Reviving the Dark Photon Explanation of the Muon g-2 Anomaly

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Based On: **Phys.Rev. D99 (2019) no.11, 115001**

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BROOKHAVEN NATIONAL LABORATORY

Main point of this talk

- Show that Inelastic dark matter with large mass splittings revives the dark photon explanation of the $(g_\mu - 2)$ anomaly

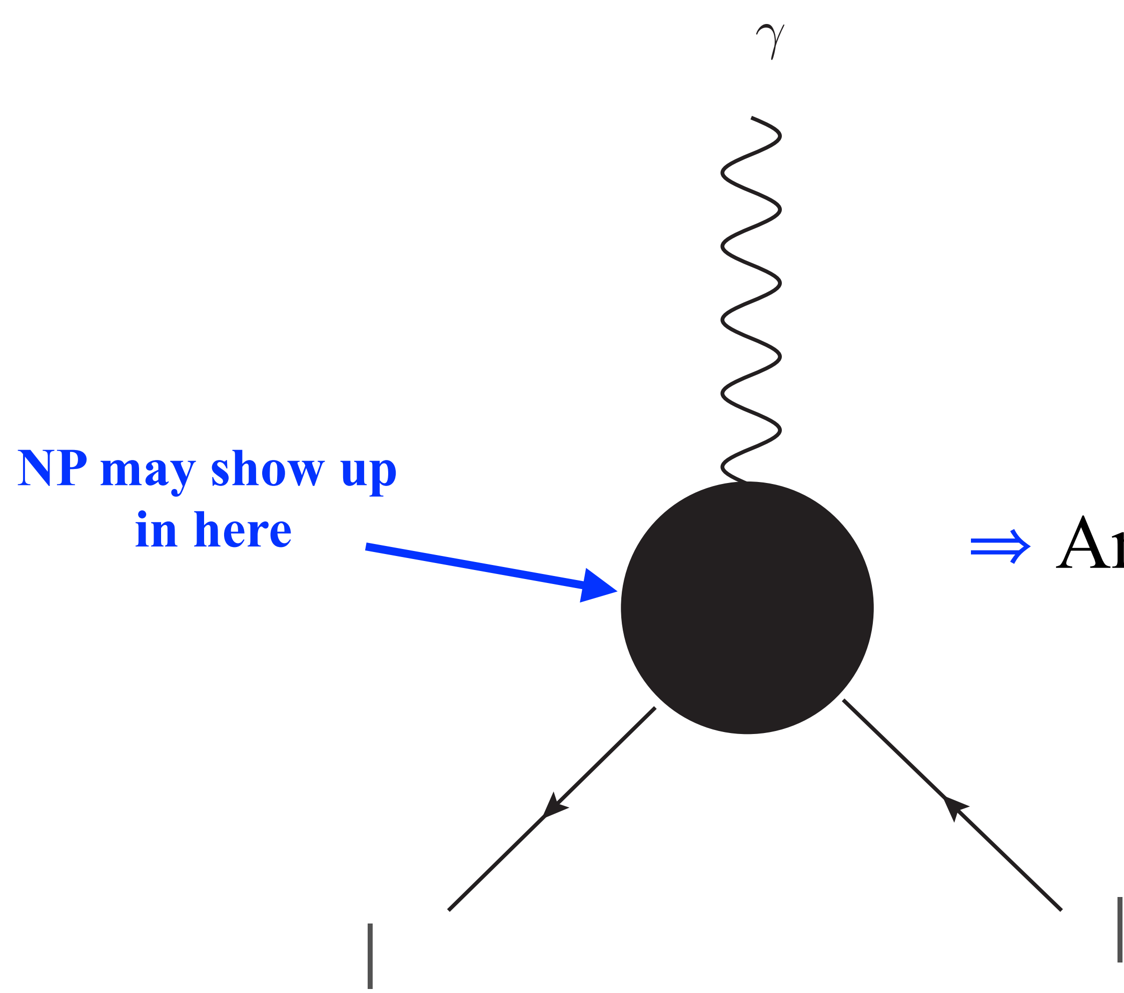
- Model gives displaced lepton signature we can search for at current beam dumps and low energy colliders

Current Status of Particle Physics

Evidence of particle physics phenomena not explained in SM points to need for *New Physics*.

One of the many ways ***New Physics*** may manifest:

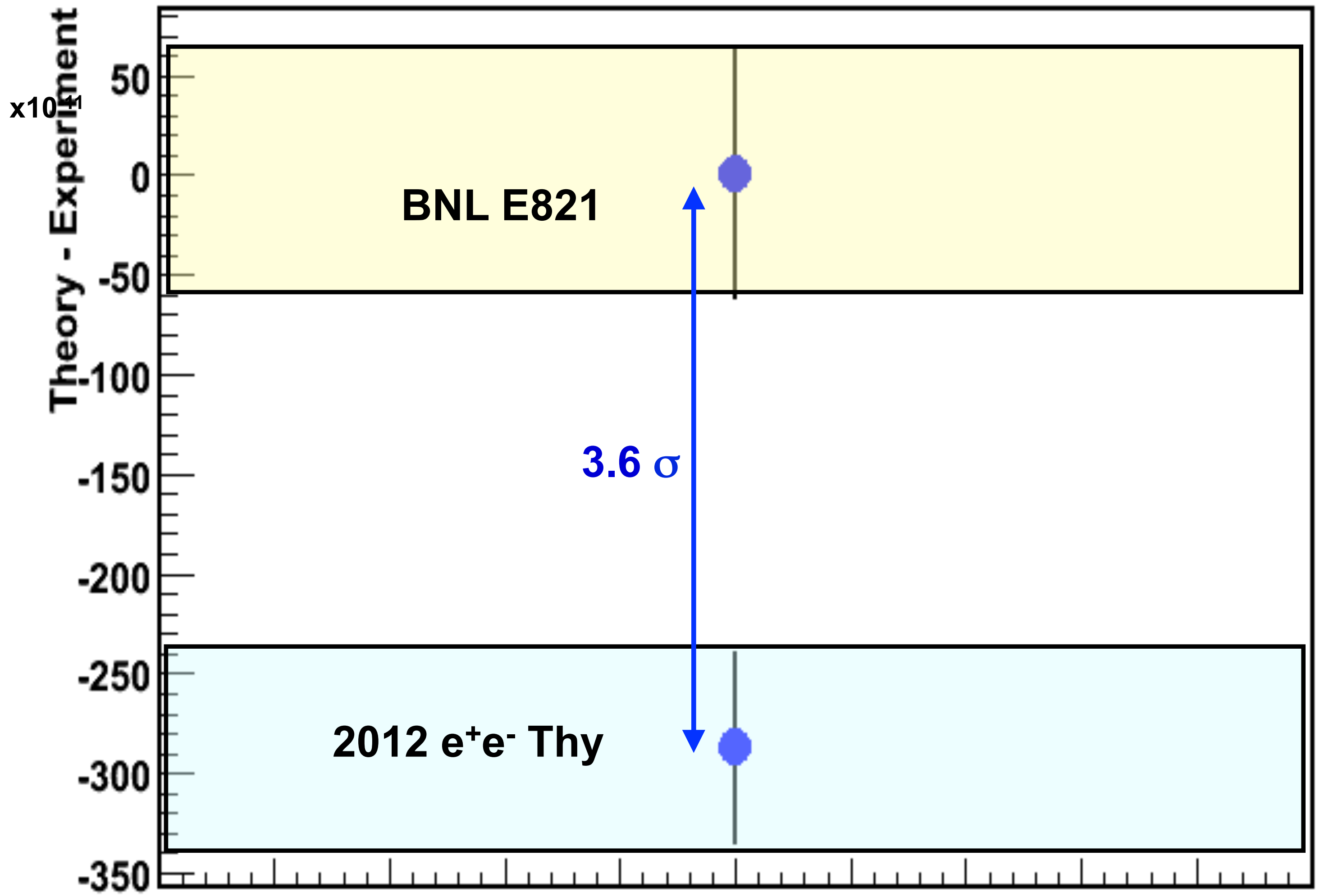
Indirectly: as deviations from SM predicted processes



$\Rightarrow$ Anomalous magnetic moments

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$$

$$= (28.1 \pm 3.6_{th} \pm 6.3_{exp}) \times 10^{-10}$$



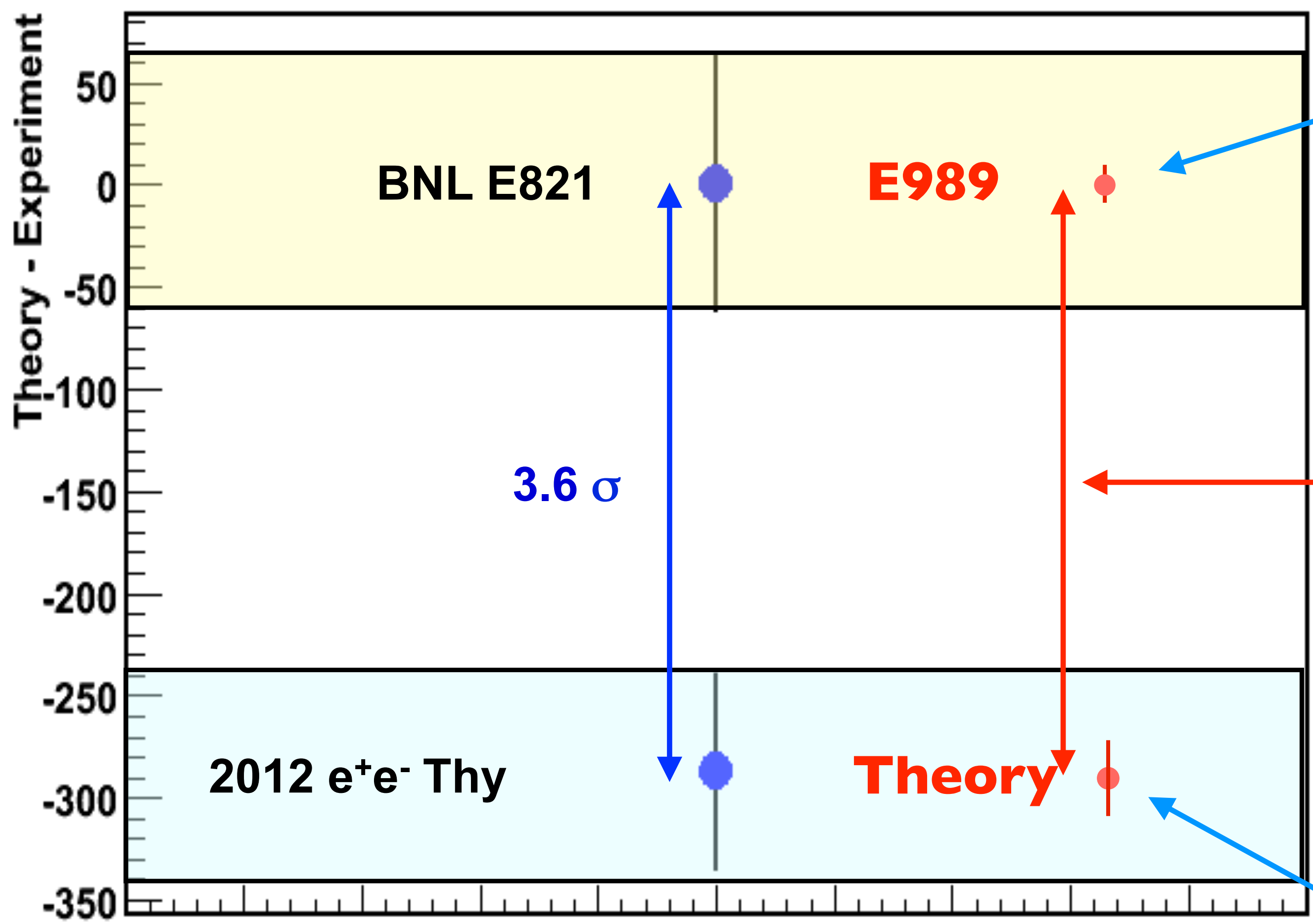
3.3 - 3.6 σ discrepancy

Hagiwara et al: **Nucl.Part.Phys.Proc. 287-288 (2017) 33-38**

What does it all mean?

