The muon g-2 and GeV-scale new physics

solving the tensions between the lattice and R-ratio SM estimates

Luc Darmé

IP2I – CNRS

08/07/2022

Based mosty on 2112.09139 and ongoing work with E. Nardi and G. Grilli di Cortona

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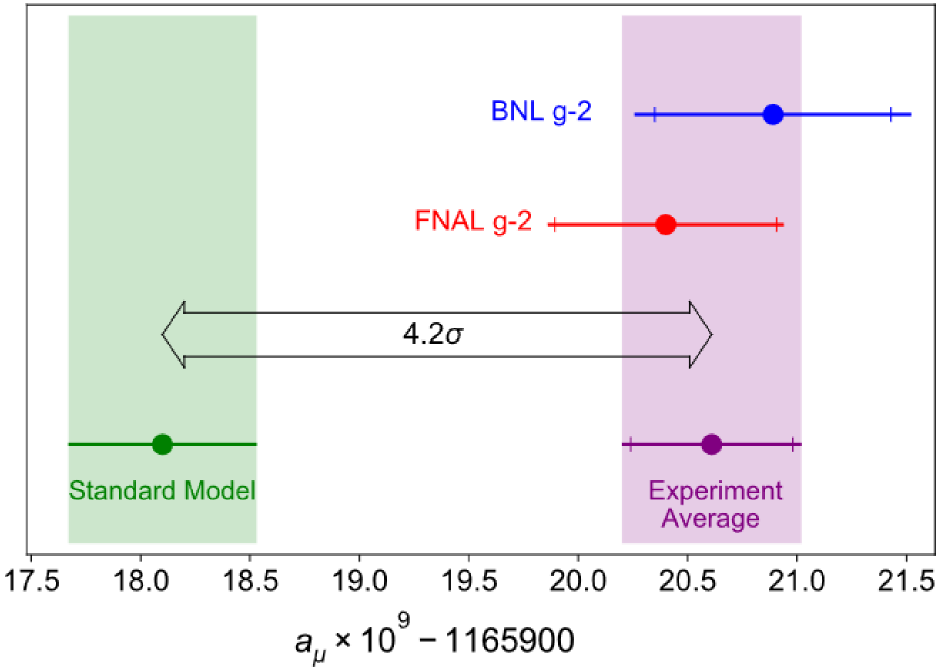
a_μ and light NP particle: the perfect time ?

- The recent result from FNAL gave a confirmation of a_μ experimental value

  → The pull w.r.t the data-driven approach is 4.2σ

- Light but feebly interacting new particles with a coupling to leptons are a very good NP candidate for a_μ

Gninenko 2001, Baek 2001, Ma 2001, Brignole 1999, … Brodsky 1967…



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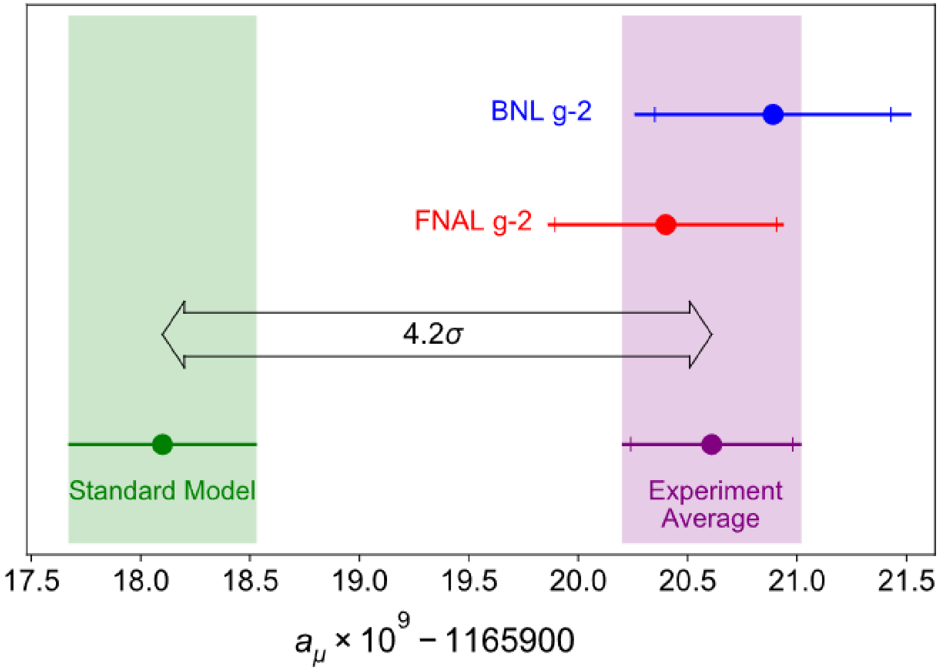
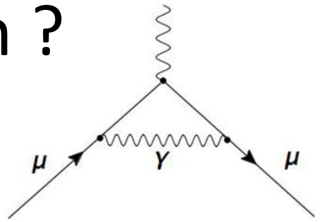


- SM prediction ?



$$a_\mu \supset \ 116\,584\,71.89 \pm 0.01 \times 10^{-10}$$

Pure QED

Adapted from Teubner 2021

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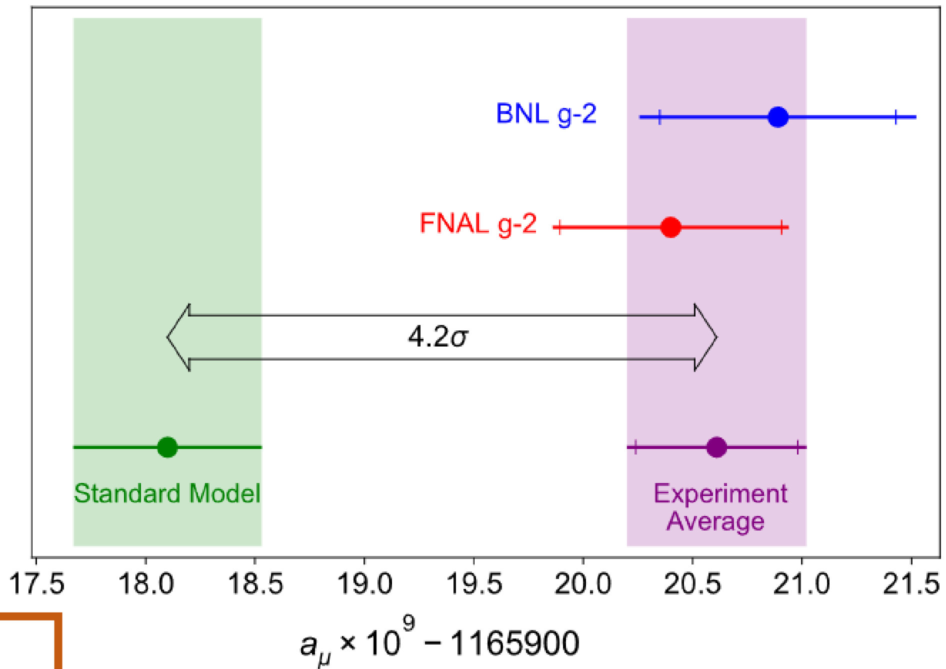

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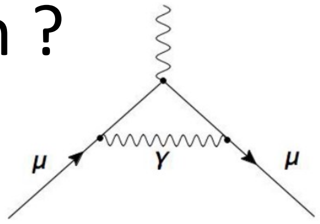

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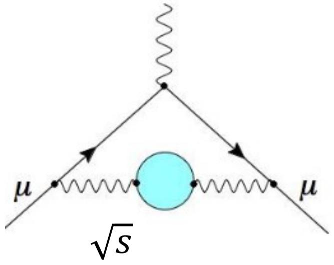

$a_\mu \supset 684.5 \pm 4.0 \times 10^{-10}$

Pure QED

Hadronic Vacuum Polarisation

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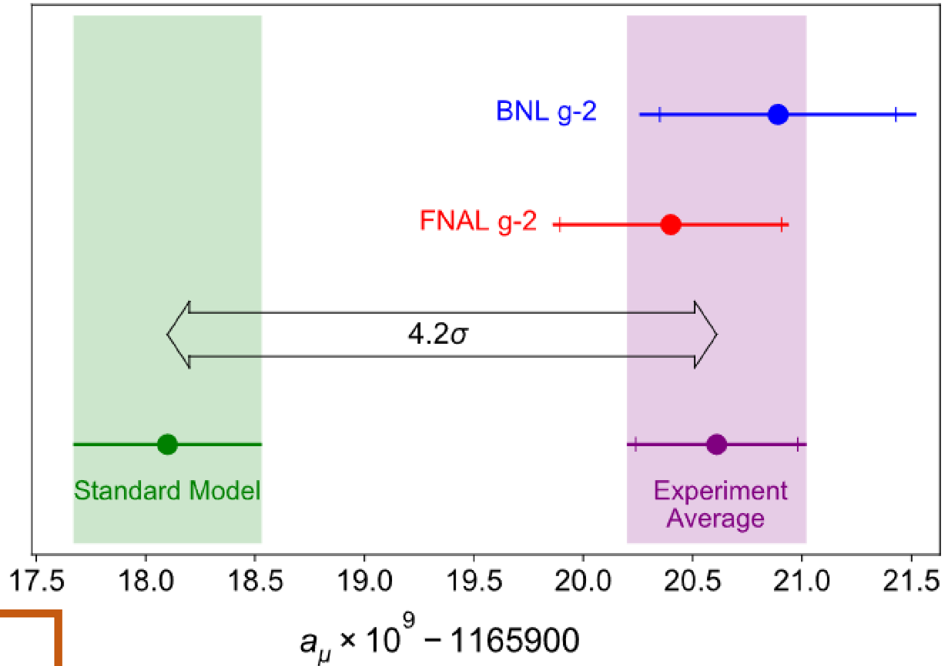

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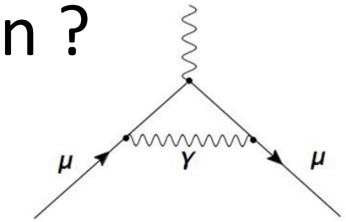

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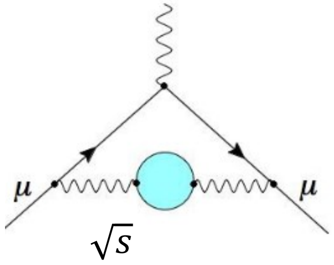
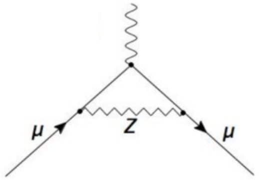


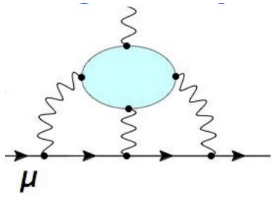
$a_\mu \supset 684.5 \pm 4.0 \times 10^{-10}$

Hadronic Vacuum Polarisation

$a_\mu \supset 15.36 \times 10^{-10}$



$a_\mu \supset 9.2 \times 10^{-10}$



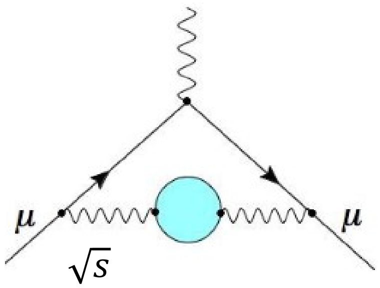
EW , Light-by-light, etc…

Adapted from Teubner 2021

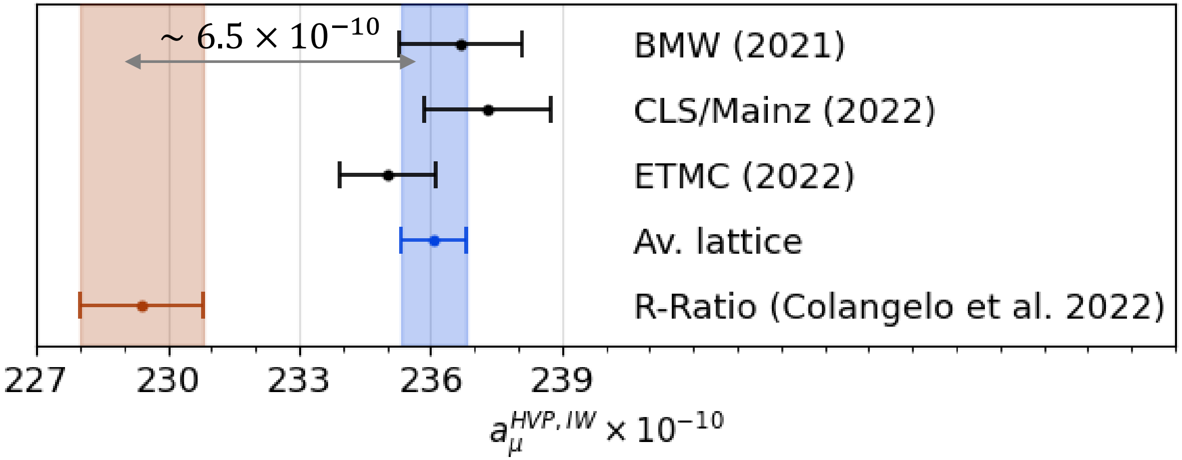
A three-body problem …

- The discrepancy between the data-driven (R-ratio) estimate and the lattice results for the Hadronic Vacuum Polarisation (HVP) term is a growing issue

  →4.2 sigma discrepancy there



«Window» HVP result, were lattice should be the most precise
→ $0.5\ \mathrm{GeV} \lesssim \sqrt{s} \lesssim 2.5\ \mathrm{GeV}$



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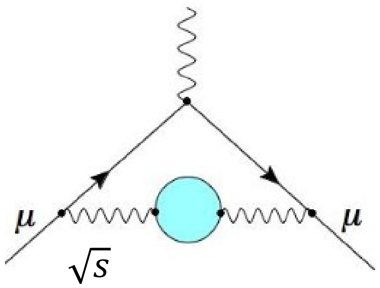

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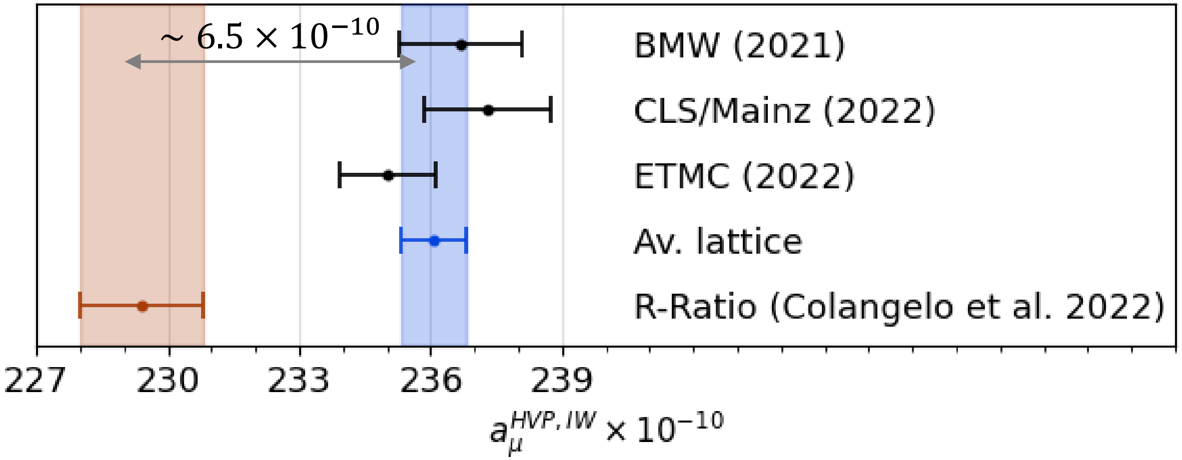

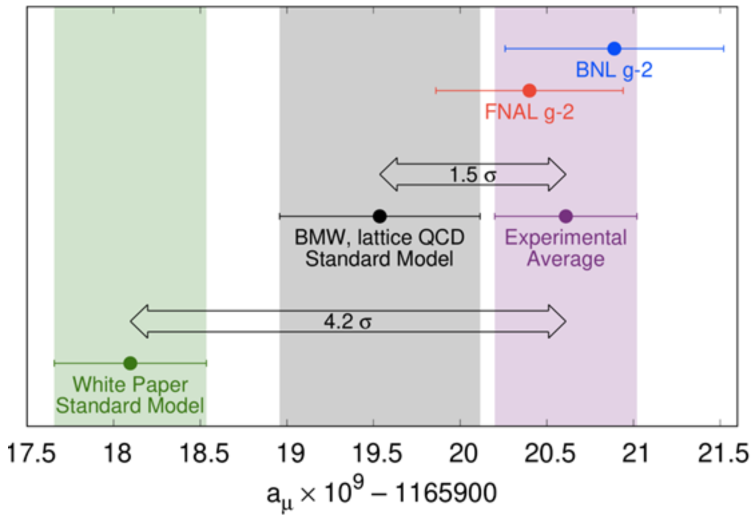

F. Jegerlehner 2021

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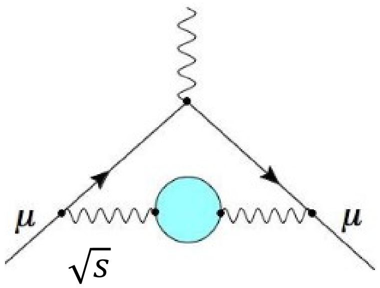

