Rabi-Fest Univ. of Maryland, College Park, MD, Oct. 20-21, 2022

The "old" and the "new" muon g-2 puzzles

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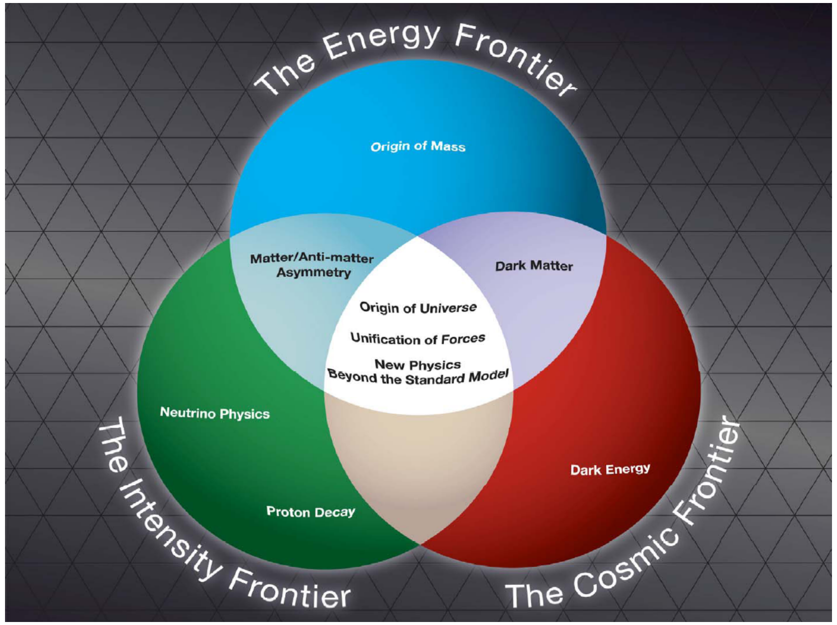
EVEN MORE INTERESTING ...

my first lesson from Rabi, MPI, 1981

Based on the work on the muon g-2 problem done in these last years in collaboration with Luca Di Luzio, Bill Marciano, Paride Paradisi and Massimo Passera

On the "old" muon g-2 puzzle



During the long sequel of restless attempts of finding experimental evidences or at least hints of **NEW PHYSICS** beyond the SM along the **traditional High-Energy (HE) and High-Intensity (HI) paths**, several 3 or even 4 σ signals at variance w.r.t. the SM expectations **have shown up**, but they have also (rather sooner than later) **invariably faded away**.

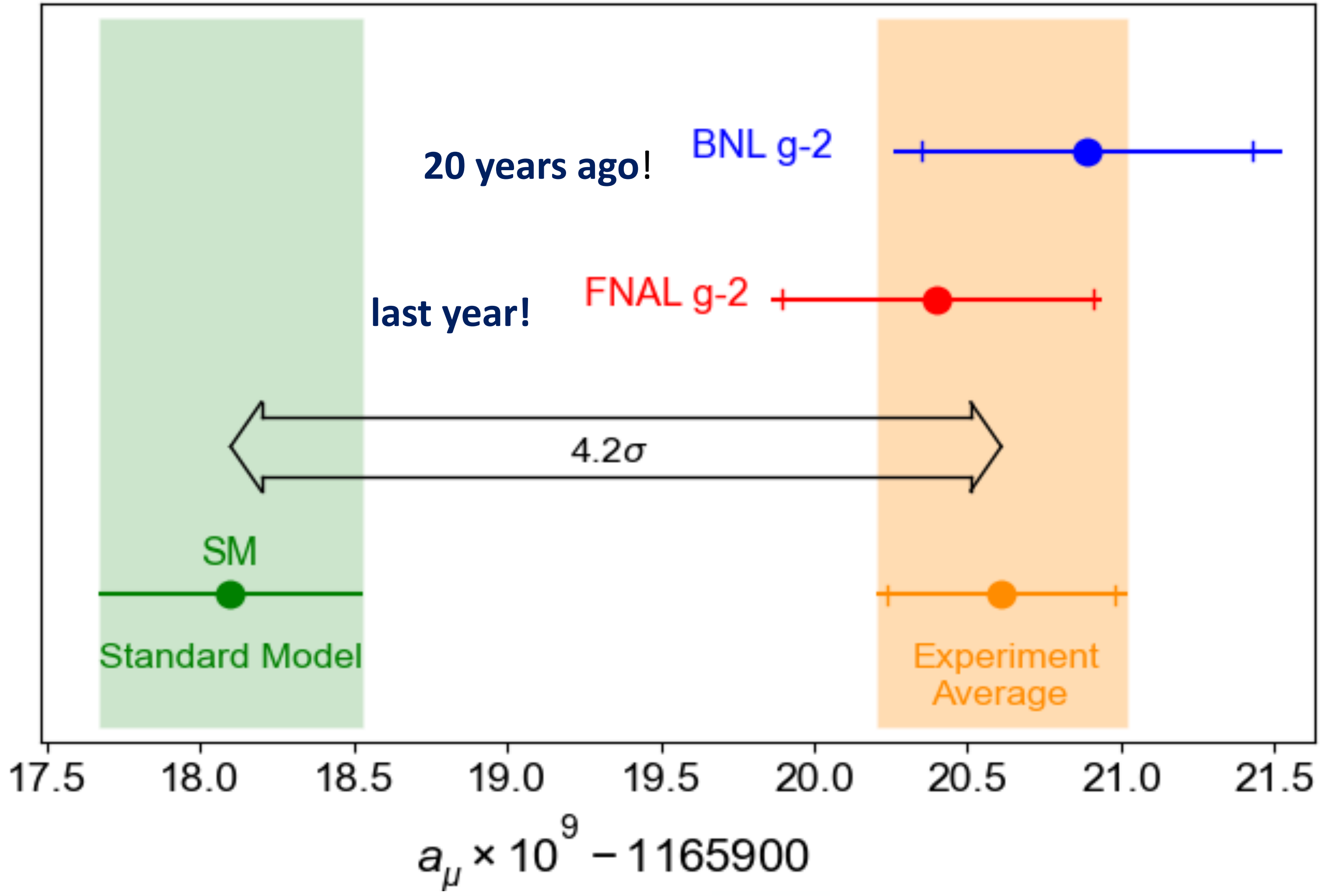
A remarkable exception is represented by

the anomalous magnetic moment of the muon

which has been for **several years now** and **still** represents a **major observational evidence along the HI frontier of the possible presence of NEW PHYSICS**

The other more recent hint of NEW PHYSICS along these two roads is again in the HI frontier, namely the possible violation of lepton flavour universality in some B-meson semileptonic decays.

The **EXP.** situation



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

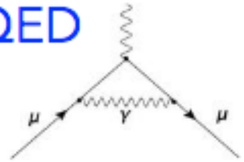
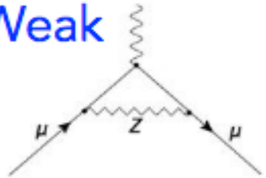
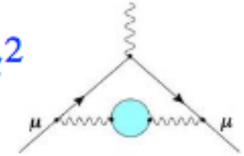
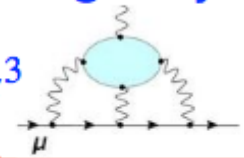
$a_\mu^{EXP} = (116592040 \pm 54) \times 10^{-11}$ [0.46ppm] FNAL E989 Run 1

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

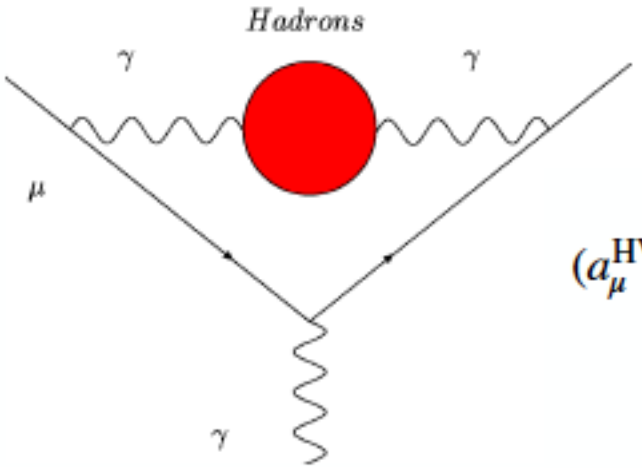
FNAL aims at 16×10^{-11}

The 4 classes of SM contributions: **uncertainty largely dominated** by the **hadronic contributions** in **Vacuum Polarization (HVP)** and **Light-by-Light** (HLbL)

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

QED 	$+\ldots$	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak 	$+\ldots$	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic…			
…Vacuum Polarization (HVP) α^2 	$+\ldots$	$6845\,(40) \times 10^{-11}$ [0.6%]	0.37 ppm
…Light-by-Light (HLbL) α^3 	$+\ldots$	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm

Numbers from Theory Initiative Whitepaper



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

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

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

$a_\mu^{EXP} = 116592061\ (41) \times 10^{-11}$ BNL+FNAL

$a_\mu^{SM} = 116591810\ (43) \times 10^{-11}$ WP20 $a^{HLO}_{\mu, e^+e^-} = 6931(40) \times 10^{-11}$

$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM} = 251\ (59) \times 10^{-11}$ 4.2 σ

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

Can Δa_μ be due to a missing contribution in σ_{had}?

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

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

Shifts below ~1 GeV conflict with the quoted exp. precision of σ(s)

Crivellin, Hoferichter, Manzari, Montuli; de Rafael; Malaescu, Schott; Colangelo, Hoferichter, Stoffer

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

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.

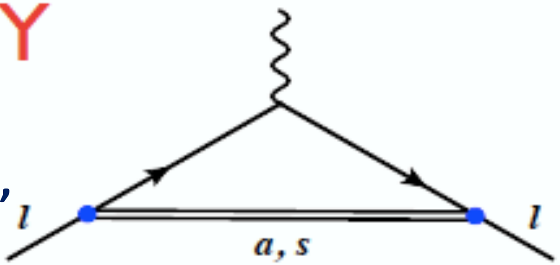
P. Paradisi, La Thuile 2021

The case of AXION-LIKE PARTICLES (ALPs)

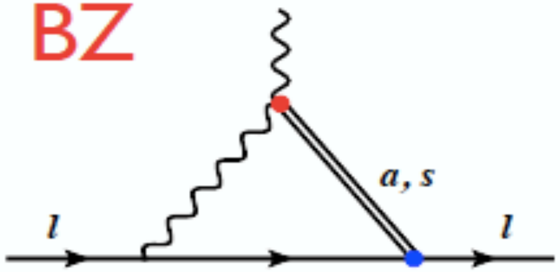
ALPs contributions to the muon g-2?