3.6σ simply not enough to celebrate New Physics

very exciting period for g-2



Fermilab E989 experiment is currently running

More precise measurement and Significant reduction in theory uncertainty could mean New Physics contribution

SM theory computation is improving

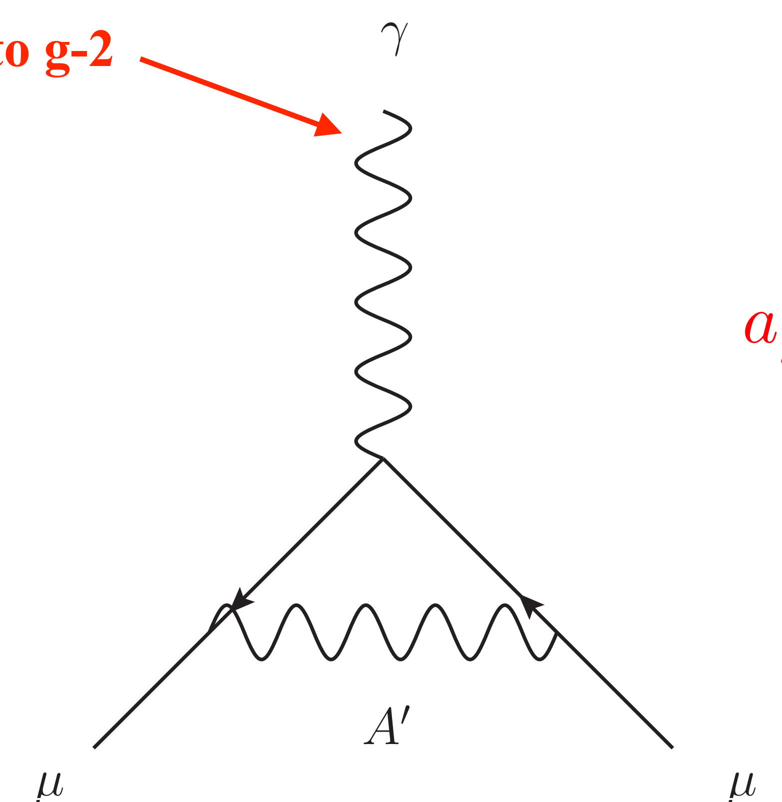
Focus for this talk: **Dark Photon** A'

Massive gauge boson in U(1)′ extension of SM

Kinetic mixing with SM photon

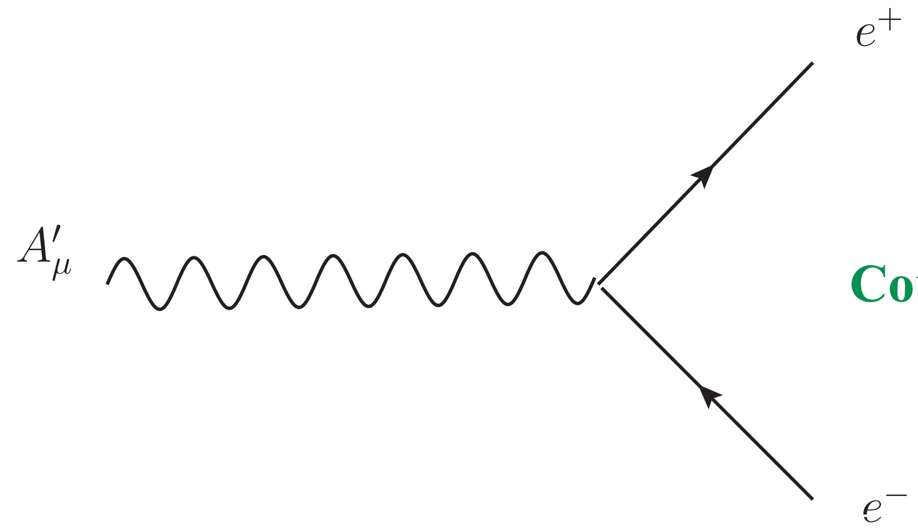
$$\mathcal{L} \supset \frac{m_{A'}}{2} A'_\mu A'^\mu + \underbrace{g_D \bar{\psi}_D \gamma_\mu A'^\mu \psi_D}_{\text{Coupling to}} + \underbrace{\epsilon e \bar{\psi}_{sm} \gamma_\mu A'^\mu \psi_{sm}}_{\text{Coupling to visible}}$$

Contribution to g-2



$$a_\mu = \frac{\alpha \epsilon^2}{2\pi} \int_0^1 dz \frac{2 m_\mu^2 z (1-z)^2}{m_\mu^2 (1-z)^2 + m_{A'}^2 z}$$