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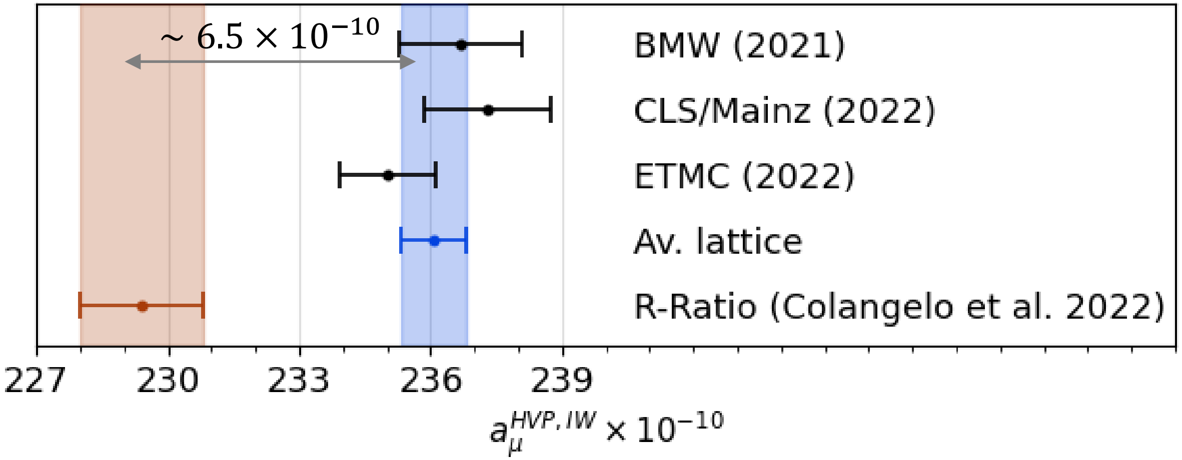

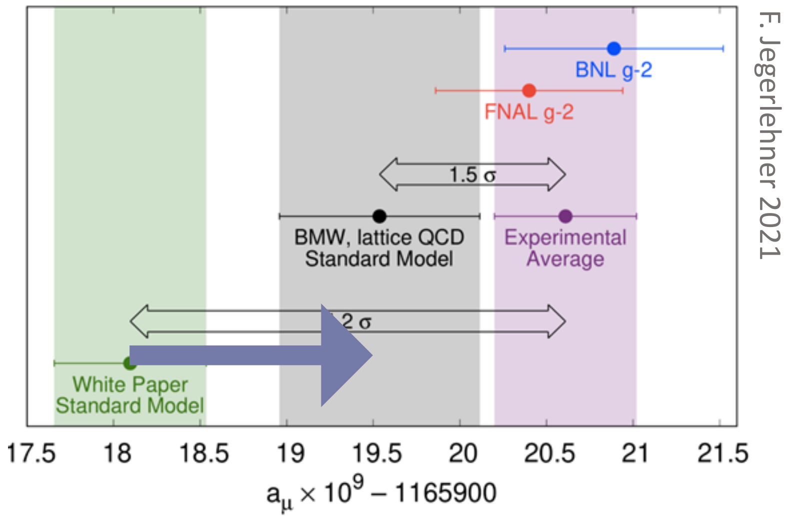

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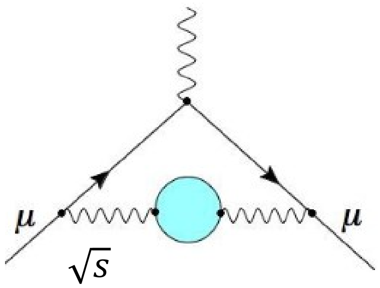

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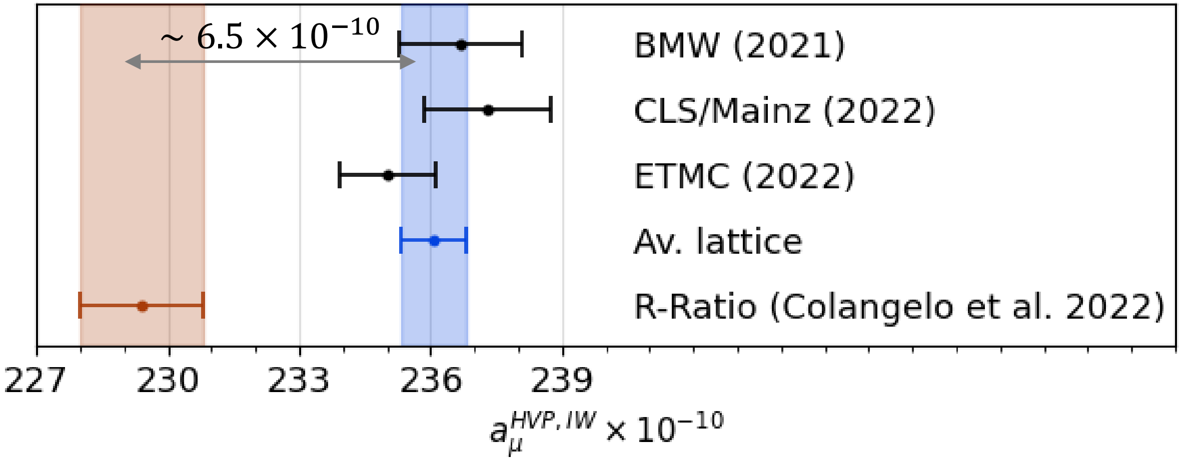

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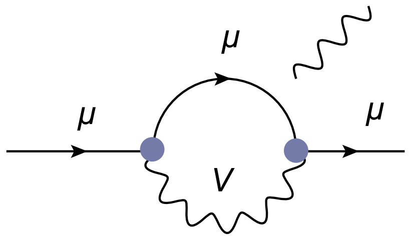
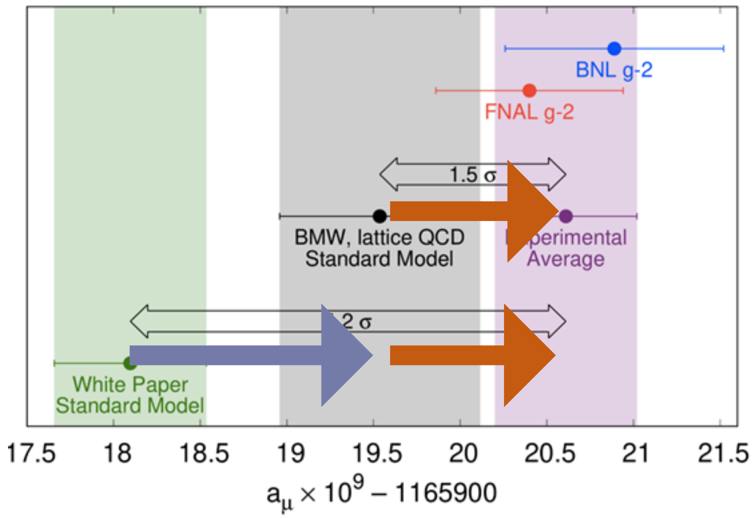
  →Adds a NP contribution to a_μ





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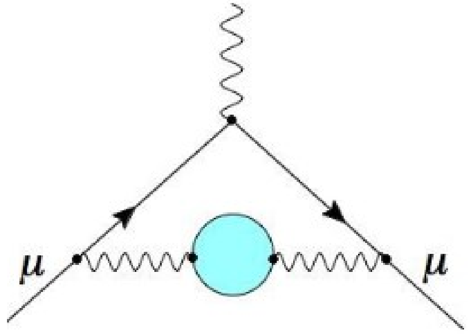
The R-ratio (data-driven) a_μ^{HVP}

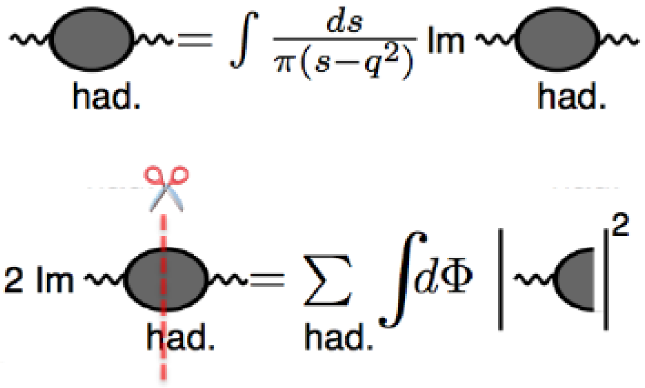


- Rely on the optical theorem to get the hadronic loop from $\mathrm{e}^+\mathrm{e}^- \to \gamma^* \to hadrons$

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

All the data goes in here, the $e^+e^- \to hadrons\ (\gamma)$ bare cross-section

Kernel function: skew the integrals toward smaller s



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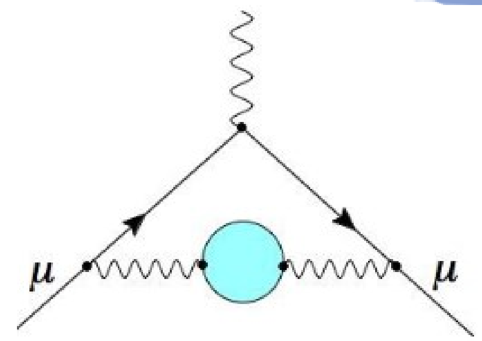

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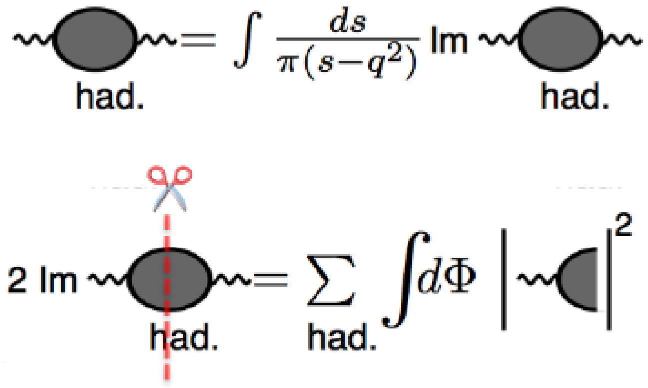
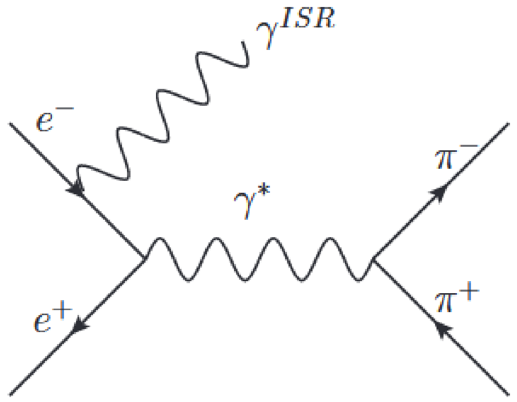


- Data + luminosity and experimental efficiencies are required at all $\sqrt{s}$
- Key idea: act indirectly on σ_{had} by impacting the experimental channels used to calibrate the luminosity.

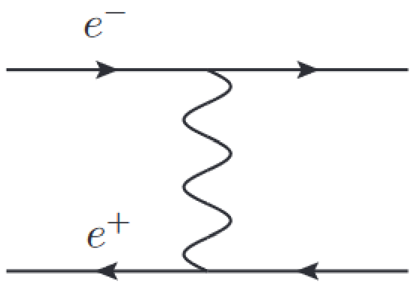


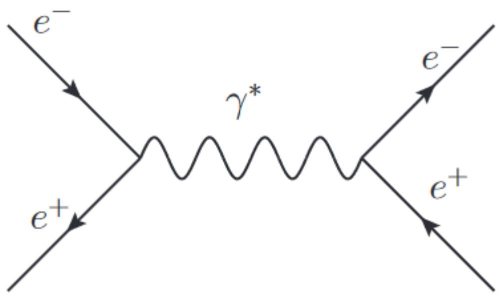
Most precise experimental datasets use ISR to dynamically fix the CoM energy

Two approaches to luminosity calibration

The «vanilla » way: % level uncertainty

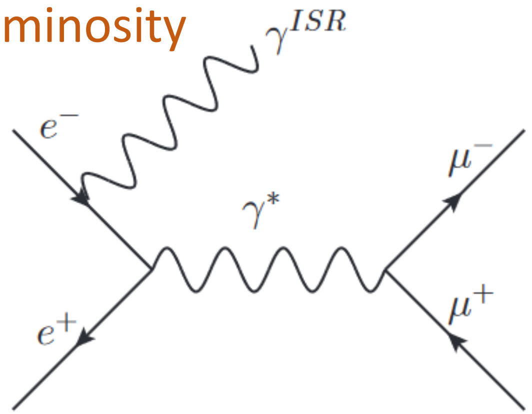
Use Bhabha scattering $e^+e^- \rightarrow e^+e^-$ to get the full time-integrated exp. luminosity once and for all + analytical radiator function





The «muons» way

Use $e^+e^- \rightarrow \gamma^{ISR}\mu^+\mu^-$ to calibrate « on the fly » the luminosity



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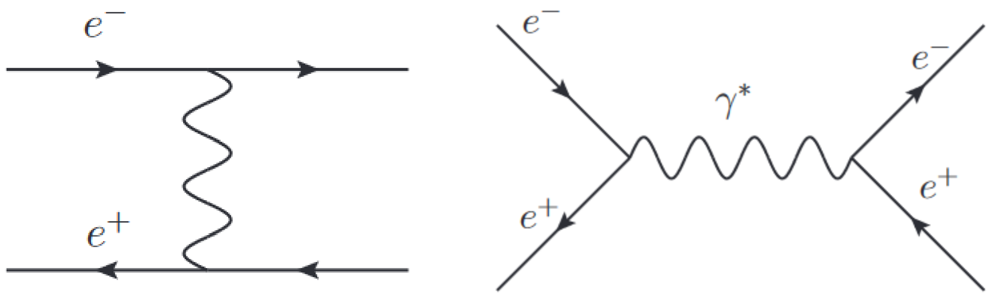

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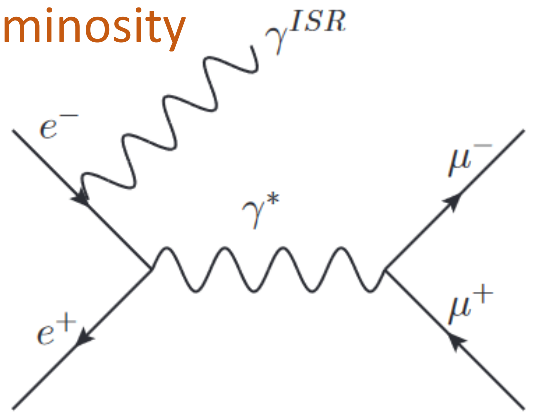

- In absence of NP, we can thus find σ_{had} by comparing hadronic final states with leptonic ones

Focusing on the di-pion final states, the dominant contribution to σ_{had}

$$\sigma^{0,exp.}_{\pi\pi} \propto \frac{N^{\text{All}}_{\pi\pi}}{N^{\text{All}}_{e^+e^-}}$$

$$\sigma^{0,exp.}_{\pi\pi} \propto \frac{N^{\text{All}}_{\pi^+\pi^-\gamma_{ISR}}}{N^{\text{All}}_{\mu^+\mu^-\gamma_{ISR}}}$$

Adding new physic to leptons final states

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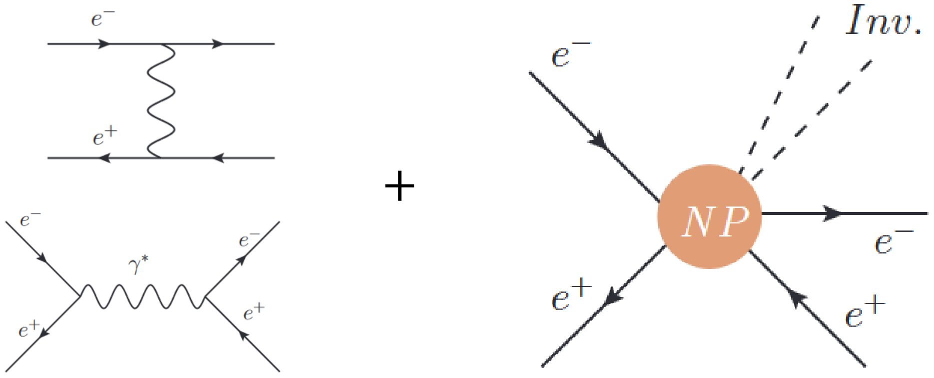

