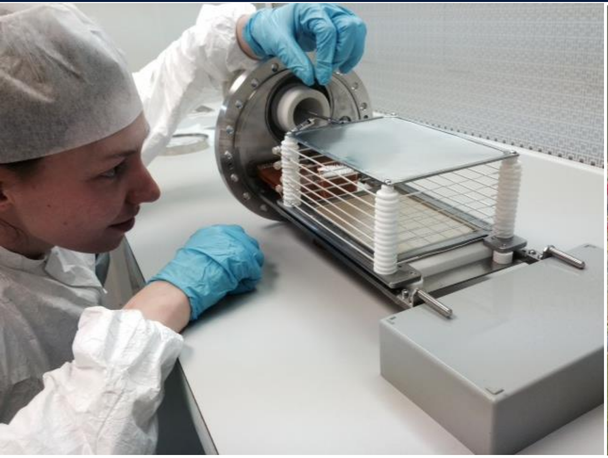
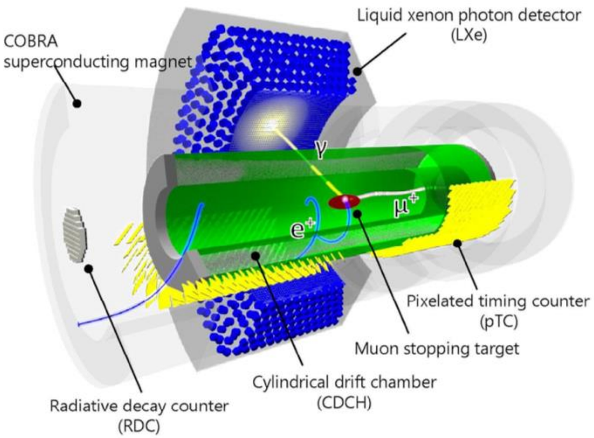
Center for Experimental Nuclear Physics and Astrophysics (CENPA)
University of Washington





Precision Muon Physics

Peter Kammel
University of Washington and CENPA

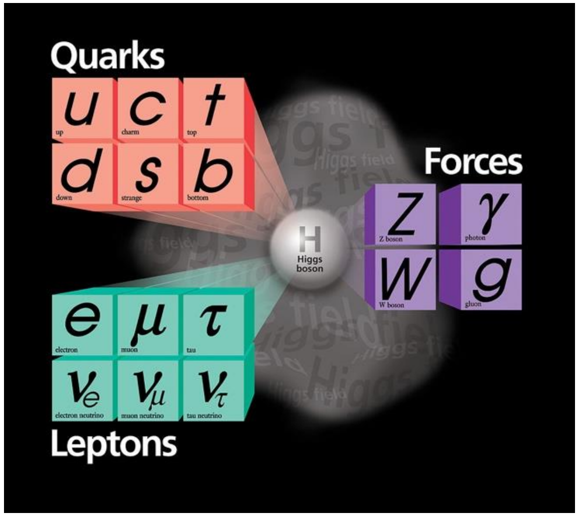
U.S. DEPARTMENT OF ENERGY | Office of Science

Lake Louise Winter Institute 2018

Anything special about the muon ?

Middle sibling

But quite spectacular personality



- Not too heavy
  - Efficient production
  - Accessible lifetime
- Not too light
  - Sensitive to high mass scales
- Clean
  - Only EW forces at tree level

Selected muon properties, decay rates and limits

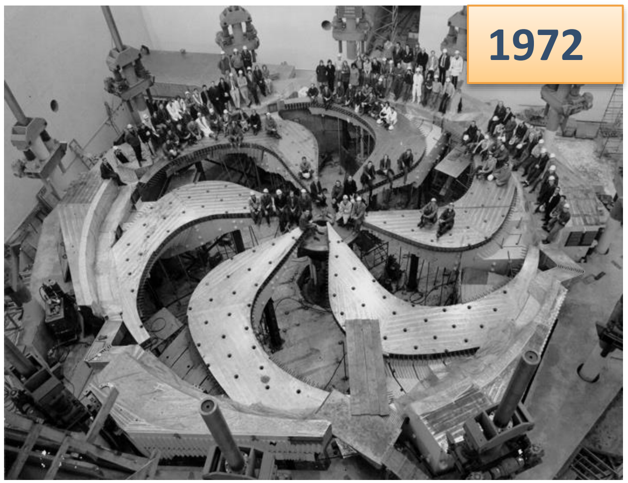
Property	Symbol	Value	Precision
Mass	m_μ	105.6583745(24) MeV	23 ppb
Mean life	τ_μ	$2.1969811(22)\times10^{-6}$ s	1 ppm
Magnetic moment anomaly	$a_\mu = \frac{g-2}{2}$	$116592089(63)\times10^{-11}$	540 ppb
Electric dipole moment	d_μ	$< 1.9\times10^{-19}$ e cm	95% CL
Branching ratio	**value**	**LFV modes**	**90%CL**
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$	$\approx 100\%$	$\mu^+ \to e^+\gamma$	$< 4.2\times10^{-13}$
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$	1.4(4) %	$\mu^+ \to e^+e^-e^+$	$< 1.0\times10^{-12}$
$\mu^+ \to e^+\nu_e\bar{\nu}_\mu e^+e^-$	$3.4(4)\times10^{-5}$	$\mu^- \to e^-$ conversion	$< 7.2\times10^{-11}$

Outline

- Introduction
  - Muon production + facilities
- Precision determination of SM parameters
  - Muon decay
  - Muons probe the nucleon via EW interactions
- New Physics searches beyond the SM
  - Muon g-2
  - Charged lepton flavor violation
- Summary

Muon facilities

- Meson factories (cyclotrons 0.6 GeV)
  - PSI
  - TRIUMF

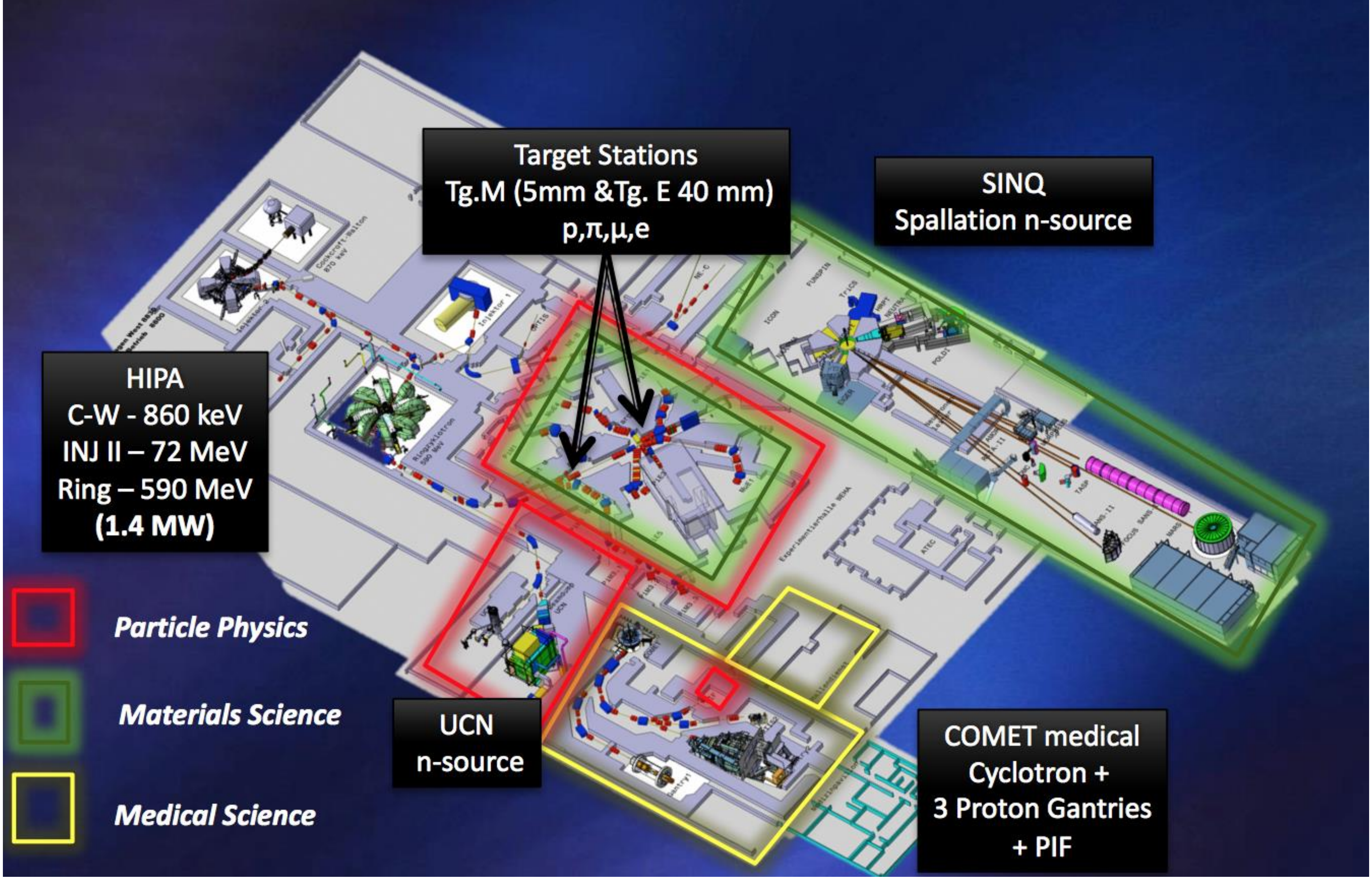


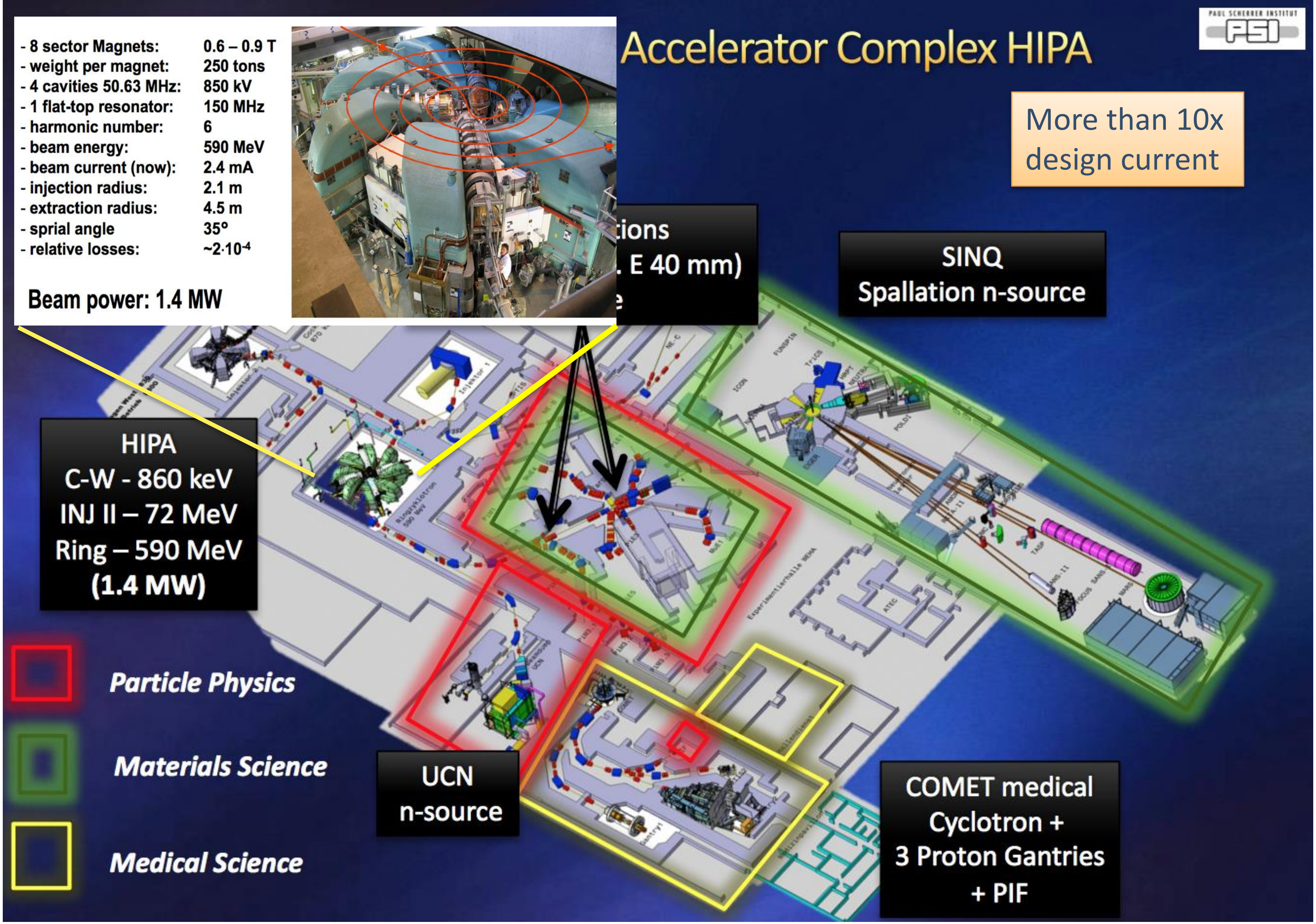
- New players
  - Fermilab (8 GeV)
  - J-PARC (3, 30 GeV)

Laboratory/ Beam Line	Energy/ Power	Present Muon μ^+/μ^- Rates Hz	Future estimated μ^+/μ^- Rate Hz
PSI (CH) - LEMS - πE5 - HiMB	(590 MeV,1.3MW, DC) " " (590 MeV, 1.3MW DC)	$4\cdot10^8$ $1.3\cdot10^8 / 10^6$	$O\{10^{10}/10^8\}$ (μ+/-)
J-PARC (JP) - MUSE - COMET	(3 GeV, 1MW Pulsed) Reached 400kW " (8 GeV, 56kW Pulsed)	$8\cdot10^7 / 4\cdot10^6$	$2\cdot10^8$ (μ+) (1MW) $1\cdot10^7$ (μ-) (1MW) 10^{11} (μ-) 2019/2020
FNAL (FermiLab) (USA) Mu2e	(8GeV, 25kW Pulsed)		$5\cdot10^{10}$ (μ-) 2019/2020
RAON/RISP (Korea)	600 MeV, 400kW DC)		$7\cdot10^8$ (μ+)
CSNS (China)	(1.6 GeV, 100kW Pulsed)		10^8 (μ+)
TRIUMF (CA) -M20/M9B	(500 MeV, 75kW, DC)	$2\cdot10^6 / 1.4\cdot10^6$	
RAL -ISIS (UK) - RIKEN-RAL	(800 MeV, 160kW, Pulsed)	$1.5\cdot10^6/7\cdot10^4$	
RCNP Osaka Univ. (JP) - MUSIC	(400 MeV, 400W DC)	$7\cdot10^5/1\cdot10^5$ *	* scaled from 8W

Peter-Raymond Kettle

High-intensity Proton Accelerator Complex HIPA

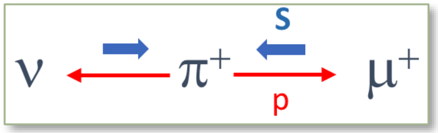



Accelerator Complex HIPA
PAUL SCHERRER INSTITUT
PSI
- 8 sector Magnets: 0.6 – 0.9 T
- weight per magnet: 250 tons
- 4 cavities 50.63 MHz: 850 kV
- 1 flat-top resonator: 150 MHz
- harmonic number: 6
- beam energy: 590 MeV
- beam current (now): 2.4 mA
- injection radius: 2.1 m
- extraction radius: 4.5 m
- sprial angle 35°
- relative losses: ~2·10⁻⁴
Beam power: 1.4 MW
More than 10x design current
ions
. E 40 mm)
SINQ
Spallation n-source
HIPA
C-W - 860 keV
INJ II – 72 MeV
Ring – 590 MeV
(1.4 MW)
Particle Physics
Materials Science
Medical Science
UCN
n-source
COMET medical
Cyclotron +
3 Proton Gantries
+ PIF

Muon production mechanism

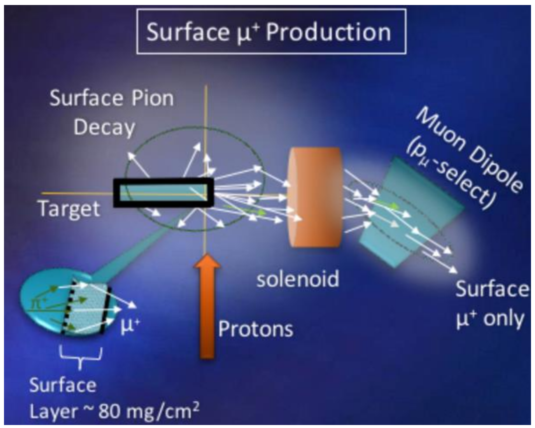
pion decay and polarization

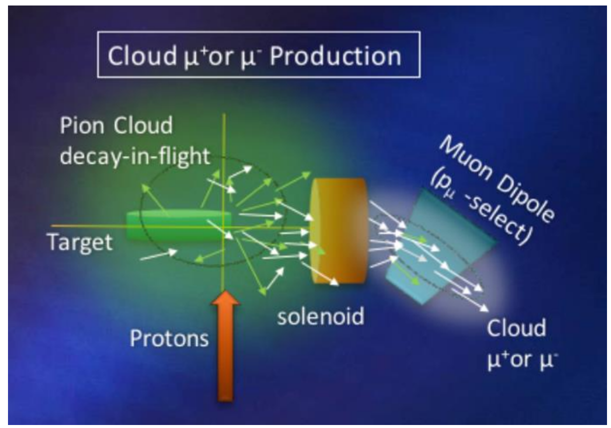
range $R \propto p^{3.5}$

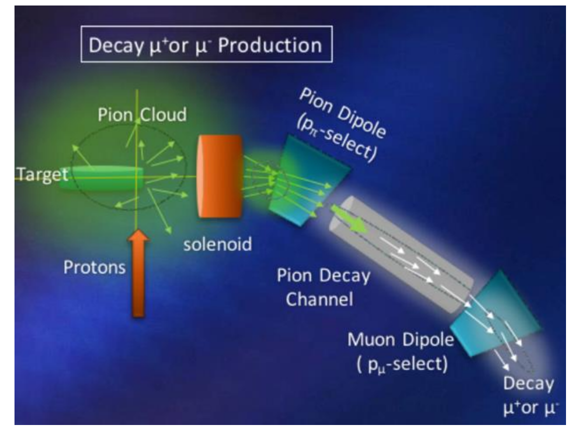


$$\Delta R \propto \sqrt{0.09^2 + (3.5\frac{\Delta p}{p})^2}\ p^{3.5}$$

Peter-Raymond Kettle







stopped π^+
p ≈ 28 MeV/c
10^8 Hz @ 28 MeV/c
physics
- MuSR
- LFV: MEG, Mu3e
- J-PARC g-2

low energy π^- decay
close to target
10^6 Hz @ 28 MeV/c
physics
- muon capture
- muonic atoms

π^- decay in flight
superconducting or
quadrupole decay channel
10^7 Hz @ 85 MeV

Fermilab, J-PARC
- g-2 @ 3.1 GeV/c
- LFV: Mu2e, COMET

PREPRINT INR – 786/92
NOVEMBER 1992

“New idea”: Capture Solenoid

1992

V.S. Abadjev, B.N. Bakhtin, O.N. Goncharenko, R.M. Djilkibaev,
V.V. Edlichka, V.M. Lobashev, V.I. Parfenov, I.A. Plisco,
V.V. Popov, S.K. Popov, A.L. Proscuryakov, I.V. Sekachev,
A.K. Skasyrskaya, O.B. Sokolova, A.P. Solodukhin,
A.N. Toropin, S.P. Toropov

MELC EXPERIMENT TO SEARCH FOR THE $\mu^- A \to e^- A$ PROCESS

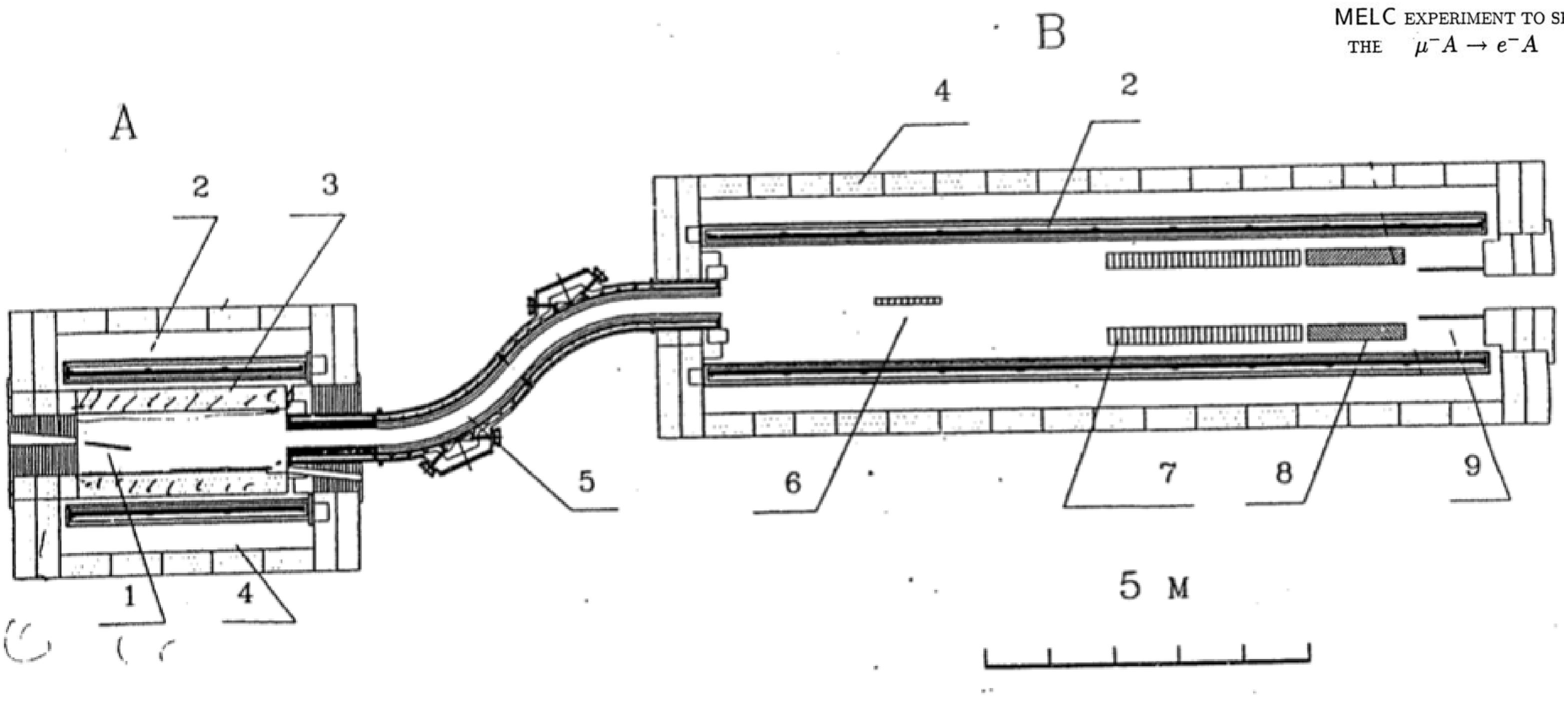


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part (T_1),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium target of the detector part (T_2),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

Muon Campus @ Fermilab

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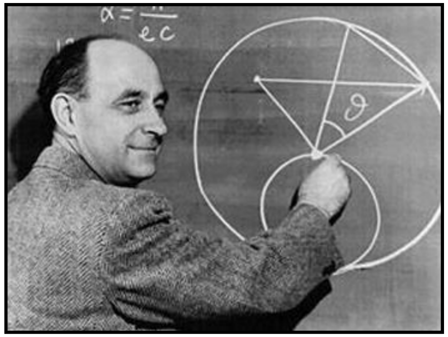
Muon Lifetime

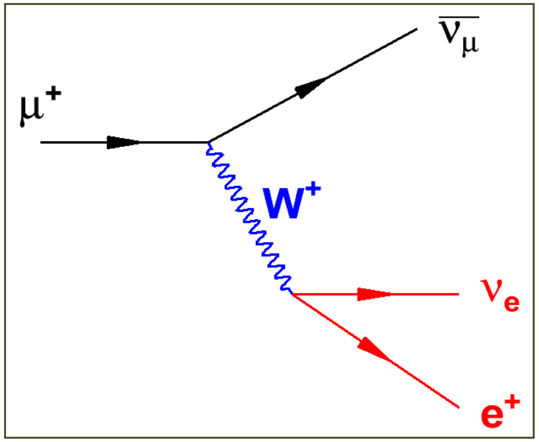


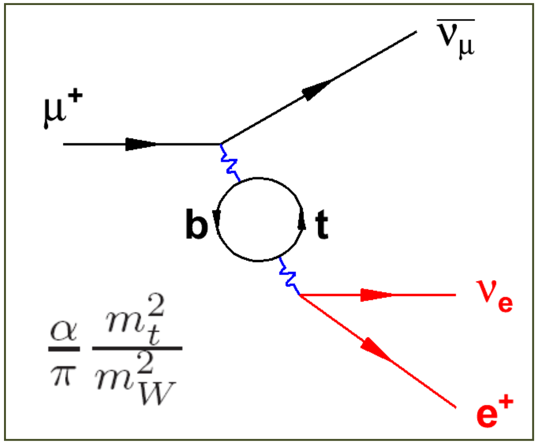
- Fundamental electro-weak couplings

G_F	α	M_Z
9 ppm → 0.5 ppm	0.23 ppb	23 ppm

- Implicit to all EW precision physics

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left(1 + \Delta r(m_t, m_H, \ldots)\right)$$

