Light dark sectors and the muon g-2 anomalies

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

Giovanni Grilli di Cortona
grillidc@lnf.infn.it

based on:
L. Darmé, G^2dC and E. Nardi, *JHEP* 06 (2022) 122 (arXiv:2112.09139)
L. Darmé, G^2dC and E. Nardi, arXiv:2212.03877

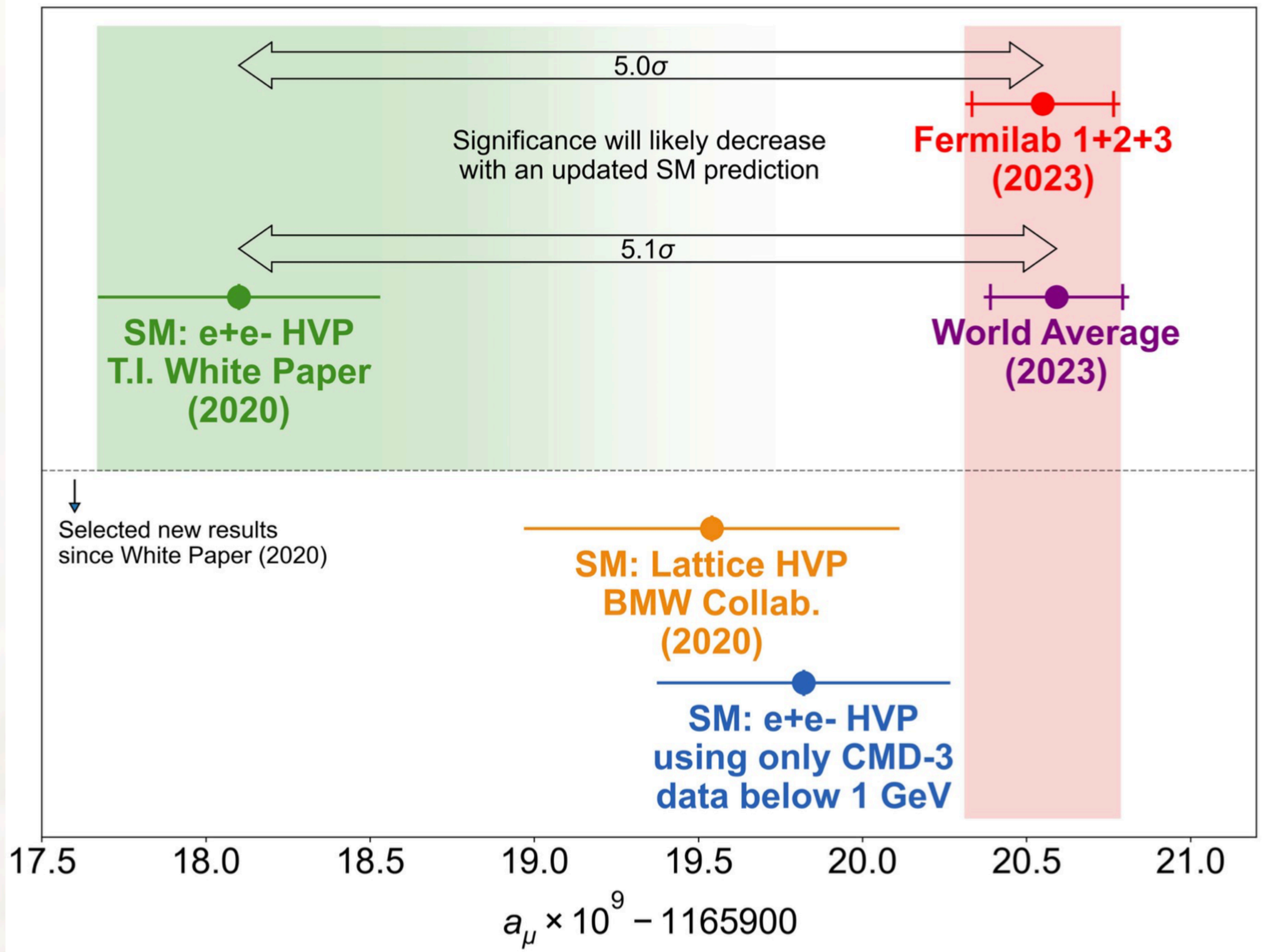
3rd DMNet International Symposium, Padova - 27/09/2023

Outline

- Introduction
- The muon (g-2) SM estimate
- New physics modification of the hadronic cross section
  1. Direct effects
  2. Indirect effects: luminosity determination and $\sigma(\mu\mu\gamma)$ method
- Solving the a_μ tensions? Model and constraints.
- Conclusions

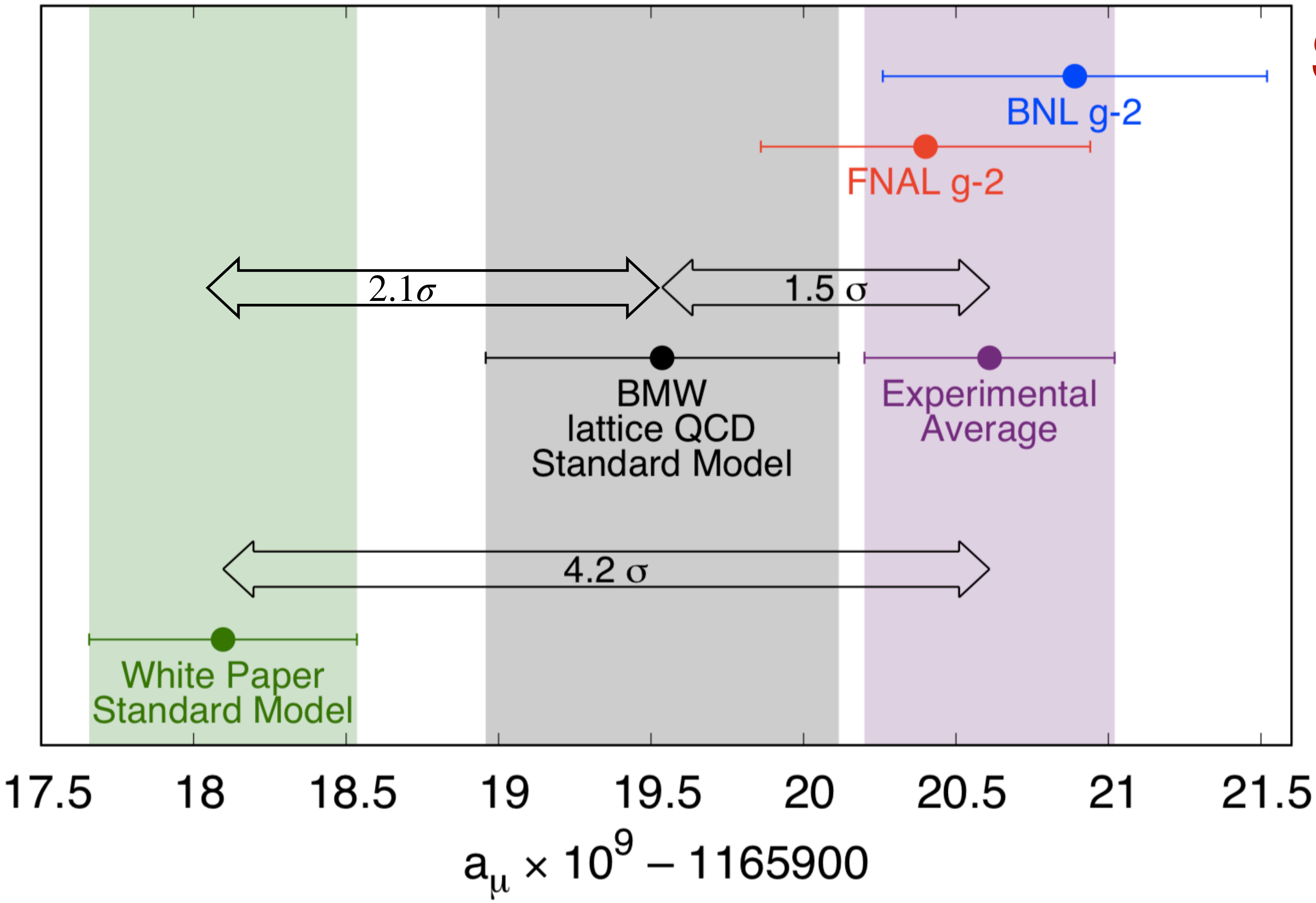
Introduction

taken from Keshavarzi's slides at Lattice 2023



Situation after August 2023

Introduction



Situation before August 2023

- Experiment vs SM estimate

$$\Delta a_\mu = 251(59) \cdot 10^{-11}$$

- SM vs lattice estimate

[full: BMW ('21)
partial: CLS/Mainz ('22), ETMC ('22), RBC/UKQCD ('23), …]

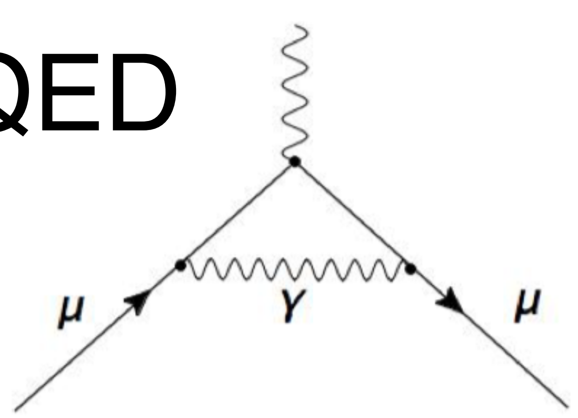
The SM estimate

[Aoyama et al, 2006.04822, Phys. Rept. 887 (2020) 1-166]

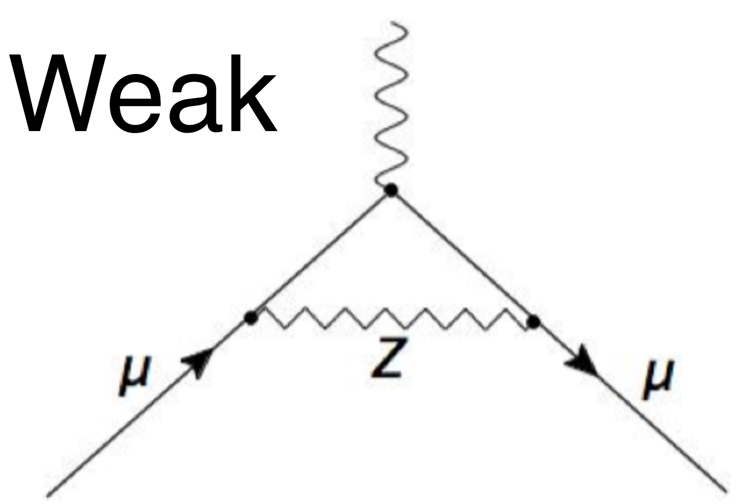
$116584718.9(1) \cdot 10^{-11}$

$6845(40) \cdot 10^{-11}$

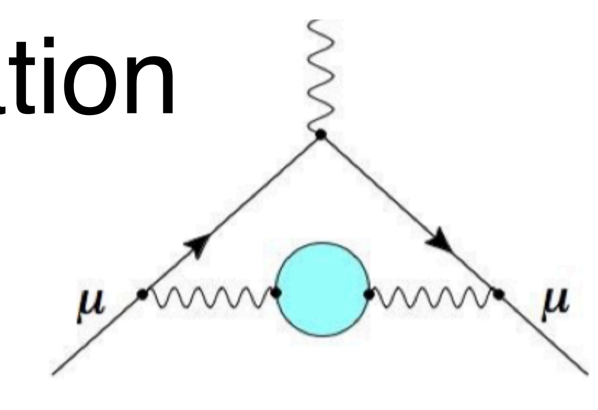
QED



Weak

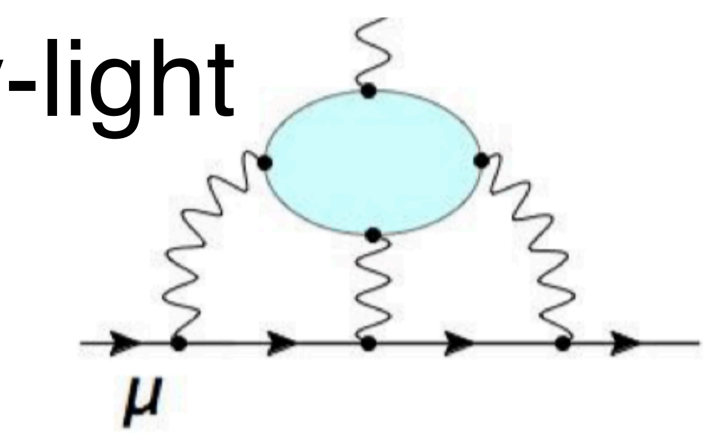


Hadronic vacuum polarization



$+ \ldots$

Hadronic light-by-light



$153.6(1.0) \cdot 10^{-11}$

$92(18) \cdot 10^{-11}$

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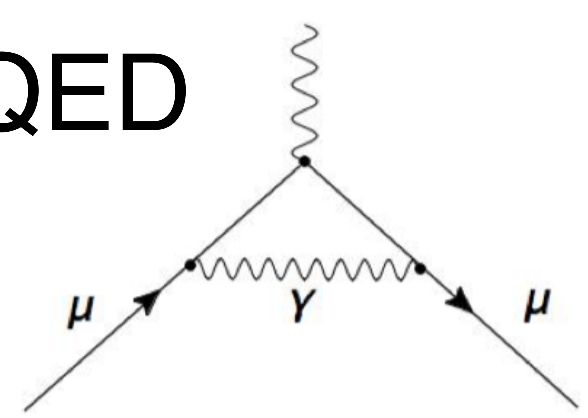

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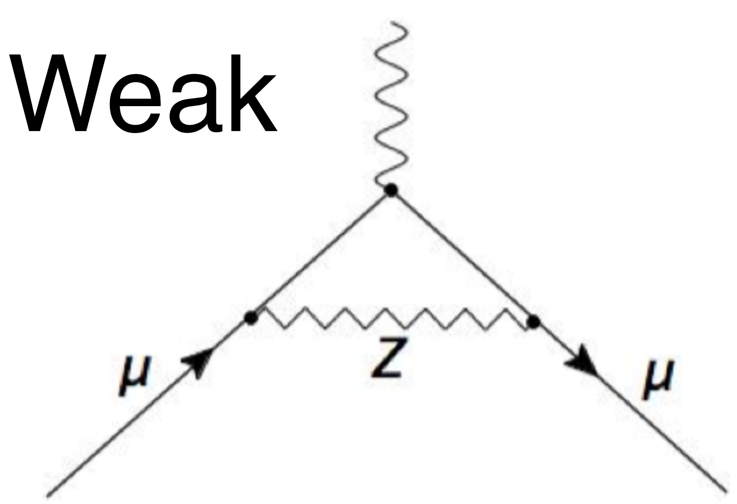

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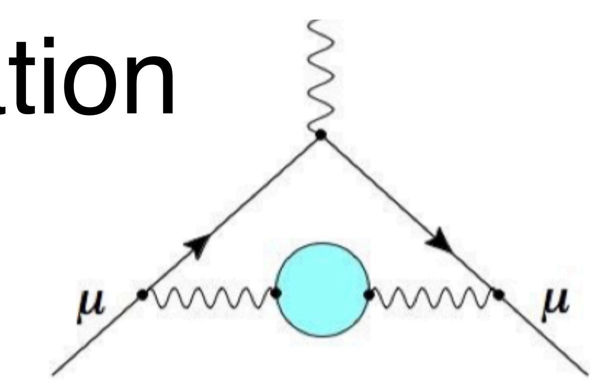
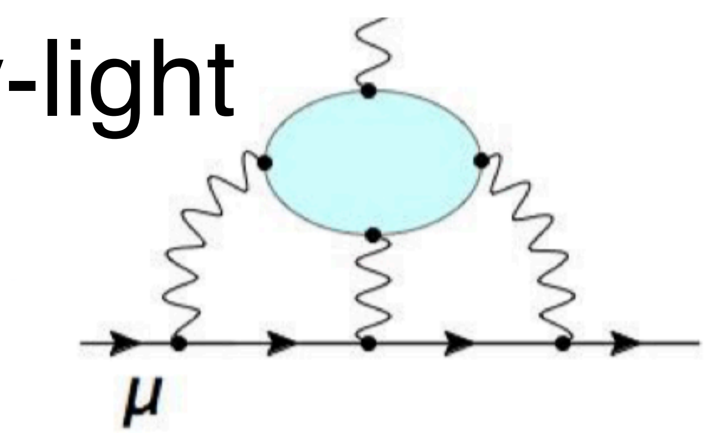


