Three approaches to muon PNC

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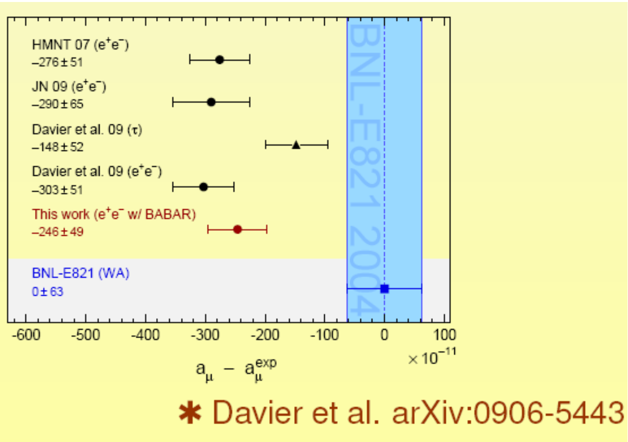
Outline of the talk

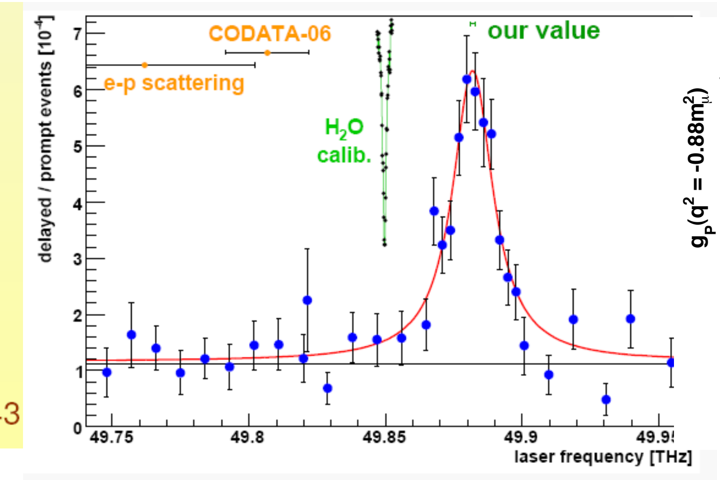
1. Motivation: Is everything OK with lepton Universality?
2. Parity violation with muons in Neutral currents. (History)

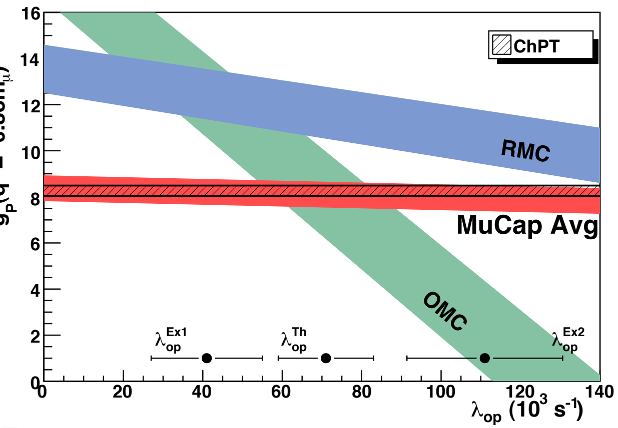
3. Options: a) scattering
   b) optical activity
   c) muonic atoms

4. Conclusion: opportunities for Fermilab and PSI

“Accumulation” of anomalies for muons







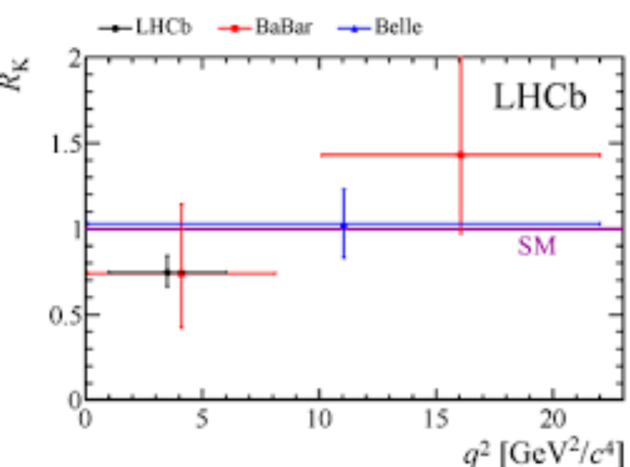
May be something happens with muonic “neutral” channels at low energy. We do not know – therefore it would be quite foolish not to explore additional possibilities of testing “NC-like” signatures in muons at low energy.