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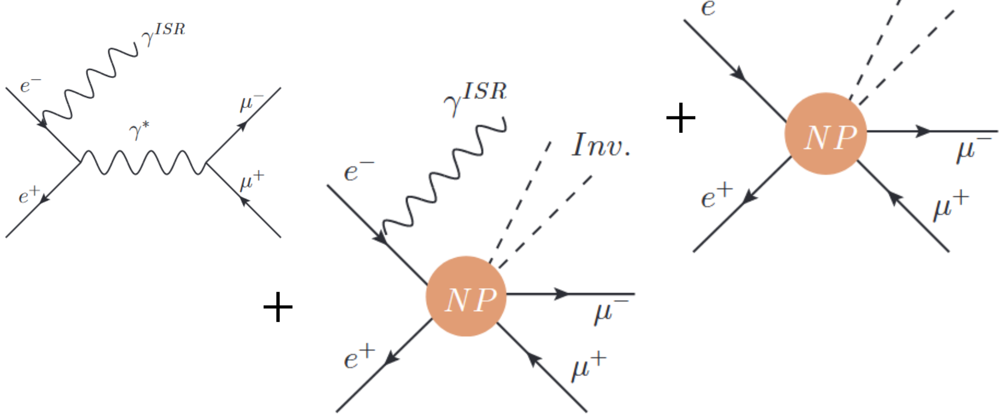

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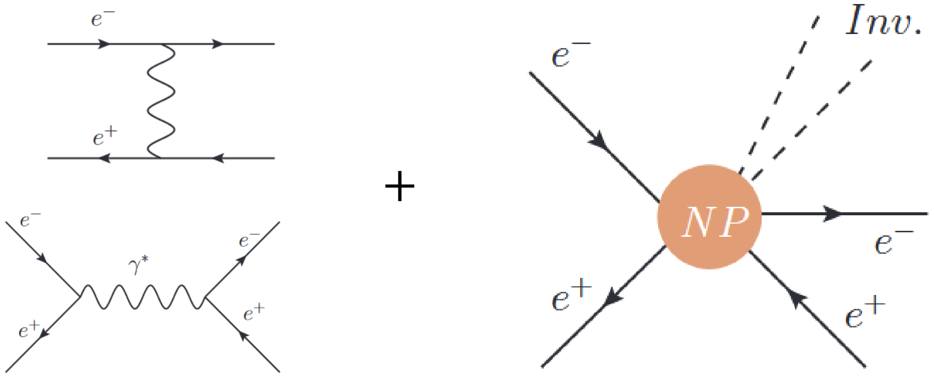

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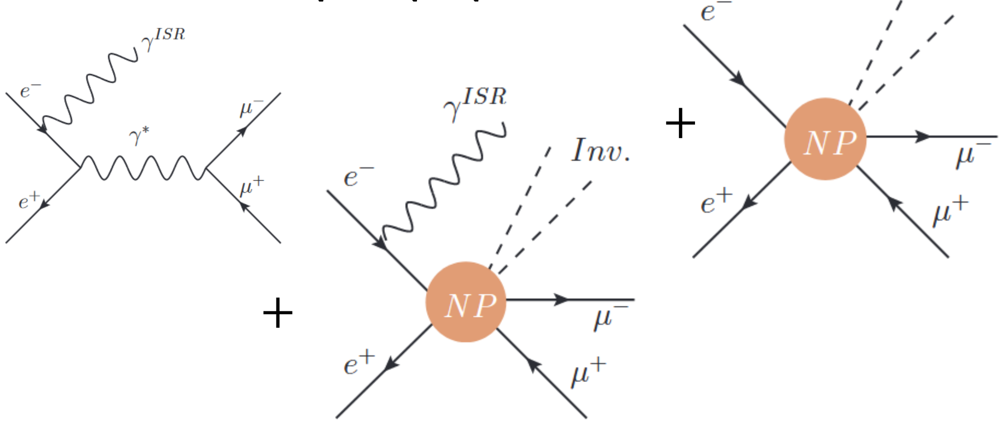
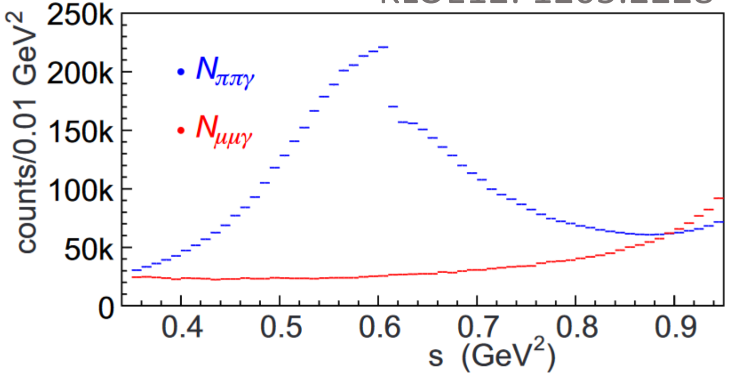


- We need to substract the NP contribution to get the SM one now !

→Note $N_{\pi\pi}^{SM} \gg N_{\mu\mu}^{SM}$

KLOE12: 1205.2228



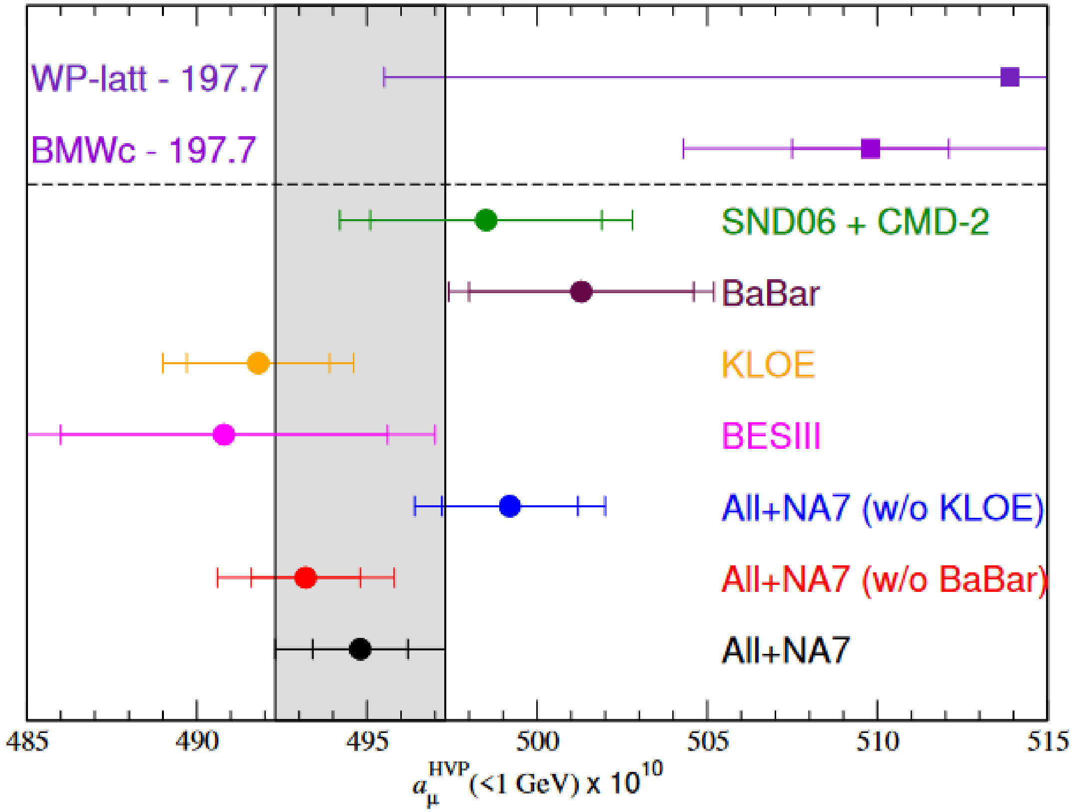
$$\sigma_{\pi\pi}^{0,exp.} \propto \frac{N_{\pi\pi}^{\text{All}}}{N_{e^+e^-}^{\text{All}} - N_{e^+e^-}^{\text{NP}}}$$

$$\sigma_{\pi\pi}^{0,exp.} \propto \frac{N_{\pi^+\pi^-\gamma_{ISR}}^{\text{All}}}{N_{\mu^+\mu^-\gamma_{ISR}}^{\text{All}} - N_{\mu^+\mu^-\gamma_{ISR}}^{\text{NP}}}$$

In summary …

- The various analysis rely on different methods to calibrate their luminosity
  → Full experimental simulation required to find the efficiencies (+3 sub-analysis for KLOE)!

Hoferichter 2021 g-2 days



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$$\delta_R = \frac{\sigma^{NP}_{e^-e^-}}{\sigma^{0}_{e^-e^-}} \frac{\epsilon^{NP}_{e^-e^-}}{\epsilon^{SM}_{e^-e^-}}$$

Faking Bhabha final states modifies KLOE08 and KLOE10

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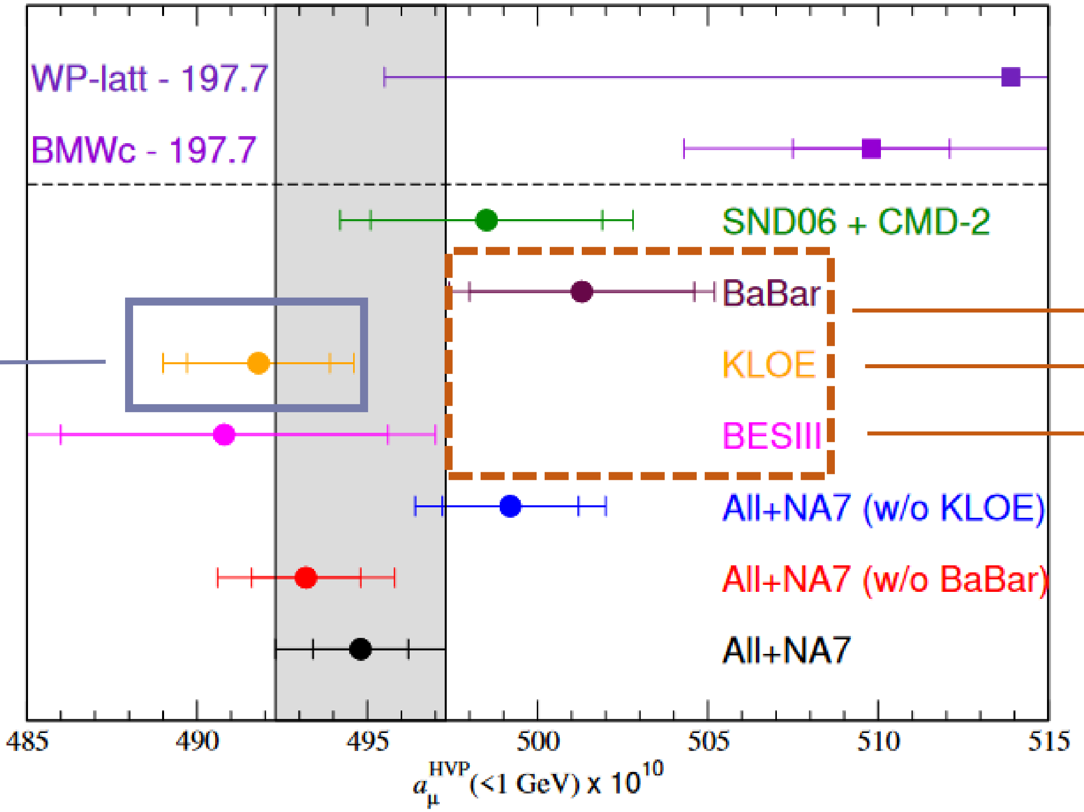

$$\delta_\mu(s') \equiv \frac{\sigma^{NP}_{\mu\mu X}(s')}{\sigma_{\mu\mu}(s')} \frac{\epsilon^{NP}}{\epsilon^{SM}}$$

Faking di-muon final states modifies KLOE12, and BESIII (and BaBaR)

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$$\delta_R = \frac{\sigma^{NP}_{e^-e^-}\ \epsilon^{NP}_{e^-e^-}}{\boxed{\sigma^0_{e^-e^-}\ \epsilon^{SM}_{e^-e^-}}}$$

Around 60 nb ! → ~nb CS required from NP

Faking Bhabha final states modifies KLOE08 and KLOE10

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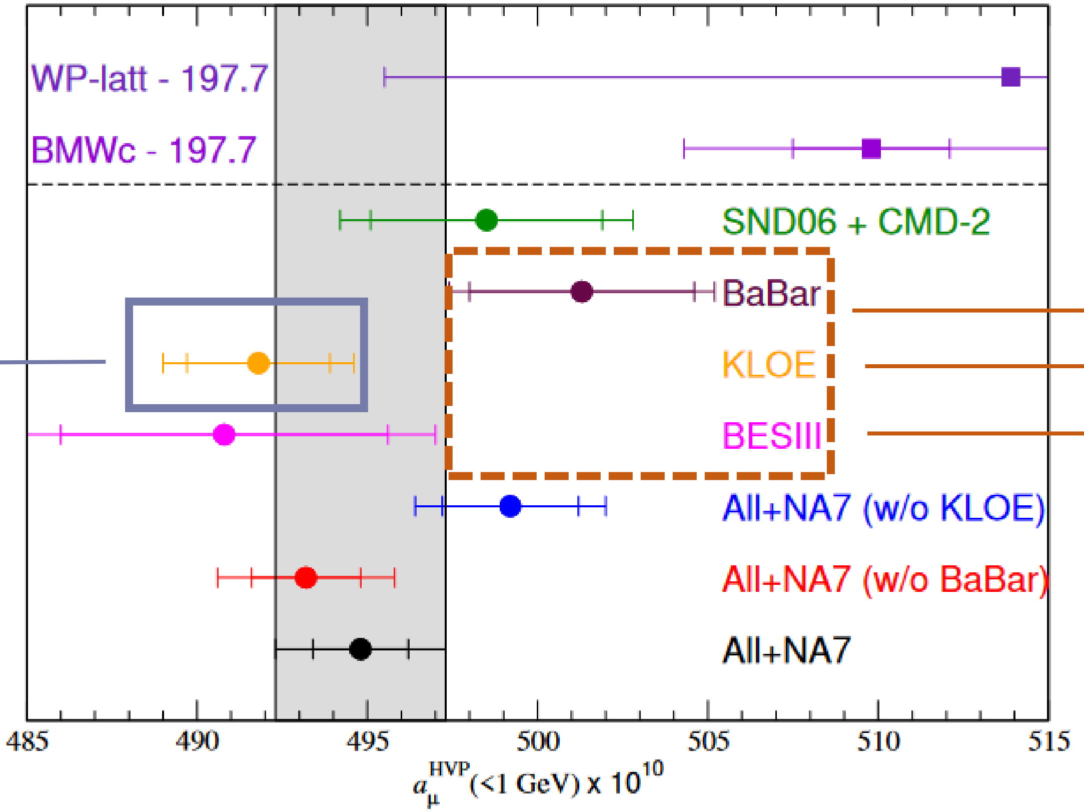

$$\delta_\mu(s') \equiv \frac{\sigma^{NP}_{\mu\mu X}(s')\ \epsilon^{NP}}{\boxed{\sigma_{\mu\mu}(s')\ \epsilon^{SM}}}$$

Around the nb, smaller CS required from NP

Faking di-muon final states modifies KLOE12, and BESIII (and BaBaR)

- Shifting the "old" e^+e^- luminosity calibration is much harder
  → We will use a new particle at *precisely* the KLOE energy to allow a resonant production.

