Muon g–2/EDM at J-PARC

Glen Marshall
TRIUMF
June 14, 2015

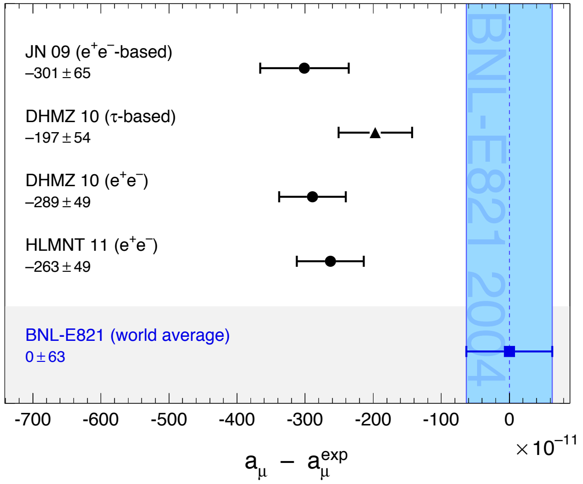
IPP LRP session
CAP Congress, 2015

See also session W2-4
Wednesday June 17 at 14:45
for scientific details

Results of BNL E821

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

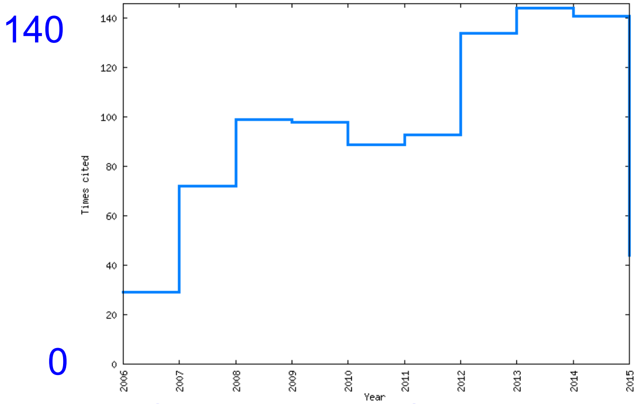
A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (September 2014)



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

Another approach: J-PARC g–2

- Improving the precision of g–2 beyond E821 is worthwhile.
  - FNAL E989 − do it the same way again, only better:
    - many problems have been solved by BNL E821
    - limitations are understood; the way to make improvements is clear
    - systematics become the limiting factor, and many systematic effects are retained
  - J-PARC E34 − do it a different way, at least as well, perhaps better:
    - make the same measurement in a much different way
    - systematics are still a major issue, but systematic effects are significantly different

- The J-PARC experiment takes a different approach.
  - high power (up to 1 MW) pulsed proton beam at 3 GeV
  - produce low energy (4 MeV) muons (μ^+ only)
  - transform μ^+ into an ultra-cold beam by formation and ionization of Mu (μ^+e^-)
    - most inefficient step in muon accumulation
  - store μ^+ in a small, uniform storage magnet constructed with MRI technology
  - track and analyze decay e^+ within the storage field by arrays of Si strips
    - storage field is the spectrometer field
  - take advantage of spin reversal; analyze asymmetry directly

Compare: Fermilab and J-PARC

Fermilab (similar to BNL)

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

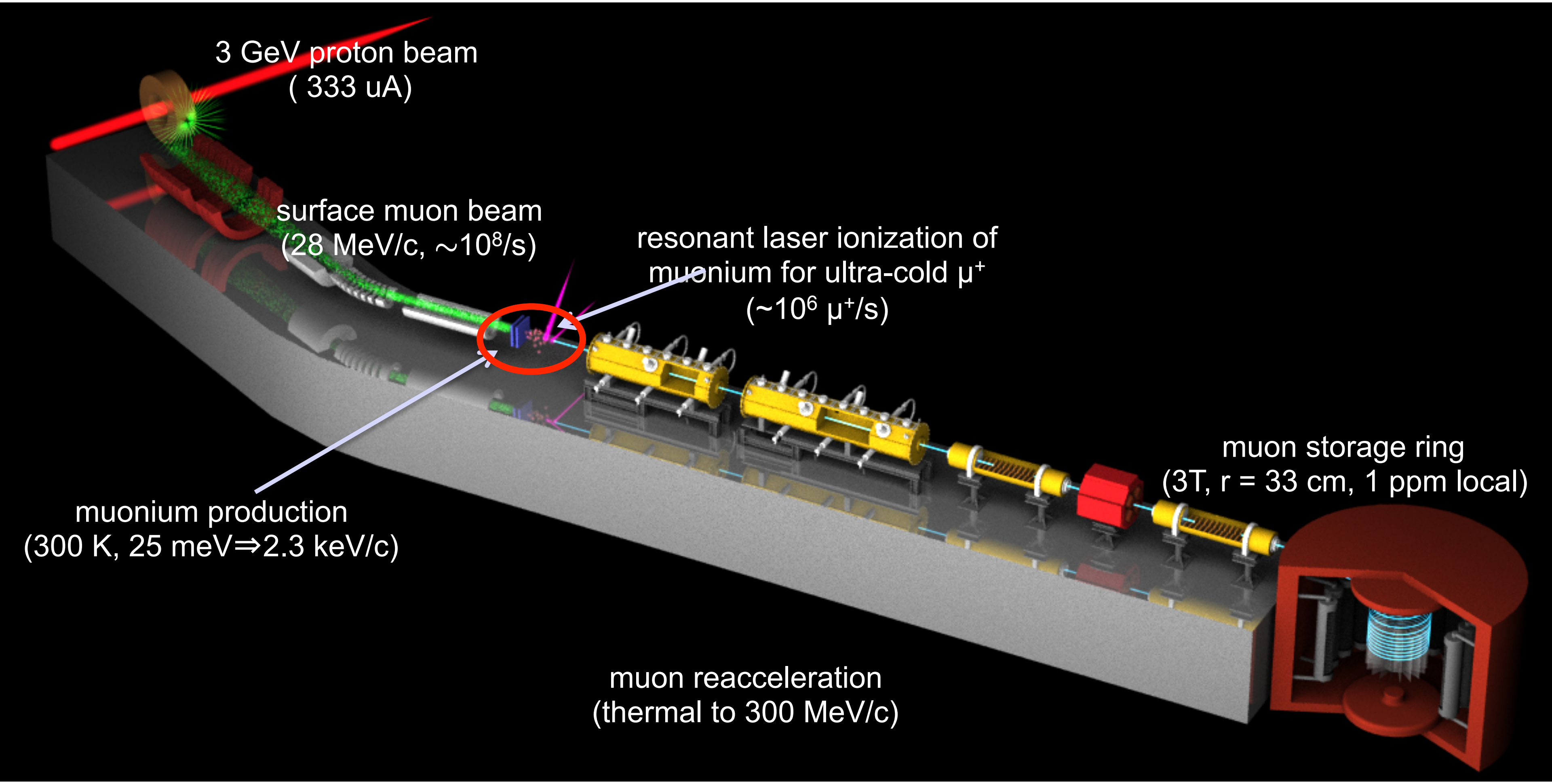
- eliminate effect of E-field via "magic" momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - p_μ = 3.09 GeV/c required
- very uniform B
- electric quadrupole field focusing
- B = 1.45 T
- ρ = 7 m
- periodic calorimeters with some tracker modules

