Precision Muon* Physics

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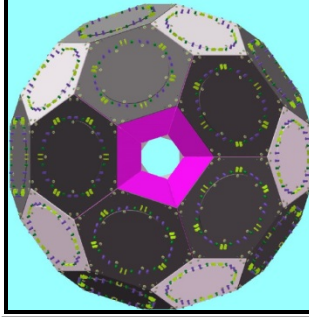
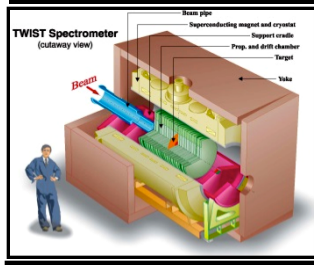
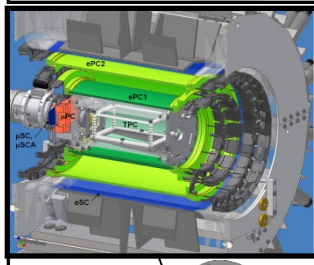
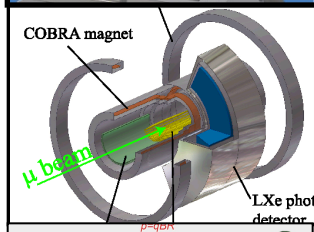
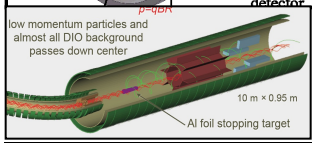
- Muon primer
- Facilities / Community (see Brad Plaster's talk)
- Landscape: Recent | Current | Future
- Accomplishments last 5 years
- U.S. driven program going forward
  - MuSun
  - g-2
  - MUSE
  - Mu2e

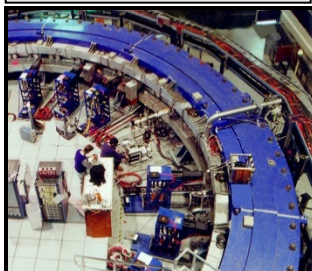












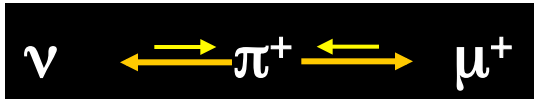
*perhaps a word on two completed pion decay experiments

Muon Primer

- **Mass ~ 207 m_e** (50 ppb)
  - $(m_\mu/m_e)^2 \approx 43{,}000$ times more sensitive to "new physics" through quantum loops compared to electrons

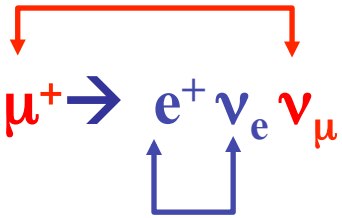
- **Lifetime ~2.2 μs** (1 ppm)
  - High-intensity beams; can stop and study; can possibly collide

- **Primary production: $\pi^+ \rightarrow \mu^+\nu_\mu$** (99.98%)
  - Polarized naturally:



- **Primary decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$** (~99%)
  - Purely weak; distribution in θ and *E* reveals weak parameters

- **Lepton number is conserved**
  (BRs < 10^{-12})



Landscape: US vs International Lead

Recent | Current | Future

US Lead		International Lead
μ^+ lifetime (G_F)		Michel Parameters
μp capture (g_P)		Lamb Shift (r_p)
μd capture (L_{1A})		cLFV $\mu \rightarrow e\gamma$
μAl capture (hadron xs)		COMET $\mu \rightarrow e$
g-2 E989		Mu HFS
μEDM		g-2 E34
μp scattering (r_p)		μEDM
Mu2e Conversion		cLFV $\mu \rightarrow eee$

Landscape: by Laboratory

Recent | Current | Future

FNAL	PSI	J-PARC
g-2 E989	μ^+ lifetime (G_F)	COMET $\mu \rightarrow e$
μEDM	μp capture (g_P)	Mu HFS
Mu2e Conversion	Lamb Shift (r_p)	g-2 E34
	μd capture (L_{1A})	μEDM
	cLFV $\mu \rightarrow e\gamma$	
	μAl capture (hadron xs)	
	μp scattering (r_p)	
	cLFV $\mu \rightarrow$ eee	
	TRIUMF	
	Michel Parameters	

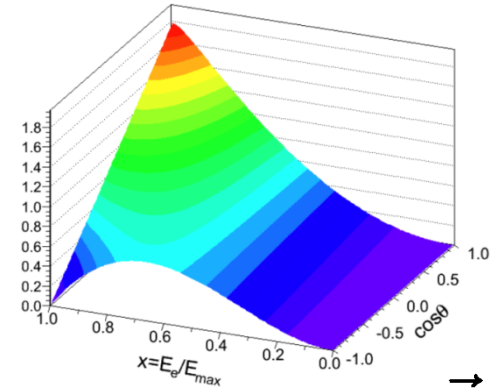
Landscape: by Community and Time

Recent | Current | Future

ATOMIC	NUCLEAR	HIGH ENERGY
Muonium **Mu HFS**		
Lamb Shift **CREMA** (r_p)	μp scattering **MUSE** (r_p)	
	μp capture **MuCap** (g_P)	
	μd capture **MuSun** (L_{1A})	
	μ^+ lifetime **MuLan** (G_F)	
	Michel Parameters **TWIST**	
	Anomalous moment **g-2 Expts**	
	μEDM **g-2 Expts**	
		cLFV **MEG**
		cLFV **Mu2e & COMET**
		cLFV **Mu3e**

Selected Recent Results:

TWIST: muon decay parameters $\rho, \eta, \mathcal{P}_\mu\xi, \delta$



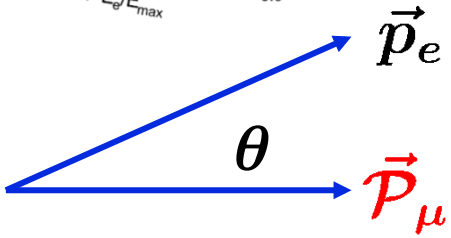
Is muon decay purely V-A?

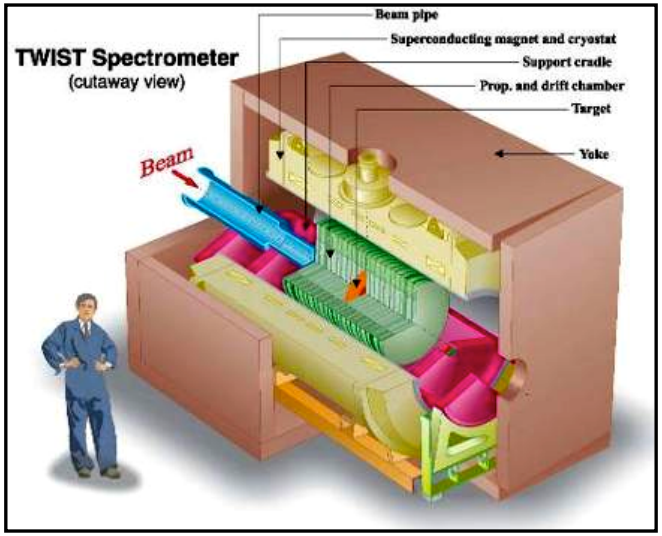
Sensitive to attractive SM extensions:

e.g. L-R symmetric models, would permit a W_R

Method

Measure the energy and angular distribution of e^+ from $\mu^+ \rightarrow e^+\nu_e\nu_\mu$





Consistent with SM at 10^{-3} level

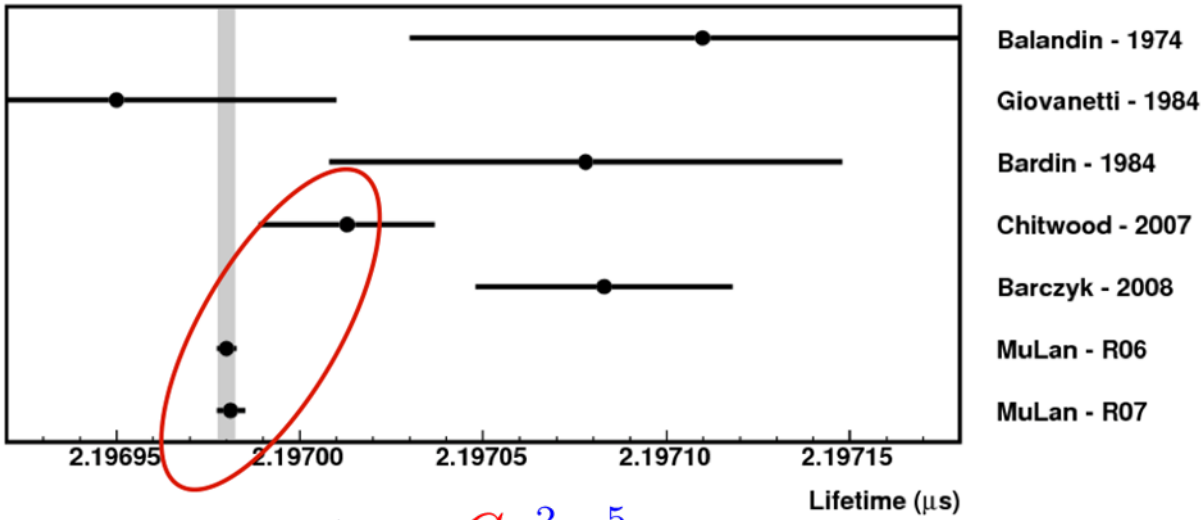
	SM
$\rho = 0.74977 \pm 0.00012\ (\text{stat}) \pm 0.00023\ (\text{syst})$	3/4
$\delta = 0.75049 \pm 0.00021\ (\text{stat}) \pm 0.00027\ (\text{syst})$	3/4
$\mathcal{P}_\mu{}^\pi\xi = 1.00084 \pm 0.00029\ (\text{stat})\ ^{+0.00165}_{-0.00063}\ (\text{syst})$	1

PHYSICAL REVIEW D 84, 032005 (2011)

Phys. Rev. D 85, 092013 (2012)

Selected Recent Results:

MuLan: Lifetime; Fermi Constant



$$\frac{1}{\tau_{\mu^+}} = \frac{{G_F}^2 m_\mu^5}{192\pi^3}(1+q)$$

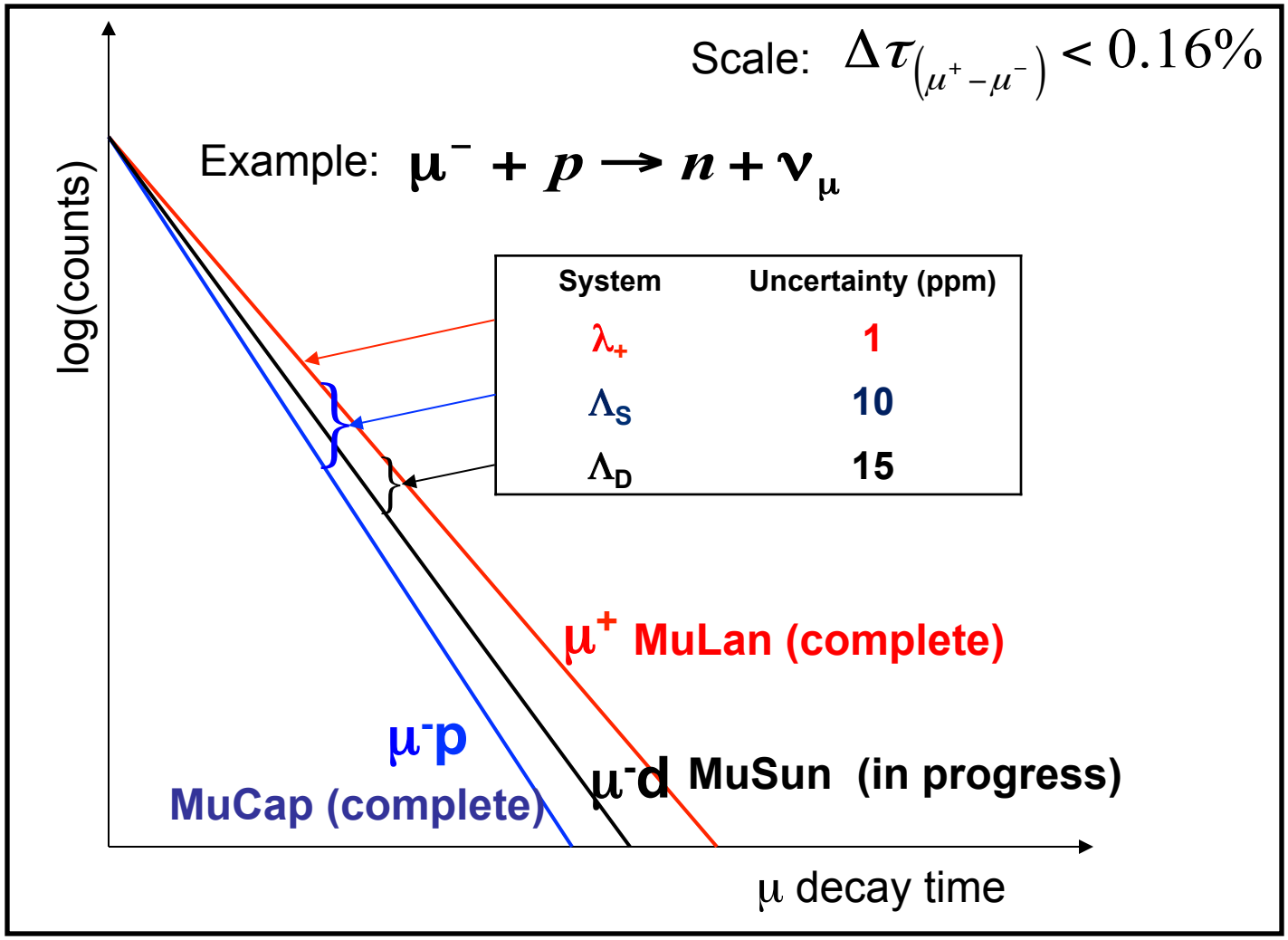
τ_μ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)
(30x improved since 1999 PDG)

The most precise particle or nuclear or atomic lifetime ever measured

PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (**2013**)

The 1 ppm μ^+ lifetime is compared to the μ^- lifetime in gaseous p or d targets to determine the capture rate



$$1/\tau = \Lambda\downarrow\text{total} = \Lambda\downarrow\text{decay} + \Lambda\downarrow\text{capture}$$

Extract physics here

Selected Recent Results:

MuCap: Muon Capture on the Nucleon

$\mu + p \rightarrow n + \nu$

Singlet capture rate: Λ_S

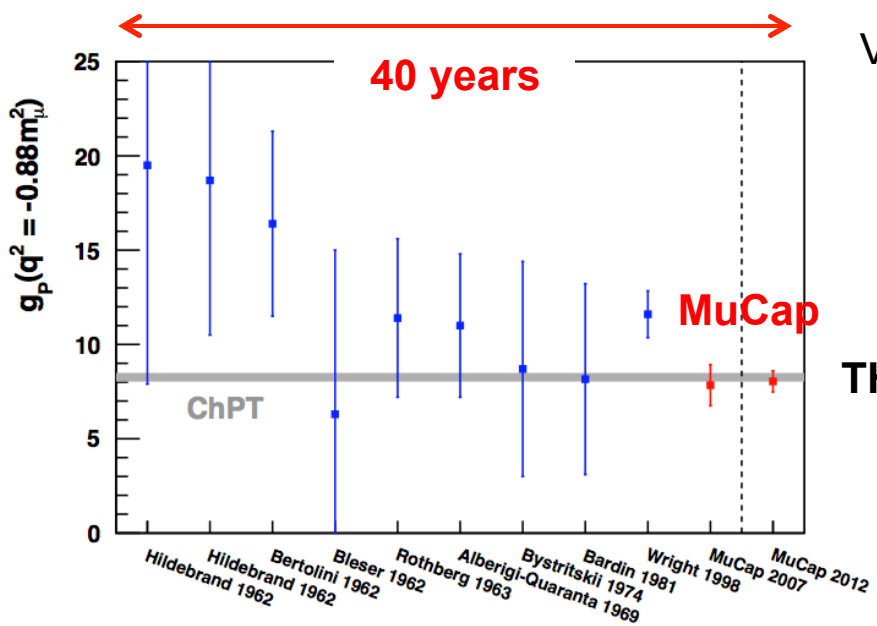
$$H_{weak} = \frac{G_F}{\sqrt{2}} V_{ud} L_\mu (V^\mu - A^\mu)$$

$$V_\alpha = g_V(q^2)\,\gamma_\alpha + \frac{i\,g_M(q^2)}{2\,M_N}\,\sigma_{\alpha\beta}\,q^\beta$$

$$A_\alpha = g_A(q^2)\,\gamma_\alpha\,\gamma_5 + \frac{g_P(q^2)}{m_\mu}\,q_\alpha\,\gamma_5$$

- χPT parameter free prediction: $g_P = 8.26 \pm 0.23$
- Final experimental result: $g_P = 8.06 \pm 0.55$

Verifies basic prediction of low energy QCD



THEORY

PRL 110, 012504 (2013)
APS Editor's spotlight
Physics World

TPC: EPJA, accepted

Current: MuSun μd capture

$$\mu + d \rightarrow n + n + \nu$$

- Motivation

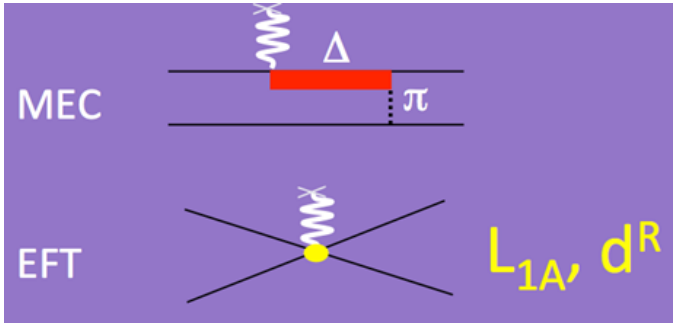
  Measure weak coupling of two-body axial current

- Theory

  Potential models and MECs

  EFT

  - pion less EFT, $\mathbf{L_{1A}}$
  - HBχPT, $\mathbf{d^R}$ sole unknown LEC up to N^3LO



