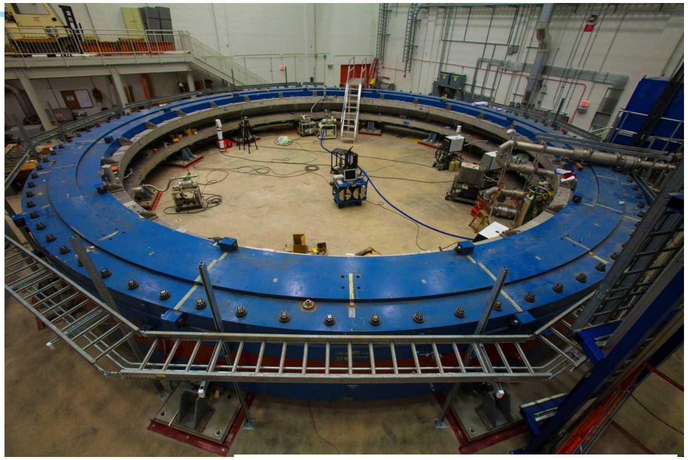
Fermilab

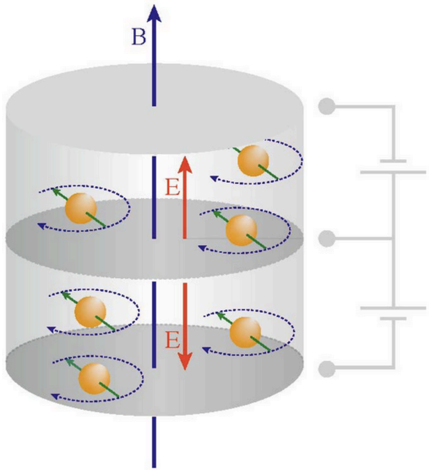
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science



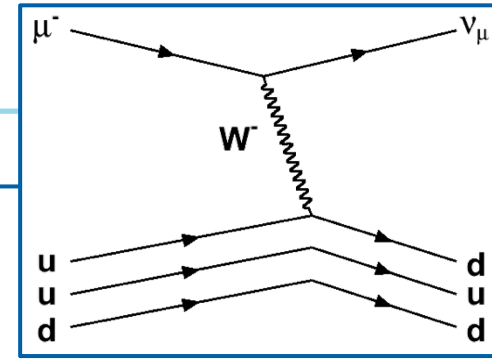
Experimental Overview of Precision Muon Physics and EDMs

- Brendan Kiburg
- Fermi National Accelerator Laboratory

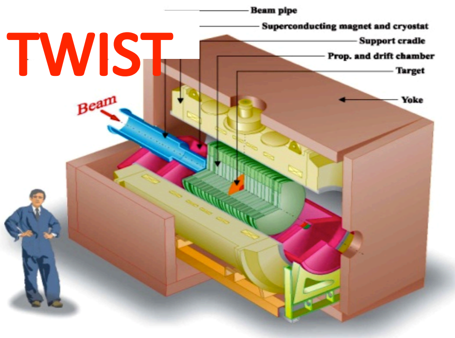
- NuFact 2015, Rio de Janeiro, Brazil
- August 12, 2015



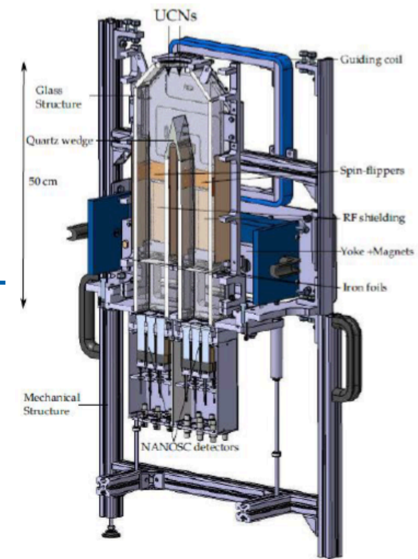
Overview



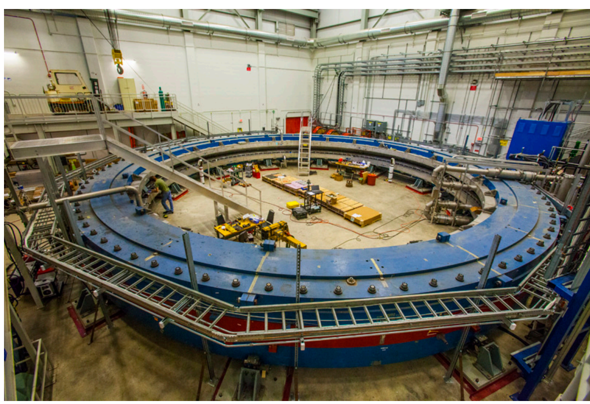
Muons as a Probe



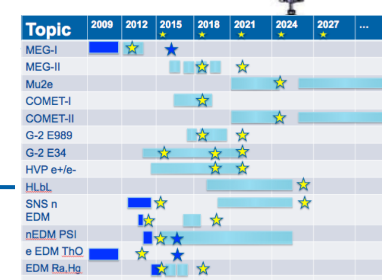
SM Measurements w/ Muons



BSM I: EDMS



BSM II: Muons



Outlook

Precision Muon Physics: Why Muons?

- We have studied the muon since its discovery 80 years ago

Exceptionally Useful Probe	
Heavy, 2nd Generation Particle	$m_\mu \approx 207 \cdot m_e$
High Sensitivity to New Physics	$\propto (m_\mu / m_e)^2$
Produced and Decay via Weak Int	
• V-A structure in pion decay	$\nu \rightleftarrows \pi^+ \leftrightarrows \mu^+$
• Muon Decay	$\mu \rightarrow e\nu\nu$
Can produce hydrogen-like atoms	$\mu^- p\,,\ \mu^+ e^-\,,\ \mu^- \mu^+$
Muon lifetime is “just right” 2.2 μs	$10^{-9}\mathrm{s} << \tau_\mu << 1\mathrm{s}$

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Muon lifetime is "just right" 2.2 μs	$10^{-9}\mathrm{s} << \tau_\mu << 1\mathrm{s}$
Much easier to detect than ν	$P(\mathrm{detection}) \approx 1$

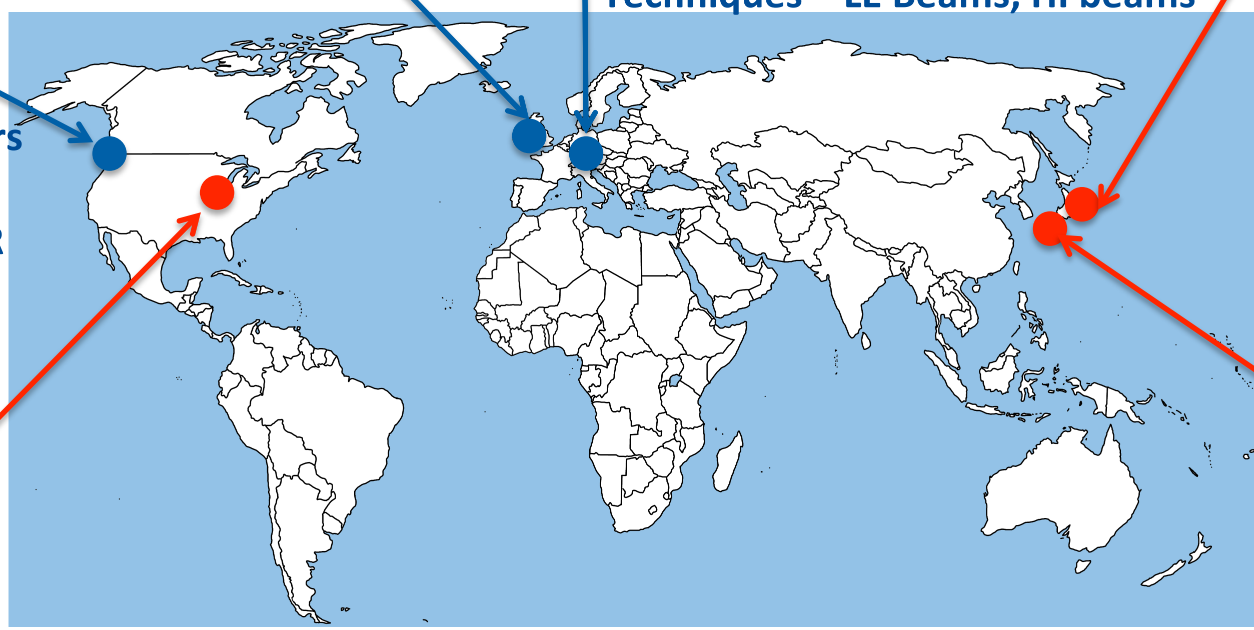
Global Precision Muon Physics Experiments

RIKEN-RAL
Materials – muSR
Techniques – LE beams

PSI
Lifetime – Fermi constant (MuLan, FAST)
Muon Capture – (Mucap, MuSun, AlCap)
Proton Radius – (mp/d Lamb Shift, CREMA, MuSE)
CLFV - (MEG, mu3e)
Materials – muSR
Techniques – LE Beams, HI beams

JPARC
Muon g-2 (E34)
CLFV – COMET, DeeMee
Muonium Spectroscopy - MUSEUM

TRIUMF
Decay Parameters - TWIST
Materials - muSR



RCNP
HI Beams Facility – MUSIC

Fermilab
Muon g-2 (E989)
Muon eDM (E989)
CLFV – mu2e

Theoretical work also very widespread

Past Present Future

For CLFV: See next talk by Y. Uchida

Precision Muon Physics to Establish the SM

- SM Electroweak Physics involves three parameters
  - Two gauge coupling constants: g, g'
  - Higgs vacuum expectation value: v

- Values fixed experimentally via precise determination of:
  - Fine structure constant α, known to 32 ppb
  - Z boson mass, known to 23 ppm
  - Fermi Coupling constant, G_F , known to 9 ppm (Giovanetti, 1984)

$$\frac{\delta G_F}{G_F} = \frac{1}{2}\sqrt{\left(\frac{\delta\tau}{\tau}\right)^2 + \left(5\frac{\delta m_\mu}{m_\mu}\right)^2 + \left(\frac{\delta\Delta q}{\Delta q}\right)^2}$$

0.14 ppm contribution from radiative corrections (Pak & Czarnecki)

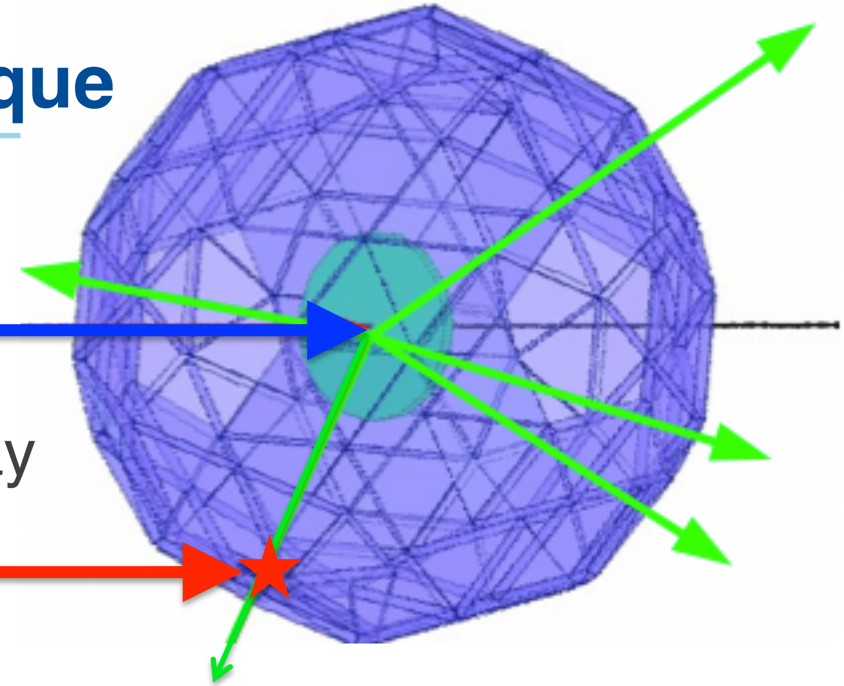
18 ppm contribution dominated uncertainty

