The new muon g-2 puzzle:

can the BMW lattice result and low-energy e^+e^- data be reconciled by new physics ?

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Plan of the Talk

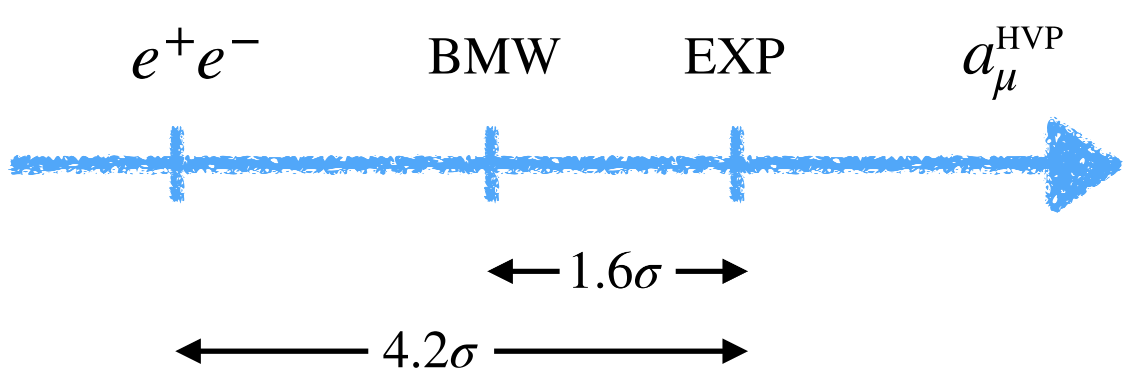
- Status of the muon g-2 as of mid 2022

  - Breakdown of the SM contributions [Courtesy of M. Passera]

  - Hadron Vacuum Polarization (HVP) & the "new g-2 puzzle"

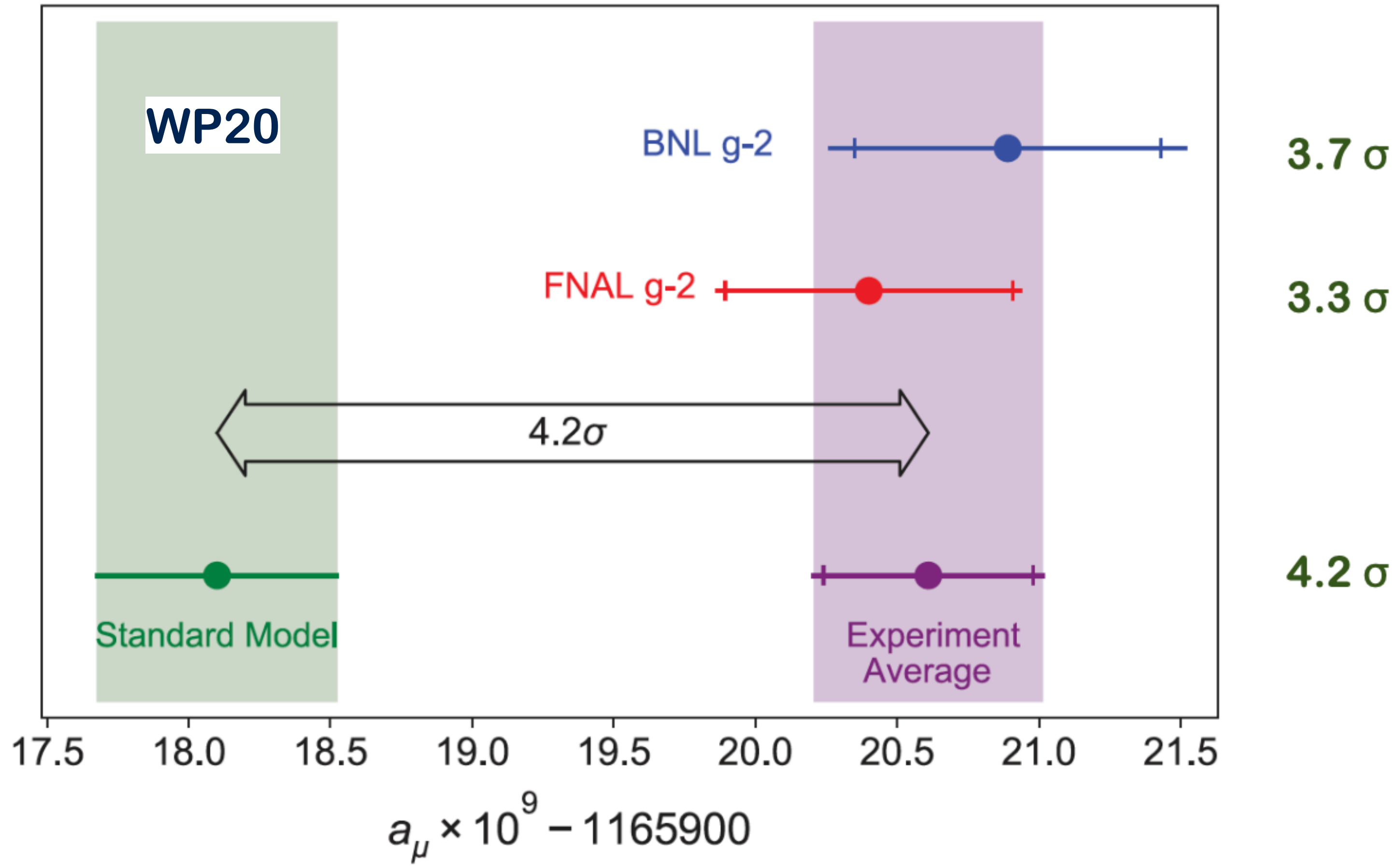
- New physics (NP) behind the "new g-2 puzzle" ? [Based on LDL, Masiero, Paradisi, Passera 2112.08312]

Working assumption: both lattice (BMW) and e^+e^- data are correct → NP hiding in e^+e^- data ?



FNAL confirms BNL

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



a_μ^{EXP} = (116592089 ± 63) x 10^{-11} [0.54ppm] BNL E821

a_μ^{EXP} = (116592040 ± 54) x 10^{-11} [0.46ppm] FNAL E989 Run 1

a_μ^{EXP} = (116592061 ± 41) x 10^{-11} [0.35ppm] WA

- *FNAL aims at* 16×10^{-11} *(first 5 runs completed)*
- *Muon g-2 proposal at J-PARC: Phase-1 with similar BNL precision*

QED contribution

$a_\mu^{\rm QED} = (1/2)\,(\alpha/\pi)$ [Schwinger, 1948]

$+\,0.765857426\,(16)\,(\alpha/\pi)^2$

[Sommerfield; Petermann; Suura&Wichmann '57; Elend '66]

$+\,24.05050988\,(28)\,(\alpha/\pi)^3$

[Remiddi, Laporta, Barbieri...; Czarnecki, Skrzypek '99]

$+\,130.8780\,(60)\,(\alpha/\pi)^4$

[Kinoshita et al. '81-'15; Steinhauser et al. '13-'16; Laporta '17]

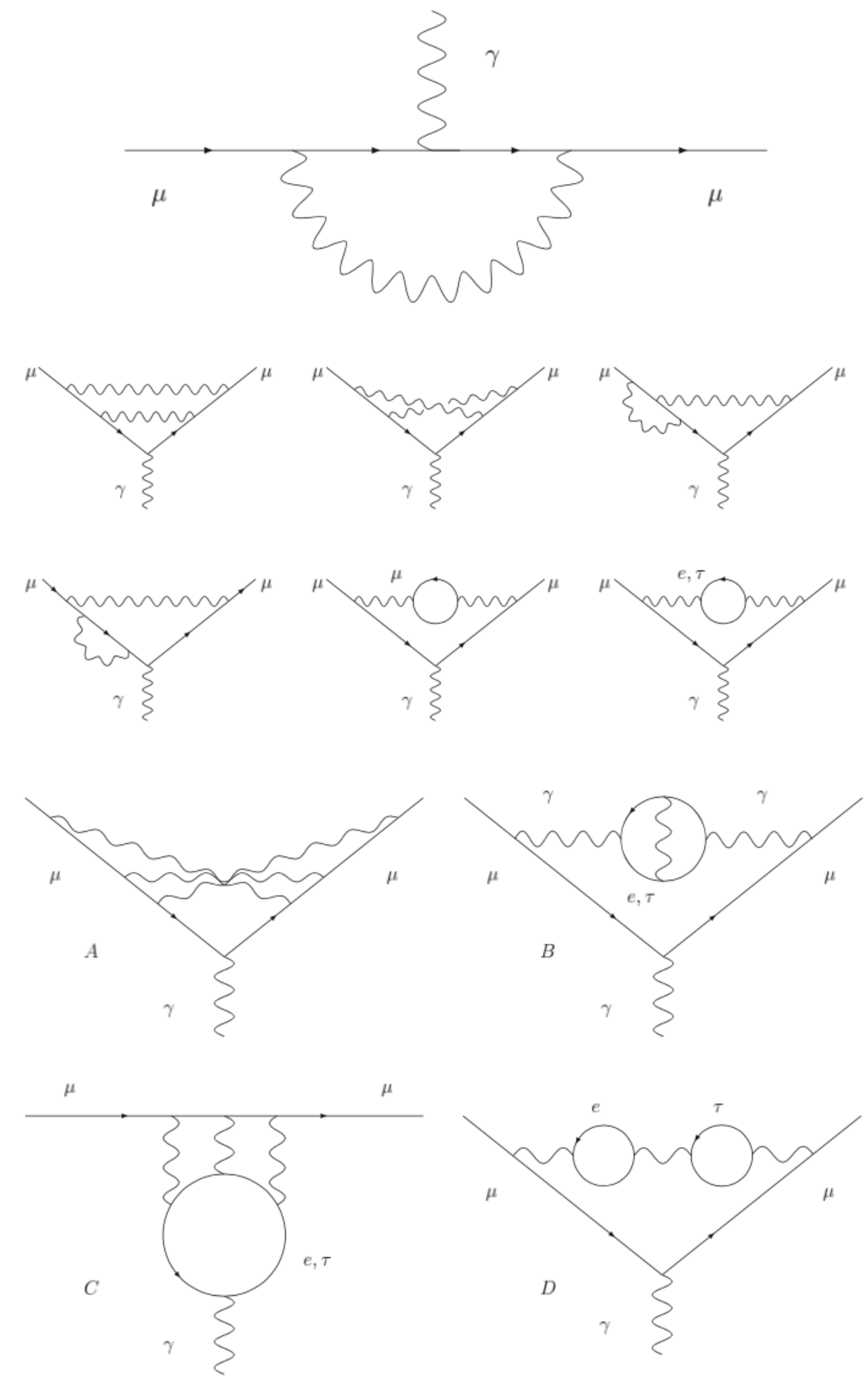
$+\,750.86\,(88)\,(\alpha/\pi)^5$ [Kinoshita et al. '90-'19]

$a_\mu^{\rm QED}$ = 116584718.931 (19)(100)(23) x 10^{-11}

mainly from 4-loop coeff. unc. | 6-loop | from α(Cs)

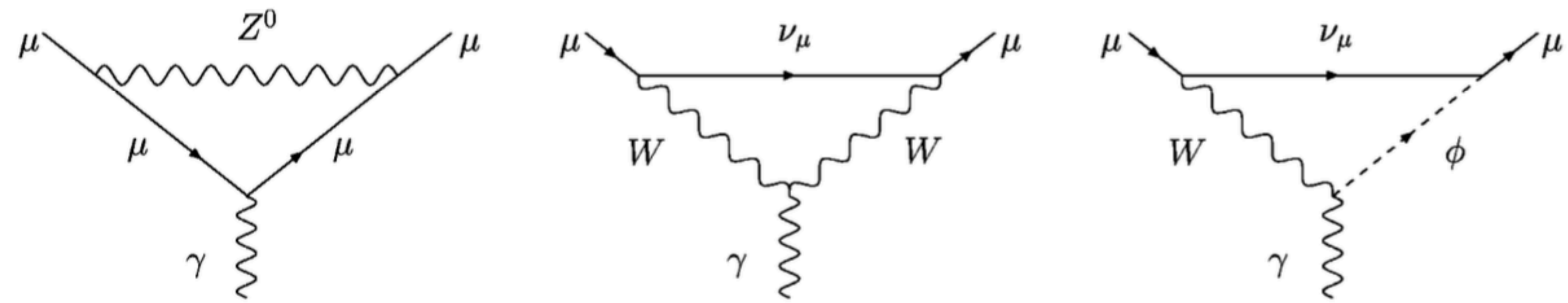
α = 1/137.035999046(27) [0.2ppb] Parker et al 2018 — WP20 value

[WP20 ≡ T. Aoyama *et al.*, Phys. Rept. '20]



EW contribution

- One-loop term



$$a_\mu^{\mathrm{EW}}(\text{1-loop}) = \frac{5 G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1 + \frac{1}{5}\left(1 - 4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

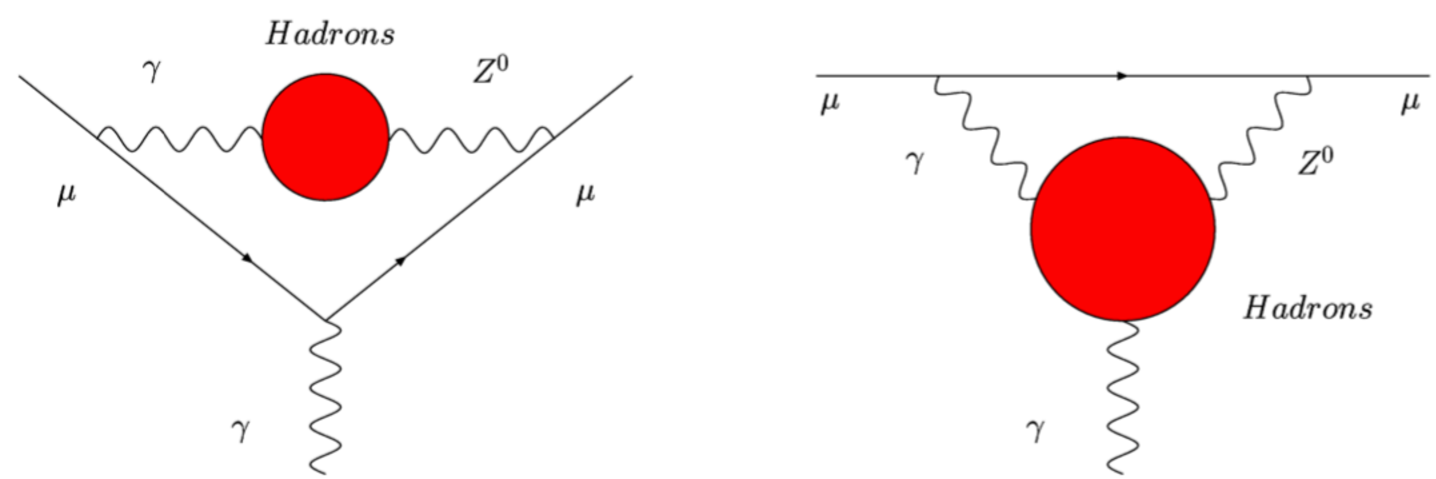
- One-loop plus higher-order terms

a_μ^{EW} = 153.6 (1.0) x 10^{-11}

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa, Yasui, 2019.

