bounds.

Charged Lepton Flavor Violation (CLFV)

CLFV not observed yet → any CLFV observation would be a clear sign of New Physics
→ a portal to High-Energy (GUT-scale?) NP or Low-Energy (feebly coupled) NP



Advanced Muon Facility at Fermilab

Muon CLFV searches → a **global experimental (and theoretical) program** underway in EU, US and Asia → **impressive sensitivity gains** expected in this decade, with up to **4 orders of magnitude** improvements in the rate of **$\mu^- N \to e^- N$** conversion and **$\mu^+ \to e^+ e^- e^+$** decay searches

LFV, $(g-2)_{\rm lept}$ and $(\rm EDM)_{\rm lept}$ 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. $(g-2)_\mu$

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

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

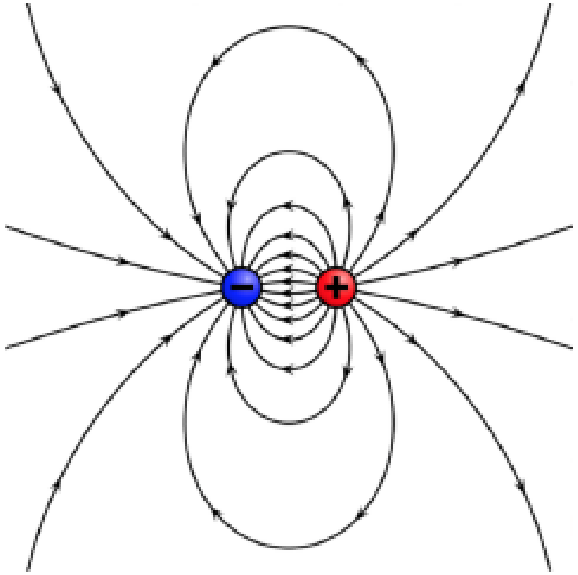
- Main messages:
  - $\Delta a_\mu \approx (3 \pm 1) \times 10^{-9}$ requires a nearly flavor and CP conserving NP
  - Large effects in the muon EDM $d_\mu \sim 10^{-22}$ $e\,\mathrm{cm}$ are still allowed!

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

Electric and Magnetic Dipole Moments

interactions of a particle with spin $\vec{S}$
with an electric and magnetic field

$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$



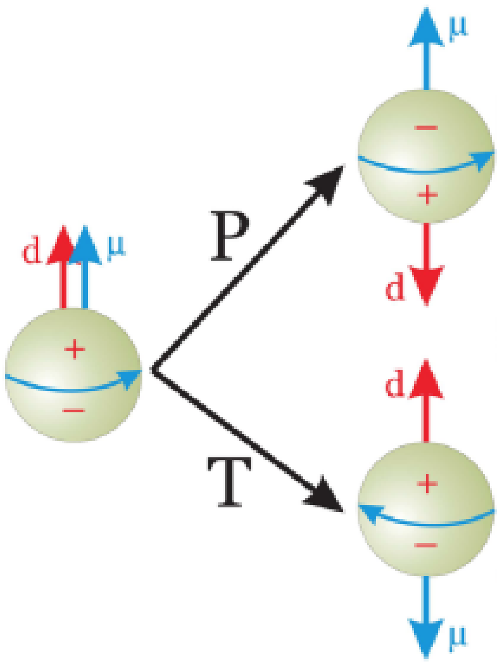
electric dipole moment d
magnetic dipole moment μ

Properties under Charge Conjugation C, Parity P, and Time Reversal T

$$T: \quad \vec{E} \to +\vec{E} \quad \vec{B} \to -\vec{B} \quad \vec{S} \to -\vec{S}$$

$$P: \quad \vec{E} \to -\vec{E} \quad \vec{B} \to +\vec{B} \quad \vec{S} \to +\vec{S}$$

$$\mathcal{H} = -\mu \frac{\vec{S}}{|S|} \cdot \vec{B} - d \frac{\vec{S}}{|S|} \cdot \vec{E}$$



MDMs are P even and T even
EDMs are P odd and T odd

assuming CPT invariance
(= pretty safe assumption):

MDMs are CP conserving
EDMs are CP violating

Relativistic generalization of EDMs and MDMs

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

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

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

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

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

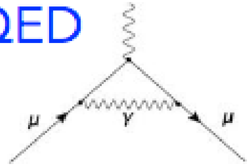
d_f and a_f are described by non-renormalizable interactions of fermions with the photon. They are absent for elementary fermions at the classical level, but can be induced by loop corrections.

The 4 classes of SM contributions to the muon g-2

uncertainty largely dominated by the **hadronic contributions in Vacuum Polarization (HVP)**

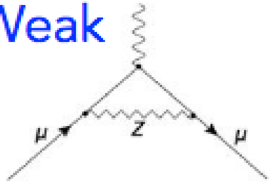
$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})$$

QED



$+\ldots$ $\quad 116\,584\,718.9\,(1) \times 10^{-11}$ $\quad$ 0.001 ppm

Weak

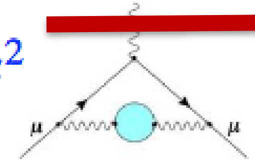


$+\ldots$ $\quad 153.6\,(1.0) \times 10^{-11}$ $\quad$ 0.01 ppm

Hadronic…

…Vacuum Polarization (HVP)

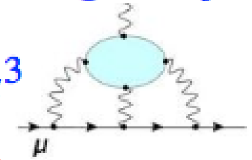
α^2



$+\ldots$ $\quad 6845\,(40) \times 10^{-11}$ [0.6%] $\quad$ 0.37 ppm

…Light-by-Light (HLbL)

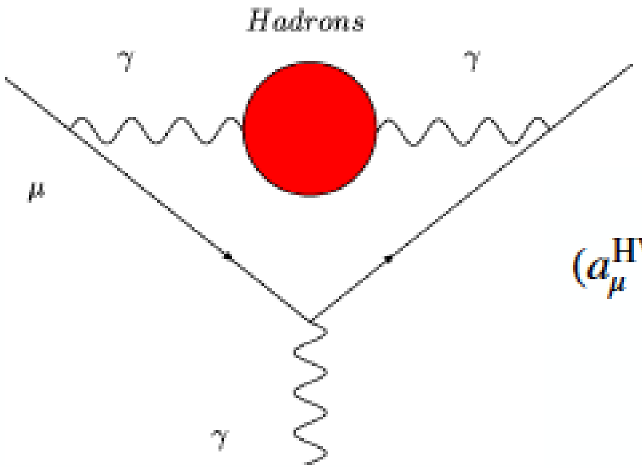
α^3



$+\ldots$ $\quad 92\,(18) \times 10^{-11}$ [20%] $\quad$ 0.15 ppm

Numbers from Theory Initiative Whitepaper

HVP: the major source of uncertainty in the muon g-2 SM computation



$\sim \quad \sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

$$(a_\mu^{\mathrm{HVP}})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\, \mathrm{Im}\,\Pi_{\mathrm{had}}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\mathrm{had}}(s)$$

dispersion relations

optical theorem

kernel function

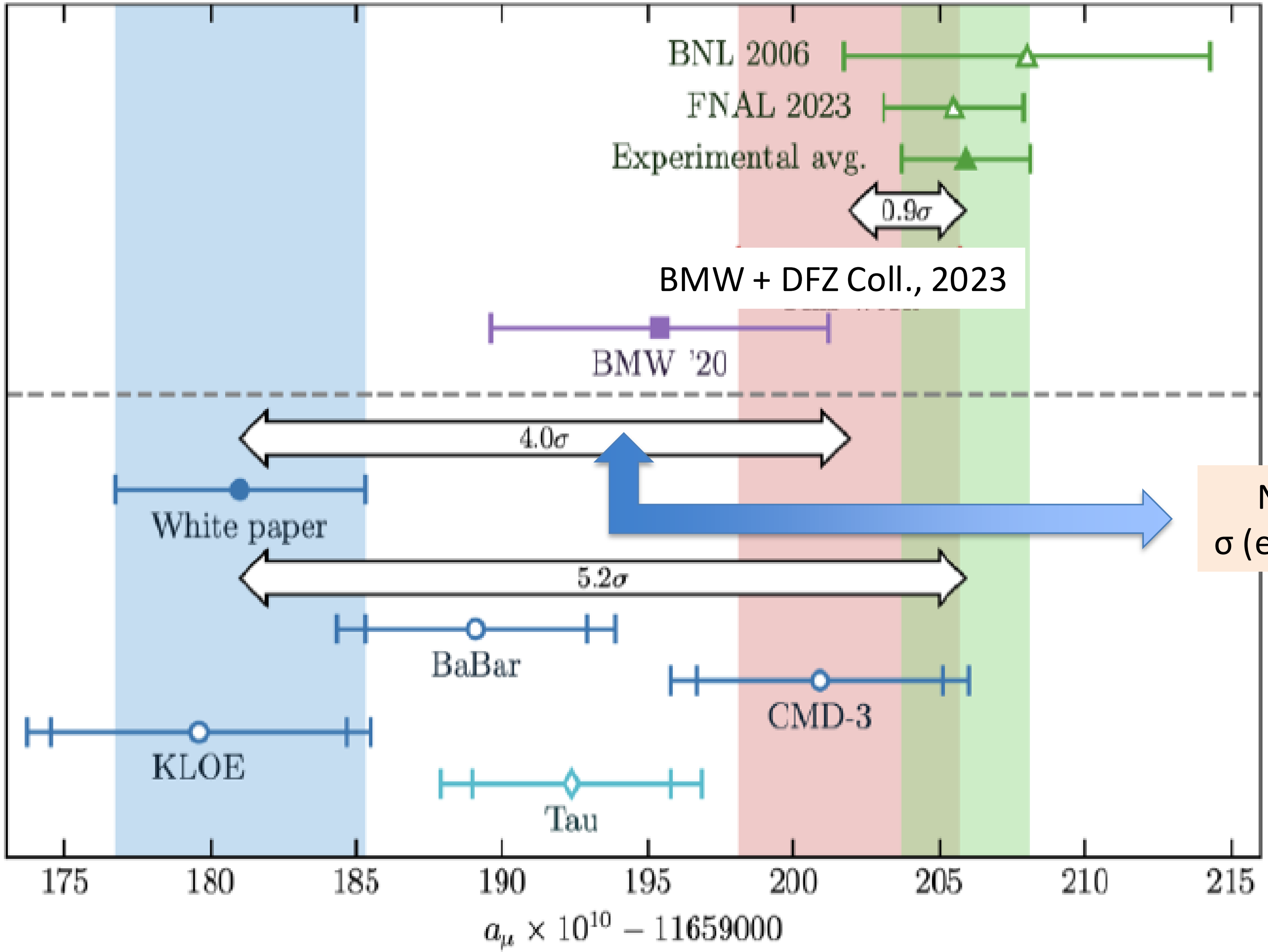
$K(s) \approx m_\mu^2/3s$ for $\sqrt{s} \gg m_\mu$