0.09 ppm contribution

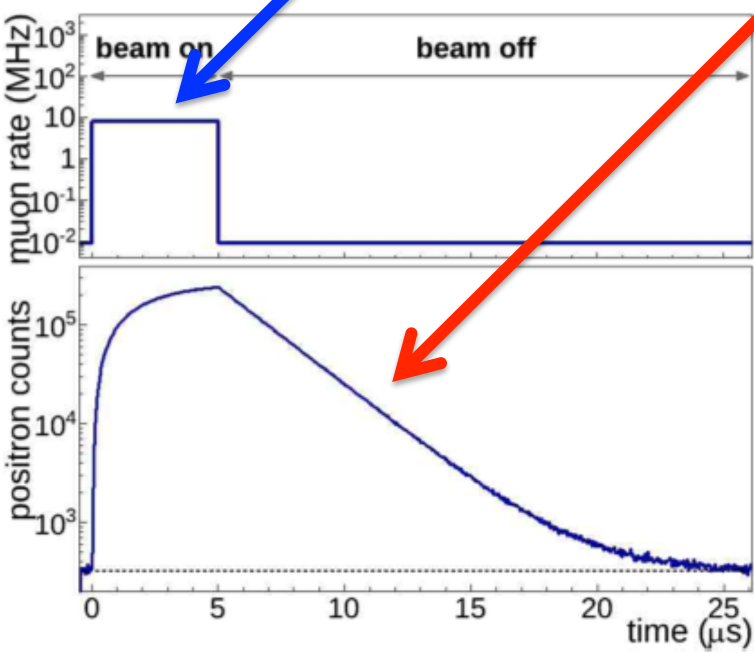
MuLan Experimental Technique

1. Prepare "radioactive source" of muons in a thin stopping target

μ^+ beam →



2. Detect decay positron



- Avoid "early-to-late" systematics
  - Gain Changes, Pileup

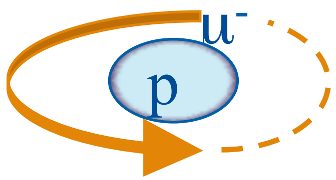
$$\tau_{\mu^+}^{\text{MuLan}} = 2196980.3 \pm 2.2\text{ps}$$

$$G_{\text{F}}^{\text{MuLan}} = 1.166\,378\,7(6) \times 10^{-5}\,\text{GeV}^{-2}$$

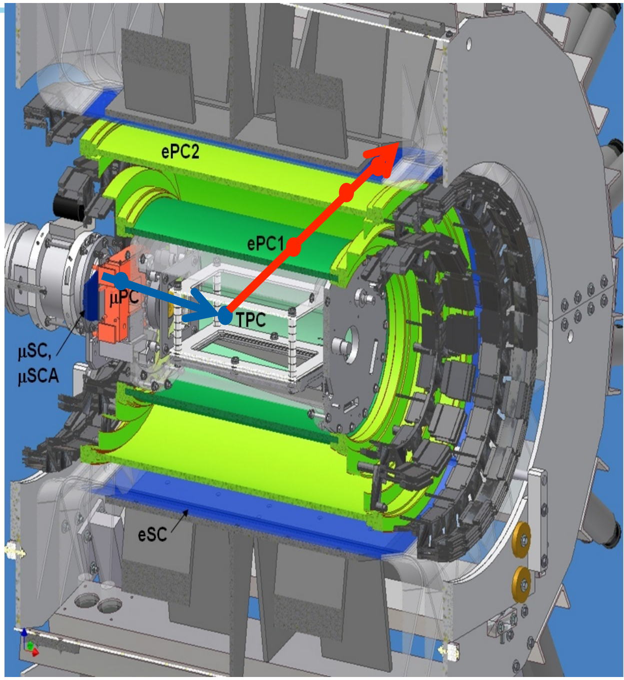
0.5 ppm!

Talk by K. Lynch, WG4, Wed AM

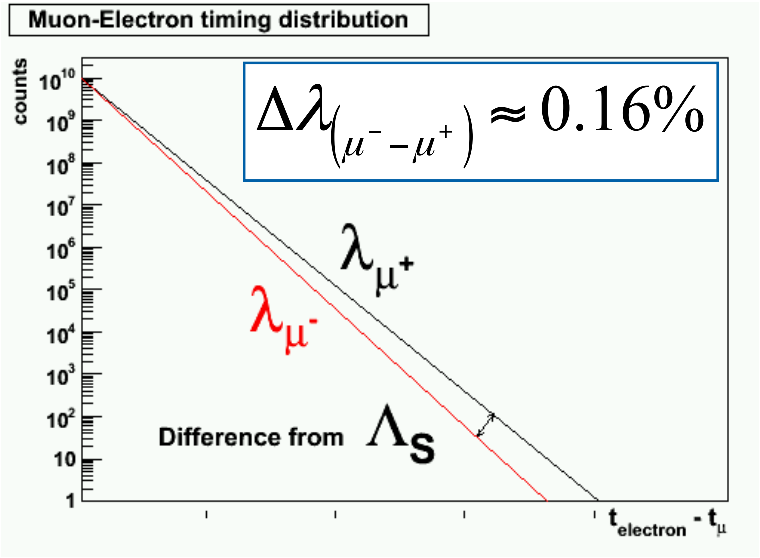
The Muon Lifetime: An Important Input to MuCap



1. Form Muonic Hydrogen Atom in an ultra-pure protium TPC



2. Use Similar Technique: Measure μ^- disappearance rate



3. Compare μ^- disappearance (via $\mu \rightarrow e\nu\nu$) to μ^+ lifetime

4. Extract very different physics

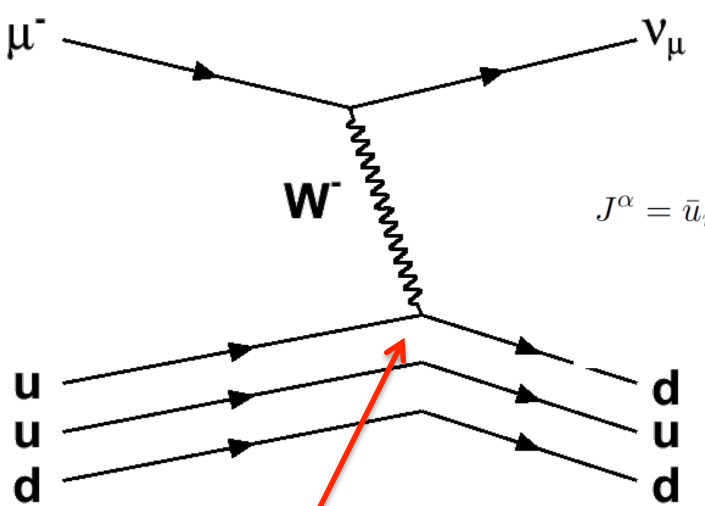
MuCap: Extracting the proton's pseudoscalar coupling, g_P

$$\boxed{\mu^- + p \rightarrow n + \nu_\mu}$$

$$M_{fi} = \frac{G_F V_{ud}}{\sqrt{2}} L_\alpha J^\alpha$$

$$L_\alpha = \bar{u}_\nu \gamma_\alpha \left(1 - \gamma_5\right) u_\mu$$

$$J^\alpha = \bar{u}_n \left(\underbrace{g_V \gamma^\alpha + \frac{i g_M}{2m_N} \sigma^{\alpha\nu} q_\nu + \frac{g_S}{m_\mu} q^\alpha}_{V^\alpha} - \underbrace{g_A \gamma^\alpha \gamma_5 - \frac{g_P}{m_\mu} q^\alpha \gamma_5 - \frac{i g_T}{2m_N} \sigma^{\alpha\nu} q_\nu \gamma_5}_{A^\alpha} \right) u_p$$



Sensitive to the nuclear environment

g_P(Chiral Pert. theory) = 8.26 ± 0.23

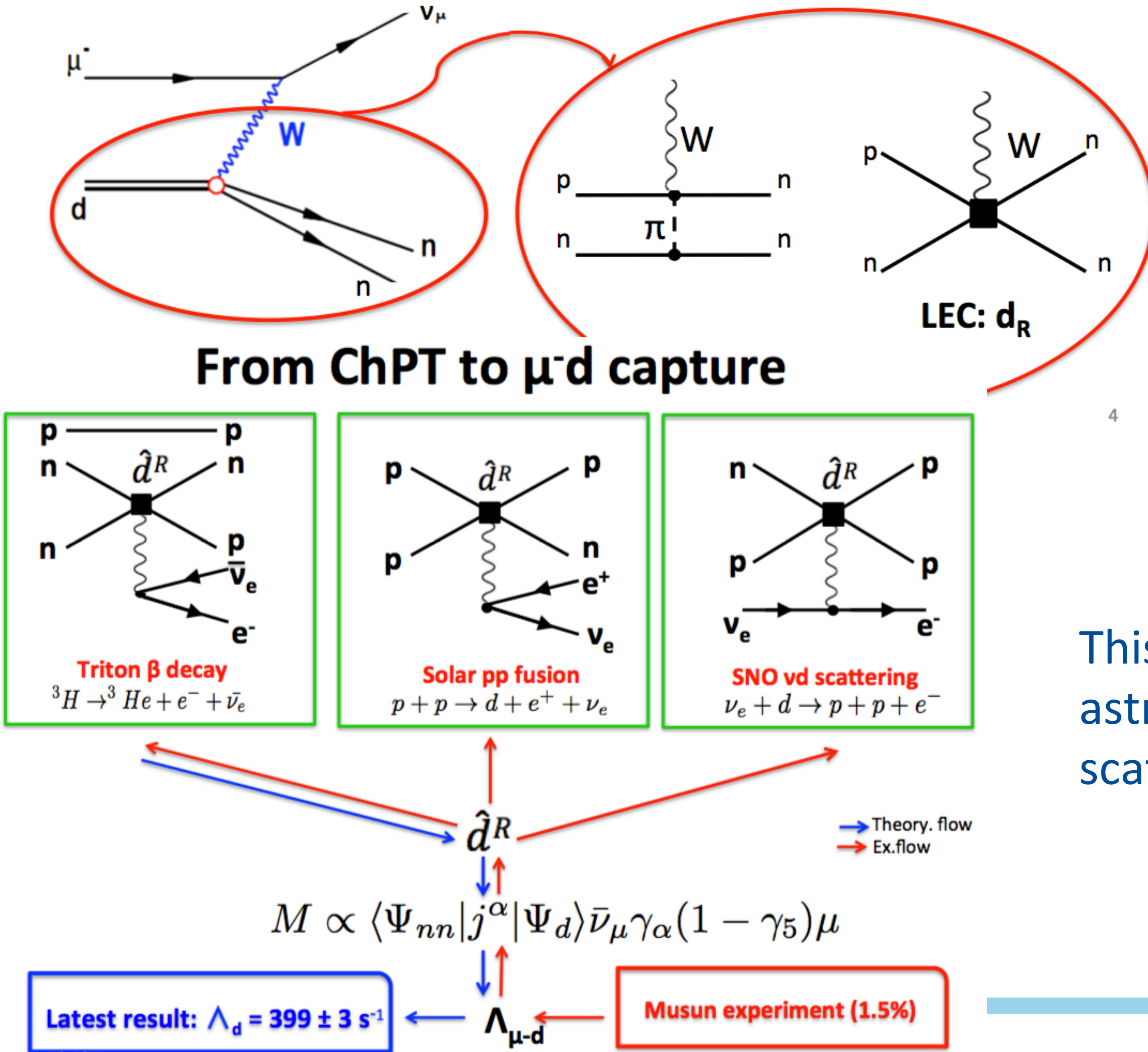
$$\boxed{g_P(\text{MuCap}) = 8.14 \pm 0.55}$$

