Proton Radis 2019, Veli Losinj, 19 Sep 2019

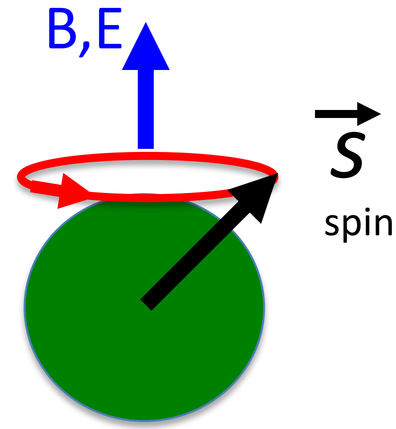
Muon g-2 and EDM experiment at J-PARC

K. Ishida (RIKEN)

on behalf muon g-2/EDM (E34) collaboration at J-PARC

(based on my presentation at FCCP2019, Capri)

muon g-2 and EDM



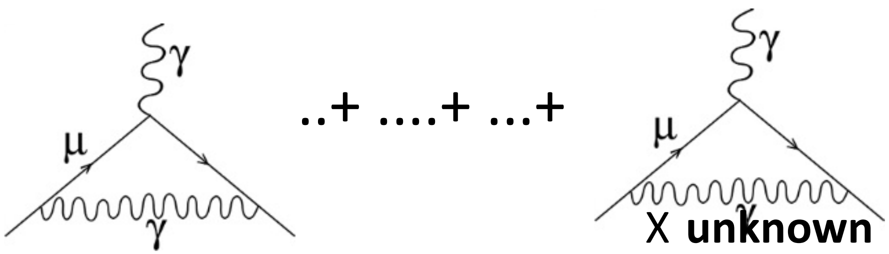
$\boldsymbol{\mu} = g_\mu (e/2m_\mu)\, \boldsymbol{s}$

$a_\mu = (g_\mu - 2)/2$: anomalous magnetic moment

Dirac equation predicts g=2.

Quantum fluctuations deviates g from 2.

a = a(QED) + a(Hadronic) +a(Weak) + ...



Contributions from all particles/interactions, even undiscovered

a_μ^{SM} =116 591 829 (49) x 10^{-11}

BNL E821

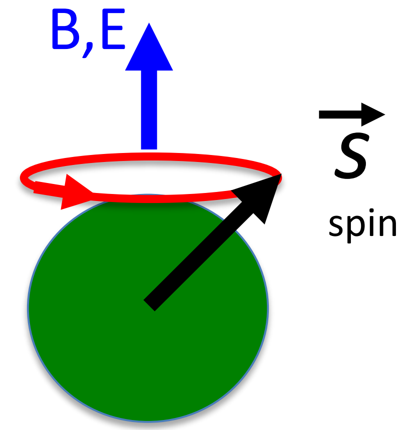
while in BNL E821 measurement (~2000),

a_μ^{exp} =116 592 089 (63) x 10^{-11}

=> 3.5 σ discrepancy (BNL E821 vs Theory)

"muon g-2 puzzle" not yet solved

muon g-2 and EDM

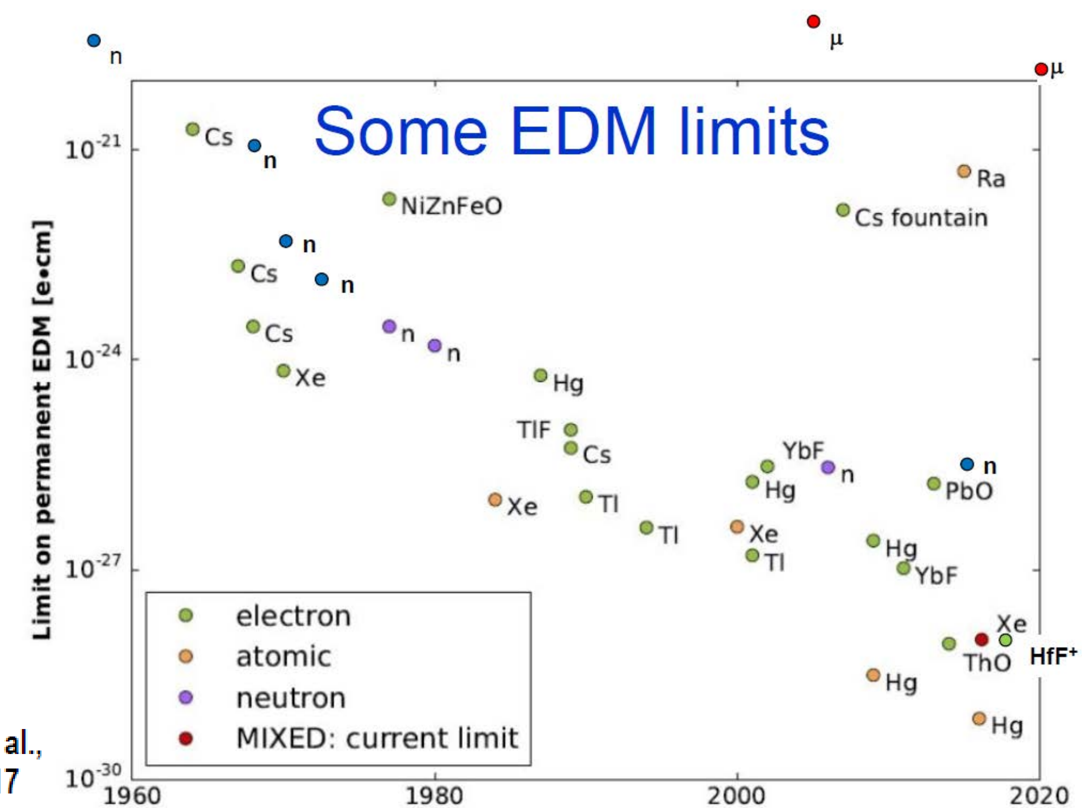


$\boldsymbol{d} = \eta\ (e/2mc)\ \boldsymbol{s}$

appears as spin precession around E field.

If EDM is nonzero -> T reversal is violated.
=> Indication of CP violation in the lepton sector.

=> Only upper limits
are known so far



K. Kirch in FCCP2019

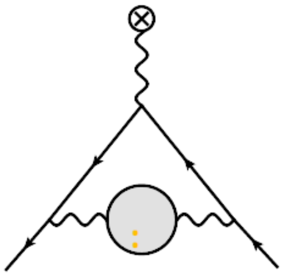
Adapted from K. Jungmann et al., JPS Conf. Proc. 18(2017)011017

Progress in muon g-2 theory calculation

QED was calculated to the 8th order
Though QED correction is large, uncertainty is small
E-Weak contribution is small

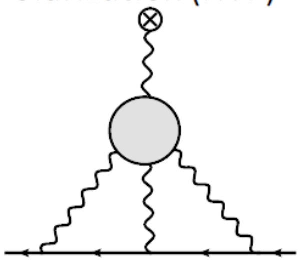
Hadronic Vacuum Polarization (HVP) contribution
Dispersive relation - connection to e+e- cross section
(at KLOE, BESIII, BarBar, SND, CMD,...)

$$a_\mu^{HVP} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had} \qquad \sigma_{had} = \sigma(e^+e^- \rightarrow hadrons)$$