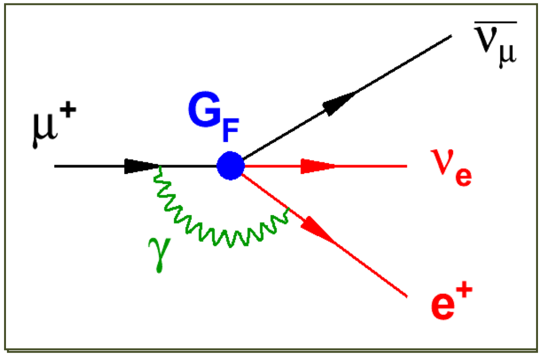




- Uniquely defined by muon decay

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

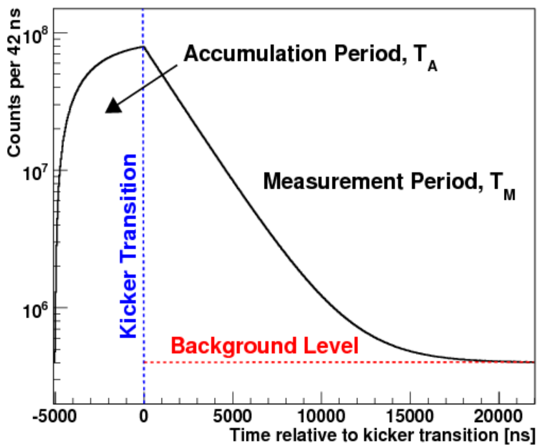
QED

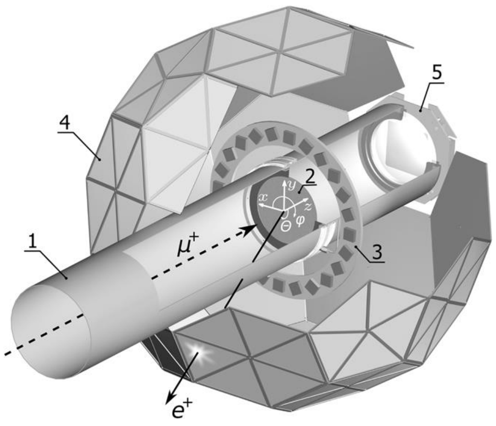


Extraction of G_F from τ_μ :
1999 two-loop calc.
reduced error from
15 to ~0.2 ppm

MuLan at PSI

- Strategy
  - pulsed time structure with kicker
  - segmented, fast, simple detector

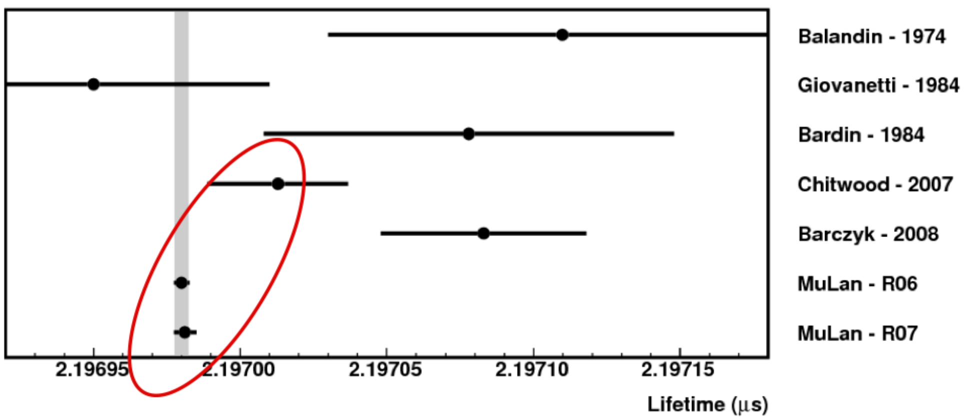




- Result
  - $\tau_{\mu+}$ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

    The most precise particle or nuclear or atomic lifetime ever measured

  - G_F (30x improved since 1999)



G_F(MuLan) = 1.1663787(6)x10^{-5} GeV^{-2} (0.5 ppm)

MuLan Collaboration
*PRD **87**, 052003 (2013)*

Is weak interaction pure V-A ?

$$\mu^+ \rightarrow e^+ \nu_e \, \bar{\nu}_\mu$$

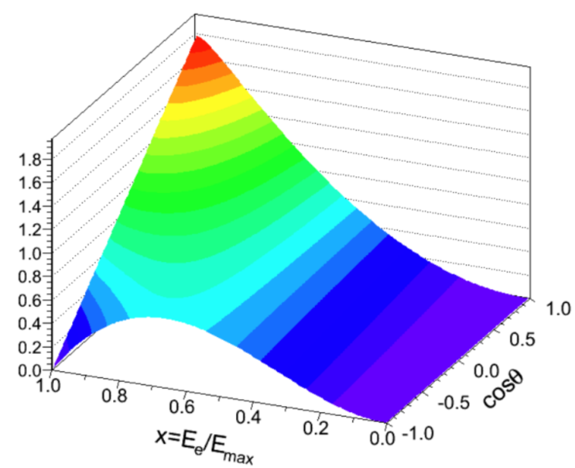
- general matrix element $$M \propto \sum_{\gamma=S,V,T}^{\epsilon,\mu=L,R} g^{\gamma}_{\epsilon\mu} \langle \bar{e_\epsilon} | \Gamma_\gamma | \nu_e \rangle \langle \bar{\nu_\mu} | \Gamma^\gamma | \mu_\mu \rangle$$

- Standard Model choice: $g^V_{LL} = 1$, all others vanish

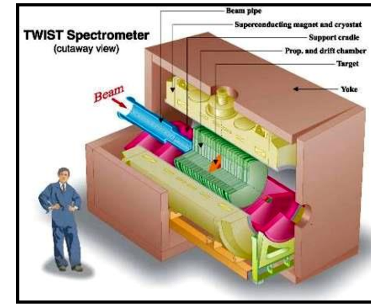
- Formalism for new physics search established by Michel:
  - Differential decay rate depends only on 4 parameters ρ, η, ξ, δ

$$\frac{d^2\Gamma}{dx \; d\cos\theta} = \frac{1}{4} m_\mu W^4_{\mu e} G^2_F \sqrt{x^2 - x_0^2} \cdot \{\mathcal{F}_{IS}(x, \rho, \eta) + \mathcal{P}_\mu \cos\theta \cdot \mathcal{F}_{AS}(x, \xi, \delta)\} .$$

$$x = E_e / W_{\mu e}$$
$$W_{\mu e} \simeq 52.8 \text{ MeV}$$

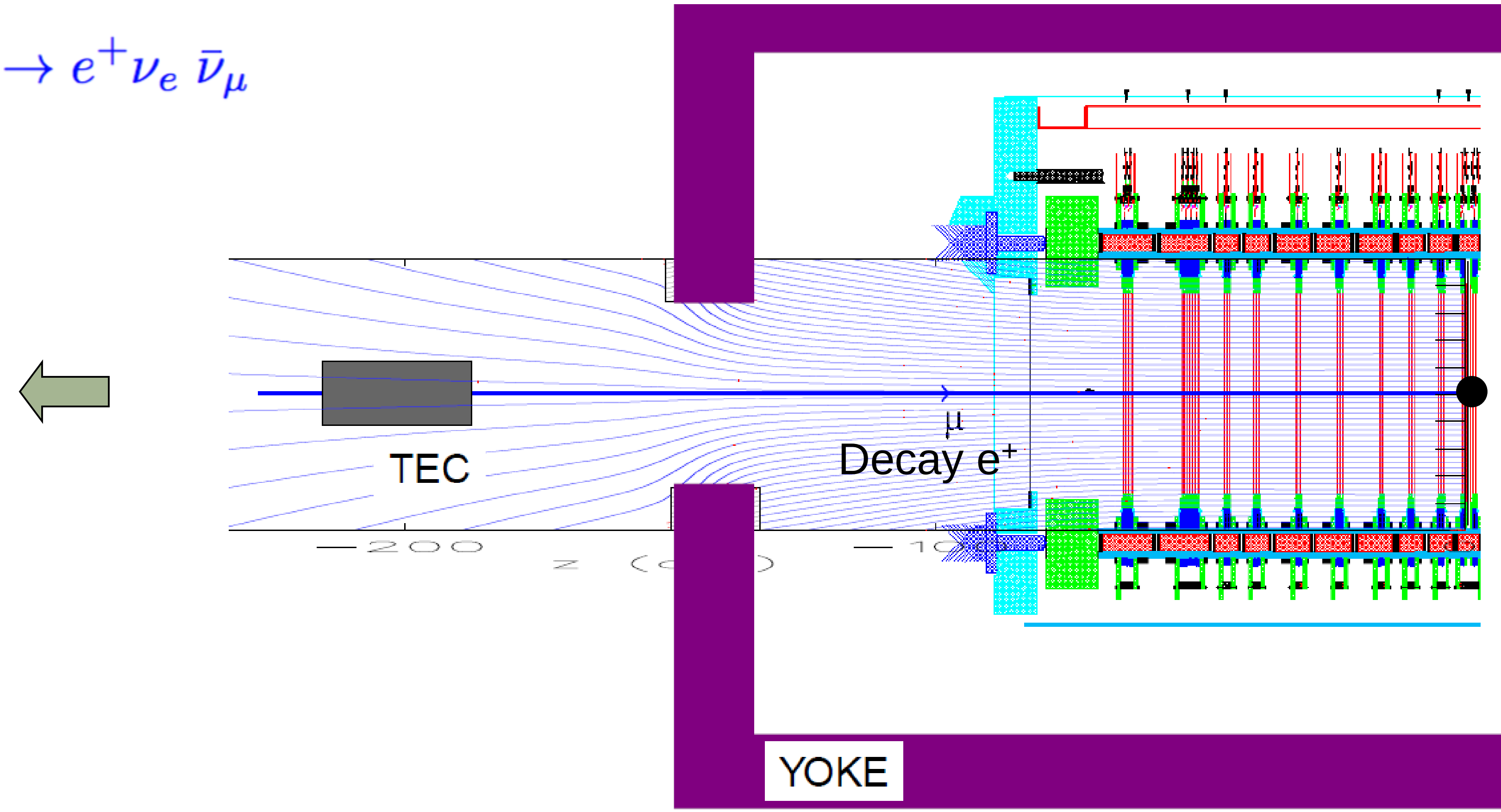


TWIST at TRIUMF

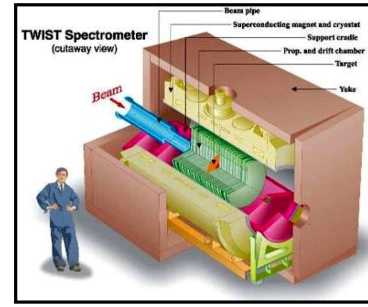


- Measure the energy and angular distribution of e^+ with unprecedented precision

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



TWIST at TRIUMF



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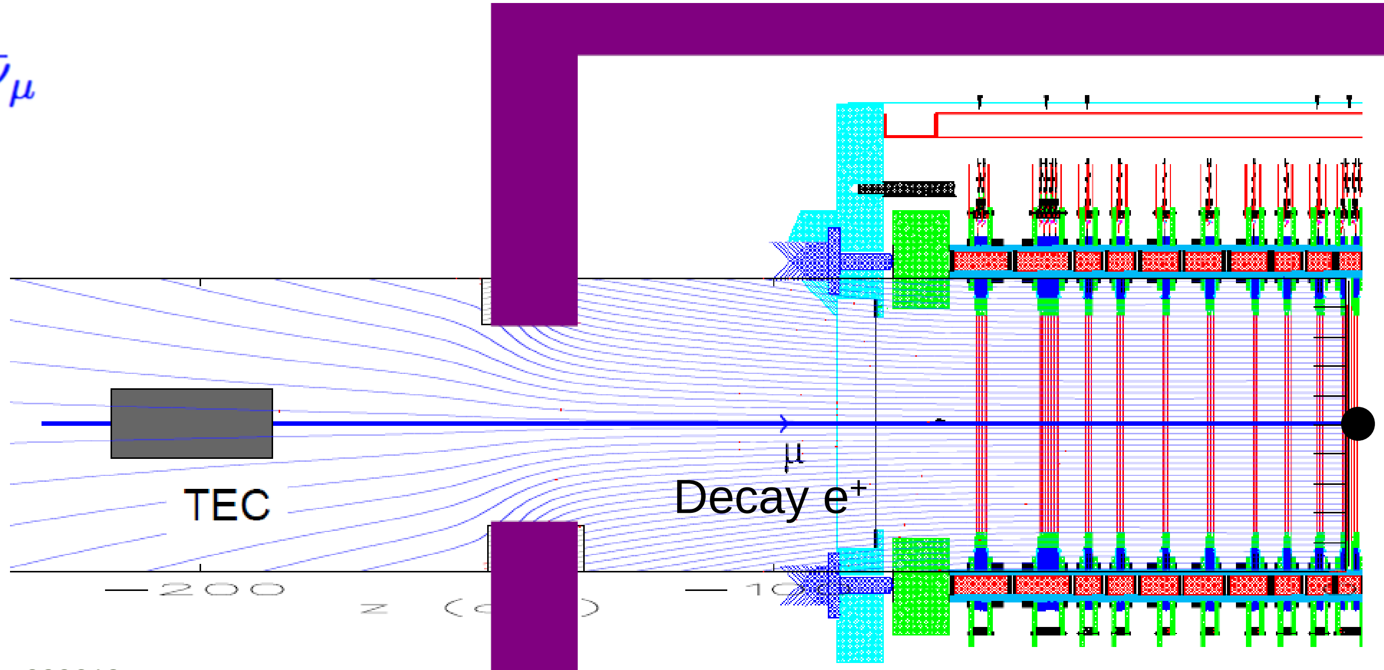


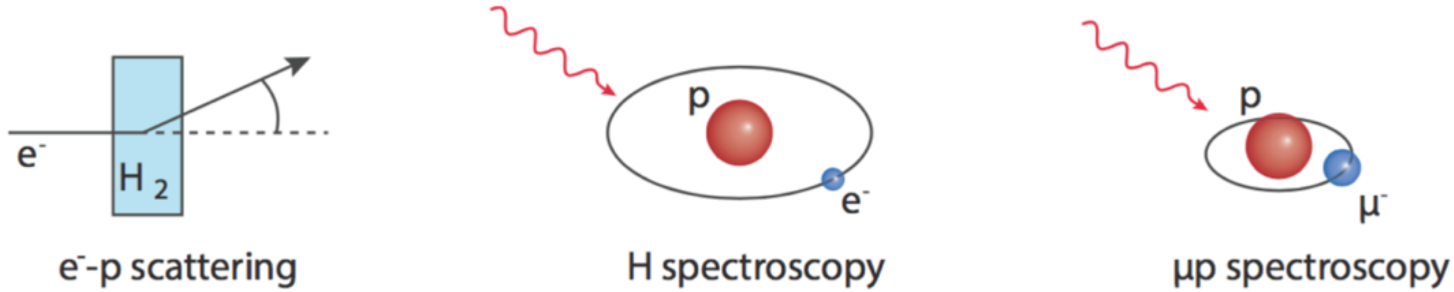
Phys. Rev. D, 85 (2012), p. 092013
Phys. Rev. D, 84 (2011), p. 032005

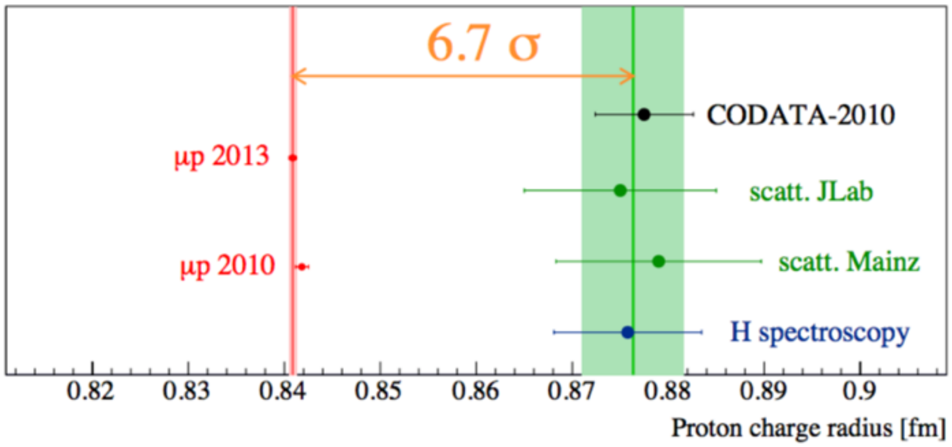
ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)

δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)

$\mathcal{P}_\mu^\pi \xi = 1.00084 \pm 0.00029\,(\text{stat})\,{}^{+0.00165}_{-0.00063}\,(\text{syst})$

Muon EM interaction with the nucleon
aka **Proton Radius Puzzle**



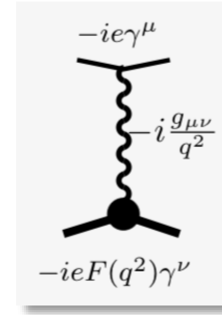


Muon EM interaction with the nucleon
aka Proton Radius Puzzle

Basics

- EM interaction

$$J^{\mu}_{em} A_{\mu}$$



  – extended proton

$$\langle f|J^{\mu}_{em}|i\rangle = \bar{u}_f\left[F_1(q^2)\gamma^{\mu} + \frac{iF_2(q^2)}{2m_N}\sigma^{\mu\nu}q_{\nu}\right]u_i$$

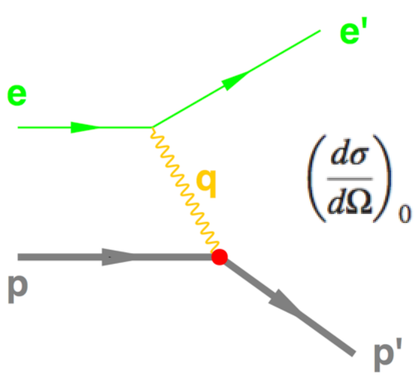
  – n.rel. interpretation: Fourier transform of space distribution

$$F(Q^2) = \int d^3r\ \rho(\mathbf{r})e^{i\mathbf{Q}\cdot\mathbf{r}} \simeq 1 - \frac{Q^2}{6}r_p^2 + \dots$$

$$r_p^2 \equiv \int d^3r \rho(\mathbf{r})\ r^2$$

  – $$r_p^2 \equiv -6\ \frac{dG_E}{dQ^2}\ |_{Q^2=0}$$

- Electron scattering

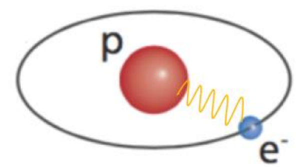


$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

- Hydrogen spectroscopy

$$\Psi = \frac{1}{\sqrt{\pi}}\ a_0^{-3/2}\ e^{-r/a_0}$$

$$a_0 = \frac{1}{m_r\alpha}$$



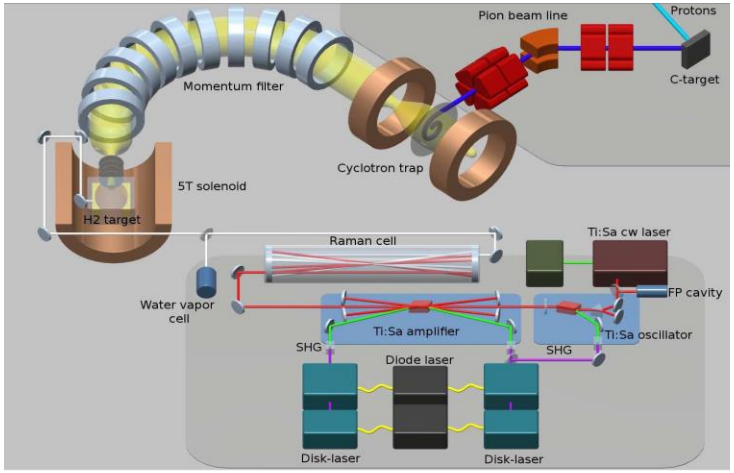
$$\begin{aligned}\Delta E^{FS} &= \frac{2\pi(Z\alpha)}{3}\ r_p^2\ |\Psi_n(0)|^2 \\ &= \frac{2(Z\alpha)^4}{3n^3} m_r^3\ r_p^2\ \delta_{l0}\end{aligned}$$

Muonic 2s-2p measurement

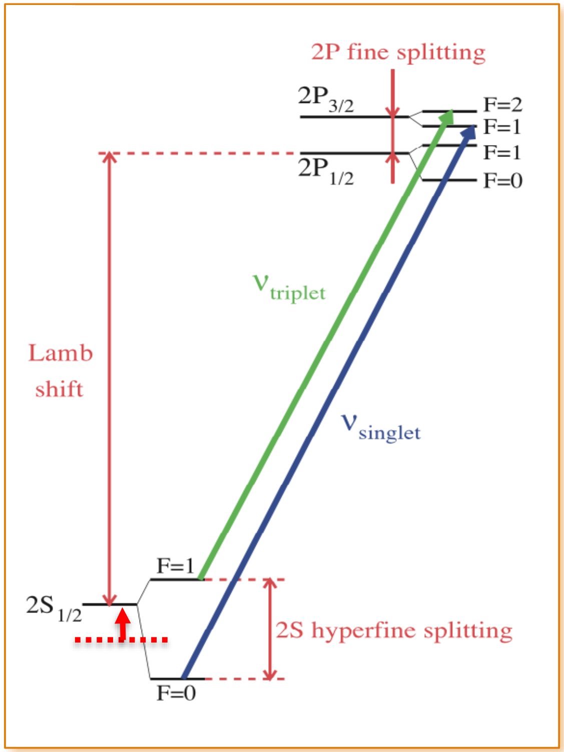
- $a_0(e) \sim 200\ a_0(\mu)$, finite size effect increases by

$$\frac{|\Psi_\mu(0)|^2}{|\Psi_e(0)|^2} = \left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$$

- produce keV μ^-



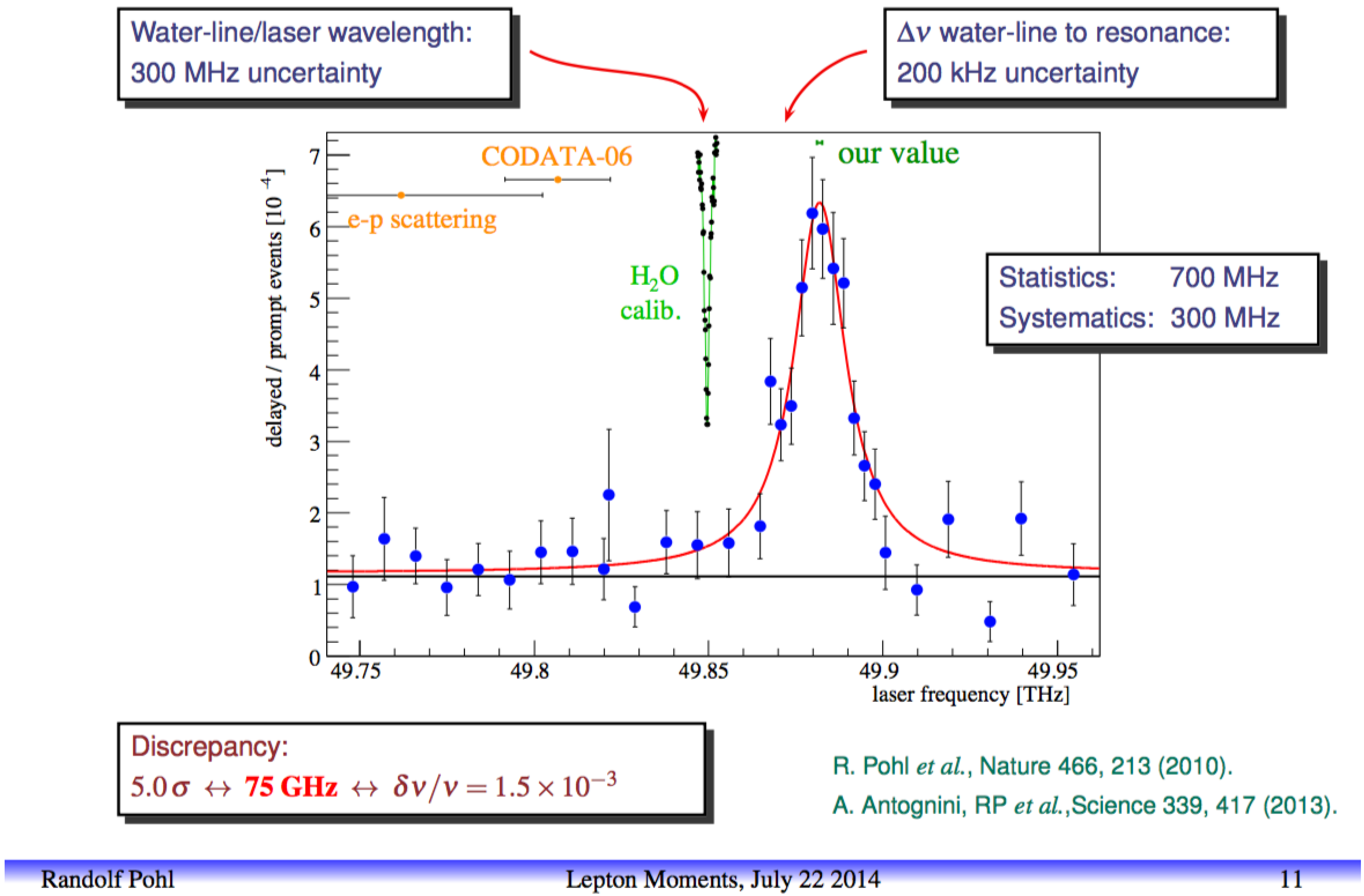
- form $\mu p(2S)$ atoms in 1 mbar H_2 gas
- delayed laser to excite 2S-2P



