New Parity-Violating Muonic Forces

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Based on
Brian Batell, DM, and Maxim Pospelov, arXiv:1103.0721

Outline

- Proton charge radius discrepancy
- A model with gauged RH muon number
- Implications of the model

P. J. Mohr et al., Rev. Mod. Phys. 80, 633 (2008)

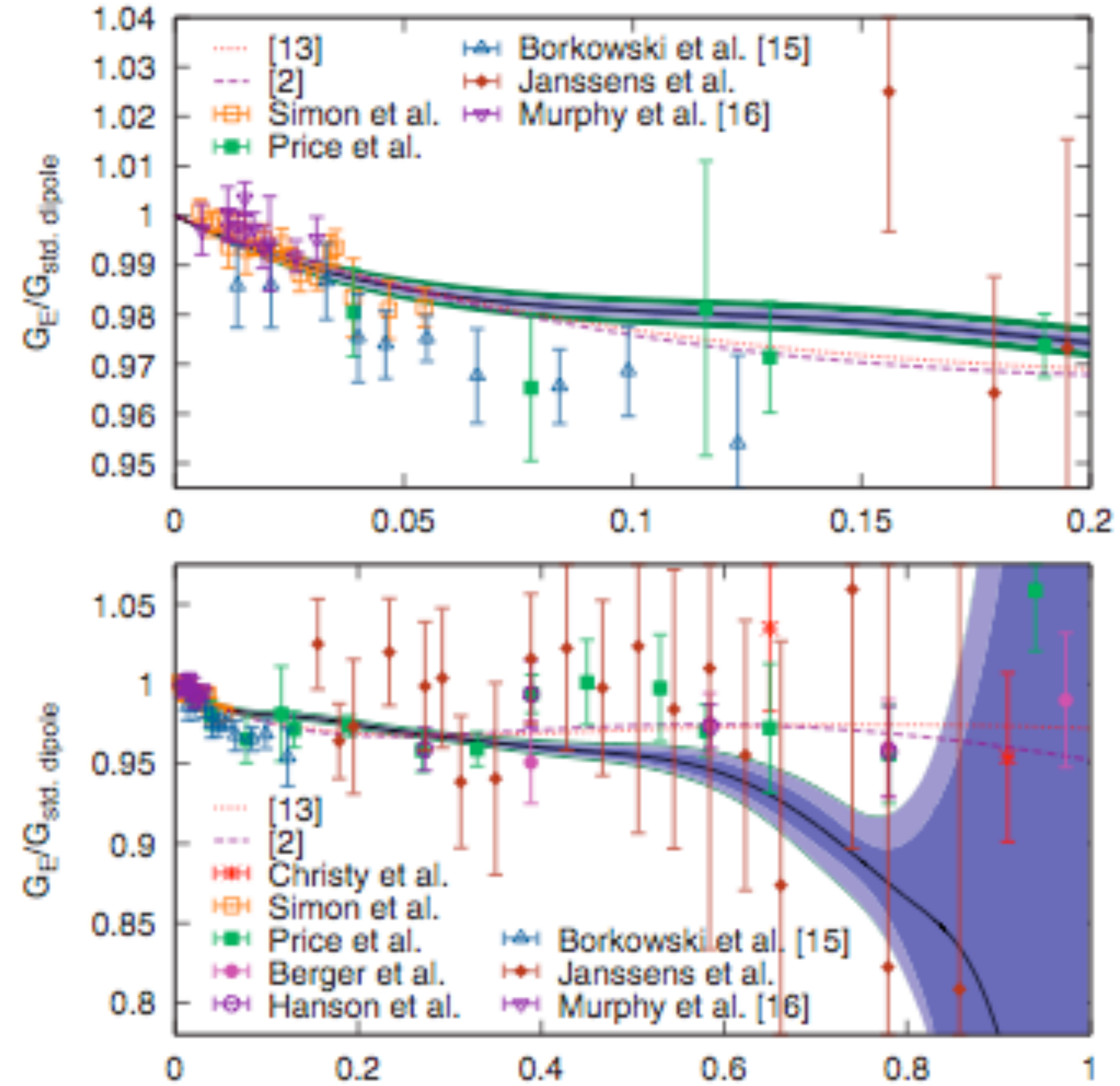
CODATA

A26	$\nu_H(1S_{1/2}-2S_{1/2})$	2 466 061 413 187.074(34) kHz	1.4×10^{-14}	MPQ-04
A27	$\nu_H(2S_{1/2}-8S_{1/2})$	770 649 350 012.0(8.6) kHz	1.1×10^{-11}	LK/SY-97
A28	$\nu_H(2S_{1/2}-8D_{3/2})$	770 649 504 450.0(8.3) kHz	1.1×10^{-11}	LK/SY-97
A29	$\nu_H(2S_{1/2}-8D_{5/2})$	770 649 561 584.2(6.4) kHz	8.3×10^{-12}	LK/SY-97
A30	$\nu_H(2S_{1/2}-12D_{3/2})$	799 191 710 472.7(9.4) kHz	1.2×10^{-11}	LK/SY-98
A31	$\nu_H(2S_{1/2}-12D_{5/2})$	799 191 727 403.7(7.0) kHz	8.7×10^{-12}	LK/SY-98
A32	$\nu_H(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	4 797 338(10) kHz	2.1×10^{-6}	MPQ-95
A33	$\nu_H(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	6 490 144(24) kHz	3.7×10^{-6}	MPQ-95
A34	$\nu_H(2S_{1/2}-6S_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-3S_{1/2})$	4 197 604(21) kHz	4.9×10^{-6}	LKB-96
A35	$\nu_H(2S_{1/2}-6D_{5/2})-\frac{1}{4}\nu_H(1S_{1/2}-3S_{1/2})$	4 699 099(10) kHz	2.2×10^{-6}	LKB-96