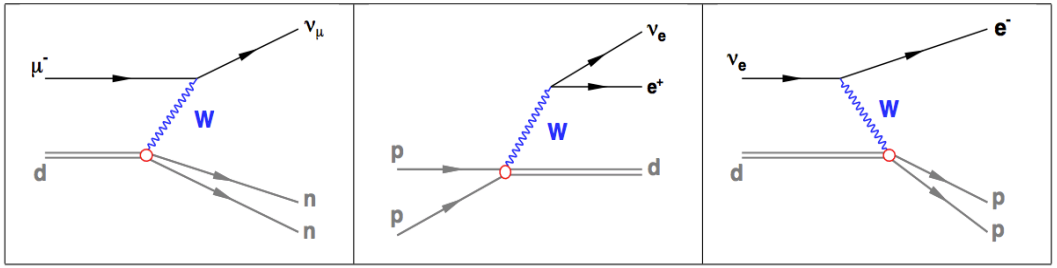
- Model independent connections via d^R

  2N weak processes

Sun $p\,p \rightarrow d\,e^+\,\nu$

SNO $\nu_e\,d \rightarrow p\,p\,e^-$ (CC)

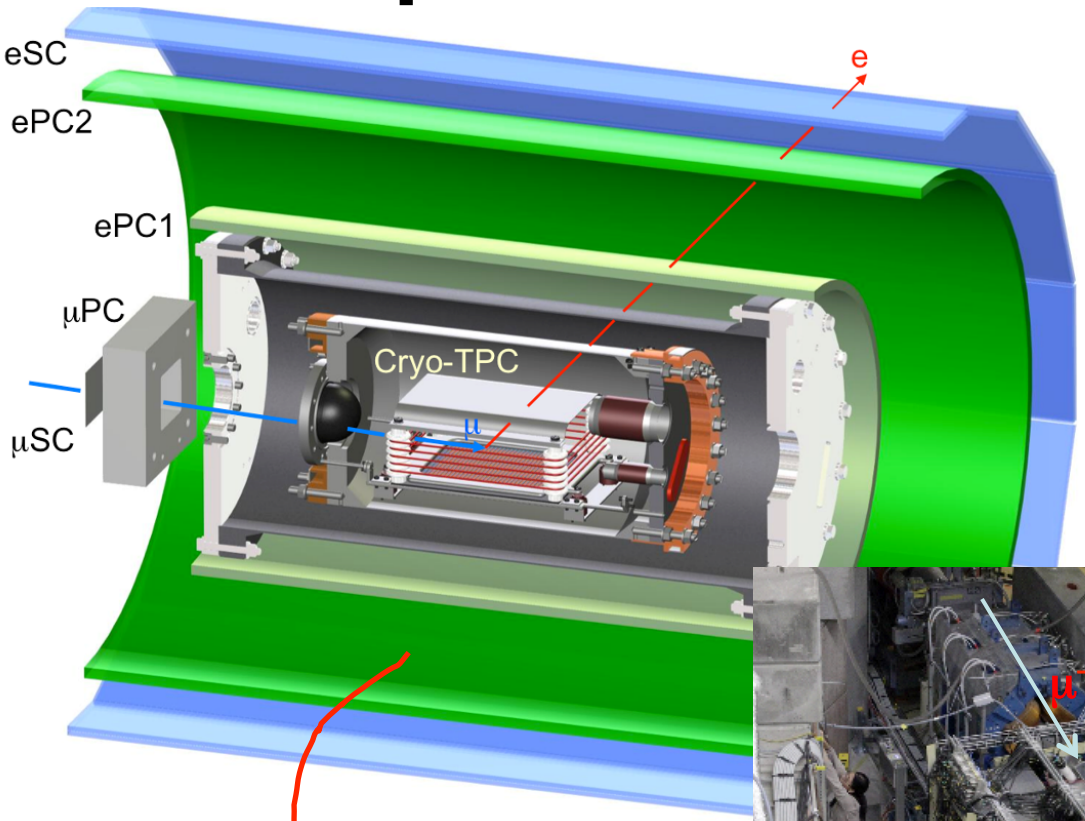
$\nu_x\,d \rightarrow p\,n\,\nu_x$ (NC)

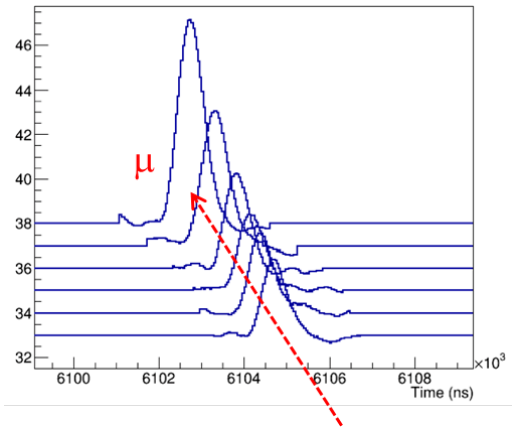


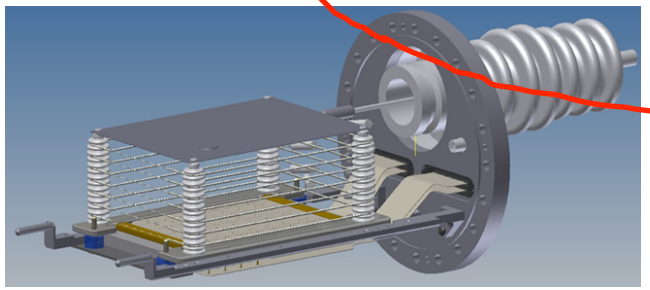
μd Capture Λ_d pp Fusion ν CC

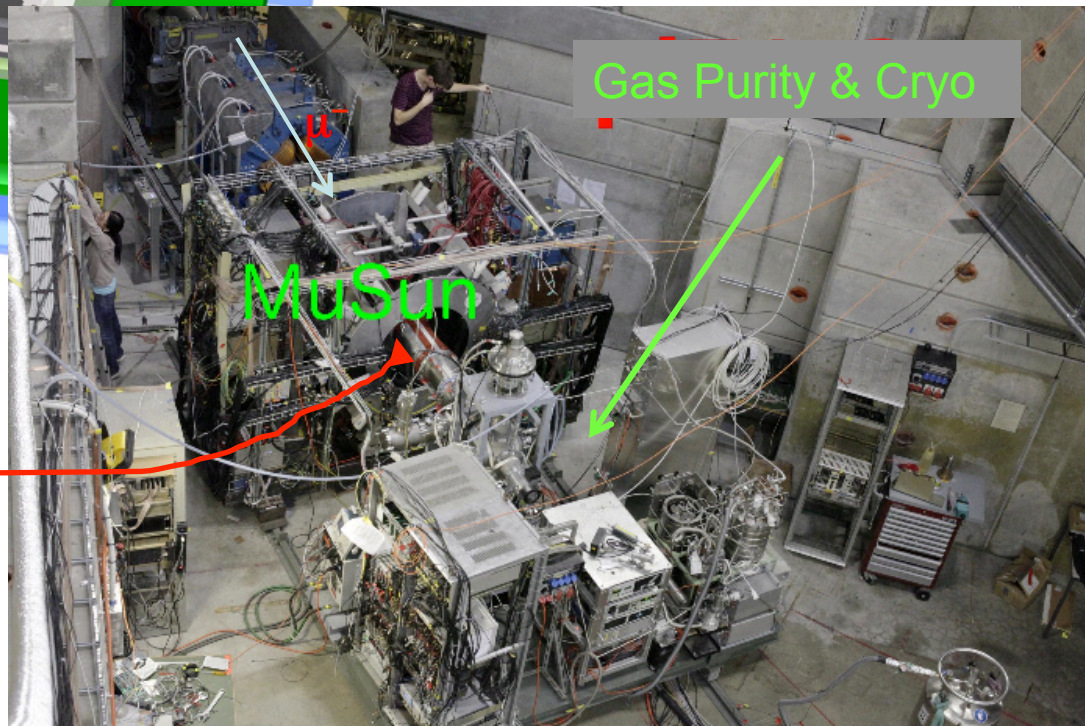
Λ_d denotes the capture rate from the doublet hyperfine state of the μd atom in its 1S ground state.

Experimental Setup at PSI



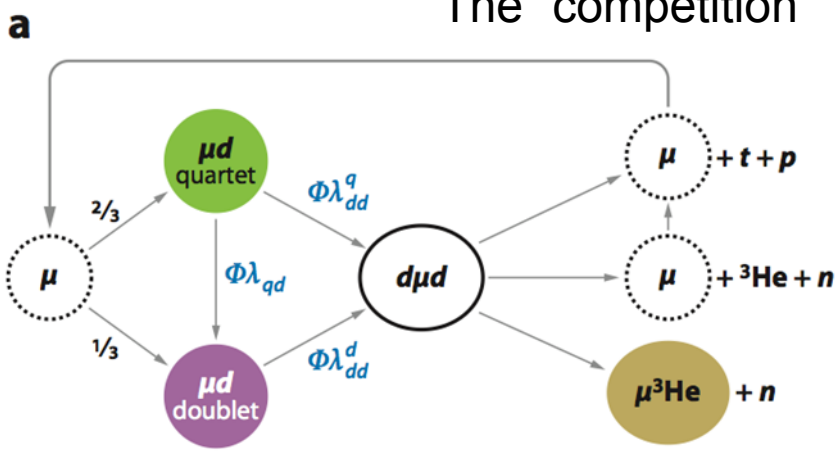


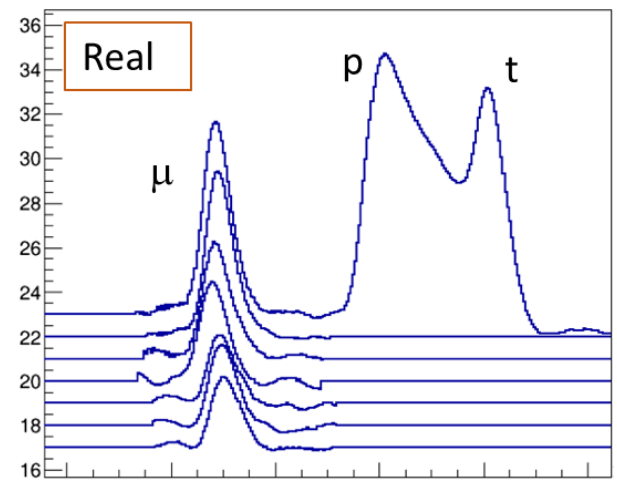




Special Challenges

The "competition"



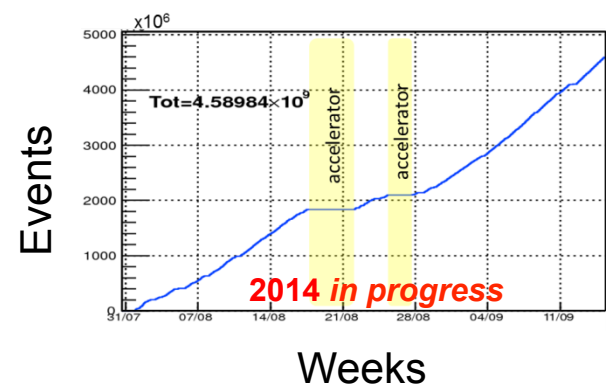


The "signal"

Muon catalyzed fusion

Status and Future

- → 2013: Development completed
- 2014: 40% statistics obtained
- 2015: complete; aim 1.5 x 10^{10} events
- Goal: Λ_d for muon capture to 1.5%

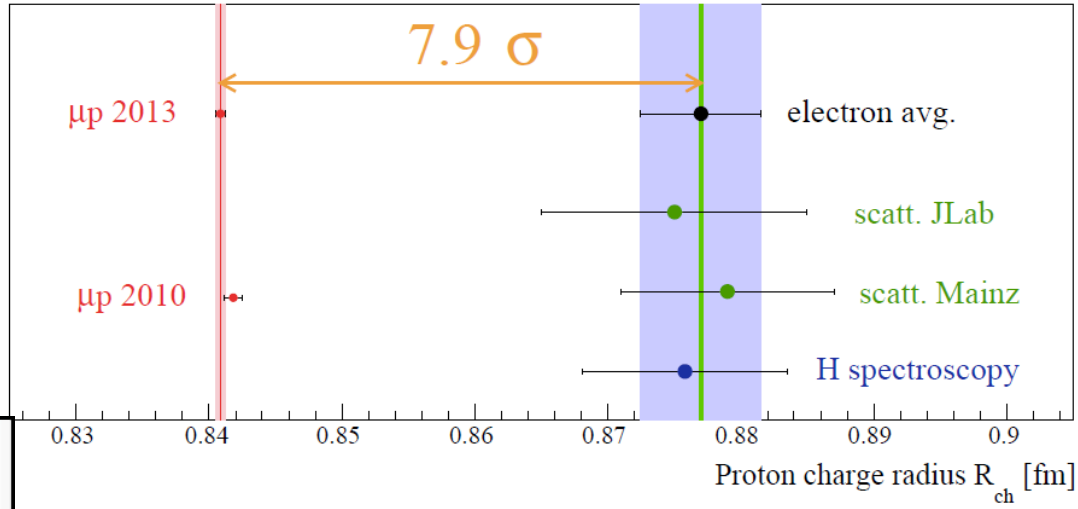


Current: Muonic p, d, He X rays

– Charge radius of the proton

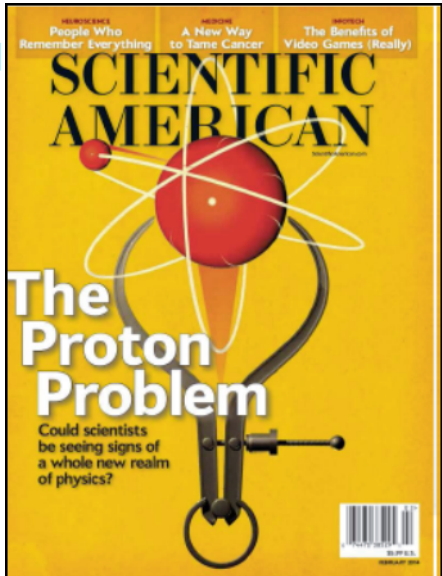
– Measure 2S → 2P Lamb shift

$$\Delta E(2S-2P) = 209.978(5) - 5.226\, r_p^2 + 0.0347\, r_p^3 \quad \text{meV}$$



WHAT COULD THIS MEAN ?

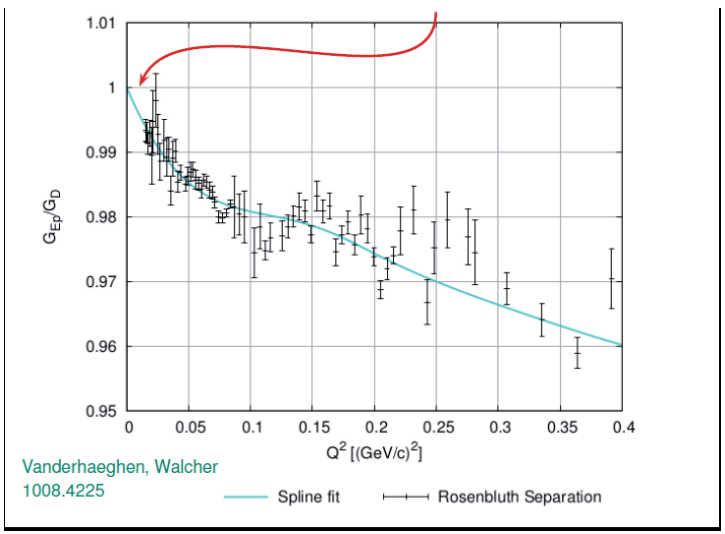
- **Experiment Wrong? Unlikely**
- **Missing conventional physics?**
- **ep scattering extrapolation or RCs?**
- **Novel BSM physics; μ and e different?**
  - Is this puzzle related to g-2 ?