Lamb shift 206.0668(25) - 5.2275(10) r_p^2 meV

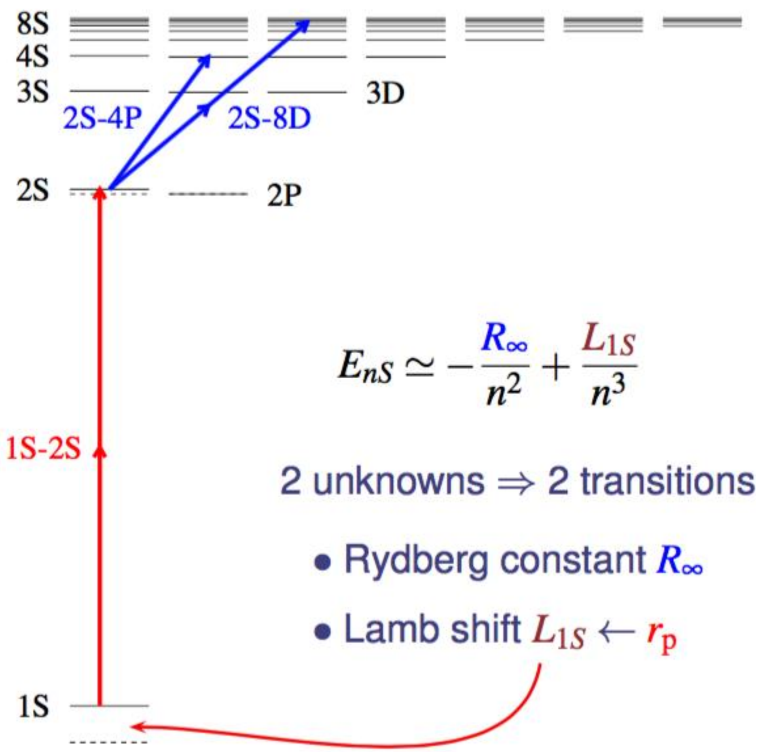
- measure (2P-1S) X-rays vs. laser frequency

Little doubt about μp experiment



Hydrogen spectroscopy

- ultra high precision and 2 transitions required
- 100% correlation to Rydberg constant R_∞ (**6 ppt** fundamental constant)

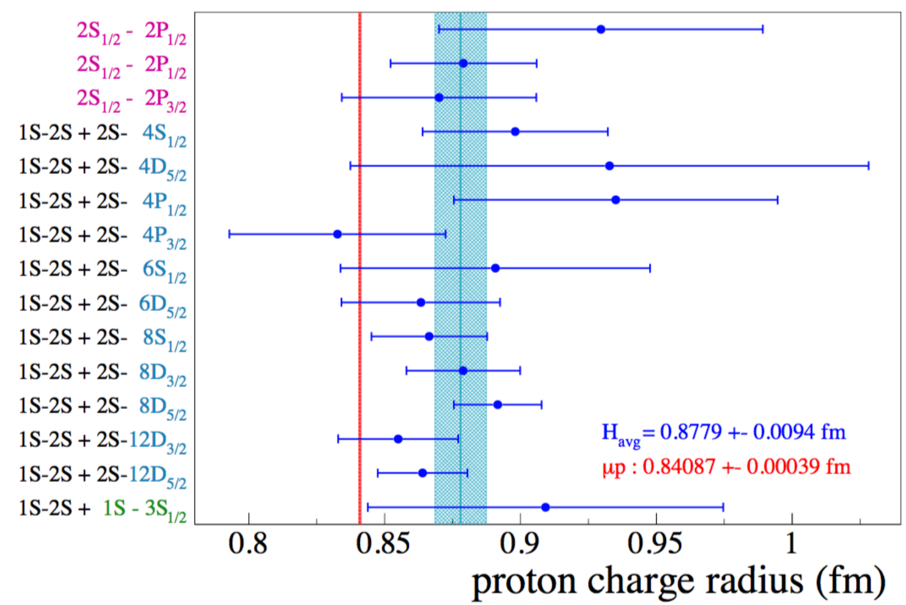


$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns ⇒ 2 transitions

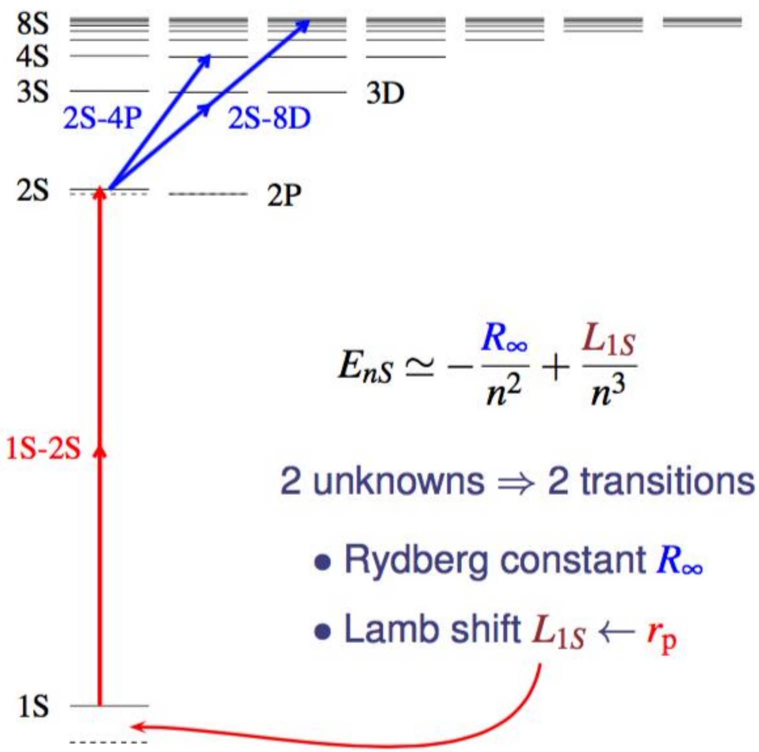
- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$

Status 2017



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

Hydrogen spectroscopy



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2 unknowns ⇒ 2 transitions

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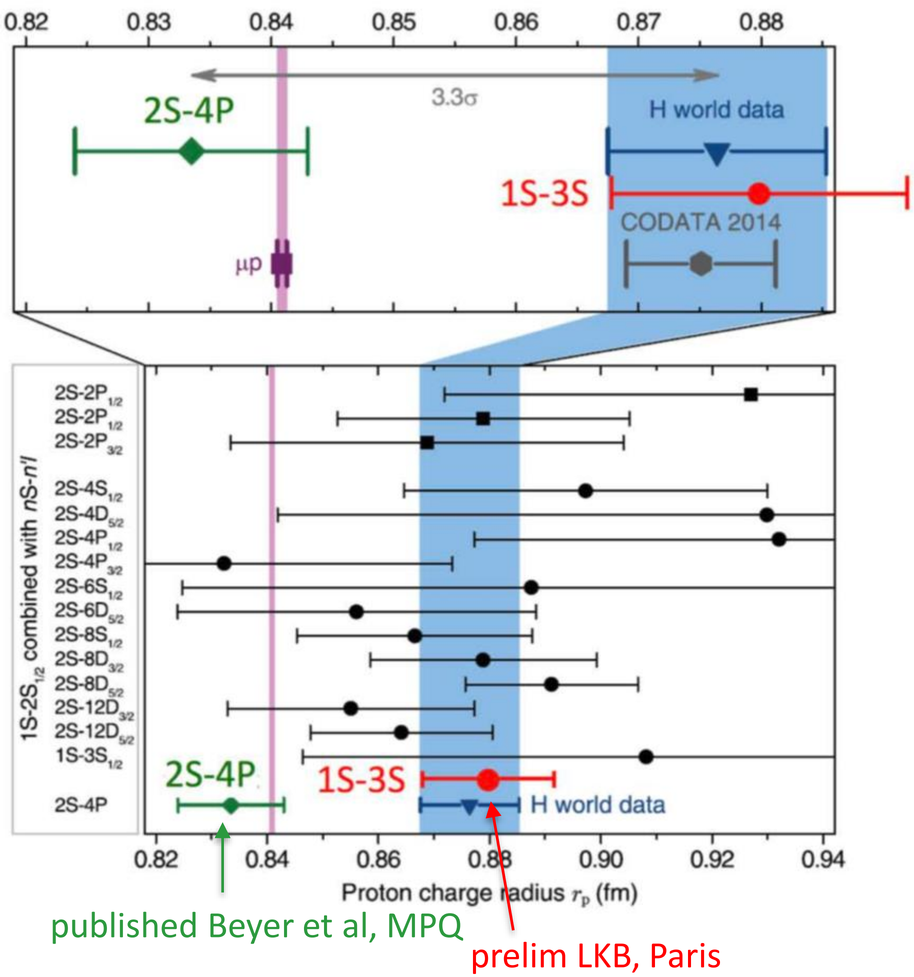
- Lamb shift $L_{1S} \leftarrow r_p$

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

determined to 1/10000 of Γ_{nat}

Status 2018



Status

Muonic hydrogen
- theory wrong ?
- experiment wrong ?

or

Hydrogen
- theory wrong
- exp. wrong, R_∞ wrong ?

+

e-p scattering
- theory problem ?
- exp. wrong?

or

New physics ?

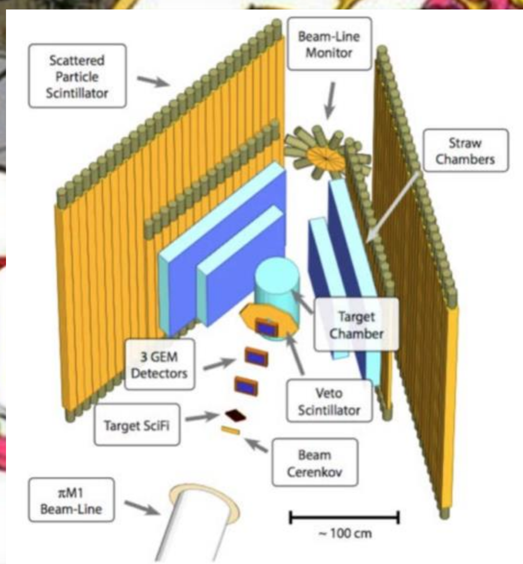
BSM pessimistic:
Barger, Chiang, Keung, Marfatia (2011, 2012), Karshenboim, McKeen, Pospelov (2014)

BSM optimistic:
Tucker-Smith & Yavin (2011), Batell, McKeen & Pospelov (2011), Brax & Burrage (2011)
Rislow & Carlson (2012, 2014), Marfatia & Keung (2015), Pauk& Vanderhaeghen (2015)
Martens & Ralston (2016), Liu, McKeen & Miller (2016), Batell et. al (2016)

The race to the proton radius solution

Atomic spectroscopy
- H(2S-2P) (Toronto)
- H(1S-3S) (LKB, MPQ)
- H(2S-4P) (MPQ)
- H_2 and H_2^+, HD (LKB, LaserLaB, ETH)
- He^+ (LaserLaB, MPQ)
- Muonium (ETH, PSI)
- H-like ions, Rydberg states (NIST)

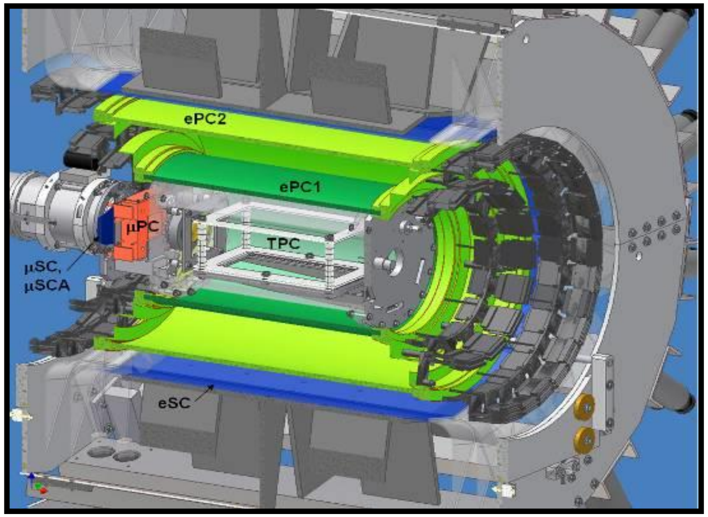
Muonic spectroscopy
- μd
- μ^3He and μ^4He (2014)
- HFS

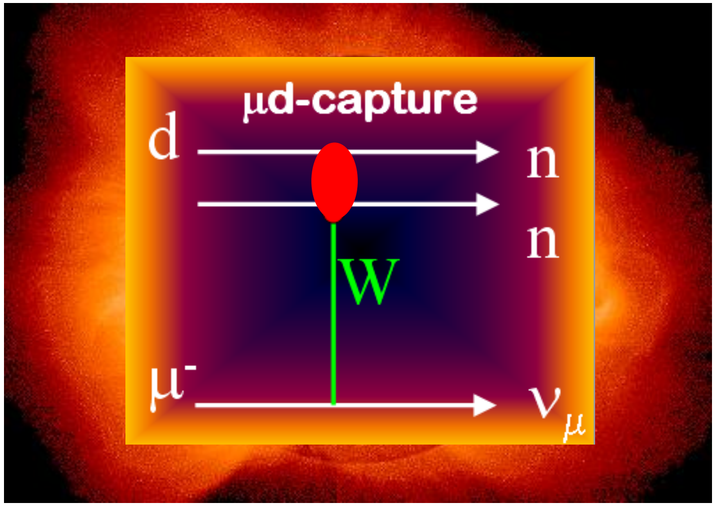


Scattering
- e-p, PRad (JLAB)
- e-p, Mami, MESA (Mainz)
- μ-p, e-p, MUSE (PSI)

PSI ETH Aldo Antognini Rencontres de Moriond 19.03.2017

Muon weak interaction with the nucleon
aka MuCap and MuSun





- Basic QCD Symmetries
- Axial nucleon current

- Weak few nucleon reactions
- Neutrino astrophysics

Muon as weak interaction probe

- Muon capture

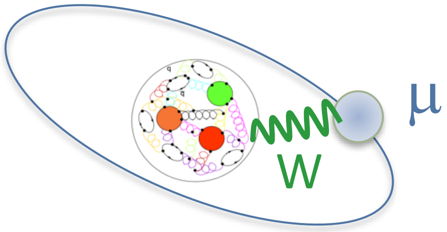
  charged-current test of weak interaction on nucleon and lightest nuclei

  - access to unique observables, where scarce information is available

  recent 10x improvement in precision with new technique

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

muon mass
$|\psi(0)|^2$ in atom



- Recent theory advances
  - *χPT*: low-energy EFT of fundamental theory QCD

    high-energy dynamics integrated out, low energy constants (LECs)

    - retains QCD symmetries → tests with precision experiments
    - model independent relations → predictions based on experimental input
  - Lattice QCD

Muon capture on the proton

- Muon capture

$\mu^- + p \rightarrow \nu_\mu + n$ rate Λ_S at $q^2 = -0.88\, m_\mu^2$

- Form factors

Lorentz, T invariance

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

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

before MuCap

All form factors precisely known from SM symmetries and data

apart from $g_P = 8.3 \pm 50\%$

- Pseudoscalar FF g_P

Foundations for mass generation
chiral perturbation theory of QCD

  – modern *χPT* prediction 2% level

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2$$

  – 50 yr efforts to measure precisely

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

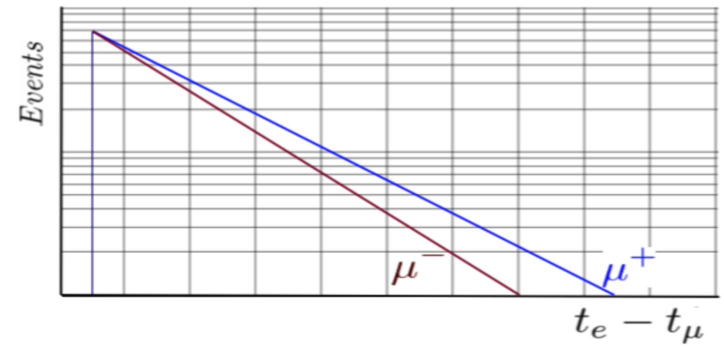
MuCap strategy

- Precision technique
- Clear Interpretation
- Clean stops in H_2
- Impurities < 10 ppb
- Protium D/H < 10 ppb
- Muon-On-Request

All requirements simultaneously

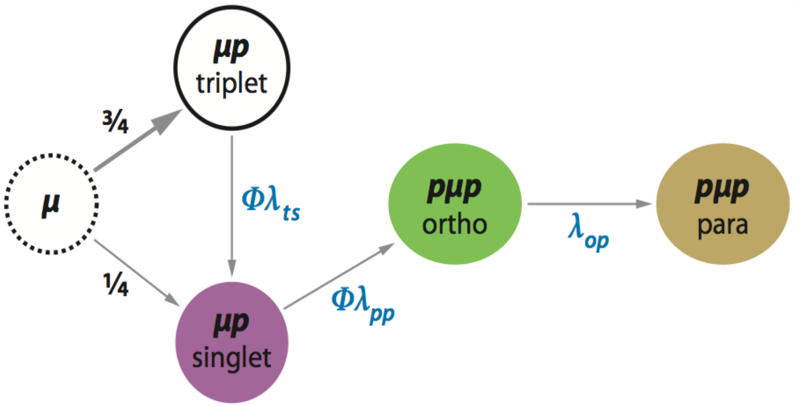
capture rare, only 0.16% of $\mu \rightarrow e\nu\nu$

Lifetime method

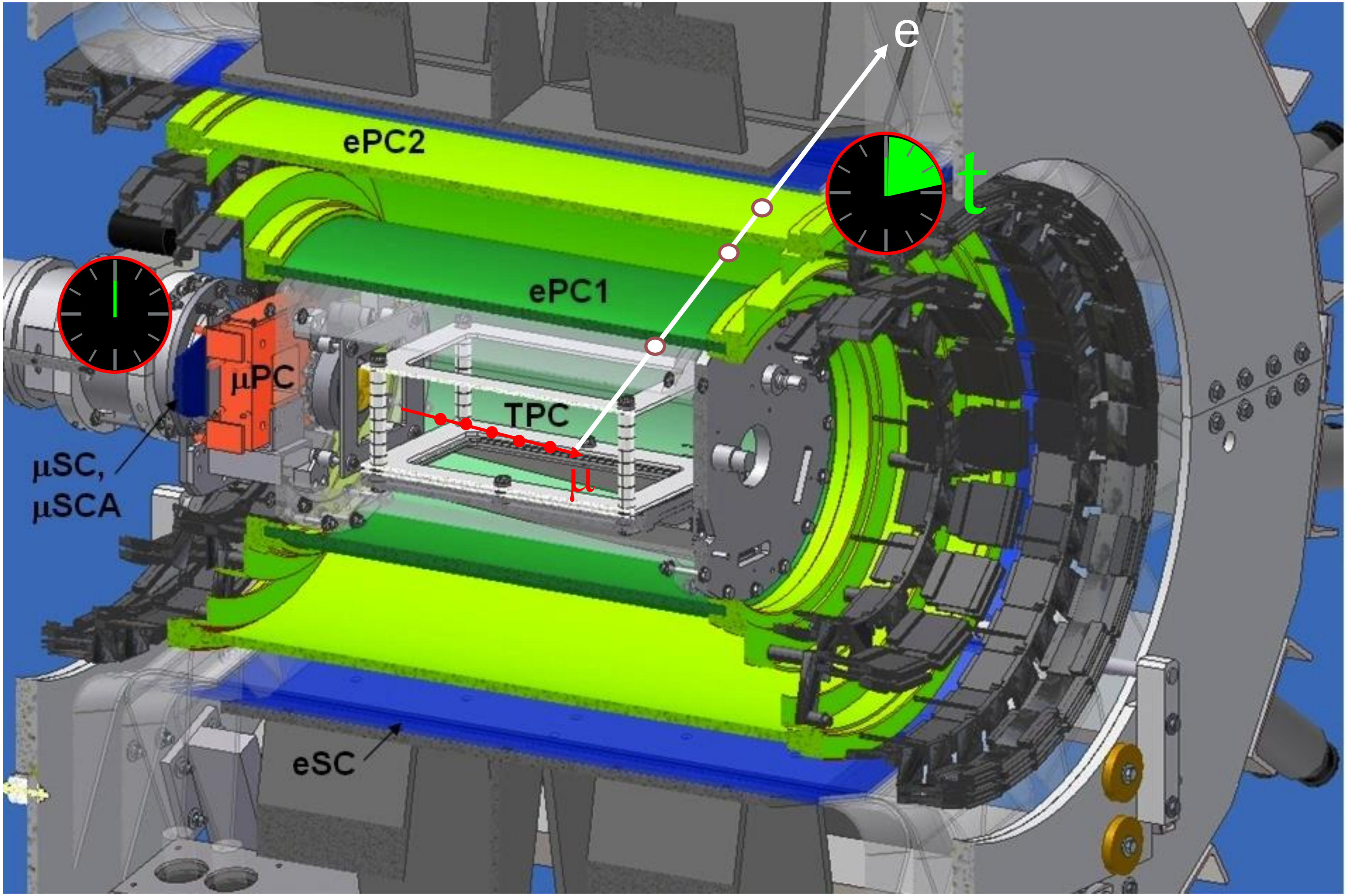


$\Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$

measure to lifetime to 10ppm

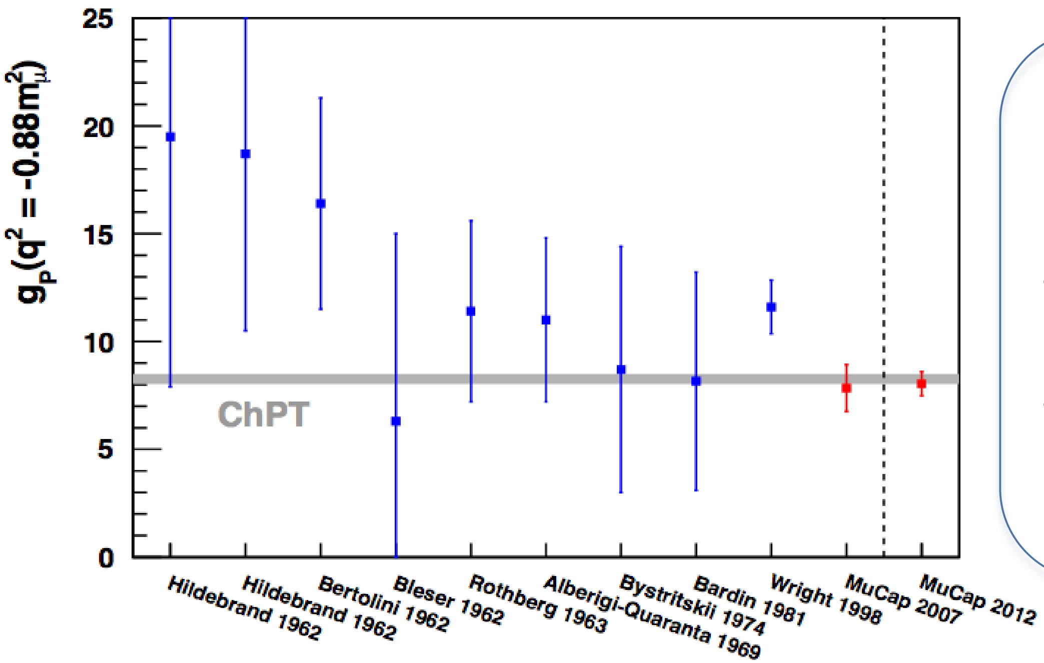


MuCap Technique



MuCap result

- *χPT* parameter free prediction: $g_P = 8.26 \pm 0.23$
  including uncertainty
- MuCap final result: $g_P = 8.06 \pm 0.55$
  – settles earlier disagreement exp/theory
  – verifies basic prediction of low energy QCD



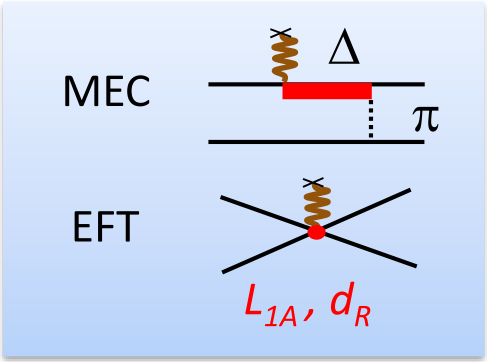
Rep. Prog. Phys., to be published

Nucleon Axial Radius and Muonic Hydrogen
Richard J. Hill, Peter Kammel, William J. Marciano, Alberto Sirlin

- r_A^2 has 50% uncertainty $\nu_\mu d \to \mu^- pp$
  important for basic ν+n cross section (DUNE)
- MuCap can reduce uncertainty
  from present MuCap result
  from 3x improved measurement

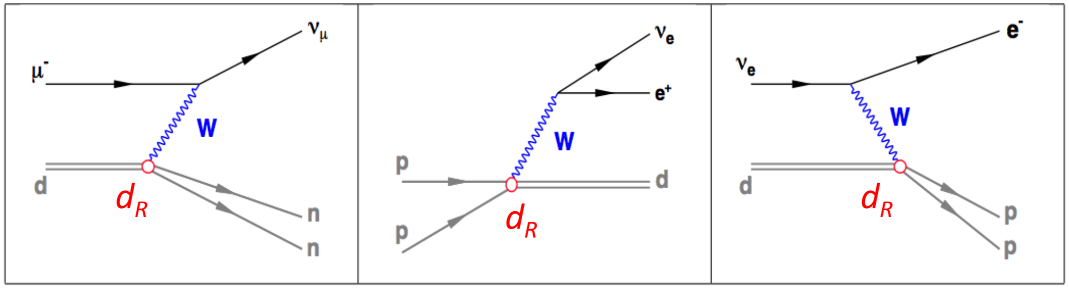
Muon Capture on the Deuteron: MuSun

- Goal: Determine
  - Axial current coupling to 2N system: "g_A of 2N system"
  - Low Energy Constant in EFT d_R



chiral 2-body currents

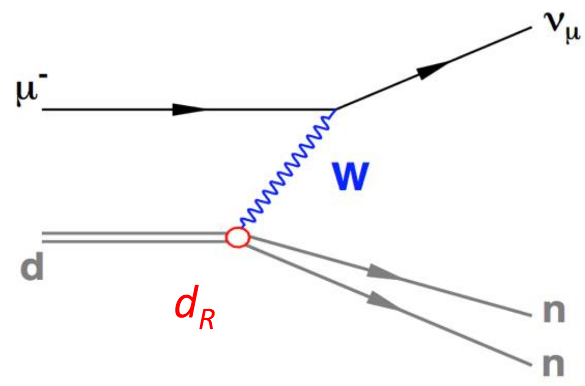
- Relevance
  - calibrate fundamental astrophysics reactions