$+\ldots$

Hadronic light-by-light



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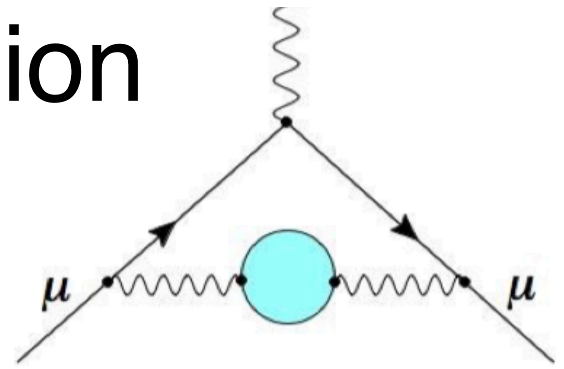


$$6845(40) \cdot 10^{-11}$$

Kernel function $\propto s^{-1}$: lower energies more important

$$a_\mu^{LO,HVP} = \frac{1}{4\pi^3} \int_{s_{th}}^{\infty} ds\, K(s)\, \sigma_{\rm had}(s)$$

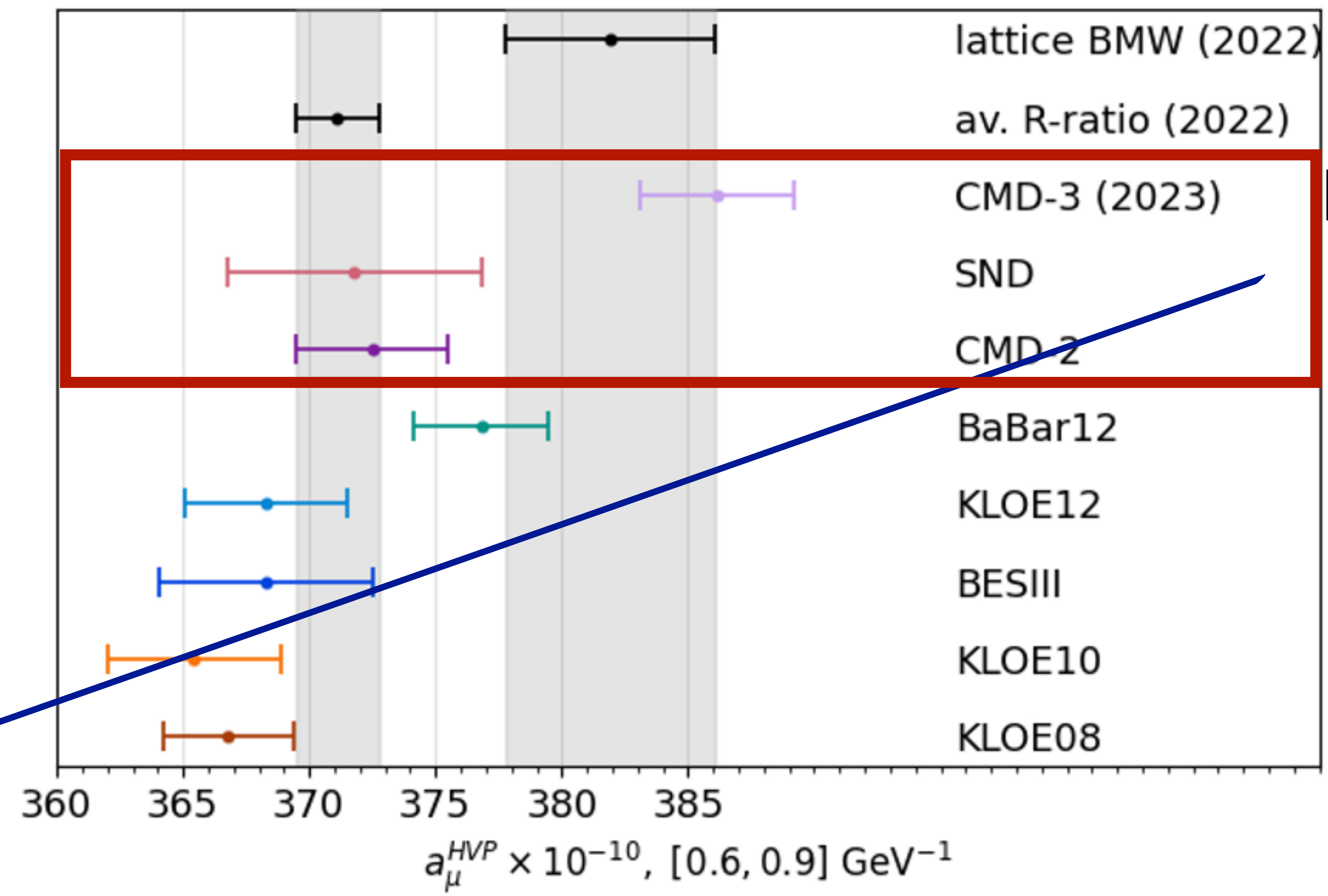
$e^+e^- \to$ hadrons bare cross section: experimental input

The SM estimate

The σ_{had} must be measured at all centre of mass energy $\sqrt{s}$:

1. Scan analysis by directly varying $\sqrt{s}$ - CMD-2, CMD-3, SND;

$$e^+ e^- \to \pi\pi$$



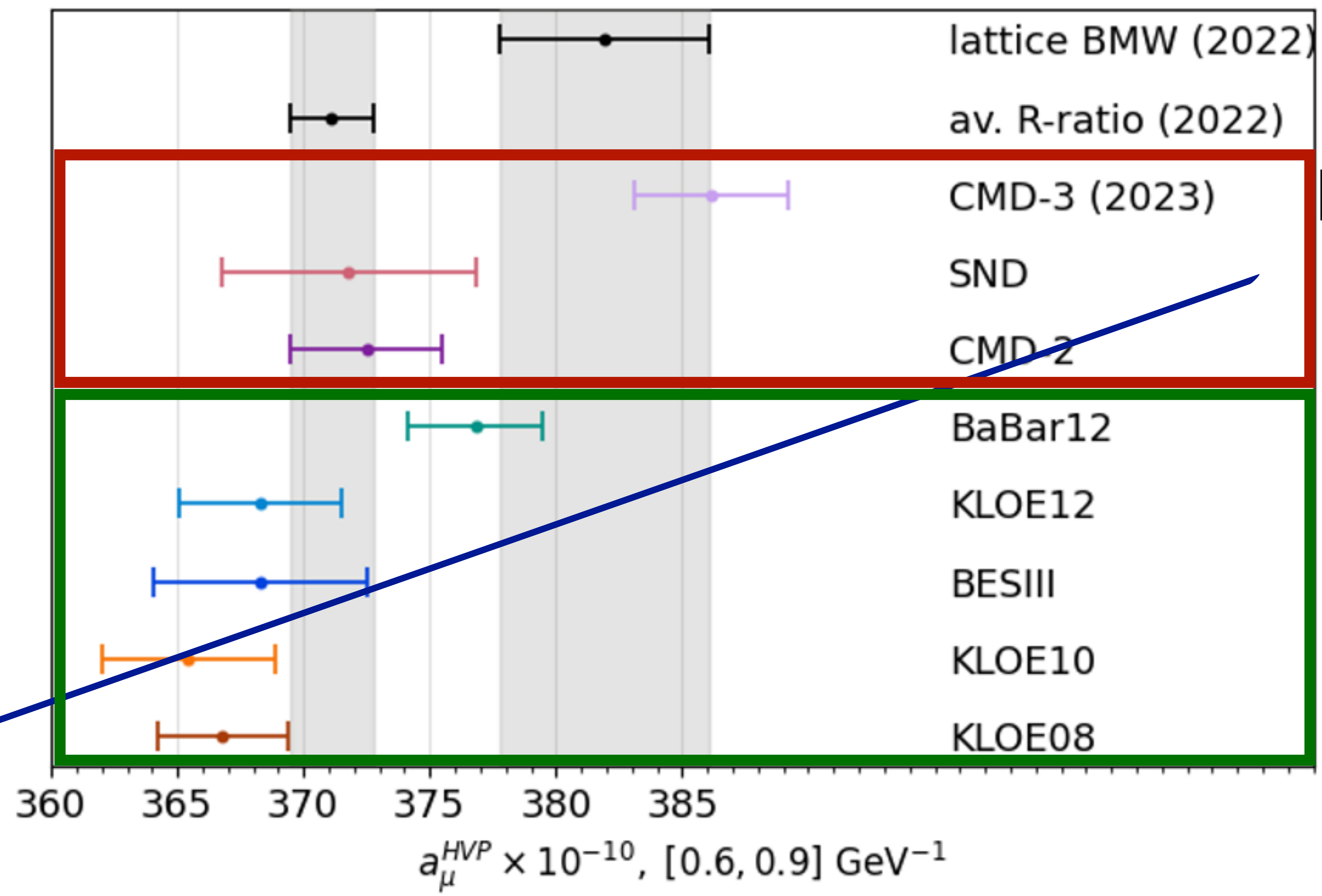
[2302.08834]

The SM estimate

The σ_{had} must be measured at all centre of mass energy $\sqrt{s}$:

1. Scan analysis by directly varying $\sqrt{s}$ - CMD-2, CMD-3, SND;
2. Use Initial State Radiation to measure the $\sqrt{s}$ of each collision - KLOE, BaBar, BESIII, CLEO.

$$e^+ e^- \to \pi\pi$$



[2302.08834]

Discrepancies

As a consequence we have the following **discrepancies**:

- **Experiment vs SM data-driven** estimate

- **SM data-driven vs lattice** estimate

- **3σ tension** between **BaBar and KLOE data** used in the SM data-driven estimate (+ recent **5σ tension** between **CMD3 and KLOE data**)

  [CMD3: 2302.08834]

Direct new physics effects

Can new physics effects impact the hadronic cross section determination?

Direct new physics effects

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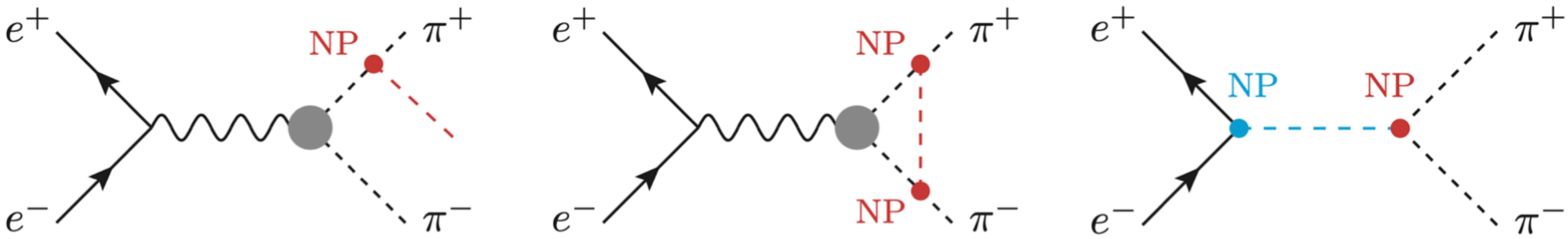
It is challenging to affect the hadronic cross-section via extra contributions since the hadronic cross sections are very large!

A shift of $\sigma_{\rm had}$ induces an increase of $\Delta\alpha^{(5)}_{\rm had}(m_Z)$, disfavoured by the EW fit if the shift happens at $\sqrt{s} \gtrsim 1$ GeV.

[Marciano et al. '08, '09, '10, Keshavarzi et al '20]

Light new physics leading to a sub-GeV modification of $\sigma_{\rm had}$

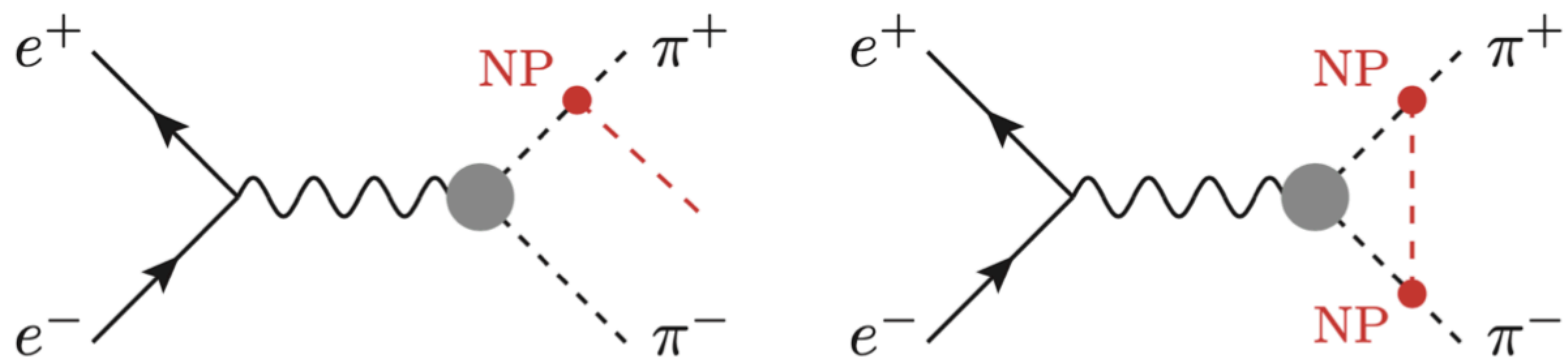
Direct new physics effects



Direct new physics effects

1. New physics coupled only to hadrons

[Di Luzio et al ’21]



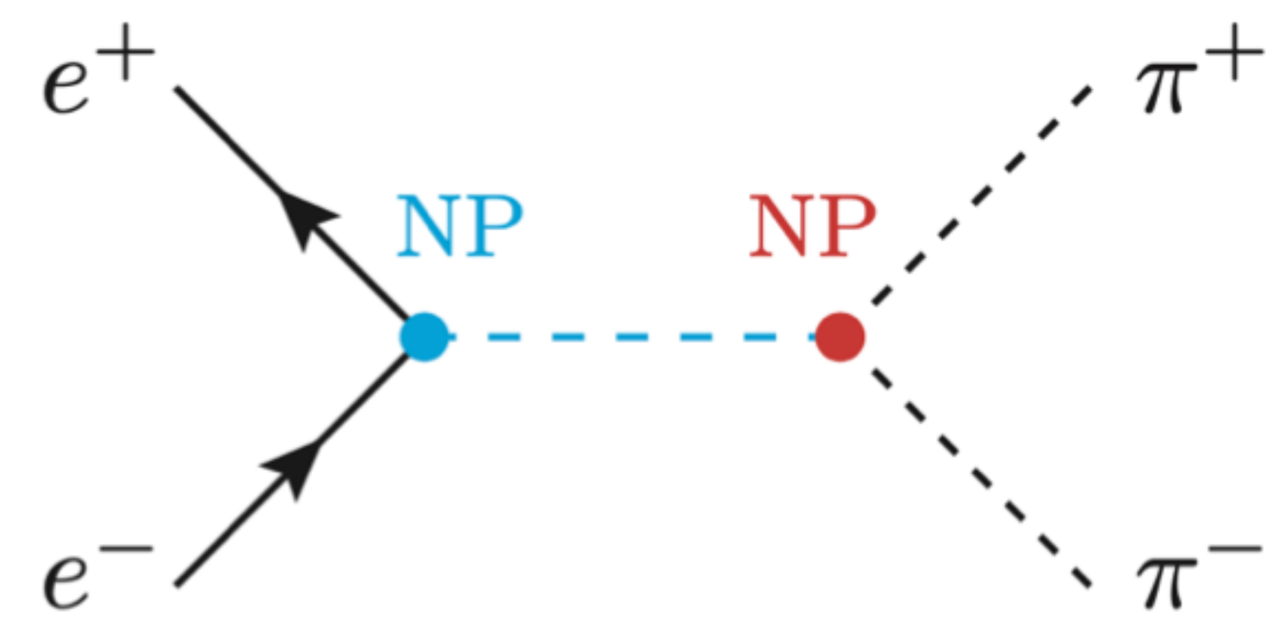
Light NP couplings to SM are strongly constrained;
Important NP FSR estimated from scalar QED are
$$50 \times 10^{-11} \ll 150 \times 10^{-11}$$

NP contributions in FSR cannot solve the muon g-2 problem

Direct new physics effects

2. New physics coupled to hadrons and electrons

[Di Luzio et al ’21]



$$a_\mu^{\rm HVP} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{\rm had}(s) \quad \Rightarrow \quad \sigma_{\rm had} = \sigma_{\rm had}^{\rm SM} + \Delta\sigma_{\rm had}$$