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$a_\mu^{\mathrm{HLO}} = 6895\ (33) \times 10^{-11}$	F. Jegerlehner, arXiv:1711.06089
$= 6939\ (40) \times 10^{-11}$	Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921
$= 6928\ (24) \times 10^{-11}$	Keshavarzi, Nomura, Teubner, arXiv:1911.00367
$= 6931\ (40) \times 10^{-11}$ (0.6%)	WP20 value

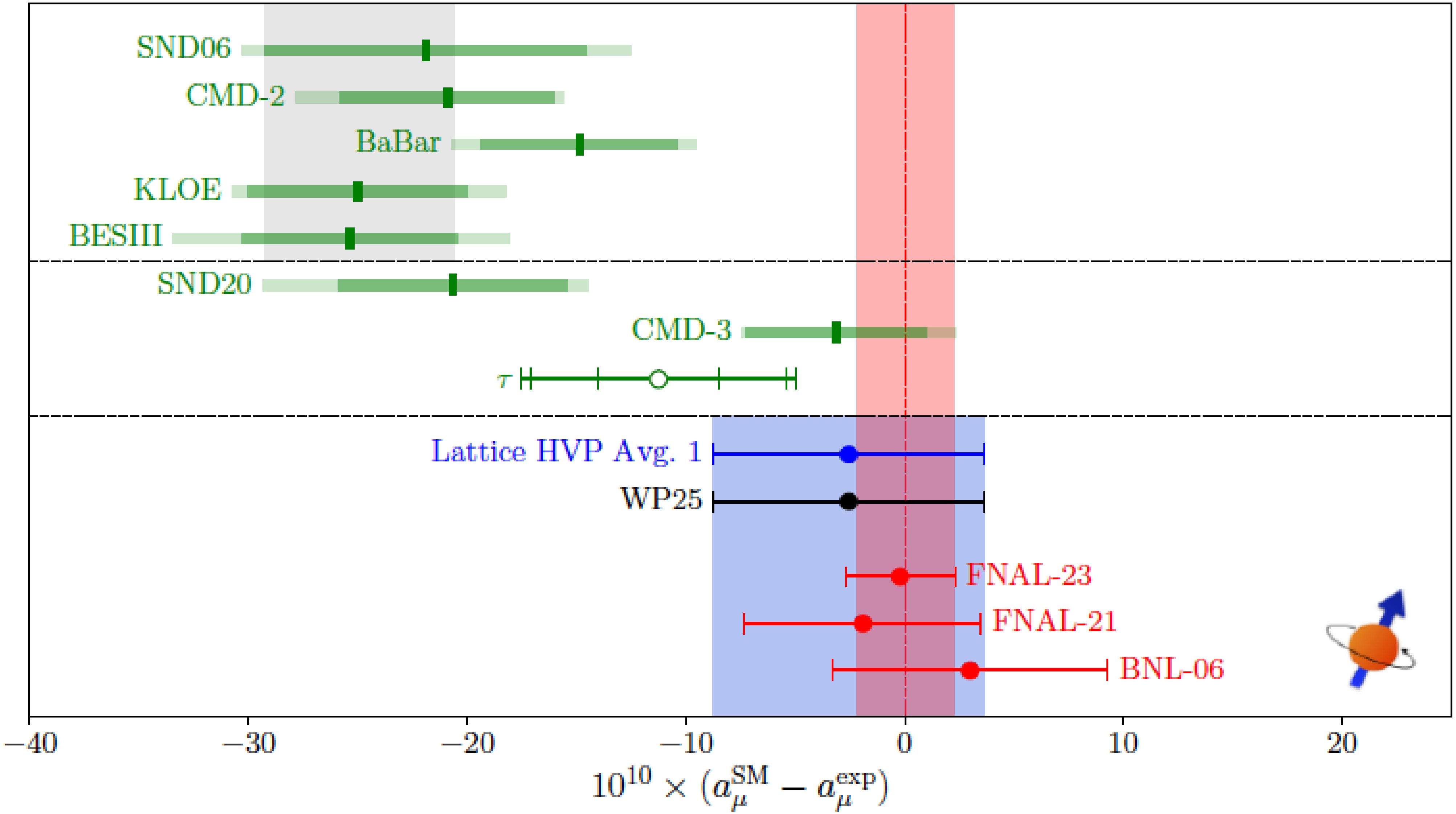
WP20 = White Paper of the Muon g-2 Theory Initiative: arXiv:2006.04822

The (vanishing) OLD and the (still existing) NEW muon g-2 puzzle

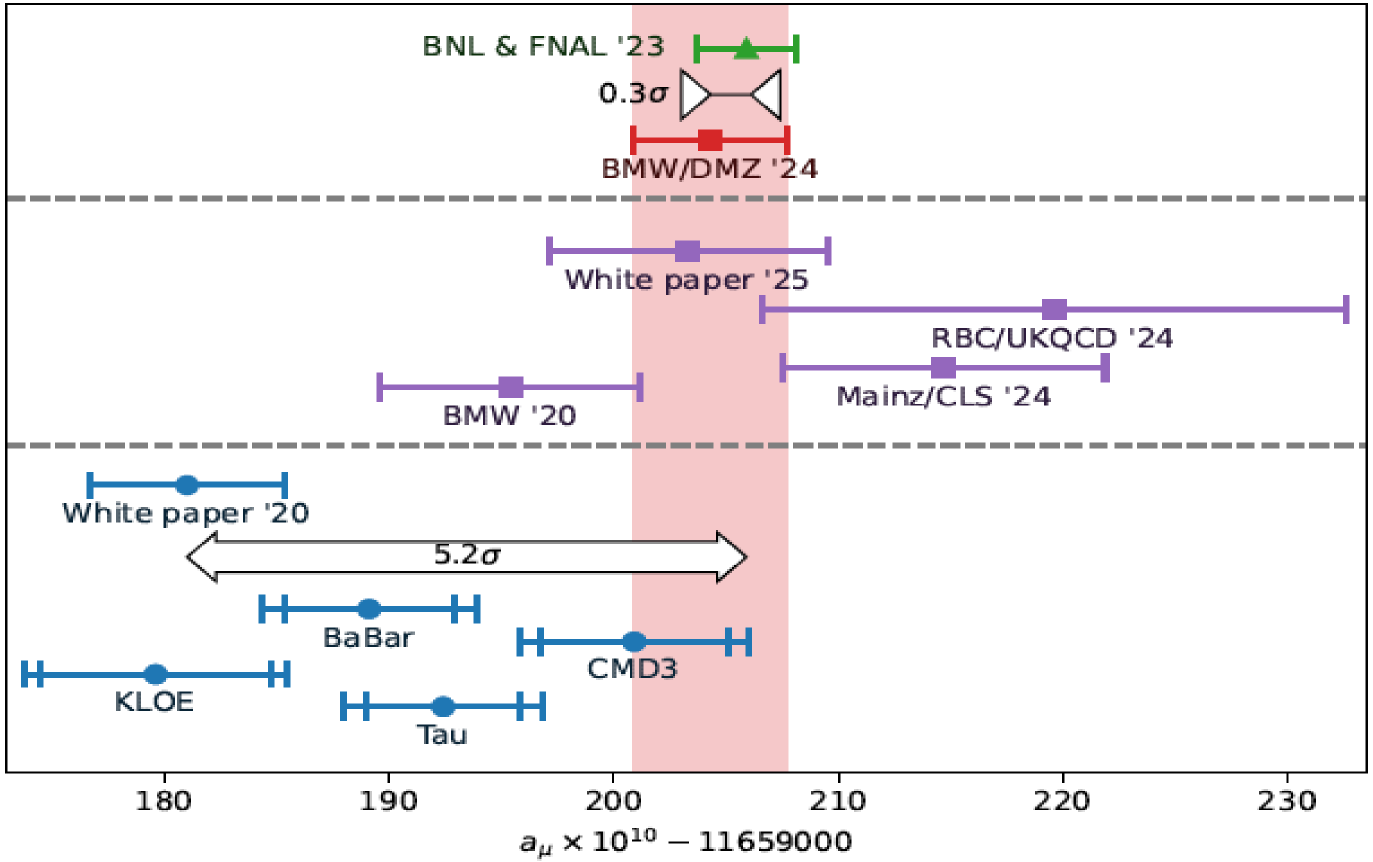


New Physics in
$\sigma\,(e^+e^- \rightarrow \text{hadrons})$?

