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Exploring New Physics Explanations For Proton Size Anomaly

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LAMB SHIFT

- Prediction of Lamb shift (2P-2S transition) is one of the first triumphs of QED, along with the g–2 factor.
- Lamb shift is due to 1-loop quantum effects.
- Two dominant, pulling contributions are: vacuum polarization and vertex correction.

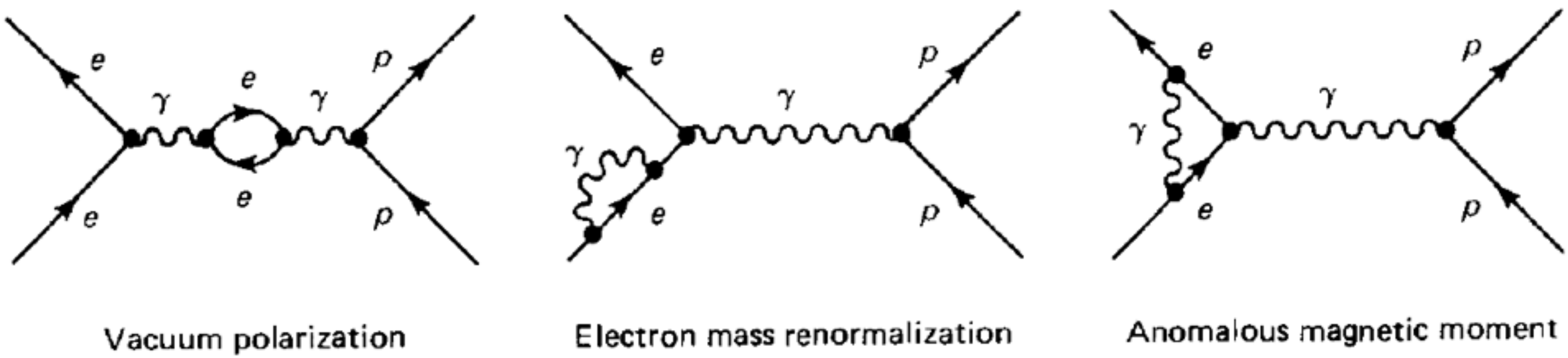
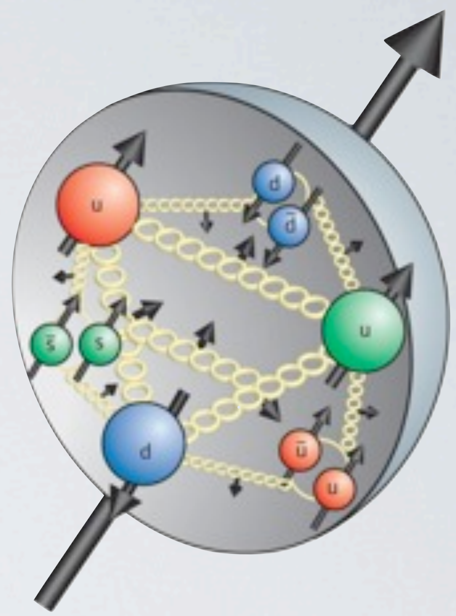


Figure 5.3 Some loop diagrams contributing to the Lamb shift.

Charge Radius of Proton

- Proton as a composite particle has an electric charge distribution over its volume, thus the concept of the charge radius (in fm)



$$r_p \equiv \sqrt{\langle \mathbf{r}_p^2 \rangle}$$

- Finite size effect (a simple one)

$$\delta E_{\mathrm{FS}} = \int d^3 r \delta V_{\mathrm{FS}}(\mathbf{r}) \phi^2(\mathbf{r}) \simeq \phi^2(0) \int d^3 r \delta V_{\mathrm{FS}}(\mathbf{r}) \underbrace{\frac{1}{6} \nabla^2 r^2}_{1}$$

$$= \frac{\phi^2(0)}{6} \int d^3 r \nabla^2 [\delta V_{\mathrm{FS}}(\mathbf{r})] r^2 = \frac{\phi^2(0)}{6} \int d^3 r 4\pi\alpha\rho(\mathbf{r}) r^2$$

$$= \frac{2\pi\alpha}{3} \phi^2(0) \int d^3 r r^2 \rho(\mathbf{r}) = \frac{2\pi\alpha}{3} \phi^2(0) \langle \mathbf{r}_p^2 \rangle$$

Proton Size From e-p System

- Regular hydrogen spectroscopy (Lamb shift) gives

$$r_p = 0.8768 \pm 0.0069 \text{ fm}$$

CODATA 2008

- Unpolarized e-p scattering gives

$$r_p = 0.879 \pm 0.008 \text{ fm}$$

Mainz 2010

- Polarized e-p scattering gives

$$r_p = 0.875 \pm 0.010 \text{ fm}$$

JLab 2008

- All are consistent with one another, triumph of QED!

