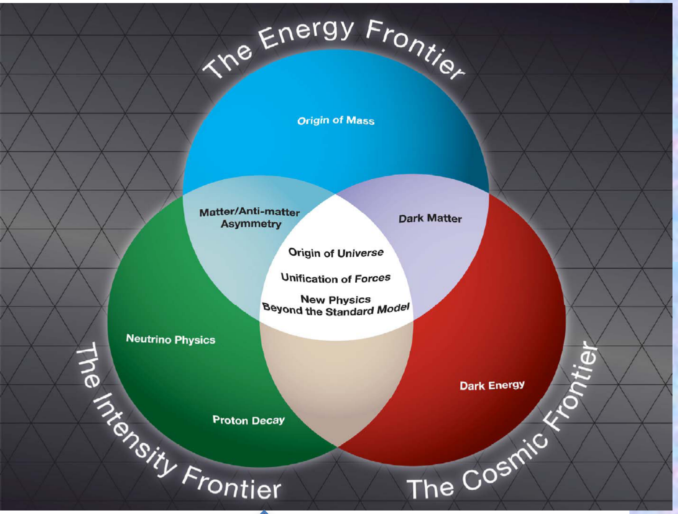
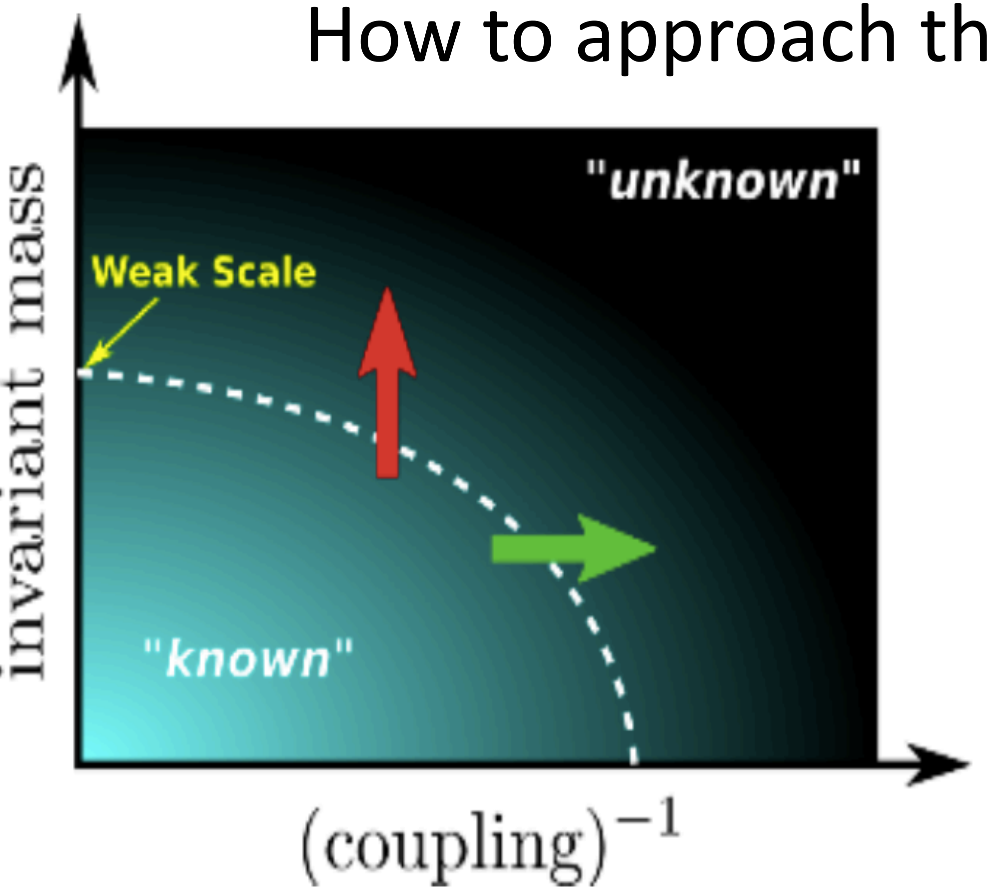


The *Precision Frontier* *of* *Particle Physics* in 2023

Antonio Masiero
Univ. of Padova and INFN, Padova

How to approach the "Unknown"



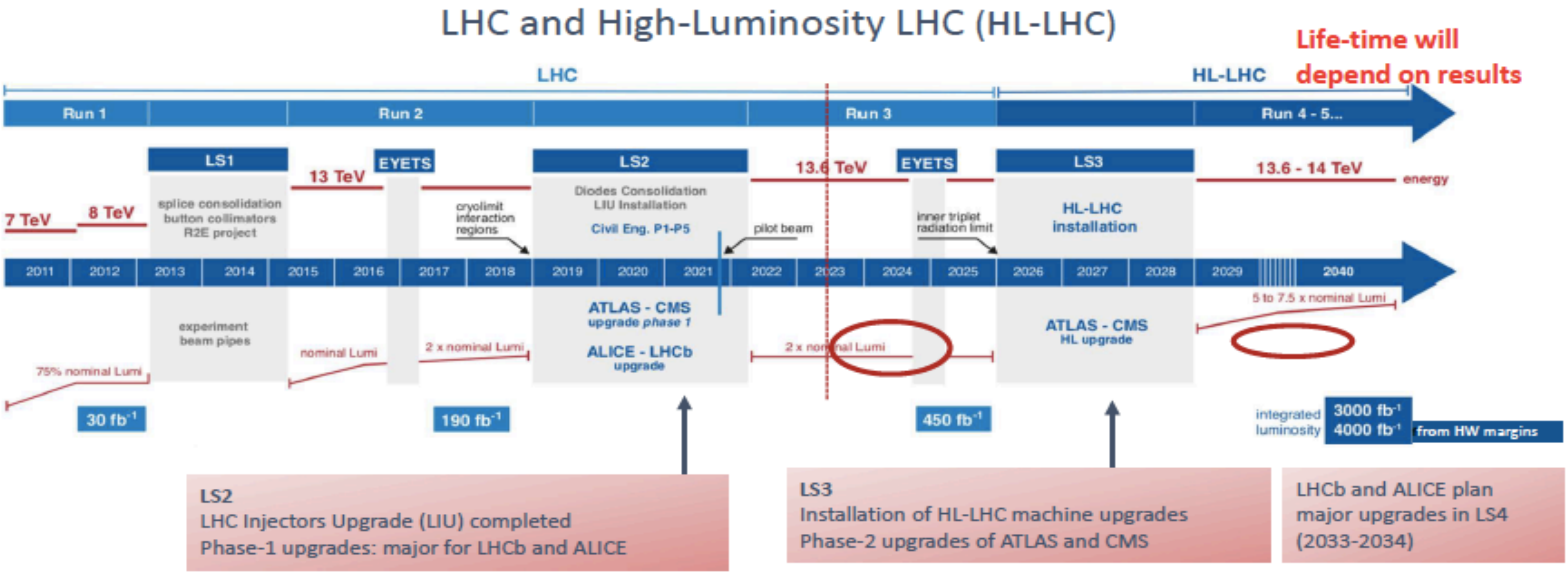
High-Energy Frontier →
New Physics (NP) at large energy scales

Next generation Astro-Particle experiments (DM, DE, neutrinoless ββ-decay, observational cosmology, multimessenger and multiwalengths physics)
→ exploring large distances and times, feebly or very feebly coupled NP

To proceed along the above two frontiers (in particular the HE one) → **LARGE-SCALE** experiments and Research Infrastructures on earth or in space (HE particle colliders, telescopes , large volume detectors) demanding increasingly **LARGER TIME-SCALES** (from the proposal to the operational phase) and **LARGER COSTS**

The HE particle collider road: past, present and future

Today: Coming Soon:



Expected integrated luminosity at the end of LHC (2025): > 450 fb^{-1} (design target: 300 fb^{-1})

Luminosity target for HL-LHC: 3000 fb^{-1} – "needed to observe HH production at ~ 5σ level in ATLAS and CMS"

C. Llewellyn Smith, Erice 2022

FUTURE CIRCULAR COLLIDER

FCC timeline

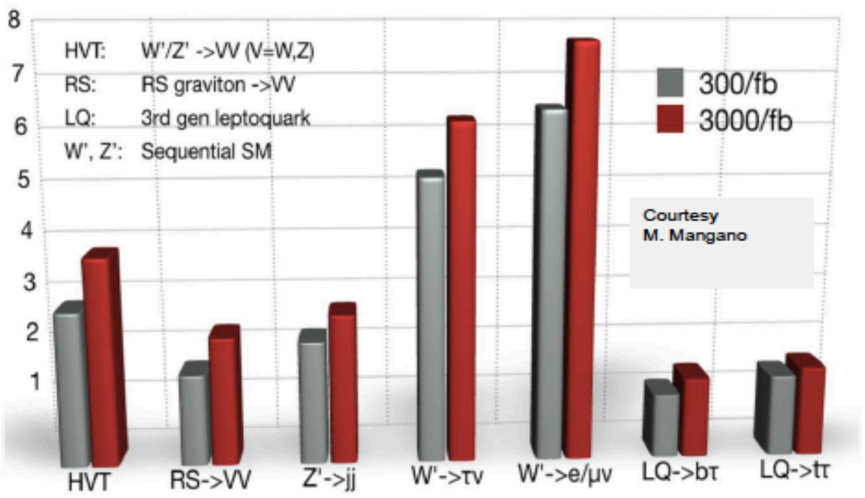
Realistic schedule takes into account:

- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

Physics potential of HL-LHC 2

5σ discovery mass reach (TeV) for new particles:



Beyond SM Searches

Following Gavin Salam, look at Z'_{SSM} as a simple measure of progress

- perhaps not very "exciting", but simple and most experiments look for it

Tevatron		LHC		FCC-hh
$p\bar{p}$, 1.96 TeV, 10 fb^{-1}	× 4 →	pp, 13.6 TeV, 139 fb^{-1}	× 7.8 →	pp, 100 TeV, 20 ab^{-1}
Exclusion limit ~ 1.2 TeV		Exclusion limit ~ 5.1 TeV		Exclusion limit ~ 41 TeV
(if they had analysed all their data in electron and muon channels; actual CDF limit 1.071 TeV, 4.7fb^{-1}, μμ only)		(electron and muon channels, single experiment)		(based on PDF luminosity scaling, assuming detectors can handle muons and electrons at these energies)

C. Llewellyn Smith, Erice 2022

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

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

The (intertwined) precision physics in this talk

- **Leptonic magnetic dipole moments** **$(g\text{-}2)_l$** $l = e, \mu, \tau$

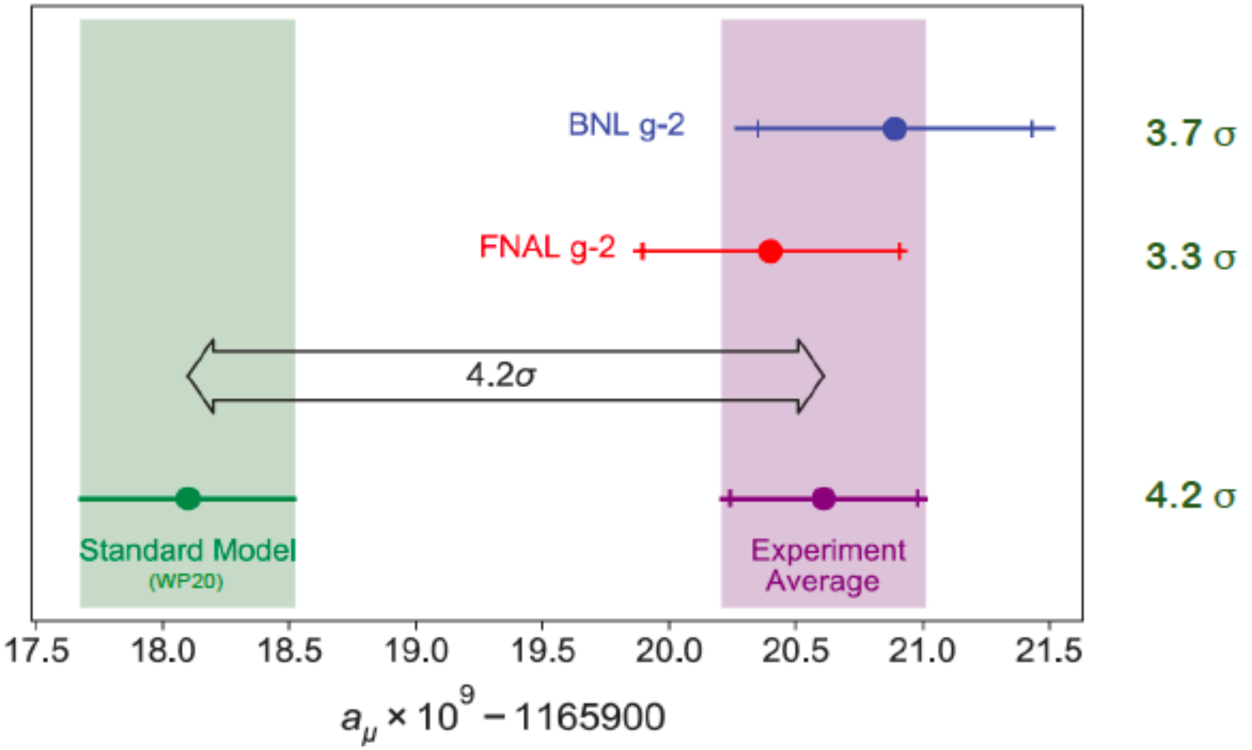
- **Electric dipole moments** (**EDMs**)

- **Lepton Flavour Universality** (**LFU**)

- **Charged Lepton Flavour Violation** (**CLFV**)