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" 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)

J-PARC g–2 schematic



3 GeV proton beam
(333 uA)

surface muon beam
(28 MeV/c, $\sim 10^8$/s)

resonant laser ionization of
muonium for ultra-cold μ^+
($\sim 10^6$ μ^+/s)

muonium production
(300 K, 25 meV⇒2.3 keV/c)

muon storage ring
(3T, r = 33 cm, 1 ppm local)

muon reacceleration
(thermal to 300 MeV/c)

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 $(-0.1\pm0.9)\times10^{-19}\ e\cdot$cm
    - $\Delta d_e < 1.05\times10^{-27}\ e\cdot$cm

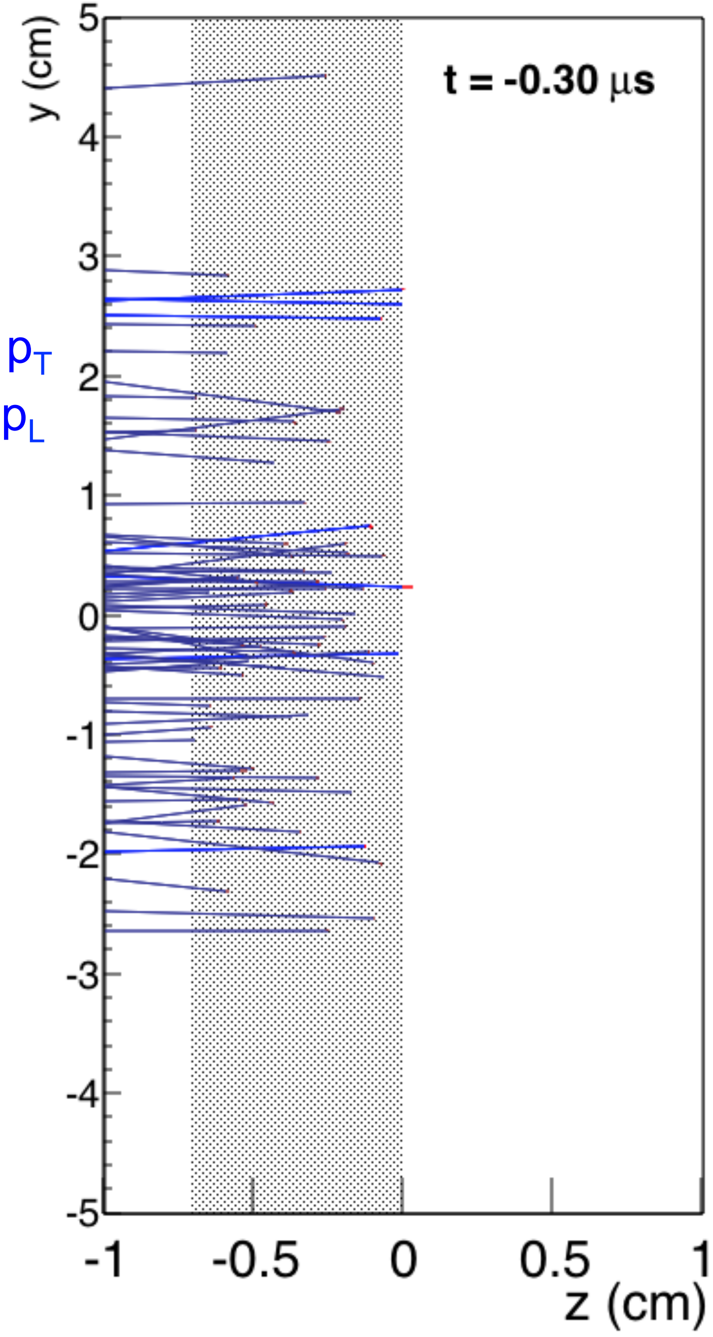
Can we improve the conversion efficiency of the muon beam to ultra-slow muons?

- 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}

Surface muons to ultra-cold muons

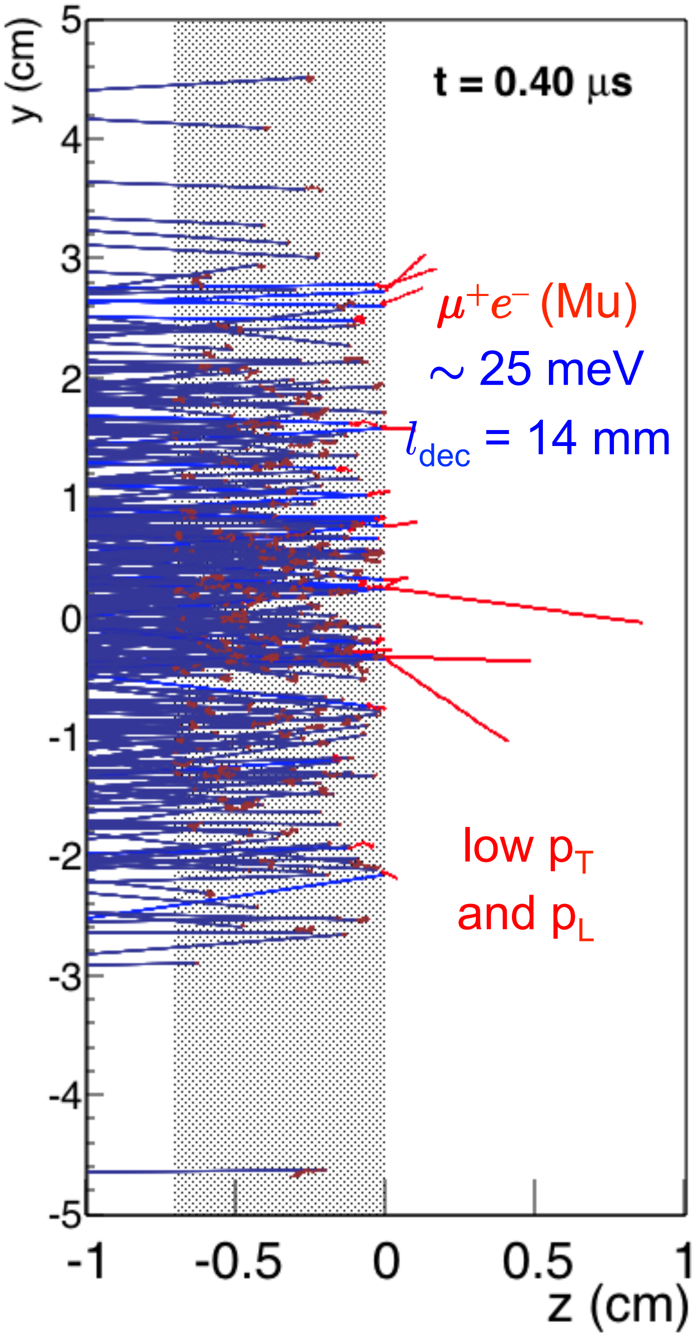
- Surface μ^+ from π^+ decay at rest
  - E_k = 3.4 MeV, p = 27 MeV/c
  - $\Delta p/p$ = 0.05 rms, Δp =1.3 MeV/c
  - $\Delta p_x/p$ = 0.04, $\Delta p_y/p$ = 0.08
- Thermalization as Mu (μ^+e^-)
  - E_k = 0.025 eV, p = 2.3 keV/c
  - $\Delta p/p$ = 0.42 rms, Δp = 1 keV/c
  - "ultra-cold" compared to surface μ^+

