Muon g-2/EDM at J-PARC

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TRIUMF

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- TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics

Outline

- What g-2/EDM measures
- Current status of Standard Model theory and measurement
- J-PARC g-2/EDM compared with BNL and Fermilab experiments
- Components of J-PARC g-2/EDM
  - muon source and TRIUMF S1249
  - muon acceleration
  - decay detection and frequency measurement

The muon's magnetic dipole moment

- The magnetic dipole moment μ of a particle is determined by its mass m, charge q, spin S and g-factor:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{S}$$

- The spin precession in a magnetic field is:

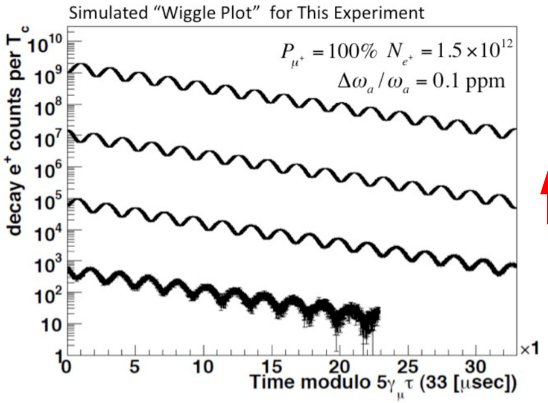
$$\vec{\omega}_s = \left(-\frac{g}{2} - \frac{(1-\gamma)}{\gamma}\right)\frac{q\vec{B}}{m}$$

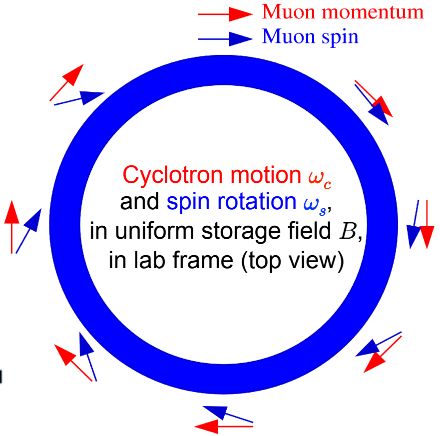
- The cyclotron frequency of rotation is:

$$\vec{\omega}_c = \left(-\frac{1}{\gamma}\right)\frac{q\vec{B}}{m}$$

- **Spin ½ fermions**: for a Dirac particle $g \equiv 2$, but corrections add an anomaly a:

$$\mu = (1+a)\left(\frac{q\hbar}{2m}\right), \quad a \equiv \frac{g-2}{2}$$





- For a **muon** with velocity β perpendicular to a magnetic field B, with an electric field E, there will be cyclotron motion at frequency ω_c while the spin will rotate at frequency ω_s, with difference ω_a:

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

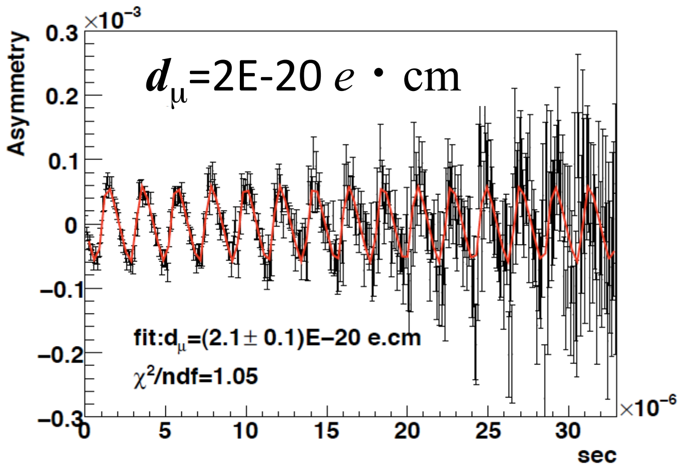
The muon's electric dipole moment

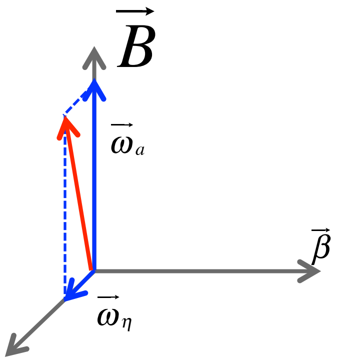
- The electric dipole moment d of is defined similarly in terms of the particle's mass, charge, and spin S, with proportionality η

$$\vec{d} = \eta \left(\frac{q}{2m} \right) \vec{S}$$

- The fermion's SM EDM is zero except for possible CP or T violation at higher orders (4 loops)

$$d_\mu^{SM} \sim 2 \times 10^{-38} \, e \cdot \text{cm}$$





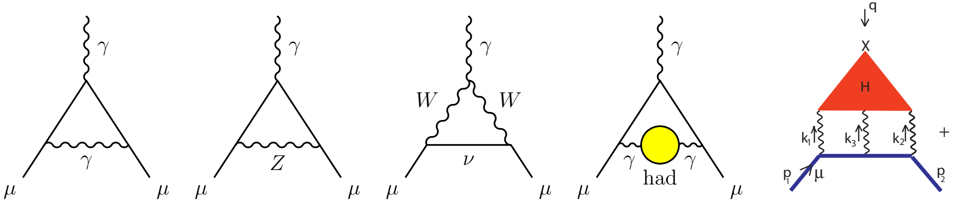
Oscillation component *perpendicular* to the storage plane