Hadronic vacuum Polarization (HVP)

Some e+e- data gives tension
HVP value dependent on treatment,
though not enough to remove g-2 discrepancy

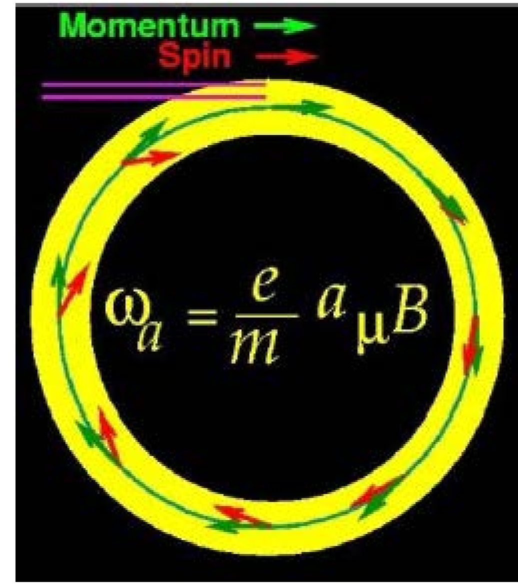


Hadronic Light-by-Light scattering (HLbL)

Hadronic Light-by-light (HLbL)
Only model calculations and some hint of upper limit
lattice QCD, dispersion relation,...

=> steady progress
Muon g-2 Theory Initiative group workshops for best SM predictions

Measurement of Muon g-2



Inject polarized muon in storage ring

Spin is kept aligned to the muon direction if g-2 = 0
due to match with cyclotron frequency

g-2 appears in the advance precession
of the spin to the muon momentum direction
=> measured by modulation in μe decay spectrum

In order to keep muons in storage orbit under uniform B
strong focusing with electric quadrupoles were used at CERN, BNL, FNL.

0 for γ = 29.3 (p = 3.1 GeV)

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

E-field vertical focusing allowed at p = 3.1 GeV (higher-order a_μ contribution cancelled)

Challenging are
Field homogeneity of 14 m Superconducting Storage Ring, ...

Status of Fermilab Muon g-2

(from presentation by Pocanic at FCCP2019)

Statistics limited the precision in BNL measurement

a_μ^{exp} =116 592 089 (54)stat (33)syst x 10^{-11}

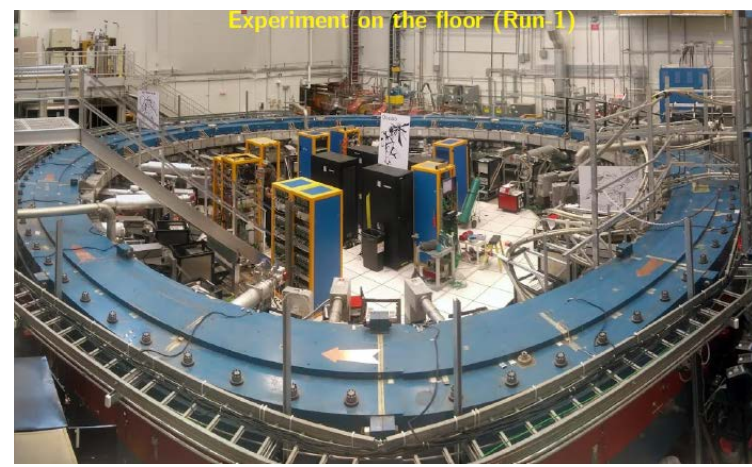
BNL muon g-2 storage ring was transported to Fermilab

Major improvement is in muon beam intensity (x 21 expected)

and other improvements in systematics

field shimming, beam injection, detectors, ...

Fermilab E989



Data taking started in 2018

comparable statistics to BNL in a few months

1st RUN data under analysis

first result ~end this year?

Goal is to reduce error from 0.54 to 0.14 ppm

Muon g-2/EDM@J-PARC - What's new?

Independent measurement at J-PARC

Reaccelerated low-emittance muon beam and MRI-type storage ring

different scheme -> different systematic errors.

BNL/FNAL method

E≠ 0, magic γ (p=3 GeV) makes (...)=0

g-2 measurement

EDM

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

Out-of plane oscillation is an indication of EDM.

J-PARC method

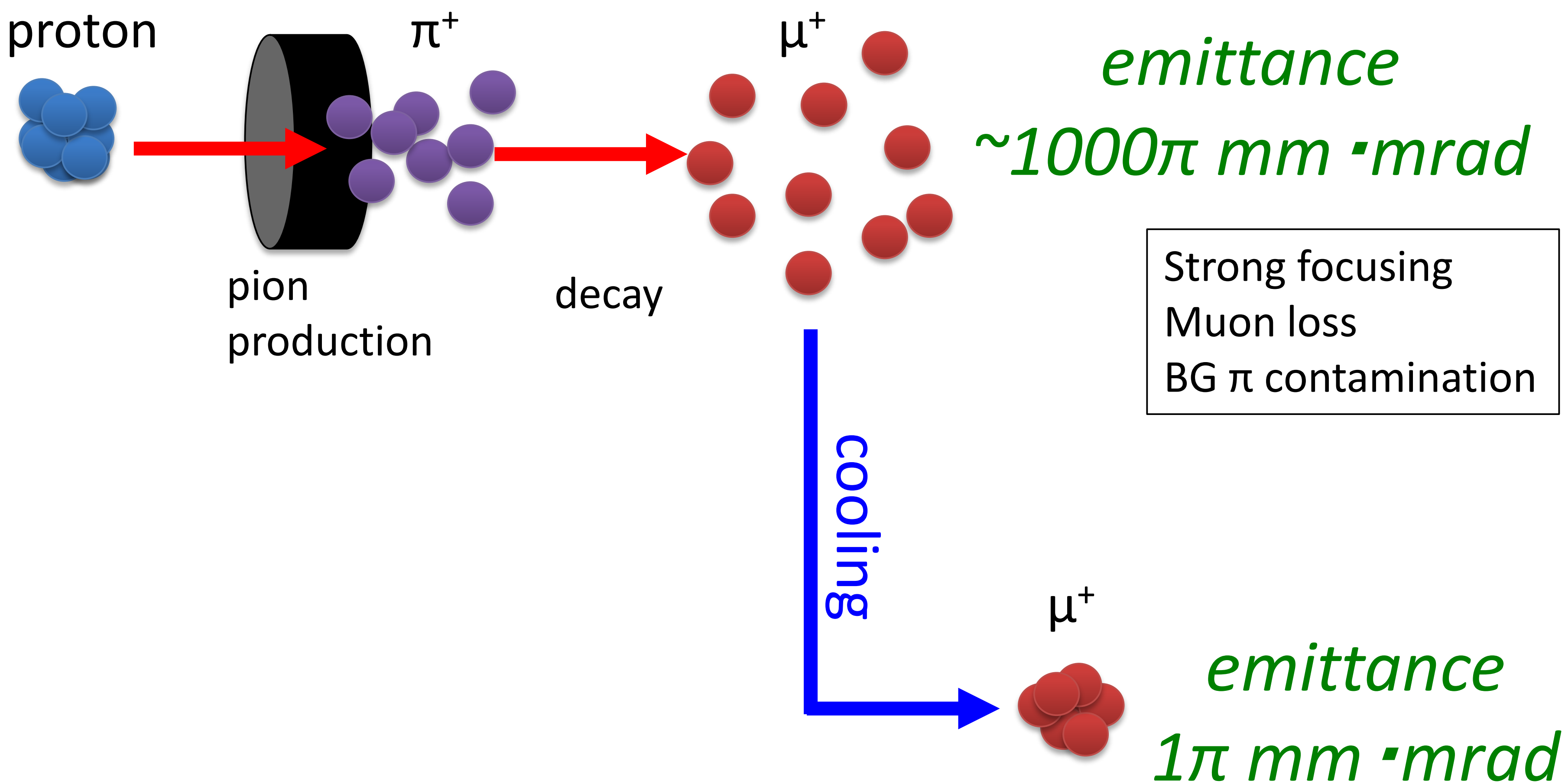
Make E=0 by removing strong focus requirement