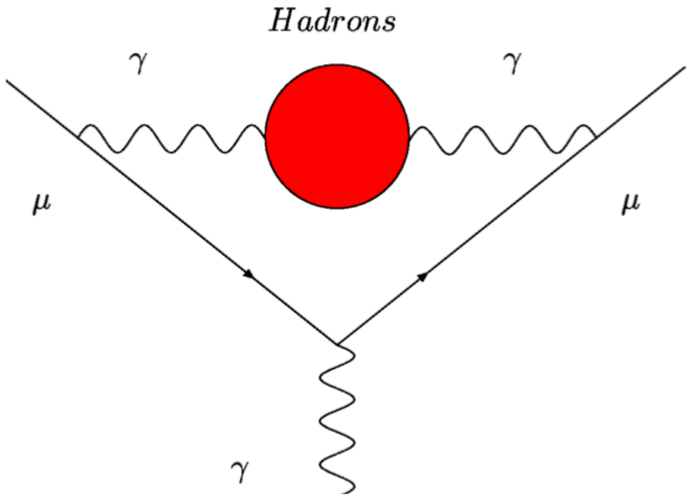
Hadronic loop uncertainties (and 3-loop nonleading logs).

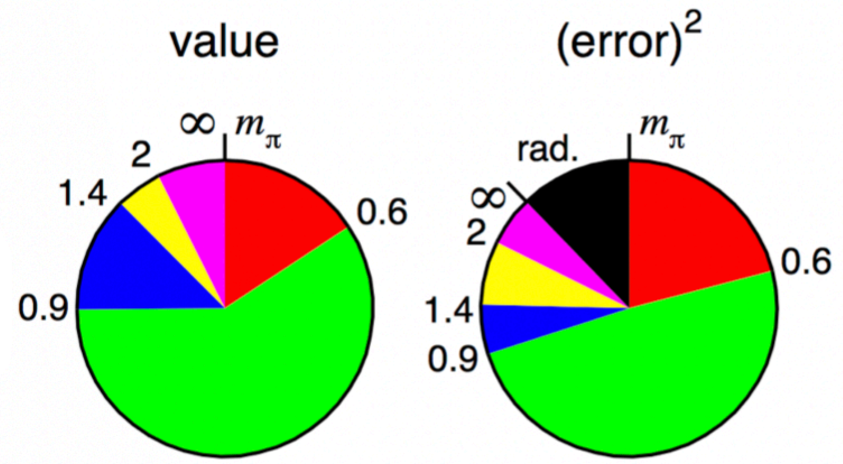
WP20 value



Hadronic LO contribution

- Hadron Vacuum Polarization (HVP)





Keshavarzi, Nomura, Teubner 2018

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

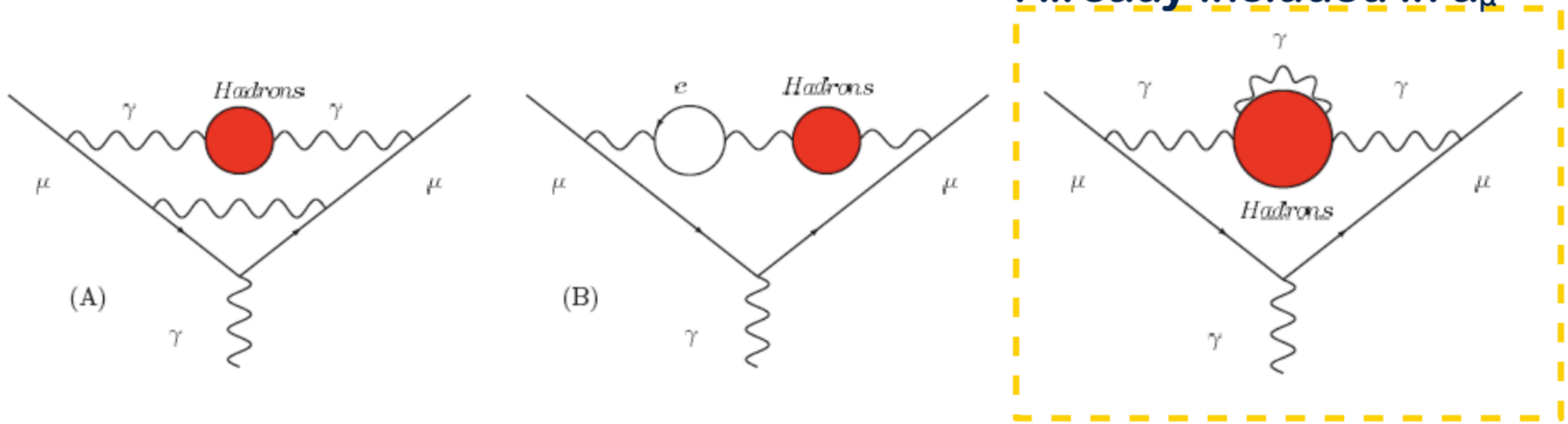
$$(a_\mu^{\rm HVP})_{e^+e^-} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{\rm had}(s) \qquad K(s) \approx m_\mu^2/3s \quad \text{for} \quad \sqrt{s} \gg m_\mu$$

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

Higher-order HVP contribution

- $O(\alpha^3)$ contributions of diagrams containing HVP insertions

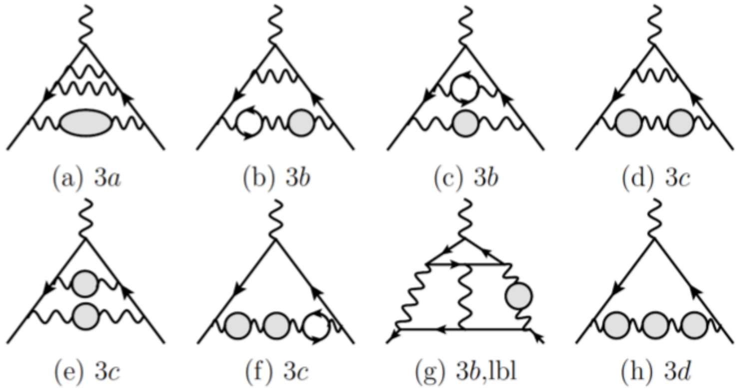
Already included in a_μ^{HLO}



$a_\mu^{HNLO}(vp) = -98.3\ (7) \times 10^{-11}$

Krause '96; Keshavarzi, Nomura, Teubner 2019; WP20.

- $O(\alpha^4)$ contributions of diagrams containing HVP insertions



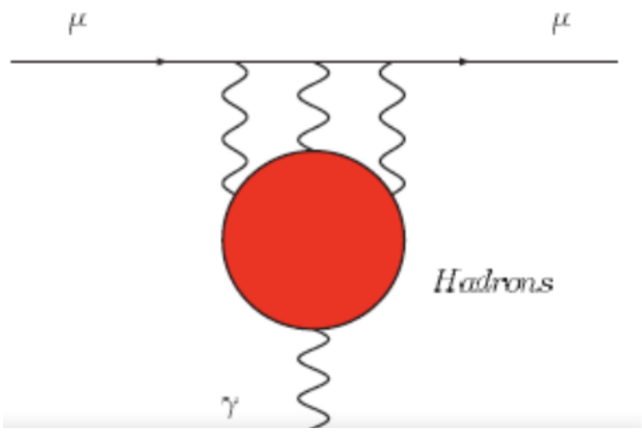
$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$

Kurz, Liu, Marquard, Steinhauser 2014

Hadronic LbL contribution

- Hadronic light-by-light at $O(\alpha^3)$

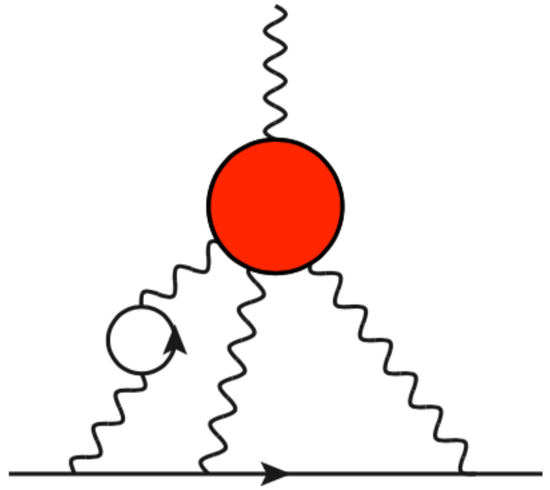
$a_\mu^{HNLO}(lbl) =$	$80\ (40) \times 10^{-11}$	Knecht & Nyffeler '02
$=$	$136\ (25) \times 10^{-11}$	Melnikov & Vainshtein '03
$=$	$105\ (26) \times 10^{-11}$	Prades, de Rafael, Vainshtein '09
$=$	$100\ (29) \times 10^{-11}$	Jegerlehner, arXiv:1705.00263
$=$	$92\ (19) \times 10^{-11}$	WP20 (phenomenology)



- Hadronic light-by-light at $O(\alpha^4)$

$$a_\mu^{HNNLO}(lbl) = 2\ (1) \times 10^{-11}$$

Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014; WP20



Breakdown of SM contributions

- a_μ from WP20 (w/o BMWc lattice result)

[Colangelo EPS-HEP2021 proceeding]

Contribution	Value $\times 10^{11}$	References
Experiment (E821)	116 592 089(63)	Ref. [3]
Experiment (FNAL)	116 592 040(54)	Ref. [1]
Experiment (World-Average)	116 592 061(41)	
HVP LO (e^+e^-)	6931(40)	Refs. [6–11]
HVP NLO (e^+e^-)	−98.3(7)	Ref. [11]
HVP NNLO (e^+e^-)	12.4(1)	Ref. [12]
HVP LO (lattice, *udsc*)	7116(184)	Refs. [13–21]
HLbL (phenomenology)	92(19)	Refs. [22–34]
HLbL NLO (phenomenology)	2(1)	Ref. [35]
HLbL (lattice, *uds*)	79(35)	Ref. [36]
HLbL (phenomenology + lattice)	90(17)	
QED	116 584 718.931(104)	Refs. [37, 38]
Electroweak	153.6(1.0)	Refs. [39, 40]
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)	
HLbL (phenomenology + lattice + NLO)	92(18)	
Total SM Value	116 591 810(43)	
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	251(59)	

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Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	251(59)	

→ HVP LO is the bottle-neck of the SM prediction

Breakdown of SM contributions

- a_μ from WP20 (w/o BMWc lattice result)

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} = 251\,(59) \times 10^{-11} \qquad \text{(4.2}\sigma\text{ discrepancy!)}$$

$$\underbrace{(0.1)_{\rm QED}\,, \quad (1)_{\rm EW}\,, \quad (18)_{\rm HLbL}\,, \quad (40)_{\rm HVP}\,,}_{(43)_{\rm TH}} \quad (41)_{\delta a_\mu^{\rm EXP}}\,.$$

($\delta a_\mu^{\rm EXP} \approx 16 \times 10^{-11}$ by the E989 Muon g-2 exp. in a few years)