Techniques that differ to get r_p

$$\langle r_p^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

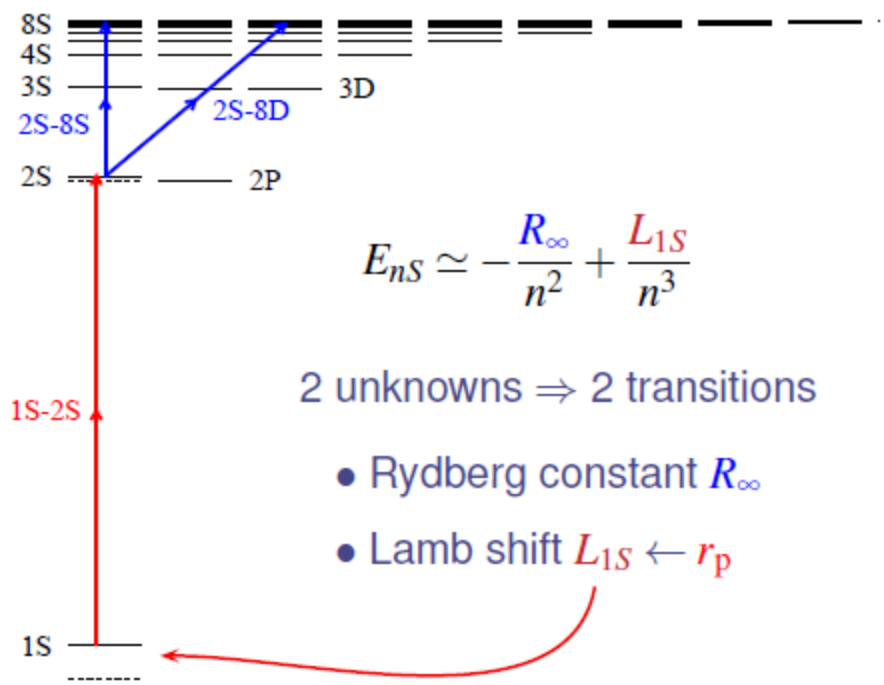
slope of G_E at $Q^2 = 0$



Electron scattering at low Q^2
(**rad corrections important**)

Hydrogen spectroscopy (Lamb shift):

$$L_{1S}(r_p) = 8171.636(4) + 1.5645\,\langle r_p^2 \rangle \quad \text{MHz}$$

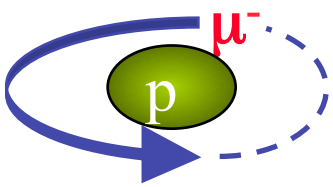


$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

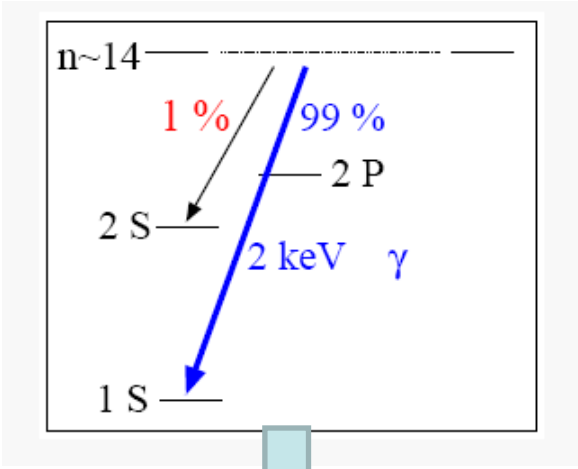
2 unknowns $\Rightarrow$ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$

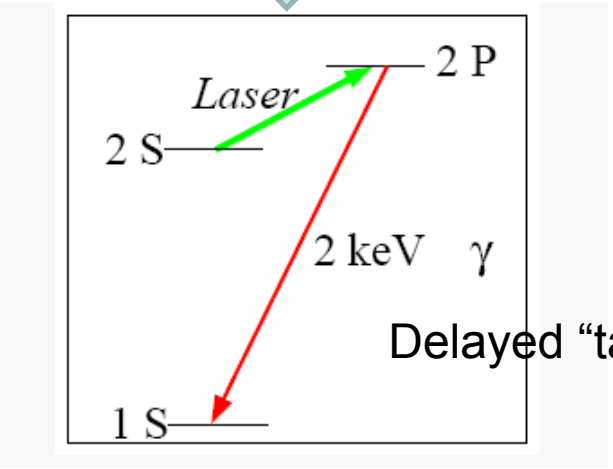
Techniques that differ to get r_p

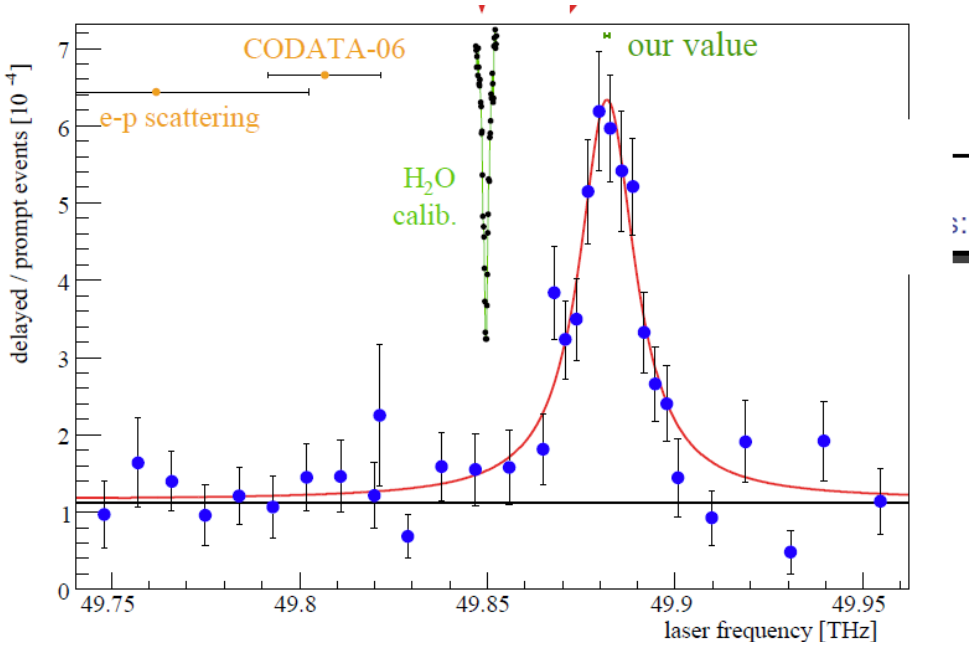


Bohr radius $r_\mu \sim 1/200\ r_e$



Pump with laser

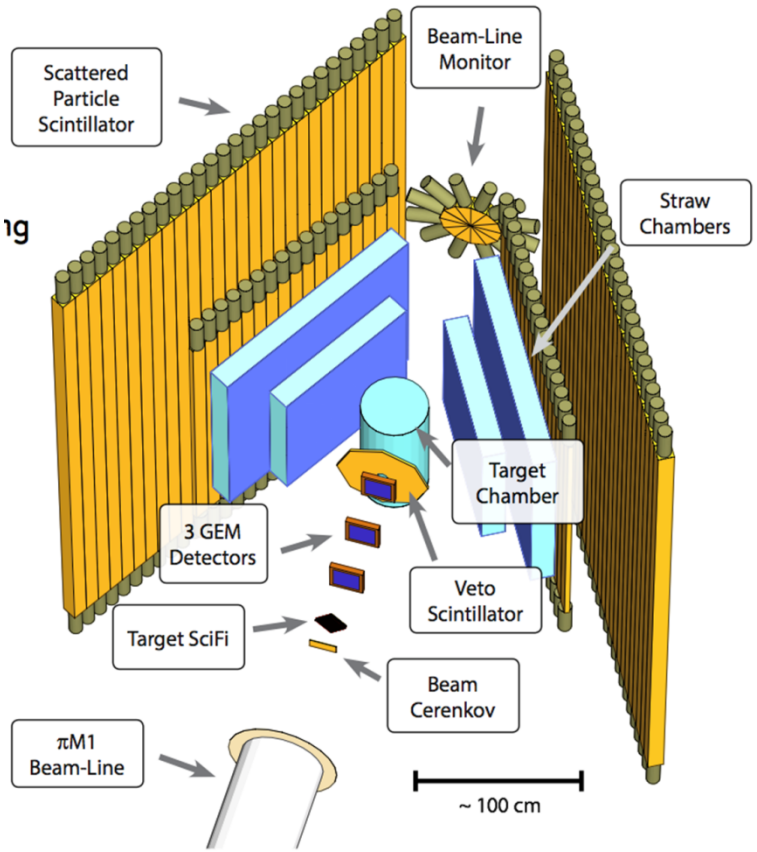




Laser frequency corresponds to 2P-2S energy level difference; "**can't get wrong**"

Future: MUSE μp scattering

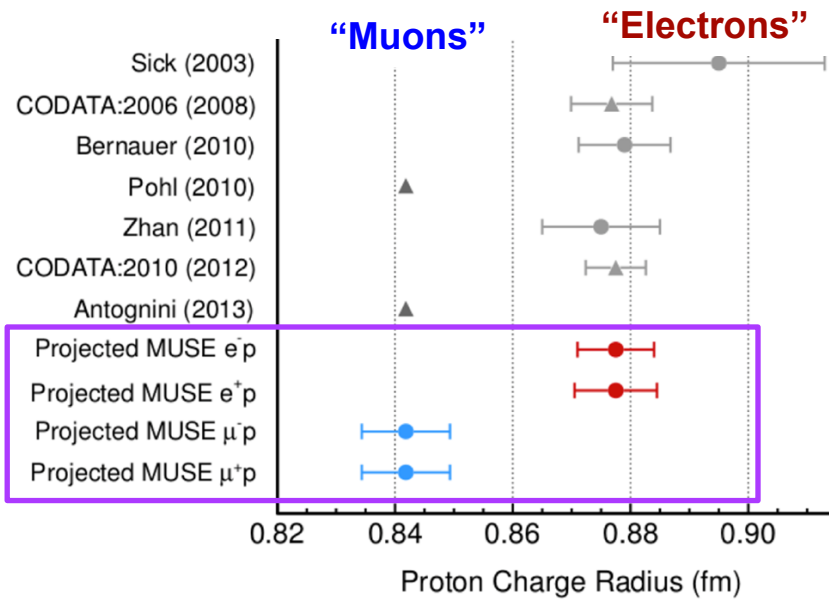
r_p	Muons	Electrons
Spectroscopy	0.84087 ± 0.00039	0.8758 ± 0.0077
Scattering	???	0.8770 ± 0.0060



μp scattering at $Q^2 \approx 0.002 - 0.07$ GeV^2

- Systematics from RCs (0.5% for e) and multiple scattering (0.3%)
- Many can be reduced to ≈ 0.1% level.
- Systematics reduced in +/- and in e/μ **comparisons**.

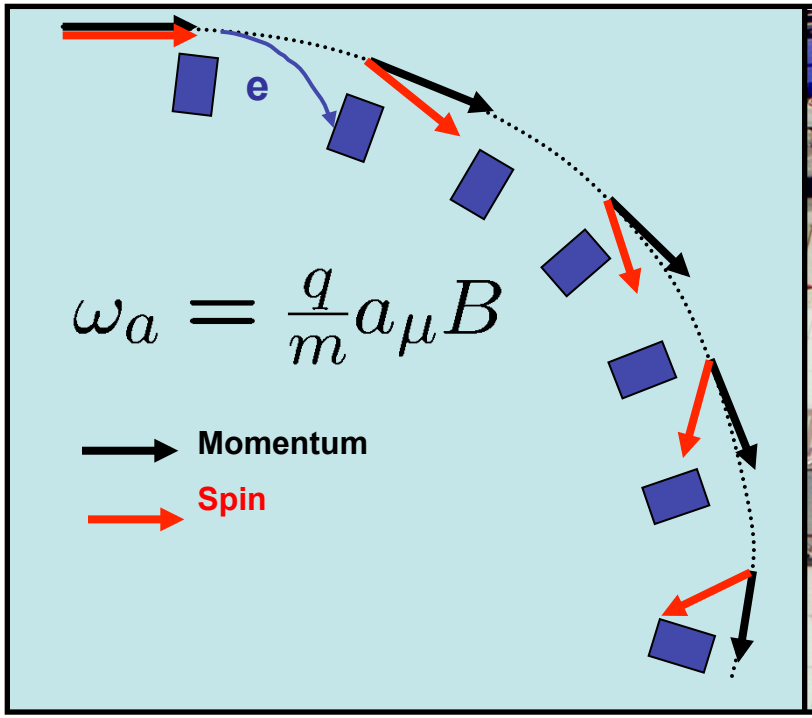
Relative radius comparison:

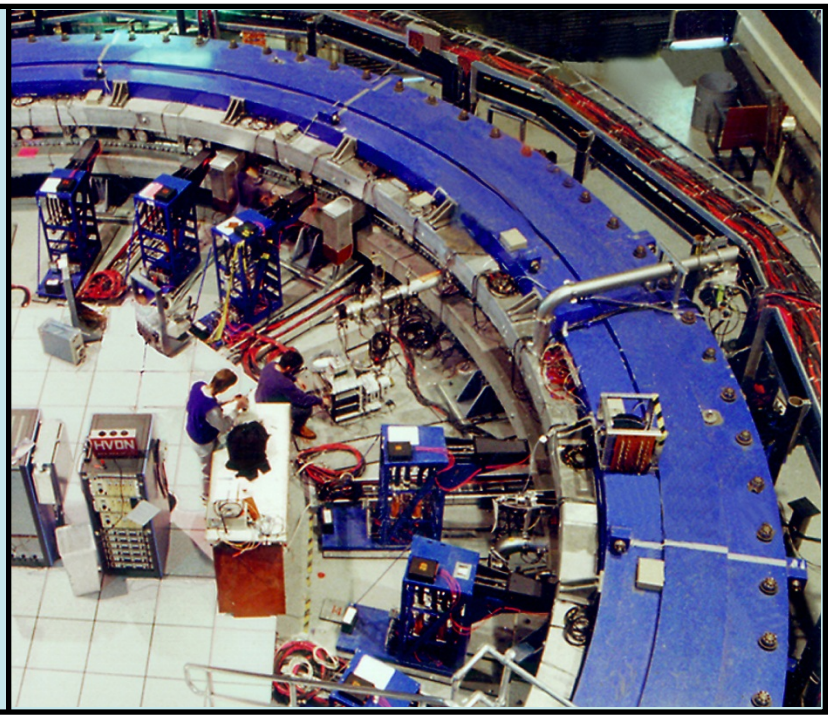


A Hint of New Physics ??

Measured $(g-2)_\mu$ vs. SM Prediction

Future: Muon g-2 and μEDM
(FNAL E989 & J-PARC E34*)





a_μ(Expt) = 116 592 089 (63) x 10^{-10}

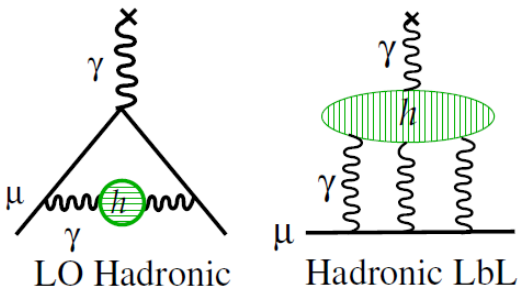
The experiment compares how fast a muon spin rotates in a magnet field compared to the predictions from theory

*A developing idea using a cold, low-energy muon beam. Can discuss if you wish

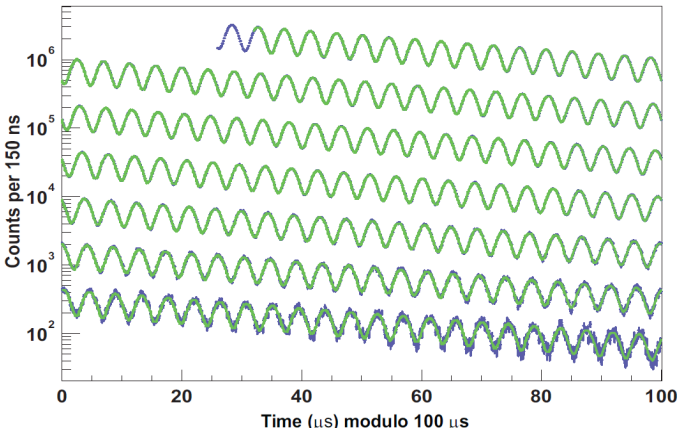
Experiment and Theory

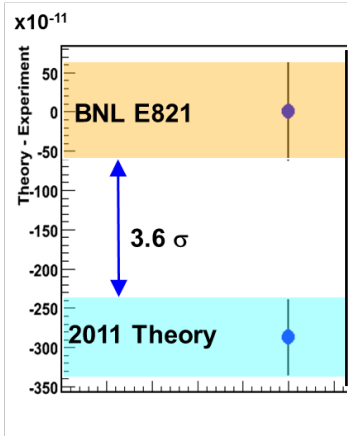
Δa_μ(Expt-Thy) = (287 ± 80) x 10^{-11} (3.6 σ)

- **Theory uncertainty: <u>0.42 ppm</u>**
  - **QED, Weak: known well**
  - **Hadronic terms: Nuclear *opportunity***



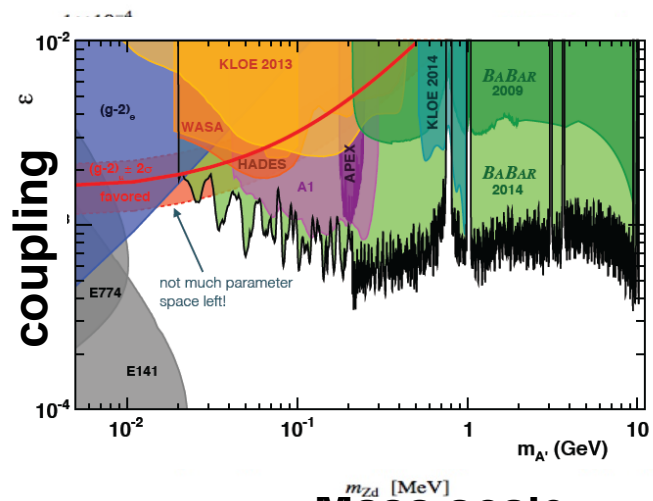
- **Experimental uncertainty: <u>0.54 ppm</u>**
  - **Method tested and sound**
  - **Statistics limited: Need more muons**





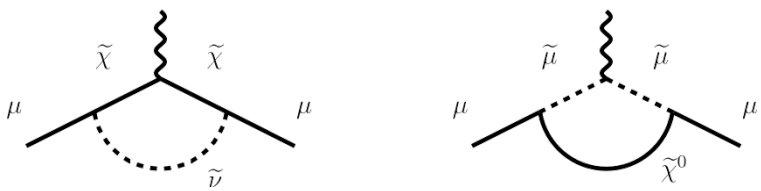
What is nature trying to tell us ?

New physics enters through *loops. What might the g-2 signal imply?*



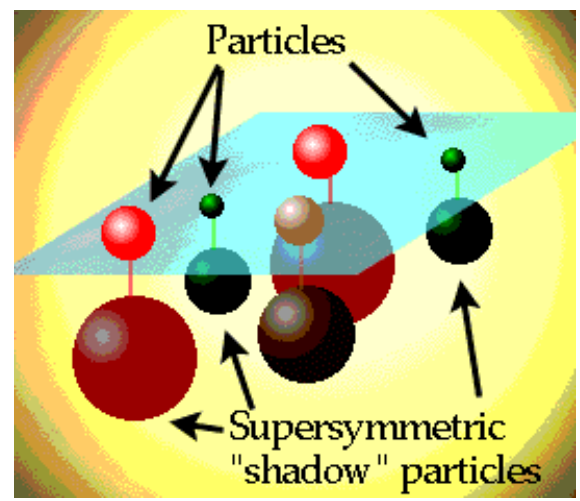
Mass scale

- **Dark Photons** (very active area)
  - light new vector particles kinetically mixed with the photon
    - Recent major updates exclude this space for *A'* → "visible" e^+e^- pairs (Phenix, BaBar, …)
- **Supersymmetry**



$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}} \right)^2 \tan\beta\ \text{sign}(\mu)$$

Difficult to measure at the LHC



- **The Uninvented**
  - Perhaps the most important of all

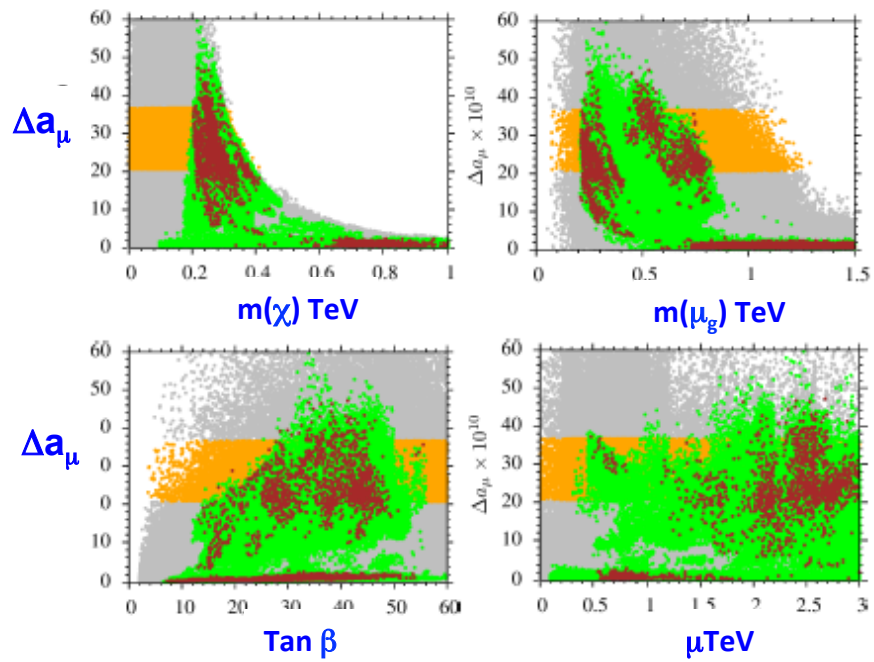
How have the LHC results – 125 GeV Higgs, no obvious new states – affected SUSY & g-2?