Verified important ChPT prediction

Talk by BK, WG4   Wed AM

Fermilab

MuSun : Similar Technique, Different Physics Goal



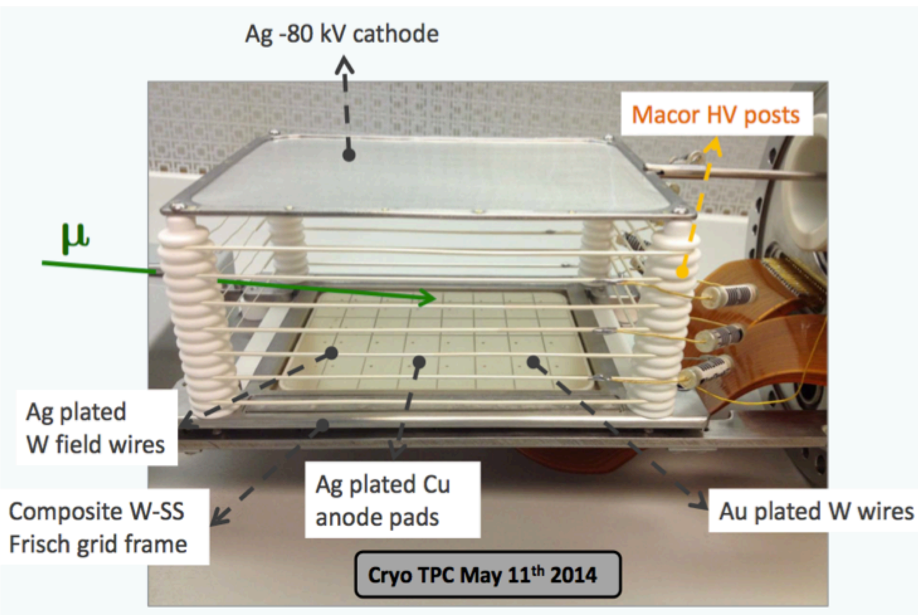
Simplest process on compound nucleus

Clean channel to determine Low Energy Constant in Effective Field Theories

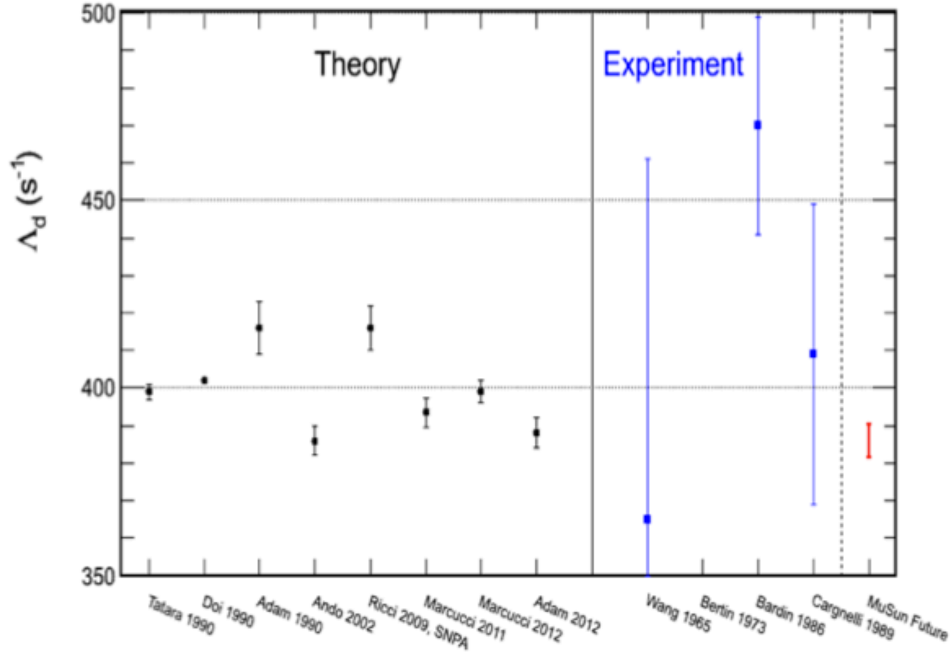
This LEC directly relates to astrophysical and neutrino scattering processes

MuSun : Similar Technique, Different Physics Goal

- Replace MuCap Protium TPC with MuSun Deuterium TPC
- Novel, compact Cryogenic TPC (30K) with ultra-pure Deuterium



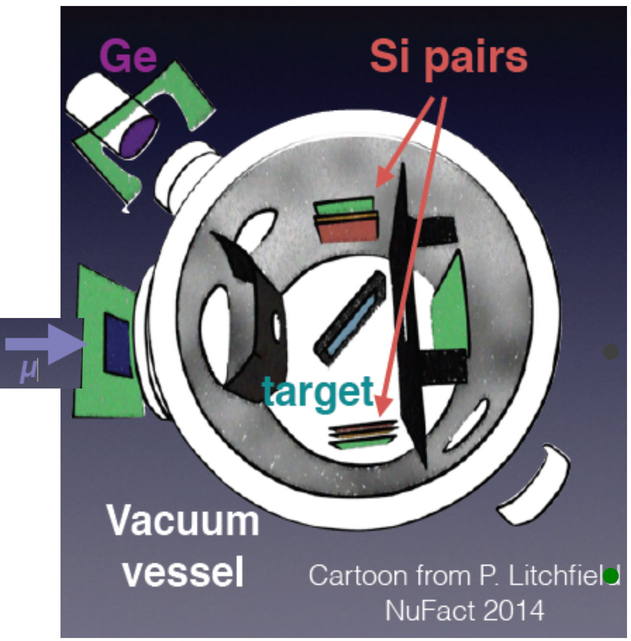
Select between competing theories



Completed run at PSI Aug 2nd → Most of production data in hand

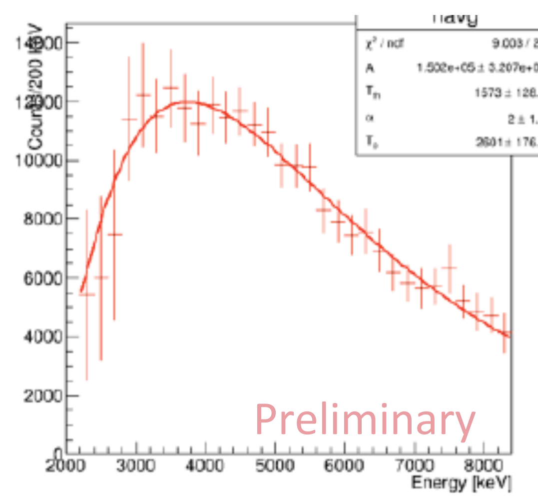
AlCap – Muon Capture on Aluminum

- Studies Particle emission in muon capture on Aluminum
  - Major source of single hit rate in trackers for mu2e and COMET



- Data Runs
  - 2013: Charged particle emission (CPE)
  - June 2015: Neutrals
  - Nov 2015: CPE w/ upgrades to DAQ, energy range
- Preliminary estimate of (3.5 ± 0.2)% CPE per muon capture

See updated results in AlCap talk by B. Krikler, WG4 Wed AM

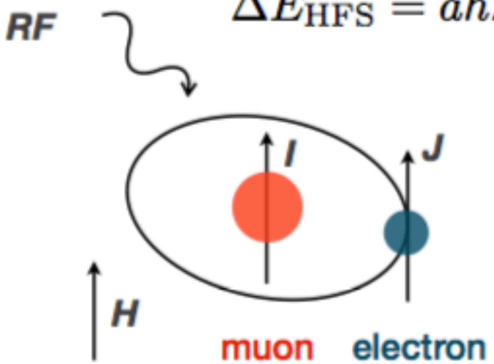


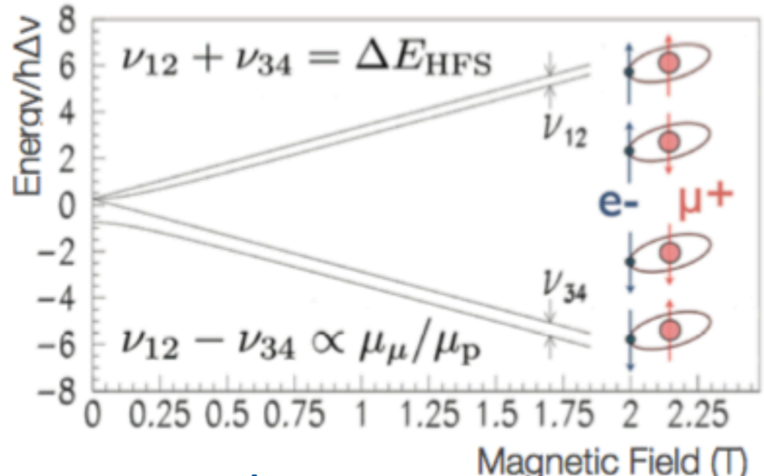
MUSEUM @ JPARC

Hamiltonian of Muonium $\mathcal{H} = \underbrace{a\vec{I}\cdot\vec{J}}_{\text{HFS}} + \underbrace{\mu_B^e g_J \vec{J}\cdot\vec{H} - \mu_B^\mu g_\mu^{'} \vec{I}\cdot\vec{H}}_{\text{Zeeman Splitting}}$ + RF term

Slide from Kanda

$$\Delta E_{\mathrm{HFS}} = ah\Delta\nu$$





Pure leptonic system, point particles

Precision test of bound state QED

$\Delta E_{\mathrm{HFS\ Theory}} = 4.463302891(272)$ GHz **(63 ppb)**
D. Nomura and T. Teubner, Nucl. Phys. B 867, 236 (2013)

$\Delta E_{\mathrm{HFS\ Exp}} = 4.463302765(53)$ GHz **(12 ppb)**
W. Liu *et al.*, PRL, 82, 711 (1999)

Important input for muon g-2

$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}}$$

540 ppb; 26 ppb

R : From storage ring experiment

λ : From Muonium HFS

$$\lambda = \frac{\mu_\mu}{\mu_p}$$

(B-field is obtained via proton NMR)