- In a non-zero electric field, the anomalous muon frequency is modified with a non-zero EDM at frequency ω_η:

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{q}{m_\mu} \Big[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c}}_{\omega_a} + \underbrace{\frac{\eta_\mu}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)}_{\omega_\eta} \Big]$$

SM calculations of muon g-2

Contribution	Value (10^{-11})
QED (leptons)	116 584 718.95 ± 0.08
Electroweak	153.6 ± 1(quark triangle loops)
HVP (leading order α^2) (hadronic loop corrections)	($e^+e^- \to$ hadrons) 6 923 ± 42(exp) ± 3(QCD) ($\tau \to \nu_\tau$ + hadrons) 7 015 ± 42(exp) ± 19(Ispin) ± 3(QCD)
Hadronic (higher order α^3)	7 ± 26(Hlbl)
Total a_μ, SM	(e^+e^-) 116 591 803 ± 1(EW) ± 42(loH) ± 26(hoH)

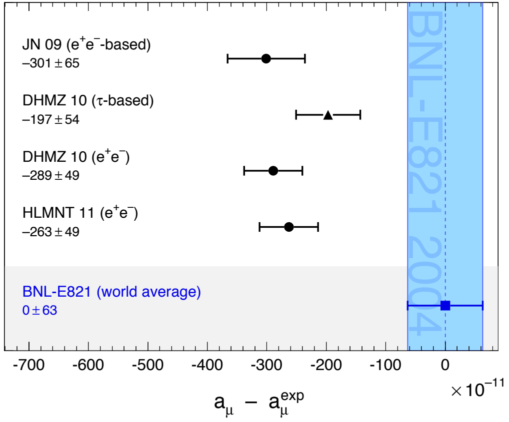


- Theoretical uncertainties are dominated by leading order hadronic vacuum polarization and hadronic light-by-light scattering contributions.
  - A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (updated 2013)
- Recent updates have reduced the uncertainties of hadronic corrections
  - Keshavari et al. (KNT17) at First Workshop of the Muon g − 2 Theory Initiative, June 2017
    indico.fnal.gov/conferenceDisplay.py?confId=13795

BNL E821 and comparison with SM

$$a_\mu^{E821} = 116\,592\,091(54)(33) \times 10^{-11}$$
$$a_\mu^{SM} = 116\,591\,803(1)(42)(26) \times 10^{-11}$$
$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(63)(49) \times 10^{-11}$$

- **a_μ differs from SM predictions by >3σ**



F. Jegerlehner and A. Nyffeler (JN), Phys. Reports 477, 1 (2009)
M. Davier et al. (DHMZ), Eur. Phys. J. C 71, 1515 (2011)
K. Hagiwara et al. (HLMNT), J. Phys. G 38, 085003 (2011)

G.W. Bennett and 75 others (E821), Phys. Rev. D 73, 072003 (2006)

Results | KNT17 update

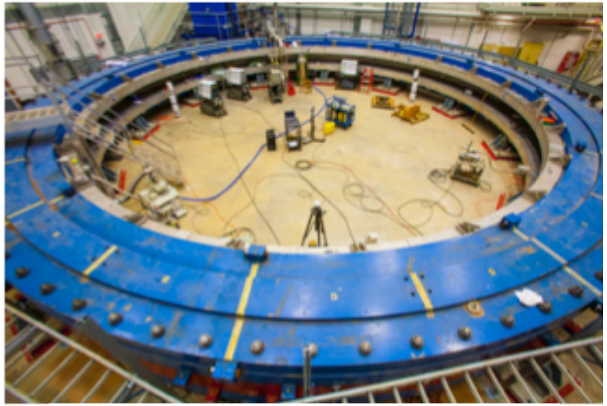
KNT17 a_μ^{SM} update

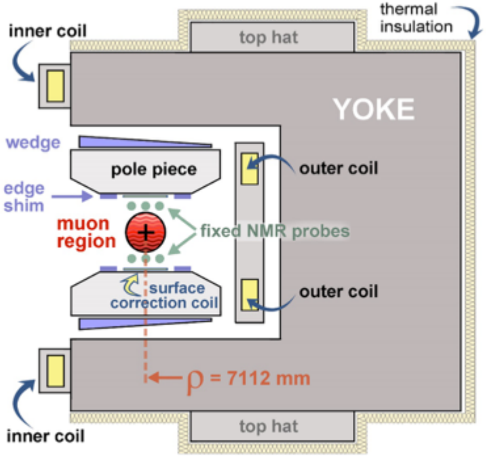
	2011		2017	*to be discussed
QED	11658471.81 (0.02)	⟶	11658471.90 (0.01)	[Phys. Rev. Lett. 109 (2012) 111808]
EW	15.40 (0.20)	⟶	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	⟶	9.80 **(2.60)**	[EPJ Web Conf. 118 (2016) 01016]*
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]*
	HLMNT11		**KNT17**	
LO HVP	694.91 (4.27)	⟶	692.23 **(2.54)** this work*	
NLO HVP	-9.84 (0.07)	⟶	-9.83 (0.04) this work*	
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144] *
Theory total	11659182.80 (4.94)	⟶	11659181.00 (3.62) this work	
Experiment			11659209.10 (6.33) world avg	
Exp - Theory	26.1 (8.0)	⟶	28.1 (7.3) this work	
Δa_μ	3.3σ	⟶	3.9σ this work	

