Muon scattering possibilities
(with focus on P-violation)

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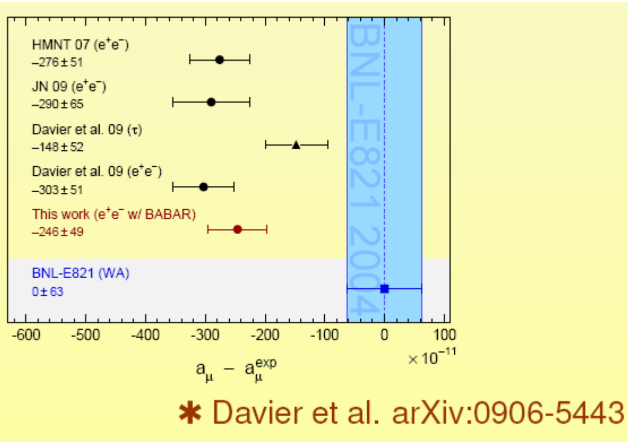
Outline of the talk

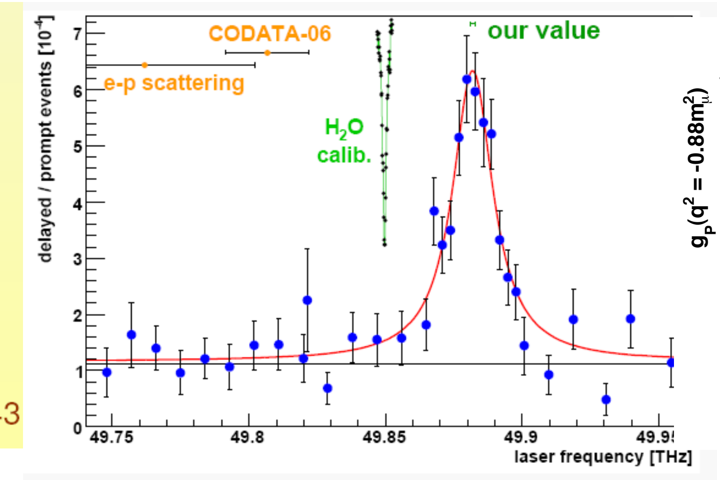
1. Motivation: Is everything OK with lepton Universality?
2. Parity violation with muons in Neutral currents. (History)

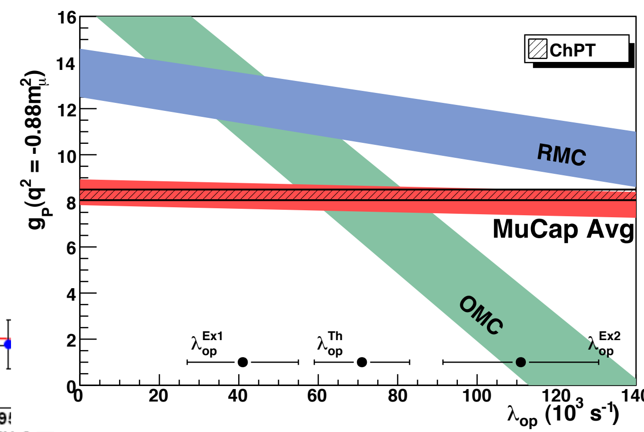
3. Options:
   a) scattering
   b) muonic atoms
   c) optical activity
   d) particle decays (e.g. eta factory)

4. Conclusion: opportunities for Fermilab.

“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.

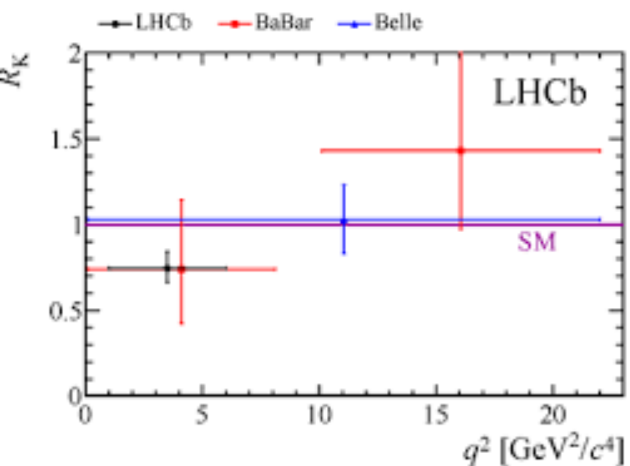
Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches of new phenomena associated with muons.

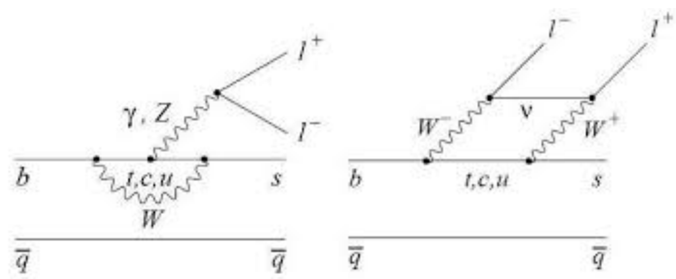
More problems recently in B-decays

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

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

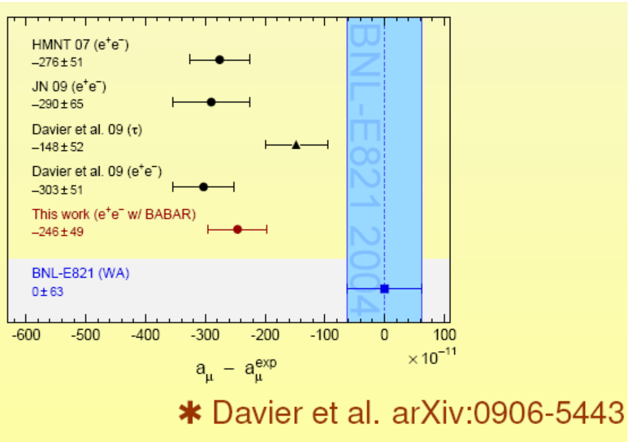
- Possible LFV in Higgs decays (talk to Roni Harnik!)

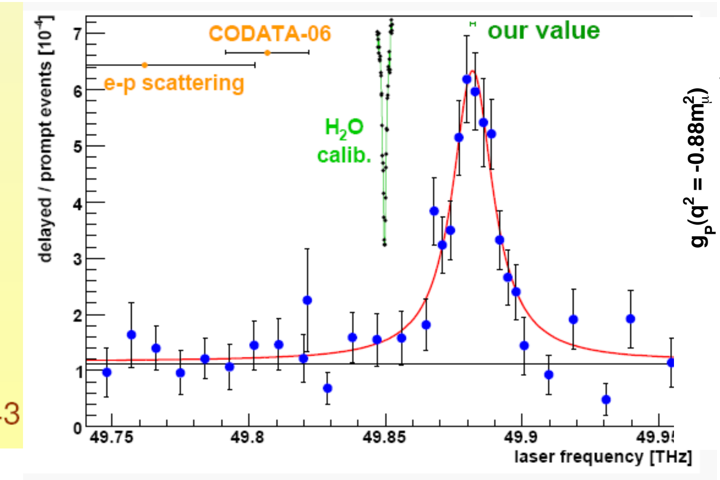


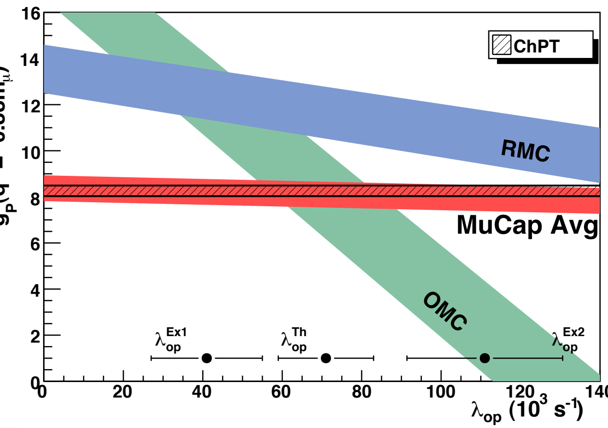


Can be result of New Physics at the TeV scale

If New Physics, heavy or light?