M. Pospelov: **Phys.Rev.D80 (2009) 095002**

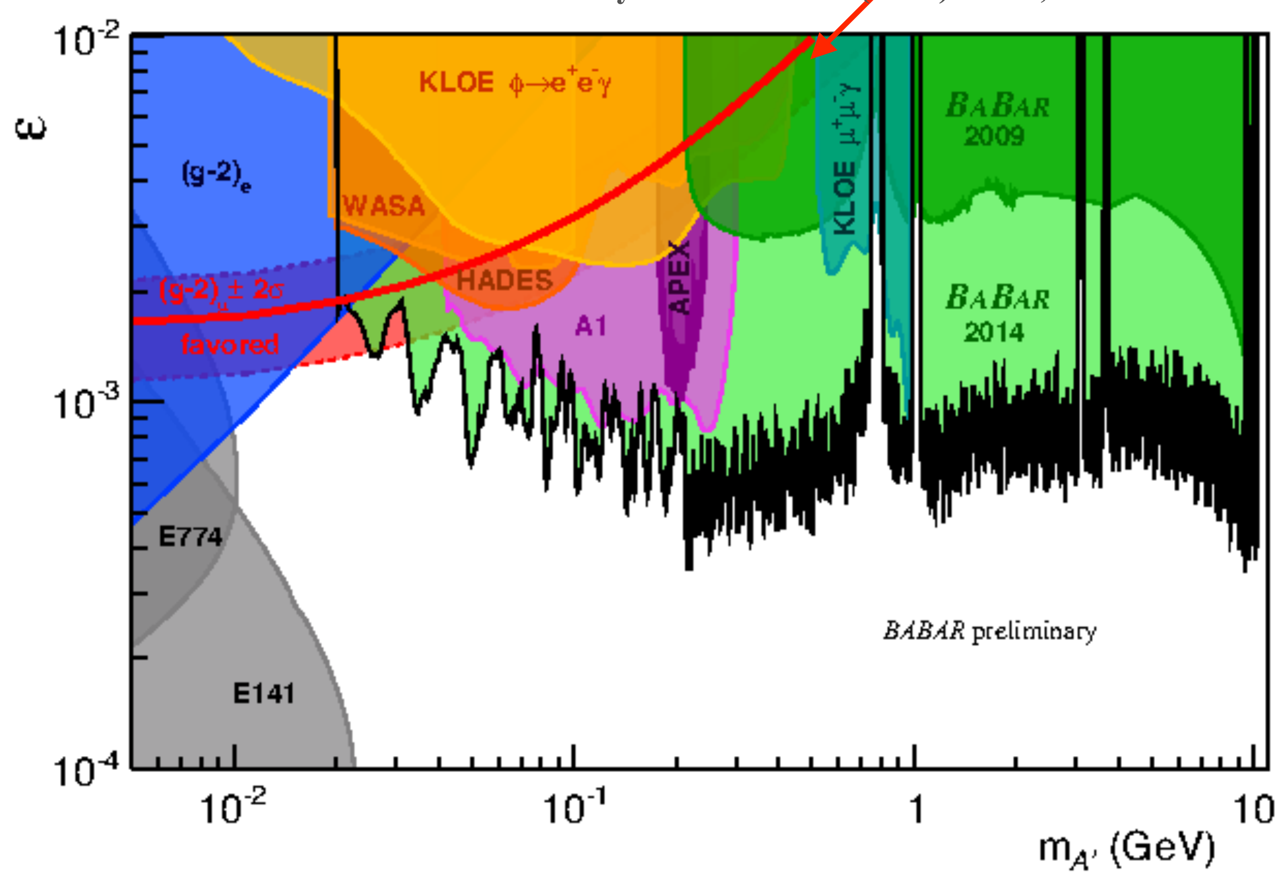


$$\epsilon e \bar{\psi}_{sm} \gamma_\mu A'^{\mu} \psi_{sm}$$

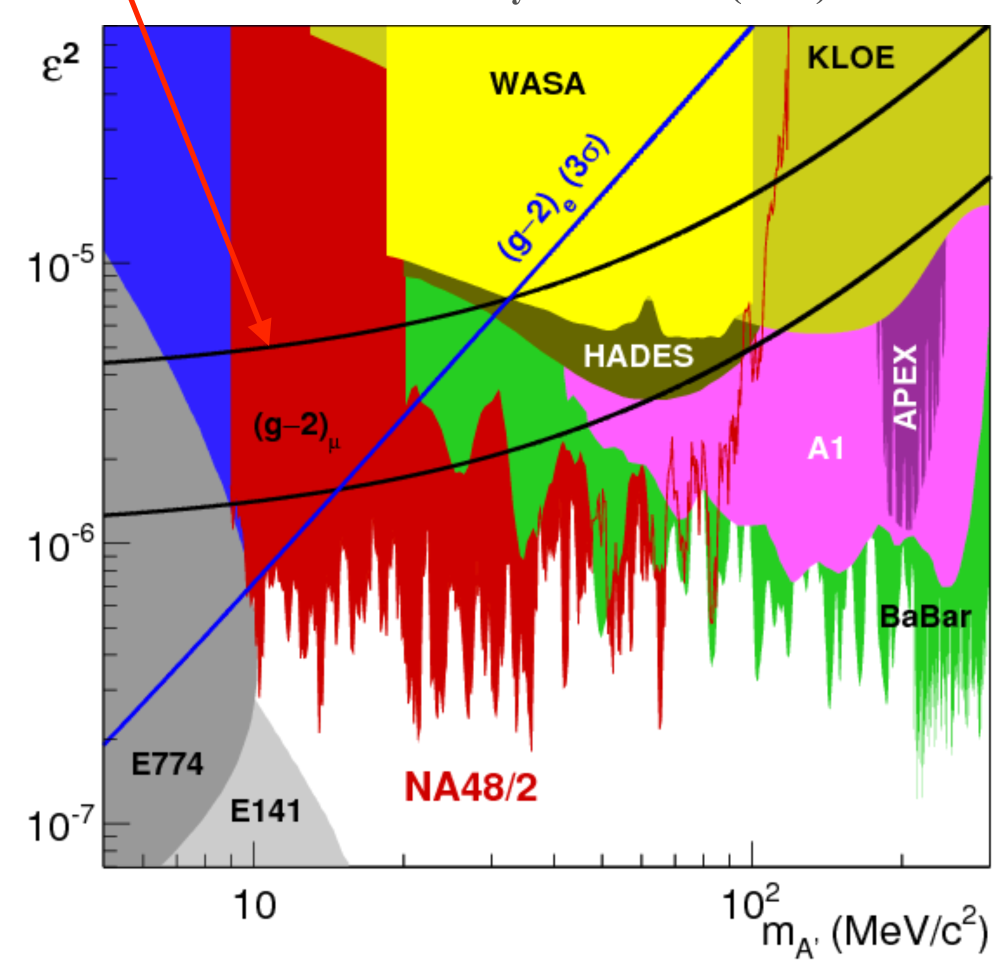
Coupling to visible sector been searched for

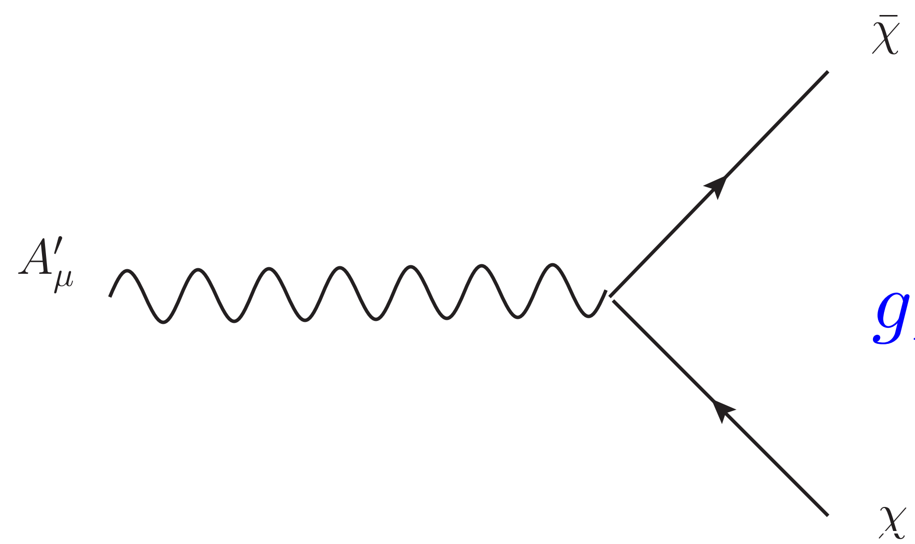
Favored to explain muon g-2

BABAR collaboration: **Phys.Rev.Lett. 113 (2014) no.20, 201801**



NA 48 collaboration: **Phys.Lett. B746 (2015) 178-185**



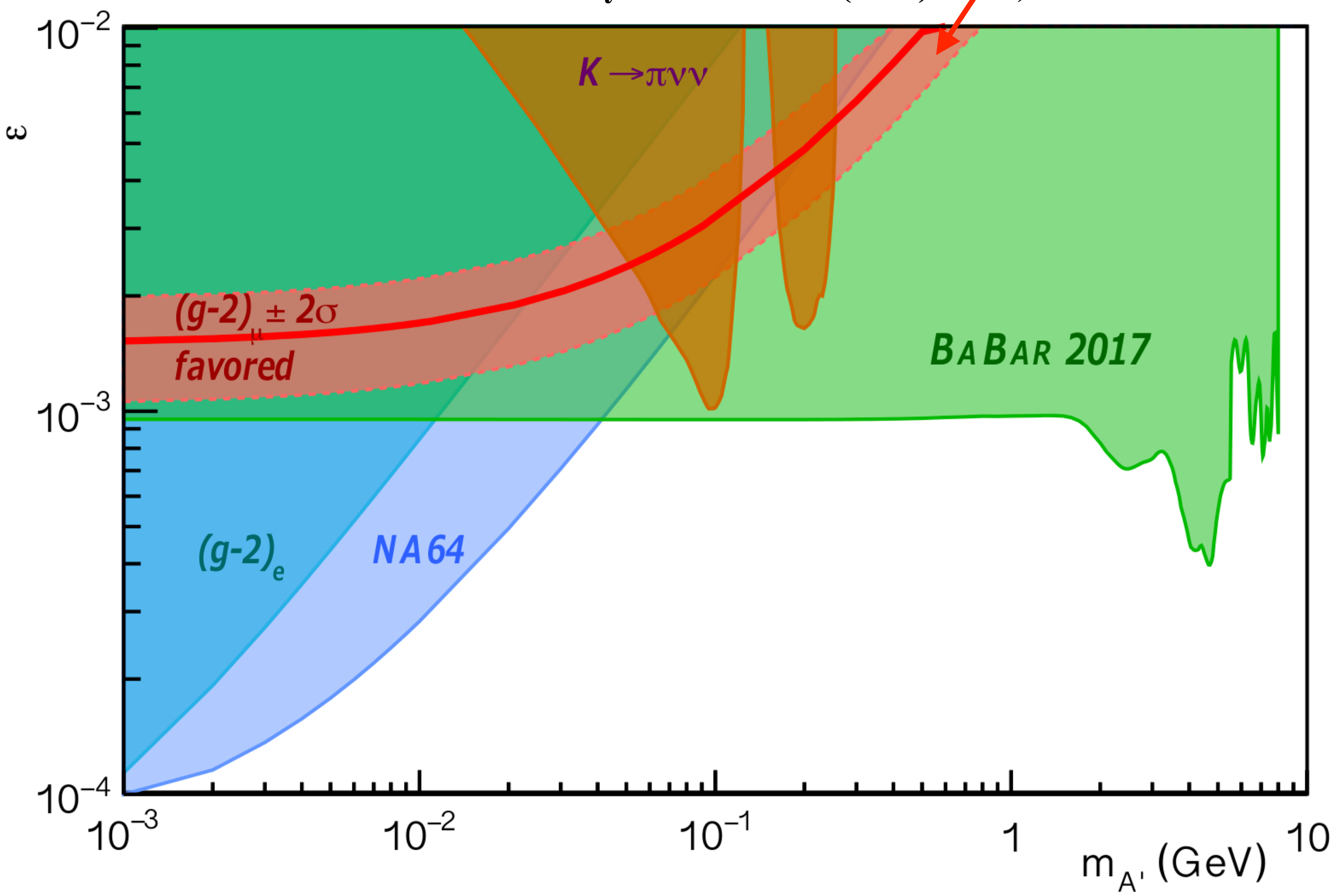


$$g_D \bar{\psi}_D \gamma_\mu A'^\mu \psi_D$$

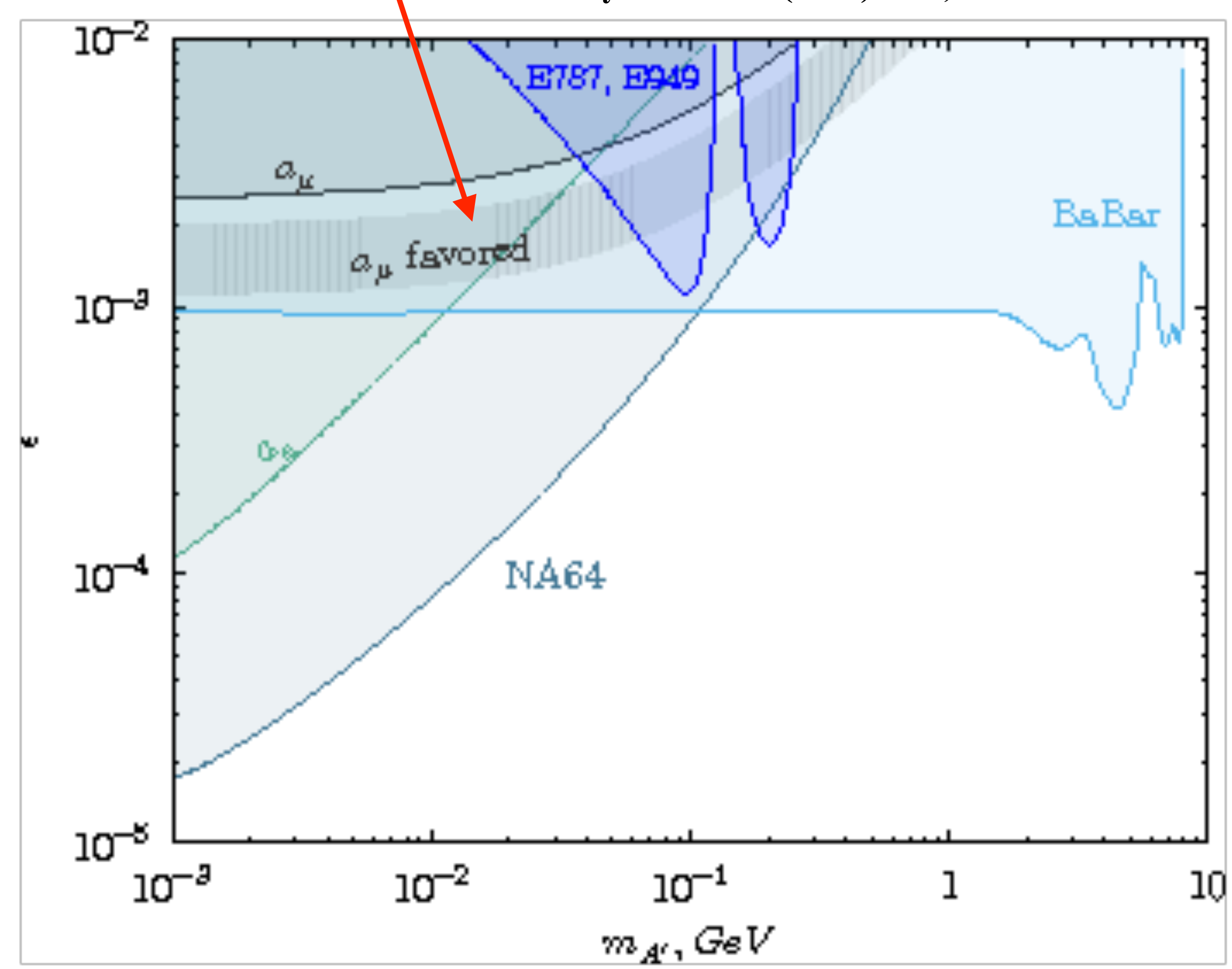
Invisible Decay

Favored to explain muon g-2

BABAR collaboration: **Phys.Rev.Lett. 119 (2017) no.13, 131804**



NA64 collaboration: **Phys.Rev. D97 (2018) no.7, 072002**



$$\mathcal{L}_M \supset m_D \bar{\psi}_D \psi_D + y < H_D > \bar{\psi}^c_D \psi_D$$

Dirac Majorana

What if Majorana mass is small but **NOT** zero ???