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

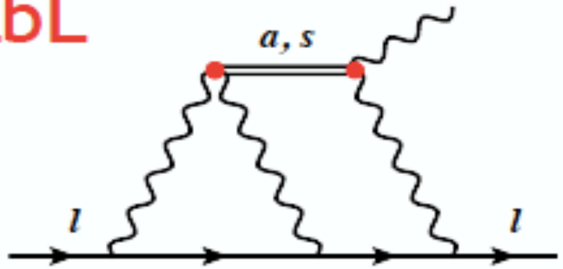
Y



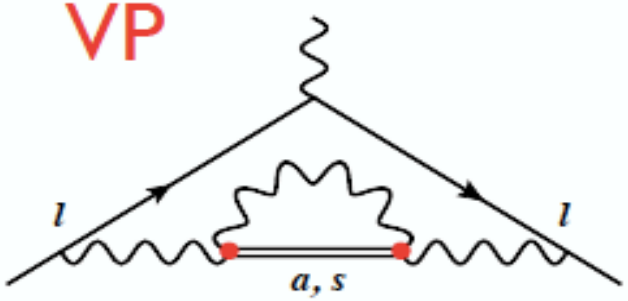
BZ



LbL



VP



- 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.

$$\mathcal{L} = e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{c_{\mu\mu}}{2} \frac{\partial^\nu a}{\Lambda} \bar{\mu} \gamma_\nu \gamma_5 \mu$$

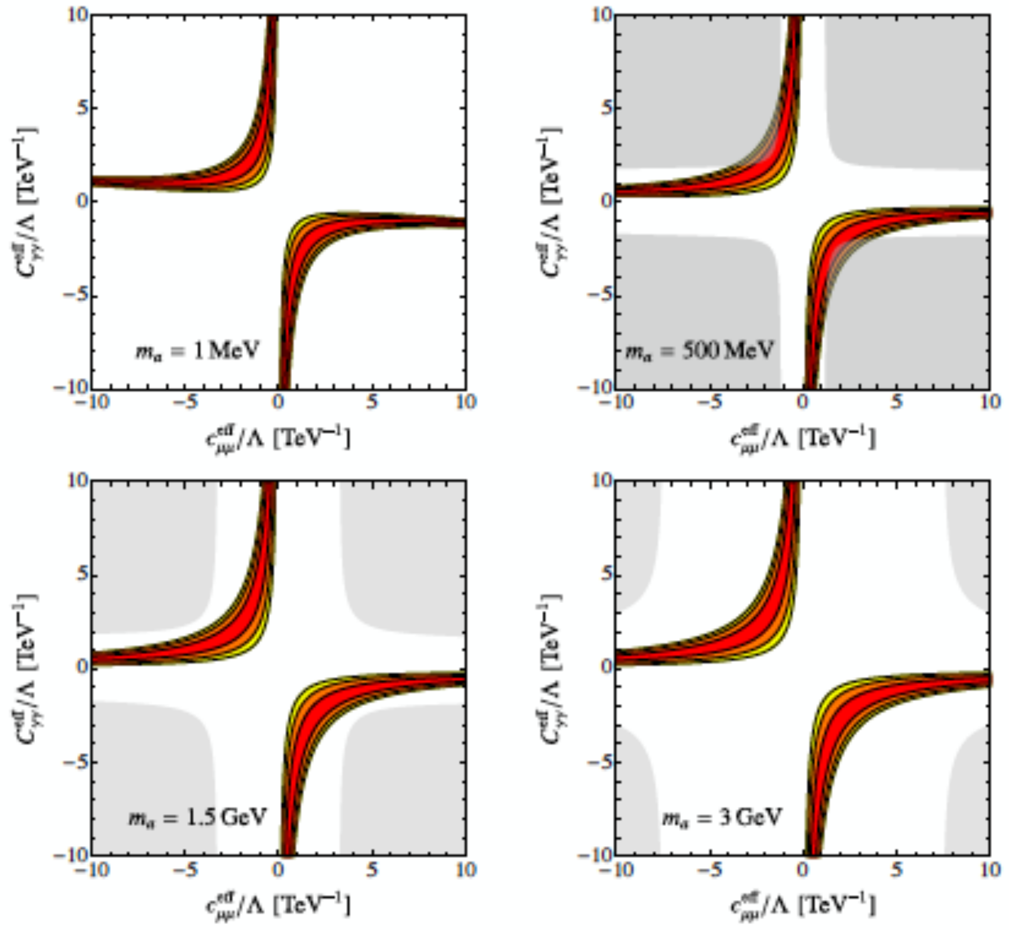
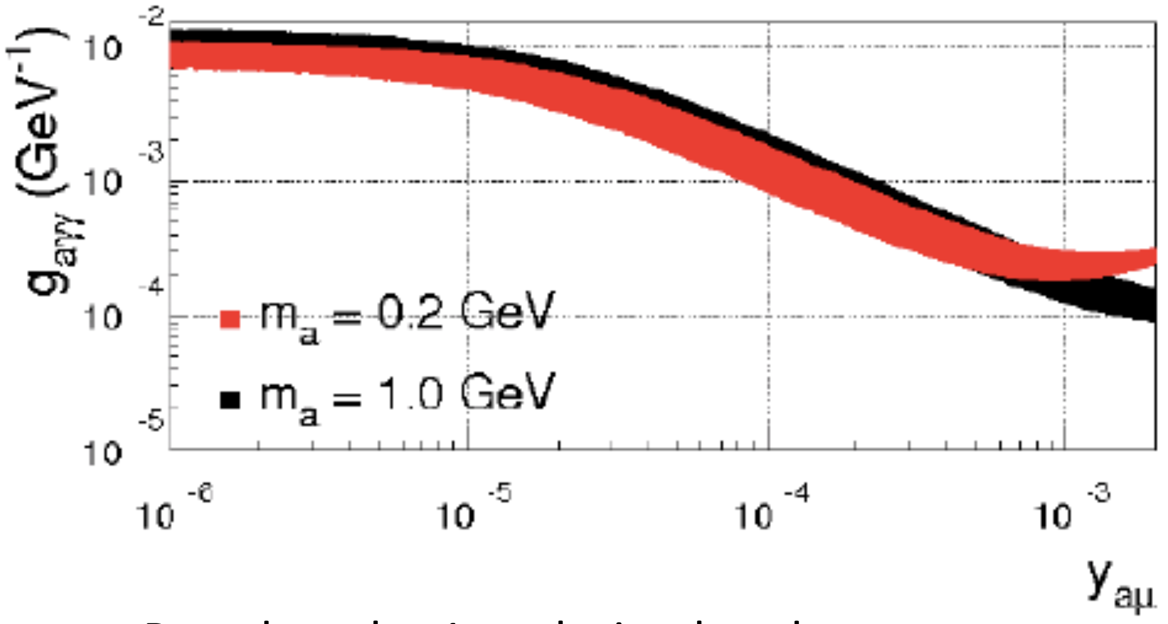


Figure: Δa_μ regions favoured at 68% (red), 95% (orange) and 99% (yellow) CL. Gray regions are excluded by the BaBar search $e^+e^- \to \mu^+\mu^- + \mu^+\mu^-$ [Bauer, Neubert, Thamm, '17]

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma}\, a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + i\, y_{a\psi}\, a\, \bar{\psi} \gamma_5 \psi$$

$$g_{a\gamma\gamma} \equiv \frac{2\sqrt{2}\,\alpha}{\Lambda} c_{a\gamma\gamma}$$

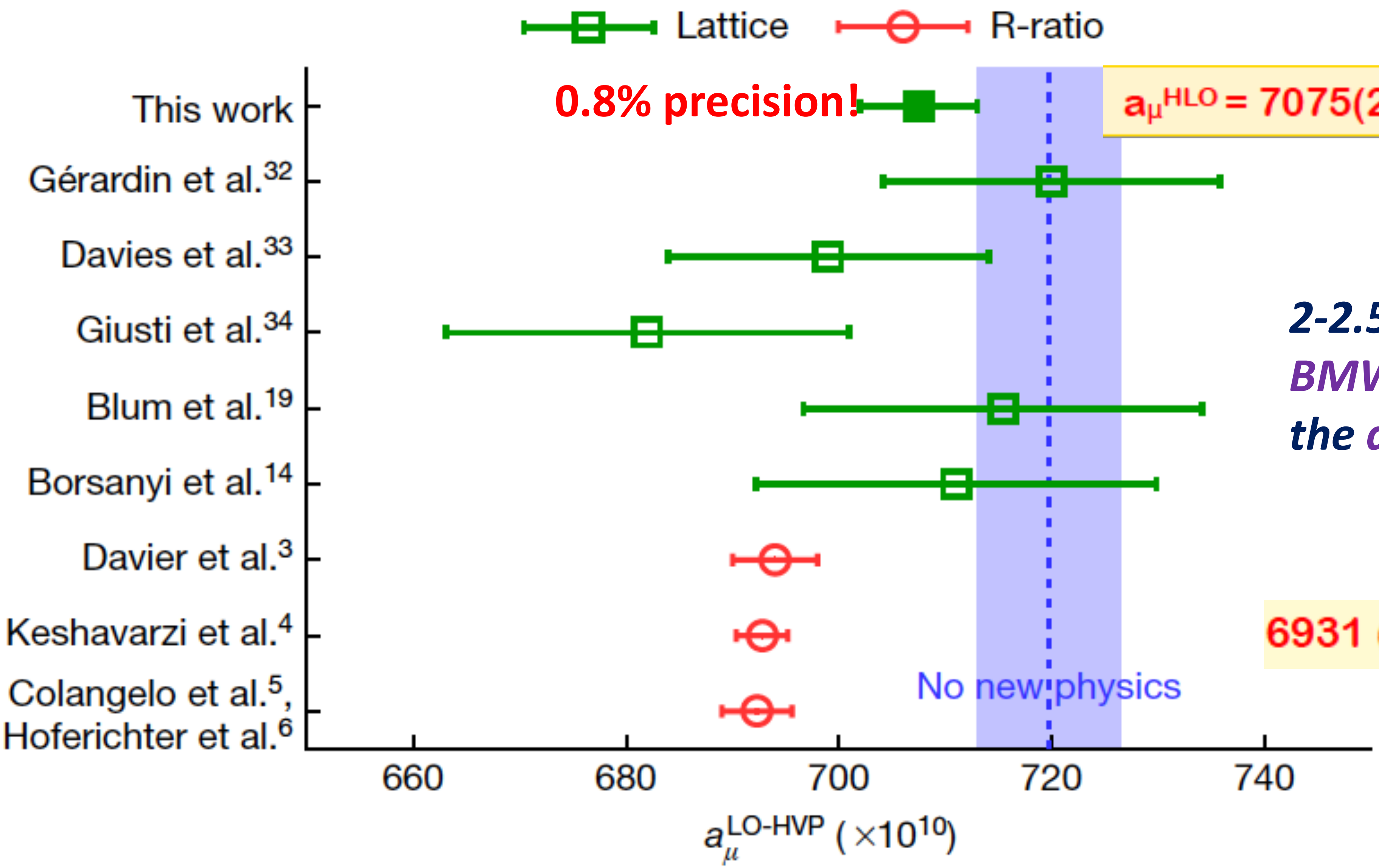


Pseudoscalar 1σ solution bands to the g-2 muon anomaly taking Λ = 1 TeV

Marciano, A.M., Paradisi, Passera '16

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

first published lattice result with sub-percent precision!