Family of weak 2N reactions
pp fusion (Sun)
νd scattering (SNO)

  - important for EFT formulation of nuclear physics
    - Three-body forces, nn scattering length
  - matrix elements for 0ν2β decay

MuSun experiment at PSI

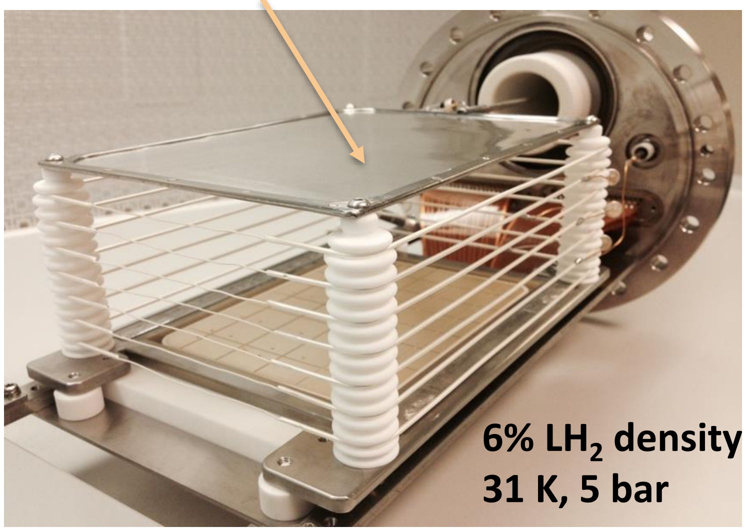


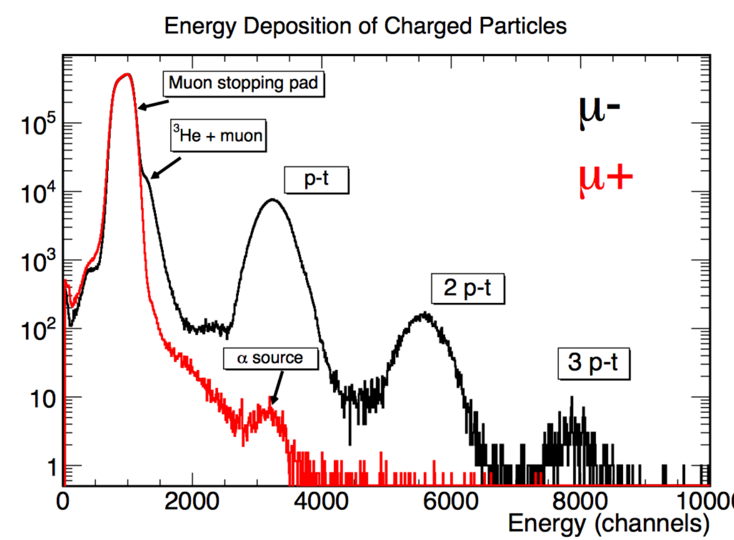
- novel device required
  - ultra-high purity
  - high pressure
  - cryogenic

  deuterium TPC
- data taking complete
- statistics: 1.3 x 10^{10} events
- analysis ongoing

Measure rate to 1.5%
determine d_R 5x better

cathode (-80 kV)





Outline

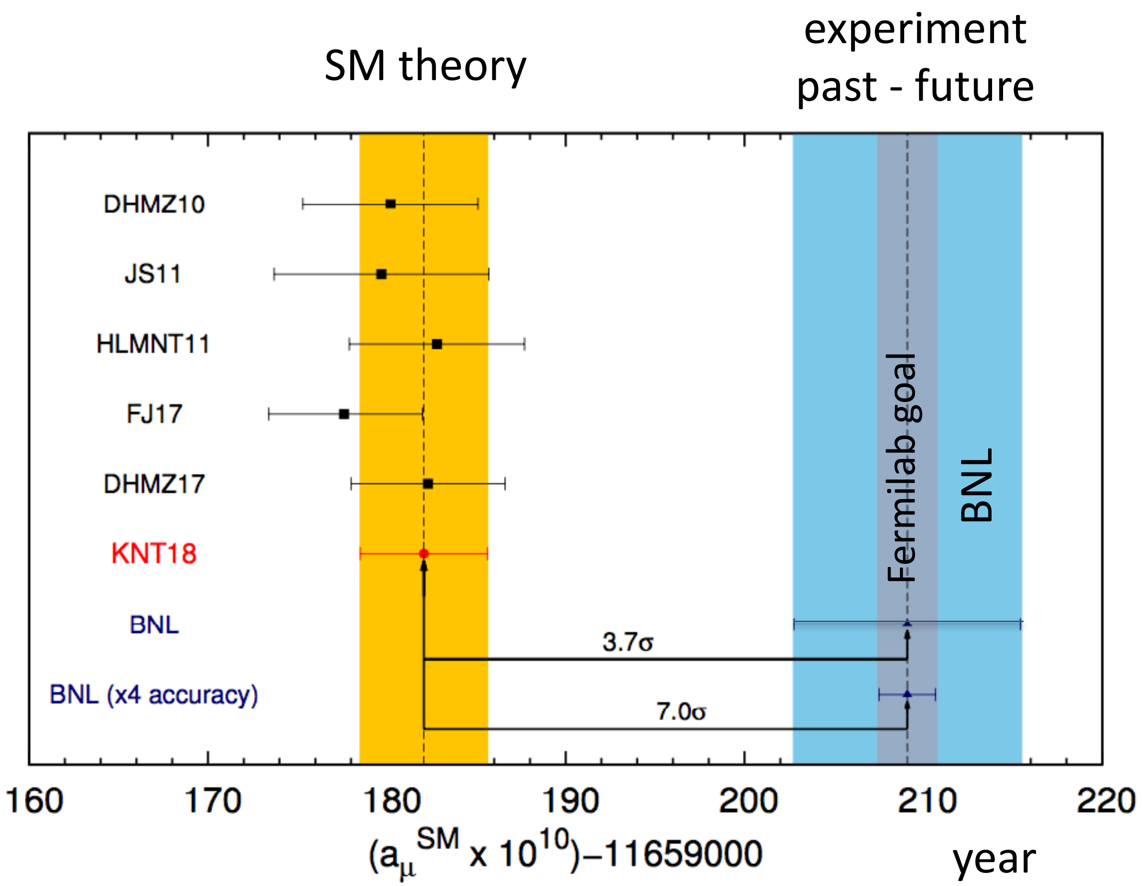
- Introduction
  – Muon production + facilities

- Precision determination of SM parameters
  – Muon decay
  – Muons probe the nucleon via EW interactions

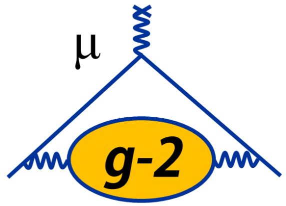
- New Physics searches beyond the SM
  – Muon g-2
  – Charged lepton flavor violation

- Summary

Muon g-2: A crack in the Standard Model?



But, it's lonely out there

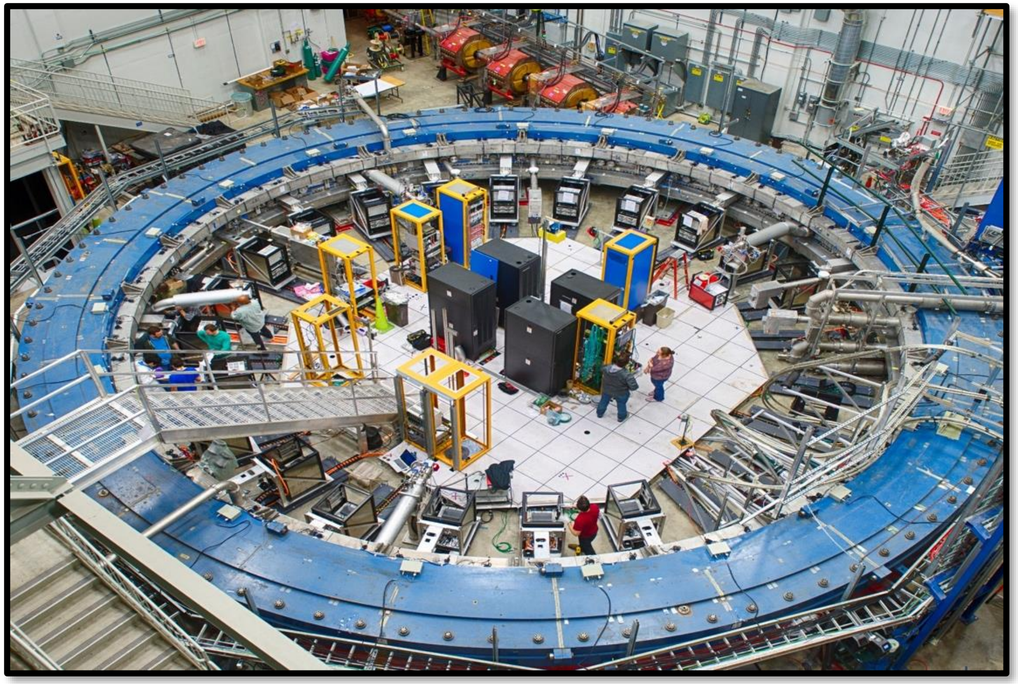


a_μ is now measured to 540 ppb; goal is 140 ppb

KNT18 Keshavarzia, Nomura, Teubner

Muon g-2: experimental effort

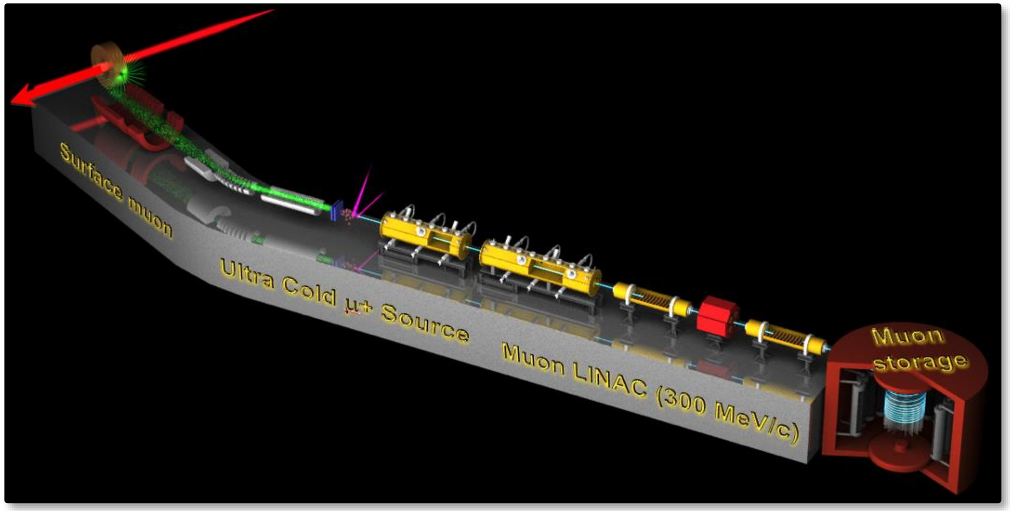
Fermilab E989
Muon g-2

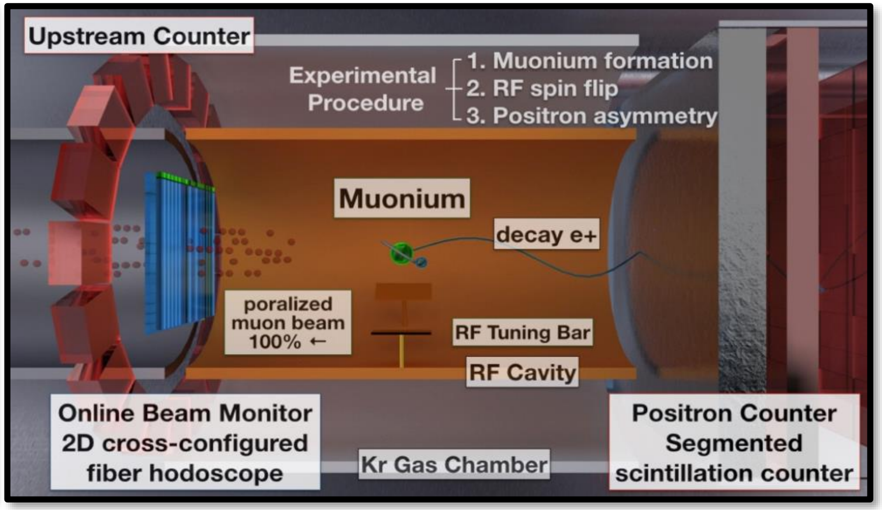


MuSEUM J-PARC
Muonium hfs

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

J-PARC g-2/EDM





Tsutomu Mibe

Shoichiro Nishimura

Gyromagnetic ratio g and anomaly a_μ

- Orbiting electron $\vec{\mu} = \frac{e}{2m}\vec{L}$

fermion S=1/2

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

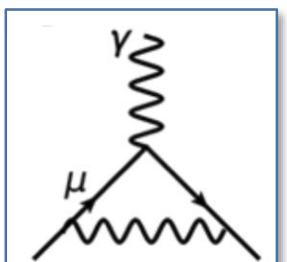
- Dirac $[\gamma^\mu(i\partial_\mu + eA_\mu) - m]\Psi = 0$

$$g = 2$$

- Spatial structure

$$\langle f|J^\mu_{em}|i\rangle = \bar{u}_f\left[F_1(q^2)\gamma^\mu + \frac{iF_2(q^2)}{2m_N}\sigma^{\mu\nu}q_\nu\right]u_i$$

- QED
  - Schwinger 1948

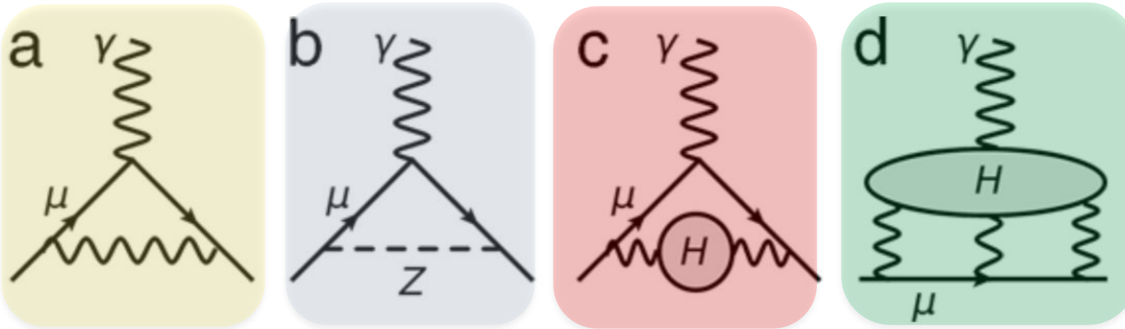


$$g = 2(1 + a_l) \text{ with } a_l = \frac{\alpha}{2\pi}$$

$$a_l \equiv \frac{g_l - 2}{2}$$

- Experiments
  - g_e=1 159 652 180.73 (28)x10^{-12} [0.24 ppb] best determination of α
    Gabrielse, Havard
  - g_μ= 116592089(63)x10^{-11} [540 ppb] sensitivity to new physics $O(\frac{m^2}{\Lambda^2})$
    BNL E821

SM predictions for a_μ



	$a_\mu\,[10^{-11}]$	$\Delta a_\mu\,[10^{-11}]$
experiment	116 592 089.	63.
QED $\mathcal{O}(\alpha)$	116 140 973.21	0.03
QED $\mathcal{O}(\alpha^2)$	413 217.63	0.01
QED $\mathcal{O}(\alpha^3)$	30 141.90	0.00
QED $\mathcal{O}(\alpha^4)$	381.01	0.02
QED $\mathcal{O}(\alpha^5)$	5.09	0.01
QED total	116 584 718.97	0.07
electroweak, total	153.6	1.0
HVP (LO) [KNT 18]	6 932.7	24.6
HVP (NLO) [KNT 18]	−98.2	0.4
HLbL [update of Glasgow consensus–KNT 18]	98.0	26.0
HVP (NNLO) [Kurz, Liu, Marquard, Steinhauser 14]	12.4	0.1
HLbL (NLO) [GC, Hoferichter, Nyffeler, Passera, Stoffer 14]	3.0	2.0
theory	116 591 820.5	35.6

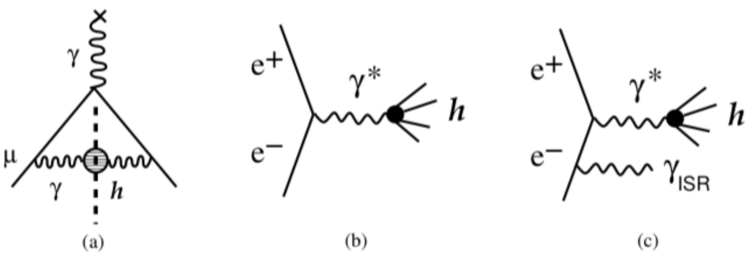
$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 268.5 \pm 72.4$$

Colangelo based on KNT18

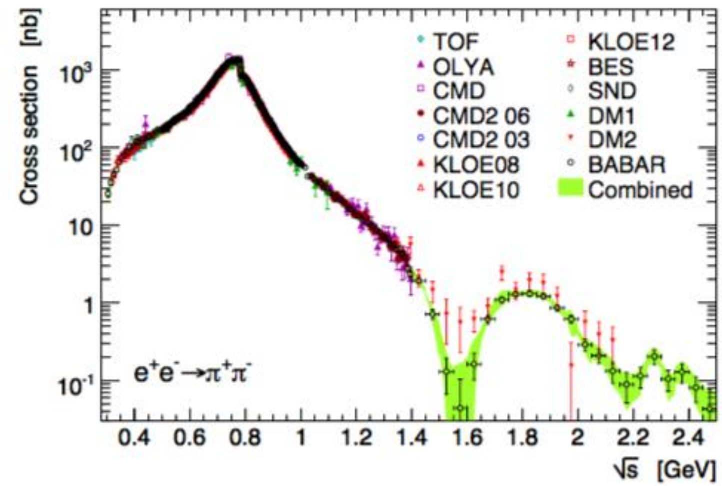
Hadronic and QCD effects

Davier 2017

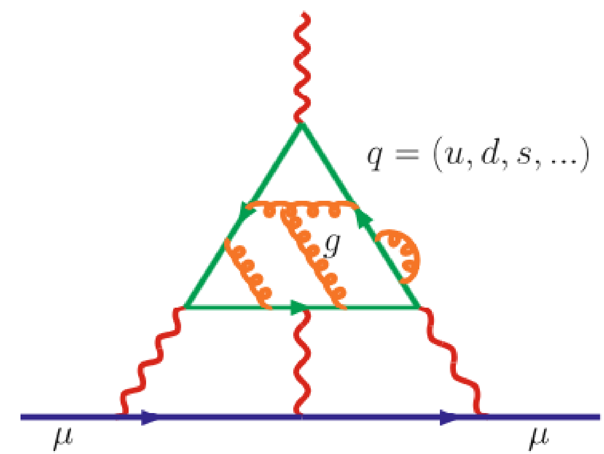
- Hadronic vacuum polarization
  - Dispersion relation approach based on data



exclusive σ(s) to 0.5-0.8% precision



- Light-by-light term
  - hadronic models ~10(2.6)x10^{-10}
  - dispersion relations
  - Lattice QCD, stat error only 5.35(1.35)x10^{-10}

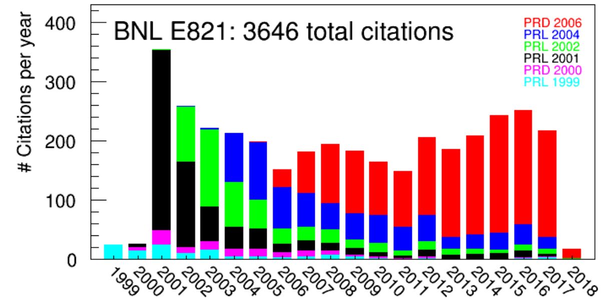


PRL **118,** 022005 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Connected and Leading Disconnected Hadronic Light-by-Light Contribution to the Muon Anomalous Magnetic Moment with a Physical Pion Mass

Thomas Blum,[1,2] Norman Christ,[3] Masashi Hayakawa,[4,5] Taku Izubuchi,[6,2] Luchang Jin,[3,*] Chulwoo Jung,[6] and Christoph Lehner[6]

Theoretical explanations

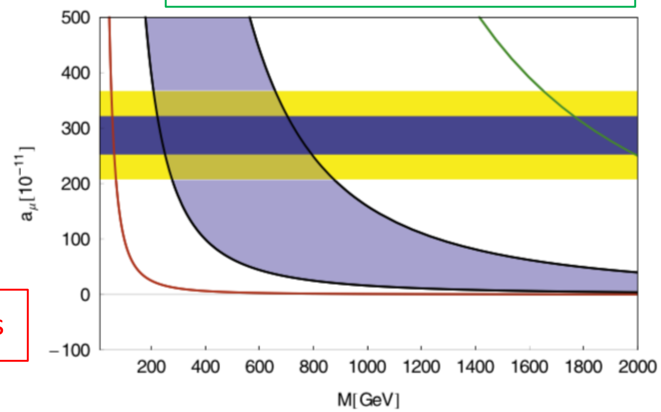


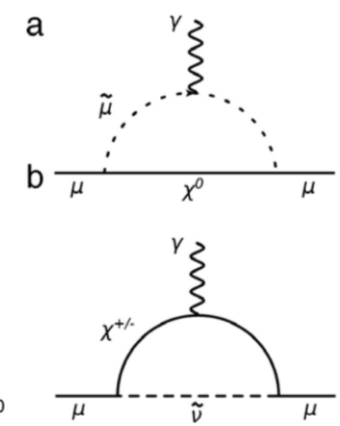
- generic new physics (NP)

  a'la Marciano, Czarnecki, Stockinger

$$\delta a_\mu \simeq \frac{\delta m_\mu(NP)}{m_\mu} \times \frac{m_\mu^2}{M^2}$$

O(1): rad. muon mass generation



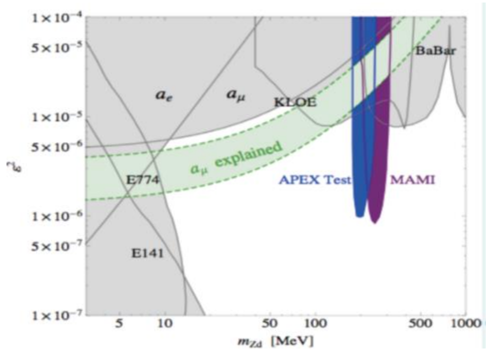


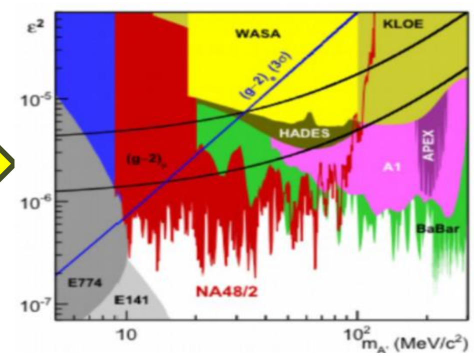
O($\frac{\alpha}{4\pi}$): Z′,W′, universal extra dimensions, or Littlest Higgs

O($\frac{\alpha}{4\pi}$ × factor): various extra dimension models, or SUSY models (tanβ=5–50), 2HDM

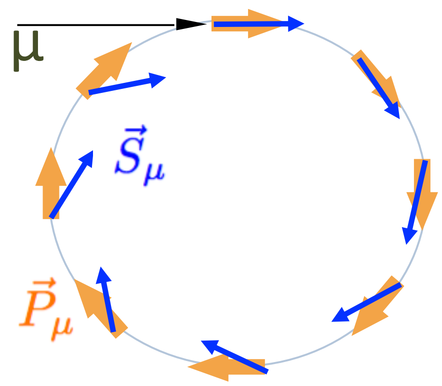
- low scale: dark photons

Pospelov





Fundamental principle of measurement



- Measure difference in muon spin precession and cyclotron motion in magnetic field

- "miracles" help experiment *Farley*
  - easy to produce polarized μ from π decay in flight
  - relative precession proportional to (g-2)

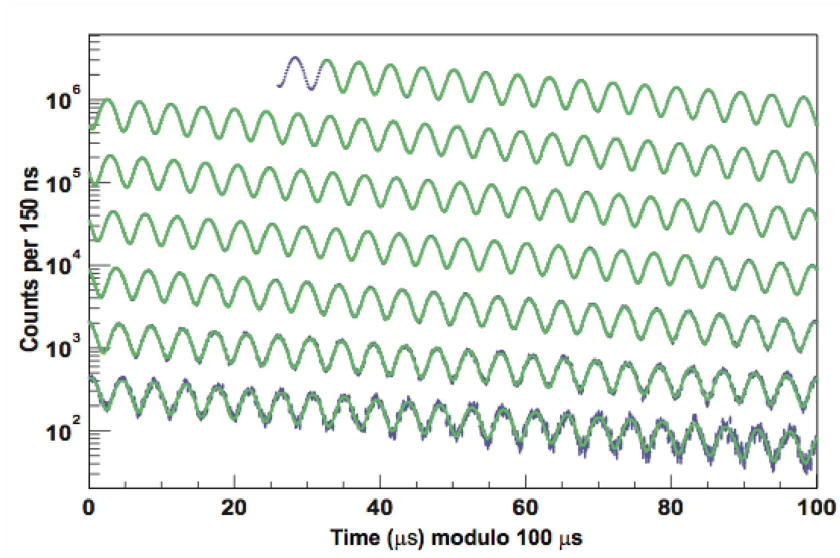
$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

  - Magic momentum P_μ=3.094 GeV/c cancels E fields, γ=29.3, τ=66 μs.