Summary plot WP25



Experiment vs SM: 27 May 2025



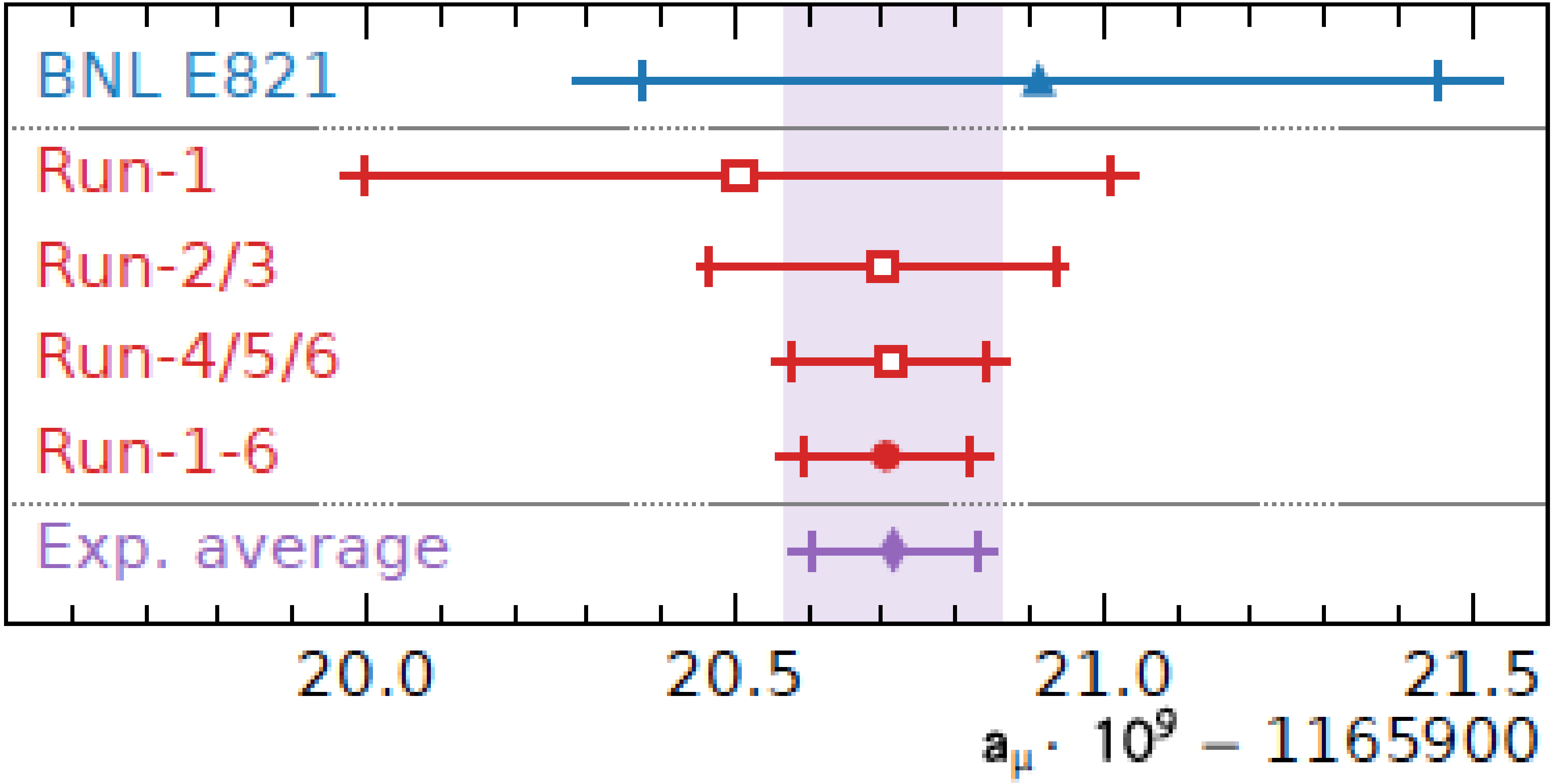
New calculation of $a_\mu^{\text{LO-HVP}}$ + WP '25 indicates SM confirmed to 0.35 ppm !

→ confirmed by two lattice calculations [RBC '24, Mainz '24] to w/in 1.5σ

→ WP '25 is consolidated combination of subcontributions from many lattice calculations

[RBC/UKQCD' 18, 23, 24; ETM '19, 22, 24; BMW '20, 24; LM '20; ABGP '22; Mainz '22, 24, 24; SL '24; FHM '24, 24]

June 3, 2025: Final resul of the Muon g-2 Coll. measuring $(g\text{-}2)_\mu$ to 127 ppb



$(g\text{-}2)_\mu$ measuments at FNAL have improved the precision on the world average by over of factor of four!

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

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

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

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

6.1σ tension

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

Di Luzio, Keshavarzi, A.M. , Paradisi arXiv:2408.01123

Observables to consider →

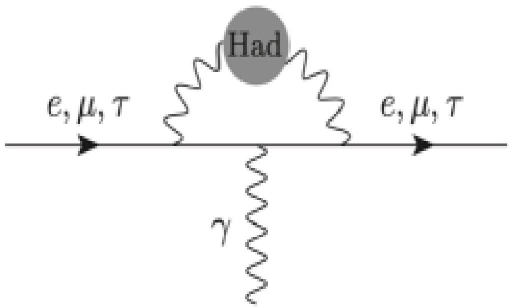
- the Electron g-2 (a_e)
- the Muonium HyperFine Splitting (HFS)
- the Tau g-2 (a_τ)
- the low-energy weak mixing angle $\sin^2\theta_W(0)$
- the running of α_{em}

Sensitivity of other physical observables to

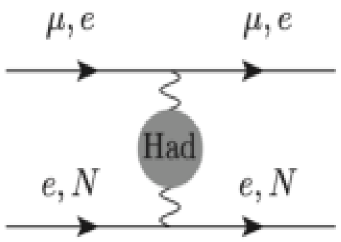
$[\delta a_\mu^{HVP}]_{NP} = [a_\mu^{HVP}]_{LQCD,CDM3} - [a_\mu^{HVP}]_{DR,WP20}$

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

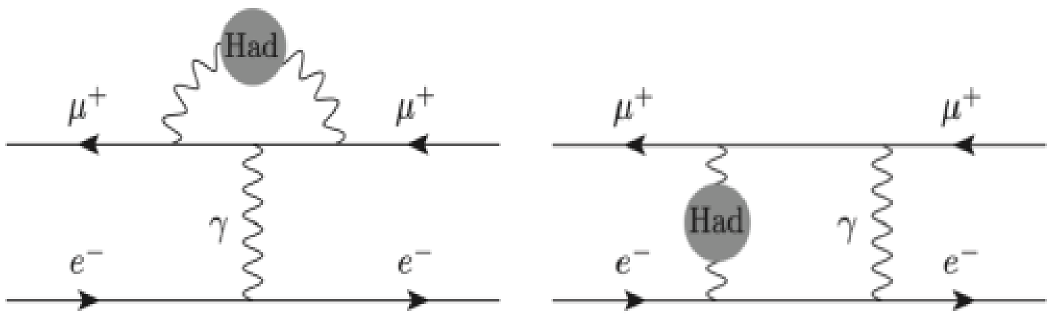
- **the Electron g-2 (a_e)**
- **the Muonium HyperFine Splitting (HFS)**
- **the Tau g-2 (a_τ)**
- **the low-energy weak mixing angle $\sin^2\theta_W(0)$**
- **the running of α_{em}**



Leptonic g-2



$\sin^2\theta_W$ and running of α_{em}



Muonium HFS

Measurement of the Electron Magnetic Moment

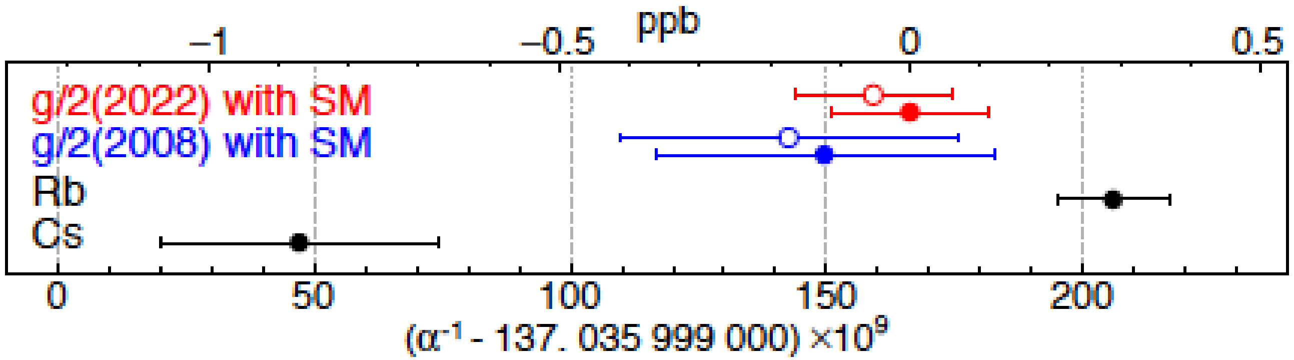
X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
(Dated: December 8, 2022)

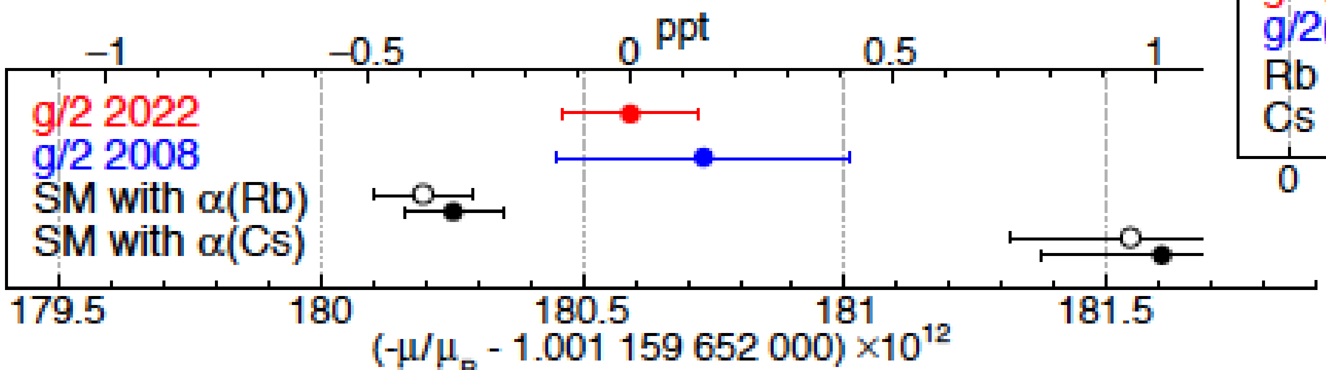
The electron magnetic moment, $-\mu/\mu_B = g/2 = 1.001\,159\,652\,180\,59\,(13)$ [0.13 ppt], is determined 2.2 times more accurately than the value that stood for 14 years. The most precisely determined property of an elementary particle tests the most precise prediction of the Standard Model (SM) to 1 part in 10^{12}. The test would improve an order of magnitude if the uncertainty from discrepant measurements of the fine structure constant α is eliminated since the SM prediction is a function of α. The new measurement and SM theory together predict $\alpha^{-1} = 137.035\,999\,166\,(15)$ [0.11 ppb] with an uncertainty ten times smaller than the current disagreement between measured α values.

$$\boxed{a_e^{\mathrm{EXP}} = 0.00115965218059(13)}$$

$$\boxed{\delta a_e^{\mathrm{EXP}} = 1.3 \times 10^{-13}}$$

In **2008** Gabrielse et al. had obtained $\boldsymbol{\delta a_e^{\mathrm{EXP}} = 2.8 \times 10^{-13}}$