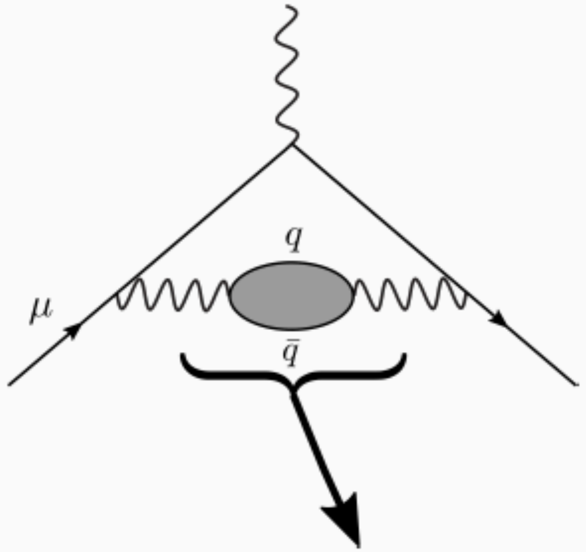


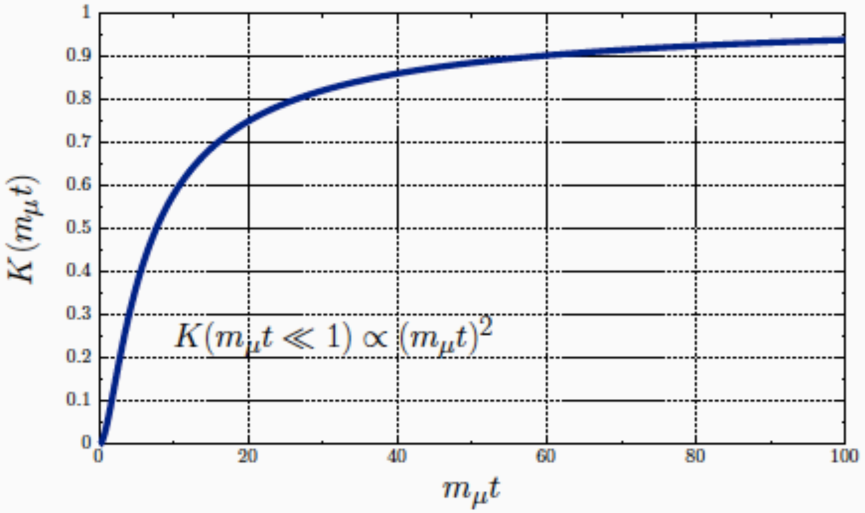
$a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst}\ [55]_{tot} \times 10^{-11}$

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

$6931\ (40) \times 10^{-11}$ (0.6%)

LO-HVP from Lattice QCD





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

$$\Downarrow$$

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

Time-Momentum representation (Bernecker & Meyer, 2011)

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

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)

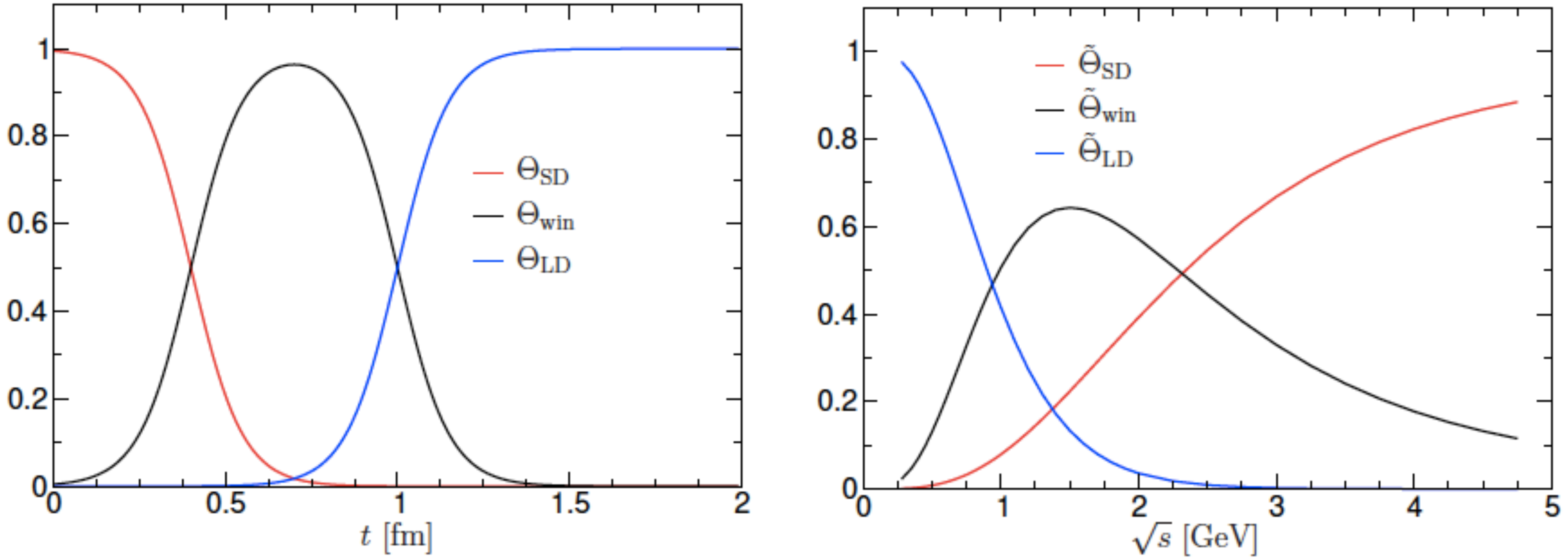
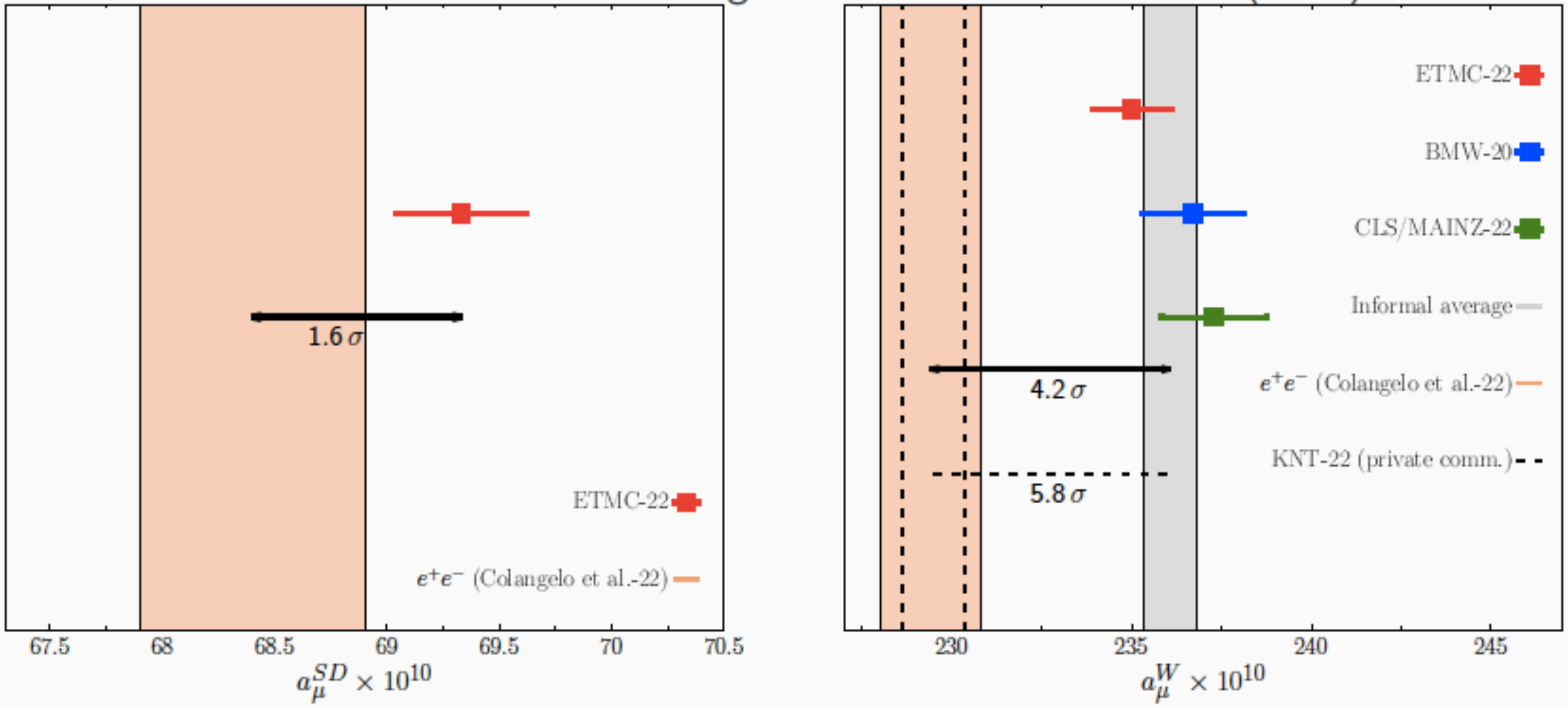


Figure 1: Short-distance, intermediate, and long-distance weight functions in Euclidean time (left), and their correspondence in center-of-mass energy (right).