LAMB SHIFT IN μ-H

- Lamb shift (between $2S_{1/2}^{F=1}$ and $2P_{3/2}^{F=2}$) in the muonic atom is more sensitive to the charge radius (~200 times smaller atom)

$$\Delta\tilde{E} = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \text{ meV}$$

terms from finite-size effect

- Expected Lamb shift

$$\Delta\tilde{E} = 205.984 \pm 0.063 \text{ meV}$$

prediction error dominates

- PSI measurement

$$\Delta\tilde{E}_{\text{exp}} = 206.2949 \pm 0.0032 \text{ meV}$$

Pohl et al, 2010

$$\delta(\Delta\tilde{E}) = 0.311 \pm 0.063 \text{ meV}$$

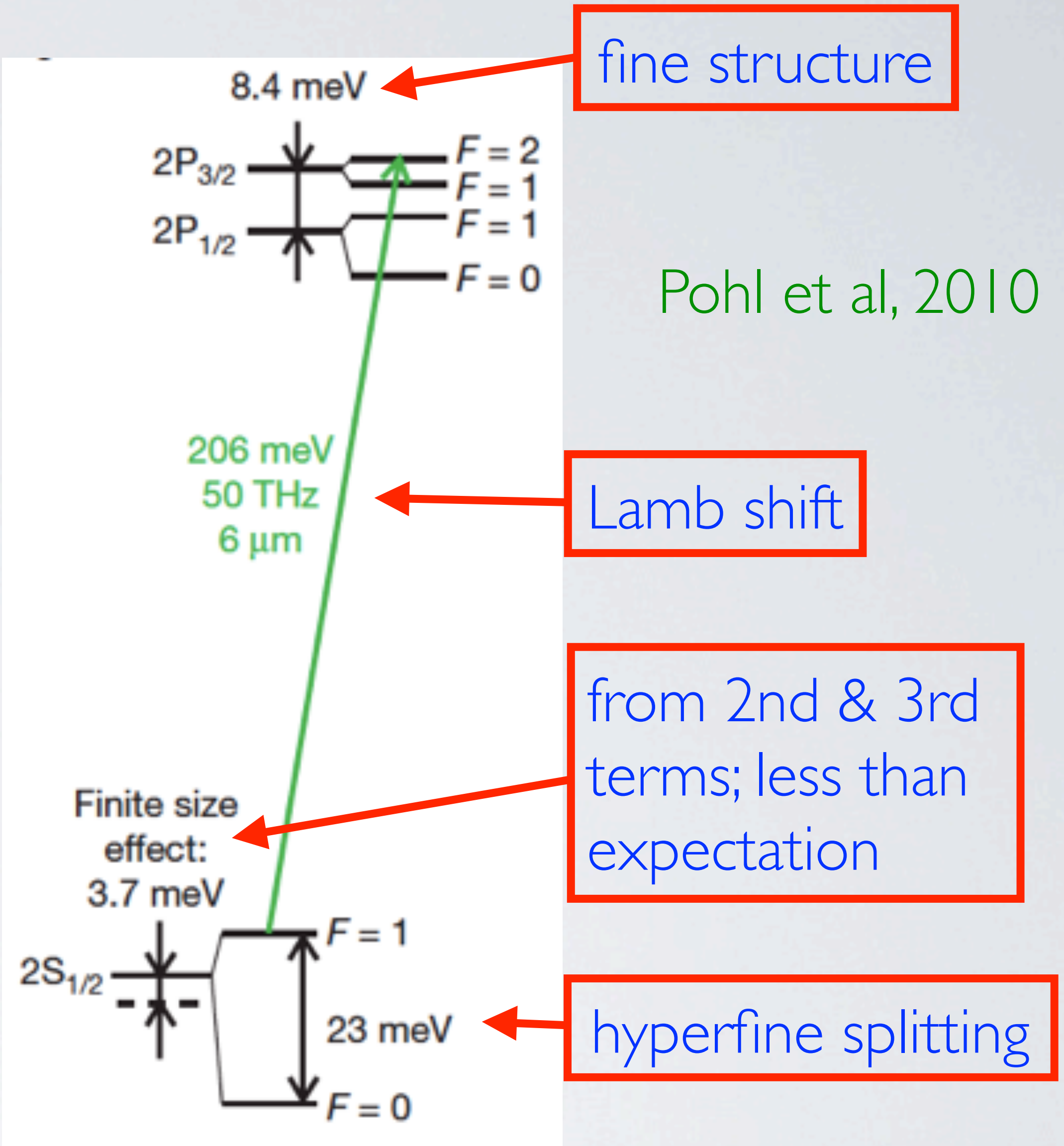
$$r_p = 0.84184 \pm 0.00067 \text{ fm}$$

more precise than H by one order

- 5σ deviation!

NEW PHYSICS POSSIBILITY

- Lessons learned:
  - Energy gap between $2S_{1/2}^{F=1}$ and $2P_{3/2}^{F=2}$ larger than expected
  - All known SM effects considered and multiple-checked, still too small to account for difference Jentschura 2010
- Possibly a new spin-dependent interaction that shifts the hyperfine splittings, faking Lamb shift
  ➠ can be checked by measuring HFS in the μH system
- Possibly an additional spin-independent, attractive force that lowers 2S state relative to 2P state



See Paz's and McKeen's talks for SM/NP explanations

MUON ALWAYS IN TROUBLE?

- Who ordered muon?

