Probing light gauge bosons using the muon (g-2)

Kushan Panchal

University of Maryland, College Park

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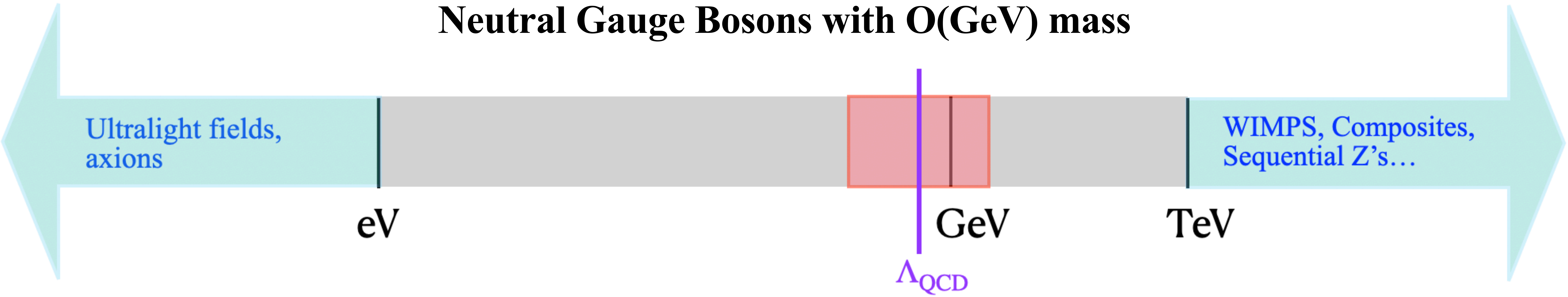
Based on work with Agashe, Banerjee, Jiang, Nussinov, **KP**, Paul, Perez, Soreq, arXiv:2412.12266, JHEP 08 (2025) 161

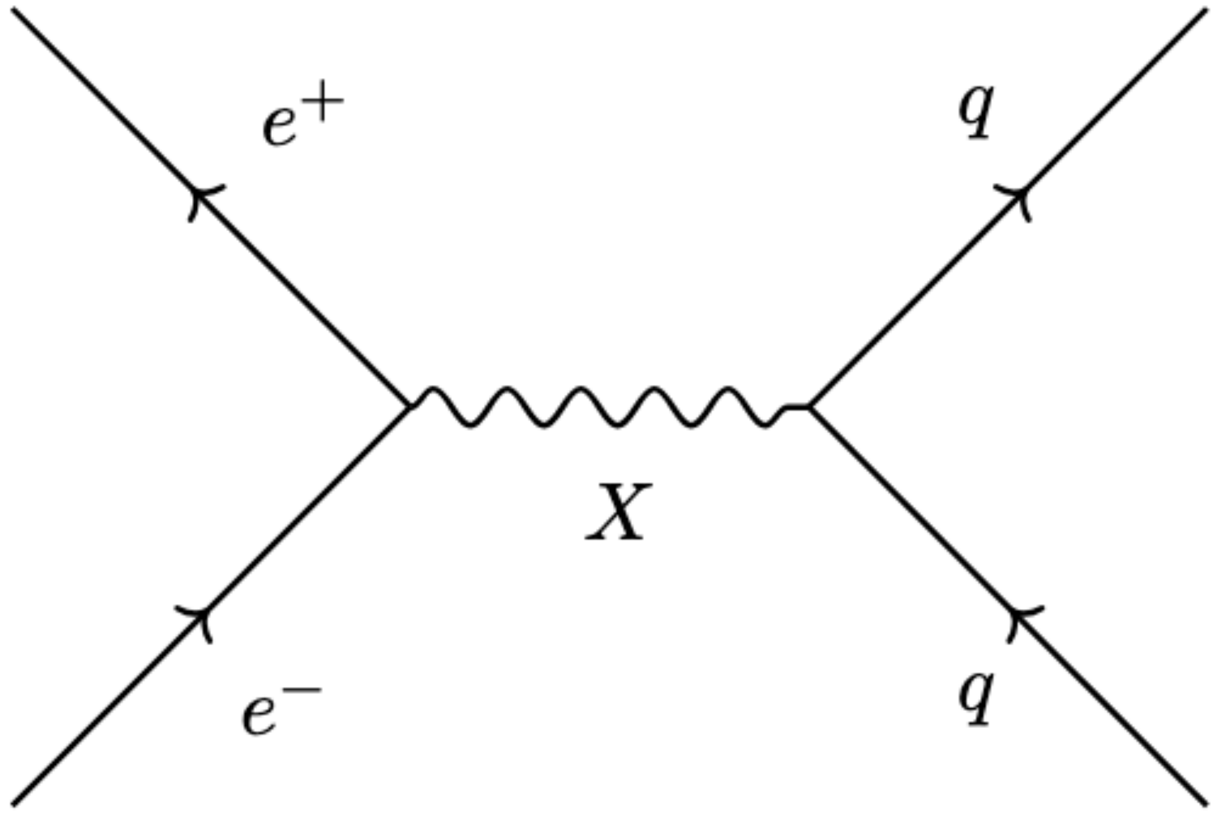
Light gauge bosons/Z'



Ways to look for Light Z's:

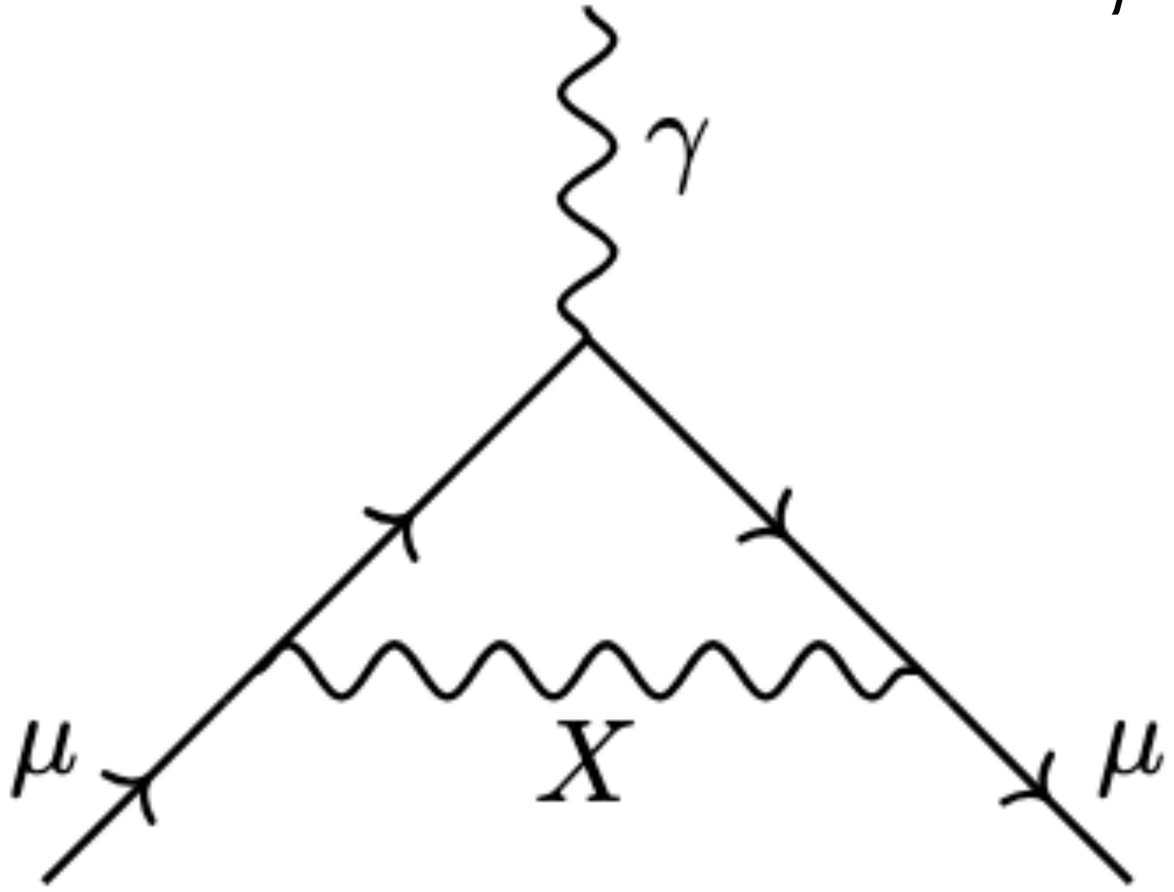
Direct effect → Indirect effect

Direct effect : $(g-2)_\mu$



Running of $\alpha(m_e^2) \to \alpha(m_Z^2)$

Related ??

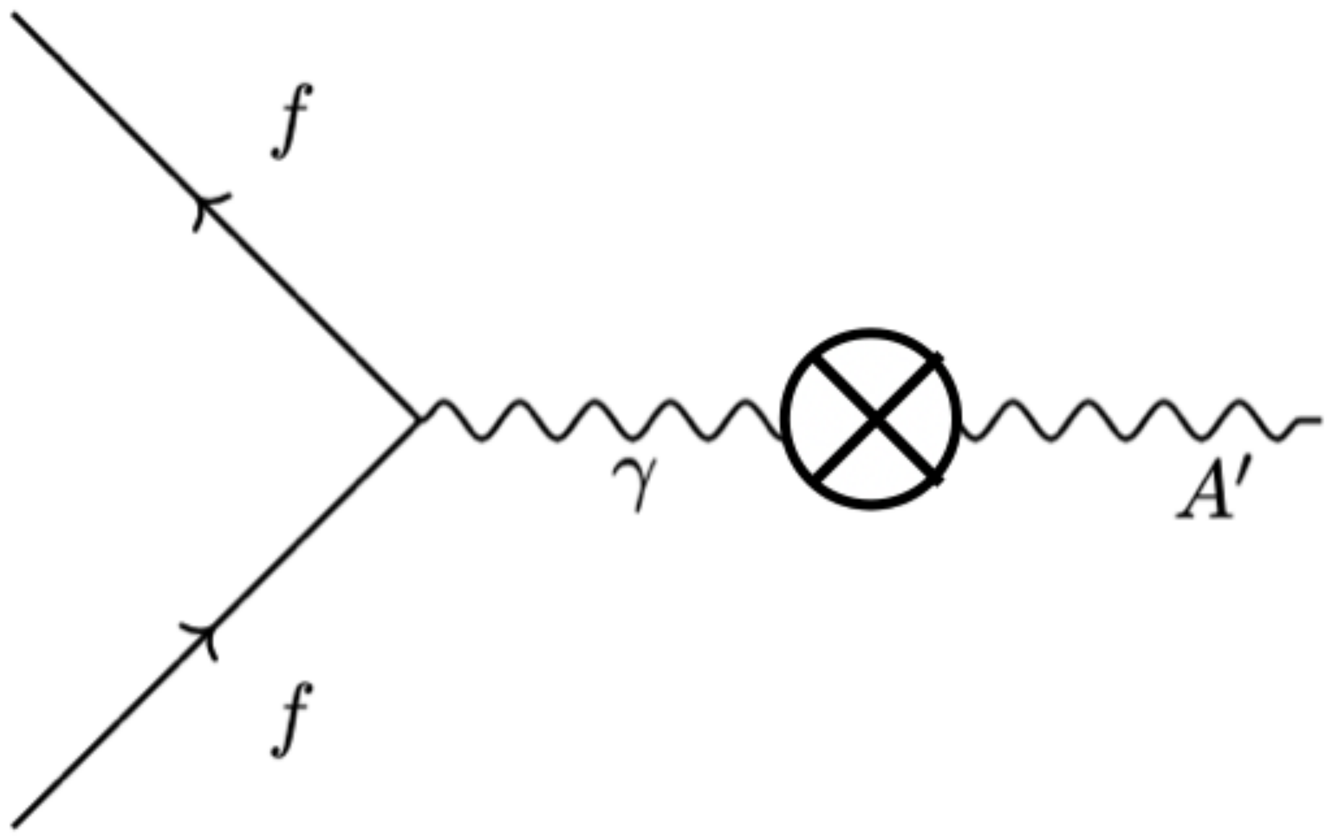


Benchmark flavour blind models

The dark photon (A'_μ)

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}\varepsilon F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

$$g_\ell = g_q = \epsilon e$$

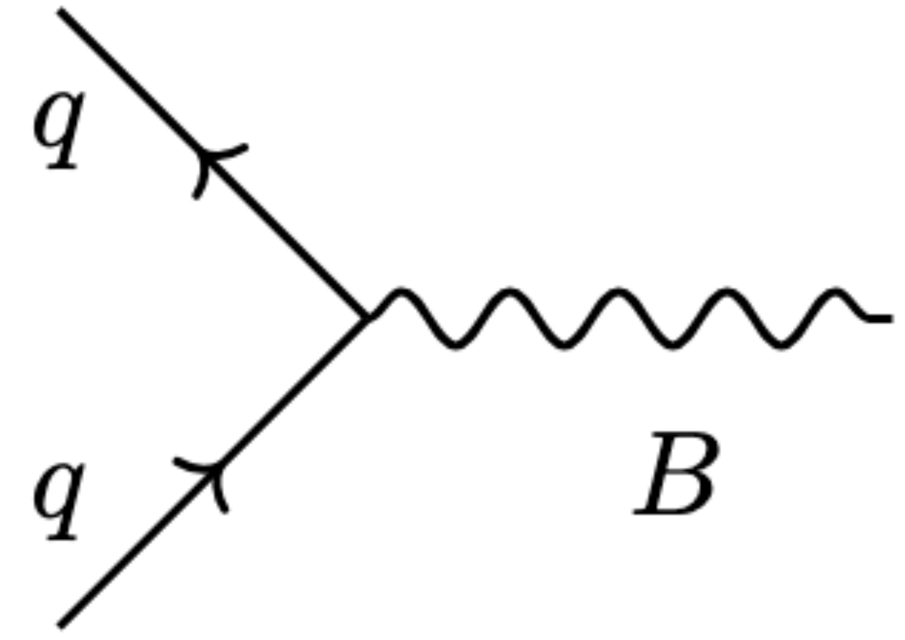


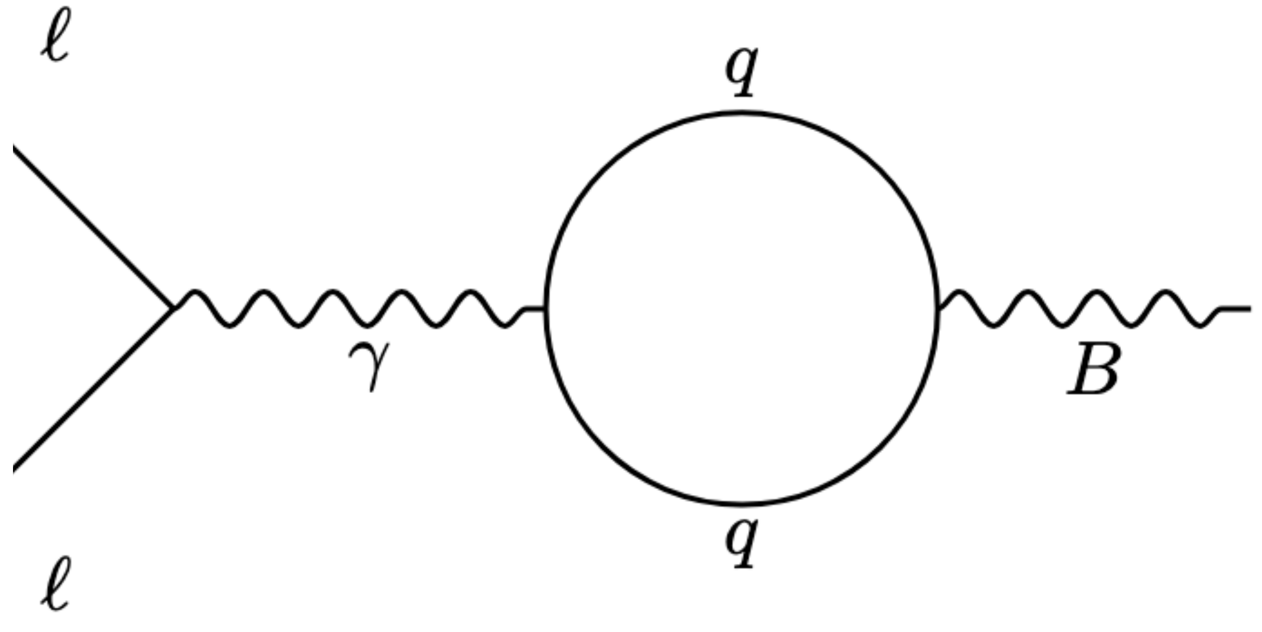
Baryon number gauge boson(B_μ)

$$\frac{\varepsilon_B}{2}B_{\mu\nu}F^{\mu\nu} + g_q B_\mu \bar{q}\gamma^\mu q \longrightarrow$$

$$B_\mu \left[(g_q + Q_q^{\mathrm{EM}} g_\ell)\bar{q}\gamma^\mu q - g_\ell \bar{\ell}\gamma^\mu \ell\right]$$