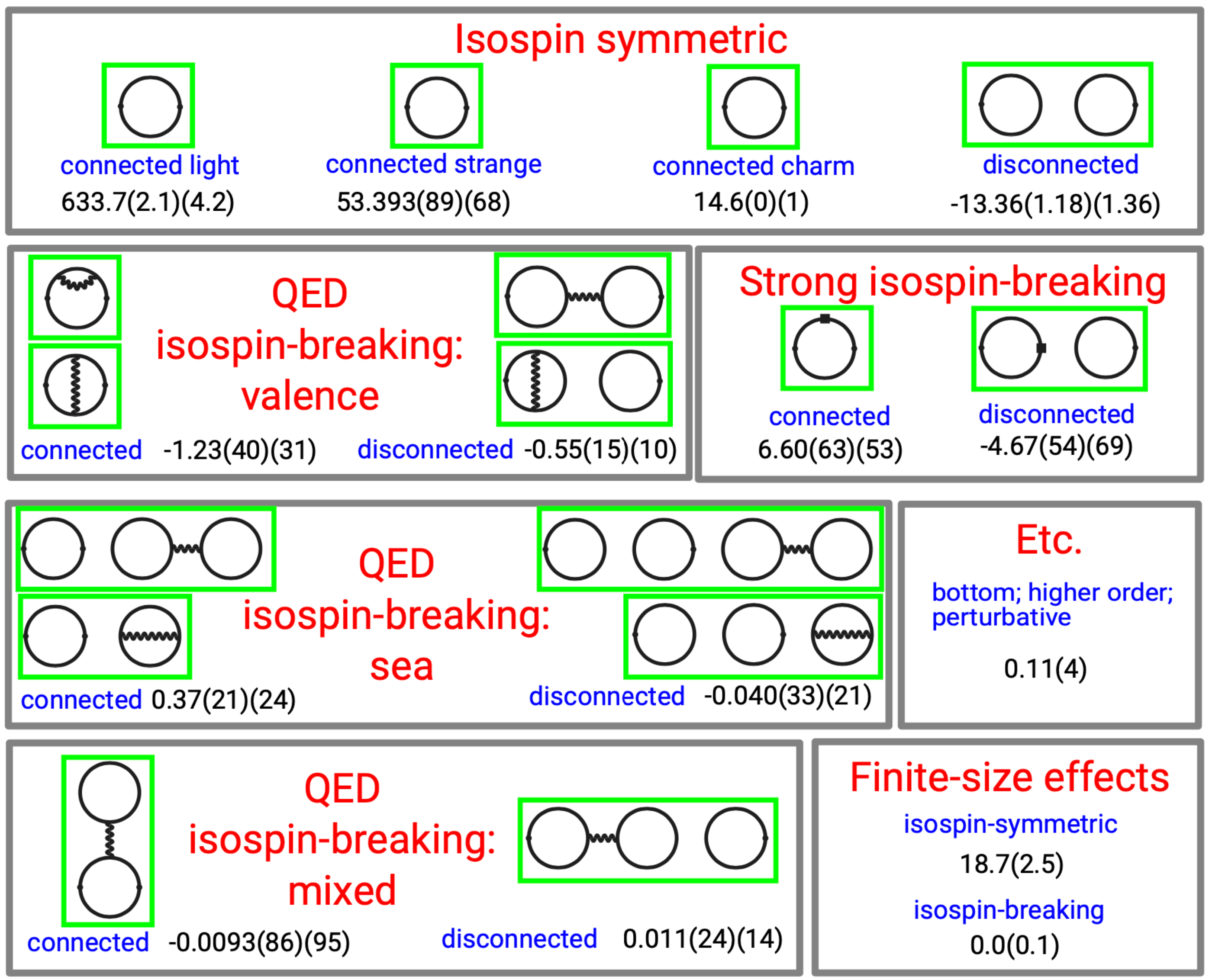
→ HVP LO is the bottle-neck of the SM prediction

LO HVP from lattice QCD

Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision:

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

55

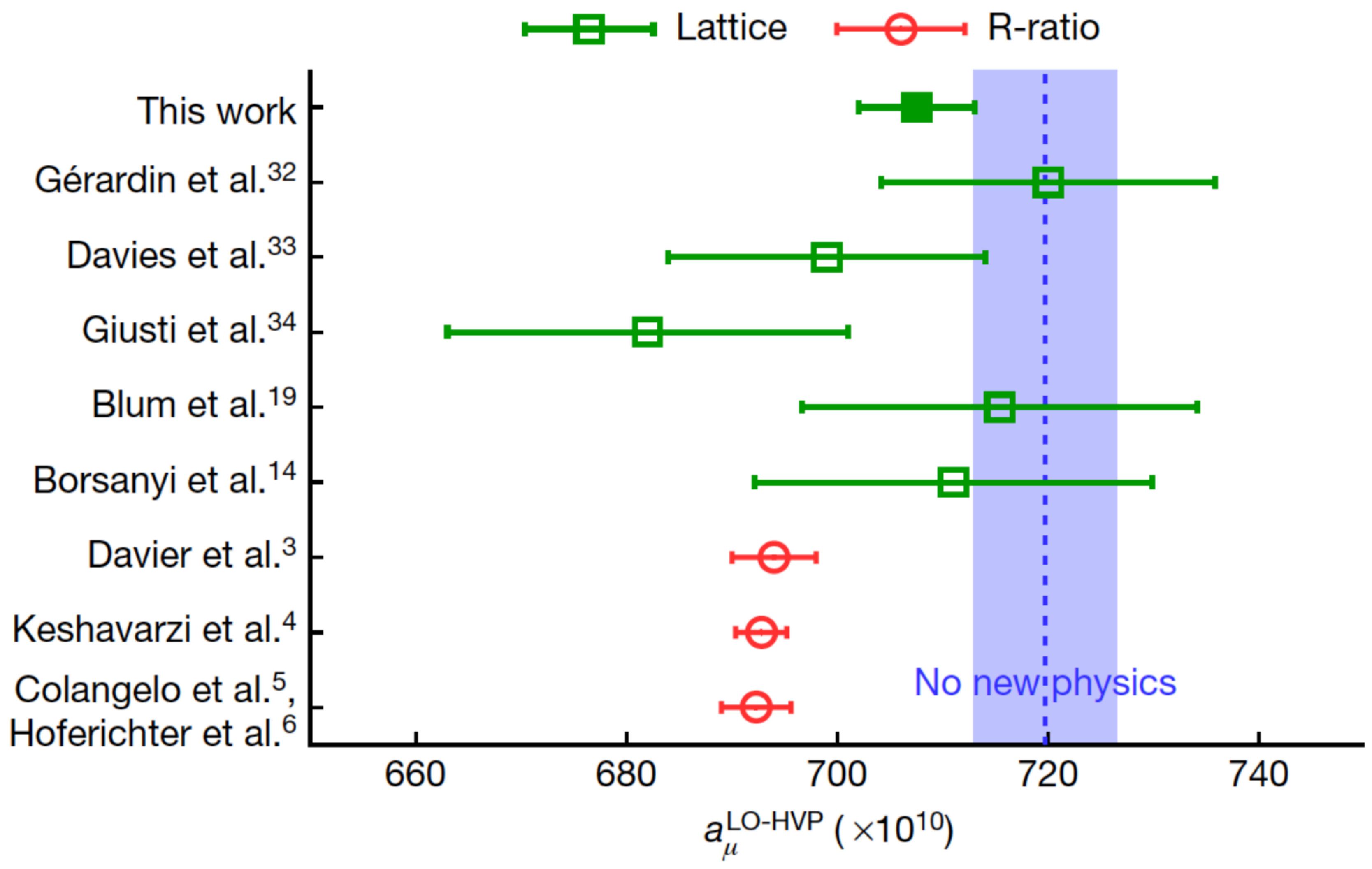


$10^{10} \times a_\mu^{LO\text{-}HVP} = 707.5(2.3)_{stat}(5.0)_{sys}[5.5]_{tot}$

Borsanyi et al (BMWc), Nature 2021

LO HVP from lattice QCD

Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision:
$a_\mu^{HLO} = 7075\underbrace{(23)_{stat}(50)_{syst}}_{55} \times 10^{-11}$. Some tension with dispersive evaluations. BMWc 2021

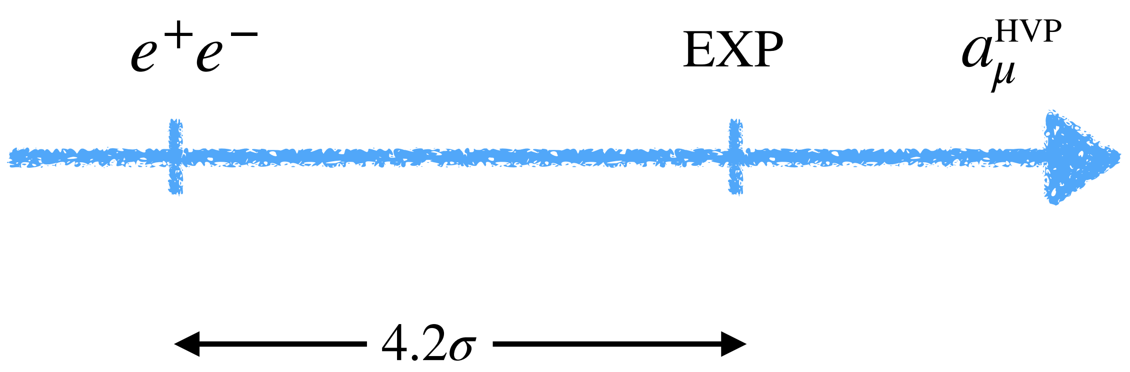


Borsanyi et al (BMWc), Nature 2021

"old vs. new" muon g-2 puzzle

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

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



“old vs. new” muon g-2 puzzle

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

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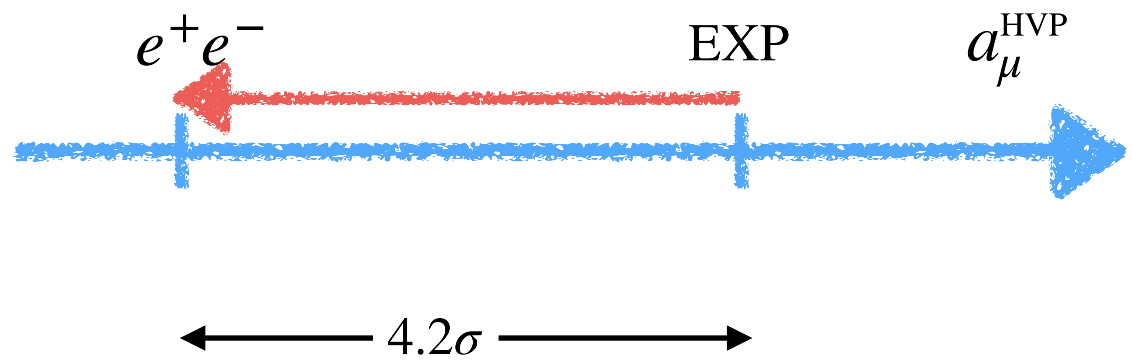


“old puzzle”: a direct NP contribution to a_μ *is required in order to match the EXP value*

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} \equiv a_\mu^{\rm NP} \approx (a_\mu^{\rm SM})_{\rm EW} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 200 \times 10^{-11}$$

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

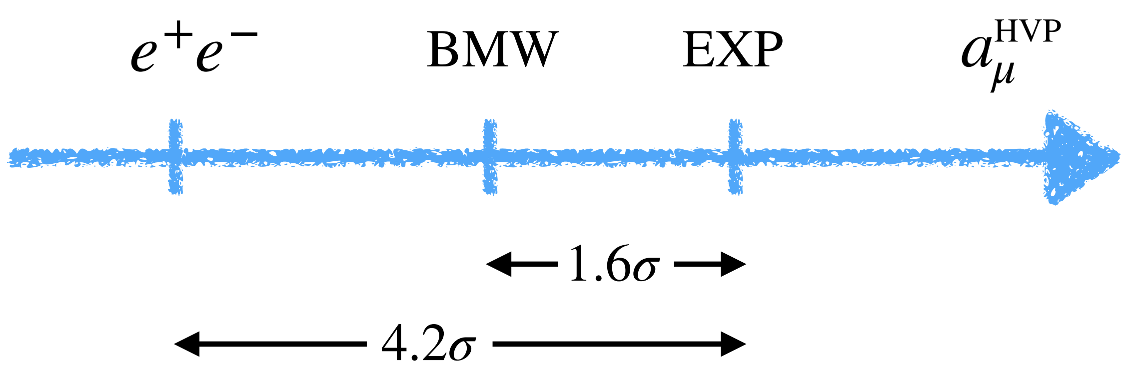
O(few x 100) papers

"old vs. new" muon g-2 puzzle

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

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

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



"new puzzle": if BMW is correct, the "old" g-2 discrepancy (4.2σ) would be basically gone

→ *however, this brings in a new tension with e^+e^- data (2.2σ)*

"old vs. new" muon g-2 puzzle

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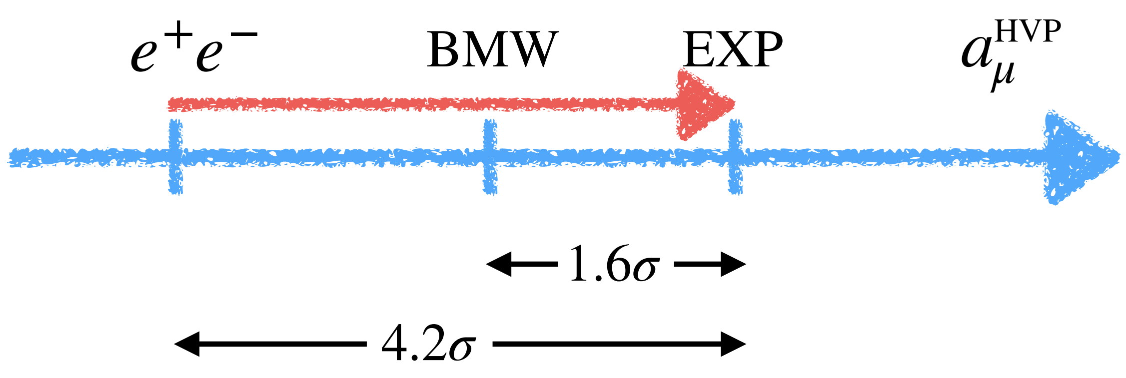


"new puzzle": if BMW is correct, the "old" g-2 discrepancy (4.2σ) would be basically gone

→ *however, this brings in a new tension with e^+e^- data (2.2σ)*

Here, NP in $\sigma_{\rm had}(e^+e^- \to \text{hadrons})$ such that [LDL, Masiero, Paradisi, Passera 2112.08312]

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)

Muon g-2 $\rightleftarrows$ $\Delta\alpha$ connection

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

[Marciano, Passera, Sirlin 0804.1142 & 1001.4528; Crivellin, Hoferichter, Manzari, Montull 2003.04886; Keshavarzi, Marciano, Passera, Sirlin 2006.12666; de Rafael 2006.13880; Malaescu, Schott 2008.08107; Colangelo, Hoferichter, Stoffer 2010.07943]