- not restricted to high "magic" momentum

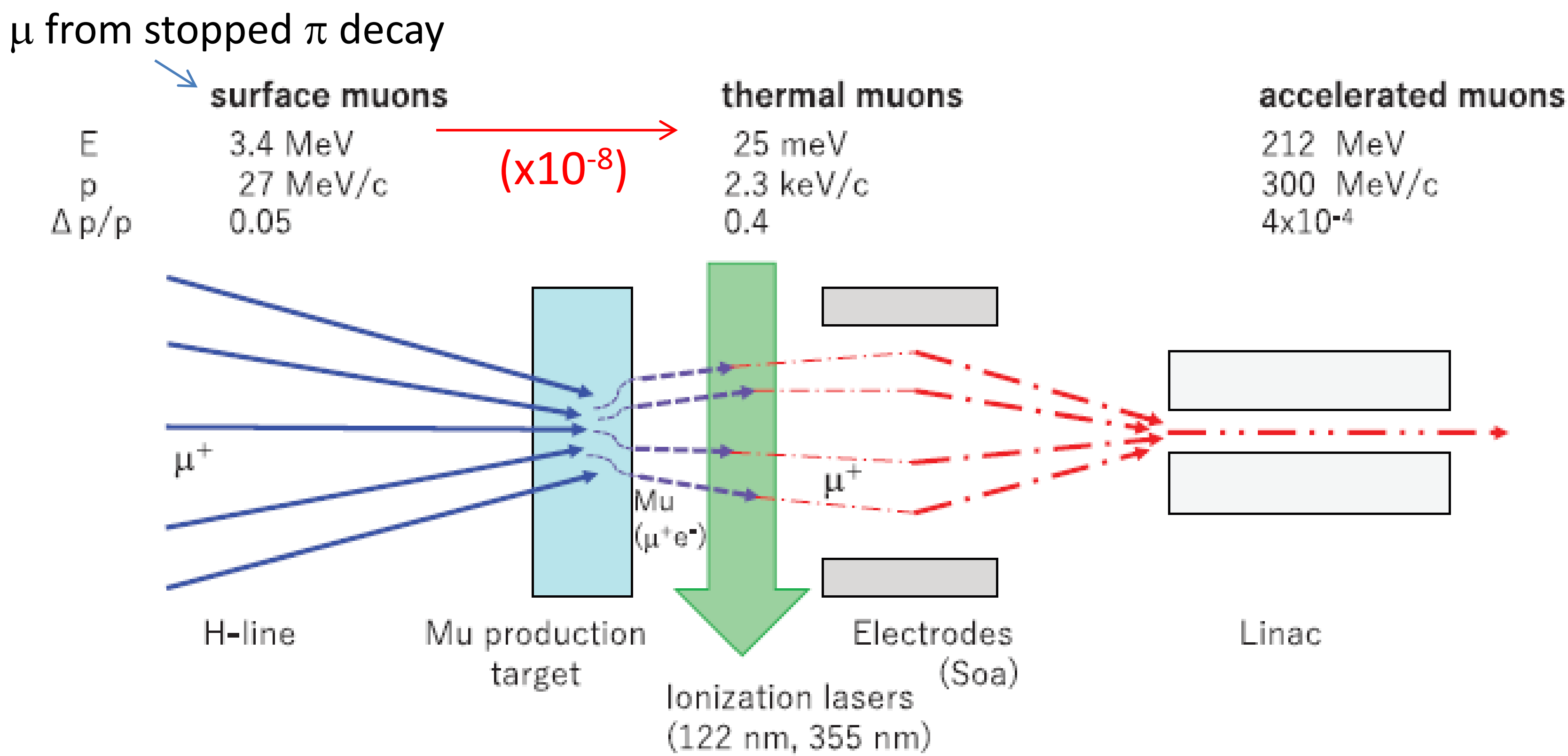
Need of well controlled muon beam

- start with ultra cold muon beam

Key technique: Reaccelerated muon beam with thermal energy emittance



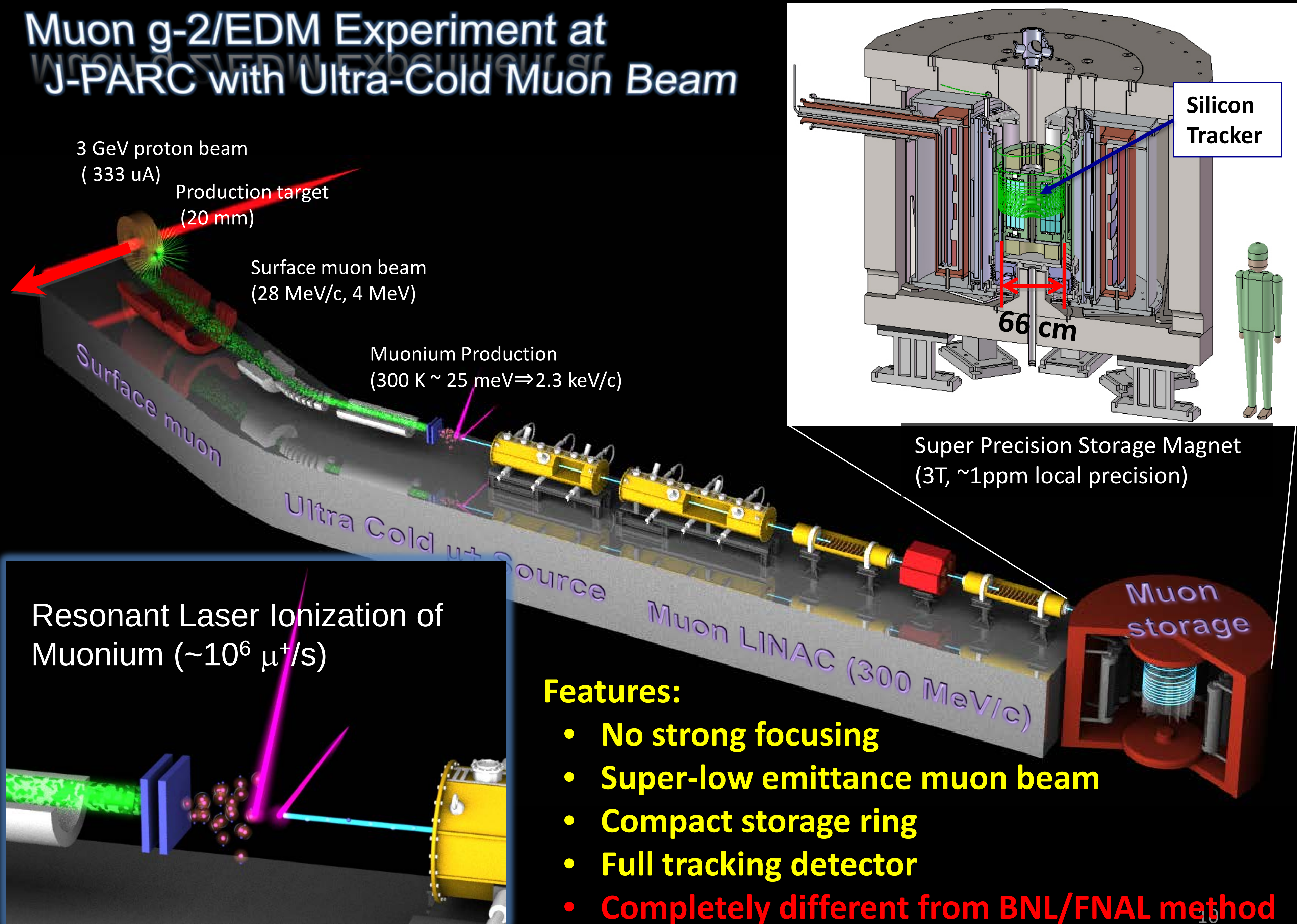
How to make it?