G. Gagliardi, Edinburgh 2022, on behalf of the ETM Collaboration

Comparison with $e^+e^- \to$ hadrons results

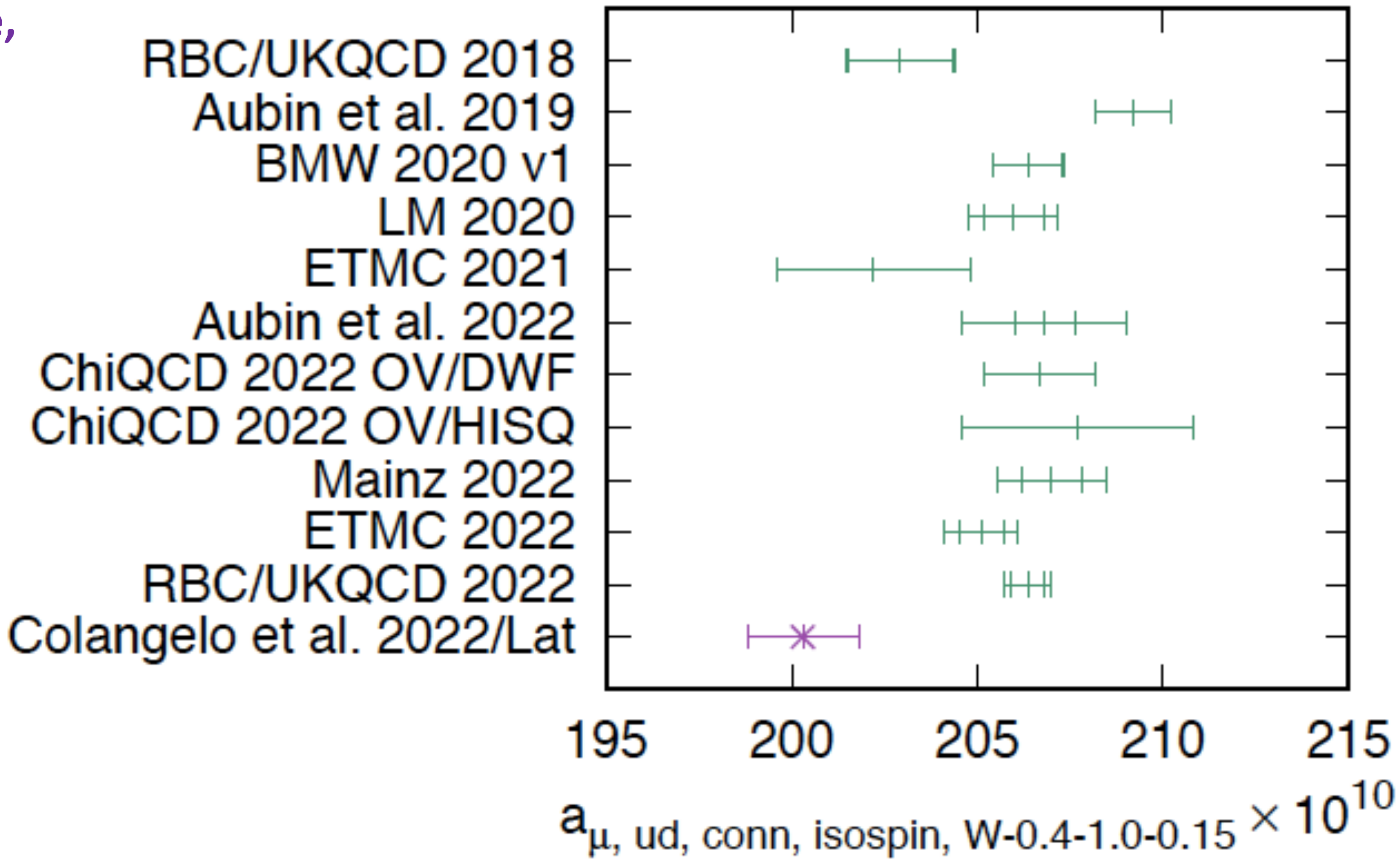
$e^+e^- \to$ hadrons from Colangelo et al. arXiv:2205.12963 (2022).



- Tension in a_μ^W rises to 4.2σ if we combine ETMC '22, BMW '20 and CLS/Mainz '22 (informal average $\to$ next WP).
- Deviation of $e^+e^- \to$ hadrons data w.r.t. the SM in the low and (possibly) intermediate energy regions, but not in the high energy region.

The RBC/UKQCD22 result in context

C. Lehner, Workshop of the Muon g-2 Theory Initiative, Edinburgh, Sept. 2022



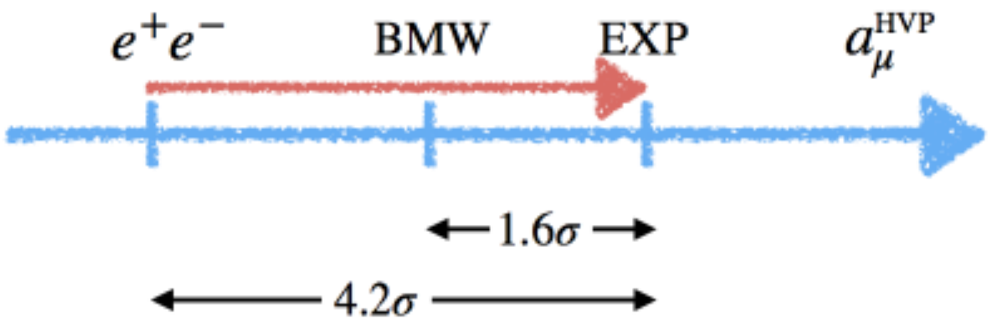
- 3.9σ tension of RBC/UKQCD22 with Colangelo et al. 22/Lattice

The NEW g-2 puzzle

$$(a_\mu^{\rm HVP})_{\rm EXP} = a_\mu^{\rm EXP} - a_\mu^{\rm SM,\,rest}$$

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

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



If the new lattice results * – i.e., **BMWc** & (only for the (SD) + W windows, but not for the relevant LD window) **Mainz 2022+ETMC 2022 + RBC/UKQCD 2022** are correct (and will be confirmed also for the LD window!), then:

i) The "old" g-2 discrepancy would be basically gone, but

ii) A new significant discrepancy between the $e^+ e^-$ data- driven and lattice QCD evaluations of a_μ^{HVP} becomes quite significant (> 4σ)

*** The lattice FNAL/QCDMILC collaboration is going to unblind its data soon**

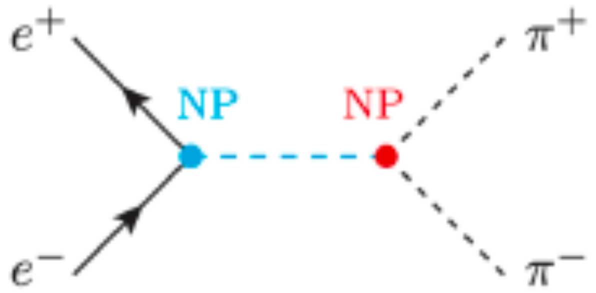
New Physics to solve the new muon g-2 puzzle ?

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

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

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

Light New Physics in σ_{had}



NP coupled both to hadrons and electrons

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

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

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

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

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**

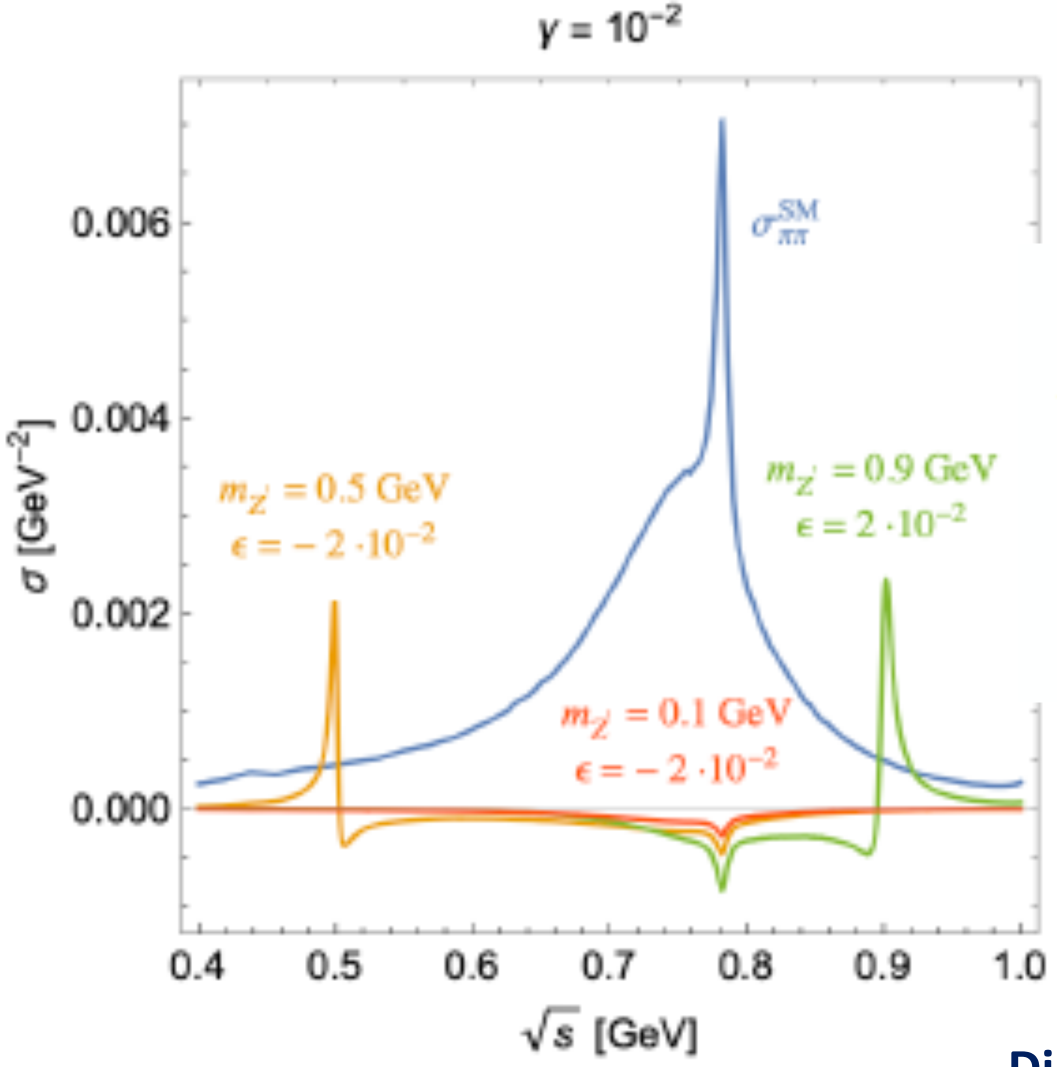
- **SIZEABLE** → **TREE-LEVEL** contribution to modify σ_{had} at $\sqrt{s}$ **< 1 GeV** (hence, **sub-GeV mediator** coupling to the hadronic and electron currents at tree-level)
- **NEGATIVE INTERF.** → NP particle couples via a **VECTOR** current to the u, d quarks (given the dominance of the $\pi^+\pi^-$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

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

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

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

Examples of benchmark values for $m_{Z'}$ and Z' couplings to electrons and up- and down-quarks suitable to solve the g-2 discrepancy



$$\Delta a_\mu = \frac{1}{4\pi^3}\int_{s_{\rm exp}}^{\infty} {\rm d}s\, K(s)(-\Delta\sigma^{\rm NP}_{\rm had}(s))$$

