Revisiting the Dark Photon Interpretation of the Muon g-2 anomaly

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BROOKHAVEN NATIONAL LABORATORY

African Conference on Fundamental Physics
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NCRST

NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

UNAM UNIVERSITY OF NAMIBIA

African School of Fundamental Physics and Applications

Standard Model of Particle Physics

matter particles

	1st gen.	2nd gen.	3rd gen.
QUARK	u *up* d *down*	c *charm* s *strange*	t *top* b *bottom*
LEPTON	ν_e *e neutrino* e *electron*	ν_μ *μ neutrino* μ *muon*	ν_τ *τ neutrino* τ *tau*

gauge particles

Strong Force

g *Gluon*

Electro-Magnetic Force

γ *photon*

Weak Force

W^+ W^- *W bosons*

Z *Z boson*

scalar particle(s)

H *Higgs* $?$ $?$ • • •

Elements of the Standard Model

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Standard Model of Particle Physics

	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Quantum Chromodynamics (QCD)

Not part of SM

Quantum Electrodynamics (QED)

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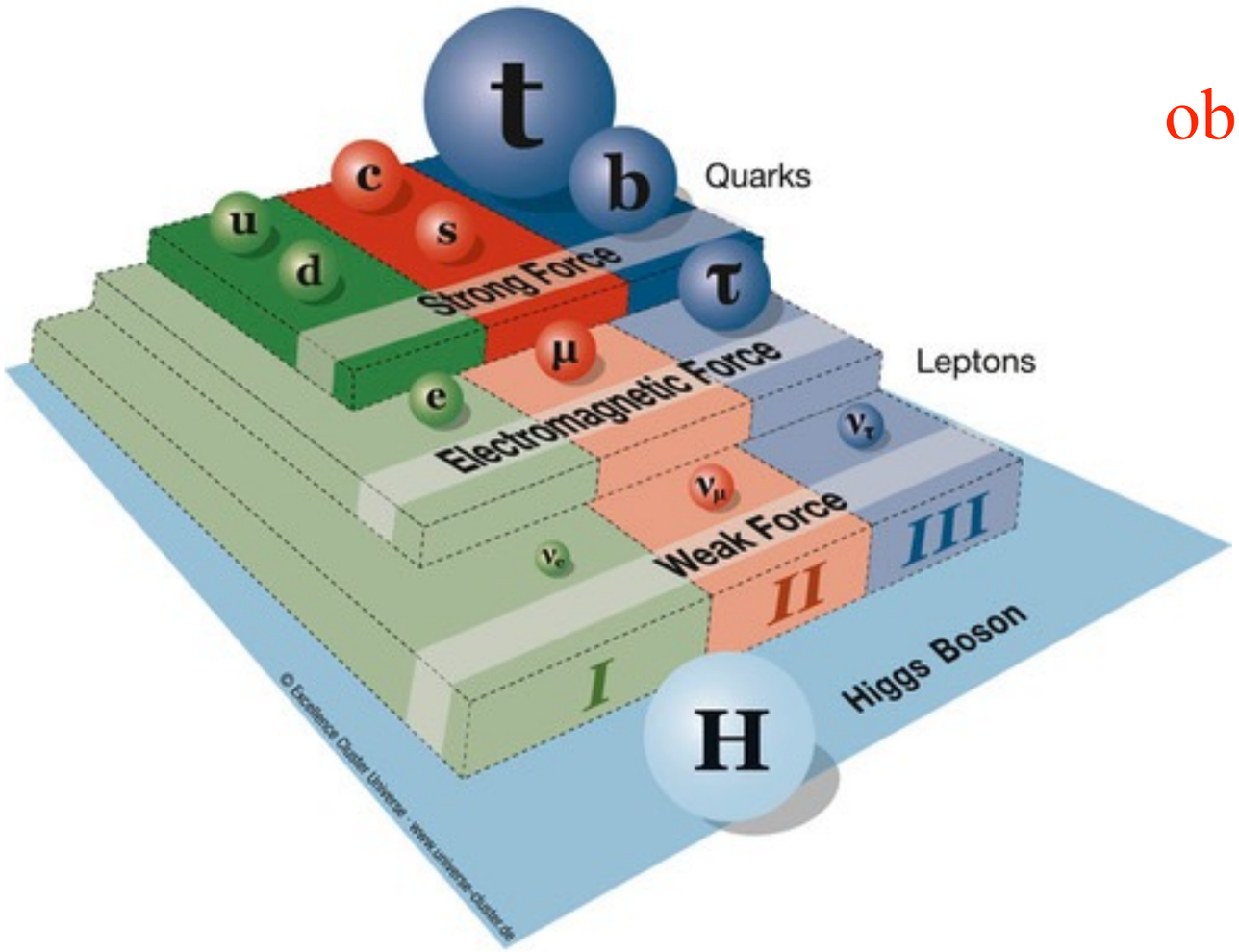
Represented by gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$

Current Status of Particle Physics



Standard Model has been very successful
in explaining much of the
observed particle physics phenomena.

To date all SM particles been
detected

Yet we have hints that it does not
tell the complete story
of the Universe.

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Some of the aspects the SM cannot explain include:

- Dark Matter

- Dark Energy

- Neutrino Mass origin

- Matter-Antimatter Asymmetry

- Many others …

These require some New Physics beyond the Standard Model (BSM) !!!

Theorists & Experimentalists are hard at work trying to turn **hints** into **evidence**

New Physics may show itself in different complementary forms:

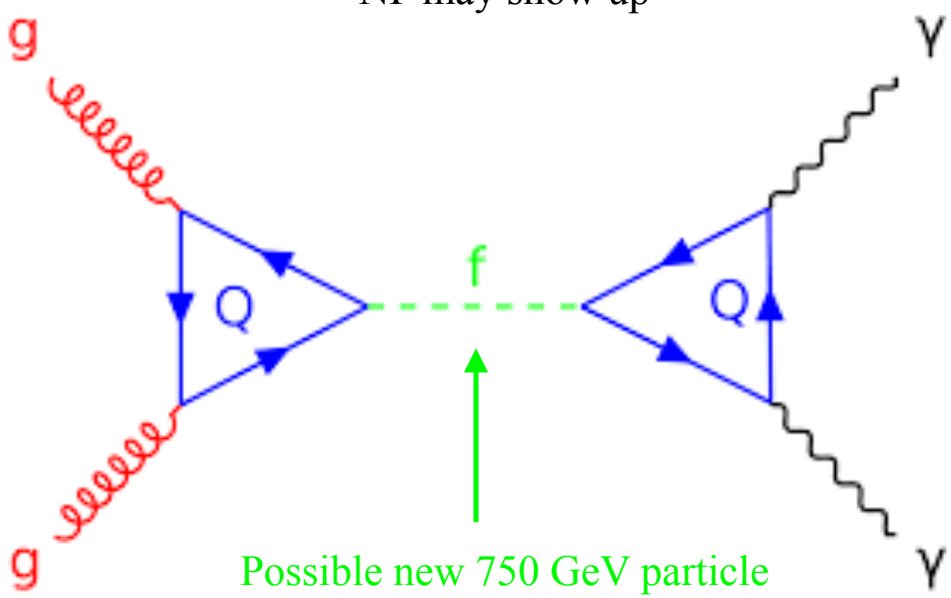
- High energy experiments

Please refer back to
Jori Sonneveld's talk from last week

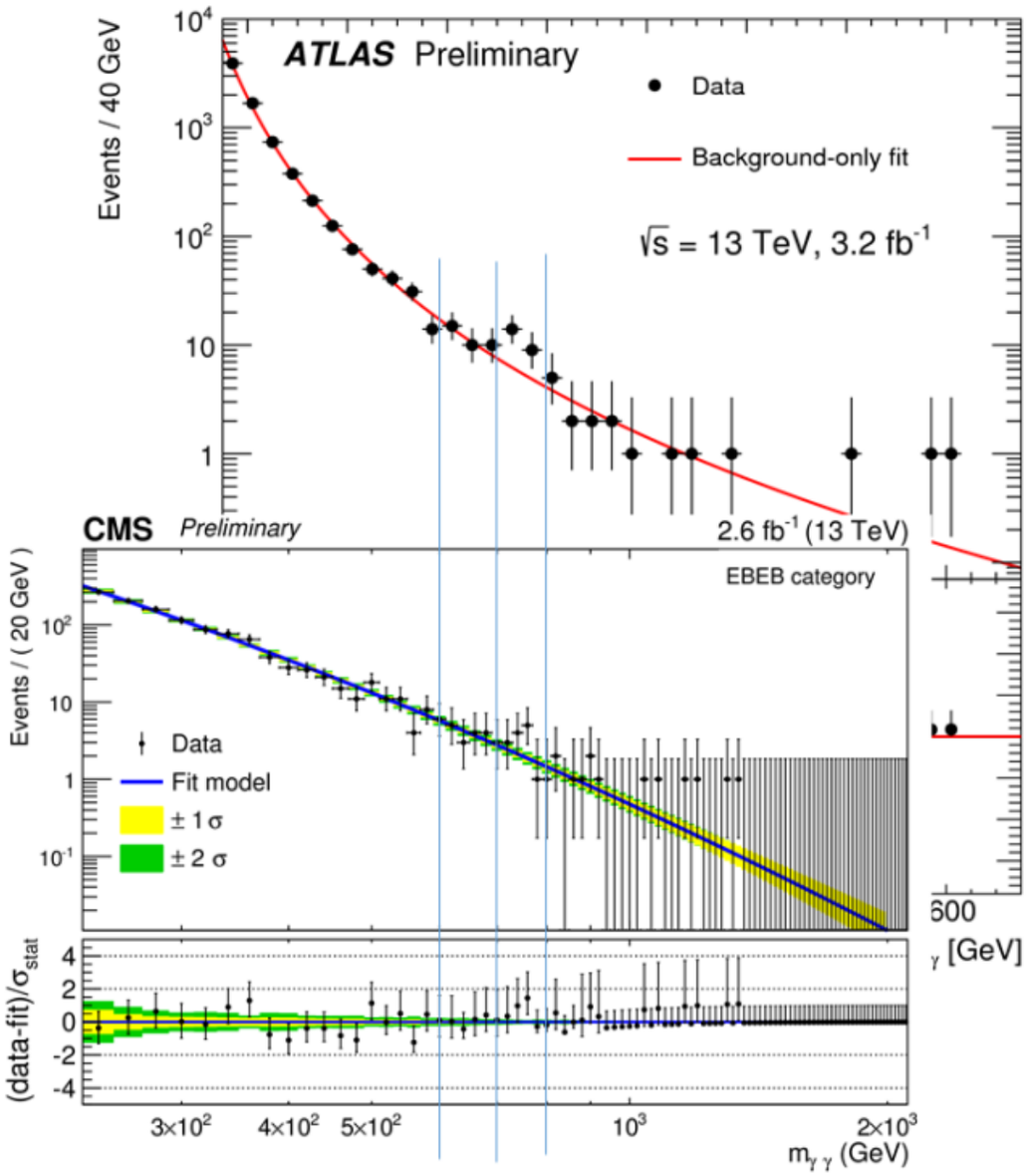
e.g. Direct production of new particles at colliders

➡ New heavy resonances produced at the LHC/bump hunting

Feynman Diagram showing how
NP may show up



Possible new 750 GeV particle



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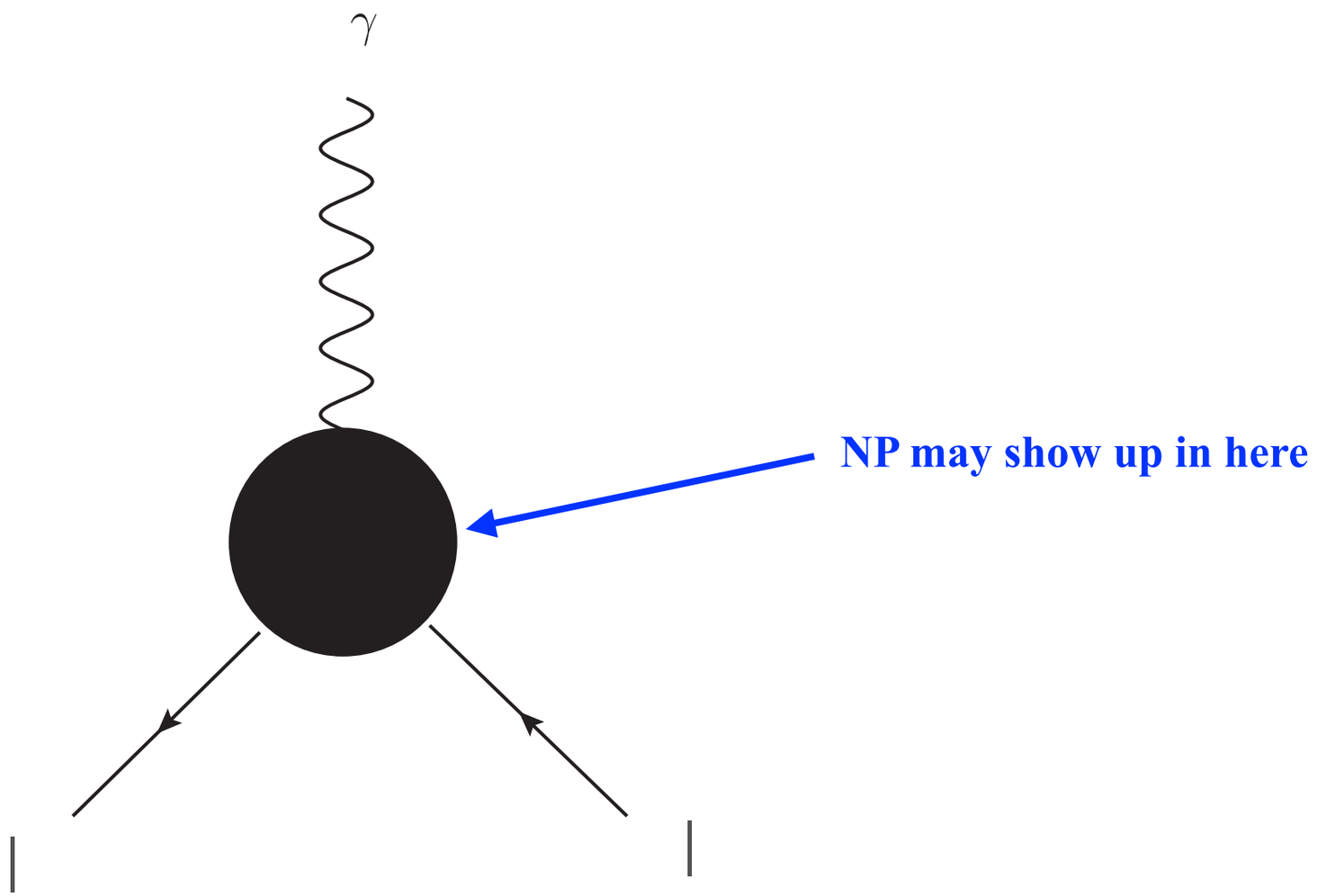
- Low energy precision physics

e.g. Anomalous Couplings: Indirect effects of new particles may show up in quantum corrections.