Requirements

1) Intense primary muon beam
2) Efficient muon cooling
3) Acceleration

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



Features:

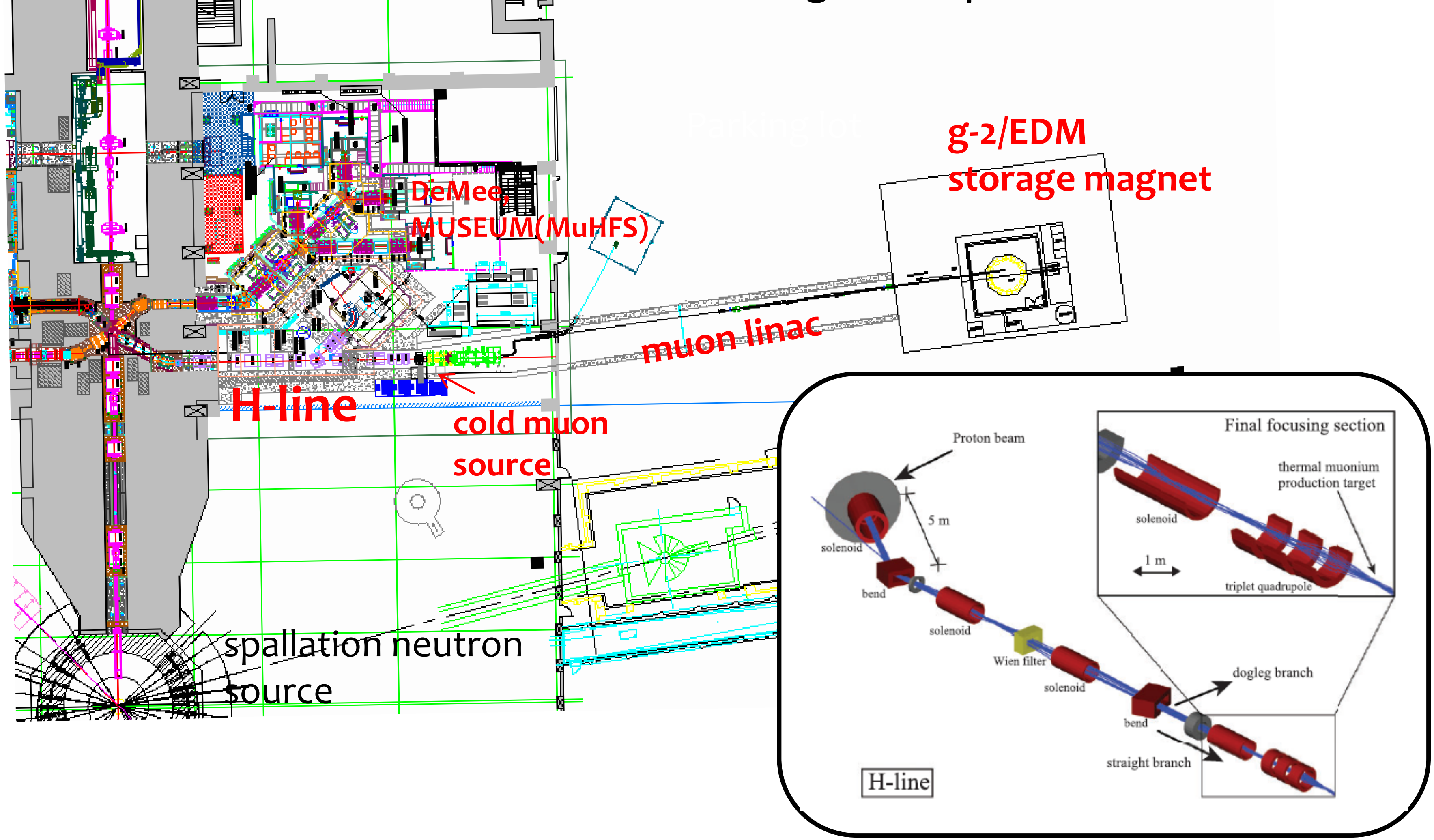
- **No strong focusing**
- **Super-low emittance muon beam**
- **Compact storage ring**
- **Full tracking detector**
- **Completely different from BNL/FNAL method**