high p_T and p_L



Surface muons to ultra-cold muons

- Surface μ^+ from π^+ decay at rest
  - E_k = 3.4 MeV, p = 27 MeV/c
  - $\Delta p/p$ = 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
  - $\Delta p/p$ = 0.42 rms, Δp = 1 keV/c
  - "ultra-cold" compared to surface μ^+
- Thermal diffusion of Mu into vacuum
  - μ^+ remains ultra-cold



$\mu^+ e^-$ (Mu)

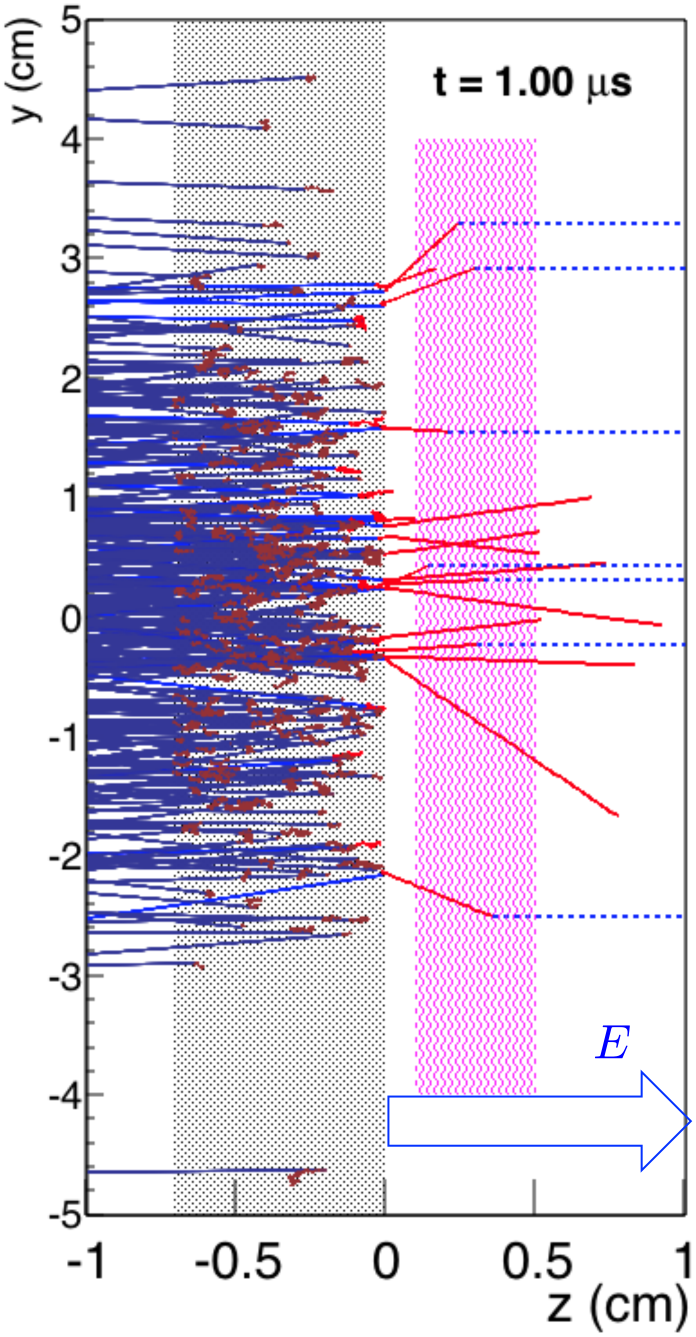
$\sim$ 25 meV

l_{dec} = 14 mm

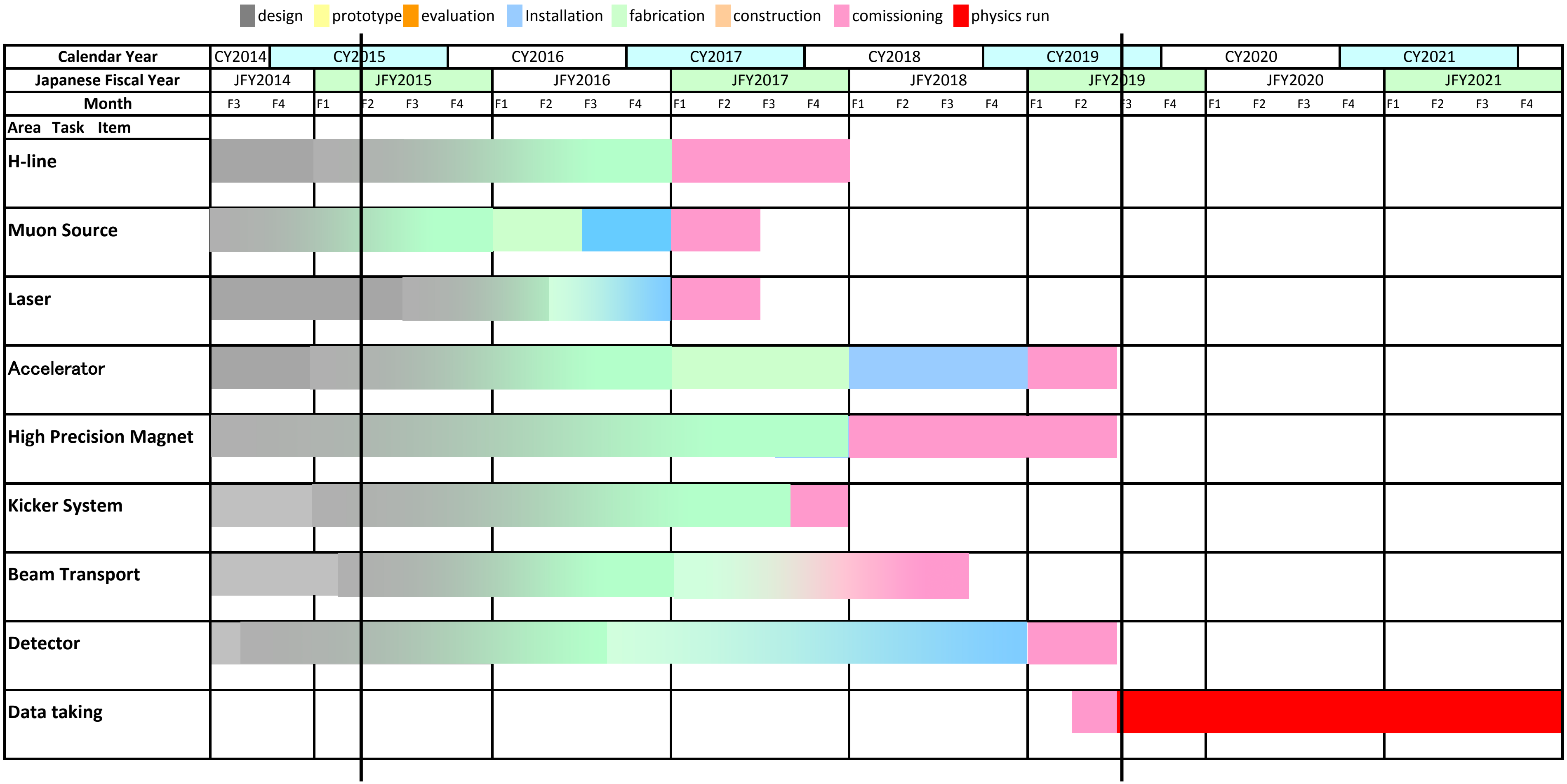
low p_T and p_L

Surface muons to ultra-cold muons

- Surface μ^+ from π^+ decay at rest
  - E_k = 3.4 MeV, p = 27 MeV/c
  - $\Delta p/p$ = 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
  - $\Delta p/p$ = 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



Proposed timeline



Now

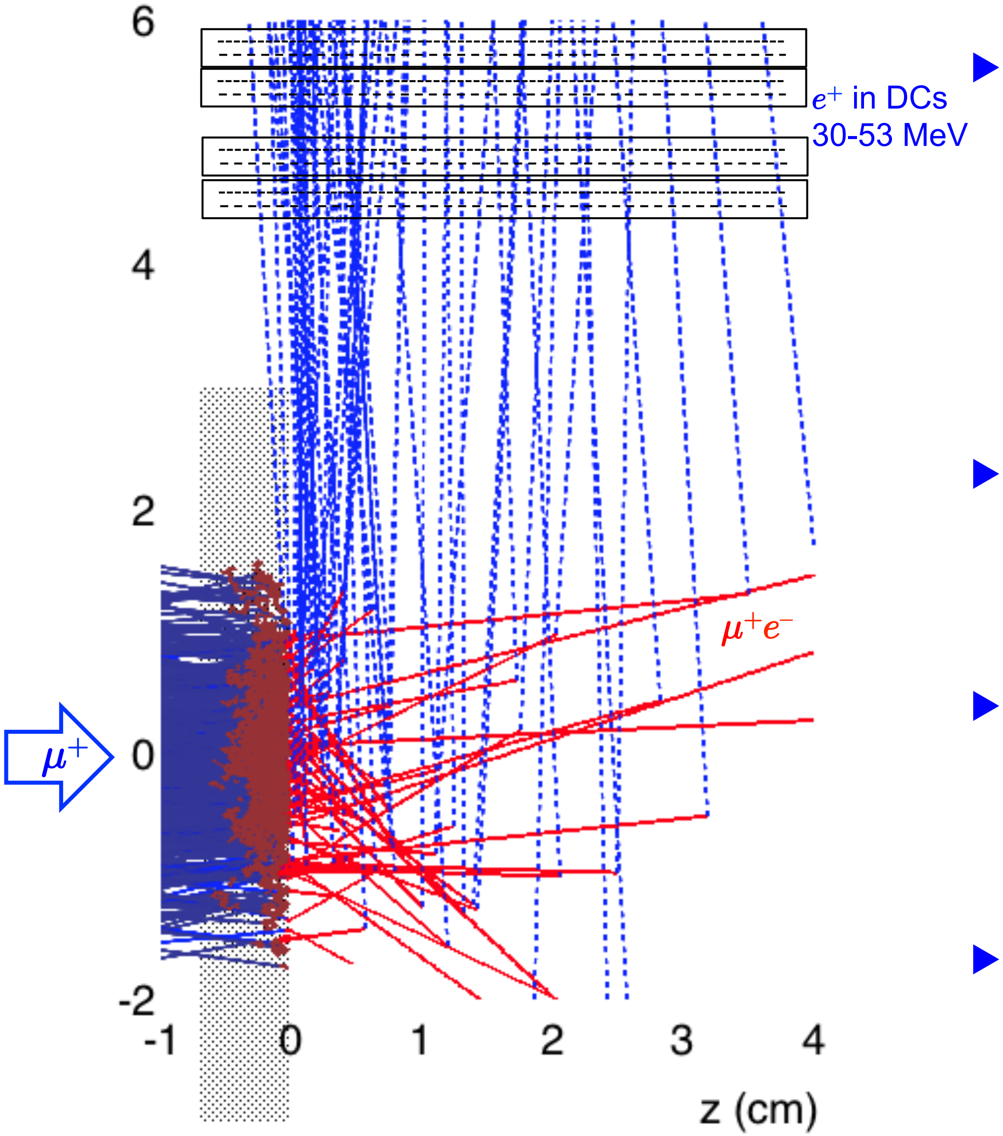
Fall 2019

Projected resource details

- HQP
  - NSERC encouragement now for 1 grad student
    - 2016-2019: demonstration of ultra-cold muon beam acceleration
  - For main running time
    - 2018-2021: one or two students and/or postdocs for ultra-cold muon beam rate and polarization monitoring
    - more opportunities if more Canadian involvement; too early to predict reliably
  - *We need more collaborators*
- Equipment and Contributions
  - Too early to identify specifically
    - collaboration is in embryonic stage
    - no MOUs yet
  - Aerogel target modifications and characterizations
    - for continued target R&D
  - Polarization monitoring (approx!)
    - at rest: ~$150K, in flight: ~$300K
  - Beam monitoring, detector, magnetic field measurements?
- Canadian relationships
  - M. Roney -- Babar data analysis for input to HVP contribution calculations
- International relationships
  - 6-y collaboration in Mu emission target R&D (KEK, RIKEN)
  - Evolution into more general contribution (e.g., TDR in 2015)