➡ Anomalous magnetic moments of leptons



In this Talk

- Discuss how precision physics can help uncover new physics

Muon anomalous magnetic moment

- Introduce anomalous magnetic moment and ongoing efforts from theory & experiment

- Discuss possible new physics contributions to muon magnetic moment

- Briefly give results

- Conclusions

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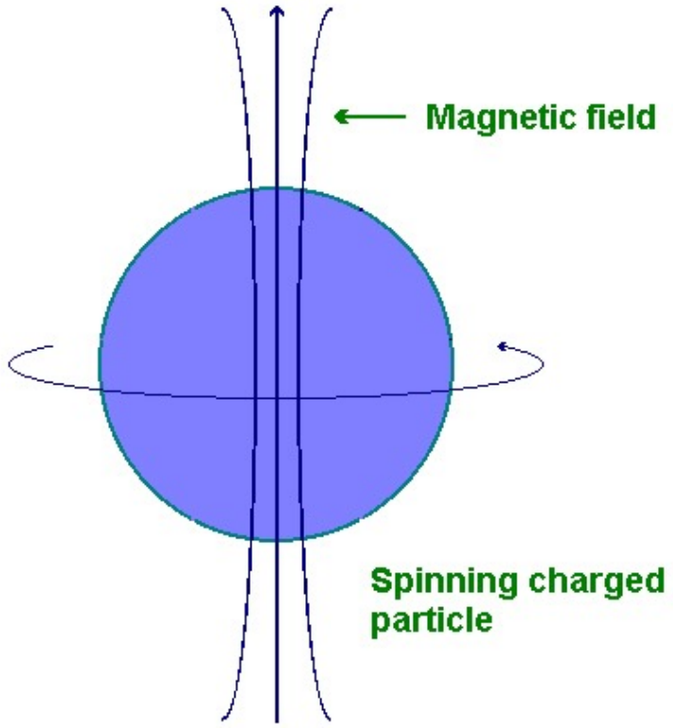
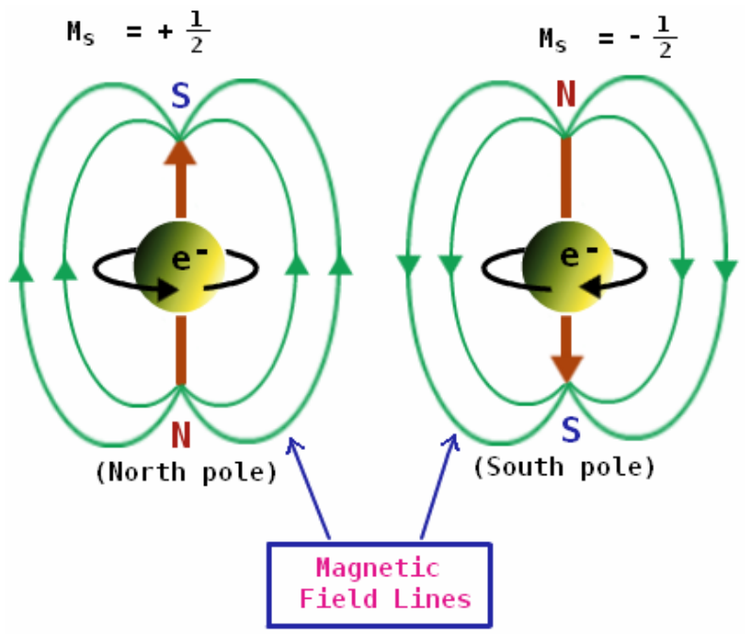
Quick Recap



Spinning charged particle in uniform magnetic field induces magnetic dipole moment

$$\bar{\mu}_l = \frac{g_l\ Q}{2m_l}\bar{s}$$



Anomalous part of dipole moment

$$a_l = \frac{g_l - 2}{2}$$

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Muon Anomalous Magnetic Moment

Experiment: BNL E821 [BNL Muon g-2 collaboration, PRD73, 072003 (2006)]

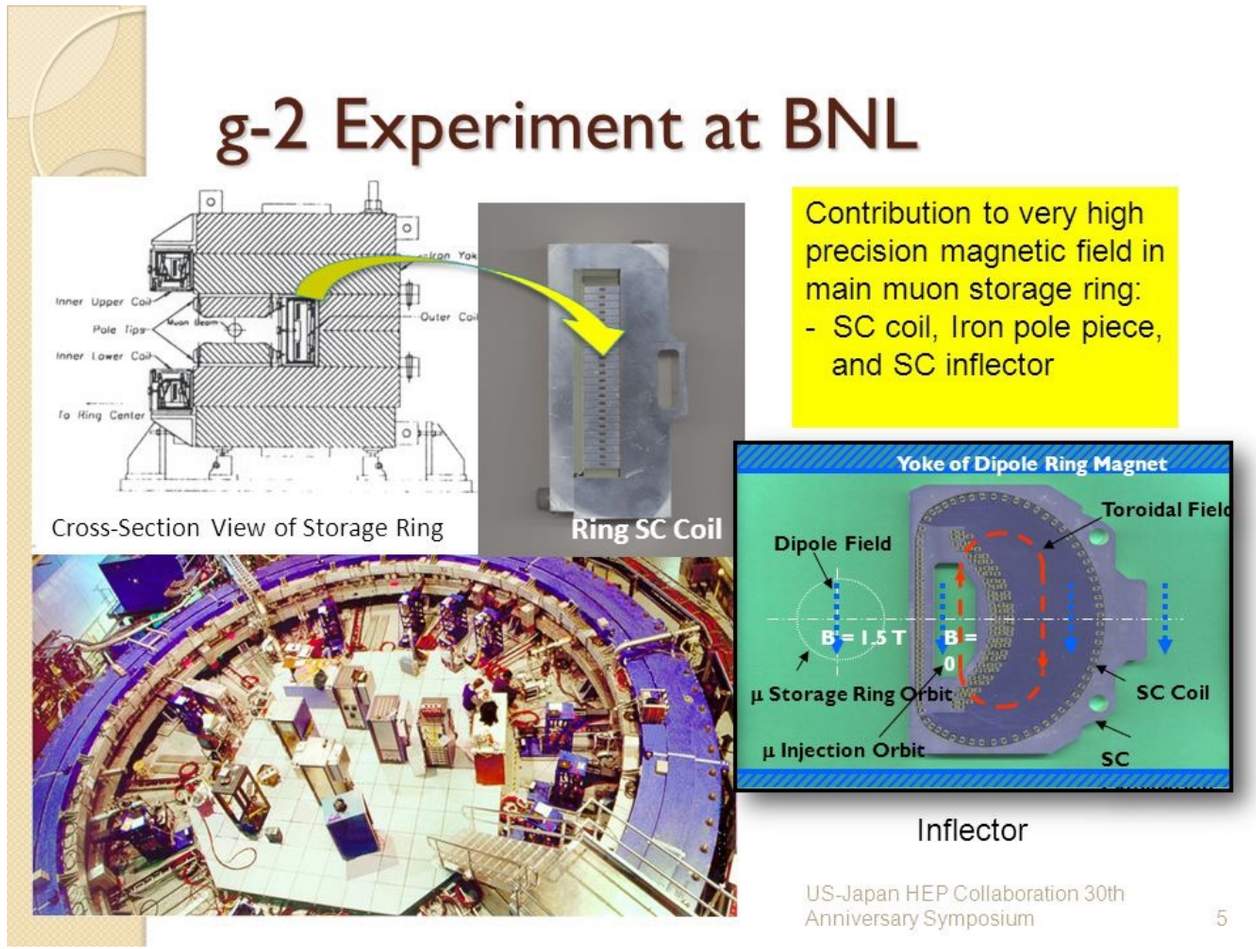
$$a_\mu^{exp} = 1.16592089(63) \times 10^{-3}$$

measured to (0.54 ppm)

Theory: Calculation in the SM

$$a_\mu^{SM} = 1.16591795(62) \times 10^{-3}$$

Jegerlehner & Nyffeler, 2009 Davier et al, 2010 Hagiwara et al, 2011



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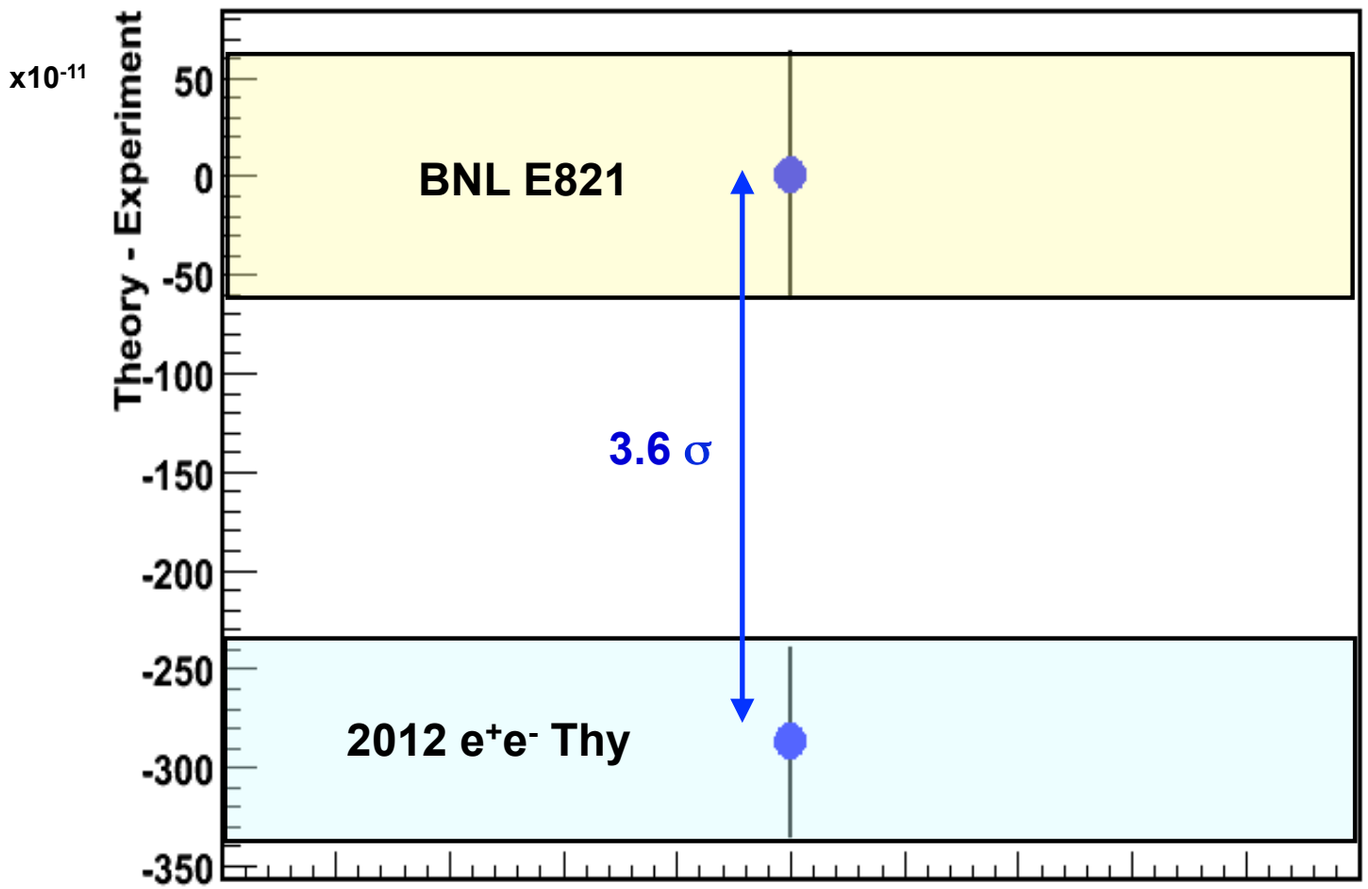
Comparison in 9th decimal place

Experiment: 0.00116592089

Theory: 0.00116591795

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$$
$$= (28.1 \pm 3.6_{th} \pm 6.3_{exp}) \times 10^{-10}$$

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



3.3 - 3.6 σ discrepancy

D.Hertzog, 2014

What is the origin of the discrepancy?

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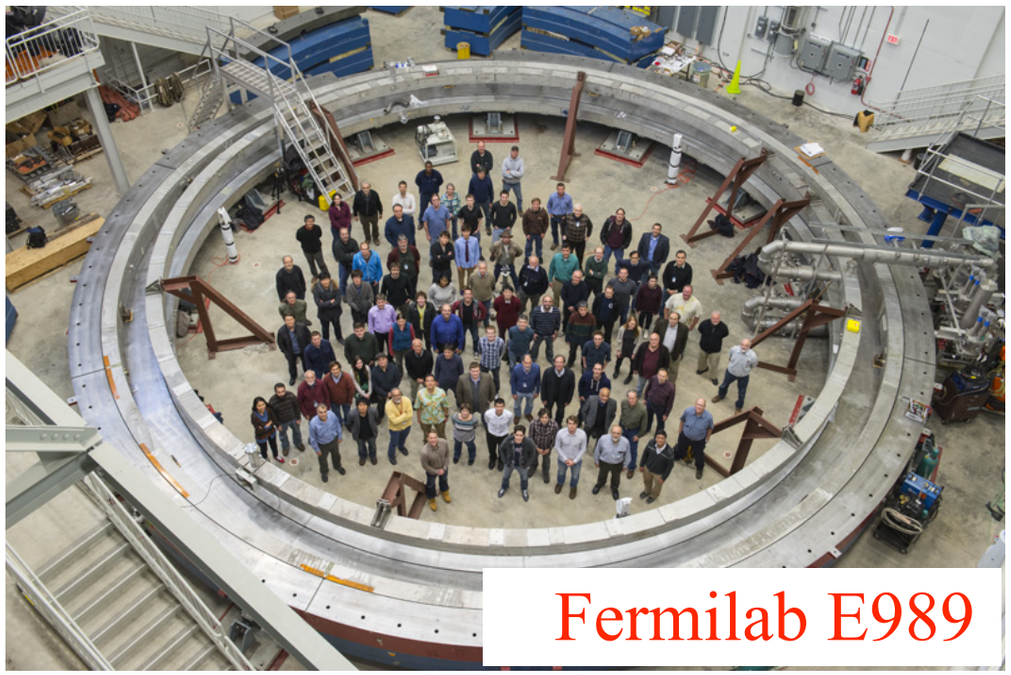
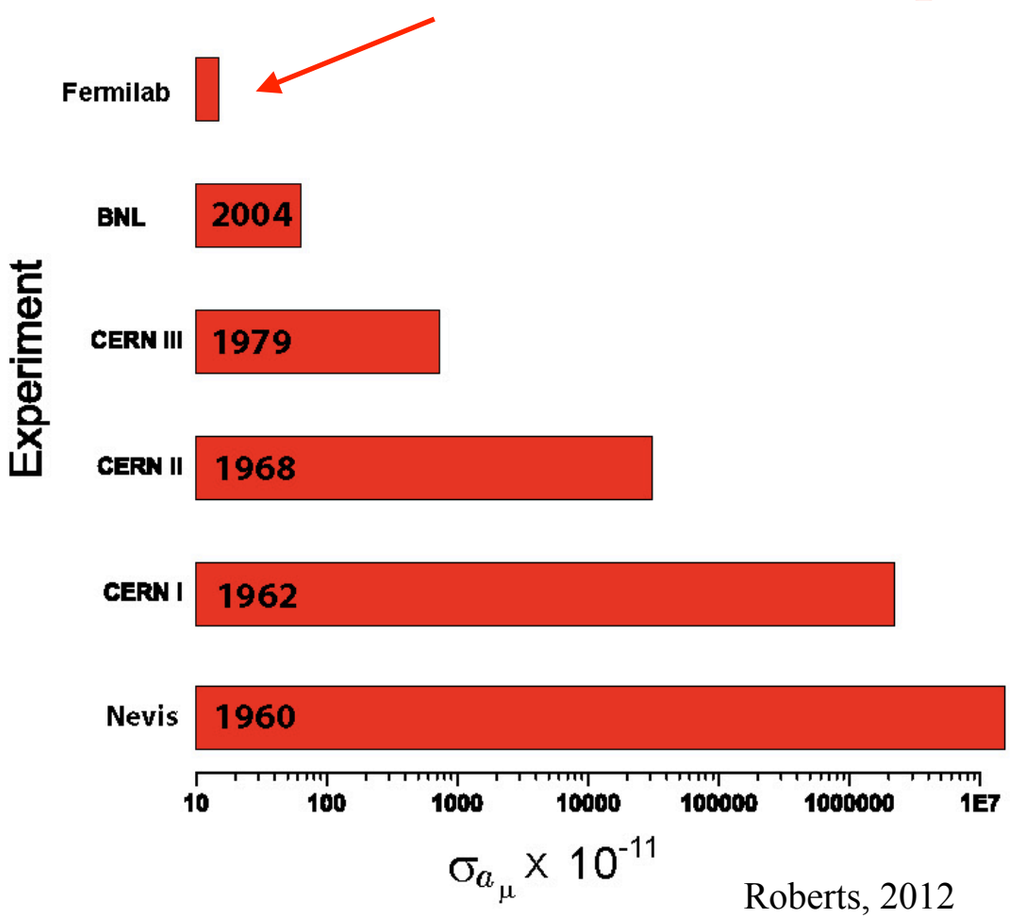
Ongoing effort in the experimental community

- Fermilab E989 experiment

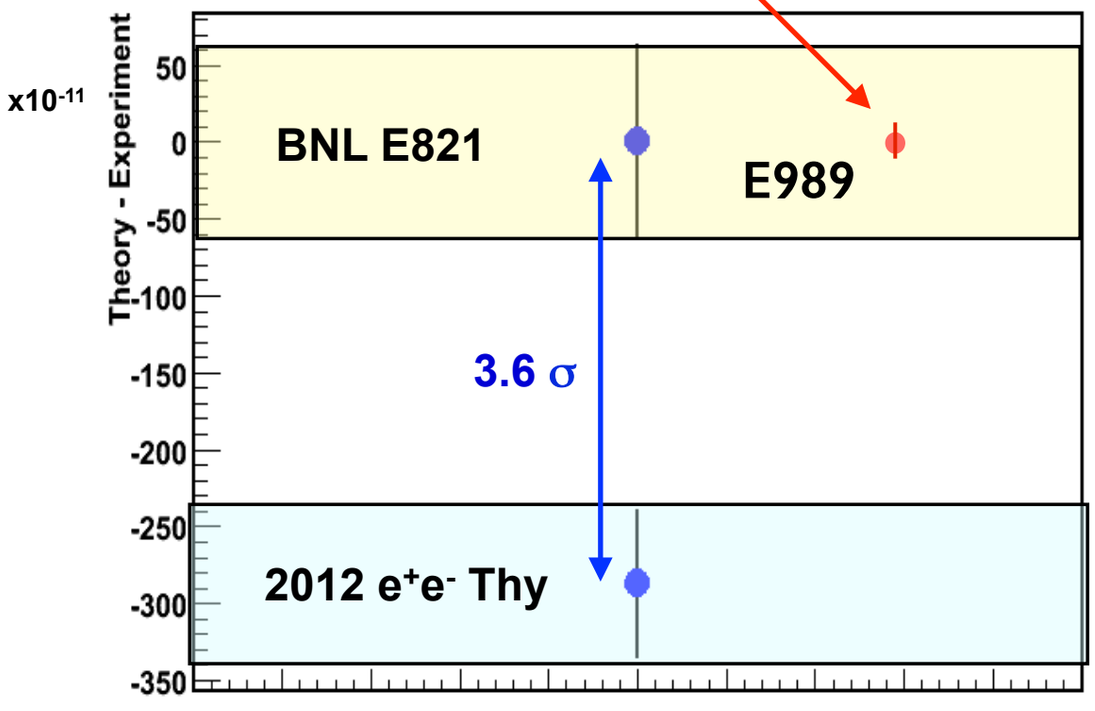
- J-PARC E34 experiment



Set to decrease experimental errors by factor 40



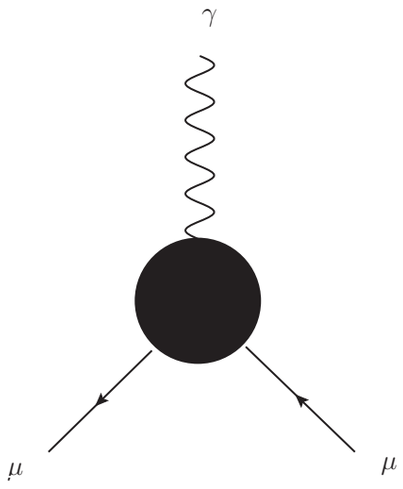
Roberts, 2012



D.Hertzog, 2014

On the Theory side

Contributions from SM:



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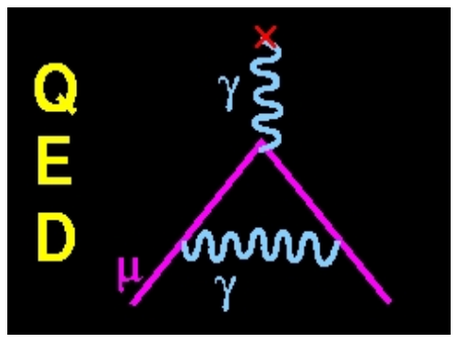

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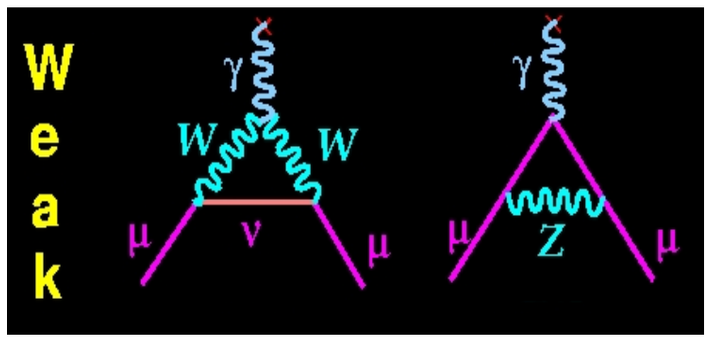
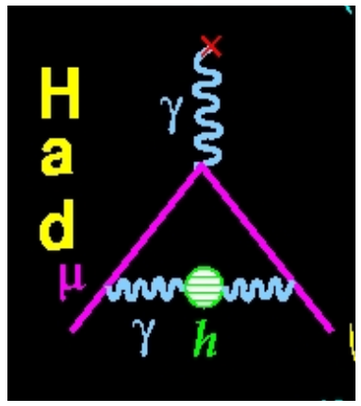


+ Diagram with Higgs

+



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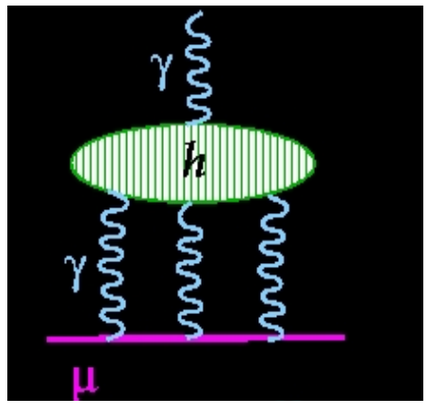
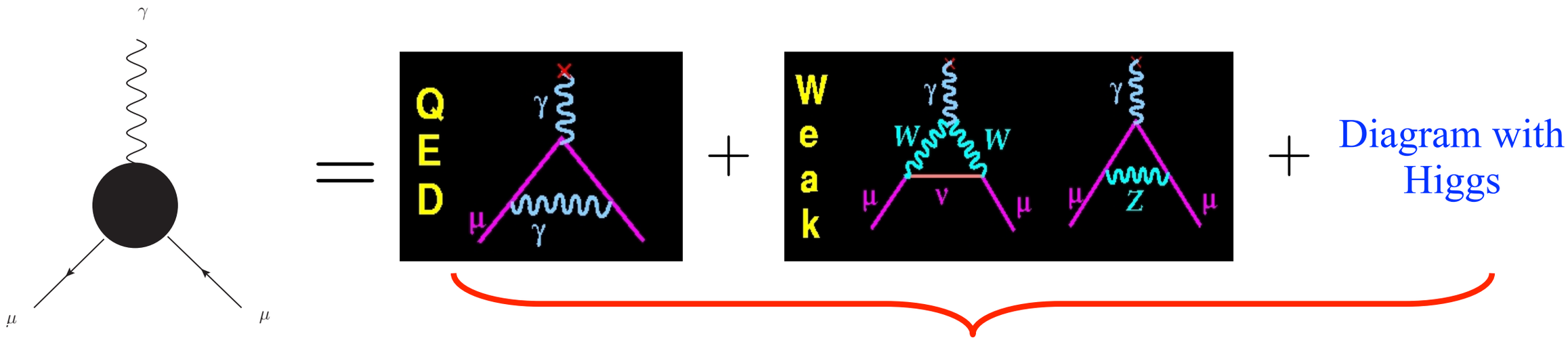
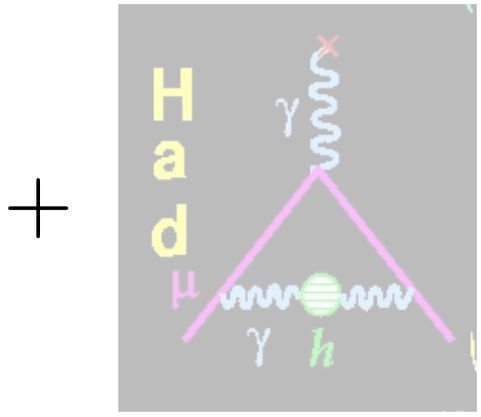
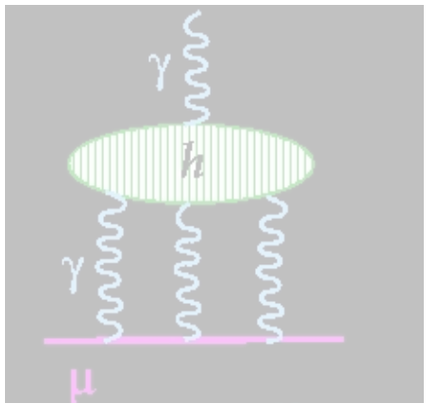


Contributions from SM:



QED + Electroweak Contribution: Well Known





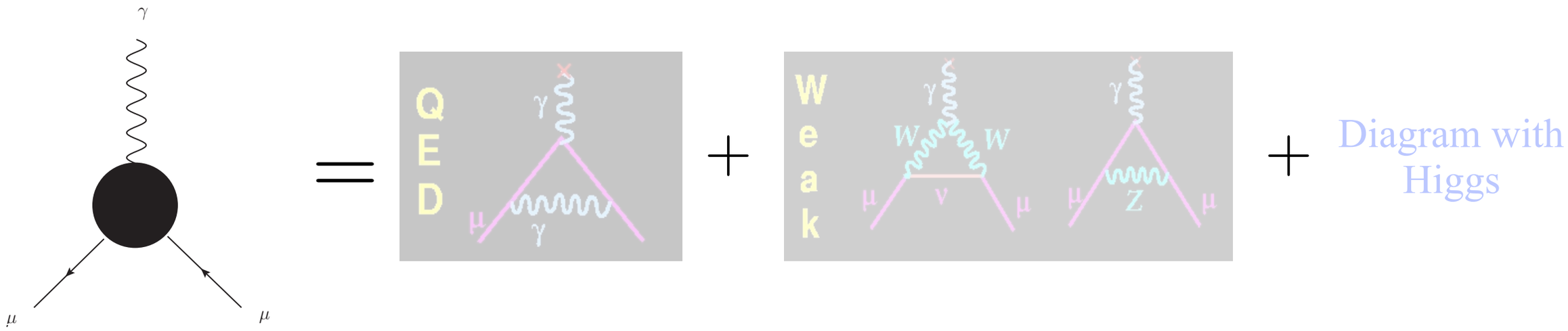
Aoyama et al: Phys.Rev.Lett. 109 (2012) 111808

Aoyama et al: Phys.Rev. D85 (2012) 033007

Numerous other high precision calculations
by Professor Kinoshita & Collaborators

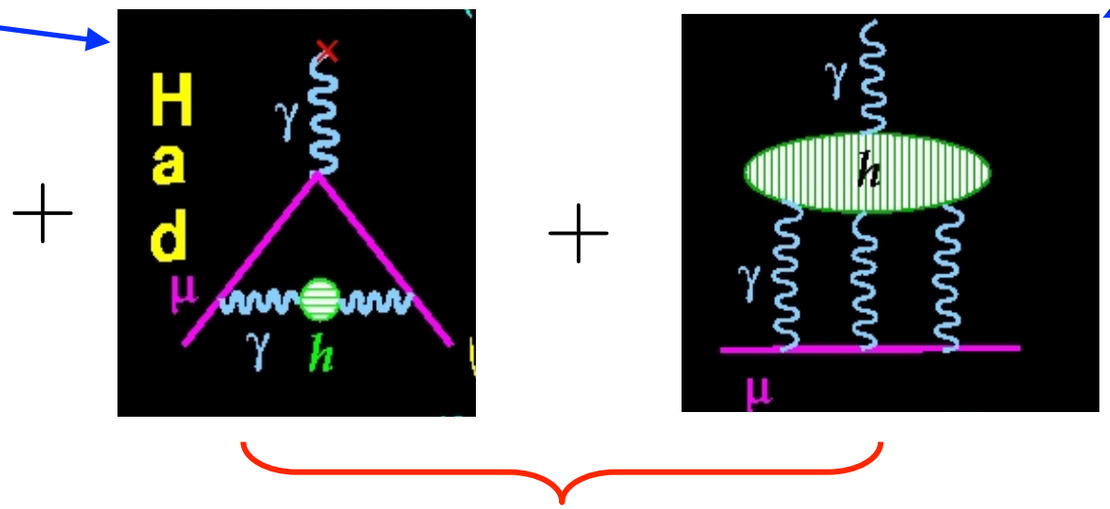
& many others

Contributions from SM:



Hadronic vacuum polarization

Hadronic Light-by-light scattering



Davier et al., Eur.Phys.J. C71(2011) 1515

Aoyama et al: Phys.Rev. D85 (2012) 093013

HP QCD collaboration:
PoS LATTICE2016 (2016) 377

RBC &UKQCD collaboration:
EPJ Web Conf. 175 (2018) 01024

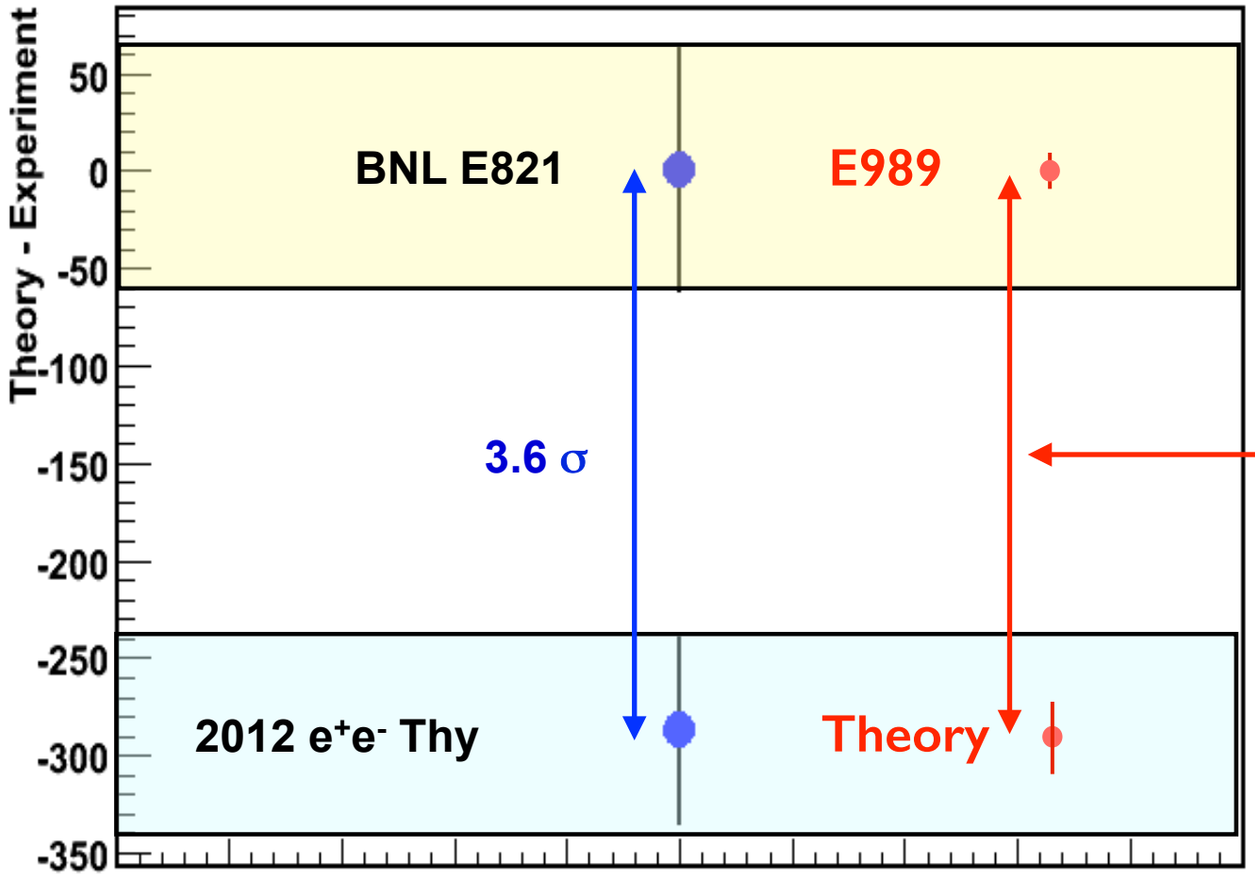
& many others

QCD Contribution: Significant progress being made

Numerous other high precision calculations
by Professor Kinoshita with Collaborators & Professor Lepage
& Collaborators

What does it all mean?

3.6σ simply not enough to celebrate New Physics



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

What possible BSM physics might be responsible for this Anomaly?

There are many theories to consider …

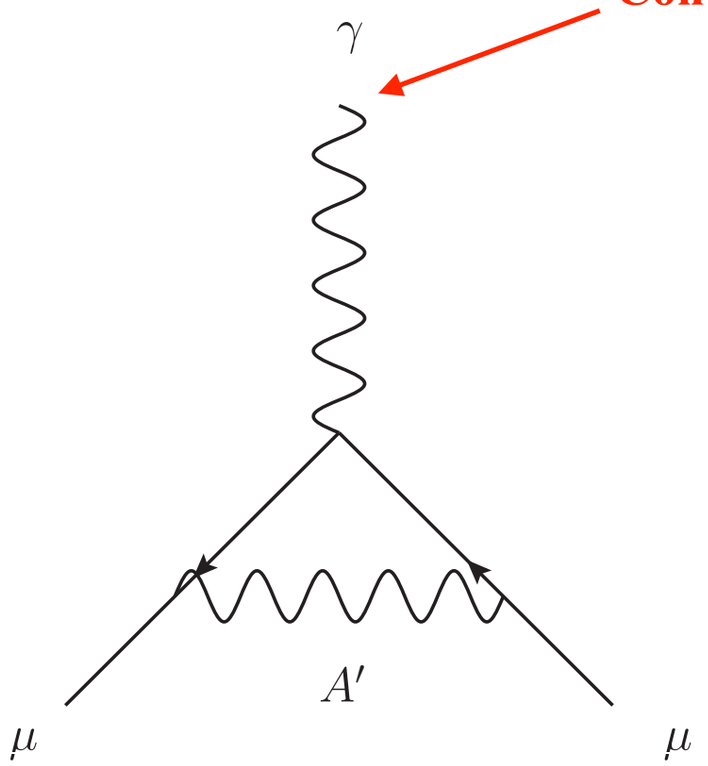
Focus for this talk: **Dark Photon** A'

