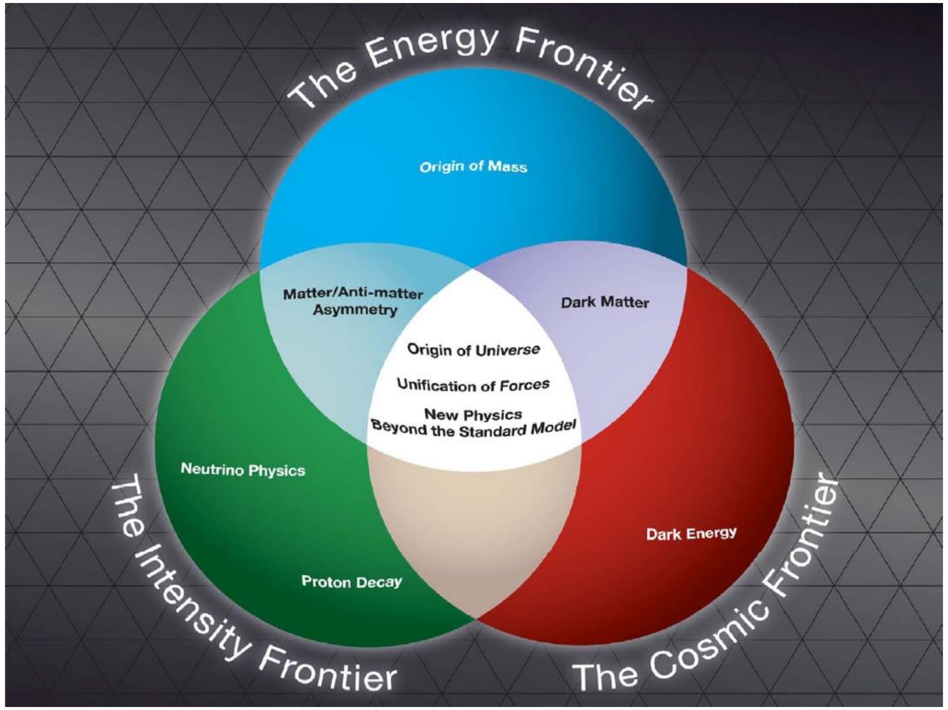
The Precision frontier of particle physics in 2024



Antonio Masiero

Univ. of Padova and INFN, Padova

3rd Liverpool Workshop on Muon Precision Physics 2024 (MPP2024)

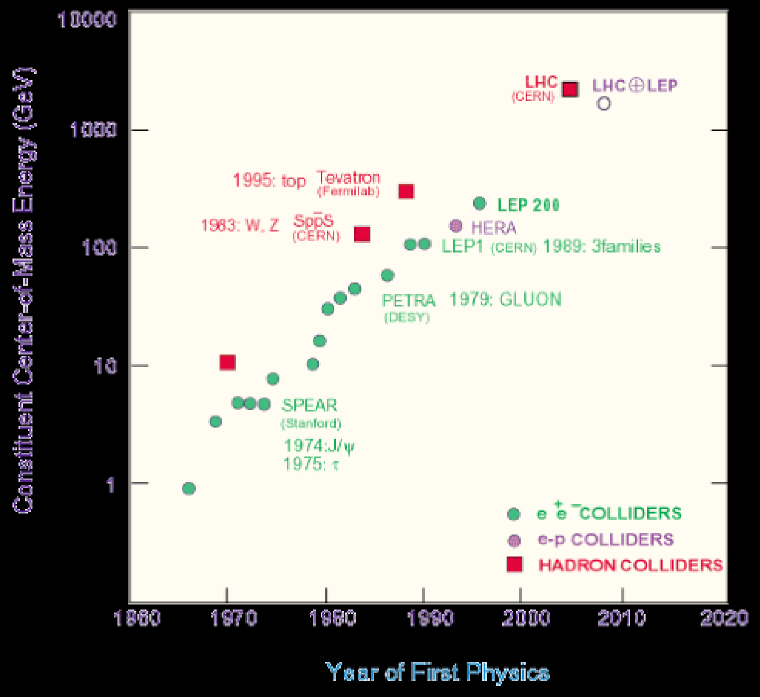
Liverpool, Nov. 12 – 14, 2024

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

THE HIGH-ENERGY ROAD



O(1 GeV) in the 70's

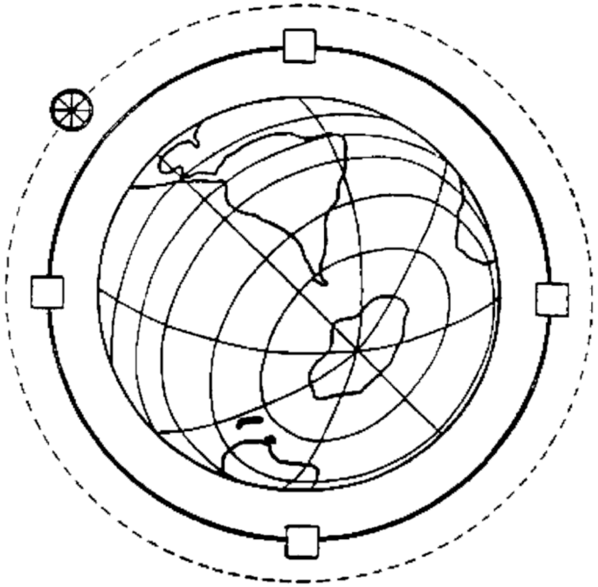
↓

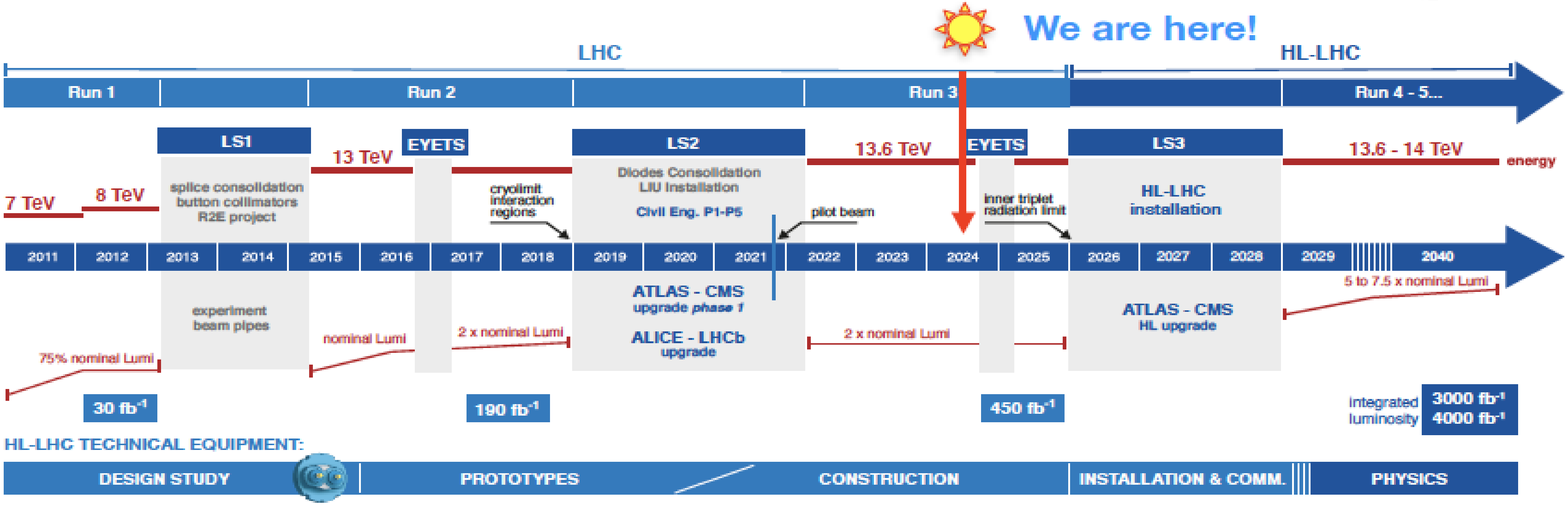
O(10 TeV) TODAY!

Ultimate Accelerator

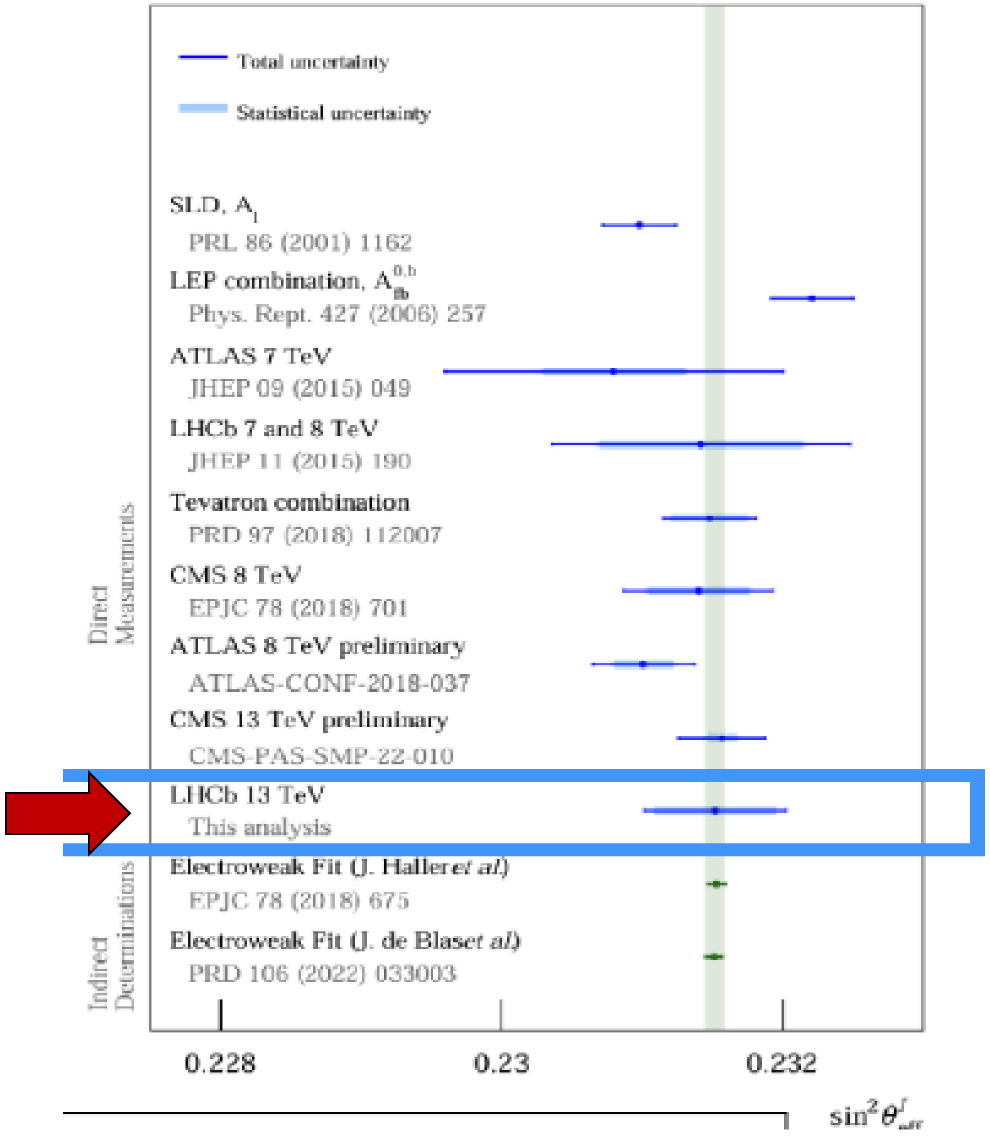
Drawn by Fermi in the 50's to reach 3 TeV.

The manifesto of HEP!

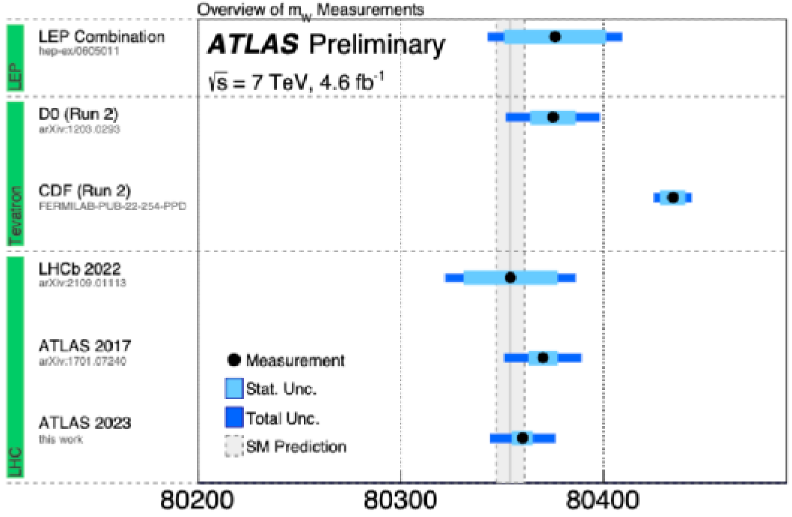




Testing the GAUGE part of the SM
LHC: from **DISCOVERY** to **PRECISION** physics

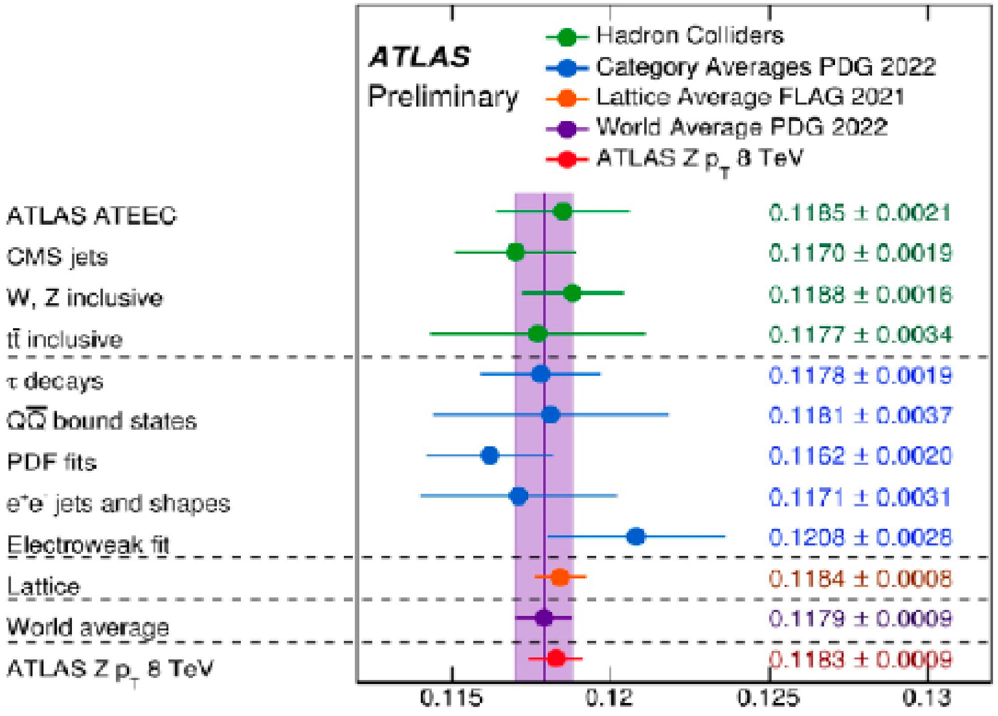


$$\sin^2\theta^{\ell}_{eff} = 0.23152 \pm 0.00044 \pm 0.00005 \pm 0.00022$$



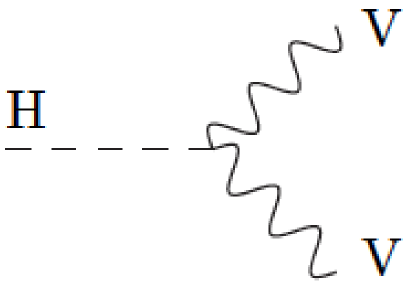
m_W (MeV)