Electron g-2

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

in good agreement with the numerical results

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

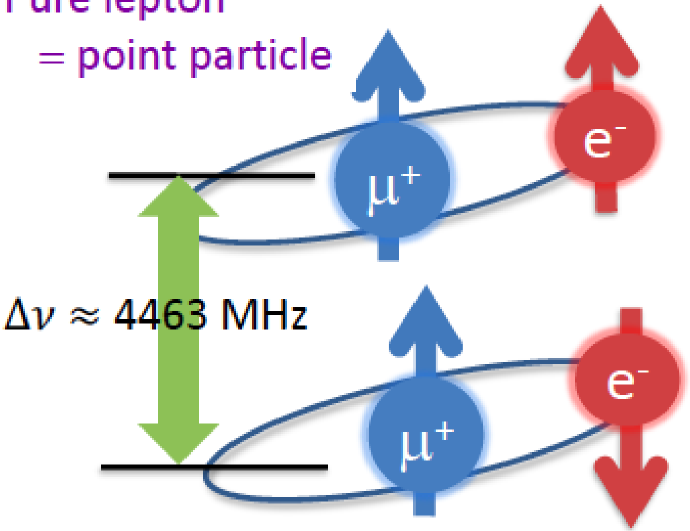
Δa_e error source	Value	% of Δa_e error
Five-loop QED, δa_e^{QED5}	6×10^{-14}	5% (Cs)/13% (Rb)
Hadronic, δa_e^{HAD}	1×10^{-14}	$< 1\%$
α(Cs), $\delta a_e^{\alpha(Cs)}$	22×10^{-14}	70%
α(Rb), $\delta a_e^{\alpha(Rb)}$	9×10^{-14}	28%
Experiment, δa_e^{exp}	13×10^{-14}	24% (Cs)/59% (Rb)

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)

The Muonium HyperFine Splitting (HFS)

Muonium: bound state of μ^+ and e^-

Pure lepton
= point particle



$\Delta\nu$: Muonium Hyperfine Structure

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

Muonium HFS of the 1S ground state

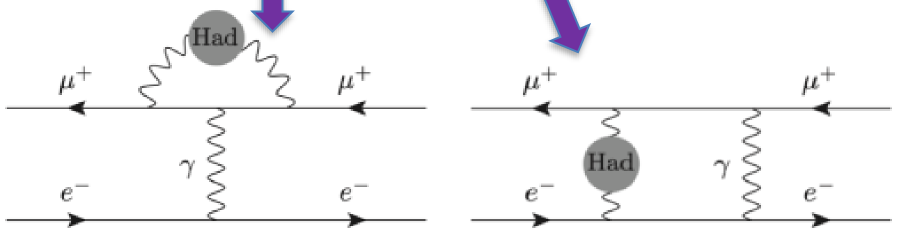
$$\frac{\nu_{\rm HFS}}{\nu_F} = 1 + a_\mu + \Delta^{\rm QED}_{\rm HFS} + \Delta^{\rm weak}_{\rm HFS} + \Delta^{\rm HVP}_{\rm HFS}$$

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

for $s \gg m_\mu^2$

$$\Delta^{\rm HVP}_{\rm HFS} \approx 6\,\frac{m_\rho^2}{m_\mu^2} K_{\rm Mu}(m_\rho^2)\,(a_\mu^{\rm HVP})_{e^+e^-}$$
$$\approx 0.63\,(a_\mu^{\rm HVP})_{e^+e^-}\,.$$

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



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

5.9σ discrepancy in the comparison!

$O^{\rm HVP}_{e^+e^-}$	(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 δa_μ^{CMD3} → to be sensitive to this shift needs a precision of O(1) Hz

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

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)

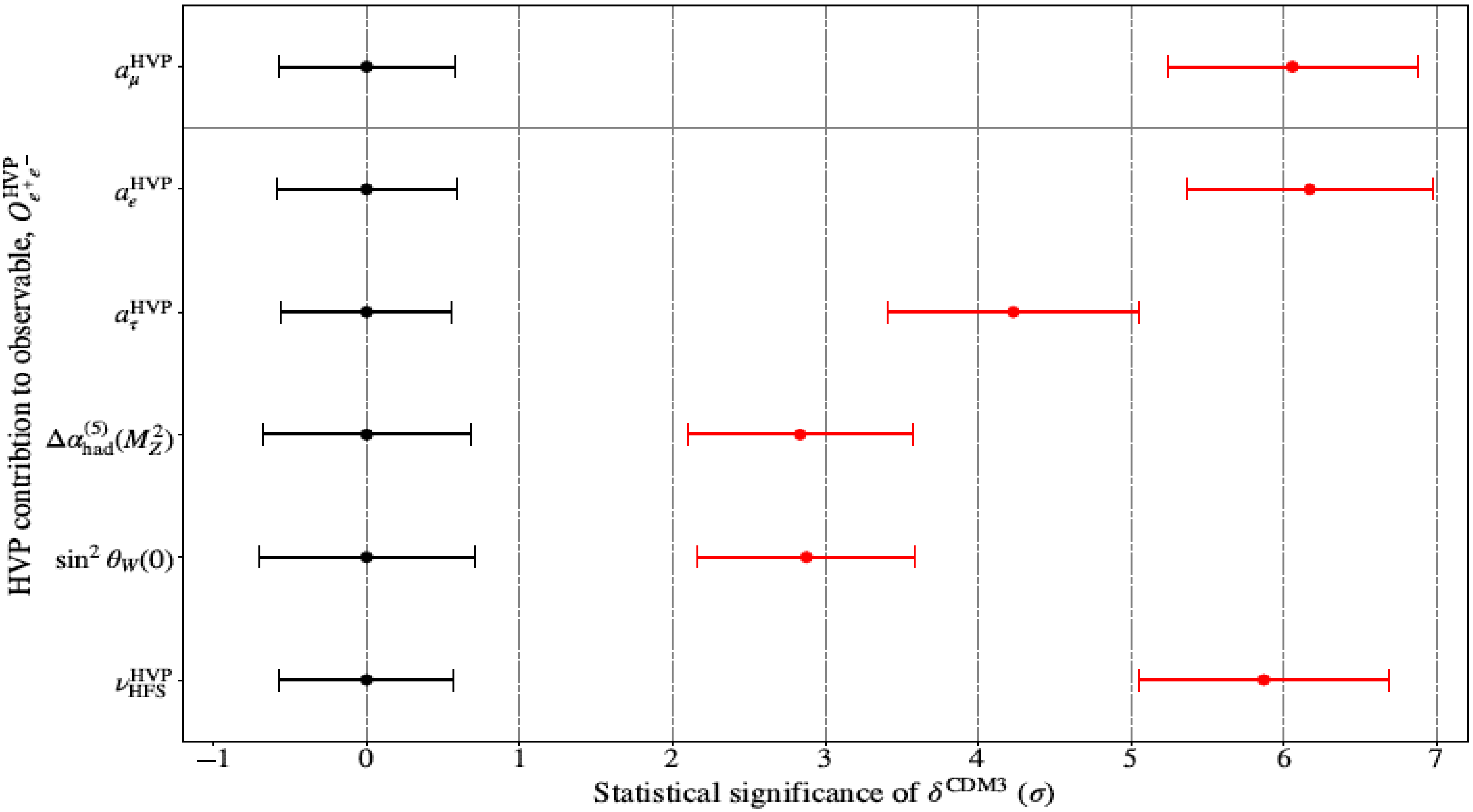
Other sources of uncertainty:

i) uncertainty on ν_F fully dominated by **m_e / m_μ** → induced error on ν_F ~ **4 x 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 ν_{HFS} from unknown **3-loop QED** contributions to δ_{HFS}^{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)

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



Di Luzio, Keshavarzi, A.M. , Paradisi arXiv:2408.01123

The impressive potentialities to explore the "*UNKNOWN*" **BSM physics** through the study of the ***EDMs***

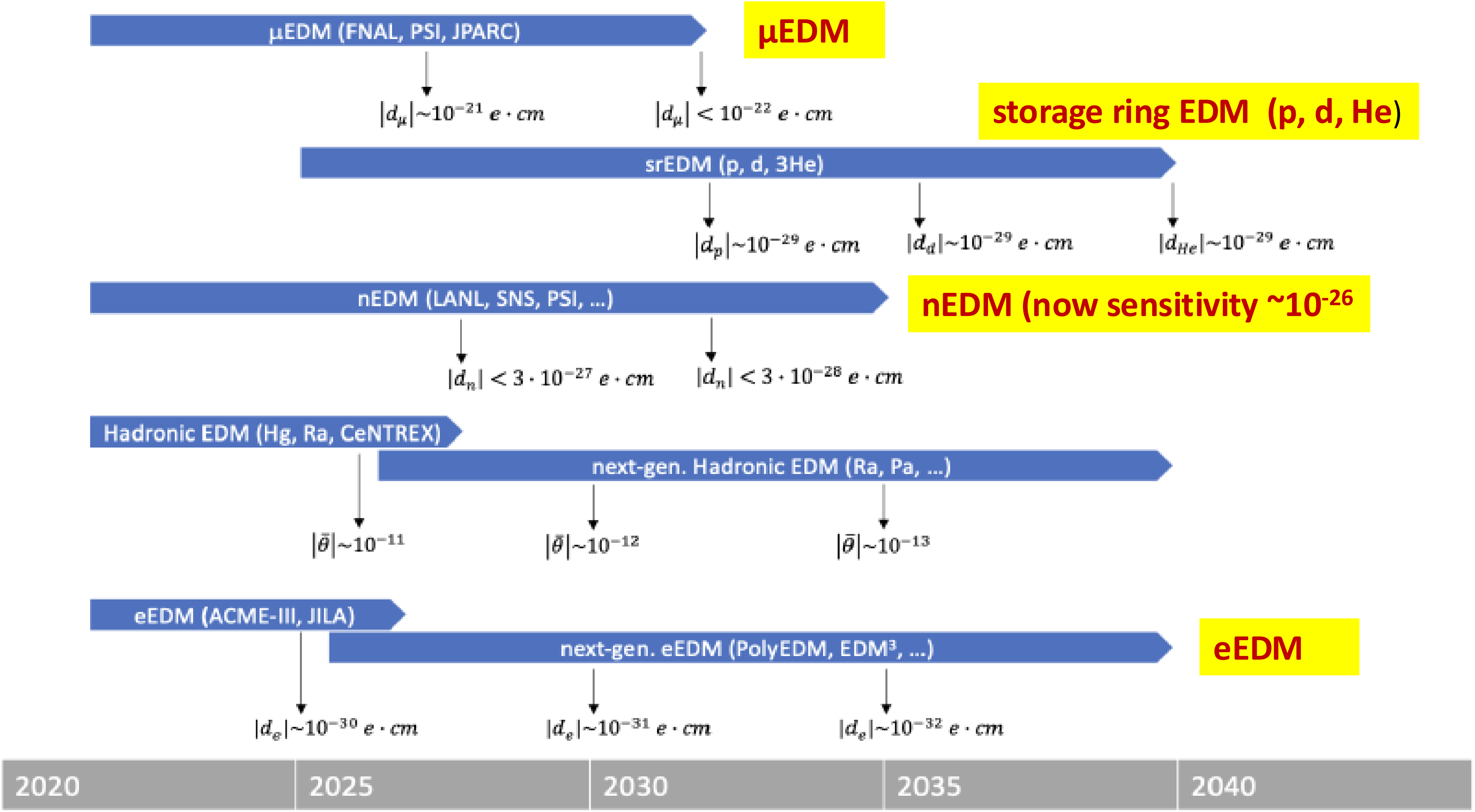
many recent ***advances in experimental techniques and technologies*** + **(experimental as well as theoretical)** ***synergies*** with adjacent areas of particle physics (atomic, molecular, optical, nuclear, particle physics)