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

  - Muon decay is self analyzing due to V-A highest decay e^+ intensity parallel to S_μ

E821 BNL



New muon g-2 experiment at Fermilab

- Goal E989: 4x improvement over E821

- If discrepancy due to nature:
  - > 5 σ effect from experimental improvement
  - much larger if SM error shrinks by ~2

- error budget

δa (ppb)	BNL	Fermilab	improvement
total	540	140	3.9
statistics	460	100	4.6
ω_a systematics	180	70	2.6
ω_p systematics	170	70	2.4

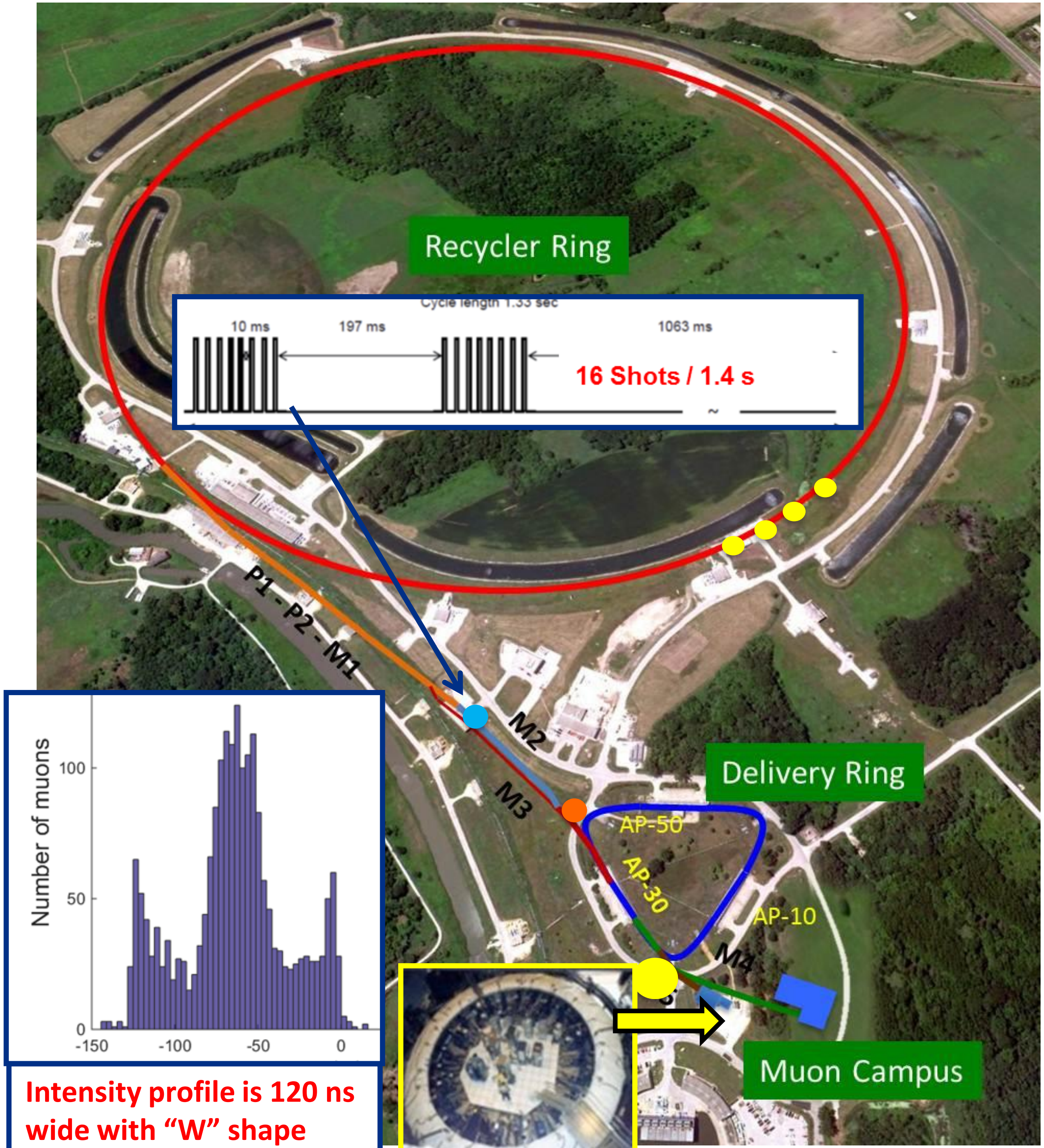
21x more statistics
- beam
- kicker

ω_a
- better beam,
- segmented calorimeter
- stability monitoring
- new, improved tracker

ω_p proton NMR measures B
- improved B homogeneity
- temperature stabilization
- absolute calibration

Creating the Muon Beam for g-2

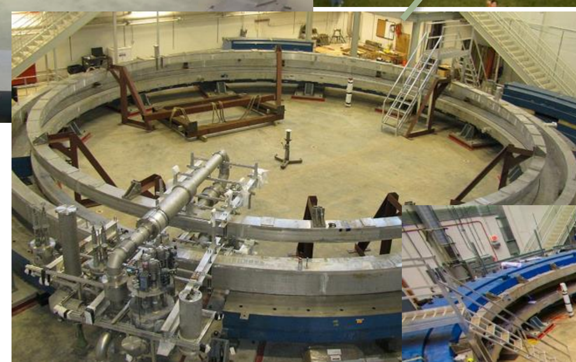
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- **μ enter storage ring**



Intensity profile is 120 ns wide with "W" shape

To measure the field ω_p we start with the BNL magnet but improve its field uniformity

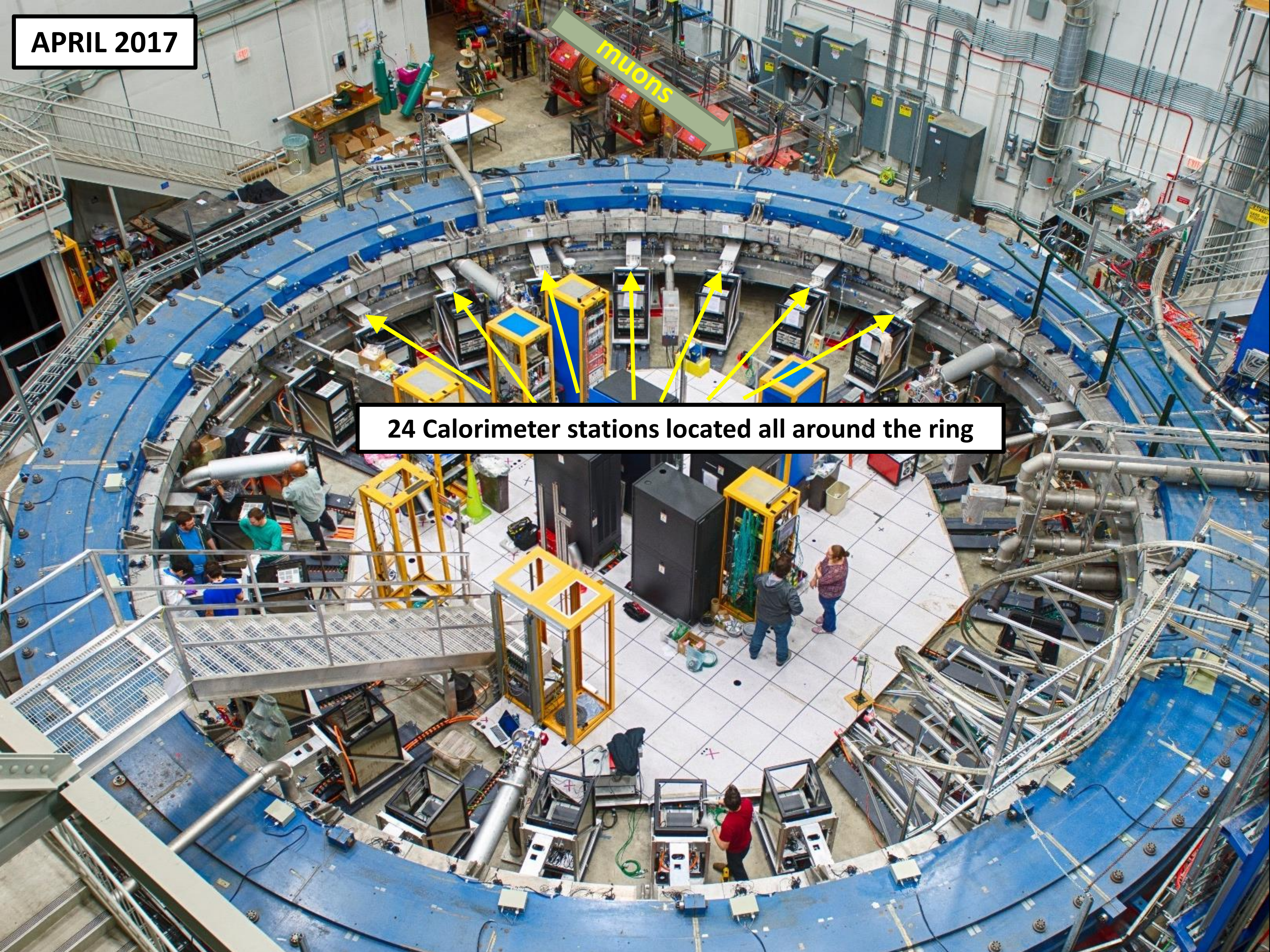
Yoke Iron
Aligned to sub-mil precision



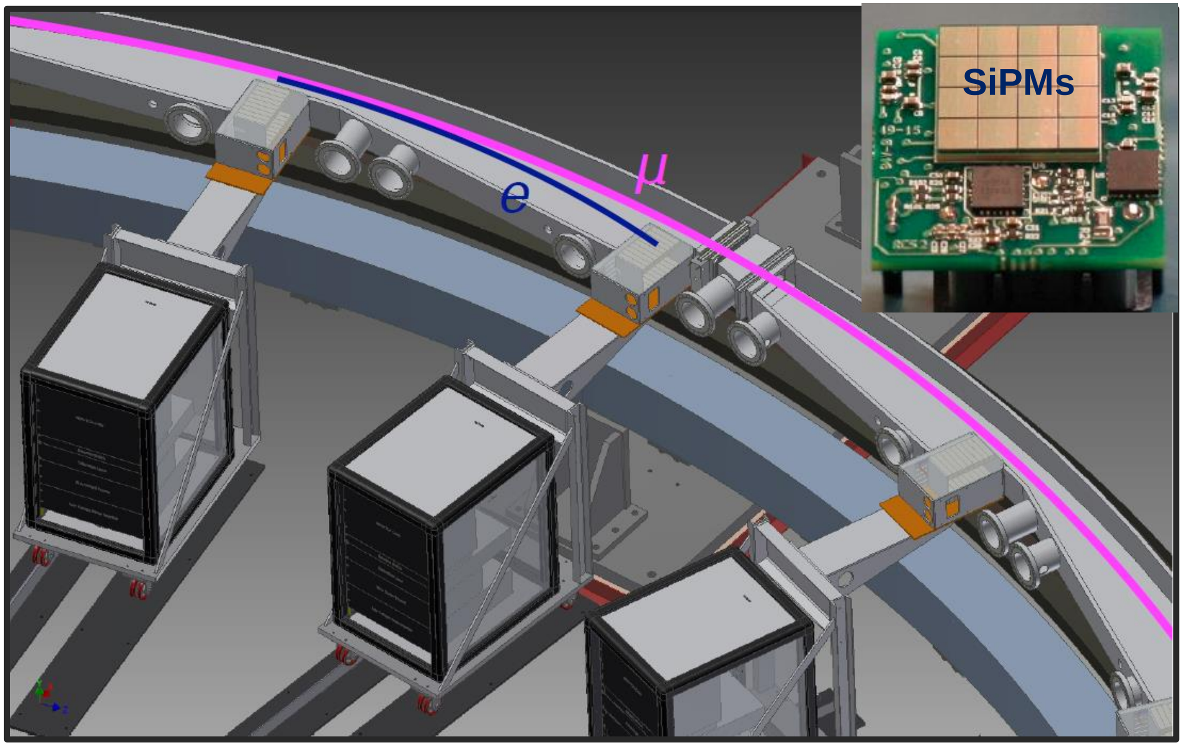
Superconducting coils
And cryostat

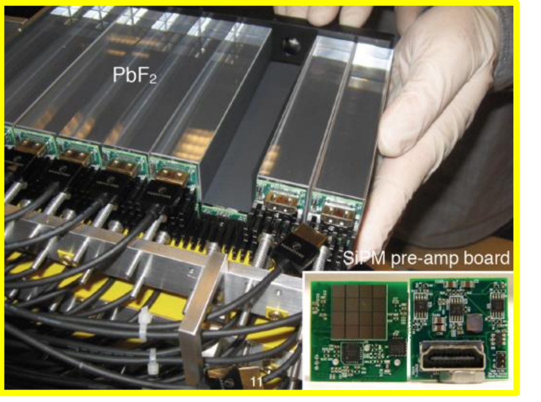
Field improvements compared to BNL

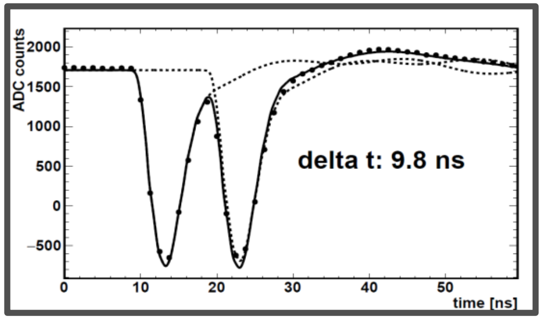
- 3x after rough shimming
- surface coil programming ongoing


APRIL 2017
muons
24 Calorimeter stations located all around the ring

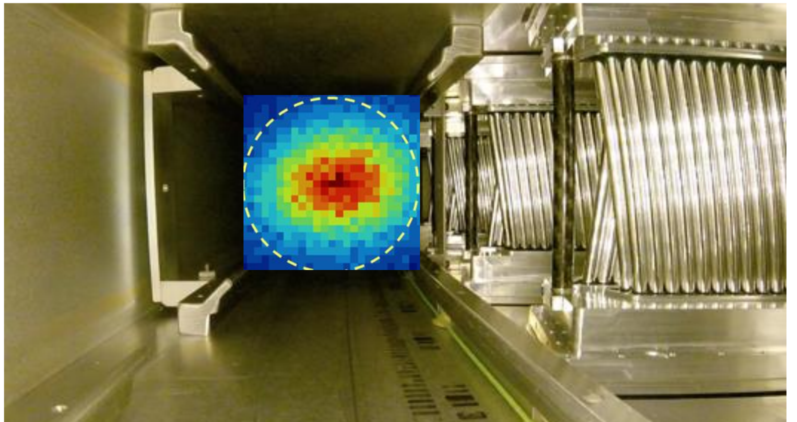
24 Calorimeter with 54 PbF_2 Cherenkov crystals detect e^+

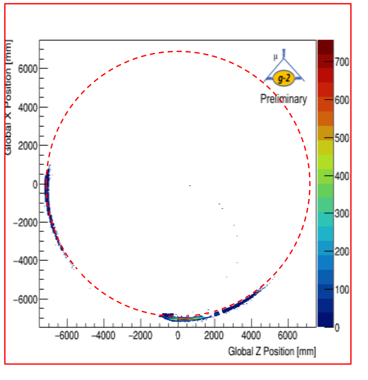






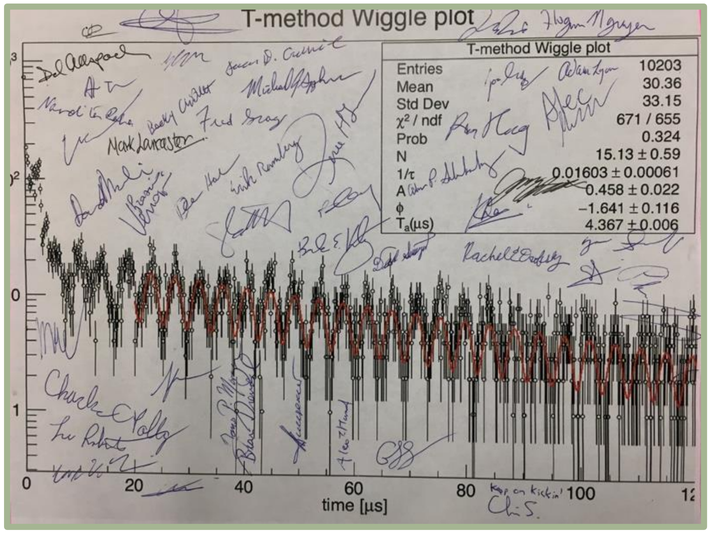
In vacuum straw trackers reconstruct muon beam profile





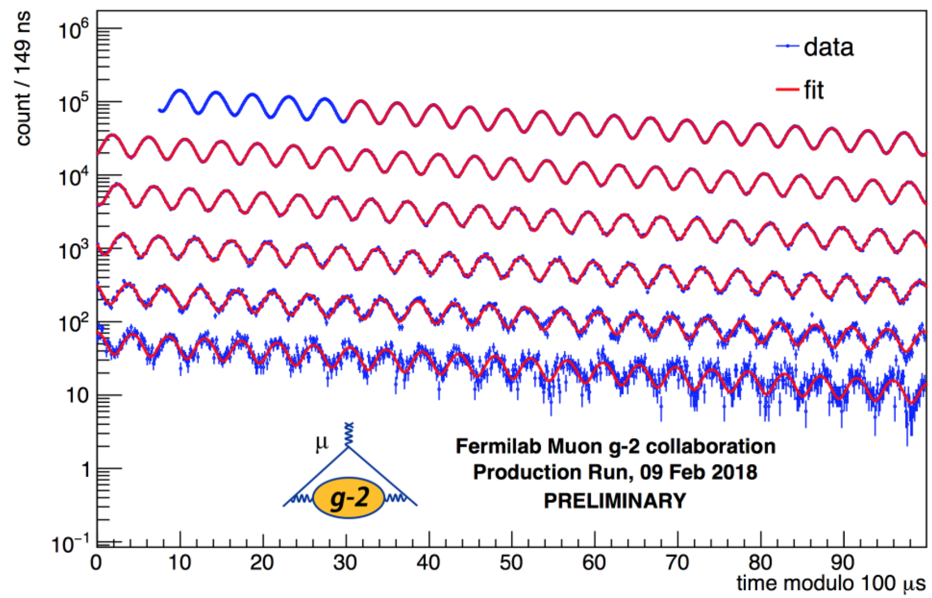
Status and outlook

- June 2017: First wiggle plot



- First physics run starting soon
  - goal 1-2x BNL statistics by summer
  - summer shut-down
    - upgrades to achieve full intensity
    - calibrations and optimization
  - continued data taking 2018-2020

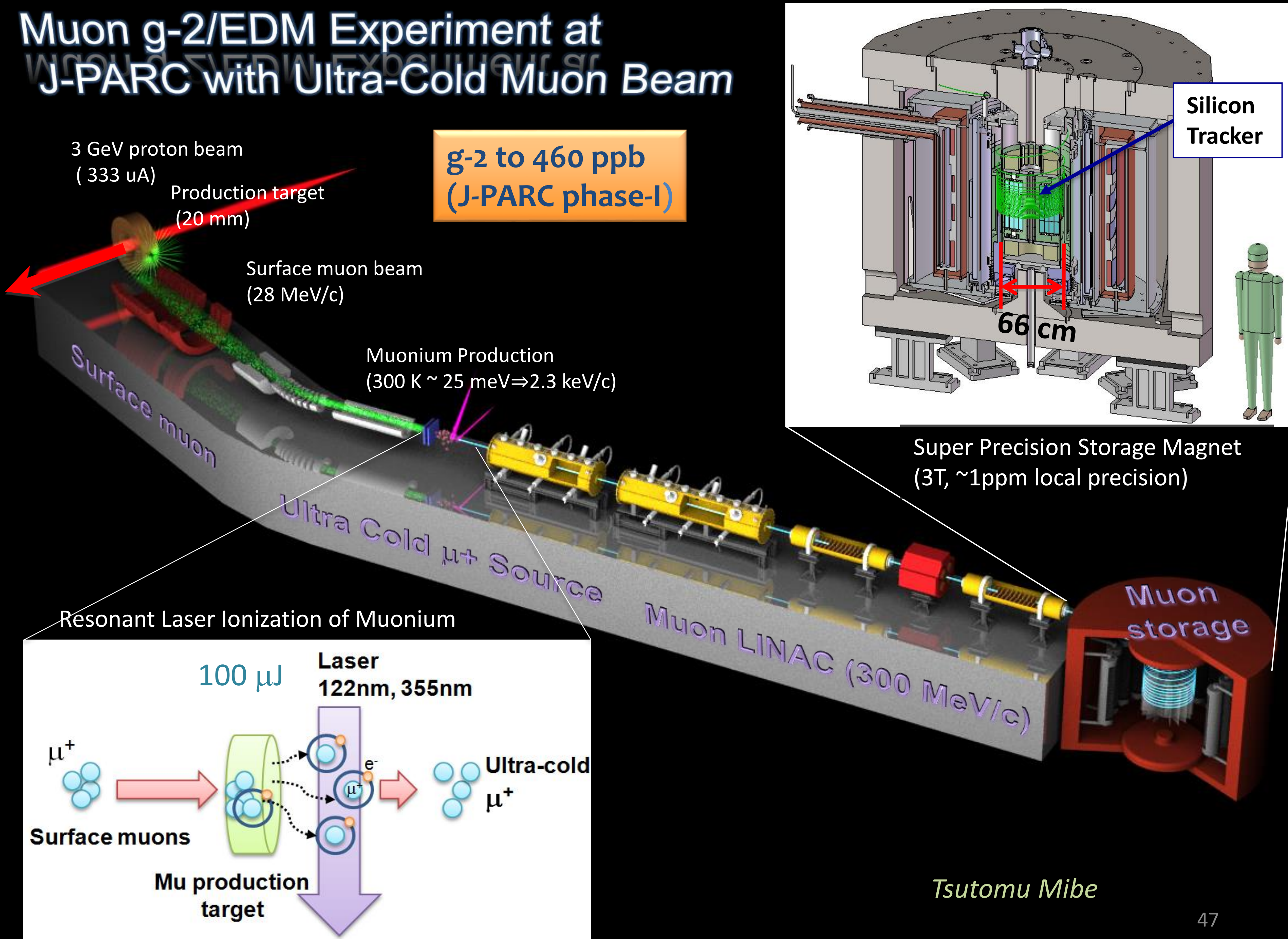
- recent run:



Not "physics" data yet.

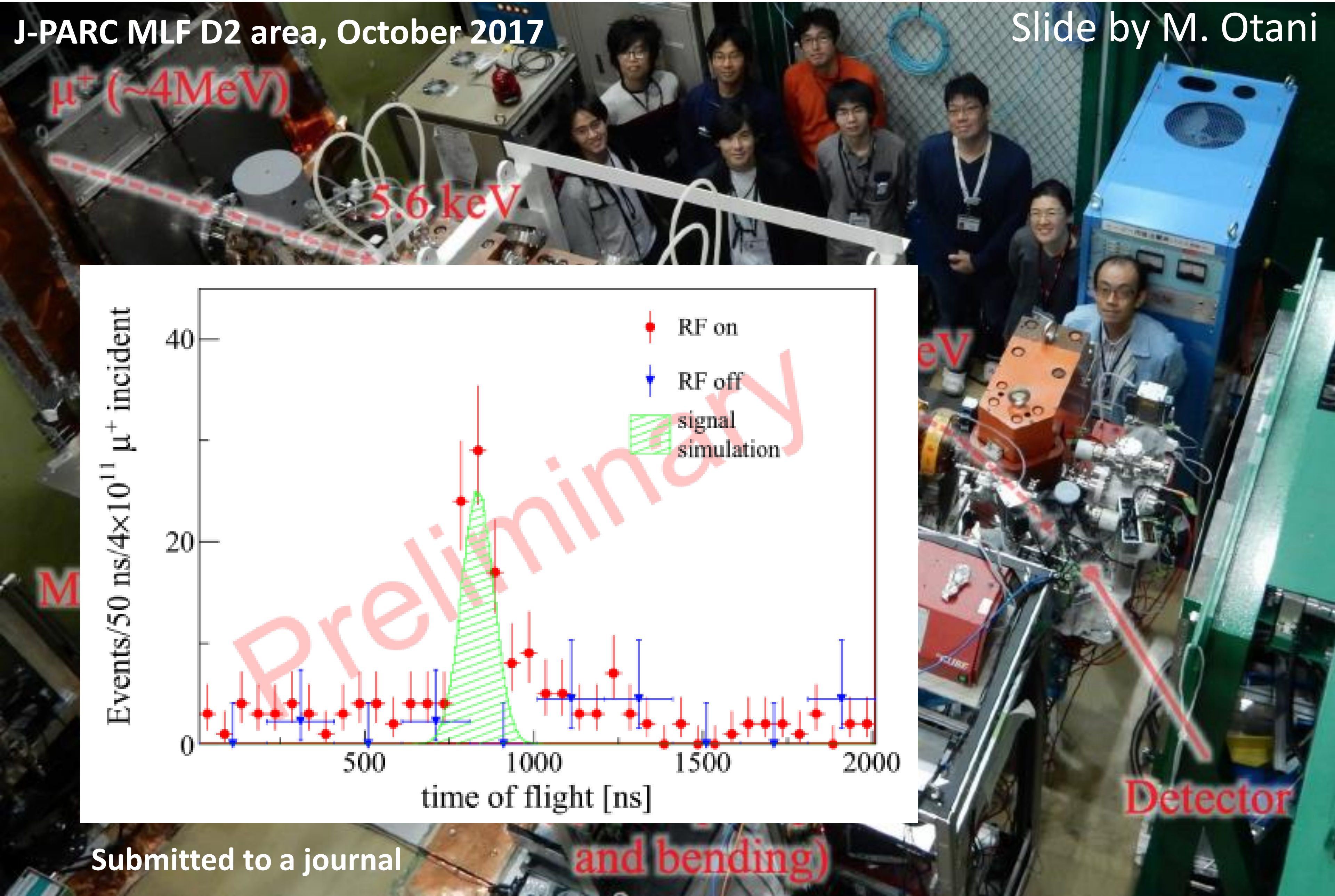
Calibrations and field mapping ongoing.