- Tension exists between light colored SUSY particles and a_μ
  - Affects: CMSSM, mSUGRA, and other highly simplified models
- New models are emerging rapidly
  - e.g: compressed spectra, split supersymmetry, with heavy colored/light non-colored or heavy 3rd gen / light 1st and 2nd generation, and many others

Muon g-2, 125 GeV Higgs and Neutralino Dark Matter in sMSSM

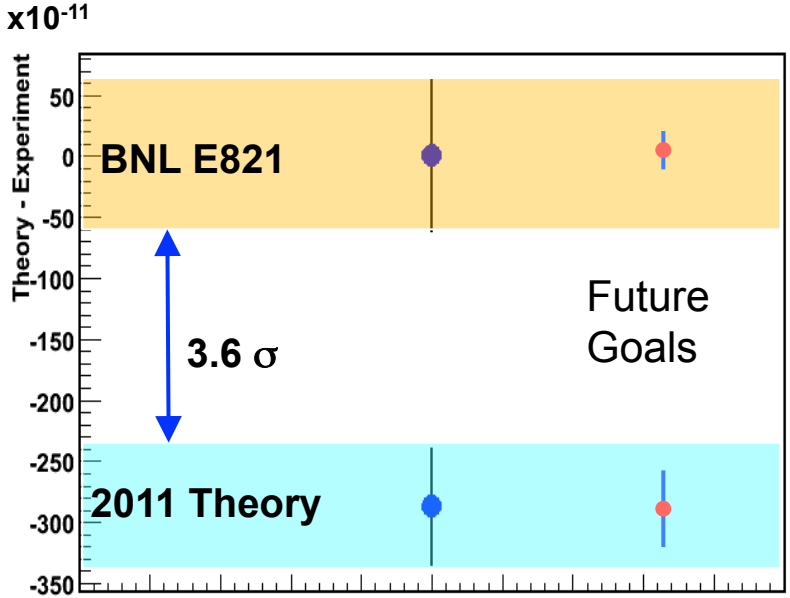
e-Print: arXiv:1406.6965

(overlap pts "allowed")



In such a framework we show that the muon g − 2 anomaly, the observed Higgs boson mass of ~ 125 GeV, and the observed relic neutralino dark matter abundance can be simultaneously accommodated. The resolution of the muon g − 2 anomaly in particular yields the result that the first two generation squark masses, as well the gluino mass, ***should be <2 TeV, which will be tested at LHC14****.*

Aiming for >5σ "Discovery." FNAL E989 will have 20x the data and a 4-fold reduction in overall uncertainty

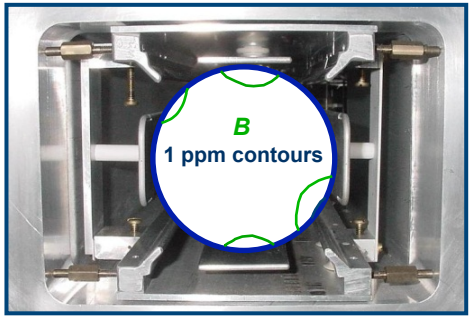


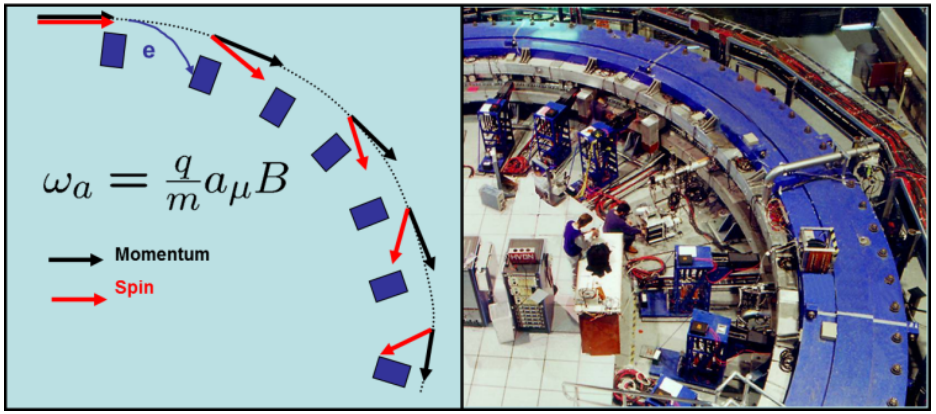
Goal: 140 ppb

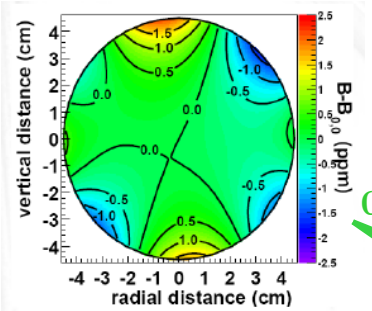
7.5 σ if same central values

Expected Improvement

Method: The anomaly is obtained from three well-measured quantities

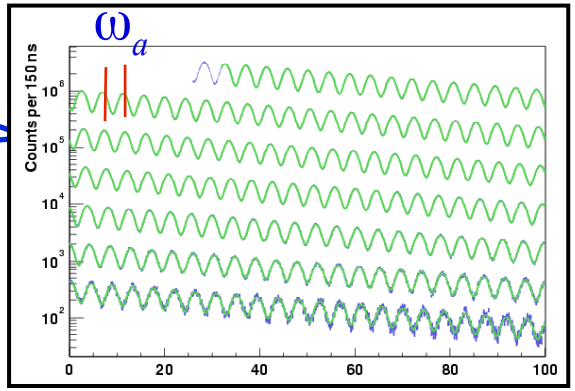


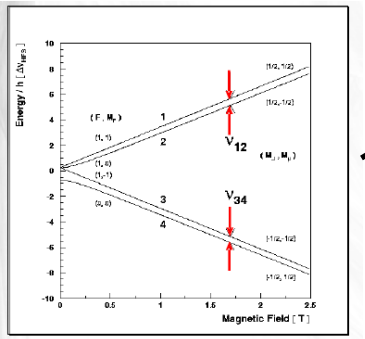




ω_p

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$



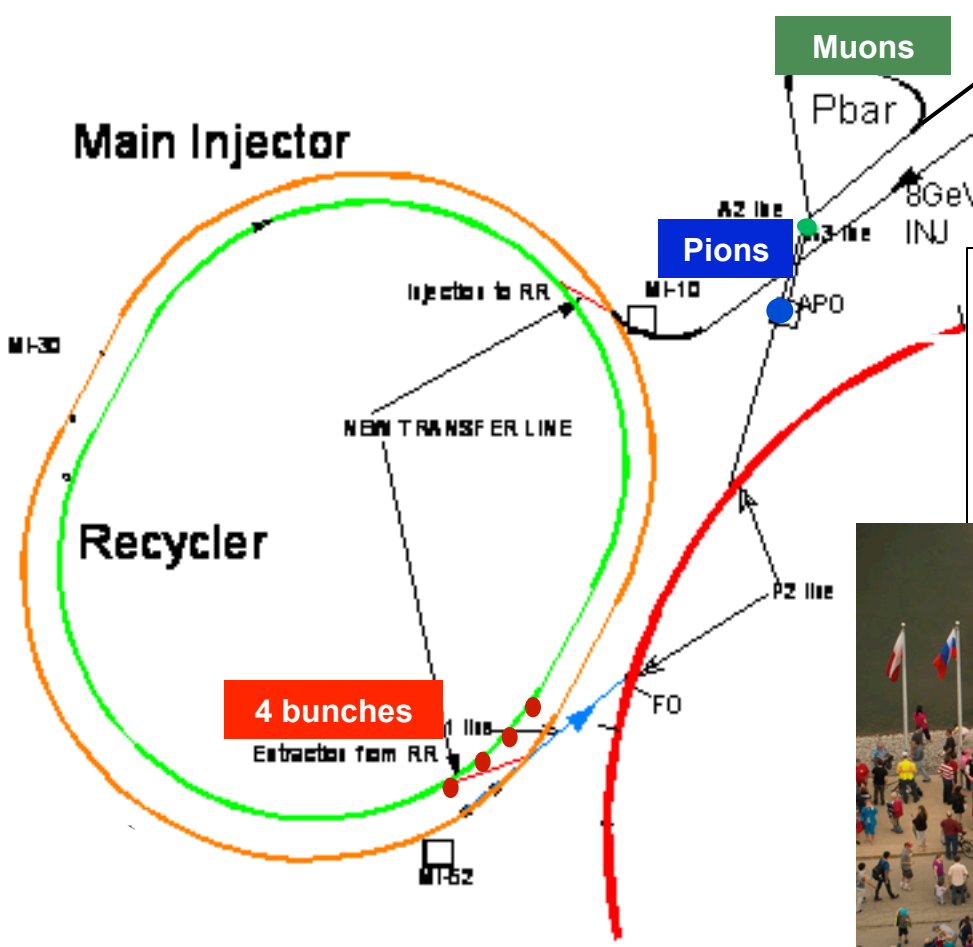


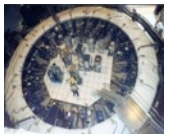
Future Japan HFS coming

μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

Major NSF MRI supports this instrumentation

Key idea: Long beamline provides intense, pure muon flux. Complemented by new ideal Kicker for max rates and new measurement instrumentation



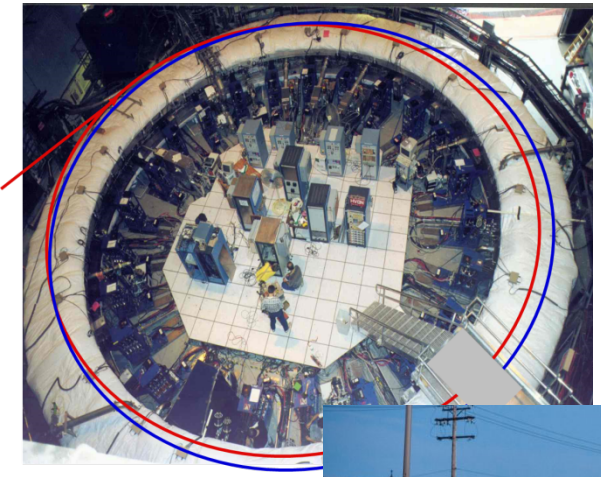


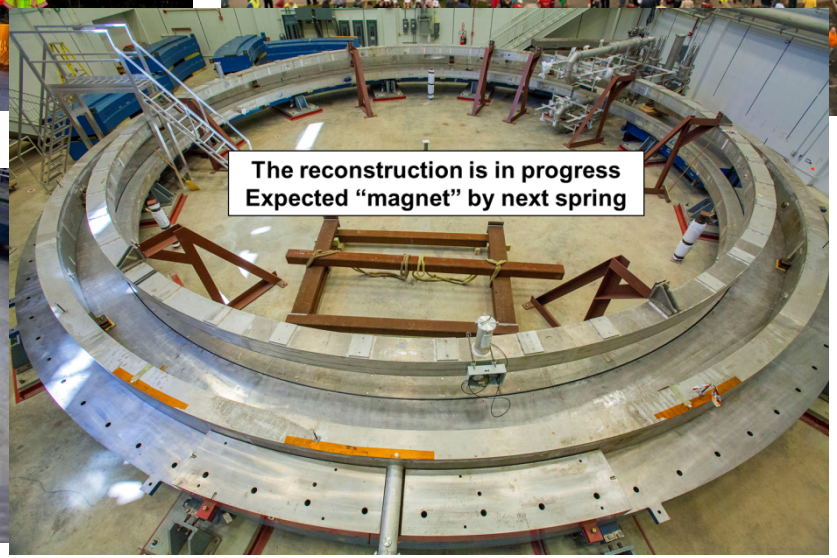
- No hadronic flash
  - Pions all decay
  - Protons removed by a kicker
- Forward muons collected

Coils arrives at FNAL

All protons are “excess” from those used for NOvA ν Program

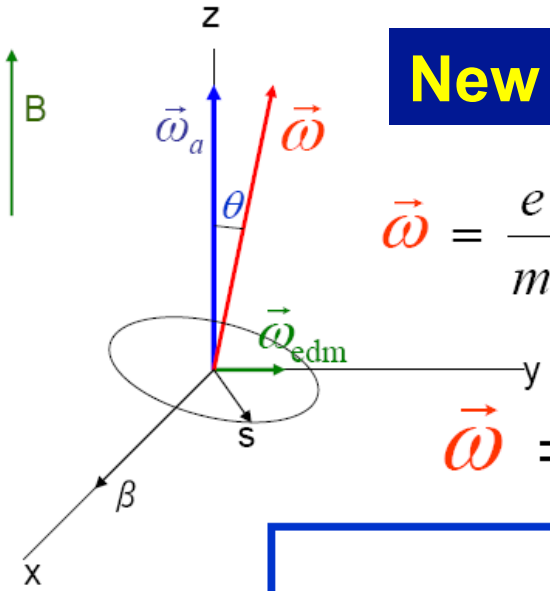
Ring moved to FNAL and Magnet being assembled





Parasitic Muon EDM Measurement using straw tube arrays

from E821 $d_\mu < 1.8 \times 10^{-19}\, e\,\mathrm{cm} \rightarrow \sim$ few 10^{-21}



New Experiment will improve limit by > x10

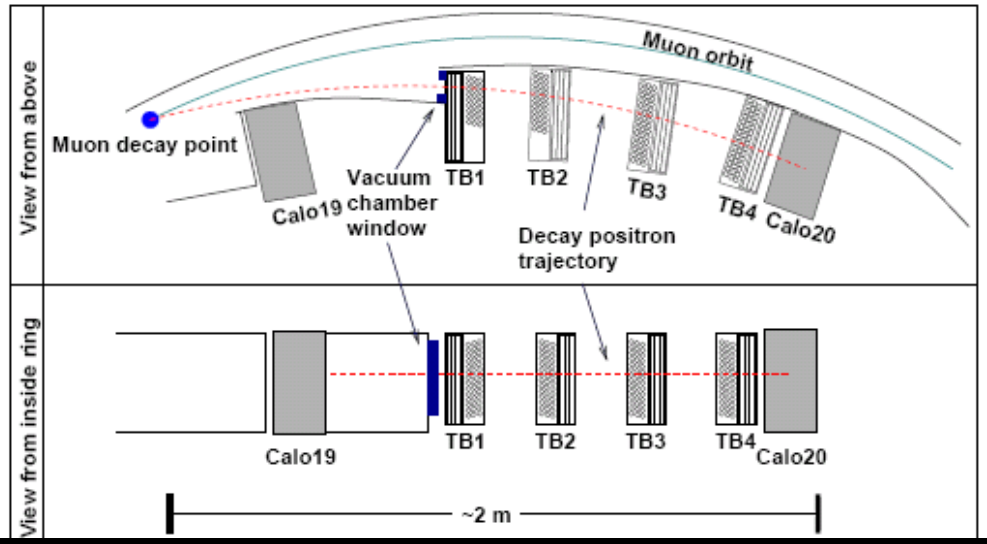
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

The EDM tips the precession plane, producing an up-down oscillation with time (out of phase with ω_a)

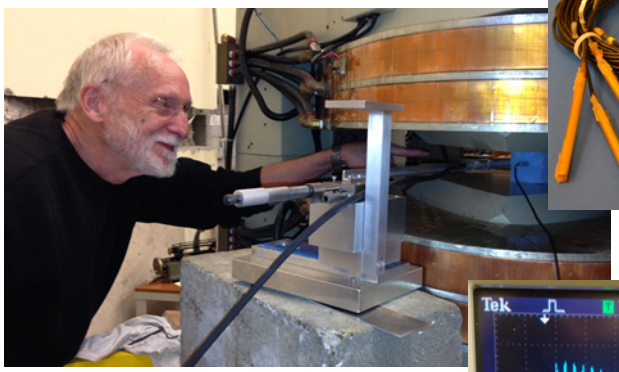
New in-vacuum straw tracker planned

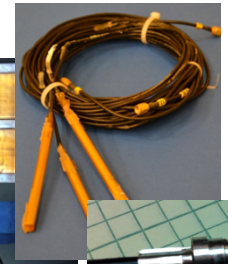


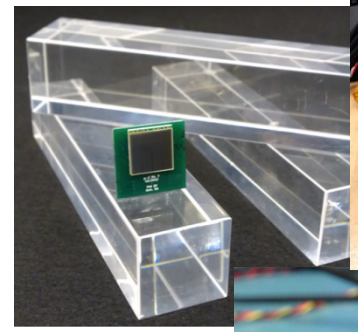
Measure upward-going vs. downward-going decay electrons vs. time with straw tube arrays

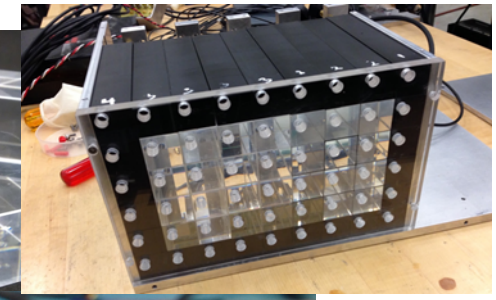
Phys. Rev. D80 (2009) 052008

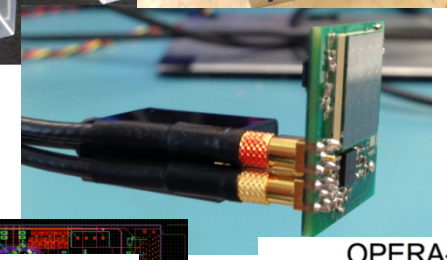
Much progress on experimental preparation
Scheduled start <u>early FY17</u>