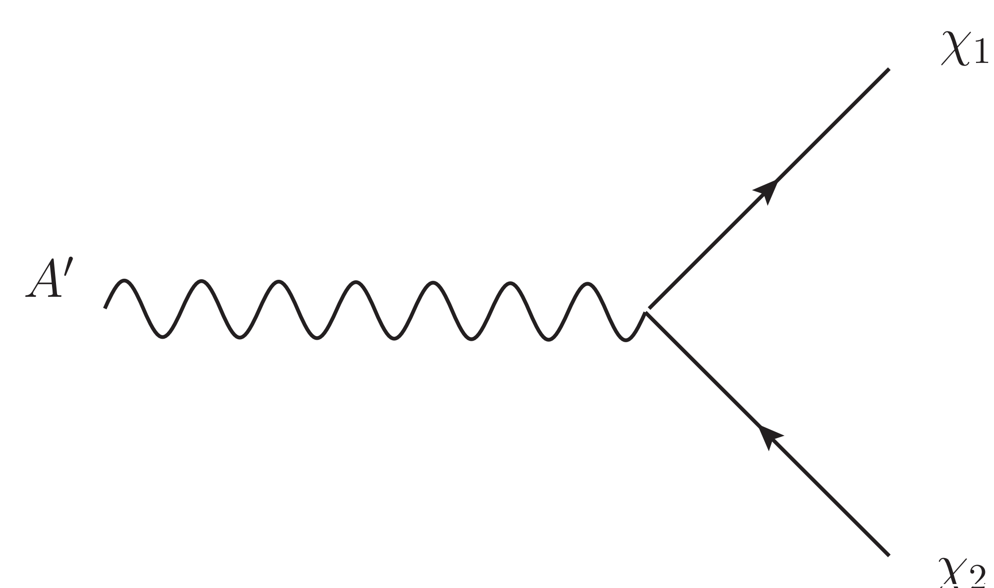
Diagonalizing from gauge basis to mass basis:

$$\psi_D = (\eta \quad \xi^\dagger) \longrightarrow (\chi_1 \quad \chi_2)$$ Pseudo-Dirac fermions

$$\mathcal{L} \supset g_D \bar{\chi}_2 \gamma_\mu A'^\mu \chi_1 + m_D \bar{\chi}_2 \chi_1 + h.c$$

With mass splitting

$$\Delta \equiv m_2 - m_1$$



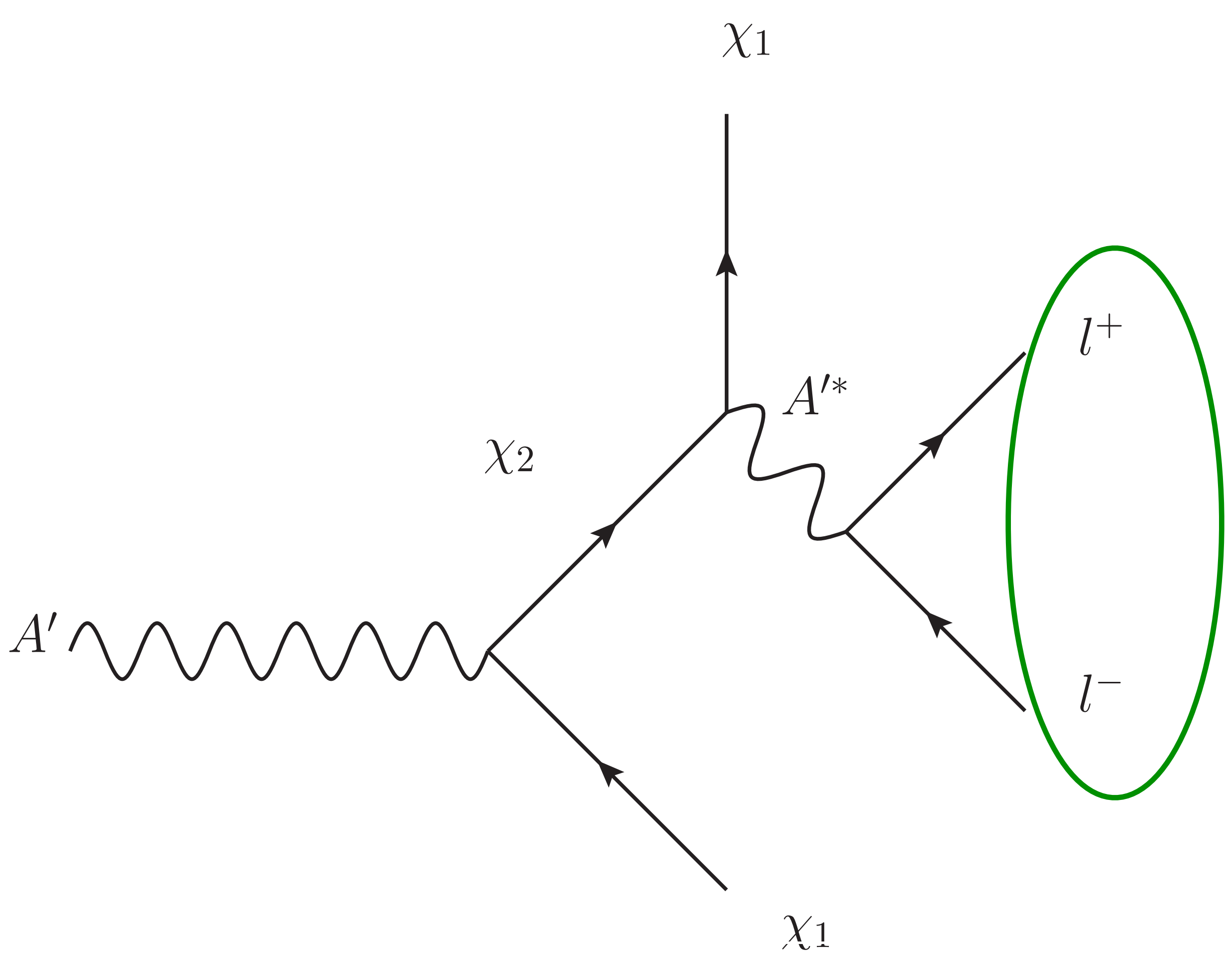
$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

Heavier state decay into lighter state & SM states

Semi-visible Decay

New signal with
semi-visible decay

If χ_2 decays inside detector => soft displaced leptons



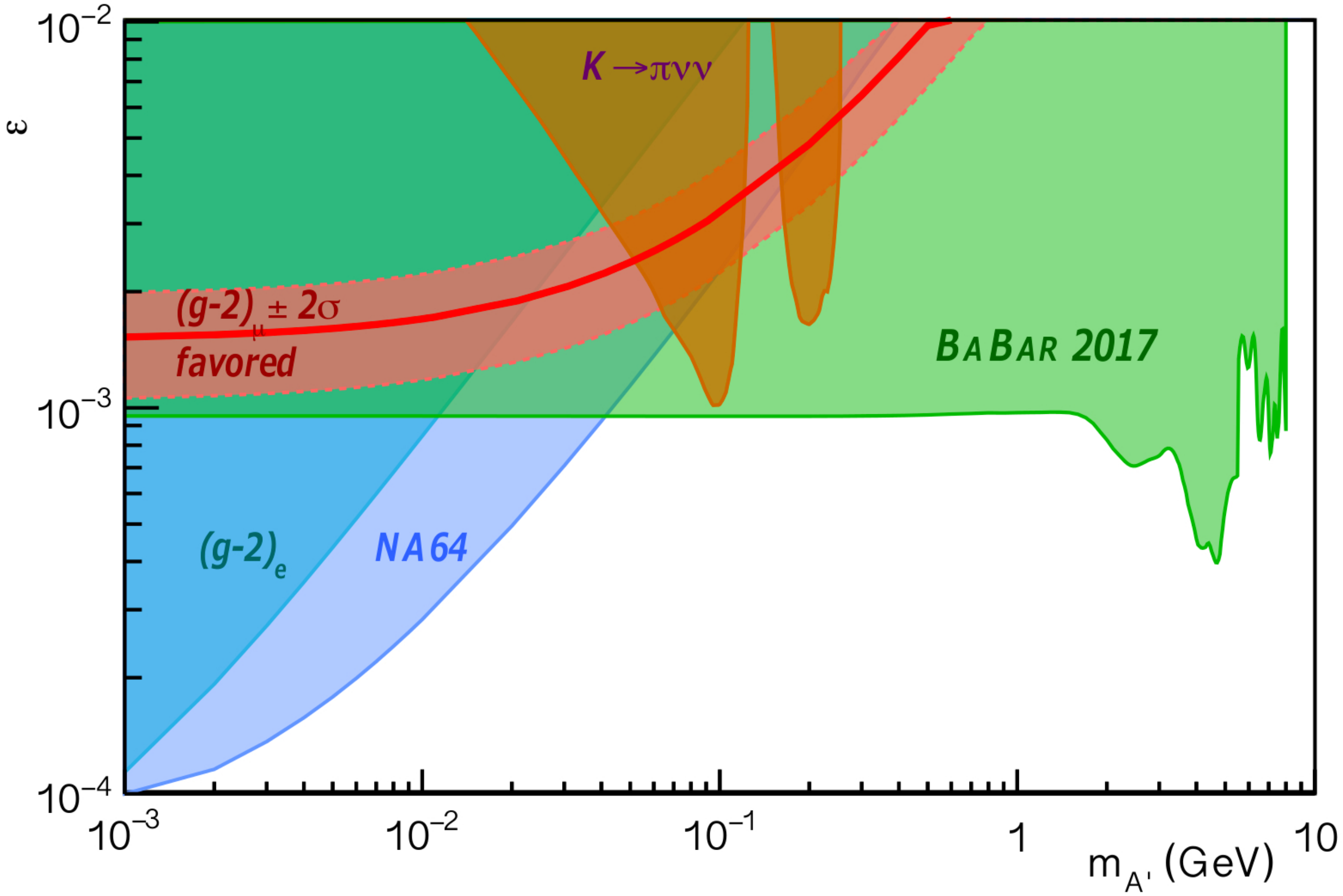
We can look for
these displaced tracks
at colliders and beam dumps