April 7^{th} 2021 — Muon g-2: FNAL confirms BNL

The OLD $(g\text{-}2)_\mu$ puzzle

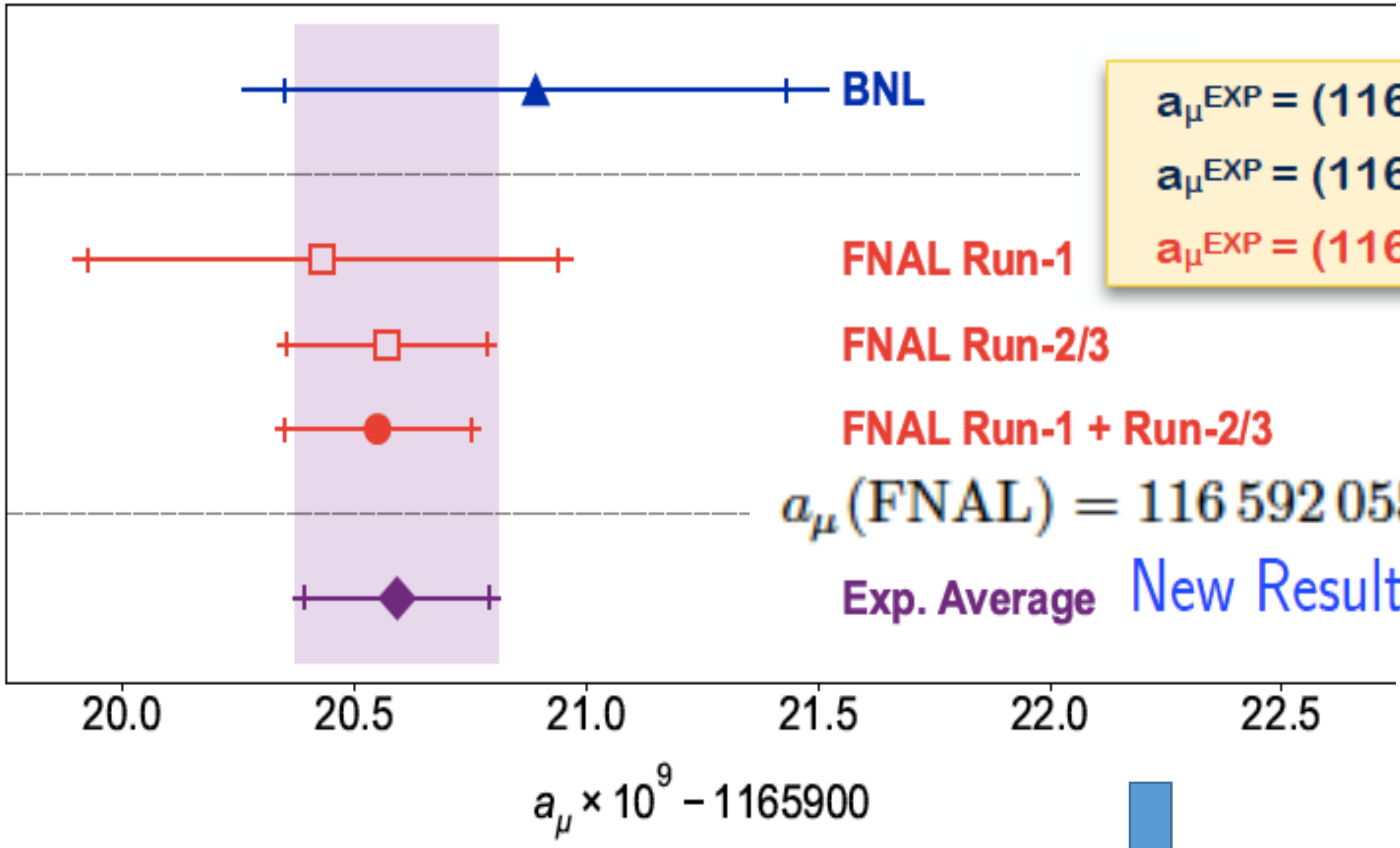


3-4σ discrepancy between exp. result and SM prediction **CONSTANTLY** with us for a couple of decades!

(and last August it even became **> 5σ** comparing the exp. result with the SM expectation in the White Paper WP20 by the Muon g-2 Th. Initiative)

$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm]	BNL E821
$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm]	FNAL E989 Run 1
$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm]	WA

- FNAL aims at 16×10^{-11}. First 4 runs completed, 5th in progress.
- Muon g-2 proposal at J-PARC: Phase-1 with ~ BNL precision.



$a_\mu^{EXP} = (116592089 \pm 63) \times 10^{-11}$ [0.54ppm] BNL E821

$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

$a_\mu^{EXP} = (116592061 \pm 41) \times 10^{-11}$ [0.35ppm] WA

$$a_\mu(\mathrm{FNAL}) = 116\,592\,055(24) \times 10^{-11} \quad (0.20\,\mathrm{ppm}),$$

New Result Aug 10, 2023: arXiv:2308.06230 [hep-ex

$$a_\mu(\mathrm{Exp}) = 116\,592\,059(22) \times 10^{-11} \quad (0.19\,\mathrm{ppm})$$

FNAL aims at 16×10^{-11} **0.14 ppm**

NEW PHYSICS for the muon g-2: at which scale?

$$\Delta a_\mu \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{weak} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

- A weakly interacting NP at $\Lambda \approx v$ can naturally explain $\Delta a_\mu \approx 2 \times 10^{-9}$
- $\Lambda \approx v$ favoured by the *hierarchy problem* and by a WIMP DM candidate.

On the other hand, HE experiments (LEP, Tevatron, LHC) have NOT provided any clue for the presence of new (charged) particles at the ELW. scale

- NP is very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles.
- NP is very heavy ($\Lambda \gg v$) and strongly coupled to SM particles.

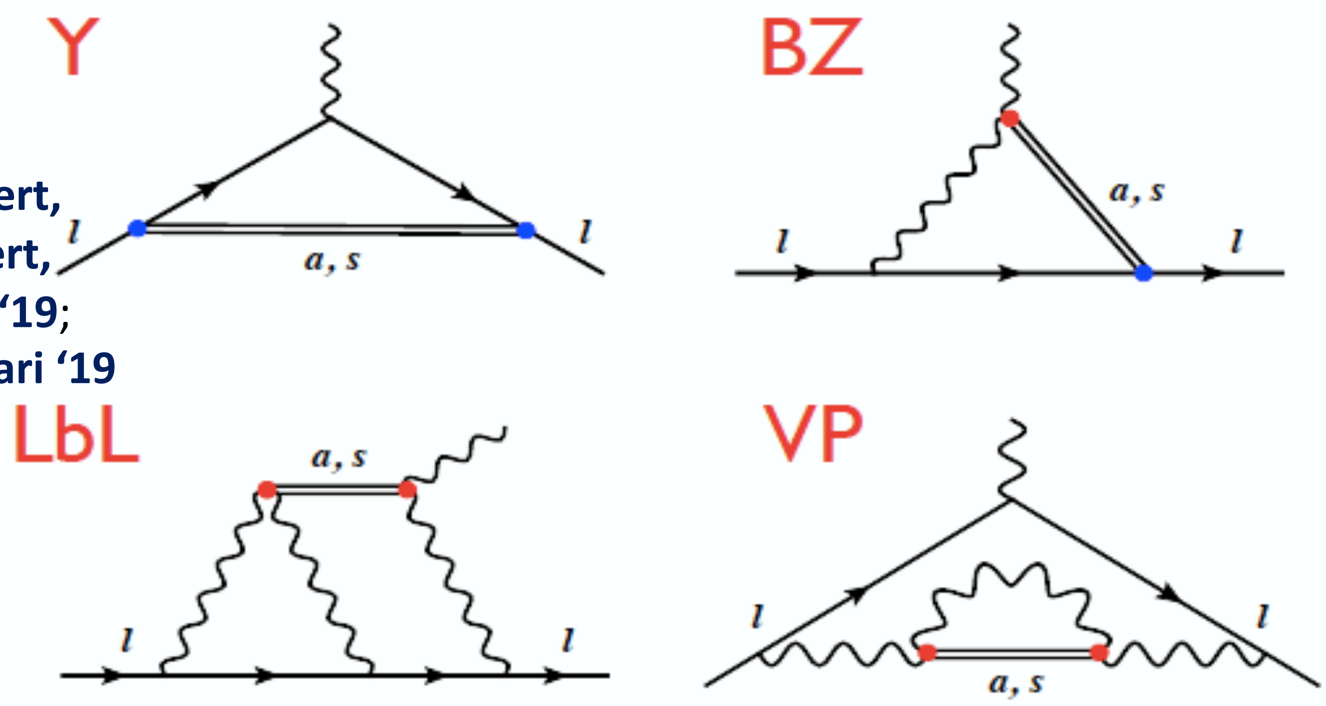
P. Paradisi, La Thuile 2021

The case of AXION-LIKE PARTICLES (ALPs)

ALPs contributions to the muon g-2?

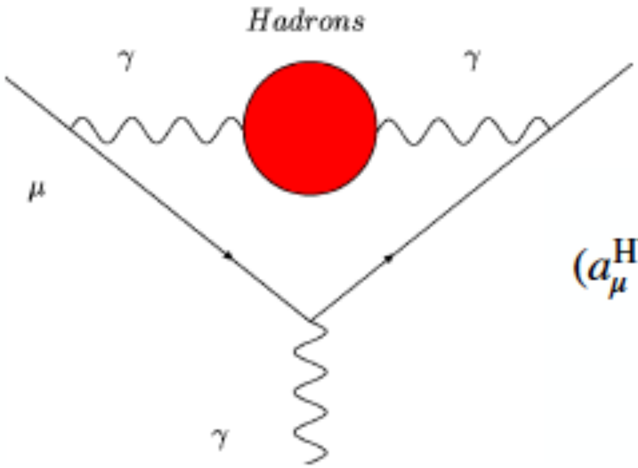
μ

Marciano, AM, Paradisi, Passera '16; Bauer, Neubert, Thamm '17; Bauer, Neubert, Renner, Schnubel, Thamm '19; Cornella, Paradisi, Sumensari '19



- Both scalar and pseudoscalar ALPs can solve Δa_μ for masses ~ [100MeV-1GeV] and couplings allowed by current experimental constraints.
- They can be tested at present low-energy e^+e^- experiments, via dedicated $e^+e^- \rightarrow e^+e^-$+ALP & $e^+e^- \rightarrow \gamma$+ALP searches.

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



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

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

dispersion relations

optical theorem

kernel function

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

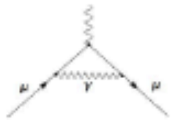
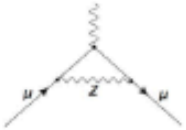
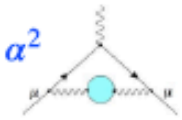
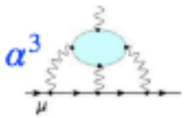
$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s) \qquad R(s) = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$a_\mu^{\rm HLO} = 6895\ (33) \times 10^{-11}$	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

Standard Model Contribution: Calculating the Anomaly

$$a_\mu = a_\mu(QED) + a_\mu(EW) + a_\mu(hadronic)$$

QED		+…	(5 loops)	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
EW		+…	x	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
HVP	α^2 	+…	(NNLO)	$6845\,(40) \times 10^{-11}$ [0.6%]	0.34 ppm
HLbL	α^3 	+…	(NLO)	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

Well-known (QED, EW)

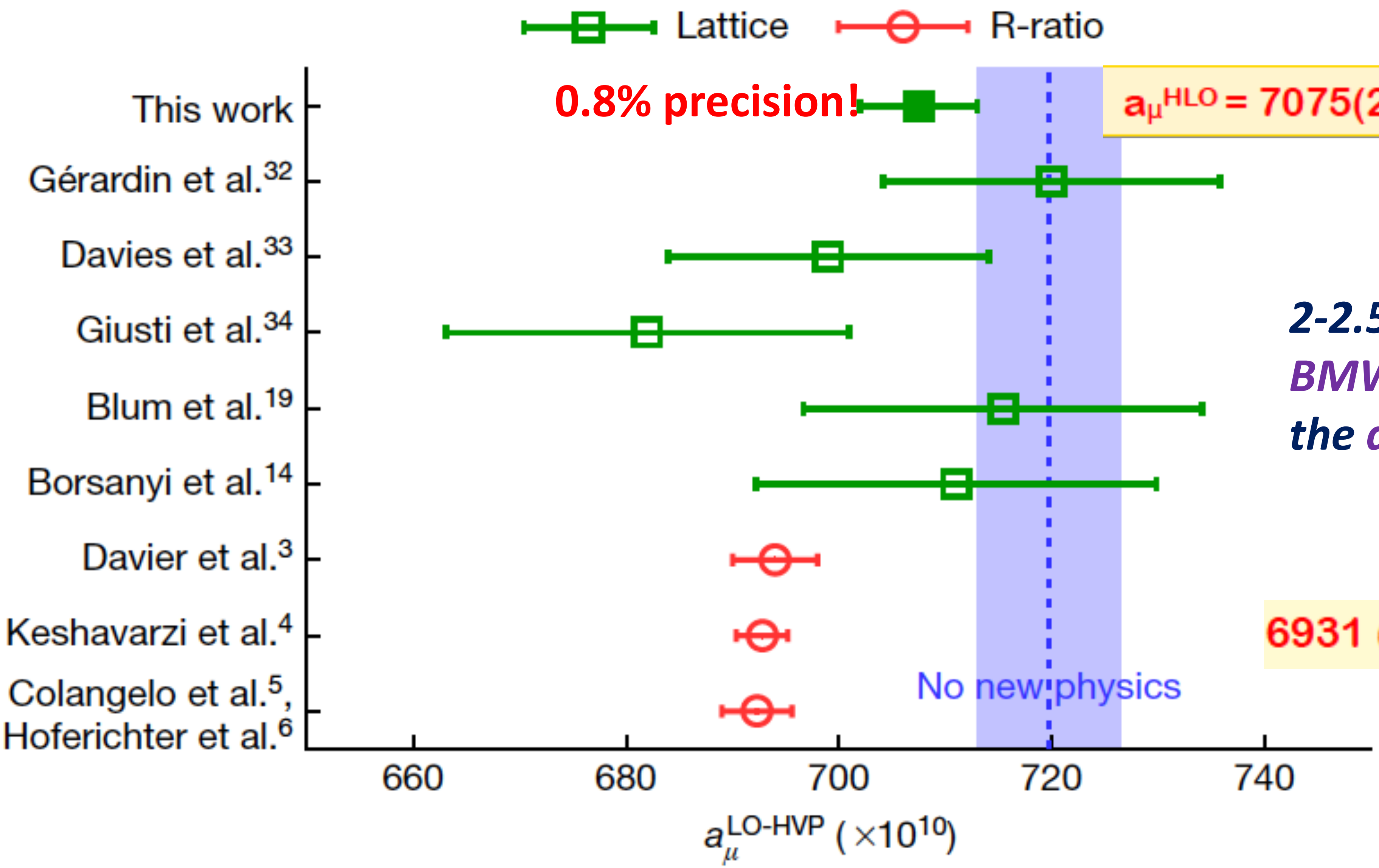
Non-perturbative (Data-driven & lattice QCD) (HVP, HLbL)

E. Barsal-Yucel, Lepton Photon 2023

- QED and EW contributions are very well-known with small uncertainties
- Hadronic contribution error dominates the uncertainty budget
- HVP needs to be on the 0.5% precision to keep up with the experiment uncertainties
- HLBL precision demand is less thank HVP, only 10% would be good enough
- Refining the SM calculations means refining the HVP calculation
- **Muon g-2 Theory Initiative** was formed to determine SM value of a_μ. Produce a single consensus theoretical value which is comparable to the experimental value.