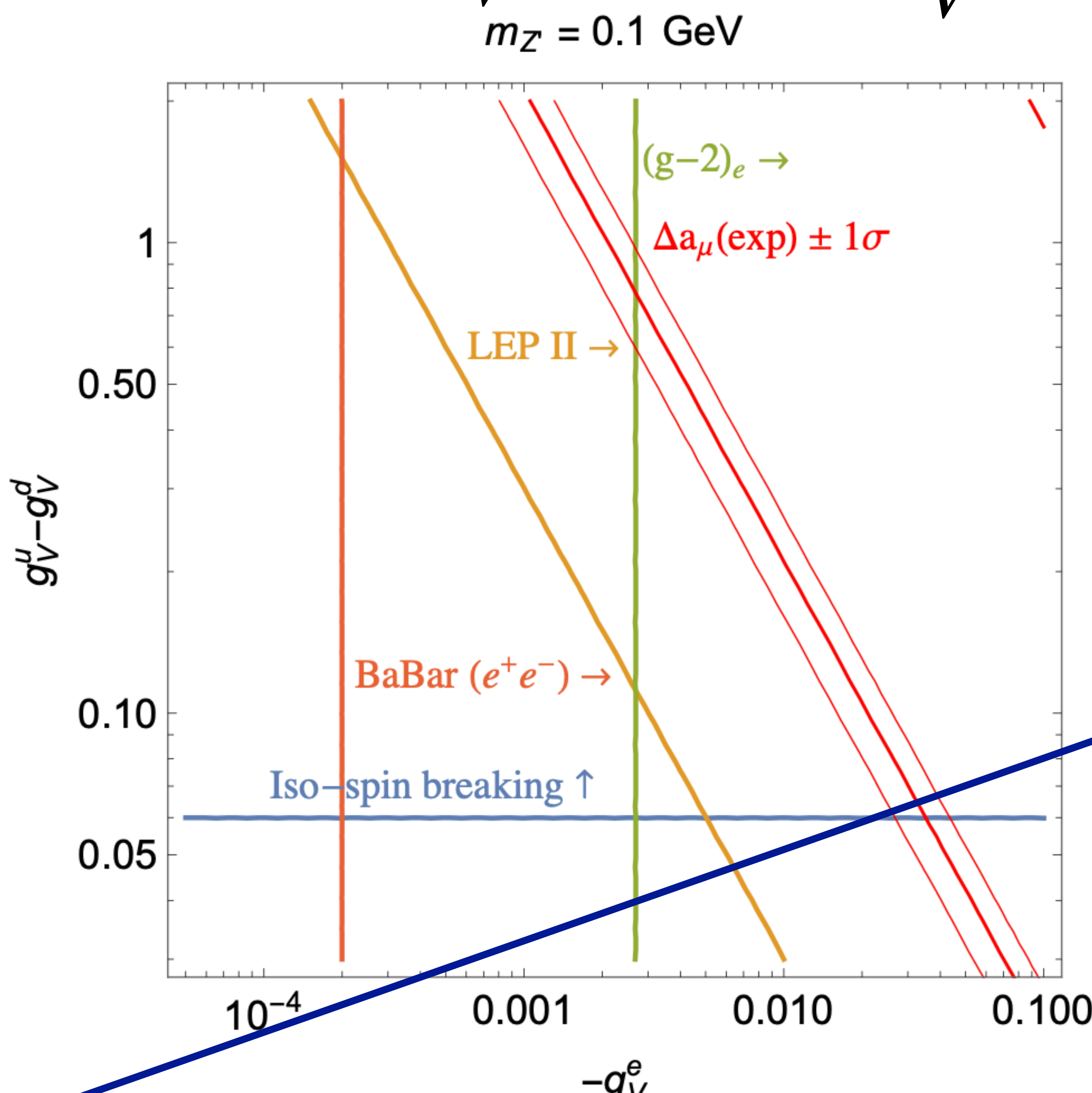
requires negative interference with SM

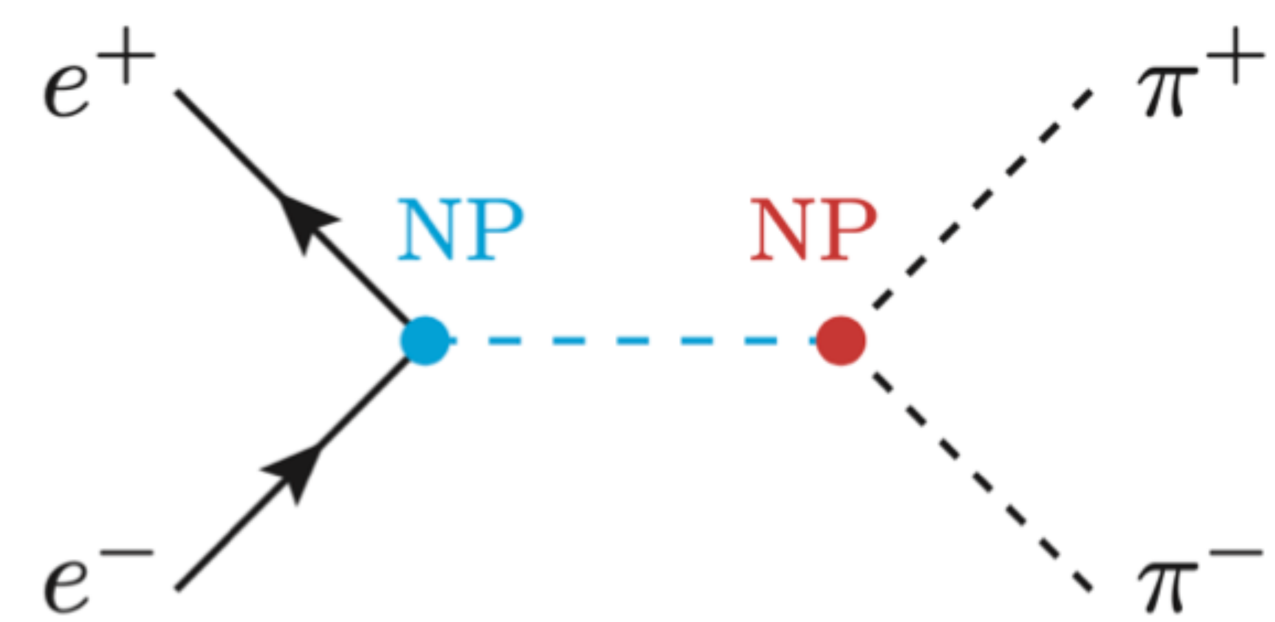
Direct new physics effects

2. New physics coupled to hadrons and electrons

[Di Luzio et al '21]

$$\mathscr{L}_{Z'} \supset (g_V^e\,\bar{e}\gamma^\mu e + g_V^q\,\bar{q}\gamma^\mu q)\,Z'_\mu$$





Disfavoured by LEP (semi-leptonic processes), BaBar (leptonic processes) and iso-spin breaking observables!

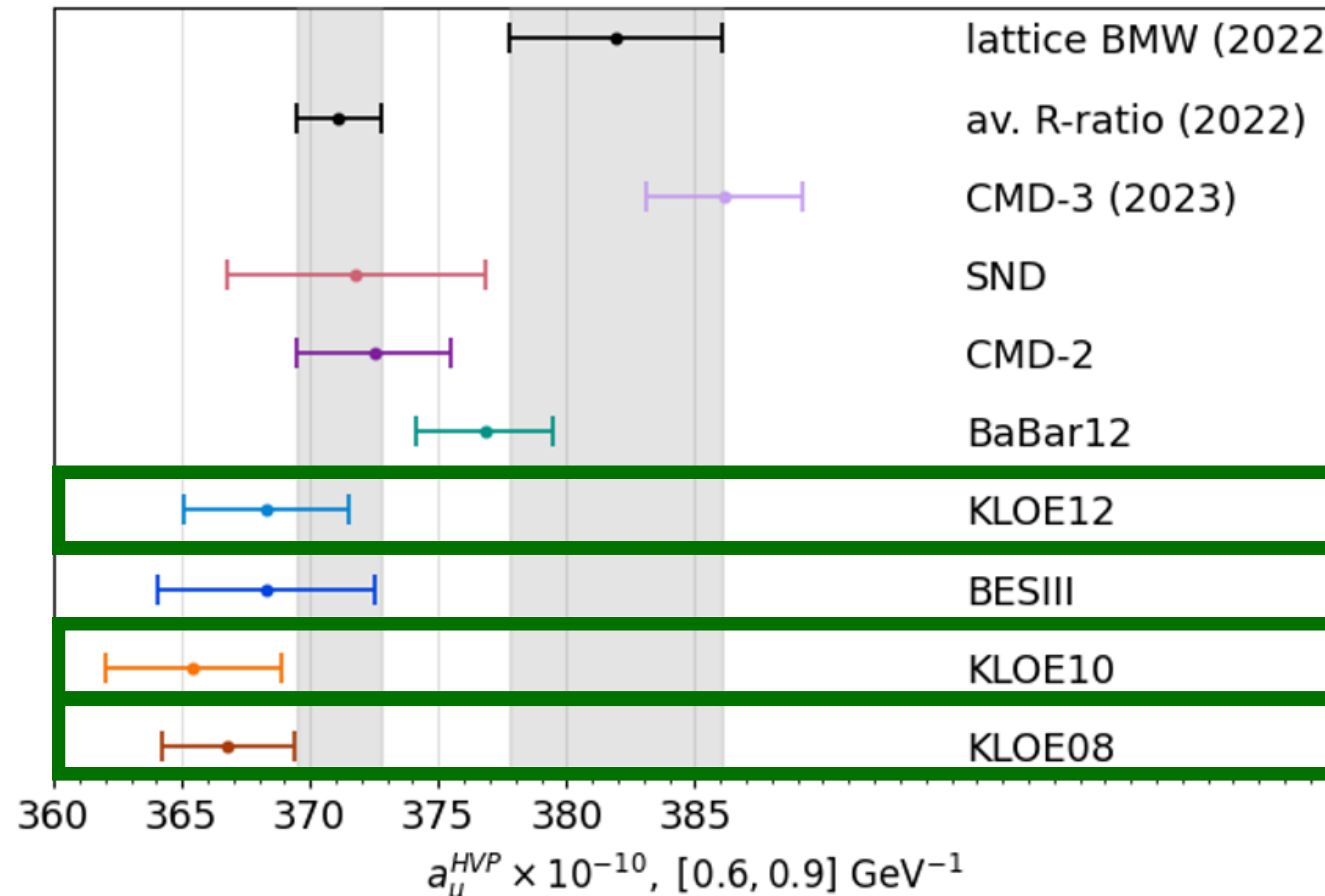
Indirect new physics effects

Can new physics effects impact indirectly the hadronic cross section determination?

Key idea:

new physics can enter the channels used to calibrate the luminosity!

The SM estimate: KLOE



Three different analysis: KLOE08, KLOE10, KLOE12.

Radiative cross section including ISR photon

Radiator function accounting for ISR

$$s\,\frac{d\sigma(\pi^+\pi^-\gamma)}{ds'} = \sigma^0_{\pi\pi}(s')\;H(s',s)$$

$s' = M^2_{\pi\pi}$ → di-pion invariant mass

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1. **KLOE08**: measurements in the range $0.35 < s'/\mathrm{GeV}^2 < 0.85$ at $\sqrt{s} = 1.0194\ \mathrm{GeV}$ (ϕ meson pole). It requires the knowledge of the **luminosity**.

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2. **KLOE10**: measurements in the range $0.1 < s'/\mathrm{GeV}^2 < 0.85$ at $\sqrt{s} = 1\ \mathrm{GeV}$ $(4.5 \cdot \Gamma_\phi$ below the ϕ meson pole). It requires the knowledge of the **luminosity**.

The SM estimate: KLOE

Three different analysis: KLOE08, KLOE10, KLOE12.

Radiative cross section including ISR photon

Radiator function accounting for ISR

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3. **KLOE12**: relies on the ratio of the number of $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ events in the range $0.35 < s'/\mathrm{GeV}^2 < 0.95$. The dependence of **the luminosity cancels in the ratio**.

Indirect new physics effects

The Luminosity determination

KLOE08 and KLOE10

$$\sigma_{\rm had} \propto \frac{N_{\rm had}}{\mathscr{L}_{e^+e^-}}$$

A smaller luminosity implies a larger hadronic cross section

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Total number of $e^+e^- \to e^+e^-$ events

$$\mathscr{L}^{\rm SM}_{e^+e^-} = \frac{N_{\rm Bhabha}}{\sigma^{\rm SM}_{\rm eff}}$$

SM prediction

Indirect new physics effects

The Luminosity determination

KLOE08 and KLOE10

$$\sigma_{\text{had}} \propto \frac{N_{\text{had}}}{\mathcal{L}_{e^+e^-}}$$

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Total number of $e^+e^- \to e^+e^-$ events

$$\mathcal{L}^{\text{SM}}_{e^+e^-} = \frac{N_{\text{Bhabha}}}{\sigma^{\text{SM}}_{\text{eff}}}$$

SM prediction

$$\mathcal{L}_{e^+e^-} = \mathcal{L}^{\text{SM}}_{e^+e^-} \frac{\sigma^{\text{SM}}_{\text{eff}}}{\sigma_{\text{eff}}}$$

Full Bhabha cross section including NP

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

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

Indirect new physics effects

The $\sigma(\mu\mu\gamma)$ method

KLOE12 and BaBar

QED $e^+e^- \to \mu^+\mu^-$ cross section

Measured value

$$\sigma^0_{\pi^+\pi^-} = \frac{N_{\pi^+\pi^-\gamma_{ISR}}}{N_{\mu^+\mu^-\gamma_{ISR}}} \sigma^0_{\mu^+\mu^-}$$

Measured value

Indirect new physics effects

The $\sigma(\mu\mu\gamma)$ method

KLOE12 and BaBar

Measured value

QED $e^+e^- \to \mu^+\mu^-$ cross section

$$\sigma^0_{\pi^+\pi^-} = \frac{N_{\pi^+\pi^-\gamma_{ISR}}}{N_{\mu^+\mu^-\gamma_{ISR}}} \sigma^0_{\mu^+\mu^-}$$

Measured value

What if we have $\mu^+\mu^- X$ **new physics** events mimicking the $\mu^+\mu^-\gamma$?

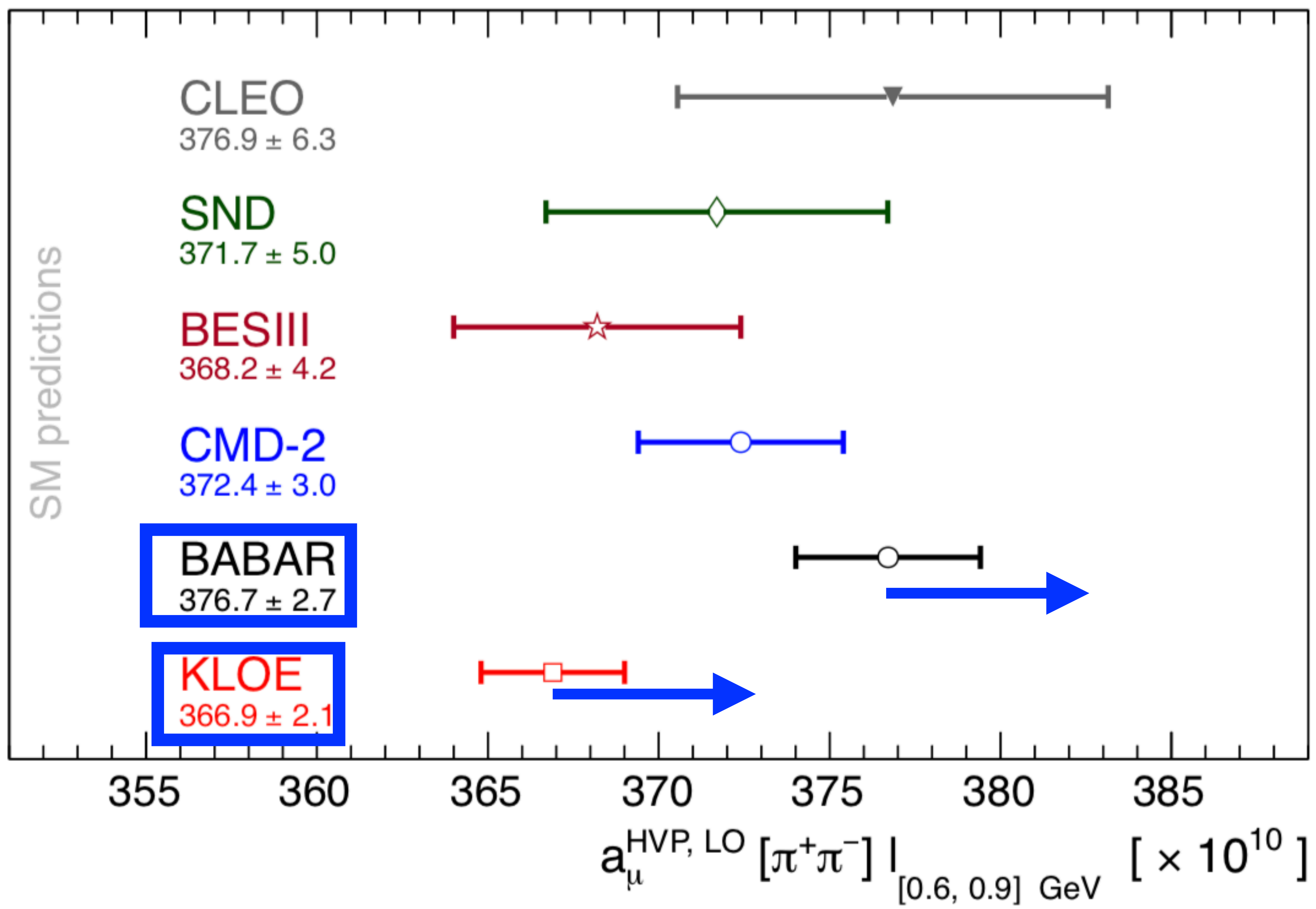
$$\sigma^{0\gamma*}_{\pi^+\pi^-} = \frac{N_{\pi^+\pi^-\gamma_{ISR}}}{N_{\mu^+\mu^-\gamma_{ISR}} - N^{NP}_{\mu^+\mu^-\gamma_{ISR}}} \sigma^0_{\mu^+\mu^-} \sim \sigma^0_{\pi^+\pi^-}(1 + \delta_\mu(s'))$$