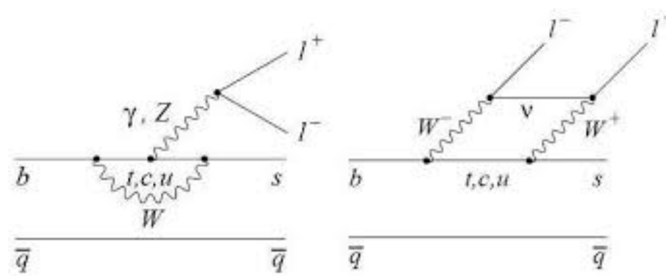
More problems recently in B-decays

- Angular correlations in muon semileptonic B decays. *3σ-ish discrepancy*

- e/μ [non]-universality in K+lepton pair bound states. *2.5σ-ish discrepancy*

- Possible LFV in Higgs decays





Can be result of New Physics at the TeV scale (A. Crivellin talk yesterday)

A discrepancy between μ and e probes

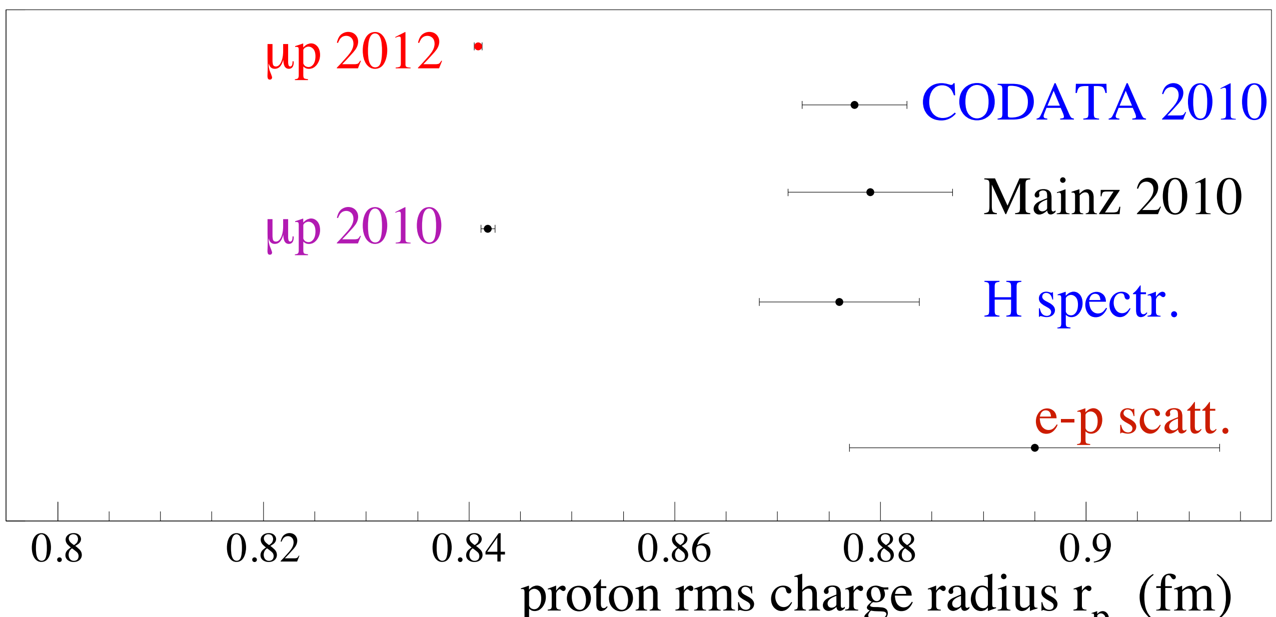
$$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2}) \quad = \quad 49881.88(76)\ \text{GHz}$$ R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz preliminary

$$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1}) \quad = \quad 54611.16(1.04)\ \text{GHz}$$ preliminary

Proton charge radius: $r_{\rm p} = 0.84089\ (26)_{\rm exp}\ (29)_{\rm th} = 0.84089\ (39)\ \text{fm}$ (prel.)

$\mu\rm p$ theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)



Importantly, *Zeemach radius* extracted from 2 lines is perfectly consistent with previous (normal hydrogen) determinations

Discrepancy in r_p

$$\begin{aligned} r_{p,1} &= 0.8768(69)\ \text{fm} && \text{atomic H, D,} \\ r_{p,2} &= 0.879(8)\ \text{fm} && e-p\ \text{scattering,} \\ r_{p,3} &= 0.84184(67)\ \text{fm} && \text{muonic H.} \end{aligned}$$

The following pattern for the discrepancy emerges:

$$r_{p,1} \simeq r_{p,2} > r_{p,3},$$
$$\Delta r^2 \equiv (r_p)^2_{e-p\ \text{results}} - (r_p)^2_{\mu-p\ \text{results}} \simeq 0.06\ \text{fm}^2.$$

On one hand it is a tiny number, especially compared to the atomic physics scales. On the other hand, it is a *gigantic* number if compared to the particle physics scales where traditionally you would expect new physics. 0.06 $\text{fm}^2 e^2$ is *four orders of magnitude larger than Fermi constant*.

New U(1) forces for right-handed muons

Batell, McKeen, MP, arXiv:1103.0721,PRL 2011 – Puts a new force into SM. Despite considerable theoretical difficulties to build a consistent model of "muonic forces" relevant for r_p discrepancy, gauged RH muon number could be still alive:

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

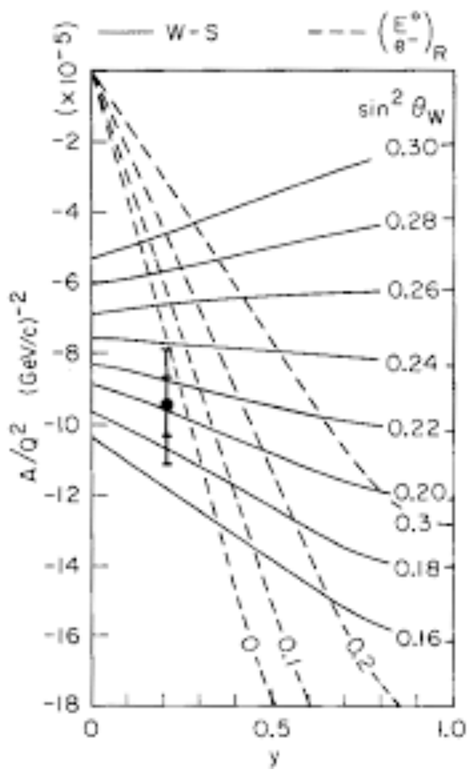
Main logical chain leading to this:

1. Scalar exchange is disfavored because of the neutron scattering constraints, and meson decay constraints.
2. Vector force has to NOT couple to left-handed leptons – otherwise huge new effects for neutrinos. Then has to couple to RH muons, $V_\alpha \bar{l}\gamma_\alpha l \subset V_\alpha(c_1\bar{L}\gamma_\alpha L + c_2\bar{R}\gamma_\alpha R),\ c_1 \neq -c_2.$

It violates parity – but wait – parity is not tested with muons at low energy!

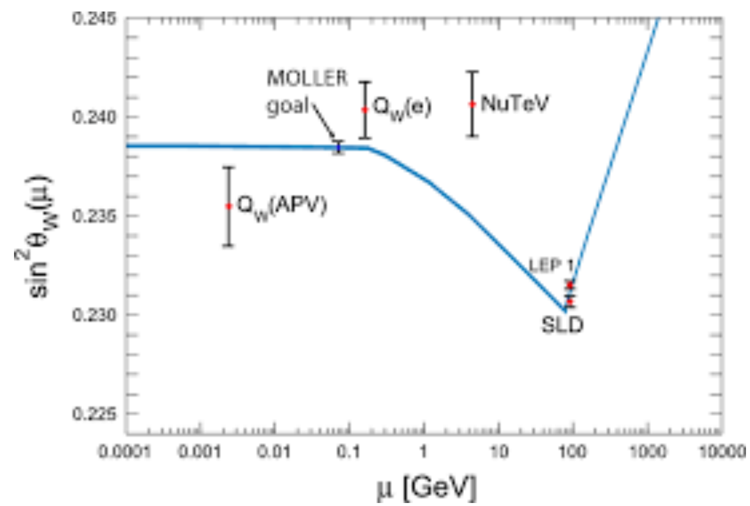
PNC with electrons

Prescott et al 1978. SLAC DIS experiment with electron scattering on deuteron clinched the SM. γ - Z interference



$$A_{PV} = \frac{S_R - S_L}{S_R + S_L} \approx \frac{M_Z}{M_\gamma} \cdot Q_W(e)$$

$$\approx \frac{Q^2}{[M(Z)]^2} \cdot Q_W(e)$$



Current accuracy in the polarized electron scattering can get the error on asymmetry below 10^{-8} .

History of μ PNC

- Theoretical μ PNC ideas with muonic atoms predate regular atom PNC literature (e.g. Chen and Feinberg, 1974). Despite many efforts (Simons et al), muonic atom PNC is not quite close to being detected.

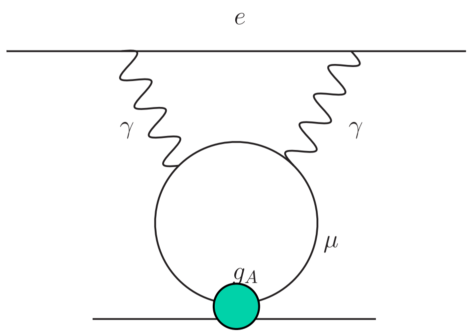
- Only one successful experiment in muonic scattering: CERN-NA-004 Collaboration: A. Argento et al., Phys. Lett. B 120 (1983) 245. Comparison of μ^+ and μ^-, sensitivity to $V_{\text{muons}} \times A_{\text{quarks}}$, but not $A_{\text{muons}} \times V_{\text{quarks}}$. $Q^2 \sim 50$ GeV^2

- Perfect agreement of muon pair-production at Z-peak with the SM (LEP and SLC).

- **Goal: test lepton universality of PNC, models of light NP with enhanced PNC, detect SM $A_{\text{muons}} \times V_{\text{quarks}}$**

How large $\mathbf{A}_{\mathbf{muons}} \times \mathbf{V}_{\mathbf{quarks}}$ could be?

The answer can be found in Karshenboim, McKeen, MP, 2014 (although not quite phrased this way)



$$\mathcal{L}_{eff} = \frac{G_F}{\sqrt{2}} (\overline{\mu}\gamma_\nu\gamma_5\mu) \times (\kappa_p \overline{p}\gamma_\nu p + \kappa_n \overline{n}\gamma_\nu n)$$

"Integrating out" muon field, we get

$$(\overline{\mu}\gamma_\nu\gamma_5\mu) \;\to\; (\overline{e}\gamma_\nu\gamma_5 e) \times \frac{3\alpha^2}{2\pi^2} \log\left(\frac{\Lambda_{\rm UV}^2}{m_\mu^2}\right)$$

and apply APV (also P-odd scattering constraints).