Alex Keshavarzi (UoL) | KNT17: $a_\mu^{had,\,VP}$ update | 3^{rd} June 2017 | 22 / 23

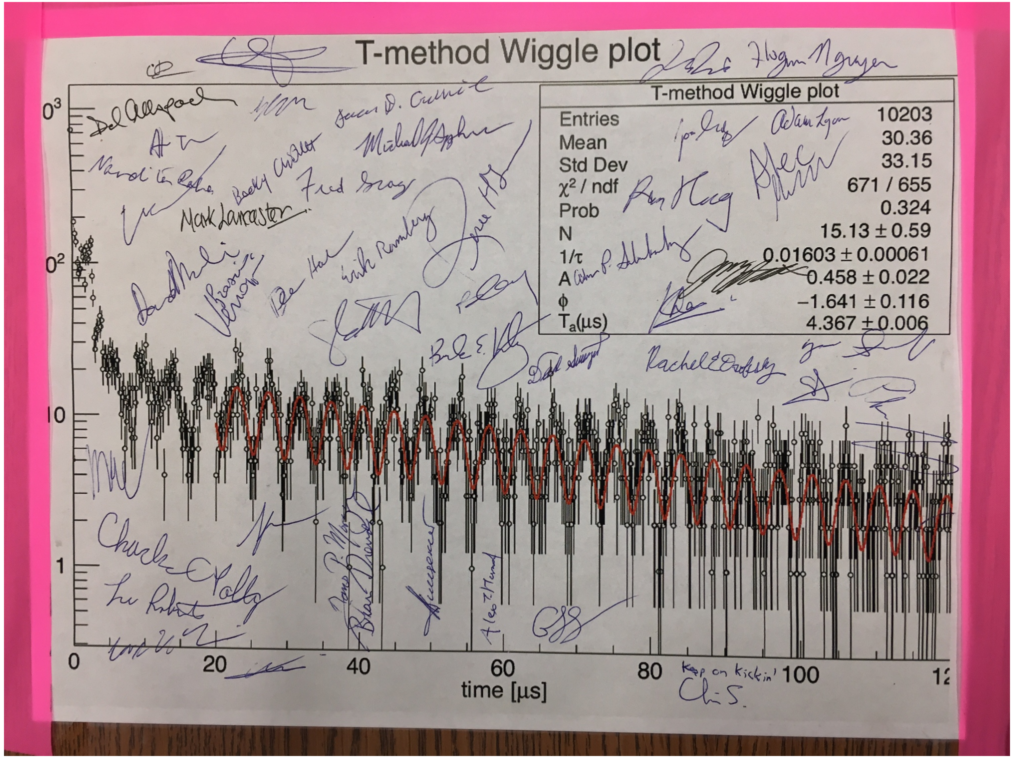
- **revised SM predictions increase the difference to ~3.9σ**
  - Keshavari et al. (KNT17)