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



$\alpha_S(m_Z)$

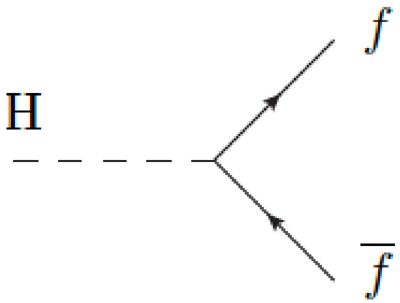
Testing the HIGGS part of the SM: present and future



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

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

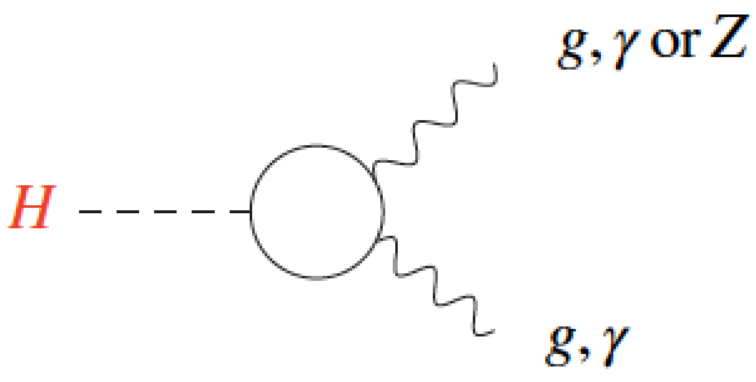
	Current	HL-LHC	FCC (ee)
$\kappa_{W,Z}$	6%	1.5%, 1.7 %	0.4%, 0.2 %

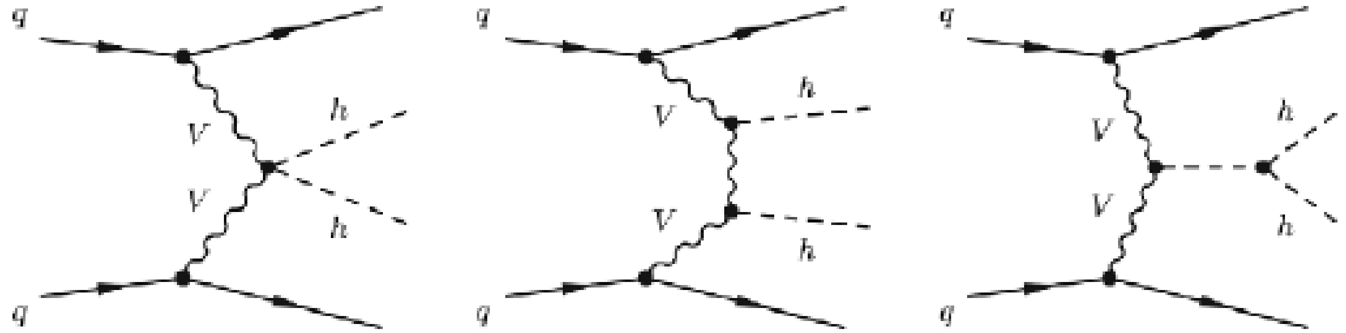


$$\frac{m_f}{v}$$

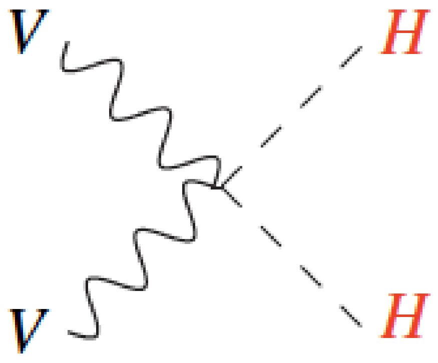
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

	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%*	





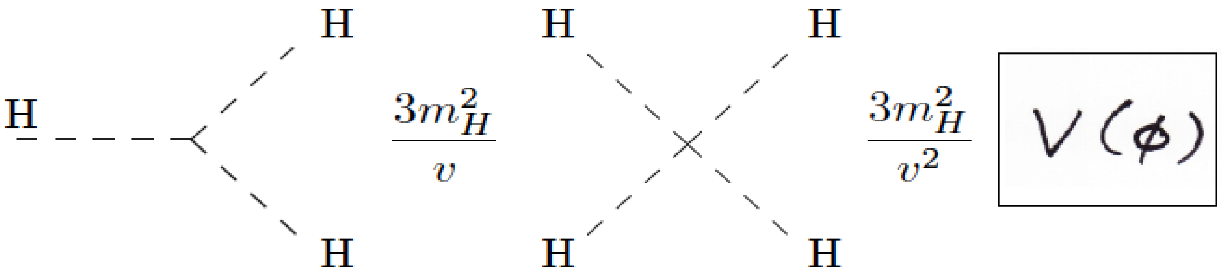
	Current	HL-LHC	FCC (ee)
κ_γ	6%	1.8%	3.9%
κ_g	7%	2.5%	1%
$\kappa_{Z\gamma}$	30%	9.8%	



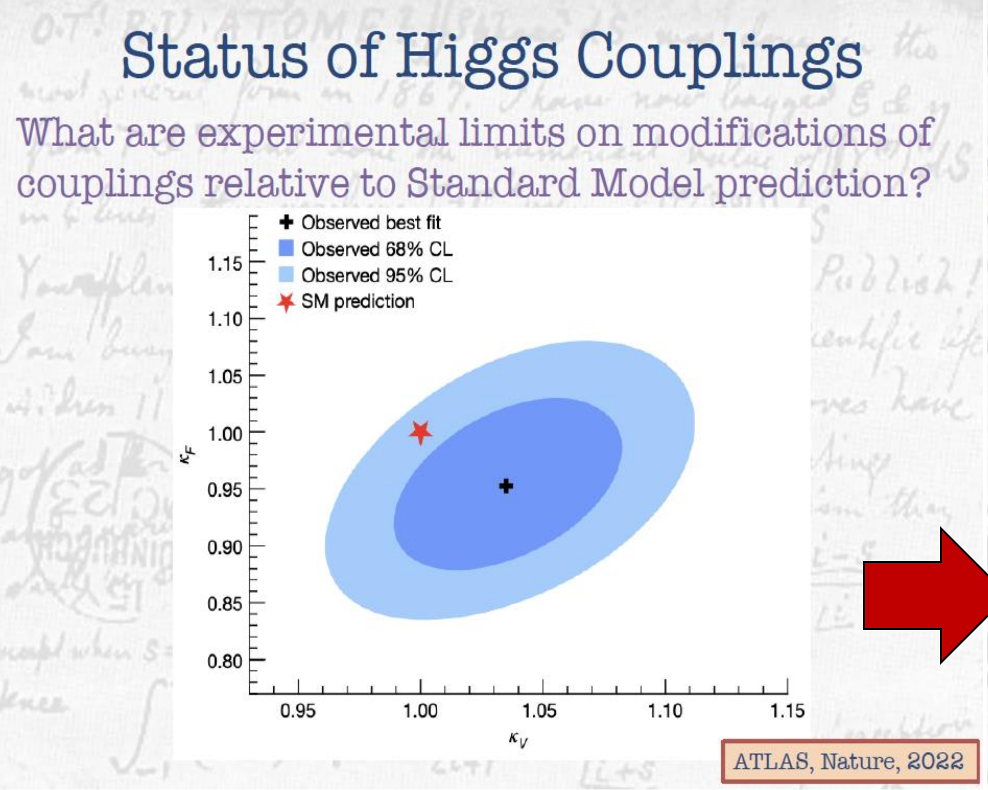
$$g_{HHVV} \sim \frac{2M_V^2}{v^2}$$

$\kappa_{2V} \in [0.67, 1.38]$ CMS result (ATLAS similar)

Higgs self-interactions



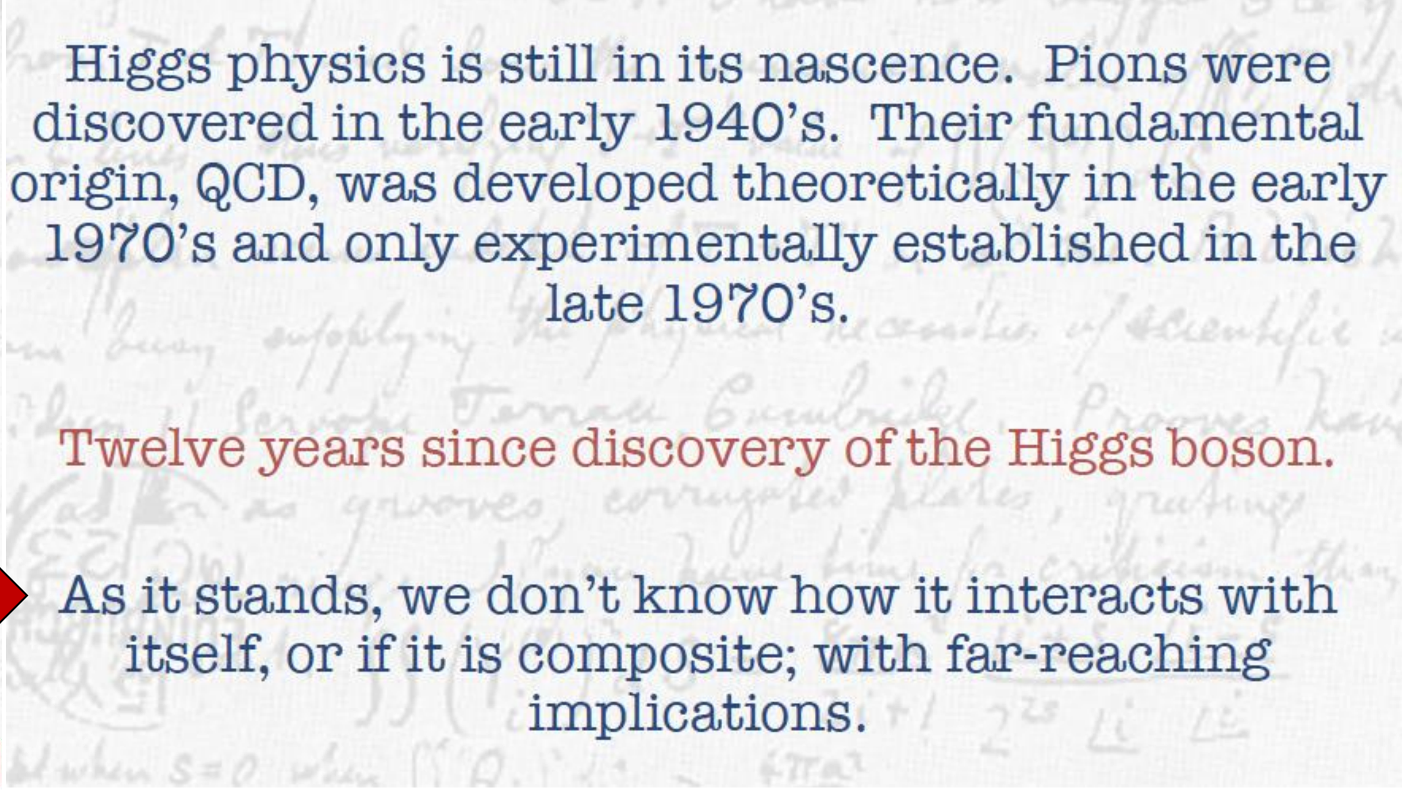
Large trilinear deviations are possible while deviations of the Higgs to Z coupling remain small



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.

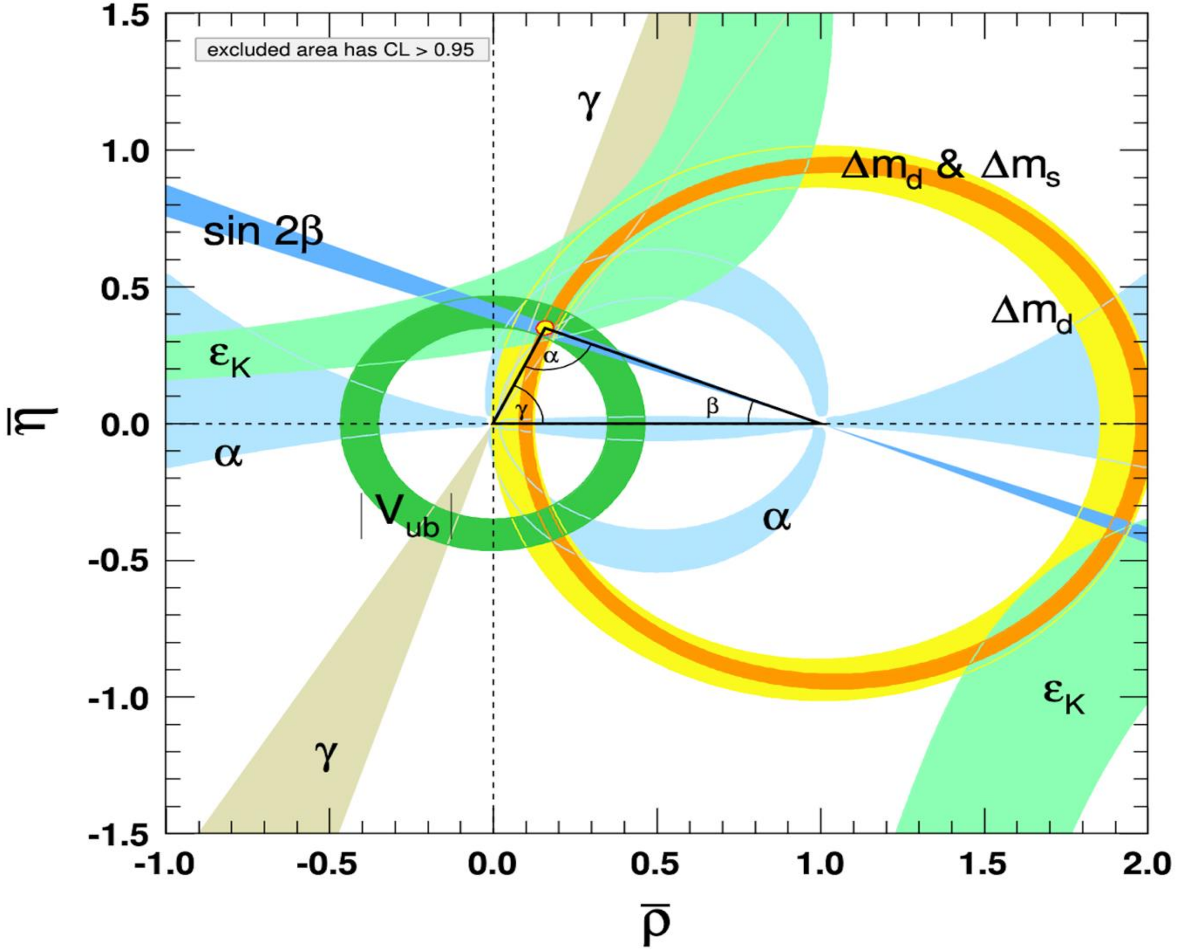
Twelve years since discovery of the Higgs boson.