Stealthy dark sector

- Light, GeV-scale mediator whose decays have both a dileptons final states and missing energy to avoid « bump search» and invisible search
- An explicit example: Inelastic dark matter models with a large splitting

Mohlabeng 2019, Duer 2019, Duer 2020, LD 2021, …

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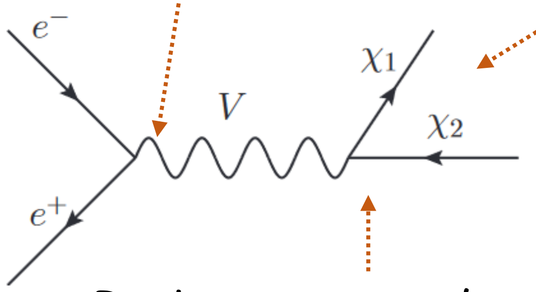
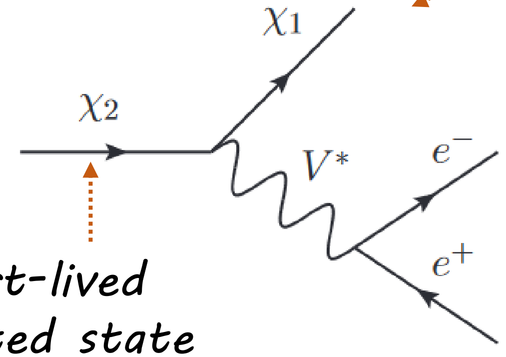
Use a dark photon mediator: $\propto \varepsilon\, e$

Main constitute part of DM: escape detectors



Dark gauge coupling mediator: $g_D \sim O(1)$

Short-lived excited state



The decay is 3-body, ensuring that bump search cannot effectively probe it

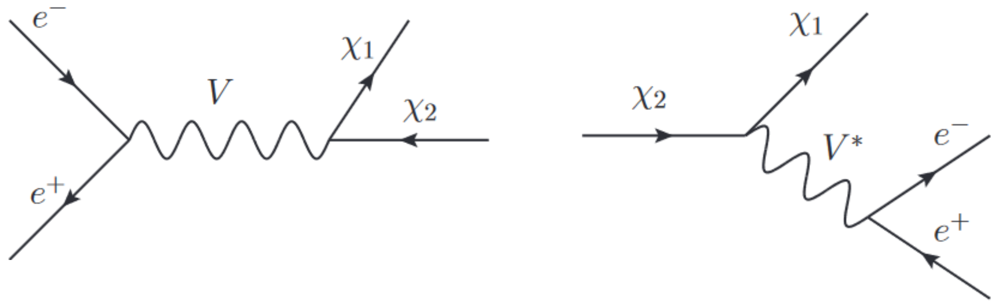
$m_1 \ll m_2, M_V$ *ensures that the* e^+e^- *pair still carries a significant energy*

→ The masses of the various states are free and control the kinematics of the final states

Constraints on stealthy darks sectors

- In e^+e^- colliders one has either
  → Invisible (mono-photon) search, requiring a single γ in the events
  → $e^+e^-\gamma$ "bump" search, requiring a visible e^+e^- pair + no missing energy
- Both are severly weakened in our case

Mohlabeng 2019, Duer 2019, Duer 2020



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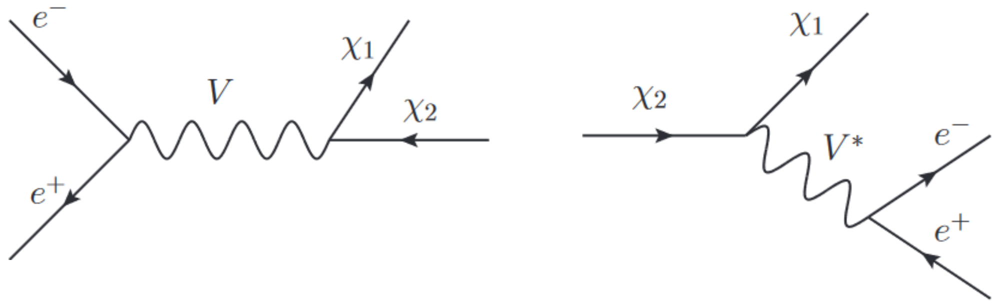
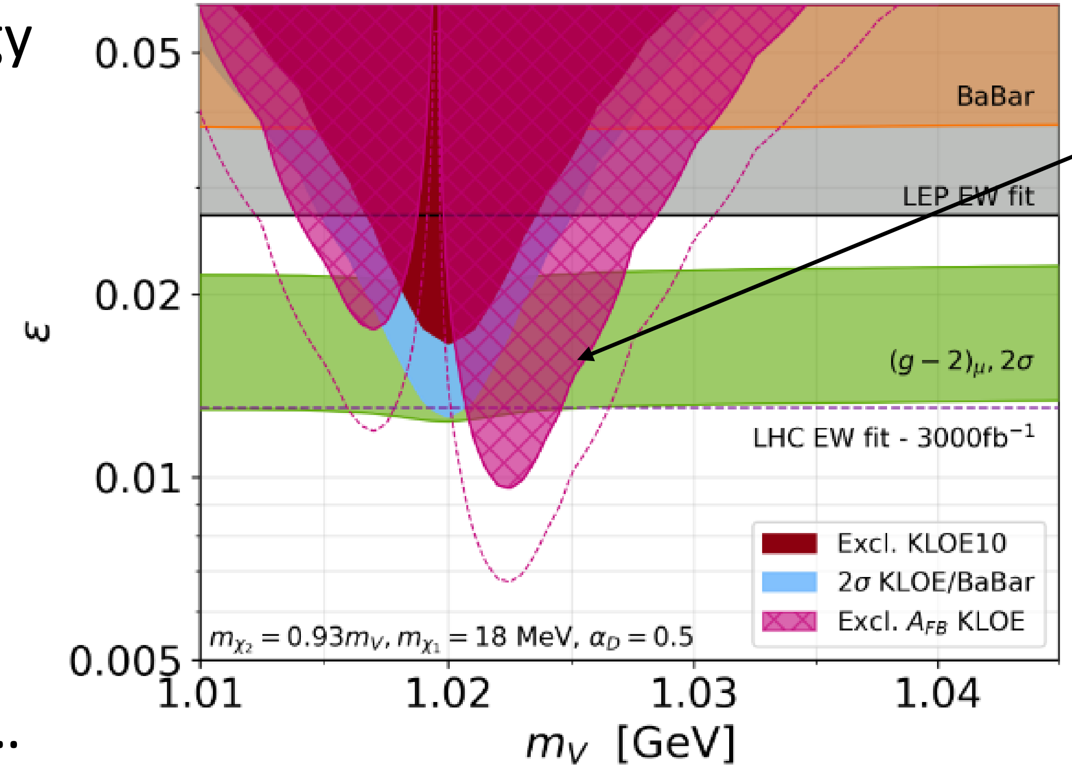
- A large range of other constraints considered
  → α_{em} shift, N_{eff} at LEP, self-consistency of KLOE measurements, A_{FB} at KLOE, etc…





We have chosen the $m_V \sim \sqrt{s_{KLOE}}$ to have a impact on KLOE and solve the KLOE/BaBar discrepancy

Constraints from leptonic cross-sections

- Most analysis cross-checks the muons $ee \to \mu\mu$ process with MC predictions, but …
  - → Typical estimate of the global luminosity come with a %-level uncertainty (systematics)
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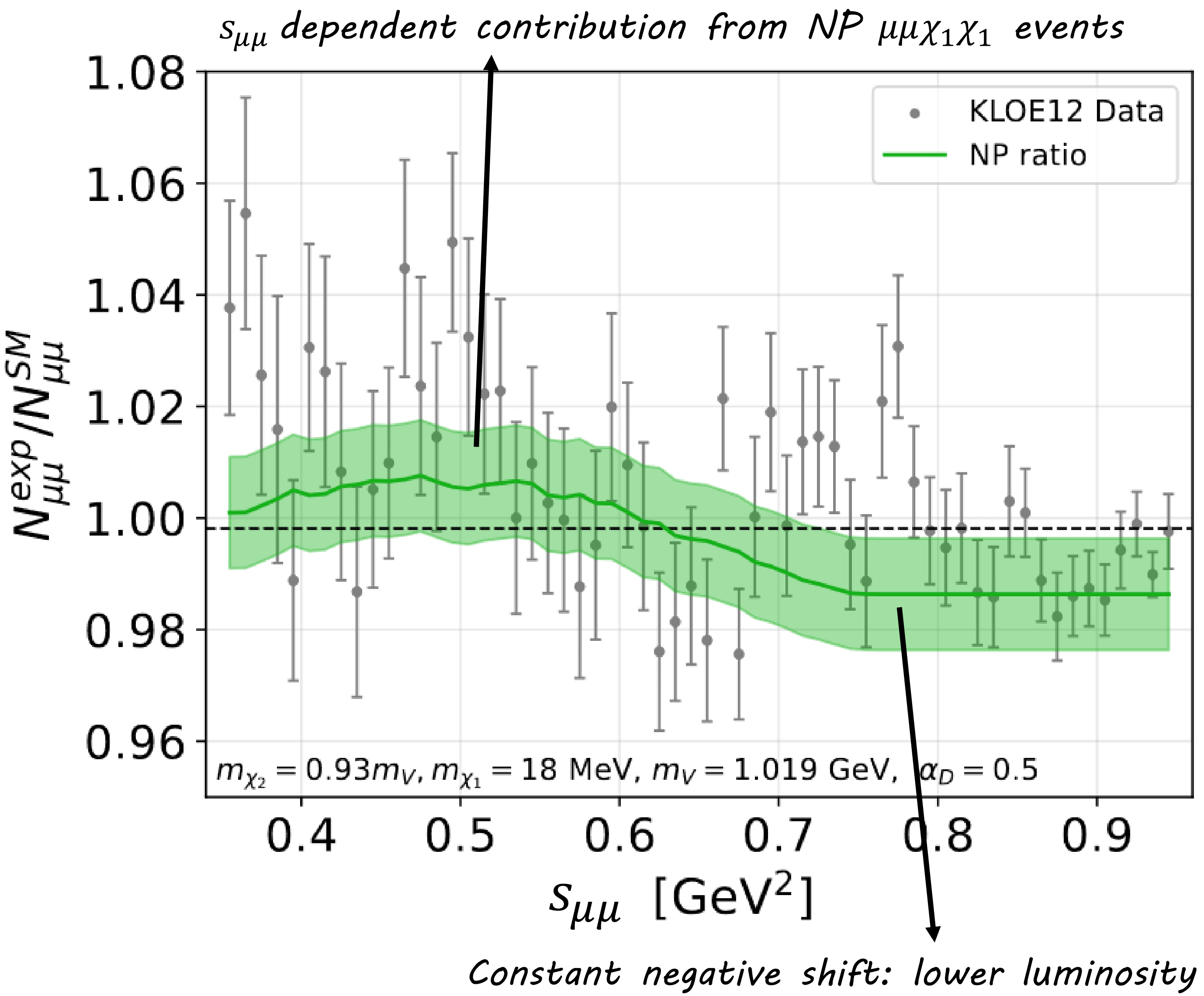
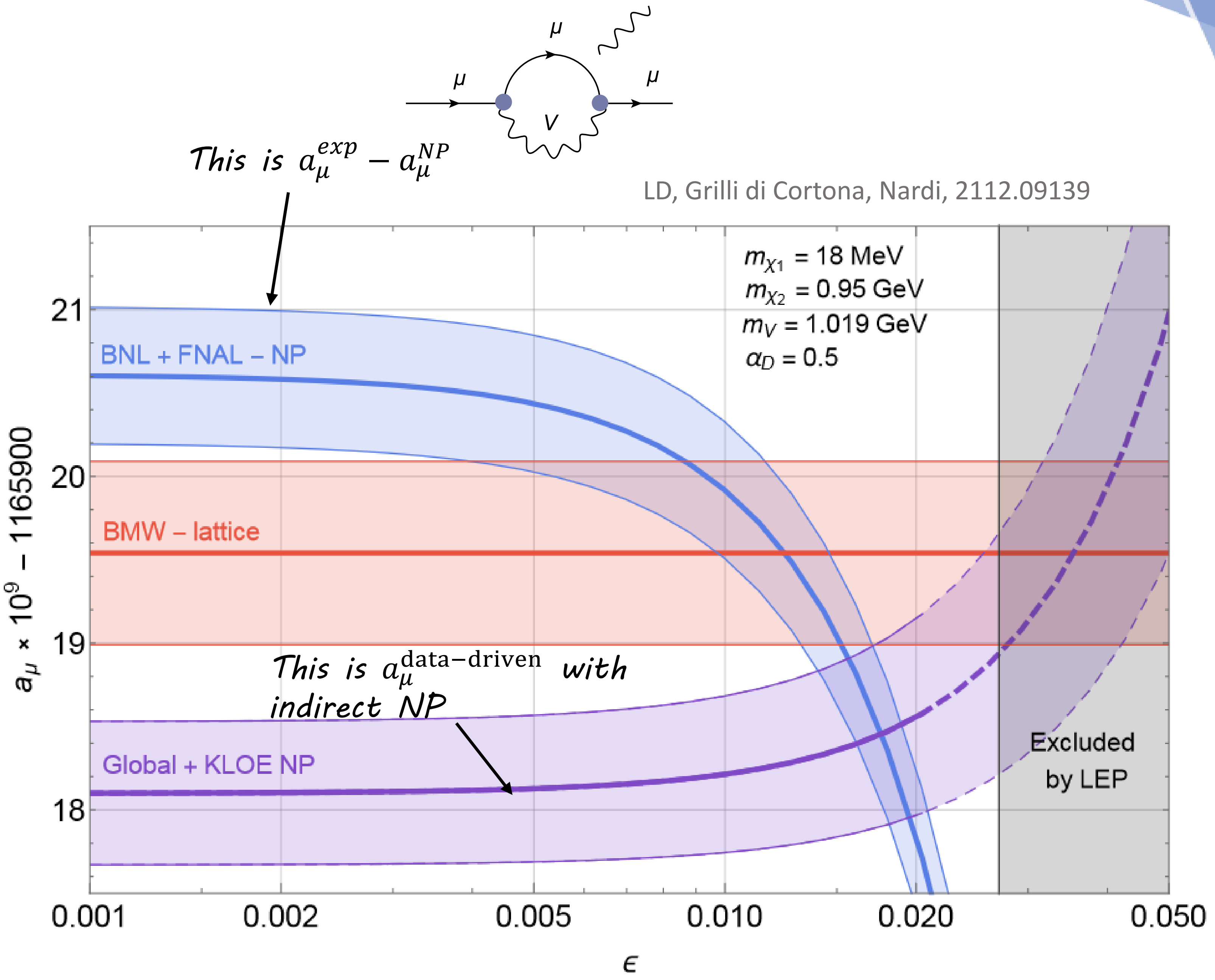


The iDM case

- Resonant FIP production at KLOE is required to act on KLOE08
  - → $m_V \sim \sqrt{s_{KLOE}}$ helps but not requirement for lattice vs R-ratio

- Solve in one go all tensions in Δa_μ-related observables !
  - →Around 3/4 of Δa_μ from NP loop and 1/4 from this effect

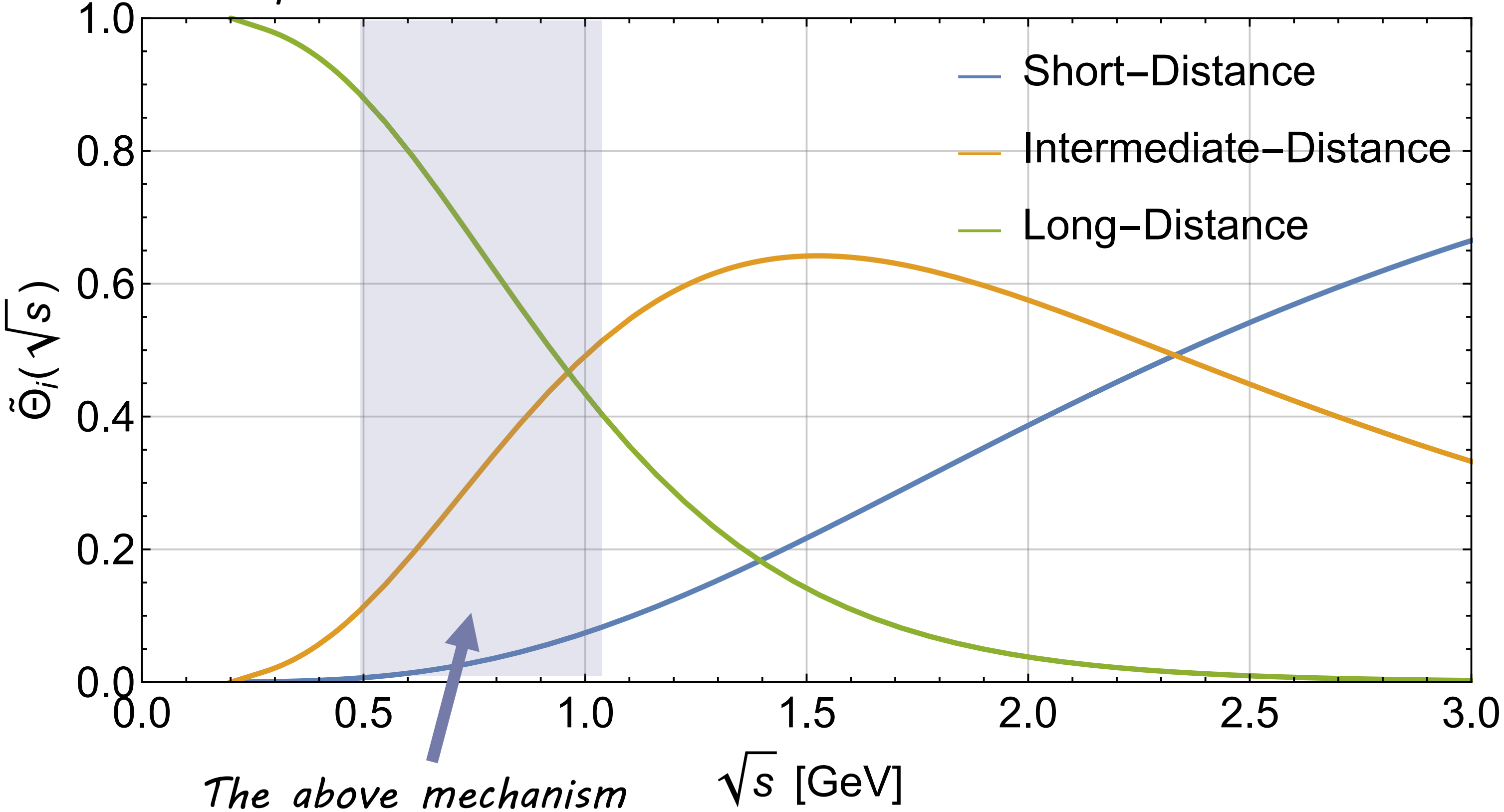
LD, Grilli di Cortona, Nardi, 2112.09139