J-PARC and Muon source

1 MW 3 GeV proton beam

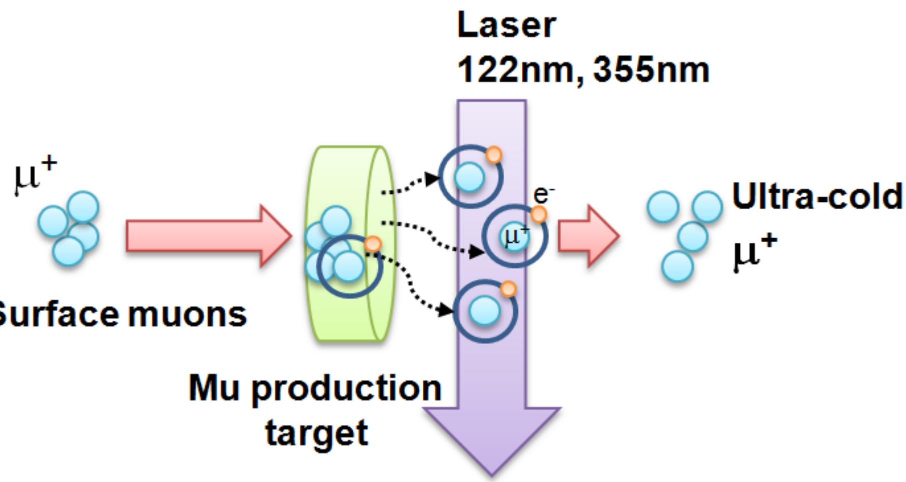
High-intensity muon beam @MLF H-line

10^8/s surface muon beam
with high acceptance muon channel



Muon Cooling-1: Thermal muonium

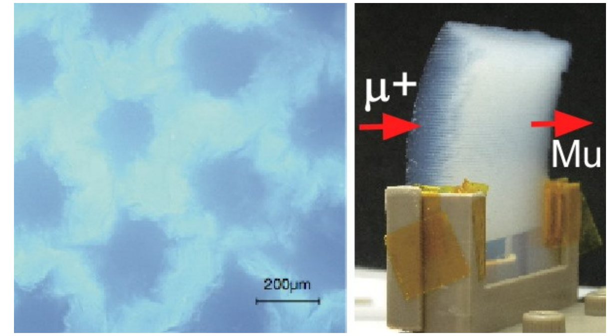
4 MeV muon -> 0.03 eV Muonium

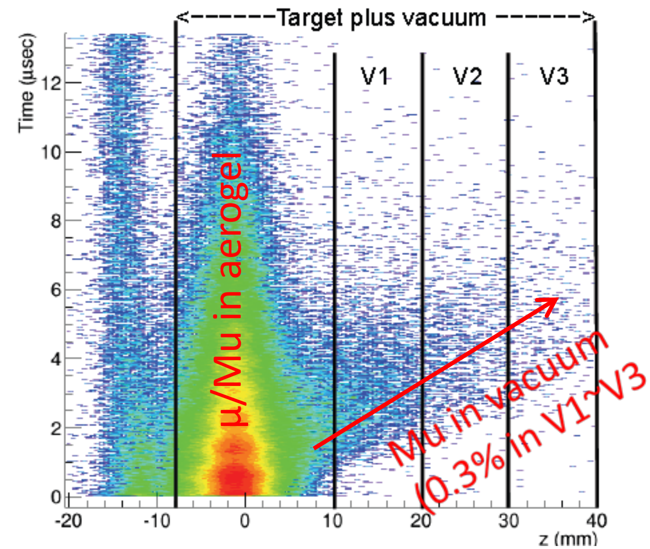


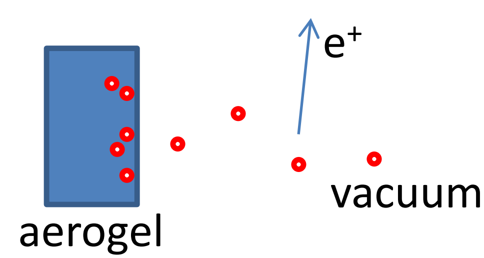
We developed silica aerogel!

Fast Mu diffusion through voids in aerogel
+ increased surface area with laser ablation
(TRIUMF S1249)

P. Bakule et al., Prog. Theor. Exp. Phys. 103C01 (2013)
G.A. Beer et al., Prog. Theor. Exp. Phys. 091C01 (2014)

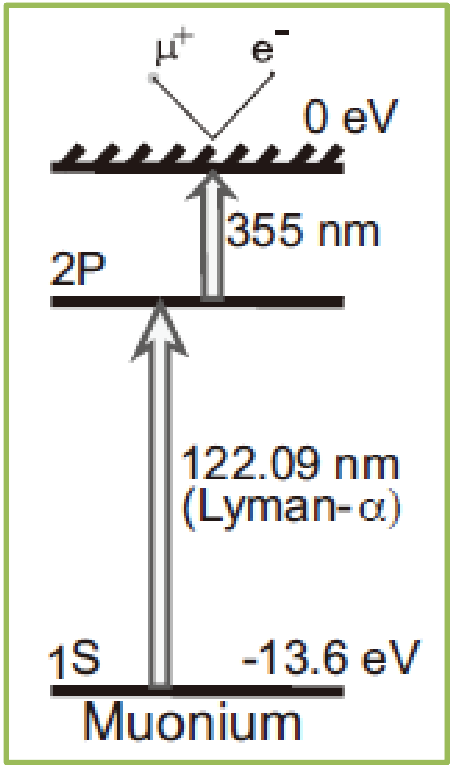




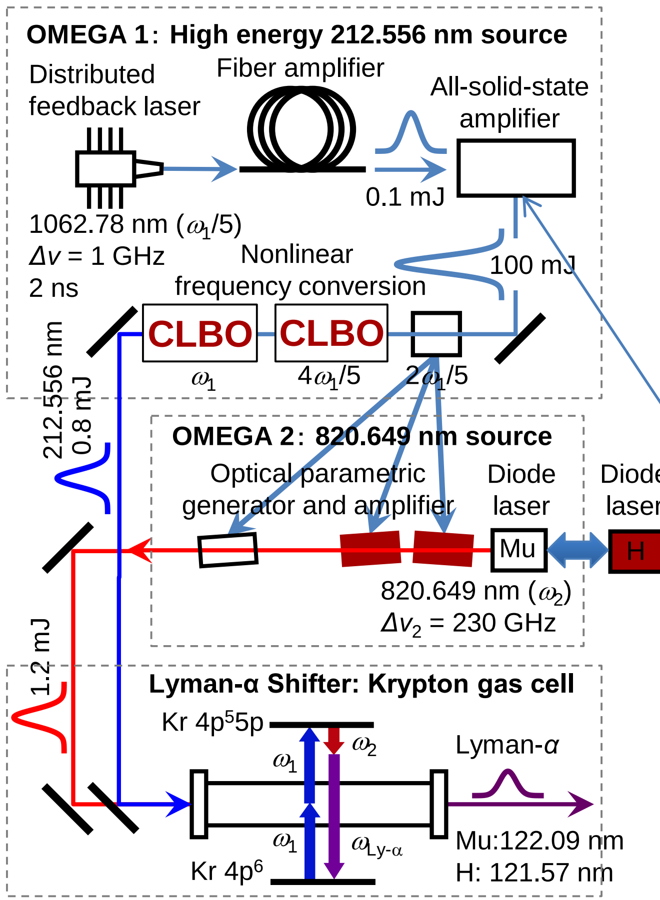


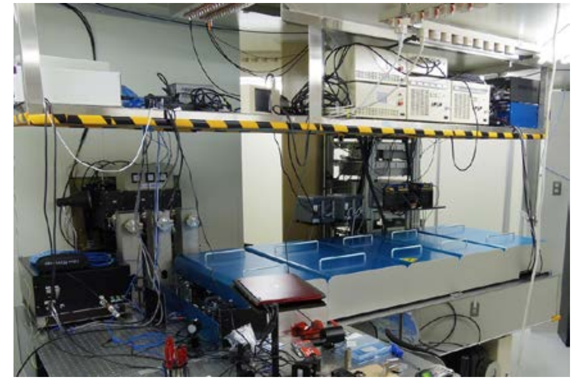
Muon cooling-2: Mu ionization with Lyman-alpha Laser