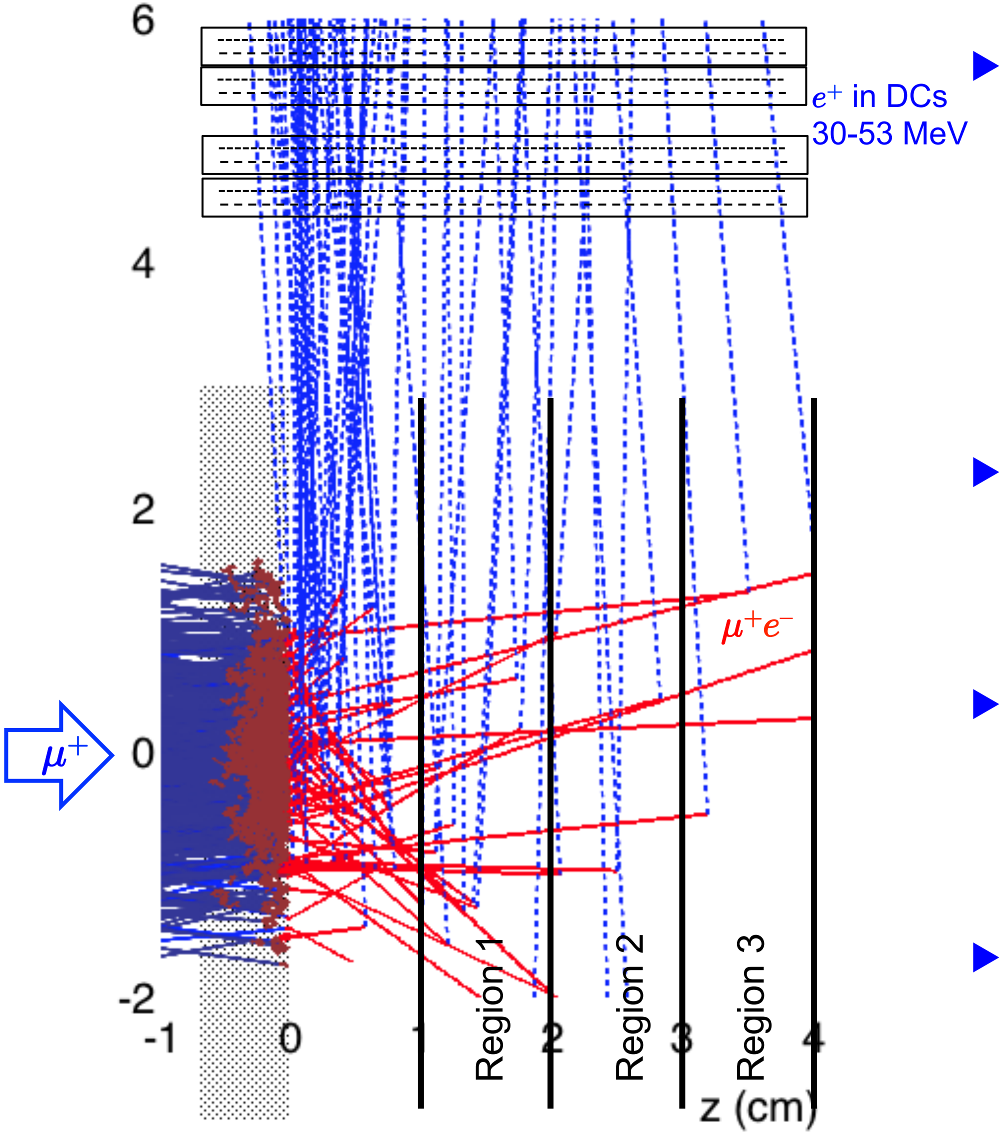
Extra slides

Identifying Mu in vacuum



- A multi-step process of:
  - μ^+ thermalization, μ^+e^- formation.
  - μ^+e^- escapes into voids in evacuated silica *nanostructure* (∼100%).
  - μ^+e^- migrates ("diffuses") to nearby material boundary (∼ 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.*

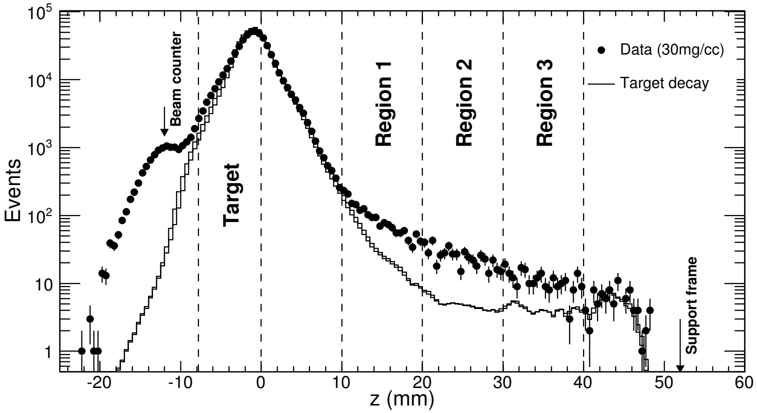
Identifying Mu in vacuum

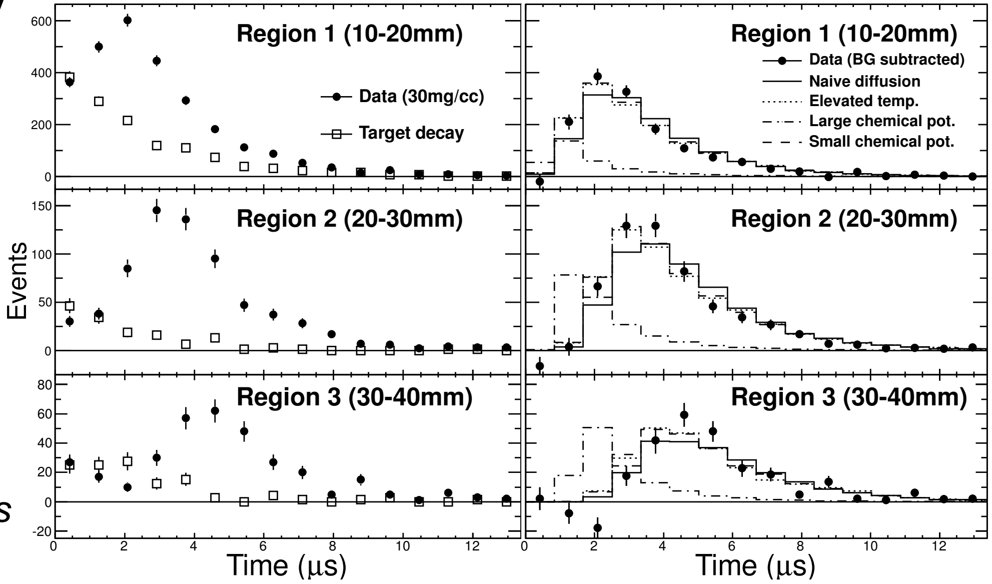


- A multi-step process of:
  - μ^+ thermalization, μ^+e^- formation.
  - μ^+e^- escapes into voids in evacuated silica *nanostructure* ($\sim$100%).
  - μ^+e^- migrates ("diffuses") to nearby material boundary ($\sim$ few %).
- Identify and characterize by:
  - time and position(y,z) correlations of 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*