BMWc20: S. Borsanyi et al. 2002.12347, published on Nature, April 7, 2021

first published lattice result with sub-percent precision!

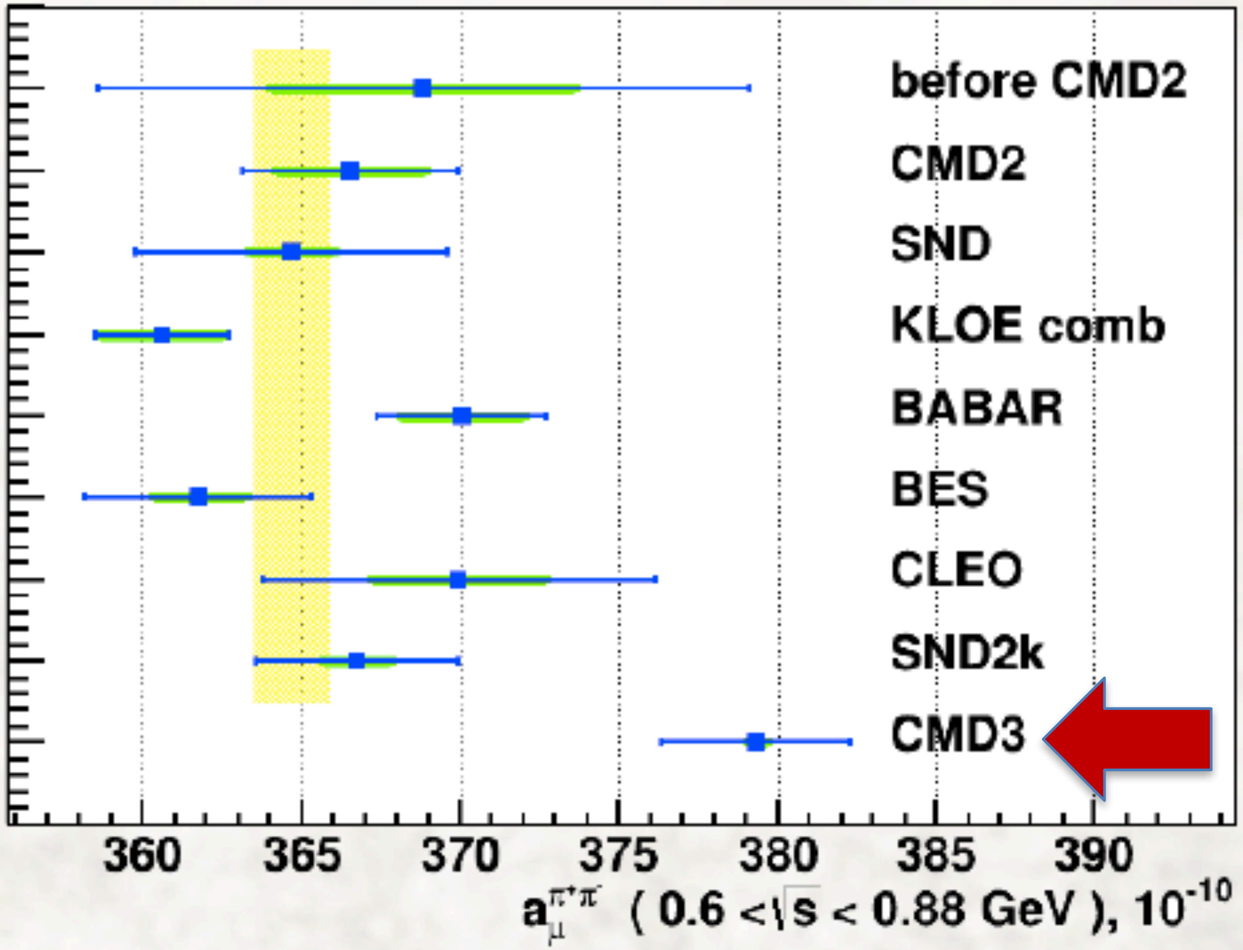


2-2.5σ tension between the BMWc lattice result and the dispersive evaluations

New result on R(s) from **CMD3**

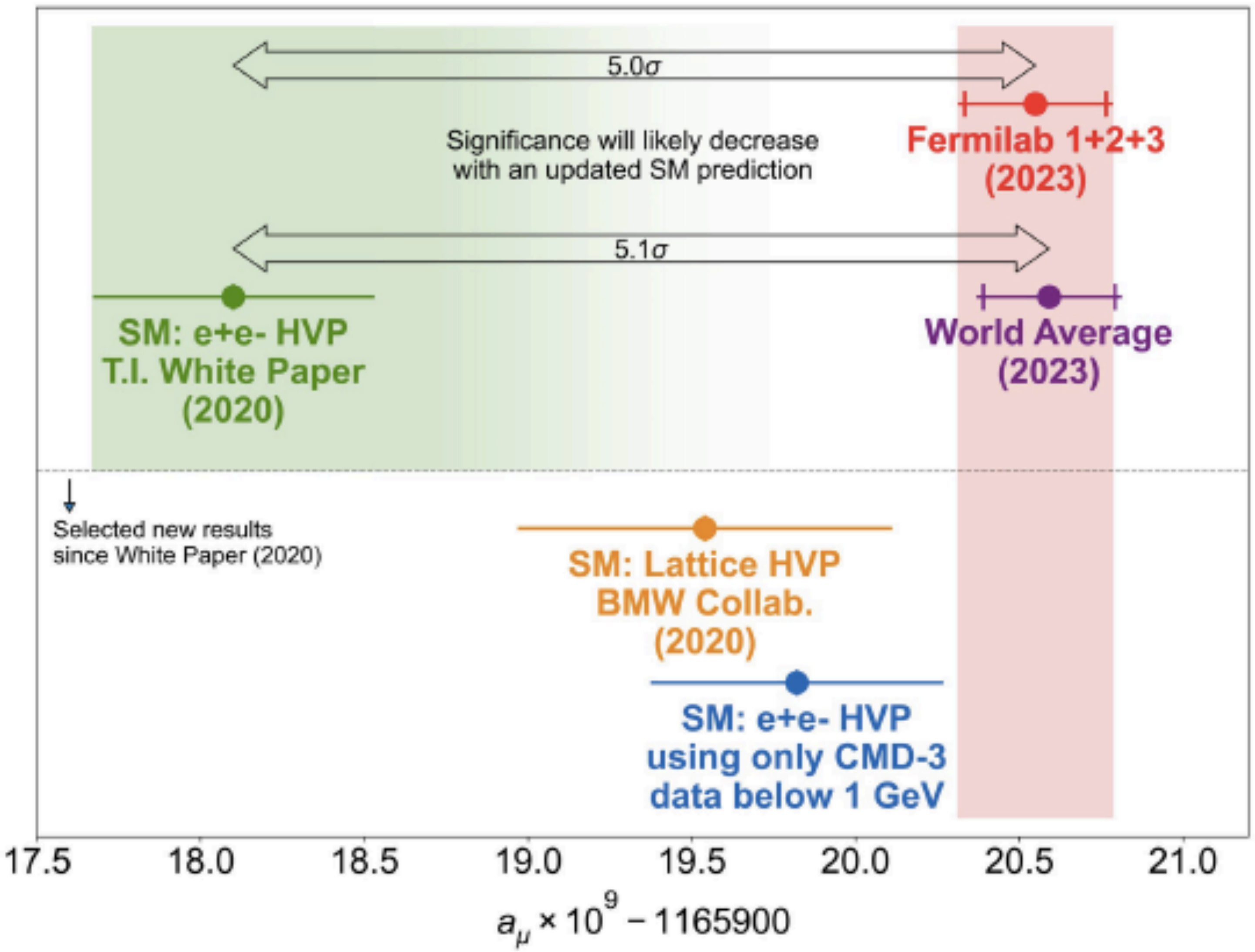
(VEPP – 2000 Novosibirsk)

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3} \int_{4m_\pi^2}^{\infty} \frac{\sigma_{e^+e^- \to \gamma^* \to hadrons}(s) K(s)}{s} ds$$



$0.6 < \sqrt{s} < 0.88$ GeV

	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

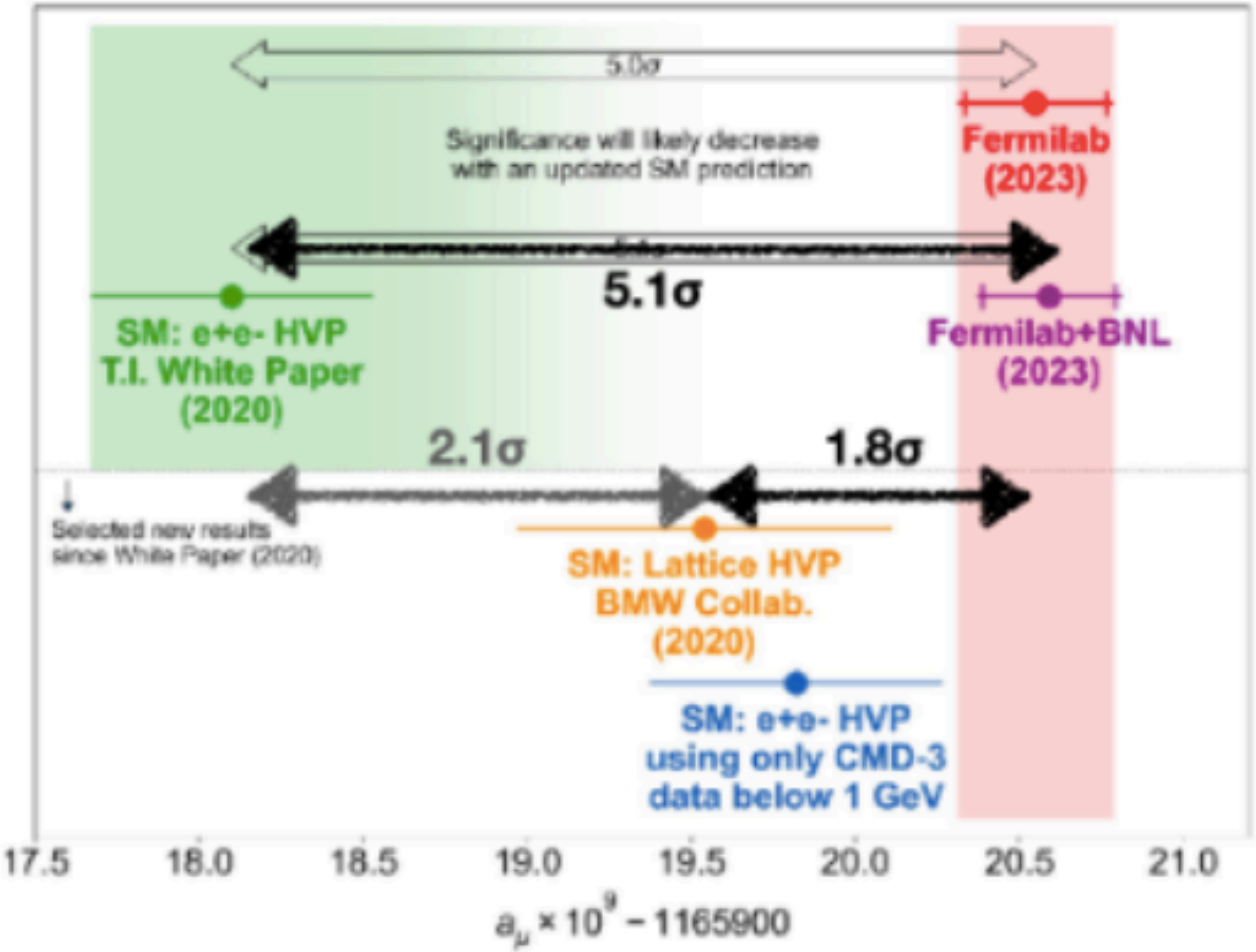


F. Ignatov (CMD-3 Coll.), 6th Plenary Workshop TI, Bern, Sept. 4 2023

The CMD-3 is only one now over many other e+e- experiments (BaBar, KLOE, BES, CMD-2, SND, ...)

Unfortunately at the moment, we don't know the reasons of the disagreement between different experiments.