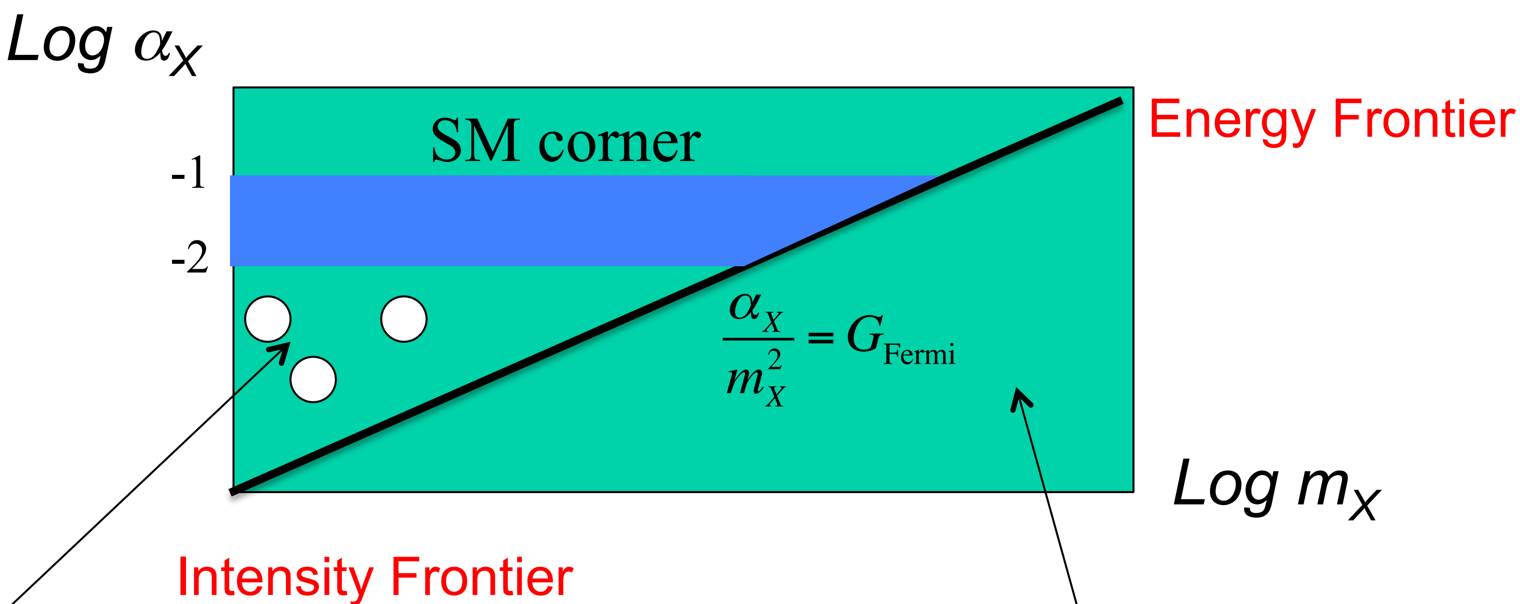




Can result from New Physics at 100 GeV scale or MeV scale

IF it is NP, it can only be light

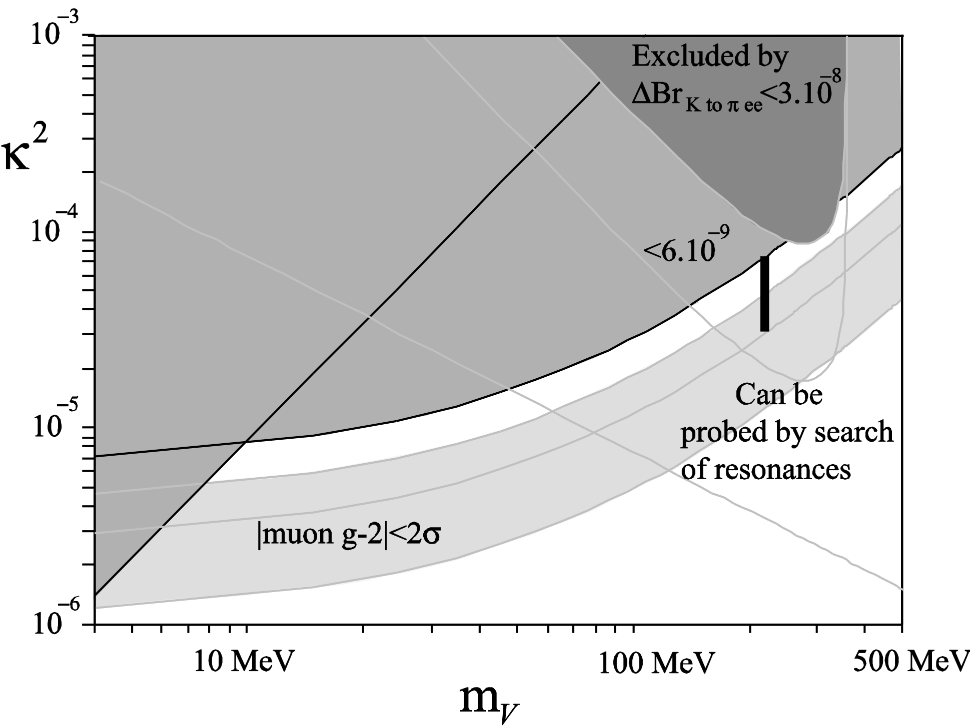
“Stronger than weak” New Physics



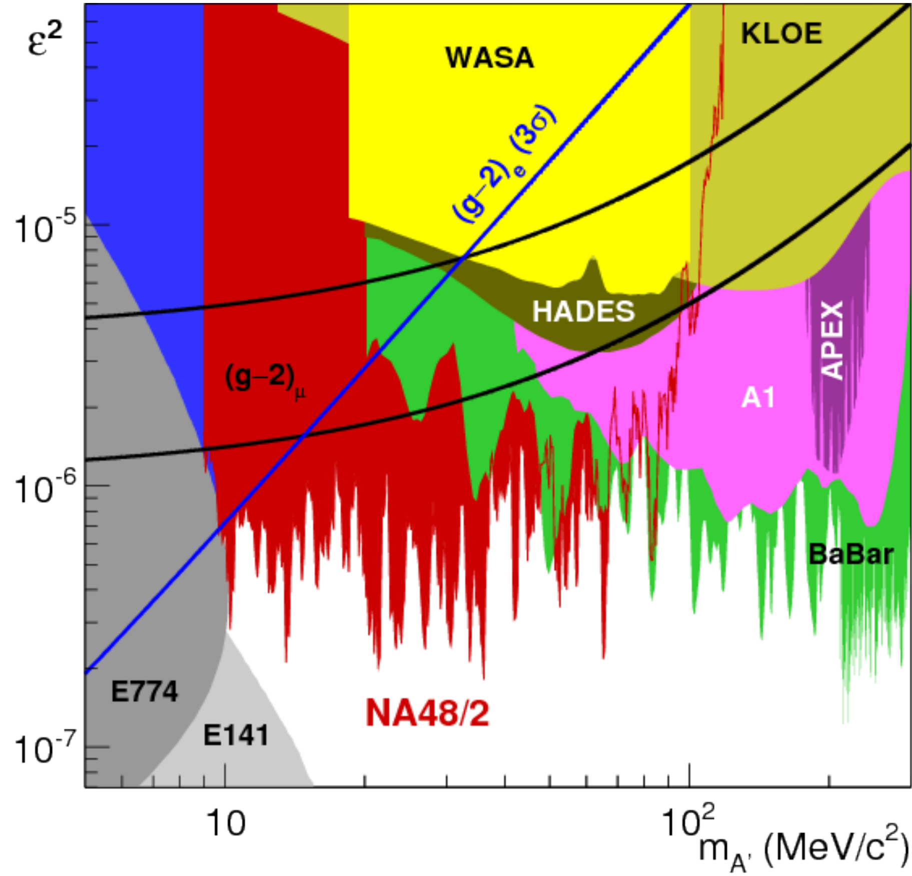
If you see new effects like e.g. $\mu \rightarrow eee$, EDM etc it’ll be here (can be 1000 TeV, difficult to access, and no pressing need for UV completion)

If you see NP effects in muon-H LS, it has to exist at $O(10^4\ G_F)$ level, deep inside the SM corner (e.g. Swiss cheese picture) *You have to specify how this NP fits into SM. Real chance to check in other exp*

Sometimes New Physics hypotheses can be ruled out faster than origin for discrepancy is found



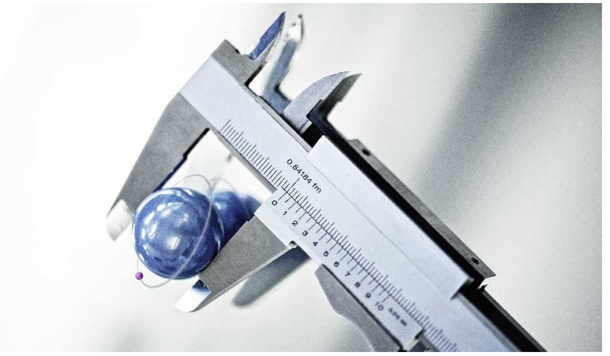
MP, 2008



aggregate exclusion plot, 2015

Since 2010 – r_p puzzle, Pohl et al, Nature2010

(just 75 years after Uehling & Serber)



After ~ 20 years of efforts the PSI experiment have worked, and we now have the most precise measurement of the [rather important for hadronic physics] observable

$$r_p = 0.84087(39) \text{ fm}$$

This is A. much more precise than previous e-p determinations

B. it is now ~7σ below the normal H LS and scattering results.

After ~5yr of collective efforts [to check, find source of errors etc] the issue remains unresolved.