Lamb Shift in μH — Pohl et al, 2010

$(g-2)_\mu$ — BNL 2004

Anomalous $\Sigma^+ \to p\mu^+\mu^-$ events — HyperCP 2005

FBA of differential $B \to K^*\mu^+\mu^-$ — BABAR 2008, Belle 2009, CDF 2011

Dimuon asymmetry in semileptonic b-hadron decays — D0 2010

New Physics Assumptions

- New attractive muon-nucleon interaction
- Mediated by spin-0, -1, or -2 boson
- Coupling only to muon among leptons
- Applicability of perturbation
- Spin-independent
- Flavor-conserving
- Isospin-conserving

New Potential

- Potential and energy shift

$$\Delta V(r) = -\alpha_\chi \frac{e^{-m_\chi r}}{r} \;, \quad \text{with } \alpha_\chi = \frac{C_\mu^{S,V,T} C_n^{S,V,T}}{4\pi}$$

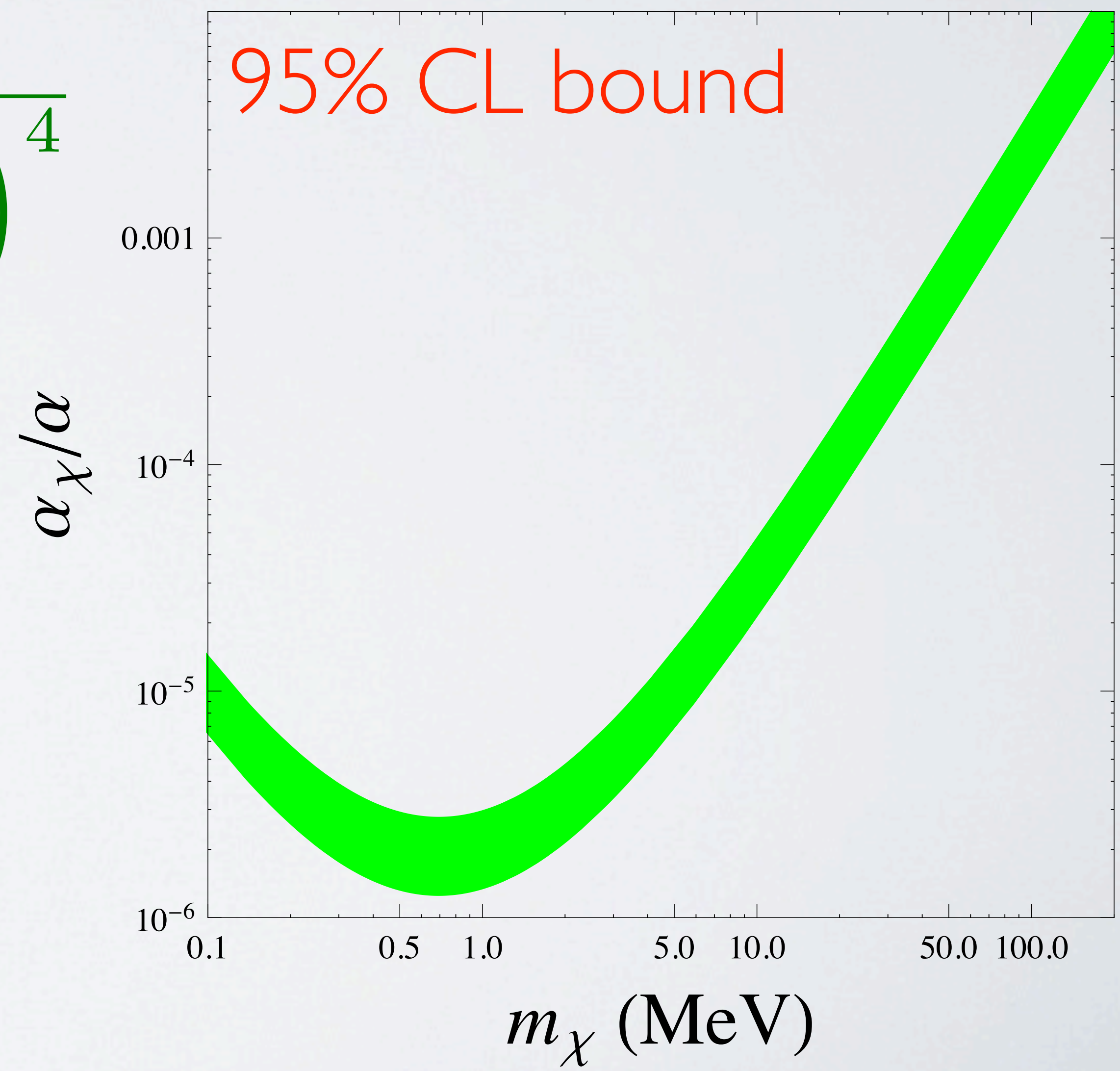
$$\delta(\Delta\tilde{E}) = \alpha_\chi m_\chi \frac{\frac{m_\chi}{\alpha m_r}}{2\left(1 + \frac{m_\chi}{\alpha m_r}\right)^4}$$

with minimum sitting at the characteristic scale

$$\alpha m_r \simeq 0.7 \text{ MeV}$$

- Perturbativity requires

$$m_\chi < 10 \text{ GeV}$$



X-RAY IN MUONIC ATOMS

- Corrections to muonic $3\mathrm{D}_{5/2} - 2\mathrm{P}_{3/2}$ transition in ^{24}Mg and ^{28}Si atoms due to new interaction induced energy shift relative to QED expectation