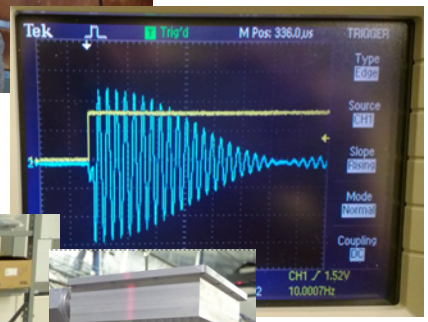


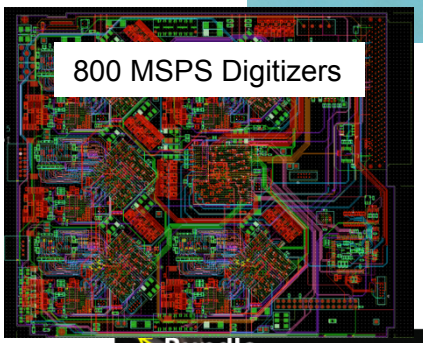


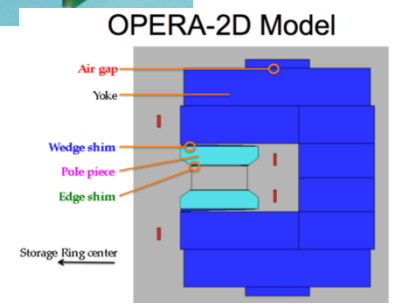


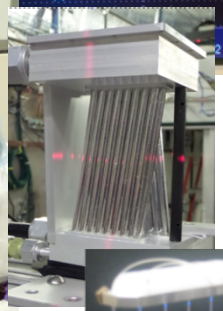


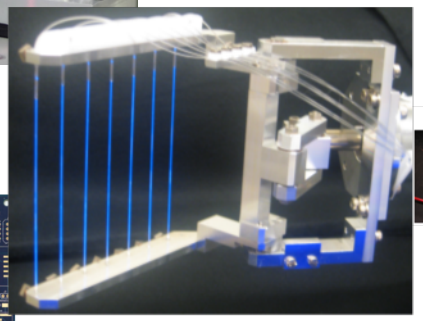


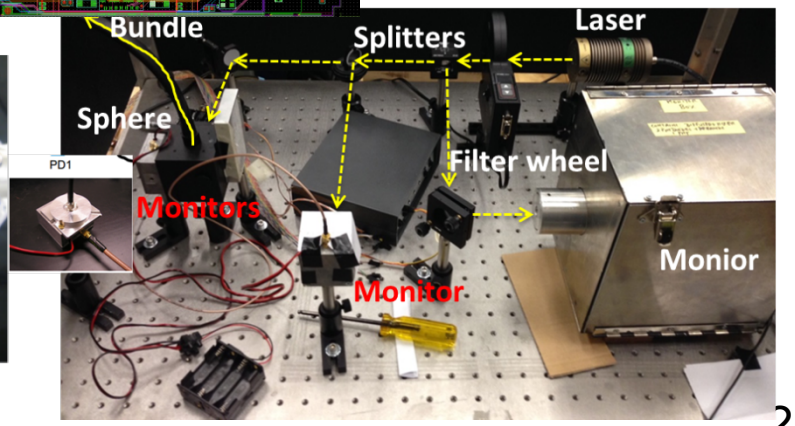












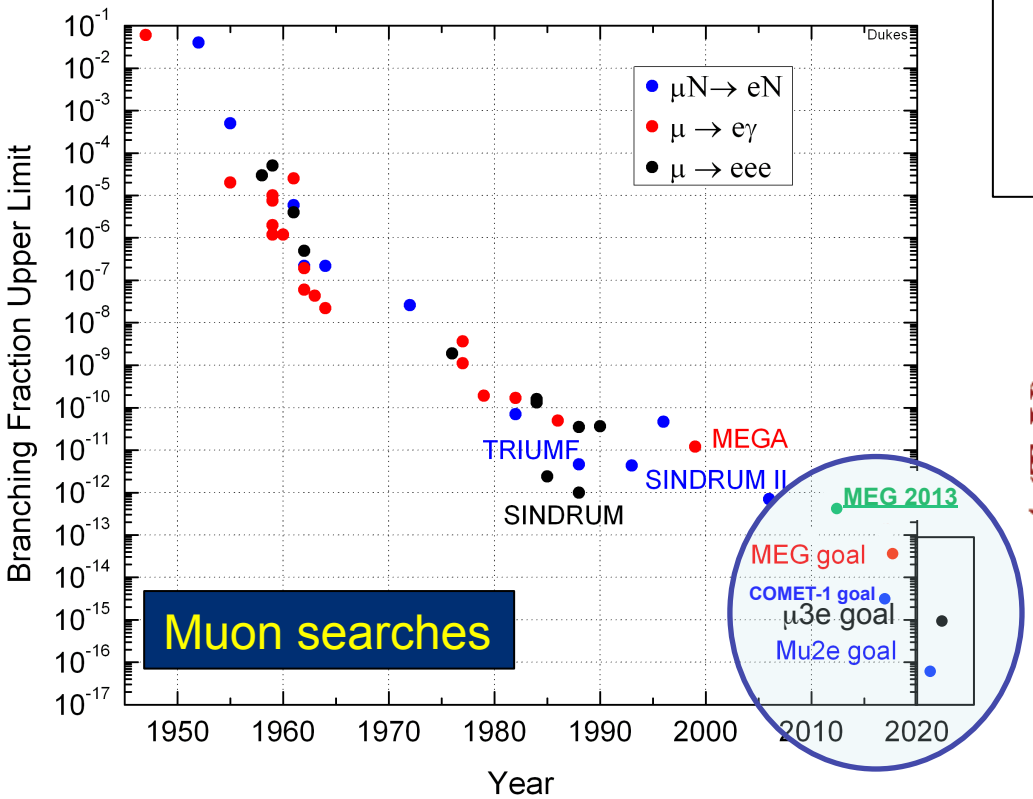
Reaching (perhaps) beyond the LHC

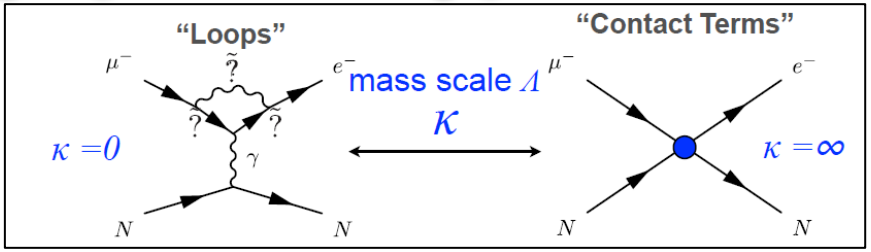
Charged Lepton Flavor Violation

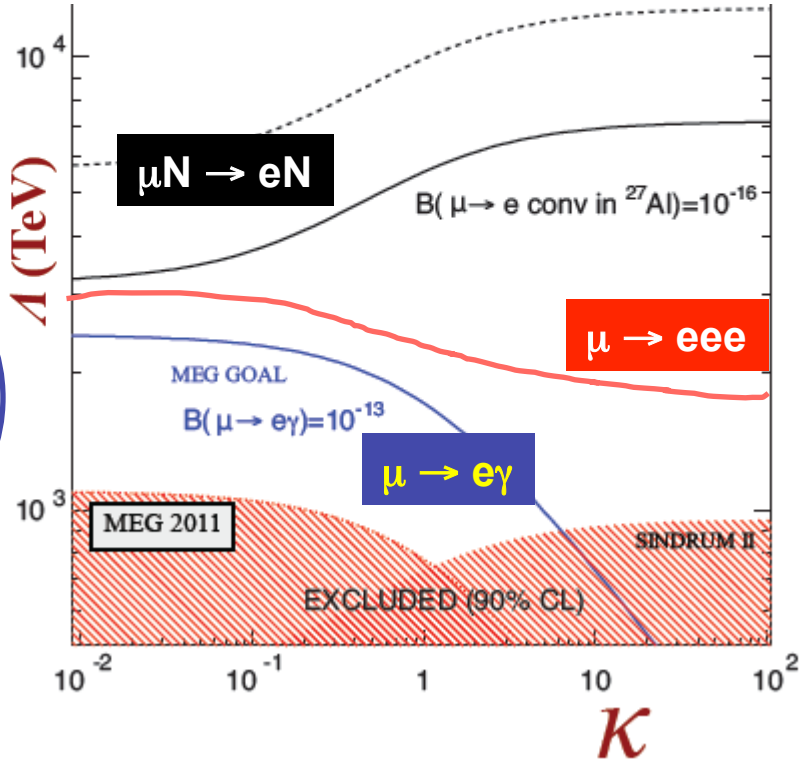
cLFV: SM "allowed" but *Unobservable*

e.g., $\mu \to e$ BR: 10^{-54} in the SM

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$



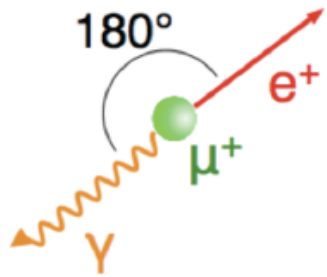


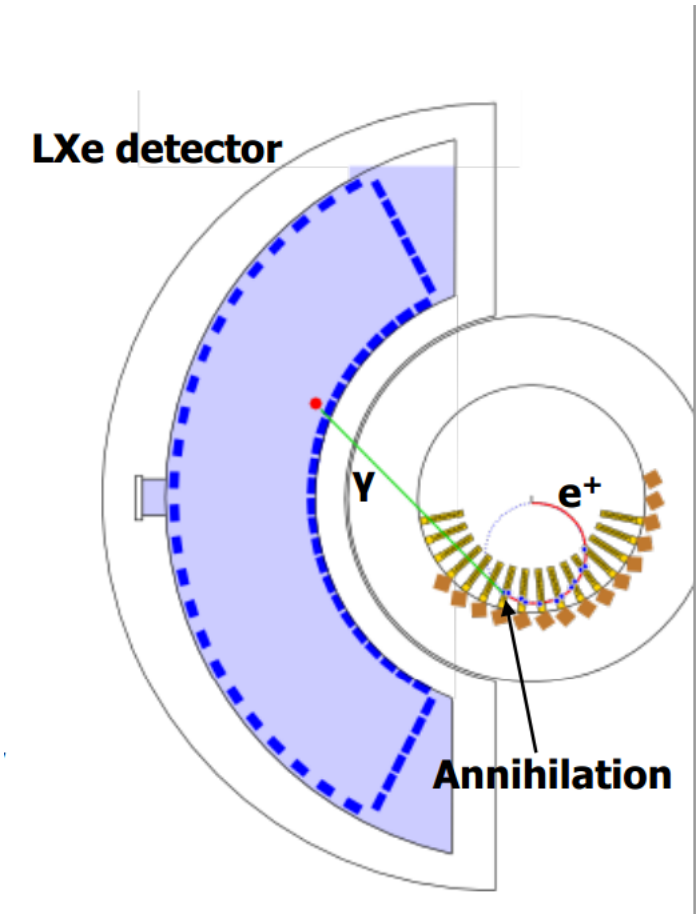


Current & Future: MEG / MEG II at PSI

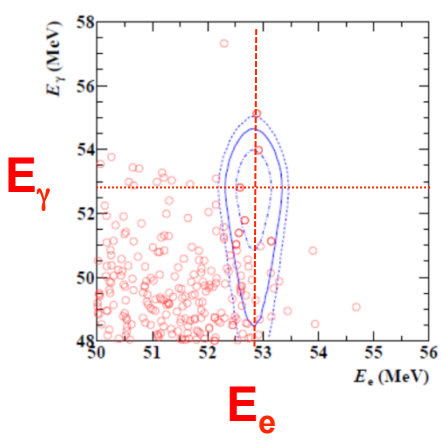
$\mu \rightarrow e\gamma$

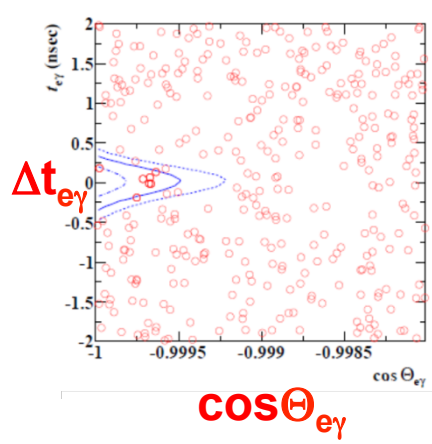
Signal is back-to-back 53 MeV γ and e^+ from positive muons at rest





- e and γ are back-to-back, $\Delta\theta = 180°$
- e and γ are simultaneous, $\Delta t = 0$
- $E_e = E_\gamma = m_\mu/2$



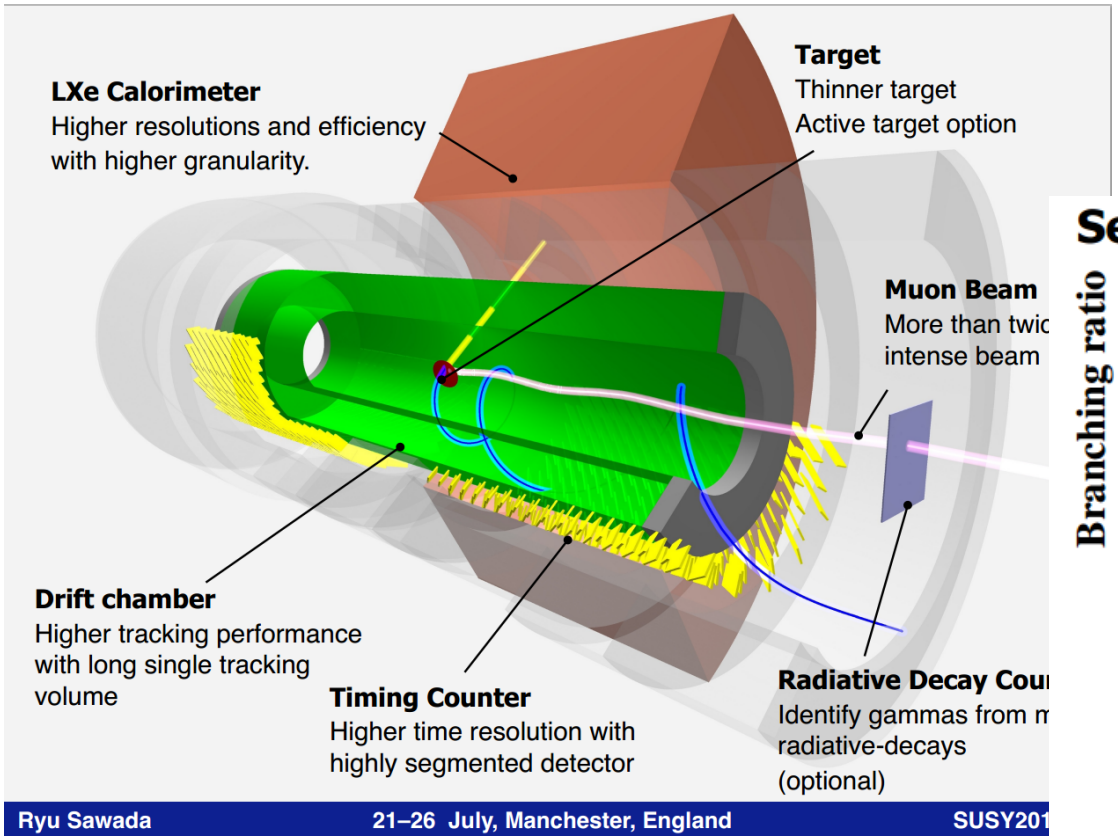


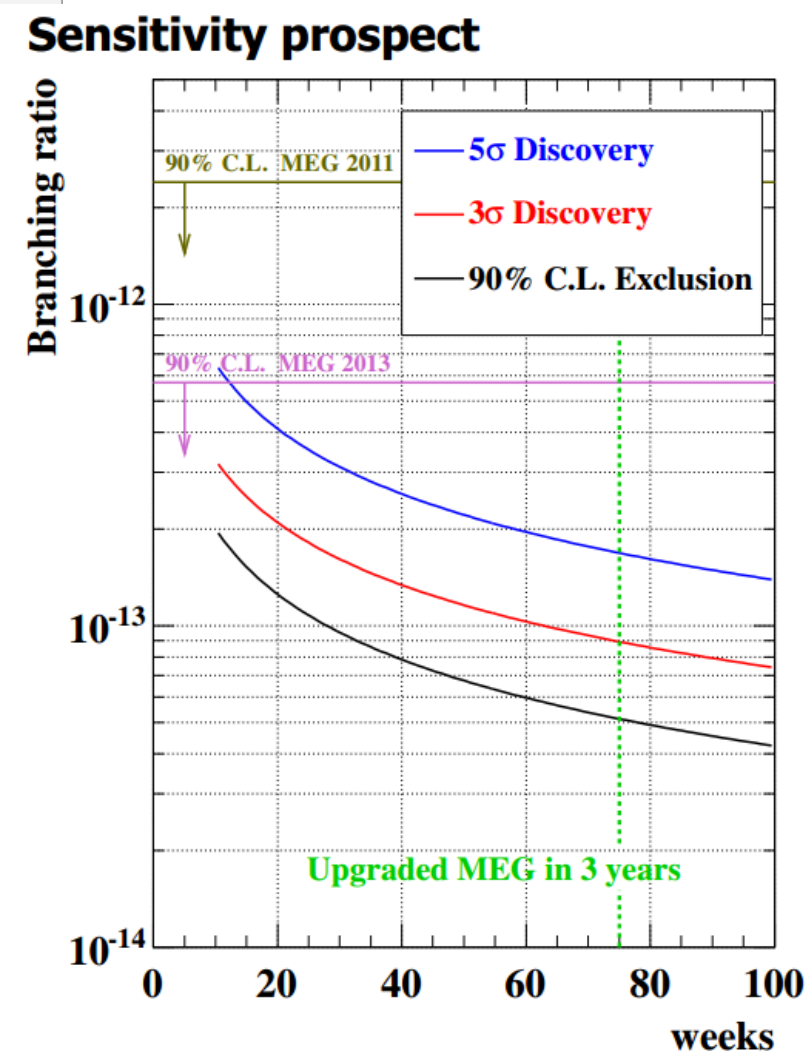
BR ($\mu^+ \rightarrow e^+\gamma$)