Izaguirre, Krnjaic & Shuve: **Phys.Rev. D93 (2016) no.6, 063523**

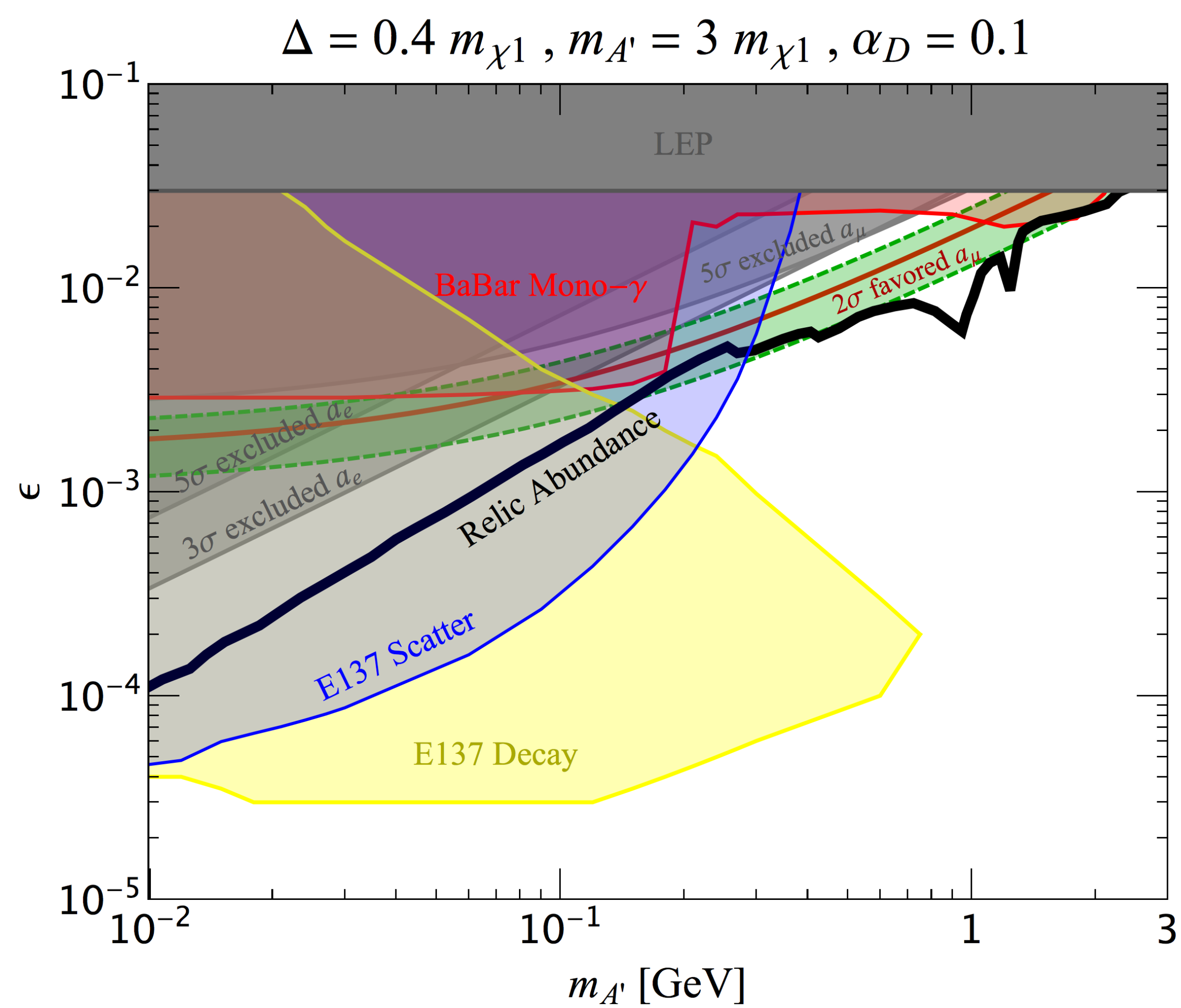
Ezaguirre, Kahn, Krnjaic, Moschella, **Phys.Rev. D96 (2017) no.5, 055007**

G.M**: Phys.Rev. D99 (2019) no.11, 115001**

Can dark photon still explain muon g-2?



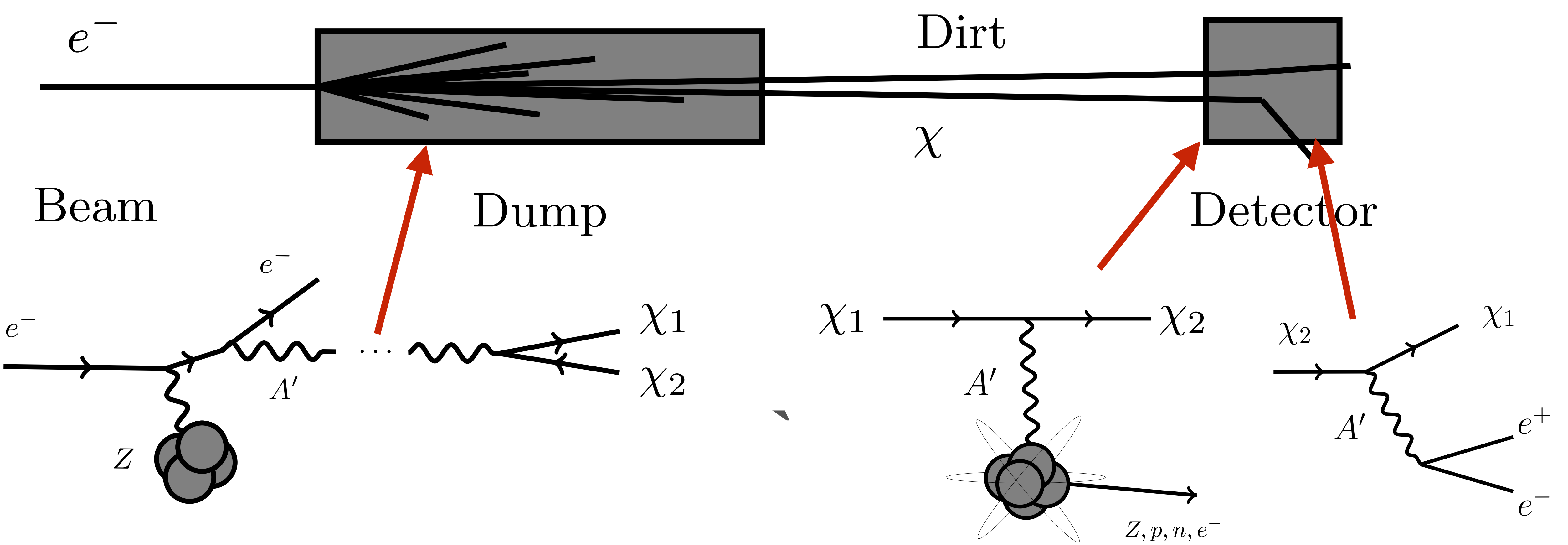
BABAR collaboration: **Phys.Rev.Lett. 119 (2017) no.13, 131804**



G.M: **Phys.Rev. D99 (2019) no.11, 115001**

Signatures @ Electron Beam Dumps

(quasi) elastic scattering & decays



A' production modes

- Dark Bremstrahlung

E137 (SLAC 1988)

E ~ 20 GeV, 1e20 EOT

~ 400 m baseline, no BG

Batell, Essig, Zurjuron: **Phys.Rev.Lett. 113.171802**

Izaguirre, Krnjaic, Schuster, Toro: **Phys.Rev. D88 (2013) 114015**

BDX (JLab 2020?)

E ~ 11 GeV, 1e22 EOT

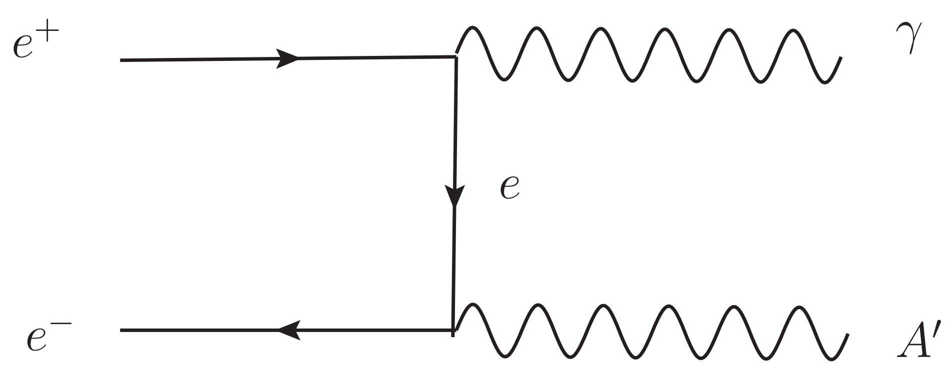
~ 20 m baseline, few BG evts.