Current status

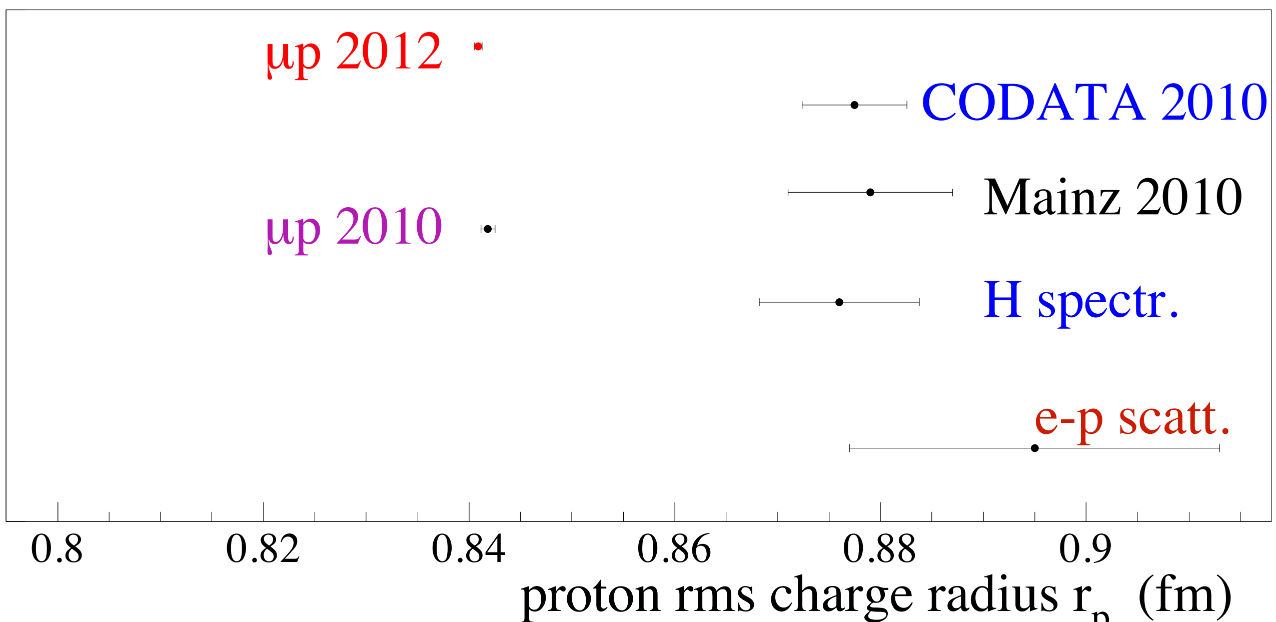
$\nu(2S_{1/2}^{F=1} \to 2P_{3/2}^{F=2})$ = 49881.88(76) GHz R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz preliminary

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

Proton charge radius: r_p = 0.84089 $(26)_\mathrm{exp}$ $(29)_\mathrm{th}$ = 0.84089 (39) fm (prel.)

$\mu\mathrm{p}$ theory: A. Antognini *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

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

The following pattern for the discrepancy emerges:

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

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 $\mathrm{fm}^2 e^2$ is *four orders of magnitude larger than Fermi constant*.

Arrington, Sick, 1505.02680, Lee, Arrington, Hill, 1505.01489

Source	r_E [fm]	r_M [fm]
Published results		
μH [9]	0.8409(4)	0.870(60)
eH [8]	0.8758(77)	-
Mainz A1 [7, 45]	0.8790(110)	0.777(19)
Zhan [3]	0.8750(100)	0.867(20)
Sick [5, 6]	0.8870(80)	0.855(35)
CODATA12 average [8]	0.8775(51)	-
New updates		
Mainz updated	0.8750(150)	0.799(28)
world updated	0.8810(110)	0.867(20)
naive global average	0.8790(90)	0.844(16)
suggested global average	0.8790(110)	0.844(38)

What are the possible origins of discrepancy?

1. Problems with experiments: either with μH, or with scattering and normal H. ??
2. Problems with QED calculations, either in μH or eH ??
3. A completely miscalculated "hadronic effect" in the two-photon proton polarization diagram ??

…

4. *May be some very new forces (= new physics) are at play that would have to be much weaker than EM and much stronger than EW* ??

More info on the whole issue can be found in the slides from workshops:
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Workshop/Talks

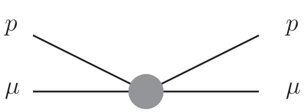
Why should we care about r_p problem?

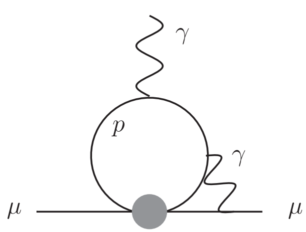
g-2 experiment "migrated" from BNL to Fermilab. *Cost of new exp is substantial.*

r_p problem is a huge challenge: if by any chance the muon-proton interaction is "large": either the two-photon strong interaction diagram or "light new physics", then g-2 is not really calculable with required precision!

$$\Delta\mathcal{L} \simeq C(\bar{\psi}_\mu \psi_\mu)(\bar{\psi}_p \psi_p),$$

$$C \text{ needs to be} \sim (4\pi\alpha) \times 0.01 \text{ fm}^2$$





$$\Delta(a_\mu) \sim -C \times \frac{\alpha m_\mu m_p}{8\pi^3} \times \begin{cases} 1.7; & \Lambda_{\rm had} \sim m_p \\ 0.08; & \Lambda_{\rm had} \sim m_\pi \end{cases}$$

$$5 \times 10^{-9} \lesssim |\Delta(a_\mu)| \lesssim 10^{-7}.$$

Shift is much larger than hadronic LBL error! Larger than discrepancy…

New physics attempts

Barger, Marfatia, Chiang, Keung; Tucker-Smith, Yavin; Batell, McKeen, MP; Brax, Burrage; Carlson, Winslow.

Common features of these attempts:

1. If *all* experiments and SM calculations are to be believed, it got to be a new force, that differentiates between e-p and μ-p.
1. Light, e.g. ~10 MeV in mass, particles are involved as careers.
2. Typically one or more of other constraints require additional tuning (g-2 of the muon, neutron scattering) – and one has to "model-build" yourself out of trouble.
3. Each model has its own problems (scalar model – needs to tune down neutronYukawa coupling; vector models – have to couple to μ_R) *Nobody on this list would ever claim that these are very natural or believable models.*

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, $V_\alpha \bar{l}\gamma_\alpha l \subset V_\alpha(c_1 \bar{L}\gamma_\alpha L + c_2 \bar{R}\gamma_\alpha R),\ c_1 \neq -c_2.$

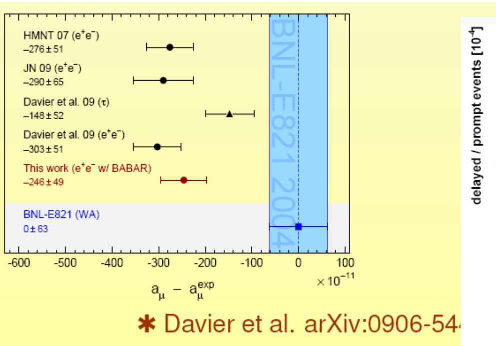
Other models??