90% C.L. upper limit: $< 5.7 \times 10^{-13}$

PRL 110 201801 (2013)

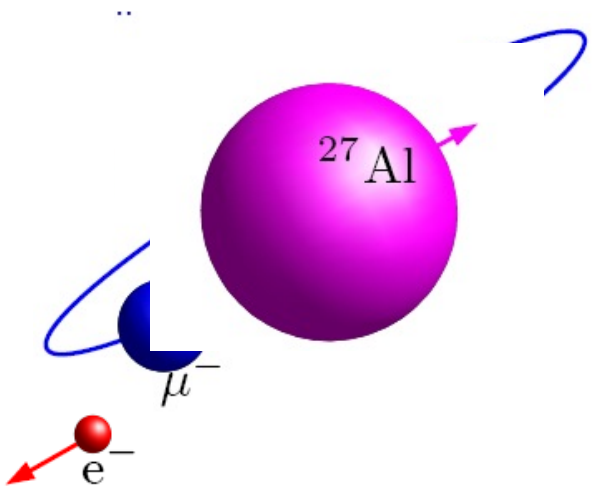
MEG II: 2016 start; Goal: <5x10^{-14}





No U.S. nuclear groups involved

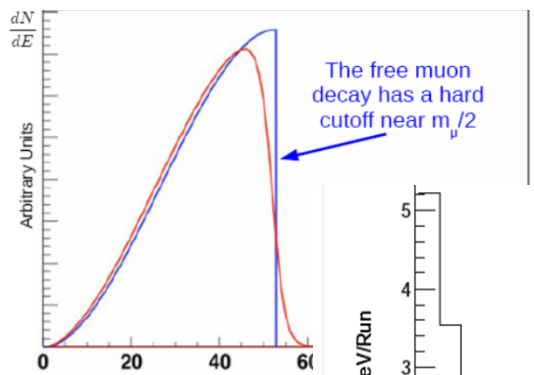
Future: Muon to Electron Conversion
Mu2e and COMET

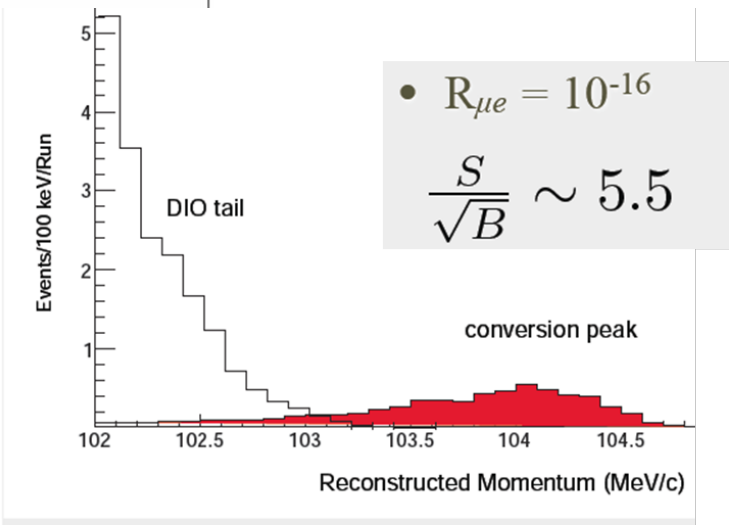


105 MeV monoenergetic e$^-$

$$\mu^- N \rightarrow e^- N$$

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$



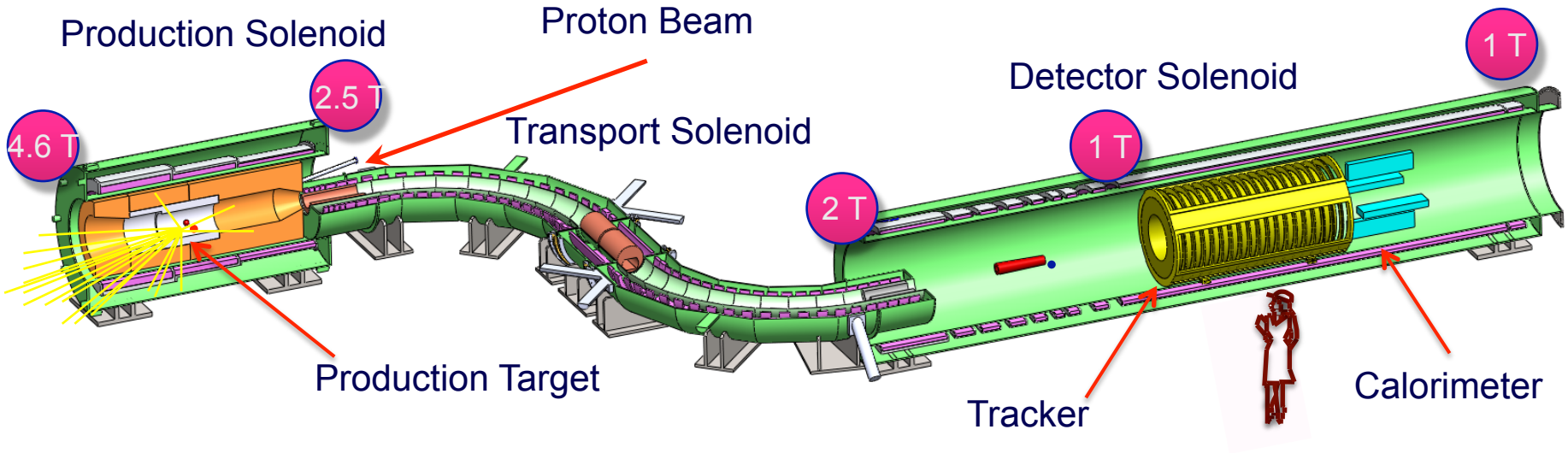


- **This signature is quite unique**
- **Goal $R_{\mu e}$ to < 6 x 10^{-17} (90% C.L.)**

4 order of magnitude gain !!

How it is done (using FNAL example, involves our community)

- Need intense pulsed source of low-energy muons
- Stop in thin Al target
- Form muonic Al atoms
- Observe
  - 40% will decay "in orbit";
  - 60% will capture; protons and neutrons can be emitted

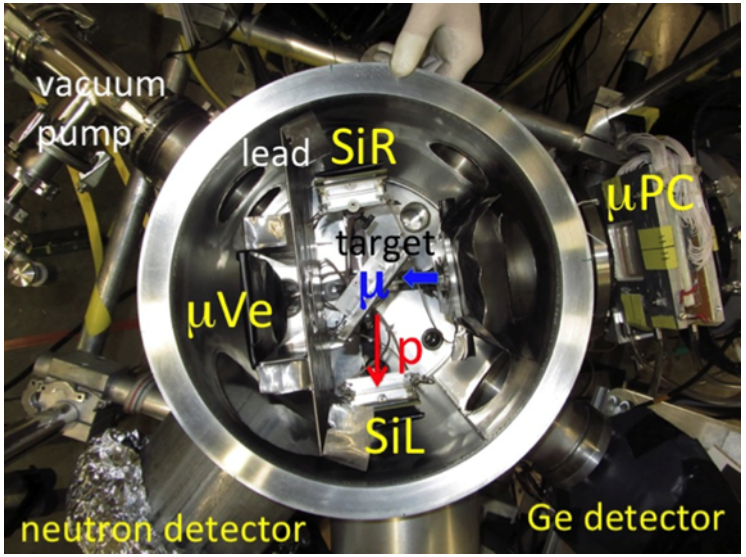


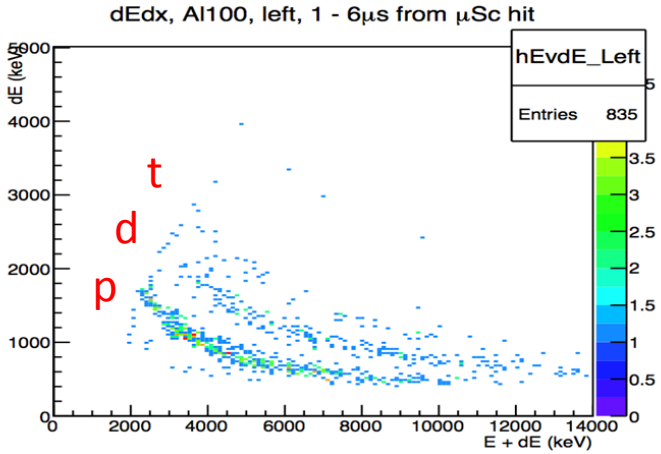
Current: AlCap at PSI

U.S. nuclear led μAl capture; proton and neutron emissions

Emitted secondaries from "ordinary" μAl capture include protons and neutrons. Cross sections information is poorly known, but important for backgrounds.

Example: A **5 MeV proton** has the momentum of the "signature" 105 MeV electron

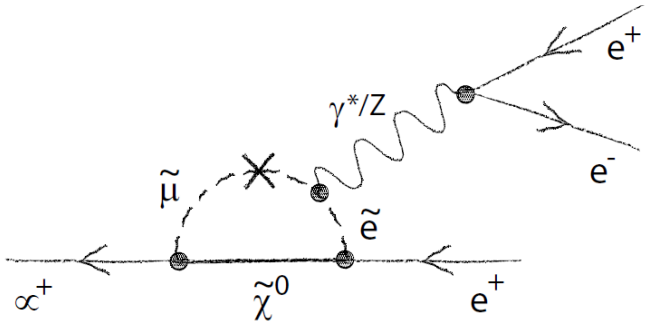




Dec. 2013 run (7 PhD students) from both collaborations; Run again in 2015

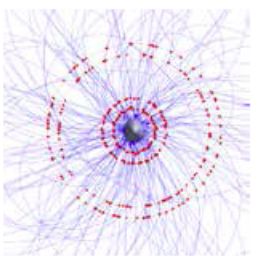
Future: $\mu \rightarrow eee$ at PSI

(2013: approved; being designed)

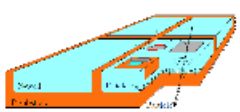


Typical comparison to $\mu \rightarrow e\gamma$ *without enhancement*

$$\frac{B(\mu \rightarrow eee)}{B(\mu \rightarrow e\gamma)} = 0.006 \quad (\text{essentially } \alpha_{em})$$



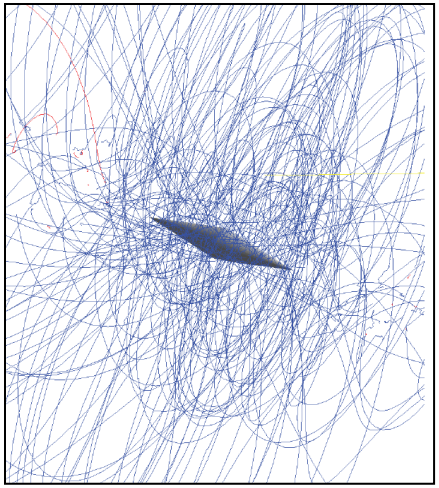
- Goal:
  - Finding 1 in 10^{16} muon decays



- Special technique
  - High-voltage monolithic active pixel sensors

- The detector
  - Minimum material, maximum precision

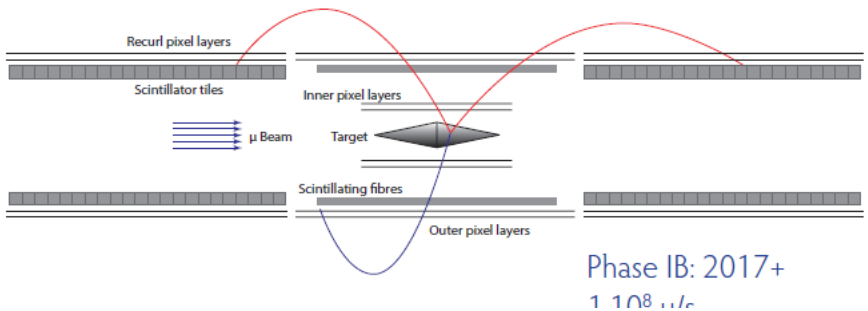
2 x 10^9 μ decays/sec !!

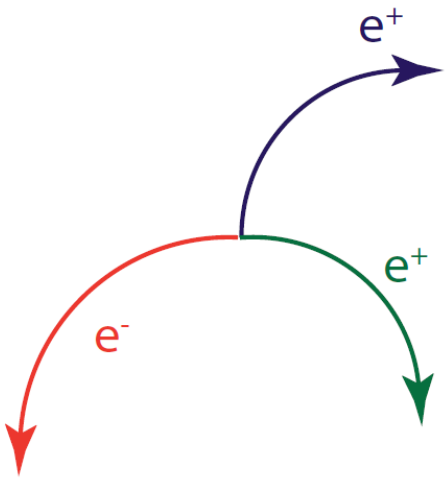


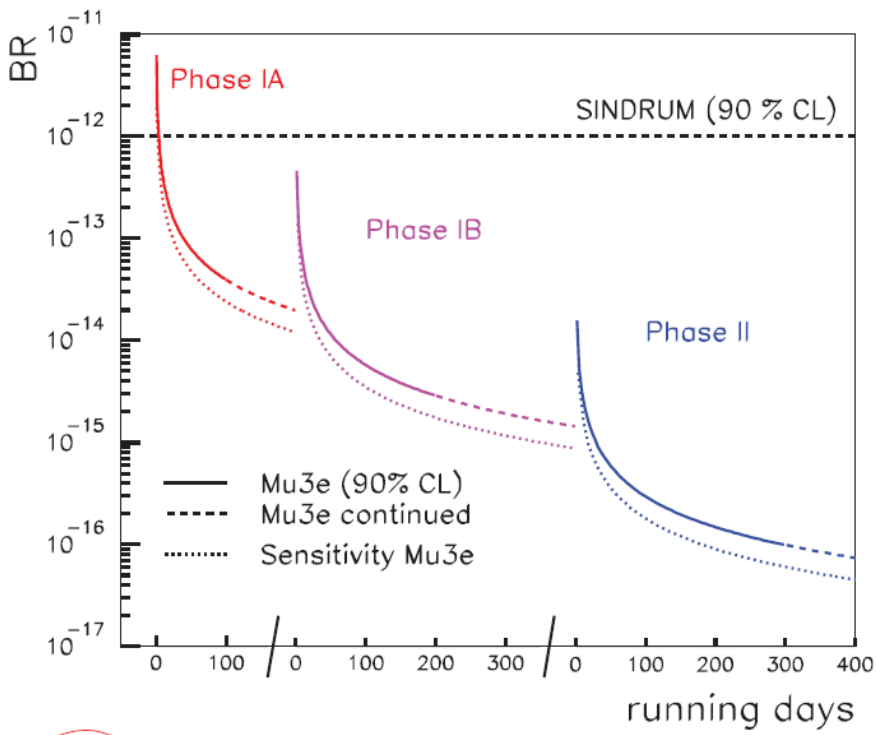
50 ns 1T field

Again, a unique and challenging signature

To achieve statistics, extraordinary high rates …
~4000 muons are “sitting” on the target at any time !



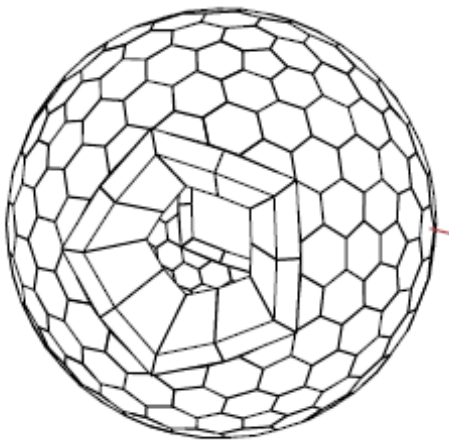


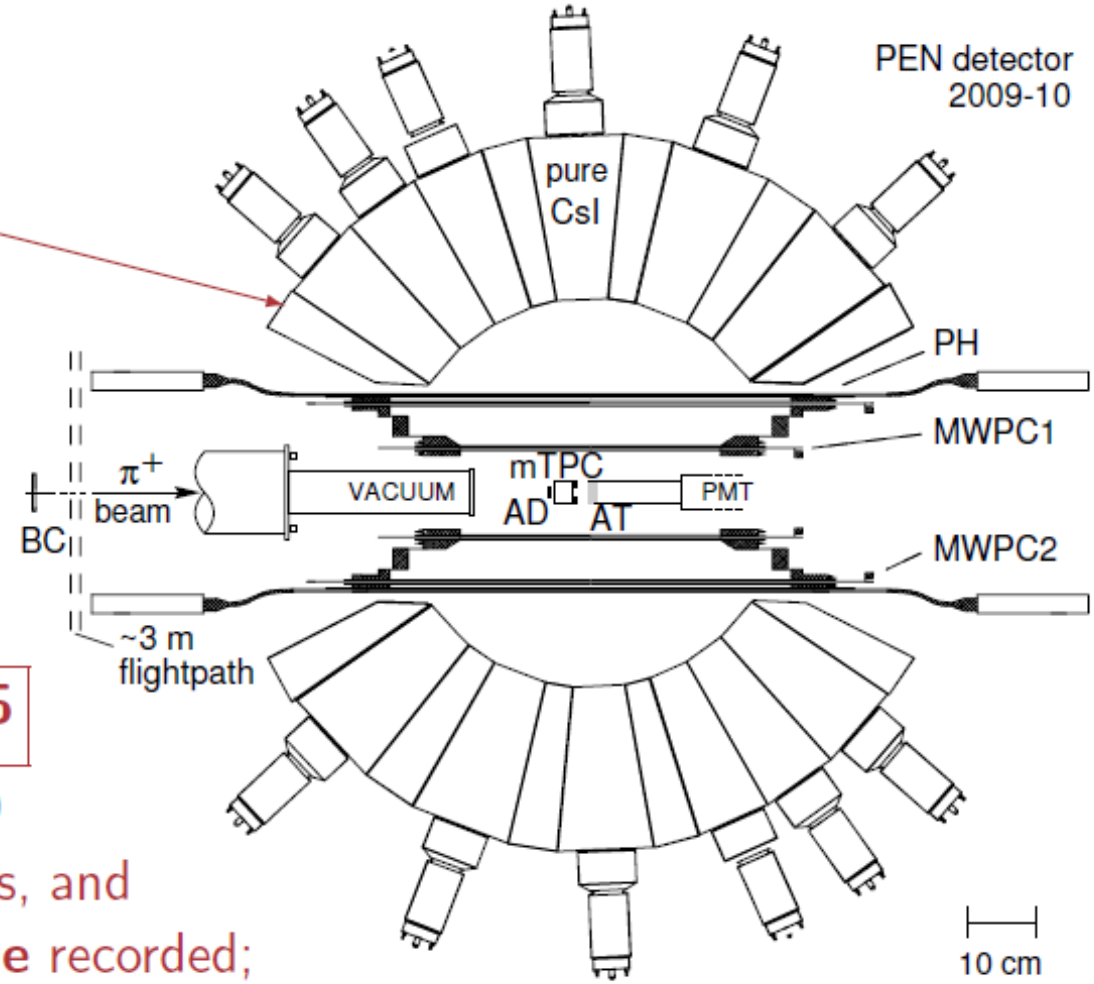


Possible US Role here ???