$$g_\ell \ll g_q$$



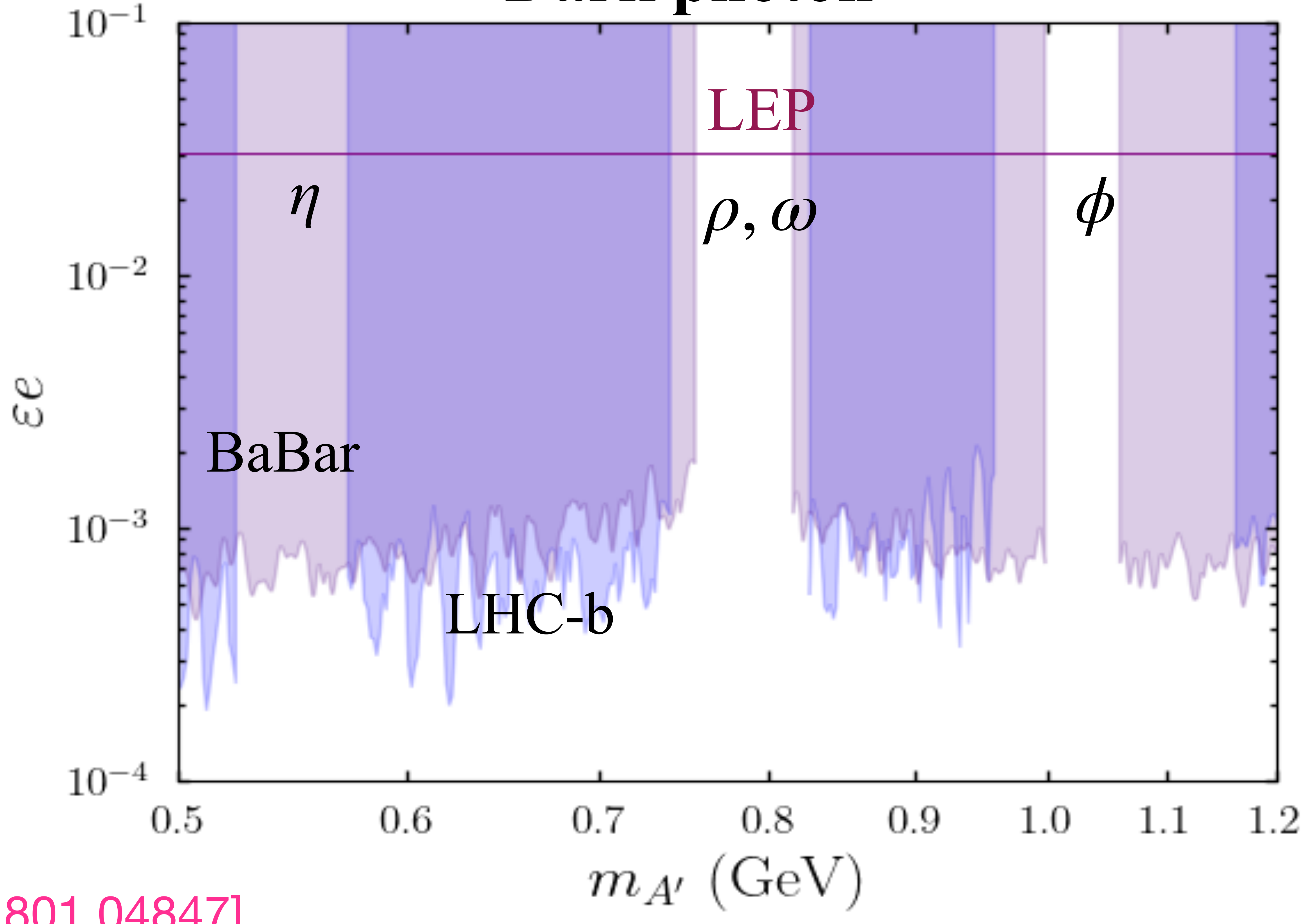


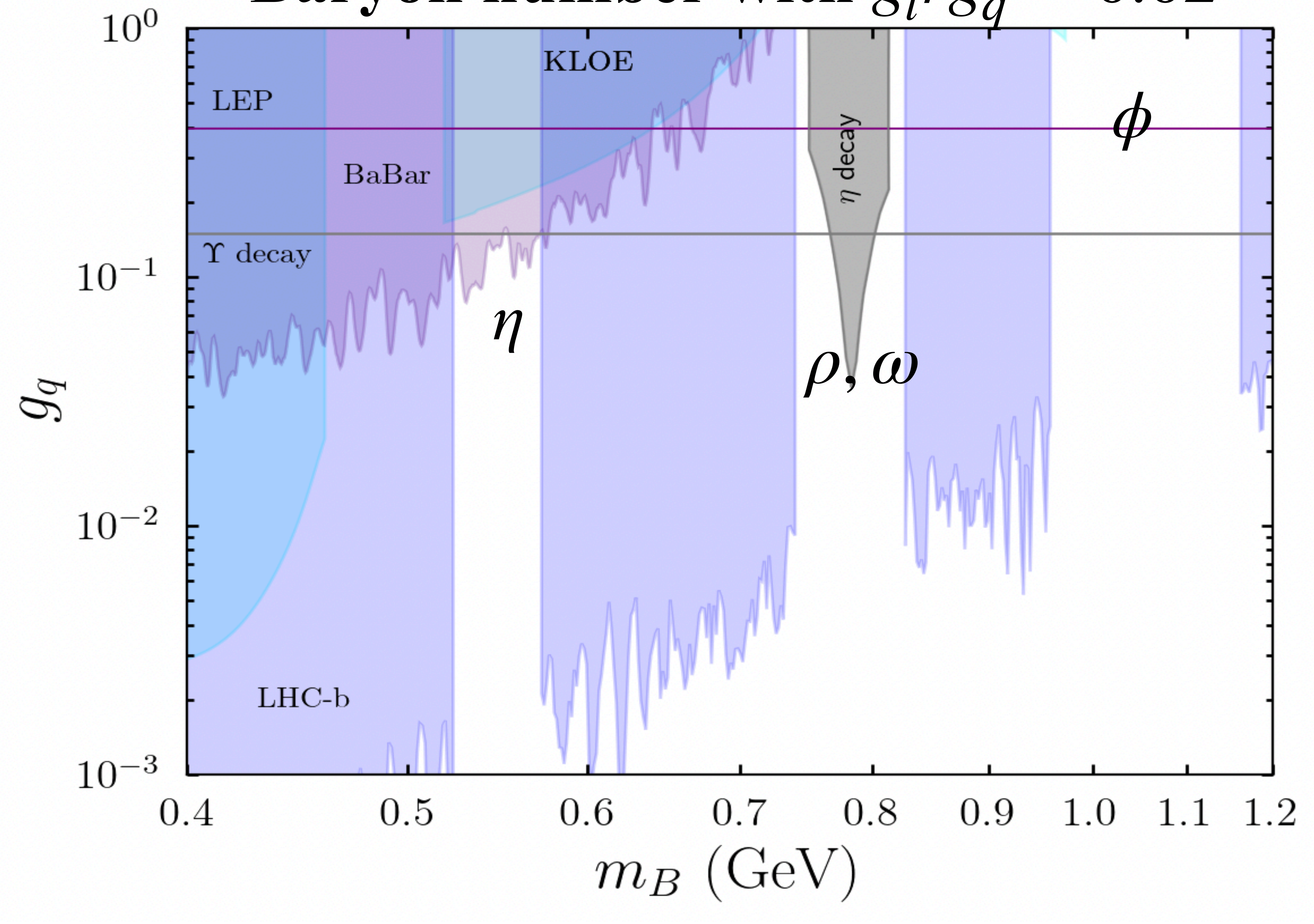
Collider bounds on the two models

Gaps near Hadronic resonances, either due to BR to leptons being small or

due to QCD background

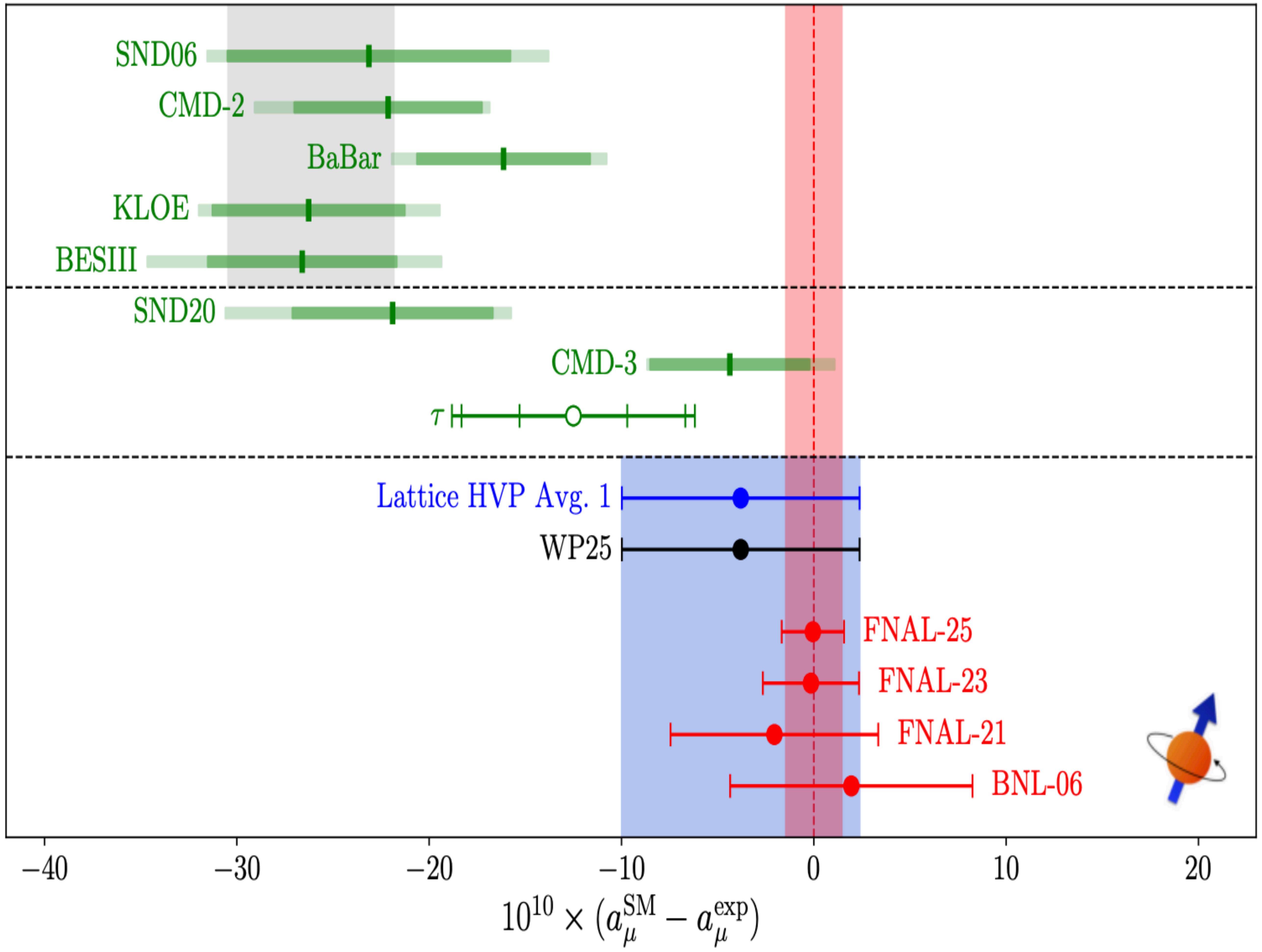
Can we cover the gaps??





[1801.04847]

New Physics in $(g-2)_\mu$?



Simplest comparison would be between:

(a) **Experiment** a_μ^{exp}

(b) **Theory**: Lattice a_μ^{lat}

Does exp agree with theory?

Exp vs Lattice: 0.6σ

So we can use this as a constraint to place bounds like colliders!

White paper '25 [2505.21476]

1 loop contributions

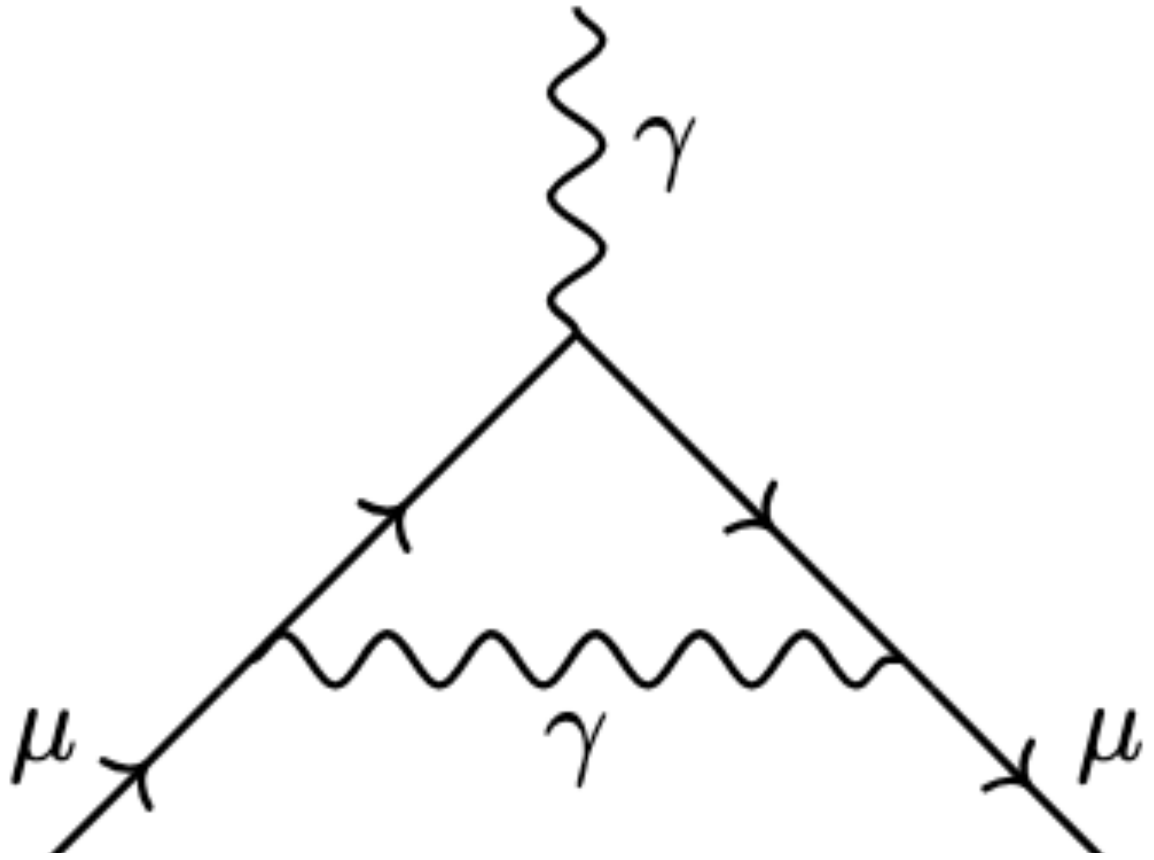
Photon contribution

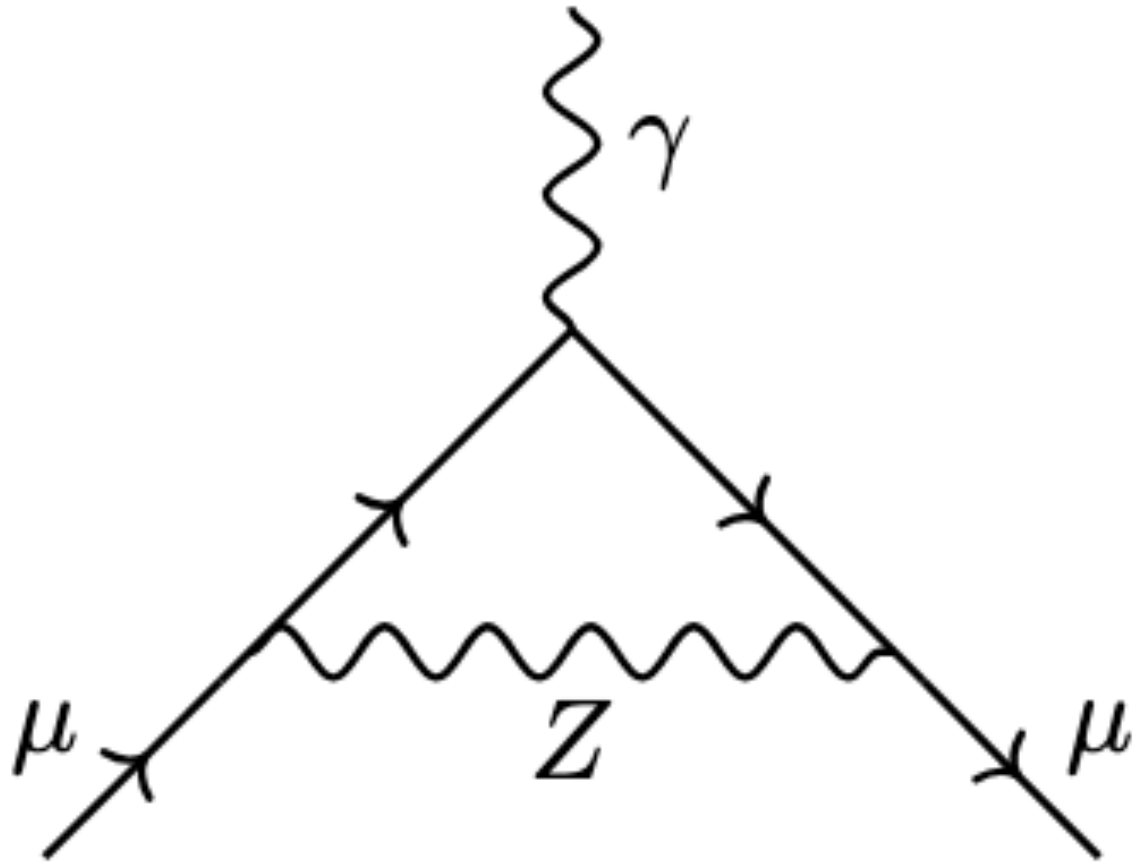
$$a_\mu^\gamma = \frac{\alpha}{2\pi} \approx 116{,}140{,}970 \times 10^{-11}$$

Electroweak contribution

$$a_\mu^W + a_\mu^h + a_\mu^Z = \approx 194.8 \times 10^{-11}$$

SM :





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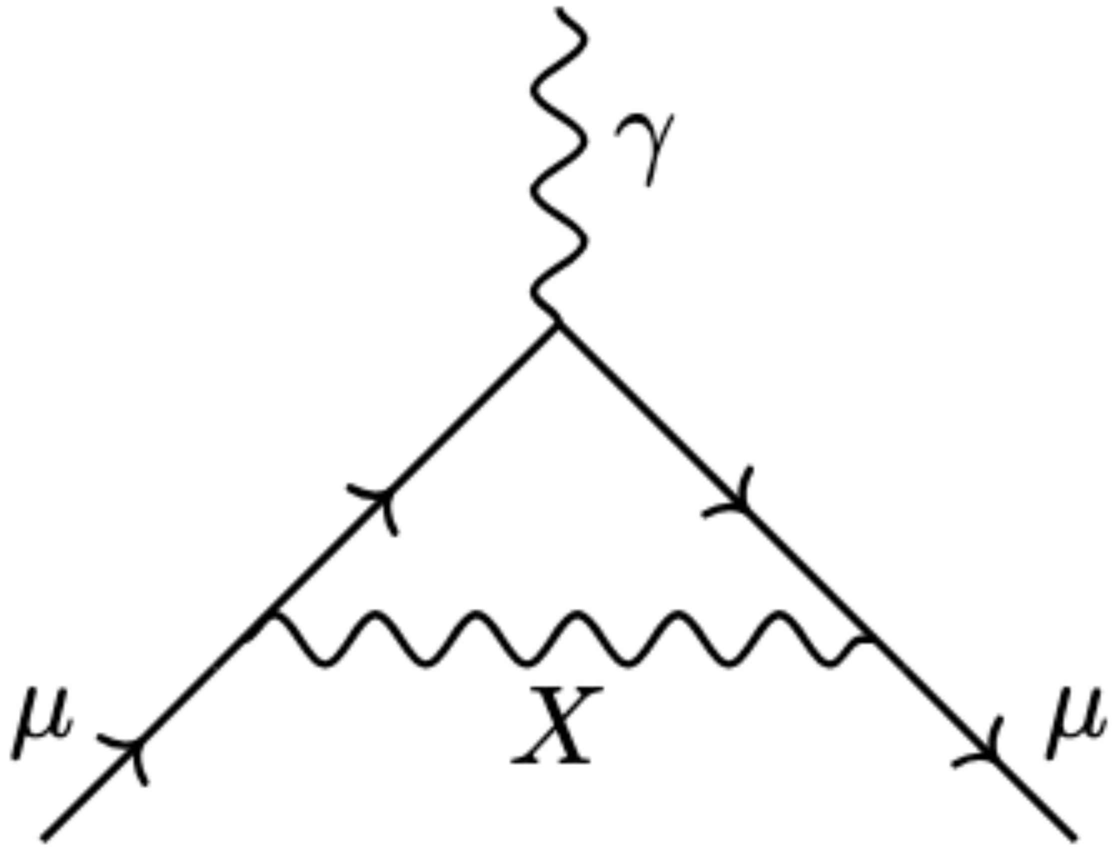
NP :



X=NP gauge boson

$$a_\mu^X \approx 196 \times 10^{-11} \left(\frac{g_\ell}{3 \times 10^{-3}}\right)^2 \left(\frac{0.6\ GeV}{m_X}\right)^2$$

Comparable to EW contribution for small g_ℓ!