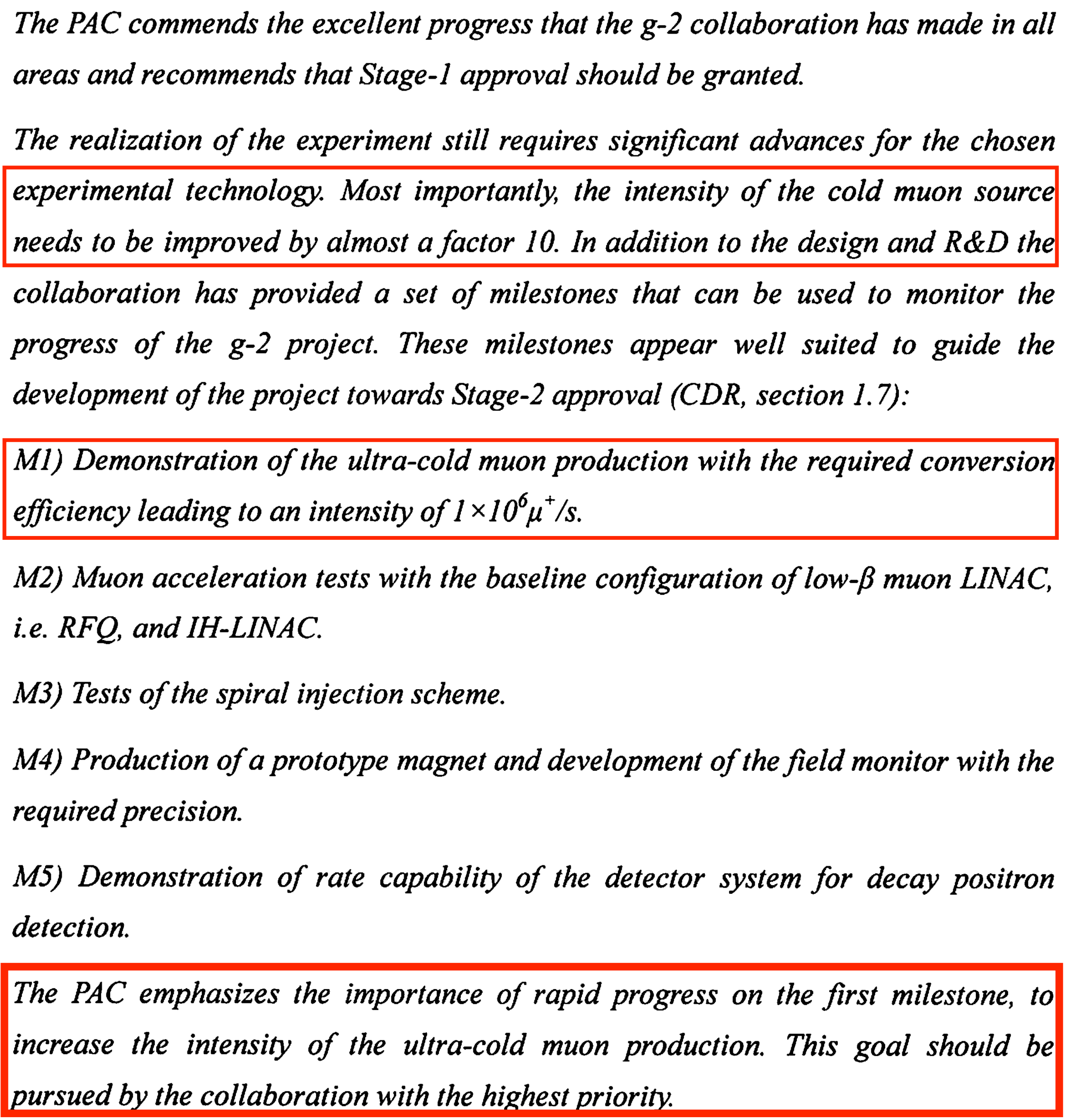




P. Bakule et al., Prog. Theor. Exp. Phys. 2013, 103C01 (2013).

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.*

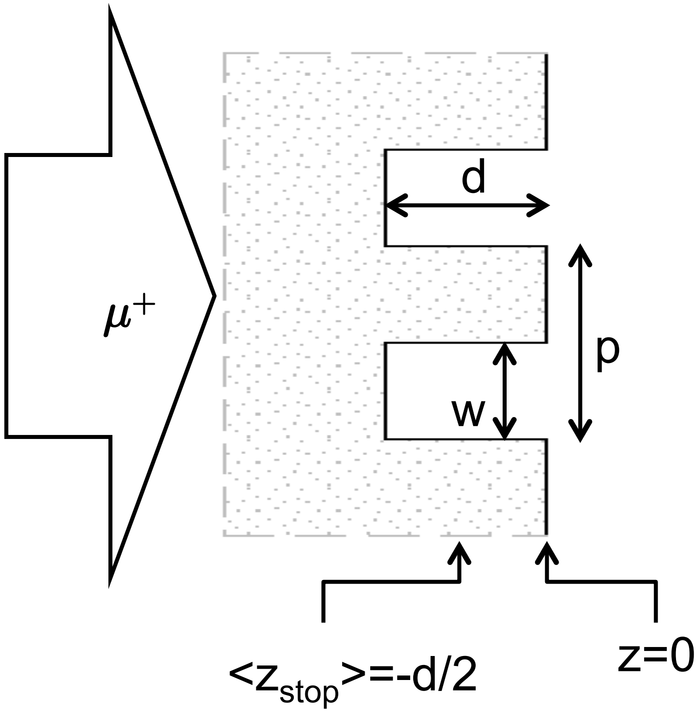
M3) Tests of the spiral injection scheme.

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

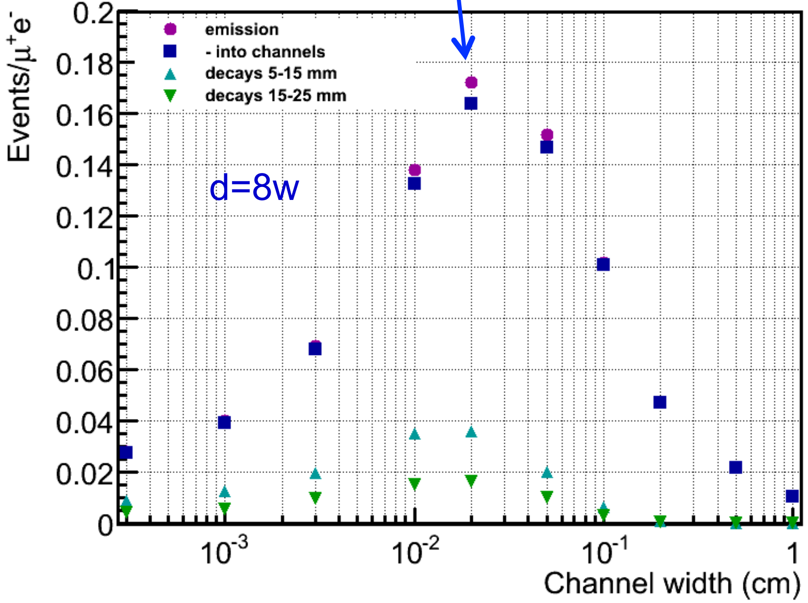
M5) Demonstration of rate capability of the detector system for decay positron detection.