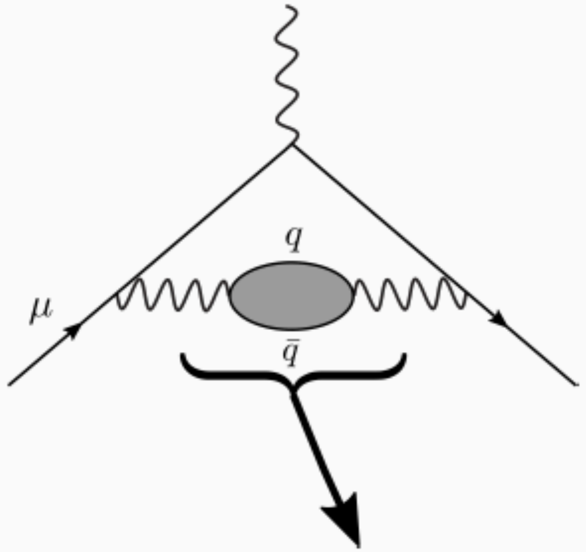
James Mott: https://indico.fnal.gov/event/60738/
Alex Keshavarzi: https://indico.fnal.gov/event/57249/contributions/271581/

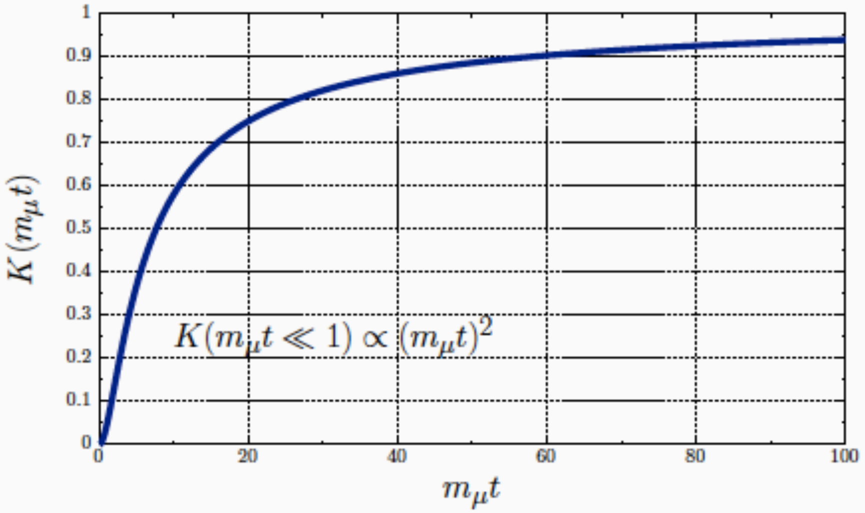


From
G. Venanzoni, EPS-HEP2023, Hamburg,

The **CMD-3** data in e+e- → ππ provides an R-ratio result compatible with the lattice one

LO-HVP from Lattice QCD





$$\Pi_{\mu\nu}(Q) = \int d^4x\, e^{iQ\cdot x} \langle J_\mu(x) J_\nu(0) \rangle = (\delta_{\mu\nu} Q^2 - Q_\mu Q_\nu)\, \Pi(Q^2)$$

$$\Downarrow$$

$$a_\mu^{\text{LO-HVP}} = 4\alpha_{em}^2 \int_0^\infty dQ^2 \frac{1}{m_\mu^2} f\left(\frac{Q^2}{m_\mu^2}\right) \cdot \left(\Pi(Q^2) - \Pi(0)\right).$$

Time-Momentum representation (Bernecker & Meyer, 2011)

$$a_\mu^{\text{LO-HVP}} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t), \quad V(t) \equiv \frac{1}{3} \sum_{i=1,2,3} \int d\vec{x} \langle J_i(\vec{x}, t) J_i(0) \rangle$$

G.Gagliardi, Workshop of the Muon g-2 Theory Initiative, Edinburgh, Sept. 2022

Colangelo, El-Khadra, Hoferichter, Keshavarzi, Lehner, Stoffer, Teubner, arXiv:2205.12963v2 (2022)

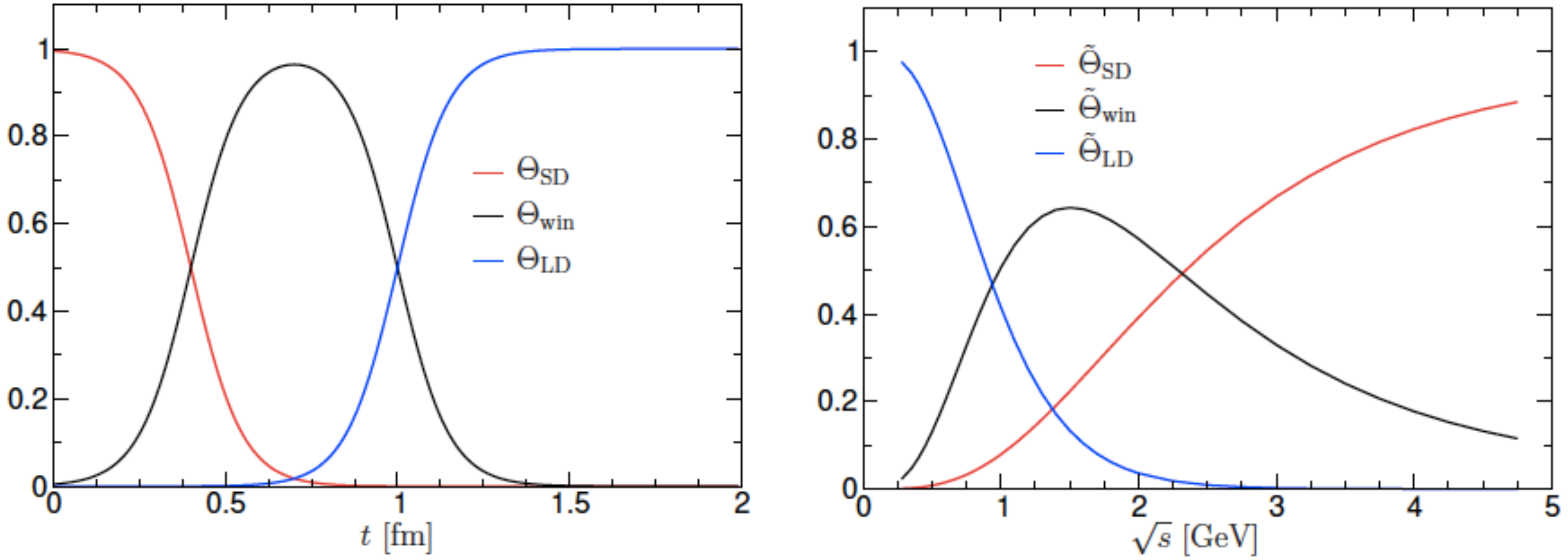
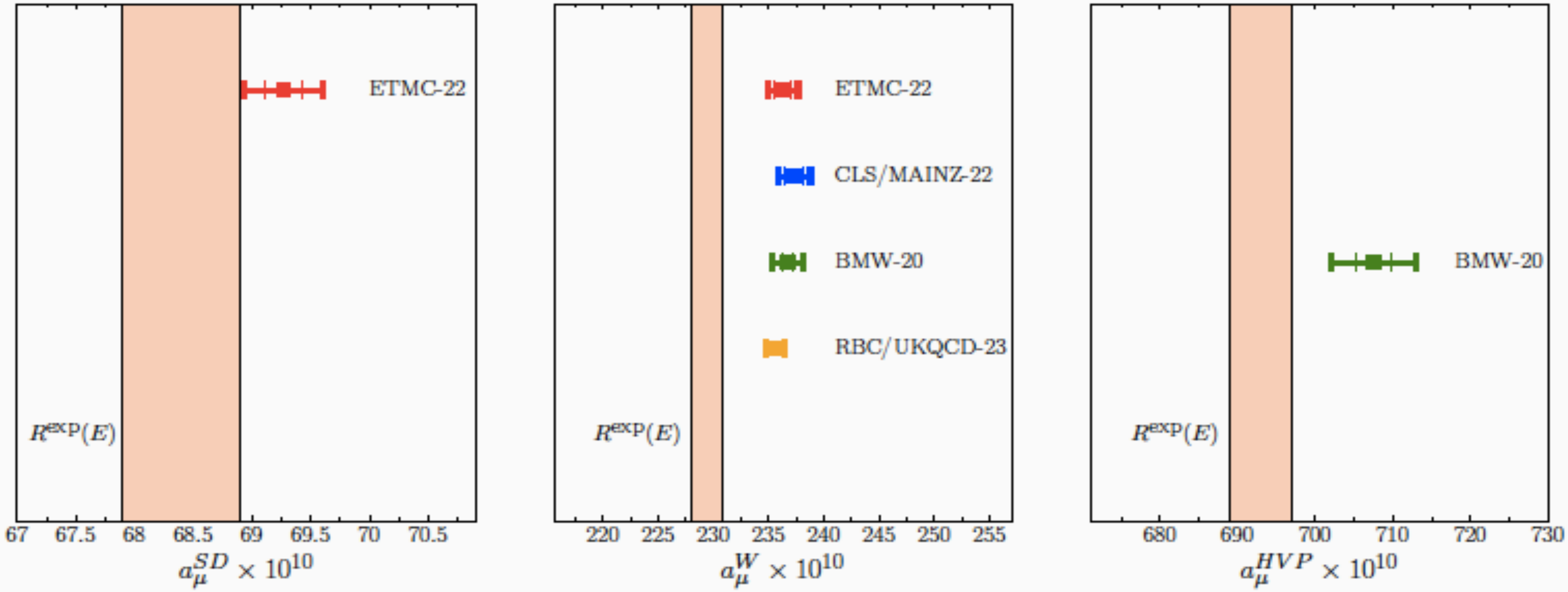


Figure 1: Short-distance, intermediate, and long-distance weight functions in Euclidean time (left), and their correspondence in center-of-mass energy (right).

The experimental ($R^{\exp}(E)$-based) and the SM lattice QCD determination of the intermediate window are in significant tension [without CMD-3].

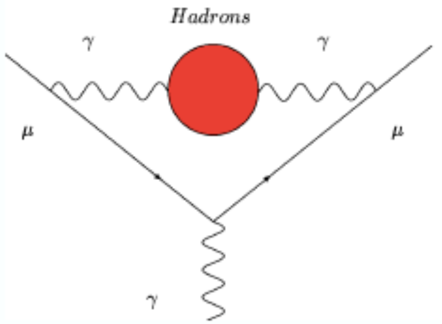


- Tension in a_μ^W is larger than 4σ (depending on how lattice results are combined).
- Substantial agreement for a_μ^{SD} suggests that the tension is localized at intermediate/low energies E.

G. Gagliardi, 6th Plenary Workshop TI, Bern, Sept. 4 2023

Spacelike proposal for a_μ

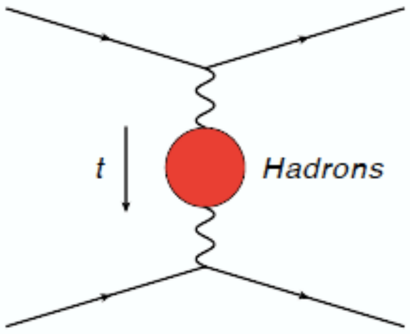
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the **timelike** formula:



$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^0_{\rm had}(s)$$

$$K(s) = \int_0^1 dx\, \frac{x^2 (1-x)}{x^2 + (1-x)\,(s/m_\mu^2)}$$

- Alternatively, exchanging the x and s integrations in a_μ^{HLO}



$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi} \int_0^1 dx\, (1-x)\, \Delta\alpha_{\rm had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the **spacelike** region: **a_μ^{HLO} can be extracted from scattering data!**

Carloni Calame, MP, Trentadue, Venanzoni, 2015

New Physics extracting $\Delta\alpha_{had}(t)$ at MUonE? Padova and Heidelberg 2020

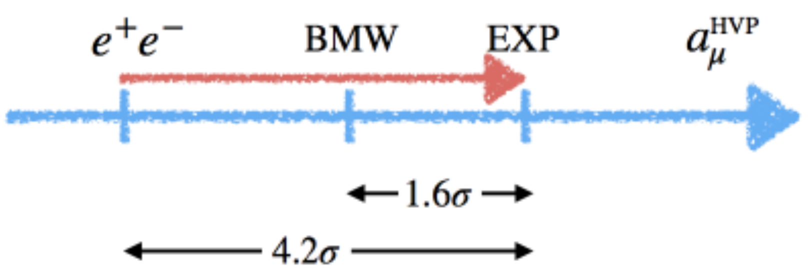
→ NO, NP cannot spoil the validity of such extraction

New Physics to solve the new muon g-2 puzzle ?

Not including CMD3 → $(a_\mu^{\rm HVP})_{\rm EXP} = a_\mu^{\rm EXP} - a_\mu^{\rm SM,\, rest}$

$(a_\mu^{\rm HVP})_{e^+e^-}^{\rm WP20} = 6931(40) \times 10^{-11}$

$(a_\mu^{\rm HVP})_{\rm BMW} = 7075(55) \times 10^{-11}$



NP in $\sigma_{\rm had}(e^+e^- \to \text{hadrons})$ such that

1. $(a_\mu^{\rm HVP})_{e^+e^-}^{\rm WP20} \approx (a_\mu^{\rm HVP})_{\rm EXP}$
2. the approximate agreement between BMW and EXP is not spoiled
3. w/o a direct contribution $a_\mu^{\rm NP}$ (i.e. NP not in muons)

L. Di Luzio, A.M., P. Paradisi, M. Passera, PLB 2022 (arXiv 2112.08312)

Can Δa_μ be due to a missing contribution in $\sigma_{\rm had}$?

[Marciano, Passera, Sirlin 2008 & 2010;
Keshavarzi, Marciano, Passera, Sirlin 2020.
See also Crivellin, Hoferichter, Manzari, Montull 2020;
Malaescu, Schott 2020;
Colangelo, Hoferichter, Stoffer 2020]

→ *a upward shift of* $\sigma_{\rm had}$ *induces an increase of* $\Delta\alpha^{(5)}_{\rm had}(M_Z)$

$$\alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha(M_Z) - \Delta\alpha^{(5)}_{\rm had}(M_Z) - \Delta\alpha_{\rm top}(M_Z)}$$

$$a_\mu^{\rm HLO} \simeq \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{s}, \qquad \Delta\alpha^{(5)}_{\rm had} = \frac{M_Z^2}{4\pi\alpha^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{M_Z^2 - s}$$

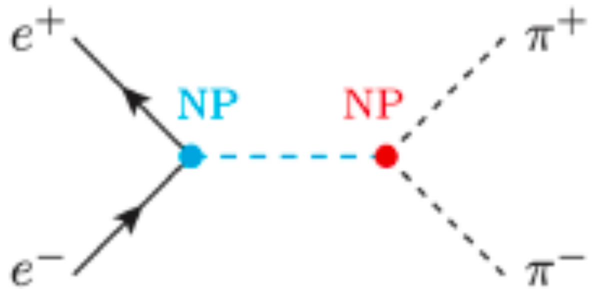
Im  ~  ~ $\sigma(e^+e^- \to \gamma^* \to \text{hadrons})$

Shifts $\Delta\sigma(s)$ to fix Δa_μ are possible,
but conflict with the EW fit if they occur above ~1 GeV

Keshavarzi, Marciano, Passera, Sirlin, PRD 2020 (updated 2021)

Light New Physics in $\sigma_{\rm had}$

Alternatively, one could invoke NP intervening in Bhabha scattering, see Darmé, Grilli di Cortona and Nardi, arXiv 2112.09139



NP coupled both to hadrons and electrons

but **not** directly to the **muons** !