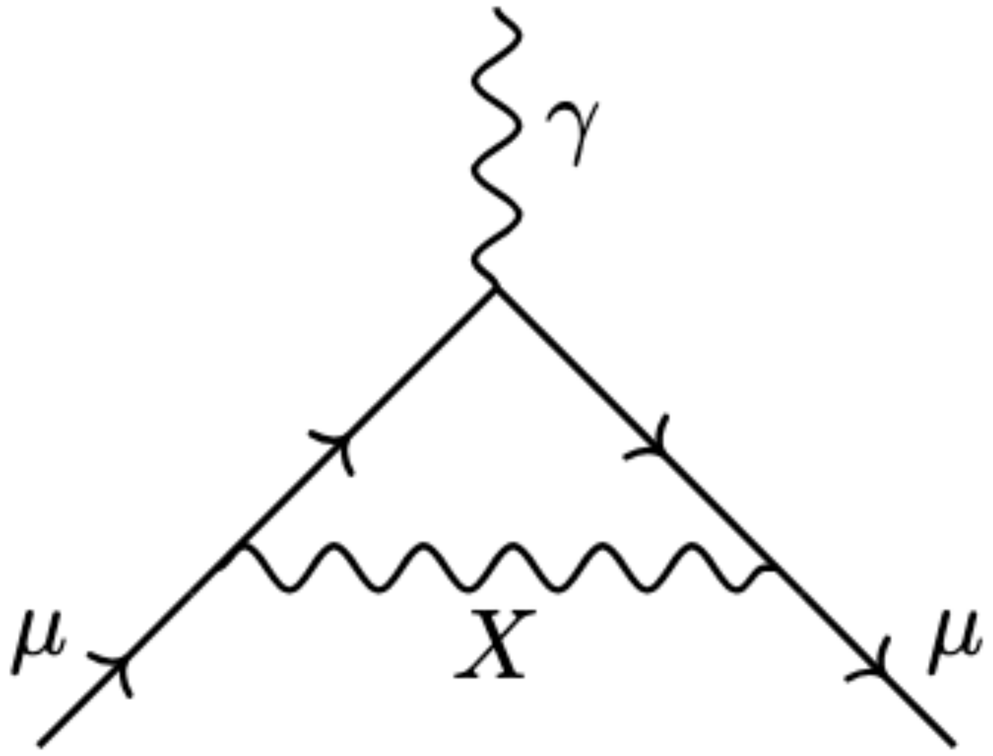
pdg.lbl.gov/2024/reviews/rpp2024

The a_μ test

Discrepancy between experimental and SM=lattice numbers should be due to NP. This is the **lattice a_μ test**

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{lat}} = a_\mu^{X} + a_\mu^{\gamma-X} + a_\mu^{X-X} \approx a_\mu^{X} + a_\mu^{\gamma-X} \quad (\pm 2\sigma)$$

$a_\mu^{\text{exp}} - a_\mu^{\text{lat}} =$



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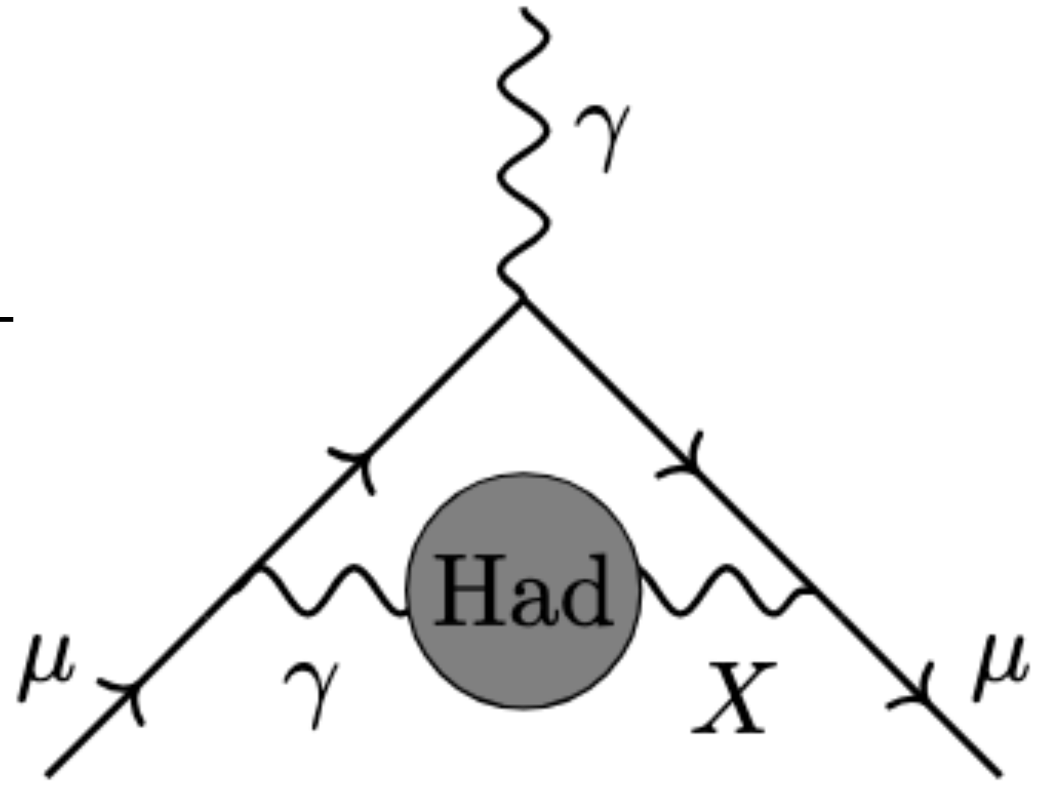

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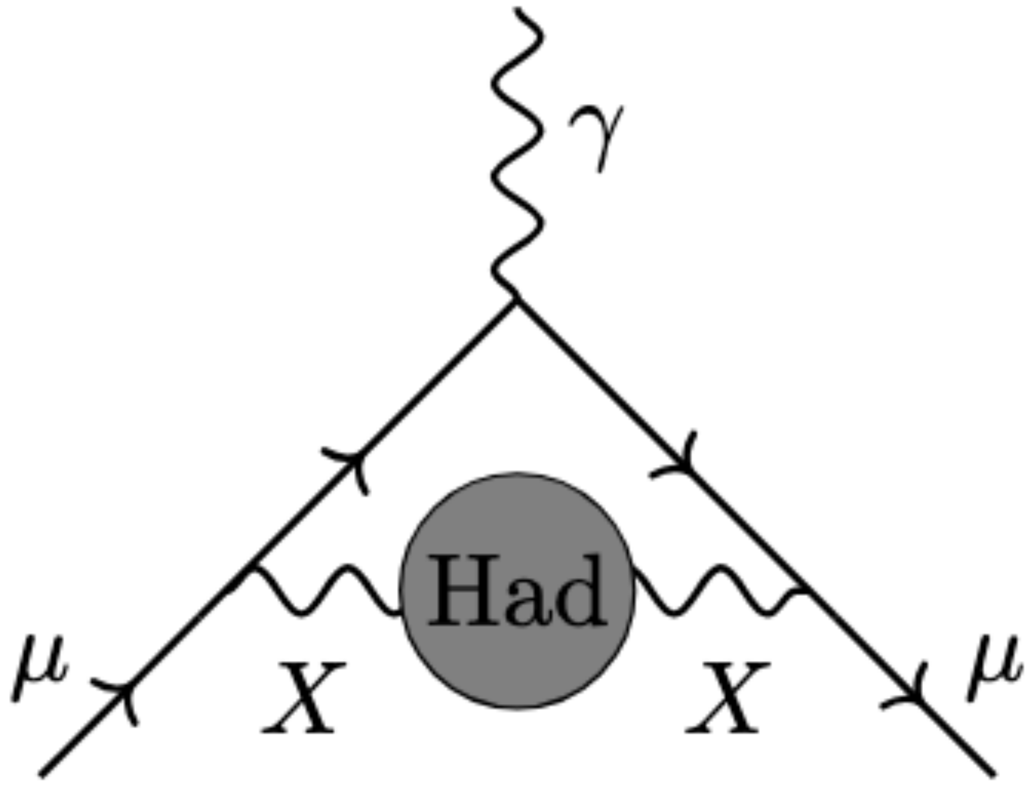
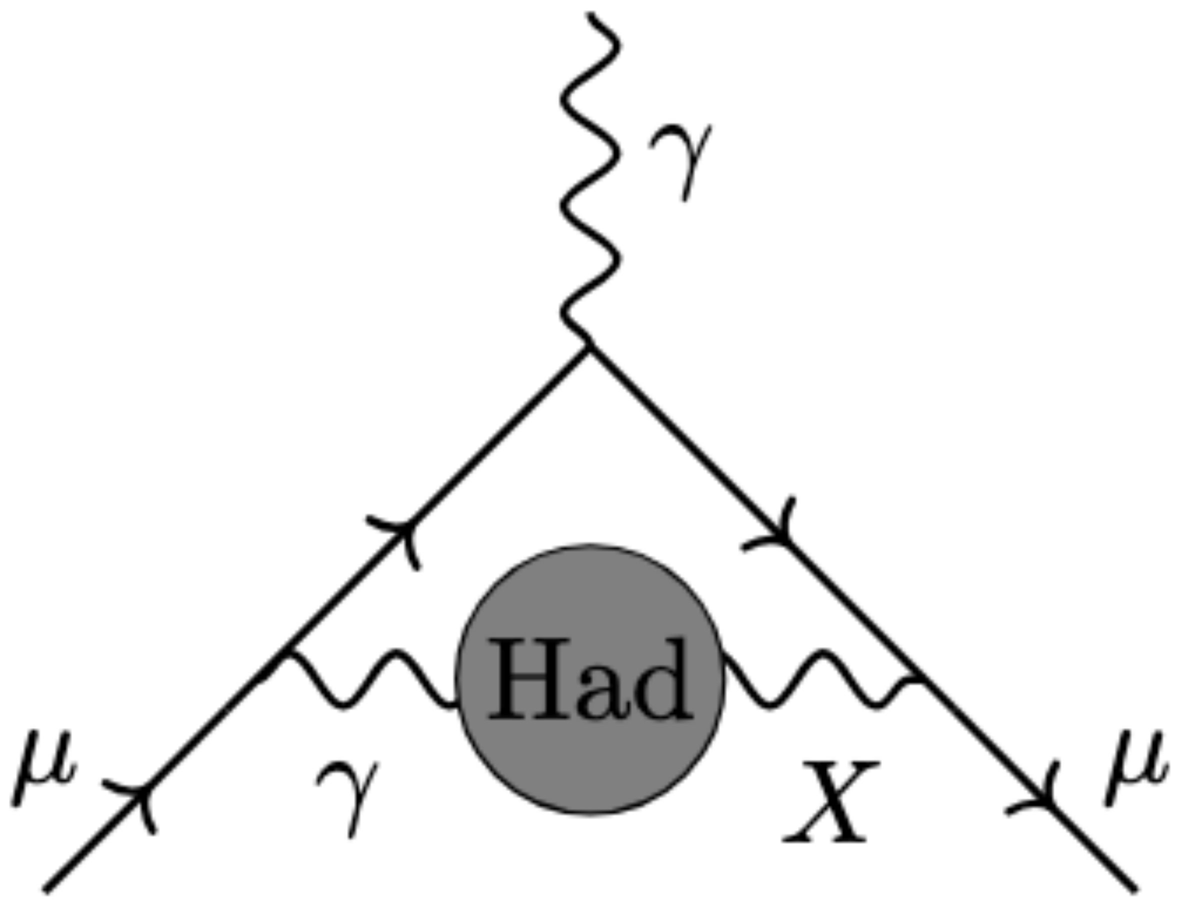


2 loop effects are important !

Compare this to "old" a_μ test:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{lat}} = a_\mu^X \quad (\pm 2\sigma)$$

How much will you miss?



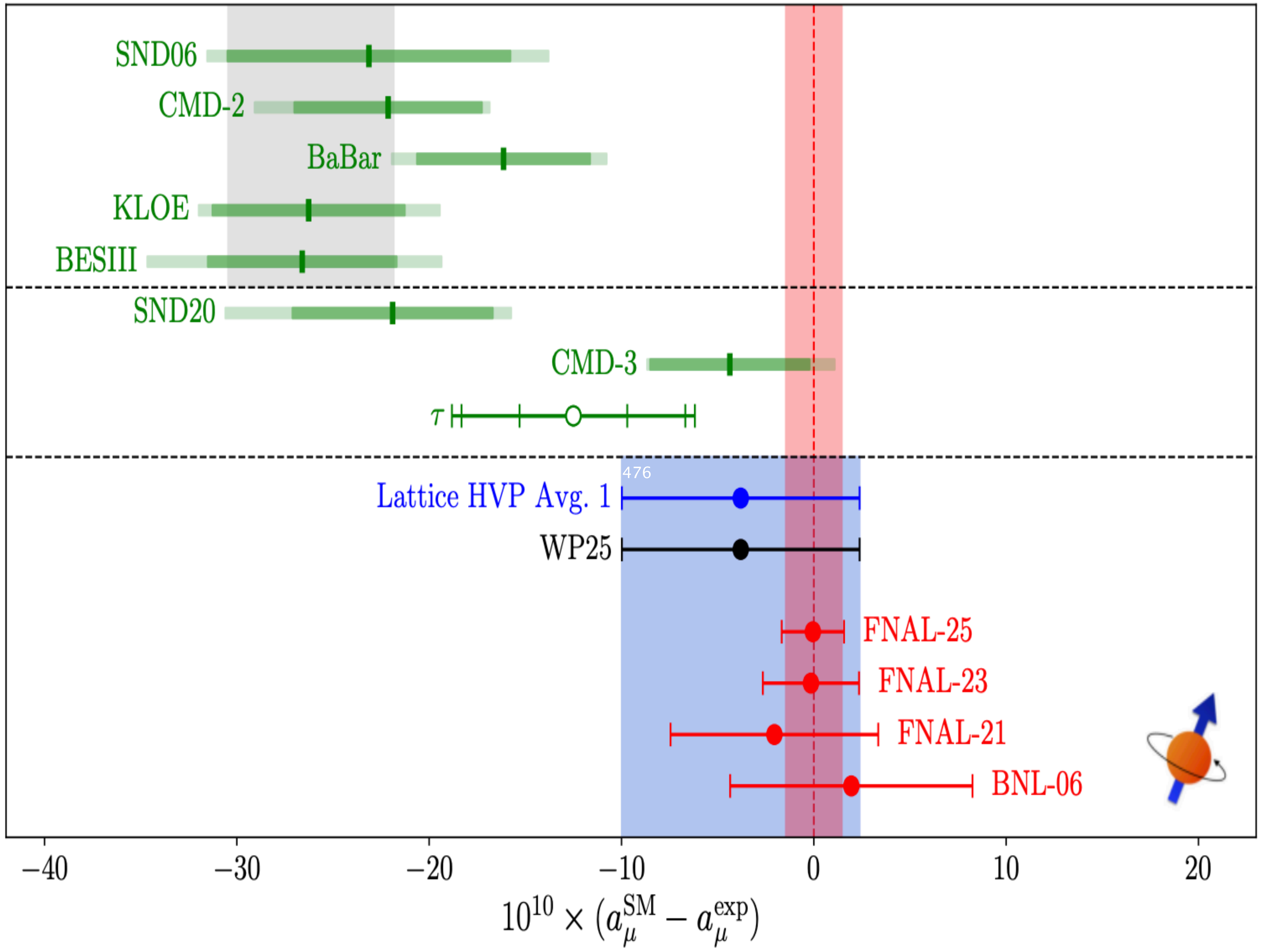
Perturbative estimate:

$$a_\mu^{\gamma-X} \sim 10 \times 10^{-11} \left(\frac{g_\ell}{3\times 10^{-3}}\right)\left(\frac{g_q}{0.15}\right)\left(\frac{0.6\ GeV}{m_X}\right)^2$$

$a_\mu^{\gamma-X}/a_\mu^X \gtrsim 1$ for $g_\ell/g_q \lesssim 10^{-3}$. Effect is important for X with hierarchical coupling to hadrons.

Agashe, Banerjee, Jiang, Nussinov, **KP**, Paul, Perez, Soreq, arXiv:2412.12266, JHEP 08 (2025) 161

The plot thickens..