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

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

Kinetic mixing with SM photon

$$D_\mu = \partial_\mu + i g_D A'_\mu$$



Contribution to g-2

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

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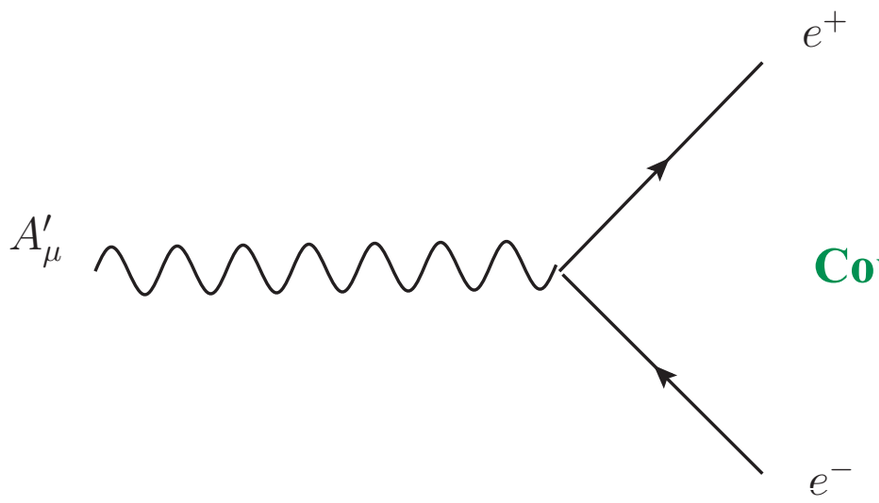
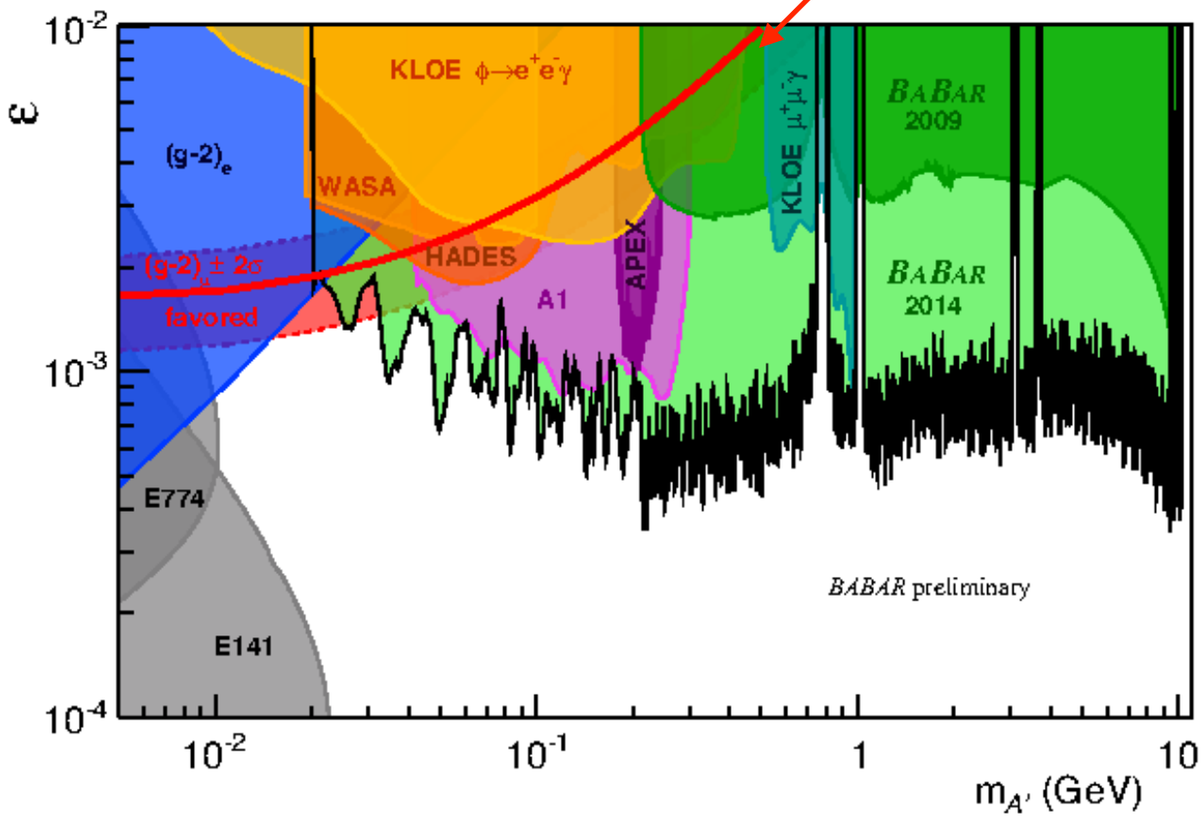


$$\epsilon\bar{\psi}_{sm} i\gamma_\mu D^\mu \psi_{sm}$$

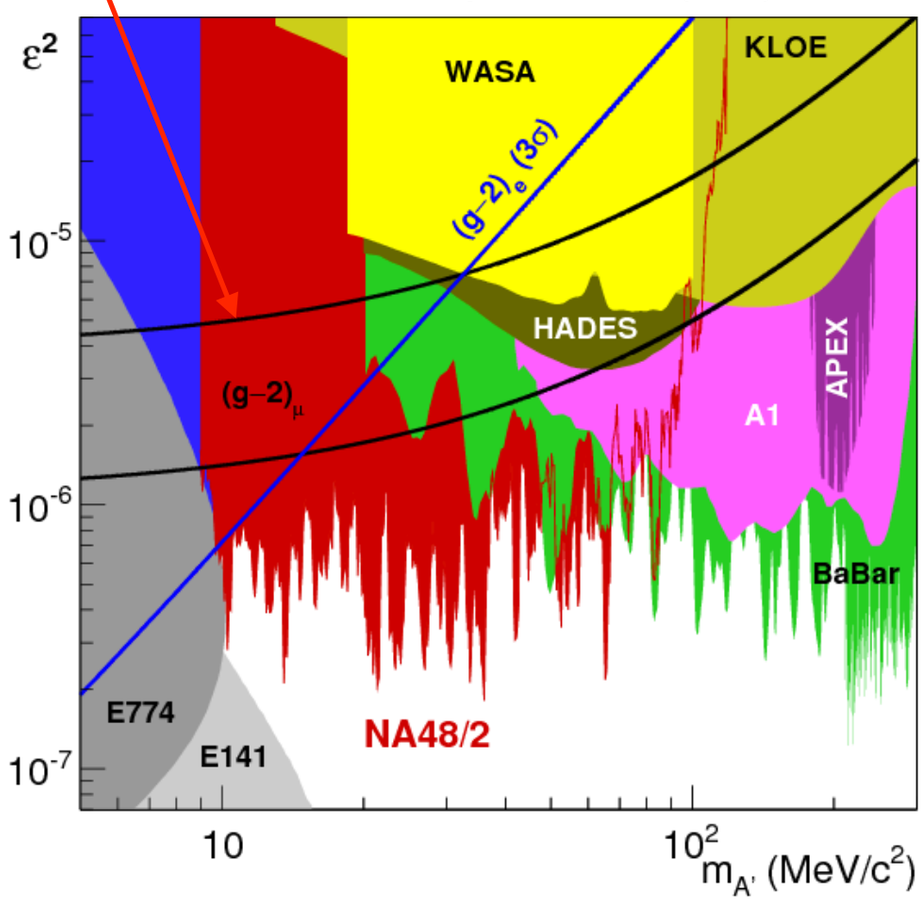
Coupling to visible sector been searched for

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



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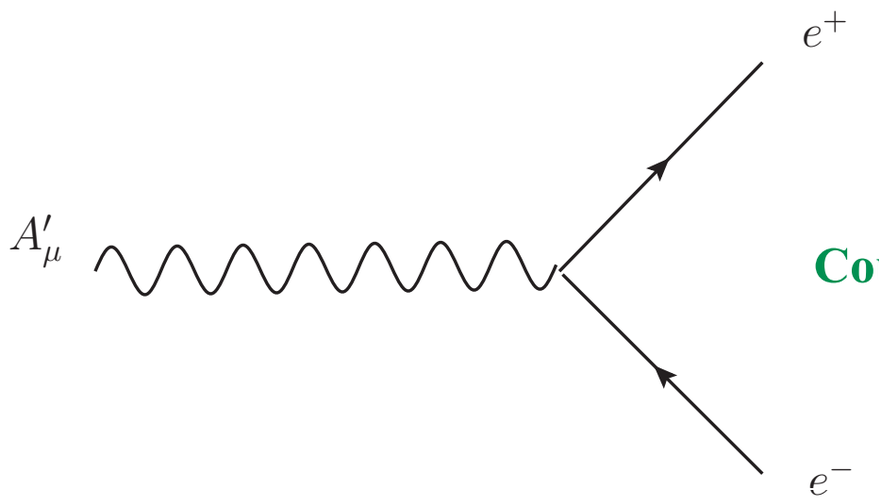

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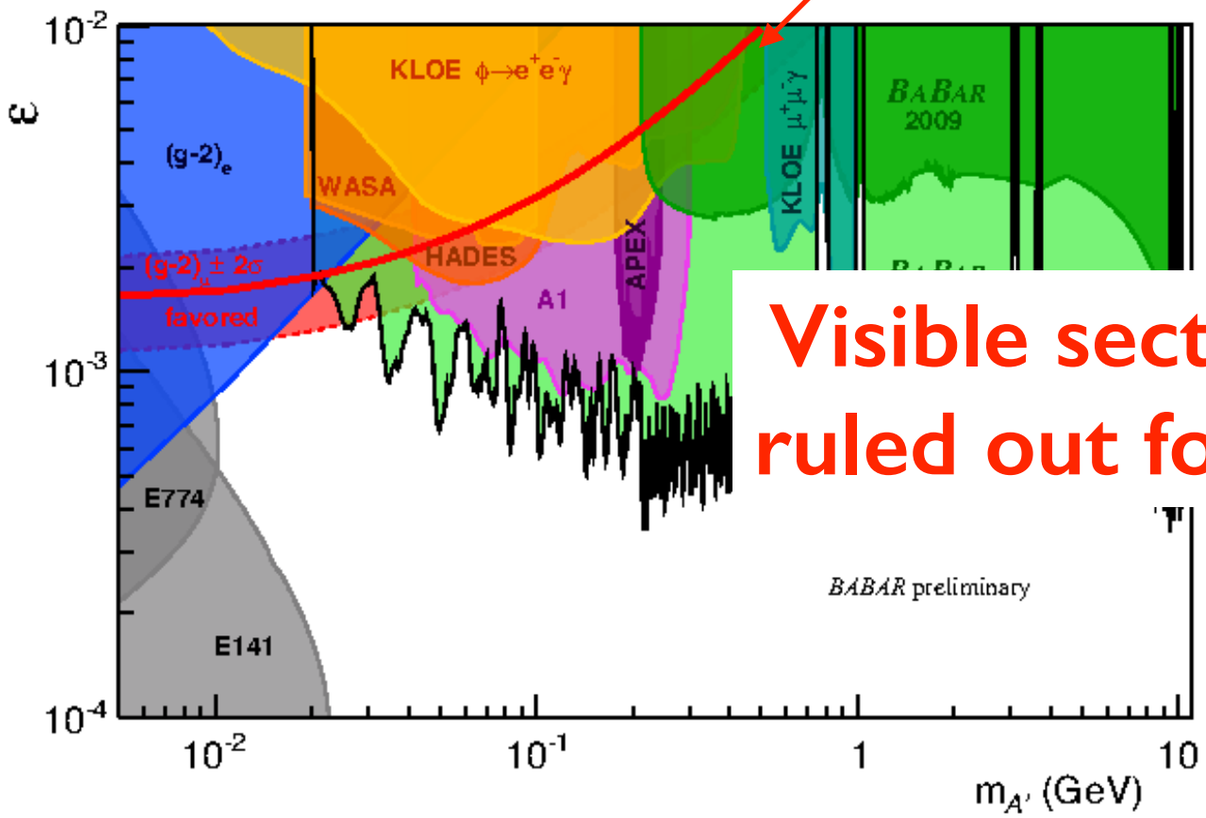

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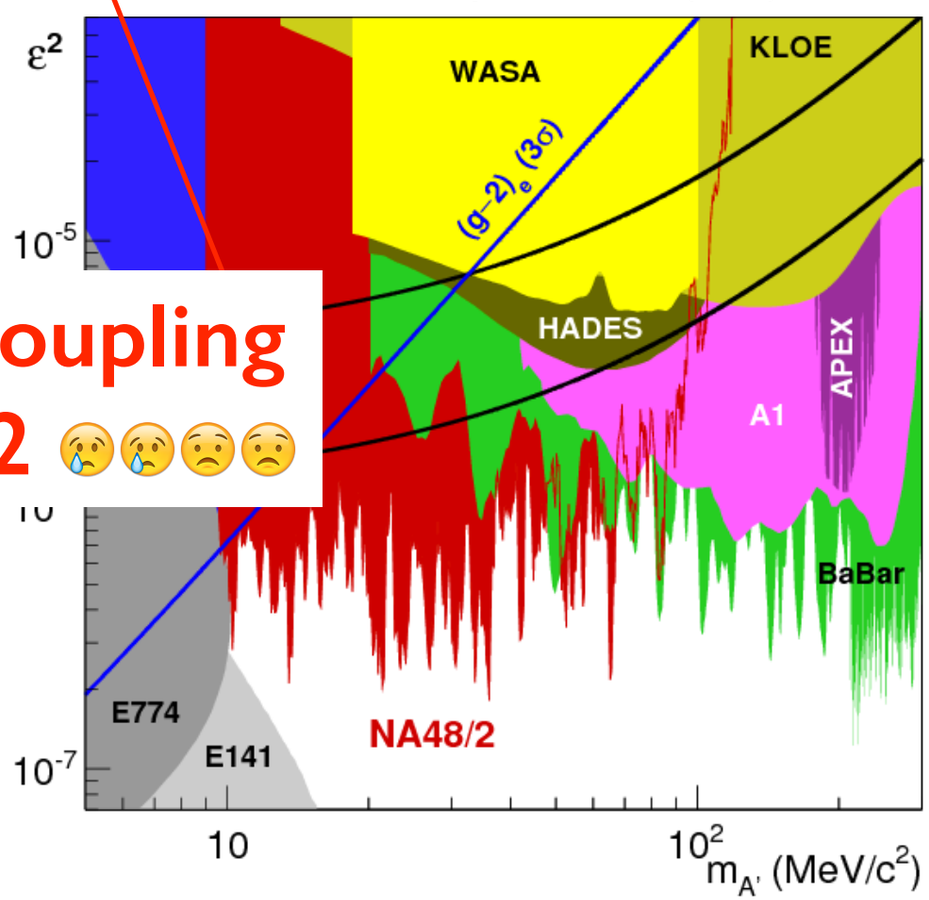

Visible sector coupling ruled out for g-2 😢😢😟😟

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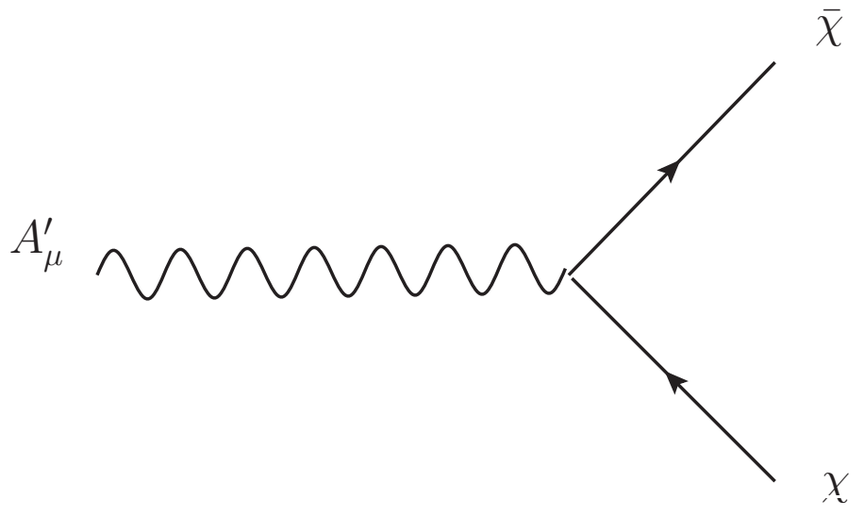
There is still hope