SM inferred value

Indirect new physics effects

New physics mimicking $\mu^+\mu^-\gamma$ final states modify KLOE12 and BaBar analyses.

$$\delta_\mu(s') = \frac{\sigma^{NP}_{\mu\mu X}}{\sigma_{\mu\mu\gamma}} \frac{\epsilon^{NP}}{\epsilon^{SM}}$$



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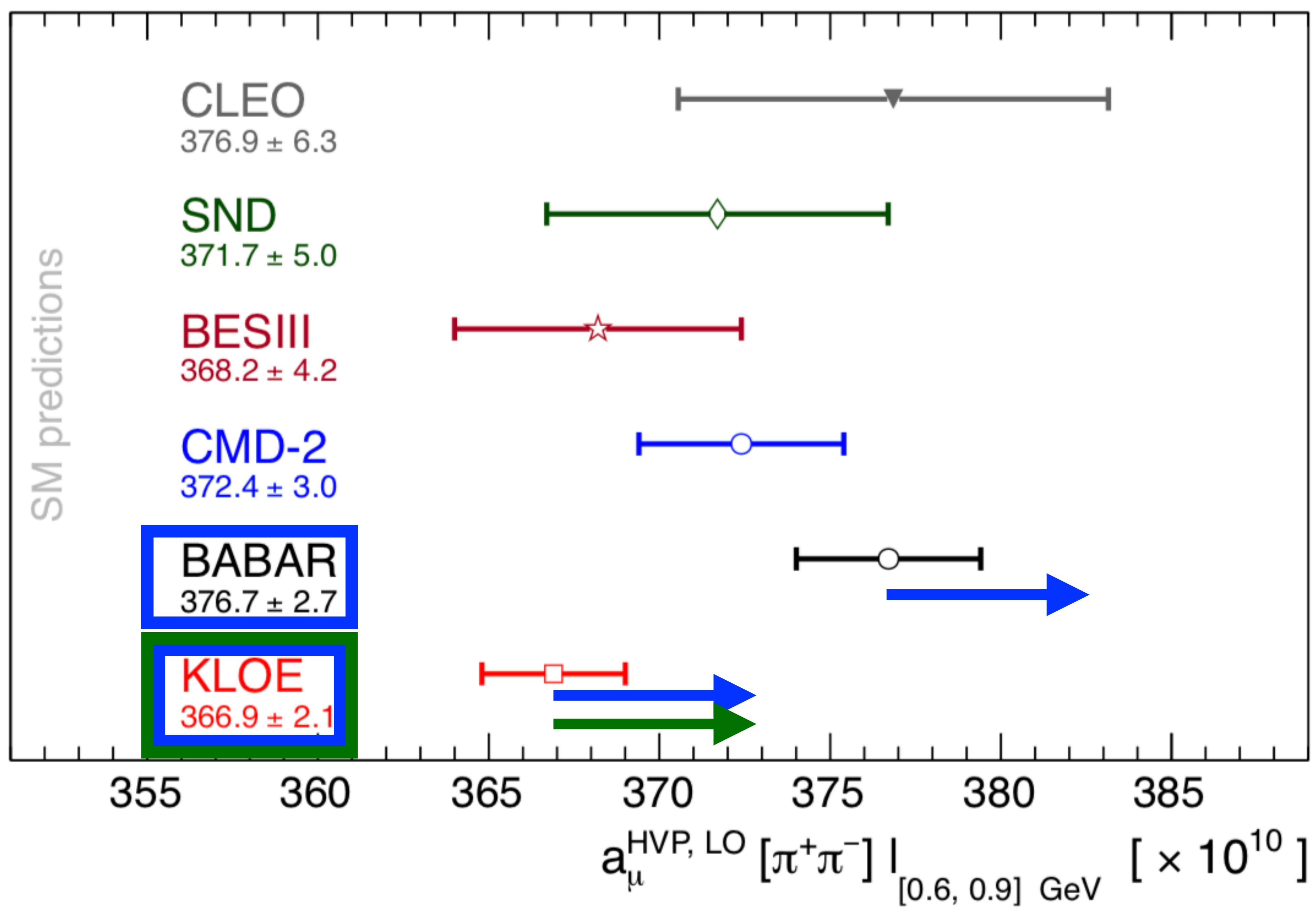

The measurements from KLOE08 and KLOE10 can be modified by new physics entering $e^+e^- \to e^+e^-$ scattering

$$\delta_R = \frac{\sigma^{NP}_{e^+e^-}}{\sigma^{SM}_{e^+e^-}}\frac{\epsilon^{NP}_{e^+e^-}}{\epsilon^{SM}_{e^+e^-}}$$

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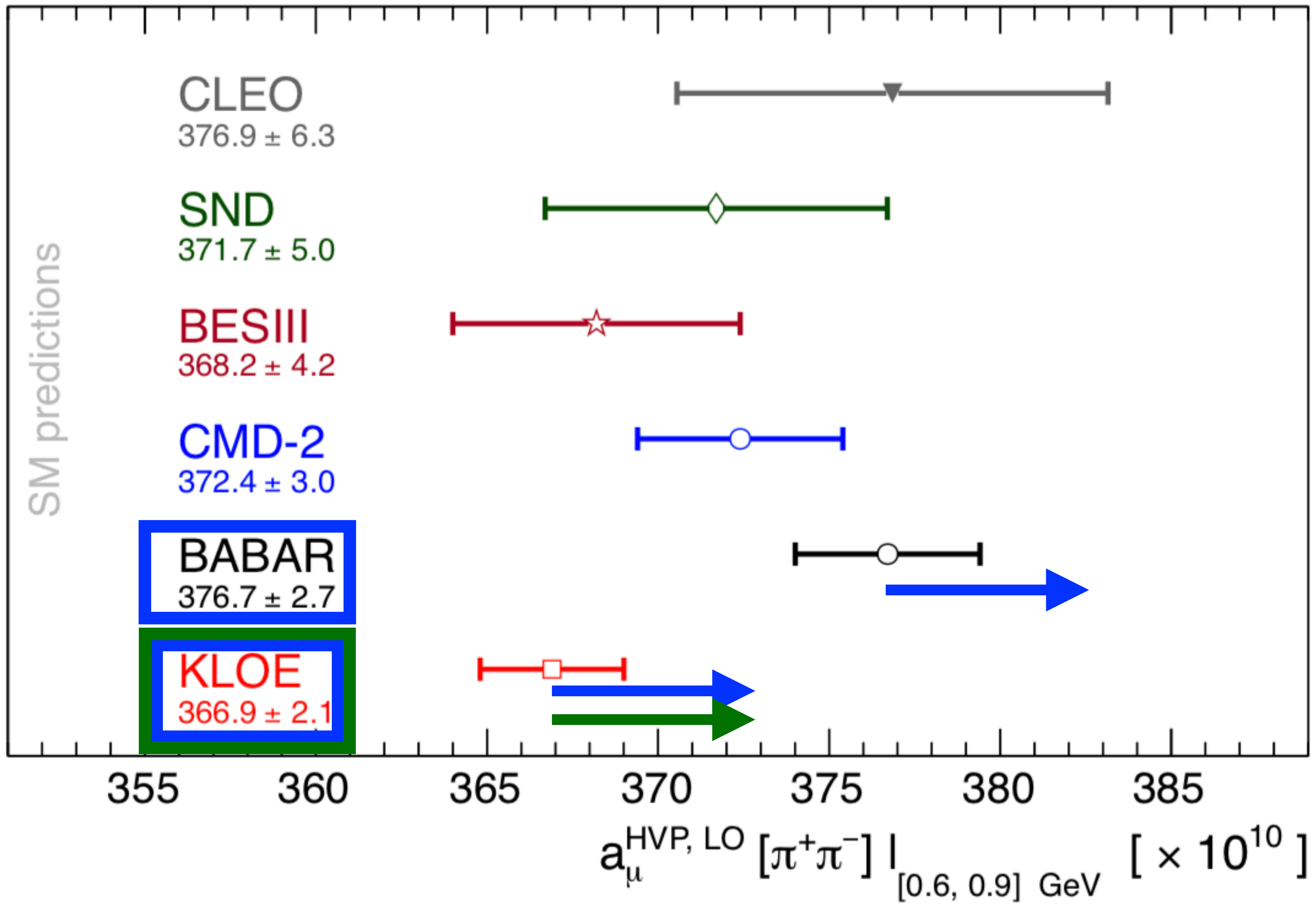

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$$\delta_R = \frac{\sigma^{NP}_{e^+e^-}}{\sigma^{SM}_{e^+e^-}} \frac{\epsilon^{NP}_{e^+e^-}}{\epsilon^{SM}_{e^+e^-}}$$

Flavour universal new physics that modifies the Bhabha scattering is expected to modify the $\gamma\mu\mu X$ process, up to differences related to the muon mass and the experiment.

Dark photon model

We need a model that fakes Bhabha scattering and $\mu\mu\gamma$ final states!

Dark photon Field strength

kinetic mixing

$$\mathscr{L} \supset -\frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} - \frac{\epsilon}{2c_W} B_{\mu\nu} F'^{\mu\nu} +$$

+ dark Higgs (S) potential +

$$+\bar{\chi}(iD_\mu \gamma^\mu - m_\chi)\chi +$$

$$+y_{SL} S \bar{\chi}^c P_L \chi + y_{SR} S \bar{\chi}^c P_R \chi + \dots$$

$$+e\,\epsilon_f \sum \bar{f} \gamma^\mu f V_\mu$$

dirac fermion dark matter

$\chi = (\chi_L, \bar{\chi}_R)$

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$$+y_{SL}\, S\, \bar{\chi}^c P_L\, \chi + y_{SR}\, S\, \bar{\chi}^c P_R\, \chi + \ldots$$

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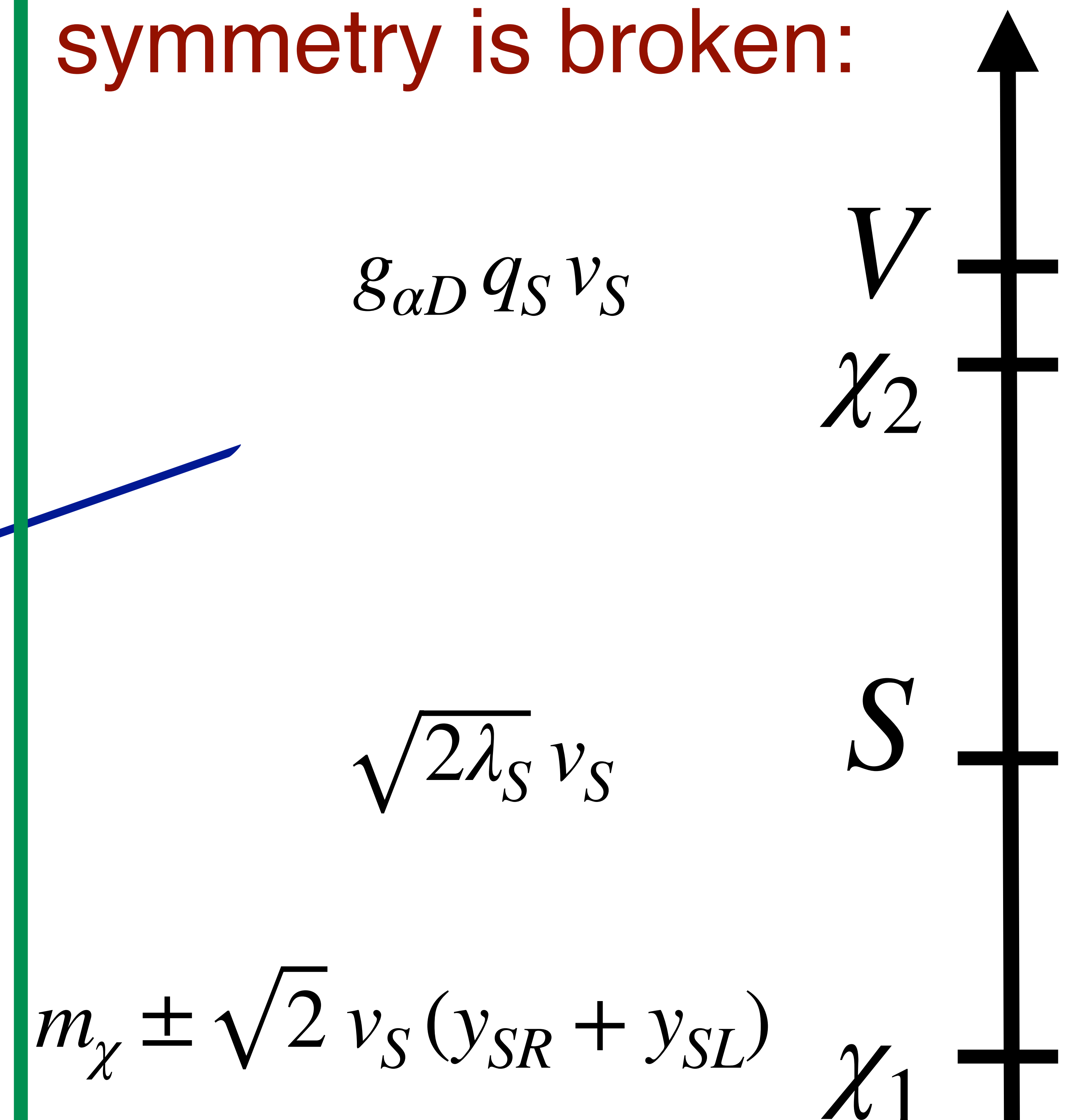
Spectrum after the U(1) symmetry is broken:



Dark photon model

In order to generate a significant shift in KLOE's luminosity and to provide additional di-muon events:

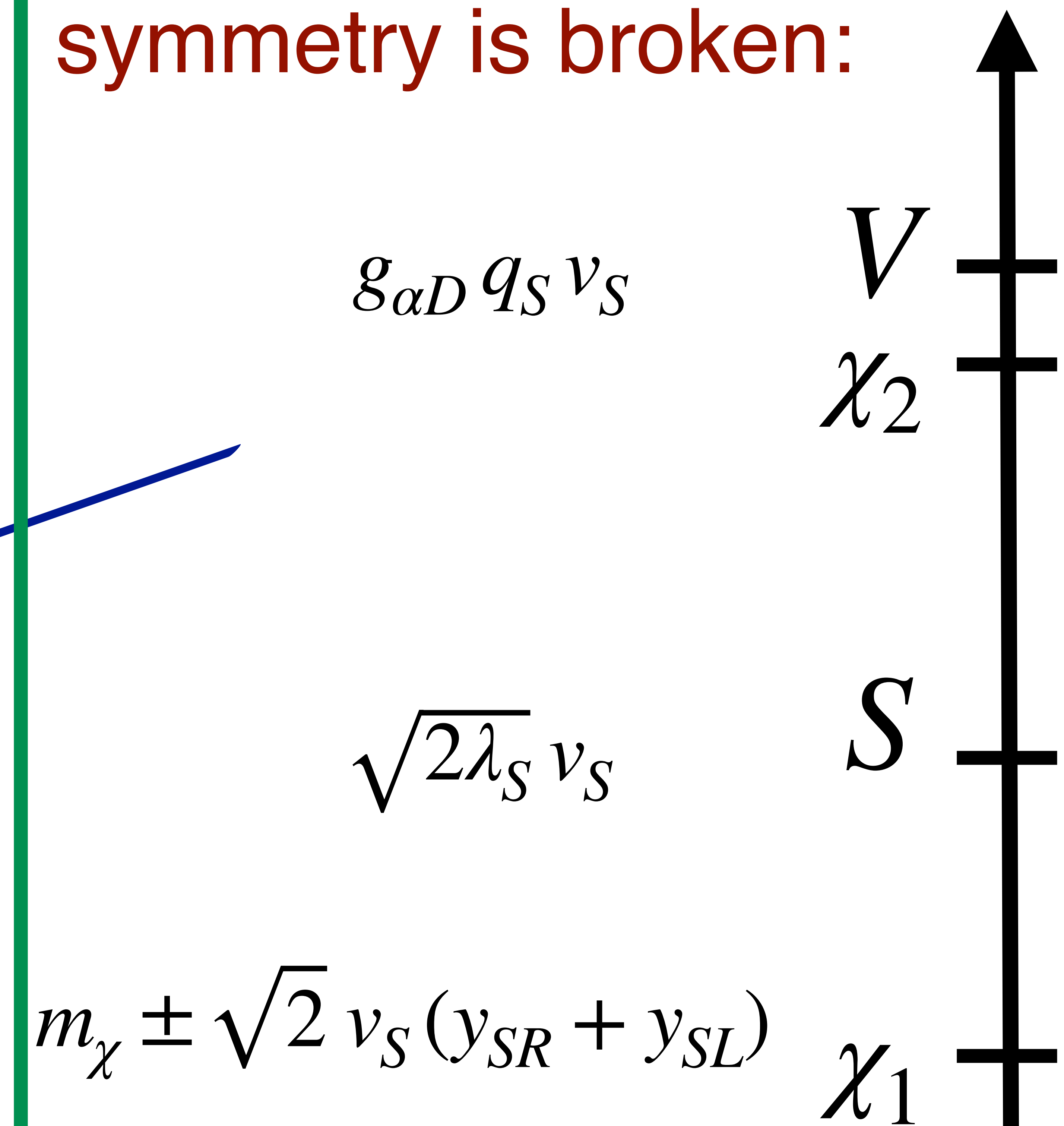
1. the dark photon mass must close to the KLOE centre of mass energies $\sqrt{s} \simeq 1$ GeV or $\sqrt{s} \simeq 1.02$ GeV;