Remove e⁻ with lasers for acceleration



Improved Coherent Lyman-α System Configuration

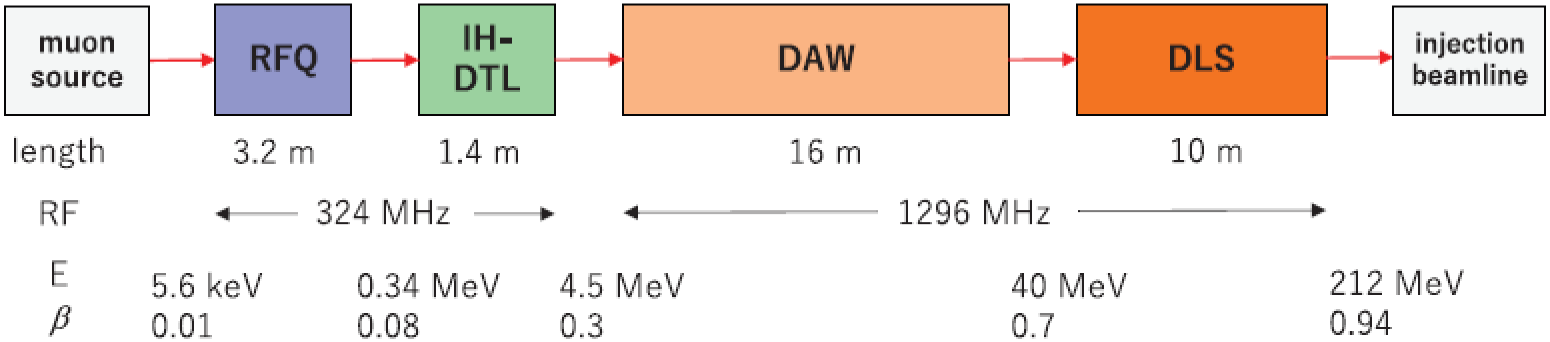




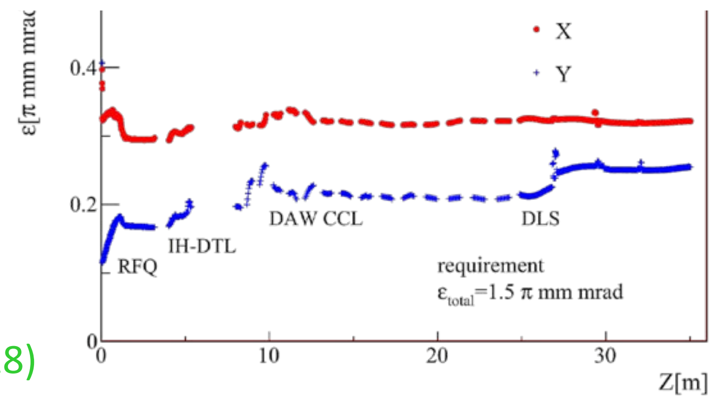
100 μJ pulsed Lyman-alpha laser + 400 mJ 355nm laser will ionize ~75% Mu

10 μJ Ly-α achieved, synthesizing larger YGAG crystal to increase $\omega_1/5$ power

Muon acceleration

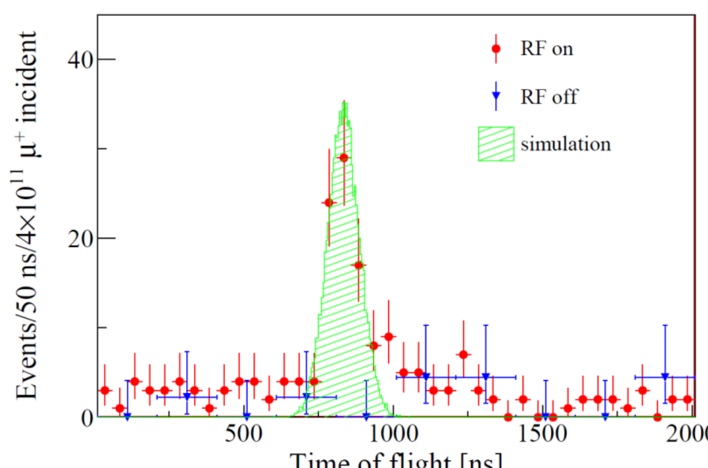


End to end simulation
- transmission loss ~7% + decay loss
- emittance growth is small

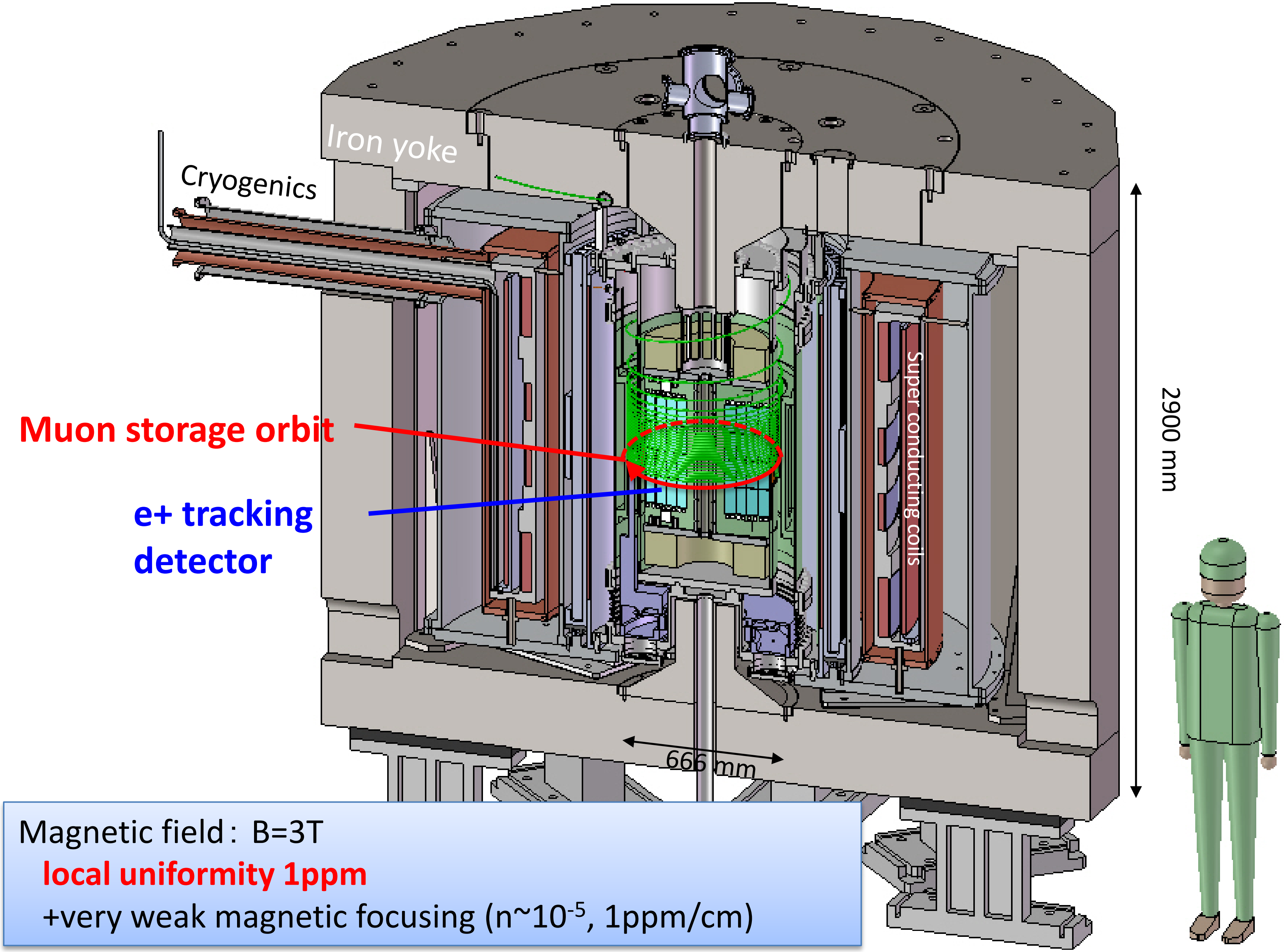


First muon acceleration with RFQ!