A36	$\nu_H(2S_{1/2}-4P_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	4 664 269(15) kHz	3.2×10^{-6}	YaleU-95
A37	$\nu_H(2S_{1/2}-4P_{3/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	6 035 373(10) kHz	1.7×10^{-6}	YaleU-95
A38	$\nu_H(2S_{1/2}-2P_{3/2})$	9 911 200(12) kHz	1.2×10^{-6}	HarvU-94
A39.1	$\nu_H(2P_{1/2}-2S_{1/2})$	1 057 845.0(9.0) kHz	8.5×10^{-6}	HarvU-86
A39.2	$\nu_H(2P_{1/2}-2S_{1/2})$	1 057 862(20) kHz	1.9×10^{-5}	USus-79
A40	$\nu_D(2S_{1/2}-8S_{1/2})$	770 859 041 245.7(6.9) kHz	8.9×10^{-12}	LK/SY-97
A41	$\nu_D(2S_{1/2}-8D_{3/2})$	770 859 195 701.8(6.3) kHz	8.2×10^{-12}	LK/SY-97
A42	$\nu_D(2S_{1/2}-8D_{5/2})$	770 859 252 849.5(5.9) kHz	7.7×10^{-12}	LK/SY-97
A43	$\nu_D(2S_{1/2}-12D_{3/2})$	799 409 168 038.0(8.6) kHz	1.1×10^{-11}	LK/SY-98
A44	$\nu_D(2S_{1/2}-12D_{5/2})$	799 409 184 966.8(6.8) kHz	8.5×10^{-12}	LK/SY-98
A45	$\nu_D(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_D(1S_{1/2}-2S_{1/2})$	4 801 693(20) kHz	4.2×10^{-6}	MPQ-95
A46	$\nu_D(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_D(1S_{1/2}-2S_{1/2})$	6 494 841(41) kHz	6.3×10^{-6}	MPQ-95

- Fit a large number of H and D atomic transitions to determine $R_\infty,\ r_p,\ r_d$
- Find $r_p = 0.8769(68)\ \mathrm{fm}$