- **New science opportunities** in the (experimental and theoretical) current and near-future exploration of EDMs for various physical systems : **electron**, **muon**, **tau neutron**, **proton**, **atom**, **molecule**
- Coordinated program (with different scientific communities) of complementary EDM searches in **AMO** (Atomic Molecular Optical), **NUCLEAR** and **PARTICLE** physics
- An exceptionally sensitive way to explore the **NEW source(s) of CP VIOLATION** necessary to develop a cosmic asymmetry between matter and anti-matter starting with a symmetric early universe
- Feasible to achieve in a few years **relevant improvements** (from **one to even 3-4 orders of magnitude**) **on EDM sensitivities** – in particular AMO physics considers it realistic to achieve 1, 2-3, 4-6 orders of magnitude improvements in the few, 5-10 and 15-20 year time-scales, respectively

Blum, Winter Snowmass 2021 arXiv 2209.08041

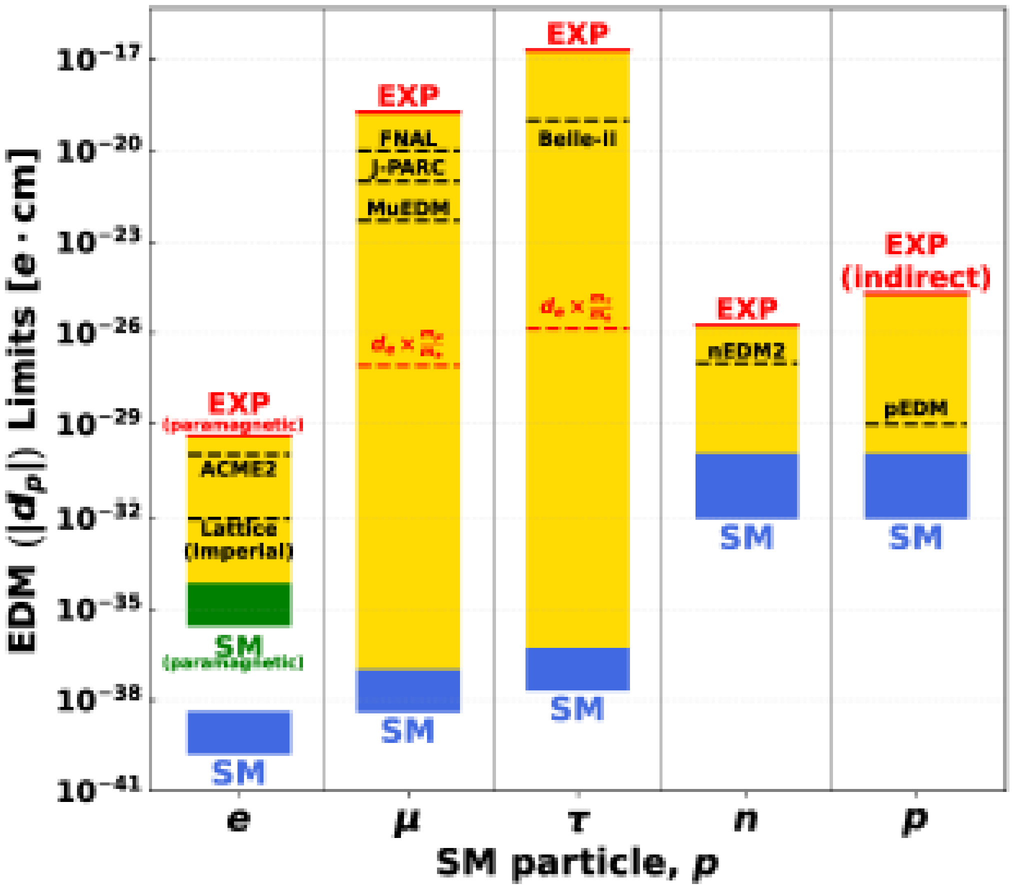
Report of the 2023 P5 (Particle Physics Project Prioritization Panel)