Proton Radius Puzzle

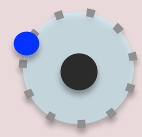
e$^-$

Muonic Hydrogen

$$m_\mu \approx 207 \cdot m_e$$

$$r_\mu \approx 1/207 \cdot r_e$$

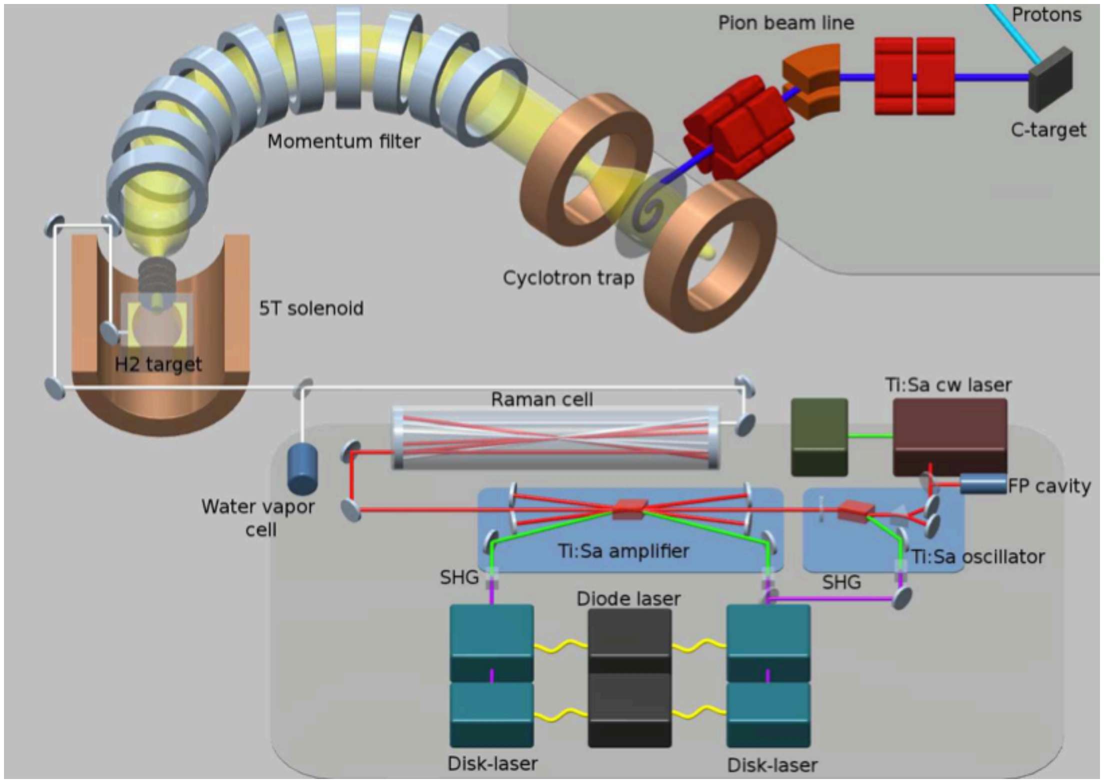
μ$^-$

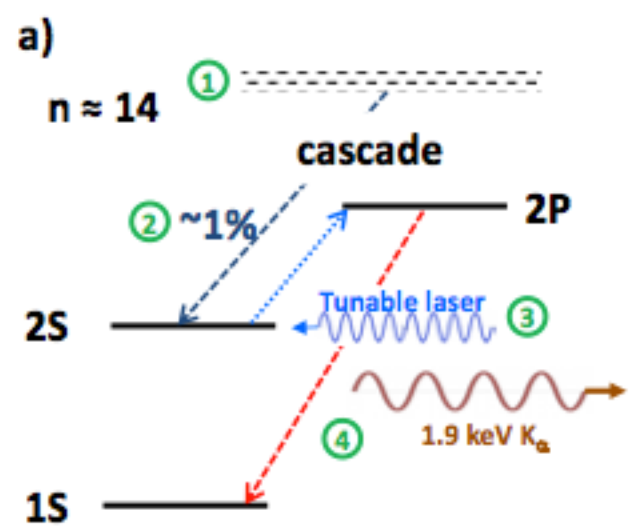


$$(r_\mu/r_e)^3 \approx (1/207)^3 \approx 10^{-7}$$

- Muons probe the proton significantly deeper than r_e
- Improve precision of the proton charge radius

Muonic Hydrogen Lamb Shift Technique

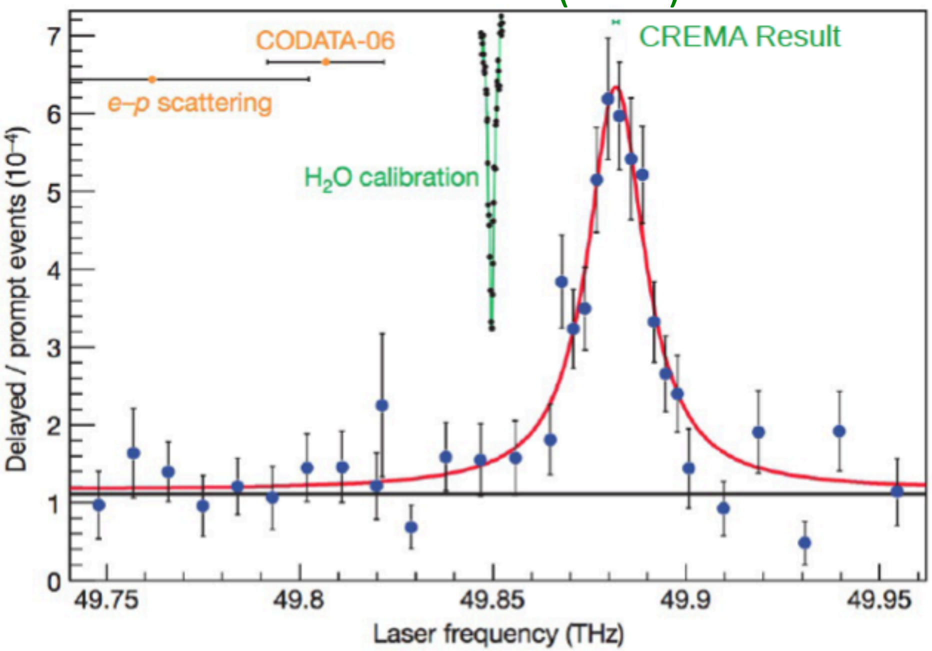




1. Form Muonic Hydrogen
2. About 1% of muons cascade to meta-stable 2S state
3. Use laser to induce 2S-2P
4. Measure 1.9 keV x-ray in 2P-1S transition

Muonic Hydrogen Lamb Shift Differs from Electronic Experiments

See: R. Pohl et al. Nature 466 (2010) 213.



$$\mu\text{p} \quad r_p = 0.8409(4)\text{fm}$$

$$\text{CODATA} \quad r_p = 0.8775(51)\ \text{fm}$$

$$\text{e-p scat} \quad r_p = 0.8790(80)\ \text{fm}$$

7σ discrepency !

- Hard to build
- Easy to interpret
- μd Lamb shift confirms observation
- Next Steps
  - μp scattering (MUSE)
  - μHe Lamb shift
  - Repeat atomic hydrogen Spectroscopy

Hints and Big Questions

- Proton Radius Puzzle
  - A true puzzle since 2010 ; not predicted by models
  - Explanation: Error or something Profound
  - Perhaps a Question we haven't formed properly yet
- Big Questions
  - What are the properties of the yet-unseen particles?
  - Where does the baryon asymmetry come from?
- If LHC doesn't see New Physics, where do we look next?
  - CLFV – See Next Talk
  - EDMs
  - Muon g-2
- If LHC sees New Physics, where do we look to understand the NP nature?
  - Same: CLFV, EDMs, Muon g-2

Baryon Asymmetry of Universe

- Observed asymmetry:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$

- Assuming asymmetry not present at the Big Bang, Existing CP-Violation insufficient to explain observation
  - CPV in kaon/B-meson systems in flavor-changing interactions
- Look in Neutrino Sector $\delta_{CP}\ ,\ P(\nu_\mu \to \nu_e) \neq P(\bar{\nu_\mu} \to \bar{\nu_e})$

EDM Basics

- Permanent Electric Dipole Moments are good candidates
  - T- & P-Violating → CP-Violating (Assuming CPT)
  - Flavor-Conserving CPV

- Types of EDMs
  - Nucleon EDM (n,p)
  - Bare lepton (e, μ)
  - Paramagnetic Atoms/Molecules → Electron EDM
  - Diamagnetic Atoms → Nuclear Shiff moment, nucleon edm, or nuclear-spin-dependent electron-nucleon interaction

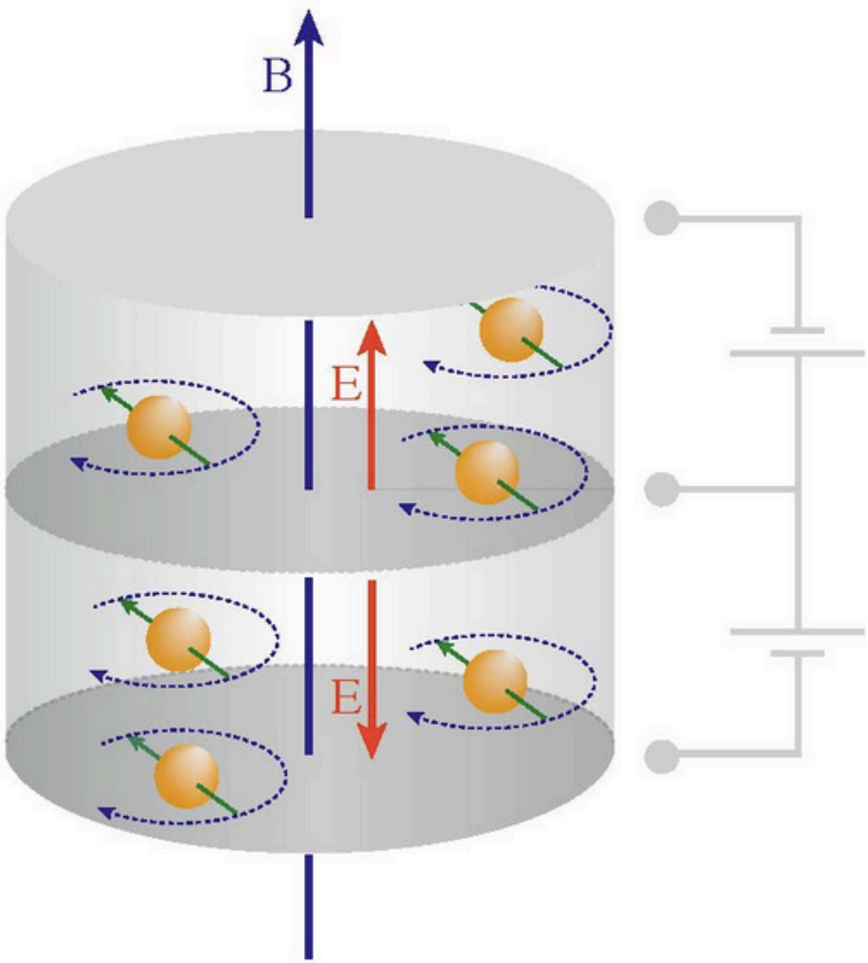
Theory must interpret

- ANY detection of an EDM would be very significant
  - So far, experiments have set impressive limits

Ref: Theory: Engel, Musolf arXiv:1303.2371
Exp: Chupp, Musolf, arXiv:1407.1064

See talk by Paradisi, Thu AM Plenary

Typical EDM Technique



1. Set up constant magnetic field
2. Bring neutral particle into the field
3. Rotate particle so that it precesses about the B-field
4. Add Electric field Parallel to field (alternate aligned/anti-aligned)
5. A permanent intrinsic EDM will manifest as a difference in the Larmor precession frequencies