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

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

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

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

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 $(a_\mu^{\rm HVP})_{e^+e^-}$ *requires* $\Delta\sigma_{\rm had}^{\rm NP} < 0$ *(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)

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

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

$$\frac{\sigma_{\pi\pi}^{\text{SM+NP}}}{\sigma_{\pi\pi}^{\text{SM}}} = \left| 1 + \frac{g_V^e(g_V^u - g_V^d)}{e^2} \frac{s}{s - m_{Z'}^2 + i m_{Z'}\Gamma_{Z'}} \right|^2$$

However, **severe constraints on the Z' couplings** to electrons and to hadrons

- for $m_{Z'} \lesssim 0.3$ GeV ($Z' \to e^+e^-$ is the main decay mode)

$e^+e^- \to \gamma Z'$ @ BaBar → $g_V^e \lesssim 2 \cdot 10^{-4}$

- for $m_{Z'} \gtrsim$ MeV

electron g-2 → $|g_V^e| \lesssim 10^{-2}\,(m_{Z'}/0.5\text{ GeV})$

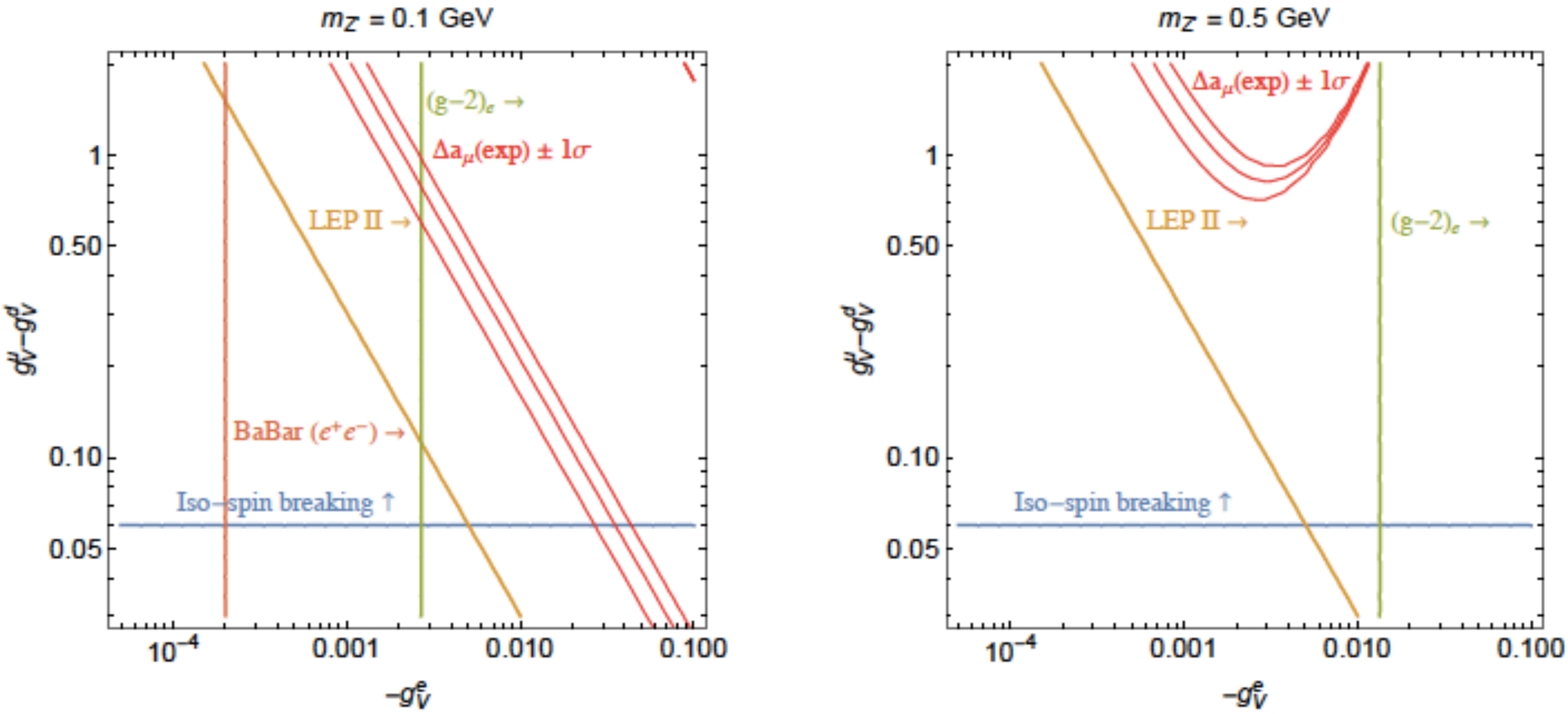
$e^+e^- \to q\bar{q}$ *has been measured with per-cent accuracy at LEP-II*

$$\frac{\sigma_{qq}^{\rm SM+NP}}{\sigma_{qq}^{\rm SM}} \approx 1 + 2\frac{g_V^e g_V^q}{e^2 Q_q} \quad \rightarrow \quad |g_V^e g_V^q| \lesssim 4.6 \cdot 10^{-4}|Q_q| \qquad (\epsilon \lesssim 3.3 \cdot 10^{-3})$$

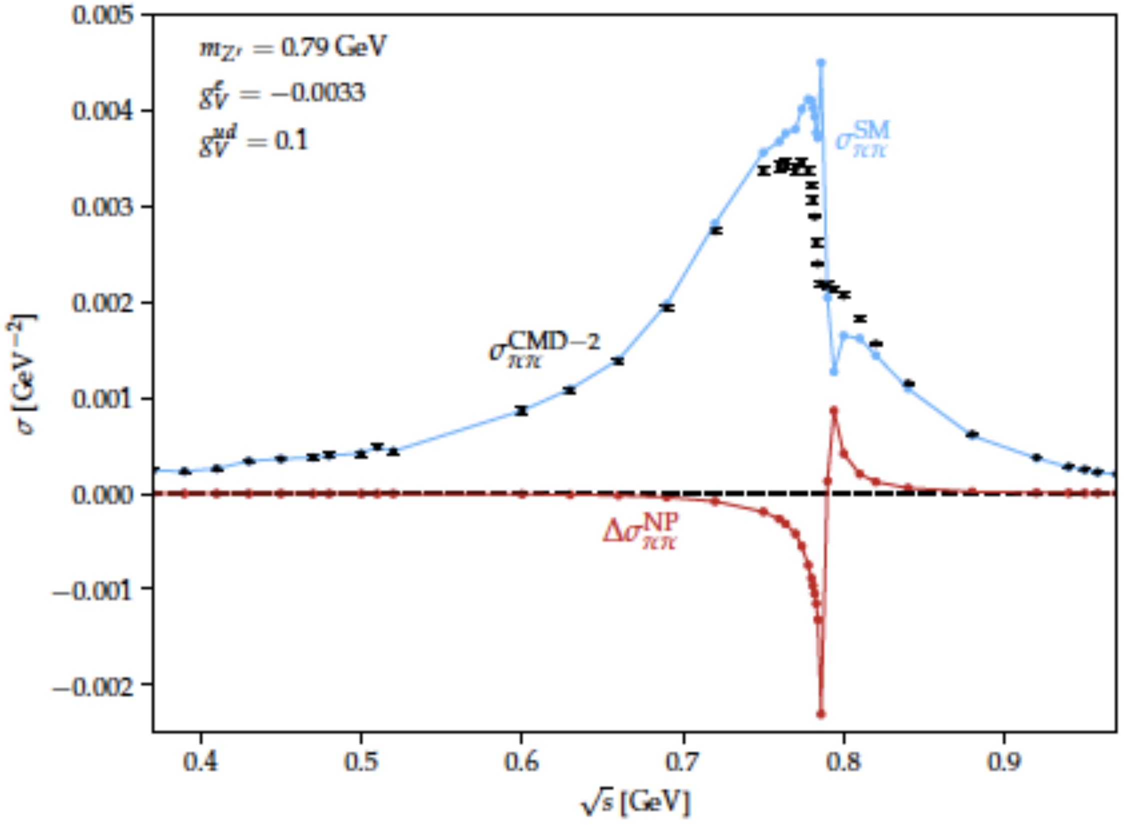
Iso-spin breaking observables → $|g_V^u - g_V^d| \lesssim 0.06$

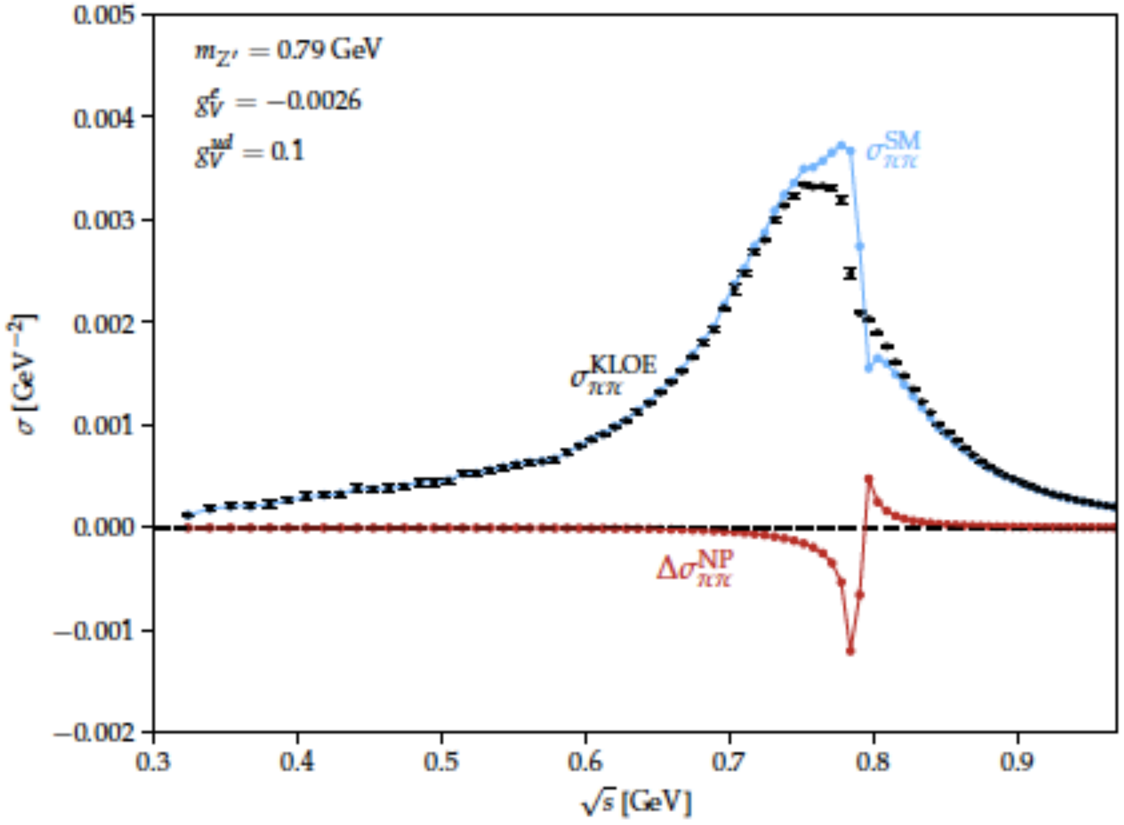
charged vs. neutral pion mass^2 difference $\Delta m^2 = m_{\pi^+}^2 - m_{\pi^0}^2$ **(rescaling the lattice QCD calculation of Frezzotti, Gagliardi, Lubicz, Martinelli, Sanfilippo and Simula 2112.01066)**

At least **TWO independent bounds prevent** to get a sizeable contribution to Δa_μ modifying σ_{had} via Z' exchange to **solve** the "**new**" μ g-2 puzzle



However, Coyle and Wagner have recently claimed that **it is possible** to overcome the mentioned obstruction (in particular the isospin breaking constraint) by taking **a large $g_V^u - g_V^d$ with a Z' mass near the ρ resonance mass of 770 MeV – a lattice-QCD calculation is needed to provide a more precise evaluation of the isospin breaking replacing the massless photon with a massive Z' boson**





Coyle and Wagner arXiv:2305.02354v2

Sensitivity of other physical observables to

$$[\delta a_\mu^{HVP}]_{NP} = [a_\mu^{HVP}]_{LQCD\&DR,CDM3} - [a_\mu^{HVP}]_{DR,WP202}$$

~3% shift

If and to which extent the discrepancy between the leading HVP to the muon g-2 computed, on one side, making use of the lattice QCD result by the BMW collaboration as well as the recent exp. results by the CMD-3 collaboration and, on the other side, using the low-energy $e^+e^- \rightarrow$ hadrons data used by the Muon g-2 Theory Initiative **can be tested via**:

- the Electron g-2 (**a_e**)
- the HyperFine Splitting (**HFS**) in the muonium system
- the Tau g-2 (**a_τ**)

Measurement of the Electron Magnetic Moment

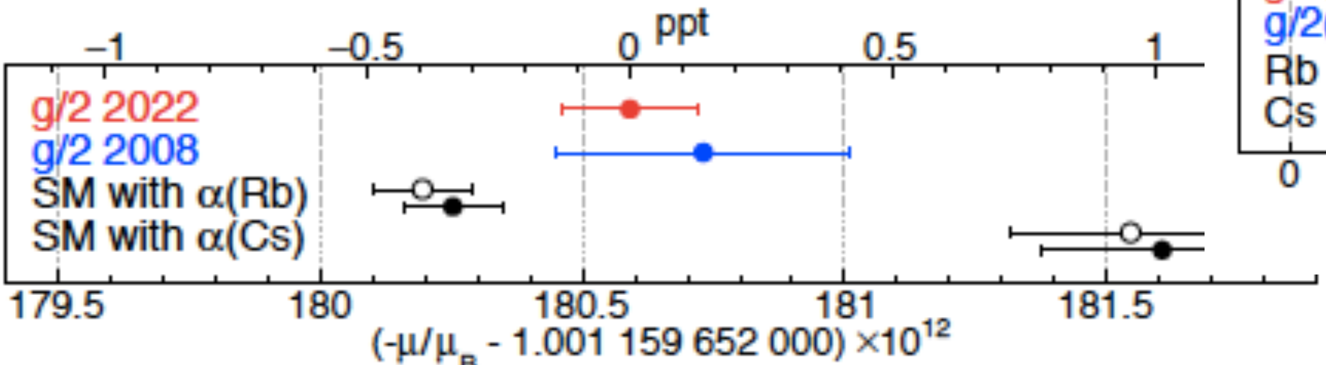
X. Fan,[1,2,*] T. G. Myers,[2] B. A. D. Sukra,[2] and G. Gabrielse[2,†]
[1]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Center for Fundamental Physics, Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA
(Dated: December 8,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

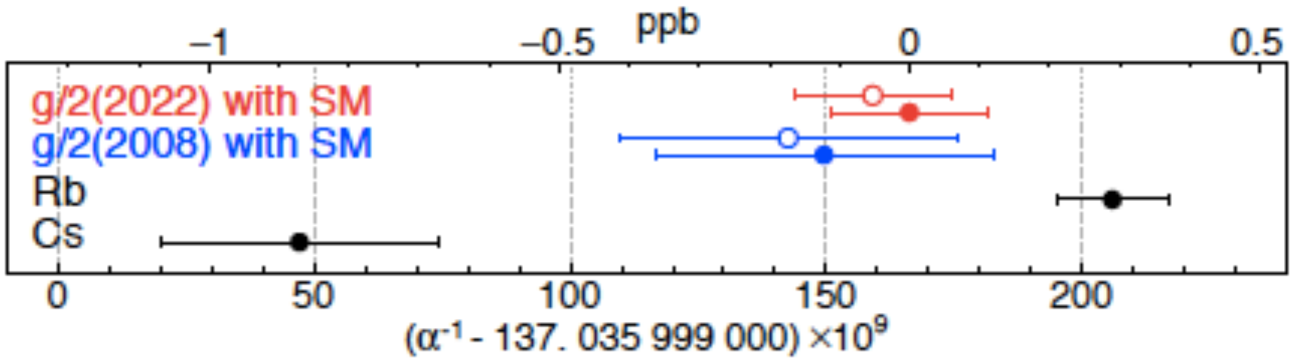
The electron magnetic moment, $-\mu/\mu_B = g/2 = 1.001\,159\,652\,180\,59\,(13)$ [0.13 ppt], is determined 2.2 times more accurately than the value that stood for 14 years. The most precisely determined property of an elementary particle tests the most precise prediction of the Standard Model (SM) to 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.

