Muon g–2/EDM at J-PARC

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TRIUMF
on behalf of the J-PARC g–2/EDM Collaboration
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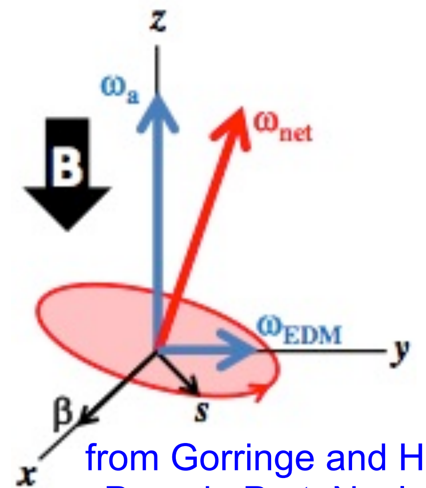
The muon's static dipole moments

- The magnetic and electric dipole moments μ and d of are defined in terms of the particle's mass, charge, and spin S, with proportionalities g and η:

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S} \qquad \vec{d} = \eta\left(\frac{e}{2m}\right)\vec{S}$$

- For a Dirac particle $g \equiv 2$, but radiative corrections add an anomaly a:

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



from Gorringe and Hertzog, Prog. in Part. Nucl. Phys. (in press)

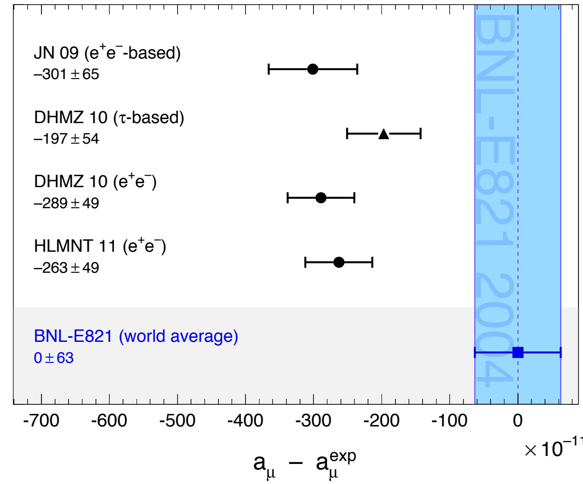
- For a **muon** with velocity β perpendicular to a magnetic field B and electric field E, there will be cyclotron motion at frequency ω_c while the spin will rotate at frequency ω_s, with *difference* ω_a, added to EDM rotation at frequency ω_η:

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

Results of BNL E821

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

A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (September 2014)

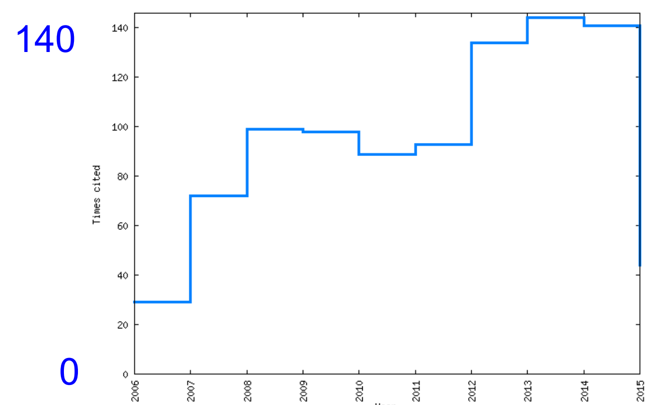


F. Jegerlehner and A. Nyffeler (JN), Phys. Reports 477, 1 (2009)
M. Davier et al. (DHMZ), Eur. Phys. J. C 71, 1515 (2011)
K. Hagiwara et al. (HLMNT), J. Phys. G 38, 085003 (2011)

G.W. Bennett et al. (E821), Phys. Rev. D 73, 072003 (2006) (corrected)

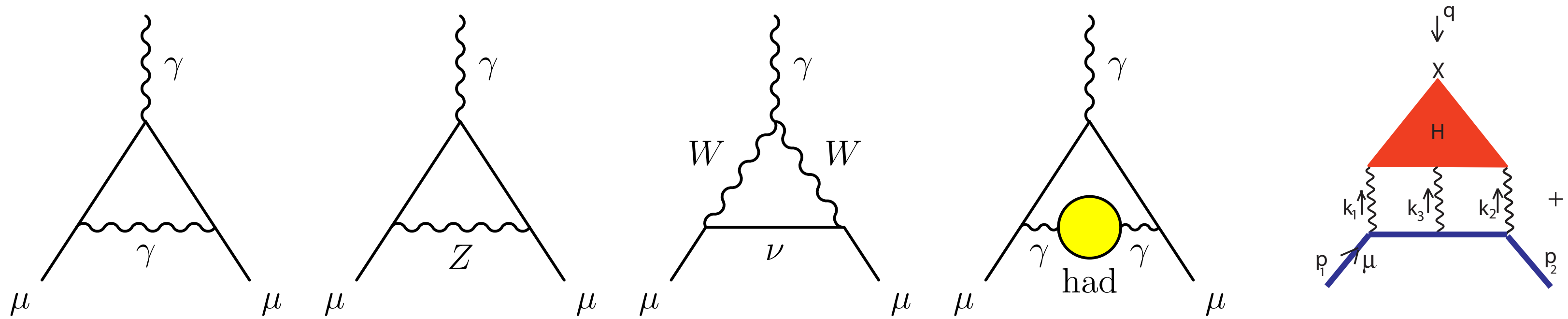
- ▶ a_μ **differs from SM predictions by $\sim$3.6σ**

- ▶ Motivation for improvements in the SM prediction, and better experiments
  - ▶ FNAL E989
  - ▶ J-PARC E34



INSPIRE citations/yr, 2006-2015

Anomalous moment a_μ in SM



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 (September 2014)

Compare: Fermilab and J-PARC

Fermilab (similar to BNL)