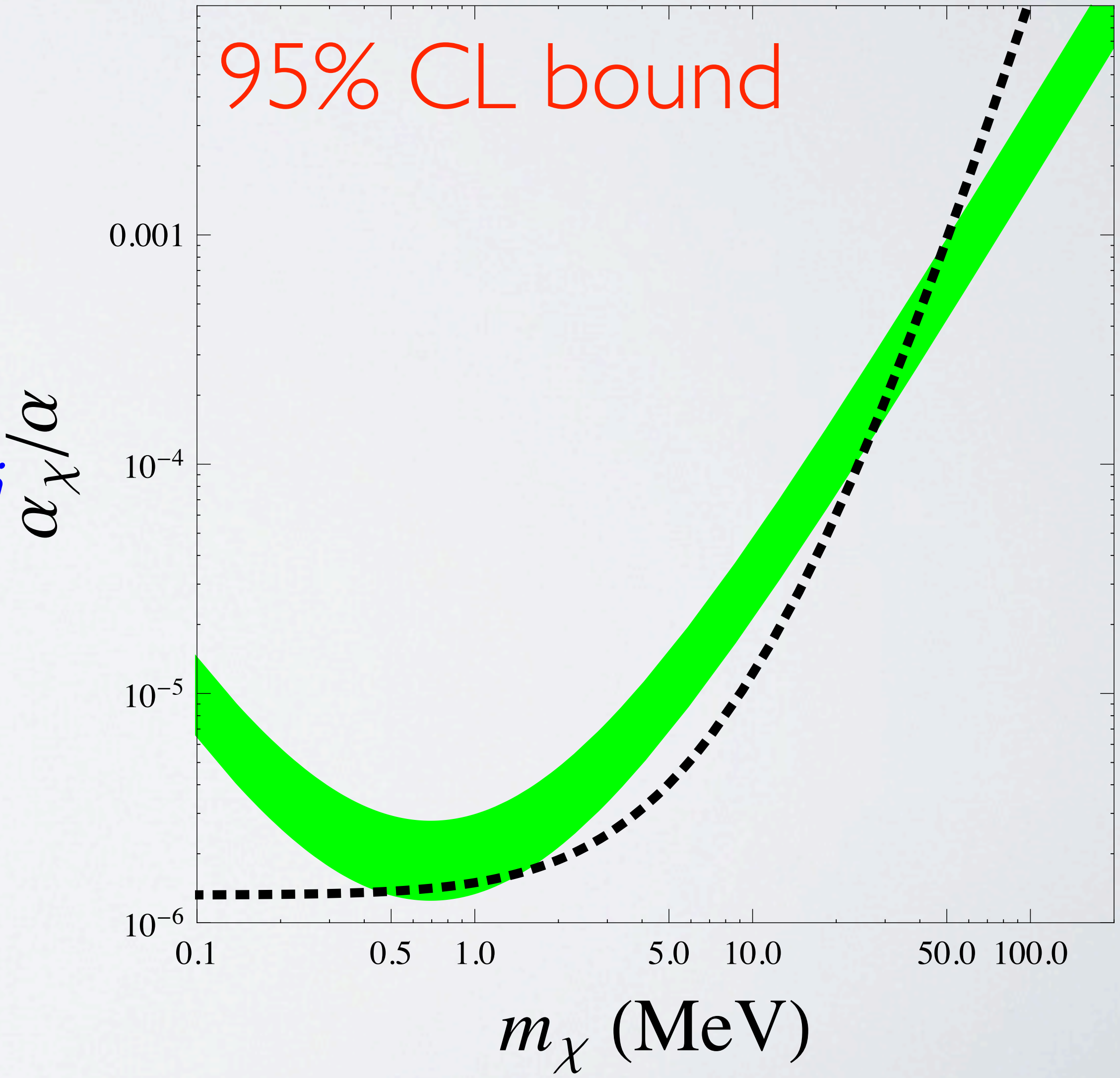
$$\frac{\Delta E}{E} = \frac{2\alpha_\chi A}{5\alpha Z}\,[9f(2) - 4f(3)]$$
$$= (0.2 \pm 3.1)\cdot 10^{-6}\ \ (\mathrm{exp})$$

Beltrami et al 1986

with

$$f(j) = [1 + j m_\chi/(2\alpha Z m_\mu)]^{-2j}$$

- Two possible mass ranges:
  ~ 0.5–1 MeV and > 30 MeV.



Neutron-Lead Scattering

- Precise n-^{208}Pb scattering experiments in keV regime performed to study electric polarizability of neutron.
- Goal: to measure interference between nuclear potential and r^{-4} potential induced by electric polarizability.
- Also probe following potential (–: scalar/tensor, +: vector):

$$\mp A \, (C_n^{S,V,T})^2 \, \frac{e^{-m_\chi r}}{4\pi r}$$

- Measure diff. cross section in partial wave expansion

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{4\pi} \, (1 + \omega E \cos\theta)$$

$$\sqrt{\sigma_0/4\pi} \simeq 10 \text{ fm and } \omega = (1.91 \pm 0.42) \cdot 10^{-3} \text{ keV}^{-1}$$

Aleksandrov and Samosvat 1966

NEUTRON-LEAD SCATTERING

- Strong and new physics contribution $\omega = \omega_s + \Delta\omega$

$$\Delta\omega = \mp \frac{16}{m_\chi^4} \frac{(C_n^{S,V,T})^2}{4\pi} \frac{A\, m_n^2}{\sqrt{\sigma_0/4\pi}}$$

under Born approximation (not valid for $m_\chi \lesssim 0.1$ MeV)

- Possible cancellation between ω_s and $\Delta\omega$ for scalar/tensor to produce experimental result
  ➠ arbitrary coupling allowed
- Not the case for vector

  ➠ conservative 95% CL (one-sided) upper limit obtained by requiring that $\Delta\omega \leq 2.6\times10^{-3}$ keV

NEUTRON-LEAD SCATTERING

- Total cross section measured between 10 eV and 10 keV employed for scalar/tensor:

$$\sigma(k) = \sigma_0 + \sigma_2 k^2 + \mathcal{O}(k^4)$$

$$k \simeq 2.2 \times 10^{-4} \sqrt{E} A/(A+1)$$

with k in fm^{-1} and E in eV.