Muon g-2 $\rightleftarrows$ $\Delta\alpha$ connection

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

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

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

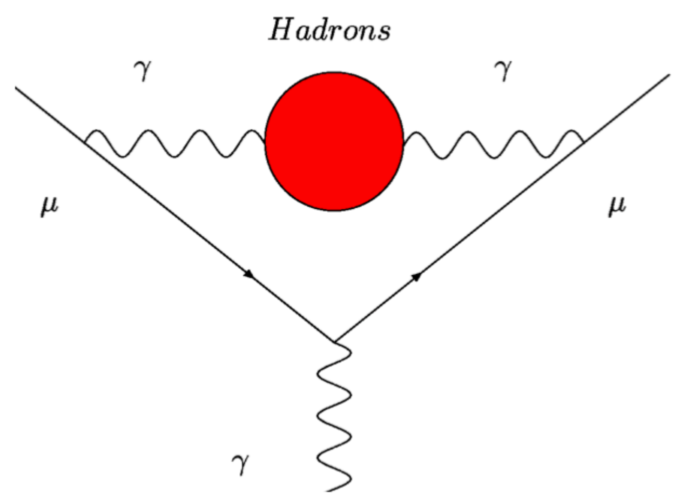
$$a_\mu^{\rm HLO} \simeq \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{s}\,, \qquad \Delta\alpha^{(5)}_{\rm had} = \frac{M_Z^2}{4\pi\alpha^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{\sigma(s)}{M_Z^2 - s}$$

- disfavoured by the EW fit (at about 2σ), if the shift happens at $\sqrt{s} \gtrsim 1\,{\rm GeV}$

→ *selects light NP inducing a sub-GeV modification of* $\sigma_{\rm had}$

A closer look at HVP LO

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



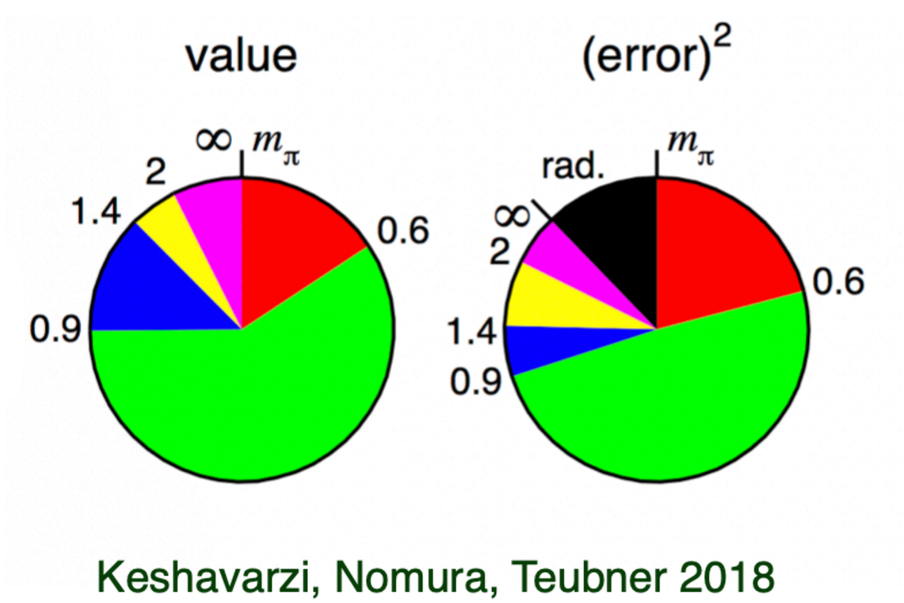
$$(a_\mu^{\rm HVP})_{e^+e^-} = \frac{\alpha}{\pi^2}\int_{m_{\pi^0}^2}^{\infty} \frac{ds}{s} K(s)\,{\rm Im}\,\Pi_{\rm had}(s) = \frac{1}{4\pi^3}\int_{m_{\pi^0}^2}^{\infty} ds\, K(s)\sigma_{\rm had}(s)$$

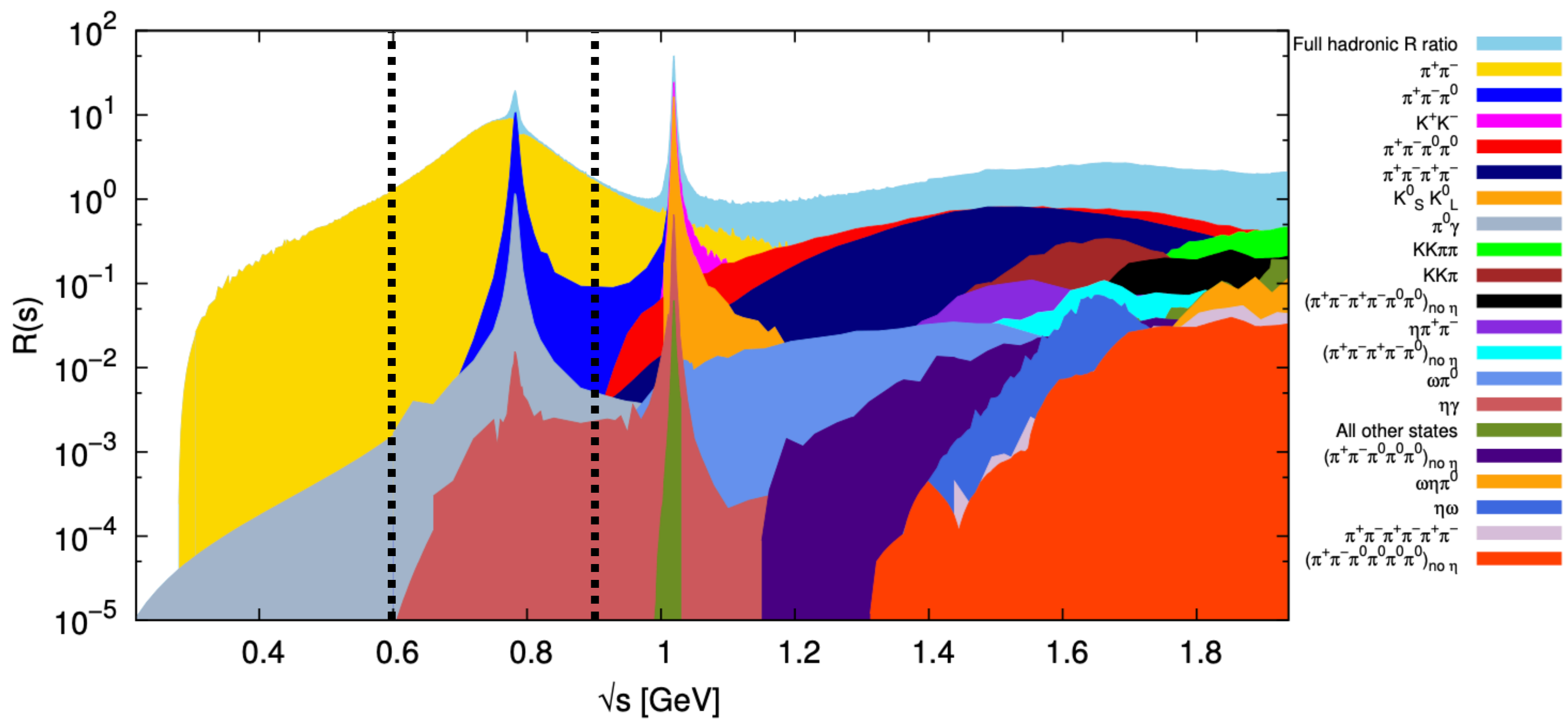
dispersion relations

optical theorem

kernel function

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





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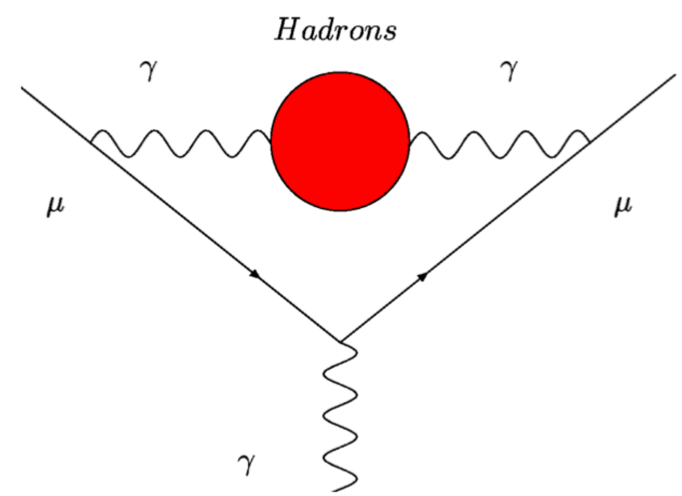
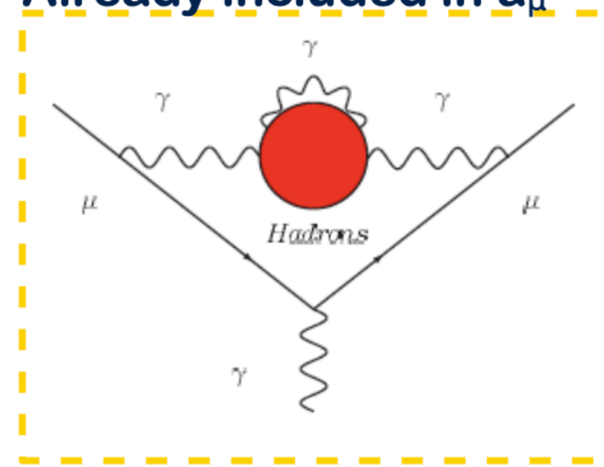


- what is $\sigma_{\rm had}(s)$?

  - Includes Final State Radiation (FSR)

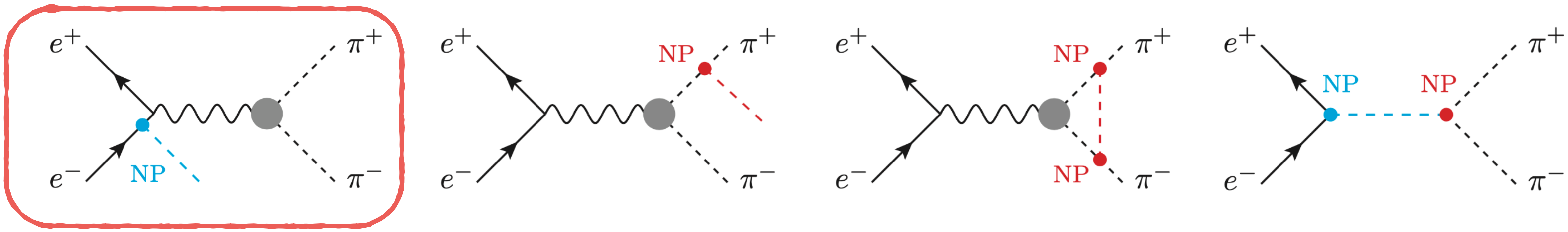
  - Initial State Radiation (ISR) and Vacuum Polarization are subtracted

Already included in a_μ^{HLO}



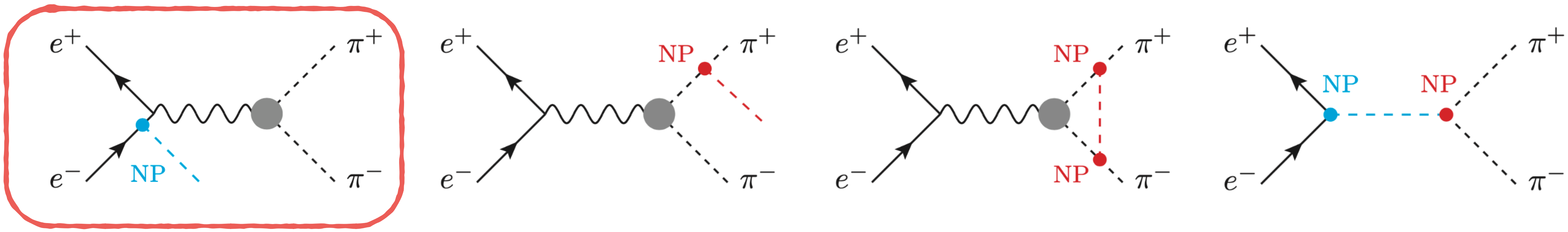
$$(a_\mu^{\rm HVP})^{\rm FSR}_{e^+e^-} \approx 50 \times 10^{-11}$$

Light NP in σ_{had}



1. NP coupled only to electrons → severe bounds / ISR should not be included into $\sigma_{\text{had}}(s)$

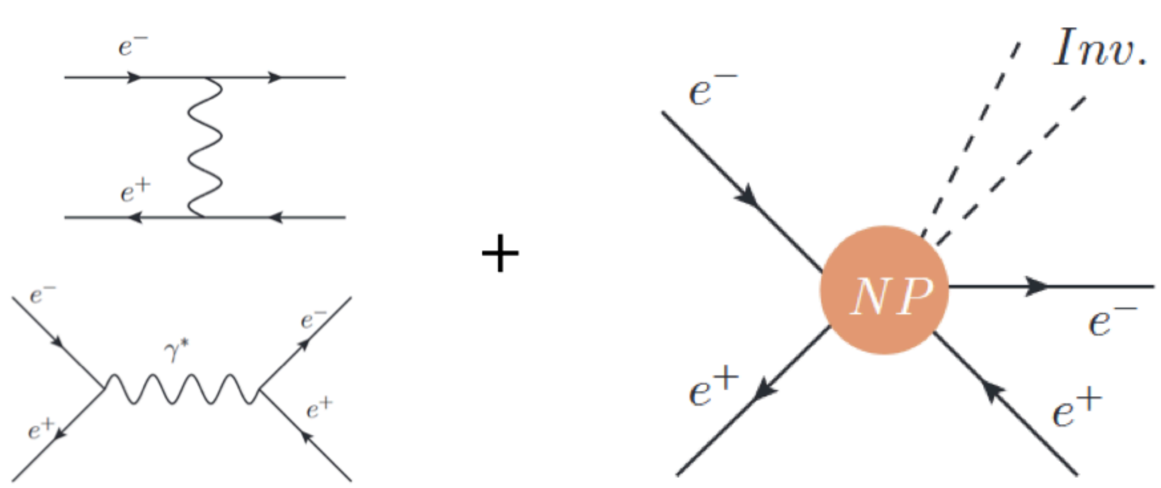
Light NP in σ_{had}



1. NP coupled only to electrons → severe bounds / ISR should not be included into $\sigma_{\text{had}}(s)$

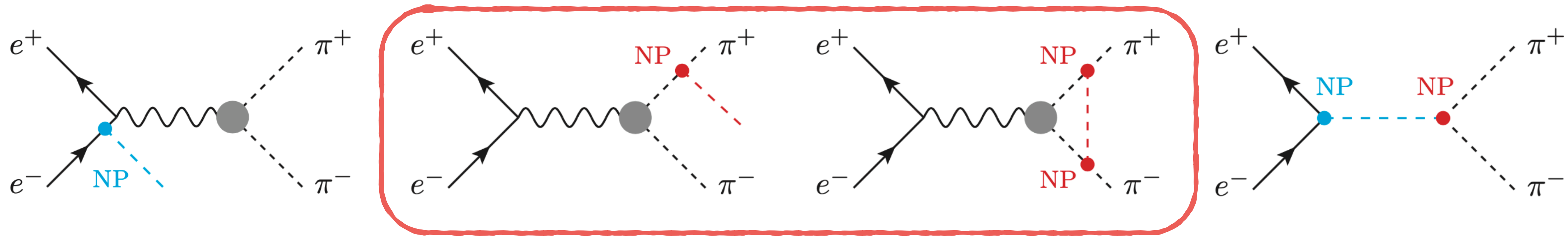
[See however Darmé, Grilli di Cortona, Nardi 2112.09139
can NP in Bhabha scattering affect KLOE luminosity ? → backup slides]