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

- 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

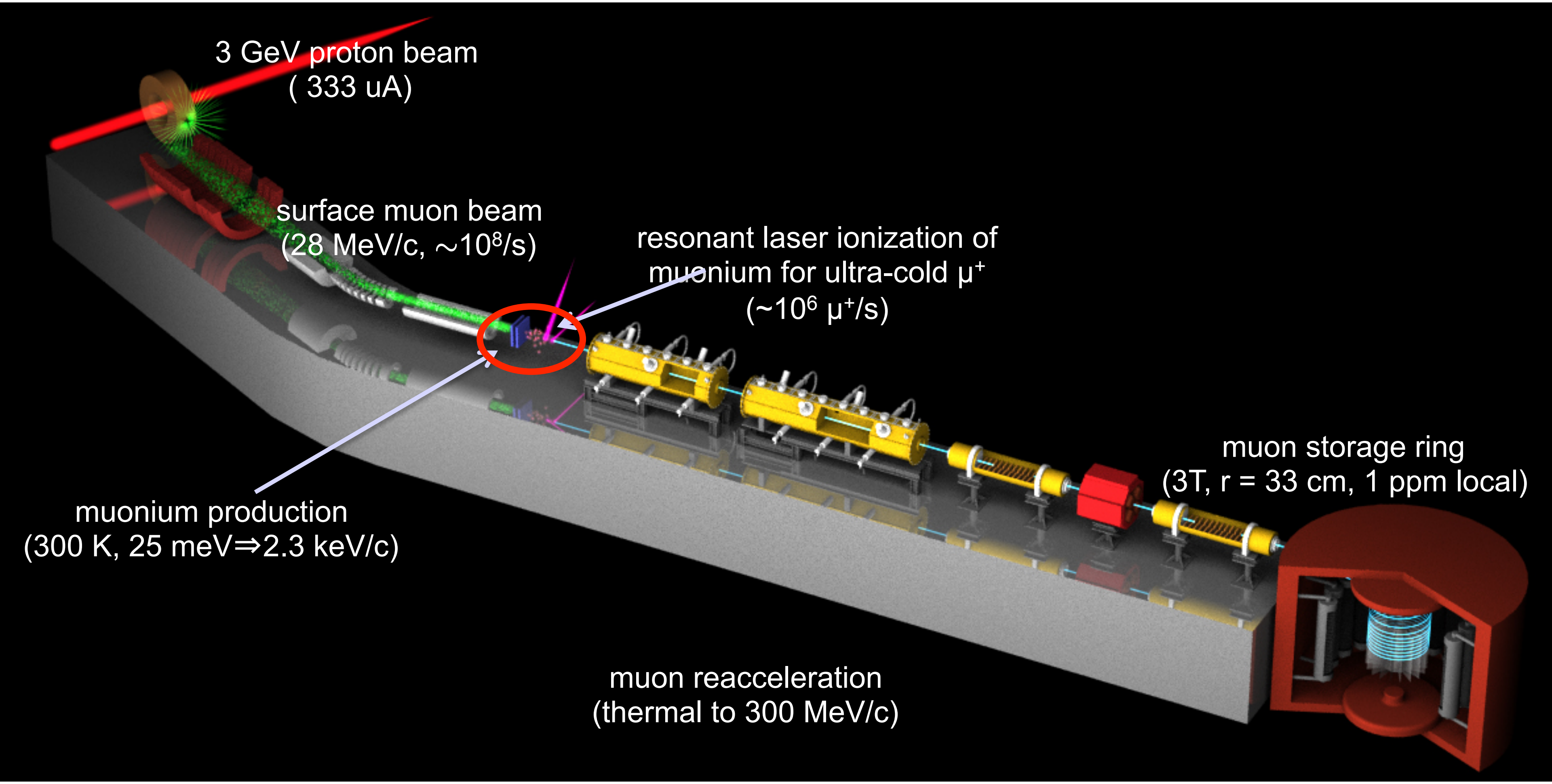
J-PARC

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

- eliminate effect of E-field via E = 0
- very uniform B in compact region
- weak B field focusing, no E focusing – must use "ultra-cold" 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)

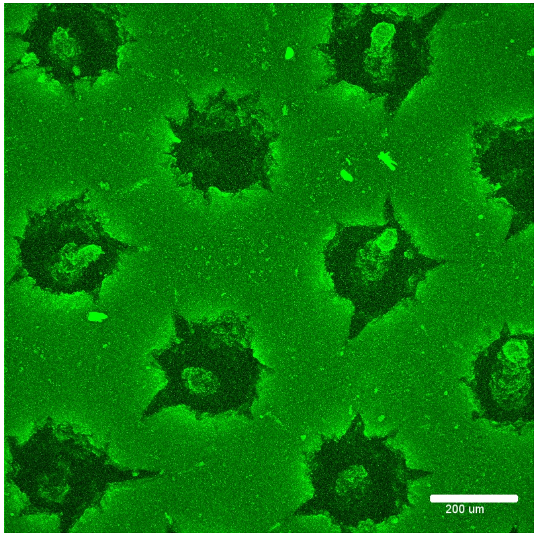
Both experiments follow time dependence of muon polarization by detecting the asymmetric PV weak decay $\mu \rightarrow e\nu\bar{\nu}$.

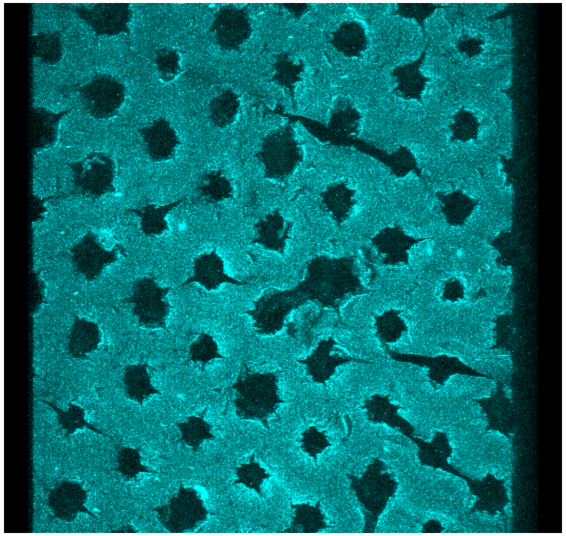
J-PARC g–2 schematic

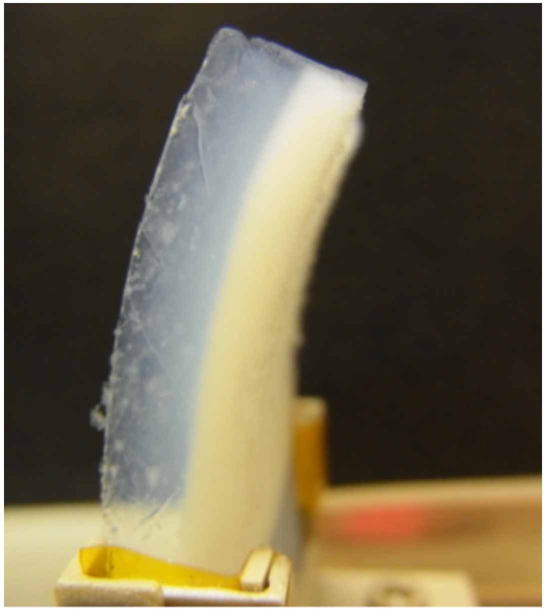


Structured aerogel surface

- Muonium is emitted into vacuum from silica nanostructures (aerogels, powders)
  - aerogels developed for J-PARC g–2 ultra-cold muon source
  - laser ablation of holes in aerogel provided $\times$10 increase in yield
  - muonium emission measurements done at TRIUMF







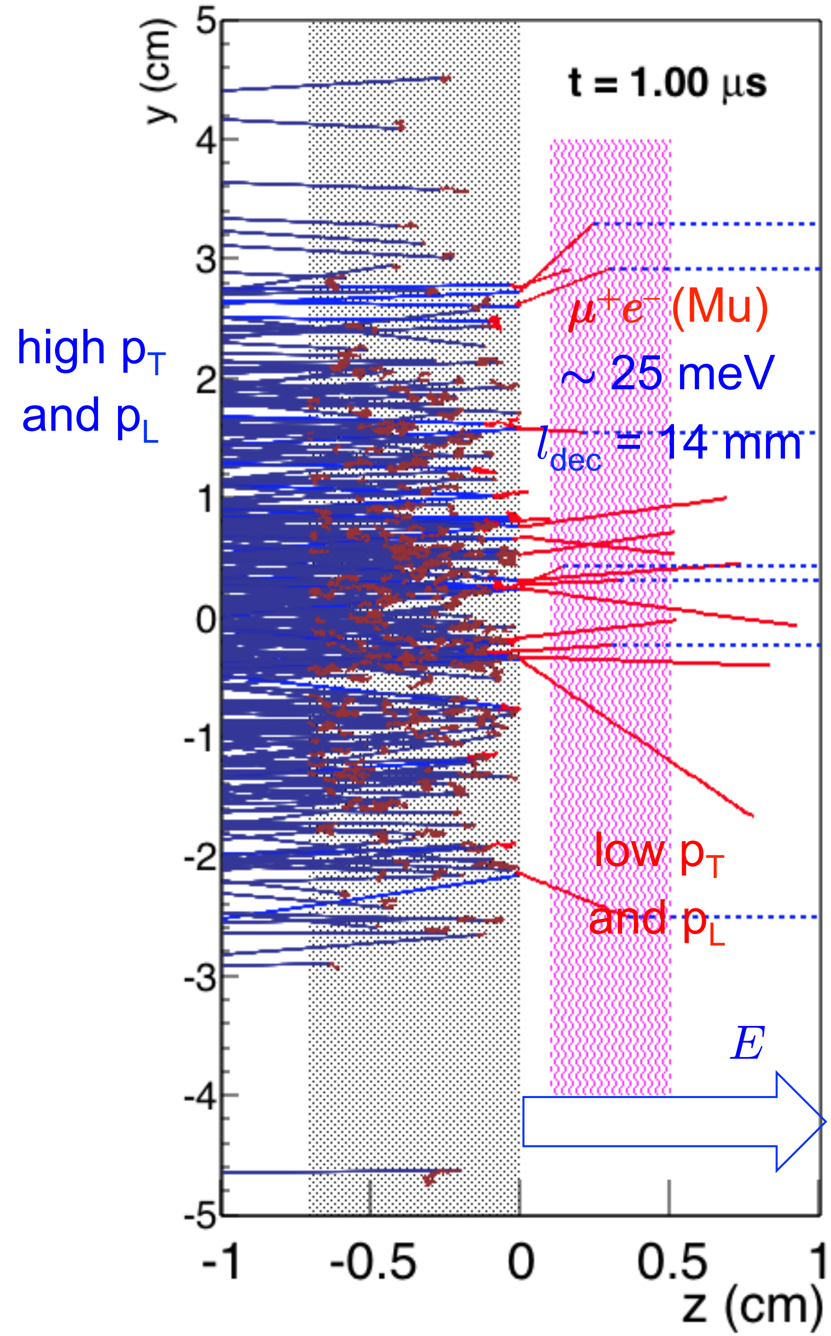
Confocal microscope images of laser-ablated surfaces of aerogel.
Left: 30 mg cm^{-3} aerogel, 500 μm spacing.
Right: 30 mg cm^{-3} aerogel, 300 μm spacing.