Fermilab g-2 (E989) begins



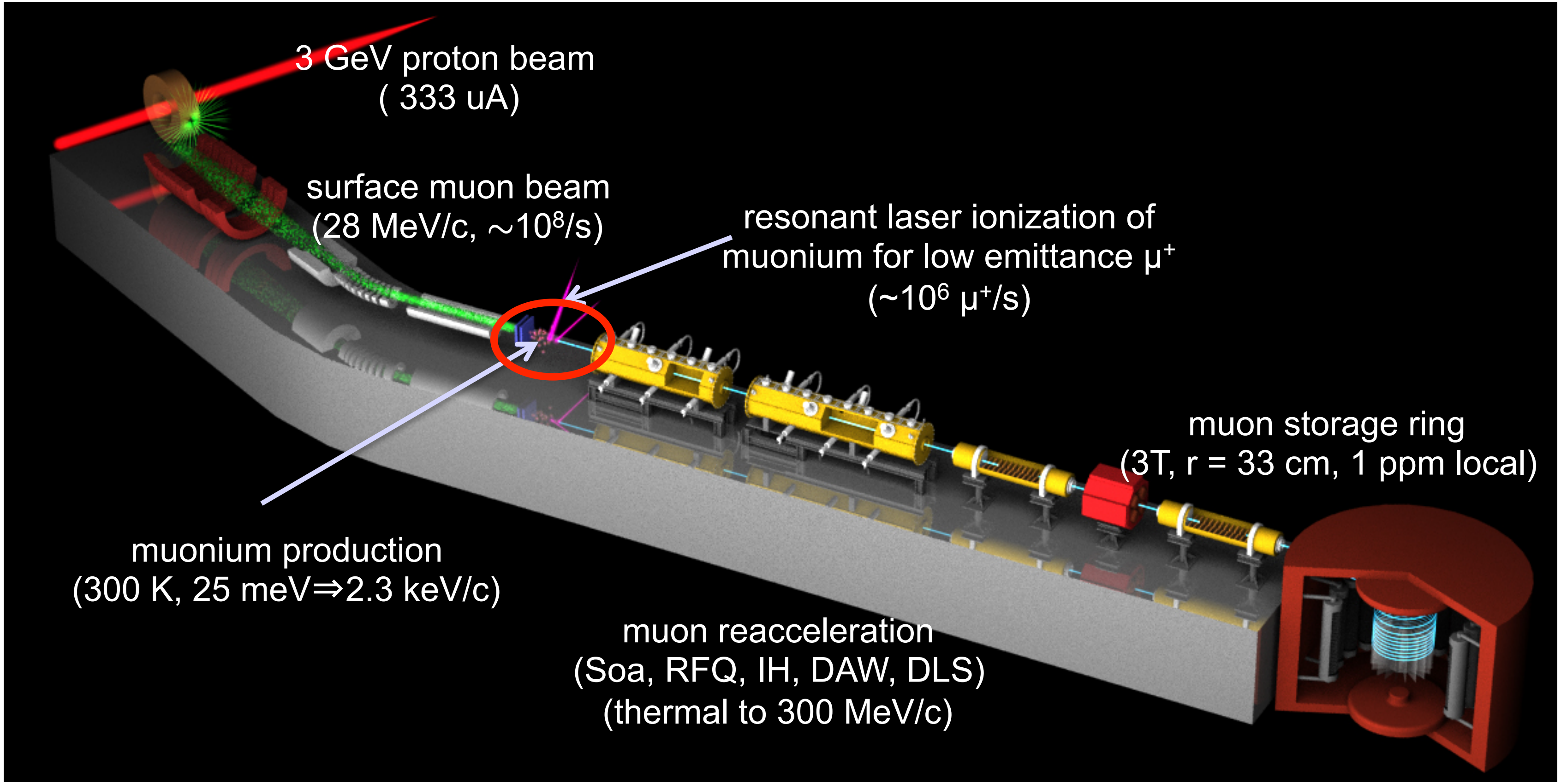


g-2 Magnet in Cross Section



- First observation of ω_a oscillations from Fermilab g-2
- First result at BNL statistics expected Spring 2018

A new and different method at J-PARC



Compare: Fermilab and J-PARC

Fermilab

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

- eliminate effect of E-field via "magic" momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - p_μ = 3.09 GeV/c required
- very uniform B
- electric quadrupole field focusing
- B = 1.45 T
- ρ = 7 m
- periodic calorimeters with some tracker modules

Improves on the BNL method

J-PARC

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

- eliminate effect of E-field via E = 0
- very uniform B in compact region
- weak B field focusing, no E focusing – must use low-emittance "cold" μ beam
  - polarization reduced to 50%
  - allows spin flipping
- choose p_μ = 0.3 GeV/c
- B = 3 T
- ρ = 0.33 m
- uniform tracker detection along stored orbit (EDM sensitivity)

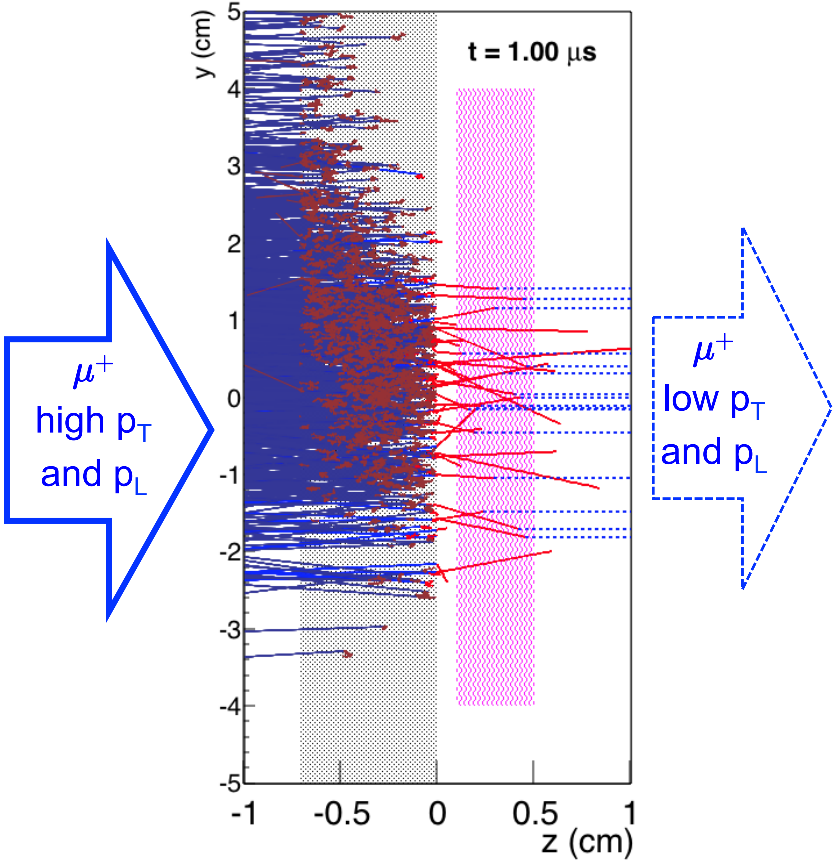
A new method with quite different systematics