Use Bhabha scattering $e^+e^- \to e^+e^-$



[Darmé ICHEP 2022]

Light NP in $\sigma_{\rm had}$



2. NP coupled only to hadrons

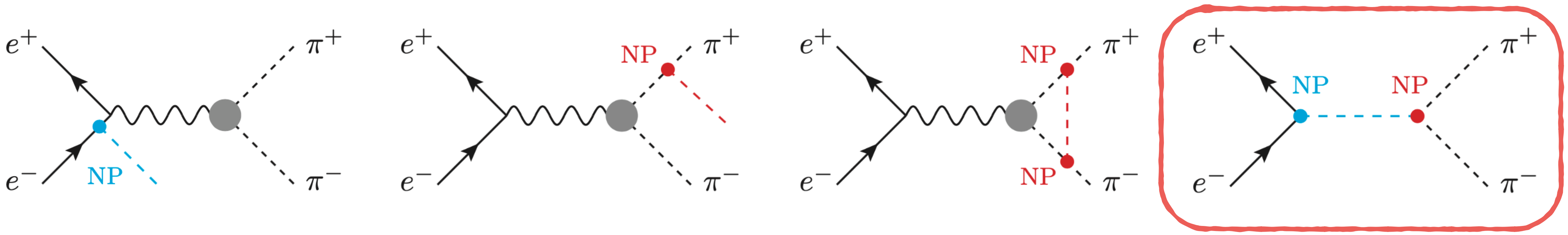
FSR effects due to NP should be included into $\sigma_{\rm had}(s)$*, not easy to be accounted for…*
(depend on exp. cuts and mass of NP)

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

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

and, moreover, we expect an extra $(g_{\rm NP}/e)^2 \ll 1$ *suppression*

Light NP in $\sigma_{\rm had}$



3. NP coupled both to hadrons and electrons

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

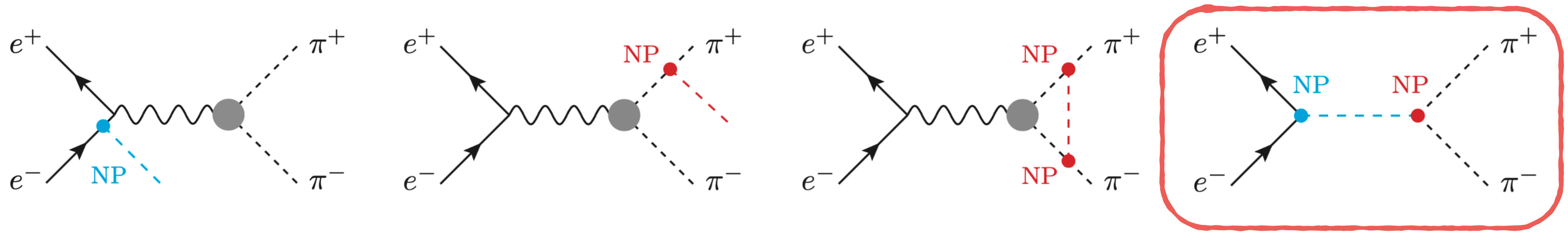
$$\sigma_{\rm had} = \sigma_{\rm had}^{\rm SM} + \Delta\sigma_{\rm had}^{\rm NP}$$

optical theorem

experimental x-section

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

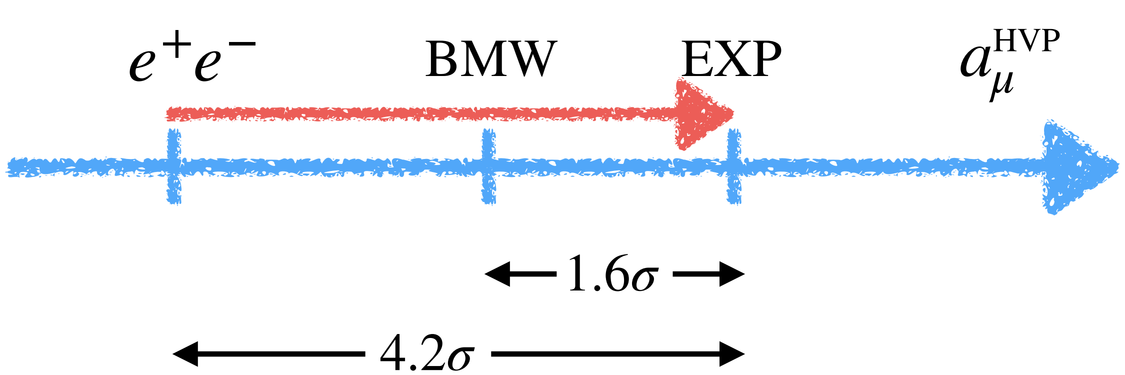
Light NP in $\sigma_{\rm had}$



3. NP coupled both to hadrons and electrons

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

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



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

should be "subtracted" by NP,
since NP does not contribute to HVP at the LO
(but it contributes at the LO to the x-section)

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

Basically, a unique scenario

- Requirements:

1. σ_{had} modified at $\sqrt{s} \lesssim 1\,\text{GeV}$ (mostly $\pi^+\pi^-$ channel) → sub-GeV mediator; → couples to u, d quarks (and electrons)
2. A sizeable negative interference with the SM
   - sizeable → tree-level mediator
   - negative interference → couples via a vector current

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

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

Z' shift on $(a_\mu^{\rm HVP})_{e^+e^-}$

- Neglecting iso-spin breaking corrections due to NP

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

- Requiring that the shift in the x-section saturates the g-2 discrepancy

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

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

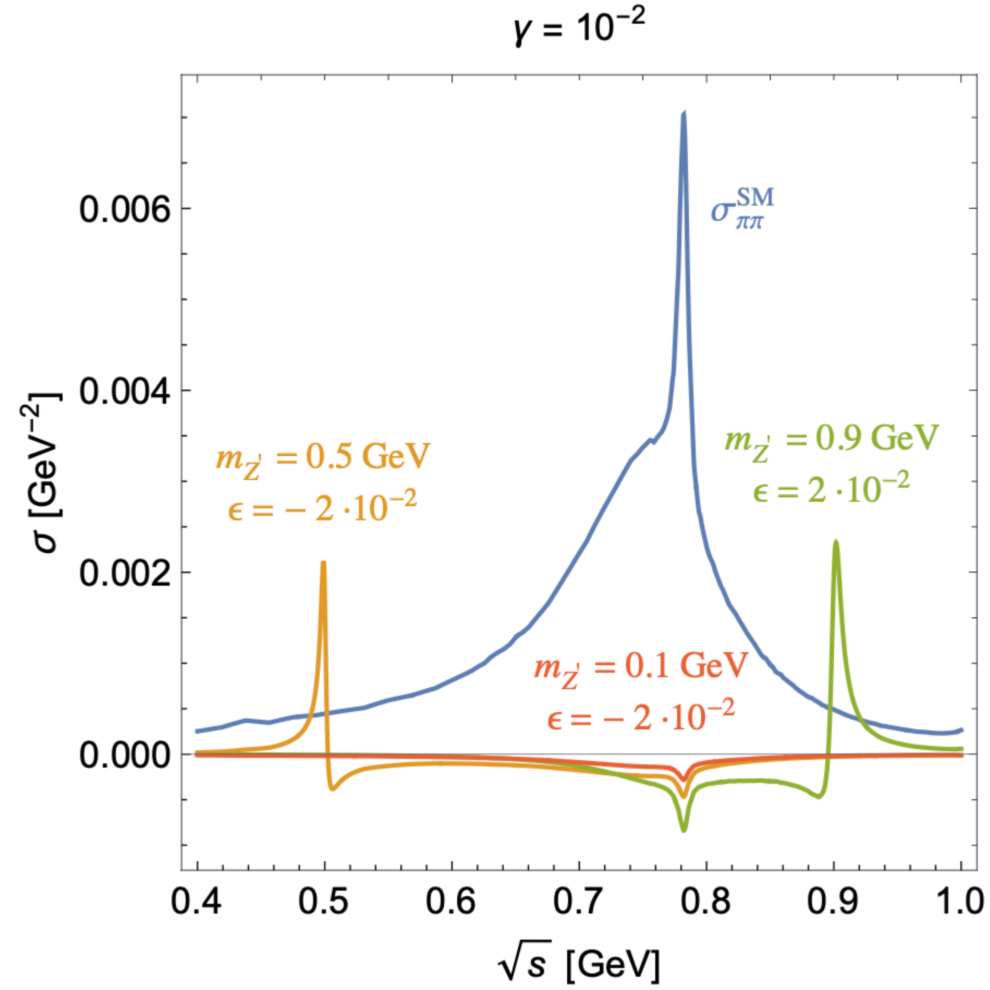
$$\Delta\sigma_{\rm had}^{\rm NP}(s) \approx \sigma_{\pi\pi}^{\rm SM}(s) \times \frac{2\epsilon s (s - m_{Z'}^2) + \epsilon^2 s^2}{(s - m_{Z'}^2)^2 + m_{Z'}^4 \gamma^2}$$

$$\epsilon \equiv g_V^e (g_V^u - g_V^d)/e^2$$

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

Z' shift on $(a_\mu^{\rm HVP})_{e^+e^-}$

- Typical benchmarks solving the g-2 discrepancy



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

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$$\epsilon \equiv g_V^e(g_V^u - g_V^d)/e^2$$

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

Z' constraints

1. Semi-leptonic processes

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

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

Z' constraints

1. Semi-leptonic processes

2. Leptonic processes

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

Z' constraints

1. Semi-leptonic processes

2. Leptonic processes

3. Iso-spin breaking observables

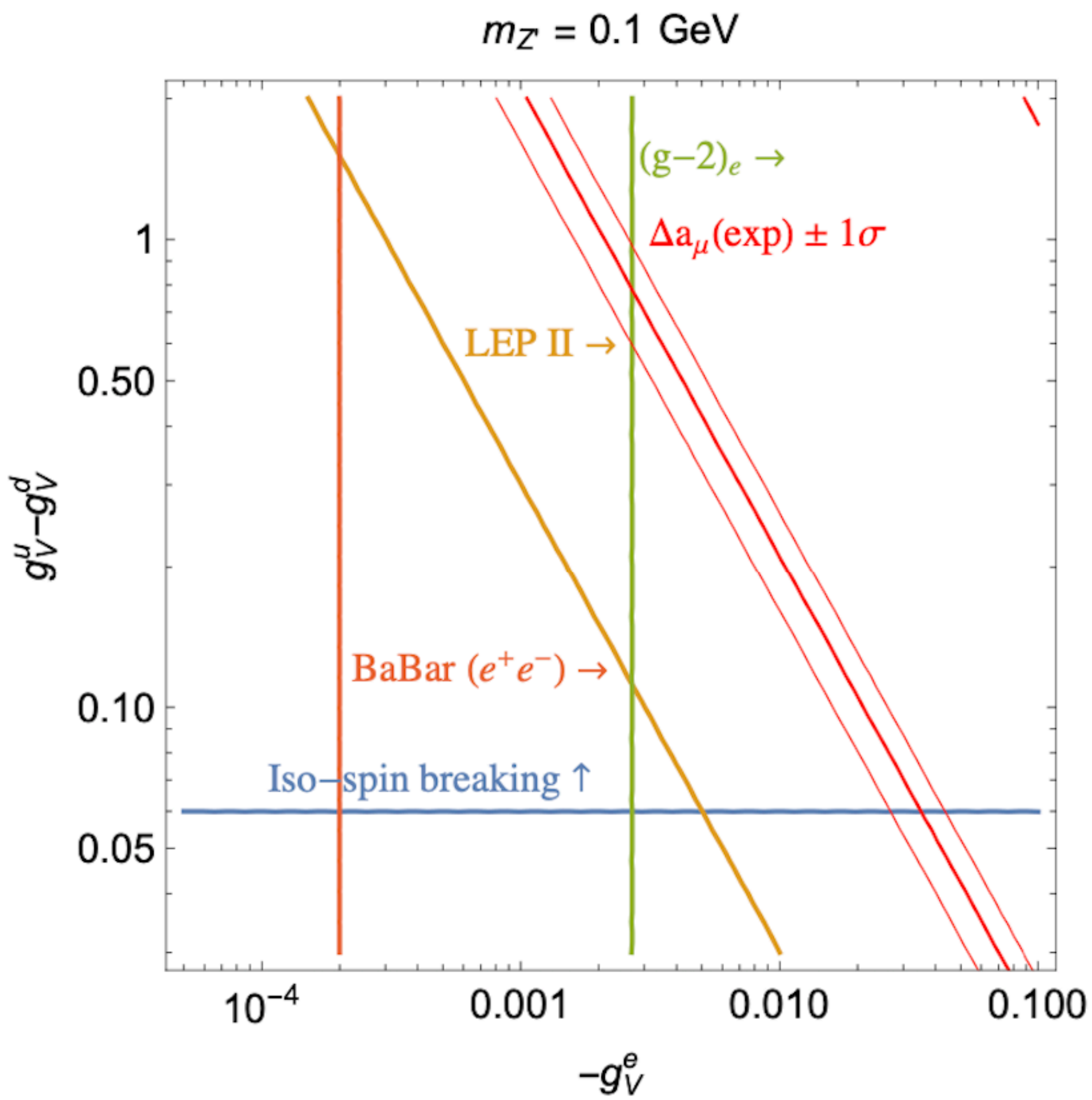
charged vs. neutral pion mass^2 difference $\Delta m^2 = m^2_{\pi^+} - m^2_{\pi^0}$