Inputs from three areas:

(a) **Experiment** a_μ^{exp}

(b) **Theory**: Lattice a_μ^{lat}

(c) **Data-driven (DD)** : a_μ^{DD}

Lattice vs DD : $\sim 2.95\sigma$

The HVP puzzle

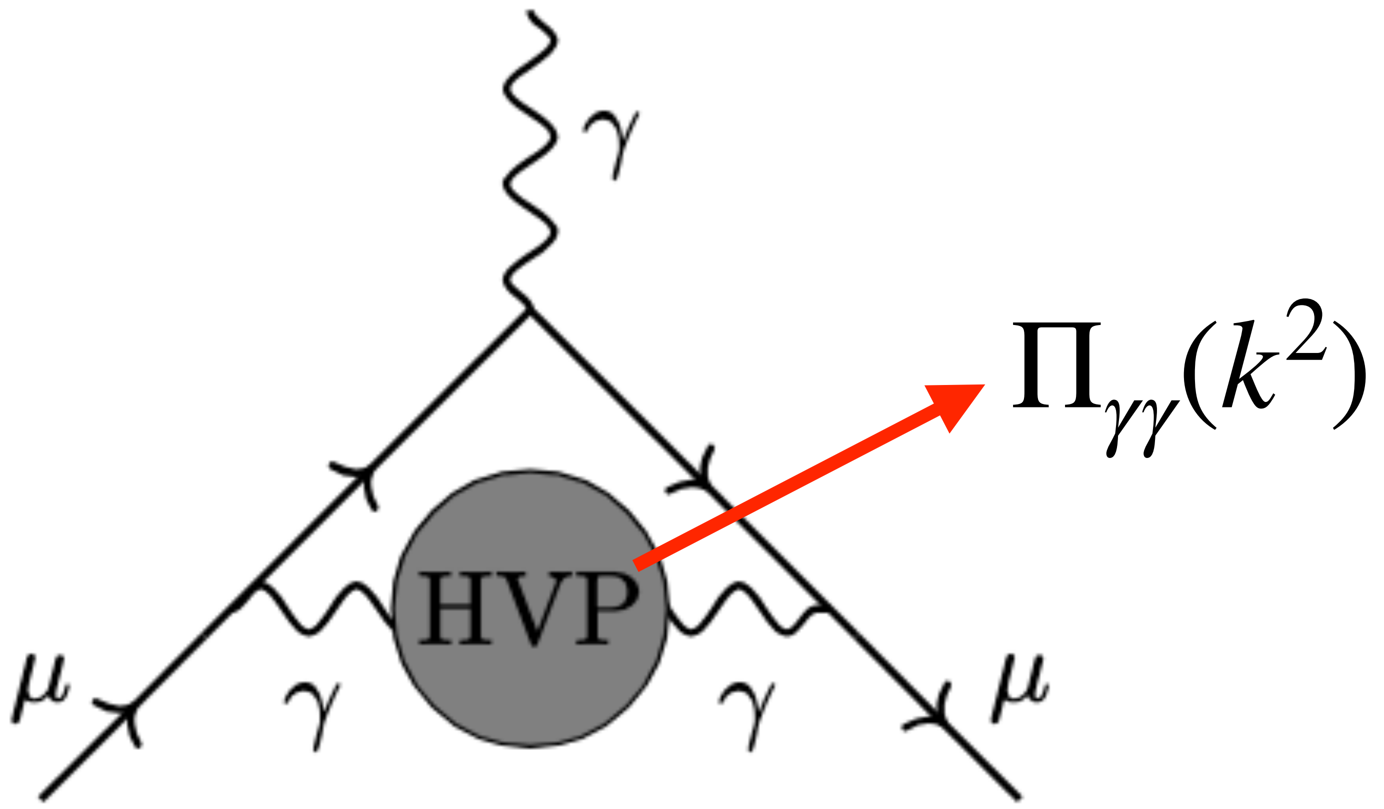
White paper ’25 [2505.21476]

The HVP puzzle

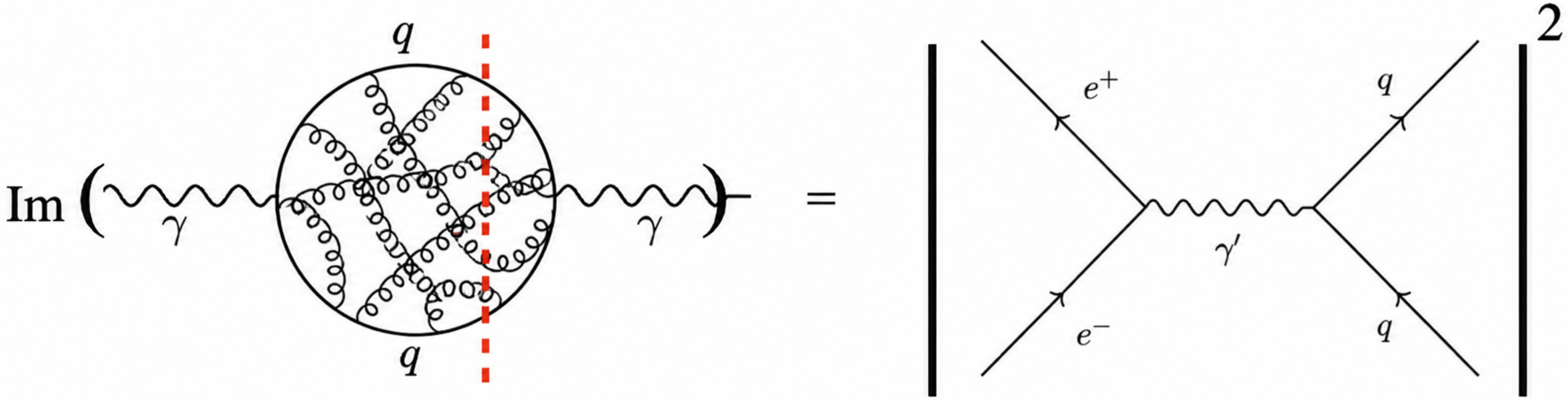
$\Pi_{\gamma\gamma}(k^2)$ = non-perturbative **hadronic vacuum polarisation (HVP)**. How to calculate it?

Method I : Lattice can directly give us $\Pi_{\gamma\gamma}(k^2)$.

Method II : Data-driven method.



$$a_\mu^{\gamma\gamma} = (\mathrm{HVP})^{\mathrm{DD}} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\ K(s)\ \boxed{\sigma(e^+e^- \to \mathrm{had})}$$ from experiment



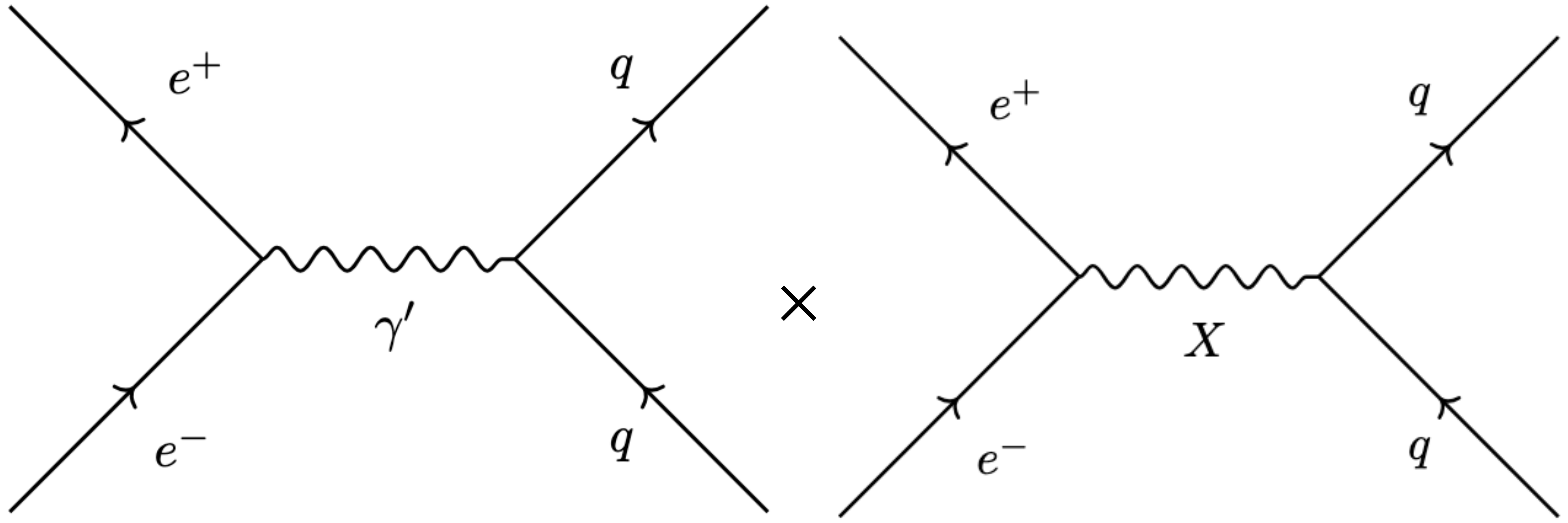
Presence of X contaminates HVP

$$a_\mu^{DD} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} ds\ K(s)\ \sigma(e^+e^- \to \text{had})$$

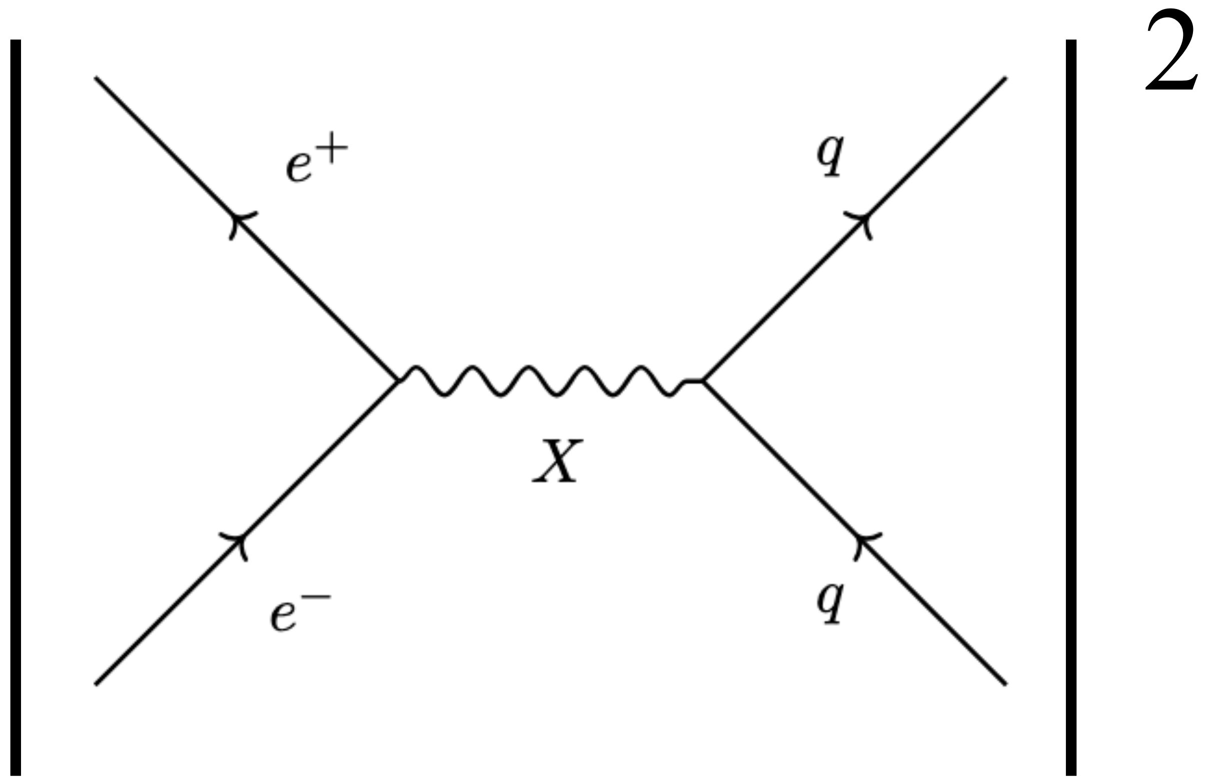
But now we have an extra cross section due to X

$$a_\mu^{DD} = \frac{1}{4\pi^3}\int_{s_{th}}^{\infty} ds\ K(s)\ \sigma(e^+e^- \to \gamma \to \text{had})$$

$$+\frac{1}{4\pi^3}\int_{s_{th}}^{\infty} ds\ K(s)\ \sigma^{\gamma-X}(e^+e^- \to \text{had})$$



$$+\frac{1}{4\pi^3}\int_{s_{th}}^{\infty} ds\ K(s)\ \sigma^{X}(e^+e^- \to \text{had})$$



$$= a_\mu^{lat} + (\text{HVP})^{\gamma-X} + (\text{HVP})^{X}$$

Lattice

L. Di Luzio, A. Masiero, P. Paradisi, and M. Passera, arXiv:2112.08312.
Nina Coyle, Carlos Wagner, arXiv: 2305.02354

The NP contributions to HVP

$$(\mathrm{HVP})^{\gamma-X} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\ K(s)\ \sigma^{\gamma-X}(e^+e^- \to \mathrm{had})$$

Small $$(\mathrm{HVP})^{X\ \mathrm{off}} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\ K(s)\ \sigma(e^+e^- \to X(\mathrm{off-shell}) \to \mathrm{had})$$

$$(\mathrm{HVP})^{X\ \mathrm{on}} = \frac{1}{4\pi^3}\int_{s_{\mathrm{th}}}^{\infty} ds\ K(s)\ \sigma(e^+e^- \to X(\mathrm{on-shell}) \to \mathrm{had})$$

Just the "contamination" of the HVP

Discrepancy between DD and lattice, should be due to the New Physics(NP) contributions.

$$(\mathrm{HVP})^{\gamma-X} + (\mathrm{HVP})^{X-\mathrm{on}} = (a_\mu)^{\mathrm{DD}} - (a_\mu)^{\mathrm{lat}} \qquad (\pm 2\sigma)$$

This gives us the **HVP test**

Existing models for HVP Puzzle : lepton flavour violation, extra isospin breaking etc.

Agashe, Banerjee, Jiang, Nussinov, **KP**, Paul, Perez, Soreq, arXiv:2412.12266, JHEP 08 (2025) 161

Both tests for flavour blind X !

HVP test: Data-driven vs. Lattice

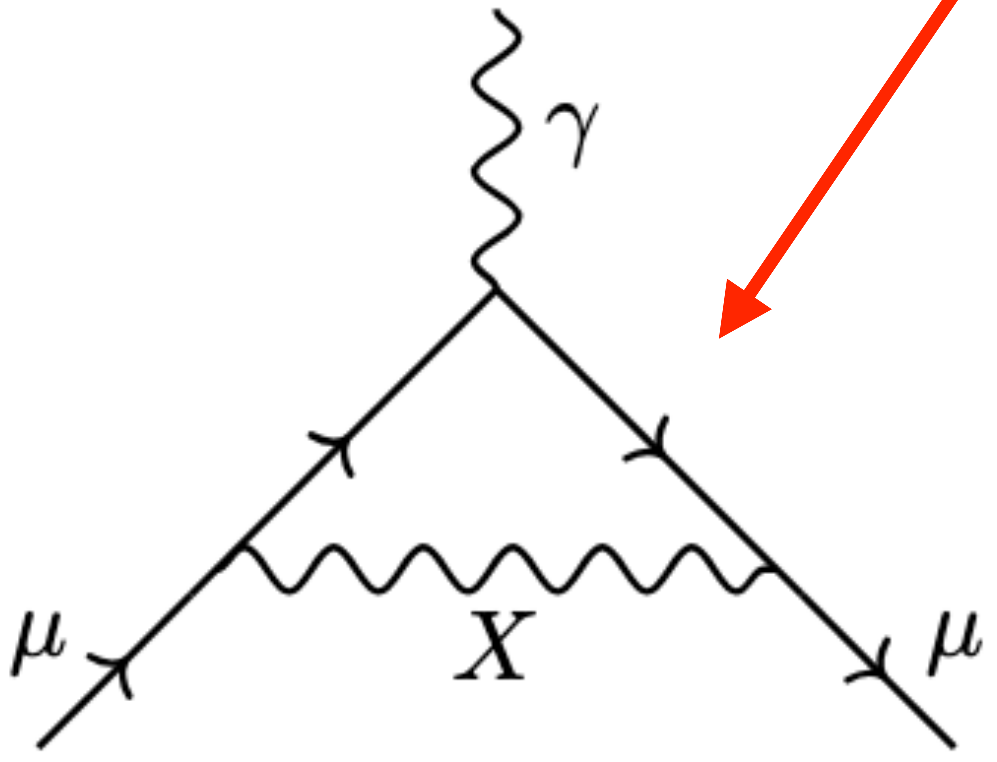
$$a_\mu^{\rm DD} - a_\mu^{\rm lat} = ({\rm HVP})^{\gamma-X} + ({\rm HVP})^{X\ \text{on-shell}} \quad (\pm 2\sigma)$$

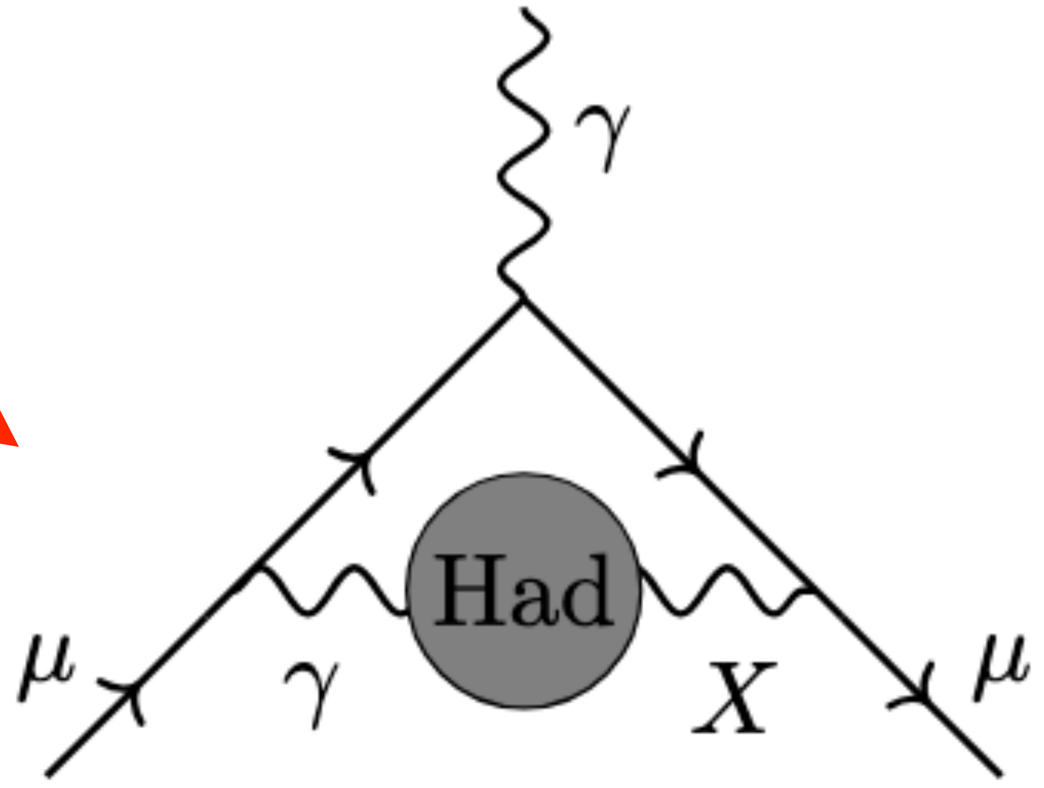
a_μ test: Experiment vs. Lattice

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm lat} = a_\mu^X + a_\mu^{\gamma-X} + a_\mu^{X-X} \approx a_\mu^X + a_\mu^{\gamma-X} \quad (\pm 2\sigma)$$