Surface muons to "cold" muons

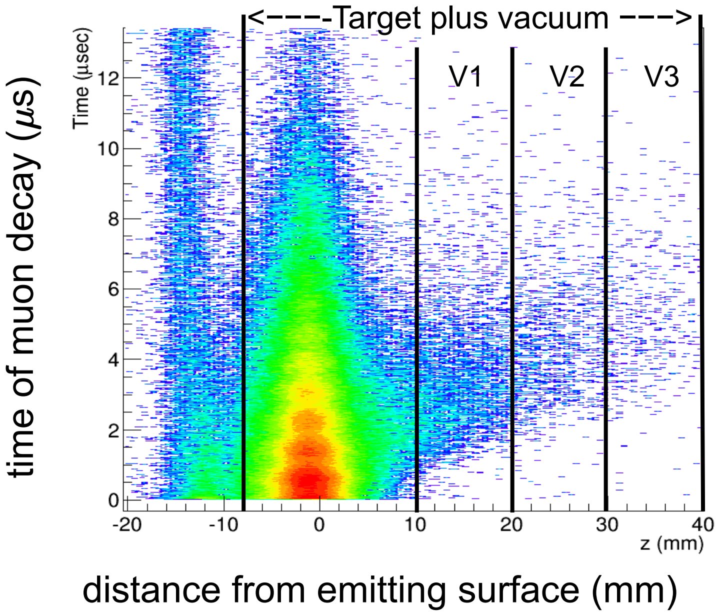
- Thermalization of ~10^8 s^{-1} surface muons

	Surface beam	Thermal beam
E_k, MeV	3.4	0.03×10^{-6}
p, MeV/c	27	2.3×10^{-3}
Δp/p, rms	0.05	0.4
Δp, MeV/c	1.3	1×10^{-3}

- Thermal diffusion of Mu (μ^+e^-) into vacuum
  - decay length $\sim$14 mm
  - TRIUMF experiment S1249
- Ionization
  - 1S$\rightarrow$2P$\rightarrow$unbound (122 nm,355 nm)
- Acceleration
  - E field, RFQ, linear structures
  - adds to p_z but not significantly to Δp



Mu from laser-ablated aerogel (S1249)



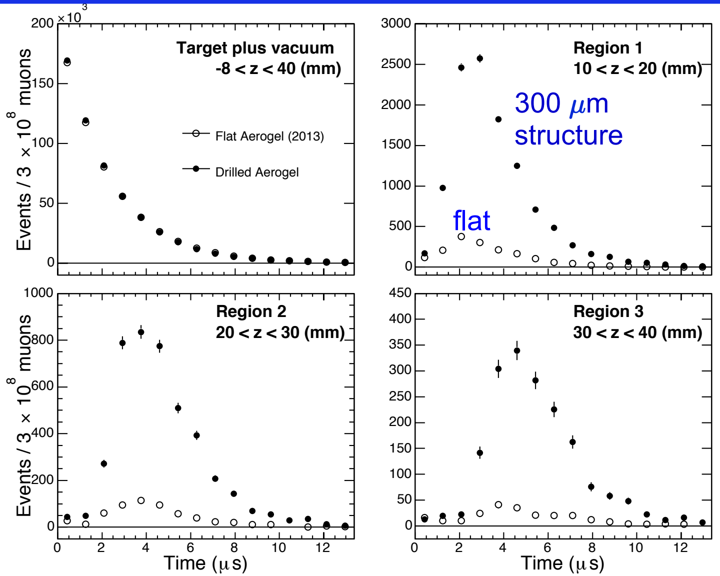


Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [7])	none	2.74 ± 0.11
Laser ablated	500 μm	16.0 ± 0.2
Laser ablated	400 μm	20.9 ± 0.7
Laser ablated	300 μm	30.5 ± 0.3

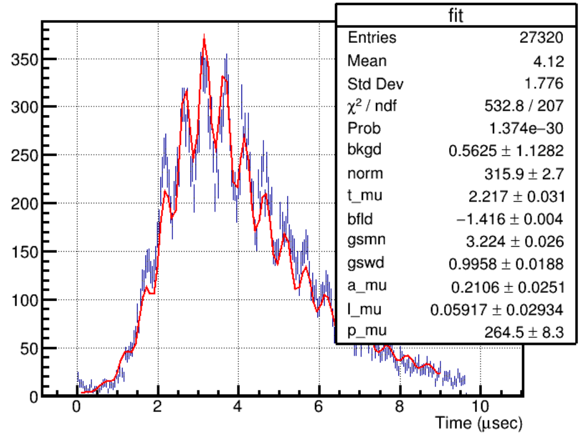
- Used a ***model-independent approach*** to estimate yields
- For 0.3 mm structure, observed 10 times yield previously reported from 2011 data.

G.A. Beer et al., Prog. Theor. Exp. Phys. 2014, 091C01 (2014).

S1249 preliminary results (July 2017)

- Confirmation of muonium polarization in vacuum (oscillations)*
- Confirmation of longer term (~days) stability of targets and Mu emission*
- Study of different ablation patterns and scales
  - hole diameter, pitch, depth
  - channel/groove structure
  - totally ablated surface
- Test of new aerogel material (PMSQ, with methyl additions)

(* resolution of issues identified in recent Focused Review)