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

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

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





$$a_e^{\rm SM} = a_e^{\rm QED} + a_e^{\rm had+weak}$$ Jegerlehner EPJ Web Conf. 218 (2019)

$$a_e^{\rm QED} = \frac{\alpha}{2\pi} - 0.32847844400254(33)\left(\frac{\alpha}{\pi}\right)^2 + 1.181234016816(11)\left(\frac{\alpha}{\pi}\right)^3 - 1.91135(182)\left(\frac{\alpha}{\pi}\right)^4 + 7.791(580)\left(\frac{\alpha}{\pi}\right)^5,$$

Improved, complete QED 5-loop contribution expected soon, Laporta work in progress

Kinoshita et al. PRD 2027; Laporta PLB 2017

$$a_e^{\rm had+weak} = 172.3(12) \times 10^{-14}$$

$$\alpha = 1/137.035999046(27) \quad \text{(from Cs}$$ Parker et al. Science2018

$$\alpha = 1/137.035999206(11) \quad \text{(from Rb}$$ Morel et al. Nature 2020

Kinoshita et al. PRD 2017 – however S. Volkov PRD 2019 disagrees by an amount of ~ 7×10^{-14}

$$\delta a_e^{\rm QED5} = 0.1 \times 10^{-13}$$ $$\delta a_e^{\rm HAD} = 0.1 \times 10^{-13}$$ $$\delta a_e^{\delta\alpha} = 0.9 \times 10^{-13}$$

Using the most precise determination of α from Rb Morel et al. Nature 2020

$$a_e^{\rm SM} = 1159652181 6.1(0.9) \times 10^{-13}$$

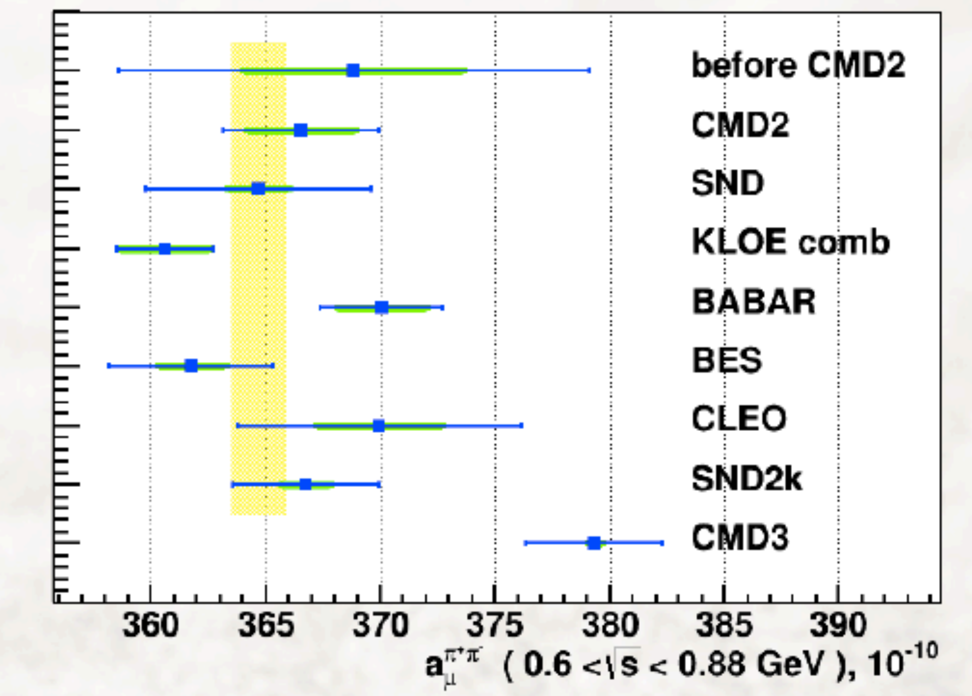
$$a_e^{\rm HVP, LO} = 186.08 \pm 0.66 \times 10^{-14}$$ Keshavarzi, Nomura and Teubner PRD 2020

$$a_e^{\rm EXP} = 0.00115965218059(13)$$ → $$\delta a_e^{\rm EXP} = 1.3 \times 10^{-13}$$

$a_e^{\mathrm{HVP,LO}} = 186.08 \pm 0.66 \times 10^{-14}$ based on low-energy $e^+e^- \to$ hadrons data **WITHOUT** the CMD-3 result

Impact of taking the CMD-3 result for the low-energy $e^+e^- \to$ hadrons on $a_e^{\mathrm{HVP,LO}}$

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3} \int_{4m_\pi^2}^{\infty} \frac{\sigma_{e^+e^- \to \gamma^* \to hadrons}(s) K(s)}{s} ds$$



$$\delta a_\mu^{\mathrm{CMD-3}} \simeq 150 \times 10^{-11}$$

$$\delta a_e^{\mathrm{CMD-3}} \; ?$$

Naïve scaling valid, for instance, in MFV models

$$\delta a_e^{\mathrm{CMD-3}} = \delta a_\mu^{\mathrm{CMD-3}} \left(\frac{m_e}{m_\mu}\right)^2 \simeq 3.5 \times 10^{-14}$$

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

$$\delta a_e^{\delta\alpha} = 0.9 \times 10^{-13}$$

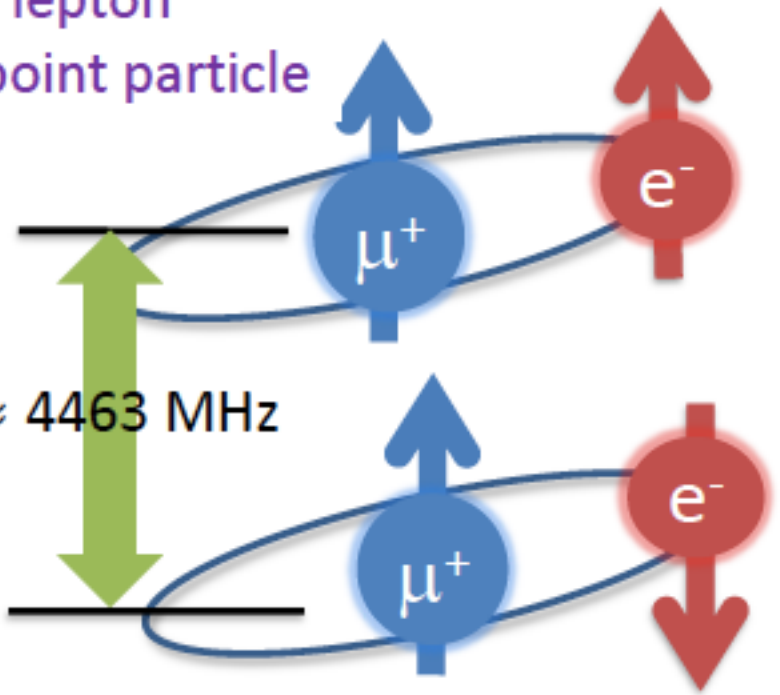
To check the a_μ^{HVP} **BMW+CMD3** ↔ **Muon g-2 TI** tension through the electron g-2 we need: a **THEORETICAL PREDICTION** & an **EXPERIMENTAL MEASUREMENT of a_e** at the level of **$O(10^{-14})$**

preliminary Di Luzio, Keshavarzi, A.M., Paradisi and Passera, work in progress

Independent muon g-2 determination from MUONIUM SPECTROSCOPY

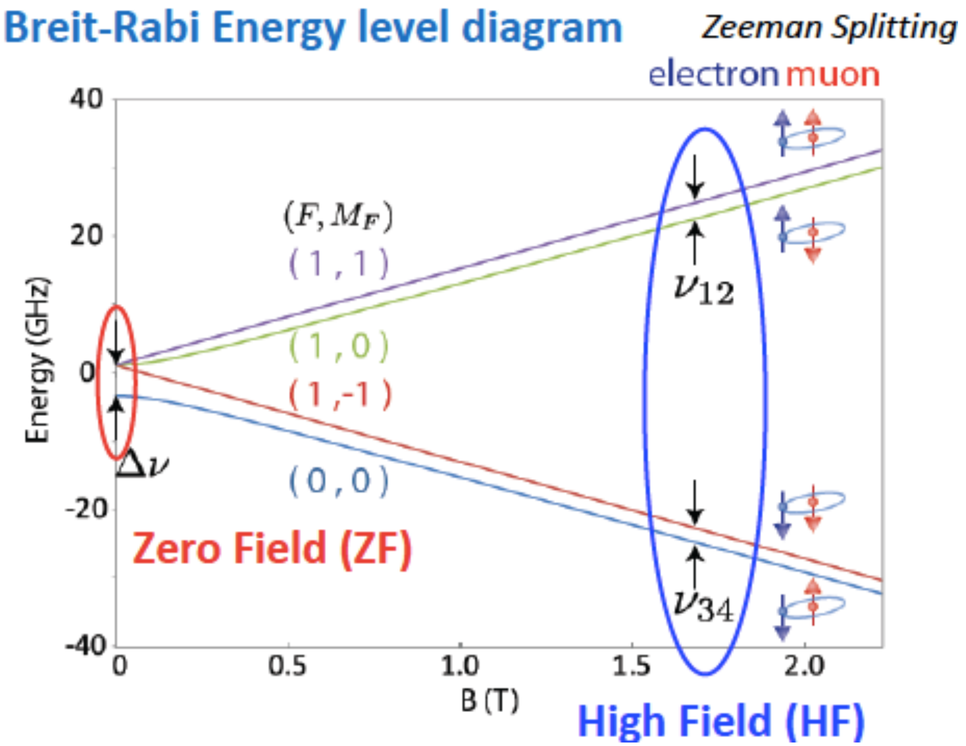
Muonium: bound state of μ^+ and e^-

Pure lepton
= point particle



$\Delta\nu$: Muonium Hyperfine Structure

Breit-Rabi Energy level diagram



$$\nu_{12} + \nu_{34} = \Delta\nu$$

$$\nu_{12} - \nu_{34} \propto \mu_\mu / \mu_p$$

Most Precise Test of Bound-State QED

Experiment:

LAMPF Experiment (1999)

W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711

ν_{HFS}(exp) 4463.302 765 (53) MHz [12 ppb]

μ_μ/μ_p = 3.18334524(37) [120ppb]

m_μ/m_e = 206.768277(24) [120ppb]

Theory:

M. I. Eides Phys. Lett. B **795** (2019) 113

ν_{HFS}(theory) 4463.302 868 (515) MHz [120 ppb]

ν_{HFS}(QED) 4463.302 720 (511) (70) (2) MHz

(m_μ/m_e) (QED) (α)

ν_{HFS}(weak) -65 Hz

ν_{HFS}(had. v.p.) 232 (1) Hz

ν_{HFS}(had. h.o.) 5 (2) Hz

$$\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

QED calculation: Effort for 10 Hz accuracy in progress (by Eides et al.)

Also Laporta is computing the full 3-loop QED contribution

$$\Delta\nu_{\mathrm{Mu}}^{\mathrm{had,\,VP}} = (232.04 \pm 0.82)\ \mathrm{Hz}$$

Keshavarzi, Nomura, Teubner PRD 2020; Eides PLB 2019

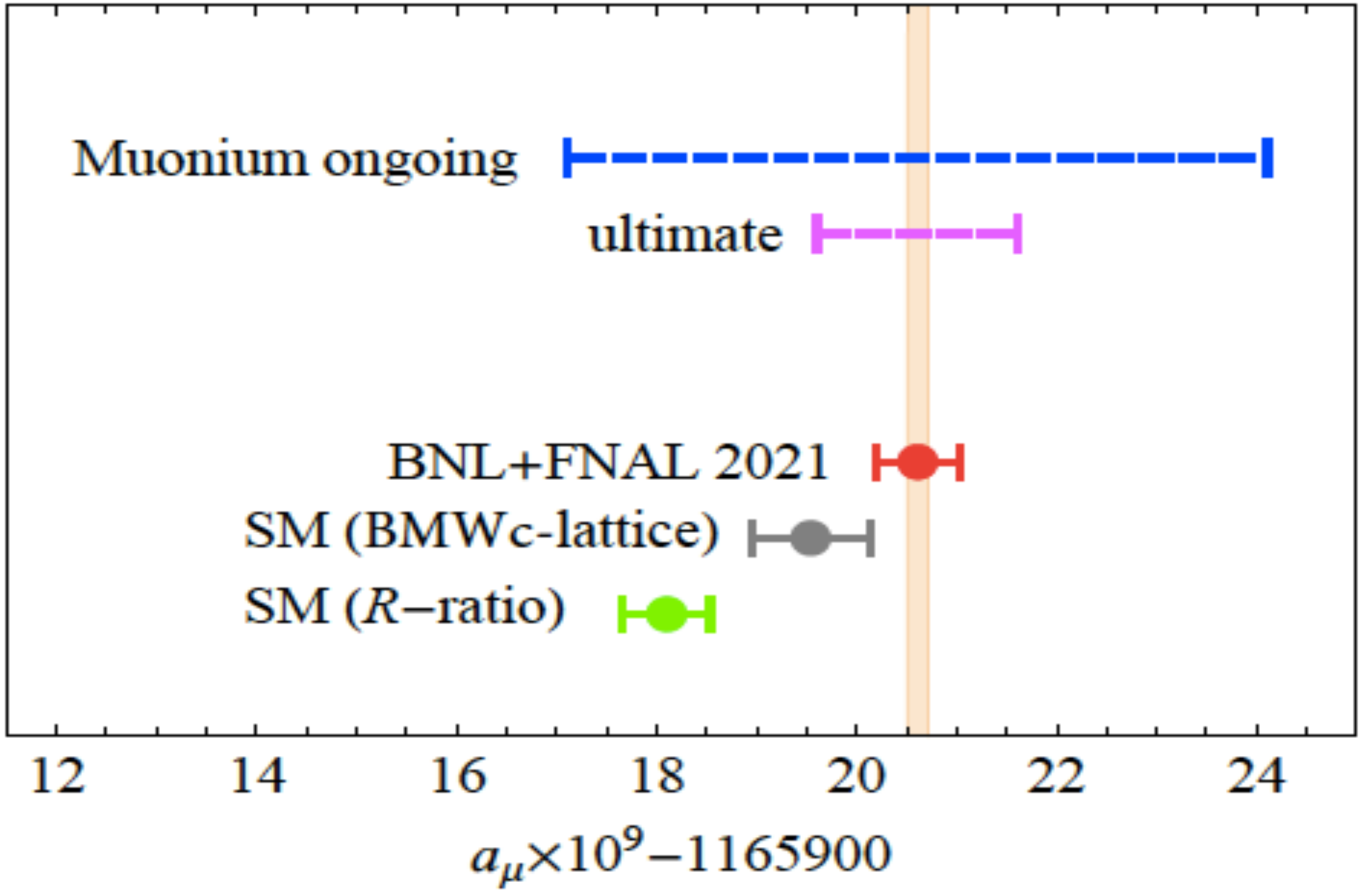
Dominated by the $\pi^+\pi^-$ channel $\Delta\nu_{\mathrm{Mu}}^{\mathrm{had,\,VP}} = (159.64 \pm 0.60)\ \mathrm{Hz}$