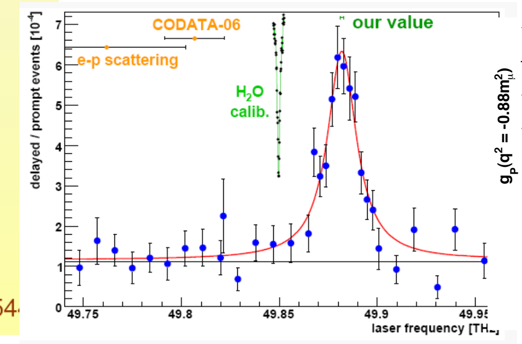
- How about the scalar force – call it *S* – that provides e-p repulsion and fixes r_p discrepancies at least between normal H and μH (Tucker-Smith, Yavin proposal)?

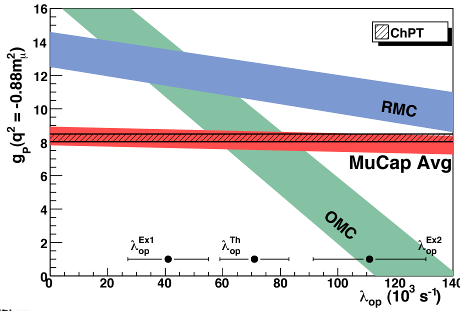
$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + (g_p \bar{p} p + g_e \bar{e} e + g_\mu \bar{\mu} \mu)\phi$$

- Couplings will be very small, and the mass will be small, O(200 keV), $y_e y_p / e^2 \sim -10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of astro and cosmo constraints
- Opportunity to study this in meson decays: e.g. decays of eta to π^0 + new light particle decaying to electrons.

Neutral Channels (NC) show discrepancies ? New tests?







Muon PNC in NC

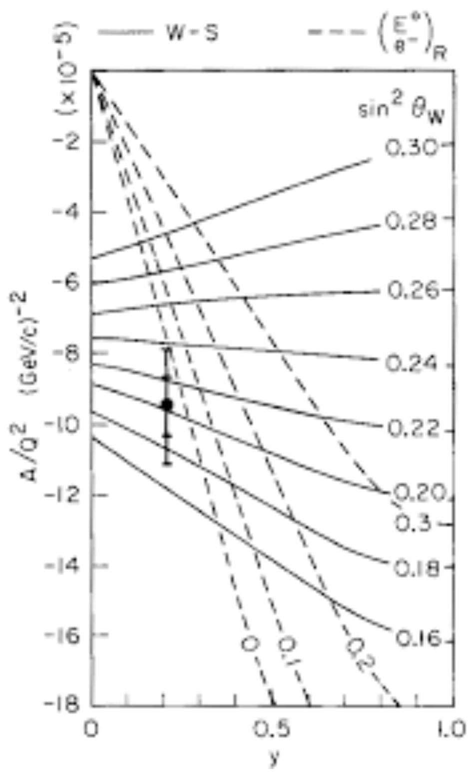
?

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.

Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches *of new phenomena* associated with muons.

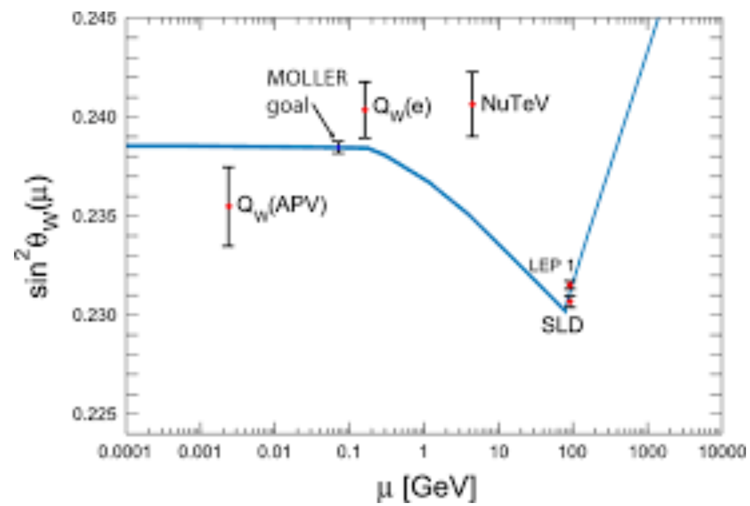
PNC with electrons

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), muonic atom PNC is not even 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 $V_{muons} \times A_{quarks}$, but not $A_{muons} \times V_{quarks}$. $Q^2 \sim 50\ \mathrm{GeV}^2$

- 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 $A_{muons} \times V_{quarks}$

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*]

A: PNC in muon scattering

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

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

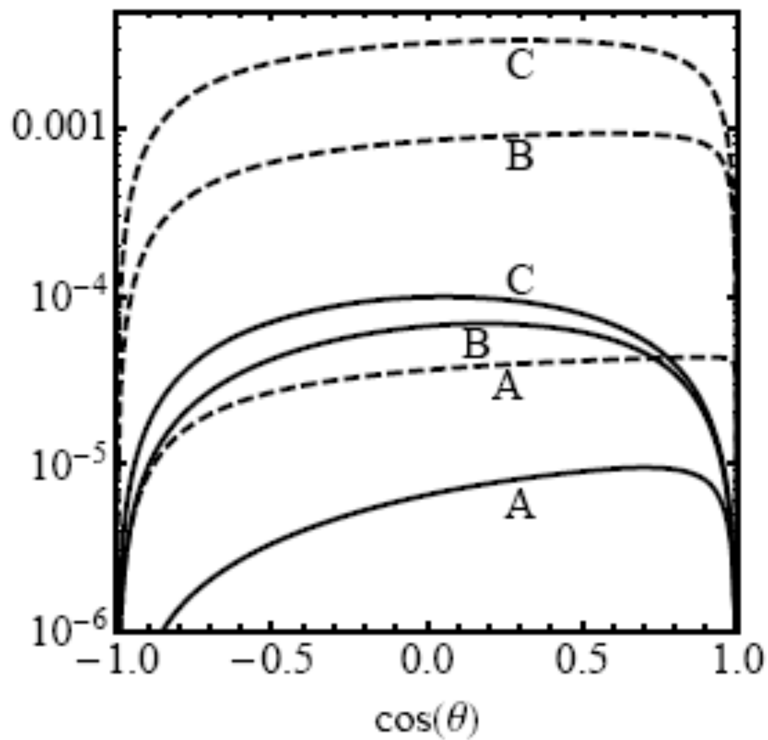


FIG. 1: The asymmetry $A_{\rm LR}(\theta)$ defined in Eq. (13) for the benchmark points labeled A, B, and C in Table I. The solid curves are for $p = 29$ MeV/c and dashed curves for $p = 100$ MeV/c.

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

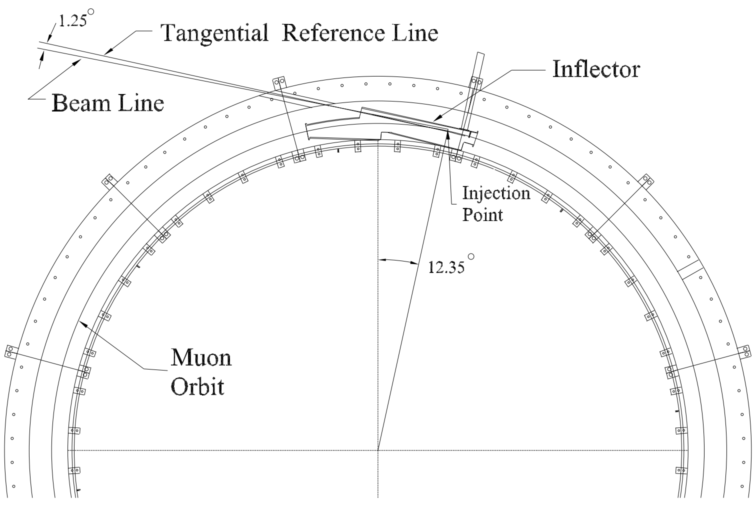
μ PNC via scattering on quarks (nuclei)

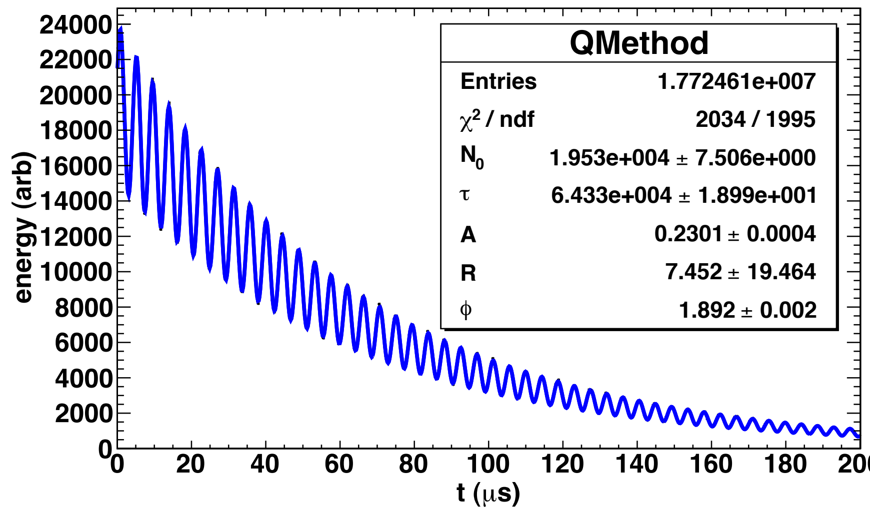
- Although muons come from pion decays with longitudinal polarization, it is difficult to flip this polarization in flight with enough reliability.