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

M. McCullogh, G. Weiglein, ICHEP 2024

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**

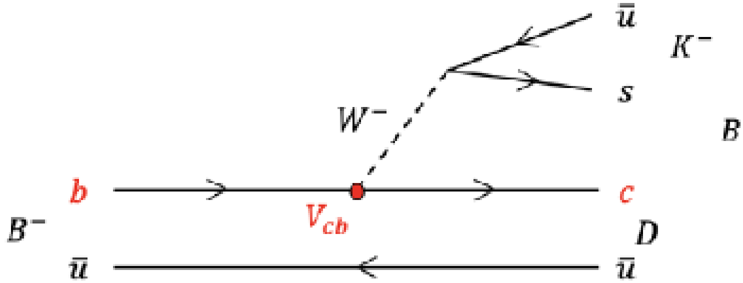


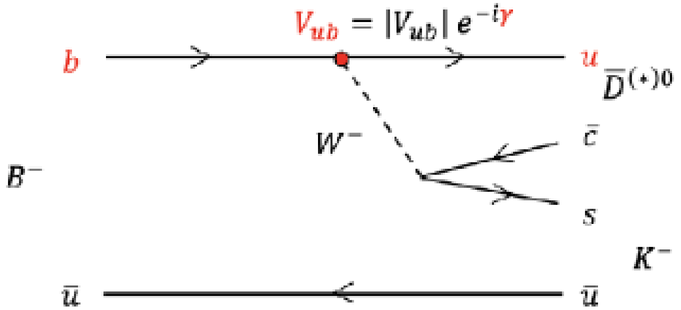
At the present level of accuracy, i.e. ~ %, all measurements are consistent and intersect at the apex of the UT → no hints for BSM New Physics, however lessons from the past (CP violation!) that % accuracy may not be enough …

Latest CKM γ News (Belle II - LHCb)

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

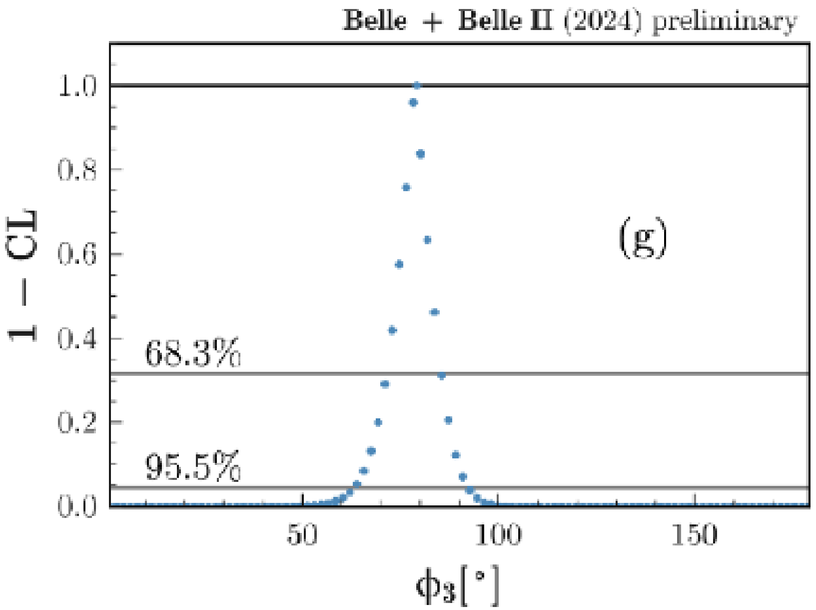
$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



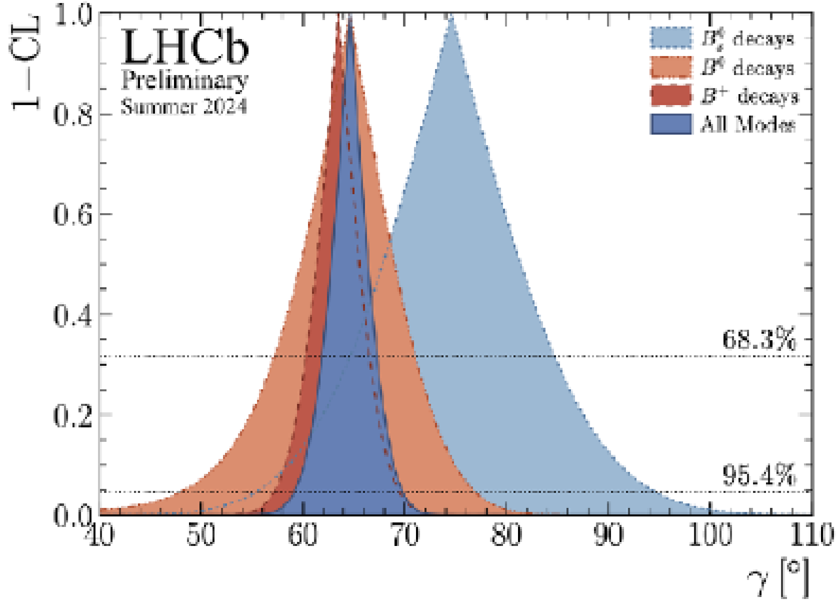


Lack of Lattice QCD needs makes it a "**pristine observable**" in flavour physics!

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!

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

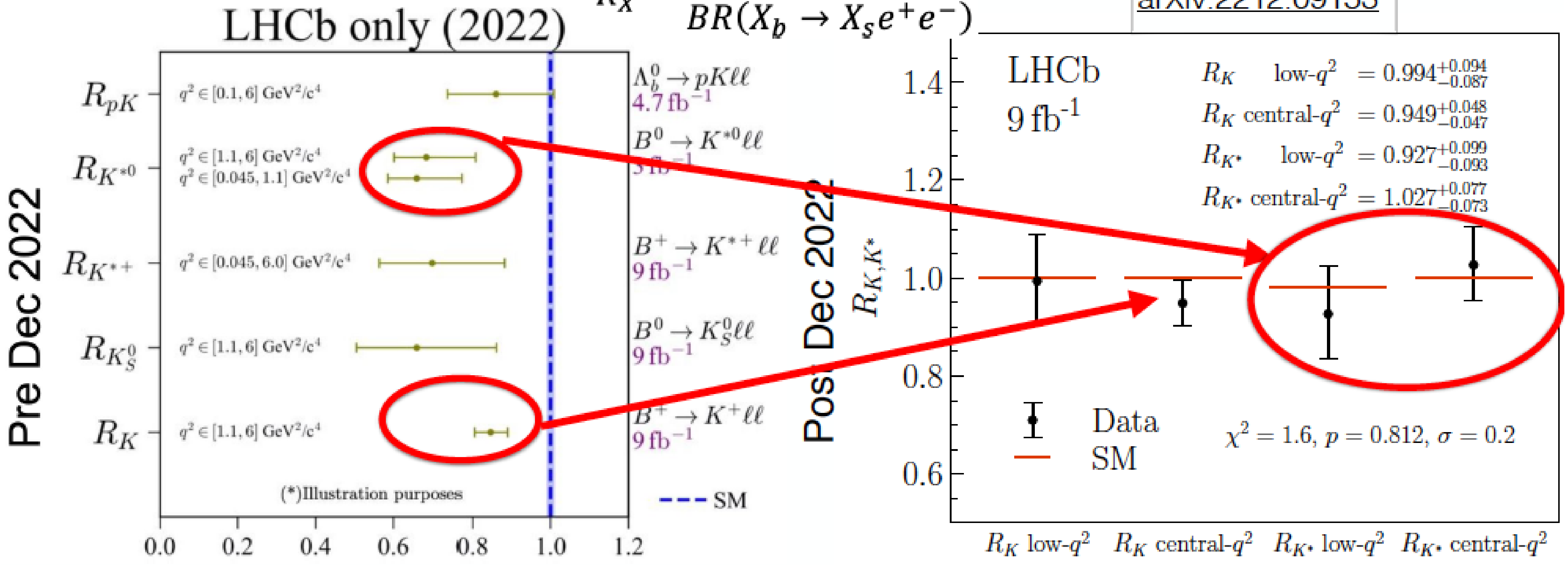
Measurement from LHCb has surpassed the target goal for Run 2!!

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

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



Low q^2 :
$q^2 \in [0.1,1.1]\,\mathrm{GeV}^2/c^4$

Central q^2 :
$q^2 \in [0.1,1.1]\,\mathrm{GeV}^2/c^4$

A remaining flavor puzzle in B physics?

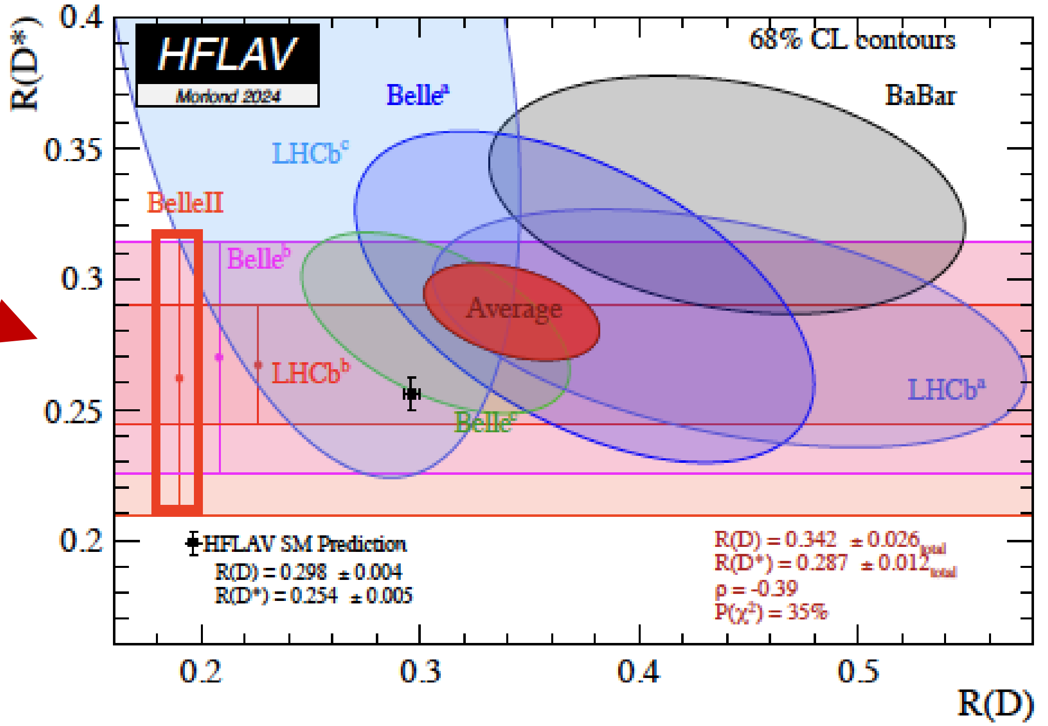
A puzzling result
in tree-level $b \to c$ transitions

~3σ tension

First Belle II RD* measurement!

Both TH and EXP clean!

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



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

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.)

What the SM does NOT account for…

- neutrino masses
- dark matter
- baryogenesis
- inflation

→ **OBSERVATIONAL REASONS**

- $M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
- $E_{VACUUM} (DE) / M_{HIGGS} \sim 10^{-14}$
- $\Theta_{CPV \text{ in STRONG INTERAC.}} < 10^{-9}$

→ **THEOR. REASONS**

\+ lack of UNIFICATION of the ELW. and strong interactions

+lack of a physical "explanation" of the (largely different) masses and mixings of the fermions

How to cope with the **Gauge Hierarchy Problem**

Naturalness or Un-naturalness?