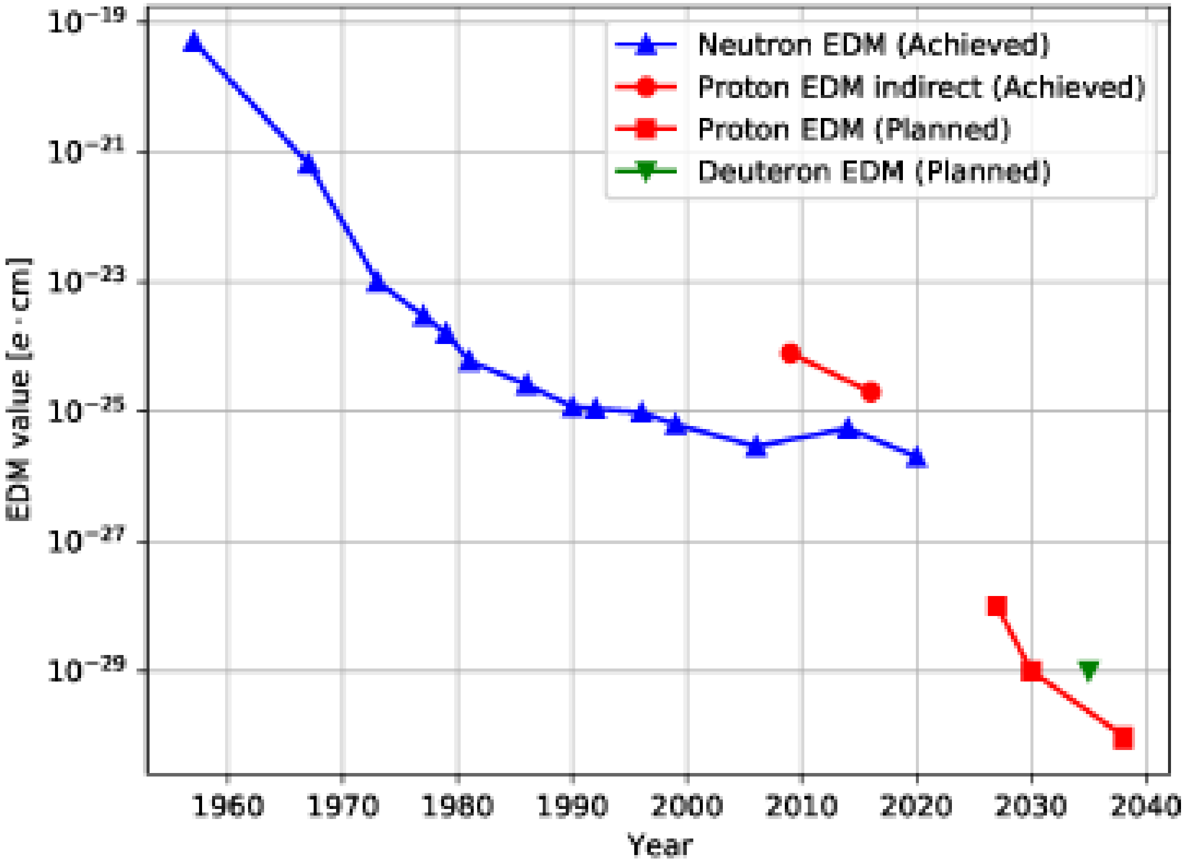
Electric Dipole Moments



Blum, Winter Snowmass 2021 arXiv 2209.08041

EDMs exciting prospects

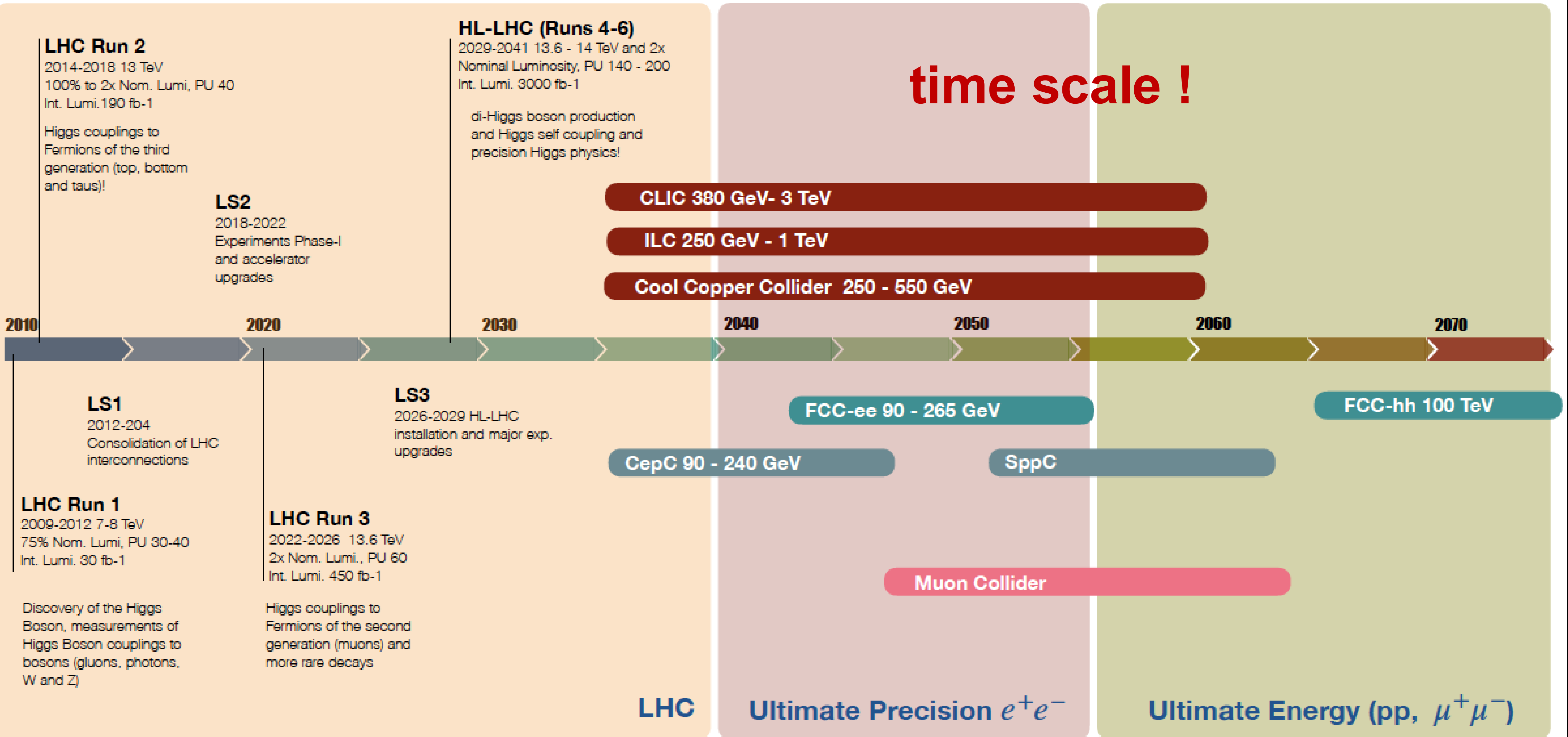




J. Alexander et al, pEDM Experiment
arXiv:2504.12797 [hep-ex]

A Scientific Mission for the 21st Century

Rende Steerenberg ICHEP 2024



some final thoughts …

The experimental and theoretical precision physics community has entered an era of **unprecedented precision experiments**

SYNERGY between small/mid-scale & large-scale experiments →
casting a wider and tighter net for possible effects of BSM physics
Synergy among the **various communities** operating in precision physics in (very) **different experimental, technological and theoretical environments**

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

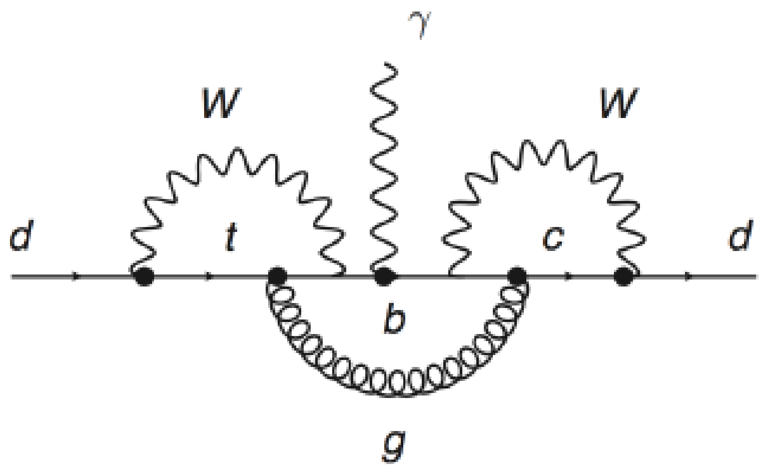
These experiments are key to paradigm-shifting discoveries, both in their own right and as incubators for new technologies and physics directions

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

BACK-UP SLIDES

Quark EDMs from the CKM matrix

first non-vanishing contribution to quark EDMs arises at the 3-loop level



$$d_d \propto \frac{e}{(16\pi^2)^2}\frac{g_s^2}{16\pi^2}G_F^2 m_c^2 m_d$$

$$\times \mathrm{Im}(V_{td}V_{tb}^*V_{cb}V_{cd}^*) \neq 0$$

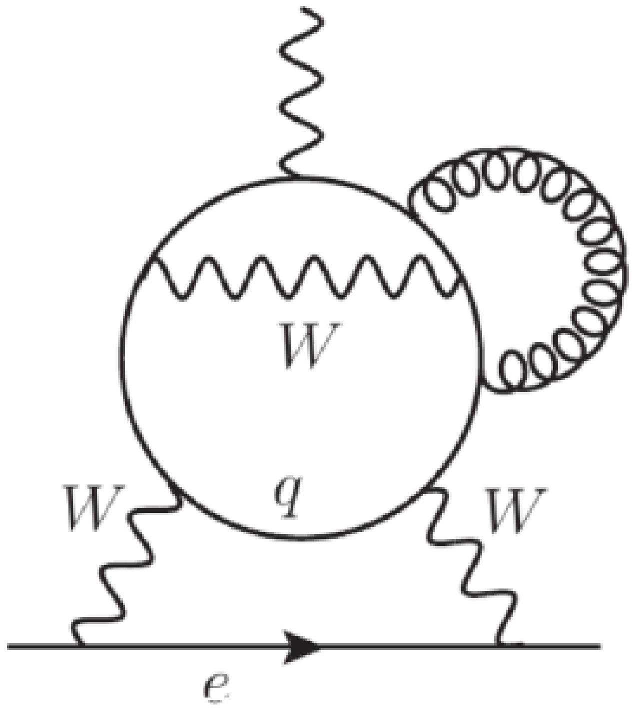
- two electro-weak loops
- one additional gluon loop

$$d_d \simeq 10^{-34}\, ecm$$

(Khriplovich 1986,
Czarnecki, Krause 1997)

Lepton EDMs from the CKM matrix

for lepton EDMs one needs at least one additional loop
to switch from leptons to quarks and to access the CKM phase
(Khriplovich, Pospelov 1991)



$$d_e \propto \frac{e}{(16\pi^2)^3} \frac{g_s^2}{16\pi^2} G_F^3 m_c^2 m_s^2 m_e$$

$$\times \mathrm{Im}(V_{td} V_{tb*} V_{cb} V_{cd}^*)$$

- three electro-weak loops
- one additional gluon loop

$$d_e \simeq 10^{-44} ecm$$

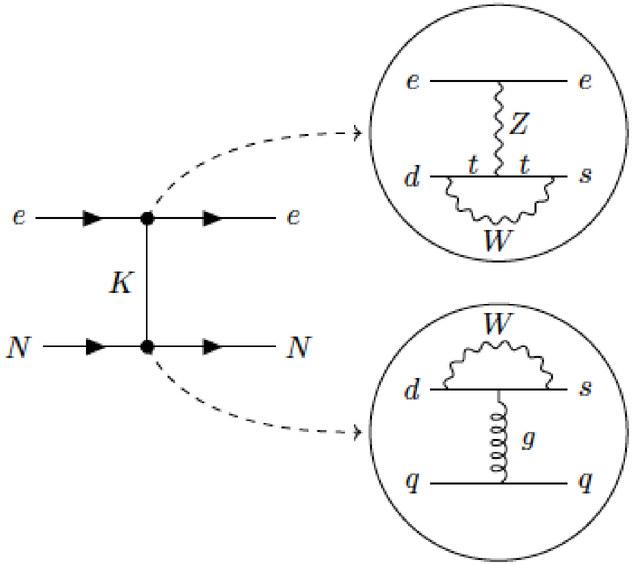
(Pospelov, Ritz 2013)

"Good news" from the theory of electric dipole moments

$$\mathcal{L}_{\mathrm{CPV}} = -\frac{i}{2} d_e \bar{e}\sigma_{\mu\nu}F^{\mu\nu}\gamma_5 e + C_S \frac{G_F}{\sqrt{2}} \left(\bar{e} i \gamma_5 e\right) \bar{N} N$$

electron EDM d_e semileptonic CP-odd operator C_S

EDM "paramagnetic experiments", i.e. experiments making use of a specific paramagnetic atom/molecule, are sensitive to a particular linear combination of d_e and C_S, the *equivalent* electron EDM d_e^{equivv}



$$C_S(\mathrm{LO}+\mathrm{NLO}) \simeq 6.9\times10^{-16}, \quad \text{or} \quad d_e^{\mathrm{equiv}} \simeq 1.0\times10^{-35}\, e\,\mathrm{cm}.$$

result >> previous estimates ~ 10^{-38} e cm.

From the exp. bounds on paramagnetic EDMs, one derives indirect constraints on muon and tau EDMs:

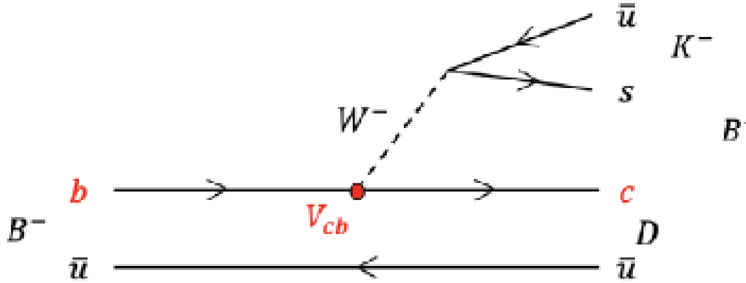
$$|d_\mu| < 1.7\times10^{-20}\, e\,\mathrm{cm}. \qquad |d_\tau| < 1.1\times10^{-18} e\,\mathrm{cm} \quad (90\%\mathrm{C.L.})$$

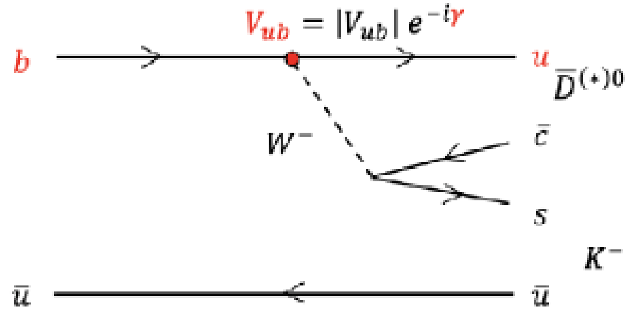
Ema, Gao, Pospelov 2024 PoS DISCRETE2022