Window approach and mass dependence

- The effect we introduce affects only GeV-scale physics → no contribution to short-range physics at $\sqrt{s} \gtrsim 2$ GeV

« Window » functions used to select a range of $\sqrt{s}$ for easy comparison with lattice



The above mechanism acts only for $\sqrt{s} < m_V$

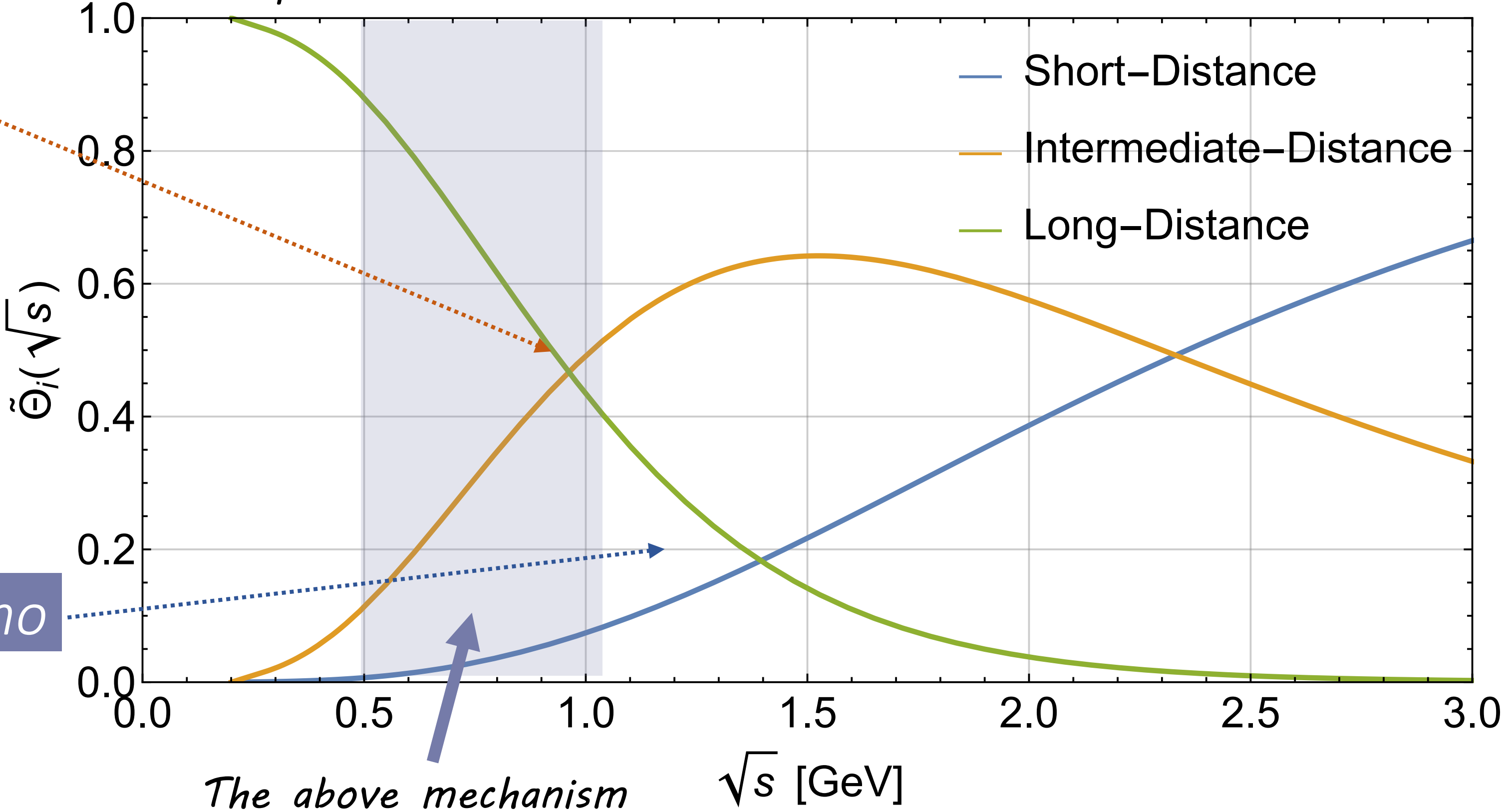
Window approach and mass dependence

- The effect we introduce affects only GeV-scale physics → no contribution to short-range physics at $\sqrt{s} \gtrsim 2$ GeV

2206.15084, ETMC collaboration

"Concerning the intermediate-distance window we confirm the two currently most accurate lattice QCD results [...] increasing the tension with [...] e^+e^- cross section data to the significant level of 4.2σ. Moreover, we have computed accurately for the first time the short-distance window, finding that there is no significant tension with the corresponding dispersive result."

« Window » functions used to select a range of $\sqrt{s}$ for easy comparison with lattice



The above mechanism acts only for $\sqrt{s} < m_V$

Conclusion

- On-shell production of GeV-scale new « stealthy » states can bring the R-ratio and lattice estimates of a_μ^{HVP} together

  → Main idea: we can inject a new physics signal in the channels used to normalise the hadronic cross-sections

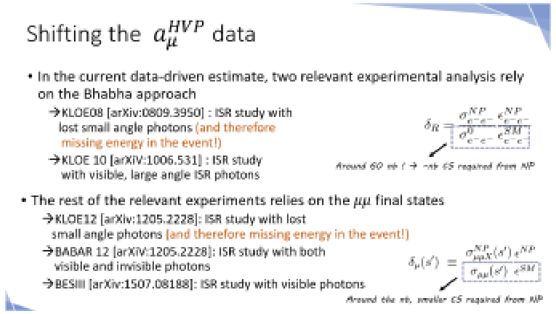
- We presented a explicit iDM model with a dark photon around the KLOE CoM energy which can solve in one go all tensions in a_μ-related observables !

- Still significant room of improvements on the model building side to obtain a NP scenario generating a larger shift with reduced tuning

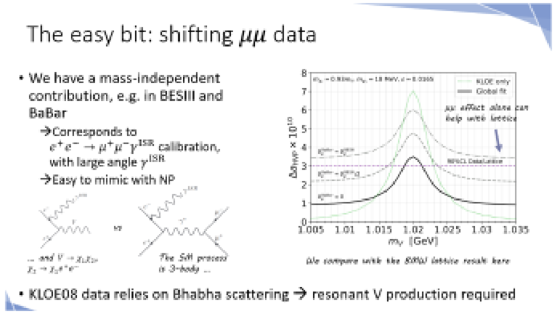
- Quantitative discussion of the window observables + better treatment of BaBar coming soon!

Backup

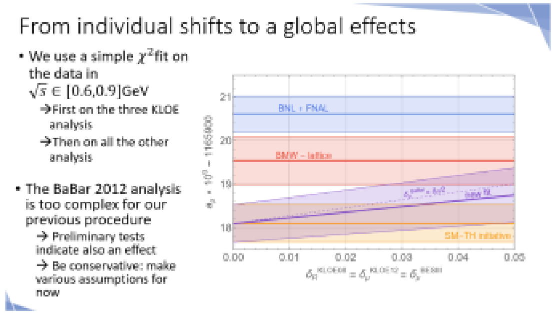
Numerical procedure



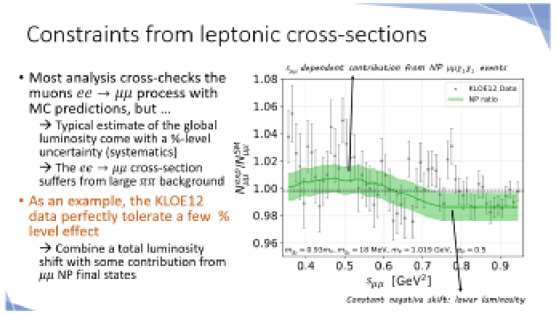
μμ vs ee shift



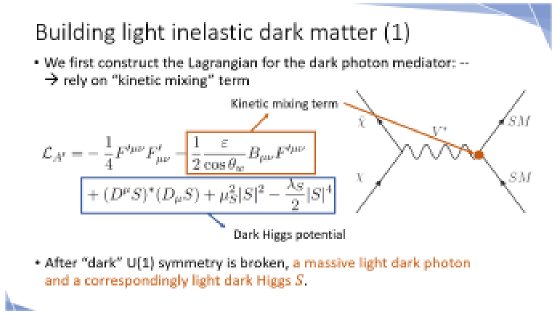
Simple fit procedure



Constraints

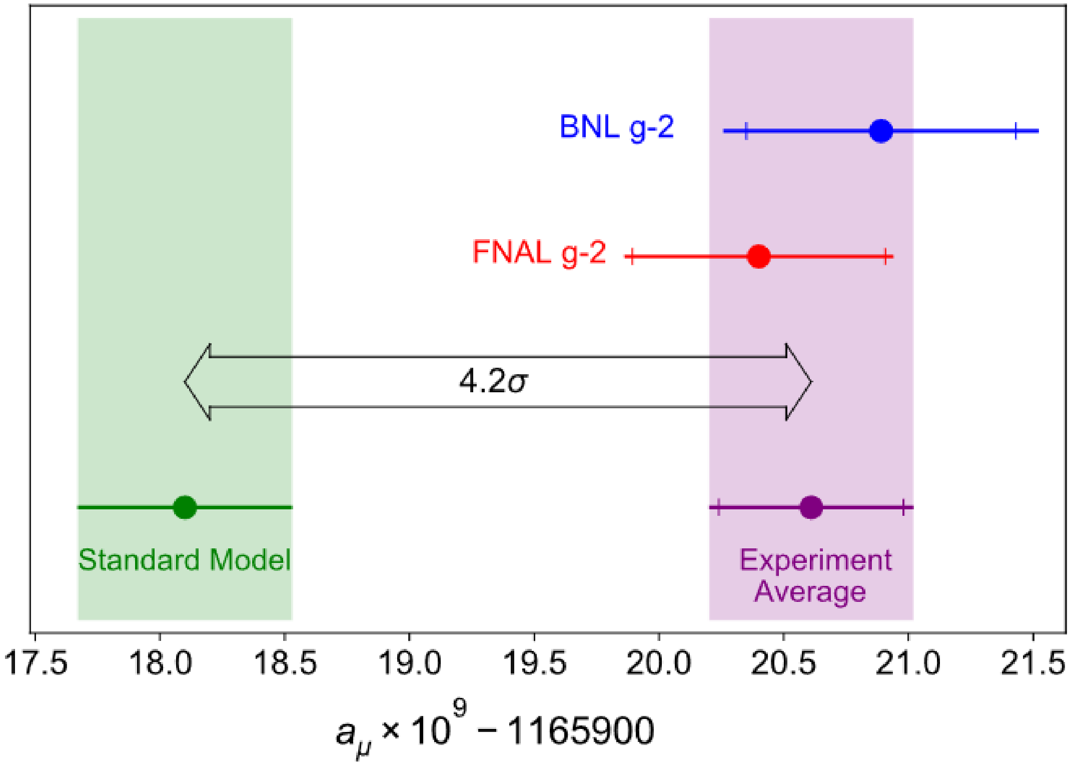


On iDM models



a_μ and light NP particle: the perfect time ?

- The recent result from FNAL gave a confirmation of a_μ experimental value
  →The pull w.r.t the data-driven approach is 4.2σ
- Light but feebly interacting new particles with a coupling to leptons are a very good NP candidate for a_μ



→ Long studied as a NP contribution for $a_{\mu,e}$ Gninenko 2001, Baek 2001, Ma 2001, Brignole 1999, … Brodsky 1967…

→ While "vanilla" dark photons are however already excluded by BaBaR mono-photon searches, a range of good candidates, from ALPs to $L_\mu - L_\tau$ still viable

Shifting the a_μ^{HVP} data

- In the current data-driven estimate, two relevant experimental analysis rely on the Bhabha approach
  - →KLOE08 [arXiv:0809.3950] : ISR study with lost small angle photons (and therefore missing energy in the event!)
  - →KLOE 10 [arXiV:1006.531] : ISR study with visible, large angle ISR photons

$$\delta_R = \boxed{\frac{\sigma^{NP}_{e^-e^-}}{\sigma^0_{e^-e^-}}} \frac{\epsilon^{NP}_{e^-e^-}}{\epsilon^{SM}_{e^-e^-}}$$

Around 60 nb ! → ~nb CS required from NP

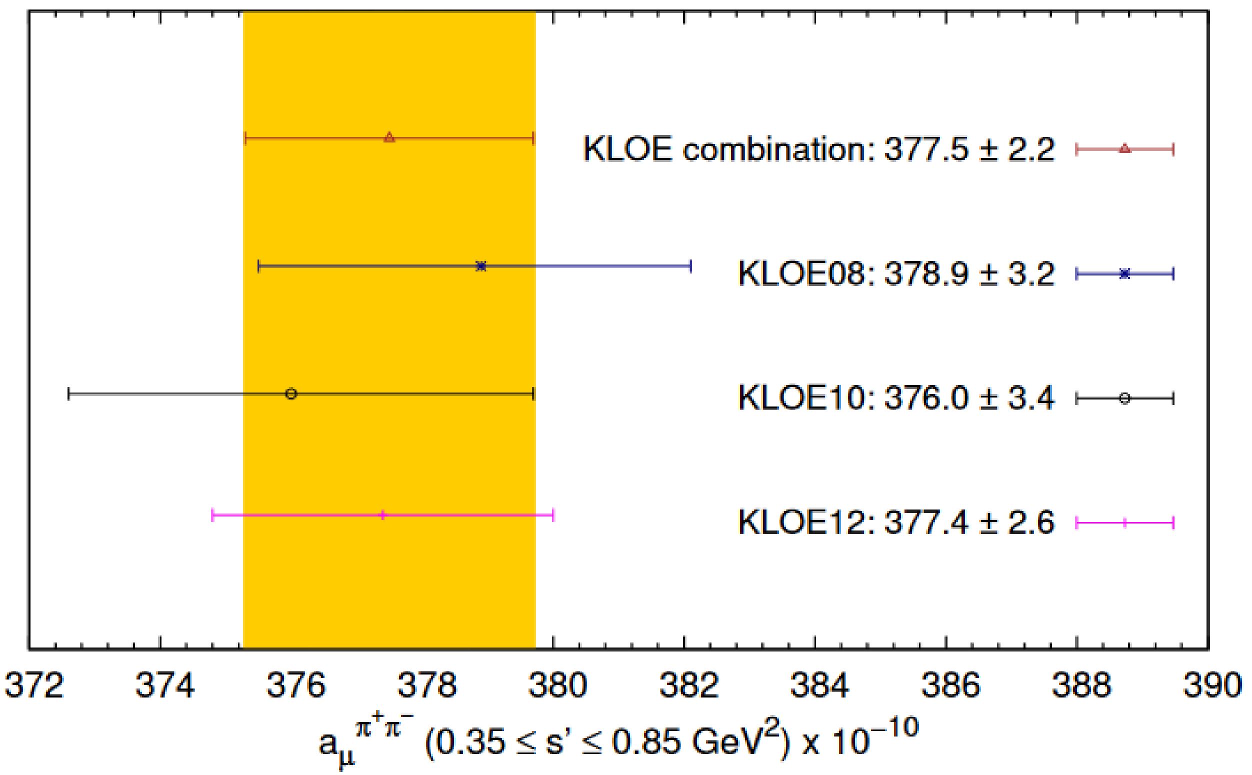
- The rest of the relevant experiments relies on the $\mu\mu$ final states
  - →KLOE12 [arXiv:1205.2228]: ISR study with lost small angle photons (and therefore missing energy in the event!)
  - →BABAR 12 [arXiV:1205.2228]: ISR study with both visible and invisible photons
  - →BESIII [arXiv:1507.08188]: ISR study with visible photons

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

Around the nb, smaller CS required from NP

a_μ^{HVP} KLOE measurements

- In the current data-driven estimate, not many relevant experimental analysis rely on this approach
  - →KLOE08 [arXiv:0809.3950] : ISR study with lost small angle photons (and therefore missing energy in the event!)
  - →KLOE 10 [arXiV:1006.531] : ISR study with visible, large angle ISR photons. BUT run at $\sqrt{s} = 1$ GeV: that gives us a constraint
  - →KLOE12 [arXiv:1205.2228]: ISR study with lost small angle photons (and therefore missing energy in the event!)