- 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





- Have a target inside the ring
- "Kick" muons into the target after variable number of revolutions. 15 revolutions flips the spin by 180 degrees.
- Measure the scattering with muon tracking detector

Disadvantage: small statistics due to muon number reductions at the injection. Alternatives: either a separate "muon spin rotator", or selection of muons with opposite polarizations

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) $A_{LR} \sim 10^{-4}$ at $Q^2 \sim 1$ GeV^2. Need more than 10^8 scattering events.
- DIS cross sections at $Q^2 \sim 1$ GeV^2 are $s_{DIS} \sim 4 \pi \alpha^2/Q^2 \times$ (order one numbers) $\sim 10^{-31}$ cm^2.
- After 20 cm of e.g. graphite target the probability to scatter at $Q^2 \sim 1$ GeV^2 is $P_{scatter} \sim 10^{-6}$. One would need over 10^{14} muons. Not feasible in the muon g-2 ring set up, 10^4 particles in the bunch, 10^8 bunches. (Scatter muons before they enter g-2 ring? How to rotate the spin?? Go to higher Q^2?)
- New Physics at low energy that enhances PNC: For example at $Q^2 \sim 0.01$ GeV^2 the cross sections are ~ 100 times larger, the asymmetry is 10 times larger. One would need 10^{10} muons to test this type of models. This appear quite feasible.

B: variation, muon optical activity

- Tip the spin 90 degrees relative to momentum – linear superposition of L and R longitudinal polarizations.
- Send muon inside the unpolarized medium. The angle of the spin will rotate in a certain direction due to PNC difference in refraction for L and R.
- Muon stops then decays, try to measure (θ_{finish} - θ_{start})
- *Never tried before.*
- SM looks too small (10^{-6} rad angles). NP-enhanced PNC?

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…

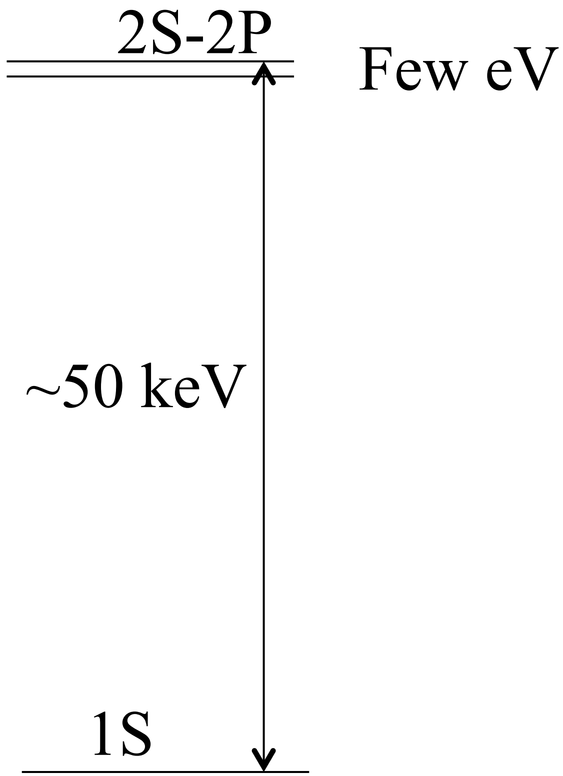
- New proposal (MP and McKeen), PRL 2012, arXiv:1205.6525

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)

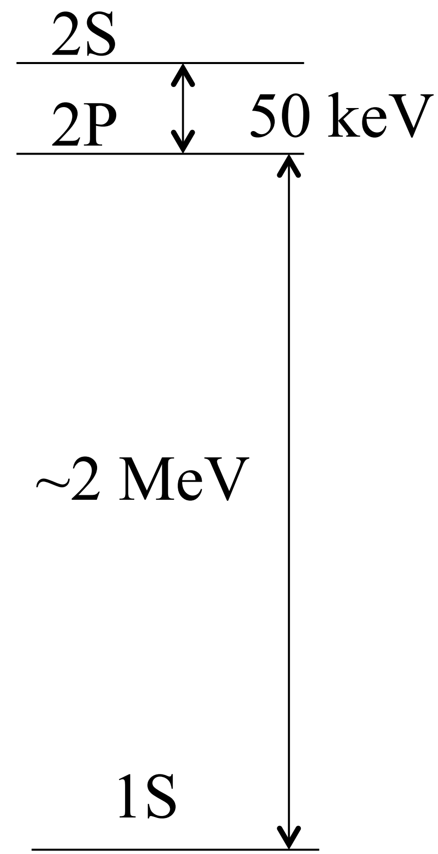
2s is pushed down by QED and up by finite nuclear charge

- Z~5



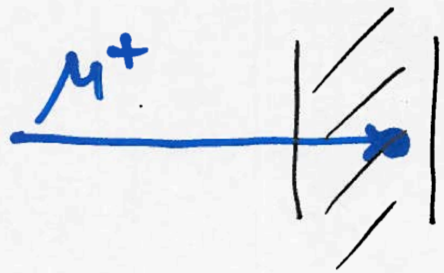
2S-1S and 2P-1S transitions cannot be distinguished on event by event basis

Z~30

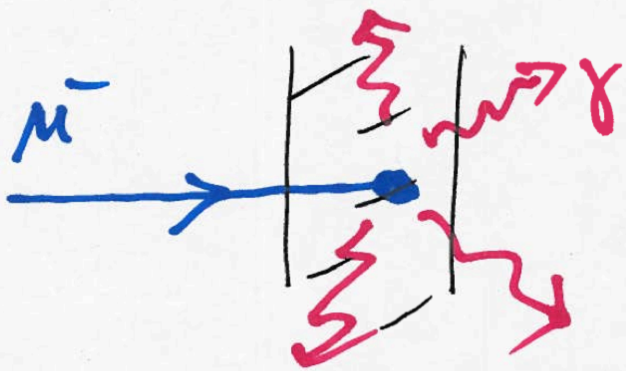


2S-1S and 2P-1S transitions can be distinguished (but was never observed)

Muonic cascade



μ^+ just stops.