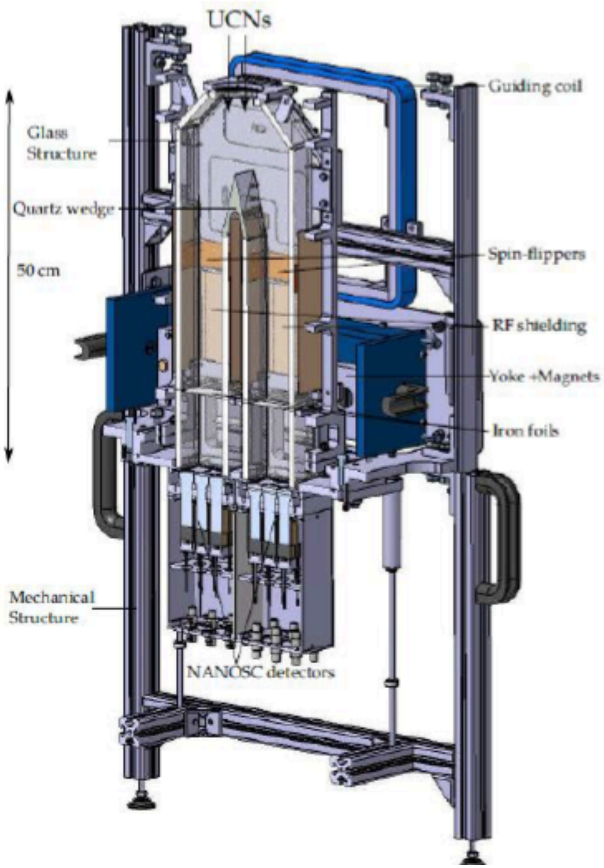
$$\omega(E\uparrow, E\downarrow) = 2\mu B \pm 2dE$$

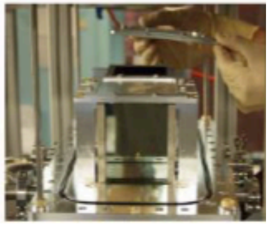
$$\Delta\omega = 4dE$$

6. Steps 6-100: Systematic variations of all of the knobs

Neutron EDM Efforts

nEDM @ PSI





- Started ~200 days neutron data to exceed ILL sensitivity $3x10^{-26}$ e-cm in 2016
- Replacing/Upgrading key detector features for n2EDM
  - Mu-metal Shield
  - Double chamber setup (two E direction)
  - Magnetometers (improved ^{199}Hg, He-3)
- Start n2EDM data 2018-2019
- Goal: $3x10^{-27}$ early 2020s

- Also: SNS EDM effort in critical component demonstration phase now, integration ~2018, data early 2020s as well

Talk by E. Wursten WG4 Tue PM

ThO electron EDM

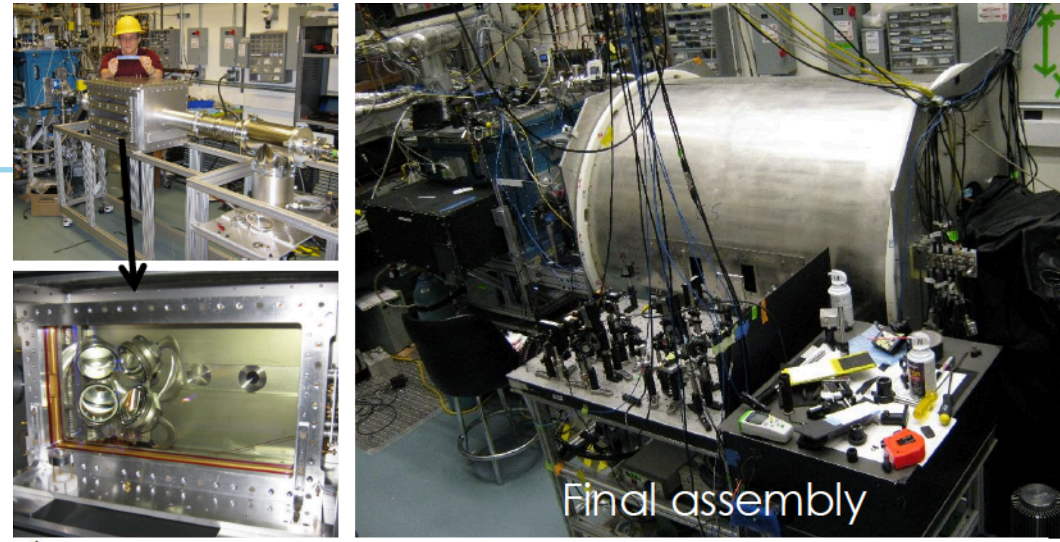
ACME Experiment Gen 1

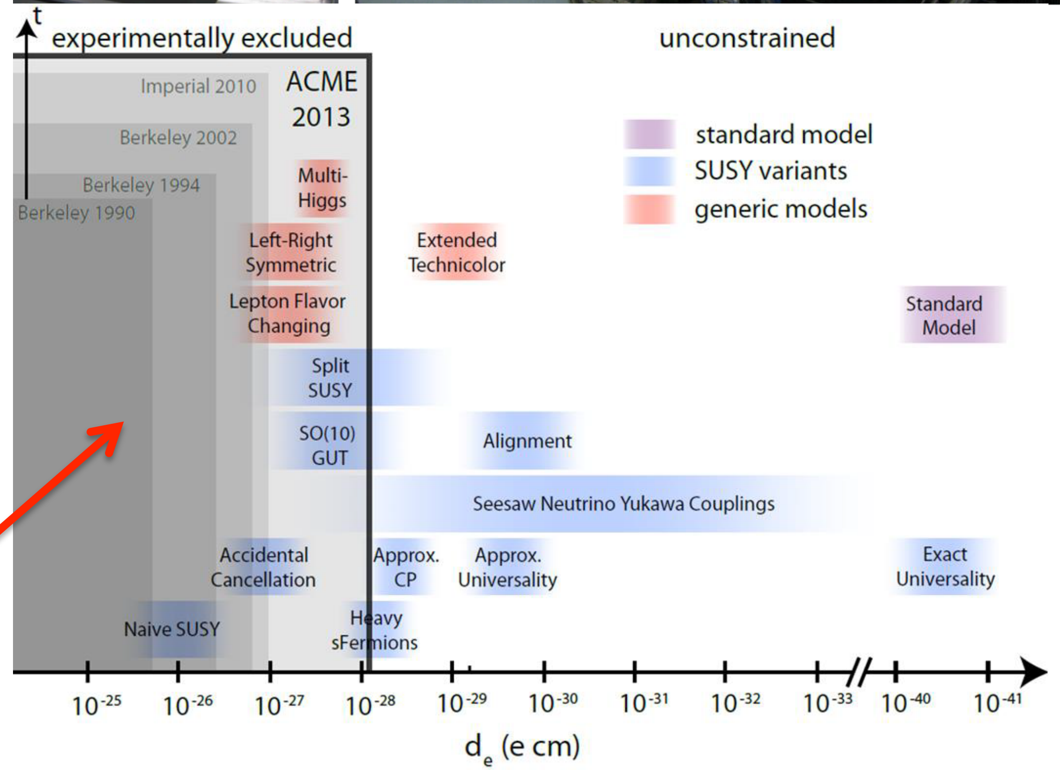
- Paramagnetic System
- Modest $E_{applied}$=10 V/cm
- Large $E_{effective}$ = 80 GV/cm
- Experimental switches
  - N (ThO molecule dir.)
  - E applied
  - B applied
- Impressive new limit

$$|d_e| < 1 \times 10^{-28}\ e{\cdot}\mathrm{cm}$$

(90 % CL)