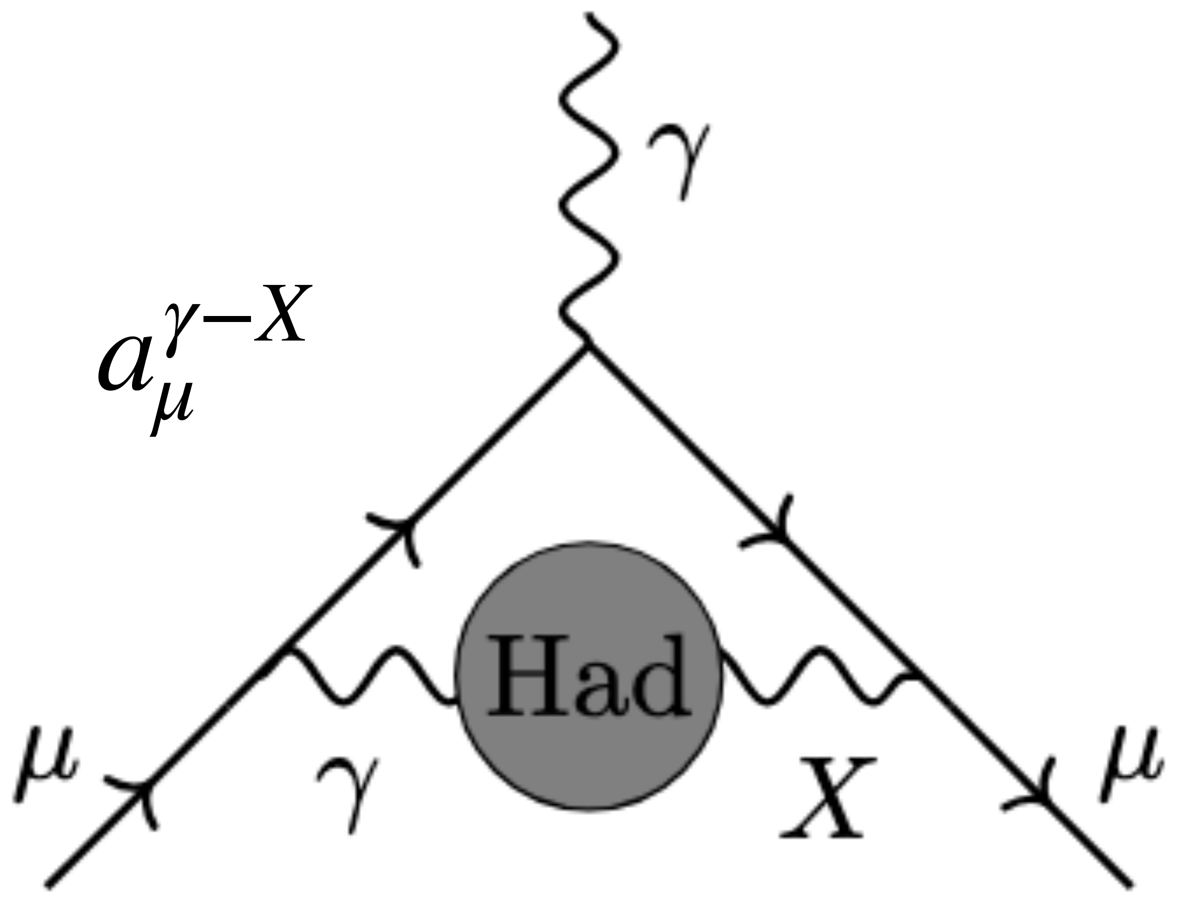
DD a_μ test:

$$a_\mu^{\rm exp} - a_\mu^{\rm DD} = a_\mu^X + a_\mu^{\gamma-X} - ({\rm HVP})^{\gamma-X} - ({\rm HVP})^{X-{\rm on}} \quad (\pm 2\sigma)$$

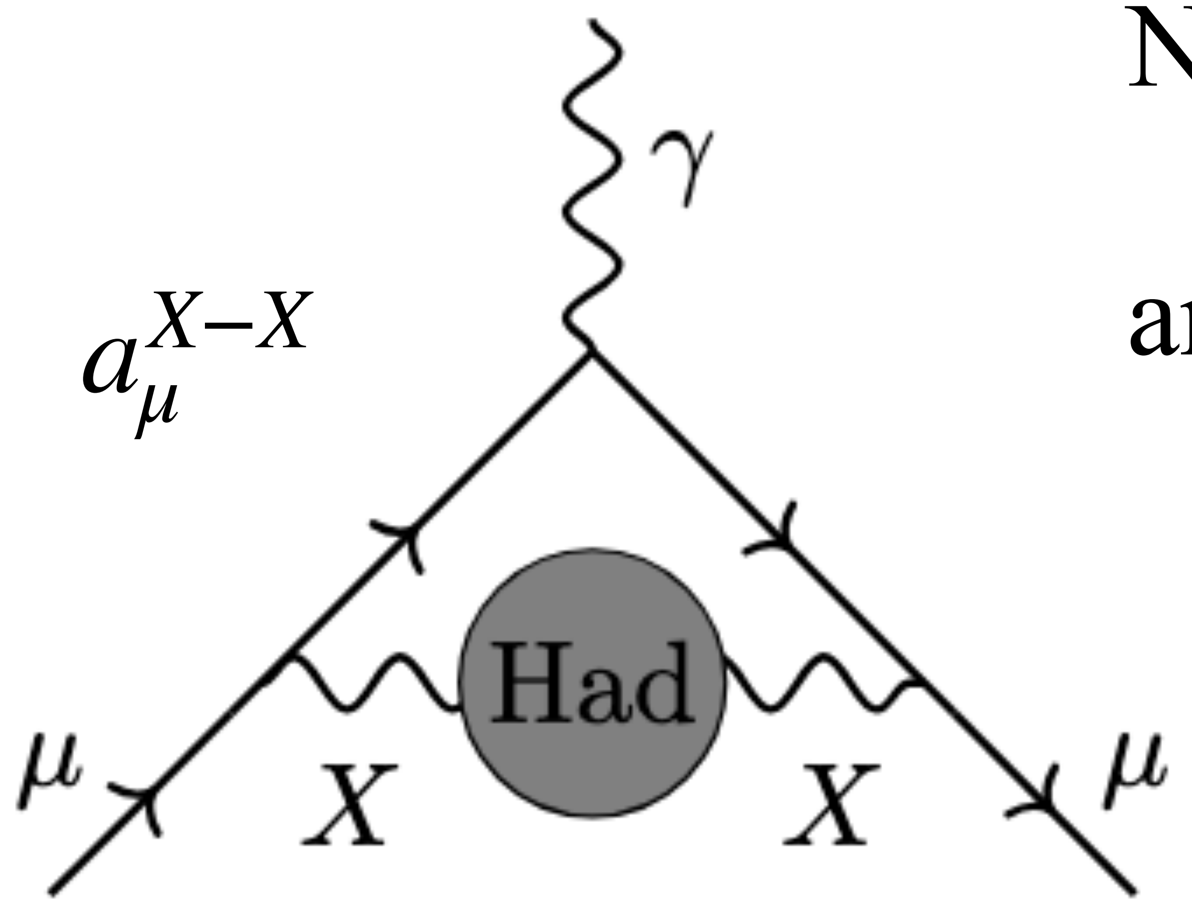




2 loop NP contribution to a_μ



$\gamma - X$ contribution



Pure X contribution

Non-perturbative blobs $\Pi_{\gamma-X}$ and Π_{X-X}

are difficult to compute

Using

(1) Optical Theorem

(2) Renormalisation choice $\Pi_{\gamma-X}(m_X^2) = 0$, $\Pi_{X-X}(m_X^2) = 0$

Just the HVP contamination

$$a_\mu^{\gamma-X} = (\mathrm{HVP})^{\gamma-X}$$
$$a_\mu^{X-X} = (\mathrm{HVP})^{X\ \mathrm{off}}$$

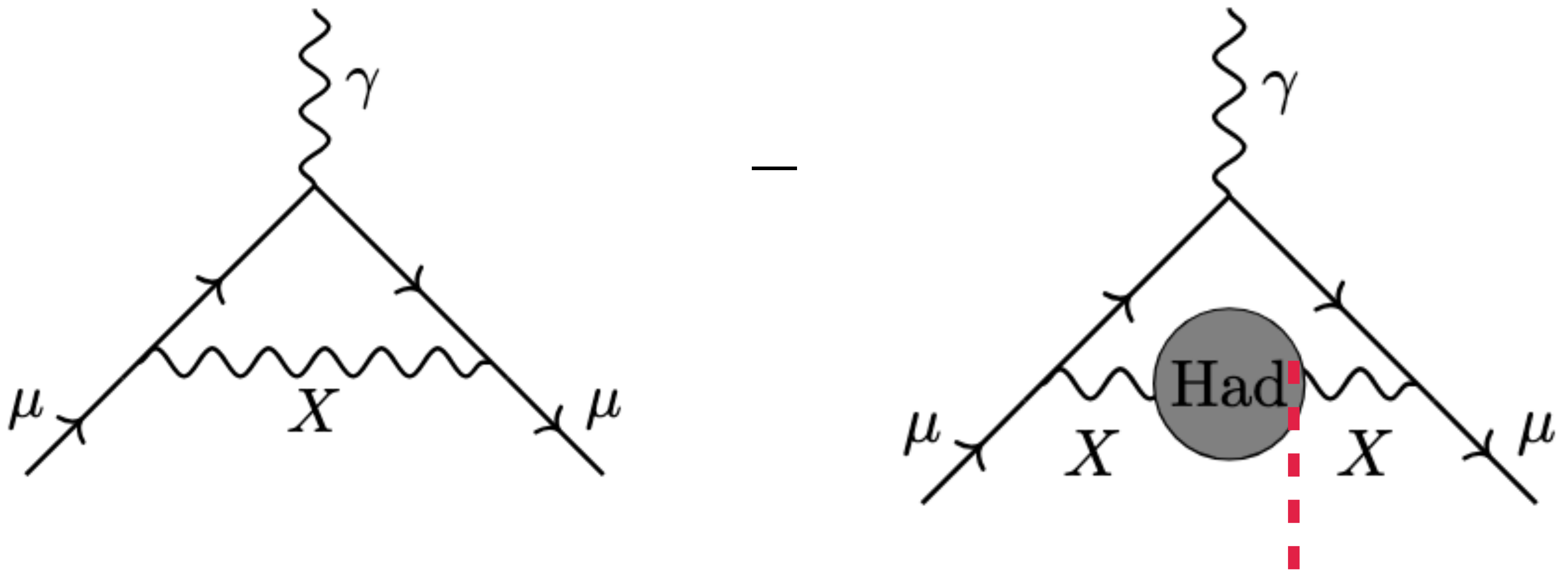
Small

Agashe, Banerjee, Jiang, Nussinov, **KP**, Paul, Perez, Soreq, arXiv:2412.12266, JHEP 08 (2025) 161

Further simplifications …

DD a_μ test: $a_\mu^{\rm exp} - a_\mu^{\rm DD} = a_\mu^X - ({\rm HVP})^{X-{\rm on}}$ $(\pm 2\sigma)$

$a_\mu^{\rm exp} - a_\mu^{\rm DD} =$



We showed..

$$({\rm HVP})^{X-{\rm on}} \approx a_\mu^X {\rm BR}(X \to {\rm had})$$

DD a_μ test: $a_\mu^{\rm exp} - a_\mu^{\rm DD} \approx a_\mu^X(1 - {\rm BR}({\rm X} \to {\rm had}))$ $(\pm 2\sigma)$

Cancellation

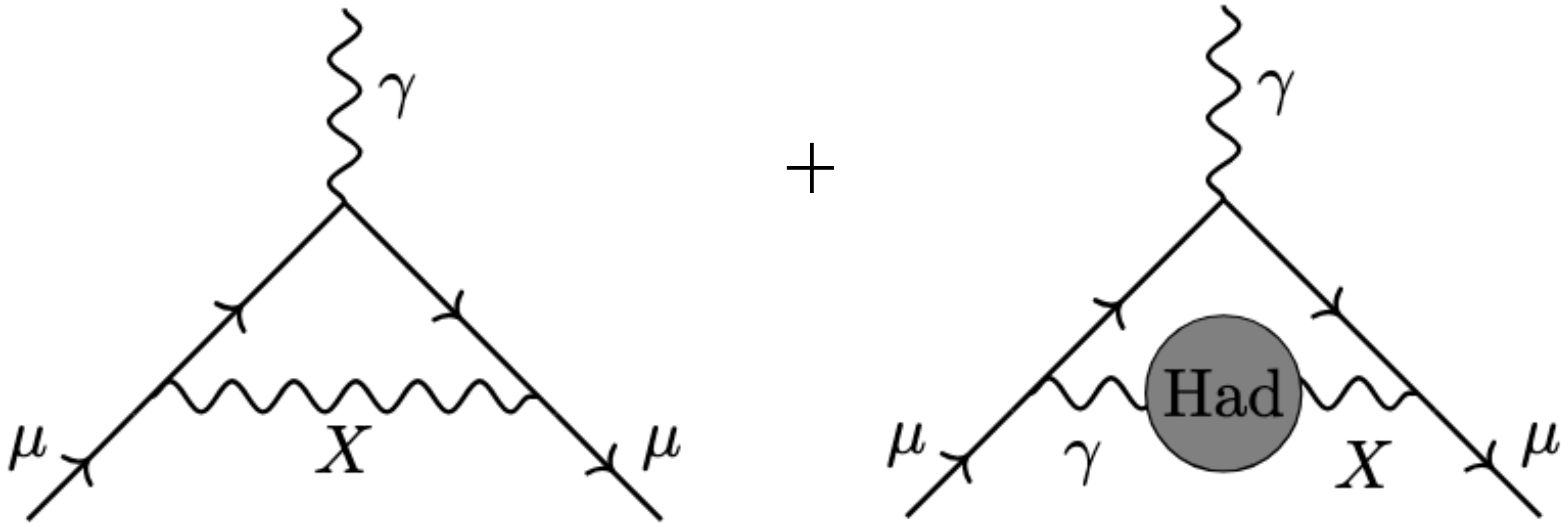
for ${\rm BR}(X \to {\rm had}) \to 1$

Putting all the tests together…

HVP Test

Lattice vs. Data-driven

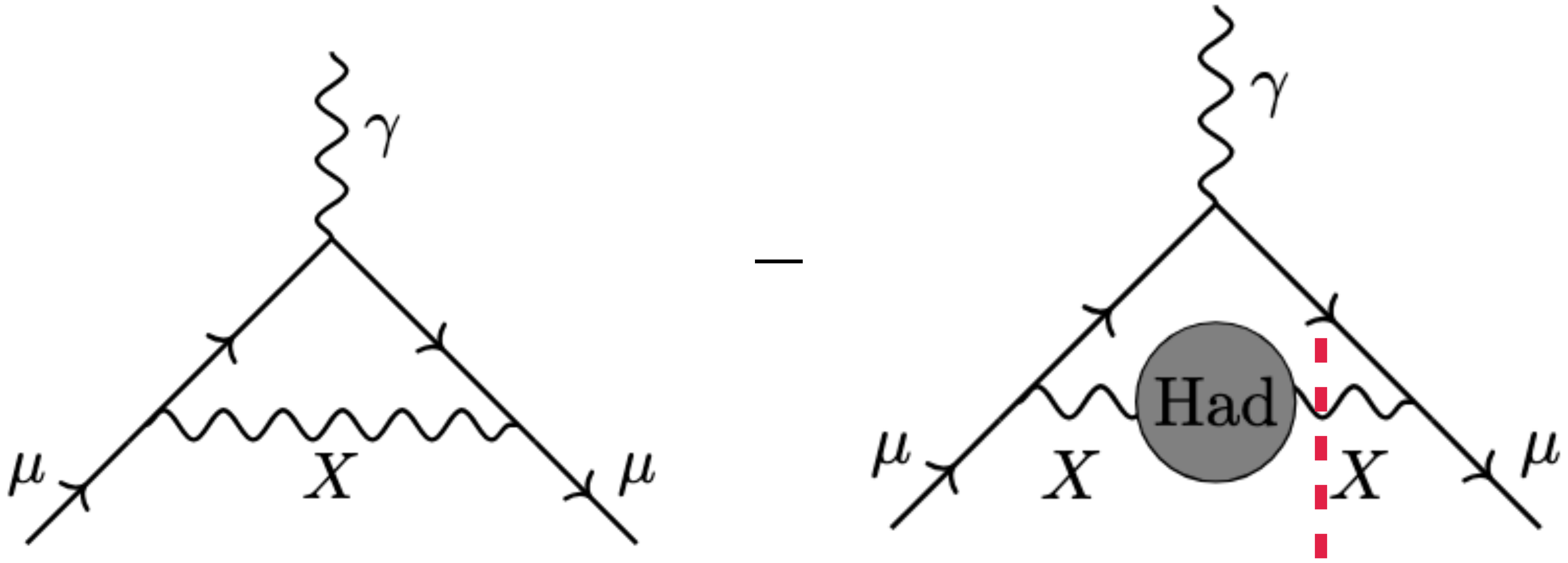
$$a_\mu^{\mathrm{DD}} - a_\mu^{\mathrm{lat}} = (\mathrm{HVP})^{\gamma - X} + a_\mu^X\ \mathrm{BR}(\mathrm{X} \to \mathrm{had}) \quad \pm 2\sigma$$



Data-driven a_μ test

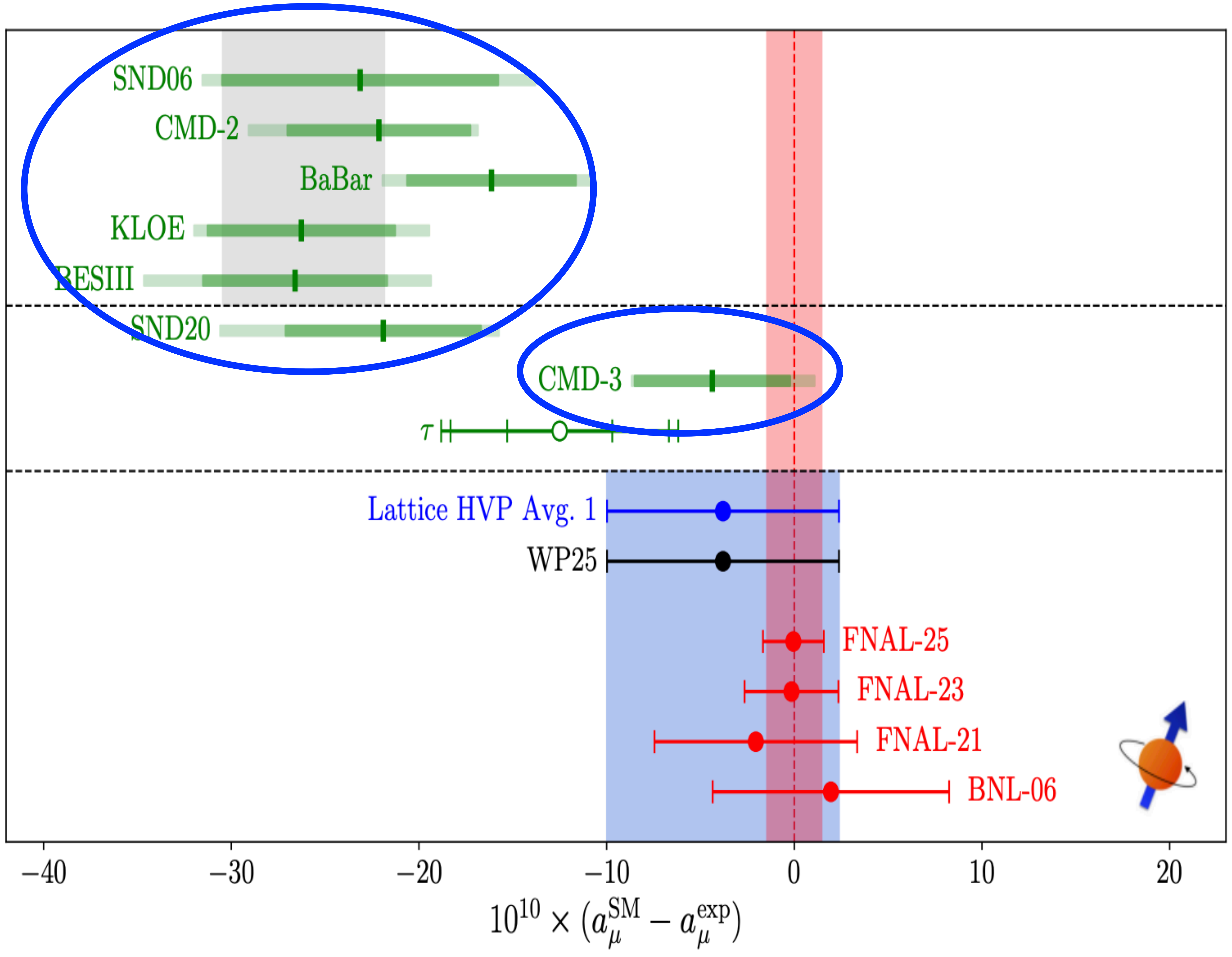
Data-driven vs. Exp

$$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{DD}} \approx a_\mu^X \left(1 - \mathrm{BR}(\mathrm{X} \to \mathrm{had})\right) \quad \pm 2\sigma$$



Revisting the tensions….