$|\kappa_{p,n}|$ can be as large as 100

(This is also gives a constraint on the *anapole moment* of the muon)

100 times larger than G_F would imply light particles (!)

Possible avenues to measure μ PNC

A. Muon Scattering, LR asymmetry

B. Muon optical activity ($q^2=0$ forward scattering)

C. Muonic atoms, FB asymmetry for the 2S-1S gamma

D. Muon pair-production by polarized electron beams or in particle decays.

…

In SM, the effect is small, $G_F\, Q^2$, and so to see the SM effect one needs some enhancement mechanisms (e.g. close levels of opposite parity in muonic atoms) and/or very large intensities.

[*In speculative models addressing r_p anomaly via a new vector force, the effect is ~ 3 orders of magnitude larger than in the SM*]

Possible avenues to measure μ PNC

A. Muon Scattering, LR asymmetry

B. Muon optical activity (q^2=0 forward scattering)

C. Muonic atoms, FB asymmetry for the 2S-1S gamma

D. Muon pair-production by polarized electron beams or in particle decays. (Soon-to-be-running super-B-factory Belle II does not have polarized beams yet. But in the upgrades, this may be possible, opening doors to a very precise parity measurements at time-like Q^2 = 100 GeV^2. M. Roney ideas.)

A: PNC in muon scattering

This is a speculative model where PNC is enhanced relative to the SM

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

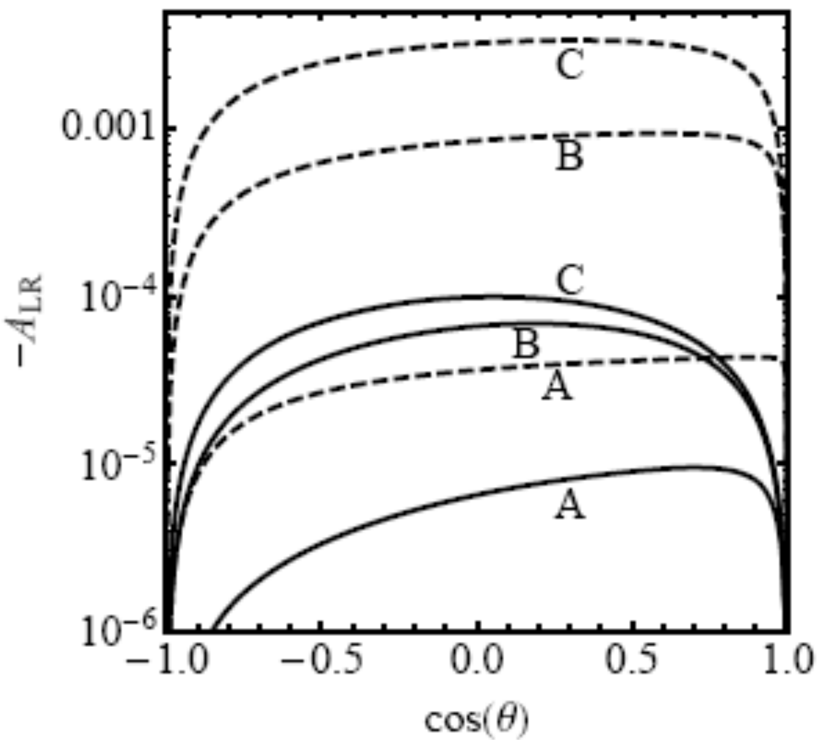


FIG. 1: The asymmetry $A_{\mathrm{LR}}(\theta)$ defined in Eq. (13) for the benchmark points labeled A, B, and C in Table I. The solid curves are for $p = 29$ MeV$/c$ and dashed curves for $p = 100$ MeV$/c$.

Considering that in e-p scattering the accuracy on parity asymmetry ~ 10 ppb, one would think that asymmetry of 10^{-3} for muons can be easily observable?

Nobody tried: it is difficult to reliably reverse muon polarization. JPARC beam may change that

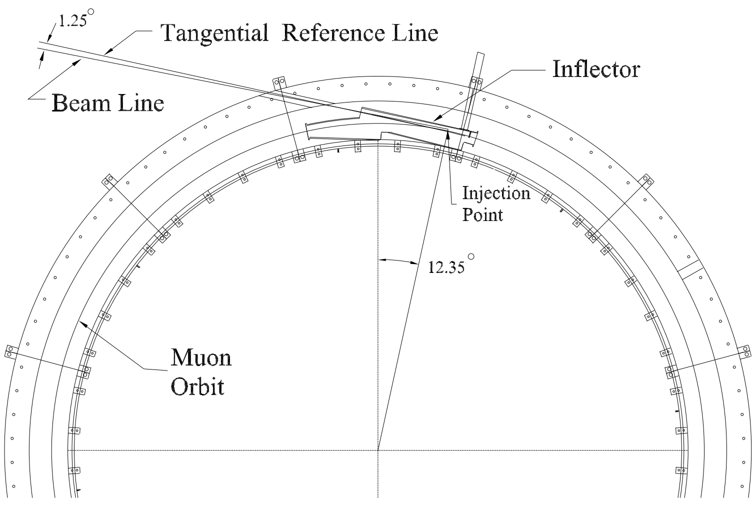
μ PNC via scattering on quarks (nuclei)