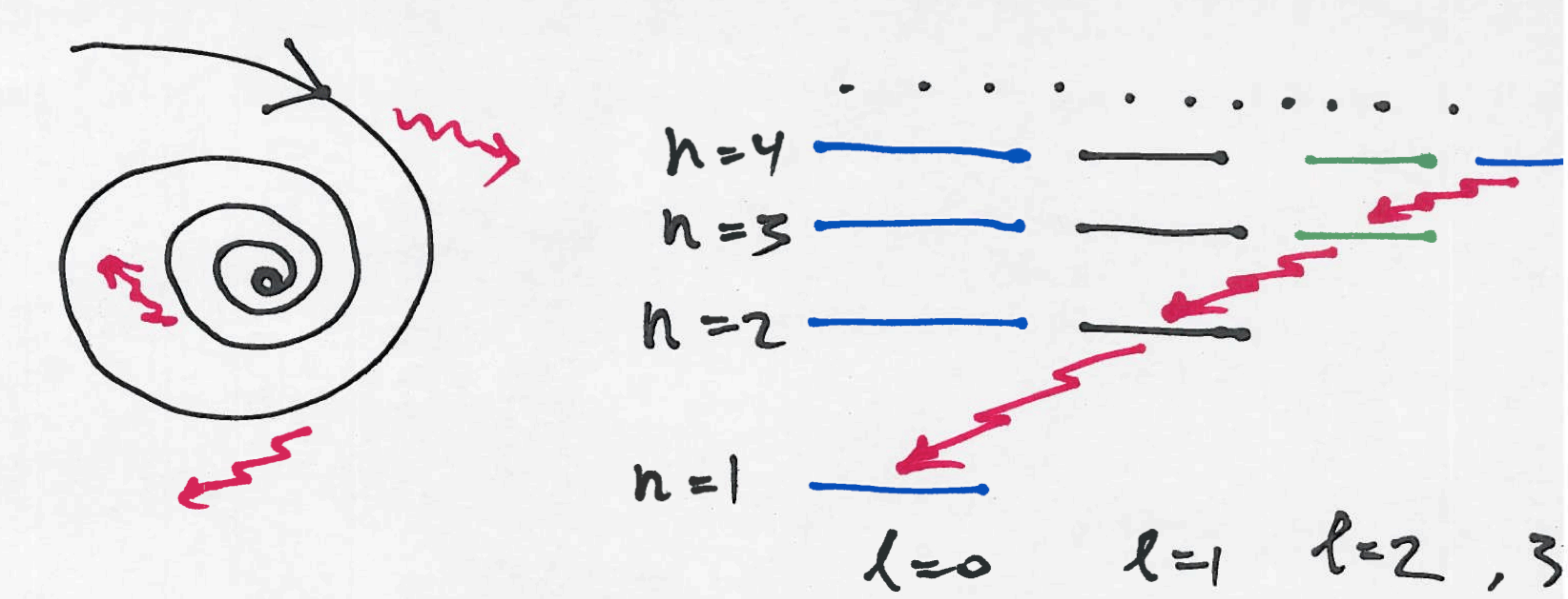


μ^-

1. Stops
2. Replaces an electron on $r \sim a_{Bohr}$ orbit ($n \cong 14$)
3. Cascades down to g.s emitting $O(10)\ \gamma$

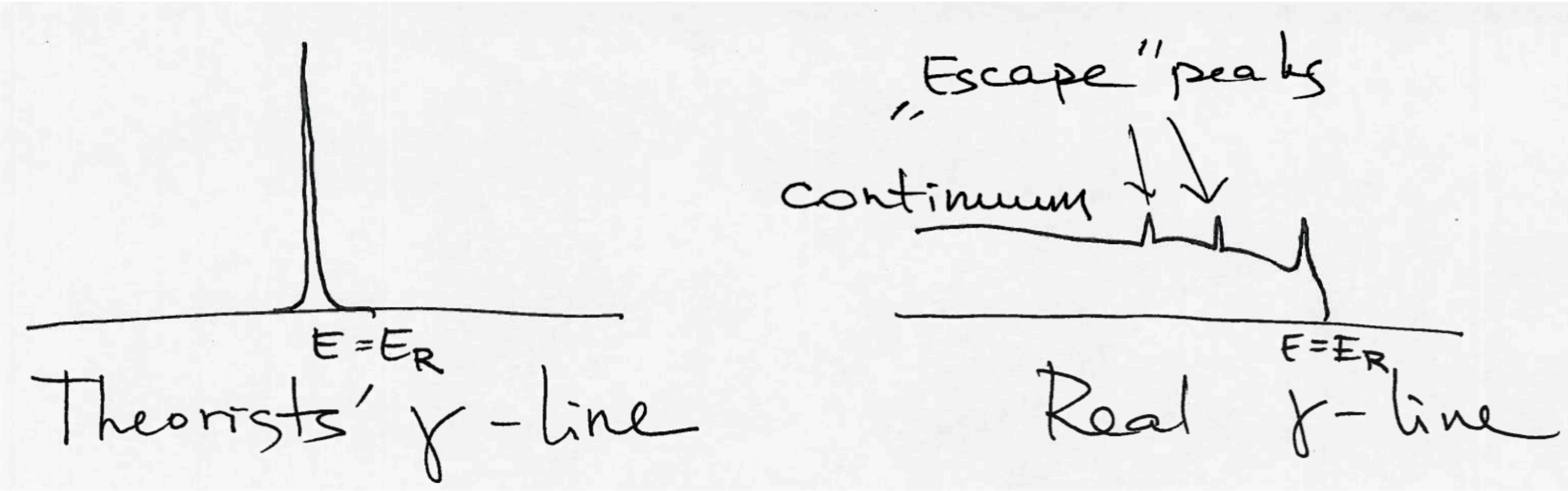
The binding energy in the ground state $E_b = \alpha^2 m_\mu/2 = 13.6\text{eV}\ (m^{red}_\mu/m_e)$ $= 2.5$ keV

2.5 keV excess energy is shed in the cascade



Muonic cascade is the only known way to make muonic atoms

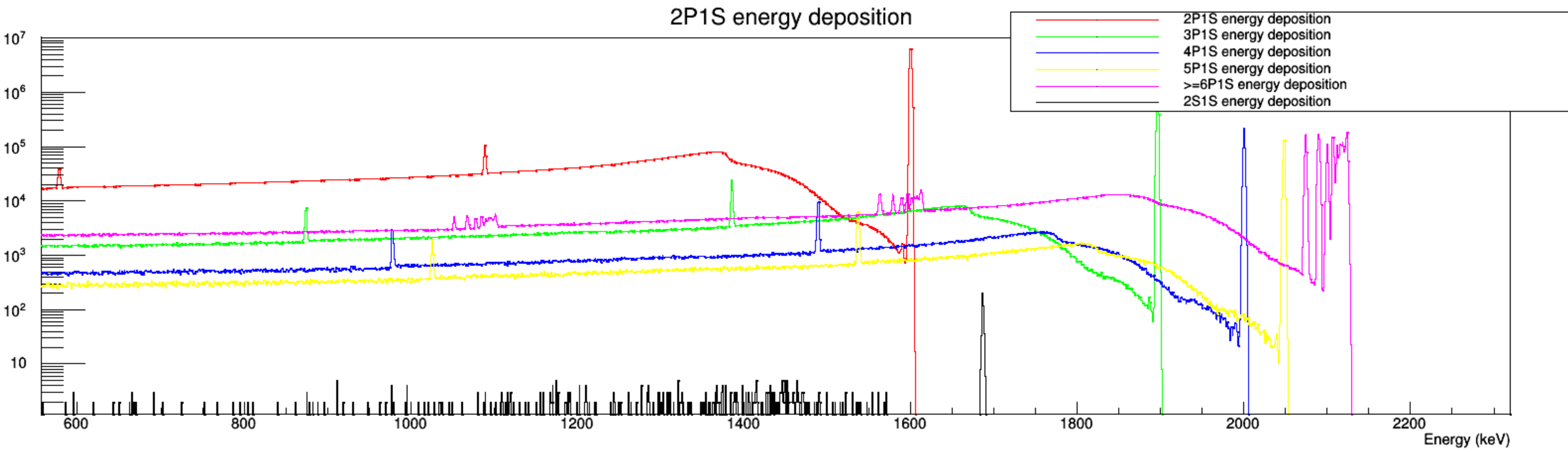
Difficulty with cascade: for 2S-1S S/B < 1%



Much more frequent nP-2S transitions from the cascade bury 2S-1S transition under their continuum !!.

I.e. too much background

2S-1S line is well-hidden under the nP-1S background in the cascade. Simulation for Z=30 by F. Wauters

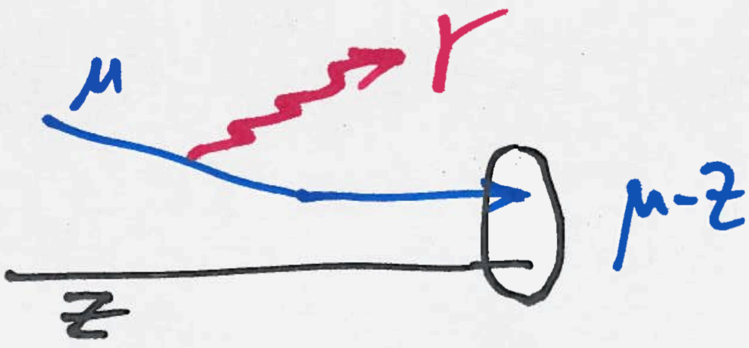


It will be very difficult to see the line in the cascade. But perhaps not impossible.