J. C. Bernauer et al., PRL 105, 242001 (2010)

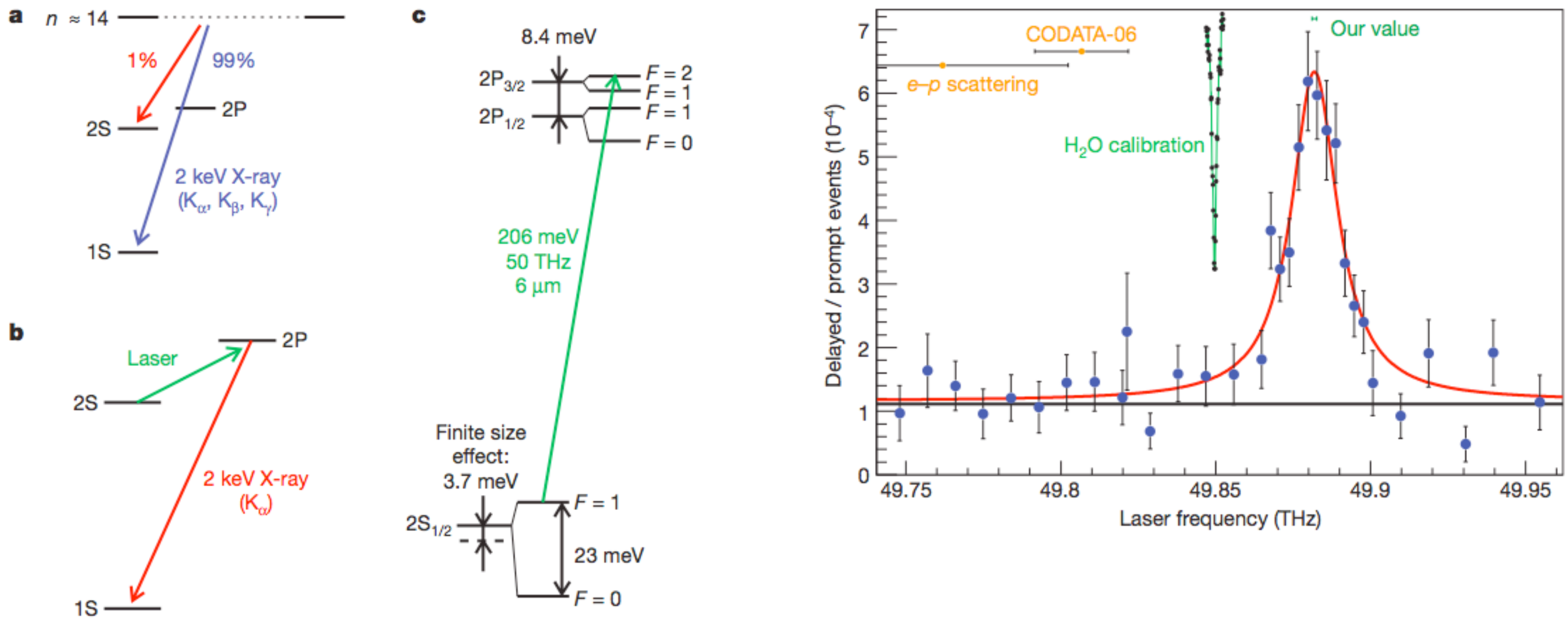
e-p Scattering



- Fit e-p scattering cross sections and extract charge radius: $r_p = 0.879(8)\ \mathrm{fm}$

R. Pohl et al., Nature 466, 213 (2010)

Muonic Hydrogen



$$\Delta E = E\left(2P_{3/2}^{F=2}\right) - E\left(2P_{1/2}^{F=1}\right)$$

$$= 206.2949(32)\ \mathrm{meV}$$

$$\Delta E_{\mathrm{th}} = \left(209.9779(49) - 5.2262 r_P^2 + 0.0347 r_p^3\right)\ \mathrm{meV}$$