2. the dark photon must contribute substantially to Bhabha scattering;

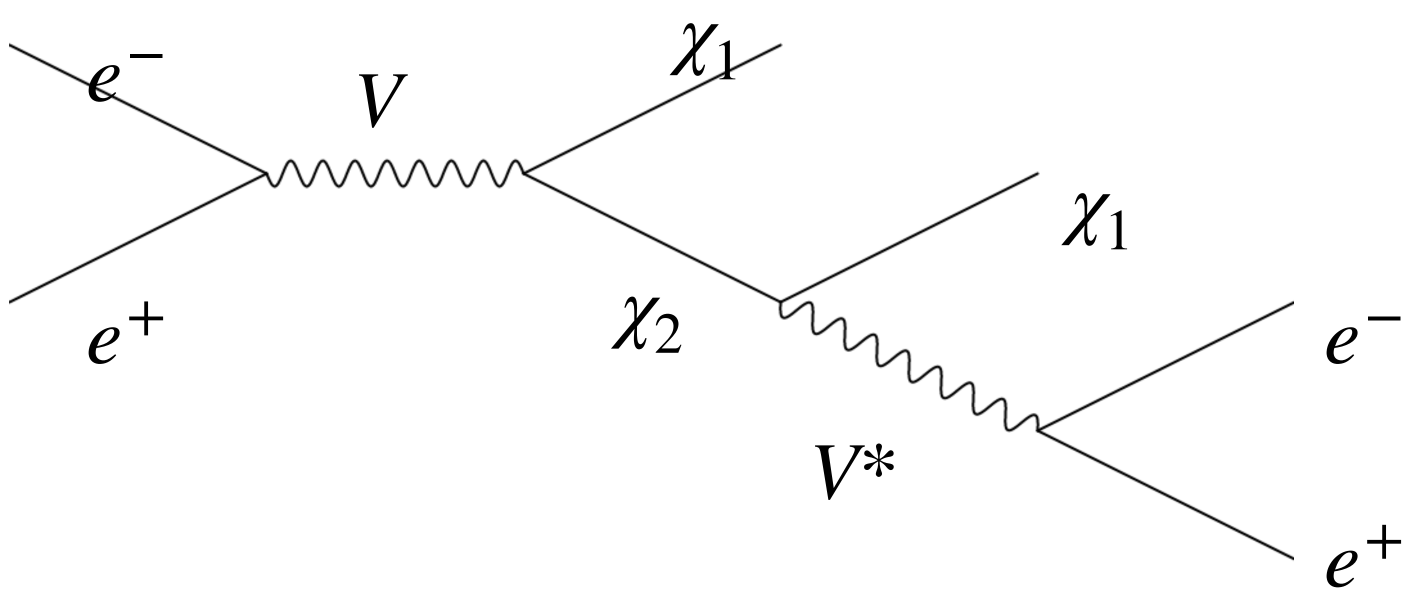
3. The dark photon must escape bump searches: the main decay channel must be multibody and include some missing energy;

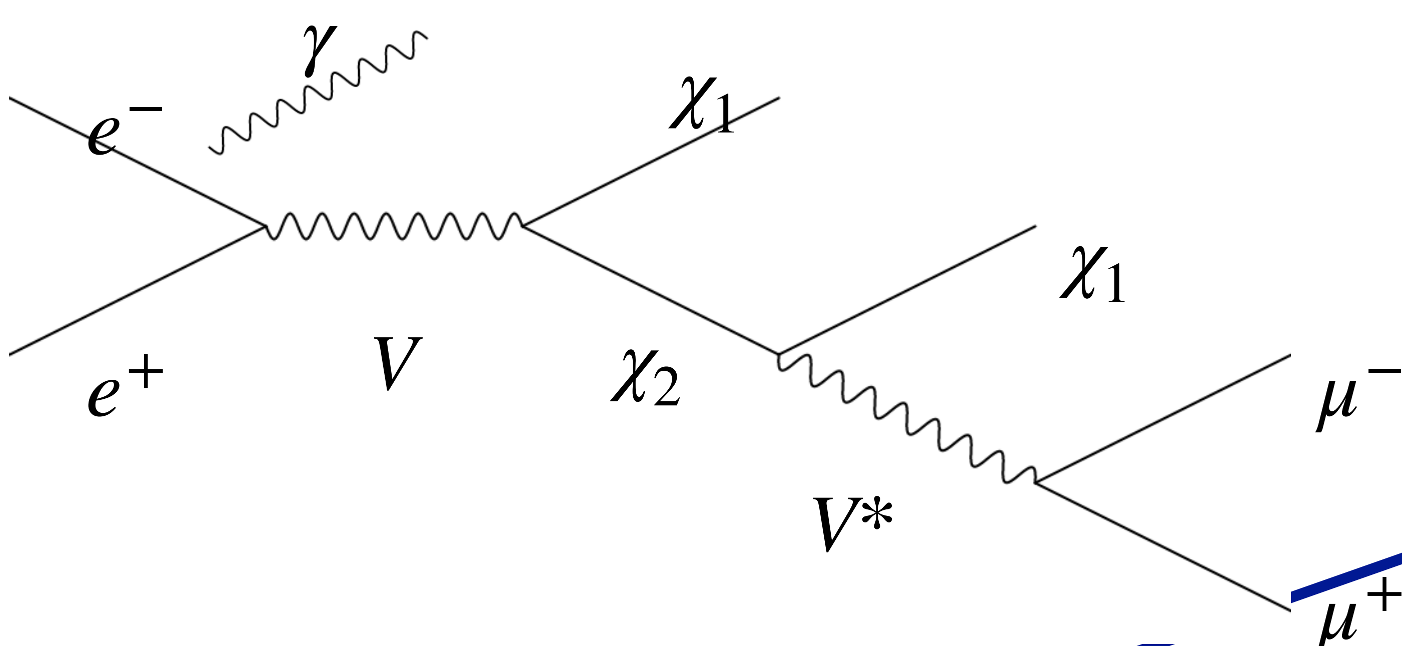
$$m_V \sim 1\,\mathrm{GeV} \gtrsim m_{\chi_2} \gg m_{\chi_1}$$

Spectrum after the U(1) symmetry is broken:



Indirect effects





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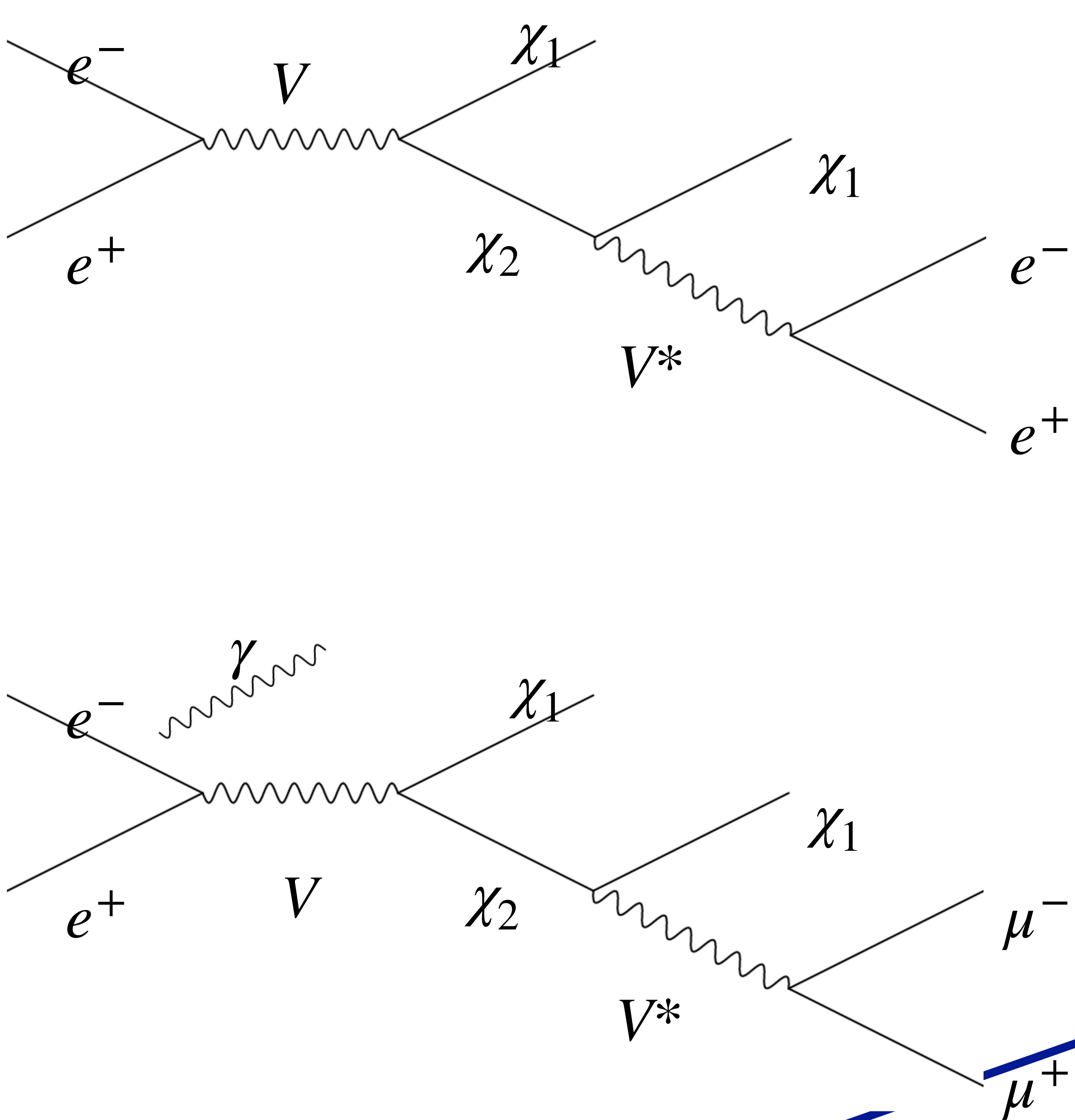

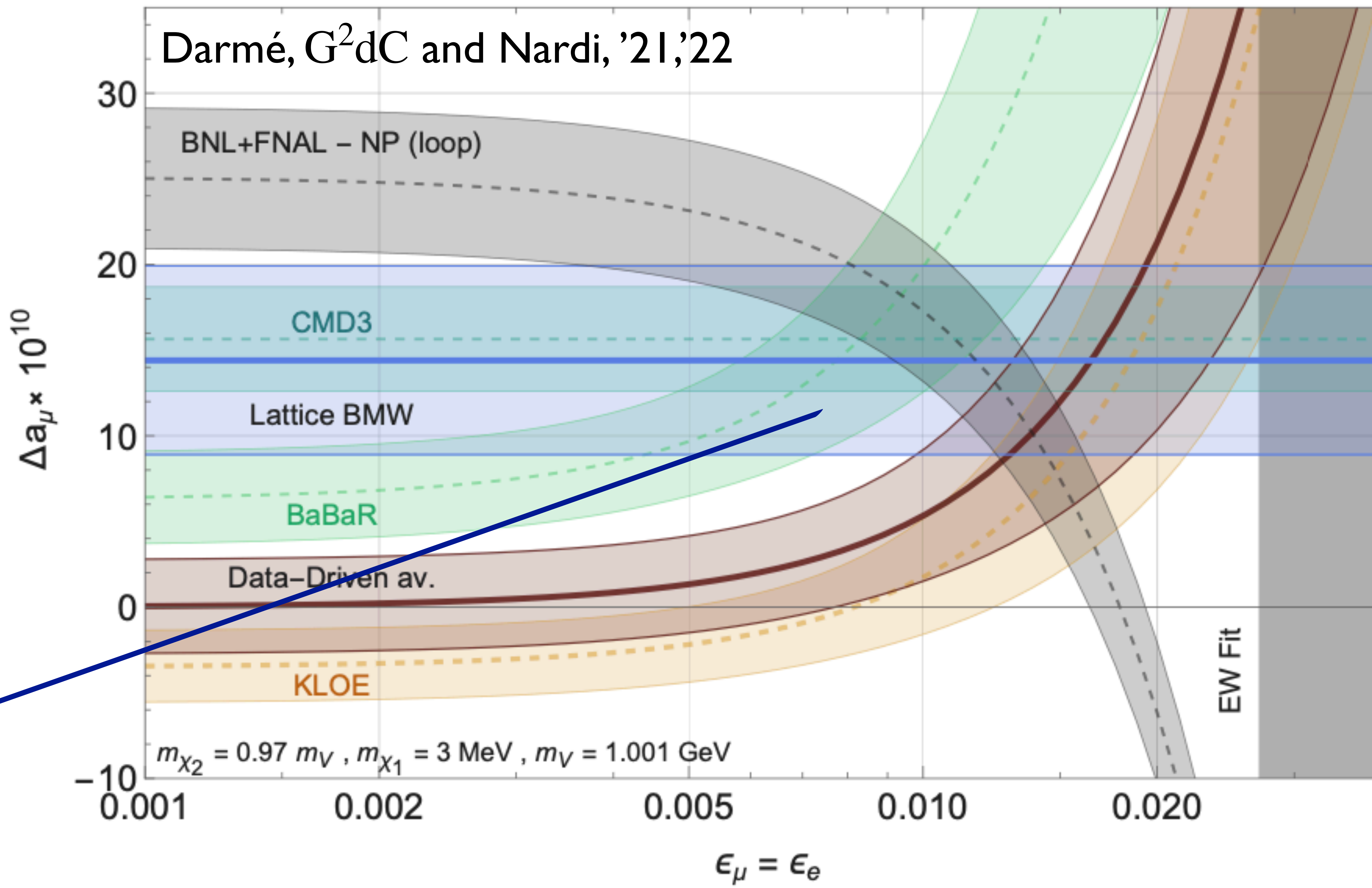

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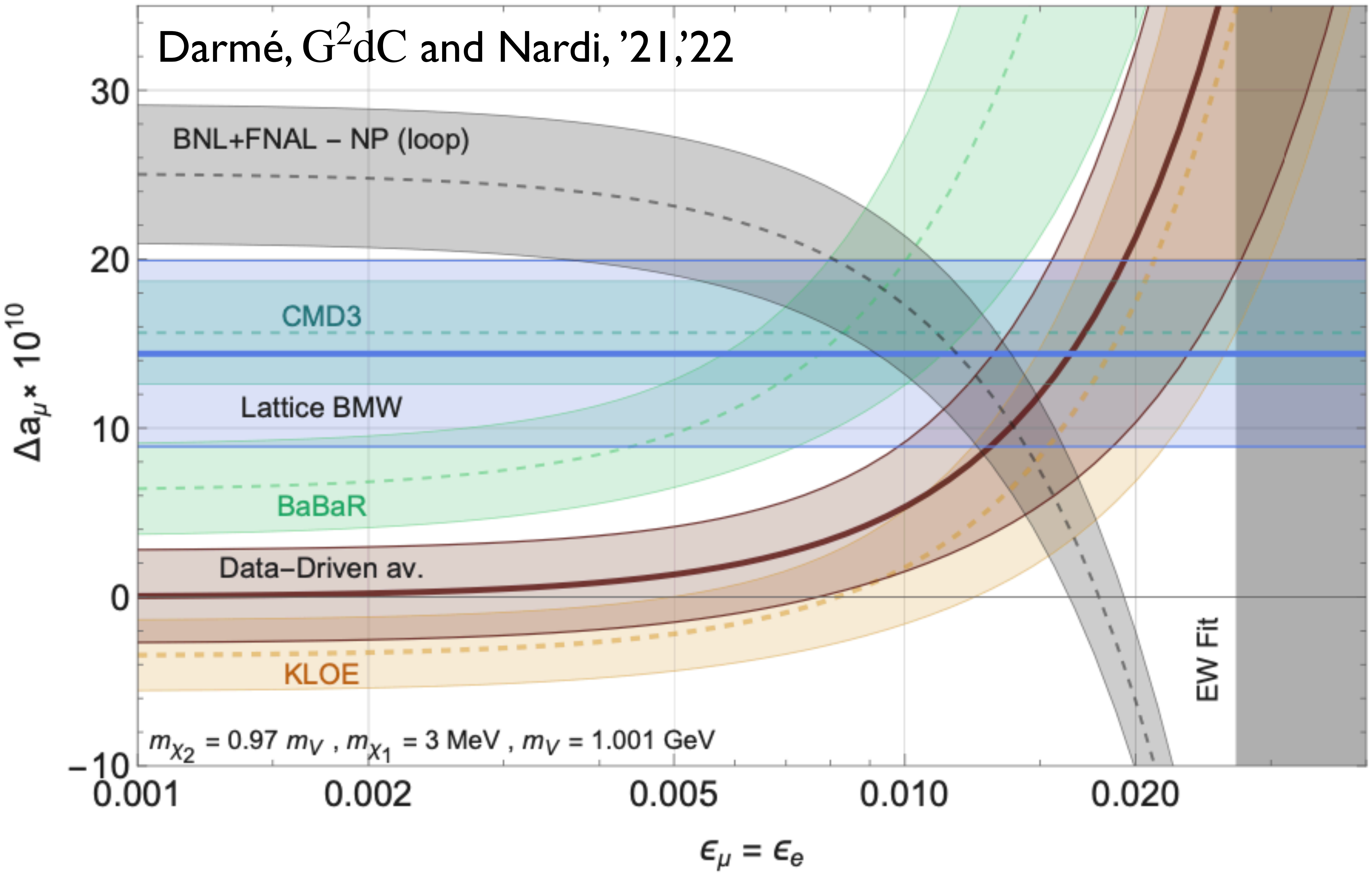