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



Tsutomu Mibe

Muon RF acceleration for the first time!



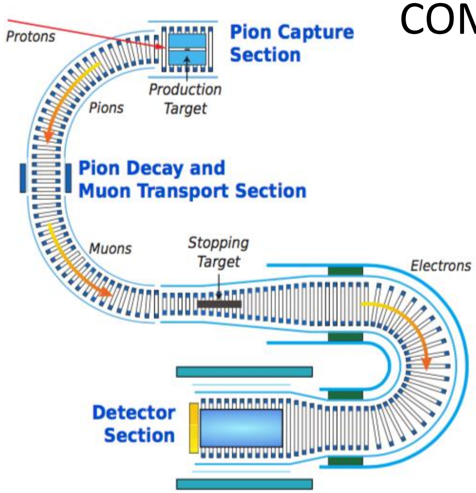
Charged Lepton Flavor Violation Experiments

$$\mu^+ \to e^+ \gamma$$
$$\mu^+ \to e^+ e^- e^+$$
$$\mu^- + Z \to Z + e^-$$

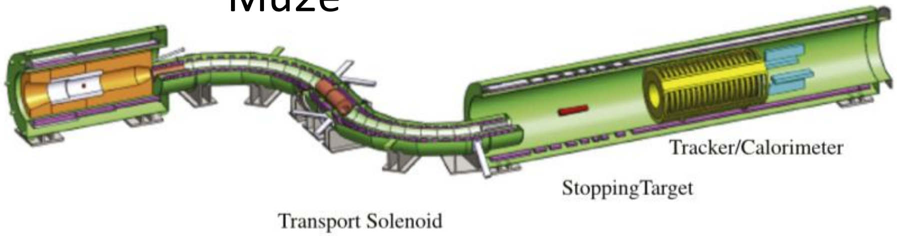
BR ~ O(10^{-53}) in SM

- low energy physics probes the TeV scale
- synergy and complementarity to LHC

COMET



Mu2e

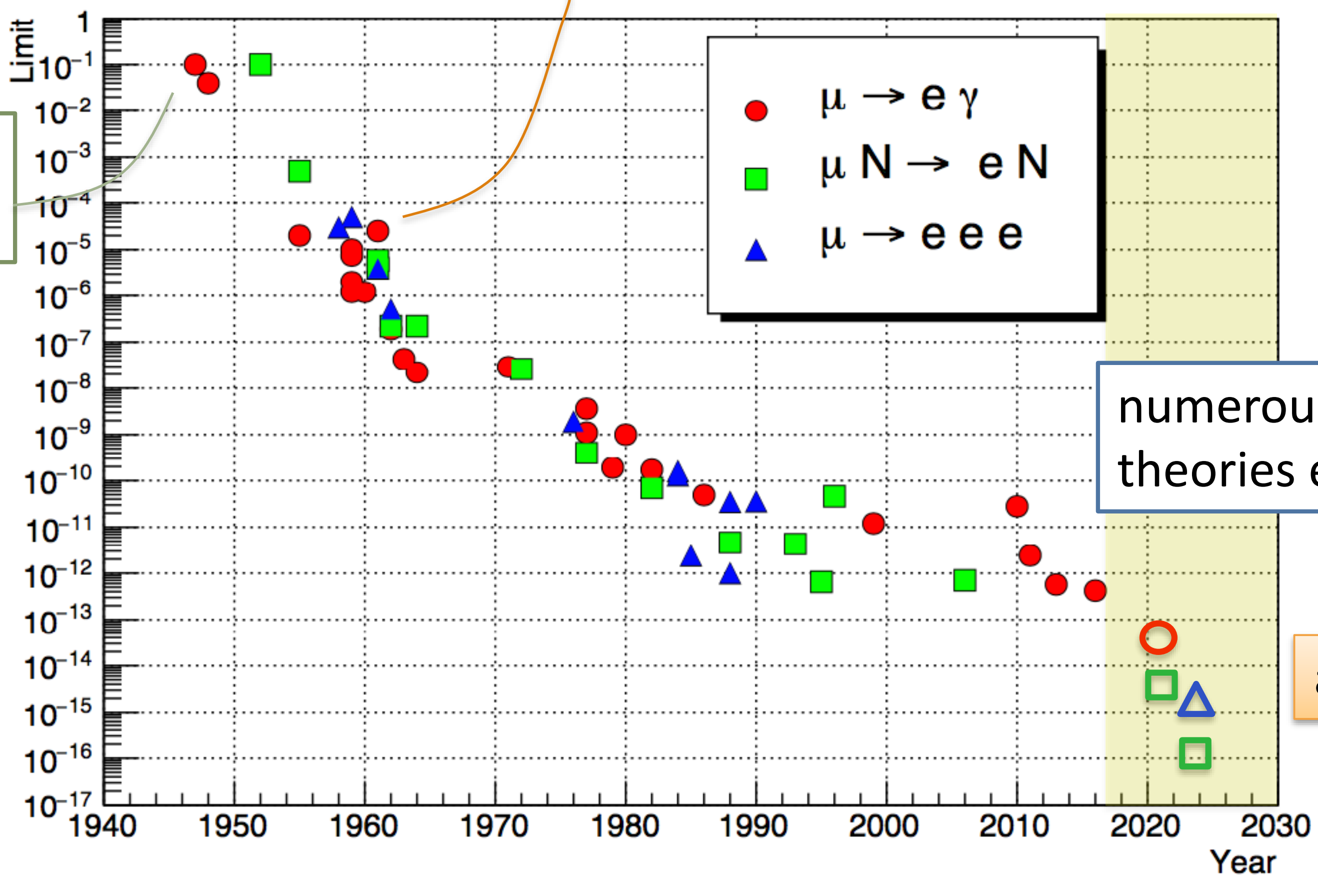


MEG

Brief history

μ to e via weak boson loop
→ two neutrino hypothesis

μ excited e ?
→ distinct



numerous theories excluded

aggressive

Flavor not conserved

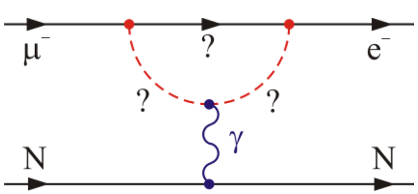
- for quarks (highly suppressed for neutral current)
- for neutral leptons (ν oscillation and PMNS matrix)

But not observed for charged leptons !

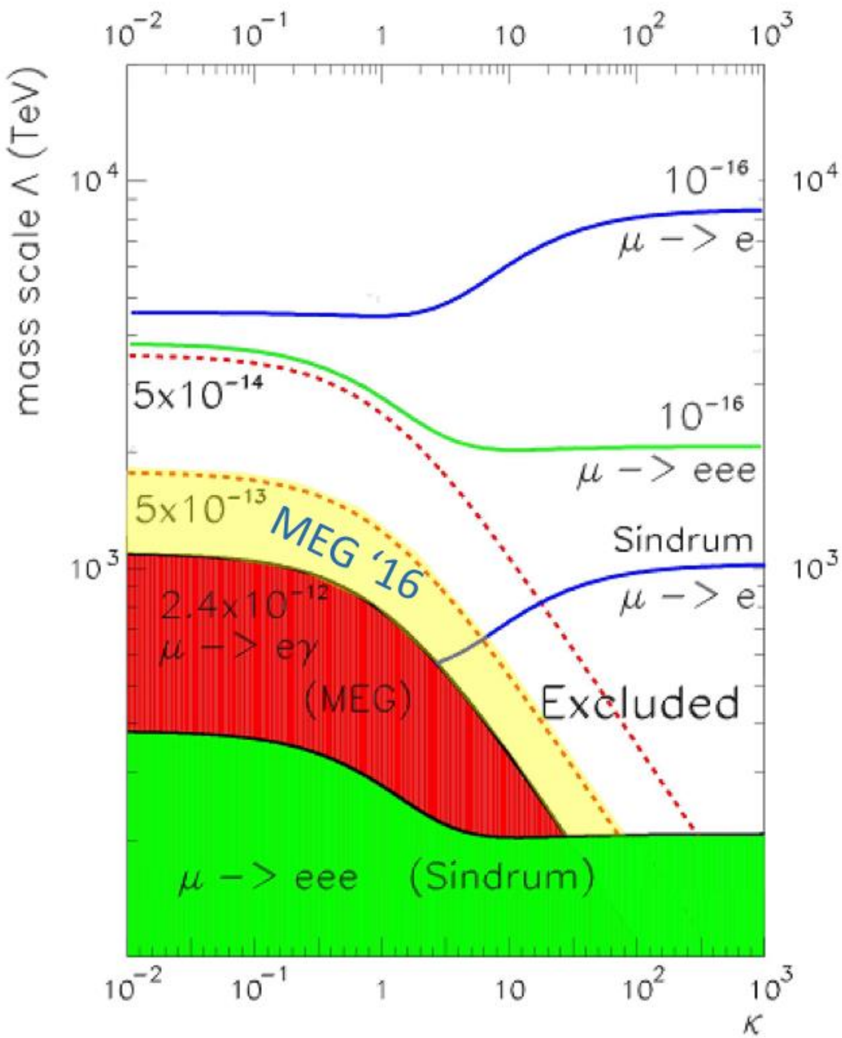
Model independent EFT

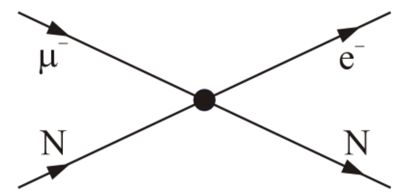
de Gouvea

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



κ<<1
magnetic moment type operator

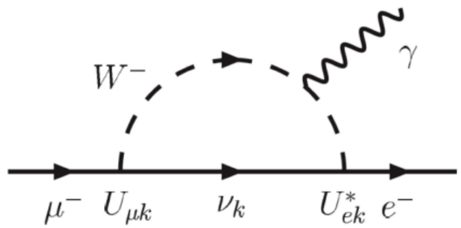




κ>>1
four–fermion interaction

Some observations

- LFV suppression in SM "accidental"



well understood
GIM suppression

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

- Many NP models
  - introduce particles with large m, not completely degenerate
  - LVF predictions close to exp. limit
  - often related to ν mass generation

- model must provide
  - mass scale NP
  - flavor mixing structure

$$\frac{1}{\Lambda^2_{CLFV}} = \frac{\theta_{e\mu}}{\Lambda^2}$$

LHC TeV scale

Interesting example for dipole coupling:

$$\frac{1}{\Lambda^2_{CLFV}} = \frac{\theta_{e\mu}}{\Lambda^2_{g-2}}$$

if g-2 real + MEG $\rightarrow \theta_{e\mu} < 10^{-4}$

- operator structure
  - Photon coupling

$$\mu \to e\gamma : \mu \to 3e : \mu^- Al \to e^- Al = 389 : 2.3 : 1$$

- κ = tree/loop unknown

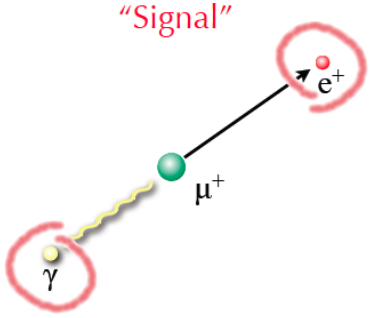
Model	$\mu \to eee$	$\mu N \to eN$	$\frac{BR(\mu \to eee)}{BR(\mu \to e\gamma)}$	$\frac{CR(\mu N \to eN)}{BR(\mu \to e\gamma)}$
MSSM	Loop	Loop	$\approx 6 \times 10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3 \times 10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1 - 3) \times 10^3$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^3$	$\mathcal{O}(10^3)$
LFV Higgs	Loop†	Loop*†	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

Calibbi, Signorelli

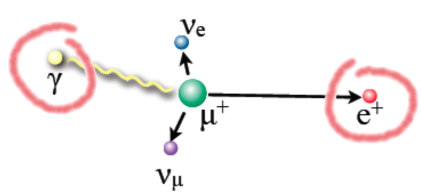
$\mu^+ \to e^+\gamma$

MEG @ PSI

"Signal"

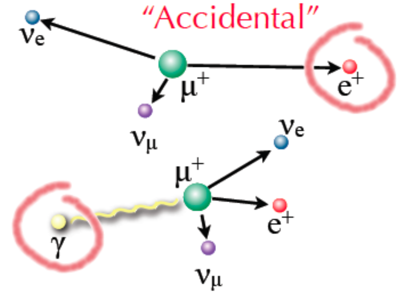


"RMD"



$\mu \to e\bar{\nu}\nu\gamma$

"Accidental"



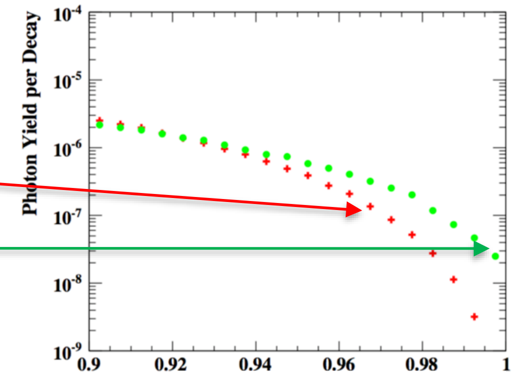
$\mu \to e\bar{\nu}\nu\gamma$

$e\mathcal{N} \to e\mathcal{N}\gamma$

$e^+e^- \to \gamma\gamma$

$\mu \to e\bar{\nu}\nu$

MEG



$y = 2E_\gamma/m_\mu$

Ee = Eγ = 52.8 MeV

$\theta_{e\gamma}$ = 180°

$t_{e\gamma}$ ~ 0

$B_{\text{prompt}} \approx$ ~~0.1~~ 0.05 $\times B_{\text{acc}}$

$B_{\text{acc}} \approx R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta^2 \Delta t$

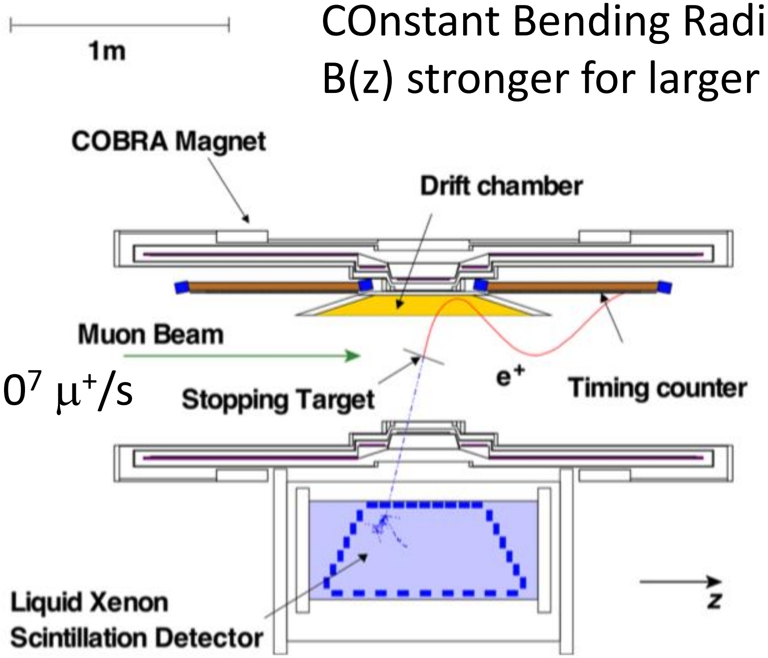
The accidental background is dominant and it is determined by the experimental resolutions

$R_{acc} \propto R_\mu^2$

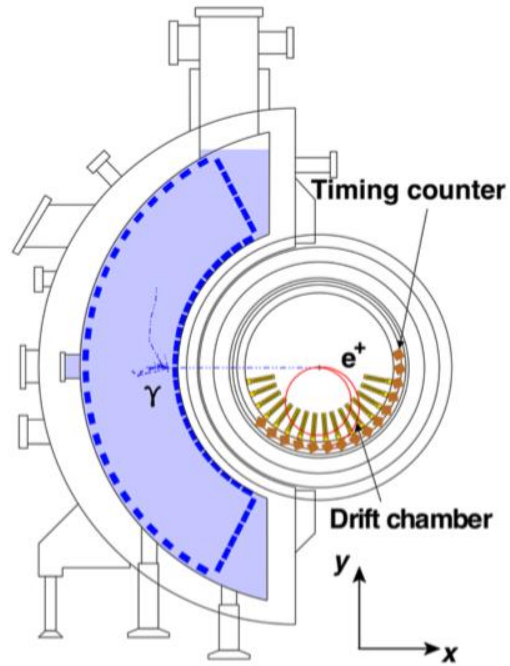
- 100% duty cycle beam (**PSI**) only choice for coincidence final states
- **accidental coincidences are the practical limit**

MEG Experiment

COnstant Bending Radius
B(z) stronger for larger p_T



$3x10^7\ \mu^+/s$



LXe
800l fiducial

Eur. Phys. J. C (2016) 76:434
DOI 10.1140/epjc/s10052-016-4271-x

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for the lepton flavour violating decay $\mu^+ \rightarrow e^+\gamma$ with the full dataset of the MEG experiment

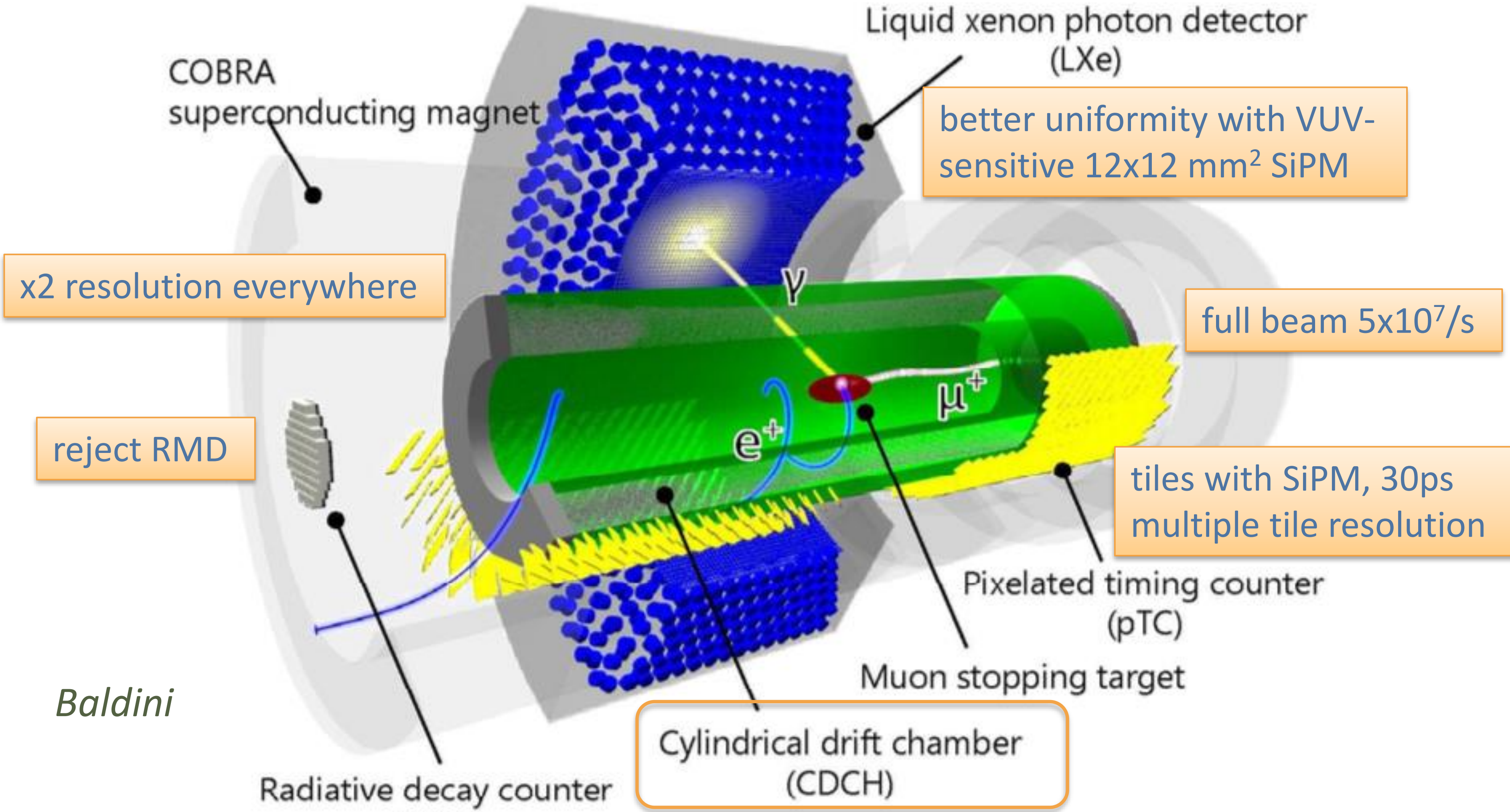
MEG Collaboration

- final result 2009-2013
  - $7.5x10^{14}$ stopped μ
  - $\text{SES} = (5.84 \pm 0.21) \times 10^{-14}$

90% CL $\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$

several records

MEG II experiment

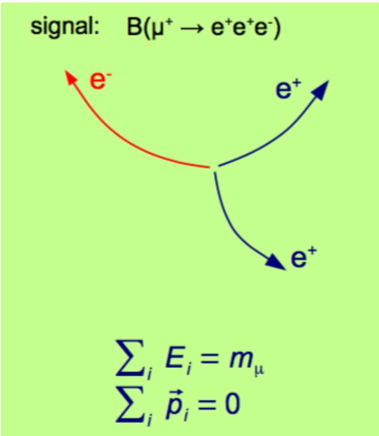


Rate [Hz]	Duty f.	ΔE_e	ΔE_γ	$\Delta t_{e\gamma}$	$\Delta\Theta_{e\gamma}$	Upper Limit
3×10^7	100%	1.5%	4.7%	0.28 ns	30 mrad	4.2×10^{-13}
7×10^7	100%	0.6%	2.3%	0.19 ns	20 mrad	5×10^{-14}*

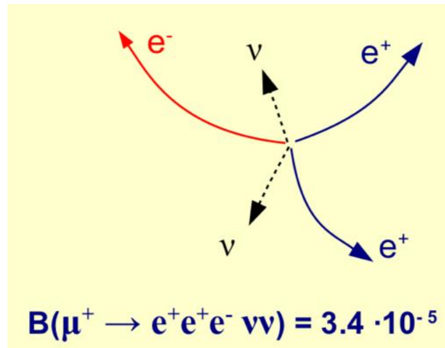
$$\mu^+ \to e^+ e^- e^+$$

Mu3e @ PSI

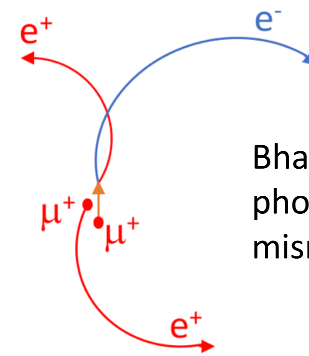
- signal



- irreducible BG

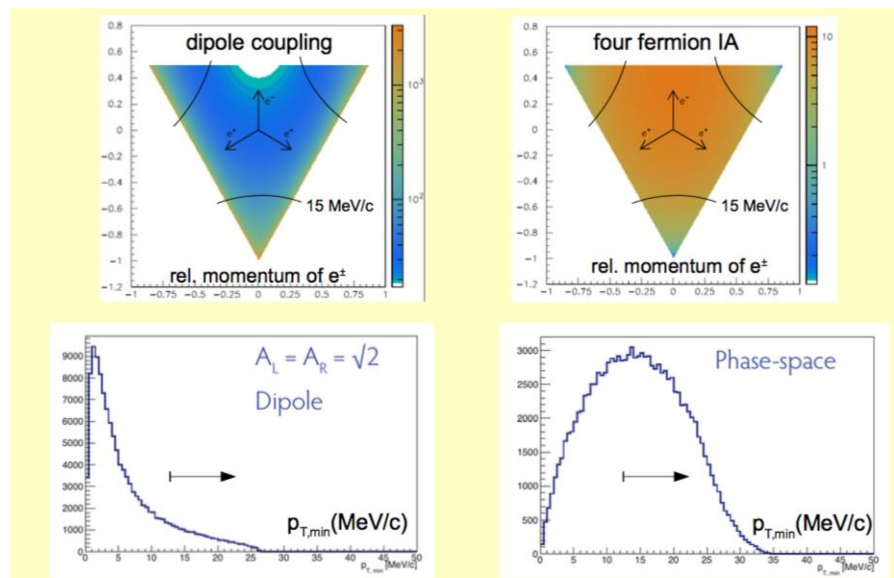


- accidental BG



Bhabha scattering, photon conversion, misreconstruction

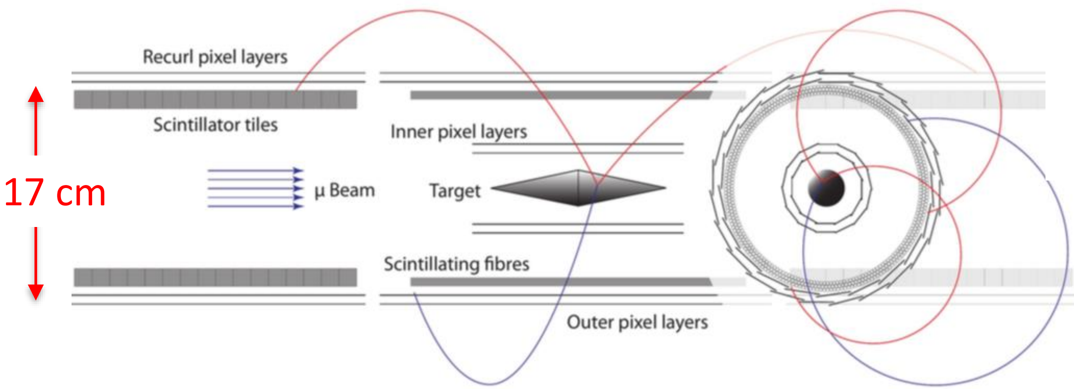
- excellent
  - vertex resolution
  - timing resolution
  - kinematic reconstruction
- Bonus
  - discriminates operator structure, if observed