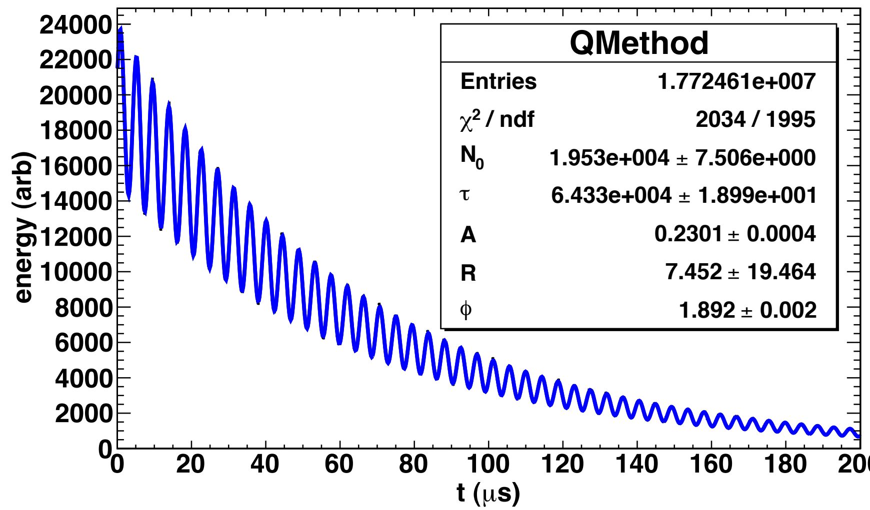
- Although muons come from pion decays with longitudinal polarization, it is difficult to flip this polarization in flight with enough reliability.

- In the future new sources of muons via intermediate muonium states (JPARC) would allow manipulation with muon spin.

- Muon storage rings, where dynamics of muon spin is well studied could be used for the PNC scattering experiment.

Possible schemes: use g-2 ring, or a delivery ring





- "Kick" muons into the target after variable number of revolutions. 15 revolutions flips the spin by 180 degrees.
- Measure muons scattering a at high Q^2.
- Delivery ring is initially designed for 9 GeV momentum particles, can be used for higher energy muon spin rotation (P. Kammel)

Running some numbers

- To measure PNC asymmetry of size A, you need $N_{events} > 1/A^2$. In the SM,
- $A_{LR} \sim (G_F\, Q^2)/(4\,\pi\,\alpha) \times$ (order one numbers)

  $A_{LR} \sim 10^{-4}\ (Q^2 \sim 1\ \mathrm{GeV}^2)$

  $A_{LR} \sim 10^{-3}\ (Q^2 \sim 10\ \mathrm{GeV}^2)$
- Need more than 10^8 scattering events at 1 GeV^2. More than 106 at 10 GeV^2.
- DIS cross sections at $Q^2 \sim 1\ \mathrm{GeV}^2$

  $\sigma_{DIS} \sim 4\,\pi\,\alpha^2/Q^2 \times$ (order one numbers)

  $\sigma_{DIS} \sim 10^{-31}\ \mathrm{cm}^2$ at $Q^2 \sim 1\ \mathrm{GeV}^2$

  $\sigma_{DIS} \sim 10^{-32}\ \mathrm{cm}^2$ at $Q^2 \sim 10\ \mathrm{GeV}^2$

Running some numbers

- Probability to scatter: $P_{scatter} = \sigma_{DIS} \times n_{nucleons} \times L_{target}$

- After 50 cm of e.g. tungsten target the probability to scatter at

$Q^2 \sim 1$ GeV^2 is $P_{scatter} \sim 2 \times 10^{-6}$.

$Q^2 \sim 10$ GeV^2 is $P_{scatter} \sim 2 \times 10^{-7}$.

Realistic number of POT at Fermilab can be 10^{15}.

So, up to 10^8-10^9 scatterings → Enough to test asymmetries in the $10^{-4} – 10^{-3}$ range.

**** It appears that one can indeed test the SM using the Fermilab beams and delivery ring capabilities ****

More studies needed!

B: Muon optical activity, forward scattering

- In an upolarized medium, L and R muons have different forward scattering amplitude, e.g. phase velocities. *Optical activity* ! !
- Tip the spin 90 degrees relative to momentum – linear superposition of L and R longitudinal polarizations.

- Rotation angle depends on the distance travelled and the number density of neutrons.

$$\Delta\phi = \frac{2G_F}{\sqrt{2}} \times n_n \times \Delta L \times \kappa_n$$

- Kappa_n is -1/2 in the SM (but can be as large as a ~ 100).

B: Muon optical activity, forward scattering

- Tip the spin 90 degrees relative to momentum – linear superposition of L and R longitudinal polarizations.
- Send muon inside the unpolarized medium, try to measure rotation angle of stopped muons via their decay.

- *Number density of neutrons in tungsten:* 3.5×10^{24} cm^{-3}

  10 GeV muons travel L = 3.5 meters before stopping

Rotation angle in the SM = 3×10^{-6} rad.