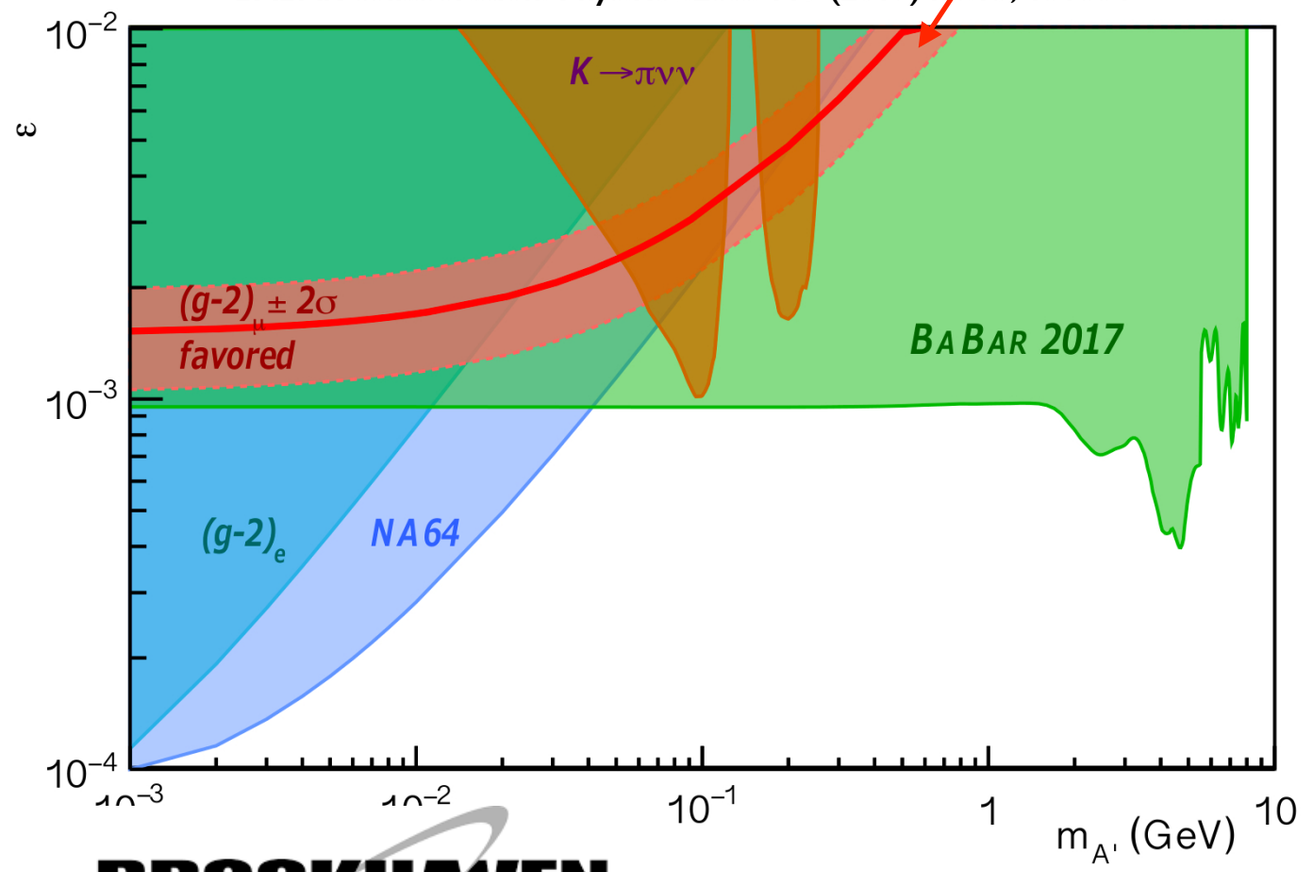


$$\bar{\psi}_D i\gamma_\mu D^\mu \psi_D$$

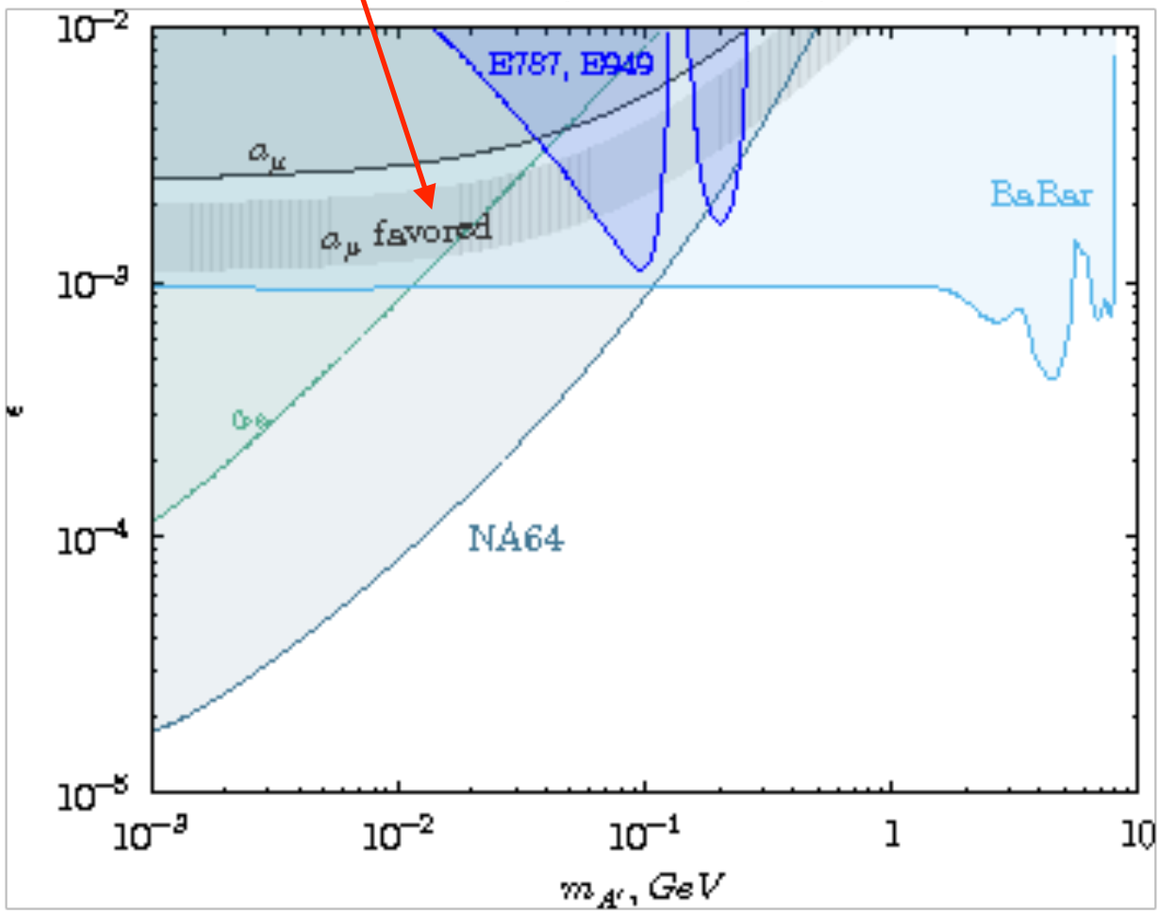
Look for coupling to sector

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



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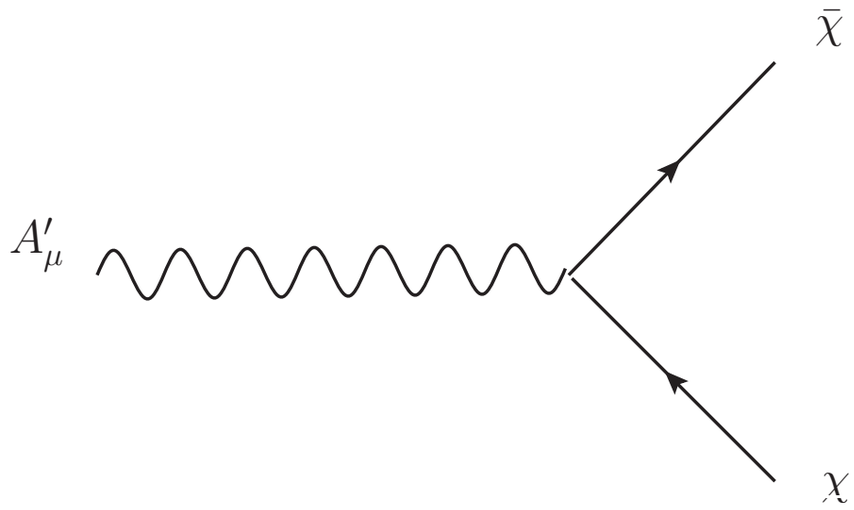
There is still hope

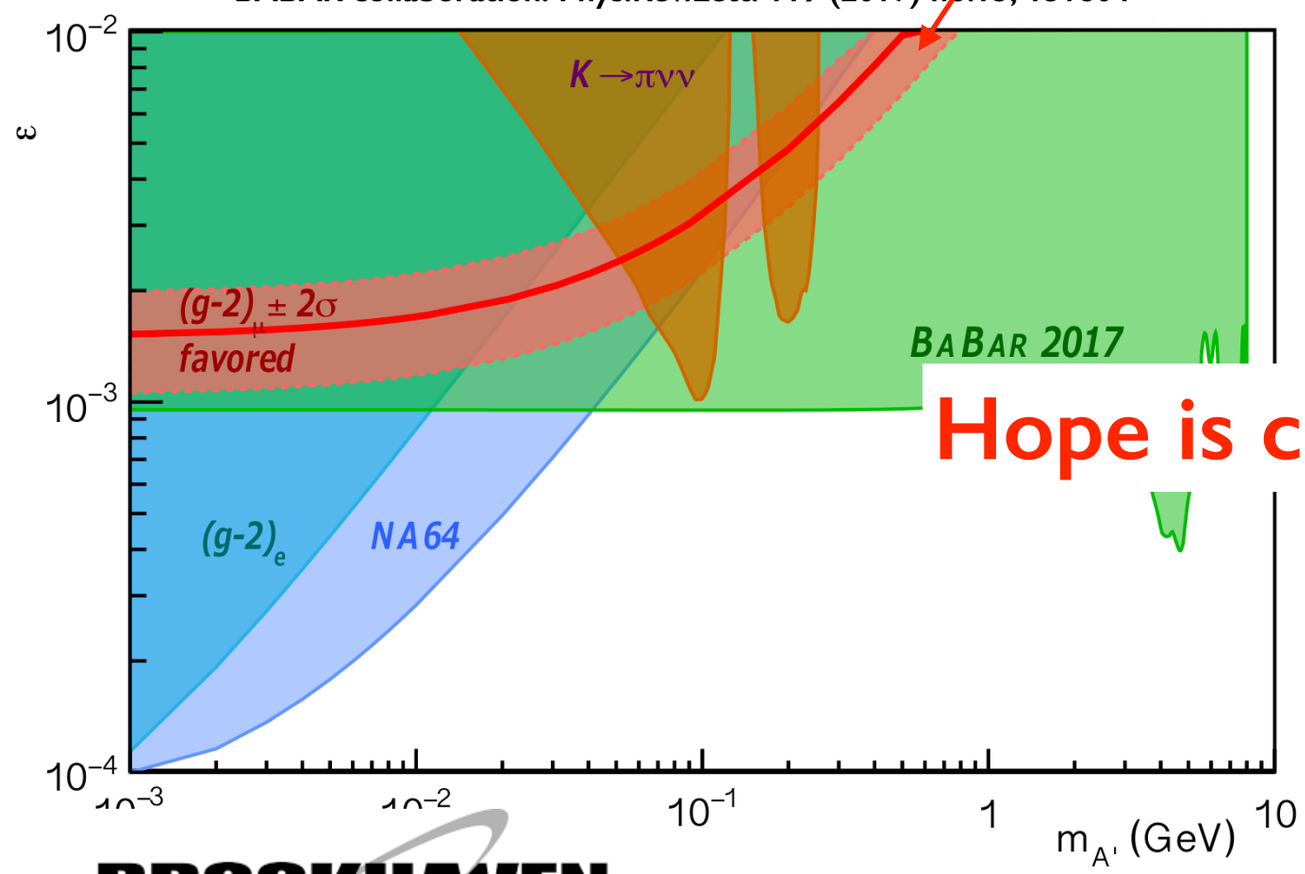


$\bar{\psi}_D i\gamma_\mu D^\mu \psi_D$

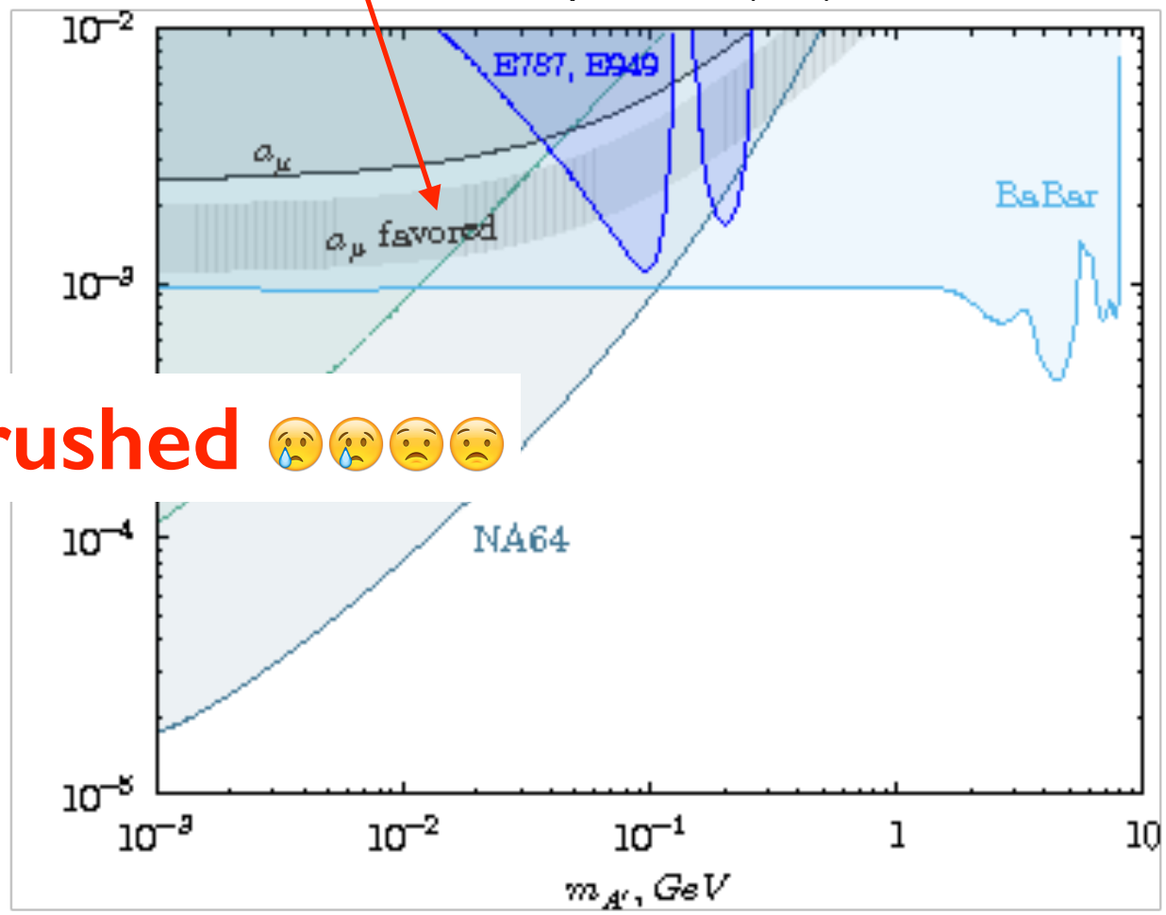
Look for coupling to sector

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



Hope is crushed 😢😢😟😟

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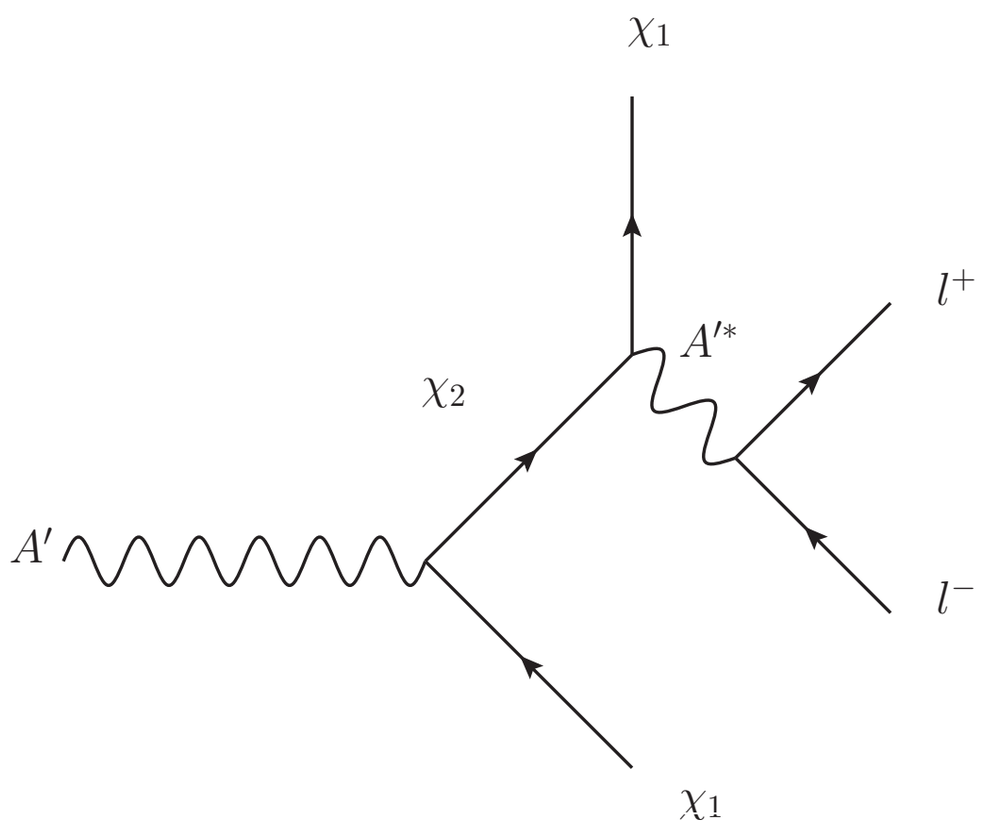
Pseudo-Dirac Dark Fermions χ_1 & χ_2

with coupling $\mathcal{L} \supset g_D A'_\mu \bar{\chi_2} \gamma^\mu \chi_1 + h.c$

With mass splitting $\Delta \equiv m_2 - m_1$

Semi-visible Decay



Heavier state decay into lighter state & SM states

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

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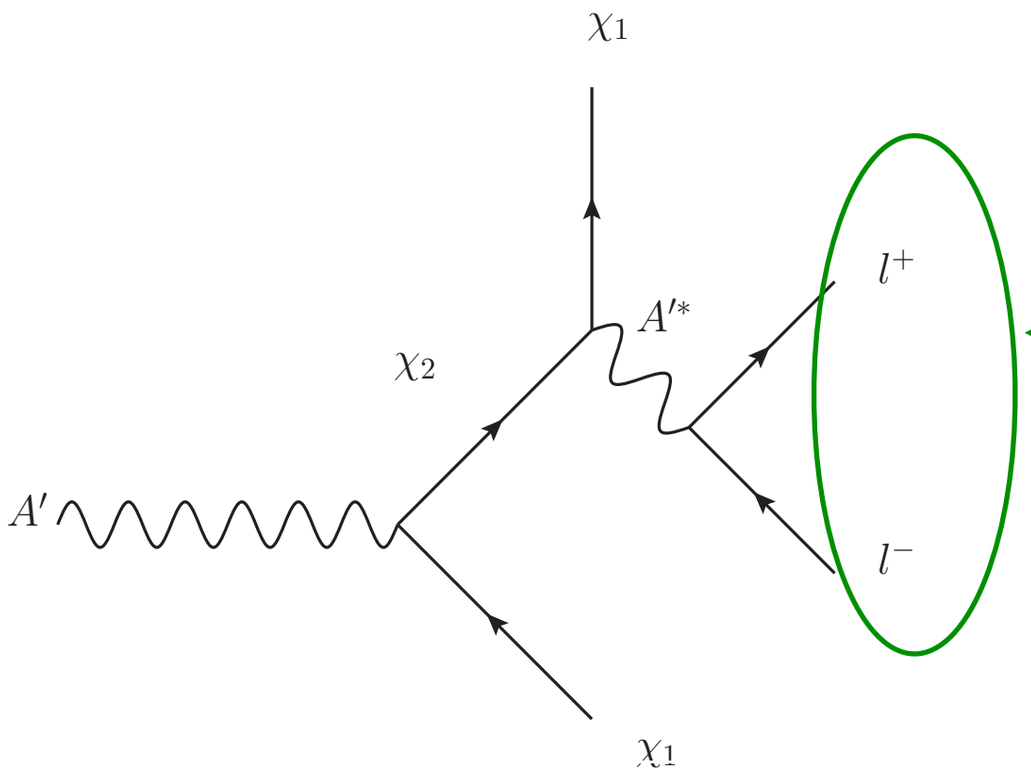
New Signal with
semi-visible decay

If χ_2 decays inside detector => soft displaced leptons



We can look for
these Displaced tracks
with BABAR DATA

Its possible BABAR could have Vetoed
these in their invisible decay search

Belle II: With dedicated Mono-Photon Trigger, Search for Invisible
& Semi-Visible events

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Where can we search for this NP?