Images by G.A. Beer and
UVic Advanced Microscopy Facility

Photo of laser-ablated aerogel used in S1249. Curvature is due to the ablation process and has been controlled in subsequent ablations.

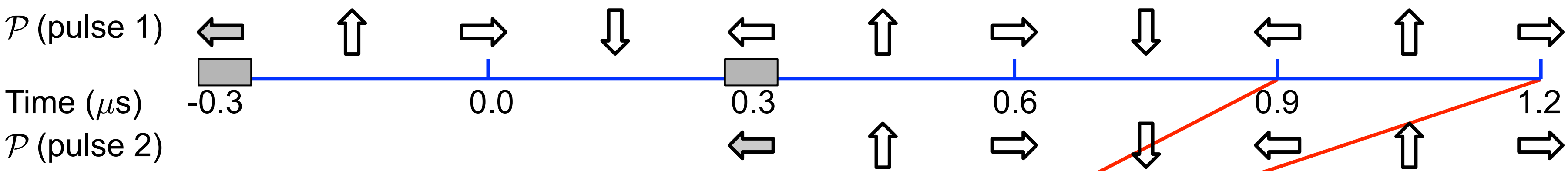
Surface muons to ultra-cold muons

- Surface μ^+ from π^+ decay at rest
  - E_k = 3.4 MeV, p = 27 MeV/c
  - Δp/p = 0.05 rms, Δp =1.3 MeV/c
  - $\Delta p_x/p$ = 0.04, $\Delta p_y/p$ = 0.08
- Thermalization as Mu ($\mu^+ e^-$)
  - E_k = 0.025 eV, p = 2.3 keV/c
  - Δp/p = 0.42 rms, Δp = 1 keV/c
  - "ultra-cold" compared to surface μ^+
- Thermal diffusion of Mu into vacuum
  - μ^+ remains ultra-cold
- Ionization
  - 1S→2P→unbound (122 nm,355 nm)
- Acceleration
  - E field, RFQ, linear structures
  - to E_k = 212 MeV, p = 300 MeV/c
  - adds to p_z but not significantly to Δp



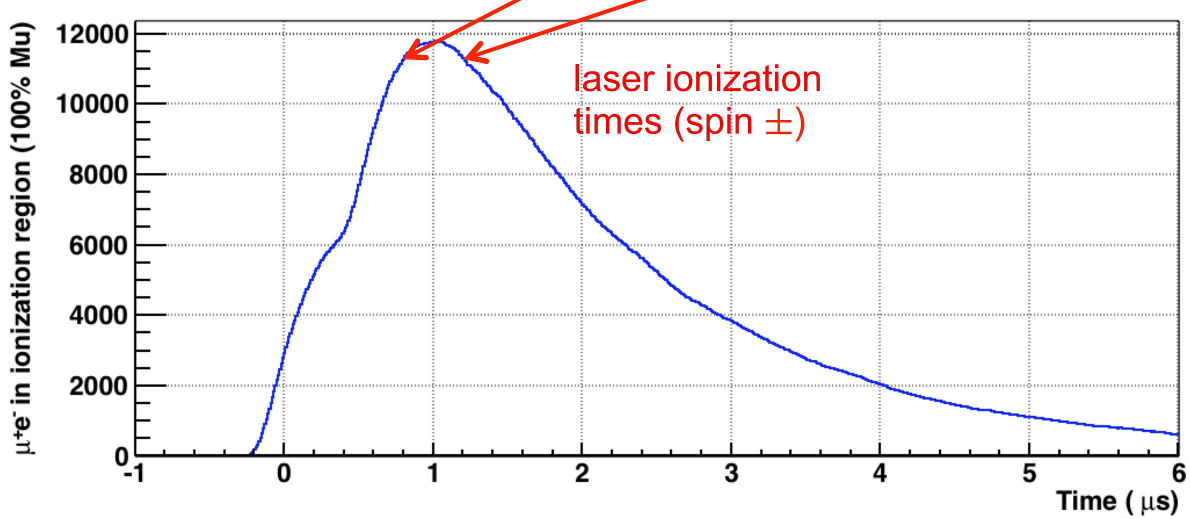
Spin manipulation via μ^+e^- precession

- Spin reversal is an important tool in polarization experiments
- Muonium polarization in aerogel target or vacuum will rotate in transverse field
  - 0.14 MHz/mT ➔ 2π rotation in 0.6 μs at 0.119 mT
  - muon beam consists of 2 pulses separated by 0.6 μs (at 25 Hz repetition)
    - polarizations are added for fields at multiples of 0.119 mT
- Selecting ionization time selects direction of polarization



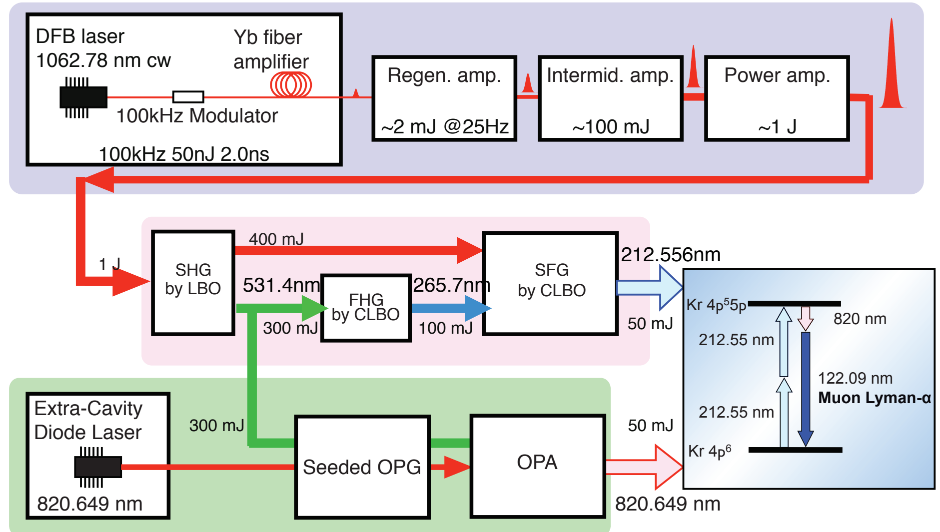
$\vec{B}\odot$

Simulation of Mu time distribution in vacuum for J-PARC beam.



Laser ionization of Mu

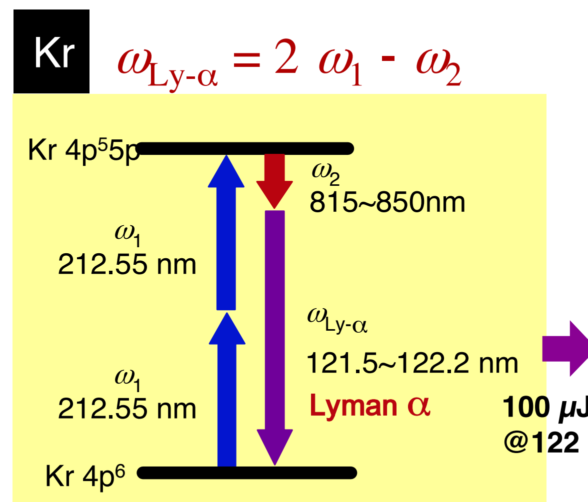
- Two steps
  - Lyman α 1S→2P at 122 nm
  - 2P→unbound at 366 nm
- Lyman α
  - two-photon resonance four-wave mixing in Kr
  - pump with 212.55 nm
  - generate 122 nm via difference mixing with 820 nm
  - goal is 100 μJ in 2 ns pulse with 80 GHz width at 25 Hz