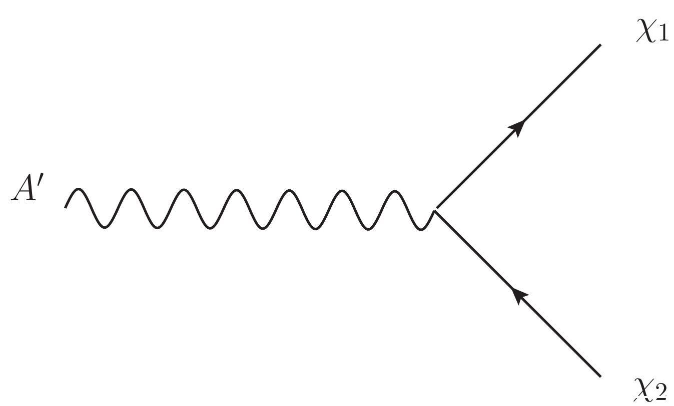
BDX Collaboration **1607.01390**

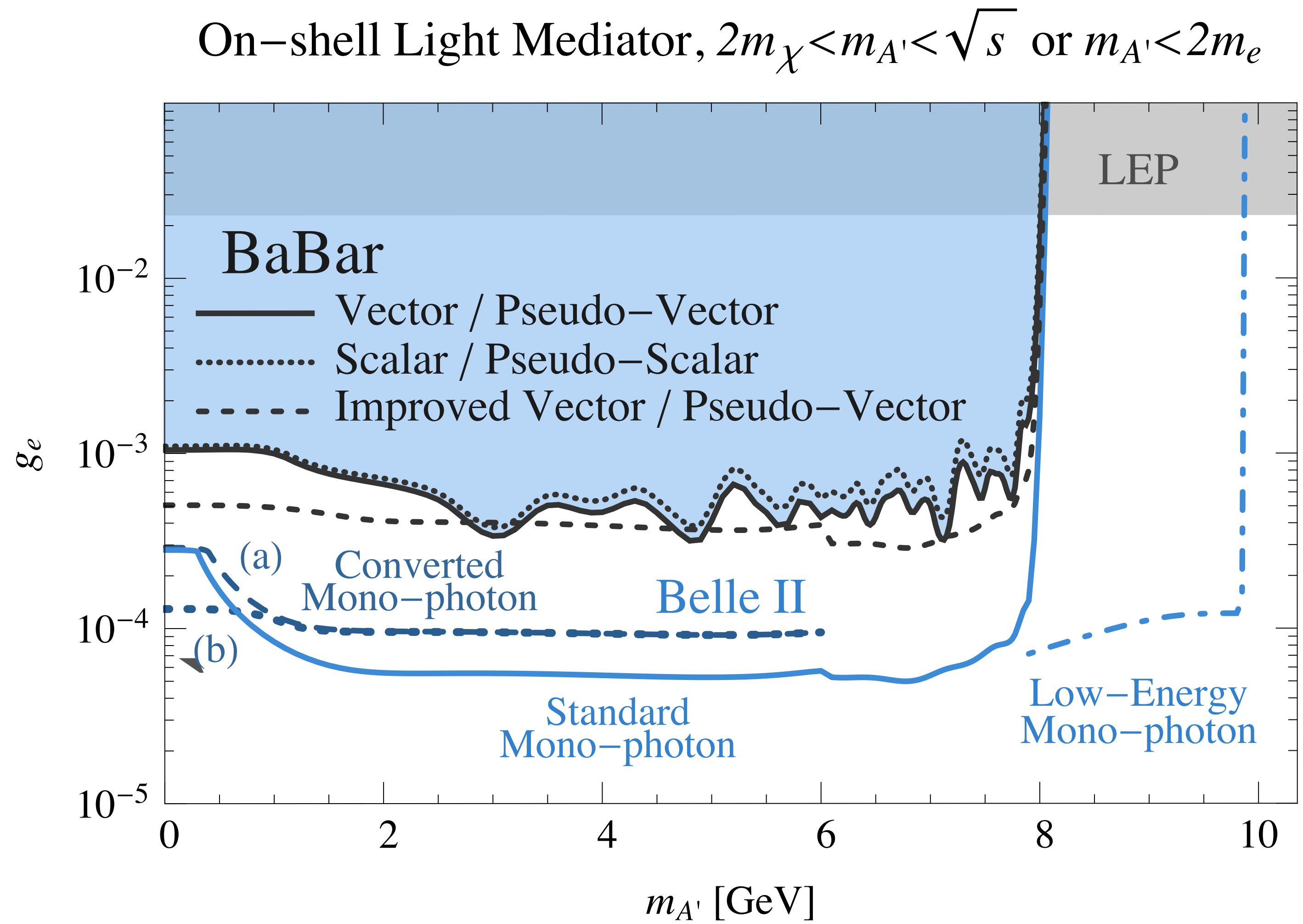
Ezaguirre, Kahn, Krnjaic, Moschella, **Phys.Rev. D96 (2017) no.5, 055007**

Signatures @ B-Factories

mono photon + missing energy







Signatures from displaced vertices and/or missing energy

BABAR	BELLE II
E~ 10.5 GeV	E~ 11 GeV
L~ 53 fb^-1	L~ 50 ab^-1 by 2025

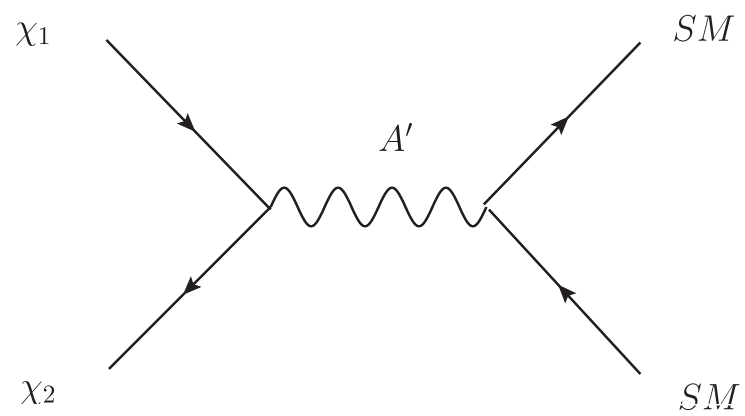
Essig, Mardon, Papucci, Volansky Zhong: **JHEP 1311 (2013) 167**

Izaguirre, Krnjaic, Schuster, Toro: **Phys.Rev. D88 (2013) 114015**

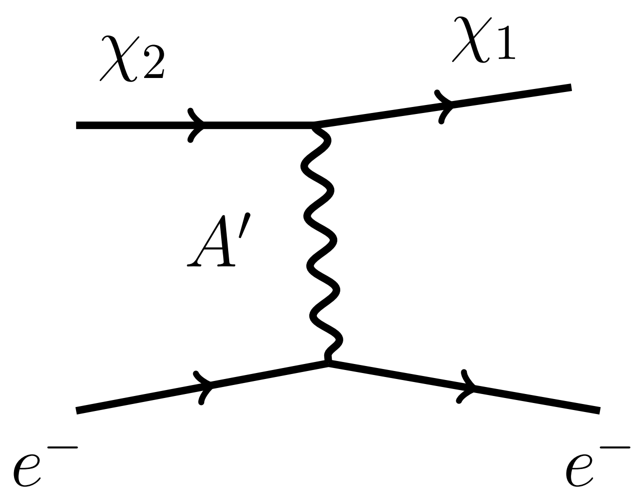
Ezaguirre, Kahn, Krnjaic, Moschella, **Phys.Rev. D96 (2017) no.5, 055007**

Inelastic dark Matter - χ_1 is thermal relic

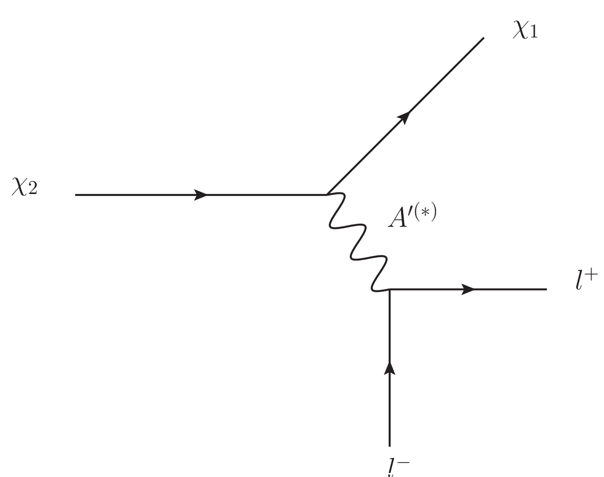
Whose relic abundance is set by:



Coannihilation

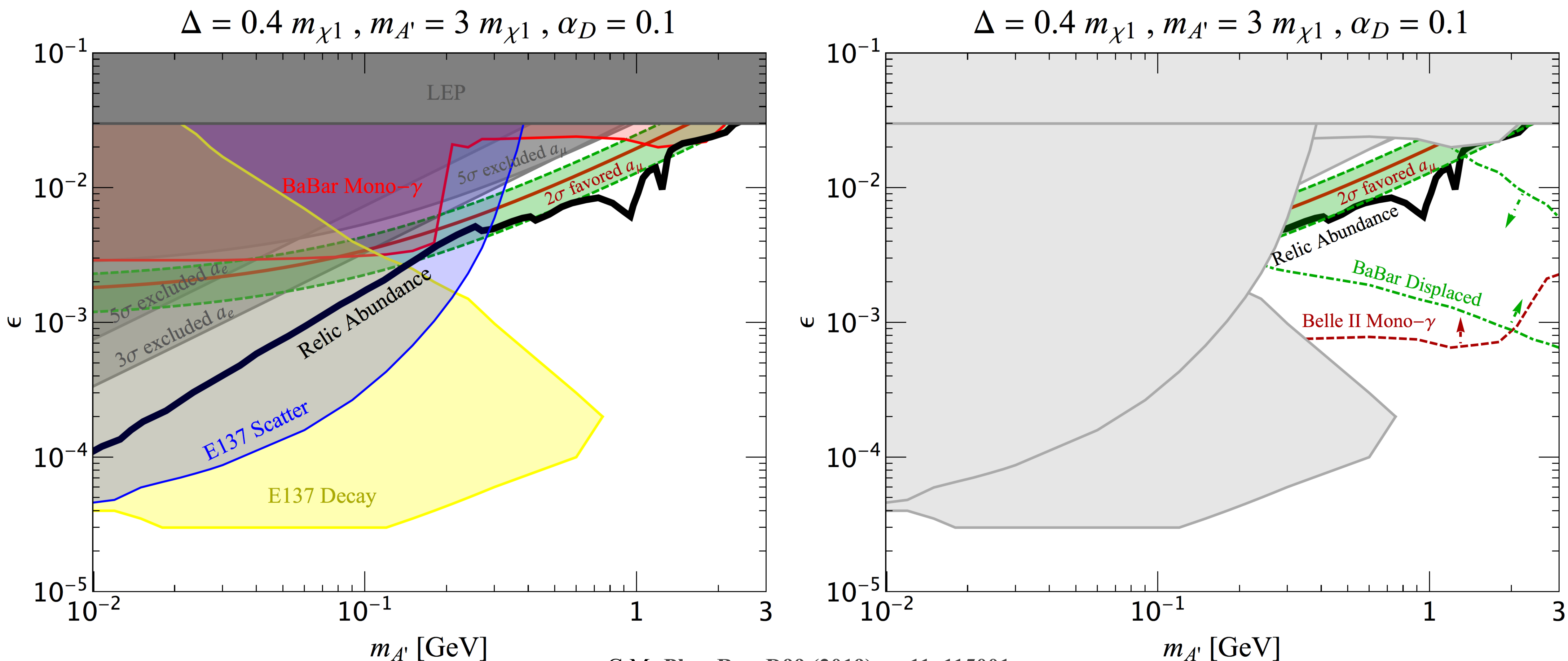


Downscattering



Decay

Can dark photon still explain muon g-2?