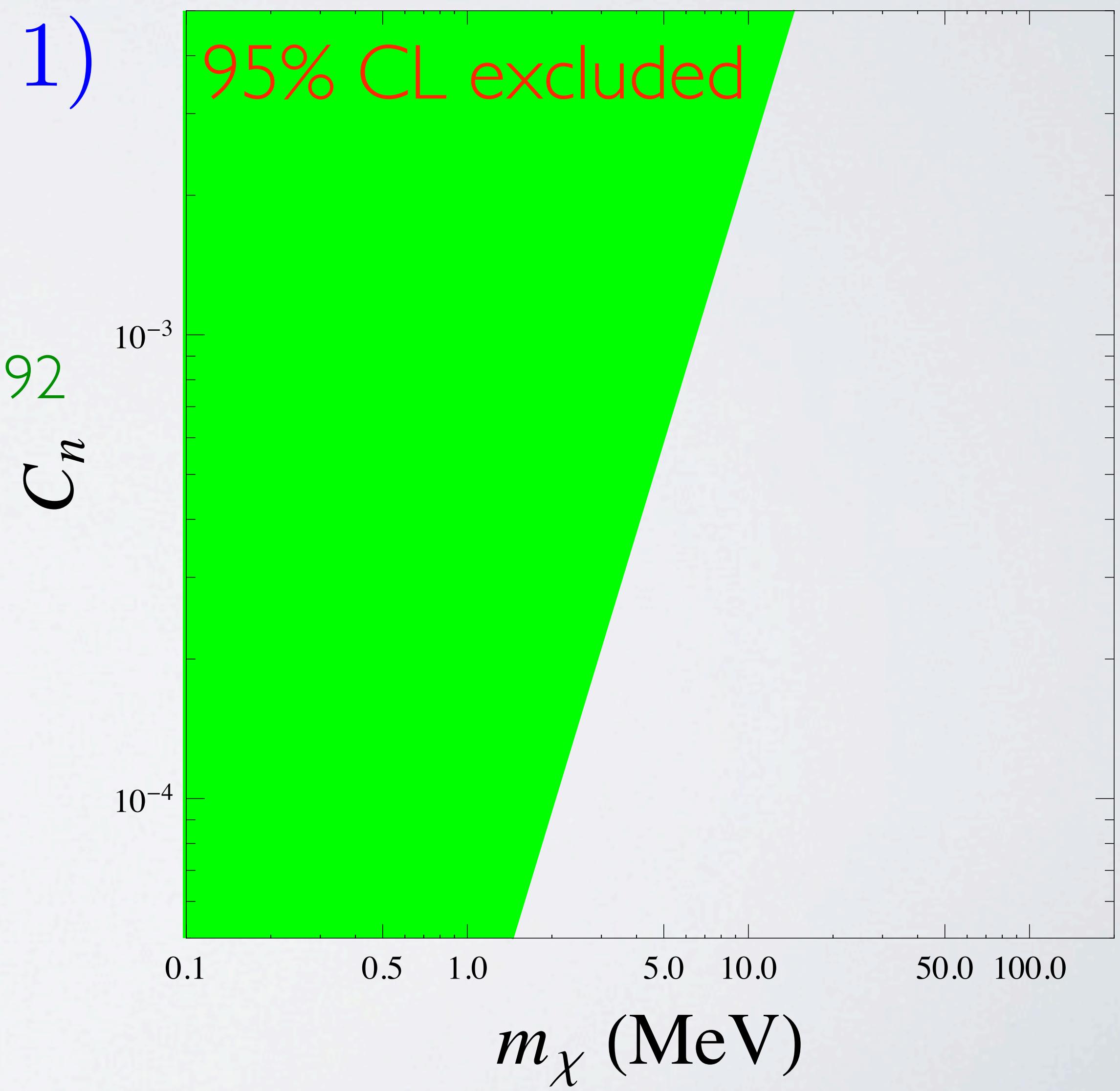
- Measurement

Schmiedmayer et al 1991
Leeb and Schmiedmayer 1992

$$\sigma_0 = 12.40 \pm 0.02 \, \text{barn}$$

$$\sigma_2 = -448 \pm 3 \, \text{barn} \cdot \text{fm}^2$$

gives almost identical 95% CL limit on $C_n^{S,T}$ as vector case



MUON g–2

- Correction to muon g–2 due to scalar/vector is

$$\Delta a_\mu = \frac{(C_\mu^{S,V})^2}{8\pi^2}\int_0^1 \frac{2x^2 - \beta x^3}{x^2 + (m_\chi^2/m_\mu^2)(1-x)}dx$$