122 nm, μJ

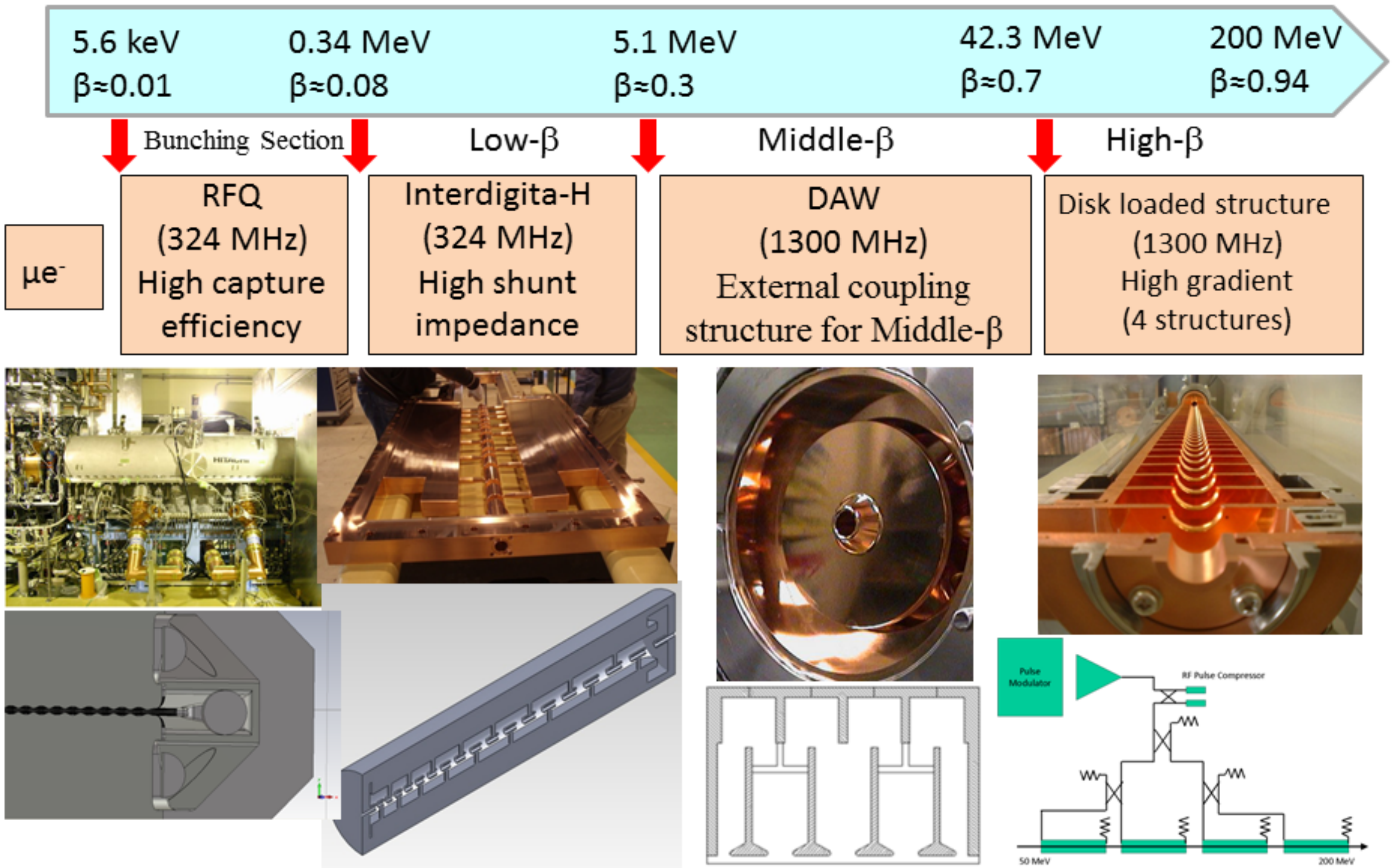
355 nm, mJ	20	40	60	80	100	120
50	0.097	0.151	0187	0.210	0.226	0.238
100	0.171	0.268	0.327	0.366	0.393	0.412
150	0.228	0.356	0.433	0.482	0.516	0.540
200	0.273	0.424	0.514	0.570	0.608	0.635
250	0.310	0.479	0.577	0.639	0.679	0.708
300	0.339	0.521	0.627	0.691	0.733	0.762
350	0.363	0.556	0.666	0.733	0.775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

Calculated ionization efficiencies (2 cm² area)



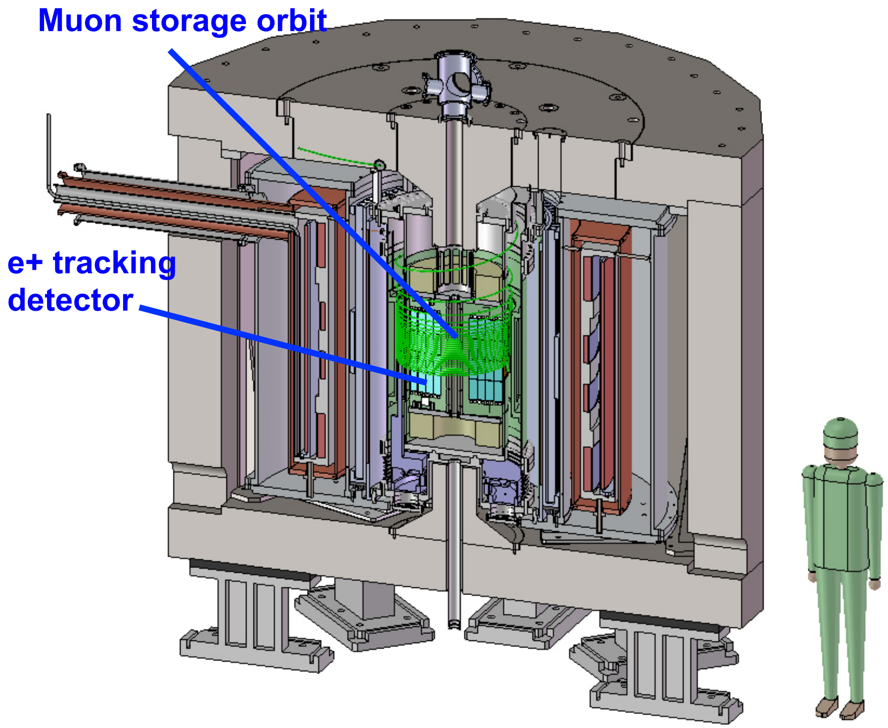
Ultra-cold muon acceleration

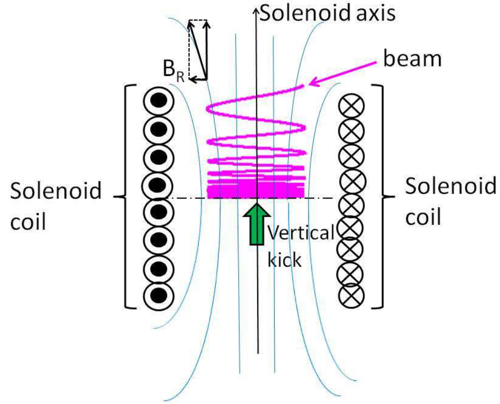
- Requirements
  - fast acceleration to reduce decay losses (τ_μ = 2.2 μs at rest)
  - small emittance growth to enable injection and capture by storage ring



Muon storage ring

- 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 × 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





J-PARC g–2 statistics goals (Stage 1)

Statistical uncertainties

- Goals
  - $\Delta\omega_a/\omega_a$ = 0.36 ppm (0.163/PN$^{1/2}$)
    - BNL E821 σ_{stat} = 0.46 ppm
  - $\Delta d_\mu = 1.3\times10^{-21}\ e\cdot$ cm
    - E821 (-0.1±0.9)×10^{-19} e·cm
    - $\Delta d_e < 1.05\times10^{-27}\ e$·cm