$\sqrt{s_{\rm exp}} \approx 0.3$ GeV for $\pi^+\pi^-$ channel

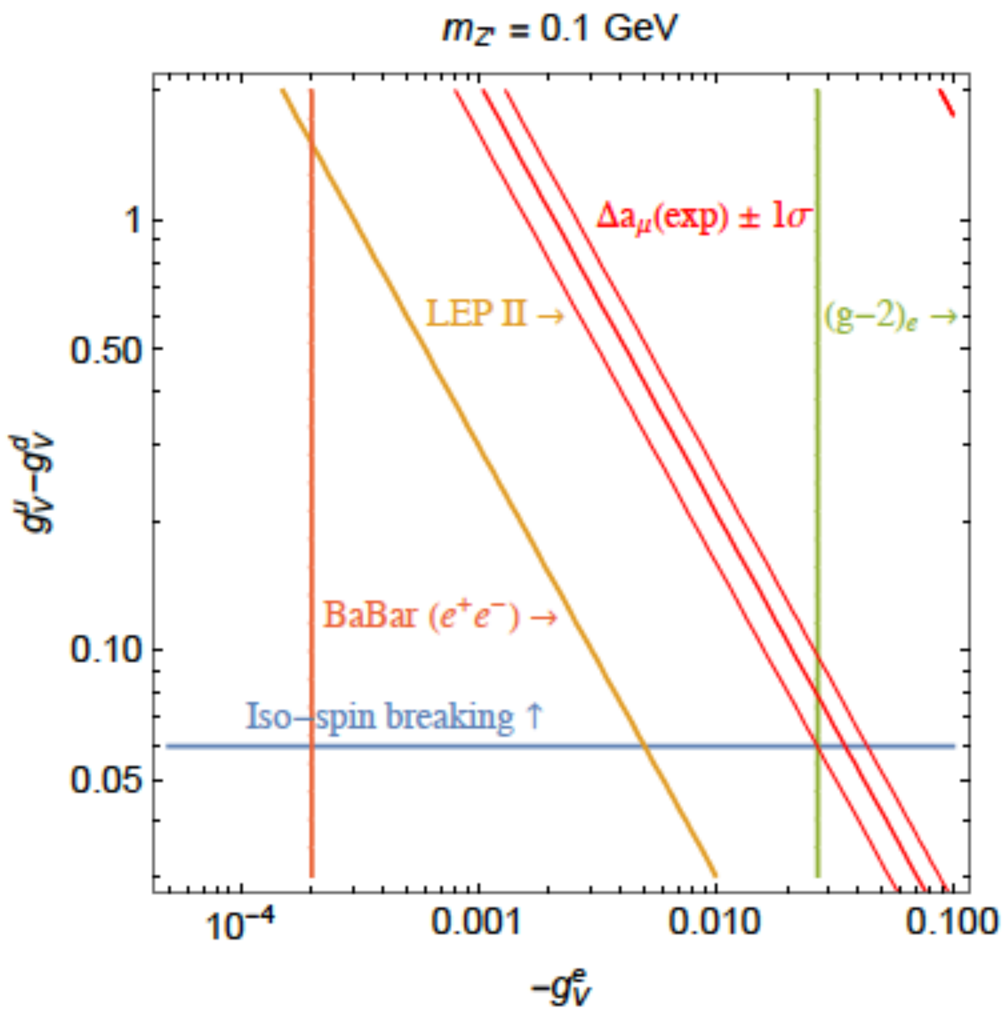
$$\Delta\sigma^{\rm NP}_{\rm had}(s) \approx \sigma^{\rm SM}_{\pi\pi}(s) \times \frac{2\epsilon s(s-m^2_{Z'})+\epsilon^2 s^2}{(s-m^2_{Z'})^2+m^4_{Z'}\gamma^2}$$

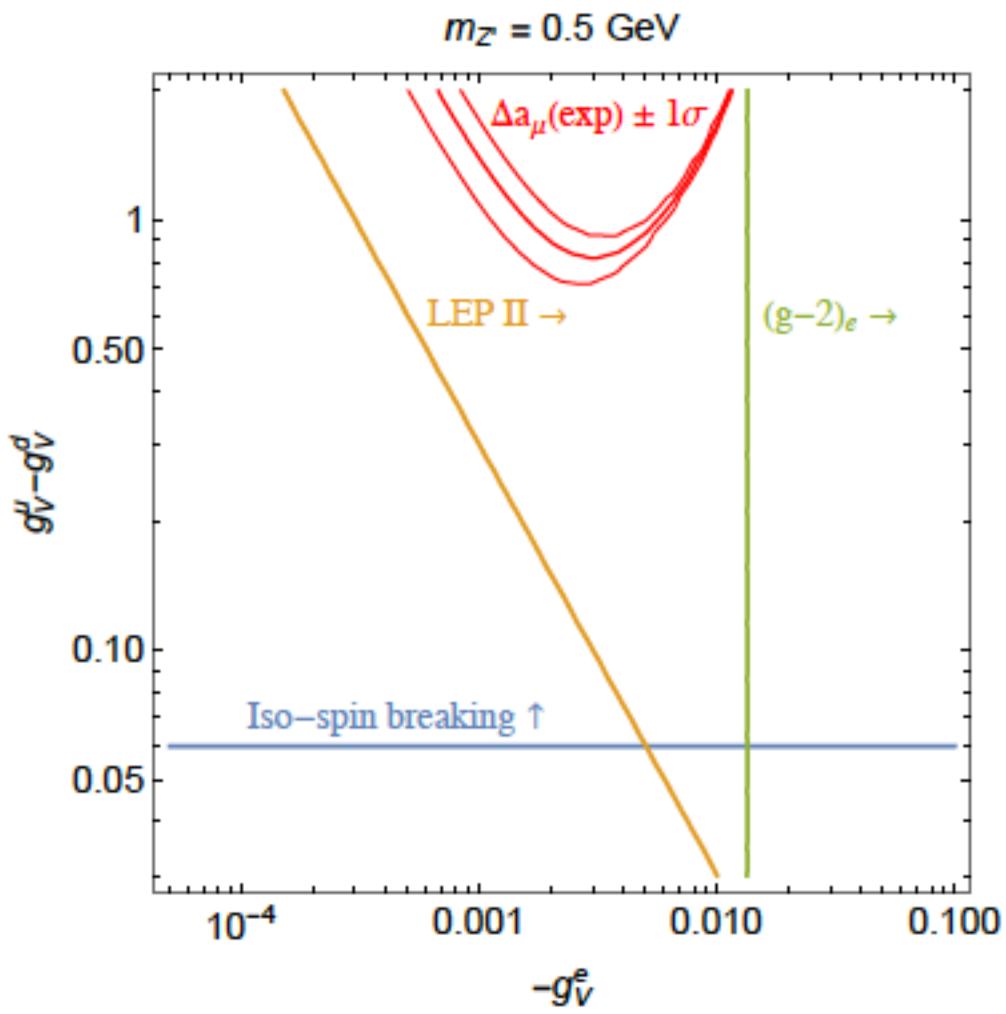
$$\epsilon \equiv g^e_V(g^u_V - g^d_V)/e^2$$

$$\gamma \equiv \Gamma_{Z'}/m_{Z'}$$

Di Luzio, A.M., Paradisi, Passera 2112. 08312

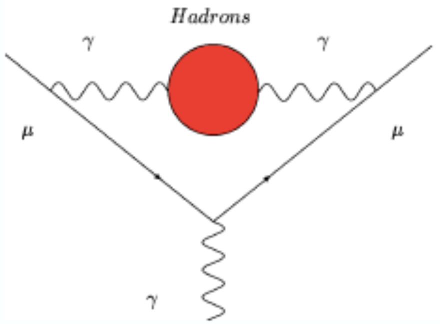
At least TWO independent bounds prevent to get a sizeable contribution to Δa_μ modifying σ_{had} via Z' exchange to solve the "new" μ g-2 puzzle





Spacelike proposal for a_μ

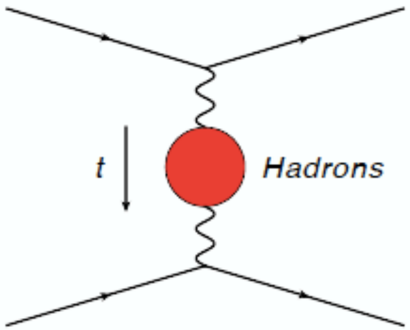
- At present, the leading hadronic contribution a_μ^{HLO} is computed via the **timelike** formula:



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

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

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



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

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

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

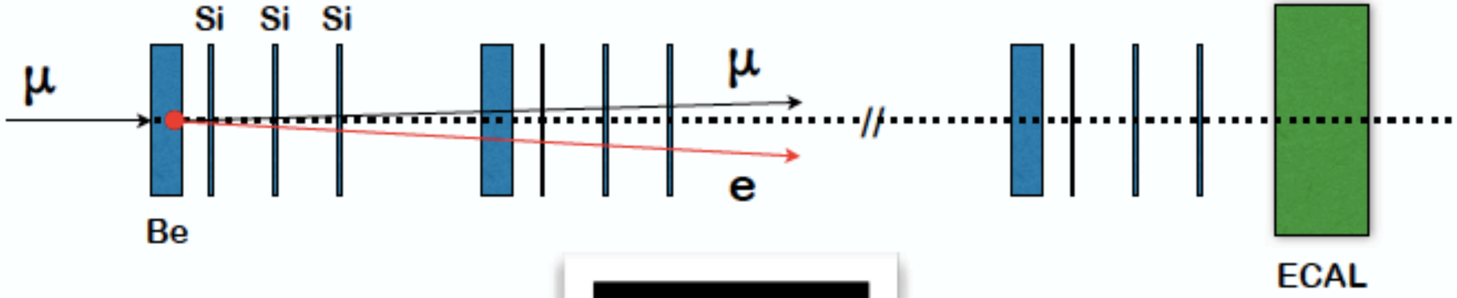
New Physics extracting $\Delta\alpha_{had}(t)$ at MUonE? Padova and Heidelberg 2020

→ NO, NP cannot spoil the validity of such extraction

MUonE: a new determination of $\Delta\alpha_{had}$

MUonE: Muon-electron scattering @ CERN

- $\Delta\alpha_{had}(t)$ can be measured via the elastic scattering $\mu\, e \to \mu\, e$.
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each station has one layer of Beryllium (target) followed by several thin Silicon strip detectors.



Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna,
Nicrosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

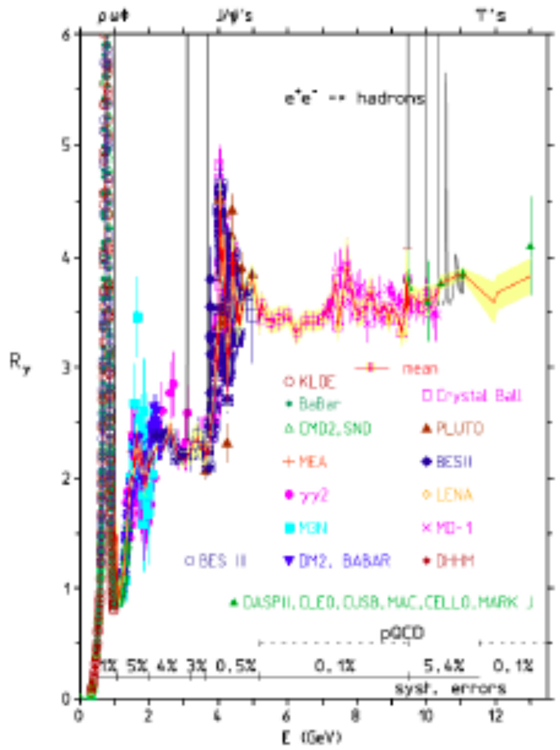
[Courtesy by M. Passera]

- Letter of Intent submitted to CERN SPSC in 2019: Test run approved for 2021

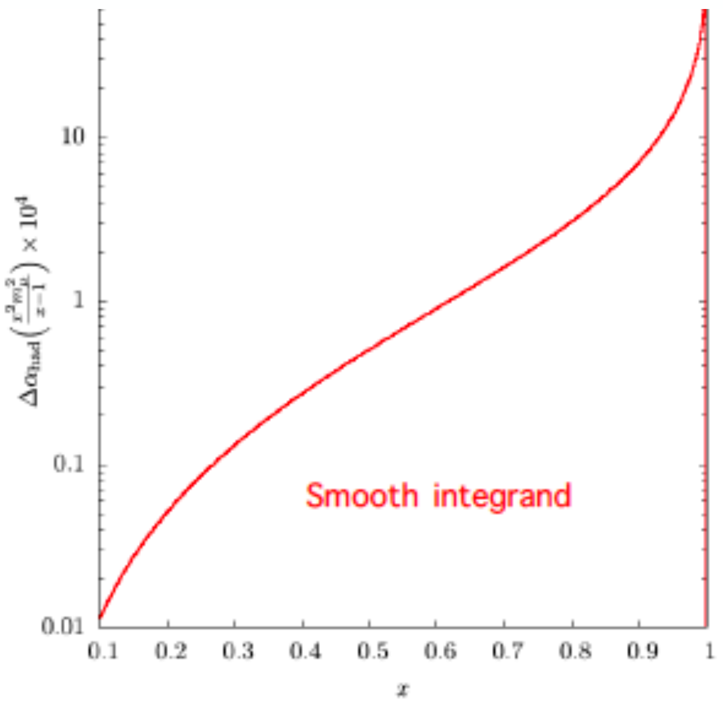
a_μ^{HLO} : timelike vs spacelike method

Timelike → Spacelike

$\Delta\alpha_{had}(t)$ can be measured via the elastic scattering $\mu\, e \to \mu\, e$.

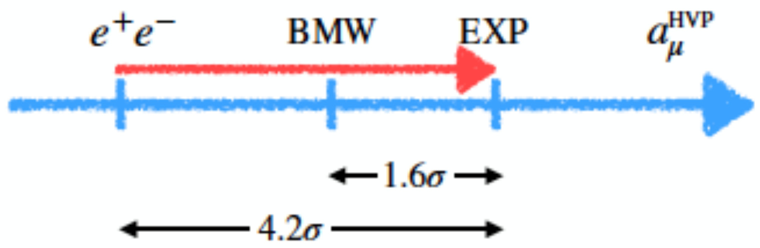


F. Jegerlehner, arXiv:1511.04473



Carloni Calame, Passera, Trentadue, Venanzoni, PLB 2015

- ☑ Inclusive measurement
- ☑ Smooth integrand
- ☑ Direct interplay with lattice QCD

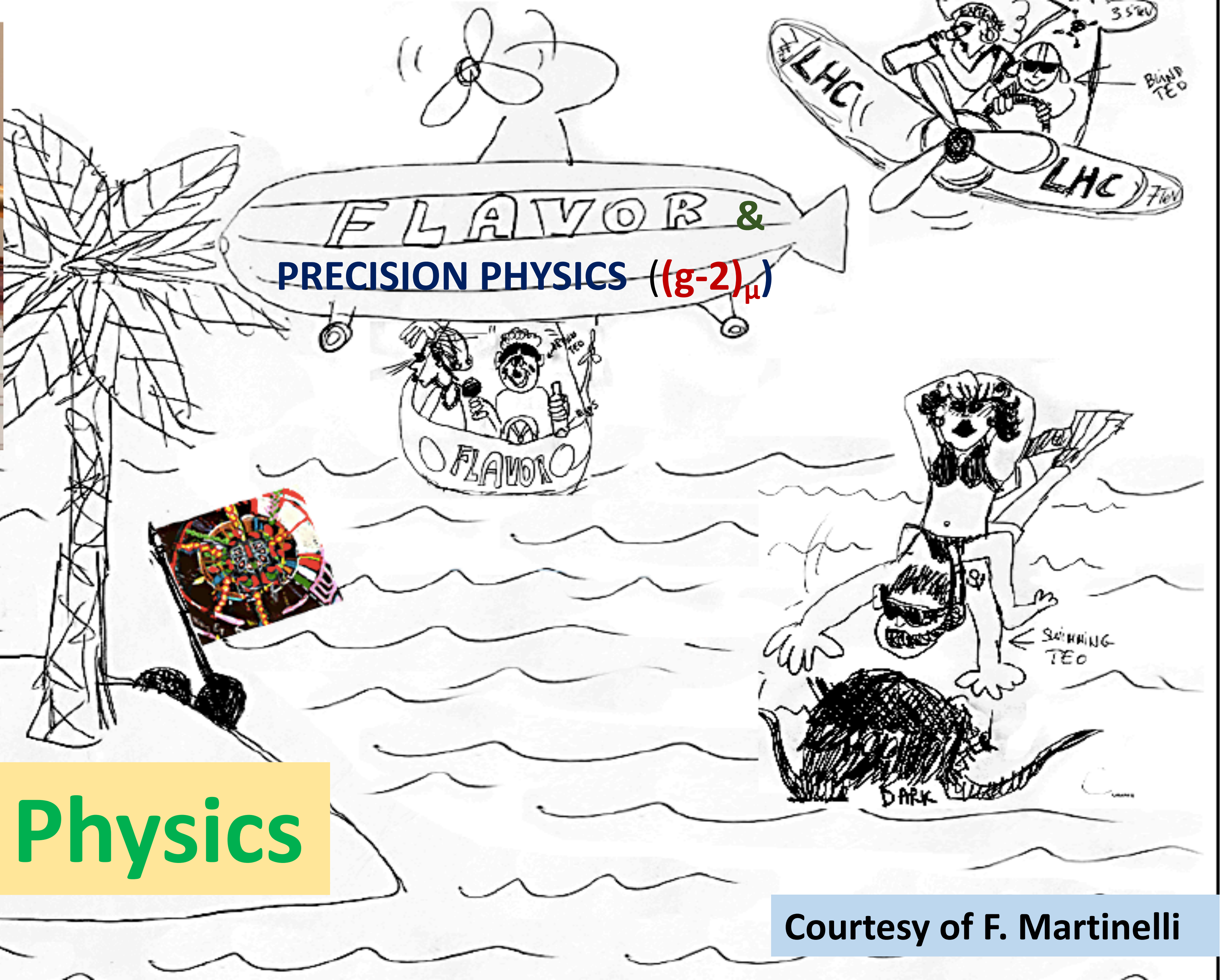


some conclusive thoughts:

- attempt **to solve the "new" muon g-2 puzzle introducing NP which modifies σ (e^+e^- → hadrons), but without affecting a_μ^{HVP}** :
  a) NP → light (<1 GeV) vector **Z'** coupling only to electrons and hadrons;
  b) the **experimental constraints** on the size of such couplings **prevent** the Z' exchange to provide the needed enhancement of the hadronic σ to suitably address the new g-2 puzzle

- **Two** directions to be vigorously pursued:
  i) perform **new** independent **lattice QCD** computations of the HVP contribution to a_μ to assess the validity of the **BMWc result** ;
  ii) identifies **new** experimental ways to probe a_μ^{HVP} (the **MUonE** exp. can (hopefully reasonably) soon provide an **independent determination** of the leading hadronic contributions to a_μ alternative to both the dispersive and lattice methods)

GRAZIE!

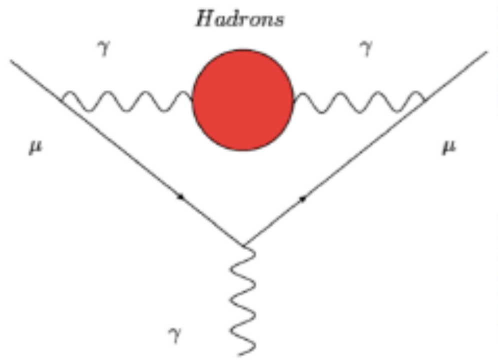


Courtesy of F. Martinelli

BACK-UP SLIDES

A closer look at σ_{had}

- dominated by $e^+e^- \to \pi^+\pi^-$ channel (70% of the full hadronic)



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

- what is $\sigma_{\text{had}}(s)$?

  - Includes Final State Radiation (FSR)

  - Initial State Radiation (ISR) and FSR/ISR interference are subtracted

  - Vacuum polarization also subtracted (by rescaling exp. cross-section by $|\alpha/\alpha(s)|^2$)

  → part of higher-order HVP

[WP20, 2006.04822]