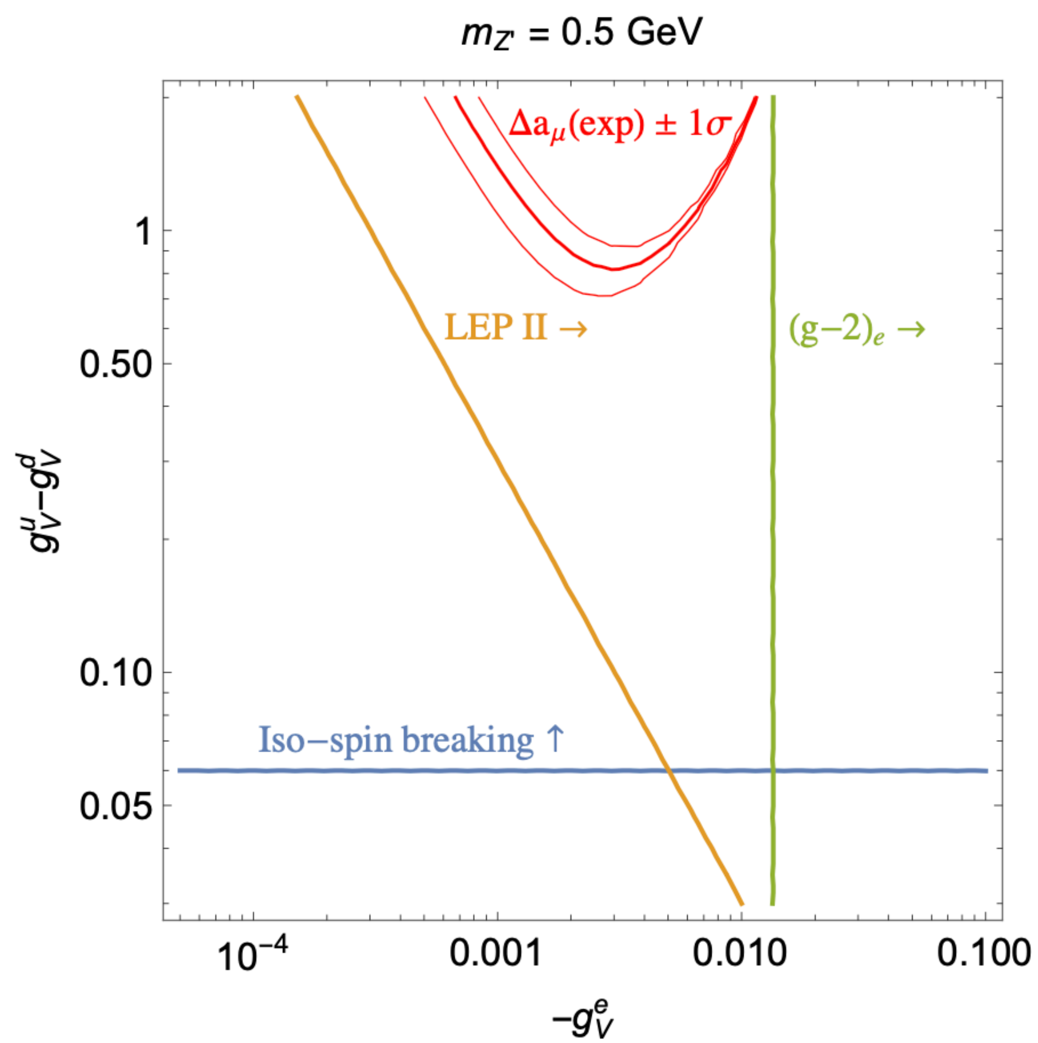
$$(\Delta m^2)_{Z'} \sim \frac{(g_V^u - g_V^d)^2}{(4\pi)^2} \Lambda_\chi^2 \qquad (\Lambda_\chi \approx 1 \text{ GeV})$$

→ $\left| g_V^u - g_V^d \right| \lesssim 0.06$ [Rescaling lattice QCD calculation of Frezzotti et al 2112.01066]

Z' constraints

$\sqrt{s_{\rm exp}} \approx 0.3$ GeV



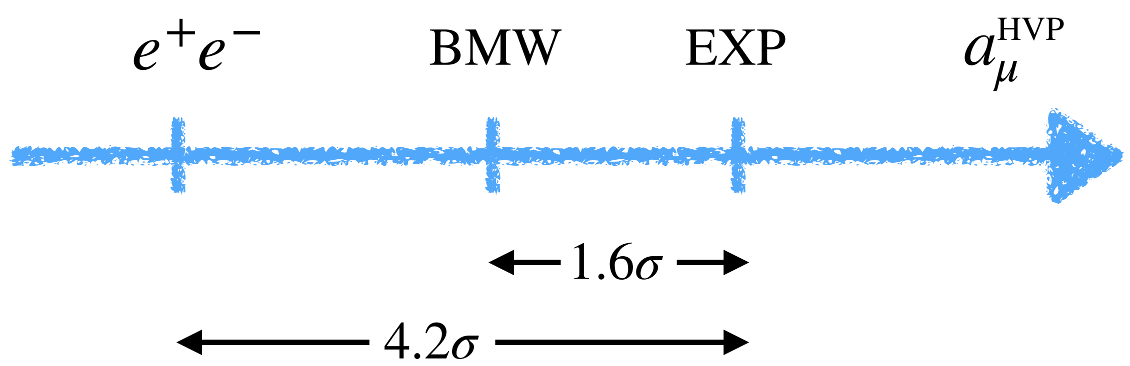


→ *at least two independent bounds preventing to solve the "new muon g-2 puzzle"*

Conclusions

- Fermilab's Muon g-2 experiment confirms BNL's result
- The BMWc lattice result weakens the exp-SM discrepancy, but brings in a tension with e^+e^- data

→ *"new muon g-2 puzzle"*



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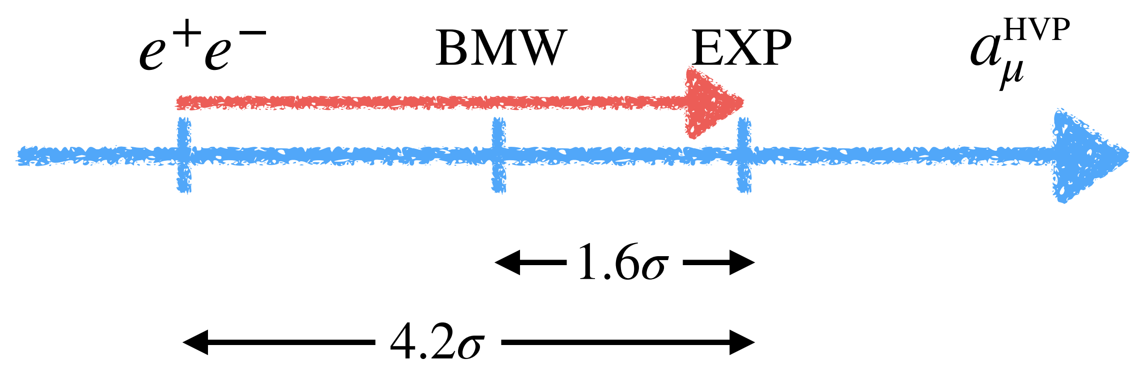

- Here, we considered the possibility this is due to NP (not in muons) that modifies $\sigma_{\rm had}$

→ *excluded by a number of exp. constraints*

Conclusions

- Fermilab's Muon g-2 experiment confirms BNL's result

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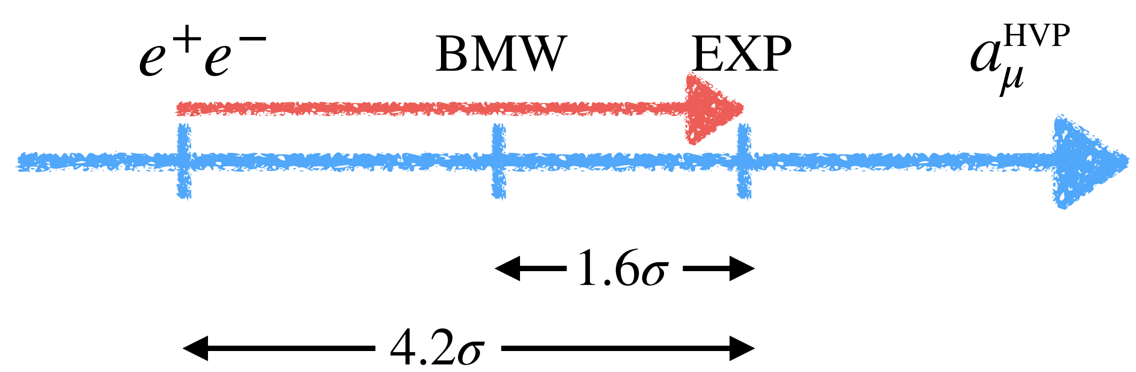


- Here, we considered the possibility this is due to NP (not in muons) that modifies $\sigma_{\rm had}$

→ *excluded by a number of exp. constraints*

other ways in which NP can address this puzzle ? → [Darmé, Grilli di Cortona, Nardi 2112.09139
NP in Bhabha scattering ? → backup slides]

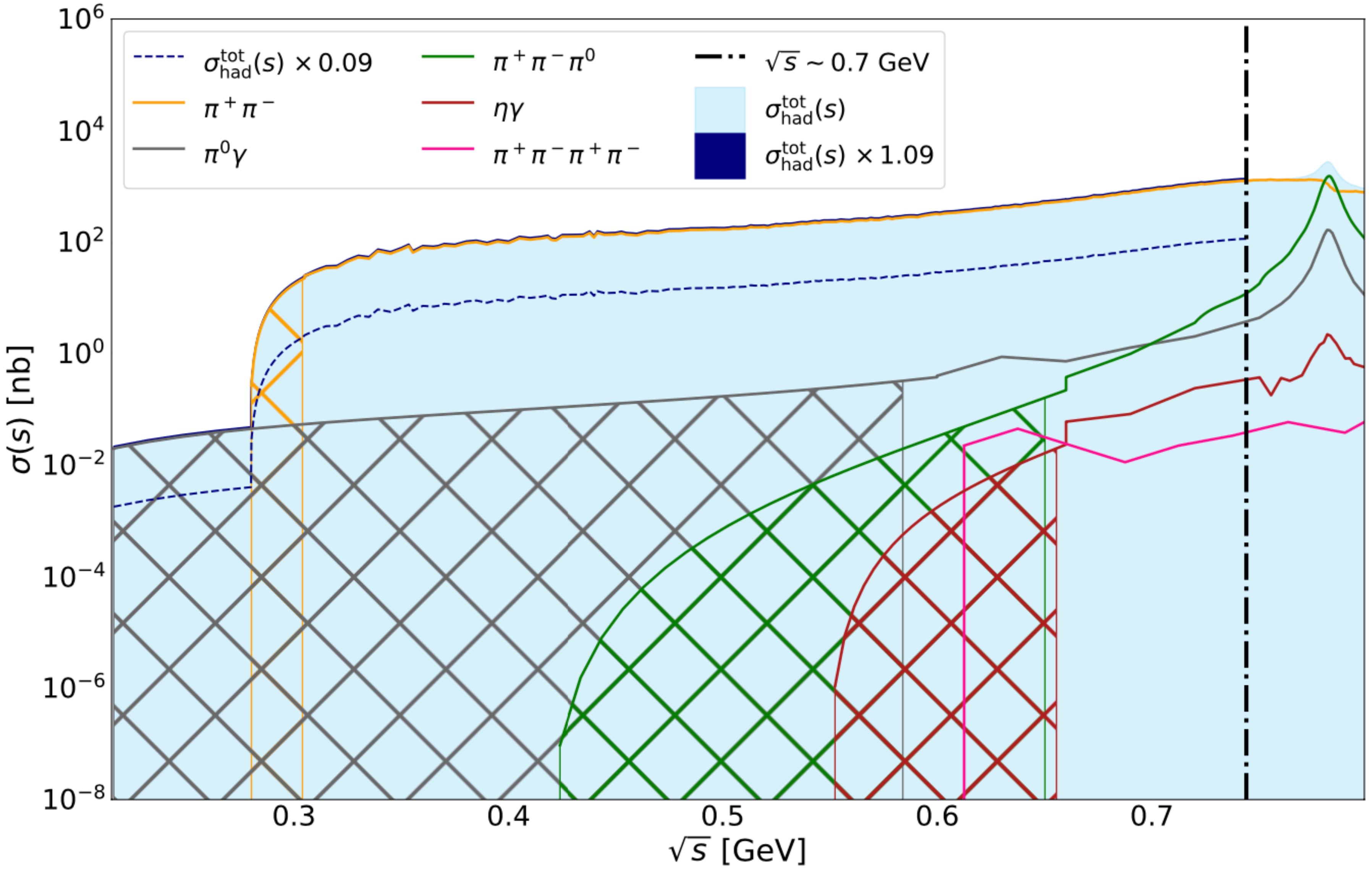
- Alternative confirmations of HVP contribution will be crucial (lattice, MUonE, …)

Backup slides

Thank you for your attention !