Further development of aerogel microstructure planned to optimize this fraction

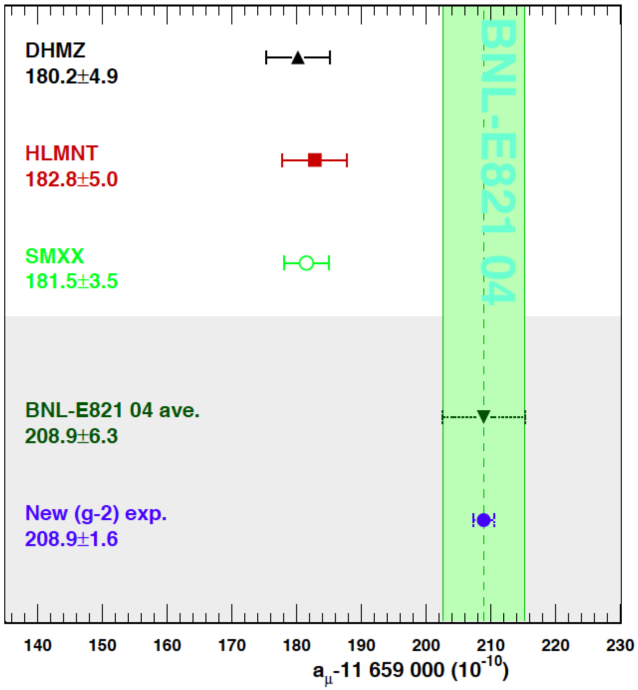
- Running time
  - measurement only: 2×10^{7} s
- Muon rate from H-line
  - 1MW, SiC target: 3.2×10^{8} s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization
  - lose polarization: 100% → 50%
  - 2.15×10^{-3} (*Stage 2 goal is 0.01*)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, kick
  - 0.92
- Stored muons
  - 3.3×10^{5} s^{-1}
- Detected positrons (ϵ = 0.12)
  - 4.0×10^{4} s^{-1}

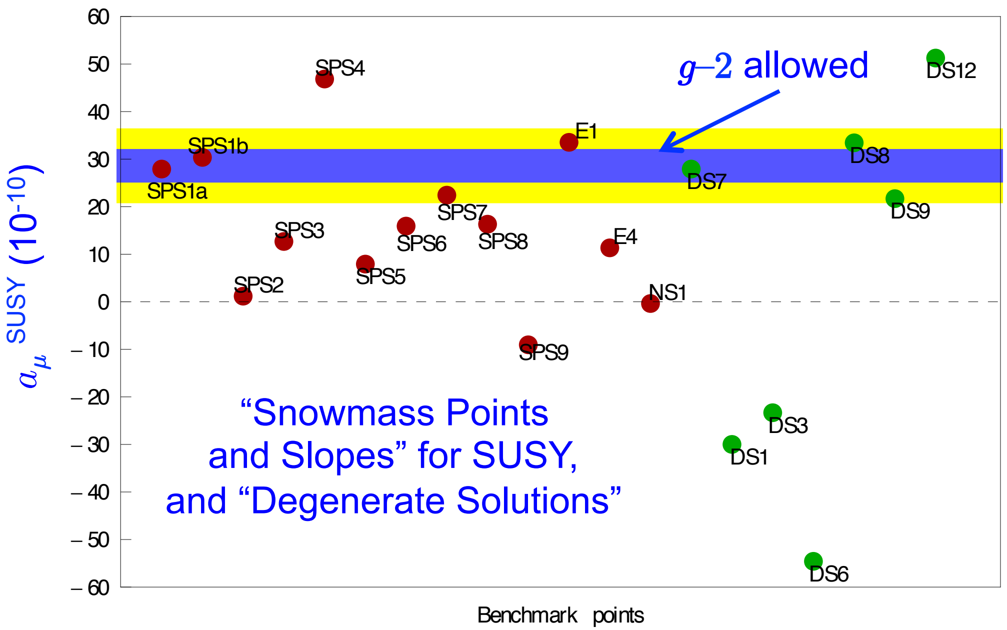
Summary

- The BNL E821 measured value of the muon magnetic moment a_μ may be an indication of physics beyond the Standard Model.
  - it needs to be verified with increased precision (FNAL E989)
  - it deserves to be verified in an independent experiment (J-PARC E34)
- The J-PARC method has systematic uncertainties different from BNL E821.
  - smaller and more precise magnetic storage field
  - compact detector with tracking capability
  - flip spin to analyze asymmetry rather than decay time distribution
  - ultra-cold muon beam using muonium in vacuum as an ion source
- R&D phase evolving to construction phase with a growing collaboration (136 members, 8 countries).

Extra slides

Goals for the next generation of $g\!-\!2$



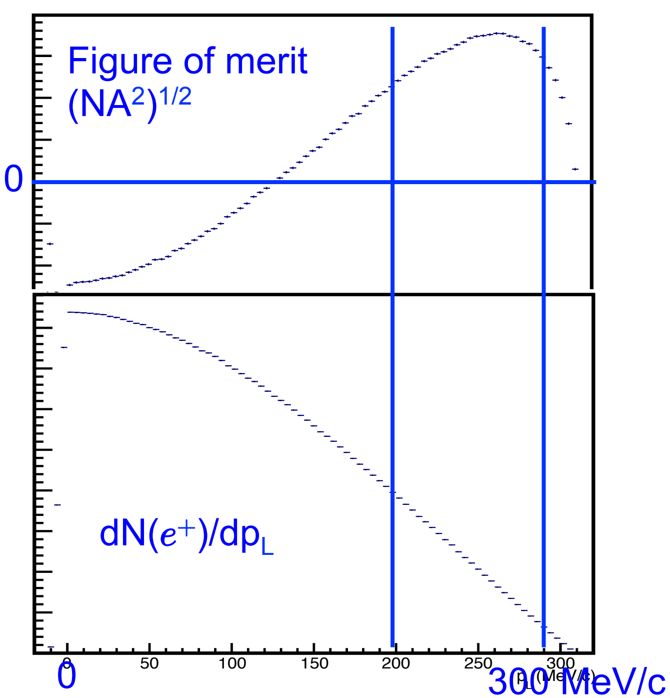


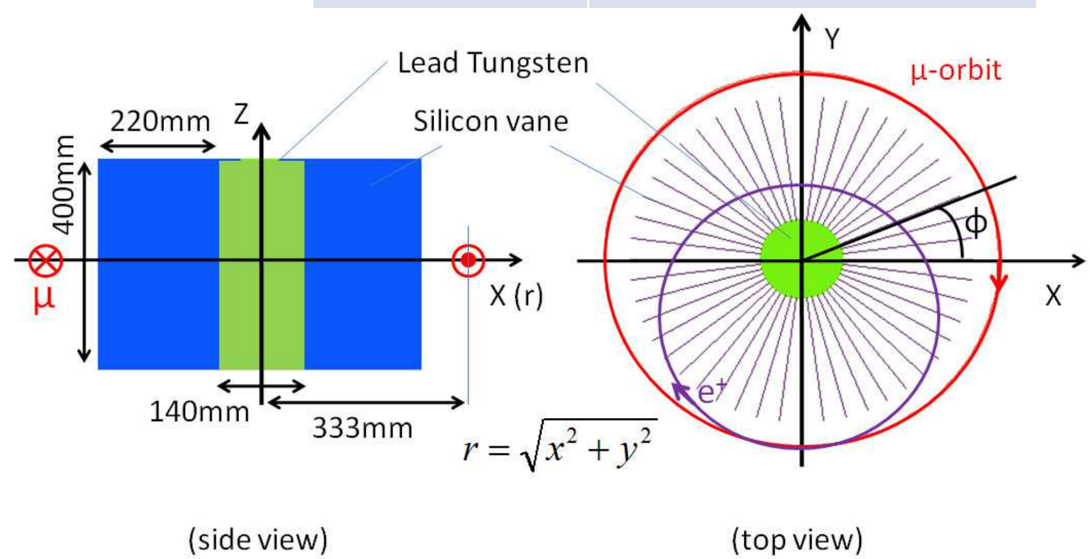
- Reduced experimental uncertainties (x4), coupled with a modest (x1.5) reduction for the SM prediction, will decrease the uncertainty in the difference by x2. With the same central values, the significance grows to 7−8 σ.
- Regardless of the central value, this precision will discriminate among possible extensions to the SM, in a way complementary to LHC discoveries.