Very difficult. (May be not out of question – muon EDM proposals plan to measure ~ 10^{-7} angles)

C: PNC in muonic atoms - revisited

- Old (1980s) proposal (Going back to Chen & Feinberg. See Missimer & Simons review):

1. Start with slowing down muons in cyclotron trap (they loose their polarization), send them on Z~5 low density gas target
2. Let muon cascade take place; nl->n-1,l-1…. Some 1% reaches 2S states. Look for one photon decay of 2S which occurs due to suppressed M1 amplitude and parity suppressed E1. Beta-decay of the muon will provide a correlated direction of beta electron and M1(E1) gamma. Did not work out…

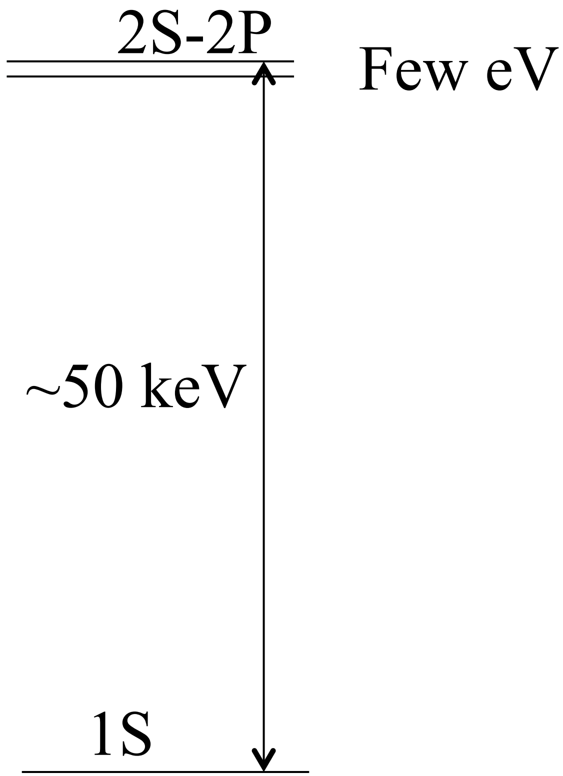
- New proposal (MP and McKeen), PRL 2012, arXiv:1205.6525

1. Use fast (~50 MeV) polarized muons with high intensity beam,
2. Use thin target of Z~30 (perhaps best is Z=36, Kr) does not capture muons apart from small fraction that gets into 2S state via *atomic radiative capture* (ARC) , $\mu^- +$ Atom -> (μAtom) + γ
3. The signal is parity-violating forward-backward asymmetry of 2S-1S gamma.

Level structure (schematically)

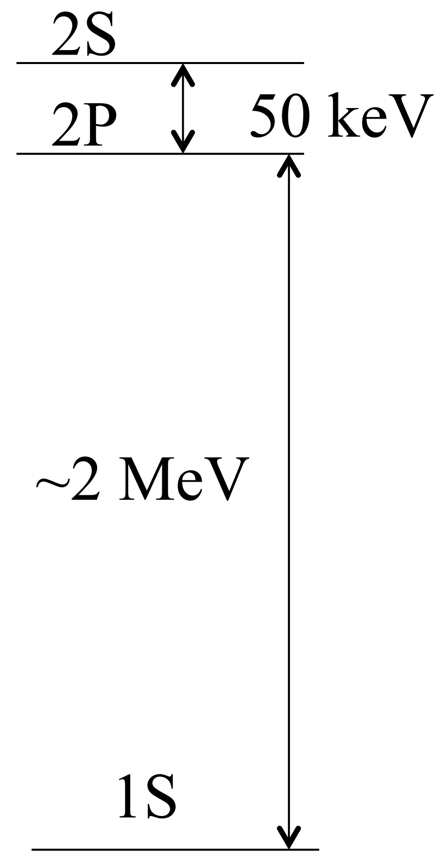
2s is pushed down by QED and up by finite nuclear charge

- Z~5



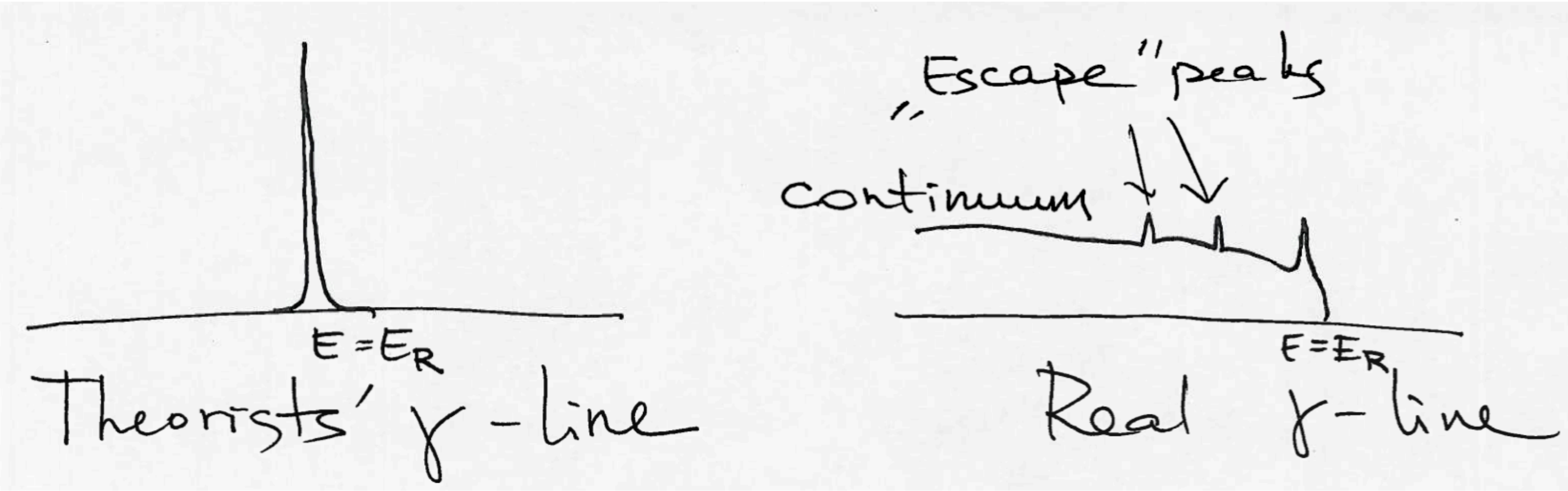
2S-1S and 2P-1S transitions cannot be distinguished on event by event basis