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



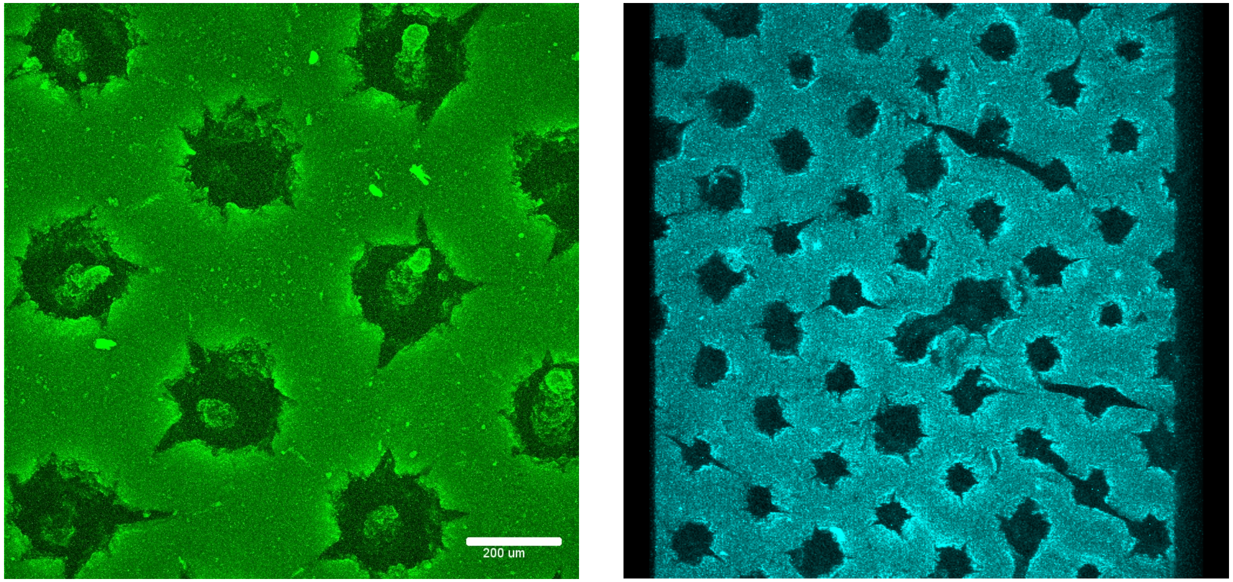
Optimum channel width w~0.2mm



- 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?

Structured aerogel surface

- Different methods were tested:
  - deformation with pin array prior to drying aerogel
  - laser ablation of holes using laser at RIKEN



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

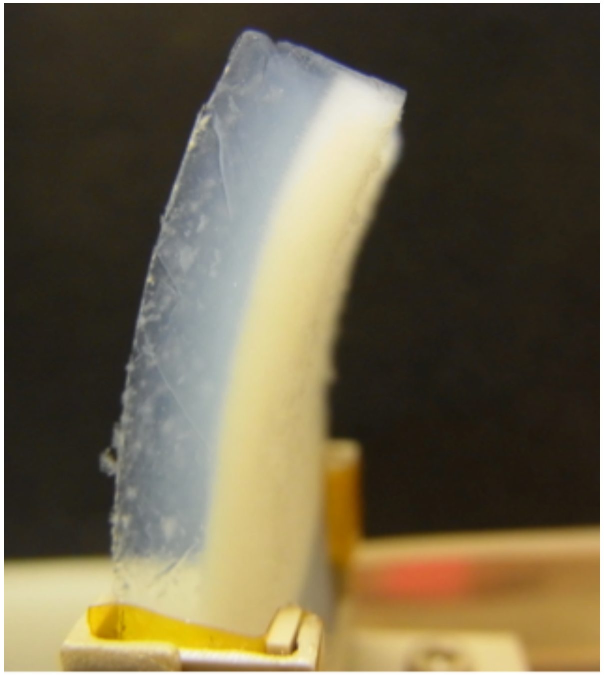
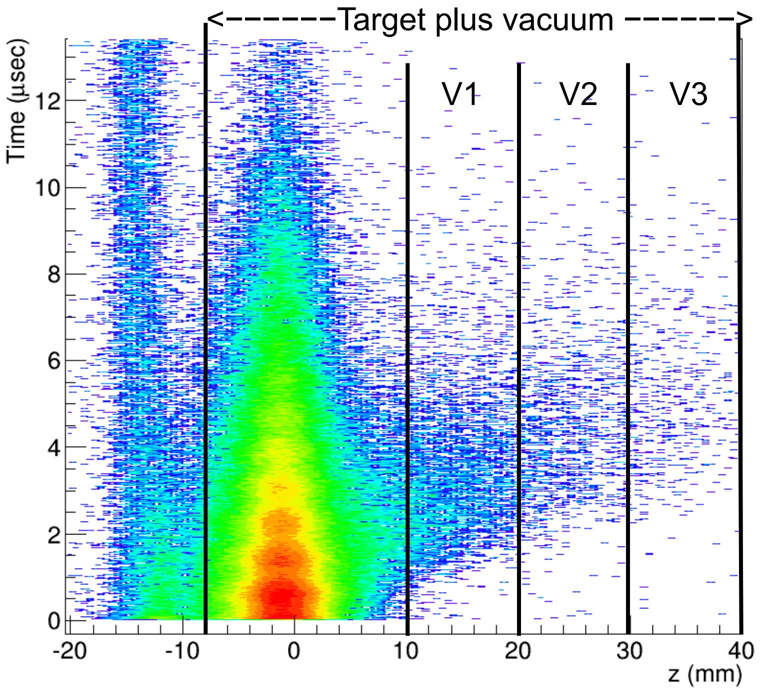
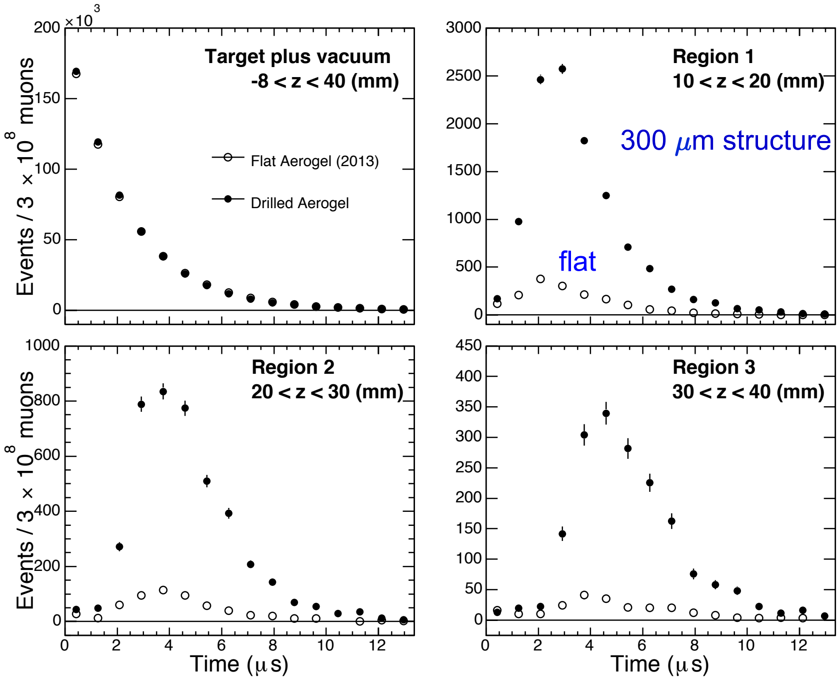