Decay positron tracking detector

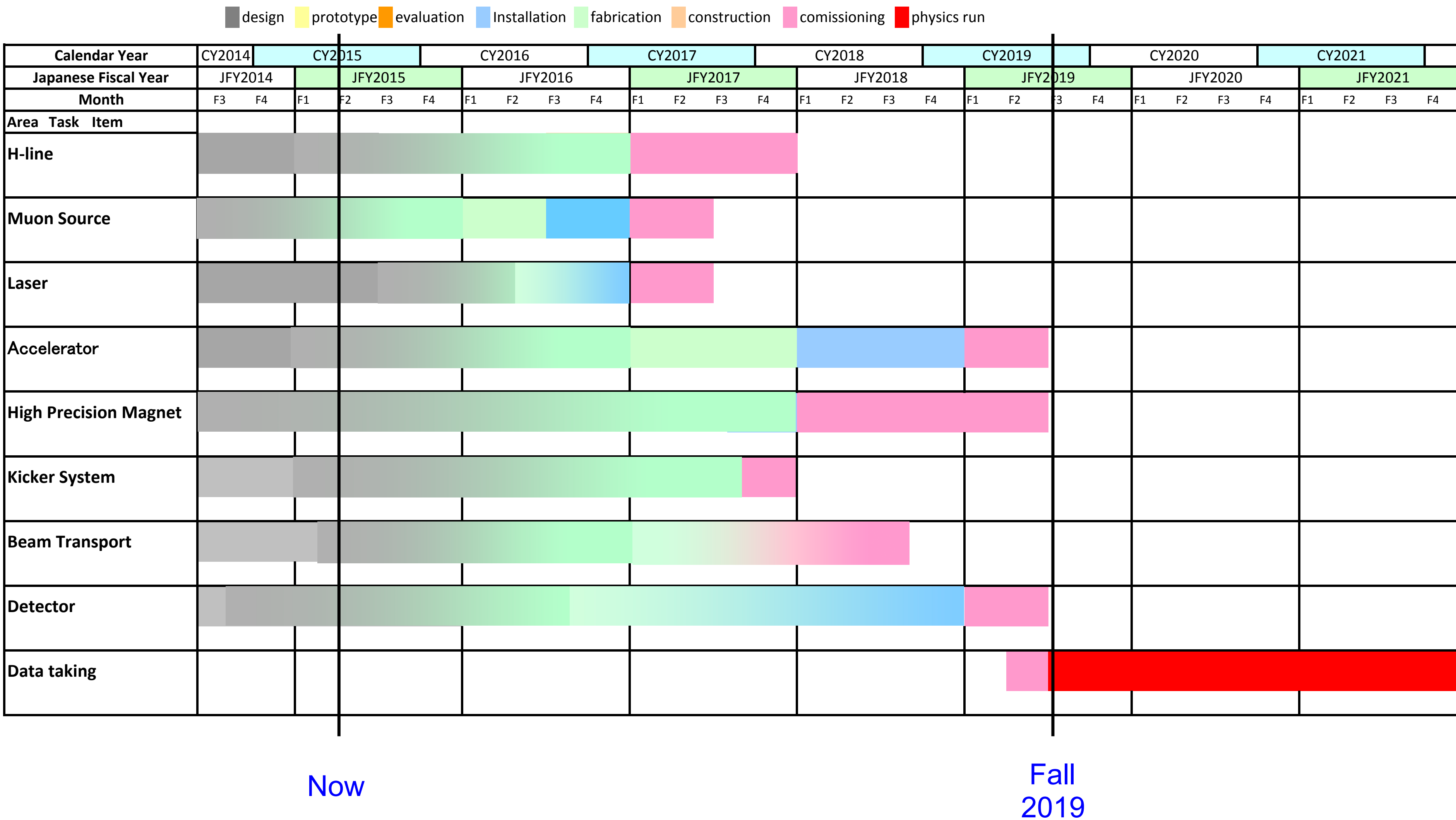
- Detect e^+ at higher range of energies (200−290 MeV/c)
  - A<0 for lower energies
  - want typically one turn
- Radial vanes of axial and radial Si strips
- Core of lead-tungsten to absorb multiple turns