Z~30



2S-1S and 2P-1S transitions can be distinguished (but was never observed)

Difficulty with cascade: for 2S-1S S/B < 1%



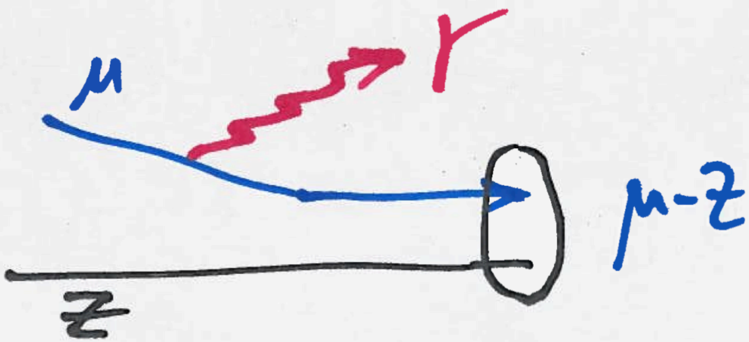
Much more frequent nP-2S transitions from the cascade bury 2S-1S transition under their continuum (Missimer, Simons review)

I.e. too much background

New way to make muonic atoms

(1 per 10^6 gets captured but mostly to 1S and 2S states)

Atomic radiative capture



$$E_\gamma = E_{binding} + E_{kinetic}$$

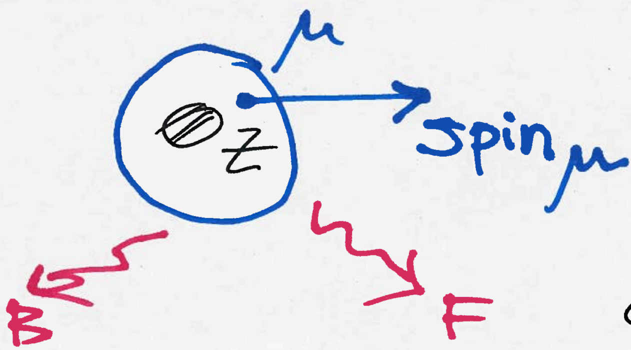
(e.g. $p = 40$ MeV muon capture to 1S state gives $E_\gamma \simeq 10.5$ MeV, much larger than γ's in the cascade)

Muons remain fully polarized

PNC idea

(1) ARC to 2S state
in $Z>30$ elements
detection of very hard γ_1

(2)



Observe
2S-1S
transition
$E_{\gamma_2} = E_{2S} - E_{1S}$

(3) $$A_{FB} = \frac{N(\gamma_2, F) - N(\gamma_2, B)}{N(\gamma_2, F) + N(\gamma_2, B)}$$

Single photon transition in 2S-1S enhances parity violation because:

- 2S-2P are close and this enhances PNC mixing of atomic levels
- Main M1 transition is highly suppressed, $E1*M1/(M1)^2$ is enhanced

PNC in muonic atoms - revisited

- Old (1980s) proposal

$$\ldots \rightarrow 2S_{1/2} \xrightarrow{M1-E1} 1S_{1/2} + \gamma; \; (\mu^-)_{1S} \rightarrow e^- \nu_\mu \bar{\nu}_e$$

- New proposal (avoid the cascade),

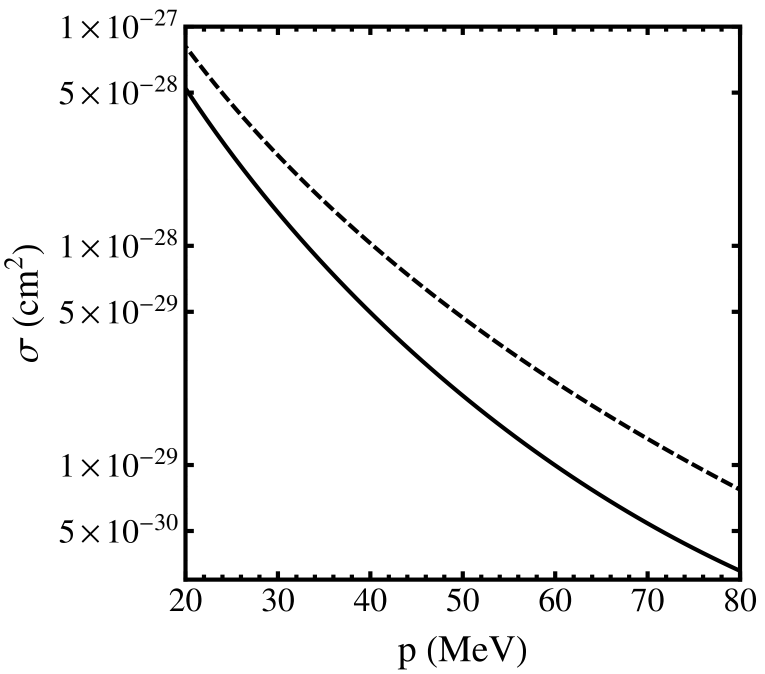
$$\mu^-_{\rightarrow} + Z \rightarrow (\mu^-_{\rightarrow} Z)_{2S_{1/2}} + \gamma_1; \quad 2S_{1/2} \xrightarrow{M1-E1} 1S_{1/2} + \gamma_2. \tag{8}$$