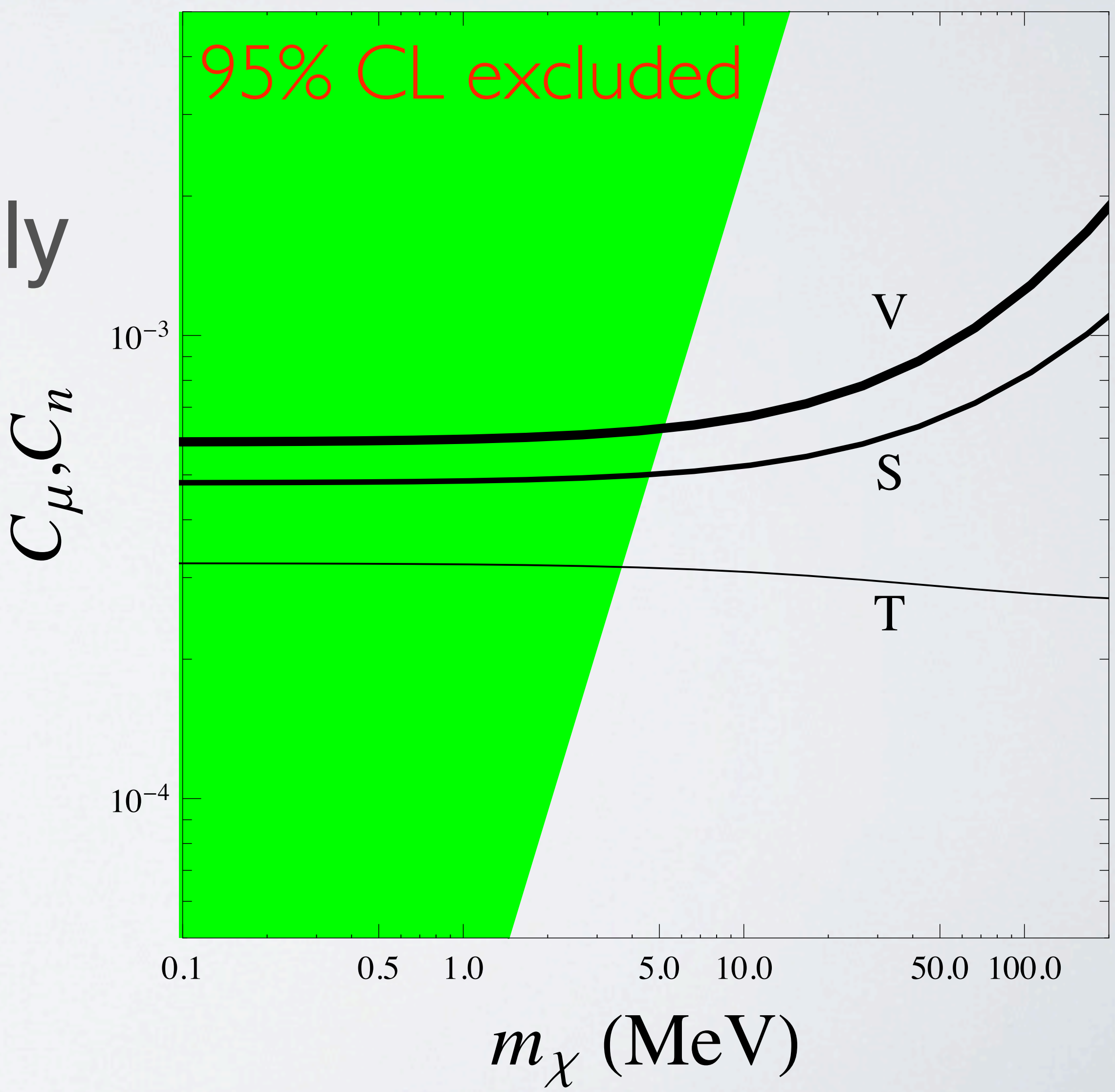
where β = 1 (scalar), 2 (vector).

- Formula for tensor case is slightly more complicated. Graesser 1999

- Experimentally,

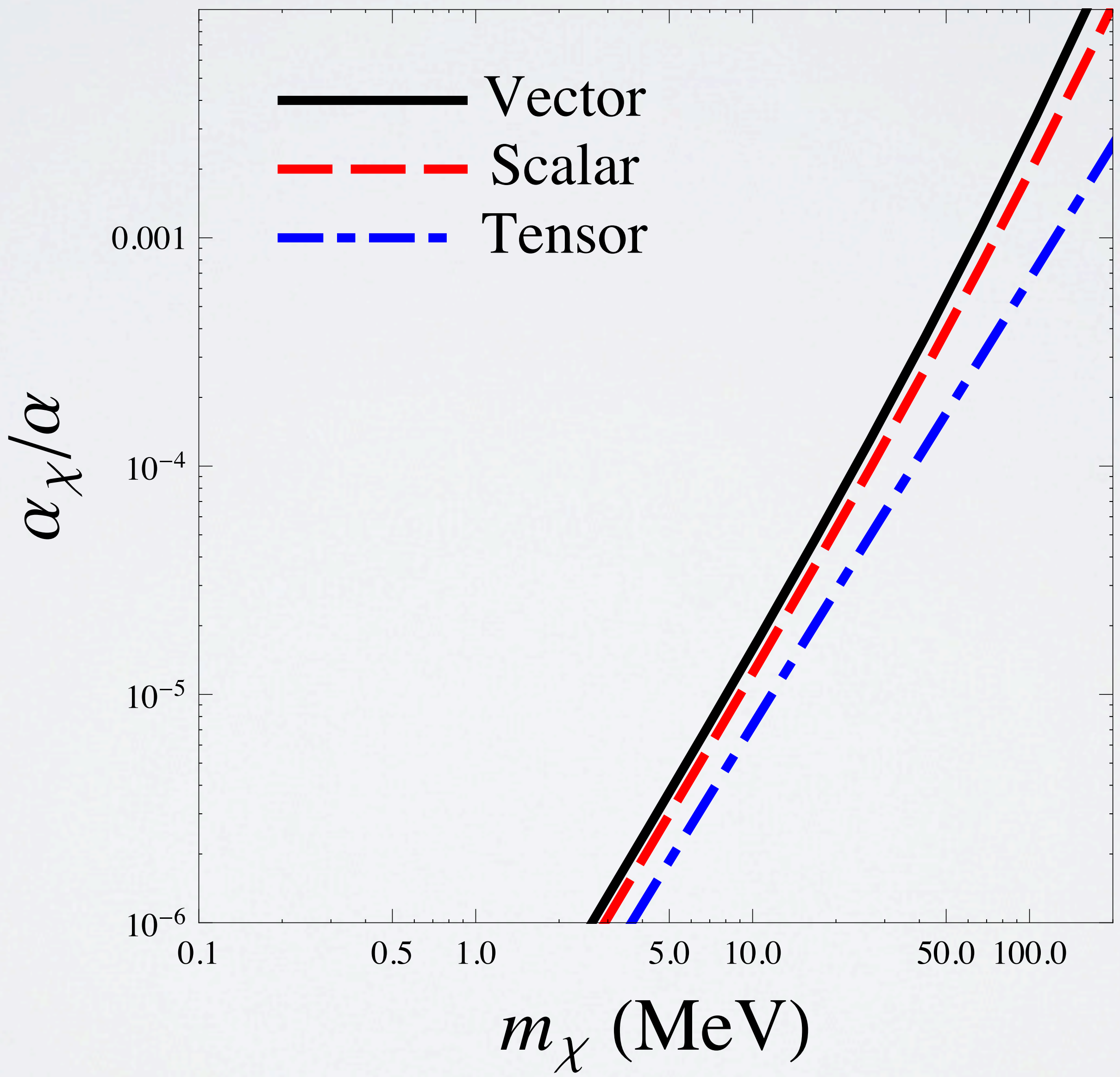
$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm th}$$
$$= (29 \pm 9)\times 10^{-10}$$