- Models constrained

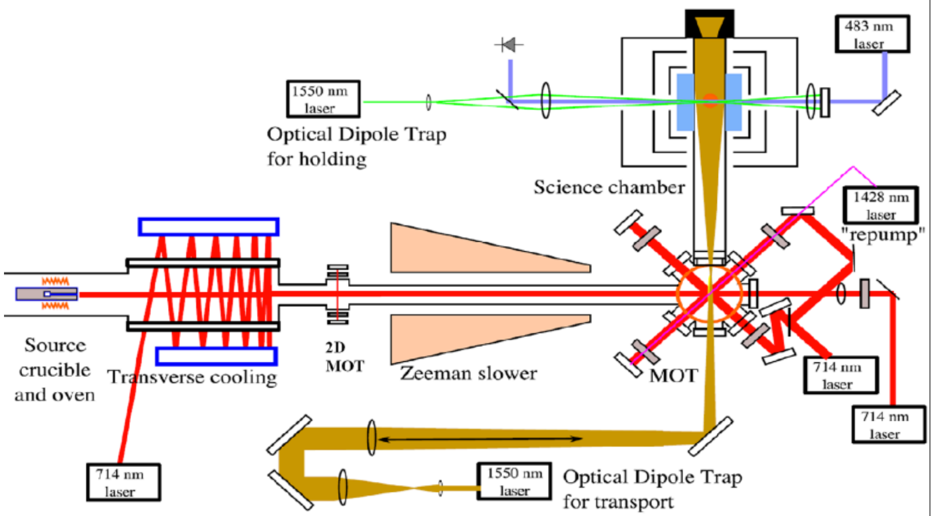




Atomic EDMs

First Radium 225 Measurement - ANL

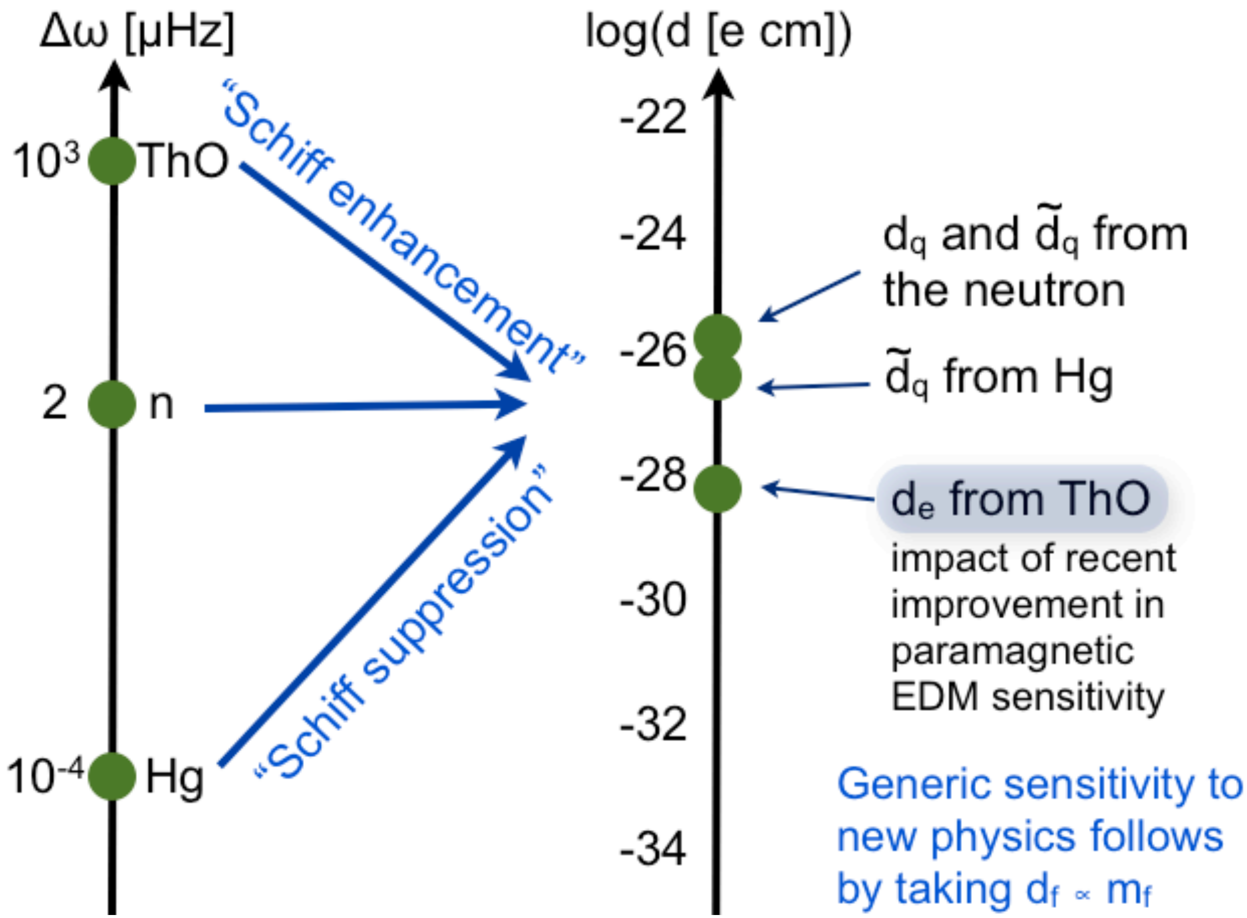
- Octupole deformation → large Schiff moment
- Reports $d_{Ra} < 4\text{x}10^{-22}$ e-cm
- Increase: Trap lifetime, E-field, radium production
- Goal: $4\text{x}10^{-25}$ e-cm sensitivity



- Also: ^{199}Hg at Washington is the standard-bearer of atomic EDMs
  - Existing limit: $d_{\mathrm{Hg}} = 3.1 \times 10^{-29}$, $\tilde{d}_q = 6 \times 10^{-27}$ e-cm
  - Controlling Systematics → x5 improvement in 2015

Experimental Summary of EDM bounds

Measurement ------> EDM Implication

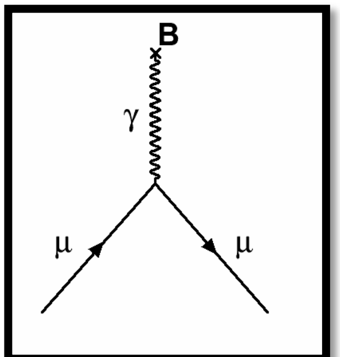


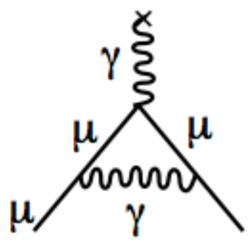
Significant experimental progress in last few years

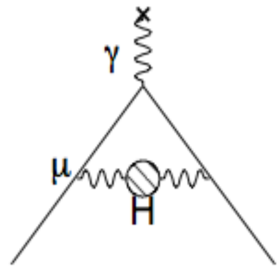
Courtesy: A. Ritz @ CIPANP 2015

Muon g-2 : Motivation

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

g = 

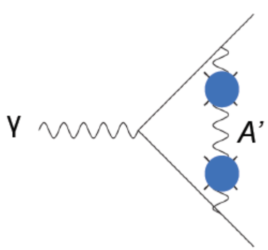
+ 

+ 

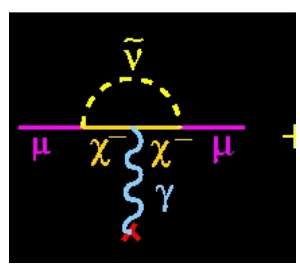
+...

$g = 2 + \alpha/2\pi + 6\text{x}10^{-8} + \ldots$

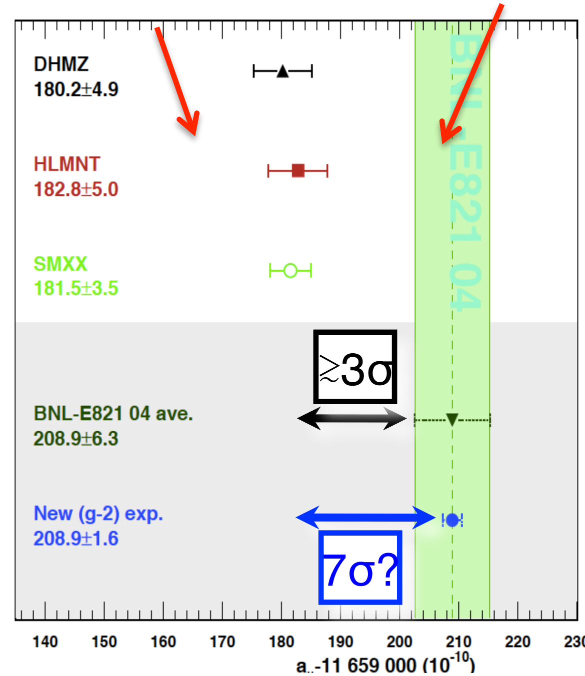
Dark photon

+? 

SUSY

+? 

Theory Exp

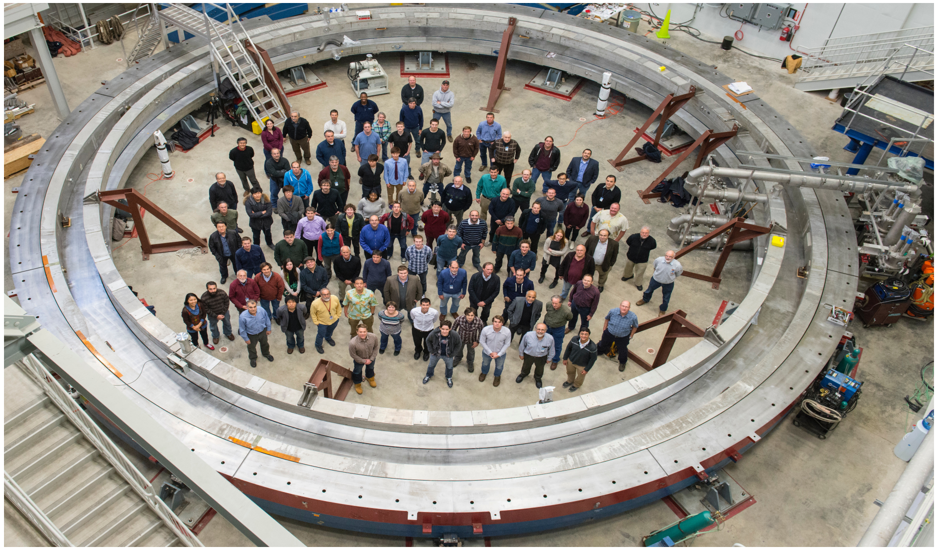


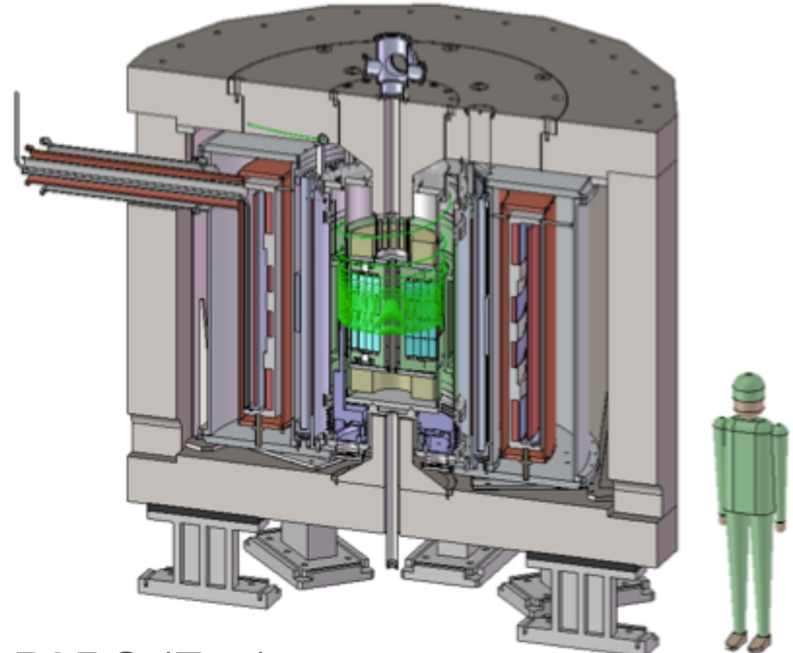
[Blum et al., arXiv:1311.2198]

Hints at potential new physics

Next-Generation Experiments

G-2 + Muon EDM





Fermilab (E989)

- High-rate 3.09 GeV/c muon beam
- Highly polarized (97%)
- 1.45 Tesla, 7-meter-radius storage ring

J-PARC (E34)

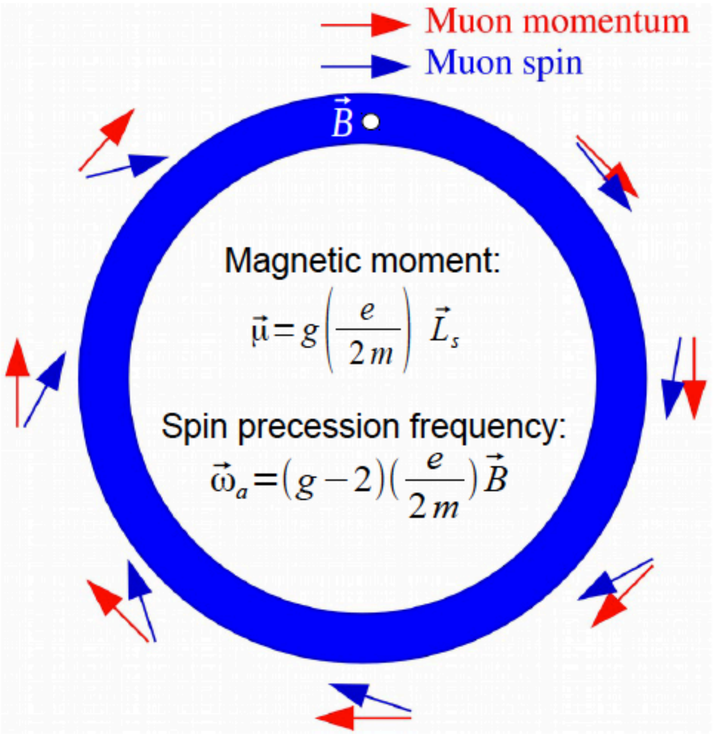
- Surface muon beam → muonium → 0.3 GeV/c muon beam
- Polarization ~ 50%
- 3 Tesla, 0.33-meter-radius storage ring