σ_{had}: theory vs exp. region

[Keshavarzi, Marciano, Passera, Sirlin 2006.12666]



σ_{had} data

[WP20, 2006.04822]

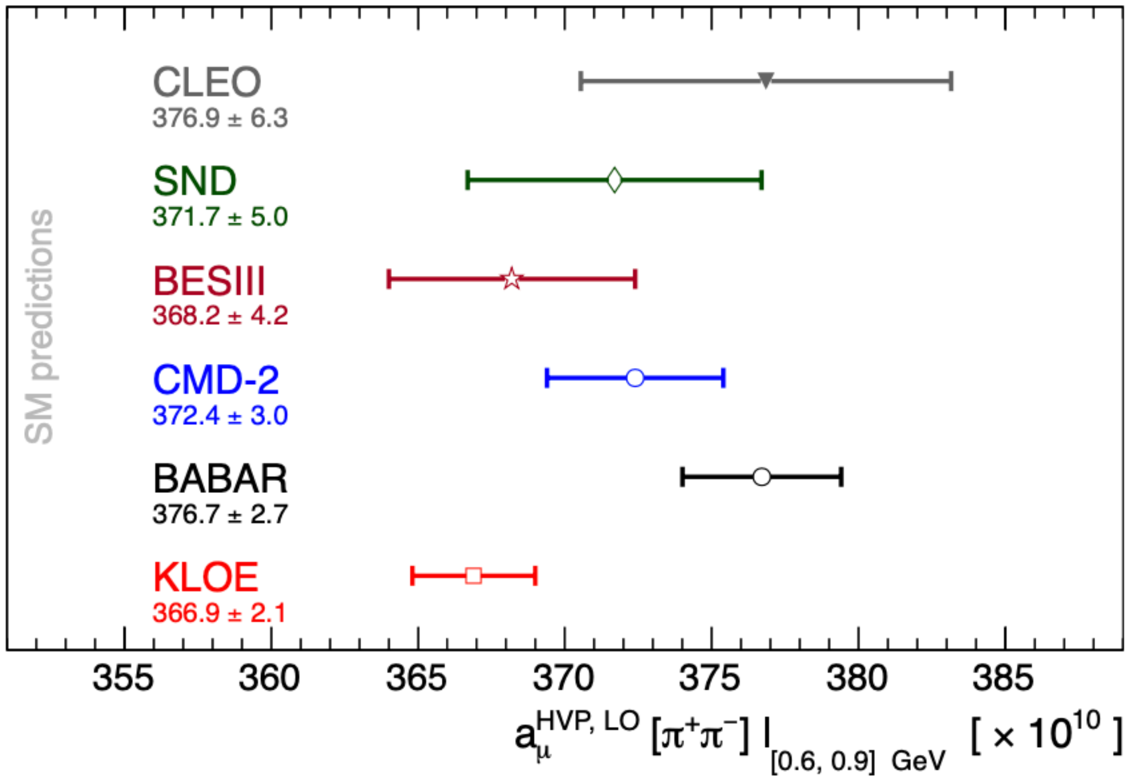


Figure 15: Comparison of results for $a_\mu^{\text{HVP, LO}}[\pi\pi]$, evaluated between 0.6 GeV and 0.9 GeV for the various experiments.

σ_{had} data

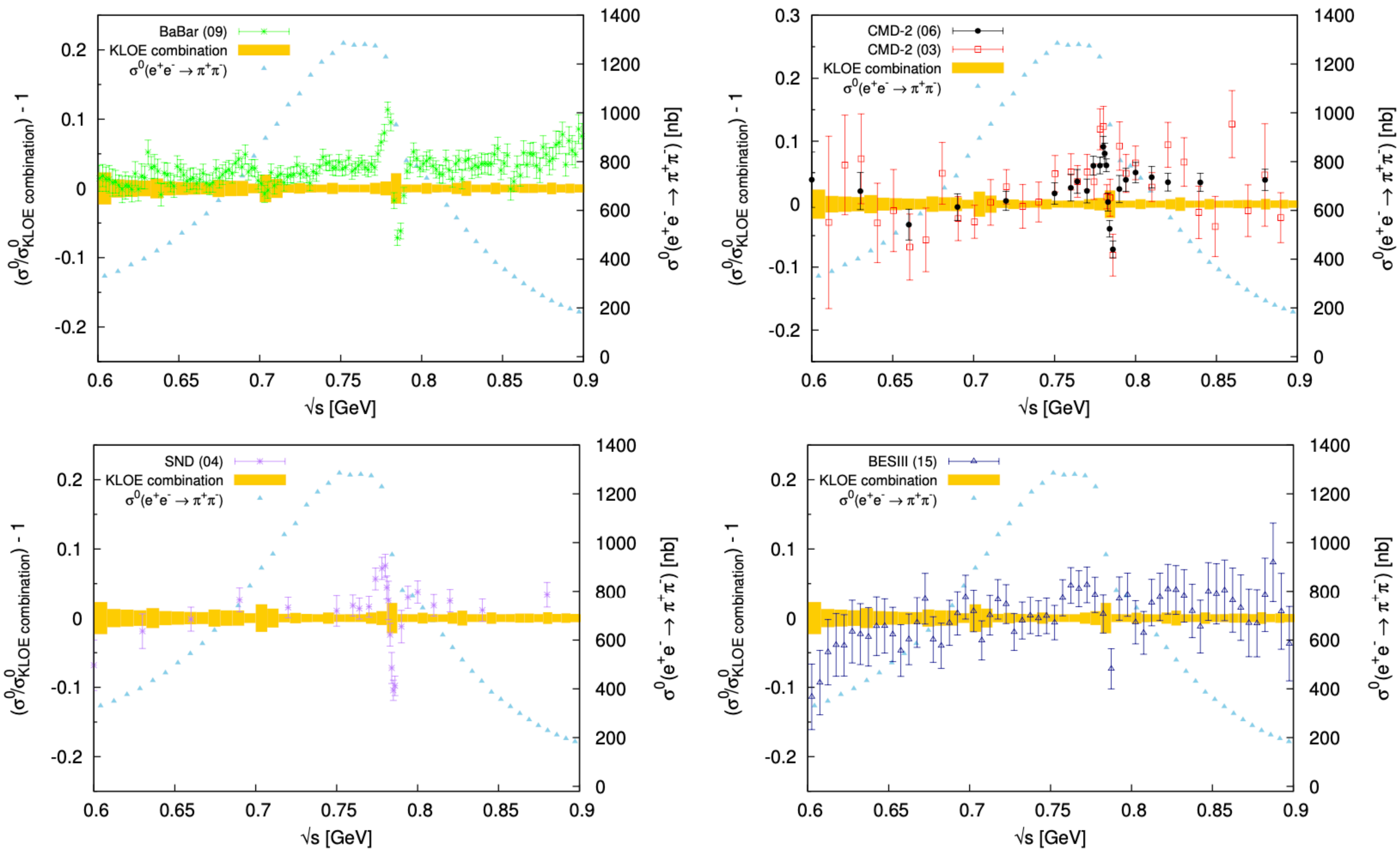


Figure 13: The $\pi^+\pi^-$ cross section from the KLOE combination compared to the BABAR, CMD-2, SND, and BESIII data points in the 0.6–0.9 GeV range [82]. The KLOE combination is represented by the yellow band. The uncertainties shown are the diagonal statistical and systematic uncertainties summed in quadrature. Reprinted from Ref. [82].

Pion matrix element

- Vector form factor (VFF) defined via

$$\langle \pi^\pm(p')|J^\mu_{\rm em}(0)|\pi^\pm(p)\rangle = \pm(p'+p)^\mu F^V_\pi(q^2)$$

$$J^\mu_{\rm em} = \tfrac{2}{3}\overline{u}\gamma^\mu u - \tfrac{1}{3}\overline{d}\gamma^\mu d$$

$$q = p' - p$$

Using iso-spin and C invariance

$$\langle \pi^\pm|J^\mu_{\rm em}|\pi^\pm\rangle = \langle \pi^\pm|\overline{u}\gamma^\mu u|\pi^\pm\rangle = -\langle \pi^\pm|\overline{d}\gamma^\mu d|\pi^\pm\rangle$$

we can cast the matrix element of the Z' quark current in terms of the VFF

$$\langle \pi^\pm(p')|J^\mu_{Z'}(0)|\pi^\pm(p)\rangle = \pm(p'+p)^\mu F^V_\pi(q^2)(g^u_V - g^d_V)$$

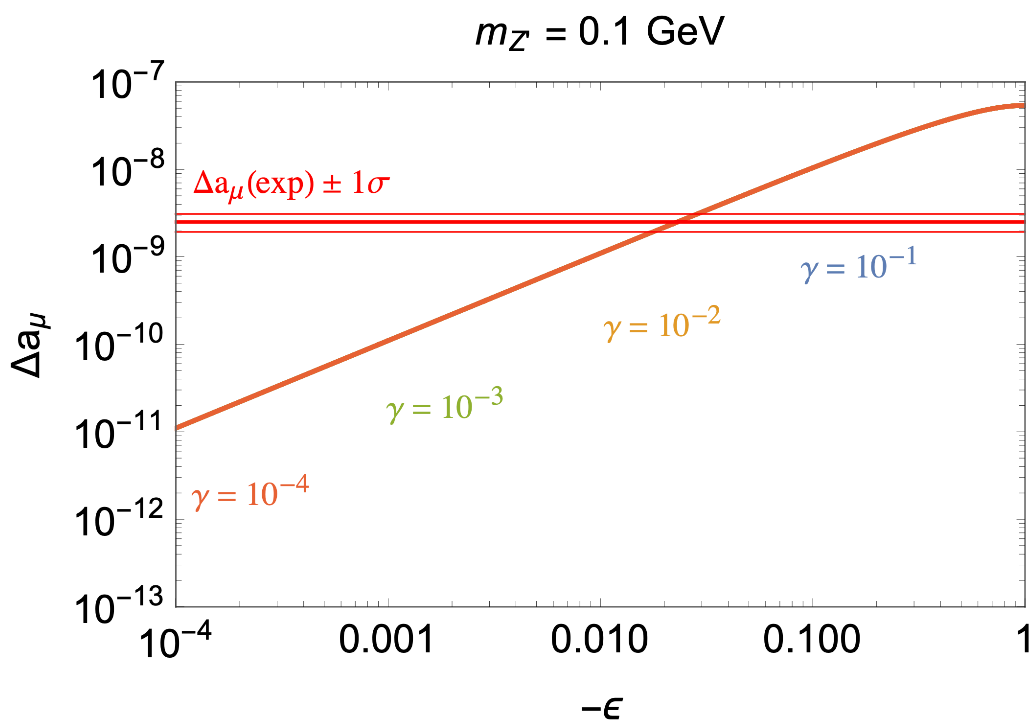
$$J^\mu_{Z'} = g^u_V\overline{u}\gamma^\mu u + g^d_V\overline{d}\gamma^\mu d$$

$$\frac{\sigma^{\rm SM+NP}_{\pi\pi}}{\sigma^{\rm SM}_{\pi\pi}} = \left|1 + \frac{g^e_V(g^u_V - g^d_V)}{e^2}\frac{s}{s - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}}\right|^2$$

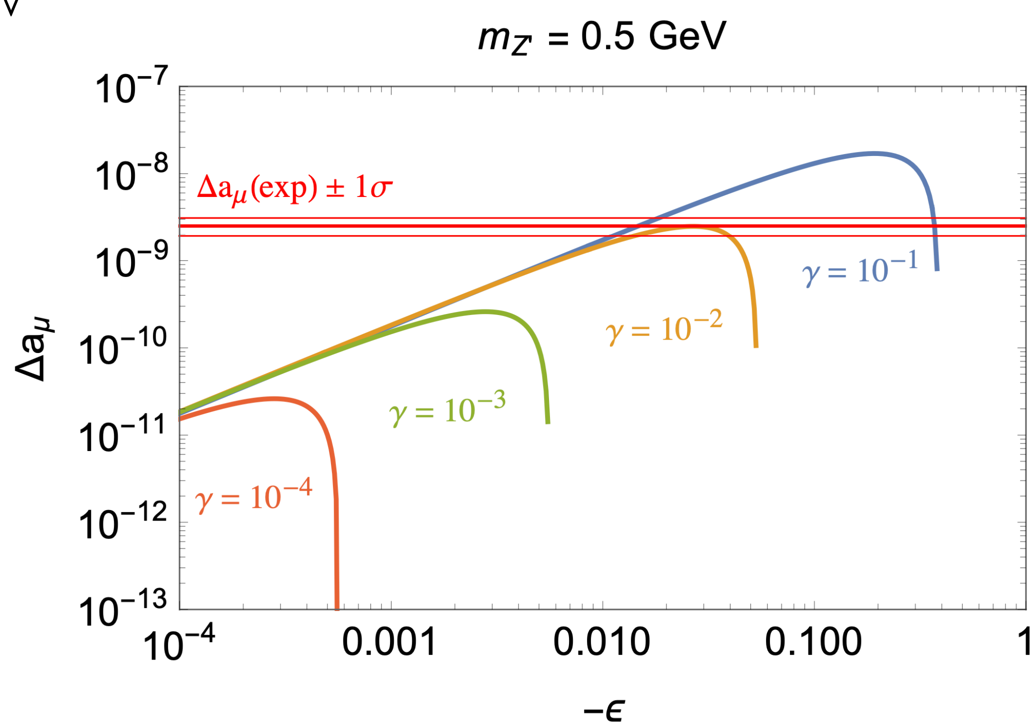
Z' shift on $(a_\mu^{\rm HVP})_{e^+e^-}$

- Typical benchmarks solving the g-2 discrepancy

$\sqrt{s_{\rm exp}} \approx 0.3$ GeV



$|\epsilon| \gtrsim 10^{-2}$



$|\epsilon| \gtrsim 10^{-2} \quad |\gamma| \gtrsim 10^{-3}$

$$\epsilon \equiv g_V^e (g_V^u - g_V^d)/e^2$$

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

$$\gamma_{ee} \approx \frac{(g_V^e)^2}{12\pi} = 2.7 \times 10^{-10} \left(\frac{g_V^e}{10^{-4}}\right)^2 \qquad \gamma_{\pi\pi} = \frac{(g_V^u - g_V^d)^2}{48\pi} |F_\pi^V(m_{Z'}^2)|^2 \left(1 - \frac{4m_\pi^2}{m_{Z'}^2}\right)^{3/2}$$

NP in Bhabha scattering ?