Lattice = BMW ’20, Exp= World avg. value



Exp. and lattice nos converge but DD numbers don’t due to different $\sigma(e^+e^- \to \text{had})$.

Current Scenario : Take white paper (TI 2020) result. HVP and DD a_μ test :

$$(\text{HVP})^{\gamma-X} + a_\mu^X\,\text{BR}(\text{X} \to \text{had}) = -201 \pm 2(73) \times 10^{-11}$$

$$a_\mu^X\left(1 - \text{BR}(\text{X} \to \text{had})\right) = 261 \pm 2(45) \times 10^{-11}$$

Futuristic Scenario : DD to be on top of lattice, discussed in our paper.

White paper ’25 [2505.21476]

For the current numbers

DD a_μ test rules out most points because of the cancellation between a_μ^X and $(\mathrm{HVP})^{X-\mathrm{on}}$.

$$a_\mu^X(1 - \mathrm{BR}(\mathrm{X} \to \mathrm{had})) = 261 \quad \pm 2\sigma \quad (\text{in units of } 10^{-11})$$

Dark photon | **Baryon No. with $g_l/g_q = 0.05$**

For the current numbers

For dark photon , far from resonances, BR_{had} ~0.5-1, so cancellation is not complete.

$$a_\mu^X(1 - \mathrm{BR}(X \to \mathrm{had})) = 261 \quad \pm 2\sigma \quad (\text{in units of } 10^{-11})$$

For the current numbers

For Baryon number gauge boson, $\mathrm{BR}_{\mathrm{had}} \approx 1$, hence complete cancellation.

$$a_\mu^X(1 - \mathrm{BR}(X \to \mathrm{had})) = 261 \quad \pm 2\sigma \quad (\text{in units of } 10^{-11})$$

For the current numbers

Almost all the parameter space is excluded now.

$$(\mathrm{HVP})^{\gamma-X} + a_\mu^X \ \mathrm{BR}(\mathrm{X} \to \mathrm{had}) = -201 \quad \pm 2\sigma \ \ (\text{in units of } 10^{-11})$$

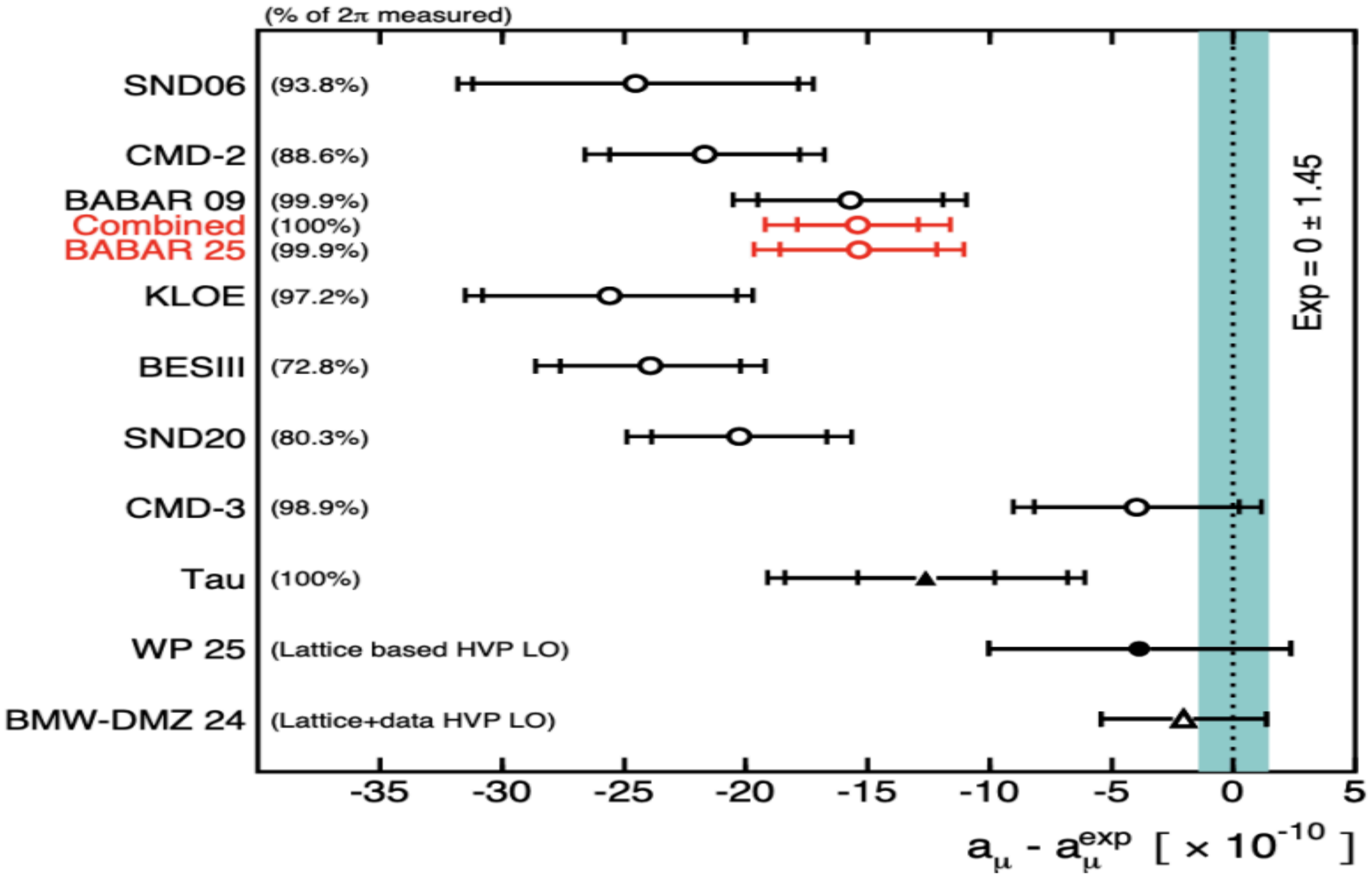
+ve

Dark photon **Baryon No. with $g_l/g_q = 0.05$**

Conclusions

- $(g-2)_\mu$ provides a model independent way to probe light Z'.
- Two independent tests proposed:
  - a_μ test: Exp. vs. Lattice or Exp. vs. DD
  - HVP test: Lattice vs DD (Current vs. Futuristic)
- Cancellations between 1-loop and 2-loop on-shell effects leads to exclusion.
- Based on current lattice, experiment and data-driven (TI '20), **both** dark photon and Baryon number gauge boson are excluded. The **standard Model** is also excluded!

Outlook



Babar 2025 update to HVP

KLOE update coming soon!

Model building for Baryon No.

to solve the HVP puzzle

Direct search for Baryon

No. gauge boson at Babar,

KLOE , $e^+e^- \to 3\pi$

BABAR, Lepton-Photon 2025, Zhiqing Zhang

Thank You!

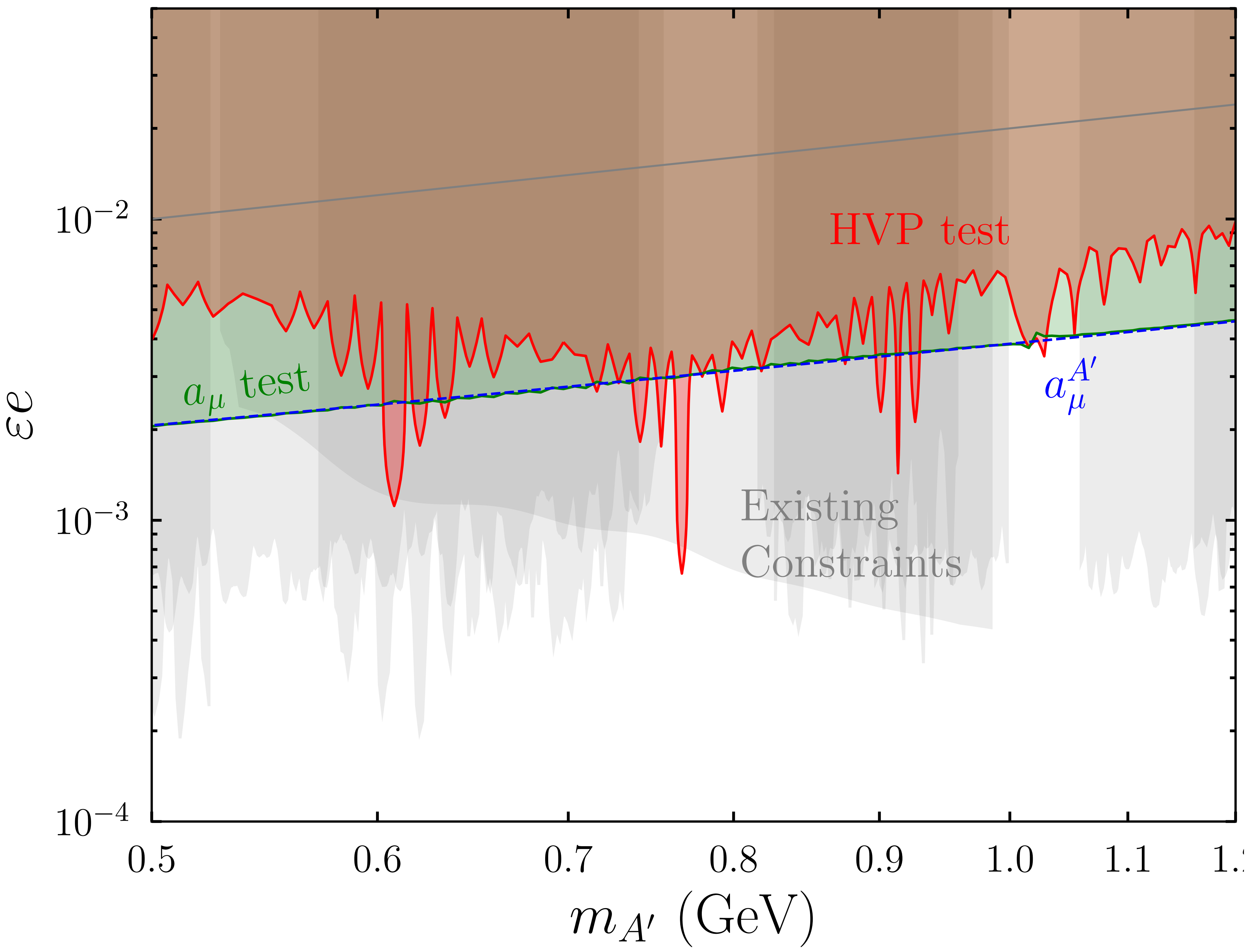
BACKUP

For the futuristic case

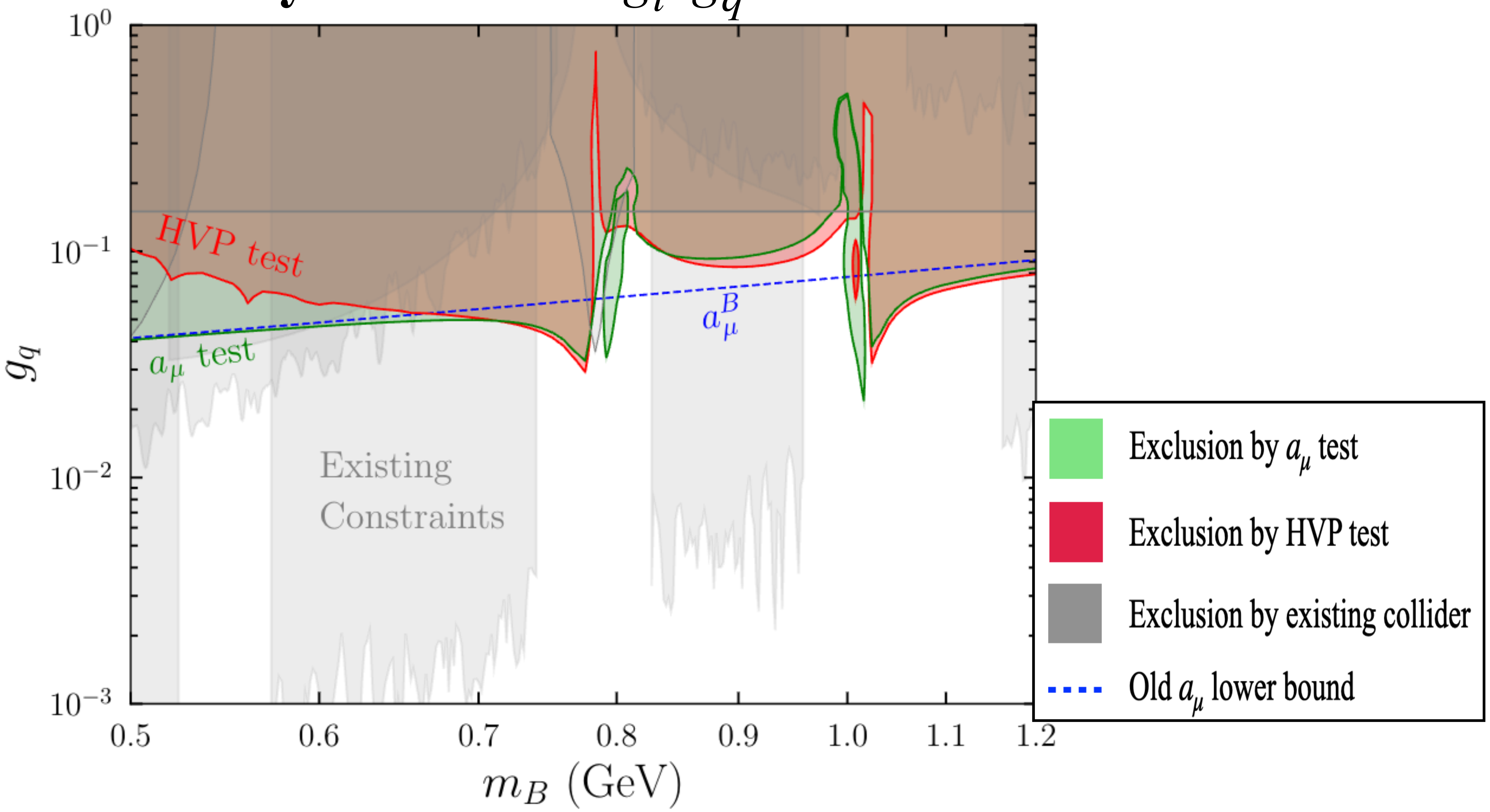
This time the tests are less stringent. SM is consistent with both tests