- **New SYMMETRY** giving rise to a cut-off at

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

- **Space-time modification (extra-dim., warped space)**

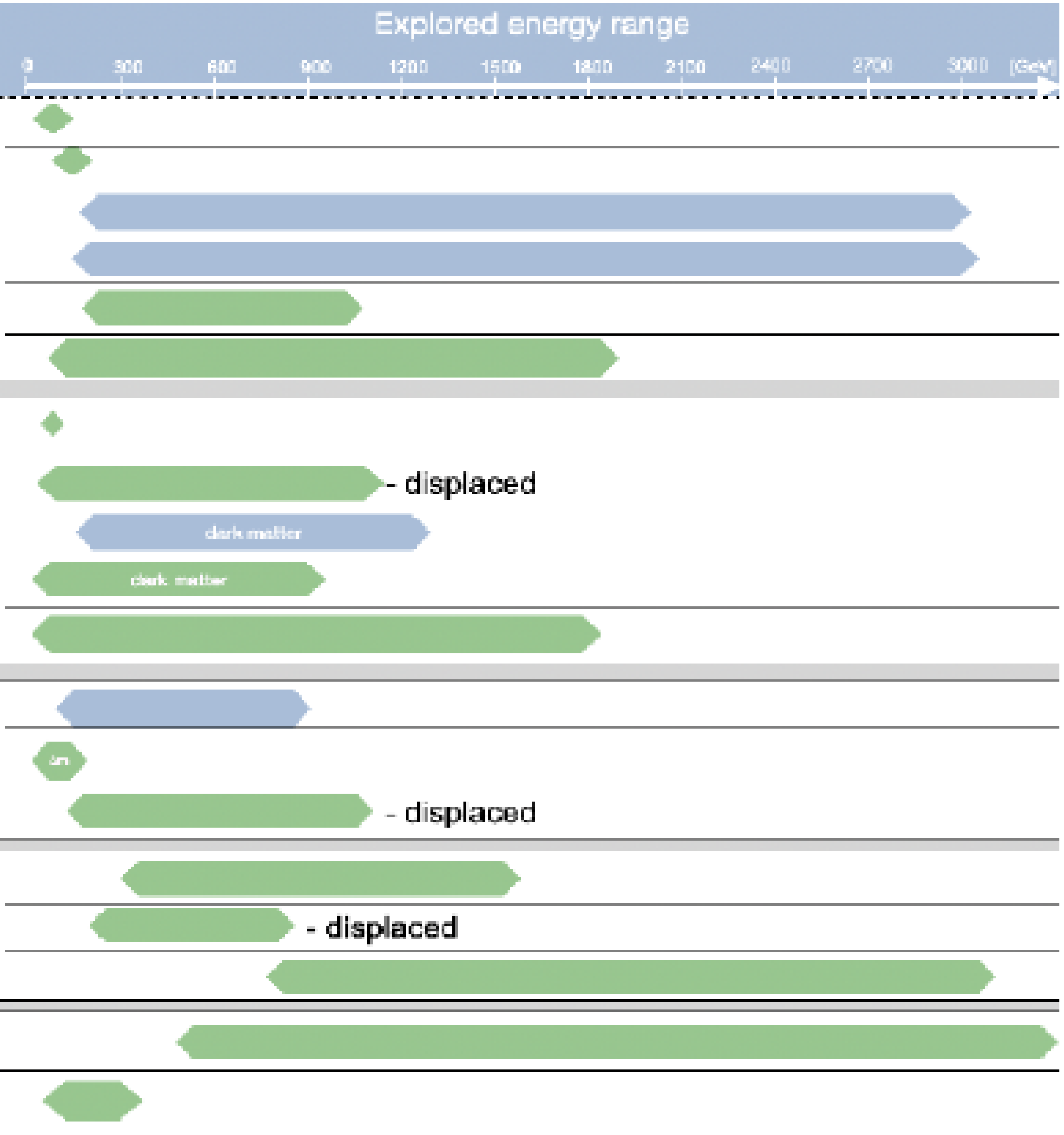
- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**

(Desperately) seeking SUSY particles or many other kinds of new particles beyond the SM particle spectrum

Reference	Topic	Experiment	Model
HDBS-2021-07	$H \to aa \to bb\tau\tau$	ATLAS	Extended Higgs Sector
HDBS-2020-11	$H^{\pm} \to cs$	ATLAS	
HDBS-2023-19	Combination of charged H	ATLAS	
HIG-24-002	$H \to ZZ \to 4l$	CMS	
HIG-22-004	$A \to Zh(\tau\tau)$	CMS	
SUS-24-001	$\phi \to bb$	CMS	
EXOT-2018-55	Prompt Leptonjets	ATLAS	Dark Sector +ALPs
EXOT-2022-04	Neutral LLP into displaced jets	ATLAS	
SUS-23-004	$\mathrm{mono}-t$	CMS	
SUS-23-012	$\mathrm{mono}-h(\tau\tau)$	CMS	
SUS-23-018	$H \to Za \to ll\chi\chi$	CMS	
SUS-24-004	pMSSM	CMS	Supersymmetry
SUS-23-003	Compressed SUSY w/ RJR	CMS	
ATLAS-2024- 011	Run3 displaced leptons	ATLAS	
ATLAS-2024-008	$\mathrm{VLL} \to \tau b$	ATLAS	Heavy Fermions
EXO-23-015	$\mathrm{VLL} \to \tau a(\gamma\gamma)$	CMS	
B2G-22-005	$t^* \to tg$	CMS	
EXO-23-010	$ll + \mathrm{b-jets, non-resonant}$	CMS	EFT
EXO-24-007	Low mass dijet+ISR	CMS	Z' Mediator
EXO-22-006	$Z' \to \mu\mu + \mathrm{b-jets, resonant}$	CMS	



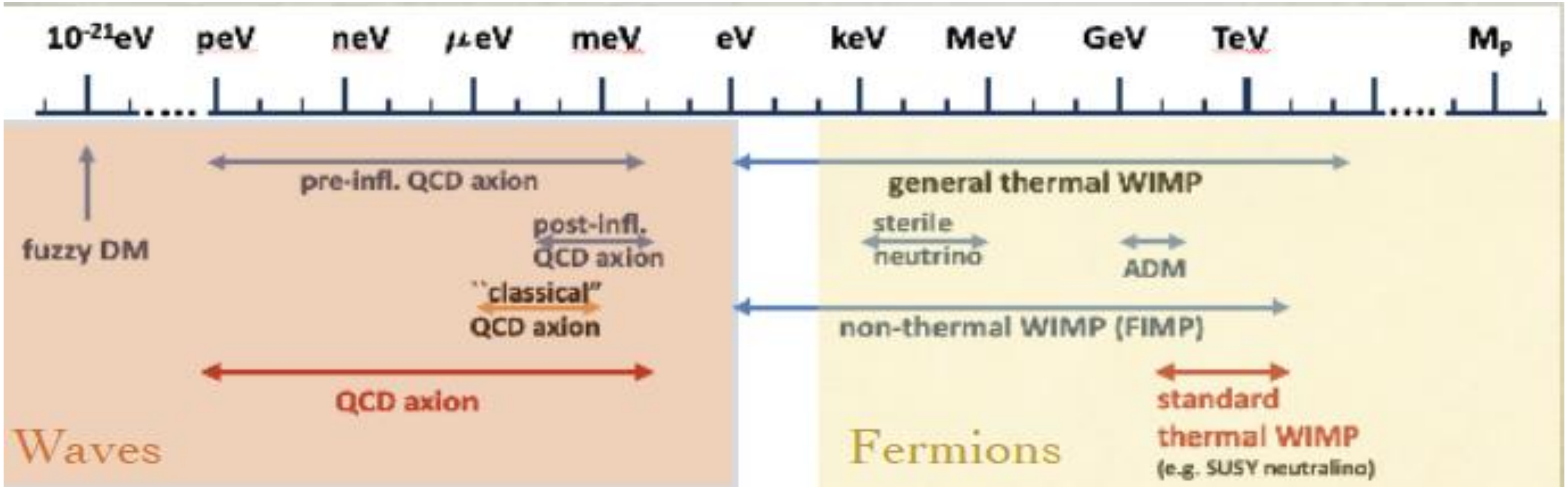
L. Soffi, ICHEP 2024

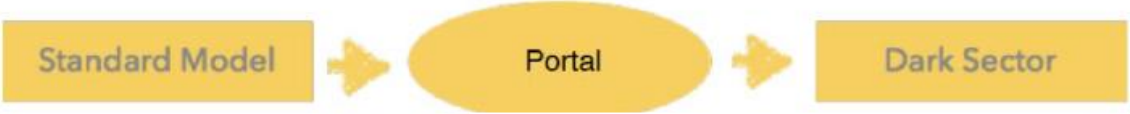
CONNECTION DM – ELW. SCALE

THE WIMP MIRACLE

	SUSY	**EXTRA DIM.**	**LITTLE HIGGS.**
1) **ENLARGEMENT OF THE SM**	(x^μ, θ) Anticomm. Coord.	(x^μ, j^i) New bosonic Coord.	SM part + new part to cancel Λ^2 at 1-Loop
2) **SELECTION RULE** → **DISCRETE SYMM.** → **STABLE NEW PART.**	***R-PARITY LSP*** Neutralino spin 1/2 m_{LSP} ~100 - 200 GeV	***KK-PARITY LKP*** spin1 m_{LKP} ~600 - 800 GeV	***T-PARITY LTP*** spin0 m_{LTP} ~400 - 800 GeV

R-parity is an ADDITIONAL discrete symmetry imposed to prevent SUSY particles with masses at the electroweak scale to mediate a too fast proton decay!

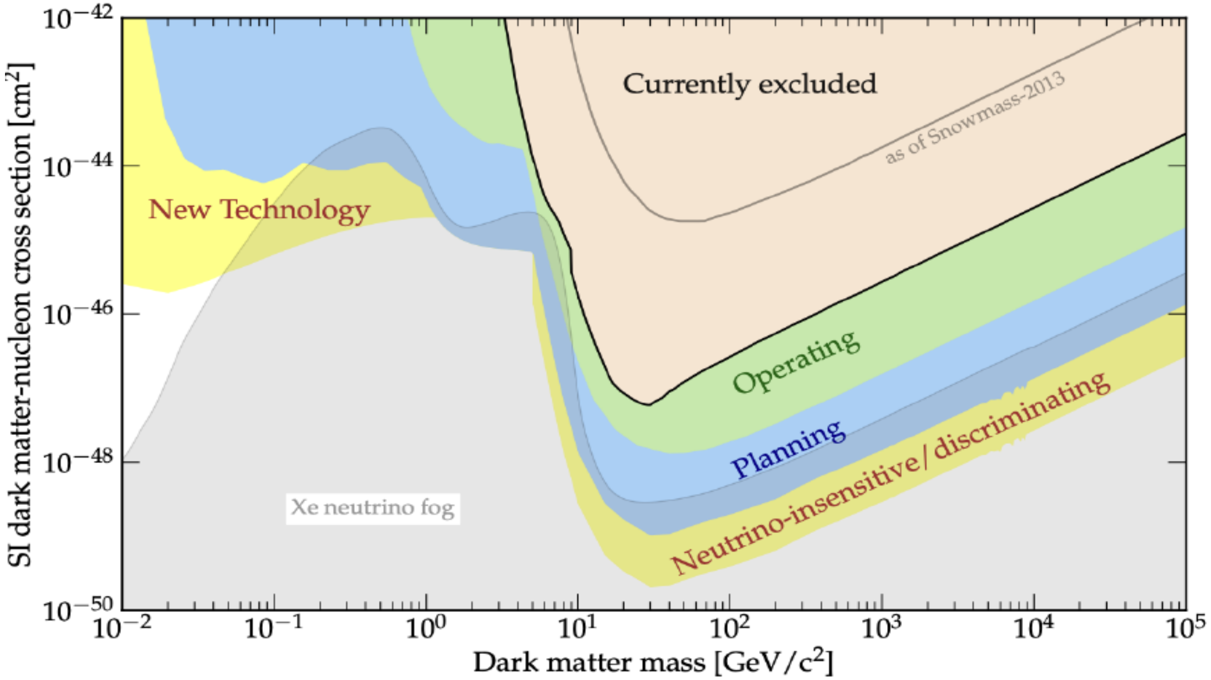




"Portals":

Dark photon	$\epsilon Z^{\mu\nu} A'_{\mu\nu}$
Higgs	$\kappa \lvert H\rvert^2 \lvert S\rvert^2$
Neutrino	$y H L N$
Axion	$\frac{1}{f_s} F_{\mu\nu}\tilde{F}_{\mu\nu} a$

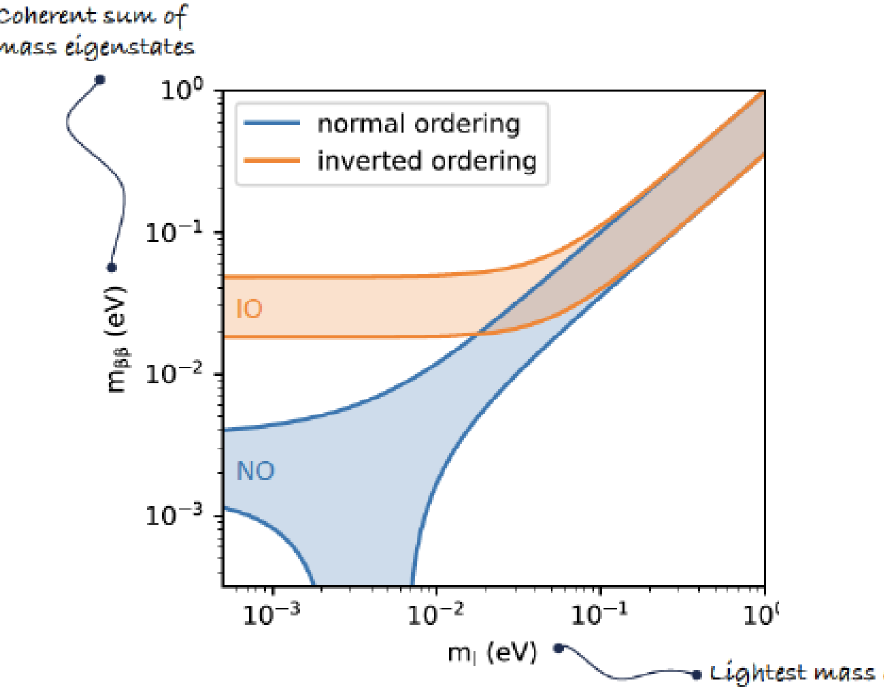
Feebly coupled dark sector particles → can provide sizeable contributions to low-energy observables (e.g. leptonic dipole moments)



Neutrino mass → RH neutrino → L is no longer an automatic symmetry of the SM

Is LEPTON Number a (global) symmetry of Nature?