Latest CKM γ News (Belle II - LHCb)

Recent Measurements of γ in the golden channel $B^{\pm} \to DK^{\pm}$

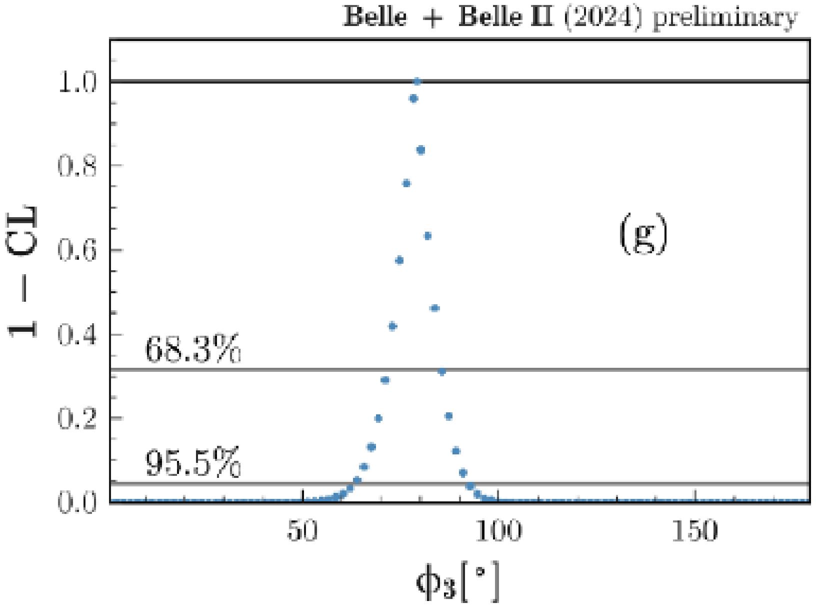
$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



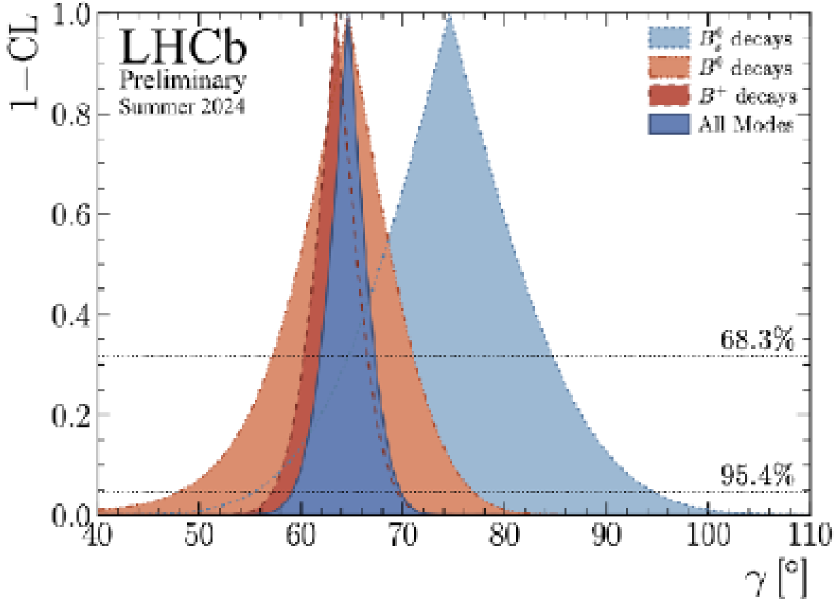


Lack of Lattice QCD needs makes it a "**pristine observable**" in flavour physics!

Charm input from BESIII/CLEO is critical



New for ICHEP 2024



Combination from Belle II

$$\gamma = (78.6^{+7.2}_{-7.3})^o$$

Combination from LHCb!

$$\boxed{\gamma = (64.7 \pm 2.8)^o}$$

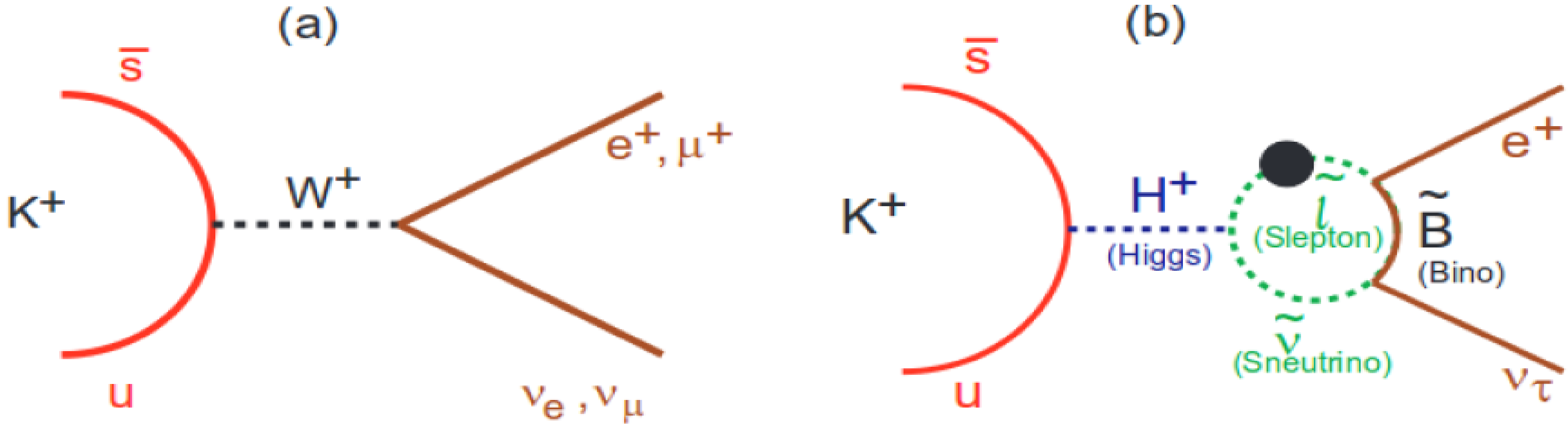
Measurement from LHCb has surpassed the target goal for Run 2!!

From CKM fitter $\gamma = (66.3^{+0.7}_{-1.9})^o$

Probing New Physics through $\mu - e$ Universality in $K \to \ell\nu$ PRD 74 (2006) 011701

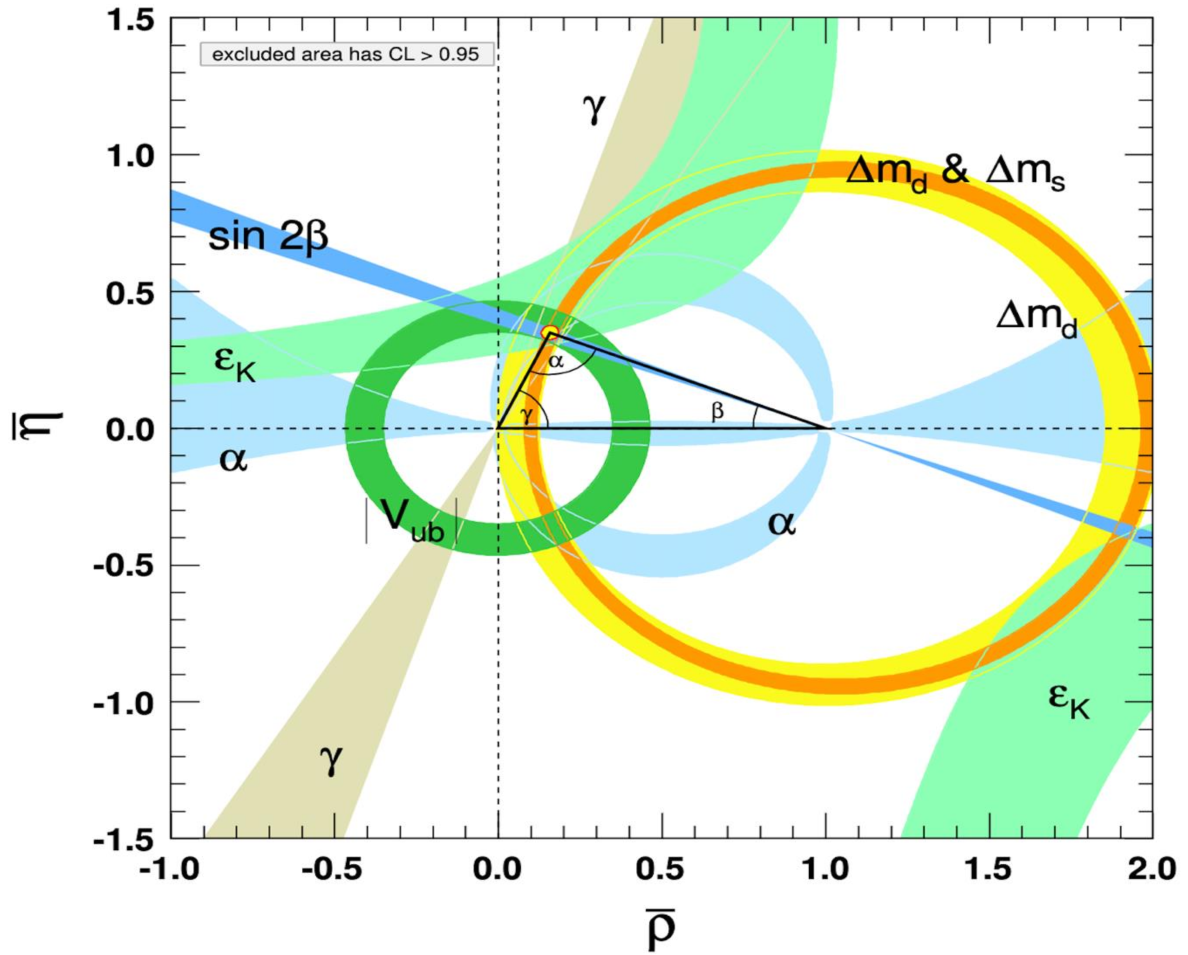
A. Masiero,[1] P. Paradisi,[2] and R. Petronzio[2]

Anatomy and phenomenology of the lepton flavor universality in SUSY theories JHEP 11 (2008) 042