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

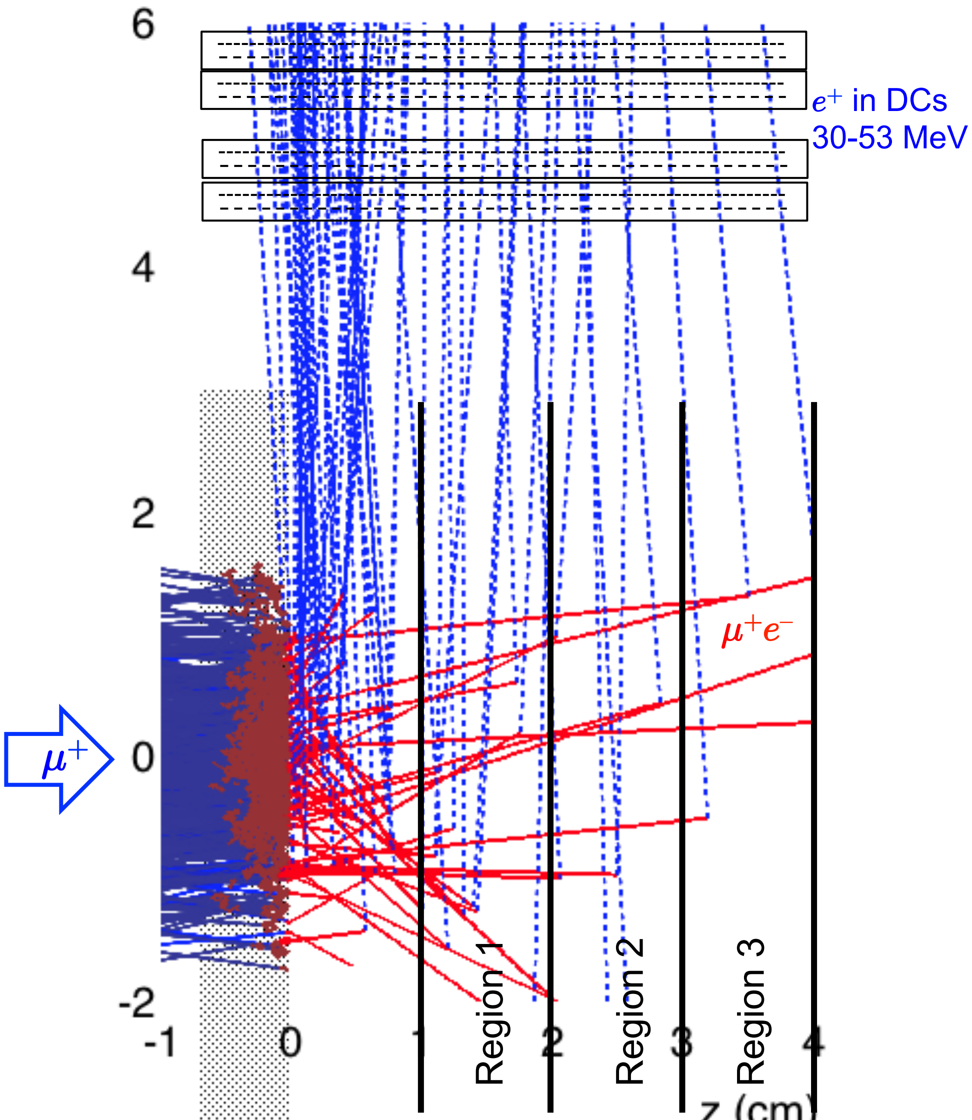




Proposed timeline



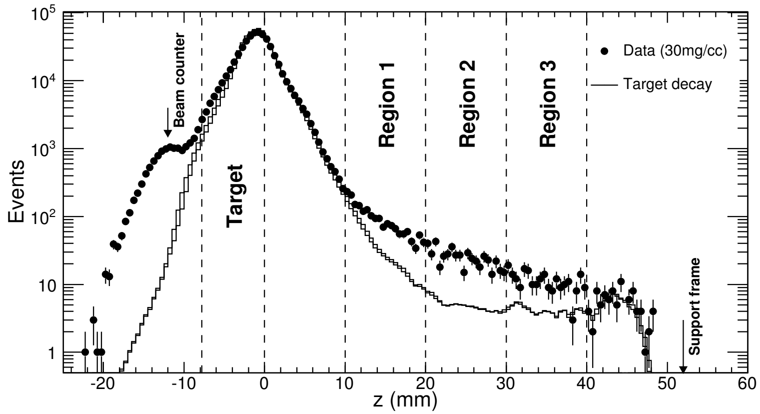
Identifying Mu in vacuum

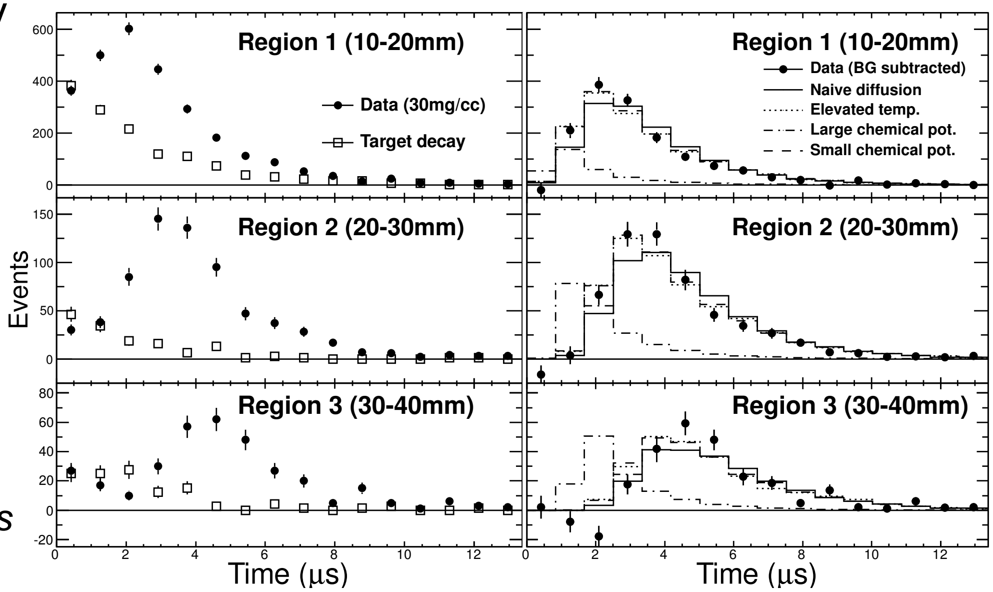


- A multi-step process of:
  - μ^+ thermalization, μ^+e^- formation.
  - μ^+e^- escapes into voids in evacuated silica *nanostructure* ($\sim$100%).
  - μ^+e^- migrates ("diffuses") to nearby material boundary ($\sim$ few %).
- Identify and characterize by:
  - time and position(y,z) correlations of muon decays from e^+ tracking (drift chambers).
- Muons decay in:
  - the target, as μ^+e^- and μ^+.
  - vacuum, in flight, as μ^+e^-.
  - surrounding materials (μ^+e^- or μ^+).
- *Provides image of decay locations in (y,z), as a function of time.*

Mu in vacuum: 2010 and 2011

- Aerogel samples
  - all high uniform and optically transparent
  - different preparations
    - hydroscopic nature of surfaces
  - different densities: 27−180 mg/cm^3
- Observations
  - no obvious dependence on density or preparation
  - speed larger than thermal?
- Partial yields ~0.003
  - into regions 1−3, distance 10−40 mm from aerogel surface
  - normalized to all muon decays observed
    - *some care required to interpret yield expected with different beams and targets*





P. Bakule et al., Prog. Theor. Exp. Phys. 2013, 103C01 (2013).

J-PARC PAC milestones, 2012

- Stage 1 status granted, September 2012
- Milestones established
- "The PAC emphasizes the importance of rapid progress on the first milestone, to increase the intensity of the ultra-cold muon production"

The PAC commends the excellent progress that the g-2 collaboration has made in all areas and recommends that Stage-1 approval should be granted.

The realization of the experiment still requires significant advances for the chosen experimental technology. Most importantly, the intensity of the cold muon source needs to be improved by almost a factor 10. In addition to the design and R&D the collaboration has provided a set of milestones that can be used to monitor the progress of the g-2 project. These milestones appear well suited to guide the development of the project towards Stage-2 approval (CDR, section 1.7):

M1) Demonstration of the ultra-cold muon production with the required conversion efficiency leading to an intensity of $1\times10^6\mu^+/s$.

M2) Muon acceleration tests with the baseline configuration of low-β muon LINAC, i.e. RFQ, and IH-LINAC.

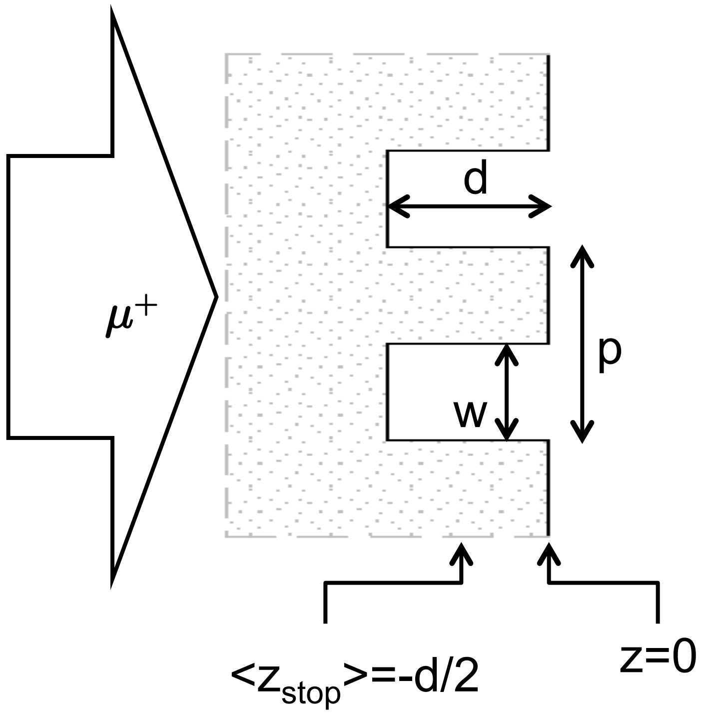
M3) Tests of the spiral injection scheme.

M4) Production of a prototype magnet and development of the field monitor with the required precision.

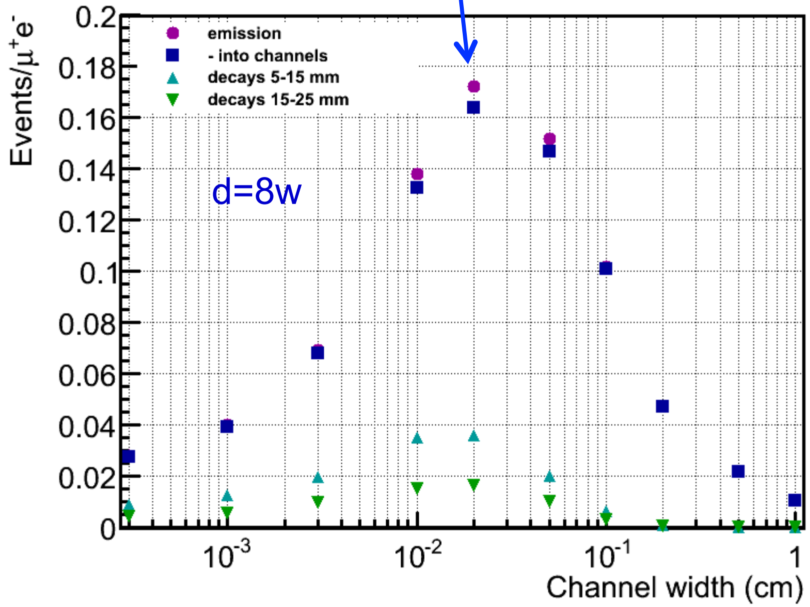
M5) Demonstration of rate capability of the detector system for decay positron detection.

The PAC emphasizes the importance of rapid progress on the first milestone, to increase the intensity of the ultra-cold muon production. This goal should be pursued by the collaboration with the highest priority.