New way to make muonic atoms

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

Atomic radiative capture



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

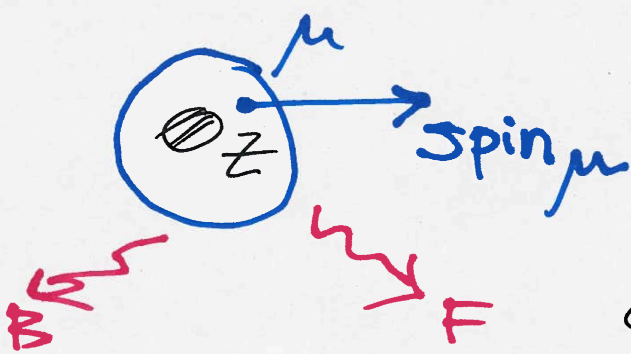
(e.g. $p = 40$ MeV muon capture to 1S state gives $E_\gamma \simeq 10.5$ MeV, much larger than γ in the cascade)

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

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

- New proposal (avoid the cascade),

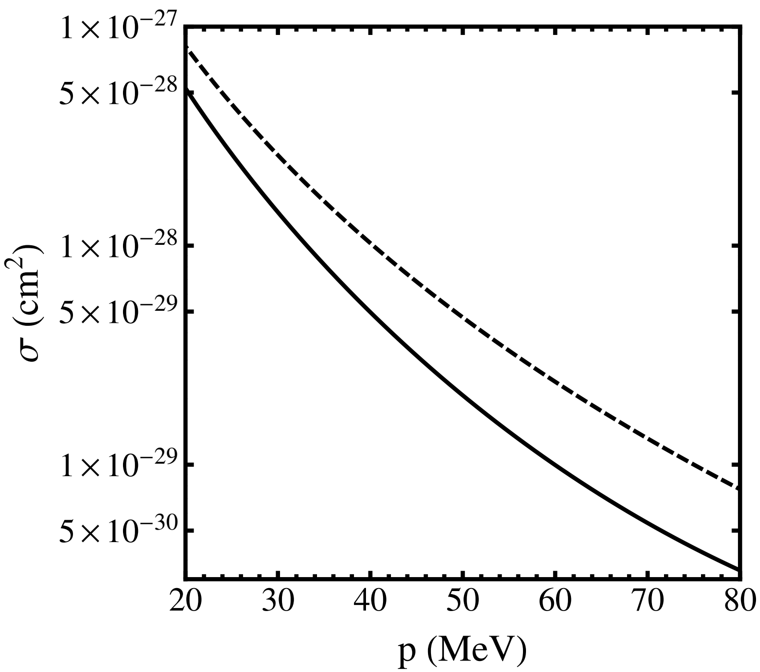
$$\mu^-_{\to} + Z \to (\mu^-_{\to} Z)_{2S_{1/2}} + \gamma_1; \quad 2S_{1/2} \xrightarrow{M1-E1} 1S_{1/2} + \gamma_2. \tag{8}$$

- *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

Atomic radiative capture

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

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



- 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.

PAUL SCHERRER INSTITUT

PSI

A new experimental effort underway (Klaus Kirch, Peter Kammel, Andreas Knecht, Frederik Wauters et al):

A. detect ARC process

B. B. try to detect 2S-1S transition either in the cascade or after ARC

C. Explore the feasibility of the future PNC experiment.

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.)

The REDTOP

experiment

Rare Eta Decays with a
Tpc for Optical Photons

Relevant for today's discussion because it will be a well-controlled source of muon pairs.

Corrado Gatto

For the REDTOP Collaboration

(slides are modified by M. Pospelov)

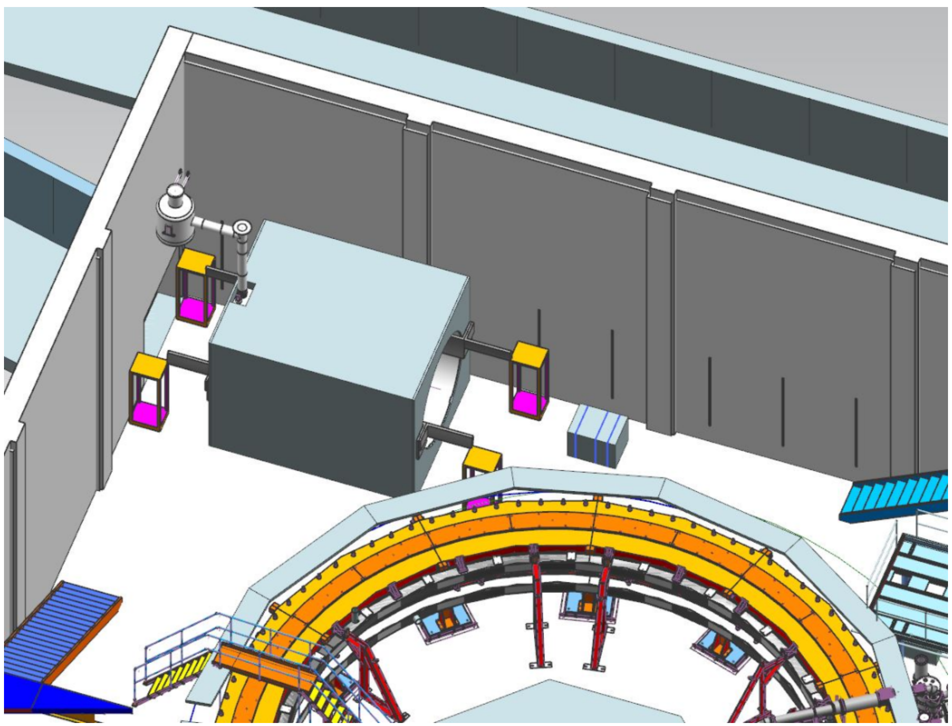
The Physics Case

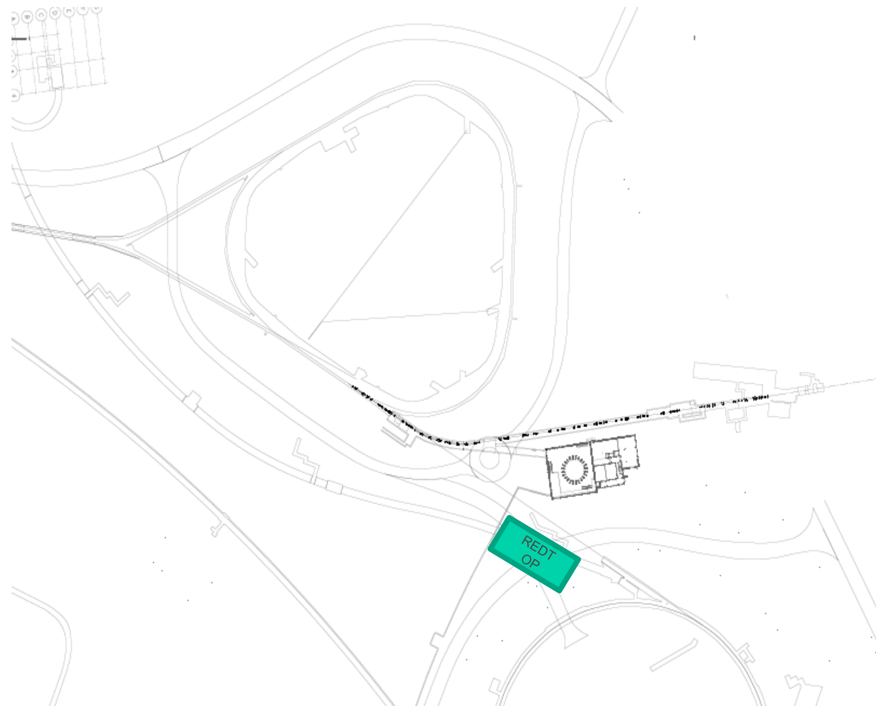
- *The η meson is a Goldstone boson: a very nice laboratory for physics BSM if you produce* $> 10^{10}$
- *Largest η meson sample would come from WASA:*

  $\sim 10^{8}\ pp \qquad pp$
- *Expected REDTOP production: $2x10^{12}$ - 10^{13} η mesons/year from p+Be*
- *Light new physics in the decays to $ee\gamma$, $\mu\mu\gamma$, $\pi^{0}\mu\mu$ can be tested. Dark photons and baryon current coupled vectors etc. Discrete symmetries can be tested, including Parity in $\mu^{+}\mu^{-}\gamma$ (via muon polarimeter).*