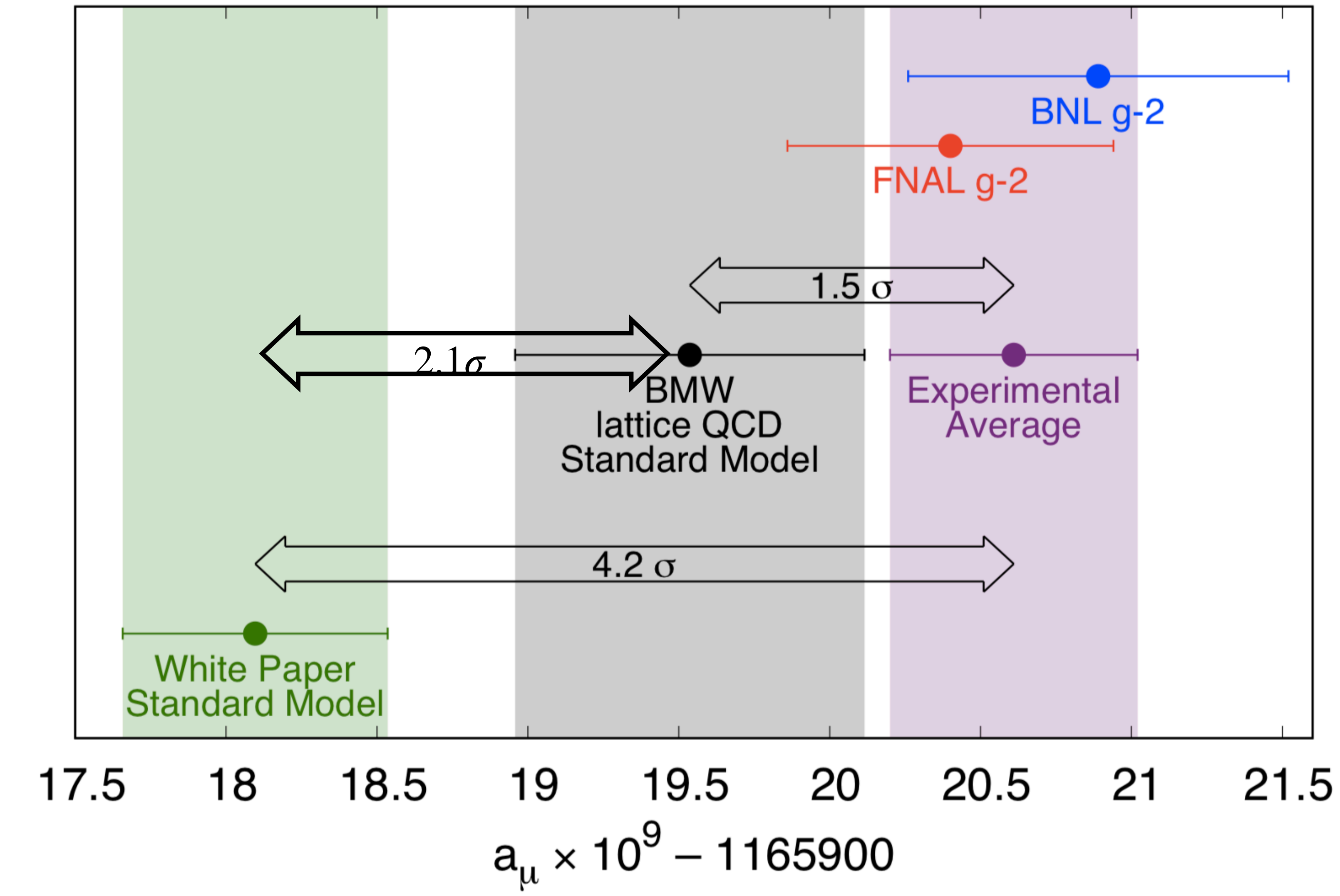
Many constraints evaded:

1. BaBar dark photon searches;
2. KLOE10 off resonance measurement;
3. KLOE forward-backward asymmetry;
4. KLOE12 muon cross section measurement;
5. LEP precision measurements;

LHC EW fit with ~3000 fb^{-1} will be sensitive to this model.

Energy windows

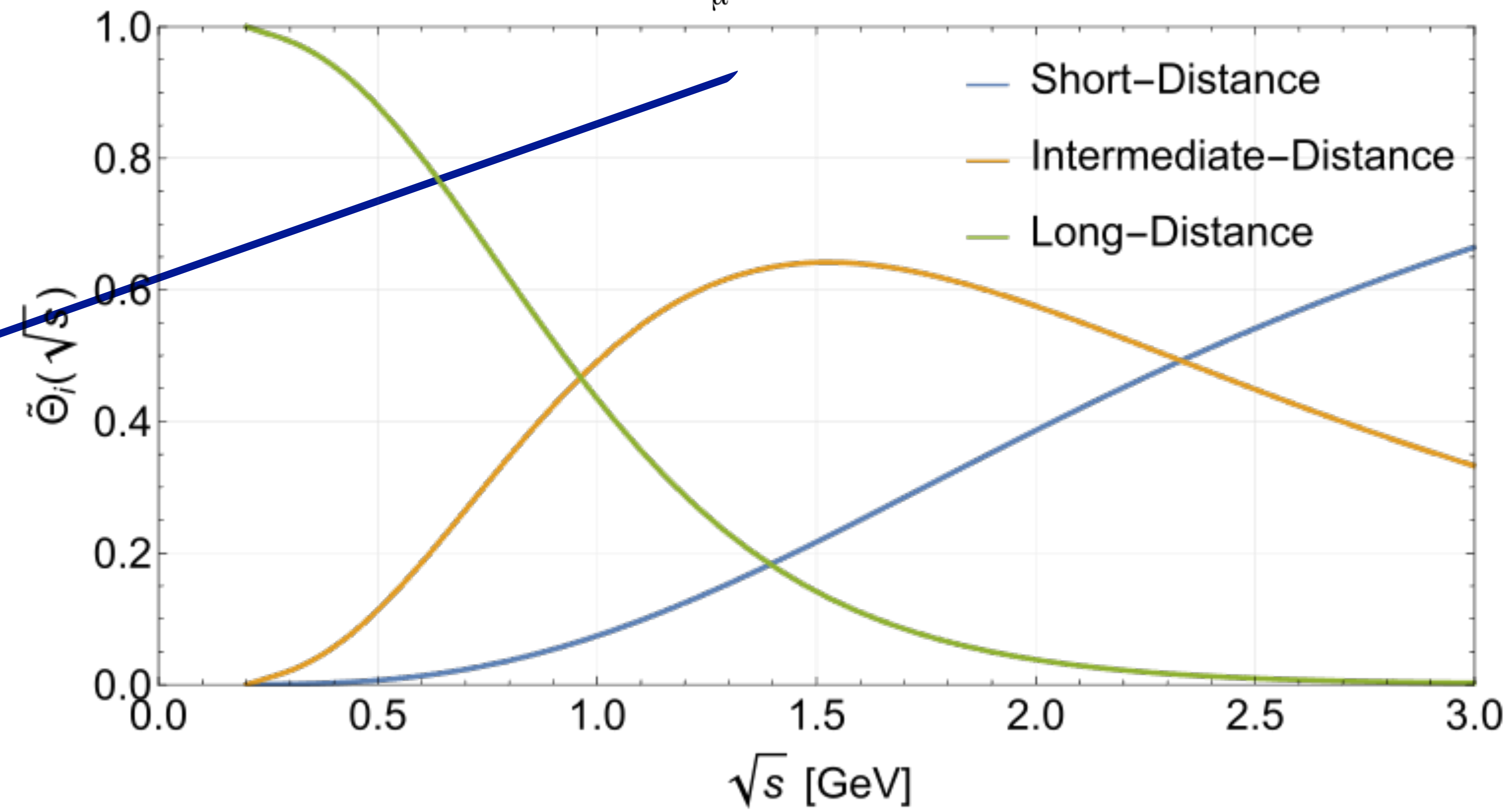
Which scale is problematic?



[RBC/UKQCD ’18]

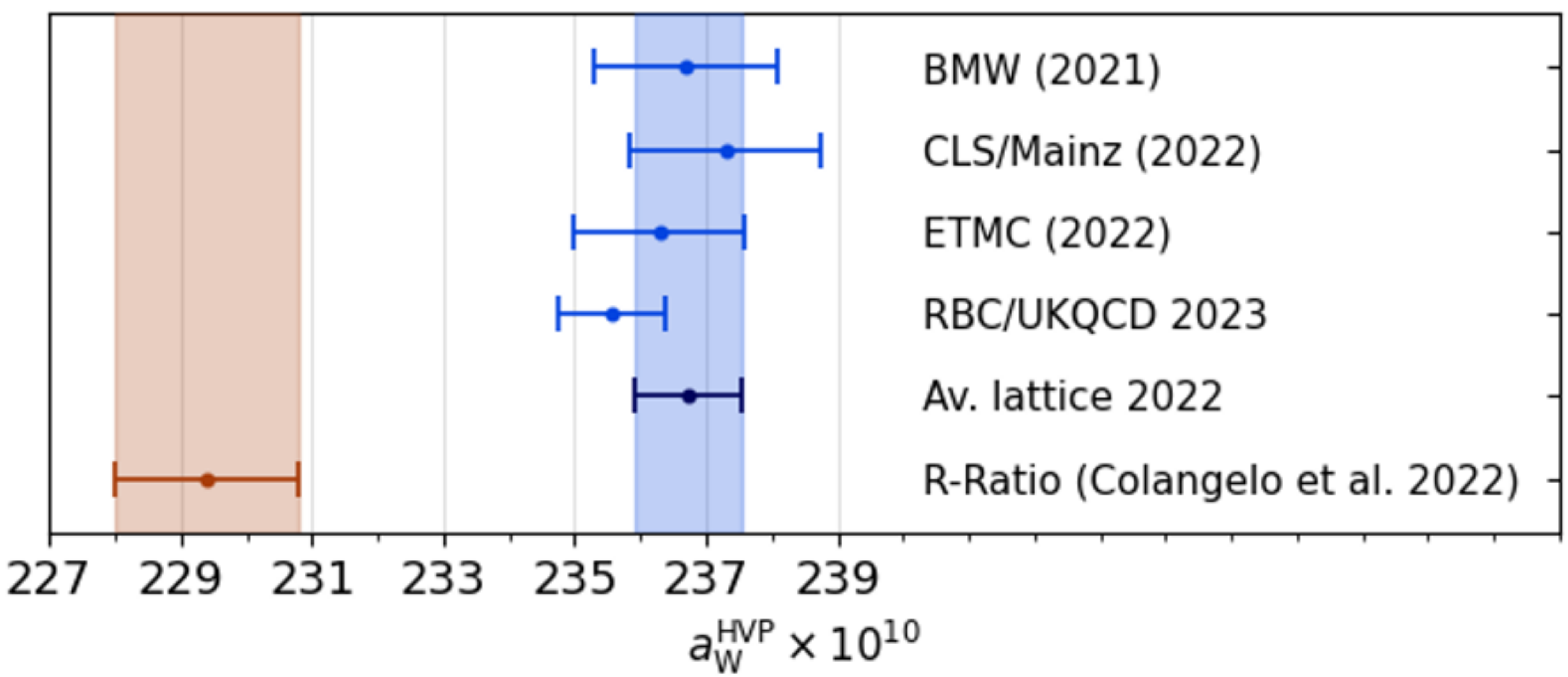
Select particular scales in the lattice estimate exploiting weight functions:

1. avoid long-distance contributions (ie small momenta) where lattice has large uncertainties
2. allow for a scale-by-scale comparison with the data-driven approach
3. allow lattice collaboration to give partial results



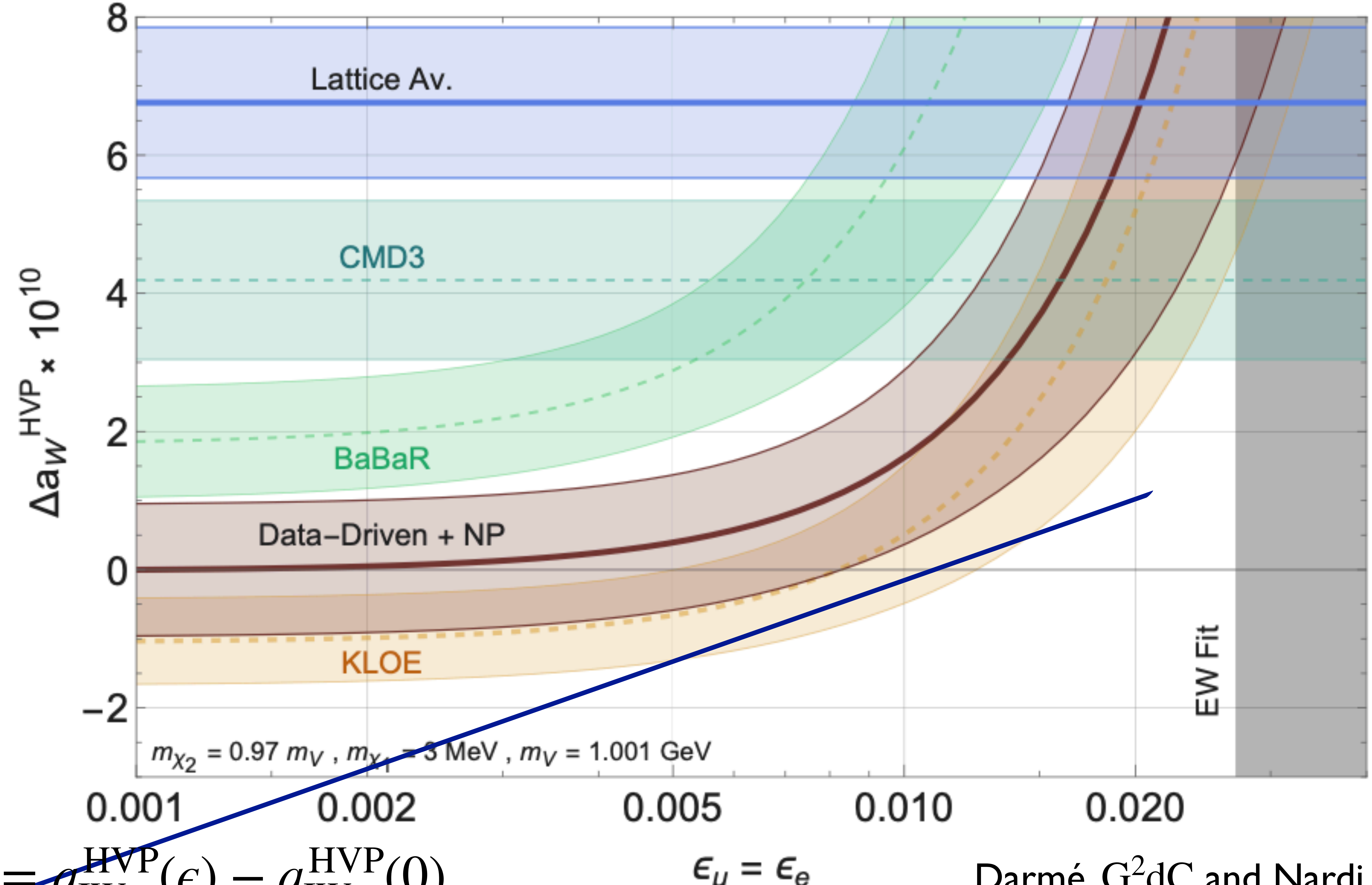
Intermediate window

The data-driven approach and the lattice results differ at the **4σ level** in the intermediate window!



ETMC (2206.15084) computed also the short distance (high energy) window finding no significant tension with the corresponding dispersive result!

Intermediate window



$$\Delta a_{\rm IW}^{\rm HVP} = a_{\rm IW}^{\rm HVP}(\epsilon) - a_{\rm IW}^{\rm HVP}(0)$$

Darmé, G^{2}dC and Nardi, '22

Conclusions

- The **4.2 sigma discrepancy** between the Theory Initiative SM prediction for the g-2 and the experimental results is accompanied by other anomalies: **data-driven vs lattice** & **KLOE vs BaBar (CMD3)** in the data-driven estimate.