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

[Darmé, Grilli di Cortona, Nardi 2112.09139]

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

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

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

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

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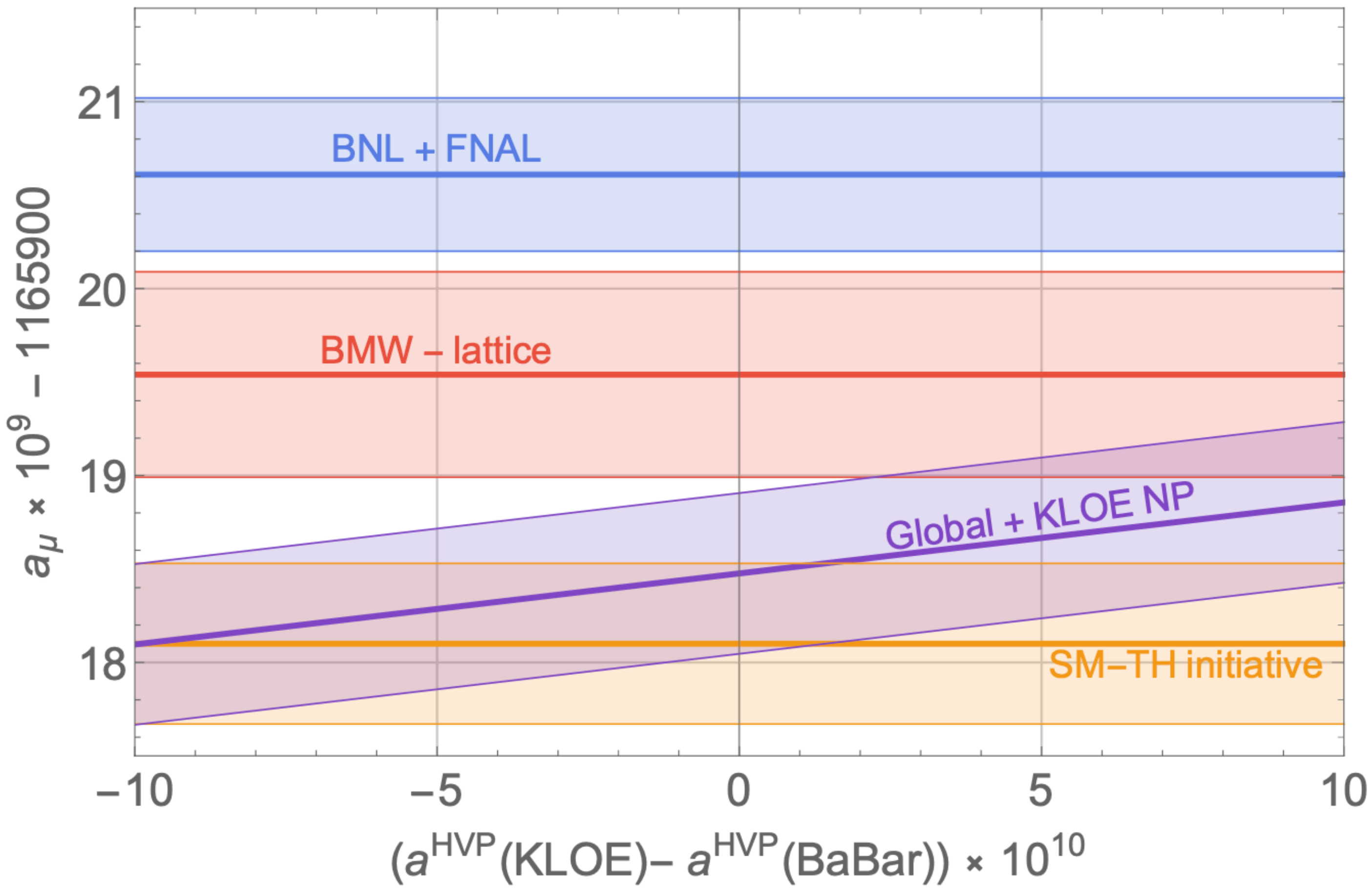

Figure 1. Theoretical prediction for a_μ obtained by modifying the KLOE result in the data driven global fit to $a_\mu^{LO,HVP}$ (oblique violet band). The blue band corresponds to the combined BNL and FNAL experimental results, the red band to the prediction obtained with the BMW lattice estimate of $a_\mu^{LO,HVP}$, and the orange band to the one obtained from σ_{had} without modifications of the KLOE results. The width of the bands represents $1\,\sigma$ uncertainties.

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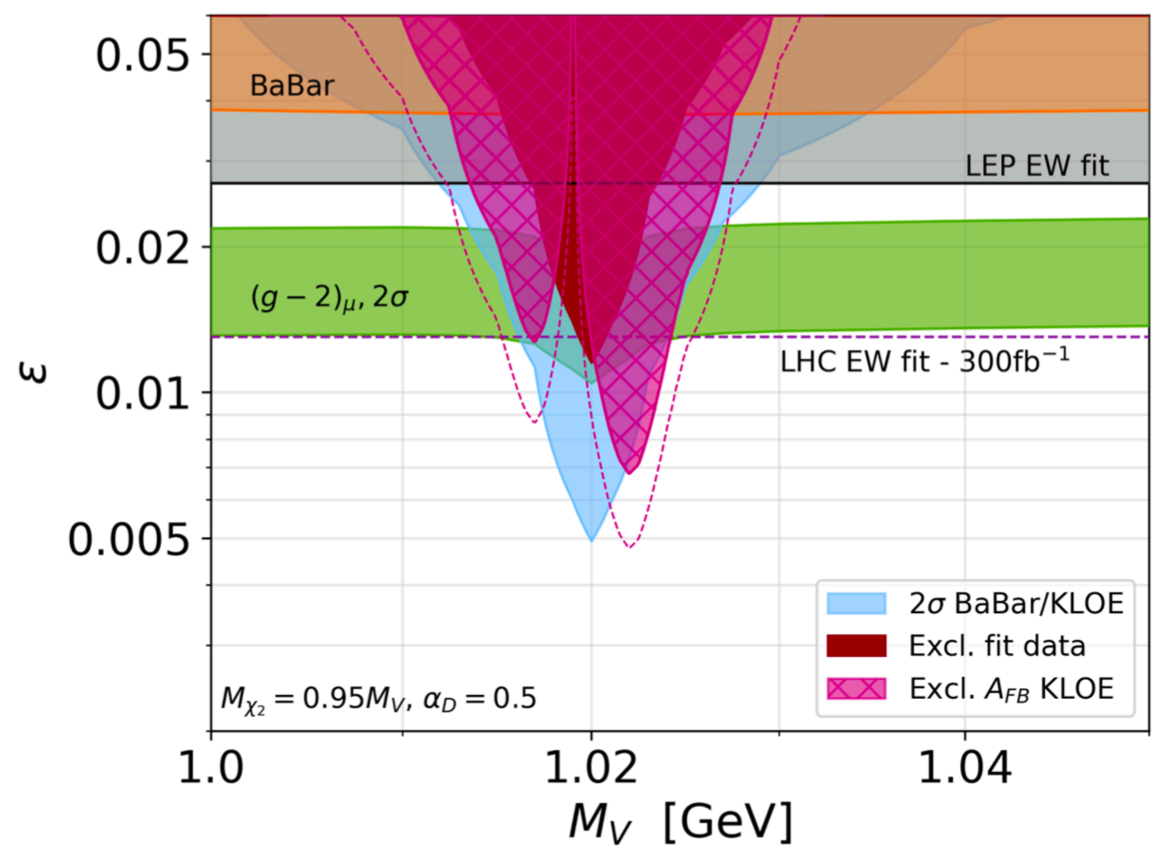

Figure 3. Parameter range compatible at 2σ with the experimental measurement of Δa_μ (green region) resulting from a redetermination of the KLOE luminosity, for $\alpha_D = 0.5, m_{\chi_2} = 0.95 m_V$ and $m_{\chi_1} = 25$ MeV. In the blue region the KLOE and BaBar results for σ_{had} are brought into 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. The limit from the electroweak fit at LEP (gray band), the projection for LHC run-3 [73] (violet dashed line), and the recasting of the BaBar limit [51] (orange band) are also shown (see text). The hatched magenta region corresponds to the conservative 2σ exclusion from ΔA_{FB}, while the magenta dashed line corresponds to the more aggressive exclusion limit

NP in Bhabha scattering ?

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

[Darmé, Grilli di Cortona, Nardi 2112.09139]

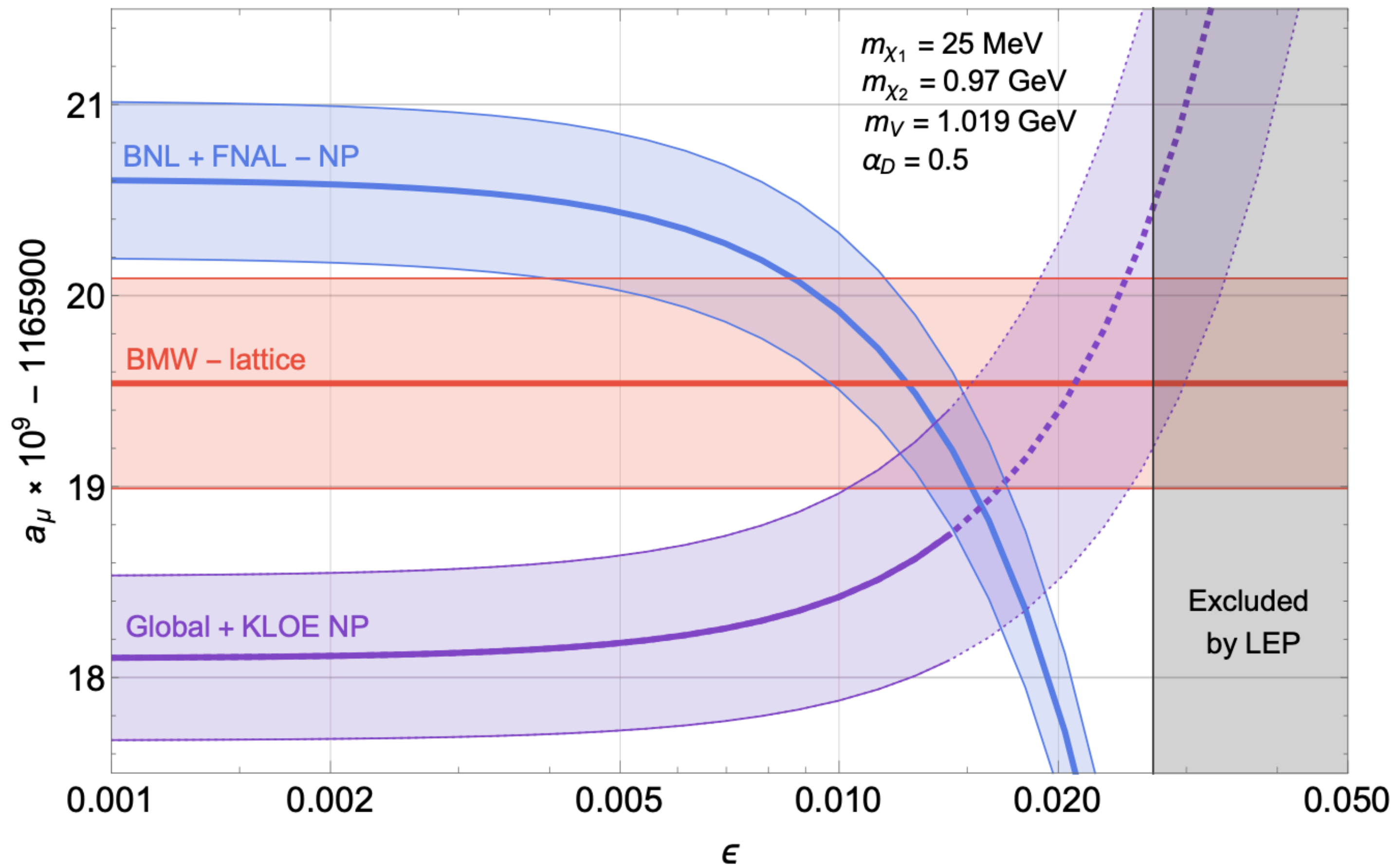

Figure 4. Theoretical prediction (purple) for a_μ as a function of ε for a dark photon model with $m_{\chi_1} = 25$ MeV, $m_{\chi_2} = 0.9$ GeV, $m_V = 1.019$ GeV and $\alpha_D = 0.5$. The dashed purple curve denotes the region where the KLOE and BaBar results are more than 2σ away. The blue band corresponds to the combined BNL and FNAL experimental results after subtracting the direct NP contribution from the dark photon. The red band shows the prediction obtained with the BMW lattice estimate of $a_\mu^{\text{LO,HVP}}$. The width of the bands represents $1\,\sigma$ uncertainties. The grey region is excluded by LEP.