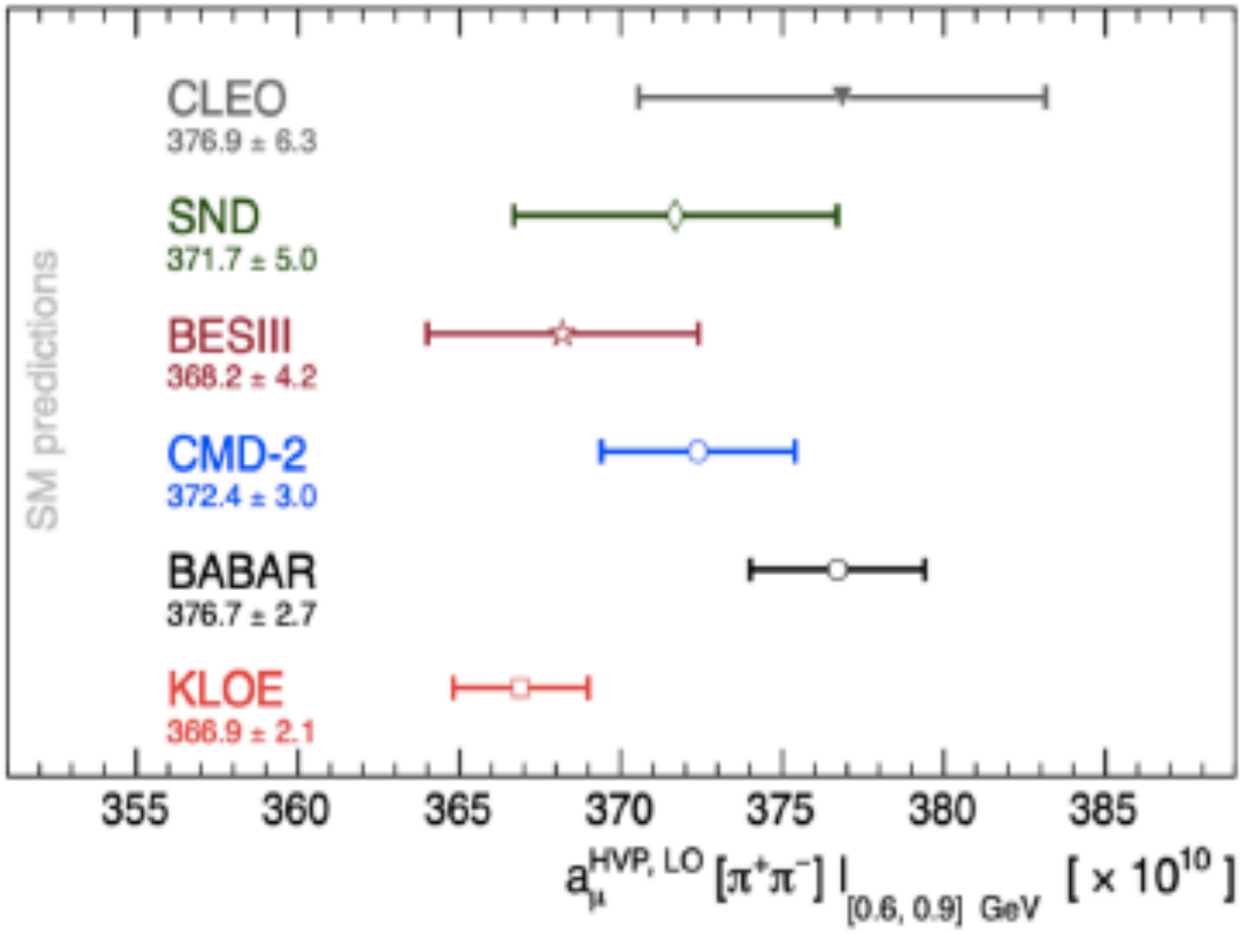


Figure 15: Comparison of results for $a_\mu^{\text{HVP, LO}}[\pi\pi]$, evaluated between 0.6 GeV and 0.9 GeV for the various experiments.

NP in Bhabha scattering?

- What if the measurement of the KLOE luminosity is affected by NP ?

[Darmé, Grilli di Cortona, Nardi 2112.09139]

$$\mathcal{L}^{\rm SM}_{e^+e^-} = \frac{N_{\rm Bha}}{\sigma^{\rm SM}_{\rm eff}} \longrightarrow \mathcal{L}_{e^+e^-} = \mathcal{L}^{\rm SM}_{e^+e^-}\frac{\sigma^{\rm SM}_{\rm eff}}{\sigma_{\rm eff}}$$

$$\sigma_{\rm eff} = \sigma^{\rm SM}_{\rm eff}(1+\delta_R)$$

$$\sigma_{\rm had} \propto N_{\rm had}/\mathcal{L}_{e^+e^-} \longrightarrow \sigma_{\rm had} \to \sigma_{\rm had}(1+\delta_R)$$

$$a_\mu^{\rm LO,HVP} \to a_\mu^{\rm LO,HVP}\,(1+\delta_R)$$

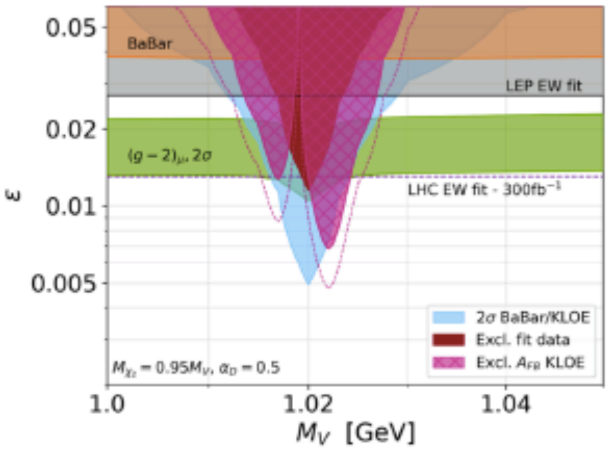
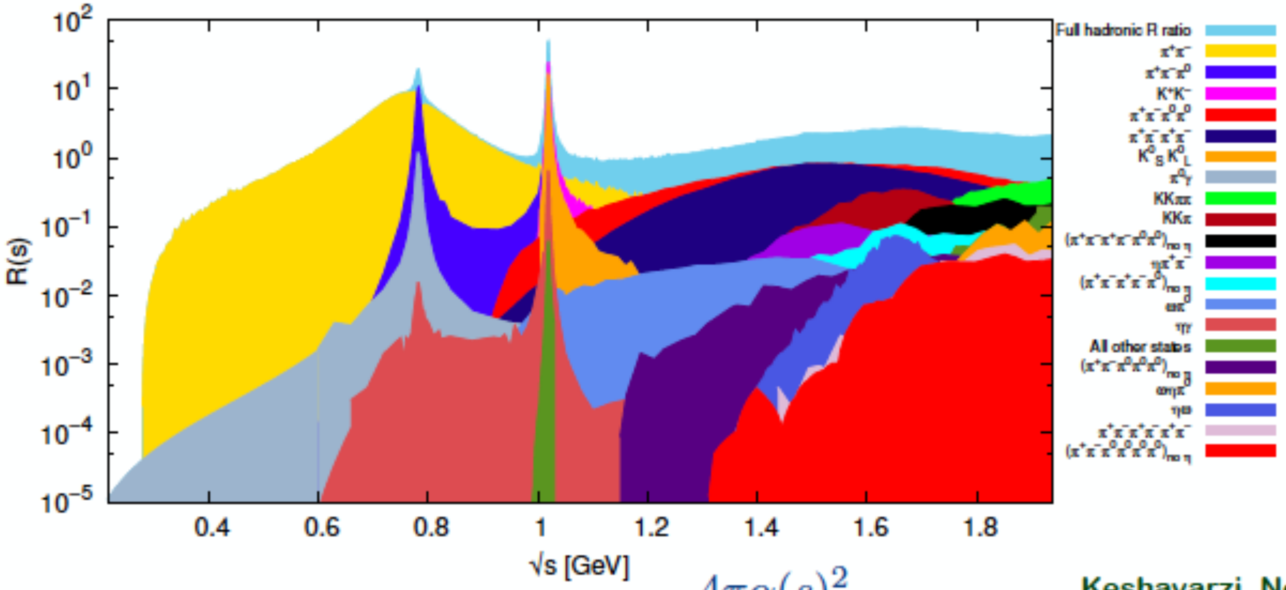


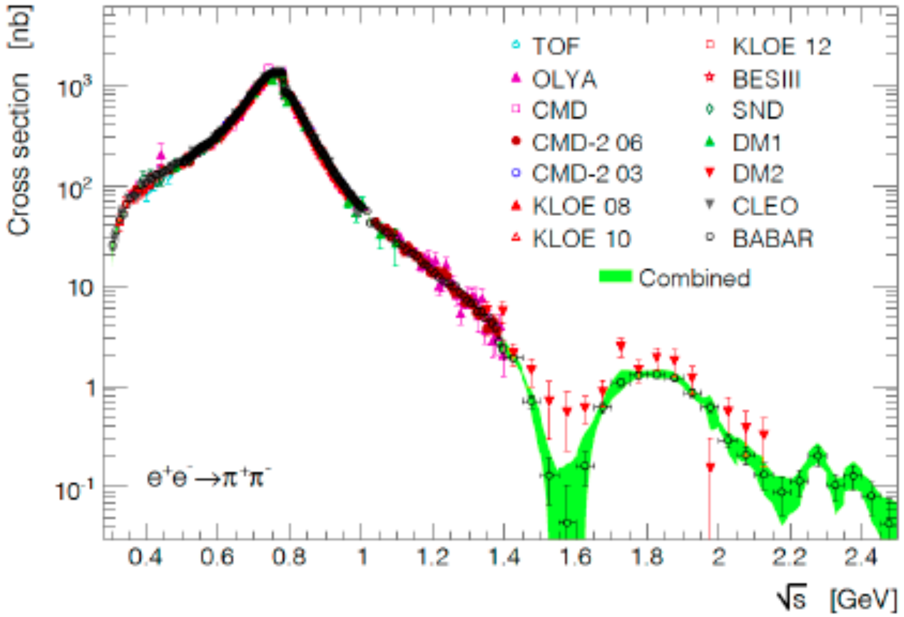
Figure 3. Parameter range compatible at 2σ with the experimental measurement of Δa_μ (green region) resulting from a redetermination of the KLOE luminosity, for $\alpha_D = 0.5$, $m_{\chi_2} = 0.95 m_V$ and $m_{\chi_1} = 25$ MeV. In the blue region the KLOE and BaBar results for $\sigma_{\rm had}$ are brought into agreement at 2σ. The red region corresponds to a shift of the KLOE measurement in tension with BaBar (and with the other experiments) at more than 2σ.

$e^+e^- \rightarrow \pi^+\pi^-$ dominance of the low-energy hadronic cross-section



$$R(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner
PRD 2018



Davier, Hoecker, Malaescu, Zhang
EPJC 2020

$\Lambda \approx v$: SUSY and the muon $(g-2)$

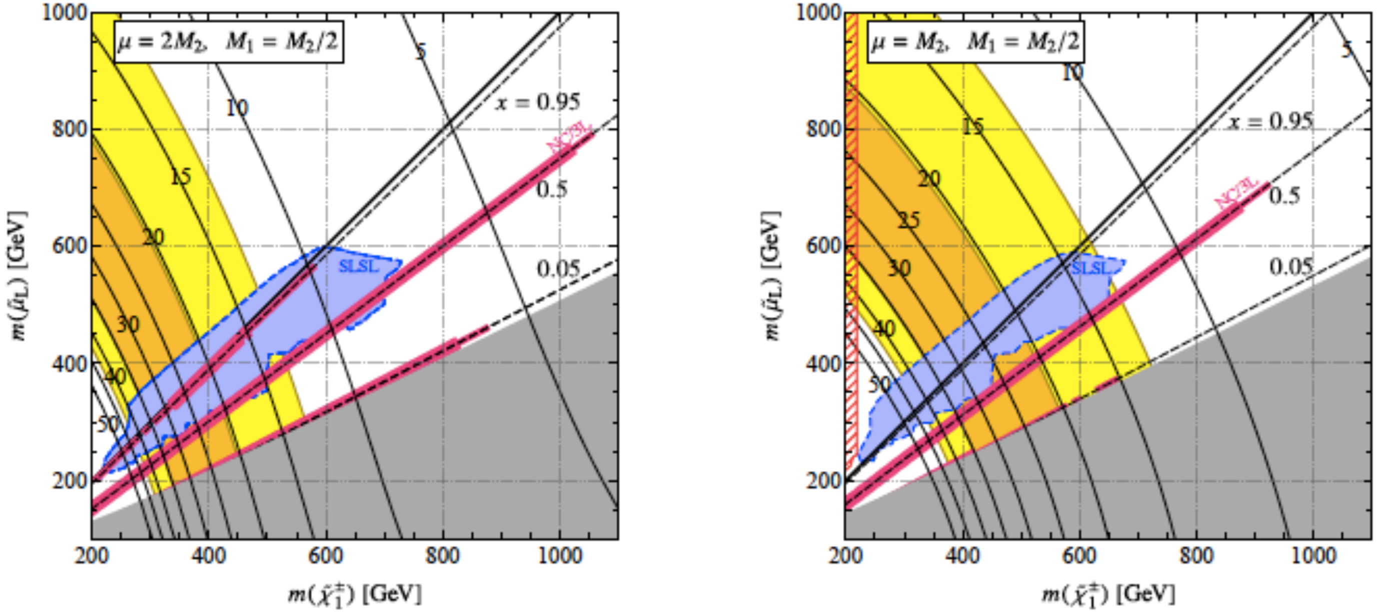
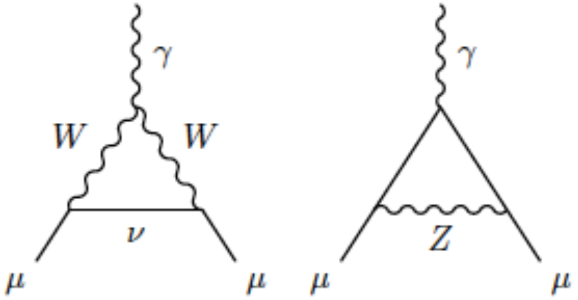
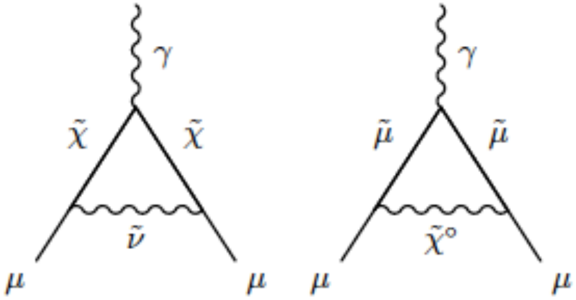