S. Bae et al., Phys. Rev. Accel. Beams 21, 050101 (2018)



Muon storage magnet and detector



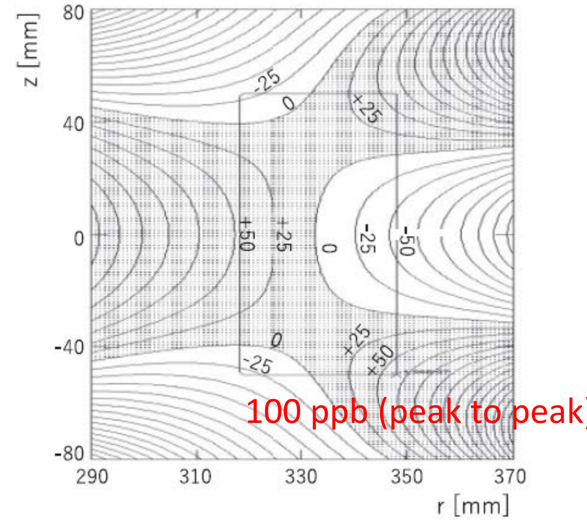
Magnetic field : B=3T

local uniformity 1ppm

+very weak magnetic focusing ($n \sim 10^{-5}$, 1ppm/cm)

Magnetic field

design field (in ppb)



Detailed Magnet Design in progress

fabrication 2 years, commissioning 1 year

M. Abe et al., Nucl. Instrum. Meth. A 890, 51 (2018)

$$B_r = -n\frac{B_{0z}}{R}z,$$

$$B_z = B_{0z} - n\frac{B_{0z}}{R}(r-R) + n\frac{B_{0z}}{2R^2}z^2,$$

n~1.5 x 10^{-4}

Shimming study with Mu HFS Coil (1.7 T)

With shim plate, achieved local homogeneity

5.31 ppm -> 0.45 ppm in 30cm DSS

+ correction coils

Field monitor

Cross calibration of J-PARC and FNAL NMR probes in progress at ANL

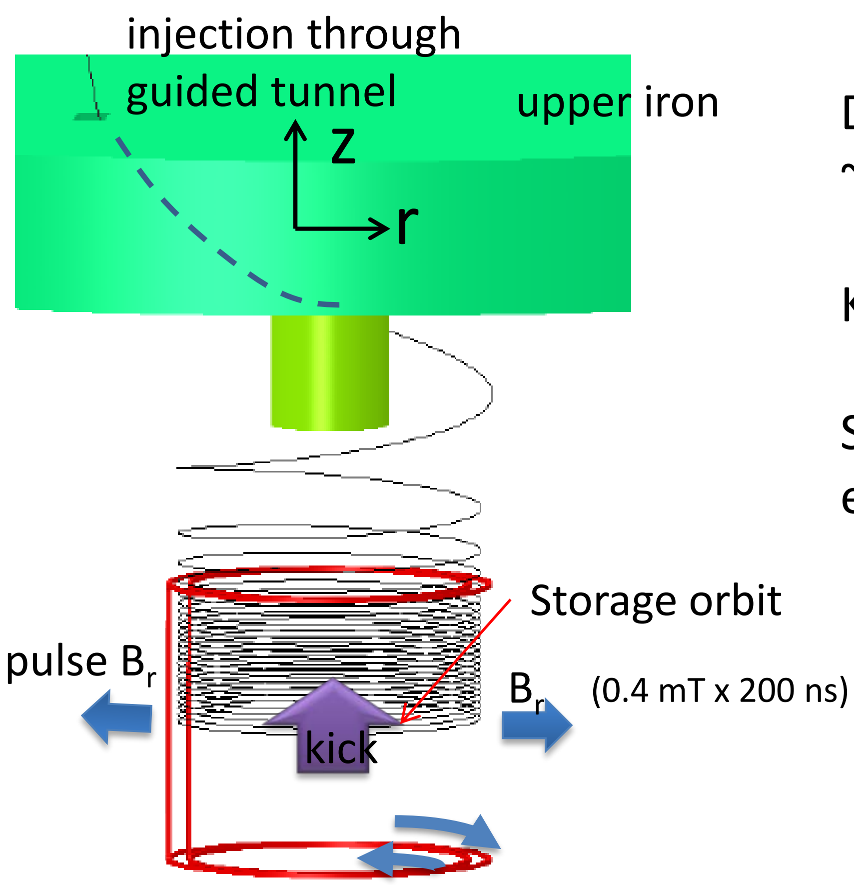
Study of material effect

$$B_{\text{Measure}} = B_0 + \delta_s$$

Spiral beam Injection

Spiral injection + weak magnetic kick (8 mr) to storage-orbit

H. Iinuma et al., NIM A 832, 51 (2016)



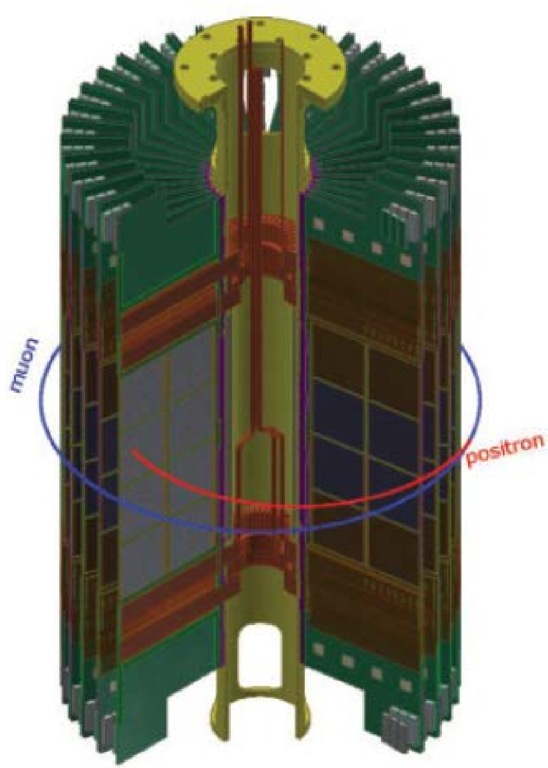
Detailed trajectory design with OPERA field
~80% injection efficiency