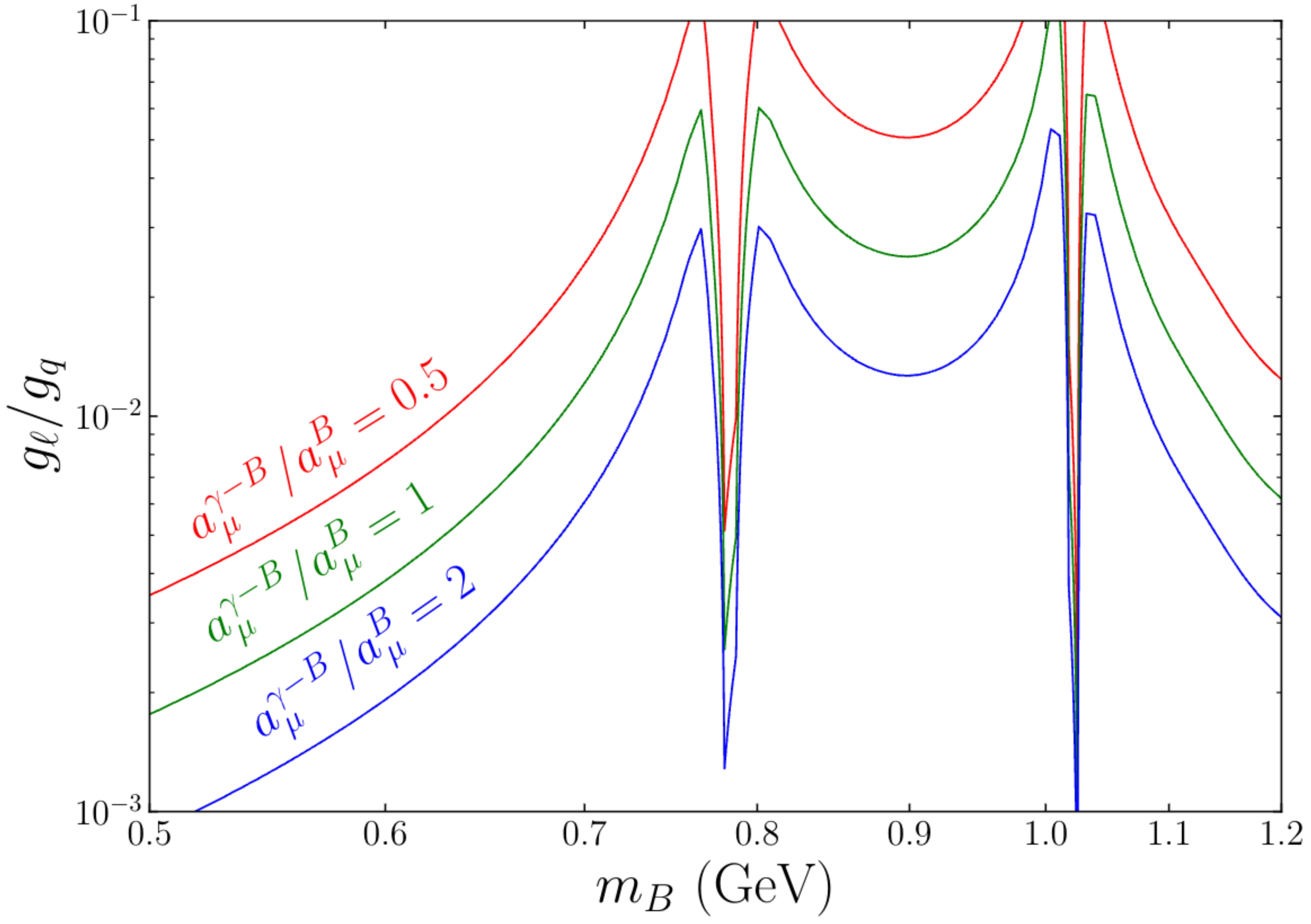
$$a_\mu^{\gamma-X} + a_\mu^X \ \mathrm{BR}(X \to \mathrm{had}) = 0 \qquad\qquad a_\mu^{\gamma-X} + a_\mu^X = 40$$

Dark photon



Baryon No. with $g_l/g_q = 0.05$





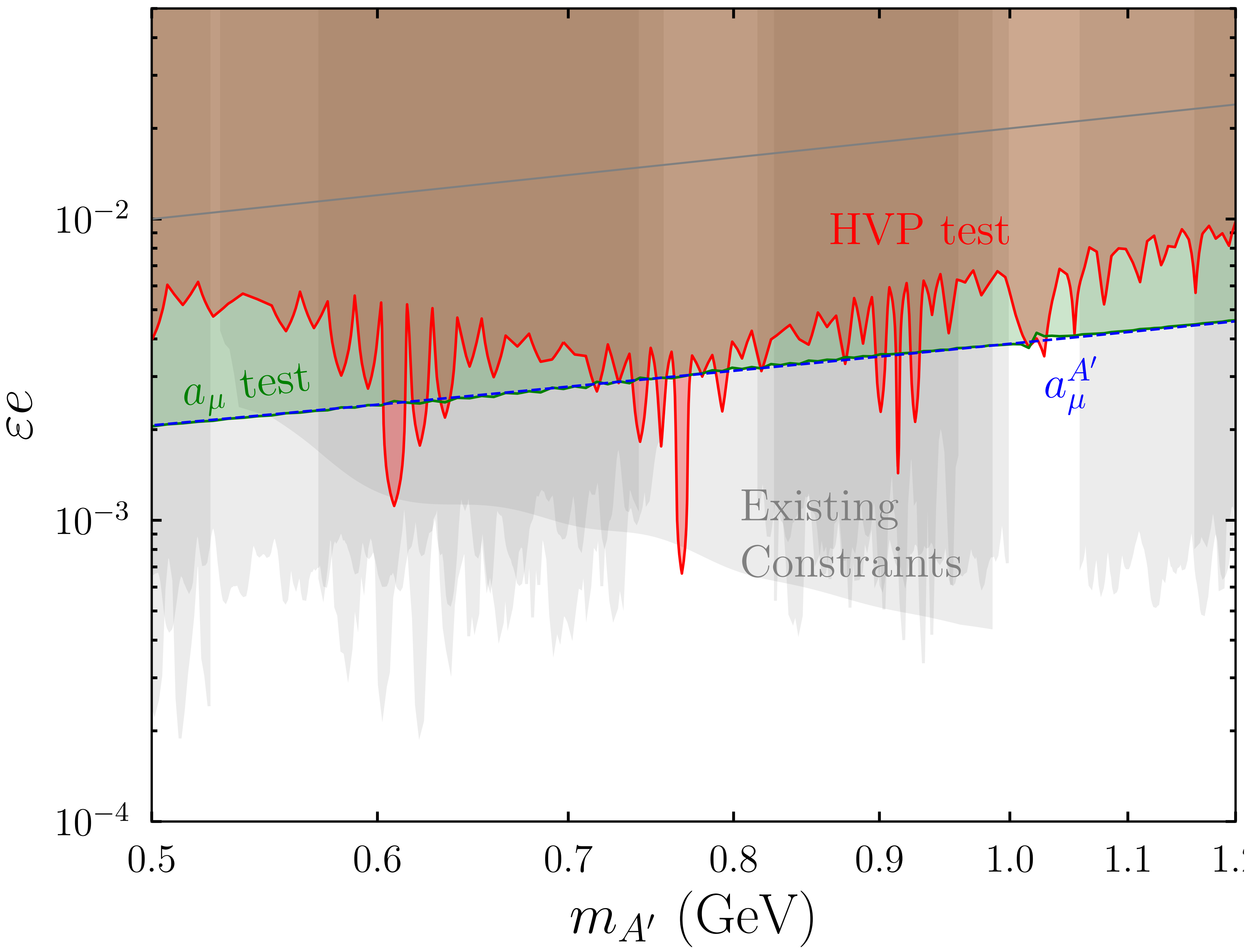
10^{-1}
10^{-2}
10^{-3}
g_ℓ/g_q
$a_\mu^{\gamma-B}\,/\,a_\mu^{B} = 0.5$
$a_\mu^{\gamma-B}\,/\,a_\mu^{B} = 1$
$a_\mu^{\gamma-B}\,/\,a_\mu^{B} = 2$
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
m_B (GeV)

For the futuristic case

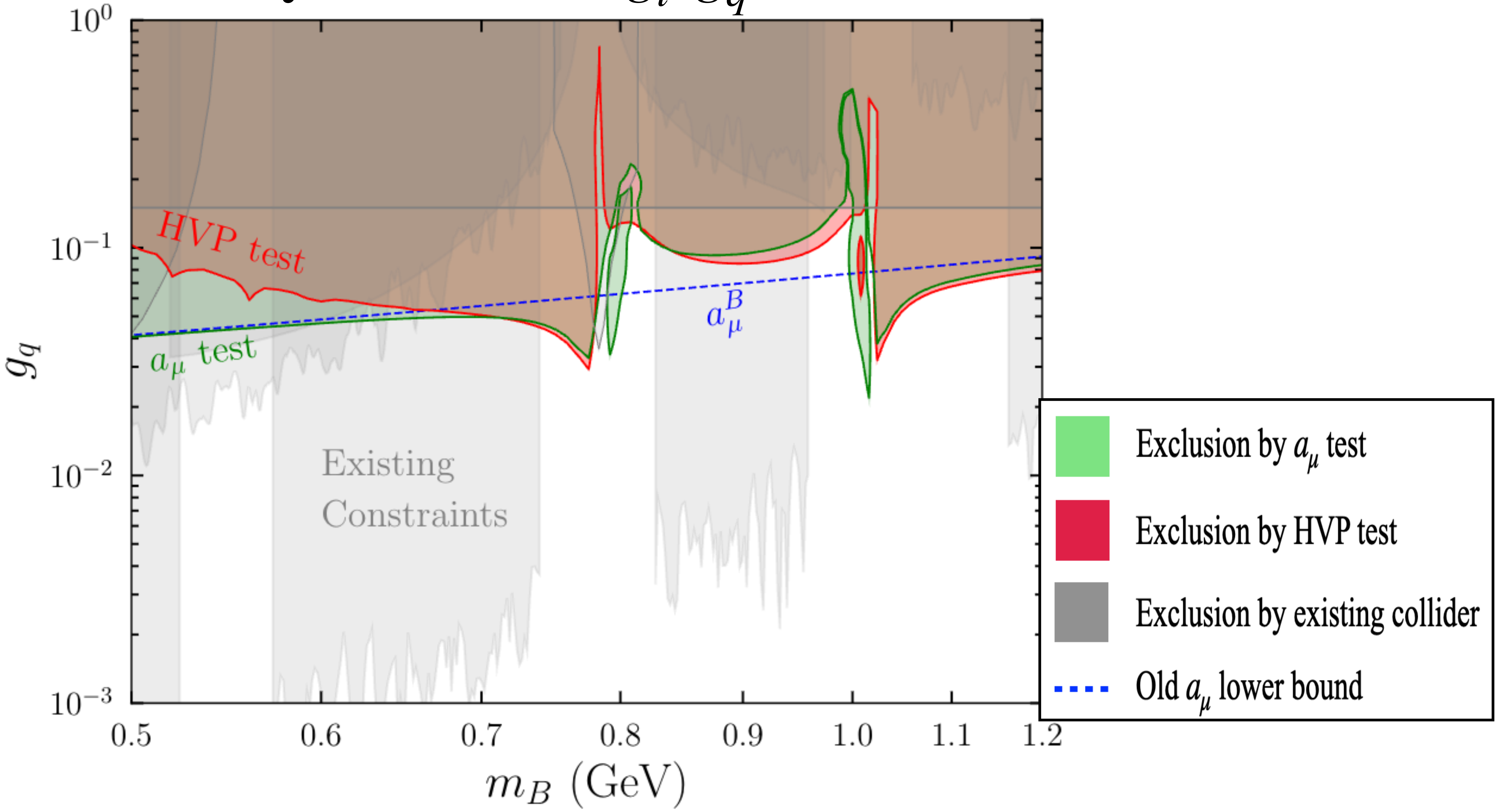
We see that $a_\mu^{\gamma-X} \ll a_\mu^X$ for dark photon so a_μ test doesn't add much value

$$a_\mu^{\gamma-X} + a_\mu^X \ \mathrm{BR}(\mathrm{X} \to \mathrm{had}) = 0 \qquad\qquad a_\mu^{\gamma-X} + a_\mu^X = 40$$

Dark photon



Baryon No. with $g_l/g_q = 0.05$

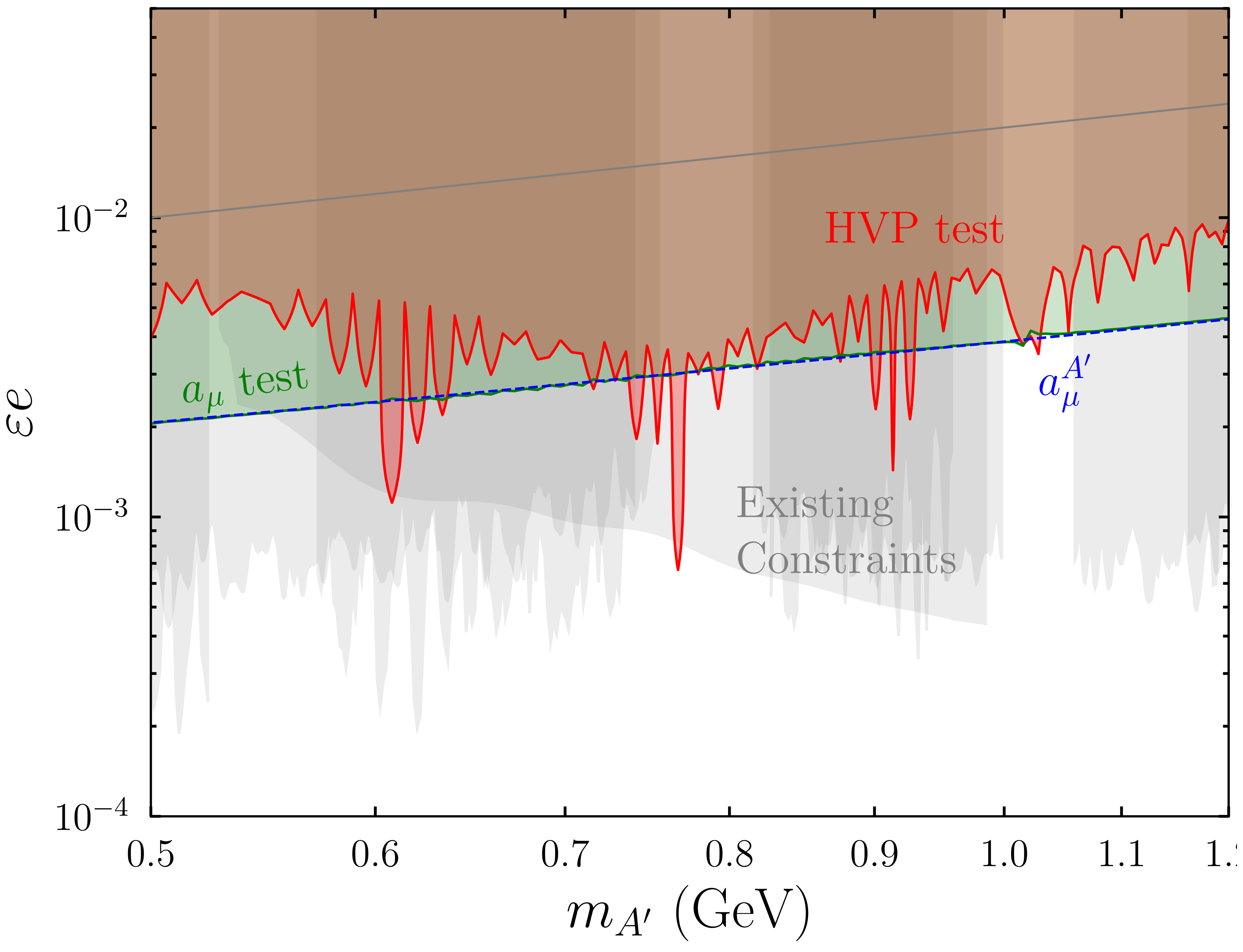


For the futuristic case

We are able to cover the QCD resonances.

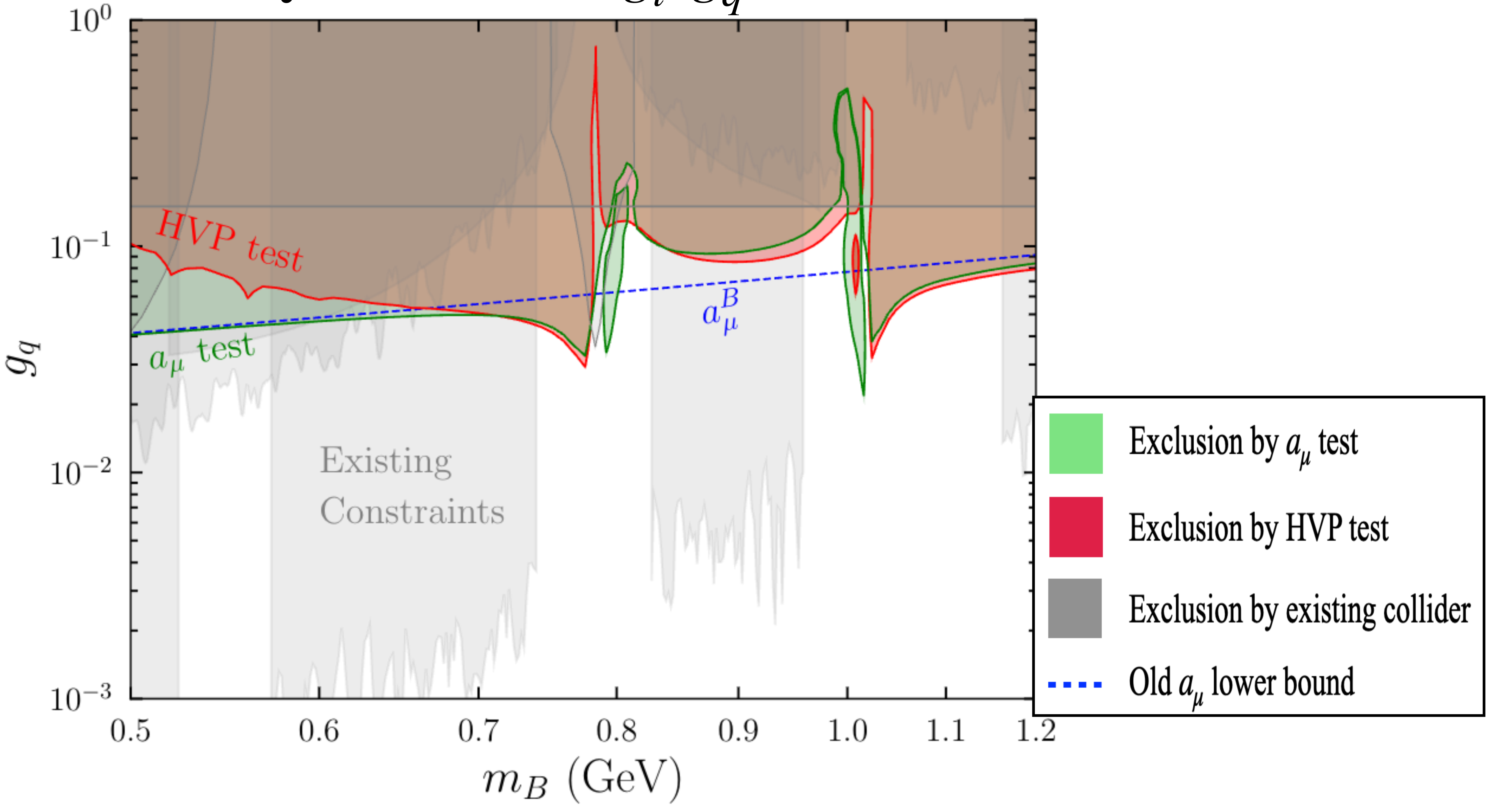
$$a_\mu^{\gamma-X} + a_\mu^X \, \mathrm{BR}(X \to \mathrm{had}) = 0$$