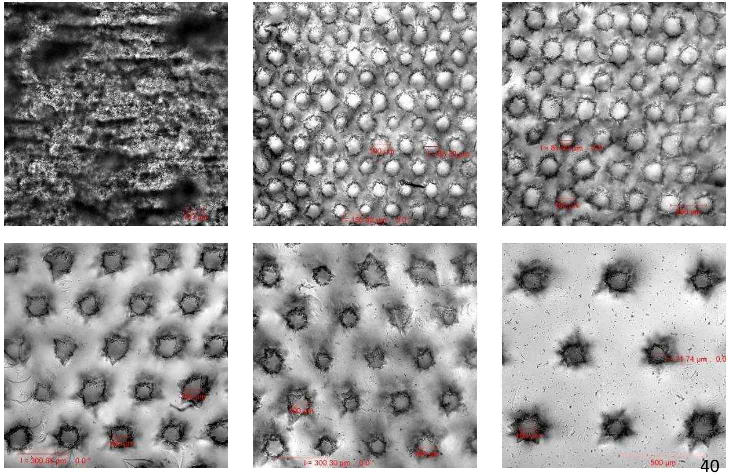


Photo and ablations by S. Kamal, UBC

Laser ionization of Mu

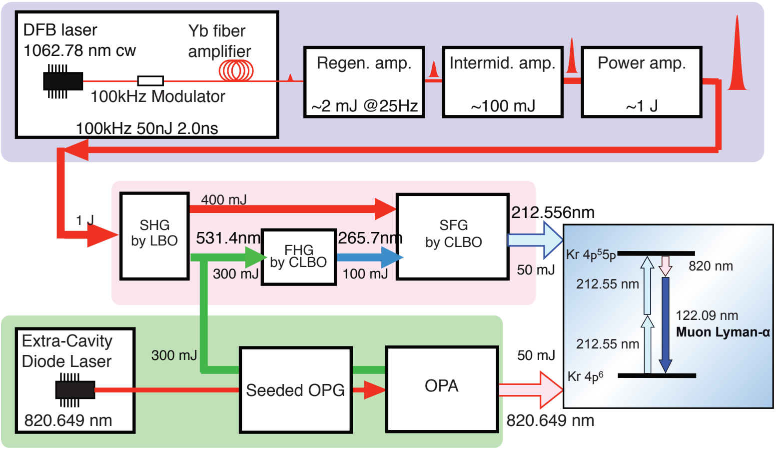
- Two steps
  - Lyman α 1S→2P at 122 nm
  - 2P→unbound at 355 nm
- Lyman α
  - two-photon resonance four-wave mixing in Kr
  - pump with 212.55 nm
  - generate 122 nm via difference mixing with 820 nm
  - goal is 100 μJ in 2 ns pulse with 80 GHz width at 25 Hz

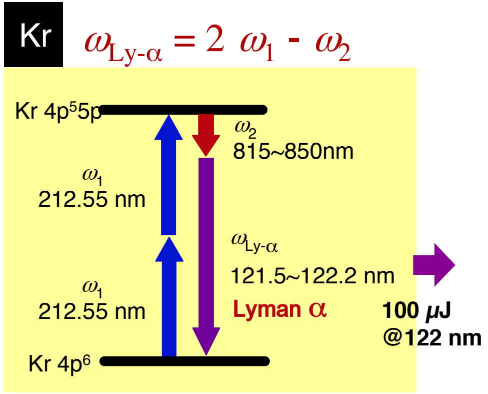
122 nm, μJ

355 nm, mJ

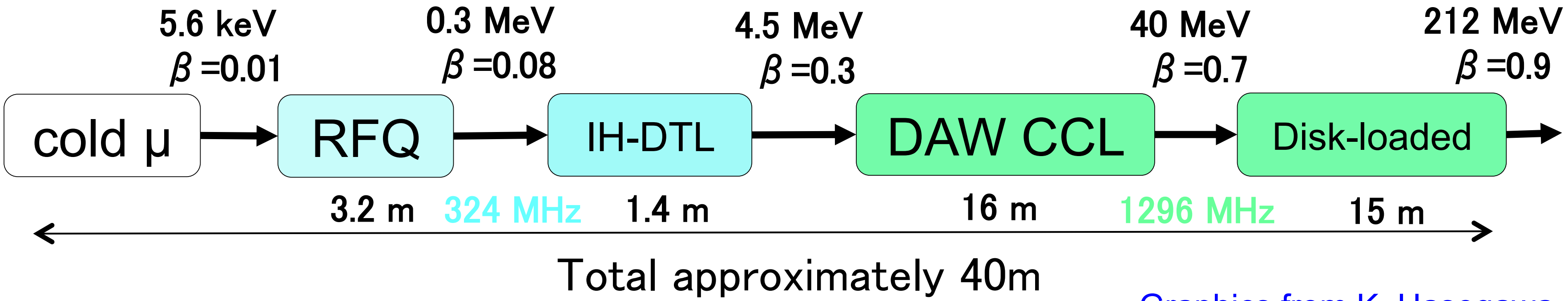
	20	40	60	80	100	120
50	0.097	0.151	0187	0.210	0.226	0.238
100	0.171	0.268	0.327	0.366	0.393	0.412
150	0.228	0.356	0.433	0.482	0.516	0.540
200	0.273	0.424	0.514	0.570	0.608	0.635
250	0.310	0.479	0.577	0.639	0.679	0.708
300	0.339	0.521	0.627	0.691	0.733	0.762
350	0.363	0.556	0.666	0.733	0.775	0.804
400	0.383	0.585	0.698	0.766	0.809	0.857

Calculated ionization efficiencies (2 cm^2 area)