Recasting the experimental analysis

iDM Model

↓ FEYNRULES

MadGraph5_aMC@NLO

For KLOE08

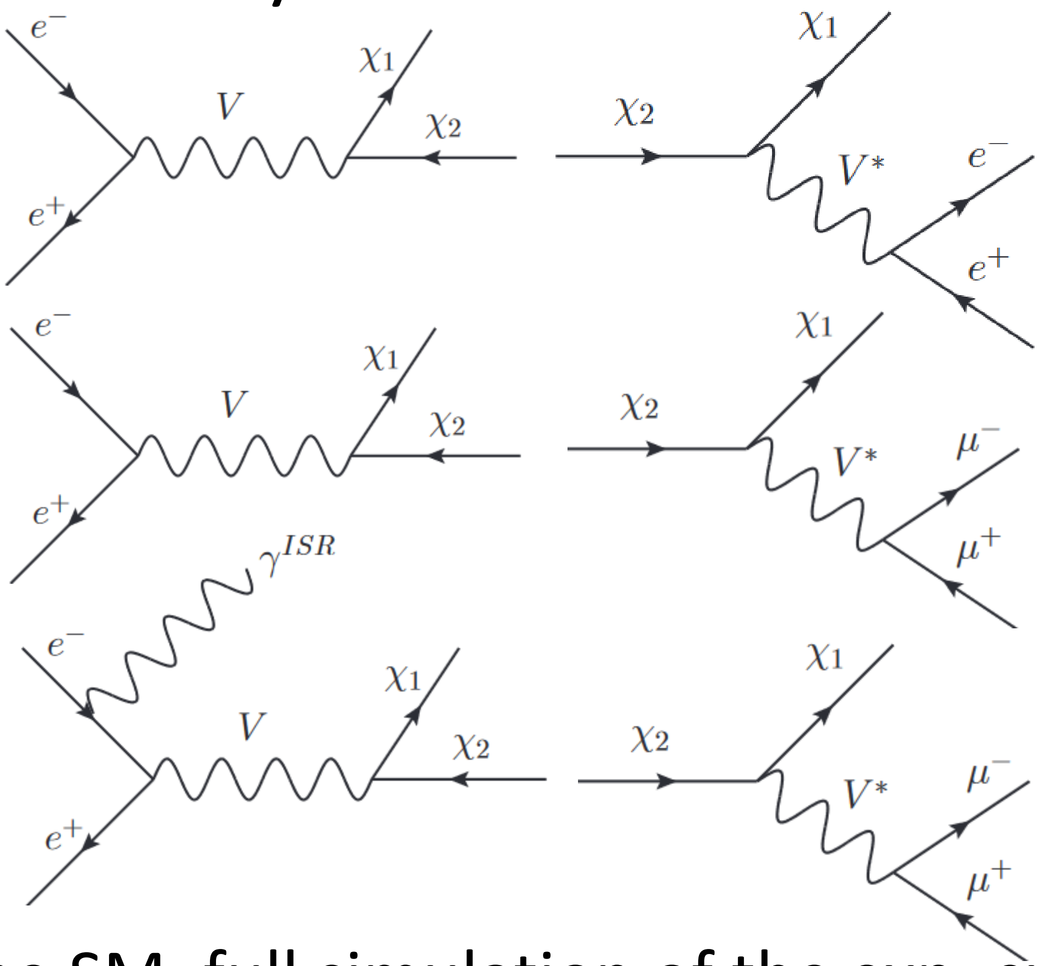
$e^+e^- \to e^+e^-\chi_1\,\chi_1$

For KLOE12

$e^+e^- \to \mu^+\mu^-\chi_1\,\chi_1$

For BESIII

$e^+e^- \to \mu^+\mu^-\gamma\,\chi_1\,\chi_1$

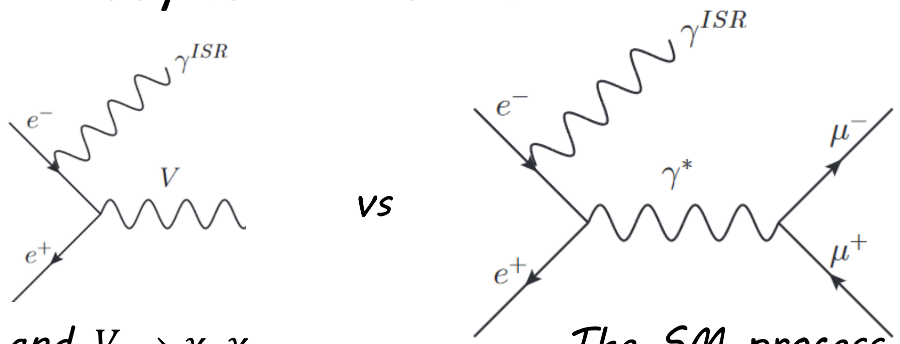


- Since the final states are different from the SM, full simulation of the exp. cuts critical, we obtain the shifts δ_R^{KLOE08} , δ_μ^{BESIII} , δ_μ^{KLOE12}

  → Needs to be combined to get the final change to the data-driven prediction for a_μ^{HVP}

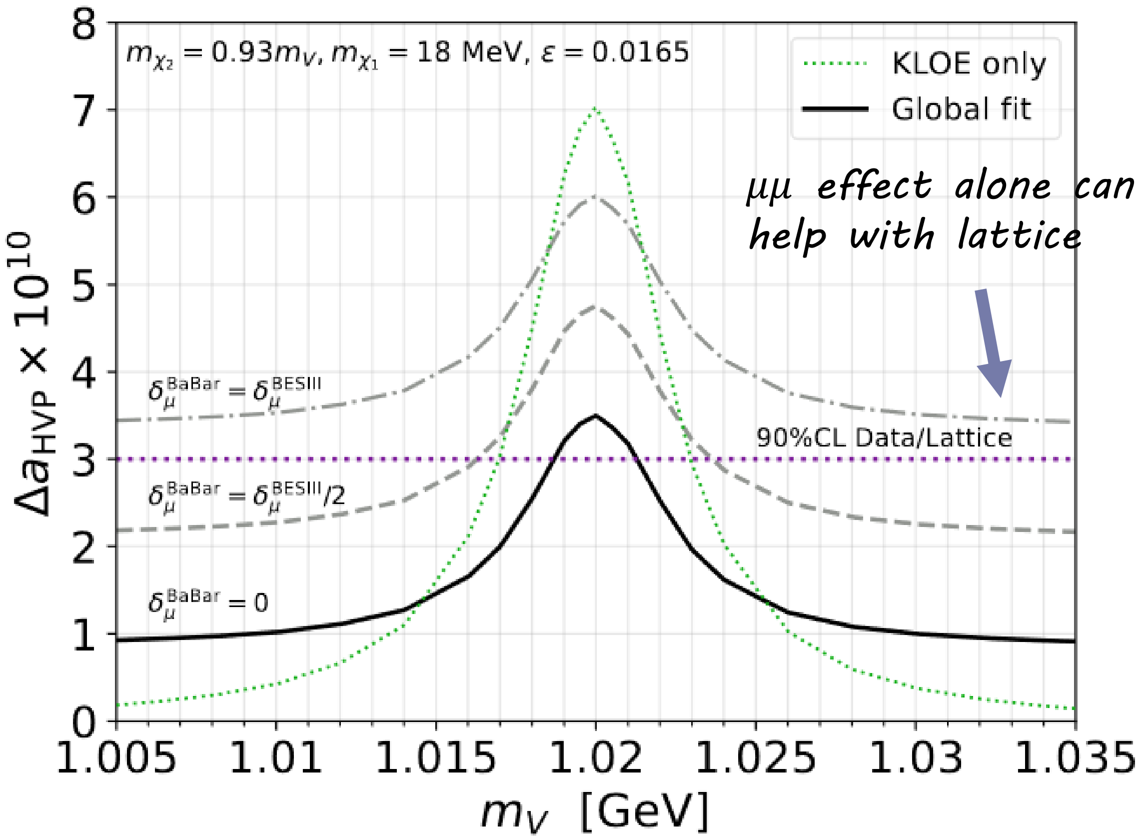
The easy bit: shifting $\mu\mu$ data

- We have a mass-independent contribution, e.g. in BESIII and BaBar
  - →Corresponds to $e^+e^- \to \mu^+\mu^-\gamma^{\mathrm{ISR}}$ calibration, with large angle γ^{ISR}
  - →Easy to mimic with NP



… and $V \to \chi_1\chi_2$, $\chi_2 \to \chi_1 e^+e^-$

The SM process is 3-body …



We compare with the BMW lattice result here

- KLOE08 data relies on Bhabha scattering → resonant V production required

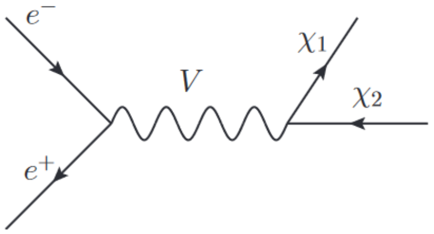
The hard bit: shifting KLOE08

- KLOE08 data relies on Bhabha scattering

  → Large NP cross-section required: we need $\sqrt{s} \simeq M_V$ to allow a resonant production

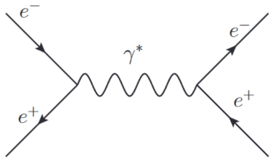
- The strategy is to have

  → $m_{\chi_1} \ll m_{\chi 2} \sim m_V$ (reduce the missing energy)

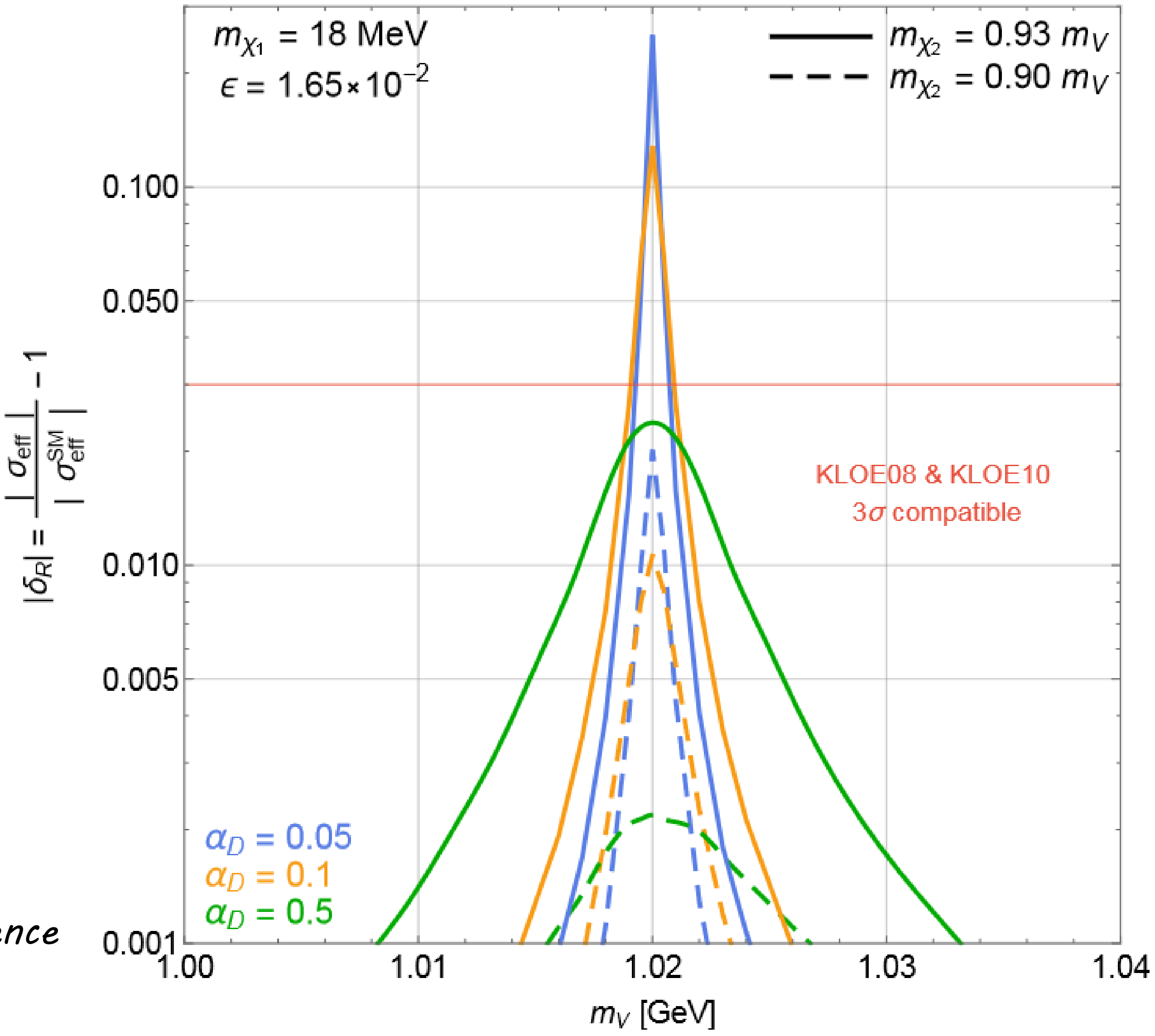


… and $\chi_2 \to \chi_1 e^+ e^-$

vs



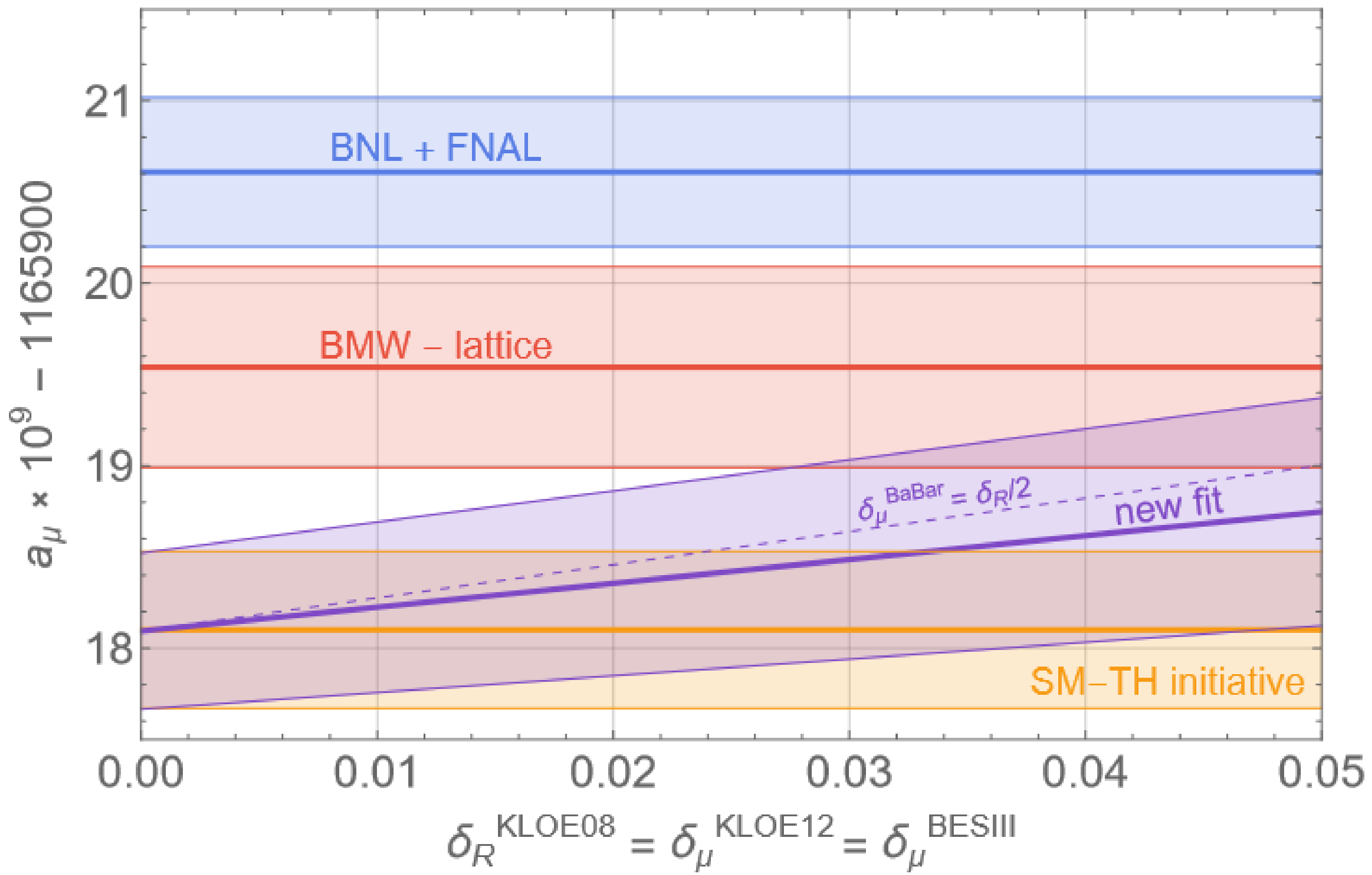
Experimental acceptance help
→ avoid the t-channel divergence