Recent: PION Decay at PSI and TRIUMF

PEN experiment: $\pi^+ \to e^+\nu_e$ at PSI





PEN Goal:

$$\Delta R^{\pi}_{e/\mu} / R^{\pi}_{e/\mu} \simeq 0.05$$

PEN runs: 2008–2010

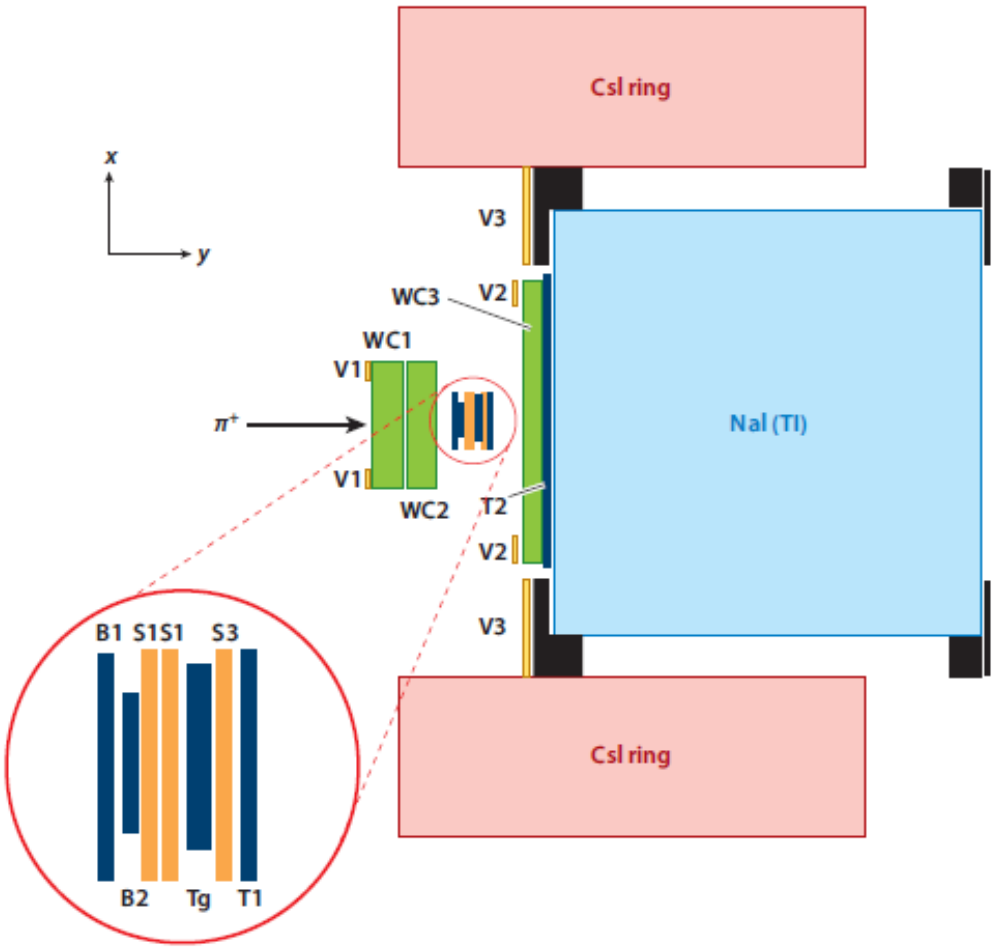
$>$ 22M $\pi \to e$ events, and

$>$ 200M $\pi \to \mu \to e$ recorded;

Analysis is under way.

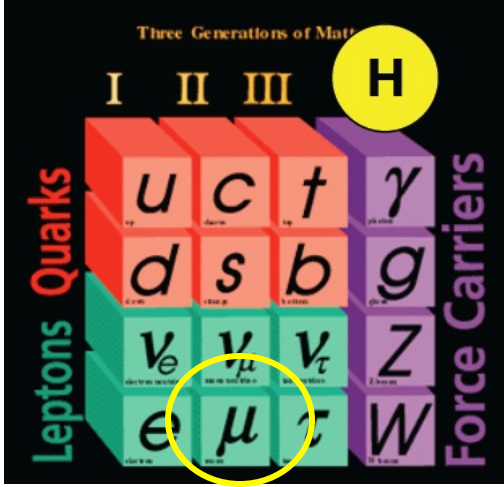
Recent: PION Decay at PSI and TRIUMF

PiENu experiment at TRIUMF



- PiENu Goal:
  $\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 0.001$
- Excellent **E** resolution
- Precise tracking with Si-strip detectors and MWPCs
- Data taking completed in 2012
- $\mathcal{O}(10^7)$ π_{e2} events collected
- analysis under way

Summary: in context to LRP



- **Productive field**: specialized experiments
  - Flagship effort in coming period: **g-2**
  - Smaller important efforts of very high quality
- **Operations Support** required
  - Science blurs traditional NP/HEP funding boundaries
  - Complex for some participants
  - Facilities generally supported outside of DOE NP
    - **This is a good deal !**
  - Targeted Major **equipment support*** from NSF and DOE do enable opportunities and have big leverage factors
- **Nuclear theory** critical *and complementary*
  - *Hadronic corrections, R*Cs, interpretations, ….

Thanks to: P. Kammel, R. Pohl, D. Pocanic, T. Mori, R. Gilman, J. Miller, “Lepton Moments 2014”

Backups

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

3 GeV proton beam
(333 uA)

Graphite target
(20 mm)

Surface muon beam
(28 MeV/c, 4×10^8/s)

Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)

Surface muon

Ultra Cold μ+ Source

Muon LINAC (300 MeV/c)

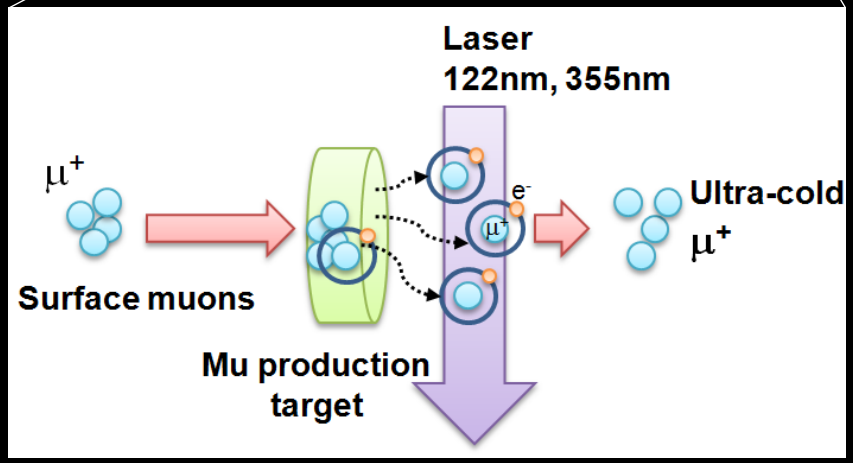
Muon storage

Silicon Tracker

66 cm

Super Precision Storage Magnet
(3T, ~1ppm local precision)

Resonant Laser Ionization of Muonium (~10^6 μ^+/s)



$\Delta(g\text{-}2)$ = 0.1ppm

EDM ～ 10-21 e・cm

SUSY with caption

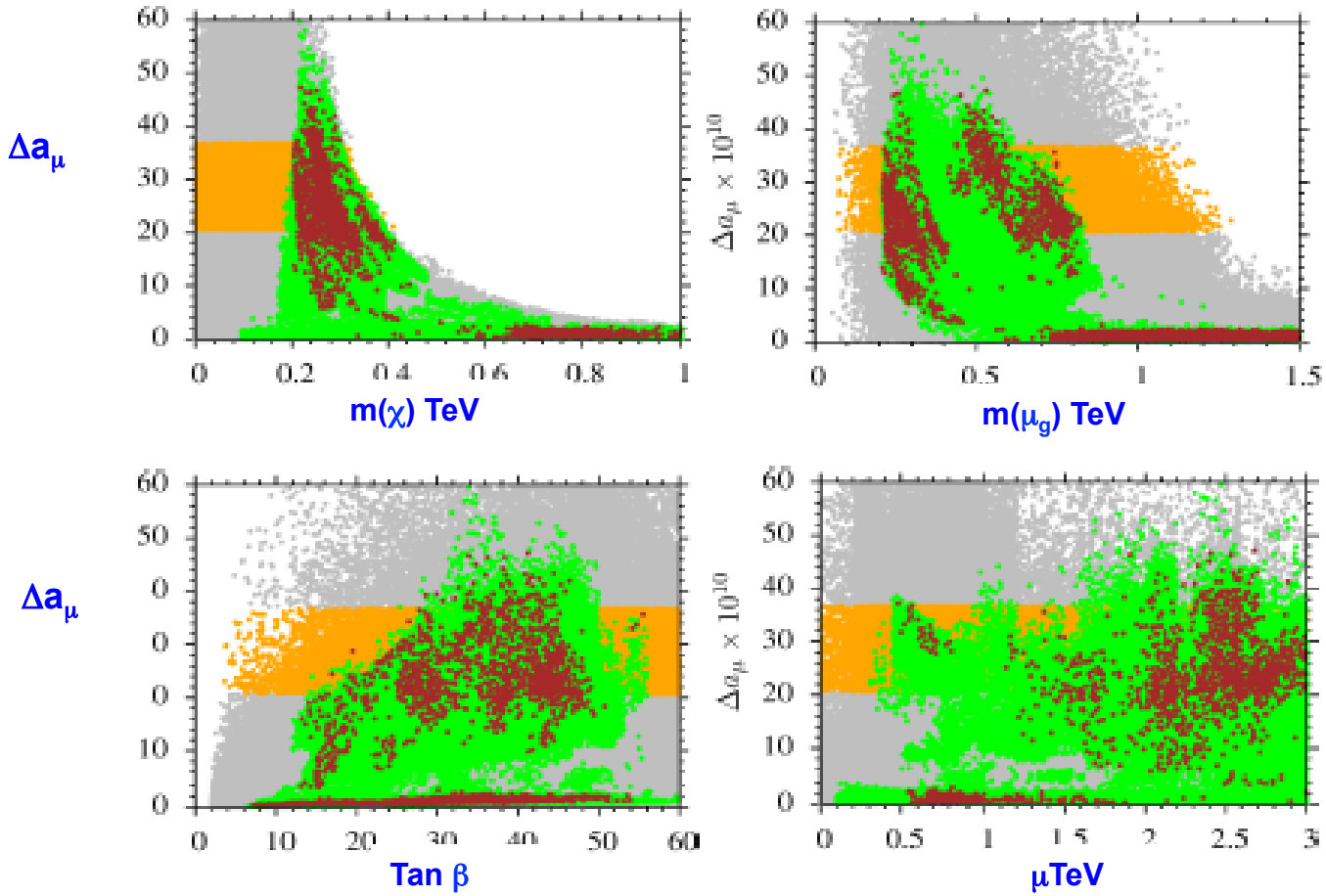


Figure 1: Plots in the $\Delta a_\mu - m_{\tilde{\chi}_1^0}$, $\Delta a_\mu - m_{\tilde{\mu}_R}$, $\Delta a_\mu - \tan\beta$, $\Delta a_\mu - \mu$ planes. Gray points are consistent with REWSB and neutralino LSP. Yellow points represent values of Δa_μ that would bring theory and experiment to within 1σ. Green points form a subset of gray points and satisfy sparticle mass and B-physics constraints described on Table 1. In addition these points satisfy the lightest CP-even Higgs mass range $123\,\text{GeV} \leq m_h \leq 127$ GeV. Brown points belong to a subset of green points and satisfy the WMAP bound (5σ) on neutralino dark matter abundance.

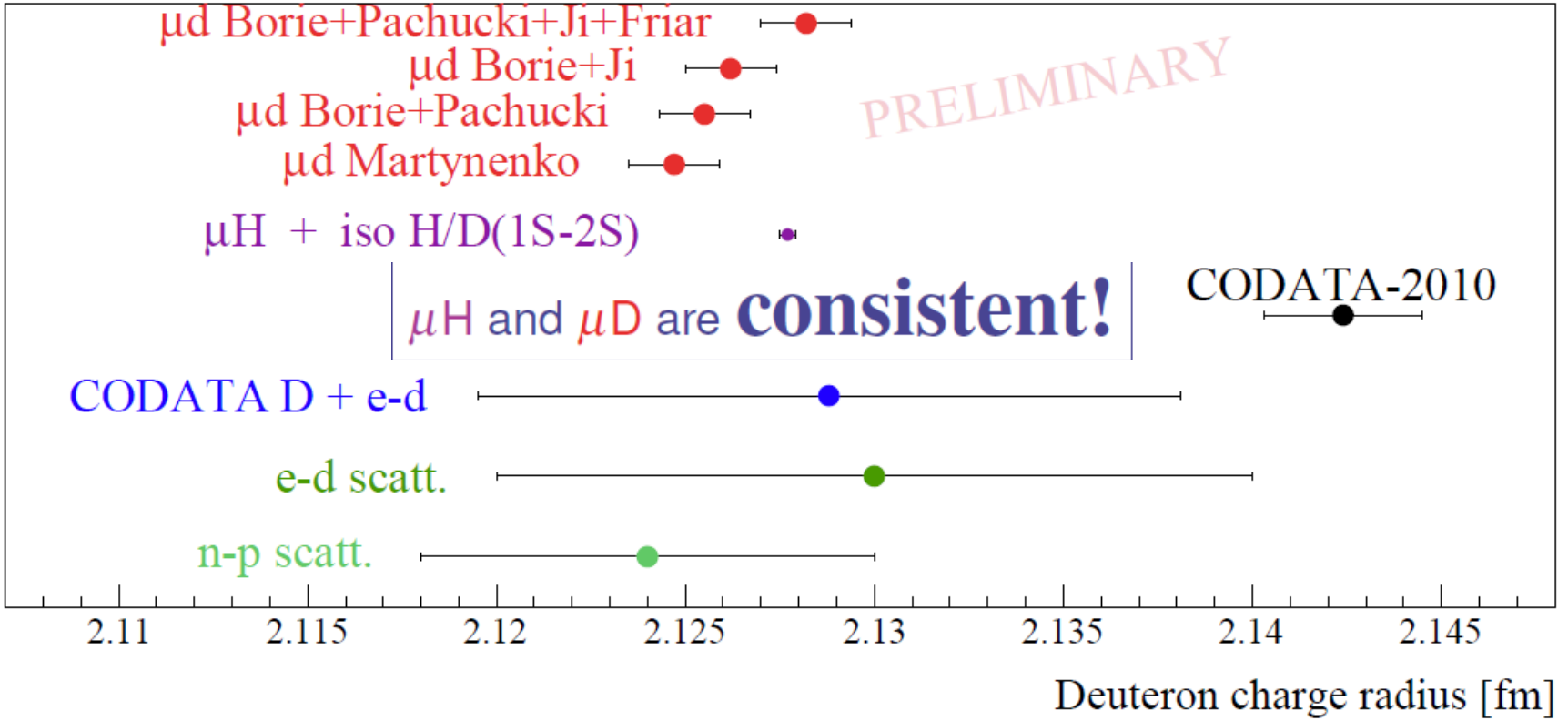
Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \mathrm{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010 r_d = 2.1424(21) fm

r_p= 0.84087(39) fm from μH gives r_d = 2.1277(2) fm

Lamb shift in muonic DEUTERIUM r_d = 2.1282(12) fm PRELIMINARY!