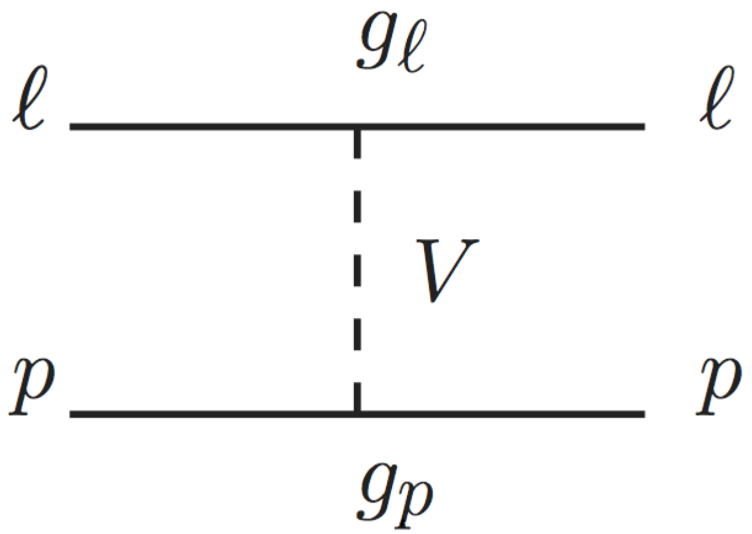
$$r_p = 0.84184(67)\ \mathrm{fm}$$

Data Summary

- H & D Spectroscopy: $r_p = 0.8769(68)\ \mathrm{fm}$
- e-p Scattering: $r_p = 0.879(8)\ \mathrm{fm}$
- Muonic H: $r_p = 0.84184(67)\ \mathrm{fm}$
- e-p measurements agree with each other
- discrepancy (5.1 for spectroscopy and 4.6 for scattering) with muonic H

See also Barger et al., arXiv:1011.3519;
Tucker-Smith and Yavin, arXiv:1011.4922

New Forces



- Consider additional potential between leptons and protons given by exchange of particle V with spin s. Leads to:

$$\Delta r_p^2 = (-1)^{s+1}\,\frac{6 g_\ell g_p}{e^2 m_V^2}\,\frac{(a m_V)^4}{(1 + a m_V)^4} \qquad a = \frac{m_\ell + m_p}{\alpha m_\ell m_p}$$

$$\Delta r_p^2 \simeq 0.06\ \mathrm{fm}^2 \Rightarrow \frac{g_\ell g_p}{m_V^2} \sim 10^4 G_F$$

New Forces (cont'd)

- The pattern of charge radii disfavors a simple attractive or repulsive proton-lepton force: $(r_p)^H_{ep} \sim (r_p)^{\rm scatt.}_{ep} > (r_p)^{\mu H}_{\mu p} \Rightarrow g_e \ll g_\mu$
- (Old) neutron scattering experiments constrain couplings of MeV-scale particles to neutrons: $g_n \lesssim g_{\ell,p}/10 \Rightarrow s = 1$
- Neutrinos can't couple to a new force carrier this strongly: $g_\nu \ll g_\mu$

Gauged μ_R

- Suggests a possible resolution
- Gauge μ_R so that couplings to electrons and neutrinos are unimportant
- Couple to charge by kinetic mixing with the photon so that one couples to protons and not neutrons

Gauged μ_R (cont'd)

The Lagrangian is

$$\mathcal{L} = -\frac{1}{4}V_{\alpha\beta}^2 + |D_\alpha \phi|^2 + \bar{\mu}_R i \not{D} \mu_R - \frac{\kappa}{2} V_{\alpha\beta} F^{\alpha\beta} - \mathcal{L}_m$$