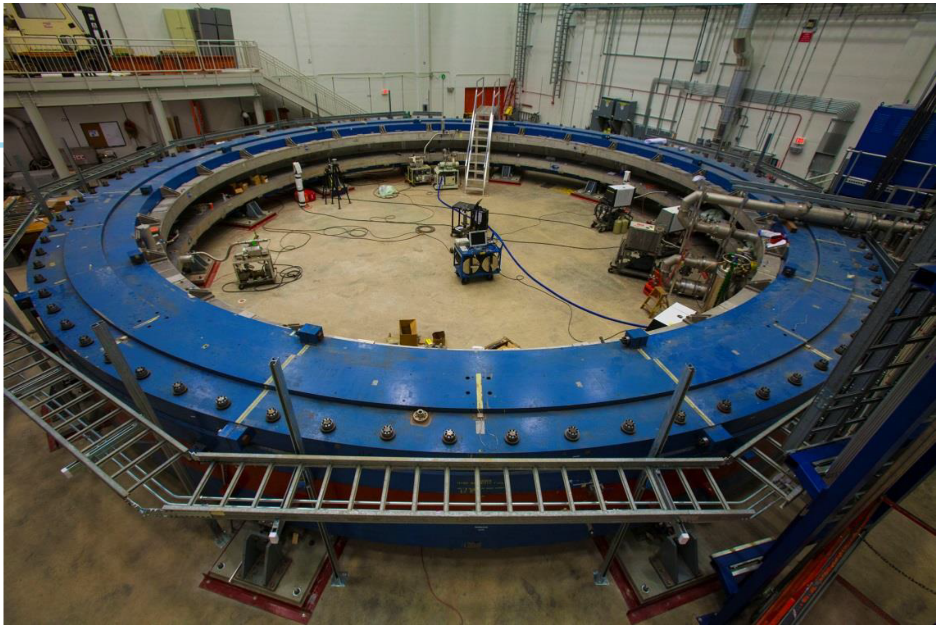
Talk by K. Lynch WG4 Tue AM

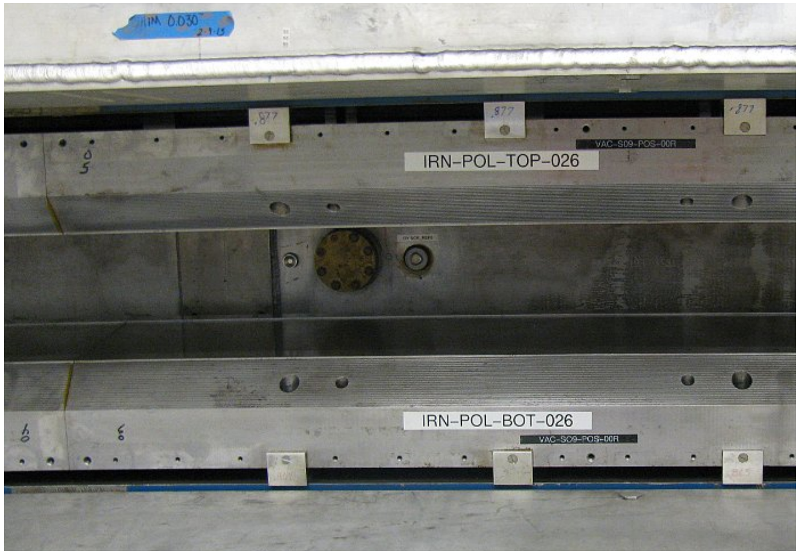
Talk by M. Otani WG4 Tue AM

Note: Also large Lattice QCD Effort to improve theory prediction for HVP, HLBL

g-2 Storage Ring





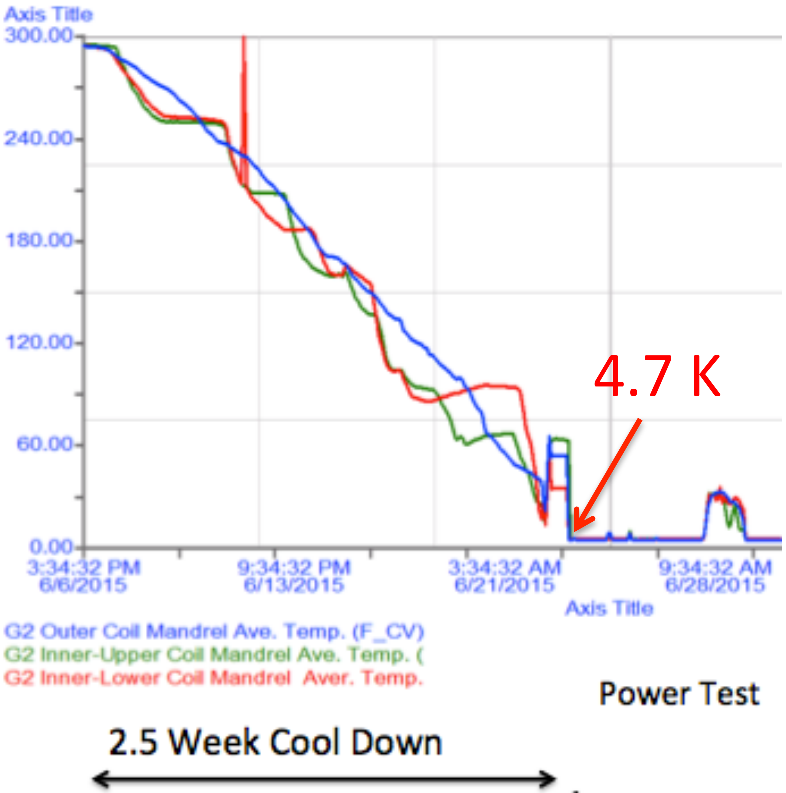


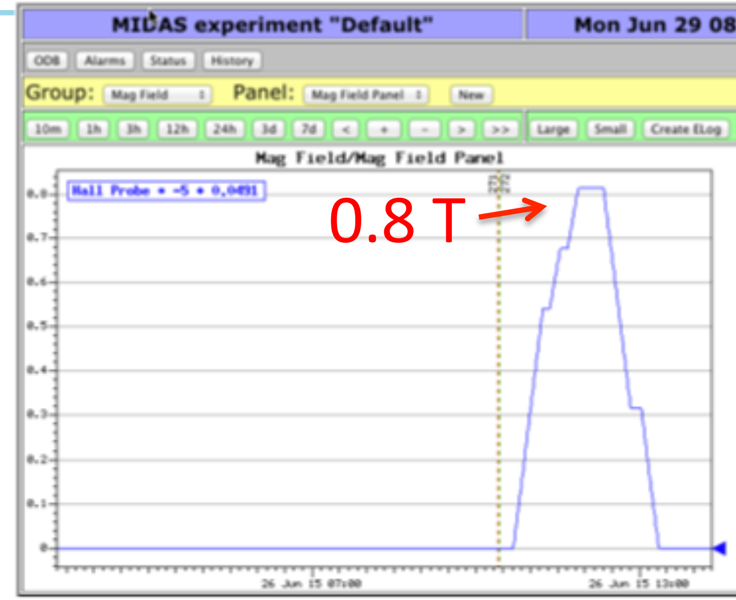
$$\omega_a = \omega_S - \omega_C = (e/m)\, \mathbf{a_\mu}\, B$$

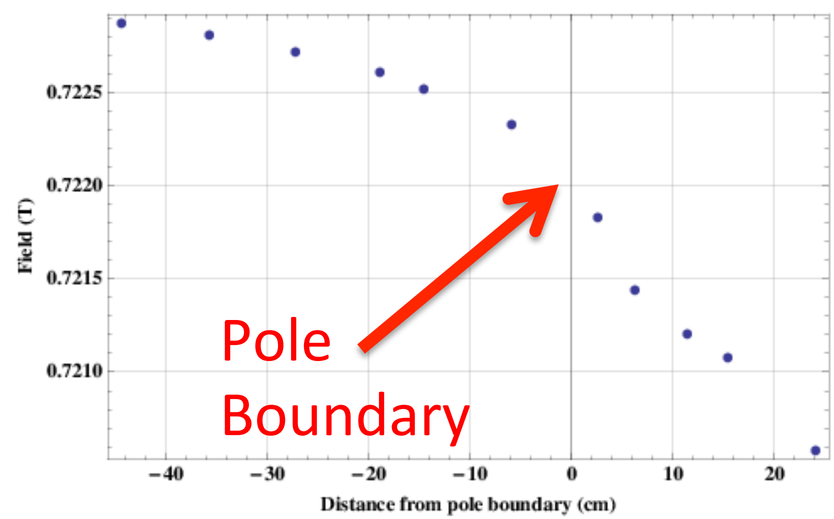
Precise measurements of

- Precession frequency
- Magnetic Field

First Muon g-2 Field Maps







- First field measurements
- Shim <B> Field to ~100 ppb
- We are starting now
- First results expected in 2017

Summary

Precision measurements using the well-established muon as a probe continue to validate critical Standard Model parameters and sometimes reveal Puzzles

A suite of EDM Searches and Precision Muon Physics will discover BSM Physics over the next decade or significantly constrain BSM models

Excellent Recent Reviews

- Precision Muon Physics
  - Kammel, Kubodera, *Precision Muon Capture.* Ann. Rev. Nucl. Part. Sci. **60** p.327-353 (2010).
  - Gorringe, Hertzog. *Precision Muon Physics.* Prog. Part. Nucl. Phys. **84** p.73-123 (2015).
- EDMs
  - Engel, Ramsey-Musolf, van Kolck, *Electric dipole moments of nucleons,nuclei, and atoms: The Standard Model and Beyond.* Prog. Part. Nucl. Phys. **71** p.21-74 (2013).
  - Chupp, Ramsey-Musolf, *Electric dipole moments: A global analysis.* Phys. Rev. C **91** 035502 (2015).

Additional Slides

Muon beams

Slide: P. Winter Jul 2013

Laboratory/ Beam line	**Energy/ Power**	**Present Surface μ^+ rate (Hz)**	**Future estimated μ^+/μ^- rate (Hz)**
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	"	$4 \cdot 10^8$	
$\pi E5$	"	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10} (\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	"	$3 \cdot 10^7$	
MUSE U-line	"		$2 \cdot 10^8 (\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11} (\mu^-)$ (2019/20)
PRIME/PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12} (\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10} (\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12} (\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	"	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8 (\mu^+)$ (2012) means $> 10^{11}$ per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

Muon experiments: Beam rates

Slide: P. Winter Jul 2013

Experiment	Beam	Momentum	Rates [1/s]	Beamline
TWIST	μ^+	29.8 MeV/c	$<5 * 10^3$	TRIUMF
Muon lamb shift	π^- μ^-	100 MeV/c ~1 MeV/c	$\sim 10^8$ $\sim 2.5 * 10^2$	πE5 @ PSI
MuLan	μ^+	29.8 MeV/c	$8 * 10^6$	πE3 @ PSI
MuCap / MuSun	μ^-	34 MeV/c	$1 * 10^5$	πE3 @ PSI
MEG	μ^+	29.8 MeV/c	$3 * 10^7$	πE5 @ PSI
MEG upgrade	μ^+	29.8 MeV/c	$7 * 10^7$	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. I)	μ^+	29.8 MeV/c	$<1 * 10^8$	πE5 @ PSI
$\mu^+ \to e^+e^-e^+$ (Ph. II)	μ^+	29.8 MeV/c	$2 * 10^9$	HIMB @ PSI
Mu2e	μ^-	~40 MeV/c	10^{10}	FNAL