Figure: LHC Run 2 bounds on SUSY scenario for the muon $g-2$ anomaly for $\tan\beta = 40$. Orange (yellow) regions satisfy the muon $g-2$ anomaly at the 1σ (2σ) level [Endo et al., '20].





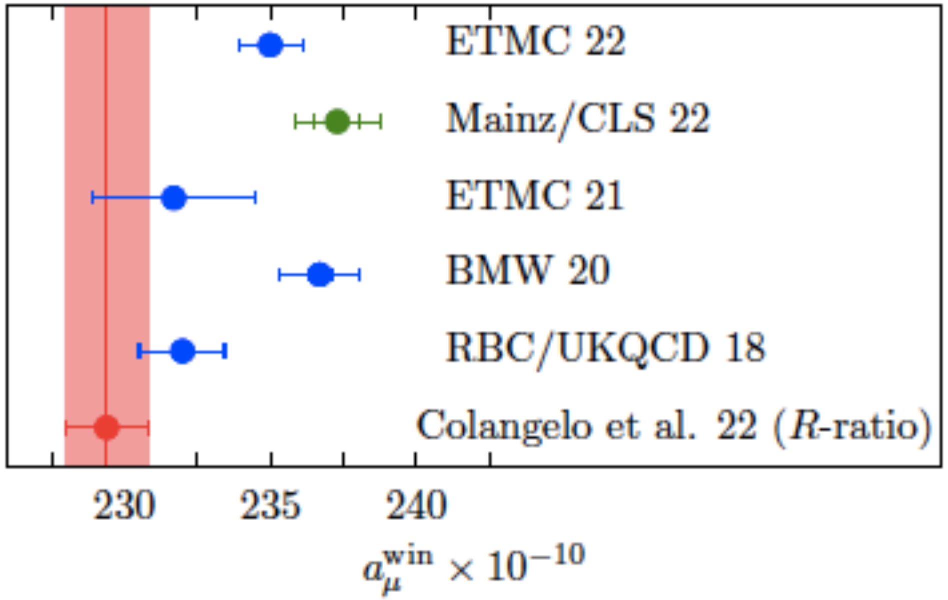
$$(a_\mu^{\rm SM})_{weak} \approx \frac{g^2 m_\mu^2}{32\pi^2 M_W^2} \approx 2 \times 10^{-9}$$

$$a_\mu^{\rm SUSY} \approx \frac{g^2 m_\mu^2 \tan\beta}{32\pi^2 \tilde{m}^2} \underbrace{\approx 2 \times 10^{-9}}_{\tilde{m} = 500\,{\rm GeV}\ \&\ \tan\beta = 40}$$

COMPARISON WITH RESULTS FOR a_μ^{win}

- Isospin-breaking correction $+(0.70 \pm 0.47) \times 10^{-10}$ included:

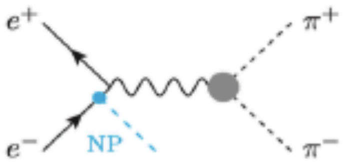
$$a_\mu^{\text{win}} = (237.30 \pm 0.79_{\text{stat}} \pm 1.13_{\text{syst}} \pm 0.05_{\text{Q}} \pm 0.47_{\text{IB}}) \times 10^{-10}$$



- 3.9σ tension with data-driven estimate in [2205.12963, Colangelo et al.].
- Genuine difference between lattice and data-driven results?

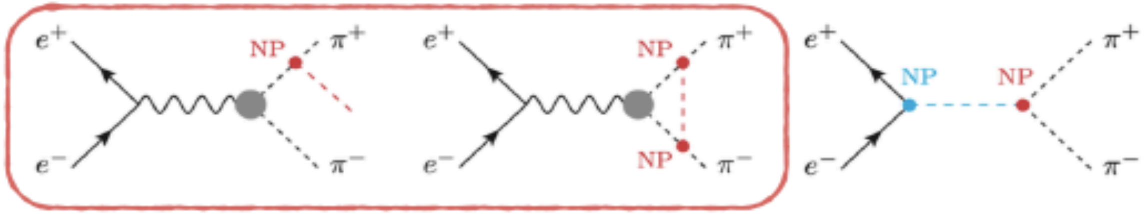
Light New Physics in $\sigma_{\rm had}$

- Light new physics inducing a sub-GeV modification of $\sigma_{\rm had}$ is the only possibility



1. NP coupled only to electrons → severe bounds

[See however
Darmé, Grilli di Cortona, Nardi 2112.09139
NP in Bhabha scattering ? → backup slides]



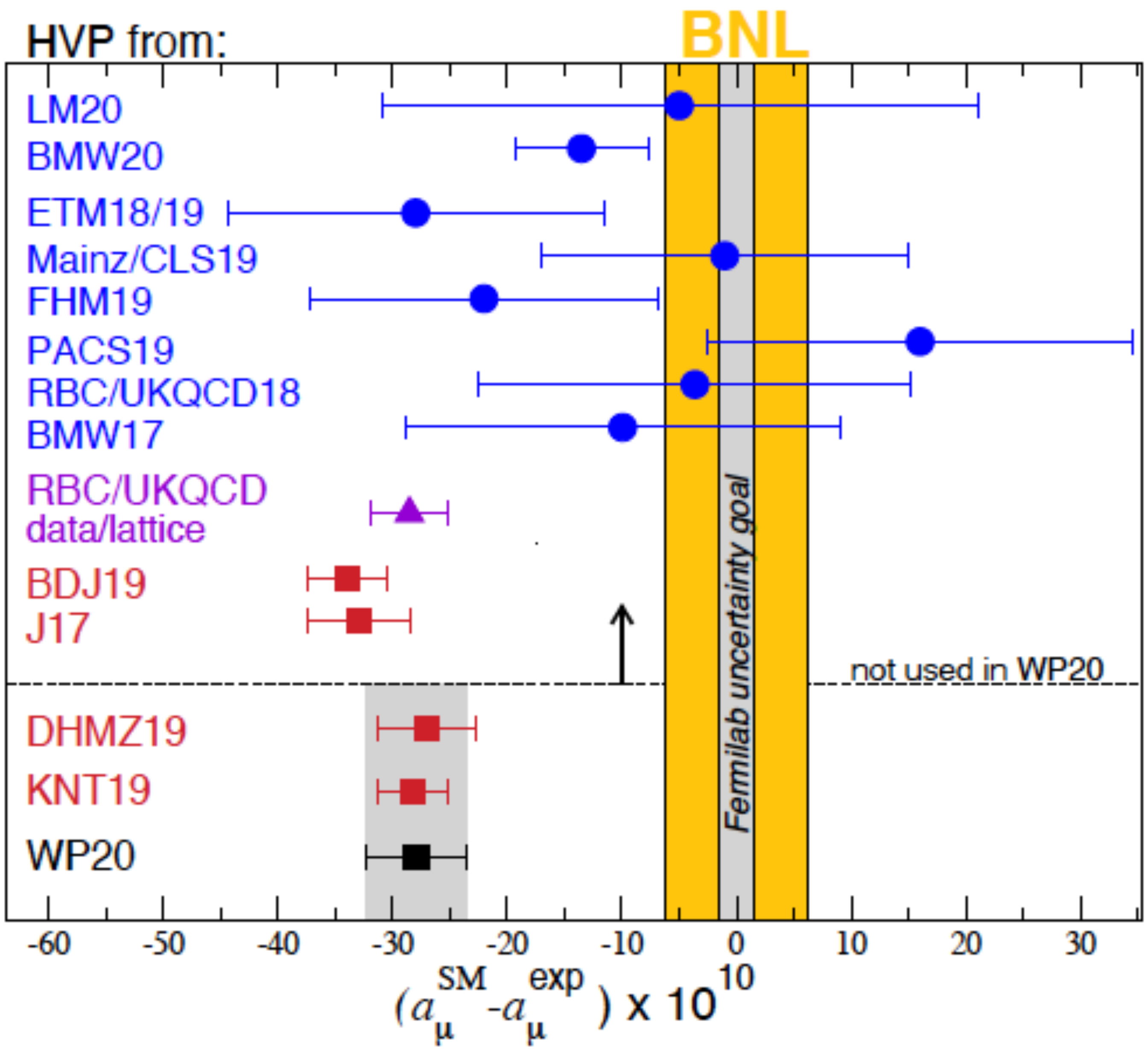
2. NP coupled only to hadrons

FSR effects due to NP should be included into $\sigma_{\rm had}(s)$, not easy to be accounted for…
(depend on exp. cuts and mass of NP)

→ *however, we know that in the QED case*

$$(a_\mu^{\rm HVP})^{\rm FSR}_{e^+e^-} \approx 50 \times 10^{-11} \quad \longleftrightarrow \quad |(a_\mu^{\rm HVP})_{\rm BMW} - (a_\mu^{\rm HVP})^{\rm WP20}_{e^+e^-}| \approx 150 \times 10^{-11}$$

HADRONIC VACUUM POLARIZATION CONTRIBUTION



Ab-initio lattice calculations

Dispersive relations,

$e^+e^- \rightarrow$ hadrons exps.

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

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

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

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)**