Acceleration of thermal muons

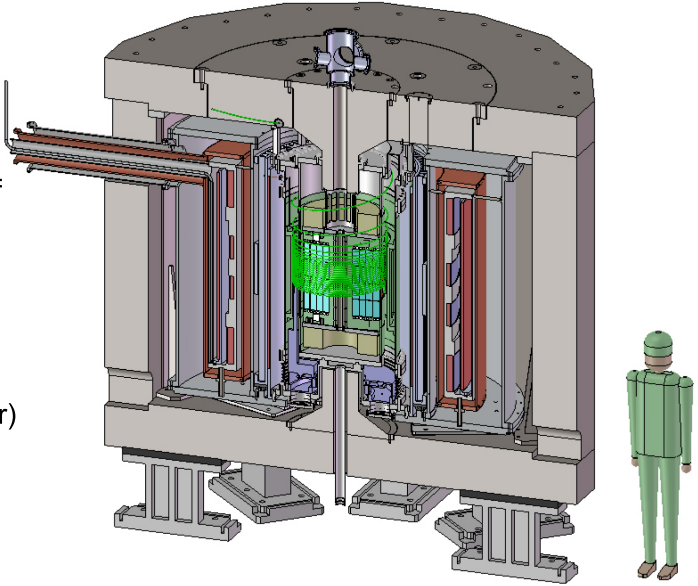


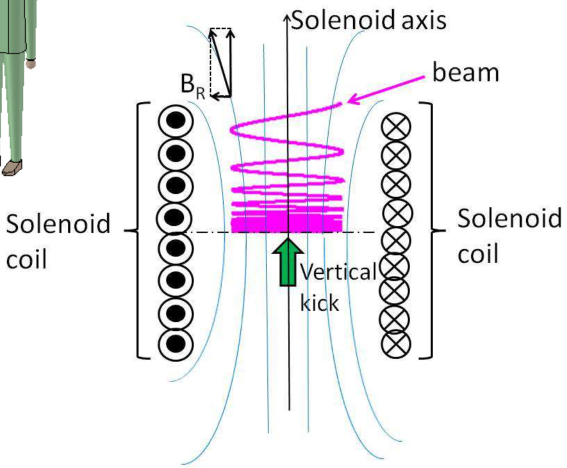
Graphics from K. Hasegawa, KEK

- Requirements
  - fast acceleration to reduce decay losses
    - (τ_μ = 2.2 μs at rest)
  - control/reduce emittance growth to enable injection and capture by storage ring

Injection and storage of muons

- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical B = 3 Tesla, <1ppm locally
  - storage region r = 33.3±1.5 cm, h = ±5 cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - $n = 1.5 \times 10^{-4}$, $rB_r(z) = -n\, zB_z(r)$ in storage region
- Spiral injection
  - transfer line from end of linac with downward deflection
  - hole in upper yoke for beam entrance
    - permits entry, shields beam from field
  - pulsed radial field on injection
    - reduces vertical momentum to match a trapped orbit

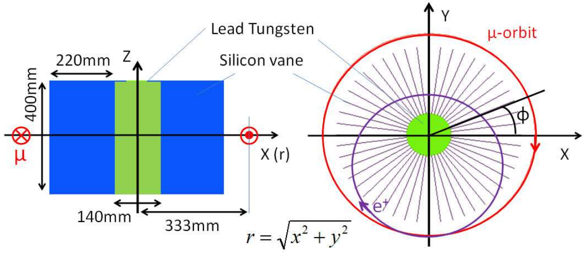




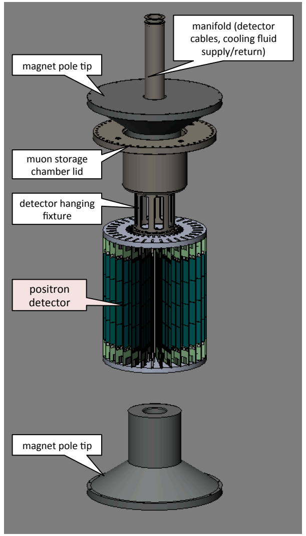
Decay positron tracking detector

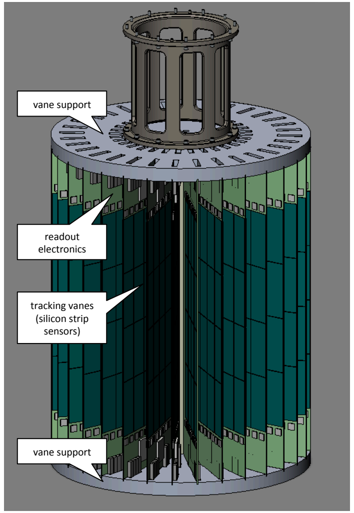
- Detect e^+ at higher range of energies (200−290 MeV/c)
  - typically one turn of track hits
- Core of lead-tungsten to absorb multiple turns

Item	Specifications
Fiducial volume	240mm (radial) x 400 mm (axial)
Number of vane	48
Sensor technology	Single-sided Silicon strip sensor (p-on-n)
Strip	axial-strip : 100mm pitch, 72mm long , 1024 ch radial-strip: 188mm pitch, 98mm long, 384 ch
Sensor dimension	74 mm x 98 mm x 0.32mm
Number of sensor	1152 (12 sensors per vane)
Number of channel	811,008ch
Time measurement	Period : 33ms, Sampling time : 5ns