Ongoing indicates the milestones set by the **Mu-MASS (MuoniuM lAser SpectroScopy) exp. at PSI** and **MuSEUM (Muonium Spectroscopy Experiment Using Microwave) at J-P**

ν_i (unit)	quantity	u_r current	ongoing	ultimate
1S-2S (ppt)	QED	8.1	5.7	0.7
	HVP	$\mathcal{O}(10^{-2})$		
	R_∞	1.9	0.65	
	α	$\mathcal{O}(10^{-3})$		
	exp	3.99×10^3	4.1	1.6
HFS (ppb)	QED	16	2.2	0.2
	HVP	0.33	0.18	
	α	0.30	0.16	
	R_∞	$\mathcal{O}(10^{-3})$		
	exp	12	2.2	0.90

parameter (unit)	quantity	u_r current	ongoing	ultimate
m_e/m_μ (ppb)	ν_{1S-2S}(exp)	825	0.84	0.34
	QED(1S-2S)	1.7	1.2	0.1
	R_∞	0.40	0.13	
	total	825	1.5	0.37
a_μ (ppm)	ν_{1S-2S}(exp)	708	0.73	0.29
	ν_{HFS}(exp)	10	1.9	0.77
	QED(1S-2S)	1.4	1.0	0.07
	QED(HFS)	14	1.9	0.2
	HVP(HFS)	0.29	0.16	
	R_∞	0.35	0.13	
	α	0.26	0.14	
	total	708	3.0	0.88

Delaunay, Ohayon, Soreq PRL 2021



Delaunay, Ohayon, Soreq PRL 2021

To start testing the NP in the mentioned a_μ^{HVP} discrepancy: $[\delta a_\mu^{HVP}]_{NP} = [a_\mu^{HVP}]_{LQCD\&DR,CDM3} - [a_\mu^{HVP}]_{DR,WP202}$ (~3% shift)

→probably **we need to reach for $\Delta\nu_\mu^{exp}$ and $\Delta\nu_\mu^{SM}$ to precisions of O(few – 10) Hz**

Di Luzio, Keshavarzi, A.M., Paradisi, Passera work in progress

An extreme challenge: testing the NP of the muon g-2 puzzle through an accurate TH. and EXP. determination of the TAU MAGNETIC MOMENT

$$-0.007 < a_\tau^{\rm BSM} < 0.005 \quad [2\sigma]$$

from global analysis of LEP and SLD data in EFT
Gonzalez-Sprinberg, Santamaria, Vidal NPB 2000

well above the Schwinger's 1-loop QED contribution!

What would be needed to be sensitive to the NP accounting for the muon g-2 tension: **rescaling with $(m_\tau/m_\mu)^2 \rightarrow a_\tau^{NP} \simeq 10^{-6}$**

ArXiv:2111.10378v2

PSI-PR-21-27, ZU-TH 56/21

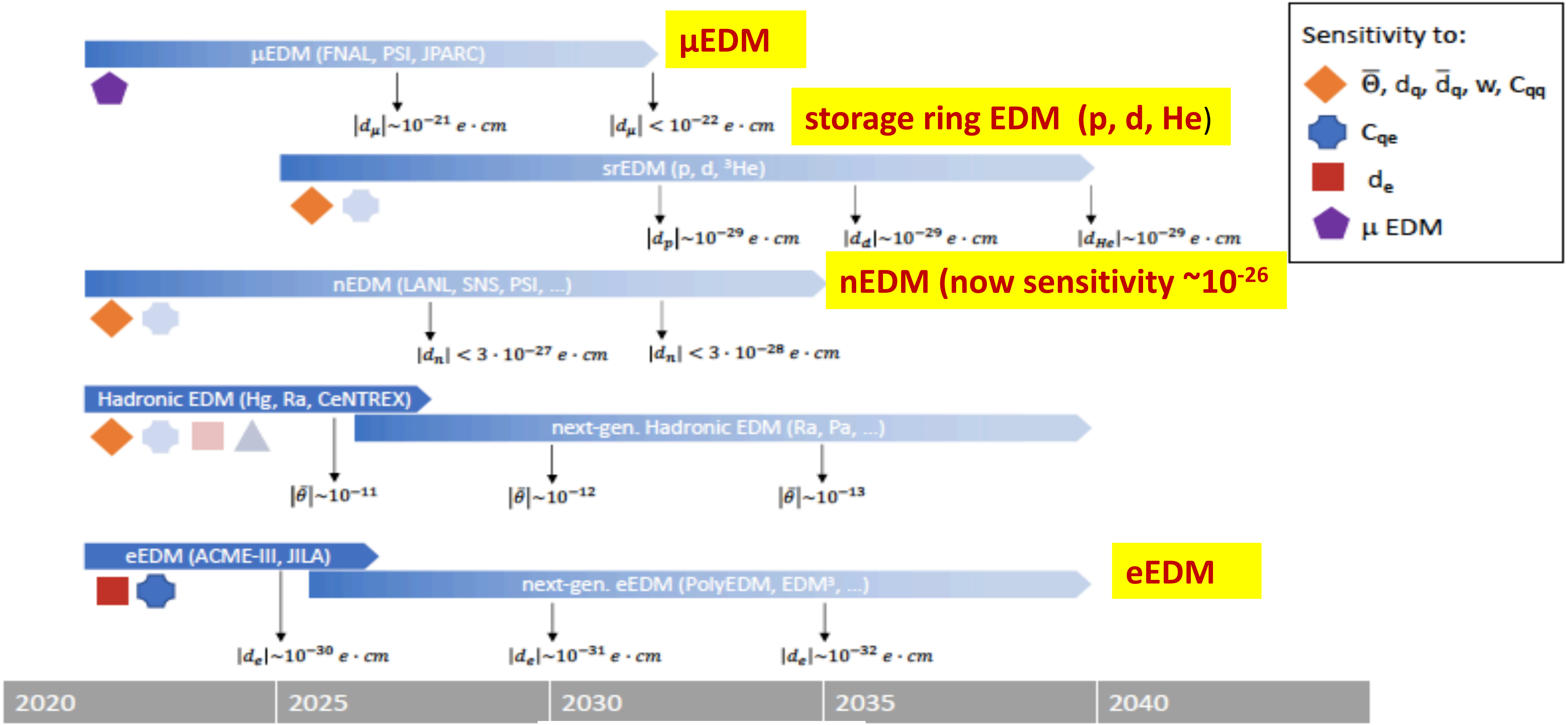
Towards testing the magnetic moment of the tau at one part per million

Andreas Crivellin,[1,2] Martin Hoferichter,[3] and J. Michael Roney[4,5]

Belle II symmetry measurements with an important polarization upgrade of the SuperKEKB

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

- **New science opportunities** in the (experimental and theoretical) current and near-future exploration of EDMs for various physical systems : **electron**, **muon**, **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



Fundamental Physics in Small Experiment T. Blum, P. Winter

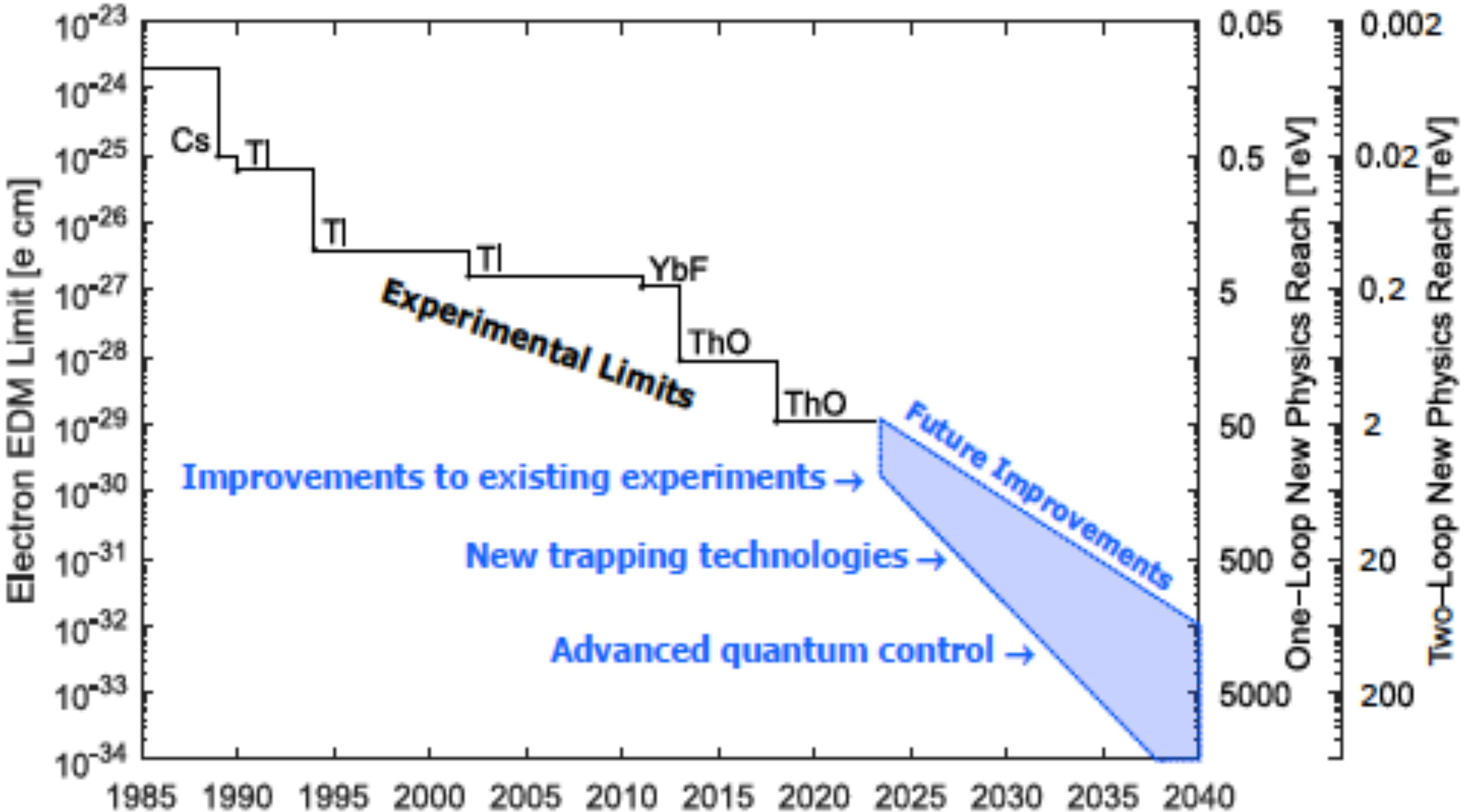
COMMUNITY PLANNING EXERCISE: SNOWMASS 2021