Photo of laser-ablated aerogel used in S1249. Curvature is due to the ablation process and has been controlled in subsequent ablations.

Results of 2013 data





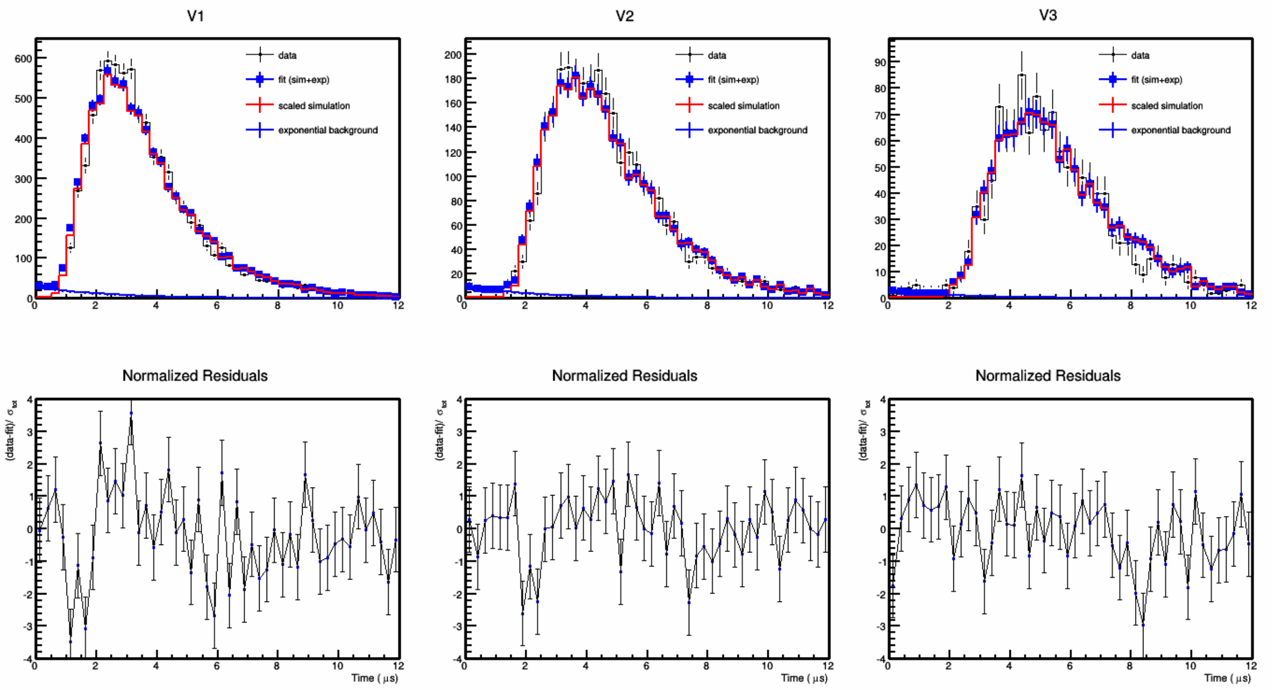
- Used a ***model-independent approach*** to estimate yields
- For 0.3 mm structure, observed 11 times yield previously reported from 2011 data, 8 times yield found in similar flat target in 2013.
- Model-independent approach cannot independently estimate *total yield* or *partial yield near target*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

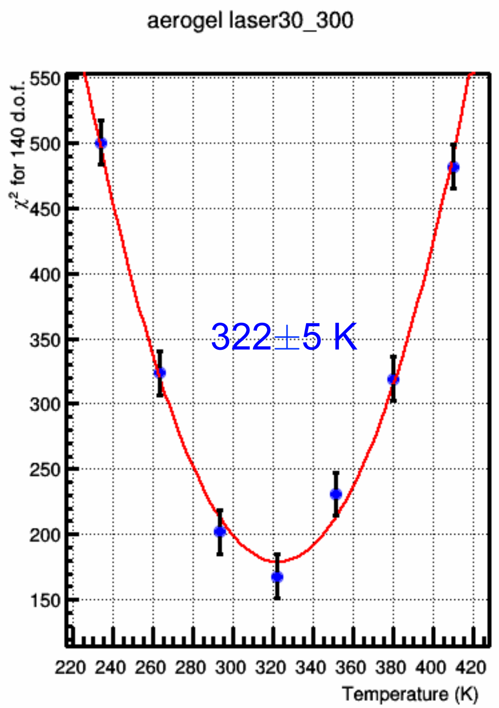
Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

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 ± 5(stat) K
  - D=870 ± 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

Simulation of J-PARC μ^+ beam

- Simulation enables use of TRIUMF result to estimate Mu in laser ionization region for $g\!-\!2$
  - J-PARC has higher momentum, larger momentum spread, pulsed time distribution
- Ingredients
  - G4beamline simulation of H-line, verified by G4beamline simulation of existing D-line at J-PARC MLF
  - G4 simulation of μ^+ stopping distribution in aerogel, after degrader
  - Diffusion simulation with same parameters found in S1249 at TRIUMF
- In 2×10^7 s measurement time, for 3.32×10^8 μ^+ s^{-1} in H-line (Stage 1 conditions)
  - $(\Delta\omega_a/\omega_a)$ = 0.35 ppm statistical precision (exceeds BNL E821 σ_{stat} = 0.46 ppm)
  - $\Delta d_\mu = 1.2\times10^{-21}$ $e\cdot$cm sensitivity (existing measure is $(-0.1\pm0.9)\times10^{-19}$ $e\cdot$cm)

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

Prediction is 3.8×10^{-3} μ^+e^- in ionization region, per incident muon.

PAC goal is 1%. Still some work to do for Stage 2.