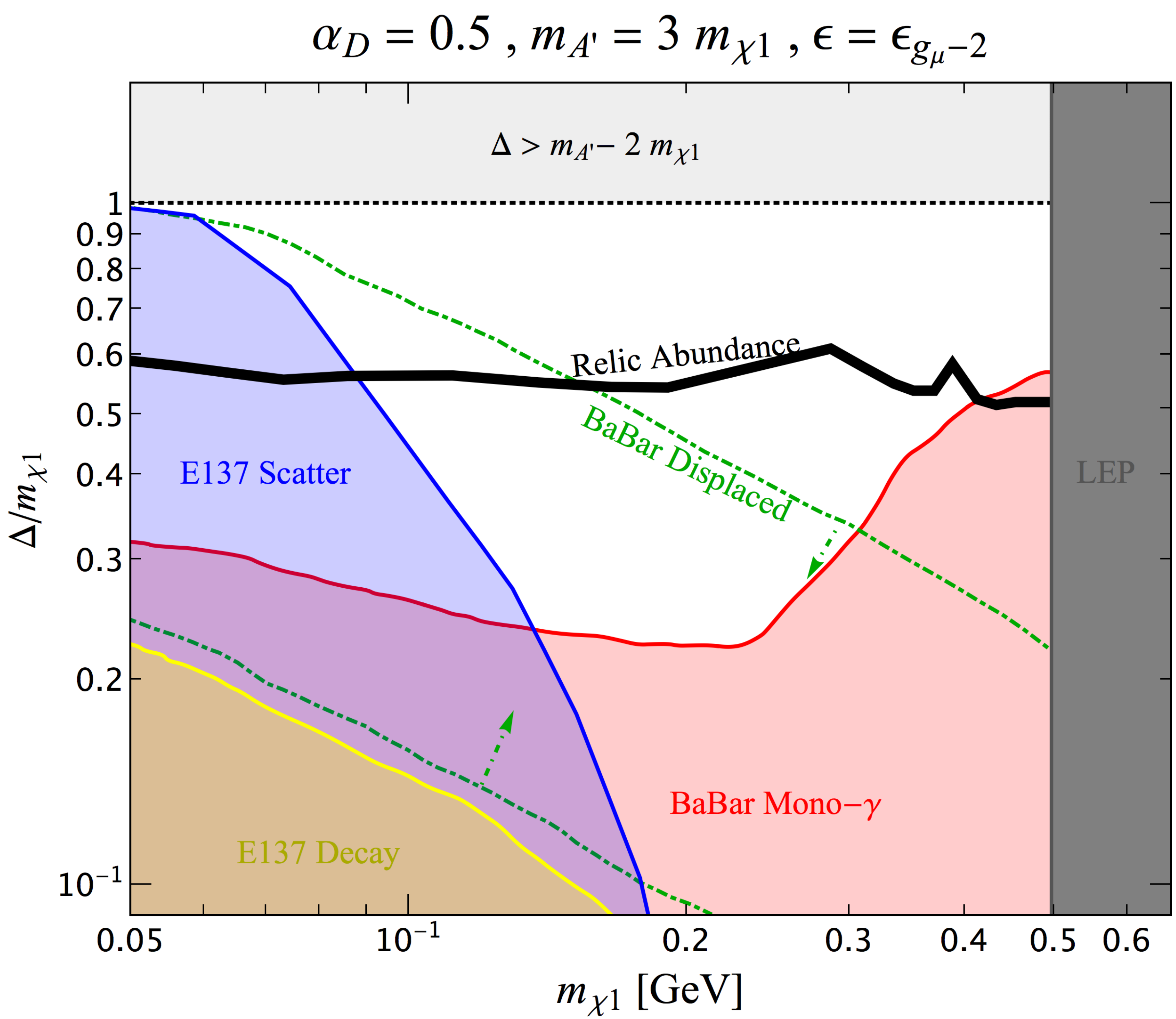


G.M: **Phys.Rev. D99 (2019) no.11, 115001**

Its possible BaBar could have vetoed lepton events in their invisible decay search

Belle II: With dedicated mono-photon trigger, search for Invisible & semi-visible events

For what splittings can we still explain g-2



G.M: **Phys.Rev. D99 (2019) no.11, 115001**

Summary

- Leptonic moments are exquisite probes of new physics

- Dark Photon coupling elastically to dark fermions robustly ruled out in muon g-2 explanation

- Dark Photon coupled inelastically to dark fermions:
  - Continues to explain muon g-2 anomaly
  - Simultaneously explains dark matter relic abundance
  - Gives displaced lepton signature to search for

- Available region of space can also be probed by:
  - Current: MiniBooNE, Nova & NA64
  - Future: LDMX, BDX, SeaQuest & FASER

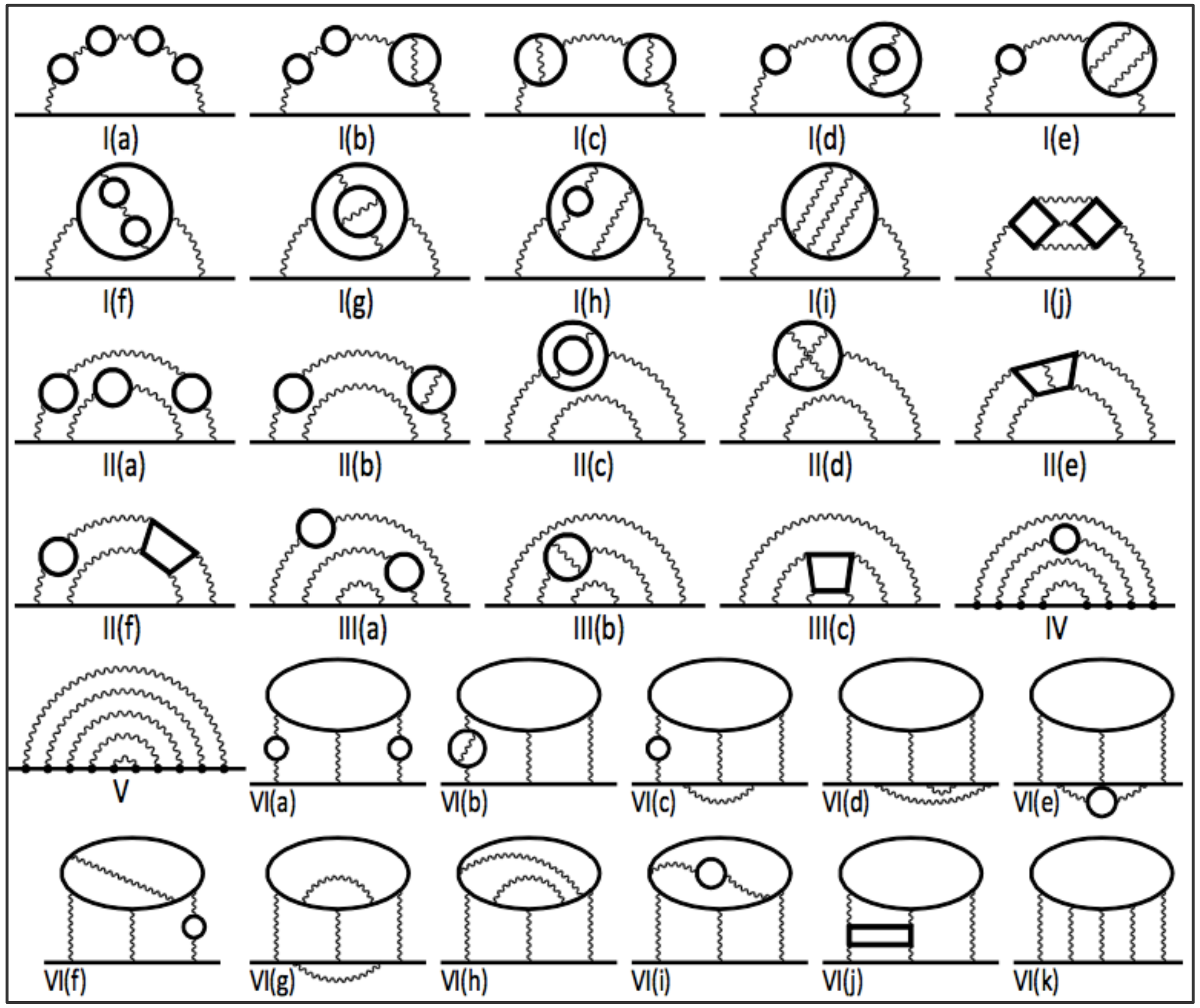
Thanks for your Attention

Back up Slides

Electron

Electron magnetic moment one of the most accurately verified predictions in nature

Aoyama, Hayakama, *Kinoshita* & Nio: PRL 109 (2012) 111808



Theory: Calculated up to 10th order in QED

Experiment: Measured with very high precision at Harvard using cylindrical Penning trap