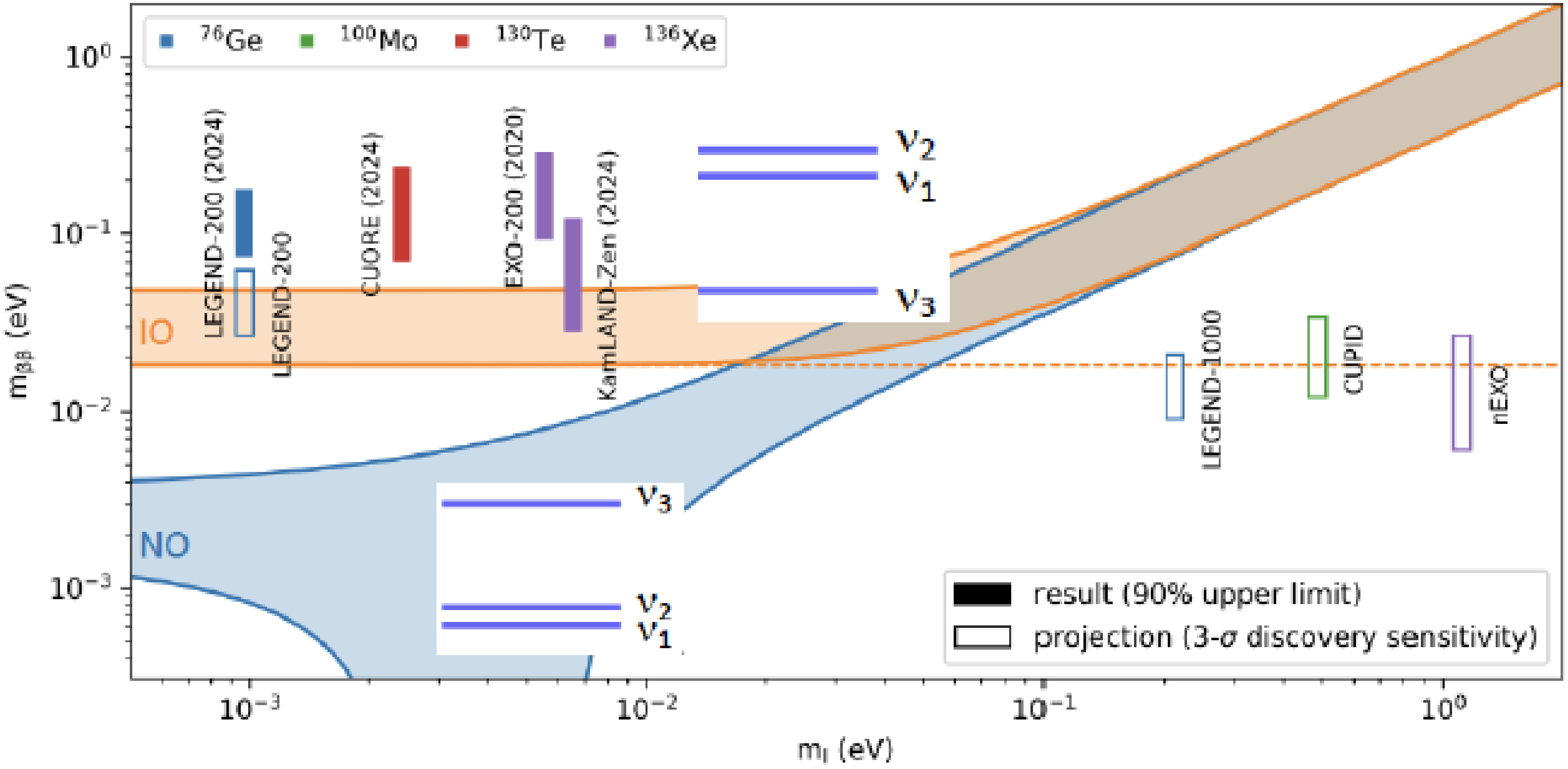
The **Neutrinoless Double Beta-Decay** to verify if the neutrino has a MAJORANA mass



KamLAND-Zen Xe-loaded liquid scintillator

$m_{\beta\beta} < 122$meV (90% CL)

arXiv:2406.11438 (2024)



Planned projects on 0νββ should fully cover the inverted ordering range

Results on $p\rightarrow e^+\pi^0$ and $p\rightarrow \mu^+\pi^0$

	Eff(%)	Exp. BG (event)	Observed (event)
$p\rightarrow e^+\pi^0$			
Lower	18.1	0.02	0
Upper	19.5	058	0
$p\rightarrow \mu^+\pi^0$			
Lower	17.3	0.05	0
Upper	17.2	0.89	1

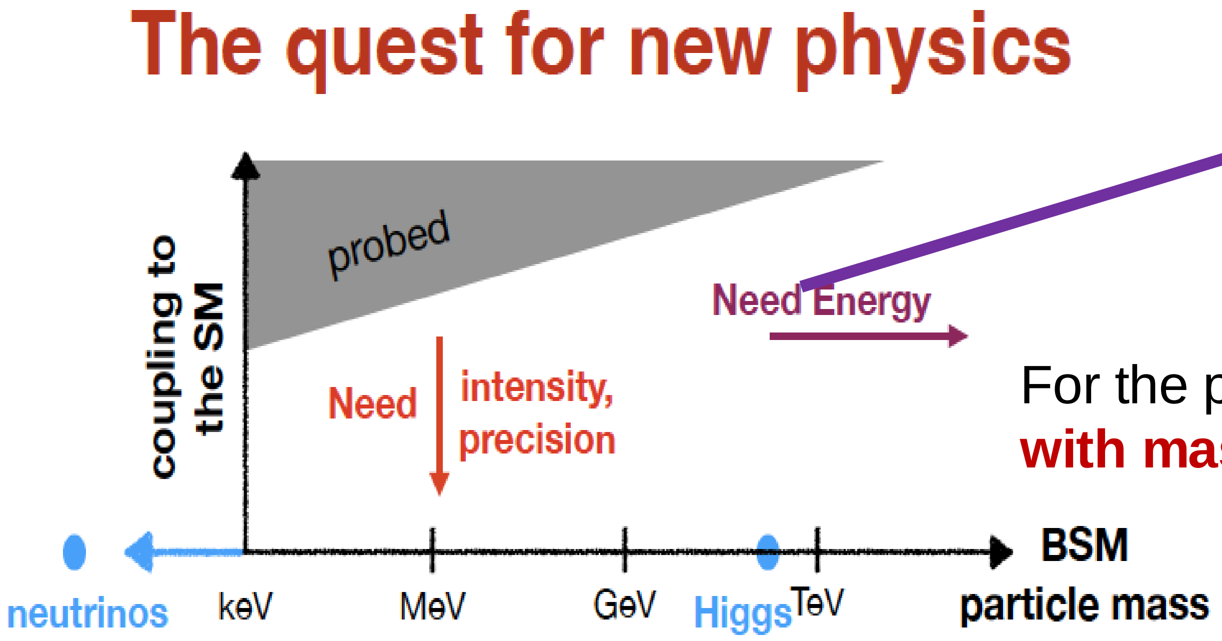
Lifetime limt (90% CL,450 kton･yrs data)

$p\rightarrow e^+\pi^{0:}$ > $2.4\text{x}10^{34}$ years

$p\rightarrow \mu^+\pi^{0:}$ > $1.6\text{x}10^{34}$ years

M. Nakahata, Erice School, 2023

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

The **HIGH-ENERGY** road: towards a **10 TeV parton-center-of-momentum** (pCM) **collider**

- **For Lepton Colliders the pCM is just the nominal collision energy in the CM frame;**
- **For Proton Colliders the parton-parton interaction energy is ~ a tenth of the CM energy**

- **Possibilities for a 10TeV pCM collider:**

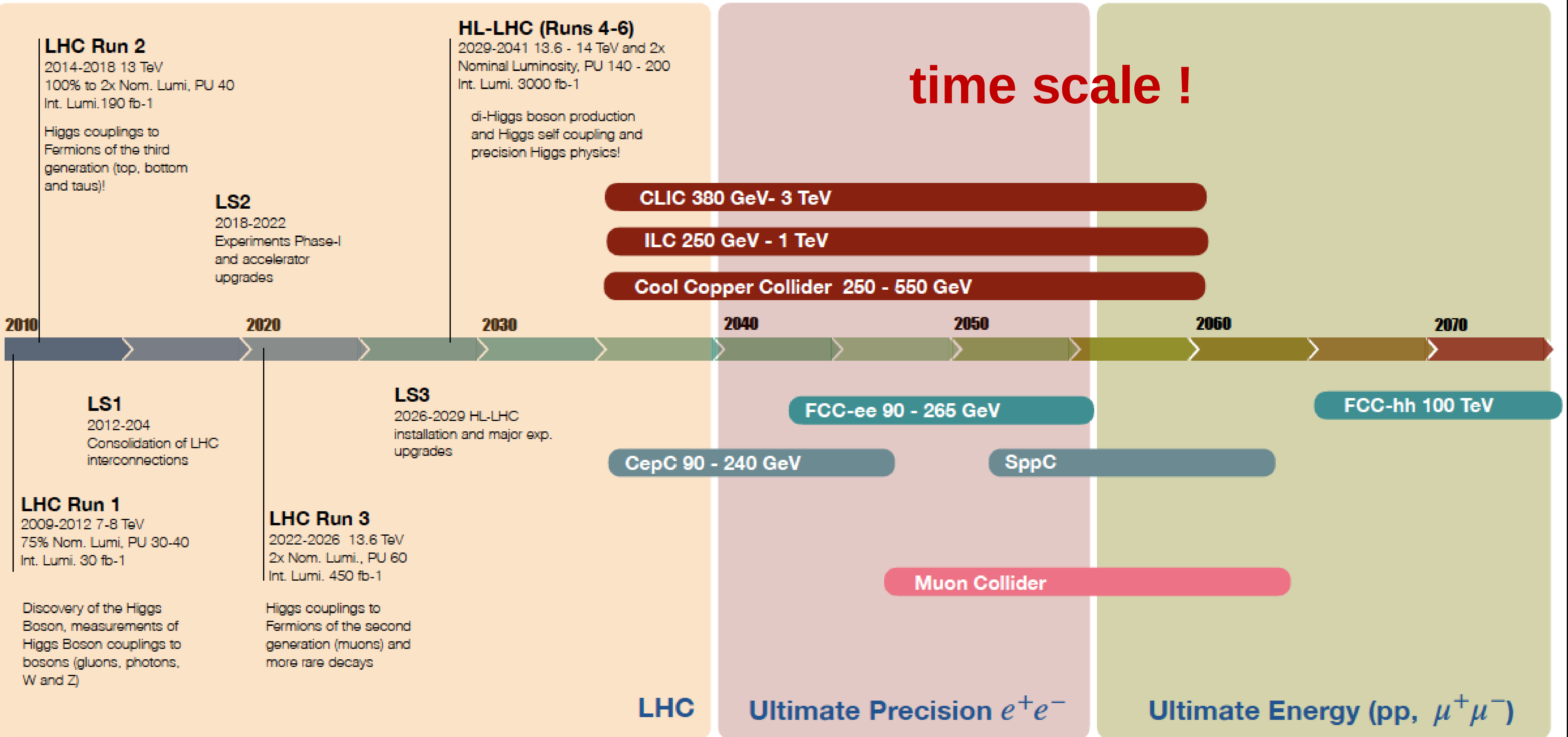
i) proton beams with high-field magnets (100TeV p-p collider such as FCC-hh at CERN)

ii) electron and positron beams with wakefield acceleration (a 10 TeV e^+e^- or $\gamma\gamma$ collider)

iii) muon beams requiring rapid capture and acceleration of muons (10 TeV muon collider)

A Scientific Mission for the 21st Century

Rende Steerenberg ICHEP 2024



LHC Run 2
2014-2018 13 TeV
100% to 2x Nom. Lumi, PU 40
Int. Lumi.190 fb-1

Higgs couplings to Fermions of the third generation (top, bottom and taus)!

LS2
2018-2022
Experiments Phase-I and accelerator upgrades

HL-LHC (Runs 4-6)
2029-2041 13.6 - 14 TeV and 2x Nominal Luminosity, PU 140 - 200
Int. Lumi. 3000 fb-1

di-Higgs boson production and Higgs self coupling and precision Higgs physics!

time scale !

CLIC 380 GeV- 3 TeV

ILC 250 GeV - 1 TeV

Cool Copper Collider 250 - 550 GeV

LS1
2012-204
Consolidation of LHC interconnections

LS3
2026-2029 HL-LHC installation and major exp. upgrades

FCC-ee 90 - 265 GeV

FCC-hh 100 TeV

CepC 90 - 240 GeV

SppC

LHC Run 1
2009-2012 7-8 TeV
75% Nom. Lumi, PU 30-40
Int. Lumi. 30 fb-1

Discovery of the Higgs Boson, measurements of Higgs Boson couplings to bosons (gluons, photons, W and Z)

LHC Run 3
2022-2026 13.6 TeV
2x Nom. Lumi., PU 60
Int. Lumi. 450 fb-1

Higgs couplings to Fermions of the second generation (muons) and more rare decays

Muon Collider

LHC

Ultimate Precision e^+e^-

Ultimate Energy (pp, $\mu^+\mu^-$)

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

Low-energy high-precision exps. can exploit :

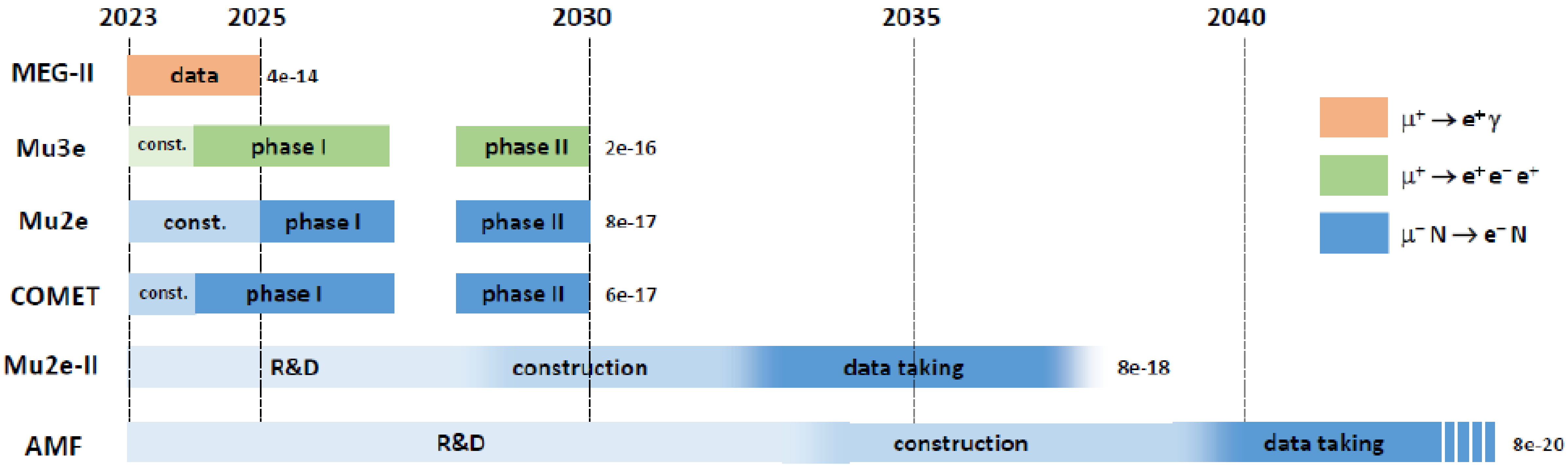
- many recent ***advances in experimental techniques and technologies*** + **(experimental as well as theoretical)** ***synergies*** with adjacent areas of particle physics (atomic, molecular, optical, nuclear, particle physics)
- the relevant impact of ***quantum mechanical virtual effects*** on physical 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