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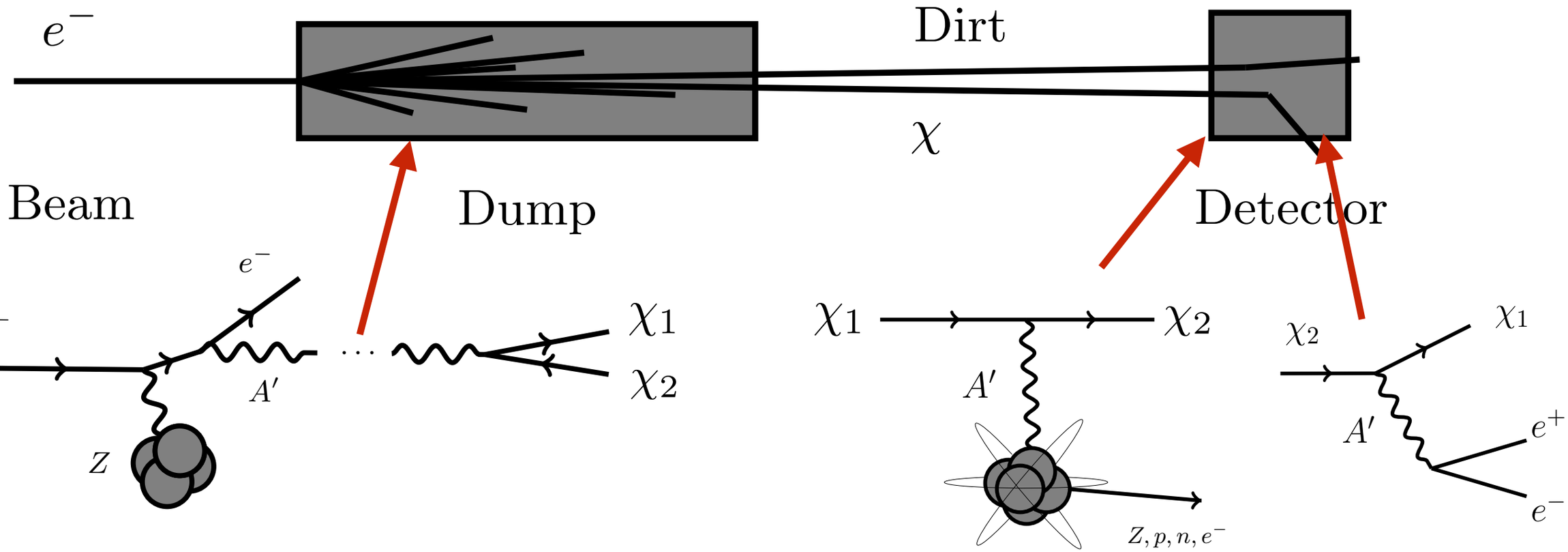
Signatures @ Electron Beam Dumps

(quasi) elastic scattering & decays



A' production modes

- Dark Bremstrahlung

E137 (SLAC 1988)

E ~ 20 GeV, 1e20 EOT

~ 400 m baseline, no BG

BDX (JLab 2020?)

E ~ 11 GeV, 1e22 EOT

~ 20 m baseline, few BG evts.

E137 Recast : Batell, Essig, Zurjuron 1406.2698

BDX: Izaguirre, Krnjaic, Schuster, Toro 1307.6554

BDX Collaboration 1607.01390

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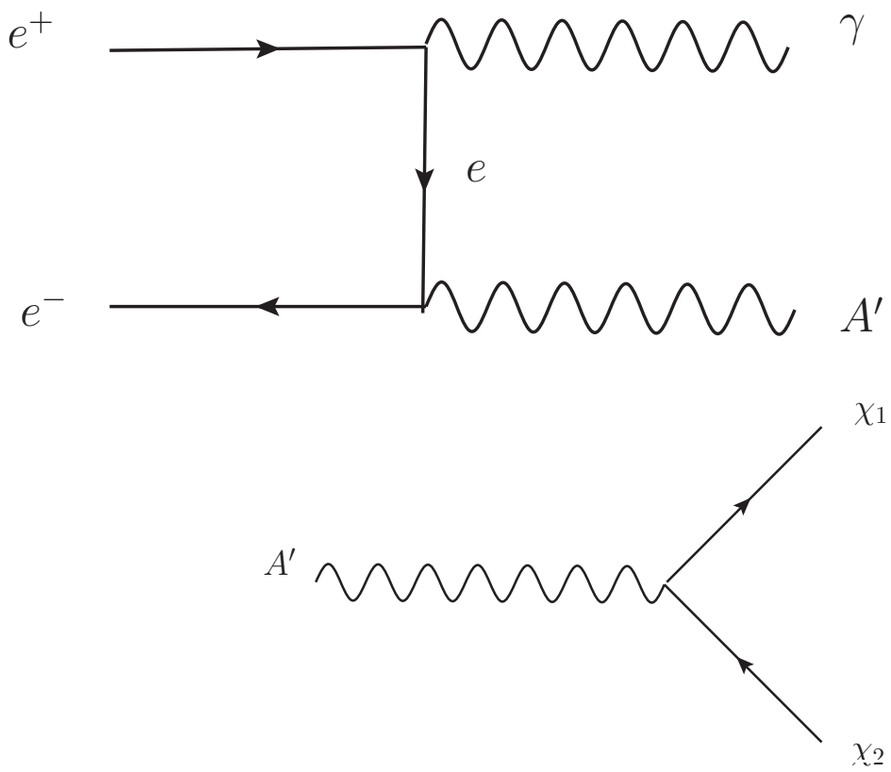
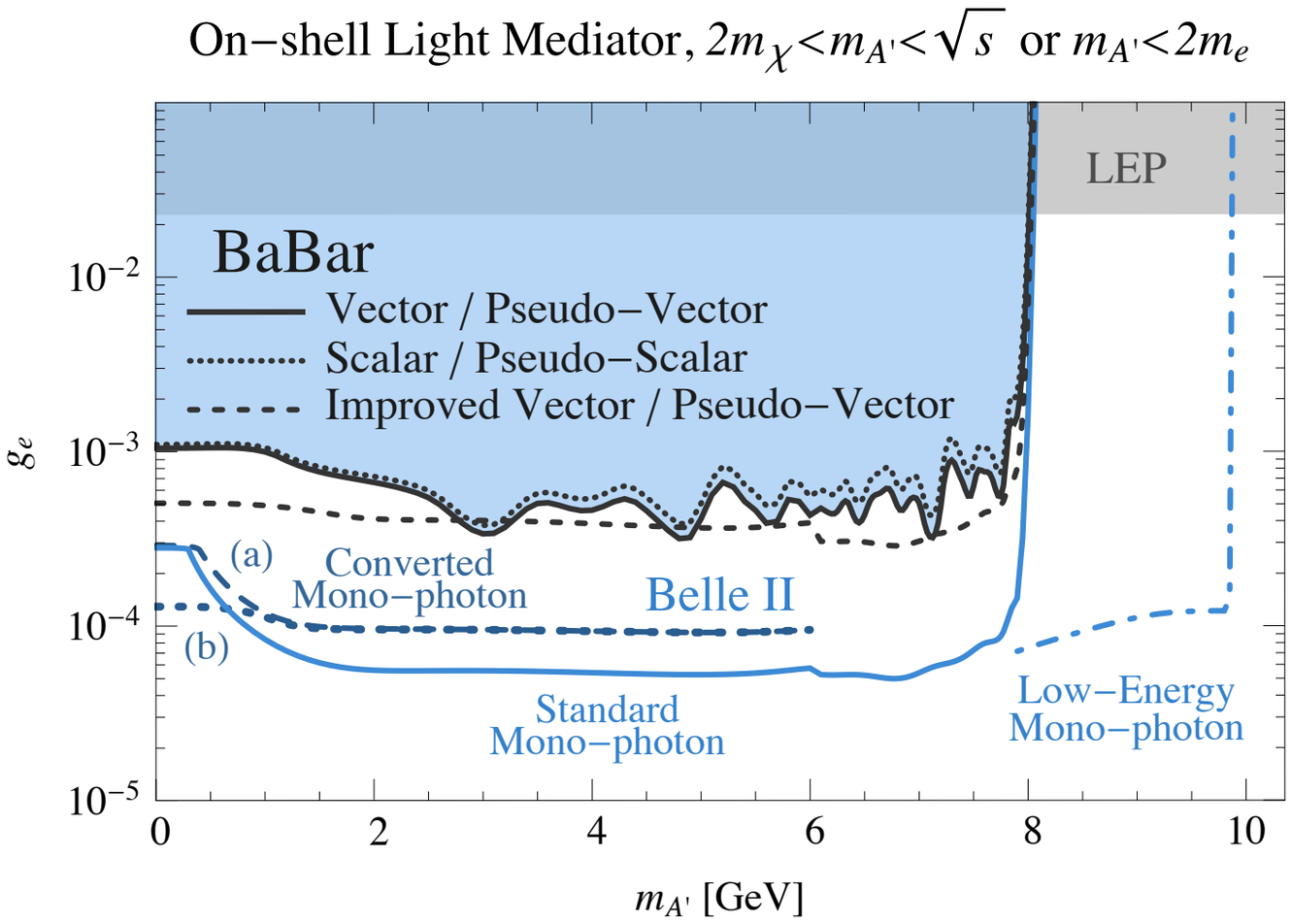
Signatures @ B-Factories

mono photon + missing energy



Signatures from displaced vertices and/or missing energy



Essig, Mardon, Papucci, Volansky Zhong 1309.5084

BABAR

E~ 10.5 GeV

L~ 53 fb^-1

BELLE II

E~ 11 GeV

L~ 50 ab^-1 by 2025

Izaguirre, Krnjaic, Schuster, Toro 1307.6554

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Results

For what splitting can we still explain g-2

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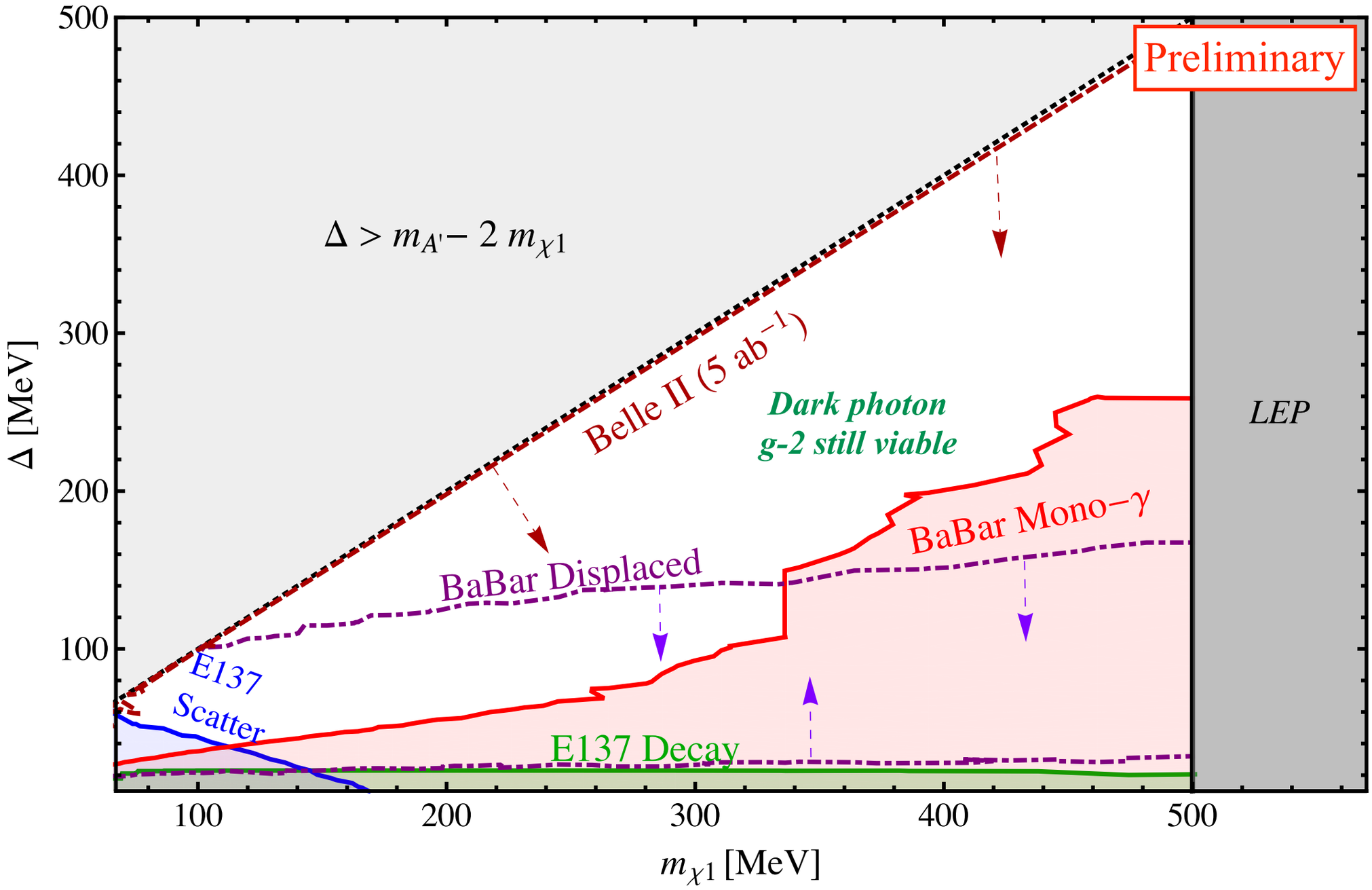
$m_{A'} = 3\, m_{\chi 1}, \epsilon_{g-2}\ , \alpha_D = 0.1$

Izaguirre, Krnjaic & **G.M** (arXiv:1808.XXXX)



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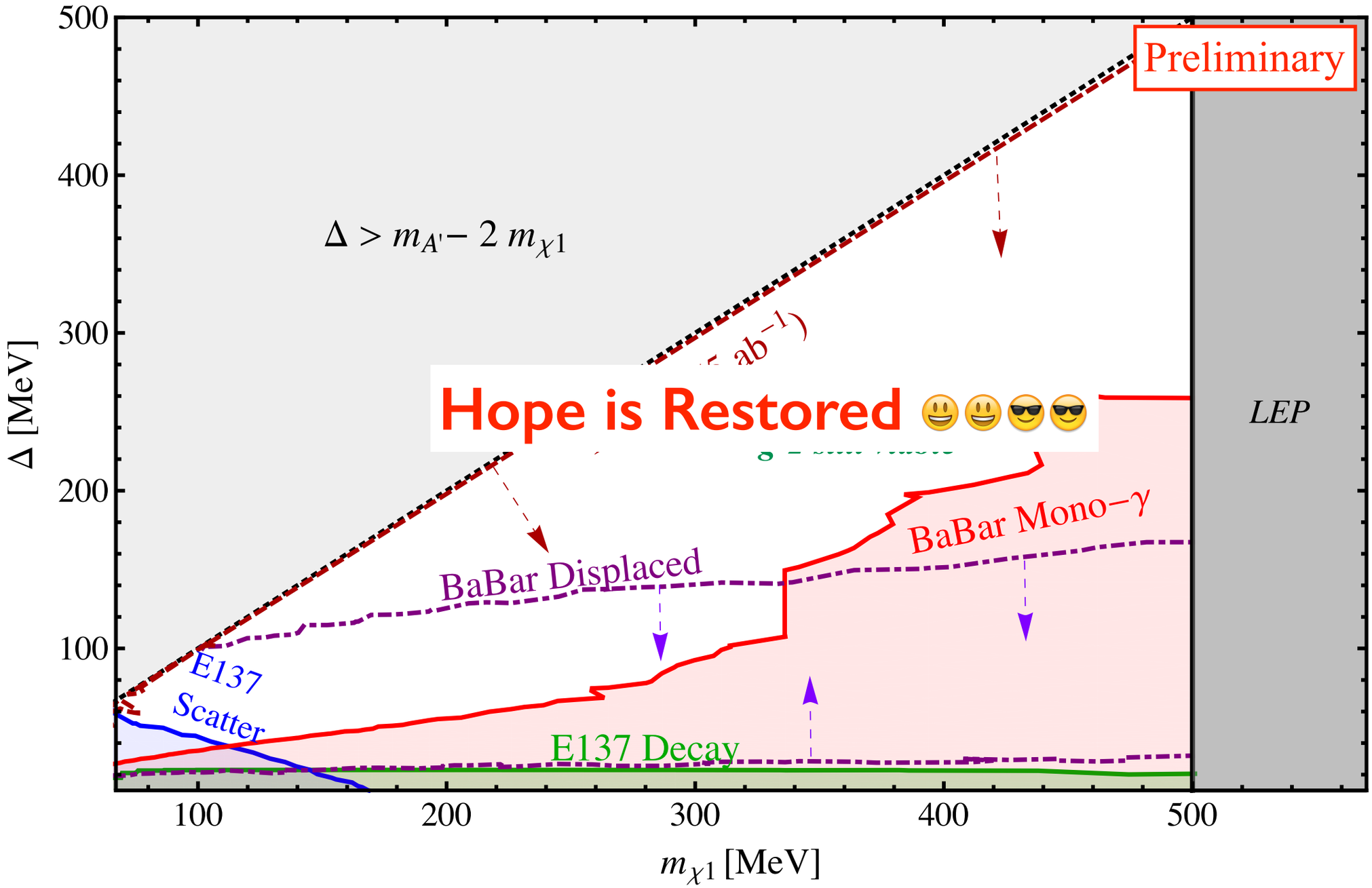

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Conclusions

- Is the Dark Photon Contribution to muon g-2 completely dead, dead?