$$D_\mu = \partial_\mu + i g_R Q_R V_\mu + i e Q_{EM} A_\mu$$

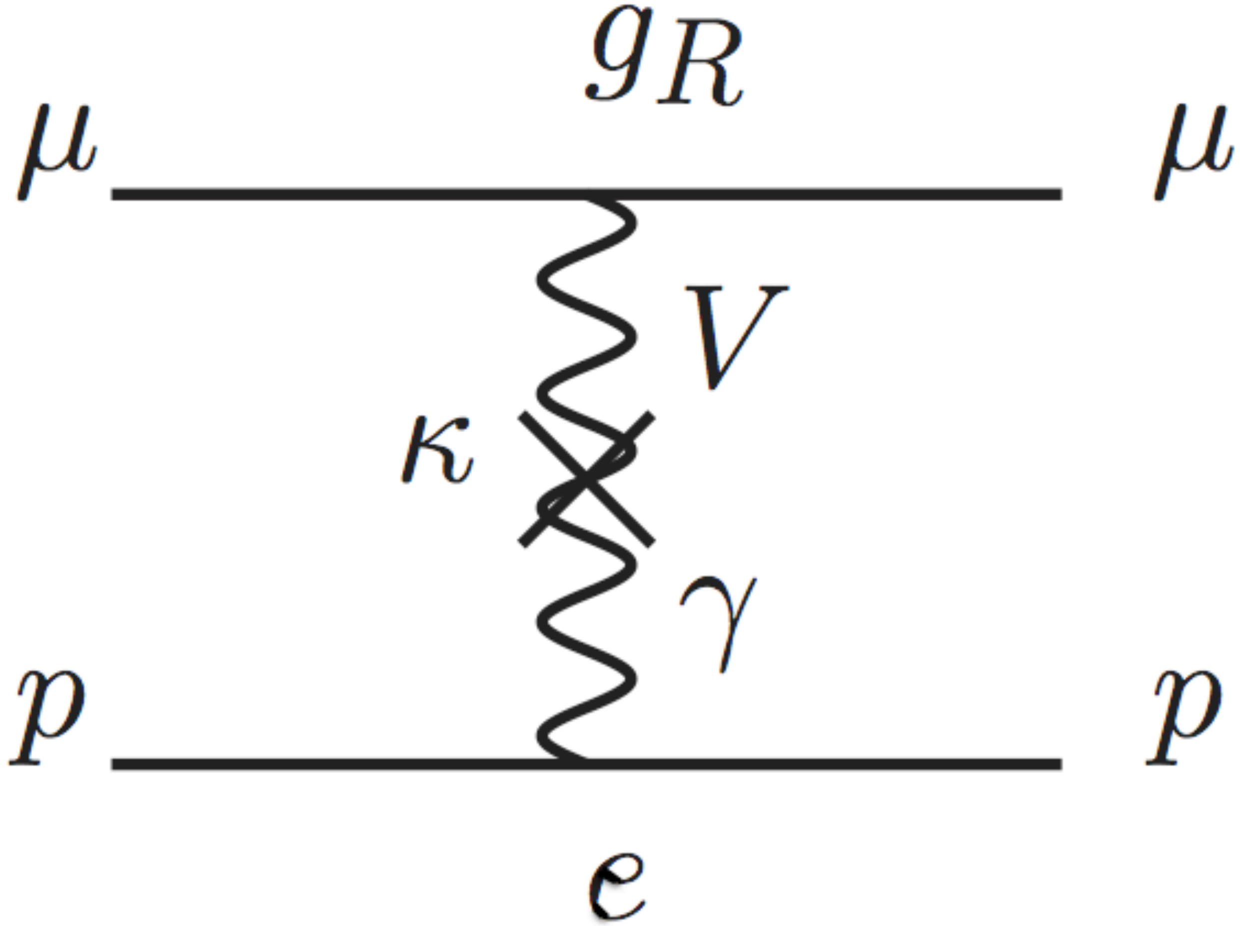
$$\mathcal{L}_m = \bar{L} \mu_R H_{SM} \frac{\phi}{\Lambda} + \text{h.c.} \to \frac{v v_R}{2\Lambda} \bar{\mu}\mu$$