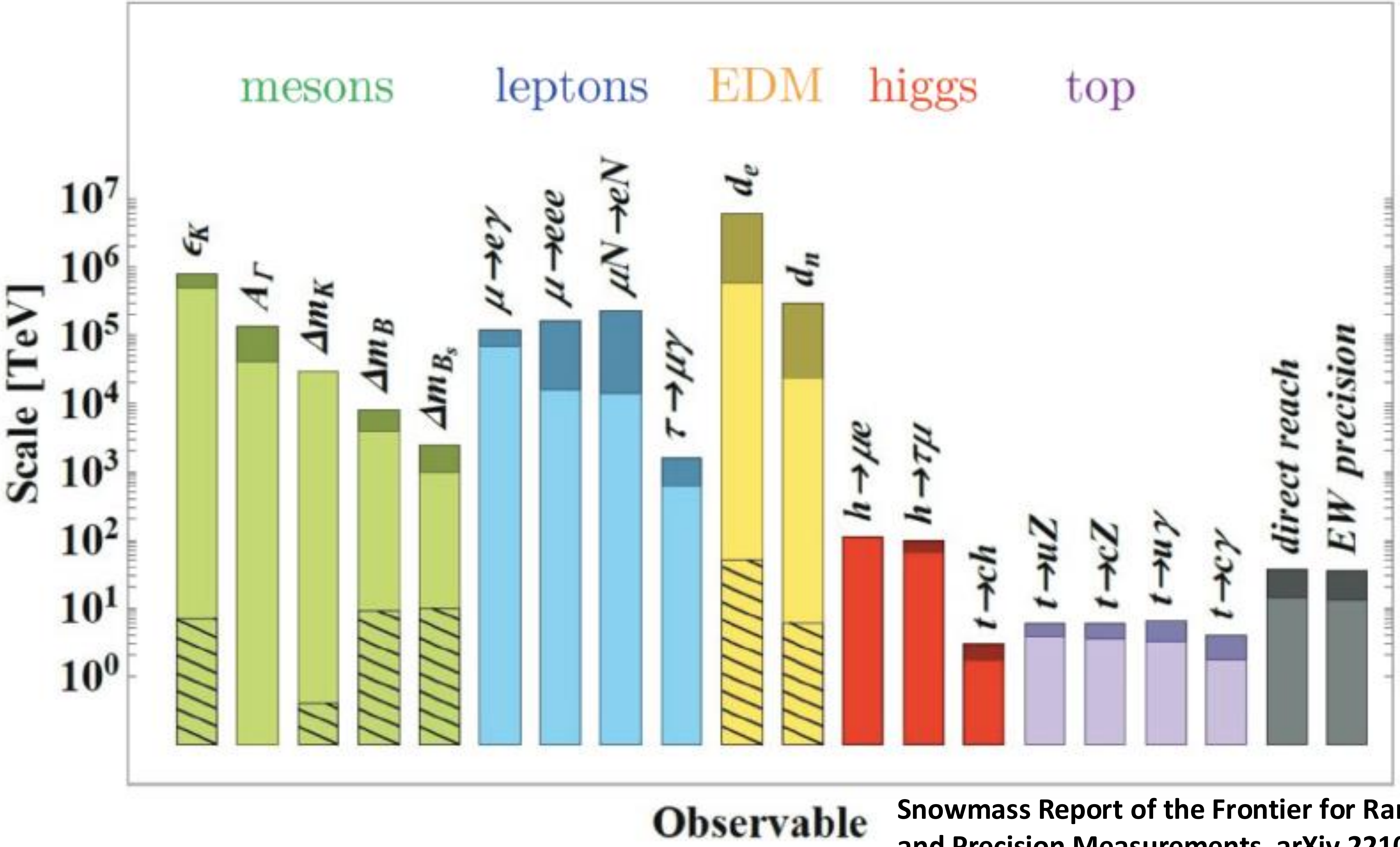
Community Planning Exercise: Snowmass 2021 Blum, Winter et al. arXiv:2209.08041v2 ⇨ **2023 P5 (Particle Physics Project Prioritization Panel) Report**

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

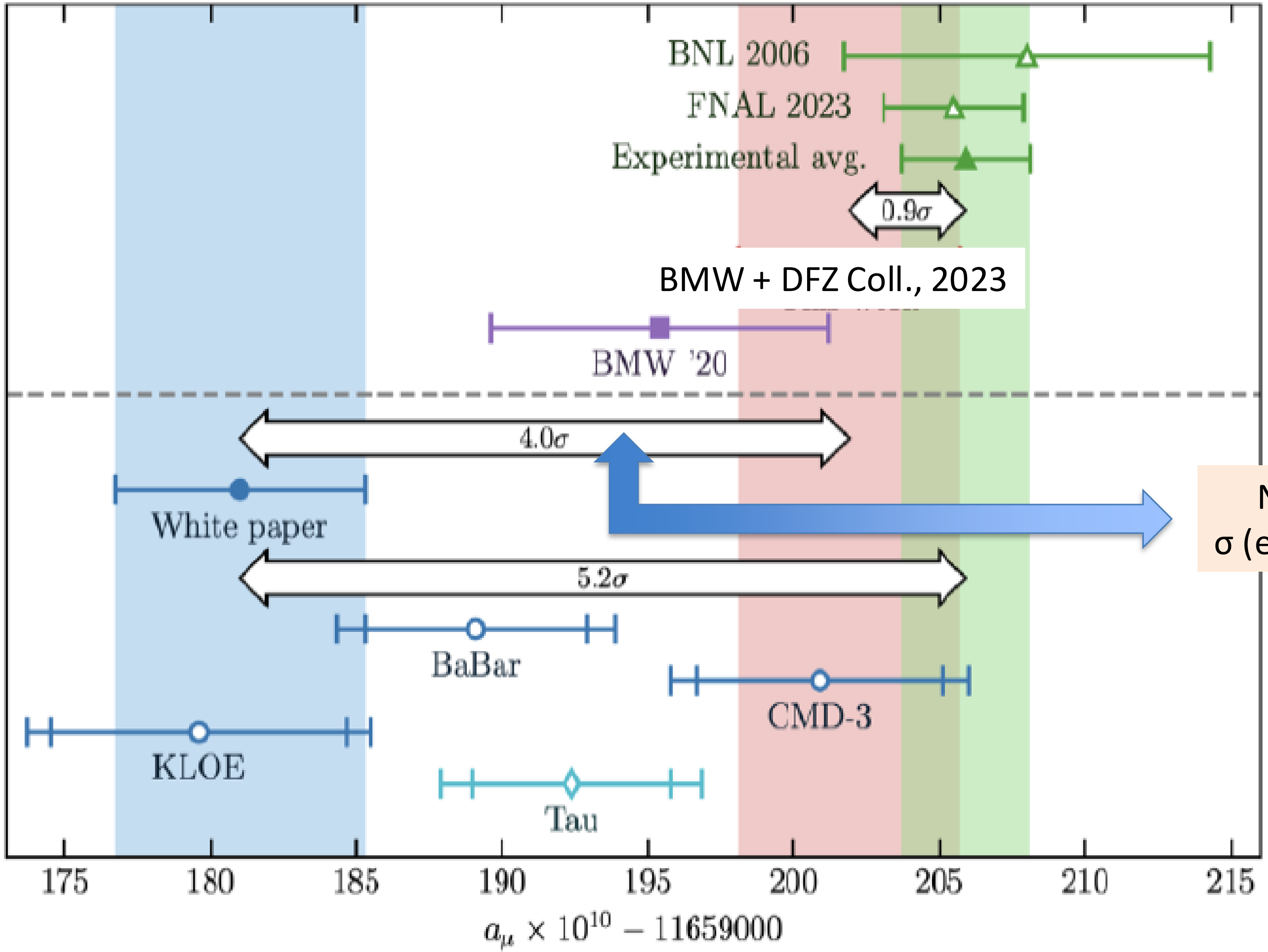


Muon CLFV searches → a **global experimental (and theoretical) program** underway in EU, US and Asia
→ **impressive sensitivity gains** expected in this decade, with up to **4 orders of magnitude** improvements in the rate of **$\mu^- N \rightarrow e^- N$** conversion and **$\mu^+ \rightarrow e^+ e^-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



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

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

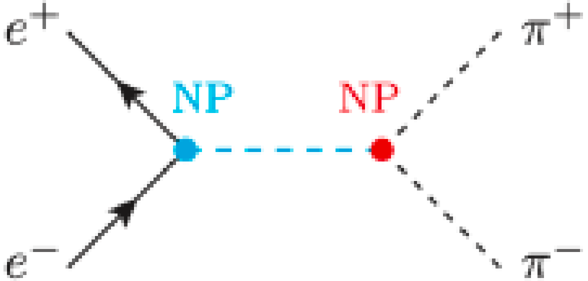


BMW + DFZ Coll., 2023

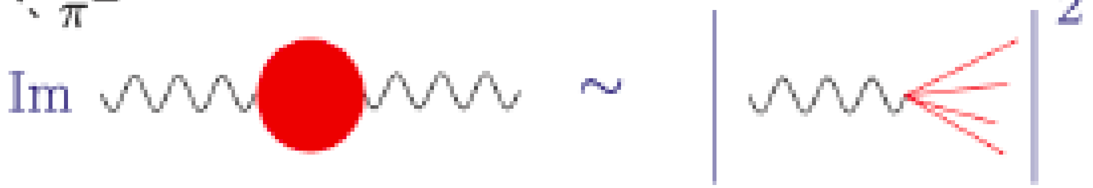
New Physics in
$\sigma\,(e^+e^- \rightarrow \text{hadrons})$?

Light New Physics in σ_{had}

Di Luzio, A.M., Paradisi, Passera PLB 2022



NP coupled both to hadrons and electrons



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

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

$$\sigma_{\text{had}} = \sigma_{\text{had}}^{\text{SM}} + \Delta\sigma_{\text{had}}^{\text{NP}}$$

$$\sigma_{\text{had}} - \Delta\sigma_{\text{had}}^{\text{NP}}$$

SUBTRACTION since NP does **NOT** contribute to the HVP at the LO, but it **DOES** contribute to the cross-section at the LO

a **POSITIVE** SHIFT on $(a_\mu^{\text{HVP}})_{e^+e^-}$ *requires* $\Delta\sigma_{\text{had}}^{\text{NP}} < 0$ *(negative interference)*

The unique scenario to obtain such a **SIZEABLE NEGATIVE interference**

- **SIZEABLE** → **TREE-LEVEL** contribution to modify σ_{had} at $\sqrt{s}$ **< 1 GeV** (hence, **sub-GeV mediator** coupling to the hadronic and electron currents at tree-level)
- **NEGATIVE INTERF.** → NP particle couples via a **VECTOR** current to the u, d quarks (given the dominance of the $\pi^+\pi^-$ channel)

→ *a light spin-1 mediator with vector couplings to first generation SM fermions*

$$\mathcal{L}_{Z'} \supset (g_V^e\,\bar{e}\gamma^\mu e + g_V^q\,\bar{q}\gamma^\mu q)Z'_\mu \qquad q = u, d \qquad m_{Z'} \lesssim 1\ \mathrm{GeV}$$

But existing bounds on light Z' **prevent to get a sizeable contribution to Δa_μ modifying σ_{had} via Z' exchange to solve the "new" μ g-2 puzzle**

Di Luzio, A.M., Paradisi,
Passera PLB 2022

possible loophole if the **Z' mass is just very near the ρ resonance mass of 770 MeV**

Coyle and Wagner JHEP 2023

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, $s>m_l$ → $K_l \sim m_l^2$

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 arXiv:2408.01123

O observables to consider

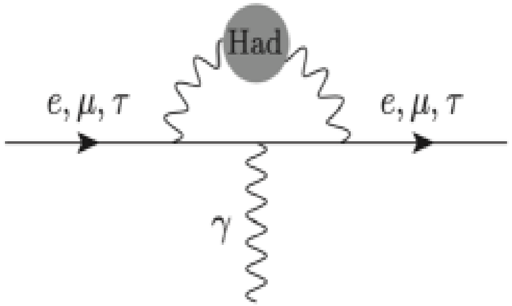
- **the Electron g-2 (a_e)**
- **the Muonium HyperFine Splitting (HFS)**
- **the Tau g-2 (a_τ)**
- **the low-energy weak mixing angle $\sin^2\theta_W(0)$**
- **the running of α_{em}**

Sensitivity of other physical observables to

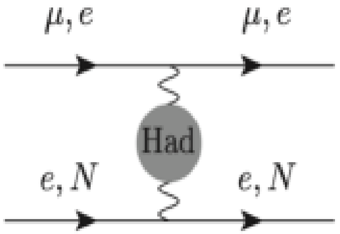
$$[\delta a_\mu^{HVP}]_{NP} = [a_\mu^{HVP}]_{LQCD,CDM3} - [a_\mu^{HVP}]_{DR,WP20}$$

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

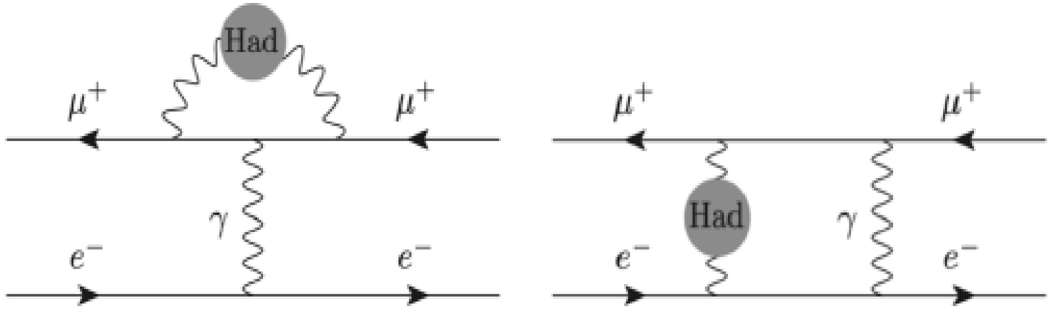
- **the Electron g-2 (a_e)**
- **the Muonium HyperFine Splitting (HFS)**
- **the Tau g-2 (a_τ)**
- **the low-energy weak mixing angle $\sin^2\theta_W(0)$**
- **the running of α_{em}**