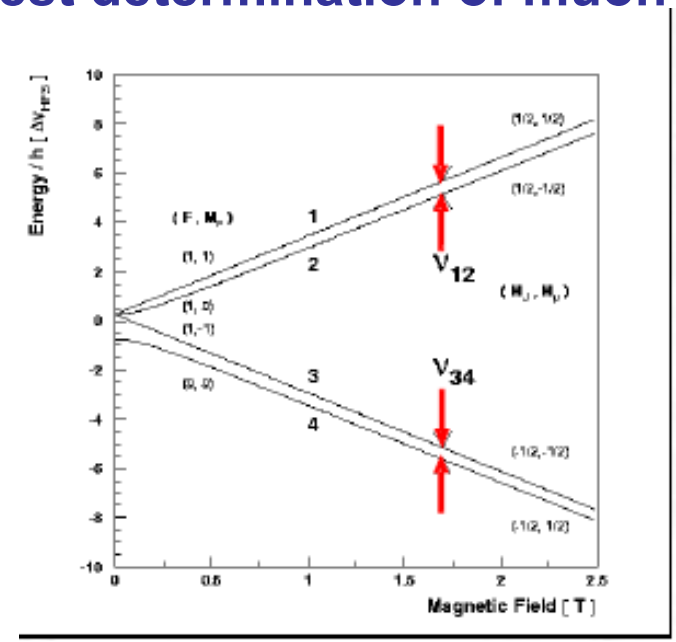
Muonium: μ^+e^- "a perfect QED-only atom"

LAMPF Hyperfine splitting experiment determined:

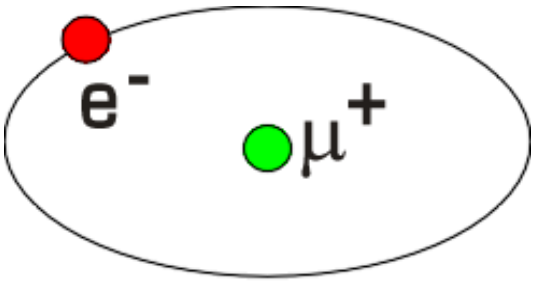
Needed for g-2

Magnetic moment ratio: μ_μ/μ_p **= 3.183 345 24(37) (120 ppb)**

Best determination of muon mass **105.6583715 ±0.0000035 MeV**



This atom has no structure



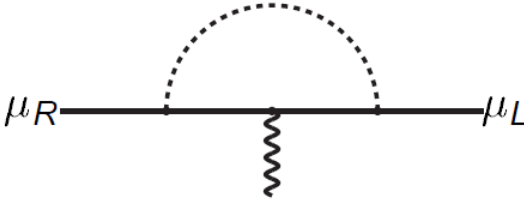
Muonium (M)

There are also efforts to measure $M \rightarrow M$ conversion as BSM tests

Chirality flipping interactions for mass and charge (moment) terms

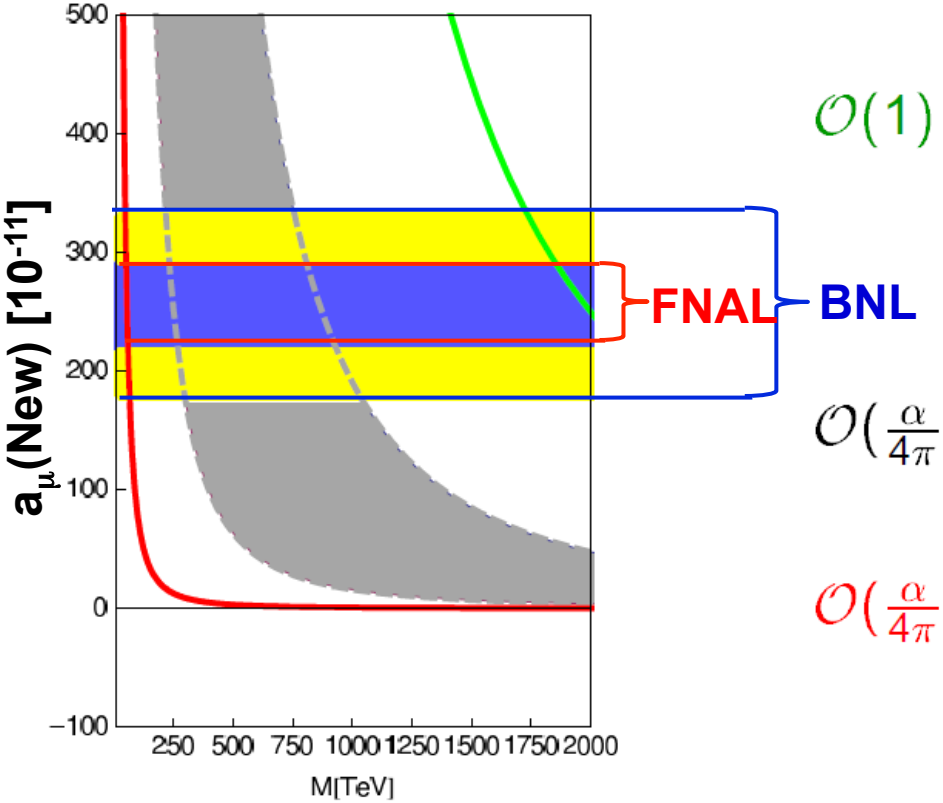
$$C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}, \quad \delta a_\mu(\mathrm{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2$$

g – 2



m_μ

The coupling *C* is VERY model dependent



$\mathcal{O}(1)$ **Radiative muon mass generation**

$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$ **SUSY (tanβ), unparticles**
Extra dimensions (ADD/RS)

$\mathcal{O}(\frac{\alpha}{4\pi})$ **Z', W', UED, Littlest Higgs (LHT) …**

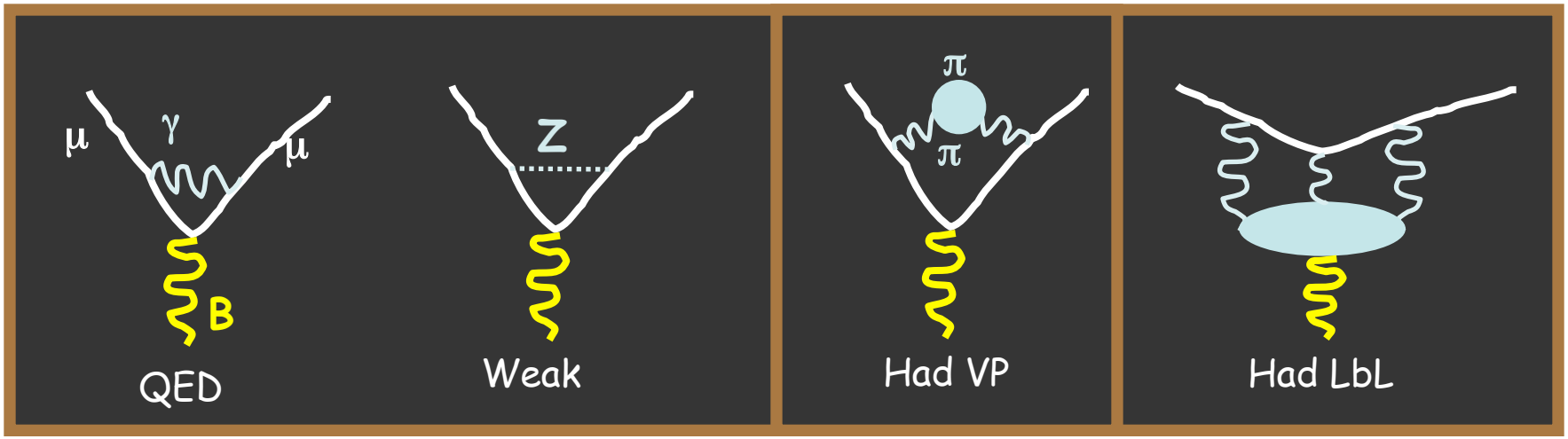
From D. Stockinger (See many of this g-2 presentations about new physics impact)

Novel Instrumentation Development

(publication worthy)

- Hydrogen TPC; deuterium cryo-TPC; cryo-preamplifiers; gas purity at ppb;
- Fast waveform digitizers
- Fast, compact calorimeters + large SiPMs
- Beamline kicker

Summary of Standard Model Contributions



Known well **Theoretical work ongoing**

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_{\alpha}$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

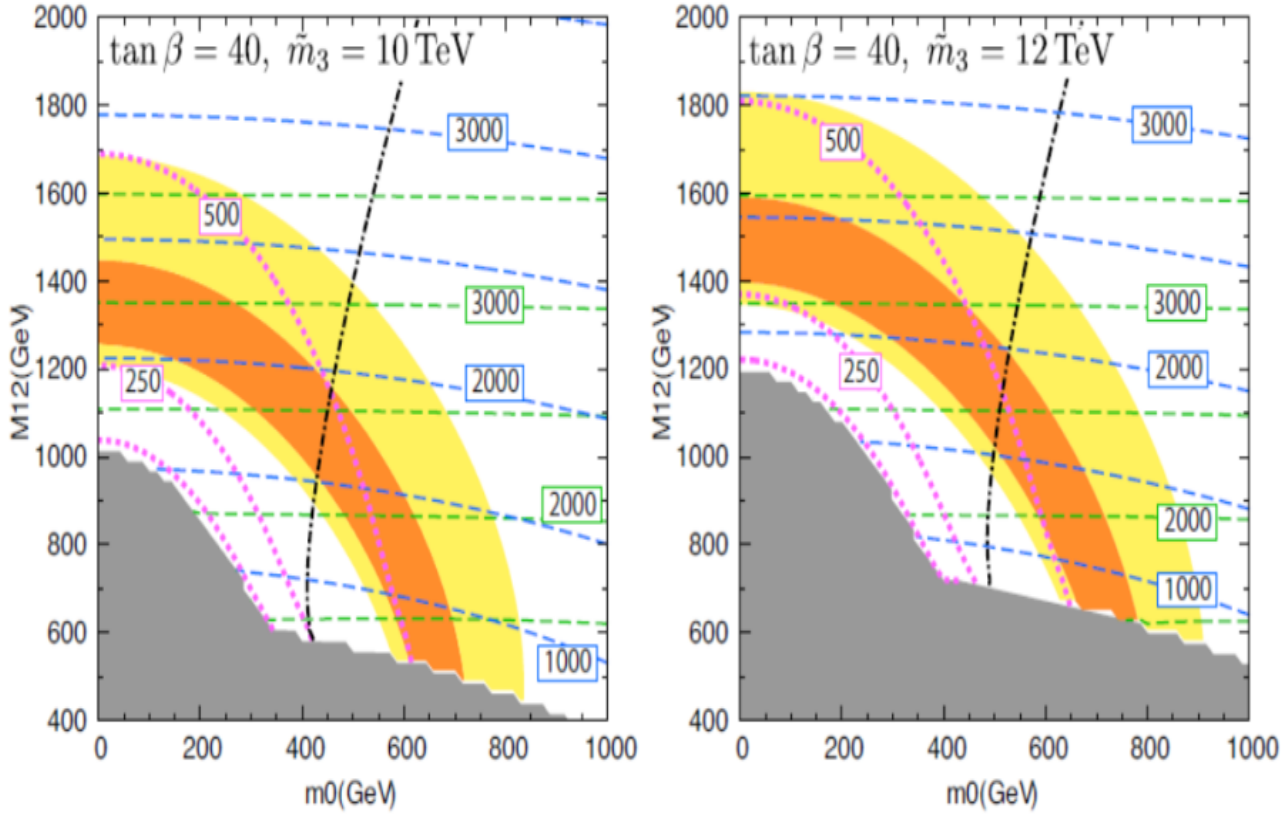
Critical

Δa_{μ}(Expt – Thy) = **297 ± 81 x 10^{-11}** **3.6 σ**

How have the LHC results – 125 GeV Higgs, no obvious new states – affected SUSY & g-2?

Example: split supersymmetry →

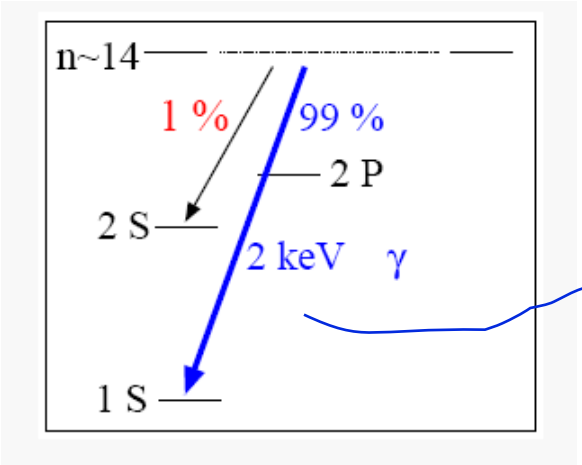
Muon g-2 and 125 GeV Higgs in Split-Family Supersymmetry

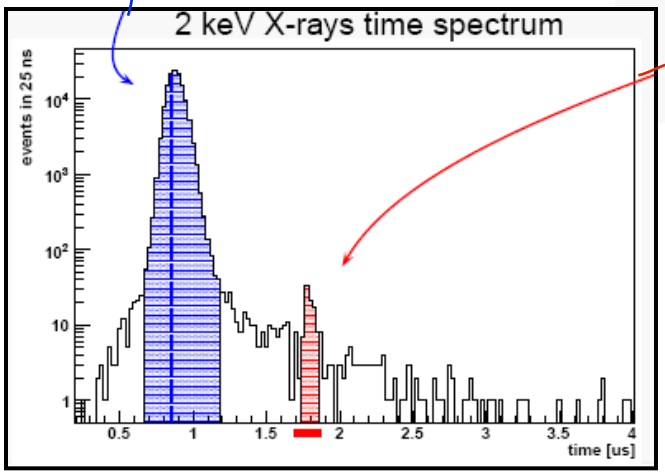


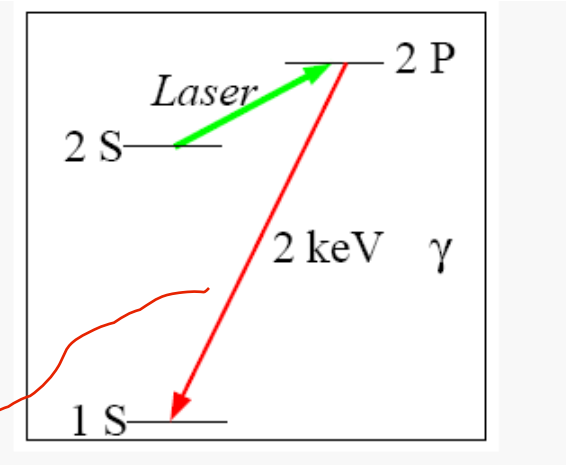
JHEP 1308 (2013) 067

The Muonic Lamb shift method is robust

1. Stop μ^- in hydrogen
2. ~1% of μp arrive in 2S atomic state
   … lifetime there ~1 μs
3. Trigger laser to excite 2S → 2P transition
   … occurs only if laser frequency is at correct ΔE
4. 2P de-excites to 1S
   … emits 2 keV X-ray as "tag"







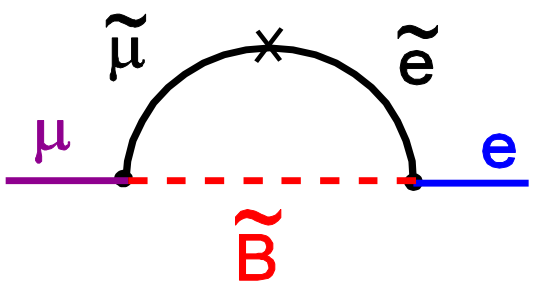
Status / Implications / Update

- Muonic deuterium also measured.
  - radius is in disagreement with CODATA, but in agreement with the muonic proton radius and the electronic H/D isotope shift
- Several transitions in He-3 and He-4 measured; will improve the corresponding charge radii by a factor of 10 (once the theory is ready).

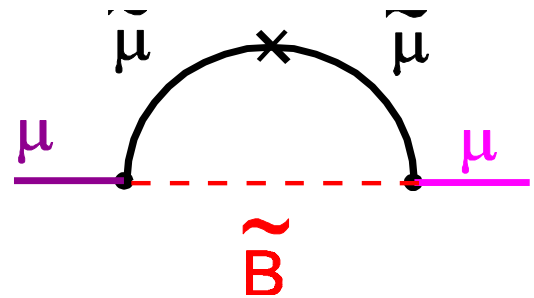
Connection between a_μ, μEDM and the cLFV transition moment $\mu \to e$

SUSY $\Longrightarrow$ slepton mixing

$\mu \to e$

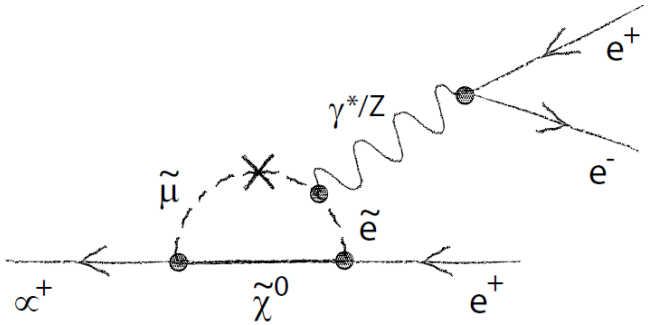


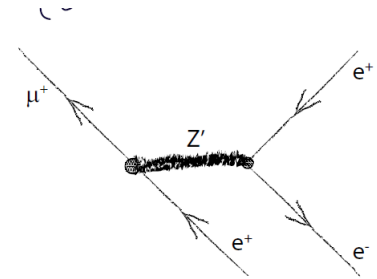
a_μ (real) EDM
(imaginary)

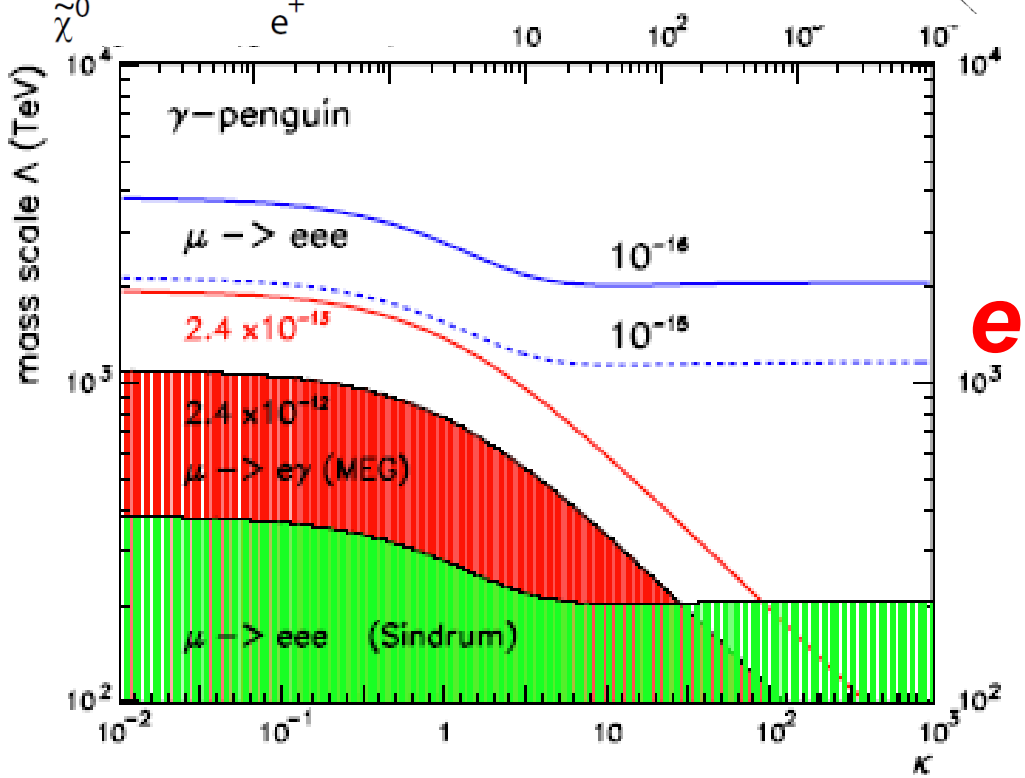


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Reminding you of the enhancements







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