$$\langle \phi \rangle \equiv v_R/\sqrt{2}$$

$$m_V = g_R v_R$$

$$m_S = \sqrt{\lambda} v_R$$

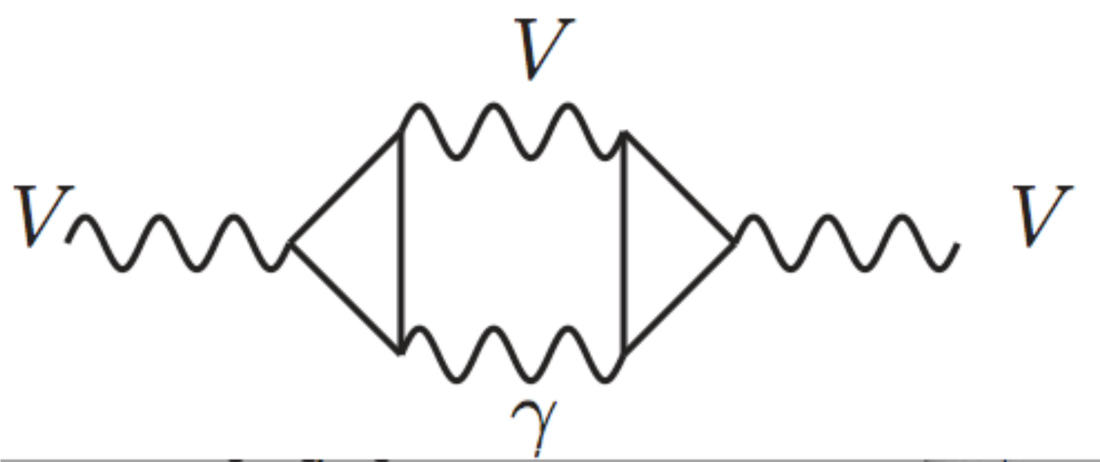
Gauged μ_R (cont'd)



Leads to a new muon-proton interaction through this diagram. Its strength is characterized by $\eta \equiv \frac{\kappa g_R}{2e}$

$$\frac{\eta}{m_V^2} \simeq \frac{\Delta r_p^2}{6} \simeq 0.01\ \mathrm{fm}^2 \simeq \frac{2.5 \times 10^{-5}}{(10\ \mathrm{MeV})^2} \simeq 2.5 \times 10^4 G_F$$