- *Single (M1) 2S-1S transition in muonic atoms have never been observed*
- *Atomic radiative capture (ARC),*
  μ⁻ (in flight)+ Atom → (μAtom) + γ, have never being observed
- P. Kammel and F. Wauters idea: detect 2S-1S transition in muonic atom cascades by coincidence (detecting nP → 2S transitions + 2S-1S. I.e. "tag" the 2S states.)

Atomic radiative capture

$$\sigma_{\mathrm{ARC}} = \frac{2\omega^2}{p^2}\sigma_{PE};\ \ \sigma_{PE} = \eta(p, R_c, Z, n, l) \times \sigma_{PE}^{(0)}(nl),$$

$$\sigma_{PE}^{(0)}(2S) = \frac{2^{14}\pi^2\alpha a^2 E_2^4}{3\omega^4}\left[1 + \frac{3E_2}{\omega}\right]\frac{\exp\{-\frac{4}{pa}\cot^{-1}\frac{1}{2pa}\}}{1 - \exp(-2\pi/pa)}$$



- Probability for ARC capture into the 2S state in a thin target approaches 10^{-6}.

Size of the effect, counting rate, etc

$$\mathcal{L}_{\rm SM} = -\frac{G_F}{2\sqrt{2}}\bar{\mu}\gamma_\nu\gamma_5\mu\left(g_n\bar{n}\gamma_\nu n + g_p\bar{p}\gamma_\nu p\right),$$

$$\mathcal{L}_{\rm NP} = \bar{\mu}\gamma_\nu\gamma_5\mu\frac{4\pi\alpha g_\mu^{\rm NP}}{m_V^2+\Box}\left(g_n^{\rm NP}\bar{n}\gamma_\nu n + g_p^{\rm NP}\bar{p}\gamma_\nu p\right)$$

$$\mathcal{A}_{\rm FB} = \frac{N_{\gamma_2}(\theta>\frac{\pi}{2}) - N_{\gamma_2}(\theta<\frac{\pi}{2})}{N_{\gamma_2}(\theta>\frac{\pi}{2}) + N_{\gamma_2}(\theta<\frac{\pi}{2})} = 2\delta\frac{({\rm E1})_{2P-1S}}{({\rm M1})_{2S-1S}}$$

$$\simeq 680\times\left(\frac{36}{Z}\right)^3\times\delta,\ i\delta = \frac{\langle 2S_{1/2}|H_{PV}|2P_{1/2}\rangle}{\Delta E},$$

$$\delta_{\rm SM} \simeq \frac{3\sqrt{3}G_F}{8\sqrt{2}\pi Z\alpha R_c^2}\left(g_p + g_n\frac{A-Z}{Z}\right),$$

$$\delta_{\rm NP} = \frac{3\sqrt{3}g_\mu^{\rm NP}}{2Z\alpha R_c^2 m_\mu^2}\frac{m_V a}{(m_V a+1)^3}\left(g_p^{\rm NP} + g_n^{\rm NP}\frac{A-Z}{Z}\right)$$

$$\mathcal{A}_{\rm FB}[{\rm SM}] \simeq 0.5\times 10^{-4},\quad \mathcal{A}_{\rm FB}[{\rm NP}] = (0.5-11)\%.$$

$$T[{\rm SM}] \sim 10^8\ {\rm s}\times\frac{10^{11}\ {\rm s}^{-1}}{\Phi_\mu},$$

$$T[{\rm NP}] \sim 3\times 10^5\ {\rm s}\times\frac{10^7\ {\rm s}^{-1}}{\Phi_\mu}\times\left(\frac{0.1}{\mathcal{A}}\right)^2$$

Starting to be sensitive to [optimistic] NP within ~ few days, digging out Z-boson exchange would require new more powerful beams.

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Conclusions:

A. Detecting P-odd effects in scattering requires some extra work: beams with spin flip possibility (JPARC), or spin-rotation via a variable number of turns at Fermilab. $Q^2 \sim 10\ \mathrm{GeV}^2$ is achievable, where asymmetry is $\sim 10^{-3}$. *SM can be tested in this setup*.

B. Optical activity at ~ 10-6 rotation angles ← difficult.

C. Muonic atom PNC – let's detect M1 2S-1S transition in any atom. Z above 30 is still an attractive possibility.