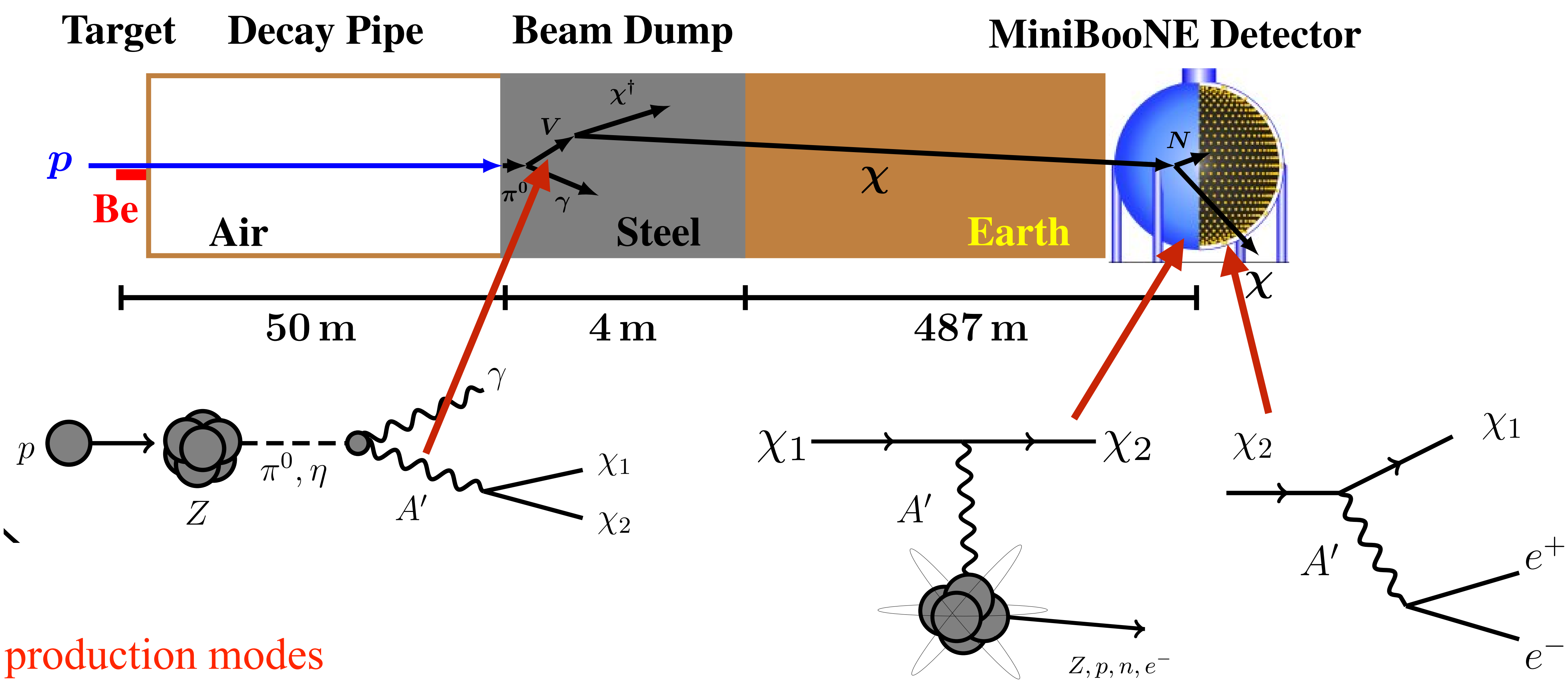
$$\Delta a_e \equiv a_e^{exp} - a_e^{SM}$$
$$= -84 \pm 36 \times 10^{-14}$$

Giving a -2.3σ discrepancy

F. Jegerlehner, arXiv:1804.07409v2

Signatures @ Proton Beam Dumps

(quasi) elastic scattering & decays



A' production modes

- neutral meson decay
- Dark Bremstrahlung

LSND (2001)

E ~ 800 MeV, 1e24 POT

MiniBooNE (2017)

E ~ 9 GeV, 1e20 POT

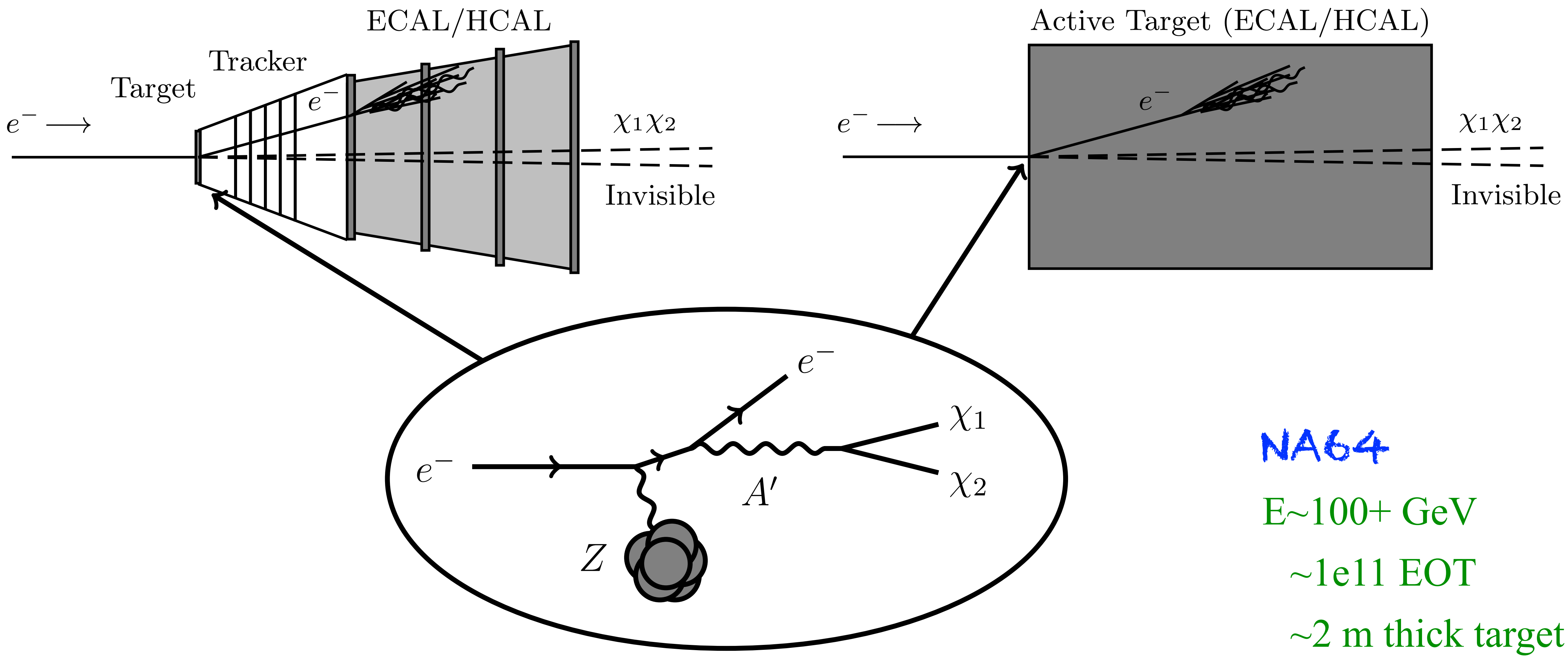
Batell, Pospelov, Ritz, **Phys.Rev. D79 (2009) 115008**

deNiverville, Chen, Pospelov, Ritz, **Phys.Rev. D95 (2017) no.3, 035006**

Batell, deNiverville, McKeen, Pospelov, Ritz, **Phys.Rev. D90 (2014) no.11, 115014**

Ezaguirre, Kahn, Krnjaic, Moschella, **Phys.Rev. D96 (2017) no.5, 055007**

Signatures @ Missing Momentum Experiments



NA64

E~100+ GeV

~1e11 EOT

~2 m thick target

Observe recoiling electron with large missing energy and/or mass (veto SM)

LDMX

E~ 8 GeV

~3e16 EOT

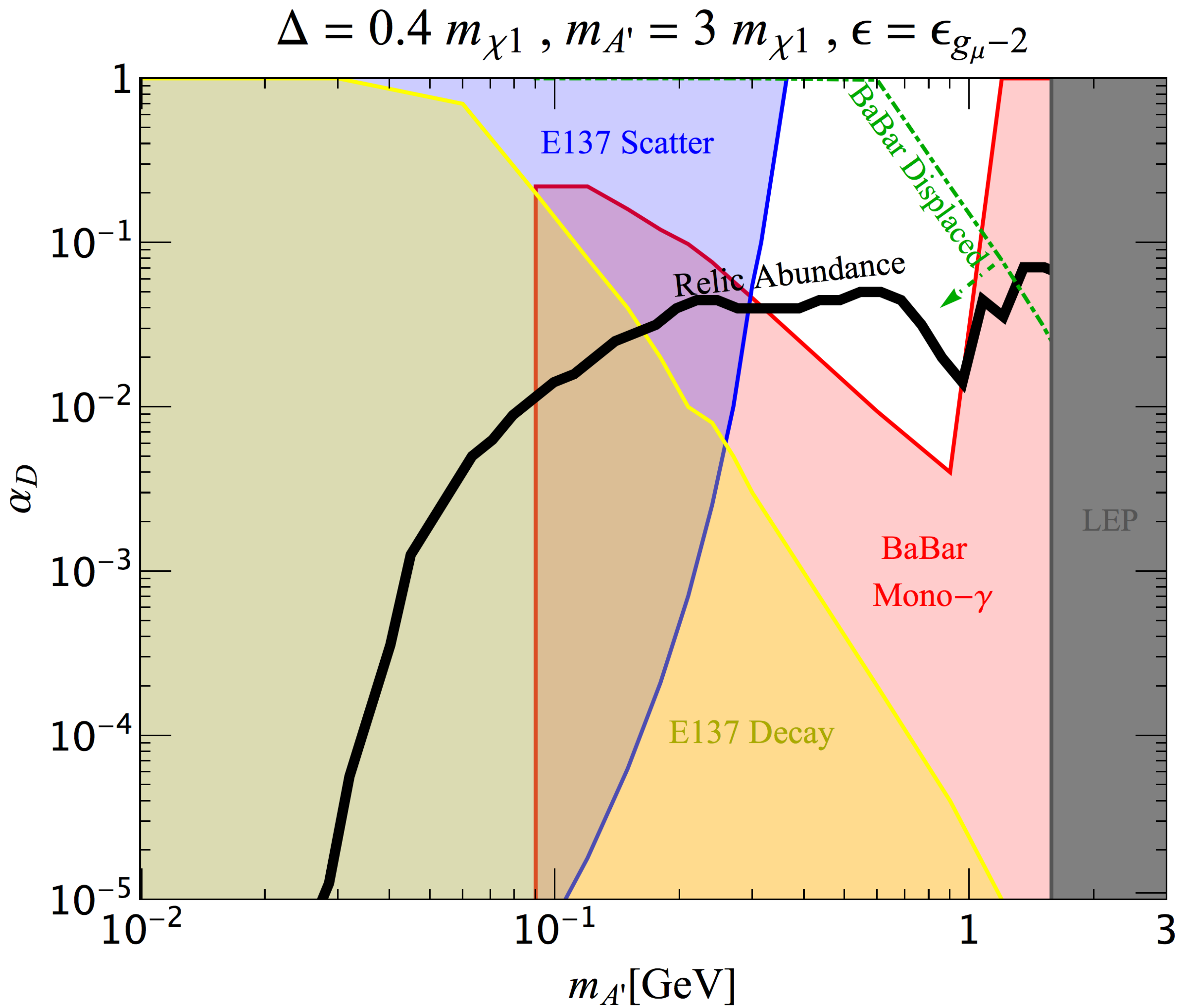
~0.1 rad. length

thin target

NA64 Collaboration: **Phys.Rev.Lett. 118 (2017) no.1, 011802**

Izaguirre, Krnjaic, Schuster, Toro: **Phys.Rev. D88 (2013) 114015**

For what couplings can we still explain g-2



G.M (arXiv:1902.05075)