Gauged μ_R (cont'd)



- This model is anomalous (canceling anomalies by gauging quarks as well causes flavor issues)
- Maintain gauge invariance but sacrifice renormalizability
- EFT valid up to some scale

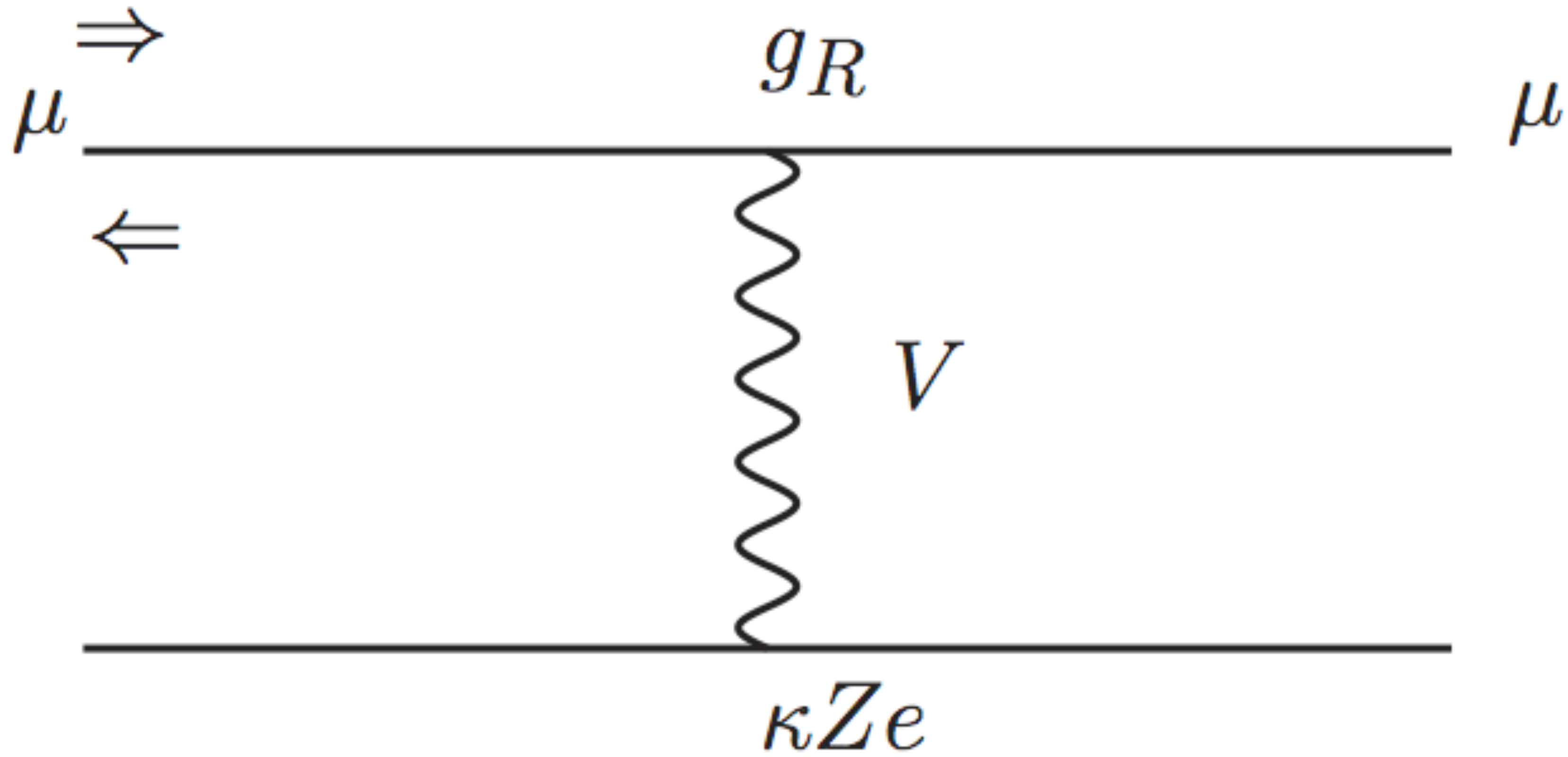
$$\Lambda_{UV} \leq \frac{(4\pi)^3}{e g_R^2} m_V \sim 700\text{GeV} \left(\frac{m_V}{10\ \text{MeV}}\right) \left(\frac{g_R}{e}\right)^{-2}$$