Jegerlehner and Nyffeler 2009



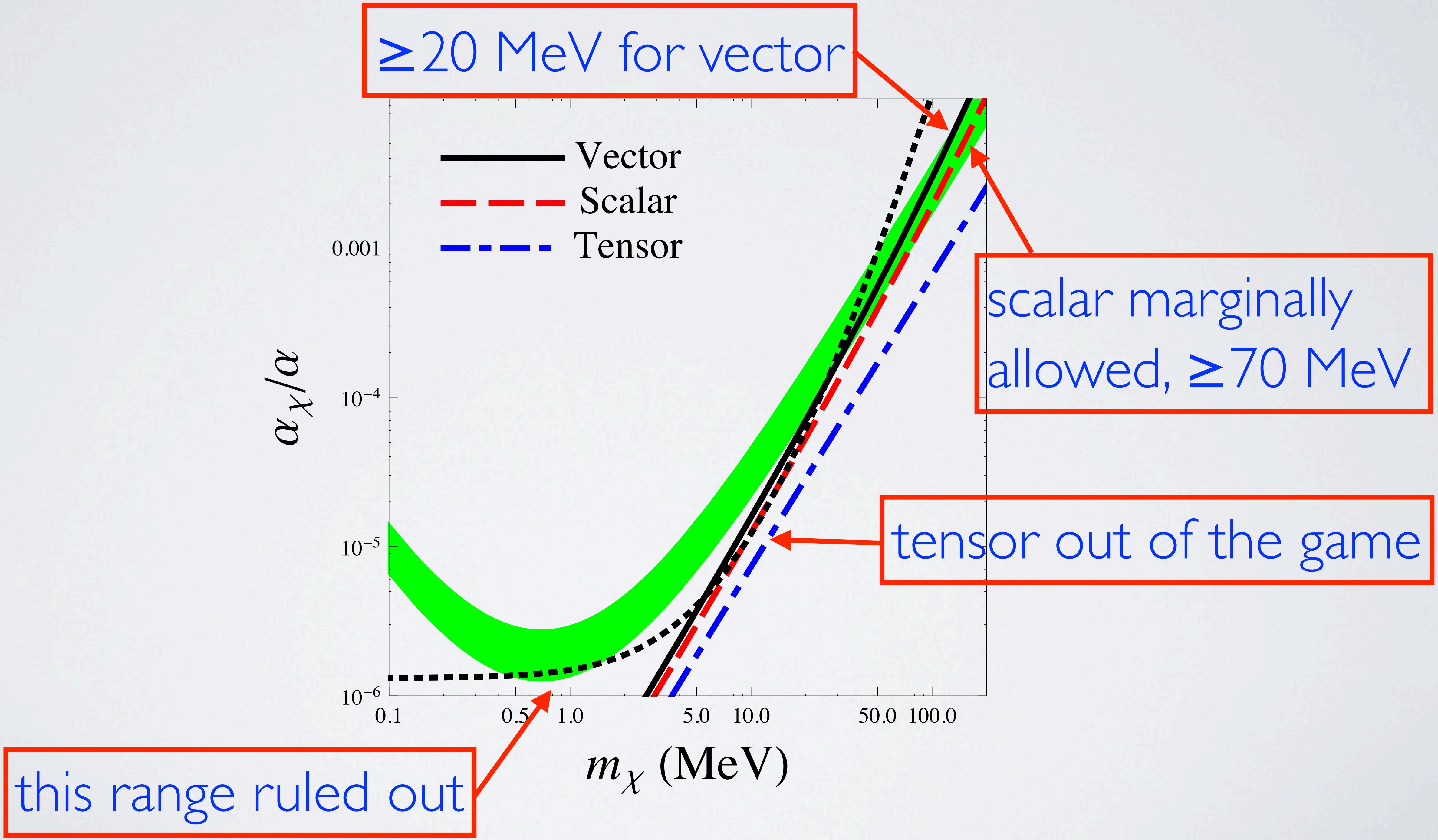
COMBINED CONSTRAINTS

- Combining (i) n-^{208}Pb scattering and (ii) muon g–2, one obtains 95% CL upper bounds on α_χ/α