(side view) (top view)





Status of J-PARC g-2/EDM

- January 2012 – Stage 1 approval recommended by PAC, granted by IPNS Director
- May 2105 – Technical Design Report submitted to PAC
- October 2016 – revised TDR submitted
- November 2016 – Focused Review on technical design

- Review recommendations:
  - **Develop a “fast track” plan** to achieve the Phase-1 result in a timely and cost-effective manner
    - ~0.5 ppm, equivalent to BNL
    - Phase-2 goal is ~0.1 ppm
  - **This committee finds that Phase-1 of the E34 experiment is technically ready for Stage-2 approval.**
    - **subject to resolution of the remaining technical issues...**

Summary

- J-PARC muon g-2/EDM can confirm the muon g-2 result at the precision of the BNL experiment (Phase 1) and possibly the Fermilab experiment (Phase 2)
  - systematic limitations are expected to be quite different
- The resource-limited schedule requires four years prior to data taking
  - unlike the Fermilab group who has done the experiment before, we would have to learn the limitations and how to control systematics
  - currently considering fast-track plan to first results
- The collaboration has over 90 registered members, with opportunities for participation in the many technologies required to make the experiment a success
  - for more information, see http://g-2.kek.jp

Thank you
Merci

Recipe for precision

- B measured with an array of NMR magnetometers
  - calibrated with respect to an absolute spherical water sample probe measuring ω_p
  - same calibration probe used in Los Alamos muonium microwave experiment measuring $\lambda = \omega_L/\omega_p$, the muon to proton magnetic moment ratio, from muonium HFS

$$\omega_L = -g_\mu \frac{qB}{2m_\mu} \quad \text{(non-relativistic } \omega_s\text{)}$$

$$\lambda = \omega_L/\omega_p = 3.183345107(84) \quad \text{(0.026 ppm, 2010 CODATA)}$$

  - other probes periodically moved by trolley through the vacuum system to map the muon beam field environment, to measure a *spatial average* ω_p^{avg}

- Dividing ω_a by ω_p^{avg} produces a_μ in terms of *ratios* of frequencies

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a} = \frac{(\omega_a/\omega_p^{\text{avg}})}{\lambda - (\omega_a/\omega_p^{\text{avg}})}$$

- Using ω_L from an independent experiment, a_μ depends on two frequencies, ω_a from muon decay time spectrum and ω_p from magnetic field measurements.

Muons produced to muons stored

Table 13.1: *Efficiency and beam intensity*

Quantity	Reference	Efficiency	Cumulative	Intensity (Hz)
Muon intensity at production target	[2]			1.99E+09
H-line transmission	[2]	1.62E-01	1.62E-01	3.22E+08
Mu emission	[3]	3.82E-03	6.17E-04	1.23E+06
Laser ionization	[4]	7.30E-01	4.50E-04	8.97E+05
Metal mesh	[5]	7.76E-01	3.49E-04	6.96E+05
Init.Acc.trans.+decay	[5]	7.18E-01	2.51E-04	5.00E+05
RFQ transmission	[6]	9.45E-01	2.37E-04	4.72E+05
RFQ decay	[6]	8.13E-01	1.93E-04	3.84E+05
IH transmission	design goal	1.00E+00	1.93E-04	3.84E+05
IH decay	[7]	9.84E-01	1.90E-04	3.78E+05
DAW transmission	design goal	1.00E+00	1.90E-04	3.78E+05
DAW decay	[8]	9.94E-01	1.88E-04	3.76E+05
High beta transmission	design goal	9.80E-01	1.85E-04	3.68E+05
High beta decay	[9]	9.88E-01	1.83E-04	3.64E+05
Injection transmission	design goal	1.00E+00	1.83E-04	3.64E+05
Injection decay	[10]	9.90E-01	1.81E-04	3.60E+05
Detector start time	[10]	9.27E-01	1.67E-04	3.34E+05
Muon at storage				3.34E+05

J-PARC g–2 error goals (work in progress)

Statistical uncertainties

- Statistical uncertainty estimates
  - $\Delta\omega_a/\omega_a$ = 0.35 ppm (0.163/$PN^{1/2}$)
    - BNL E821 σ_{stat} = 0.46 ppm
  - Δd_μ = 1.2×10^{-21} $e \cdot$ cm sensitivity
    - BNL E821 (-0.1±0.9)×10^{-19} $e \cdot$ cm
    - d_e < 0.87×10^{-28} $e \cdot$ cm
- Running time
  - measurement only: 2×10^7 s
- Muon rate from H-line
  - 1MW, SiC target: 3.32×10^8 s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization
  - 2.25×10^{-3} (stage 2 goal is 0.01)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, and kick
  - 0.92
- Stored muons
  - 3.58×10^5 s^{-1}

Systematics

- Estimations still in progress
  - simulations
  - need experience with prototypes and first stages
  - need running experience to make assessments like E989
- ω_p (B measurement)
  - + smaller stored volume, higher local precision that E821
- ω_a (decay time measurement)
  - + all tracking detectors
  - – high rate differences between early and late decay times
  - + polarization flip eliminates lowest-order rate dependences

Fermilab E989 and J-PARC E34

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.5×10^{11}	8.1×10^{11}

Gorringe and Hertzog,
Prog. Part. Nucl. Phys. 84, 73 (2015)
(arXiv:1506.01465)