Leptonic g-2



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

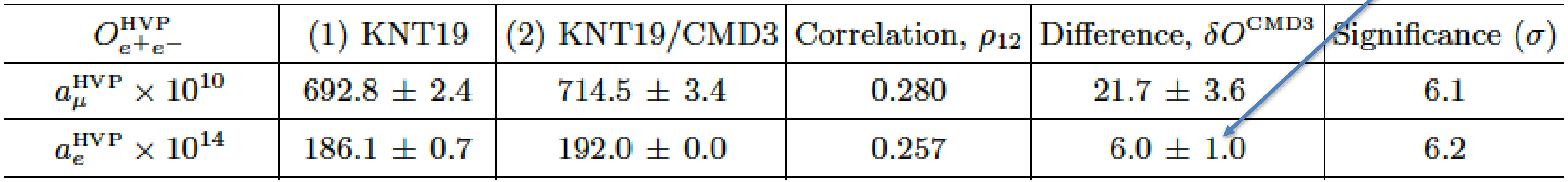


Muonium HFS

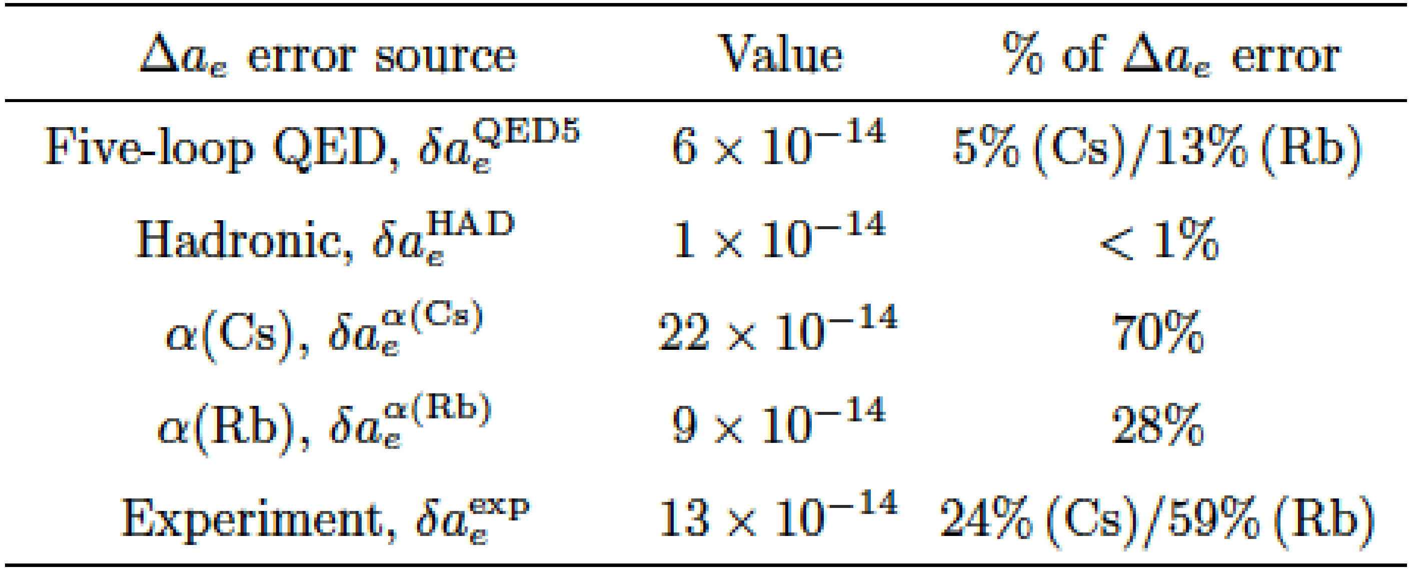
Electron g-2

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



$O_{e^+e^-}^{\rm HVP}$	(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)

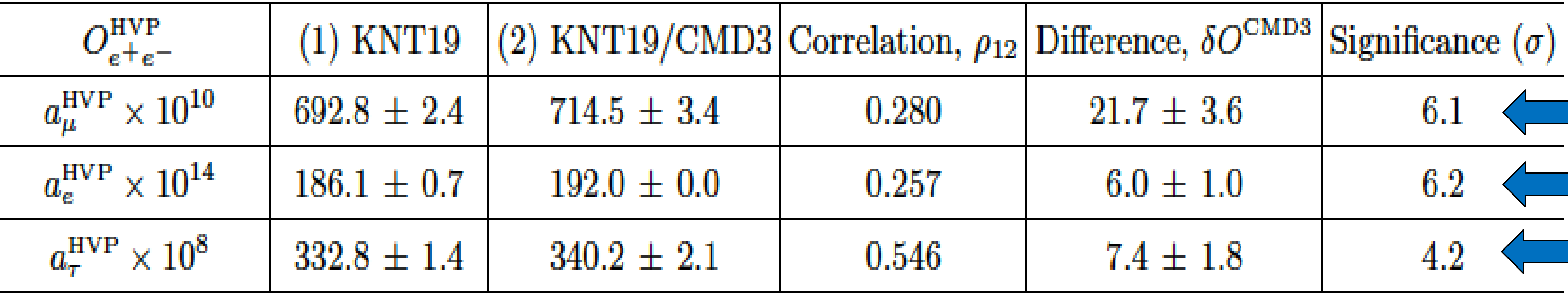
Tau g-2

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 $a_e^{\rm CDM3}$ $a_\mu^{\rm CDM3}$



$O^{\rm HVP}_{e^+e^-}$	(1) KNT19	(2) KNT19/CMD3	Correlation, ρ_{12}	Difference, $\delta O^{\rm CMD3}$	Significance (σ)
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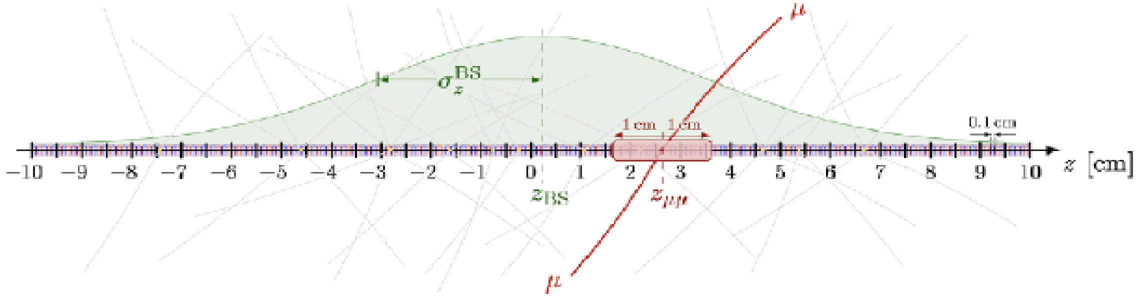
$a_\tau^{\rm HVP} \times 10^{8}$	332.8 ± 1.4	340.2 ± 2.1	0.546	7.4 ± 1.8	4.2

Tau Anomalous Magnetic Moments

Toru Lijima, Maurizio Pierini ICHEP 2024

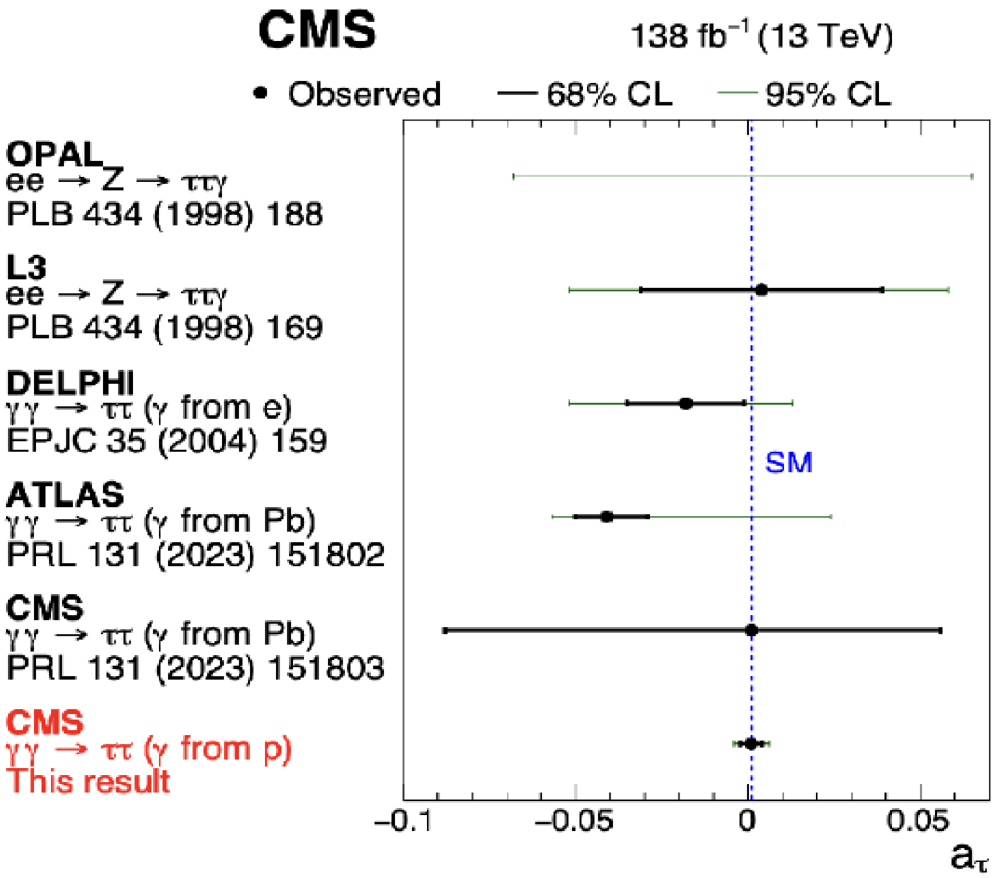


Beautiful analysis selecting isolated low multiplicity vertices, sensitive to photo-production of tau pairs!

Large gain in sensitivity! Only ~3 times larger than the Schwinger term (QED part)

However still almost 3-4 orders of magnitude above sensitive corrections e.g. EW!

$$
\begin{aligned}
a_\tau^{\mathrm{QED}} &= 1.1732 \times 10^{-3}, \\
a_\tau^{\mathrm{had}} &= 3.2(4) \times 10^{-6}, \\
a_\tau^{\mathrm{EW}} &= 4.7 \times 10^{-7}.
\end{aligned}
$$



$$a_\tau = \frac{g_\tau}{2} - 1 = 0.0009^{+0.0032}_{-0.0031}$$

expected future experimental sensitivity at Belle II with an important polarization upgrade of the SuperKEKB

O (10^{-6}), i.e. ~ one order of magnitude below $\delta a_\tau^{\mathrm{CDM3}}$ (Crivellin, Hoferichter, Roney PRD 2022)

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

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

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

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$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2) \times 10^4$	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 γ – Z mixing (Erler and Ferro-Hernández JHEP 2018)
(Keshavarzi, Marciano, Passera, Sirlin PRD 2020)

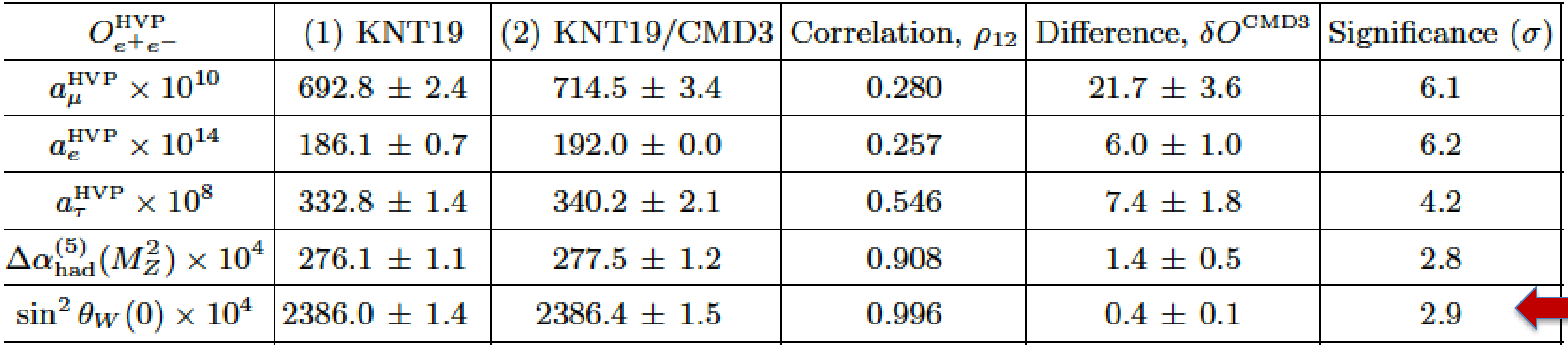
The shift from the CDM-3 data can be estimated via:

$$\delta\sin^2\theta_W(0) \approx k'\sin^2\theta_W(M_Z)\,\frac{3\pi}{\alpha}\,\frac{m_\rho^2}{m_\mu^2}\,\delta a_\mu^{\rm CMD3}$$

$$\approx (0.4 \pm 0.1)\times 10^{-4}\,,$$

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 ~ $O(10^{-4})$



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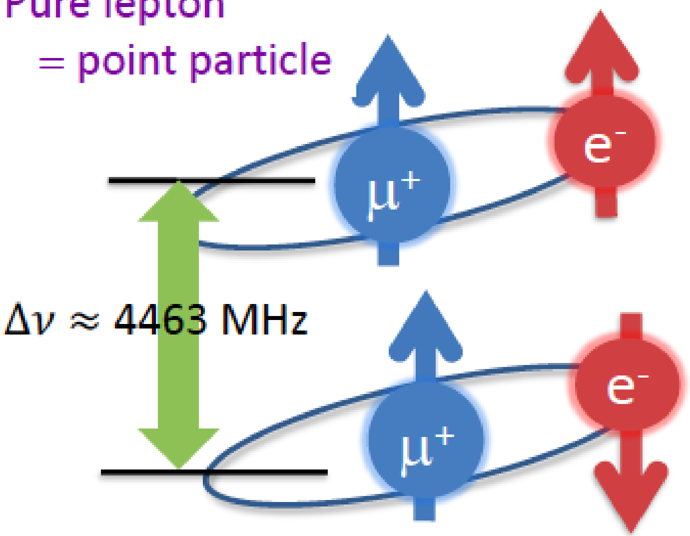
$\sin^2\theta_W(0)\times 10^4$	2386.0 ± 1.4	2386.4 ± 1.5	0.996	0.4 ± 0.1	2.9

The Muonium HyperFine Splitting (HFS)