Combined Constraints

- Putting everything up to now together,



Upsilon Decay

- Conservatively assume $\Upsilon - \chi$ coupling to be C_n^S.
  - Higgs-like ➟ $\mathcal{O}(m_b/m_n)C_n^S$
  - universal ➟ $\mathcal{O}(C_n^S)$

$$\frac{BF(\Upsilon \to \gamma\chi)}{BF(\Upsilon \to \mu^+\mu^-)} = \frac{(C_n^S)^2}{4\pi\alpha}\left(1 - \frac{m_\chi^2}{m_\Upsilon^2}\right).$$

- Non-observation of $\Upsilon \to \gamma\chi$, $\chi \to \mu^+\mu^-$ gives BaBar 2009

$$C_n^S < (0.94 - 9.4)\cdot 10^{-3} \quad \Rightarrow \quad C_\mu^S > \mathcal{O}(1)$$

  at 90% CL.
- Exclude scalar χ with mass between $2m_\mu$ and 9.3 GeV.

J/ψ Decay

- Conservatively assume $J/\psi - \chi$ coupling to be C_n^S, as in the case of Upsilon decay.

$$\frac{BF(\psi \to \gamma\chi)}{BF(\psi \to \mu^+\mu^-)} = \frac{(C_n^S)^2}{4\pi\alpha}\left(1 - \frac{m_\chi^2}{m_\psi^2}\right) .$$

- 90% CL upper limit on $\psi \to \gamma\chi$ with χ decaying invisibly (for region of $m_\chi \leq 2m_\mu$)

CLEO 2010; PDG 2010

$$C_n^S < 0.029 \quad \Rightarrow \quad C_\mu^S > 3.4 \times 10^{-3}$$

with the latter excluded by a_μ.

- Scalars are completely out now.

Upsilon Decay

- For vector χ, non-universality expected in leptonic Upsilon decays for the model:

$$R_{\tau\mu} \equiv \Gamma_{\tau\tau}/\Gamma_{\mu\mu} = 1.005 \pm 0.013 \pm 0.022 \;(\text{exp})$$
$$= 0.992 \;(\text{SM})$$

BaBar 2010;
Van Royen and Weisskopf 1967

- Multiplicative correction due to χ

$$\left[\left(1 \pm \frac{\alpha_\chi}{\alpha Q_b}\right) - \left(\frac{m_\chi}{m_\Upsilon}\right)^2\right]^2 \left[1 - \left(\frac{m_\chi}{m_\Upsilon}\right)^2\right]^{-2}$$

(+: destructive, –: constructive interference) puts a conservative constraint (corresponding to + sign)

$$\frac{\alpha_\chi}{\alpha} \lesssim 8.8 \times 10^{-3} \;\Rightarrow\; m_\chi \lesssim 230 \text{ MeV}$$

PION DECAY

- For vector χ,

$$BF(\pi^0 \to \gamma\chi) = (3.3 - 1.9) \times 10^{-5}$$

NOMAD 1998

$$\text{for } m_\chi = 0 - 120 \text{ MeV}$$

$$\Rightarrow \quad C_n^V < 4.5 \times 10^{-4} \left(1 - \frac{m_\chi^2}{m_\pi^2}\right)^{-3/2}$$

- The corresponding values of C_μ^V conflicts with the a_μ data, leaving only the range 120 to 230 MeV viable.

Invisible Eta Decay

- For vector χ,

$$\frac{BF(\eta \to \chi\chi)}{BF(\eta \to \gamma\gamma)} < 1.65 \times 10^{-3}$$

$$\Rightarrow \quad C_n^V \lesssim 0.05$$

BES II 2006

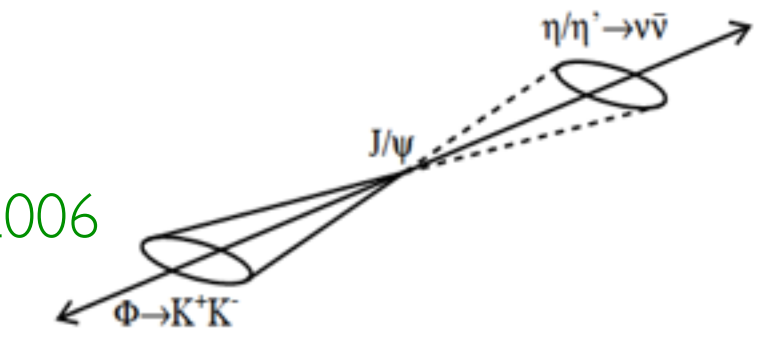


FIG. 1: Schematic of $J/\psi \to \phi\eta$ or $\phi\eta'$. The ϕ, which is reconstructed in K^+K^- final states, can be used to tag the invisible decay of the η and η'.

- This again is excluded by a_μ for m_χ between 120 MeV and $m_\eta/2 \approx 274$ MeV.
- Even the vector case is out of the question!

SUMMARY

- Considered new spin-independent, flavor- and isospin-conserving, yet lepton-non-universal interactions.
- Studied mediation of spin-0, -1, and -2 particles.
- Assumed minimal hadronic couplings to nucleons.
- Checked various low-energy experimental constraints.
- Proton radius anomaly is resistant to simple new physics explanations, which presents a major challenge to current theory and deepens the mystery.

Thank You