Accelerator complex

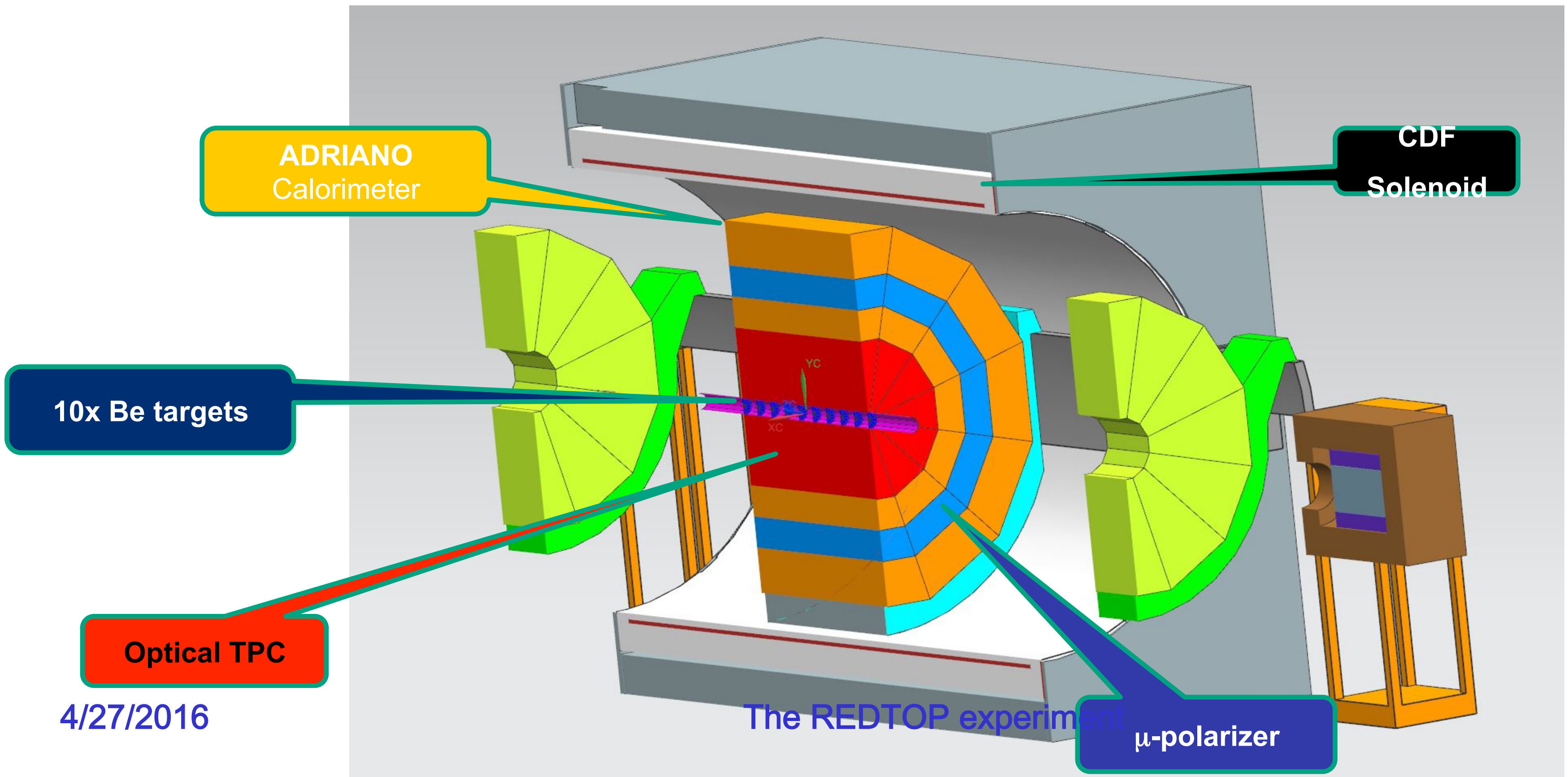
- Use g-2 accelerator complex and experimental site
- Decelerate 8 GeV beam to 1.8 GeV and debunch in the DR
- Required second RF-cavity already existing
- Minor adjustment of DR instrumentation





The REDTOP Detector

- Need to digest 1 interaction/10nsec and large pile-up (toward PIP-II era)
- Super-fast detector (based on Cerenkov effect) and electronics (ASICS)
- Three novel detectors:
  1. Optical-TPC (R&D from T1059 - UC)
  2. ADRIANO dual-readout calorimeter (R&D from T1015 a FNAL + INFN Collaboration)
  3. Active muon polarimeter (R&D for TREK at KEK)



The Experimental Apparatus

Detector

- *Beryllium or carbon fiber beam pipe, 10 cm dia x 1.5 m long*
- *1 cm dia targets disk inside the pipe, spaced 10 cm apart*
- *Aerogel around the beam pipe, 3cm thick (for most muons and fast pions detection)*
- *Optical-TPC 1m diameter x 1.5 m long*
- *γ-polarimeter in the rear section of the Optical-TPC*
- *ADRIANO calorimeter: ~20 Xo (same as ORKA) or 64 cm deep. Inner and outer sections to accommodate the μ-polarimeter in between*
- *Total detector dimensions: 2.2 m dia x 2.7 m long*
- *CDF solenoid run at 0.6 T (3 m inner diameter x 4.8 m long)*
- *A0 cryogenics infrastructure close to experiment location (Tevatron commissioning transfer tunnel) or existing cryogenics on the muon campus*

- *Potential interest from CERN-Geant4 group on instrumenting the fwd and bkg detector regions (for G4 validation of new hadronic models)*

REDTOP Physics Program (IX)

Low energy η physics

- *Nuclear models*
- *Chiral perturbation theory*
- *Non-perturbative QCD*
- *Isospin breaking due to the u-d quark mass difference*
- *Octet-singlet mixing angle*
- $\pi\ \pi$ *interactions*
- *Electromagnetic transition form-factors (important input for g-2)*
- *Lots of other bread&butter physics*

Present η Samples

A. Starostin - UCLA

	Technique	$\eta \to 3\pi^0$	$\eta \to e^- e^+ \gamma$	Total η
CB@AGS	$\pi^- p \to \eta n$	$9x10^5$		10^7
CB@MAMI-B	$\gamma p \to \eta p$	$1.8x10^6$	5000	$2x10^7$
CB@MAMI-C	$\gamma p \to \eta p$	$6x10^6$		$6x10^7$
KLOE	$e^+ e^- \to \phi(1020) \to \eta \gamma$	$6.5x10^5$	????	$5x10^7$
WASA@COSY	$pp \to \eta pp$ $pd \to \eta\ ^3He$			$>10^8$ $3x10^7$
CB@MAMI (proposed)	$\gamma p \to \eta p$	$3x10^7$	$1.5x10^5$	$3x10^8$

Near future η Samples

GlueX@JLAB (proposed) $\gamma p \to \eta\ p \to$ neutrals $4.5x10^7$/yr

REDTOP@FNAL (proposing) $pp \to \eta\ pp$, $pn \to \eta\ pp$ **$2x10^{12}$**

The Experimental Apparatus

Beam & Target

- E_{beam} = 1.8 ÷ 2.0 GeV (still under optimization)
- Intensity: 1×10^{11} POT/sec – continuous
- Beam power @ 1.8 GeV: 10^{11} p/sec × 1.8 GeV × 1.6 × 10^{-10} J/GeV = 30 Watts
- Target: 10 x 0.1mm Nb or 10 x 0.33mm Be foils, spaced 10 cm apart
- Nb is thinner (better vertex resolution) but makes more primary hadrons (final state hadron multiplicity ≈ $A^{1/3}$)
- Prob(p + target -> X) = 0.5%
- Power dissipated from target:
  - 150 mW total
  - 15 mW per target foil
- Therefore, no need for target cooling

- p-inelastic production: 5×10^{7} evt/sec (1 interaction/20 nsec in any of the 10 targets)
- production: 2×10^{5} η /sec or
- Charged mode (2% acceptance) : 1 L0 trigger/1000 nsec or
- Neutral mode (10% acceptance) : 1 L0 trigger/200 nsec or

Conclusions

- Muons seems to "accumulate anomalies". g-2, μH, etc. No measurements of PNC with muons ($A_{muons} \times V_{quarks}$) – would be interesting to do.
- New physics "explanations" of r_p discrepancy are problematic because of $\sim 10^4 G_F$ size of the effect – difficult to embed in the SM. Have to tune many observables (g-2 of the muon, possibly neutron scattering)…At the same time, $\sim 10^4 G_F$ size effect gives us a chance to look for it in a symmetry-violating channel.
- Many possibilities at Fermilab. Muonic scattering, possibly muonic atoms. [How to reach SM PNC level of sensitivity?]
- It looks like one need some new bright ideas how to test SM size asymmetries. Typically 10^{-4} and smaller. New physics contributions can be tested with non-trivial precision.