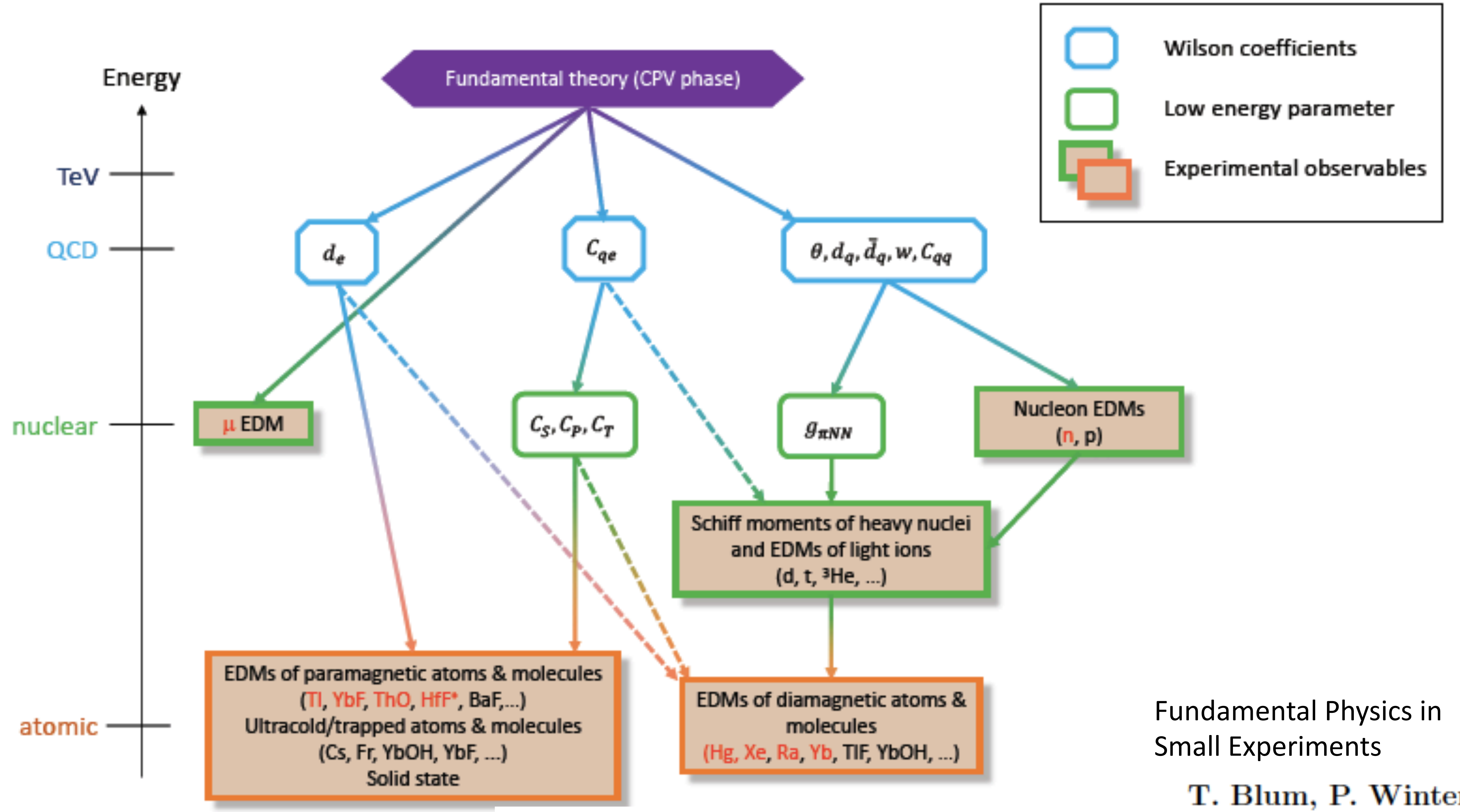
T. Bhattacharya, T.Y. Chen, V. Cirigliano, D. DeMille, A. Geraci, N.R. Hutzler, T.M. Ito, D. Kaplan, O. Kim, R. Lehnert, W.M. Morse, Y.K. Semertzidis

τEDM BelleII: now ~10^{-18} e cm with beam polarization upgrade at SuperKEKB → **reach ~10^{-20} ecm**

great prospects for the (**exp. & th.**) **progress** in the **electron EDM physics**

COMMUNITY PLANNING EXERCISE: SNOWMASS 2021





Fundamental Physics in
Small Experiments

T. Blum, P. Winter

T. Bhattacharya, T.Y. Chen, V. Cirigliano, D. DeMille, A. Geraci, N.R. Hutzler, T.M. Ito, D. Kaplan, O. Kim, R. Lehnert, W.M. Morse, Y.K. Semertzidis

Community Planning Exercise: Snowmass 2021

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

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

Physics Briefing Book, input for the European Strategy for Particle Physics update 2020, arXiv:1910.11775v2

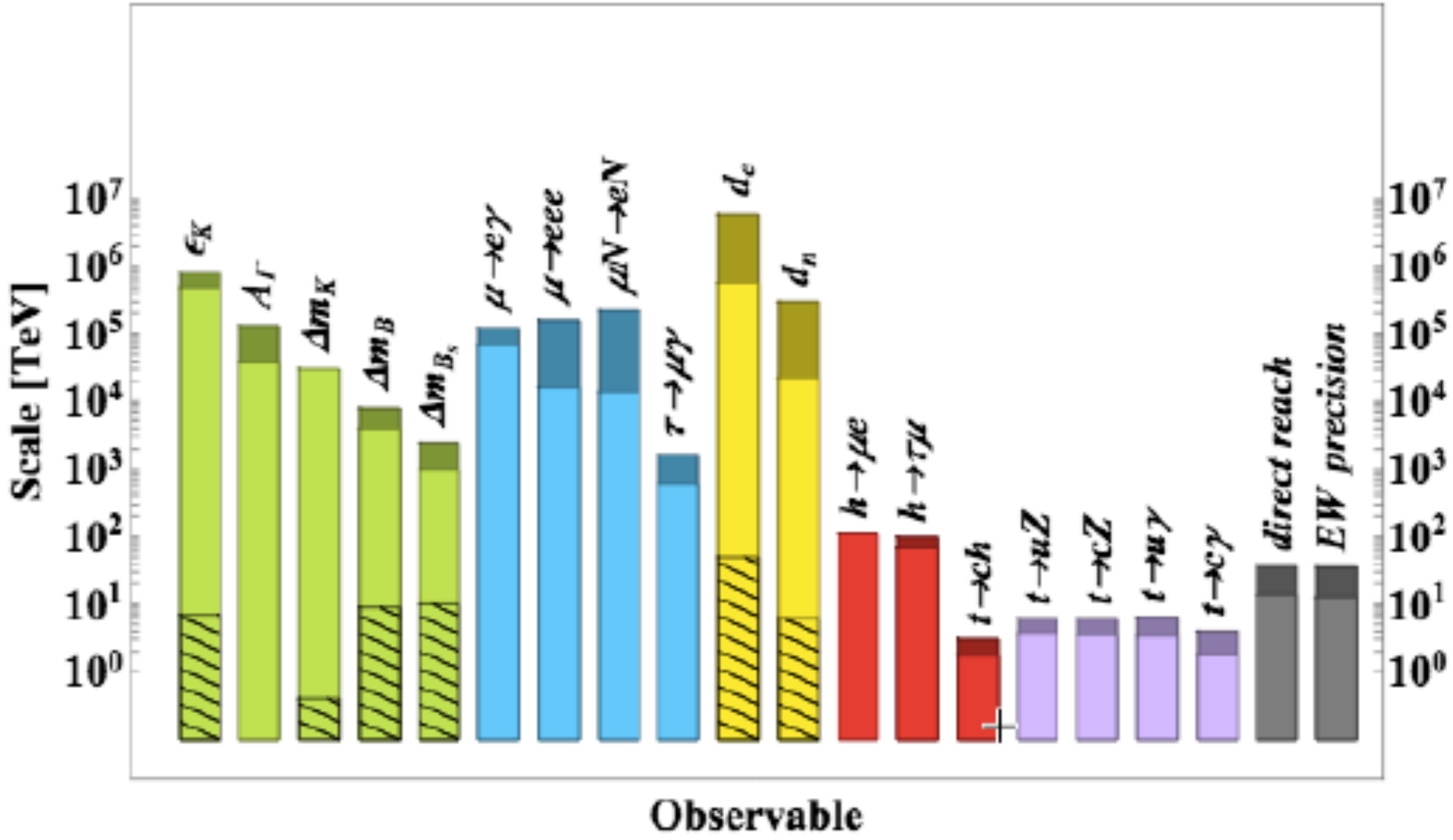
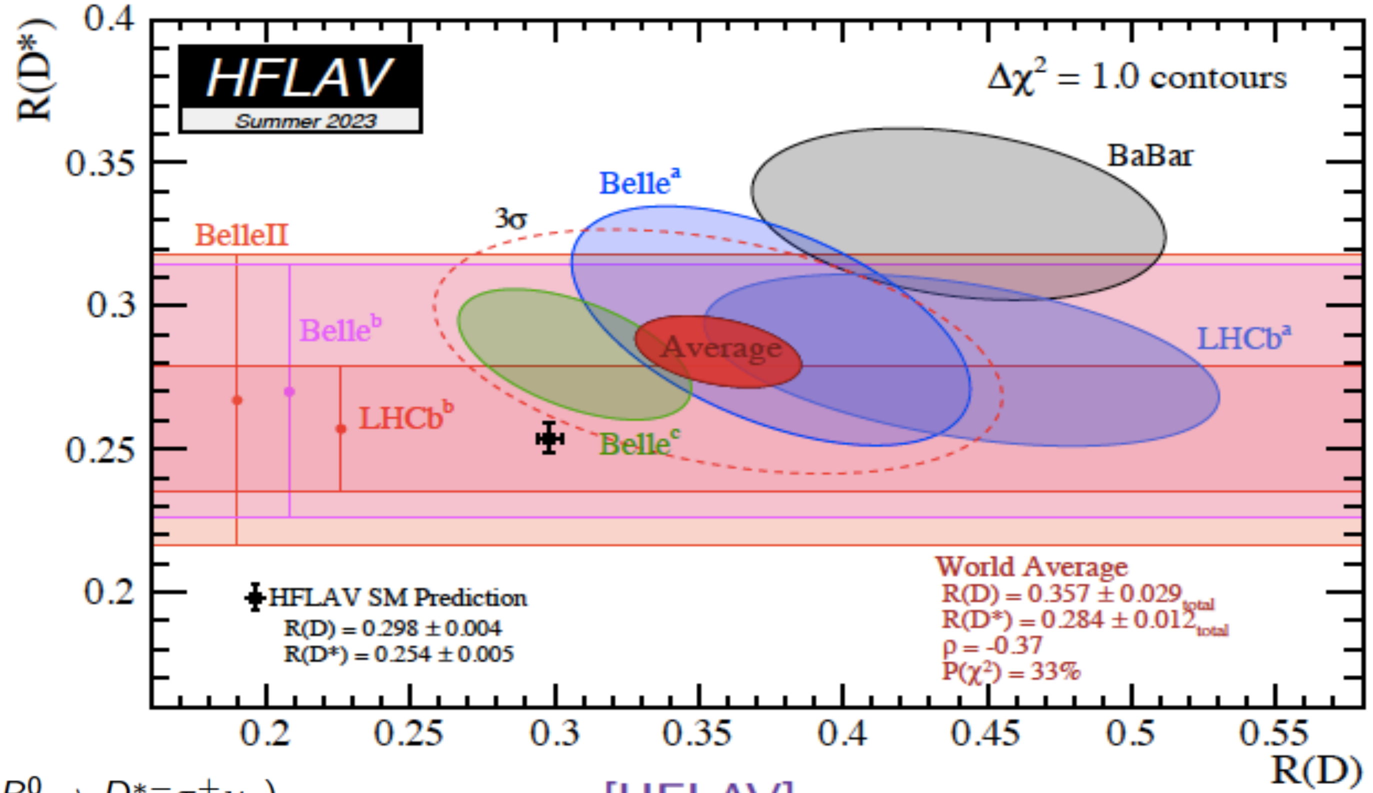


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).

Global picture



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

[HFLAV]

Tension of about 3.3σ between average of measurements and SM predictions

A new anomaly?

$$R_{\nu\nu}^{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\nu\bar{\nu})/\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\mathrm{SM}}$$

A new player in the room!

Belle II at EPS conference, 2023

Belle, 1702.03224

$$R_{\nu\nu}^{K} < 3.6 \quad (90\%\ \mathrm{C.L.})\,,$$
$$R_{\nu\nu}^{K^*} < 2.7 \quad (90\%\ \mathrm{C.L.})$$

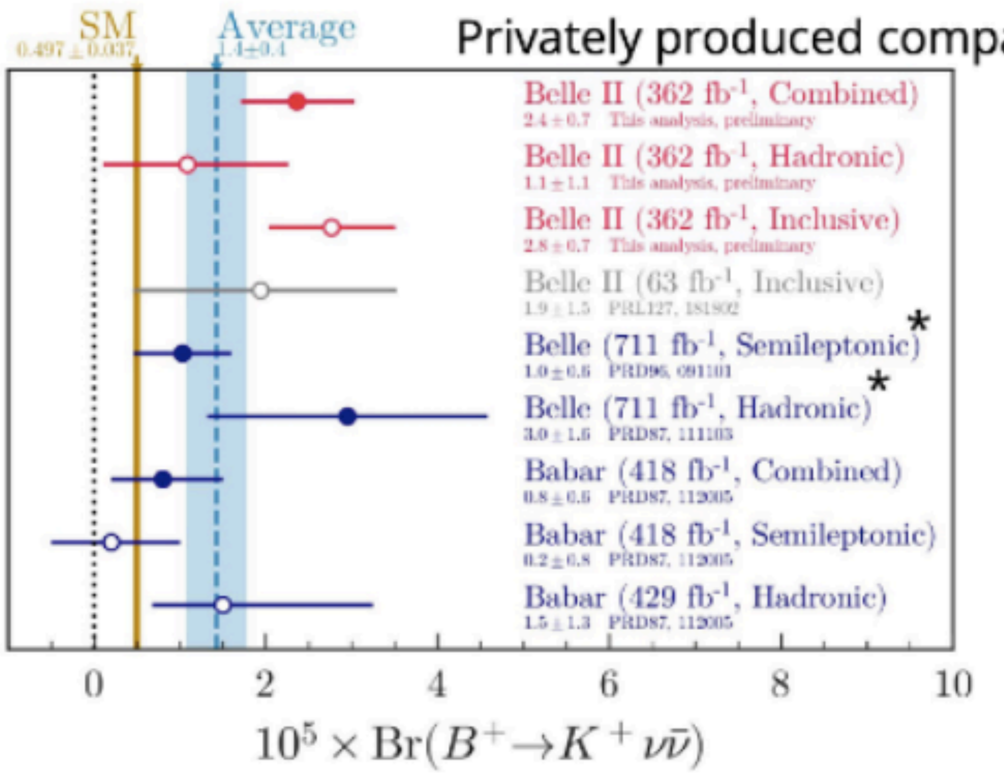
Belle II 2023

$$\mathcal{B}(B^{\pm} \to K^{\pm}\nu\bar{\nu}) = 2.40(67) \times 10^{-5}$$

2.9 σ larger then SM prediction

Glazov at EPS 2023

Privately produced comparison



Searching for explanation

Bause et al., 2309.00075

Allwicher et al, 2309.02246

Felkl et al., 2309.02940,

He et al., 2309.12741

...

$$R_{\nu\nu}^{K} = 5.4 \pm 1.5$$

S. Fajfer, Workshop on Implications of LHCb measurements and future prospects, CERN, 25-27 Oct.2023

An **exciting** (**challenging** and **promising**) **era** for the **precision frontier physics**

- The experimental and theoretical precision physics community has entered an era of **unprecedented precision experiments**
- From Snowmass 2021: **“While relatively small in size and cost compared to their energy frontiers cousins, they are large in reach and discovery potential”**
- Very relevant (I’d say, necessary) to efficiently coordinate the **many experimental and theoretical efforts** in the area through a convinced **synergy** among the **various communities** operating in precision physics in (very) **different experimental, technological and theoretical environments**