Precision Quark Flavor Physics
Mixings and CP Violation in the SM quark sector

Consistency tests of the CKM matrix; in particular, remarkable consistency between **tree-level and one-loop** (ex. meson-antimeson mixings) **determinations of the CKM elements**



At the present level of accuracy, i.e. ~ %, all measurements are consistent and intersect at the apex of the UT → no hints for BSM New Physics, however lessons from the past (CP violation!) that % accuracy may not be enough …

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^\star_{\ell\ell'} \ell_R\right) F^{\mu\nu} \qquad \ell, \ell' = e, \mu, \tau \,,$$

- **Branching ratios of $\ell \to \ell'\gamma$**

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell \bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right).$$

- **Δa_ℓ and leptonic EDMs**

$$\Delta a_\ell = 2m_\ell^2\,\mathrm{Re}(A_{\ell\ell}), \qquad \frac{d_\ell}{e} = m_\ell\,\mathrm{Im}(A_{\ell\ell})\,.$$

The running of α_{em}

Hadronic effects to the running QED coupling at the Z –boson mass (a main component of the elw. precision fit

$$\delta\Delta\alpha^{(5)}_{\rm had}(M_Z^2) \approx \frac{3\pi}{\alpha}\frac{m_\rho^2}{m_\mu^2}\,\delta a_\mu^{\rm CMD3}$$
$$\approx (1.5 \pm 0.3)\times 10^{-4}$$

Magnitude of the shift comparable with the current uncertainty on α_{em} (M_Z^2) → **very diffcult for** $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ to probe $\delta a_\mu^{\rm CMD3}$

$O^{\rm HVP}_{e^+e^-}$	(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

At future e^+e^- colliders , e.g., FCC-ee, expected to reach the unprecedented precision on α_{em} **(M_Z^2) of $O(10^{-5})$ which would provide sensitivity to the shft**

The running of $\sin^2\theta_W$

$\sin^2\theta_W(0)$ can be connected with $\sin^2\theta_W(M_Z)$ by including the $\gamma - Z$ mixing (Erler and Ferro-Hernández JHEP 2018) (Keshavarzi, Marciano, Passera, Sirlin PRD 2020)

The shift from the CDM-3 data can be estimated via:

$$\delta \sin^2\theta_W(0) \approx k' \sin^2\theta_W(M_Z) \frac{3\pi}{\alpha} \frac{m_\rho^2}{m_\mu^2} \delta a_\mu^{\mathrm{CMD3}} \approx (0.4 \pm 0.1) \times 10^{-4},$$

To make use of **$\sin^2\theta_W(0)$ to probe the HVP contribution would require a precision on $\sin^2\theta_W(0)$ and $\sin^2\theta_W(M_Z)$ at the ~ 10^{-5} level**

Future HE e^+e^- colliders aim at resolutions on $\sin^2\theta_W(M_Z)$ much better than $O(10^{-5})$, but achievable precision on $\sin^2\theta_W(0)$ in future low-energy experiments at MESA (P2) in Mainz and Jlab (Möller) should be only ~ $O(10^{-4})$

$O^{\mathrm{HVP}}_{e^+e^-}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, δO^{CMD3}	Significance (σ)
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$\sin^2\theta_W(0) \times 10^4$	2386.0 ± 1.4	2386.4 ± 1.5	0.996	0.4 ± 0.1	2.9

Tau g-2

Assuming dominant effects at the ρ-peak

$$\delta a_\tau^{\rm CMD3} \approx 0.63\,(m_\rho^2/m_\mu^2)\,\delta a_\mu^{\rm CMD3} \approx (7.2 \pm 1.4) \times 10^{-8}$$

$m_\tau >> m_\mu$, m_e → increased weight of the hadronic contributions to higher energies → influence of $\pi^+\pi^-$ and ρ-resonance contrtibutions is reduced in tau g-2 → degree of correlation between scenario KNT19 and scenario CMD-3 increases (ρ ~ 55%) w.r.t. the electron (ρ ~ 26%) and muon (ρ ~ 28%) cases →

SIGNIFICANCE of $\delta a_\tau^{\rm CDM3}$ is 4.2σ compared to > 6σ for the $a_e^{\rm CDM3}$ $a_\mu^{\rm CDM3}$

$O_{e^+e^-}^{\rm HVP}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, $\delta O^{\rm CMD3}$	Significance (σ)
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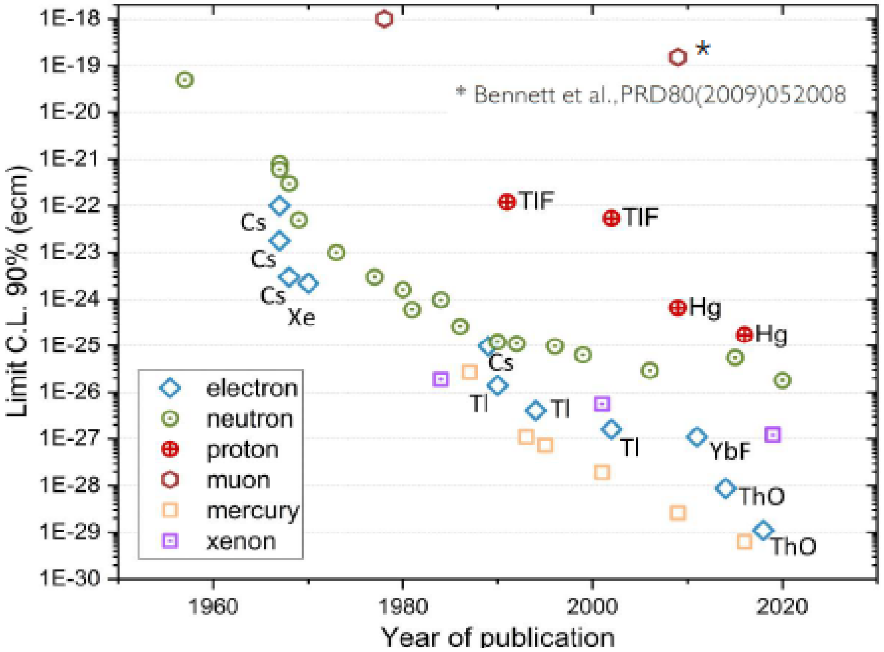
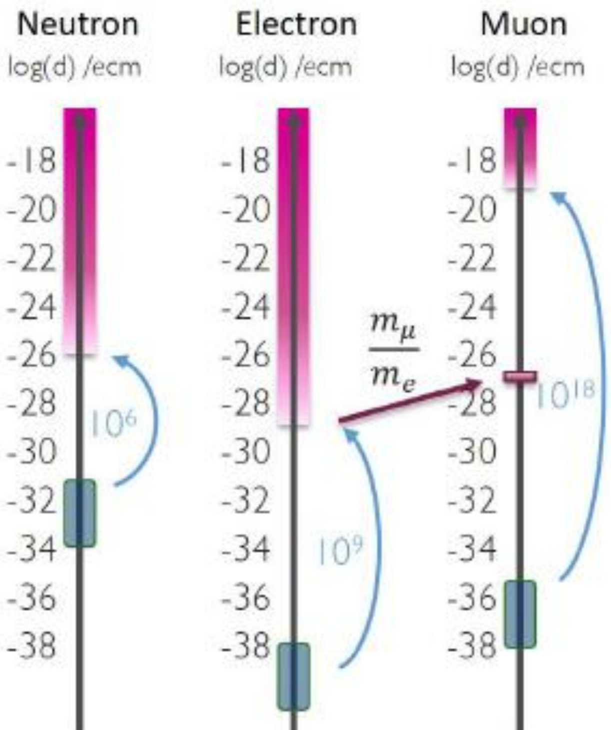




A. Papa, Planck2025

Quite poor current direct limit **d_μ <1.5×10^{-19} *e*cm (CL 90%)**

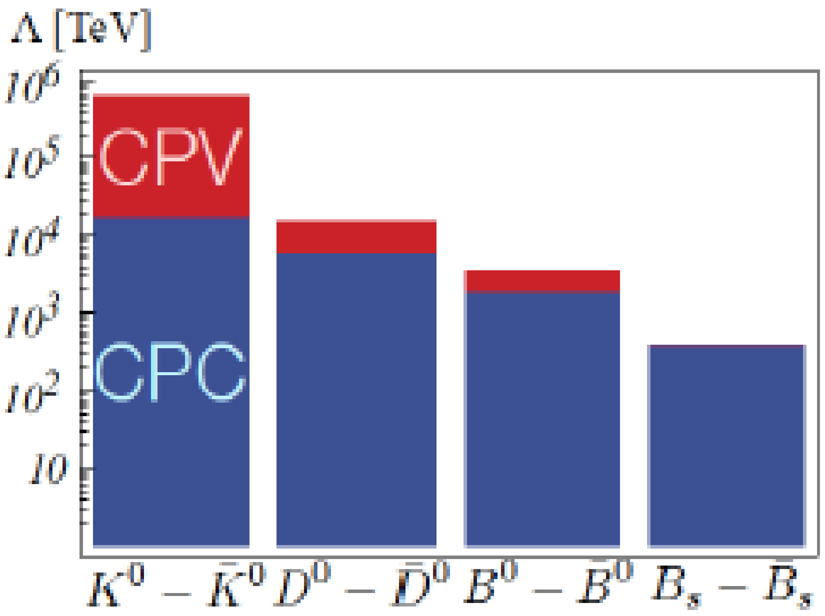
- Impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules d_e< 1.1×10^{-29} *e*cm (CL 90%) lead to d_μ<2.3×10^{-27} *e*cm (CL 90%), which is many orders of magnitude better than the direct limit d_μ
  - m_μ/m_e naive rescaling assumes minimal flavor violation (MFV), that is a model dependent assumption
- FNAL/JPARC g-2 experiments aims at d_μ ~ O(10^{-21}) *e*cm (via g-2)
- **Direct muEDM search at PSI in stages:**
  - **Precursors: d_μ < 3×10^{-21} *e*cm**
  - **Final: d_μ < 6×10^{-23} *e*cm**
- **Proof-of-principle of a complete new experimental technique that can pave the way to other EDM searches**

▶ *The flavor structure of the SM-EFT*

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5}$$

The absence of deviations from the SM predictions are usually translated into stringent bounds on the effective scale of the contact terms.

Eg.:



But these apparently high scales can be a "mirage"...

Only unambiguous message:

No large breaking of the approximate ~U(2)^n flavor symm. at near-by energy scales.

[signal of UV dynamics?]