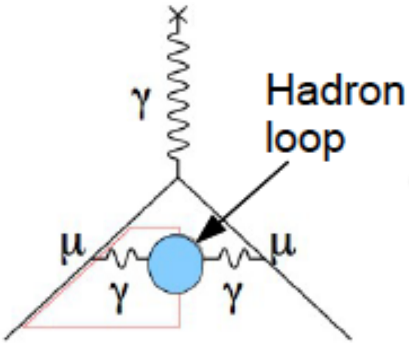
Muon g-2: The path forward

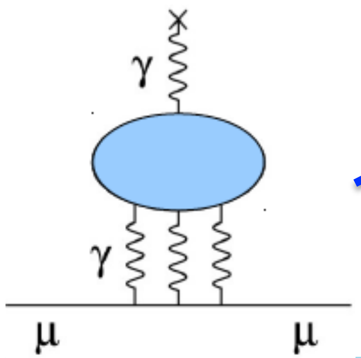
Slide: B. Kiburg May 2015

Muon precession

Proton precession

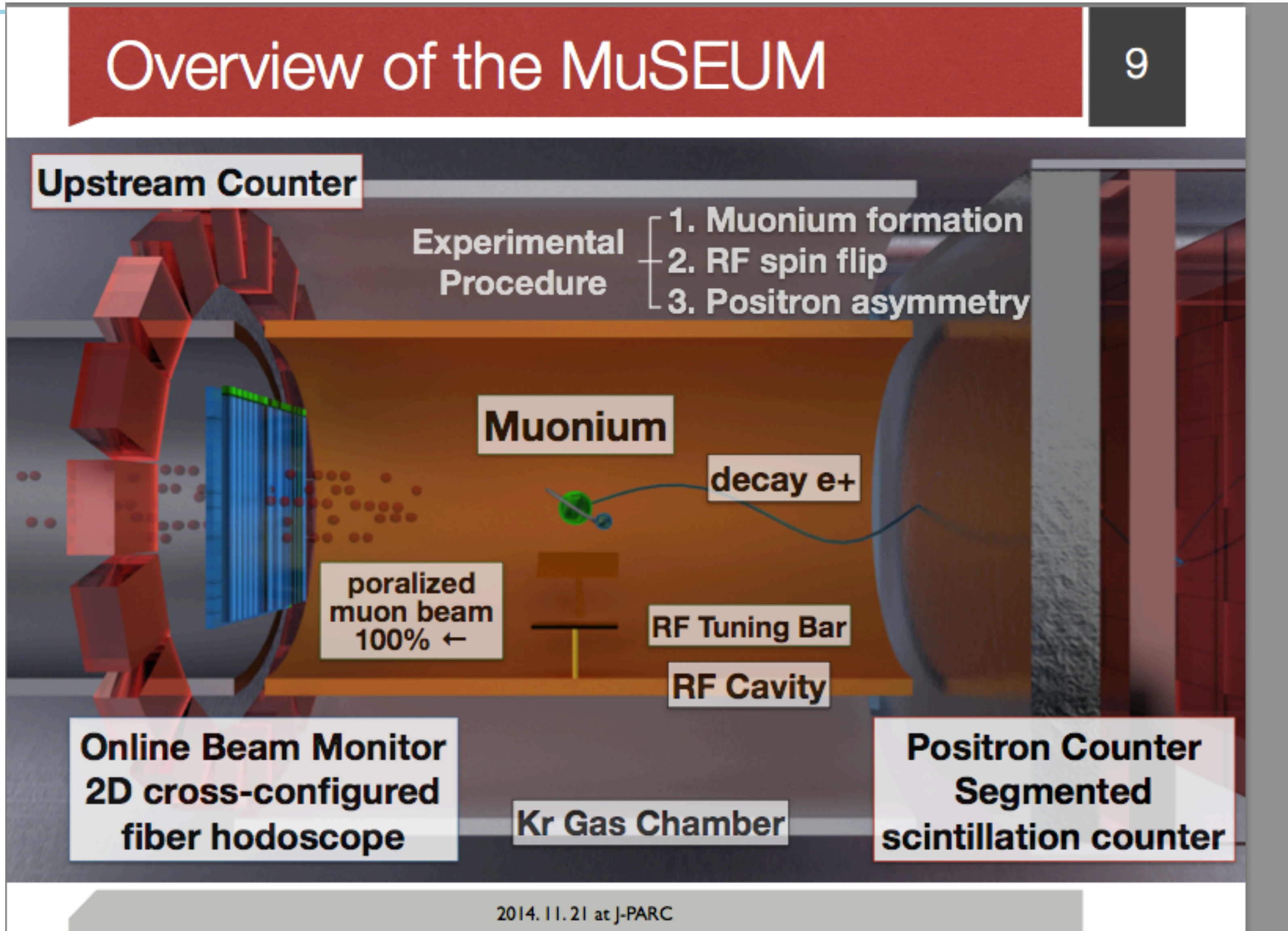
Uncertainty Source	Status 2015 [ppb]	Projected after E989 [ppb]	Goal for lattice QCD [ppb]
ω_a	180	70	
ω_p	170	70	
Statistical	460	100	
Total Exp.	540	140	
Had. Vac. Pol.	360	215 *	100**
Had LBL	225	225	100
Total Theory	420	310	140





* Projected error anticipating input from e+/e- BES III, VEPP2000,etc.
** Several lattice QCD efforts underway for g-2 HVP, novel approaches for HLBL have begun

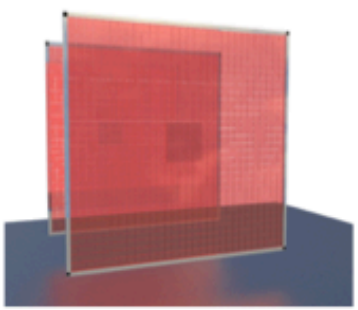
Slide: S. Kanda Nov 2014



Slide: S. Kanda Nov 2014

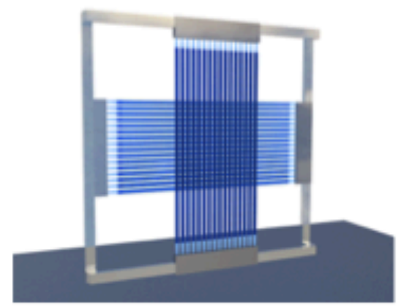
Detectors for the MuSEUM

Downstream positron counter



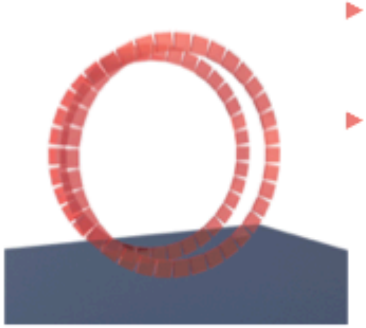
- Spectrometer for HFS measurement
- Segmented scintillator+SiPM
- High rate capability is required

Online beam profile monitor



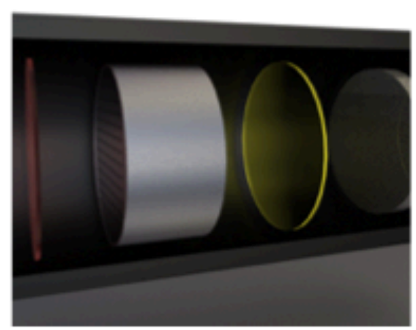
- Fiber hodoscope for beam stability monitoring
- Pulse by pulse measurement of profile and intensity

Upstream positron counter

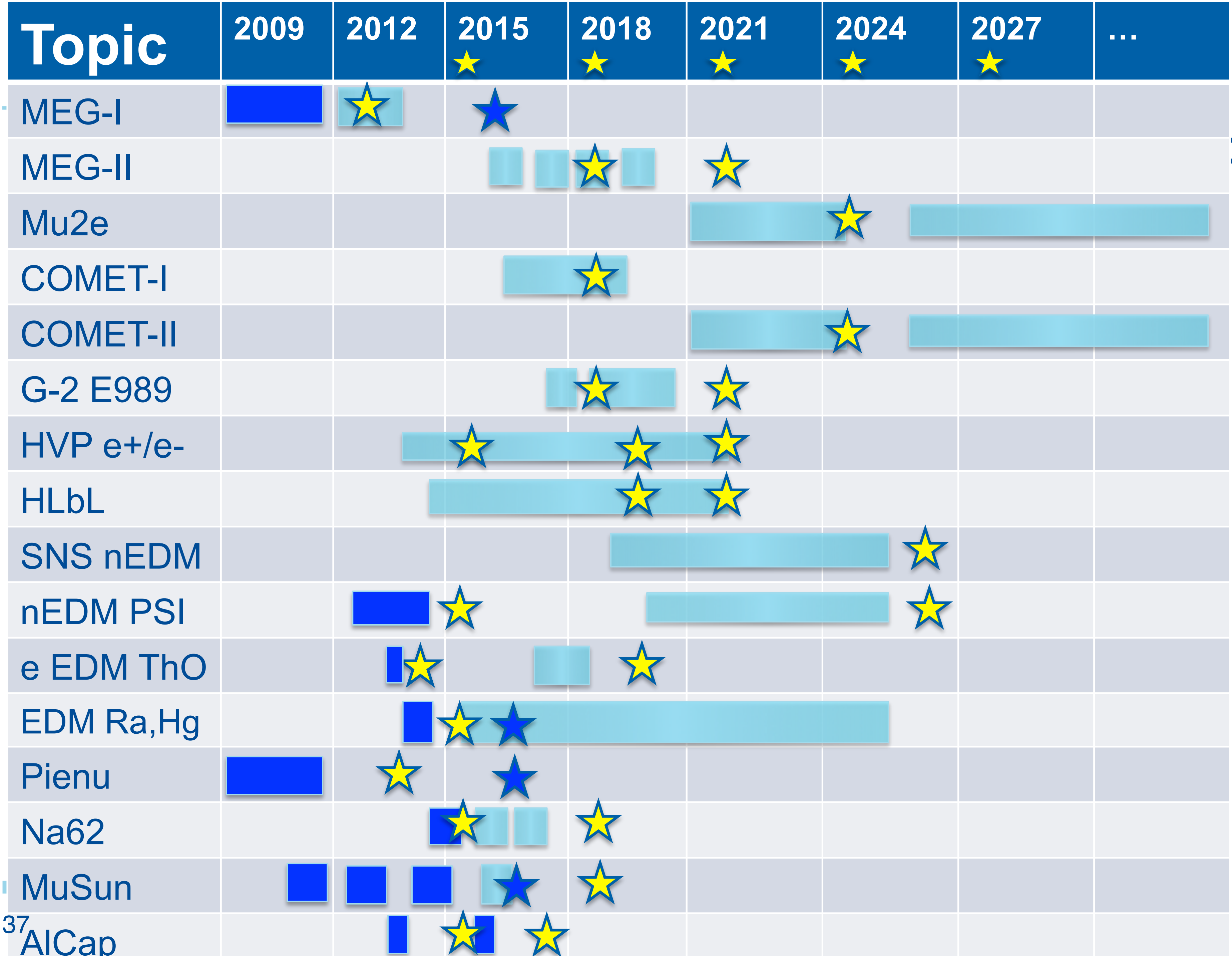


- Spectrometer for HFS measurement
- Additional counter for asymmetry measurement

Offline beam profile monitor



- IIF+CCD beam imager for muon stopping distribution
- Measurement for syst. uncertainty suppression


Topic
2009
2012
2015
2018
2021
2024
2027
…
MEG-I
MEG-II
Mu2e
COMET-I
COMET-II
G-2 E989
HVP e+/e-
HLbL
SNS nEDM
nEDM PSI
e EDM ThO
EDM Ra,Hg
Pienu
Na62
MuSun
AlCap

Our group's program: An Evolution of Precision

Time