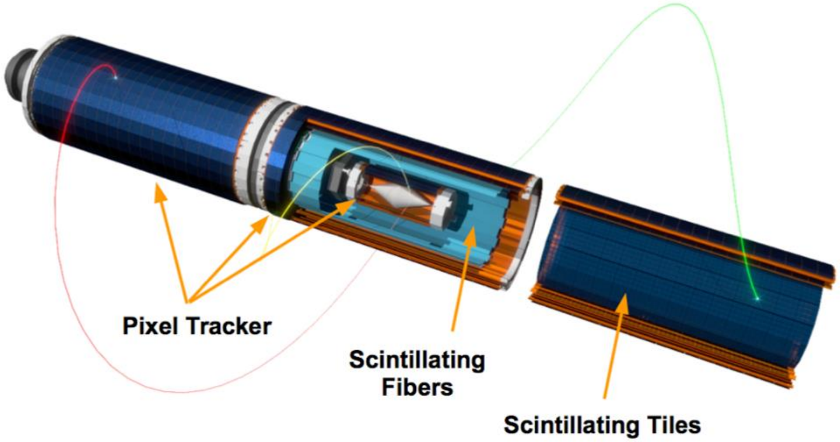


Andre Schöning, Mu3e Collaboration

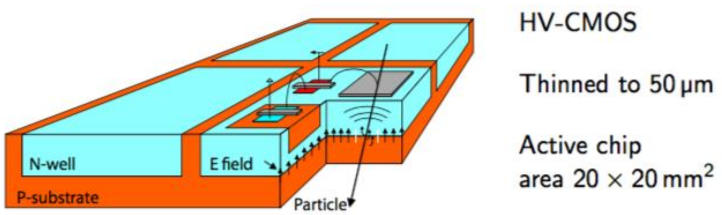
Mu3e concept

- Very compact pixel tracker





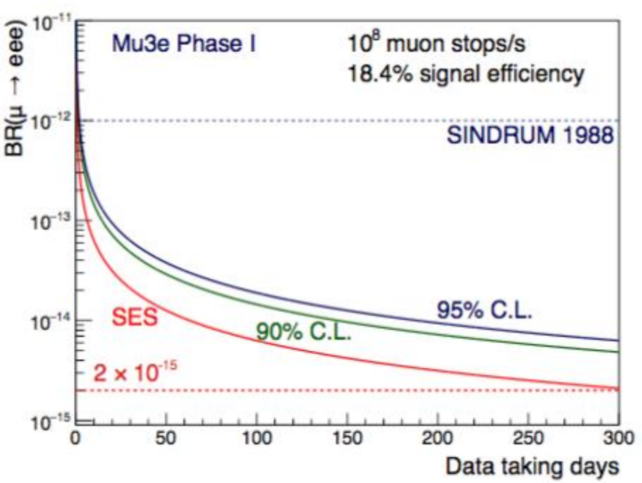
- Main features
  - good efficiency 10 < p < 53 MeV/c
  - 180^0 recurlers for excellent p resolution
  - new, 50 μm pixel detector to cope with multiple scattering, R&D



Ivan Perić, Nucl.Instrum.Meth. A582 (2007) 876-885

80x80 μm^2 pixel,
10-20 μm sens. layer

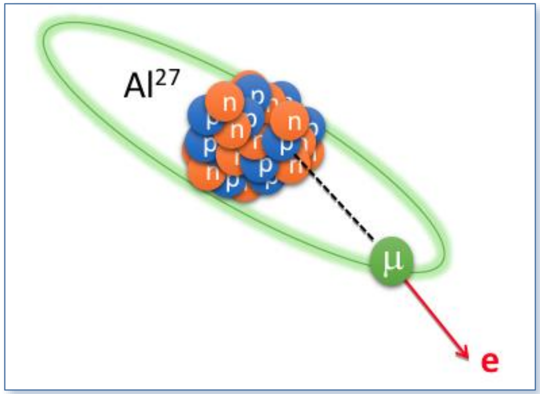
- stage 1: $2x10^{-15}$ [later 10^{-16}]
  - 1 MeV momentum resolution
  - time resolution 750 → 70 ps



$\mu^- + Z \to Z + e^-$

Muon to electron conversion

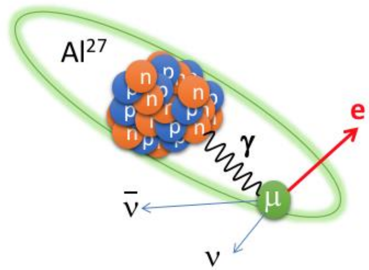
- Signal

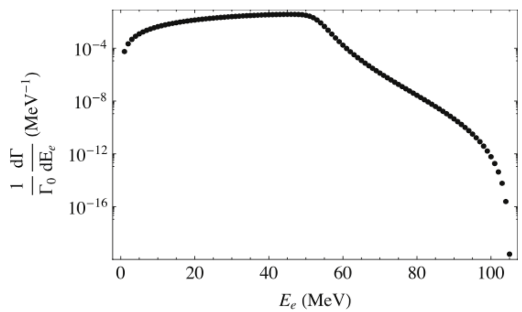


Single high energy e⁻

– Coherent interaction Z^5
– $E_e \sim m_\mu - (B.E.)_{1S}$ = 104.9 MeV
– no accidental limitation
– choice of target
  - Suitable lifetime
  - High E_e compared to DIO, RMC
– **New exp. aim at BR~10^{-16}**
  10000-fold improvement

- Decay in orbit

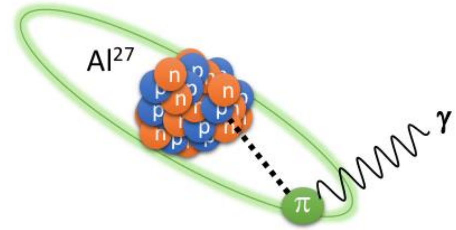




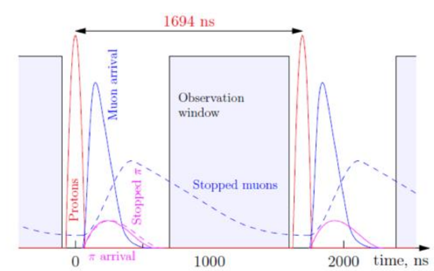
≤1MeV FWHM required

- Other BG
  – Cosmics, RMC…

- Radiative π capture



– BR=2% with $E_\gamma \leq m_\pi$
– Pulsed machines advantage



– $>10^{-9}$ p suppression required

Next generation experiments

p_T^2/R adiabatic invariant

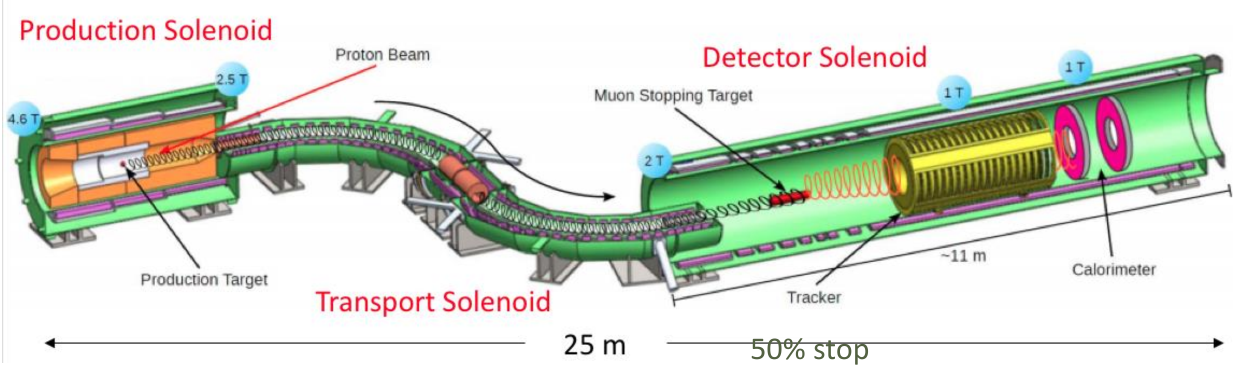
$D \propto q\, p \frac{s}{R}$ vertical displacement in bent solenoid

BR (90% CL) ~ 10^{-16}/μ-capture

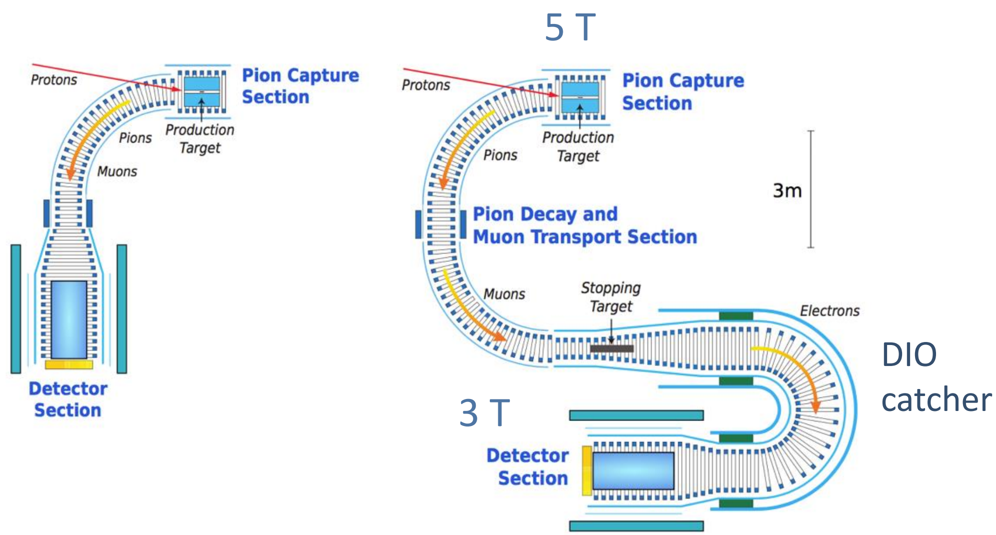
~ 10^{18} stopped μ^-

~ 10^{10} μ/s

- Mu2e @ FNAL
  - 8 GeV, 8kW
  - 20k μ per bunch



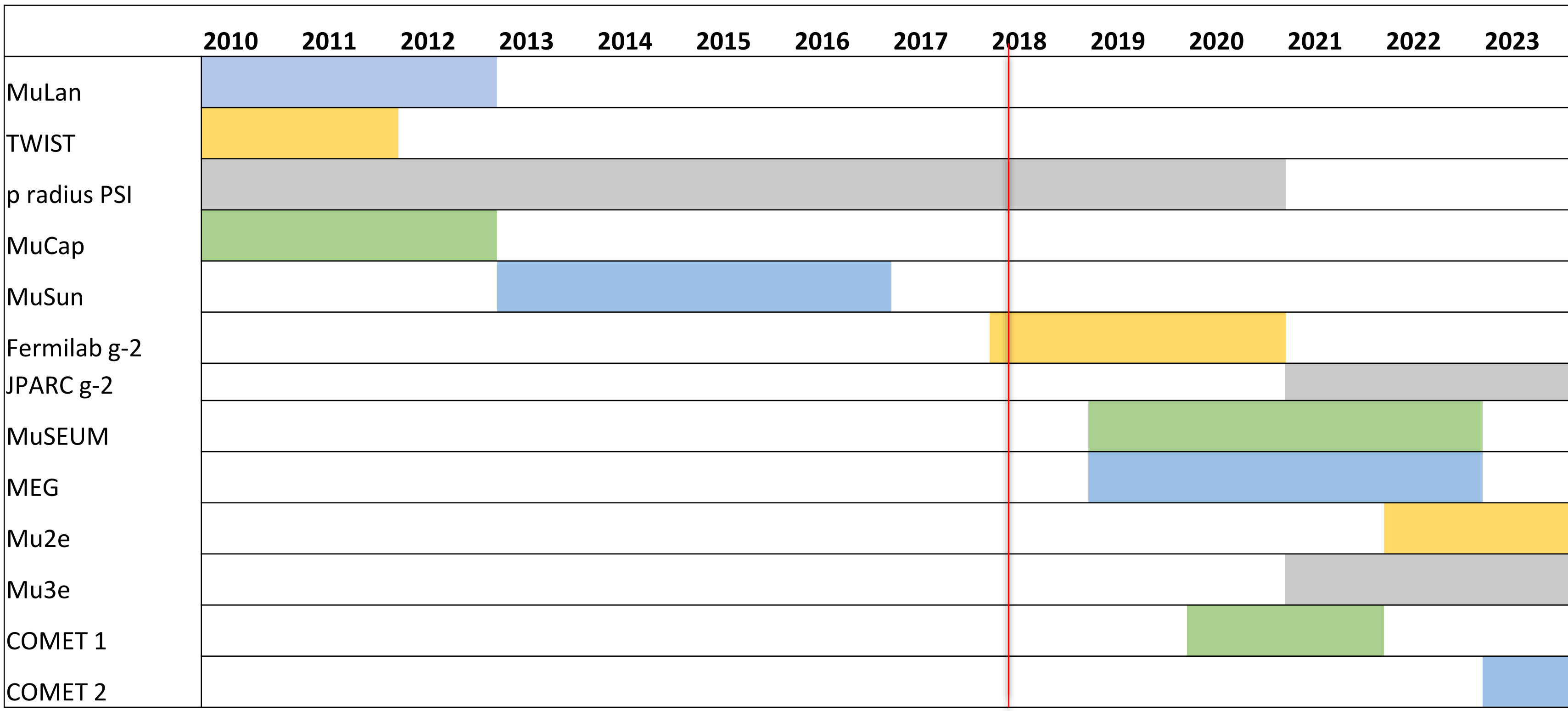
- COMET @ j-PARC
  - 8 GeV, 56 kW
  - Stage 1: 7×10^{-15}
  - Stage 2: 10^{-16}



- Next-to-next generation
  - BR ~ 10^{-18}

Summary I

- My tentative estimates for physics data taking



Summary II

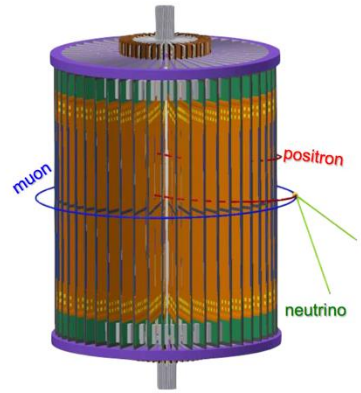
- Fascinating field with wide scientific scope
  - advanced and subtle technologies
  - medium sized collaborations 20-200+
  - extremely challenging experiments
- Achievements and expectations
  - G_F, helicity structure, g_P, MuSun 5-20 fold improvements, achieved or coming soon
  - proton radius: 10x improvement led to big surprise
  - g-2: discover or refute new physics explanation within a few years
  - MEG: 30x improvement, ~10x more in coming years
  - Mu3e, Mu2e, COMET, 10000x improvement in 5-10 yrs
- 60 yrs ago
  - world left-handed

- LHC and/or low energy fundamental symmetry program, lucky enough for yet another discovery ?

Backup

J-PARC

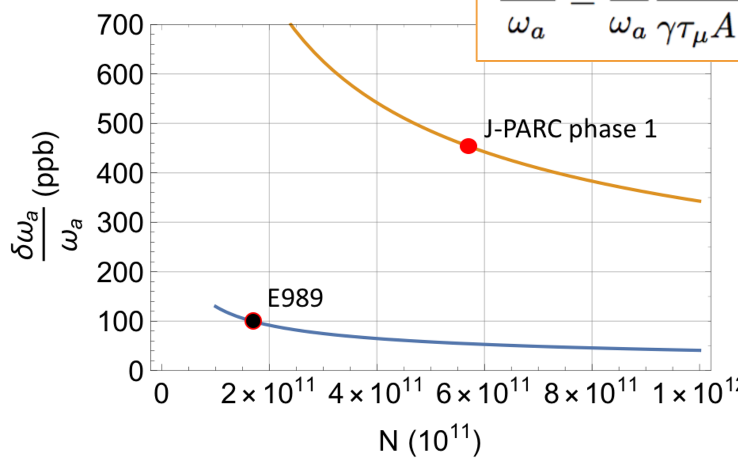
- Silicon vanes for e detection



- Very different systematics
  - fast spin flip
  - excellent field uniformity (local <1 ppm)

- Statistics

$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a}\frac{\sqrt{2}}{\gamma\tau_\mu A\sqrt{N}}$$



	BNL-E821	FNAL-E989	This Experiment
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarization	100%		50%→ 100%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric Quad.		very-weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
# of detected e^+	5.0×10^9	1.8×10^{11}	$5.7\times10^{11} \rightarrow 1.5\times10^{12}$
# of detected e^-	3.6×10^9	–	–
Statistical precision (a_μ)	0.46 ppm	0.14 ppm	0.46 ppm → 0.14 ppm
Statistical precision (EDM)	0.9×10^{-19} $e\cdot$cm	10^{-21} $e\cdot$cm	10^{-21} $e\cdot$cm

Completely different to BNL/FNAL method

J-PARC phase 1
- $\delta\omega_a$ like BNL
- δEDM 1.4 10^{-21} e cm (from <1.8 10^{-19} e cm, BNL)

R&D ending, revised TDR under review, construction phase is starting

Surface muon beamline under construction.

~3-3.5 years to start data taking when full funding is provided.

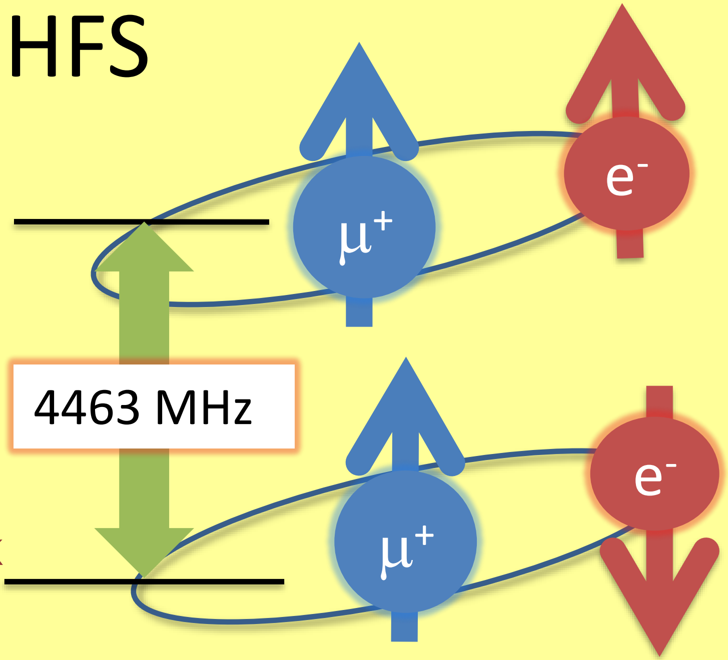
MuSEUM slides from from Simomura-san

Precise Measurement of Mu HFS at J-PARC MUSE

$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

Hyperfine Structure

Zeeman Splitting



・Pure leptonic system suitable for the precise check of QED.

ν_{HFS}(exp) 4463.302 765(53) MHz (12 ppb]) LAMPF1999

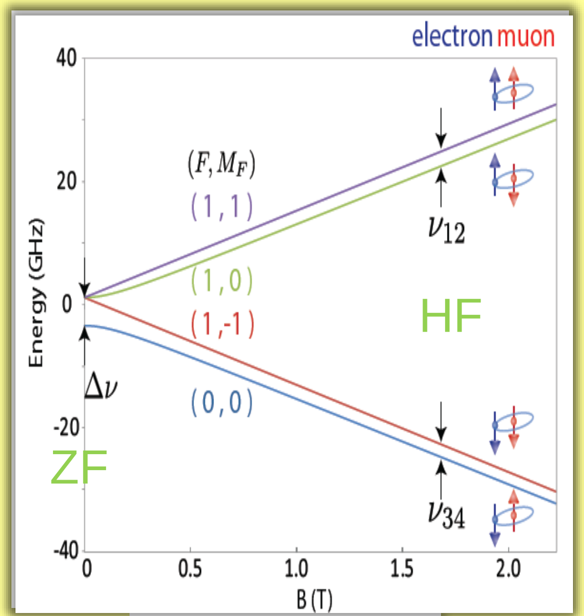
μ_μ/μ_p=3.18334524(37) (120ppb)

・Strong relationship to muon g-2 measurement

$$\Rightarrow \boxed{a_\mu = \frac{R}{\lambda - R}} \qquad R \equiv \frac{\omega_a}{\omega_p} \qquad \lambda \equiv \frac{\mu_\mu}{\mu_p}$$

From g-2 strage ring

From Muonium HFS



$\nu_{12}+\nu_{34}=\Delta\nu_{HFS}$

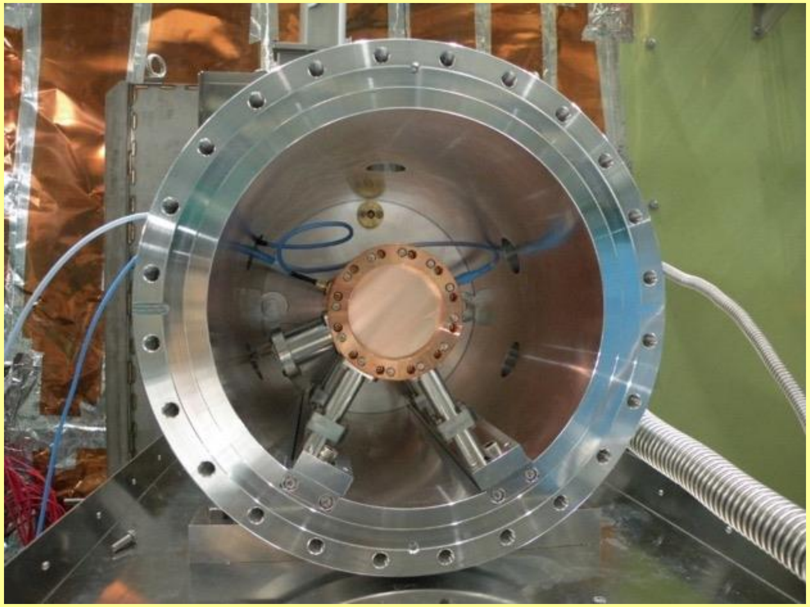
$\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p$