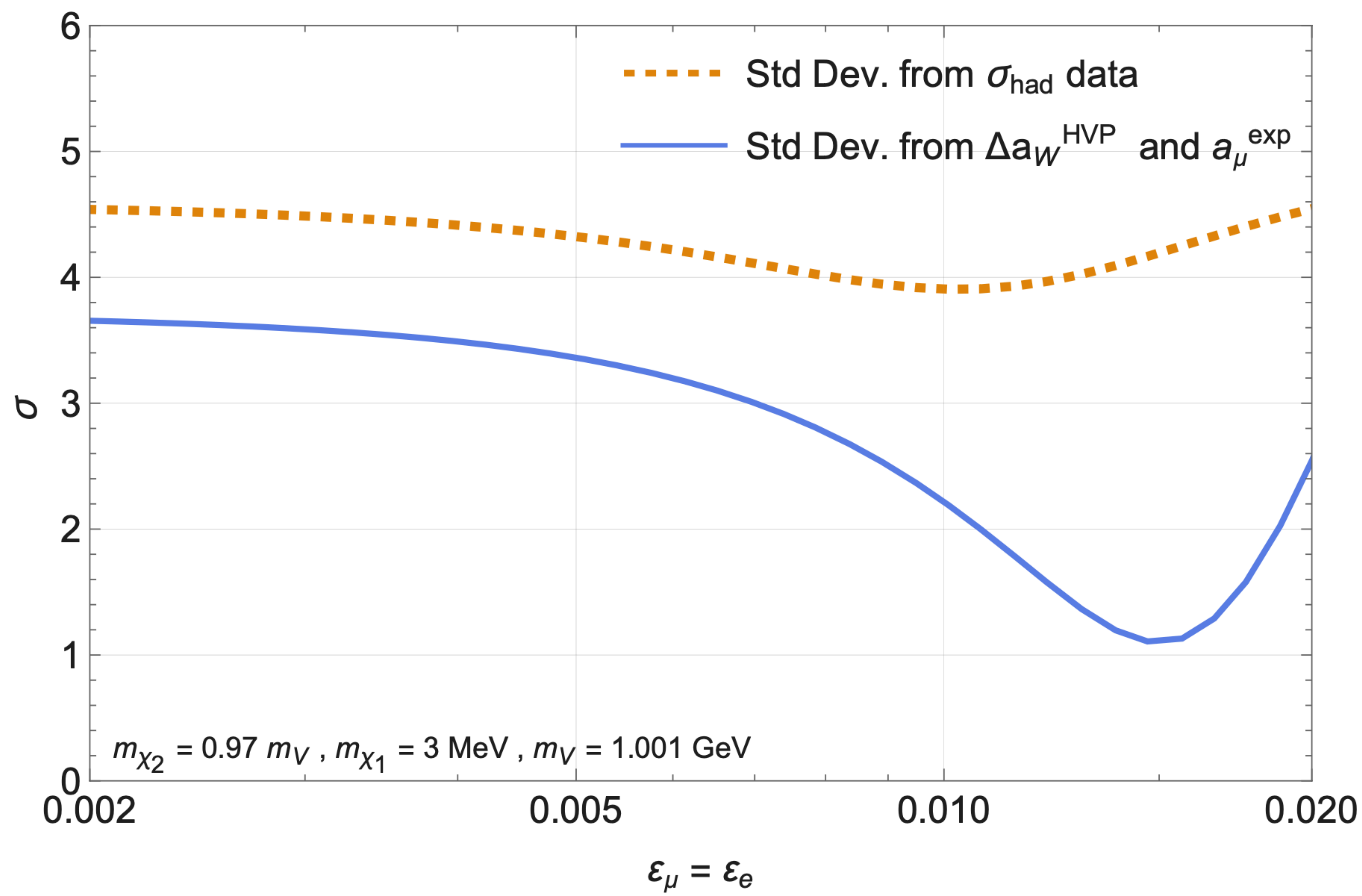
- The presence of **new physics can indirectly modify the experimental results used by the data-driven approach**, **increasing** $\sigma_{\rm had}$;

- **Dark photon models** may shift the $\sigma_{\rm had}$ measurement of KLOE and BaBar but cannot fully explain all the discrepancies among the different datasets;

- The g-2 anomalies can be mitigated by an **interplay between direct (~75%) and indirect (~25%) contributions**;

- The **largest indirect contribution is in the intermediate window**, in agreement with recent lattice results.

Backup



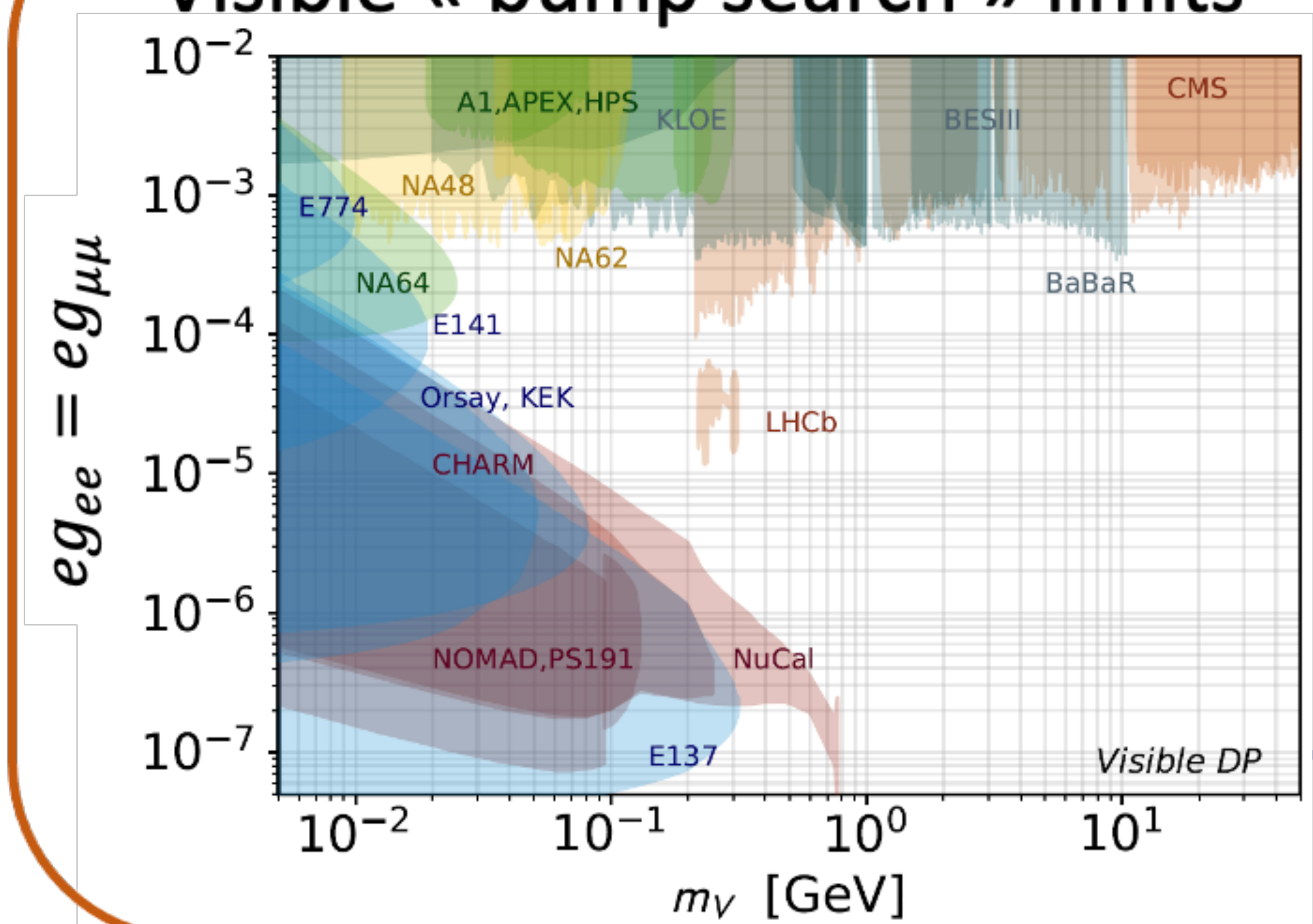
Std Dev. from σ_{had} data
Std Dev. from Δa_W^{HVP} and a_μ^{exp}
$m_{\chi_2} = 0.97\, m_V$, $m_{\chi_1} = 3$ MeV , $m_V = 1.001$ GeV
σ
$\varepsilon_\mu = \varepsilon_e$
0
1
2
3
4
5
6
0.002
0.005
0.010
0.020

Backup

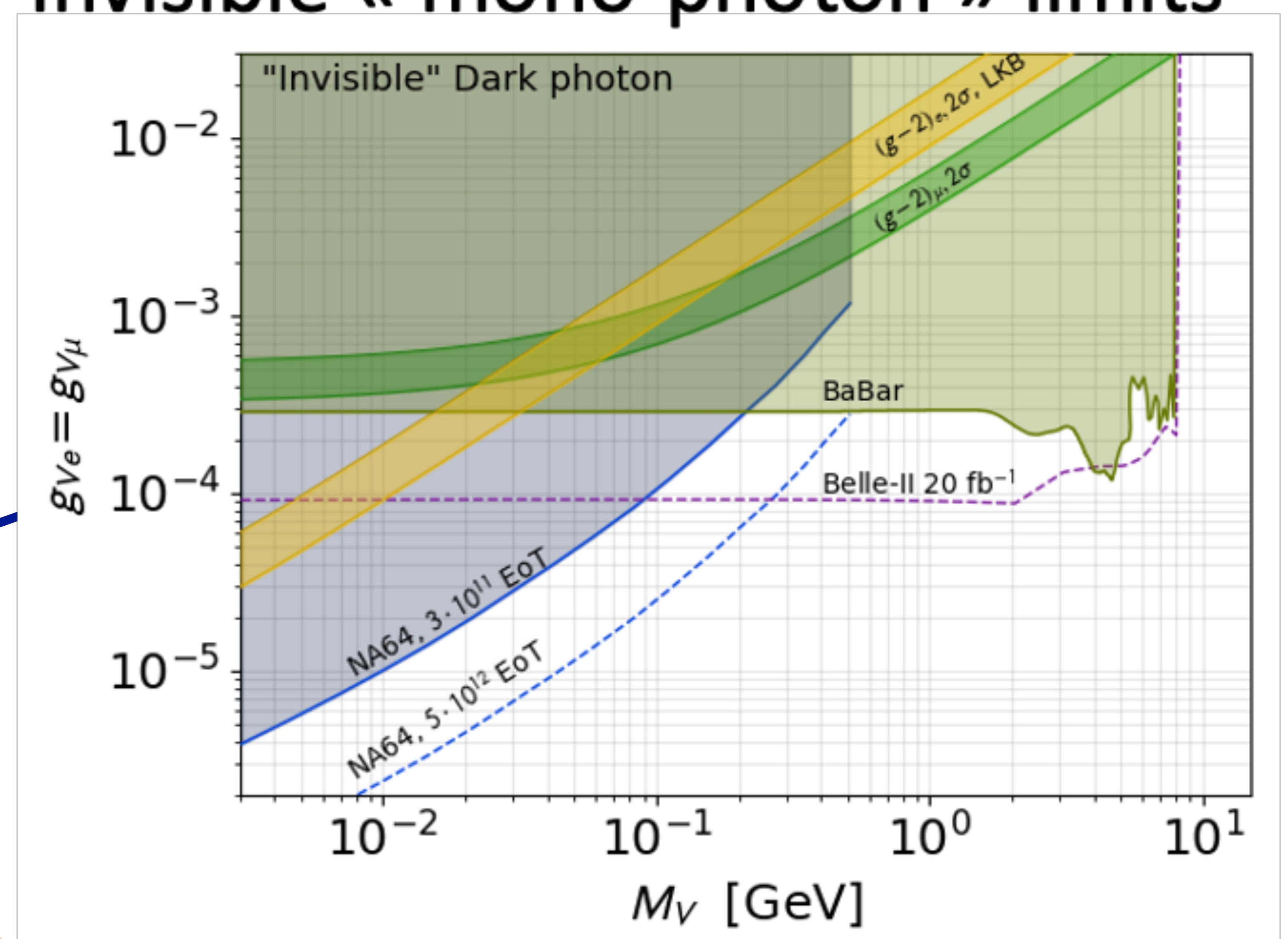
Search for $e^+e^- \to \gamma V, (V \to e^+e^-)$ at BaBar,
or $pp \to V + X, (V \to \mu\mu)$ at LHCb
Need to be able to reconstruct a resonance !

Search for $e^+e^- \to \gamma V, (V \to inv)$ at BaBar,
Requires a mono-photon final state