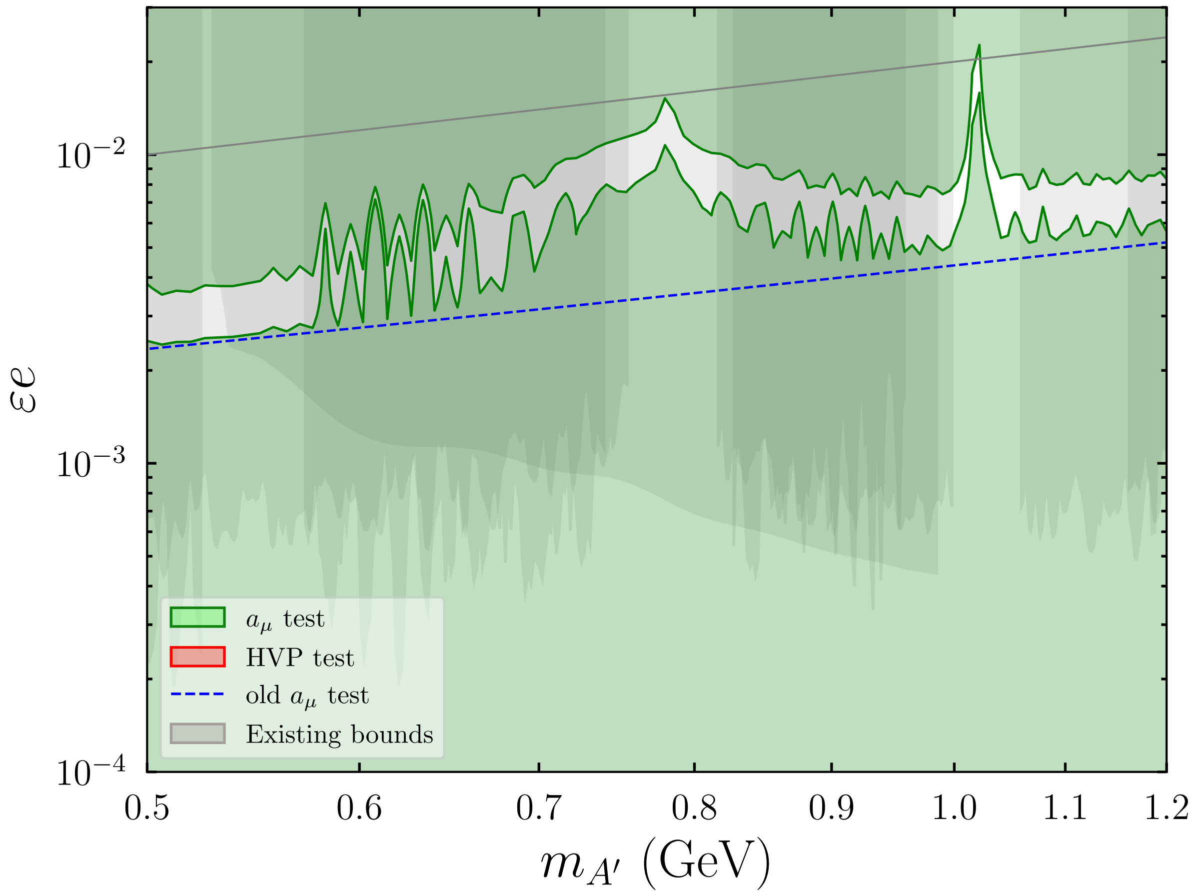
Dark photon



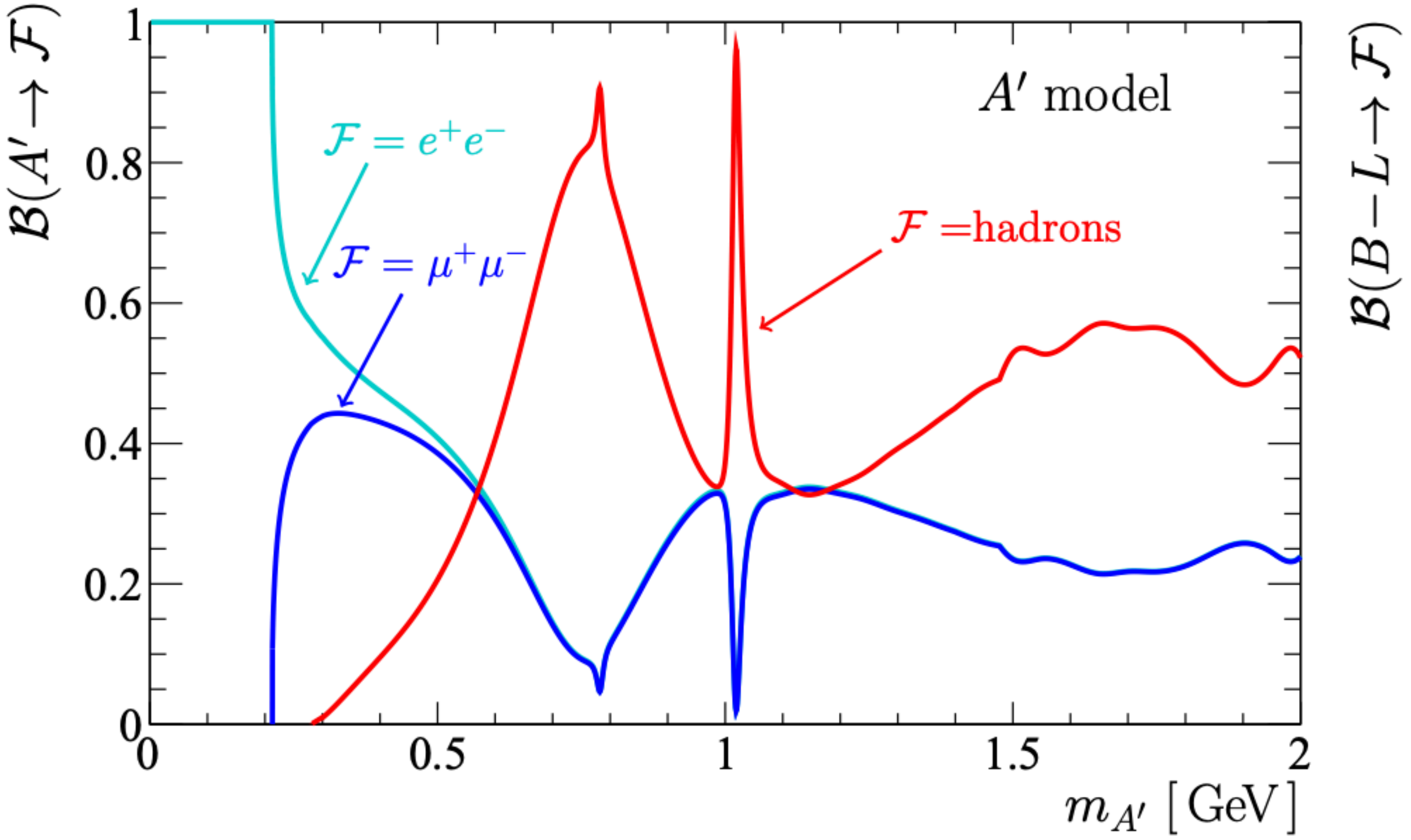
$$a_\mu^{\gamma-X} + a_\mu^X = 40$$

Baryon No. with $g_l/g_q = 0.05$

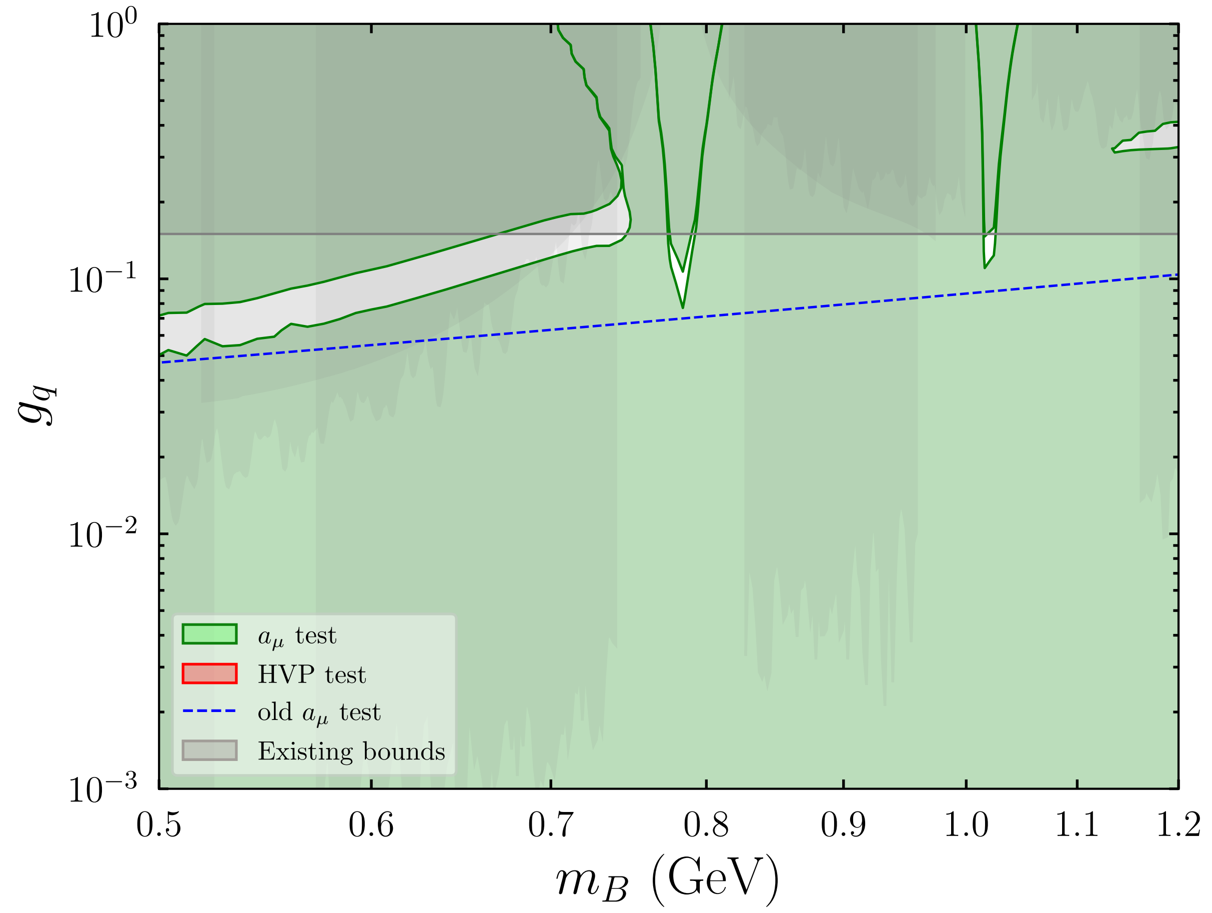




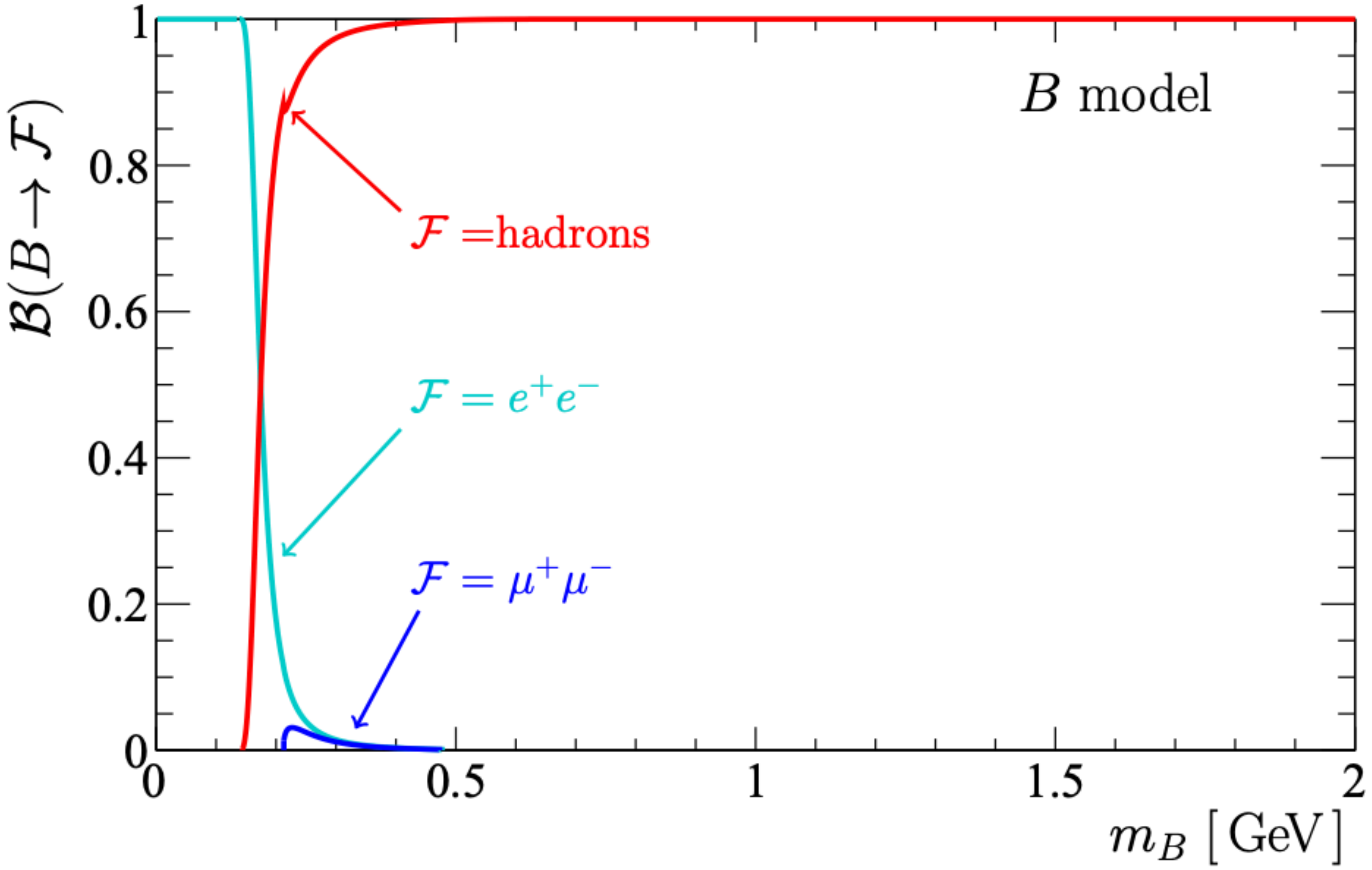
a_μ test
HVP test
old a_μ test
Existing bounds
εe
$m_{A'}$ (GeV)



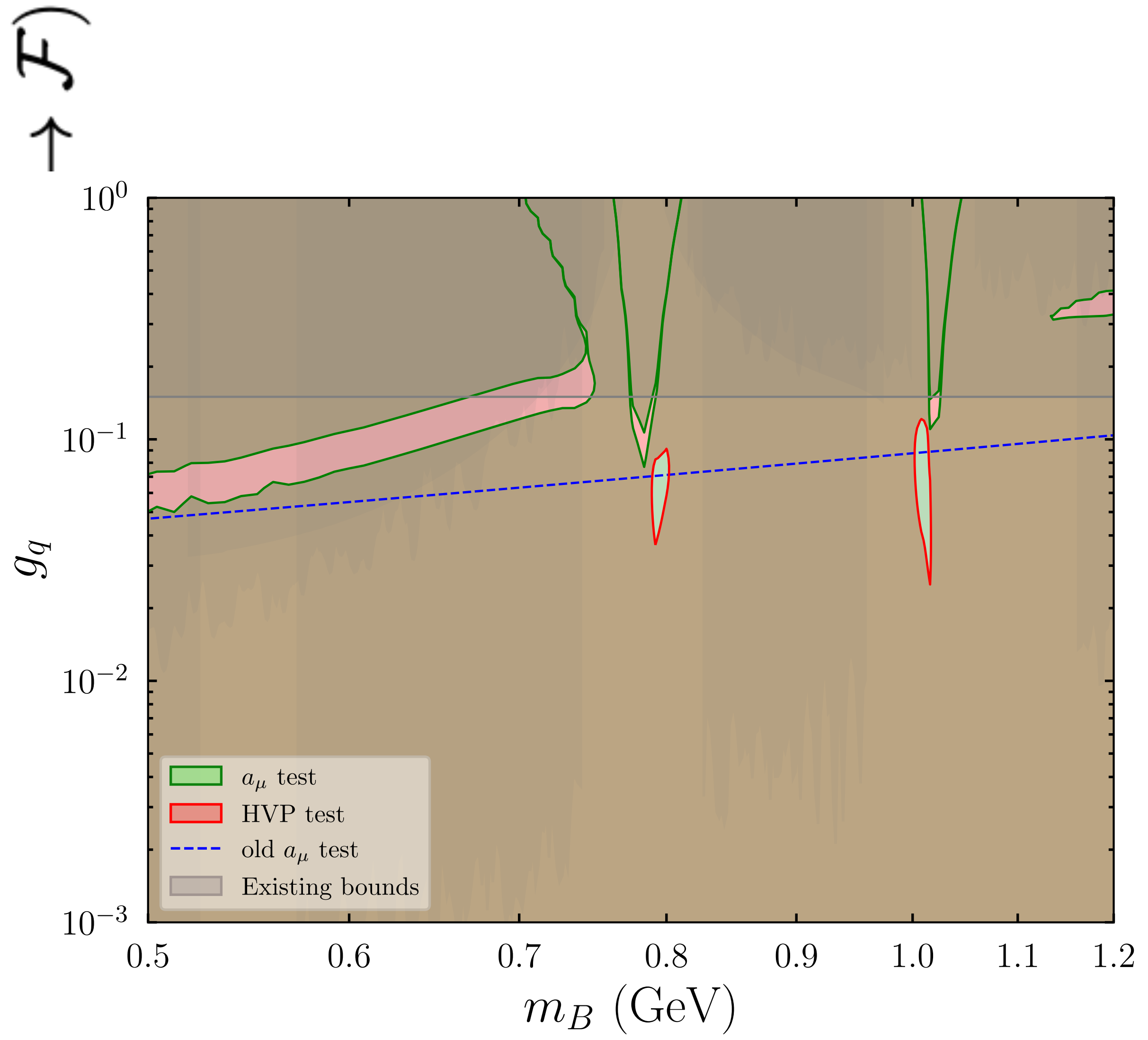
$\mathcal{B}(A' \to \mathcal{F})$
A' model
$\mathcal{F} = e^+e^-$
$\mathcal{F} = \mu^+\mu^-$
$\mathcal{F}$ =hadrons
$m_{A'}$ [GeV]
$\mathcal{B}(B-L \to \mathcal{F})$



a_μ test
HVP test
old a_μ test
Existing bounds
g_q
m_B (GeV)



$\mathcal{B}(B \to \mathcal{F})$
B model
$\mathcal{F}$ =hadrons
$\mathcal{F} = e^+e^-$
$\mathcal{F} = \mu^+\mu^-$
m_B [GeV]



a_μ test
HVP test
old a_μ test
Existing bounds
g_q
m_B (GeV)