- This is still compatible with DM

From individual shifts to a global effects

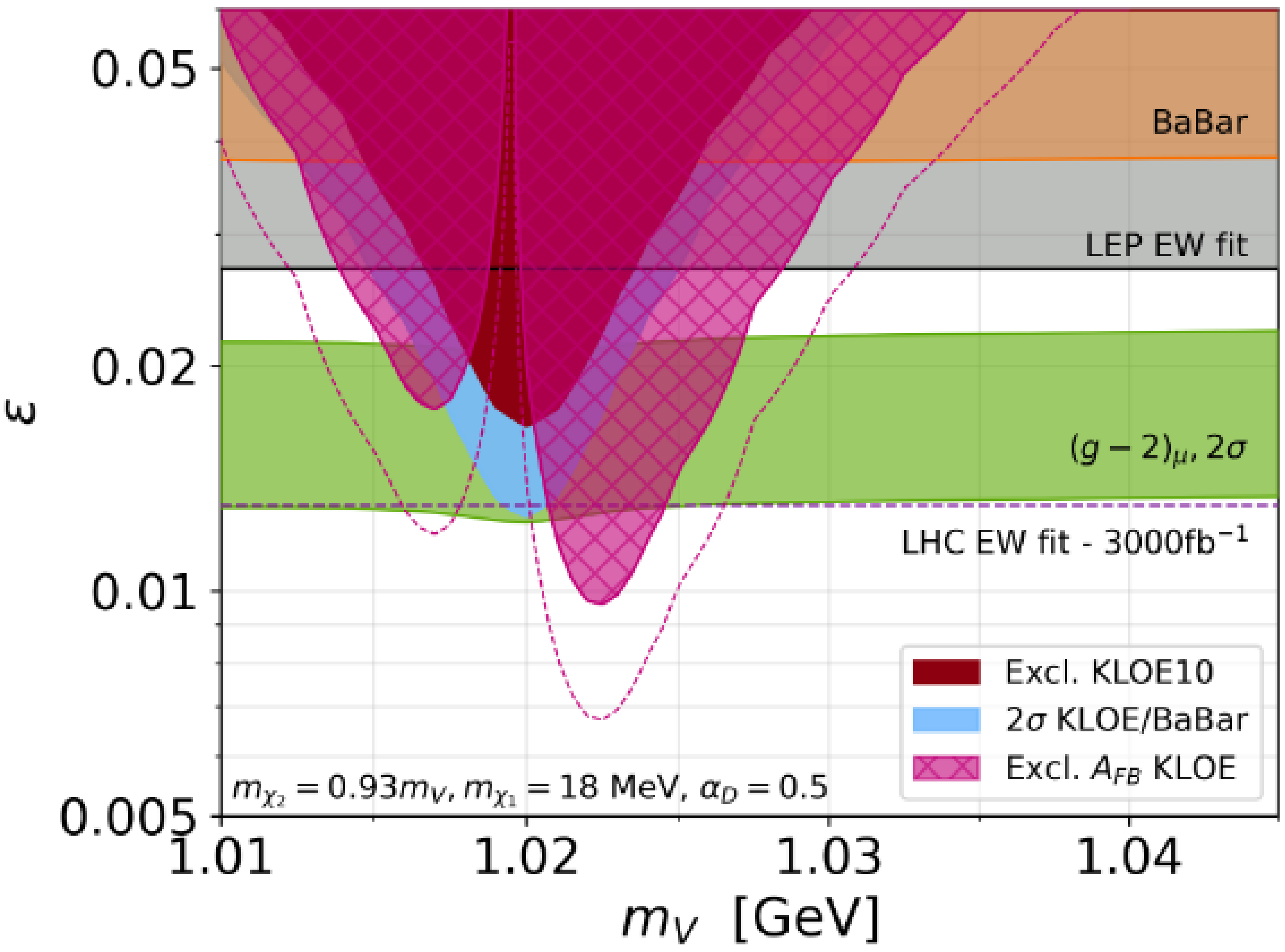
- We use a simple χ^2fit on the data in $\sqrt{s} \in [0.6,0.9]$GeV
  - →First on the three KLOE analysis
  - →Then on all the other analysis



- The BaBar 2012 analysis is too complex for our previous procedure
  - → Preliminary tests indicate also an effect
  - → Be conservative: make various assumptions for now

Putting everything together

- Due to the « stealthy» dark photon decays, BaBar constraints subdominant
- A_{FB} KLOE measurement leads to a strong constraint
- Significant parameter space remains, where we can
  - → Solve a_μ tension
  - → Solve data-driven vs lattice
  - → Solve BaBar vs KLOE
  - → Get dark matter
- Improvement w.r.t lattice everywhere from BESIII (BaBar?) shift



Constraints from leptonic cross-sections

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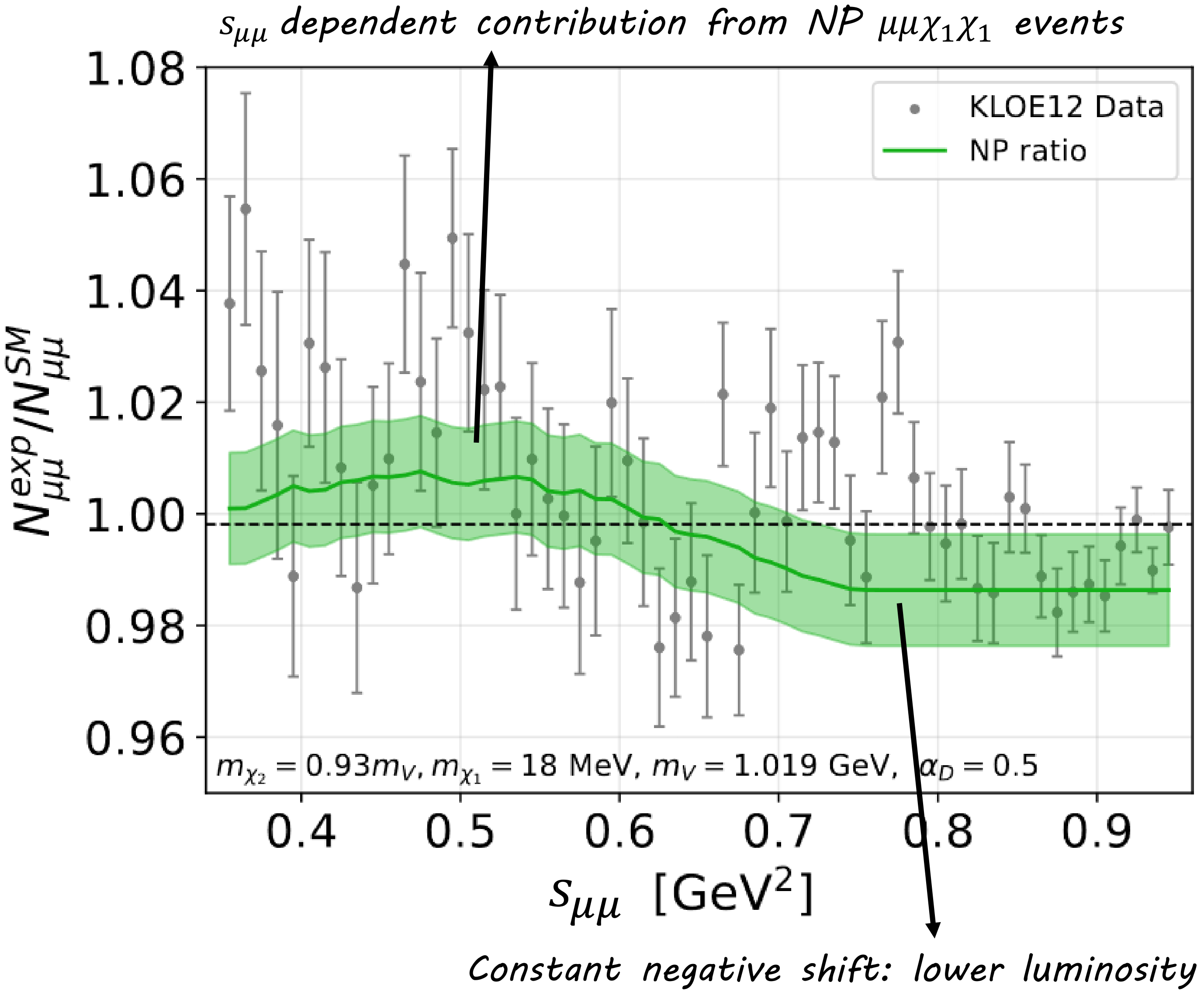


Other constraints

- Obtaining a significant shift in KLOE implies $M_V \simeq M_\Phi$ → possible mixing

$$i\frac{\partial}{\partial t}\begin{pmatrix}|\phi\rangle\\|V\rangle\end{pmatrix}=\begin{pmatrix}m_\phi - i\frac{\Gamma_\phi}{2} & M_{V\phi}\\ M_{V\phi} & m_V - i\frac{\Gamma_V}{2}\end{pmatrix}\begin{pmatrix}|\phi\rangle\\|V\rangle\end{pmatrix}$$

$$M_{V\phi} = f_\phi\frac{e\varepsilon}{6}\sim 0.25\,\mathrm{MeV}\times\left(\frac{\varepsilon}{0.01}\right)$$

→Shift the Φ meson mass and width, but an ε^2 effect as long as $\Gamma_V - \Gamma_\phi \gg M_{V\phi}$

- KLOE measured a forward-backward asymmetry in the e^+e^- final states

$$A_{\mathrm{FB}}(\sqrt{s}) = A_{\mathrm{FB}}^{\mathrm{Bhabha}}\times(1-\delta_R(\sqrt{s})) + A_{\mathrm{FB}}^{\phi} + A_{\mathrm{FB}}^{V}$$

$$\Delta A_{\mathrm{FB}} \equiv \frac{A_{\mathrm{FB}}(m_\phi - \Gamma_\phi/2) - A_{\mathrm{FB}}(m_\phi + \Gamma_\phi/2)}{A_{\mathrm{FB}}(m_\phi - \Gamma_\phi/2) + A_{\mathrm{FB}}(m_\phi + \Gamma_\phi/2}$$

T-channel Bhabha is very asymmetric but roughly independant in s

NP corrections do depend on s

Interference: ϕ

Interference: V

- Dark photon mixing with the Z from kinetic mixing parameter leads to

$$\varepsilon < 0.027 \quad (\mathrm{LEP\ -\ EW\ fit})$$

Asymmetry measurements in KLOE

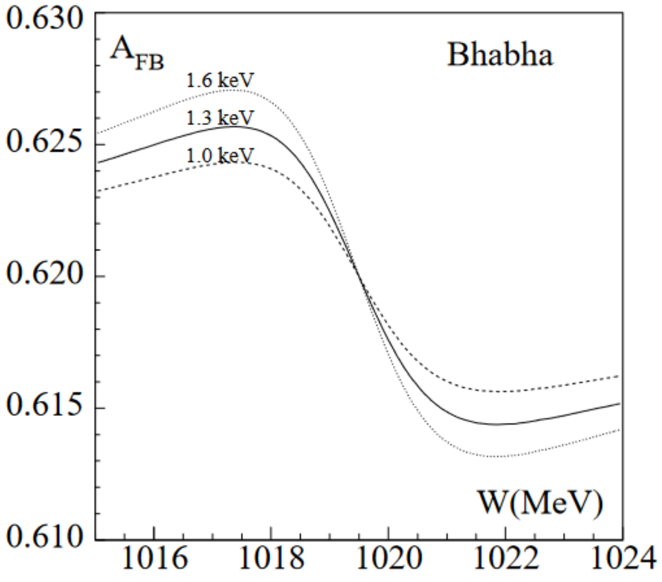
hep-ex/0411082

- KLOE looked for $e^+e^- \to e^+e^-$ events

$$A_{\rm FB}(\sqrt{s}) = \begin{cases} 0.6275 \pm 0.0003 & (\sqrt{s} = 1017.17\,\text{MeV} \simeq m_\phi - \Gamma_\phi/2) \\ 0.6205 \pm 0.0003 & (\sqrt{s} = 1019.72\,\text{MeV} \simeq m_\phi) \\ 0.6161 \pm 0.0004 & (\sqrt{s} = 1022.17\,\text{MeV} \simeq m_\phi + \Gamma_\phi/2) \end{cases}$$

$$A_{\rm FB}(\sqrt{s}) \equiv \frac{N_F - N_B}{N_F + N_B}$$

- The presence of the ϕ meson induces an interference pattern which depends on the width



$$\Delta A_{\rm FB} \equiv \frac{A_{\rm FB}(m_\phi - \Gamma_\phi/2) - A_{\rm FB}(m_\phi + \Gamma_\phi/2)}{A_{\rm FB}(m_\phi - \Gamma_\phi/2) + A_{\rm FB}(m_\phi + \Gamma_\phi/2}$$
$$= \Delta A^\phi_{\rm FB} + \Delta A^V_{\rm FB} - \frac{\delta_R(\sqrt{s_-}) - \delta_R(\sqrt{s_+})}{2}$$

W (MeV)	A_{FB}
1017.17	0.6275±0.0003
1019.72	0.6205±0.0003
1022.17	0.6161±0.0004

LEP precision measurements

- In principle, HVP affects also α_{em}

$$\Delta\alpha^{(5)}_{\rm had}(s) = \frac{s}{4\pi^2\alpha} P\int ds' \frac{\sigma_{\rm had}(s')}{s-s'} \qquad \alpha(s) = \frac{\alpha}{1-\Delta\alpha_\ell(s)-\Delta\alpha_{\rm top}(s)-\Delta\alpha^{(5)}_{\rm had}(s)}$$

- But the kernel function probes a completely different mass range (around the EW scale

  → not a strong constraint in our case, where σ_{had} is modified below the GeV …

  → Additionally, we don't aim at explaining all the excess, given that we have already a direct NP contribution

- For the other measurement (e.g. N_{eff}), the V behaves mostly as a massless dark photon, and most effects arises at ε^2 via interferences and are subdominant

Feebly-Interacting Particles

- FIPs= “new neutral particle which interacts with the SM via suppressed new interactions”

→ We focus in this talk on FIPs from MeV to tens of GeV range

The hierarchy problem	pNGB / ALPs
What is the origin of flavour?	
The nature of dark matter?	Light Dark Matter
Origin of the ν masses?	Heavy Neutral Leptons
Why does QCD respect CP ?	QCD axion