Most Certainly **NOT**

- Semi-Visible decay channel opens up narrow parameter space in which to search for Signal

- BABAR & Belle II should search for this signal

Why am I so excited about this?

If nothing is found, we would kill the dark photon contribution to g-2 dead dead.

Definite Progress

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Thanks for your Attention

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Back up Slides

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In fact: anomalous magnetic moment of the electron is one of the most precisely calculated and measured quantities in nature.

Theory: Calculated up to 10th order in QED

$$a_e^{SM} = 1.159652182032(13) \times 10^{-3}$$

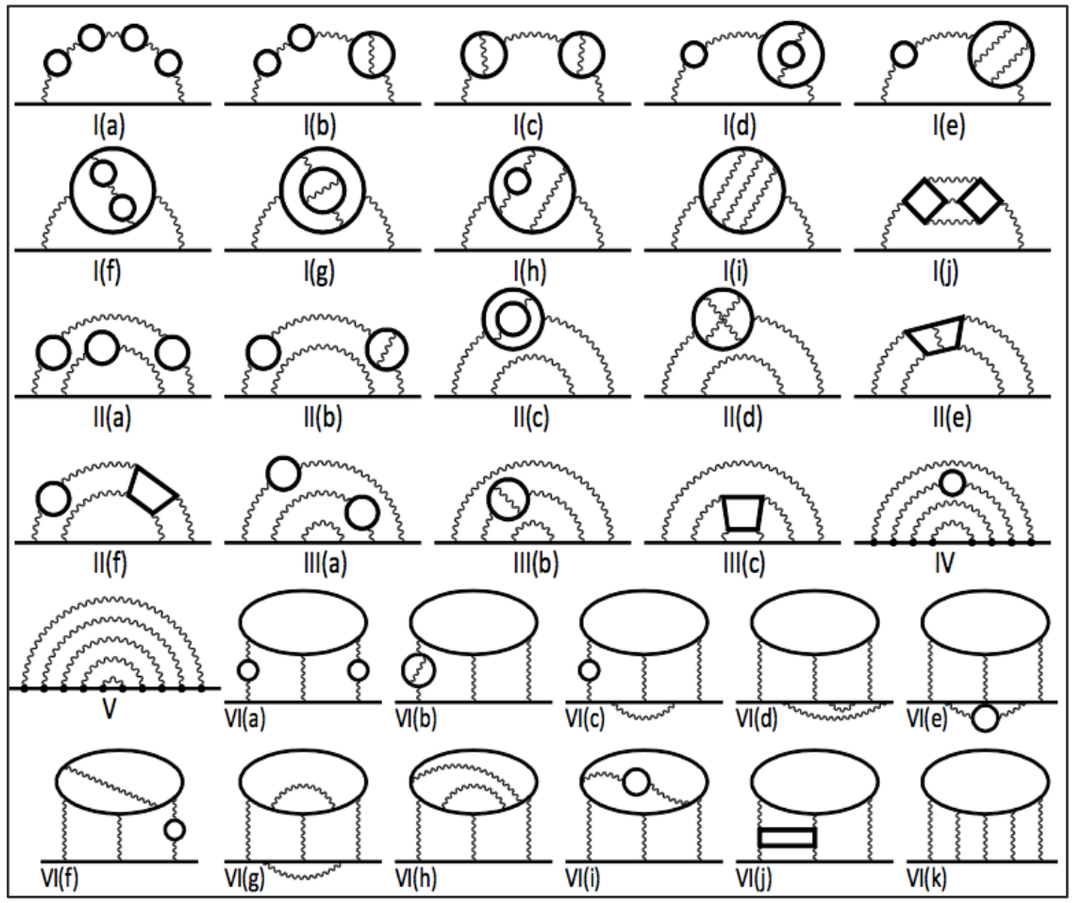
Experiment: Measured with very high precision at Harvard using cylindrical Penning trap

$$a_e^{exp} = 1.15965218073(28) \times 10^{-3}$$

measured to (0.24 ppb)

Hanneke, Fogwell, Gabrielse, PRL 100 (2008) 120801

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



$$\Delta a_e \equiv a_e^{exp} - a_e^{SM}$$

$$= -1.3 \pm 0.77 \times 10^{-12}$$

Aoyama et al, Phys.Rev. D97 (2018) no.3, 036001

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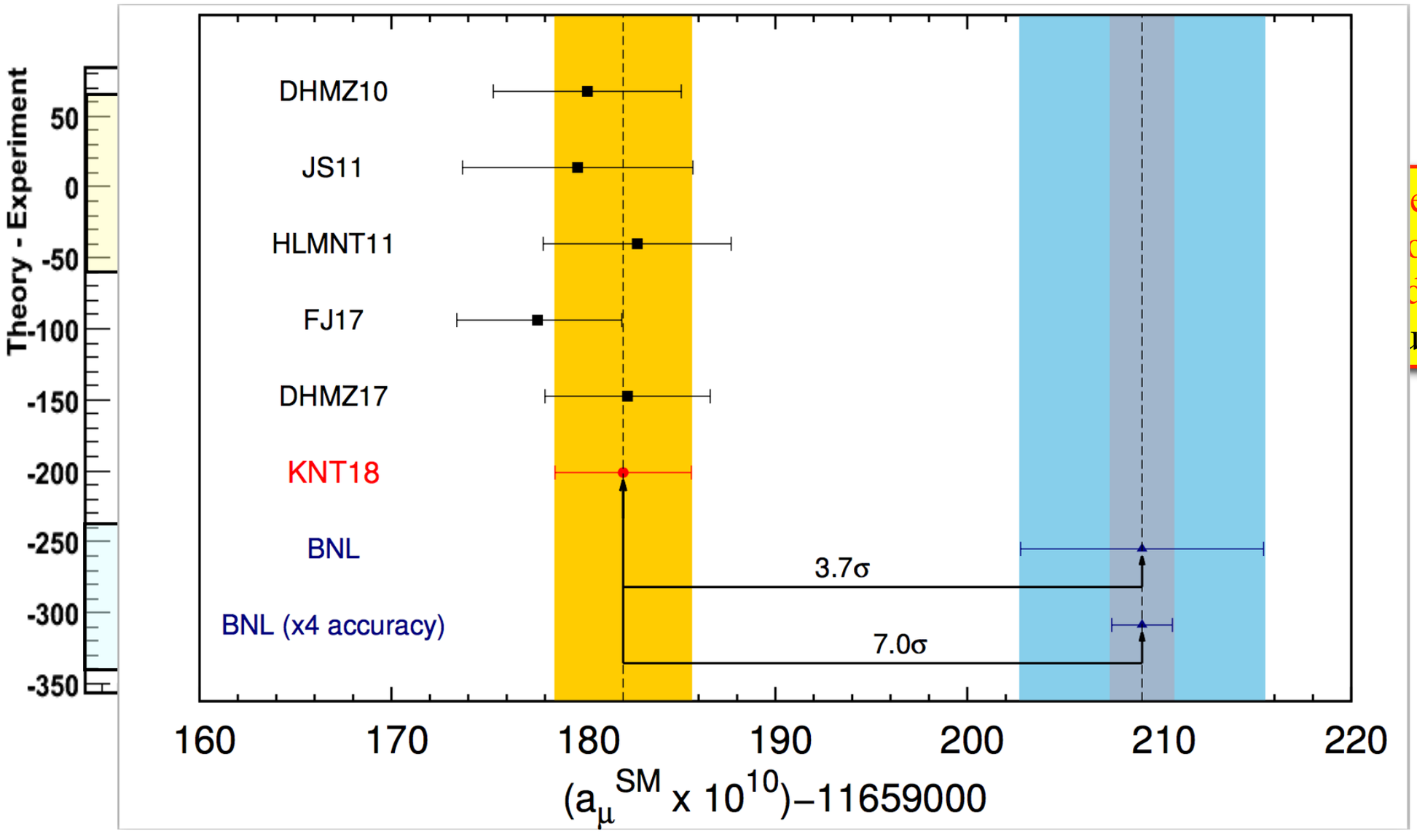
What does it all mean?

3.6σ simply not enough to celebrate New Physics



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

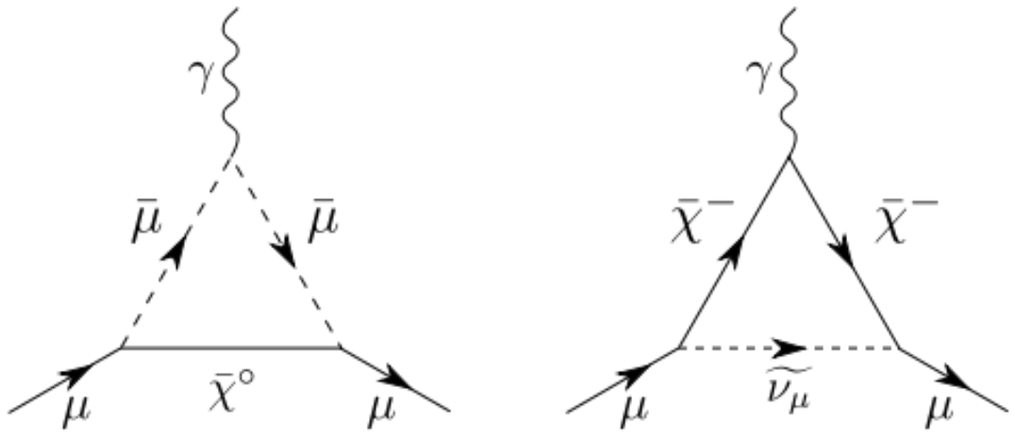
Transport of the muon g-2 storage ring

If New Physics Shows up this way, what could it be?

Many viable scenarios have been considered
Including:

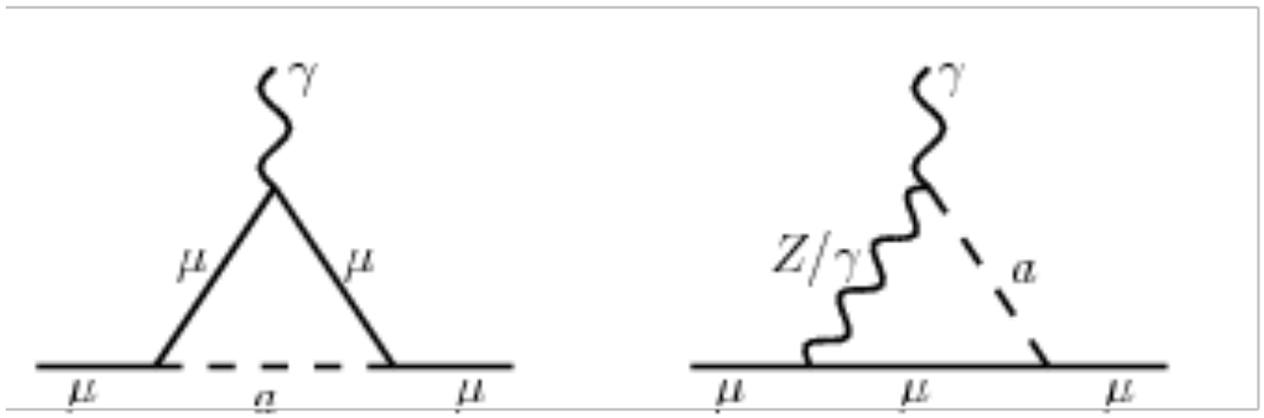
- Supersymmetry:

Czarnecki & Marciano, Phys.Rev. D64 (2001) 013014



- Axion like particle:

Bauer, Neubert & Thamm, Phys.Rev.Lett. 119 (2017) no.3, 031802



And many more…

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Turns out there could still be more hope

Look to the dark sector for help

Consider Dirac Spinor: $\psi_D = \begin{pmatrix} \eta & \xi^\dagger \end{pmatrix}$ s.t. $\bar{\psi}_D \gamma^\mu \psi_D = \eta^\dagger \bar{\sigma}^\mu \eta - \xi^\dagger \bar{\sigma}^\mu \xi$

In limit where Majorana masses smaller than Dirac mass ⟶ Off-Diagonal couplings

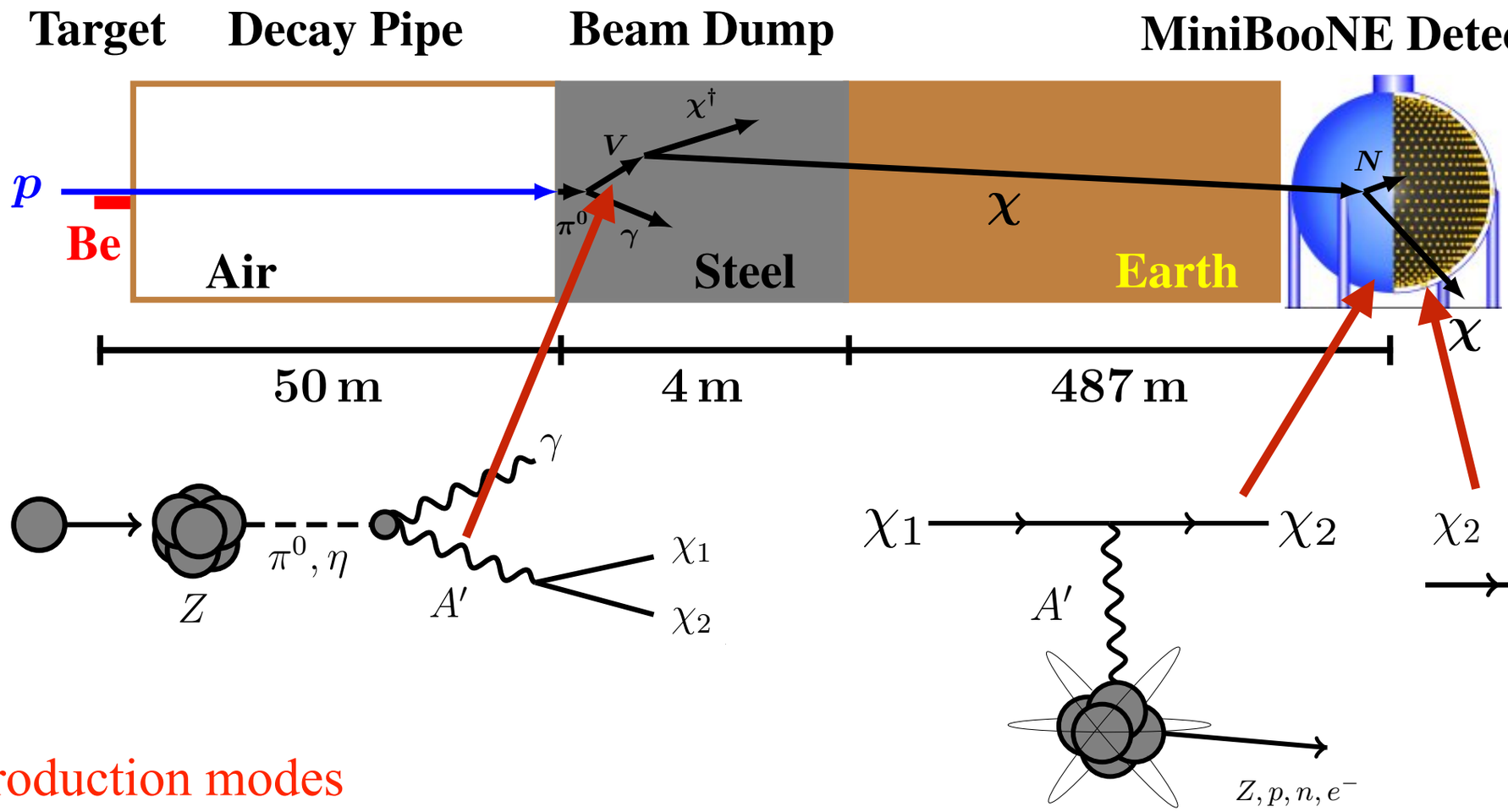
i.e. $\bar{\psi}_D \gamma^\mu \psi_D = \chi_1^\dagger \bar{\sigma}^\mu \chi_2 - \chi_2^\dagger \bar{\sigma}^\mu \chi_1$

Spectrum is split into mass eigenstates which couple inelastically to dark photon