Muonium: bound state of μ^+ and e^-

Pure lepton
= point particle



Δν : Muonium Hyperfine Structure

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

Muonium HFS of the 1S ground state

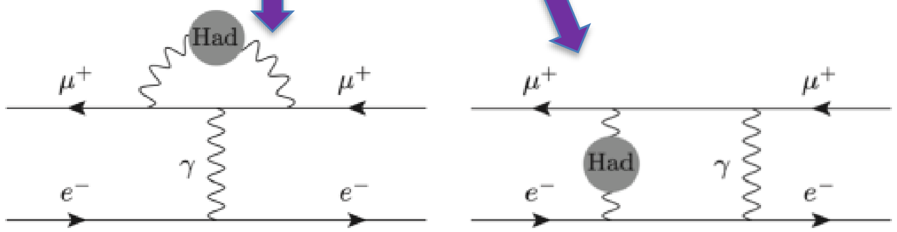
$$\frac{\nu_{\rm HFS}}{\nu_F} = 1 + a_\mu + \Delta^{\rm QED}_{\rm HFS} + \Delta^{\rm weak}_{\rm HFS} + \Delta^{\rm HVP}_{\rm HFS}$$

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

for $s \gg m_\mu^2$

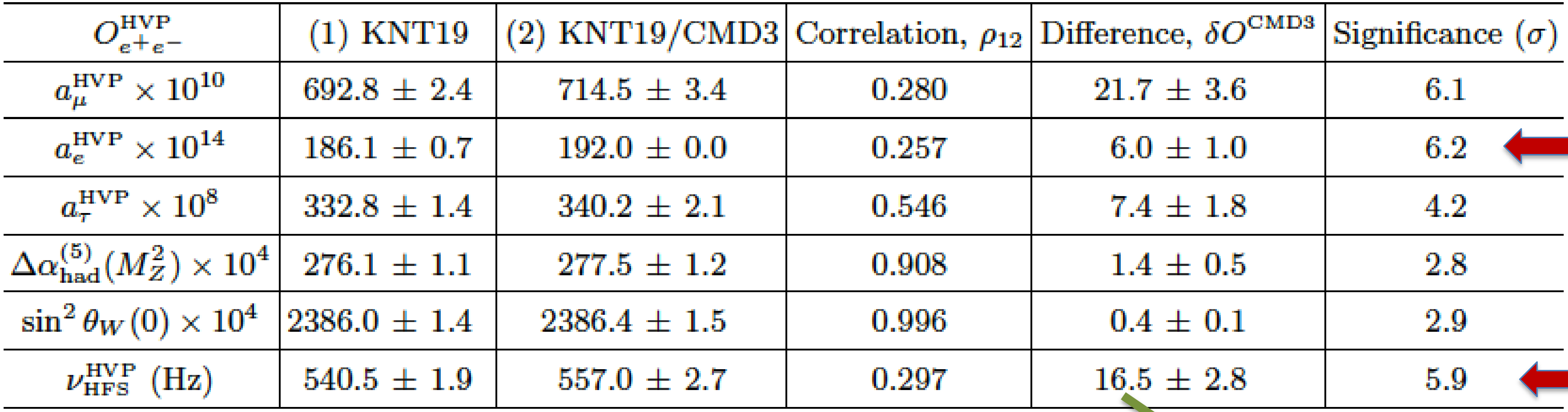
$$\Delta^{\rm HVP}_{\rm HFS} \approx 6\,\frac{m_\rho^2}{m_\mu^2} K_{\rm Mu}(m_\rho^2)\,(a_\mu^{\rm HVP})_{e^+e^-}$$
$$\approx 0.63\,(a_\mu^{\rm HVP})_{e^+e^-}\,.$$

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



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

5.9σ discrepancy in the comparison!



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$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) \times 10^4$	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
$\nu^{\mathrm{HVP}}_{\mathrm{HFS}}$ (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 $\delta a_\mu^{\mathrm{CMD3}}$ → to be sensitive to this shift needs a precision of O(1) Hz

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

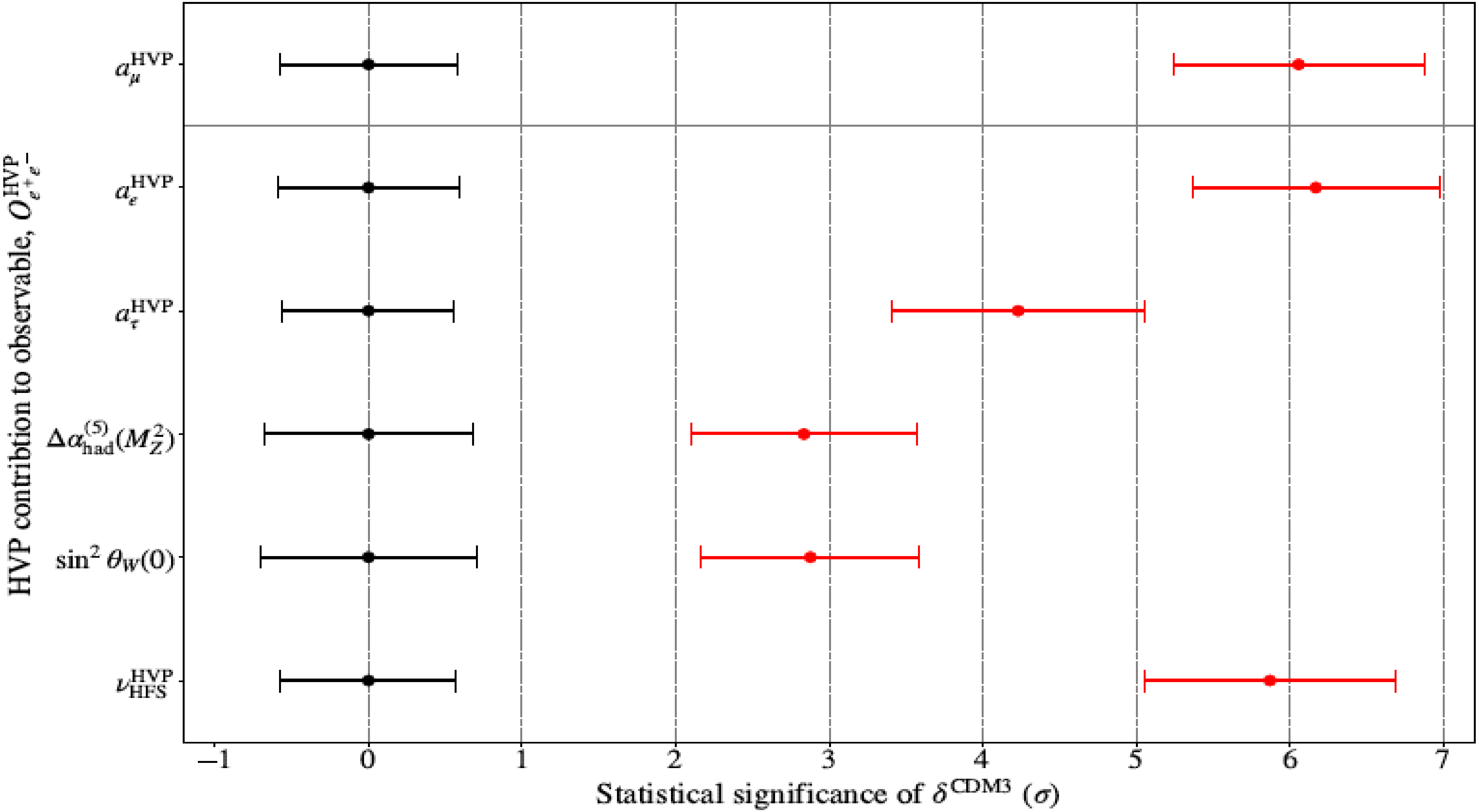
Other sources of uncertainty:

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 ν_{HFS} from unknown **3-loop QED** contributions to $\delta_{\mathrm{HFS}}^{\mathrm{QED}}$ 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



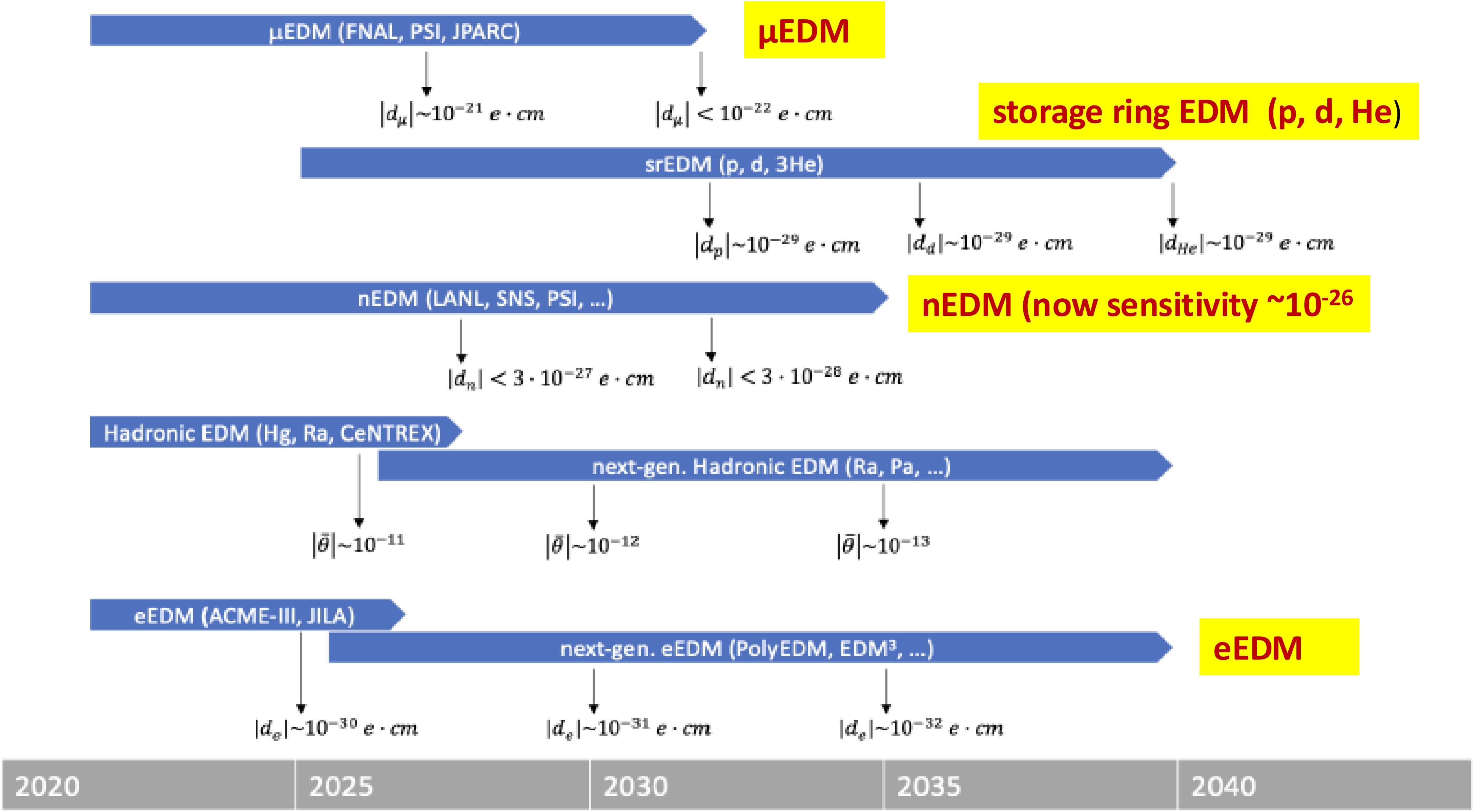
Di Luzio, Keshavarzi, A.M. , Paradisi arXiv:2408.01123

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

Electric Dipole Moments



μEDM (FNAL, PSI, JPARC)

μEDM

$|d_\mu| \sim 10^{-21}\ e \cdot cm$

$|d_\mu| < 10^{-22}\ e \cdot cm$

storage ring EDM (p, d, He)

srEDM (p, d, 3He)

$|d_p| \sim 10^{-29}\ e \cdot cm$

$|d_d| \sim 10^{-29}\ e \cdot cm$

$|d_{He}| \sim 10^{-29}\ e \cdot cm$

nEDM (LANL, SNS, PSI, ...)

nEDM (now sensitivity ~10^{-26}

$|d_n| < 3 \cdot 10^{-27}\ e \cdot cm$

$|d_n| < 3 \cdot 10^{-28}\ e \cdot cm$

Hadronic EDM (Hg, Ra, CeNTREX)

next-gen. Hadronic EDM (Ra, Pa, ...)

$|\bar{\theta}| \sim 10^{-11}$

$|\bar{\theta}| \sim 10^{-12}$

$|\bar{\theta}| \sim 10^{-13}$

eEDM (ACME-III, JILA)

next-gen. eEDM (PolyEDM, EDM³, ...)

eEDM

$|d_e| \sim 10^{-30}\ e \cdot cm$

$|d_e| \sim 10^{-31}\ e \cdot cm$

$|d_e| \sim 10^{-32}\ e \cdot cm$

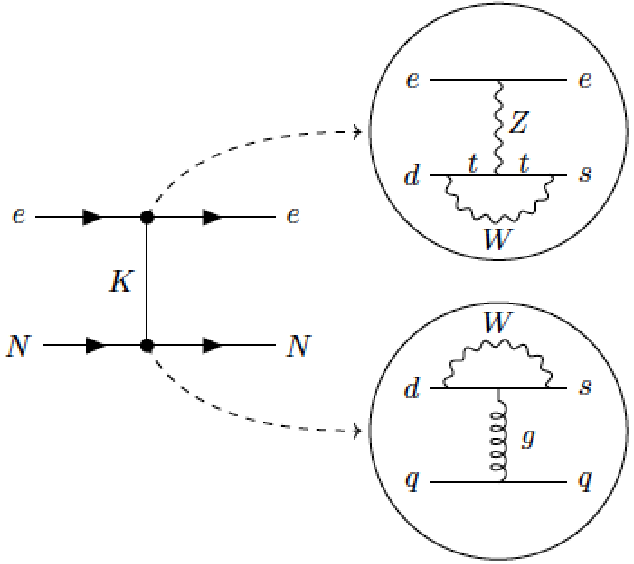
Blum, Winter Snowmass 2021 arXiv 2209.08041

“Good news” from the theory of electric dipole moments

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

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 $d_e^{\rm equivv}$



$$C_S({\rm LO+NLO}) \simeq 6.9 \times 10^{-16}, \quad {\rm or} \quad d_e^{\rm equiv} \simeq 1.0 \times 10^{-35}\, e\,{\rm cm}.$$

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

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

$$|d_\mu| < 1.7 \times 10^{-20}\, e\,{\rm cm}. \qquad |d_\tau| < 1.1 \times 10^{-18} e\,{\rm cm} \quad (90\%{\rm C.L.})$$

Ema, Gao, Pospelov 2024 **PoS DISCRETE2022**

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

Giudice, Paradisi and Passera JHEP 2012

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

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

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

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

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

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

- 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 $d_\mu \sim 10^{-22}$ $e\,\text{cm}$ are still allowed!

Paradisi, muEDM Workshop Pisa, 2022

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

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)