+ dark photons, dark Higgs…

- Long used as a NP contribution for $(g-2)_{\mu,e}$

Gninenko 2001, Baek 2001, Ma 2001, Brignole 1999, … Brodsky 1967…

- Are often used as mediators between the SM and a dark sector

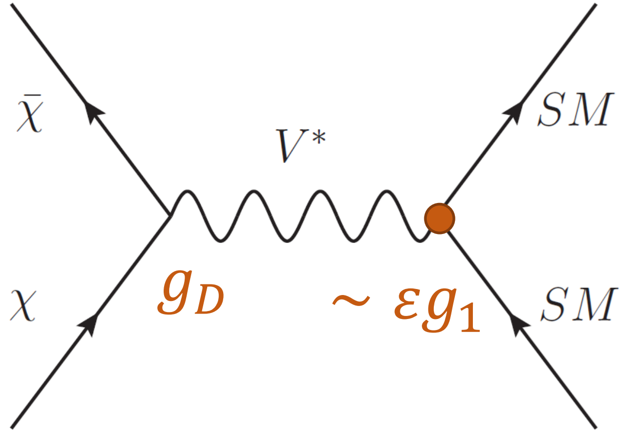
→ E.g. for models of thermal sub-GeV dark matter

Couplings to a dark sector

- Interest in FIPs also driven by building models of thermal sub-GeV DM

- Standard example: a vector portal with a Majorana fermion

  → Relic density: sub-GeV DM requires $\varepsilon \sim 10^{-3}$ suppression



- Most FIP models can be embedded in a light dark matter setup (of course with various level of complexity …)
  - ALP model with resonant annihilation e.g. Dolan et al. 1709.00009
  - most light vector FIP models assuming small kinetic mixing

Altogether an extremely rich literature of new “mechanisms” to obtain the relic density (Forbidden DM, Secluded DM, Selfish DM, Cannibal DM, etc …)

→ We will focus on a “benchmark scenario” : inelastic dark matter (iDM)

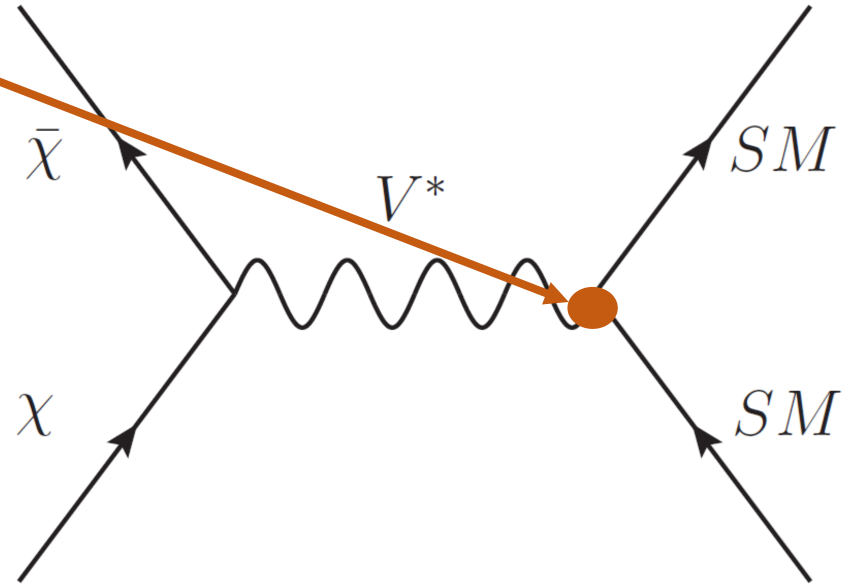
Building light inelastic dark matter (1)

- We first construct the Lagrangian for the dark photon mediator: --→ rely on "kinetic mixing" term

Kinetic mixing term

$$\mathcal{L}_{A'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \boxed{\frac{1}{2}\frac{\varepsilon}{\cos\theta_w}B_{\mu\nu}F'^{\mu\nu}}$$
$$\boxed{+\,(D^{\mu}S)^{*}(D_{\mu}S) + \mu_S^2|S|^2 - \frac{\lambda_S}{2}|S|^4}$$

Dark Higgs potential



- After "dark" U(1) symmetry is broken, a massive light dark photon and a correspondingly light dark Higgs S.

Inelastic dark matter (2)

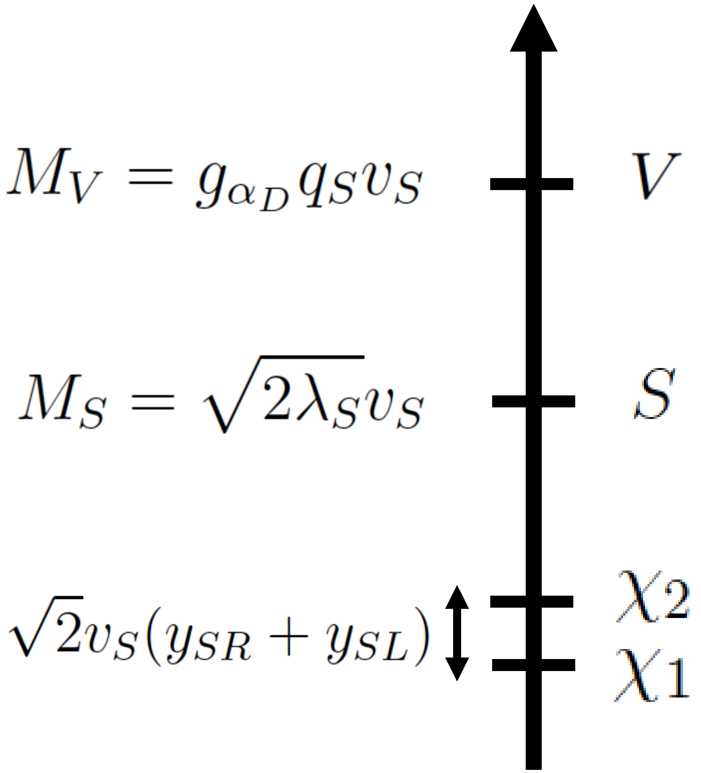
$$\mathcal{L}^{\mathrm{DM}}_{pDF} = \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + y_{SL} S \bar{\chi}^c P_L \chi + y_{SR} S \bar{\chi}^c P_R \chi \;\; + \;\; \mathrm{h.c.}$$

- Introduce a Dirac fermion dark matter
  $\chi = (\chi_L, \bar{\chi}_R)$
- The dark Higgs VEV splits both states, leading to a fermionic mass matrix:

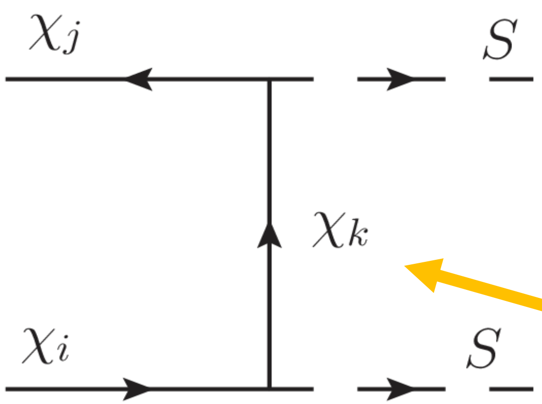
$$M_\chi = \begin{pmatrix} \sqrt{2} v_S y_{SL} & m_\chi \\ m_\chi & \sqrt{2} v_S y_{SR} \, . \end{pmatrix}$$

- After diagonalization we get two Majorana fermions
  → Lightest χ_1 state is DM
  → In the limit $y_{SL} \simeq y_{SR}$, the dark photon only interacts via

$$\mathcal{L} = \left(i g_D \bar{\chi}_2 \gamma^\mu \chi_1 + e\varepsilon \mathcal{J}^\mu_{\mathrm{em}}\right) V_\mu$$

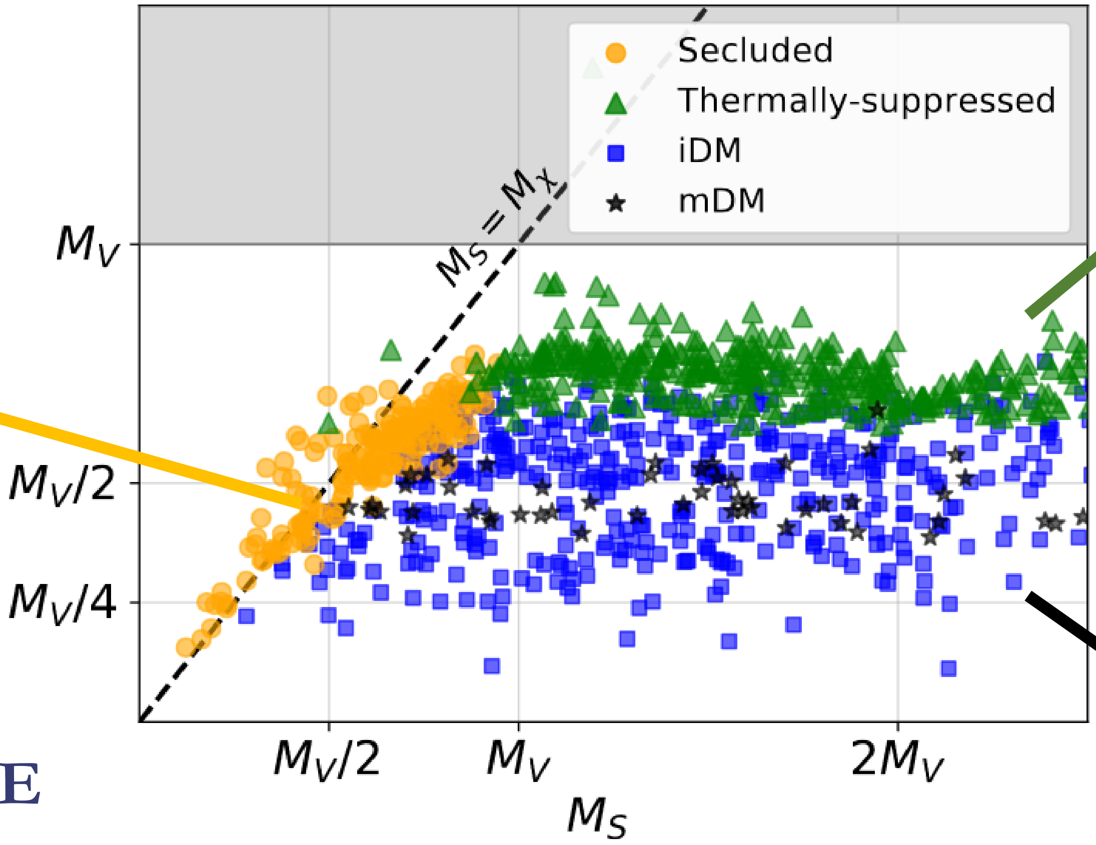


Typical regimes with correct relic density

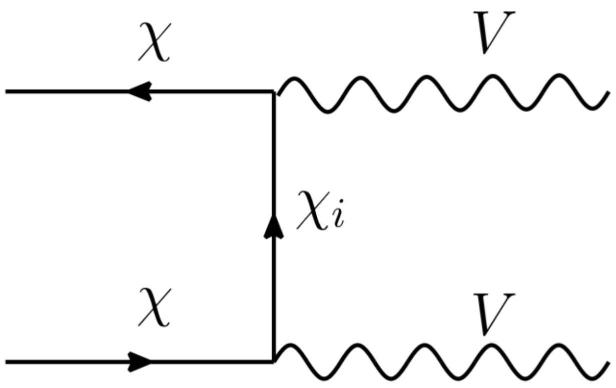


$M_\chi \gtrsim M_S$

SECLUDED REGIME

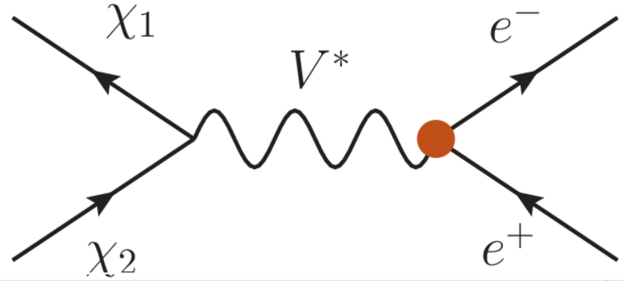


FORBIDDEN REGIME



$M_\chi \lesssim M_V \lesssim M_S$

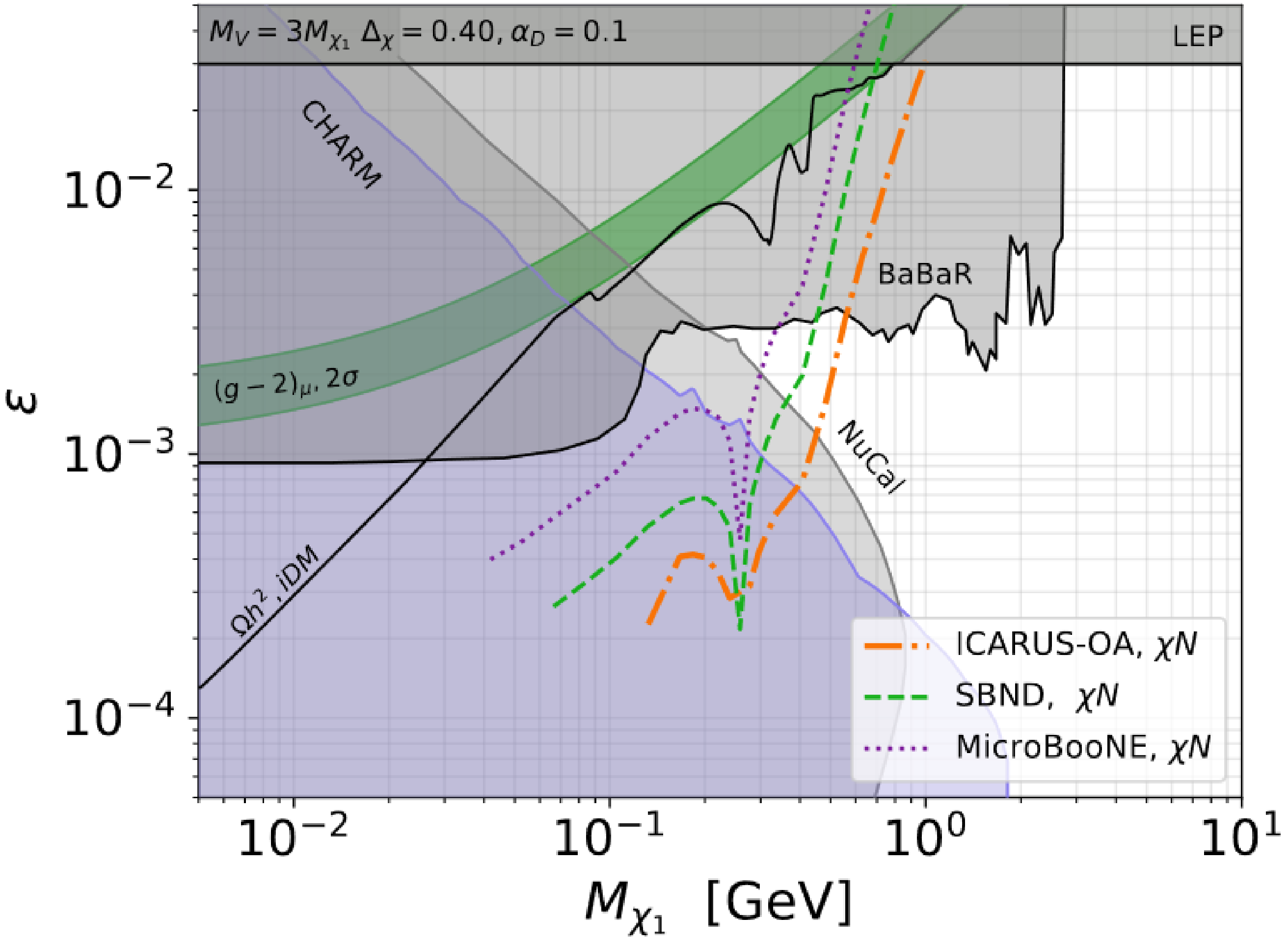
iDM/mDM REGIME



- In the following we will be typically in the « secluded regime »

Dark photon and χ_2 decays

- Once produced from charged particles, the dark photon decays only « semi-visibly »
  $V \to \chi_1 \chi_2$, $\chi_2 \to \chi_1 e^+ e^-$
  - →The χ_2 decay length is critical for LLP searches
  - → Large splitting implies no constraints from beam dumps
- Notice also the reduction of BaBar mono-photon



$$c\tau_{\chi_2} \propto 100 \text{ m} \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{10^{-3}}{\varepsilon}\right)^2\left(\frac{0.2M_\chi}{\Delta_\chi}\right)^5\left(\frac{25 \text{ MeV}}{M_\chi}\right)^5\left(\frac{M_V}{100 \text{ MeV}}\right)^4$$