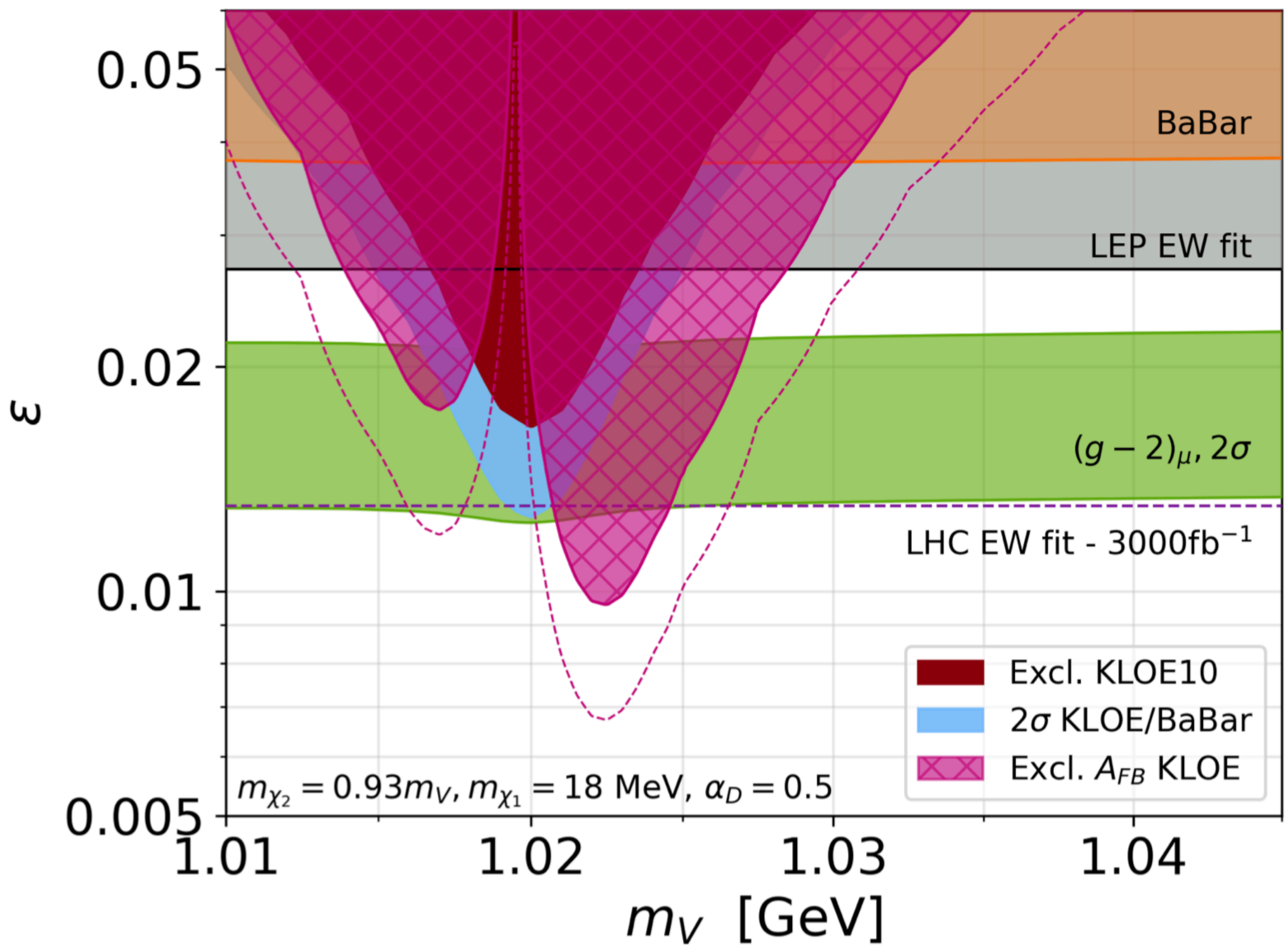
Visible « bump search » limits



Invisible « mono-photon » limits



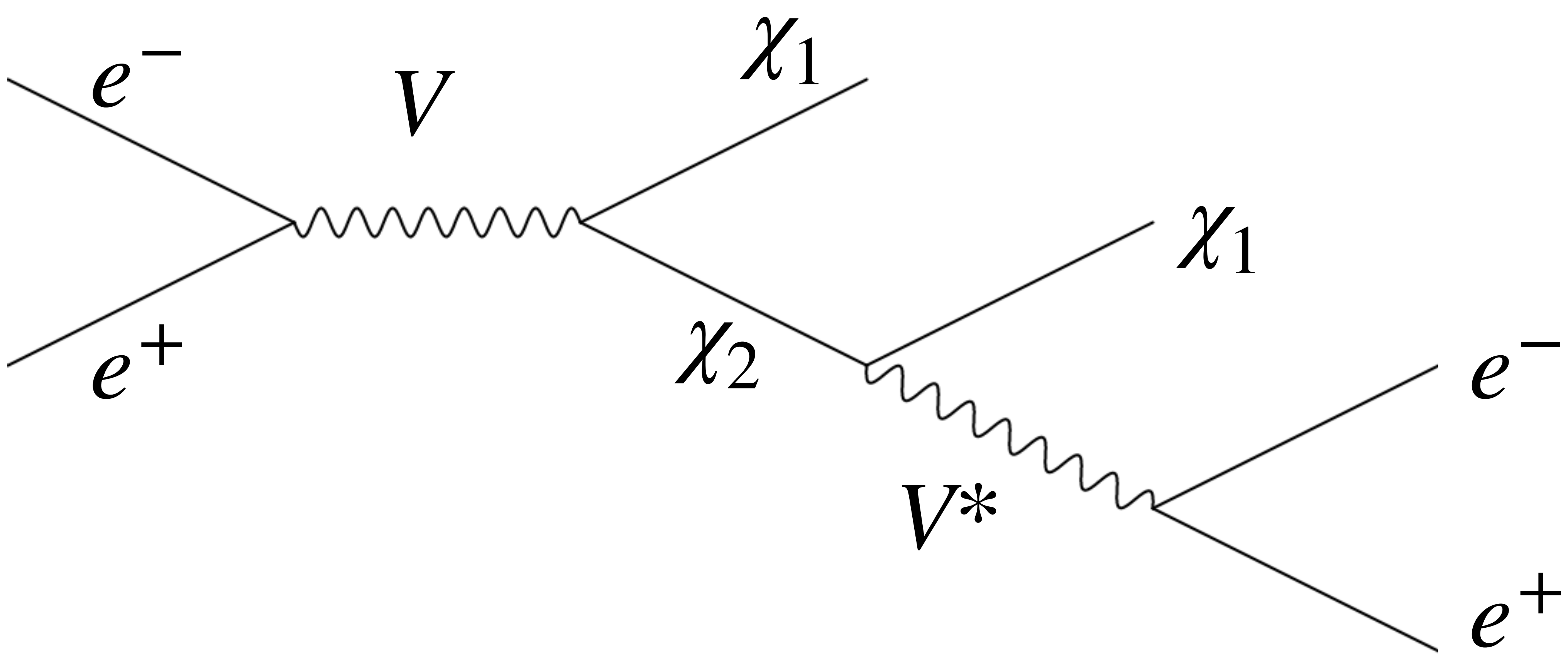
Backup



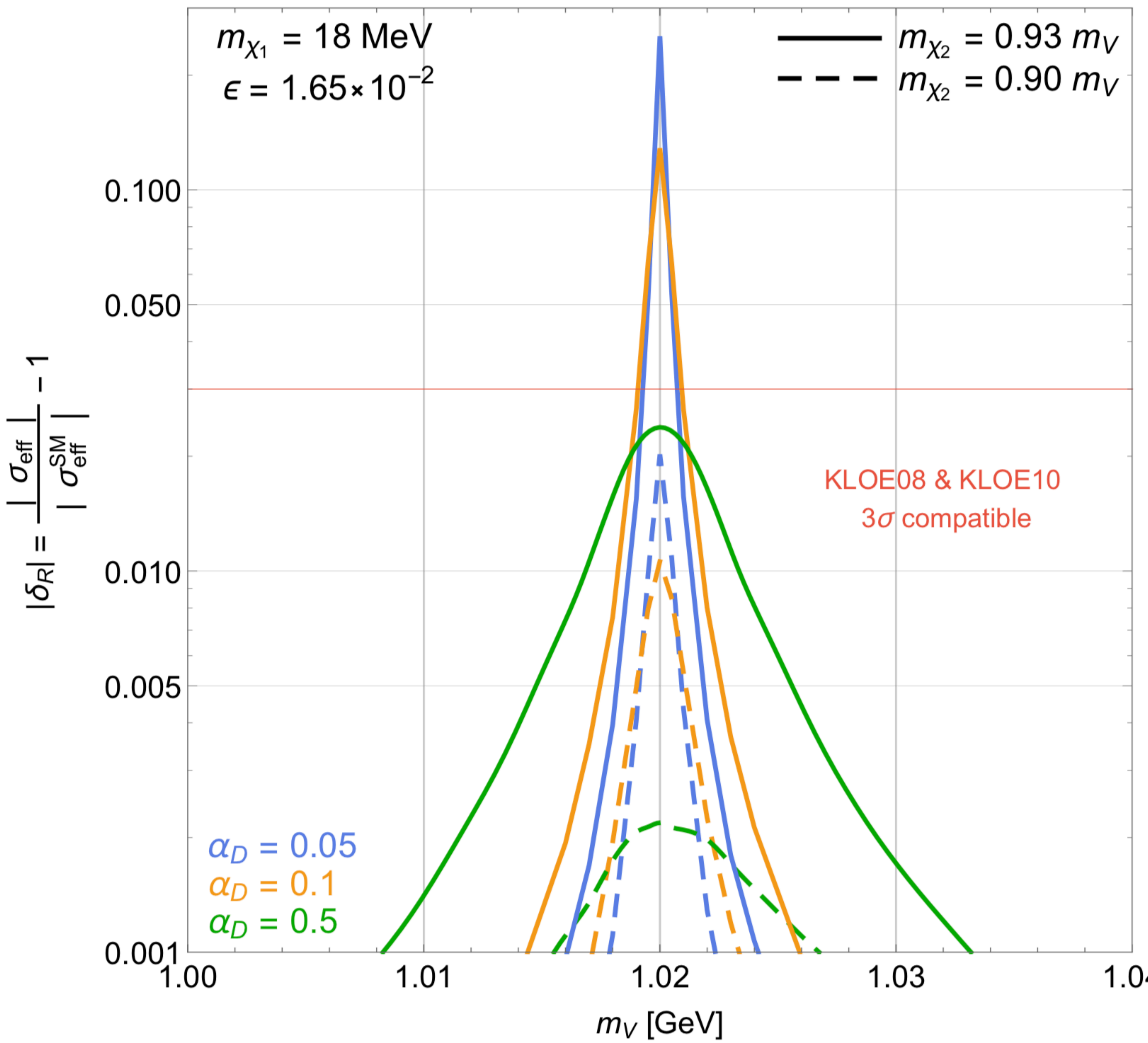
0.05
0.02
0.01
0.005
ϵ
1.01
1.02
1.03
1.04
m_V [GeV]
BaBar
LEP EW fit
$(g-2)_\mu, 2\sigma$
LHC EW fit - 3000fb^{-1}
Excl. KLOE10
2σ KLOE/BaBar
Excl. A_{FB} KLOE
$m_{\chi_2} = 0.93 m_V, m_{\chi_1} = 18$ MeV, $\alpha_D = 0.5$

Solving the a_μ tension

Shifting KLOE08



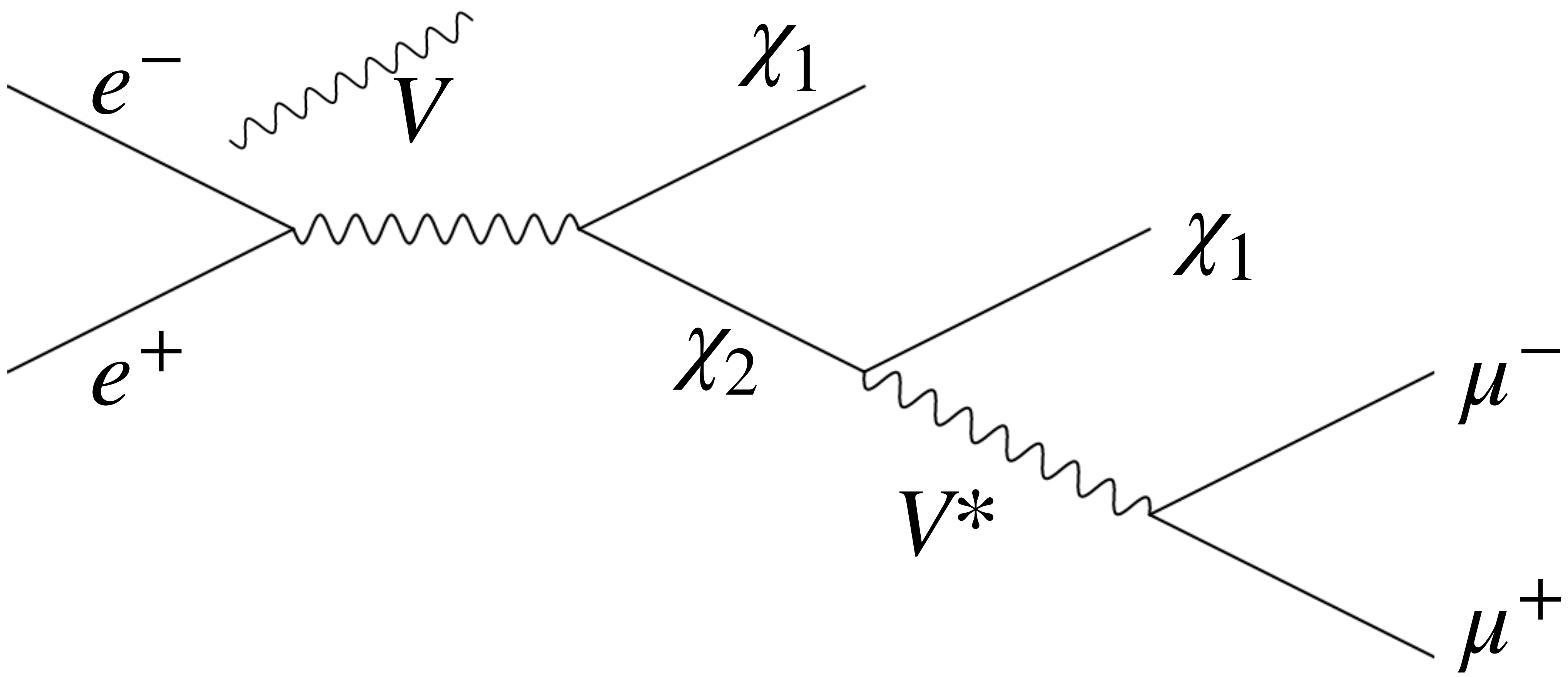
Darmé, G²dC and Nardi, '21



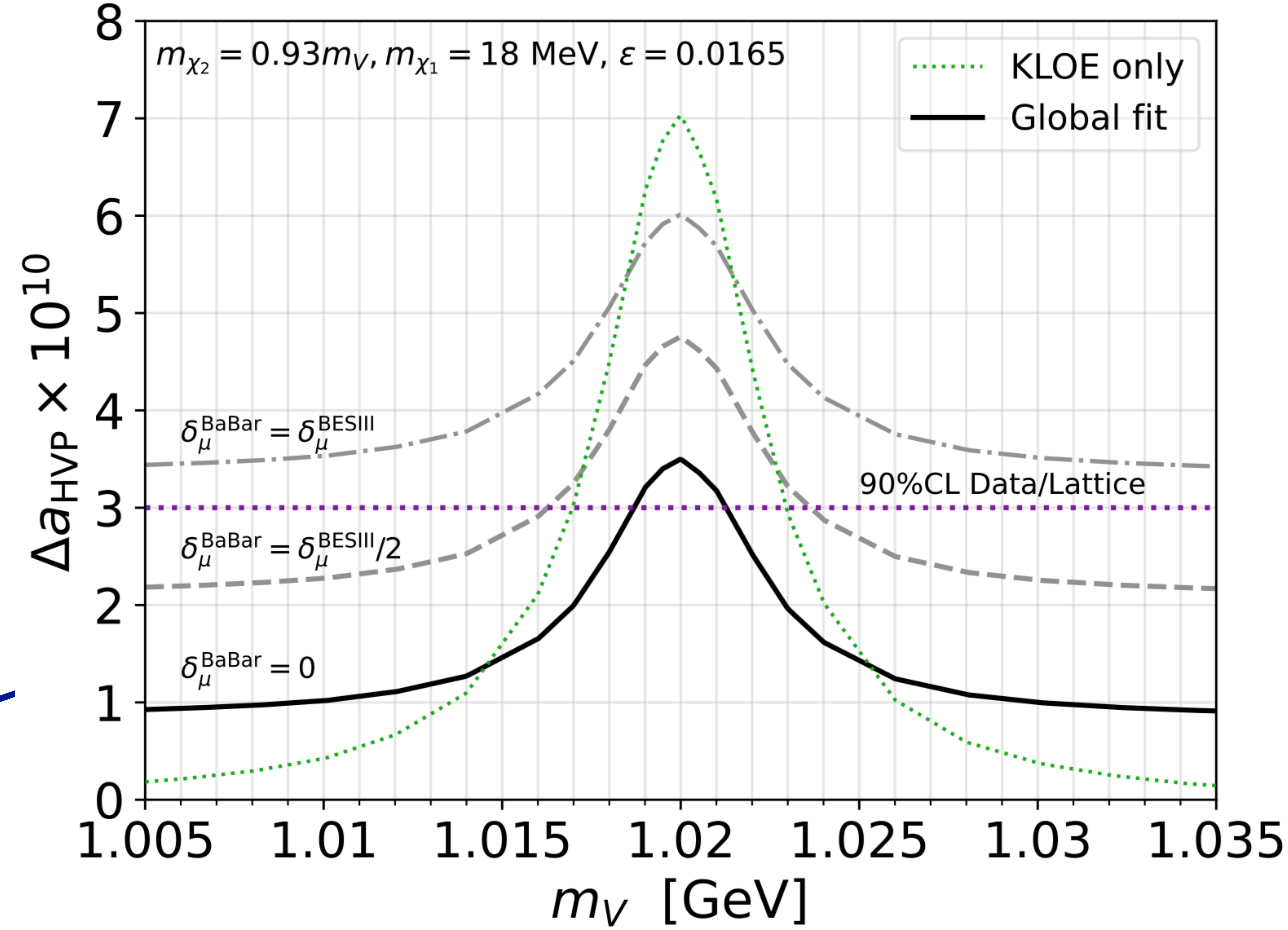
Recast KLOE08 search using Madgraph.

Solving the a_μ tension

Shifting KLOE12, BESIII and BaBar

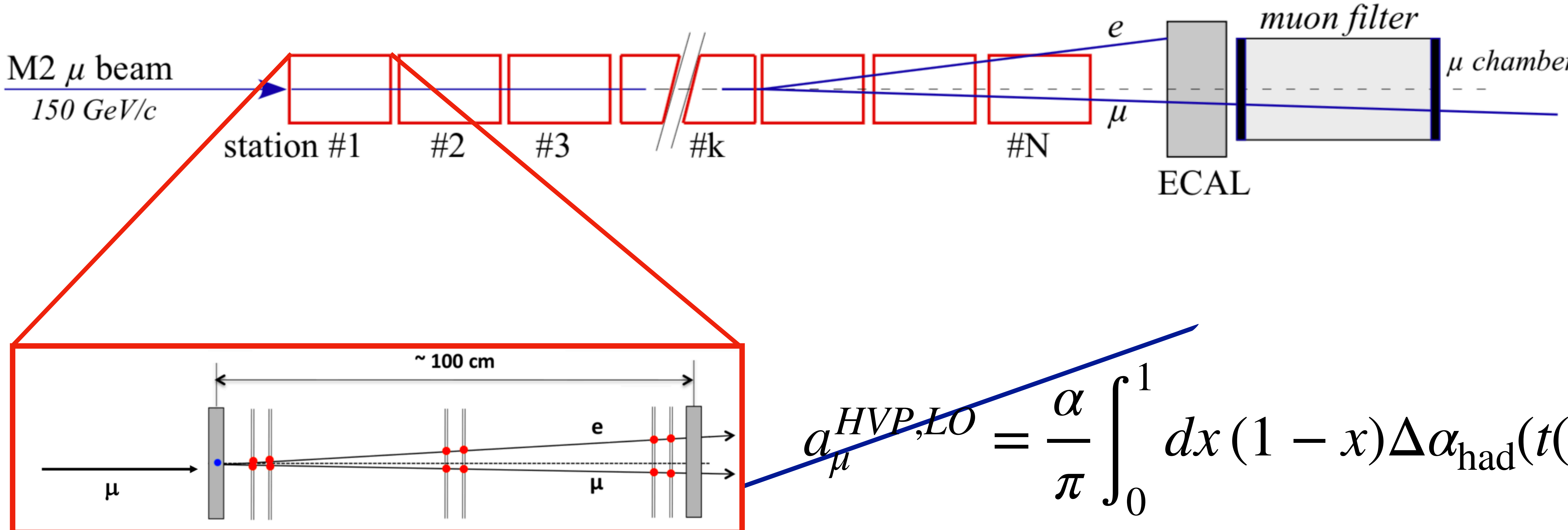


Darmé, G^{2}dC and Nardi, '21



Recast all searches using Madgraph.

MUonE



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

MUonE

[G²dC, Nardi '22]