With mass splitting $\Delta \equiv m_2 - m_1$

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

Elastic DM: Batell, Pospelov, Ritz 0903.0363

BdNMC deNiverville, Chen, Pospelov, Ritz 1609.01770

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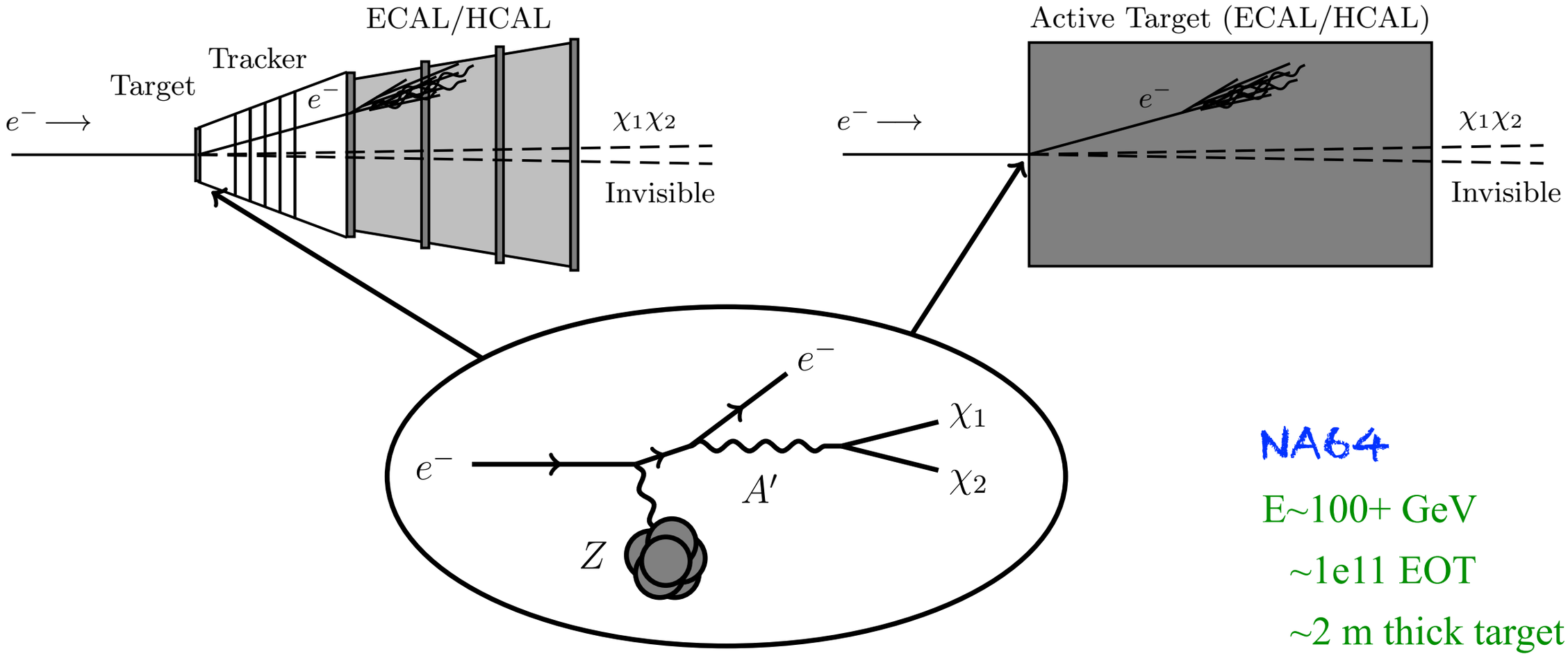
Signatures @ Missing Momentum Experiments



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

NA64

E~100+ GeV

~1e11 EOT

~2 m thick target

LDMX

E~ 8 GeV

~3e16 EOT

~0.1 rad. length

thin target

NA64 Collaboration 1610.02988

Izaguirre, Krnjaic, Schuster, Toro 1307.6554

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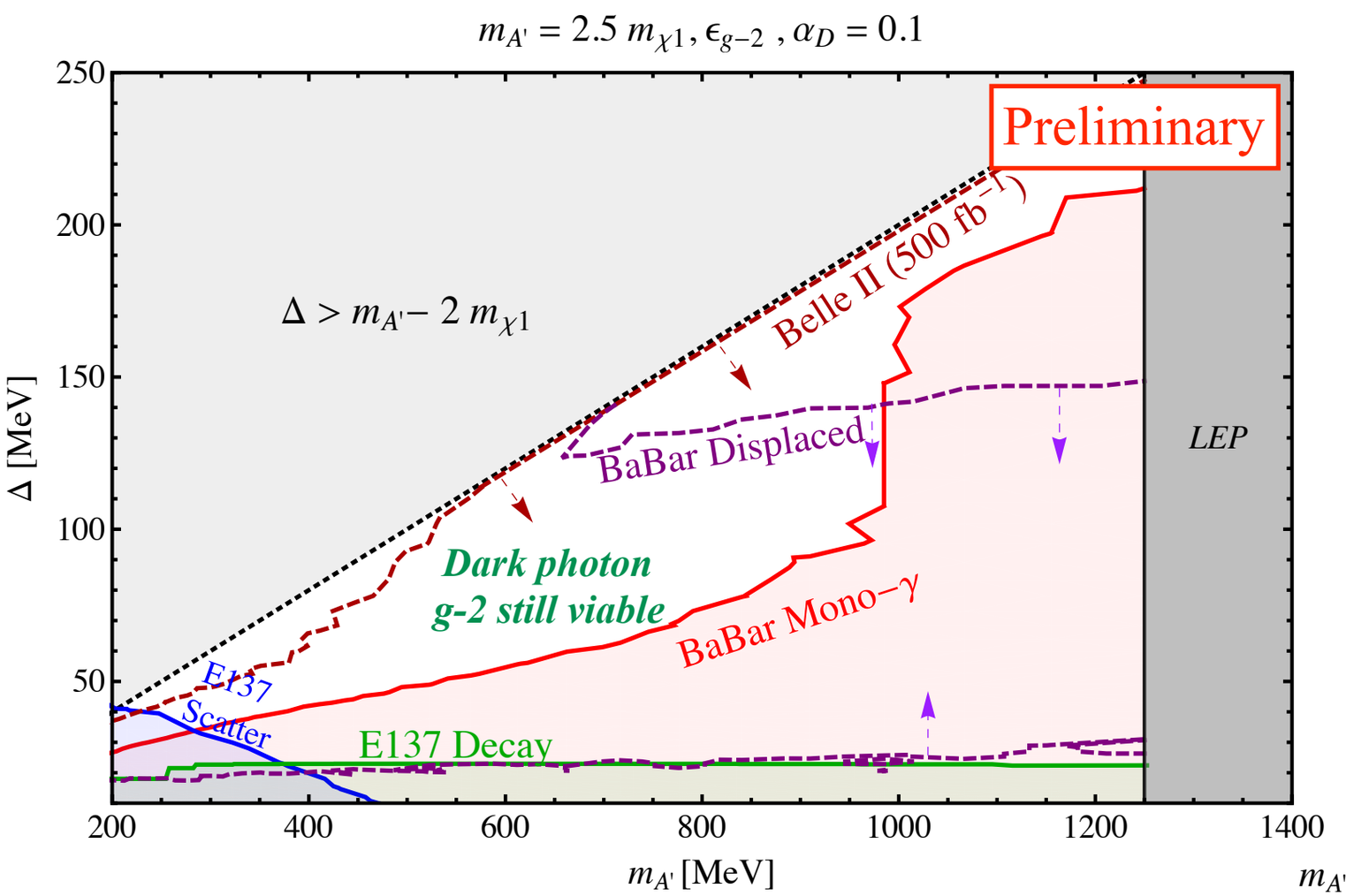

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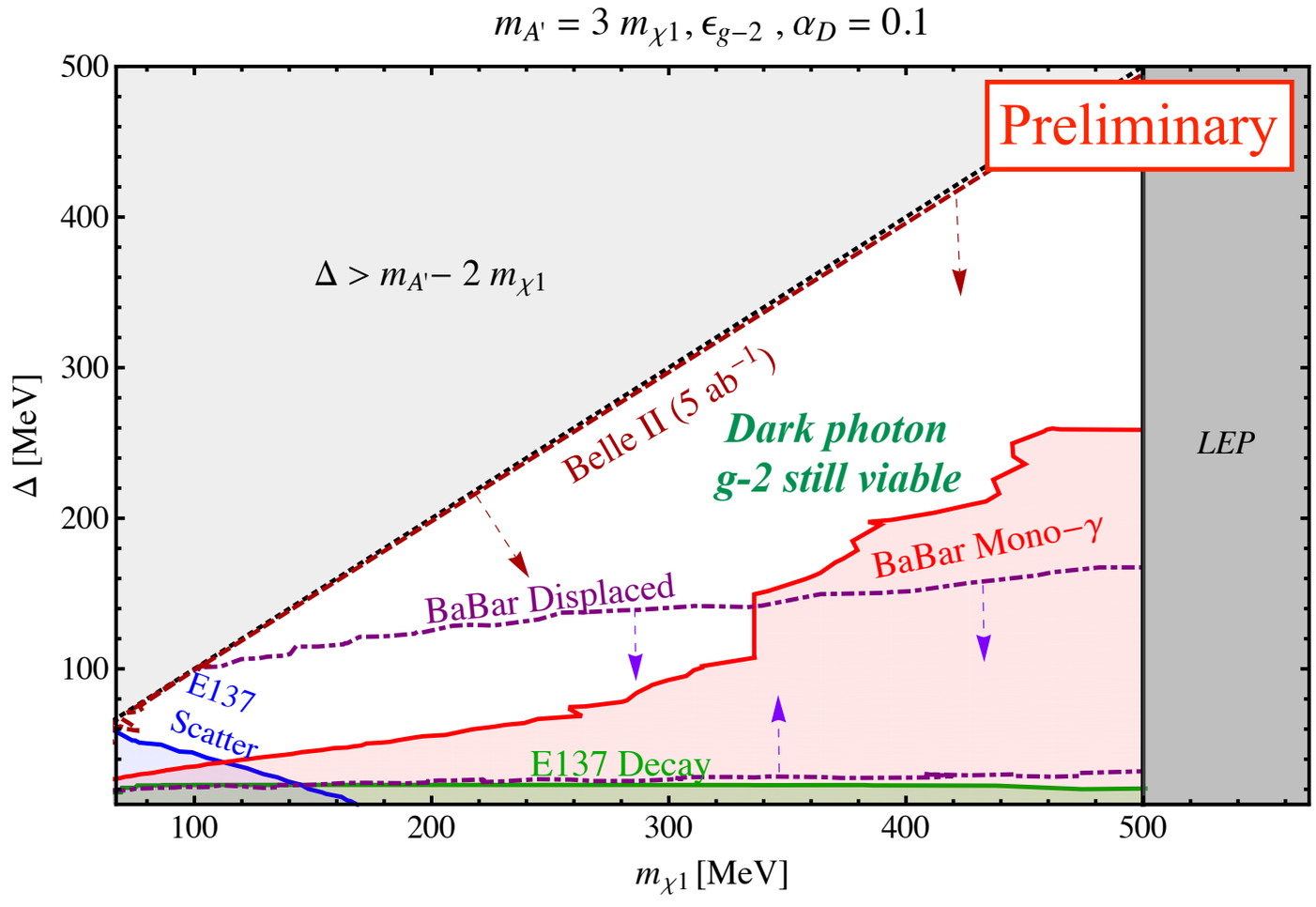

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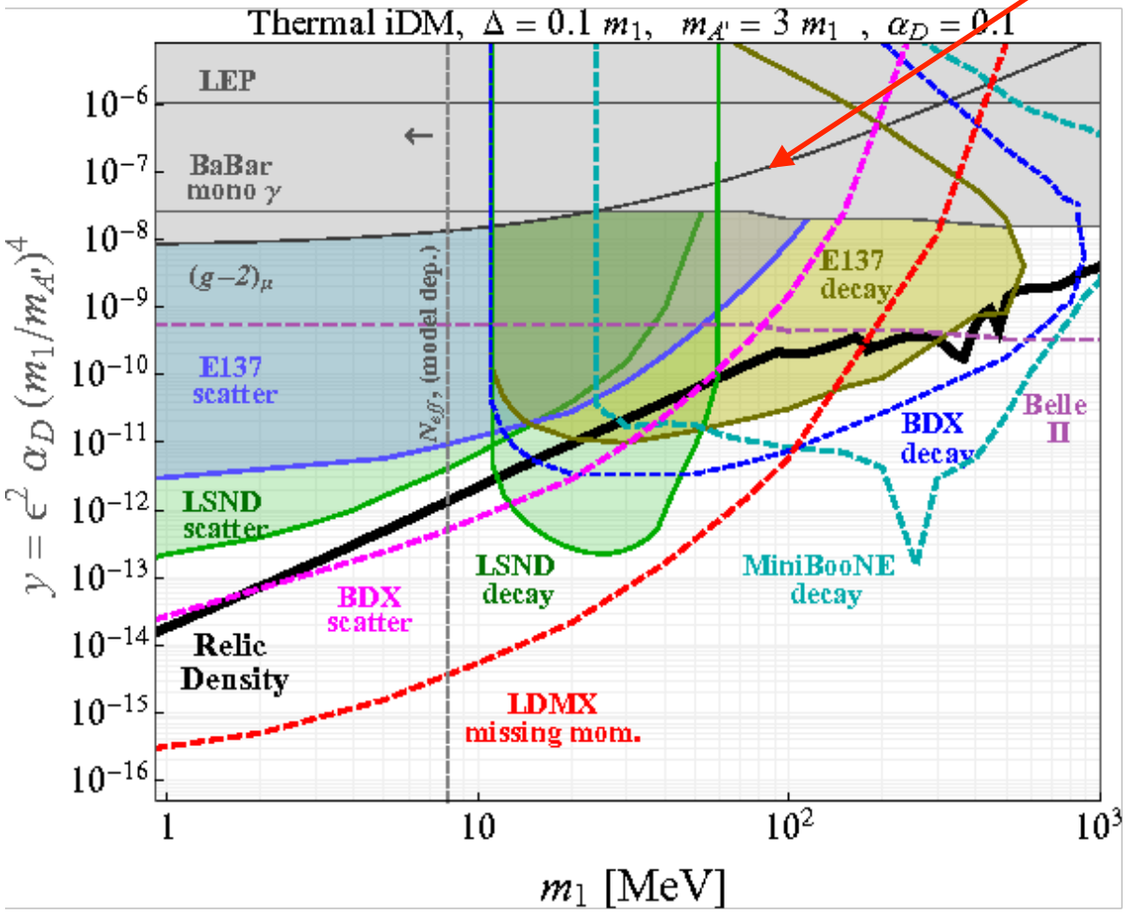
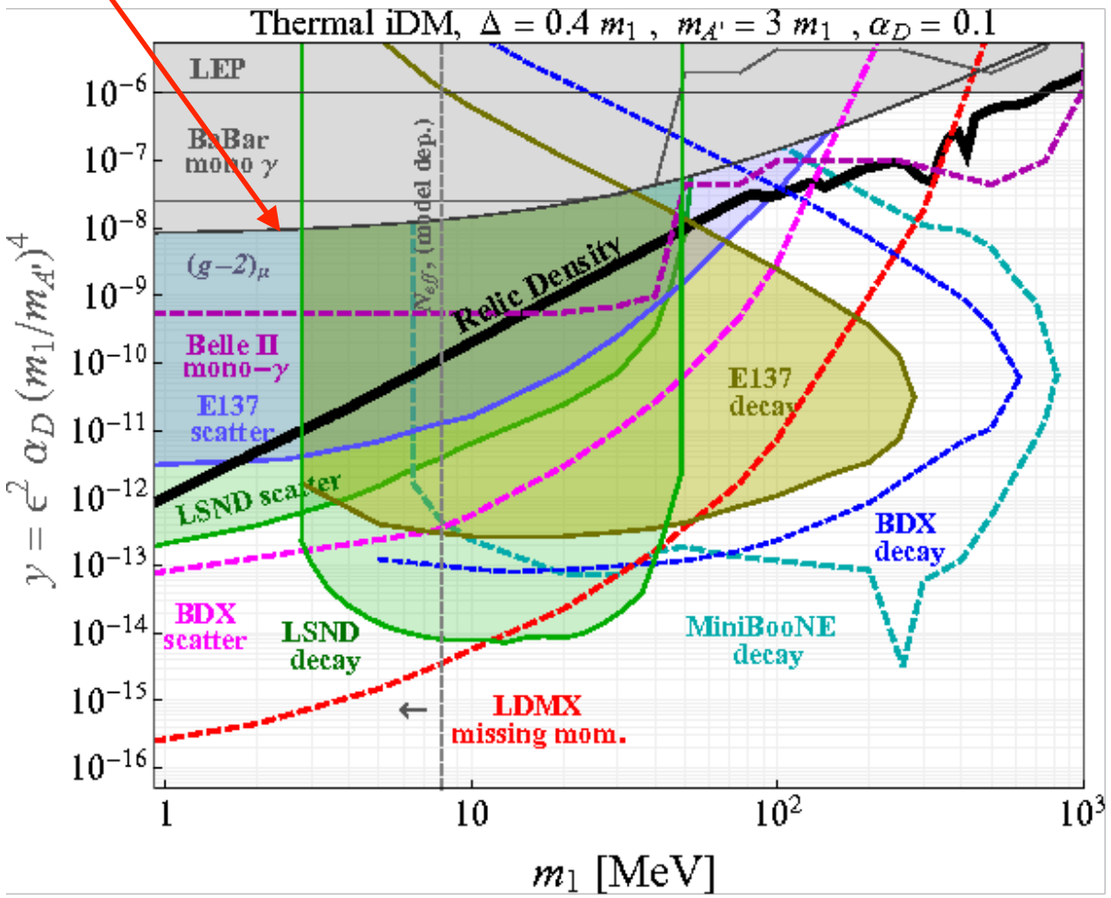
Muon g-2 line





Izaguirre, Kahn, Krnjaic & Moschella: Phys.Rev. D96 (2017) no.5, 055007

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