2013: Aerogel with surface structure

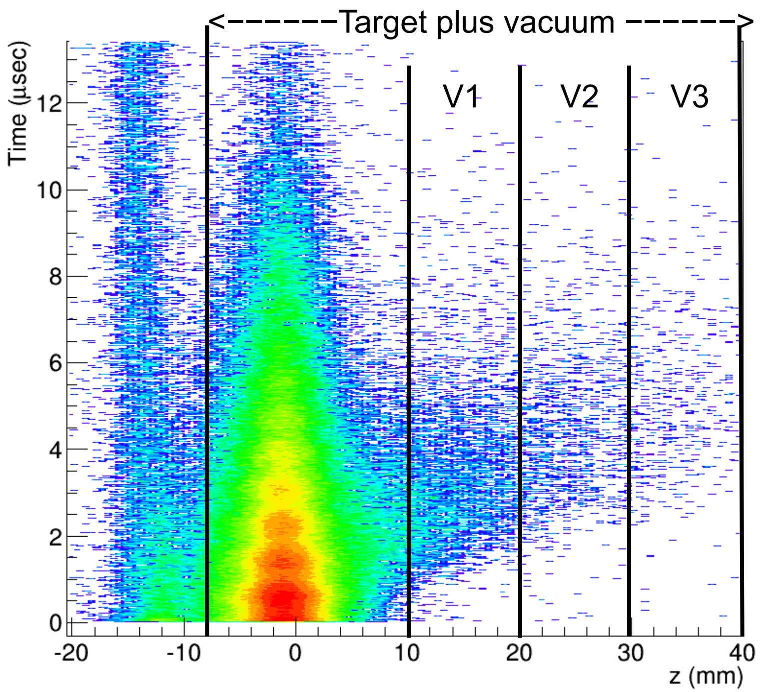


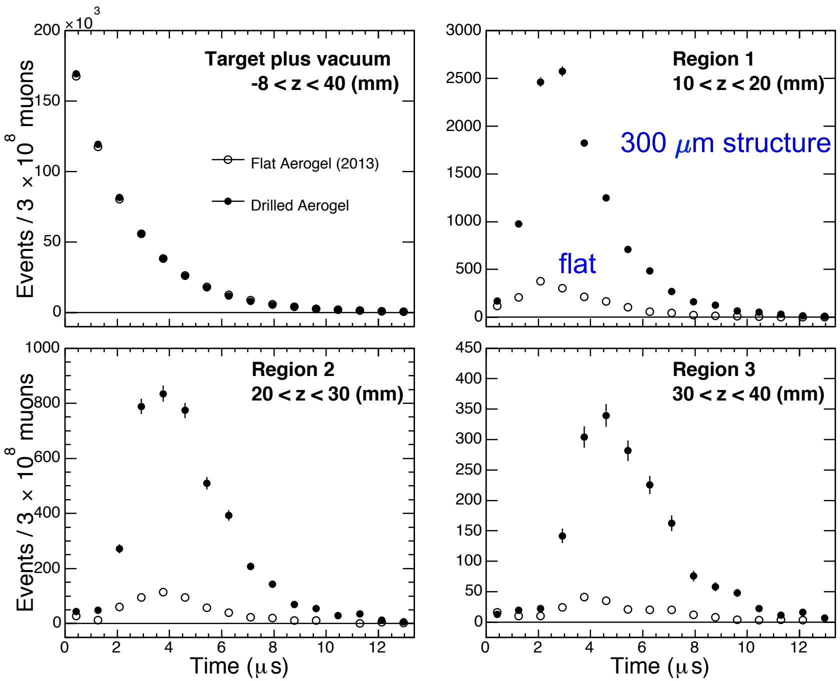
Optimum channel width w~0.2mm



- Independent *simulations* based on a diffusion model showed emission increase of ~5 for a surface with a structure of size ~0.2 mm.
- How could that structure be created in the delicate aerogel material?

Results of 2013 data





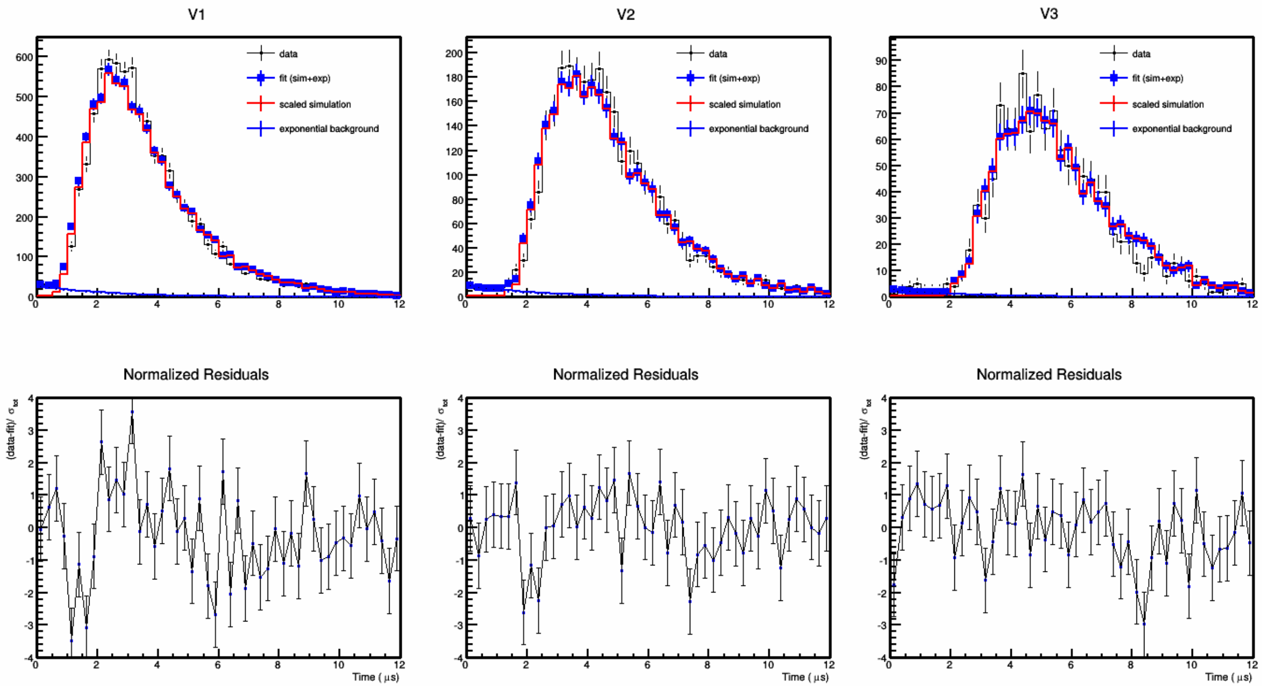
- Used a ***model-independent approach*** to estimate yields
- For 0.3 mm structure, observed 11 times yield previously reported from 2011 data, 8 times yield found in similar flat target in 2013.
- Model-independent approach cannot independently estimate *total yield* or *partial yield near target* for laser ionization estimates
  - ➔ apply diffusion model analysis

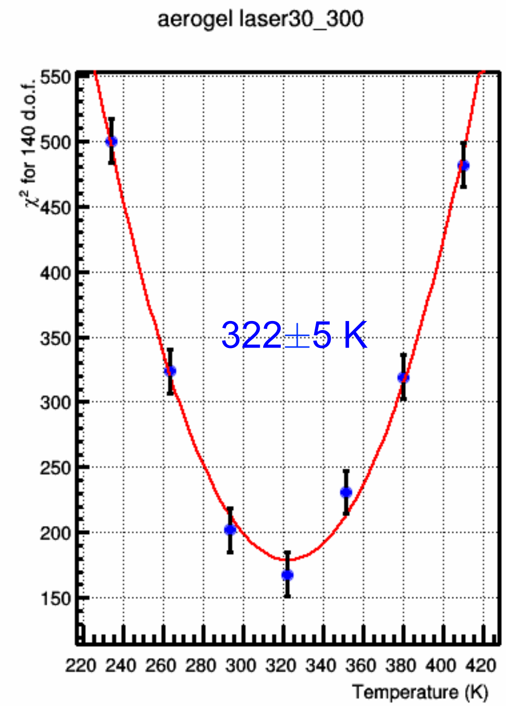
Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

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

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

Diffusion model analysis: ablated target





- Preliminary analysis for laser ablated (pitch = 0.3 mm) aerogel:
  - much better signal to background enables more reliable diffusion model comparison
    - simultaneous fit to 3 vacuum regions at T=322 K shown
  - best fit emission velocities correspond to 322 $\pm$ 5(stat) K
  - D=870 $\pm$ 20 cm^2 s^{-1}, χ^2 = 168/140 (p=5%)
  - total yield into vacuum: 0.10 per stopped μ^+ (from simulation with model) for TRIUMF beams
  - fit of yield into vacuum regions V1-V3: 0.030 per stopped μ^+, similar to model independent analysis