Constraints

- g-2 requires fine cancellation between V and S
- Muonic Mg and Si set a lower limit $m_V \gtrsim \mathrm{MeV}$
- Fixed target limits on kinetic mixing modulo decay channels
- Can find wide range of parameters

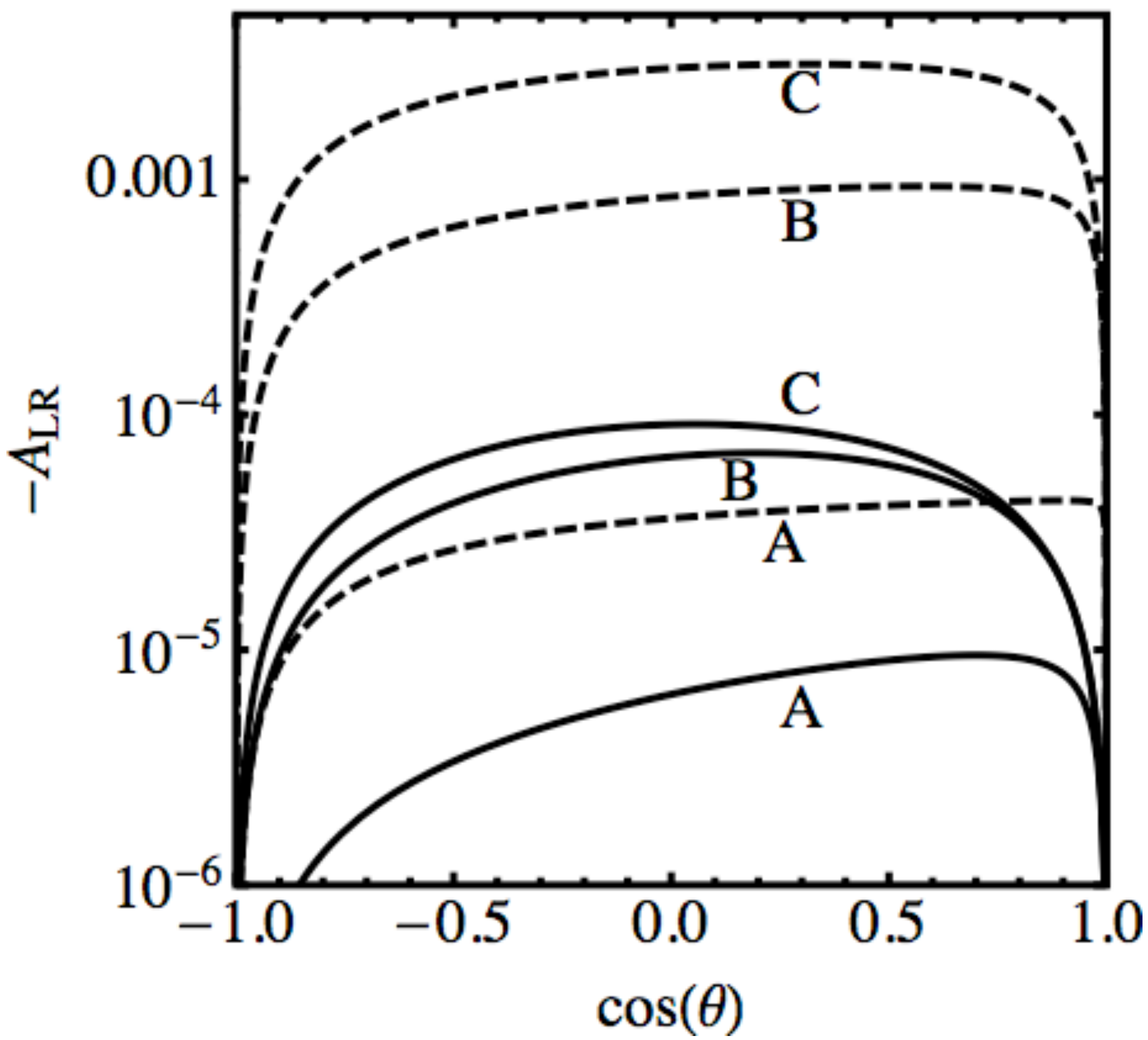
Parameter	Point A	Point B	Point C
m_V	10 MeV	50 MeV	100 MeV
m_S	102.84 MeV	90.44 MeV	84.97 MeV
g_R	0.01	0.05	0.07
κ	0.0015	0.0075	0.02
η	2.5×10^{-5}	6.2×10^{-4}	2.3×10^{-3}
v_R	1 GeV	1 GeV	1.4 GeV

Parity Violation in $\mu\ \text{Nuc.} \to \mu\ \text{Nuc.}$



Cross sections for LH and RH scattering on nuclei are different

Parity Violation in μ Nuc. $\to \mu$ Nuc.



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For tungsten target:

$$t|_{N\sim 10^8} = \frac{N}{P\Phi_\mu} \sim 1600 \text{ s} \times \frac{10^8 \text{ muons/s}}{\Phi_\mu}$$

$$A_{\mathrm{LR}} = \frac{d\sigma_{\mathrm{L}} - d\sigma_{\mathrm{R}}}{d\sigma_{\mathrm{L}} + d\sigma_{\mathrm{R}}} \simeq -\eta\beta \frac{Q^2}{Q^2 + m_V^2} \frac{1 + \cos(\theta)}{1 - \beta^2 \sin^2(\theta/2)}$$

2S-2P Mixing in muonic He

- Could possibly be probed in muonic He Lamb shift experiment
- M1 matrix element much smaller than E1. Look for single photon 2S to 1S decay:

$$\Gamma^{\gamma}_{2s\to 1s}/\Gamma^{\gamma\gamma}_{2s\to 1s} \simeq 0.018$$

Muonic He Lamb shift

- This model gives the same shift in the charge radius of muonic He vs. standard He

$$\Delta r_{\mathrm{He}}^2 \simeq 0.06\ \mathrm{fm}^2$$

- Await their results...

Conclusions

- Proton charge radius extraced from muonic H appears to be in conflict with that from e-p systems
- Difficult to explain with new physics
- Gauging RH muon # could offer a solution
- This leads to new PV observables that can be probed with existing facilities