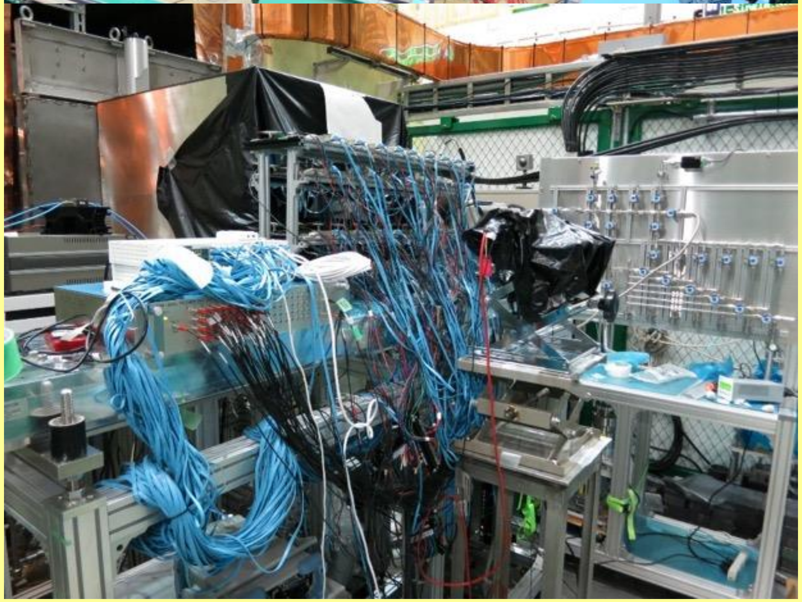
Our final goal at H line are HFS ~2ppb,

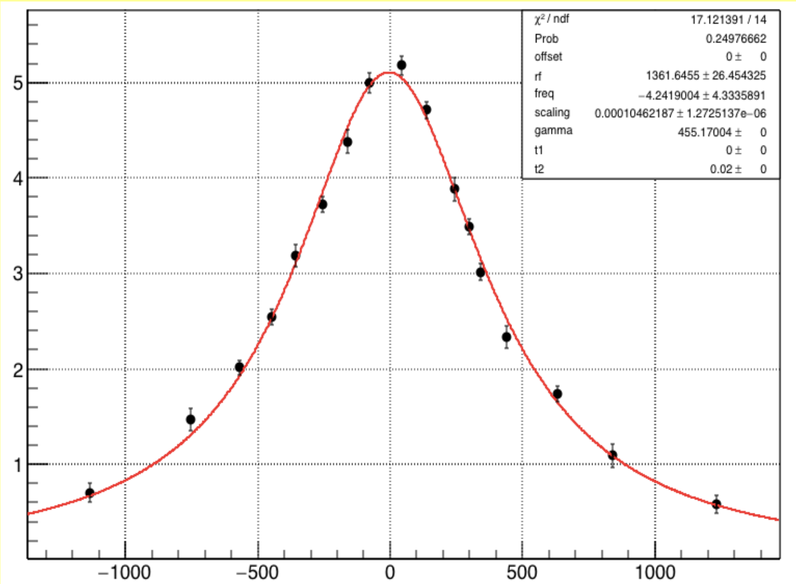
μ_μ/μ_p~20 ppb

Zero field measurement at D Line

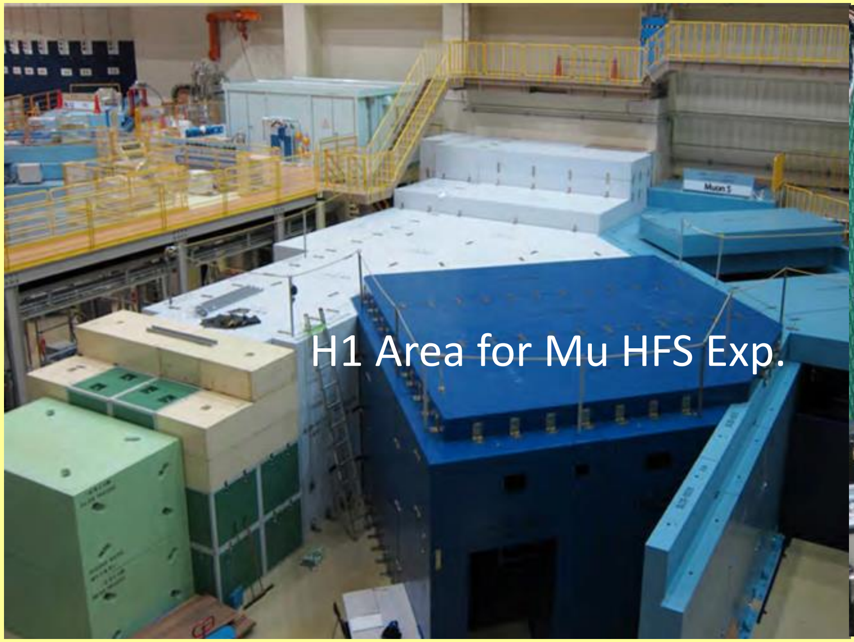
Important milestone for HF measurement

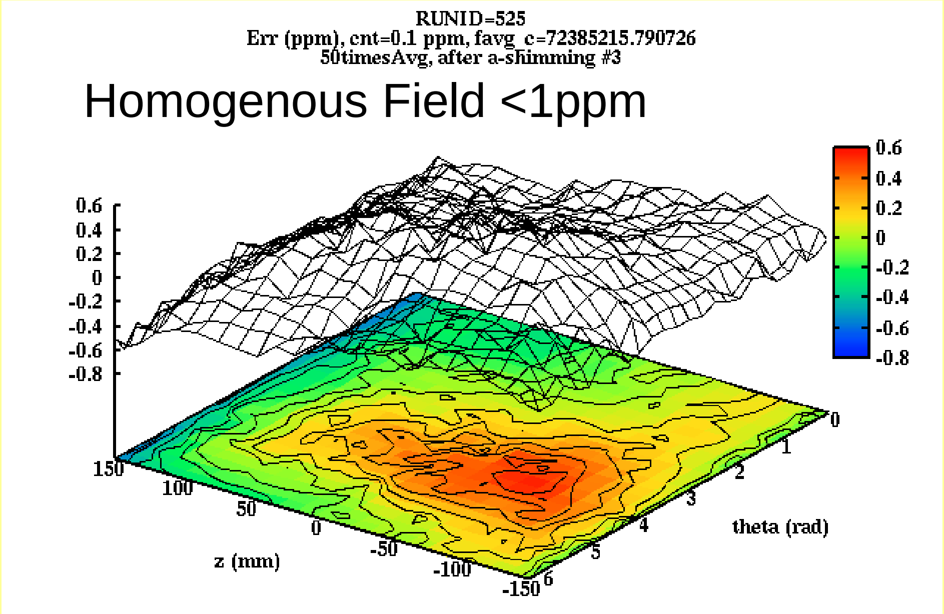




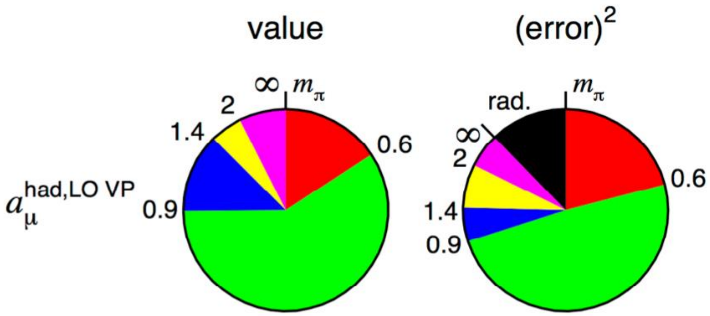


Preparation for HF measurement at H Line





g-2 SM theory



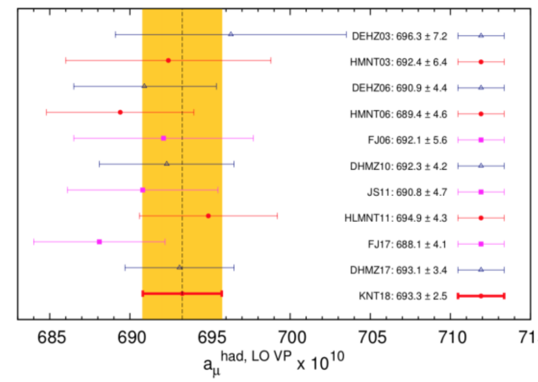
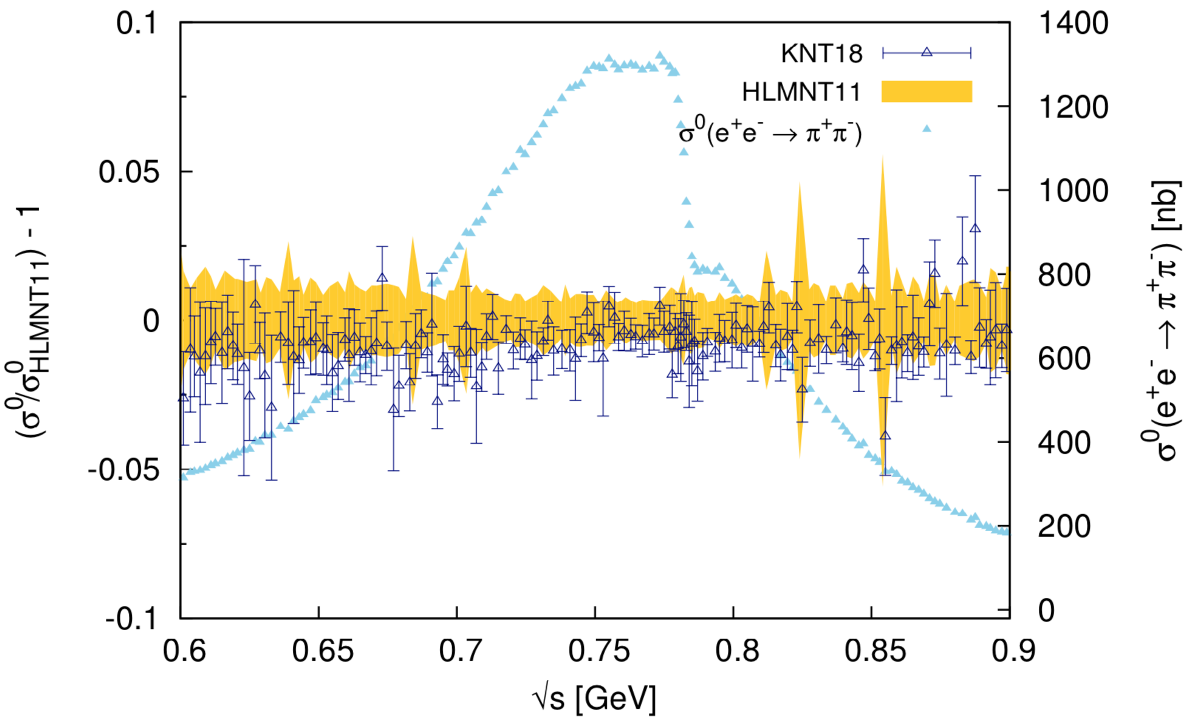


Figure 24: Comparison of recent and previous evaluations of $a_\mu^{\mathrm{had,\,LO\,VP}}$ determined from $e^+e^- \to$ hadrons cross section data. The analyses listed in chronological order are: DEHZ03 [78], HMNT03 [7], DEHZ06 [79], HMNT06 [8], FJ06 [80], DHMZ10 [81], JS11 [82], HLMNT11 [9], FJ17 [83] and DHMZ17 [77]. The prediction from this work is listed as KNT18, which defines the uncertainty band that the other analyses are compared to.



of the g-2 Test:

a_μ(New Physics) ≡ a_μ(Expt) – a_μ(SM)

- $a_\mu(SM) = a_\mu(QED) + a_\mu(Weak) + a_\mu(HVP) + a_\mu\,(Had\ HO) + a_\mu\,(HLbL)$

✓ ✓ ✓

A few remarks here

In E821 ≡ $\mathcal{R}_\mu(\text{E821}) = 0.003\,707\,206\,4(2\,0)$ **[0.54 ppm]**

$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

$\mathcal{R}_\mu$

-.001519270384(12) [8 ppb]

206.768 2843(52) **[25 ppb]**

Measuring ω_a [from BNL *realized* → FNAL *goals*]

- **Systematic error total ω_a budget**: [210 ppb → **70 ppb**]
  - **Coherent betatron oscillations** [70 ppb → **<30 ppb**]
    - **Optimized kicker, Tune choice; Harps**
  - **E and pitch corrections** [50 ppb → **30 ppb**]
    - **In-vacuum Trackers; Precision spin-tracking sim**
  - **Gain stability** [120 ppb → **20 ppb**]
    - **See Calibration effort**
  - **Pileup resolution** [80 ppb → **40 ppb**]
    - **Cherenkov, Fast SiPMs; Fast digitizers & Segmentation**
  - **Lost muons** [90 ppb → **20 ppb**]
    - **Beamline, Collimators, Monitors**

Measuring ω_p [from BNL *realized* → FNAL *goals*]

- **Systematic error total ω_p budget**: [170 ppb → **70 ppb**]

  - **Absolute field** [50 ppb → **35 ppb**]
  - **External fields** [? ppb < **5 ppb**]
  - **Many small items*** [100 ppb < **30 ppb**]
  - **Trolley probe calibrations** [90 ppb → **30 ppb**]
  - **Fixed probe interpretation** [70 ppb → **30 ppb**]
  - **Trolley measurements** [50 ppb → **30 ppb]**
  - **Muon Distribution** [30 ppb → **10 ppb**]

***was already well below statistical errors, so ignored here**

Nucleon Axial Radius and Muonic Hydrogen
Richard J. Hill, Peter Kammel, William J. Marciano, Alberto Sirlin. Aug 28, 2017. 34 pp.
FERMILAB-PUB-17-343-T
e-Print: arXiv:1708.08462 [hep-ph] | PDF

- Nucleon axial radius r_A has surprisingly large uncertainty

$$r_A^2(z\ \text{exp.}) = 0.46 \pm 0.22\ \text{fm}^2 \qquad \nu_\mu d \to \mu^- pp$$

Phys.Rev. D93 113015, (2016)

  - basic nucleon property
  - doubles uncertainty in QE νn cross section prediction (important for DUNE …)

- MuCap can reduce uncertainty on r_A

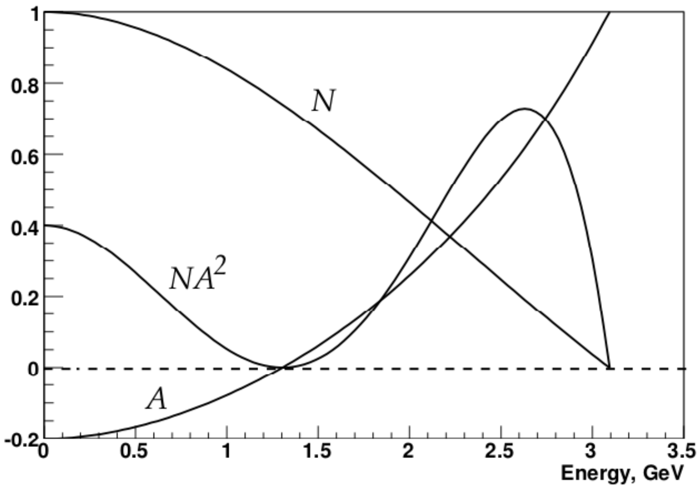
  – use g_P expression from χPT

$$F_P(q_0^2) = \frac{2m_\mu g_{\pi NN} f_\pi}{m_\pi^2 - q_0^2} - \frac{1}{3} g_A m_N r_A^2 + \dots$$

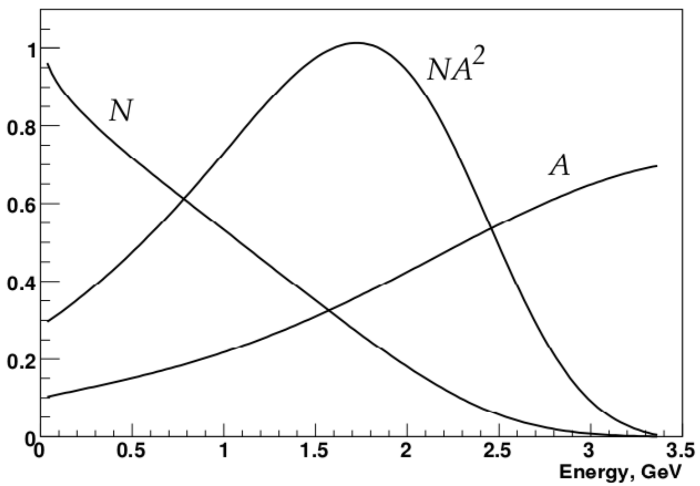
  – determine r_A from μp capture rate
    - from present MuCap result
    - from 3x improved measurement

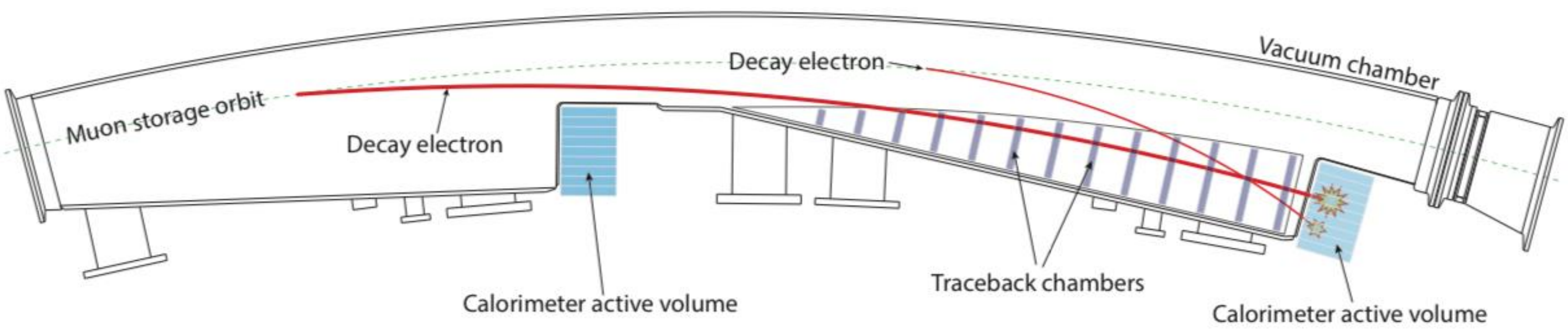
$$r_A^2(\text{MuCap}) = 0.43 \pm 0.24\ \text{fm}^2$$
$$r_A^2(\text{MuCap}^*) = \qquad \pm 0.1\ \text{fm}^2$$

g-2 details



(b) Laboratory Frame



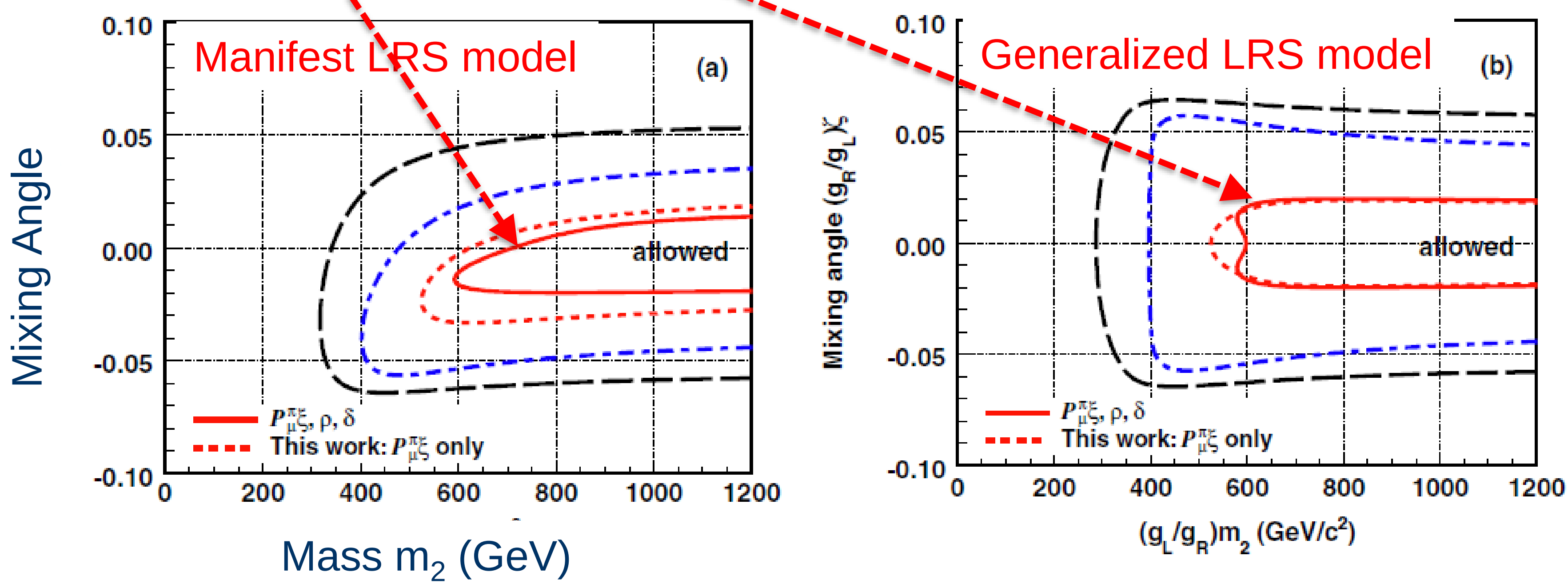


Michel Parameters: TWIST final results

"SM still okay"

SM	
¾	ρ = 0.74977 ± 0.00012 (stat) ± 0.00023 (syst)
¾	δ = 0.75049 ± 0.00021 (stat) ± 0.00027 (syst)
1	$\mathcal{P}_\mu{}^\pi\xi$ = 1.00084 ± 0.00029 (stat) $^{+0.00165}_{-0.00063}$ (syst)

Results mostly constrain right-handed muon terms

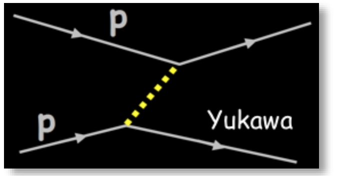


PHYSICAL REVIEW D **84**, 032005 (2011)

Phys. Rev. D 85, 092013 (2012)

Early history

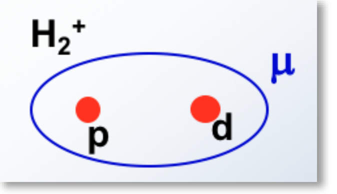
1937 μ discovered in cosmic rays
(Anderson, Neddermeyer)



1947 π □ μν decay discovered, μ is not the Yukawa particle
(Lattes, Occhialini and Powell)

Rabi: "who ordered that?"

1957 μ production & decay violates parity
(Garwin, Lederman, Weinrich)



1957 Muon Catalyzed Fusion observed
(Alvarez group)

Recent

1998-2001 Super-Kamiokande and Sudbury observed ν-oscillations,
neutrinos have mass, lepton flavor violated

2012 Higgs boson discovered at CERN

Muonic 2s-2p measurement

- $a_0(e) \sim 200\, a_0(\mu)$,
  finite size effect increases by

$$\frac{|\Psi_\mu(0)|^2}{|\Psi_e(0)|^2} = \left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$$

Lamb shift in μp [meV]:

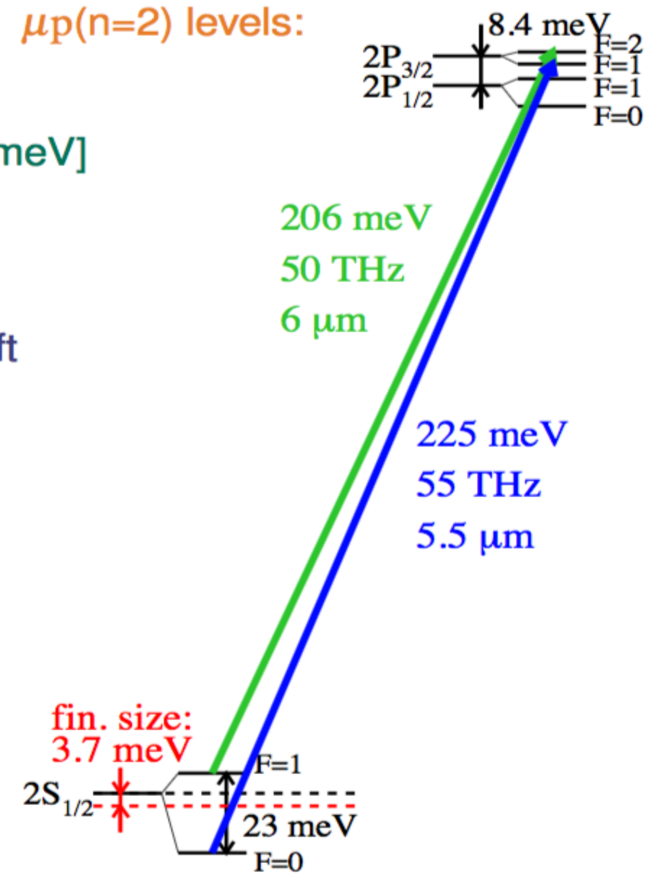
$$\Delta E = 206.0668(25) - 5.2275(10)\, r_p^2 \quad \text{[meV]}$$

Proton size effect is 2% of the μp Lamb shift

Measure to 10^{-5} $\Rightarrow$ r_p to 0.05 %

Experiment:
R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini, RP *et al.*, Science 339, 417 (2013).

Theory summary:
A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

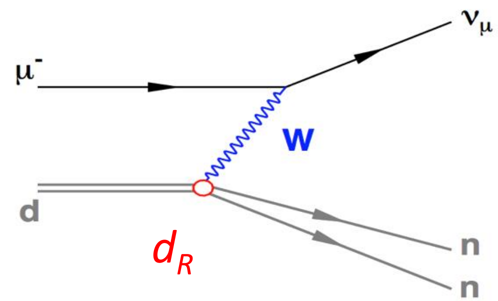


Pohl

Determine Unknown Coupling Constant in μd Capture ?

- Measure rate Λ_d for muon capture of the deuteron to 1.5%

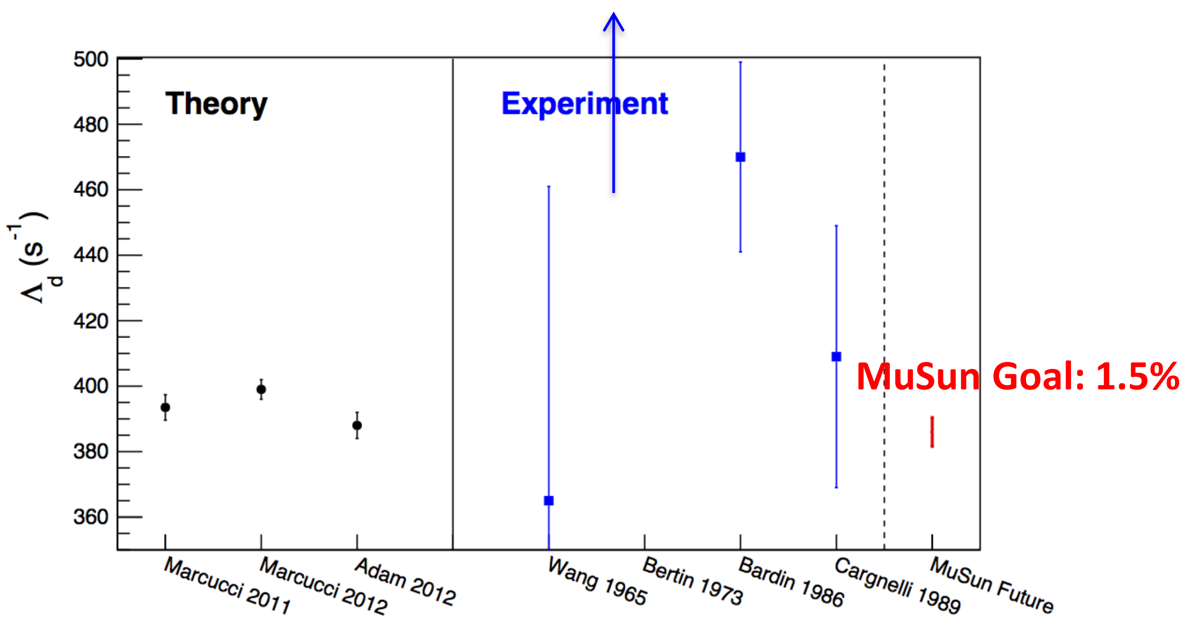
$$\mu^- + d \rightarrow n + n + \nu$$



- Determine unknown LEC d_R
  - reduce uncertainty from 100% to 20% in clean 2N system
  - Calibrate theory for fundamental astrophysics reactions
  - …

- Current status

Many calculations:
- impulse-approximation
- EFT variants



Theoretical calculations fix LEC with tritium β-decay