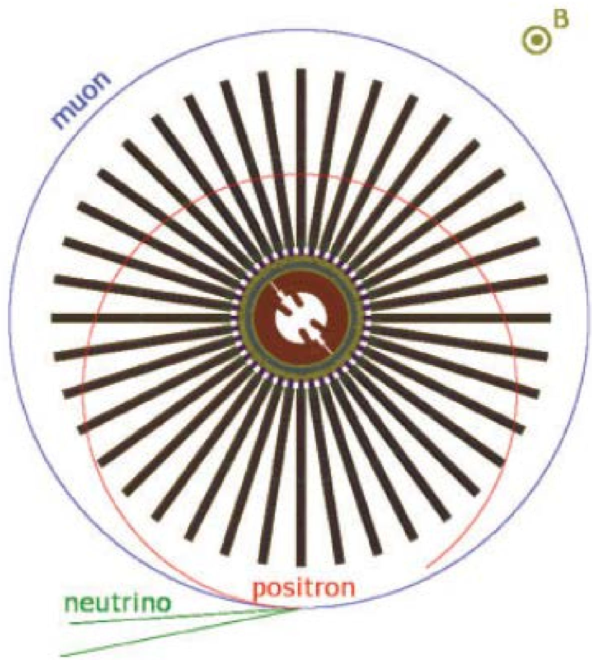
Kicker coil and power supply design

Spiral injection test with mini-solenoid and electron gun

Positron Detector

Measure muon decay positron tracks with Silicon-strip detectors
Forward/backward decay gives different positron momentum





Test boards have been studied
at J-PARC and electron at Tohoku-U

40 vanes
each 200 mm(R) x 400 mm(Z)
Single-sided Silicon strip sensor

Detectors and track reconstruction

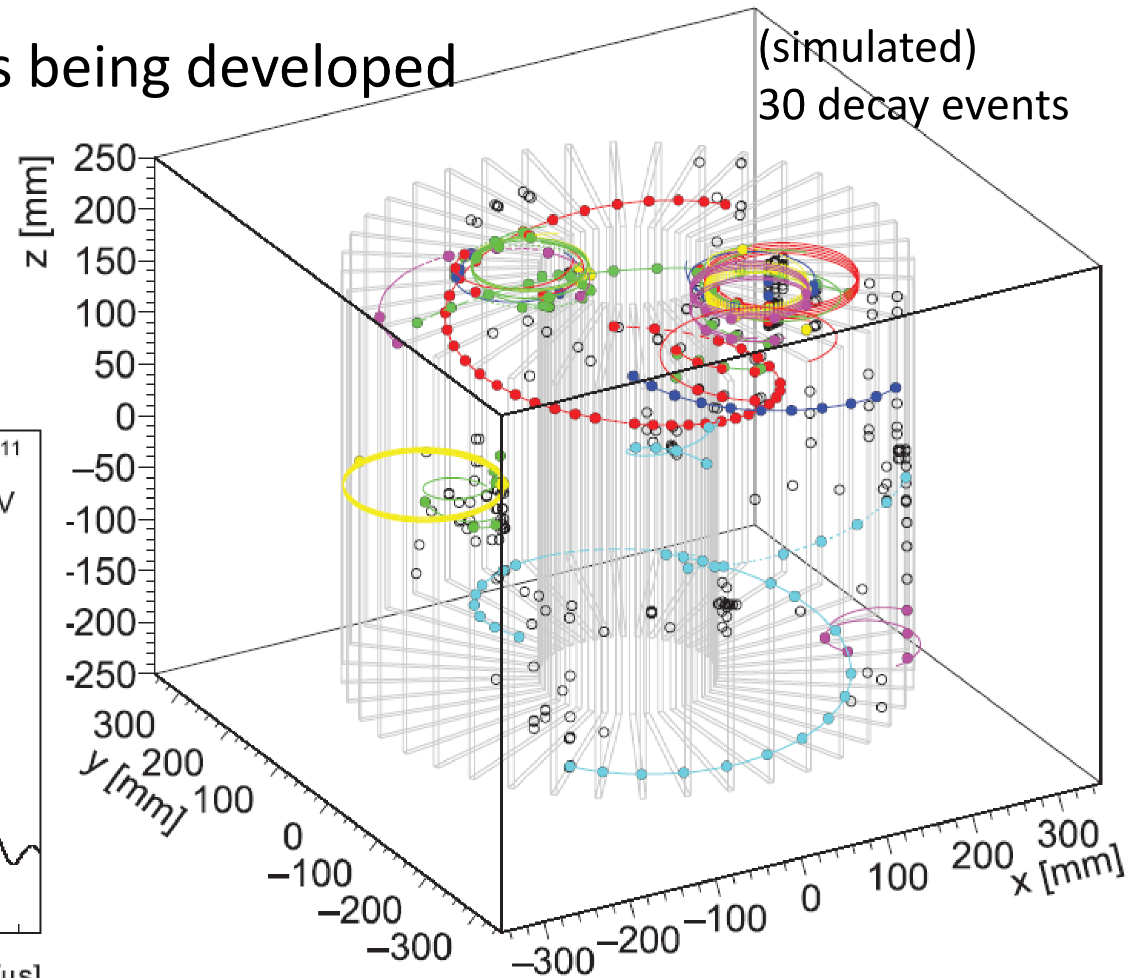
Decay of 300 MeV/c muons

Spin direction - positron energy range (sensitivity optimization)

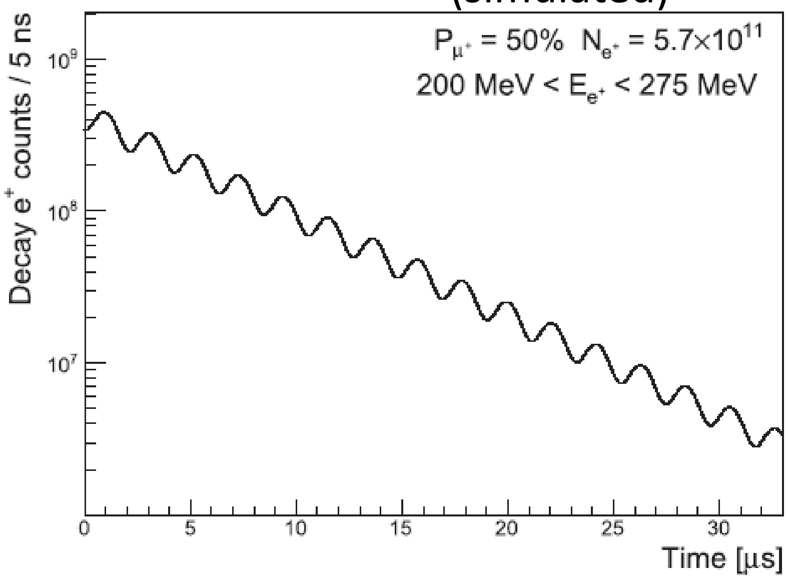
E = 200~275 MeV

Reconstruction software is being developed

(simulated)
30 decay events



(simulated)



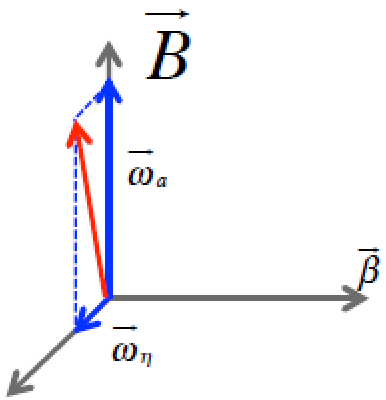
Muon EDM

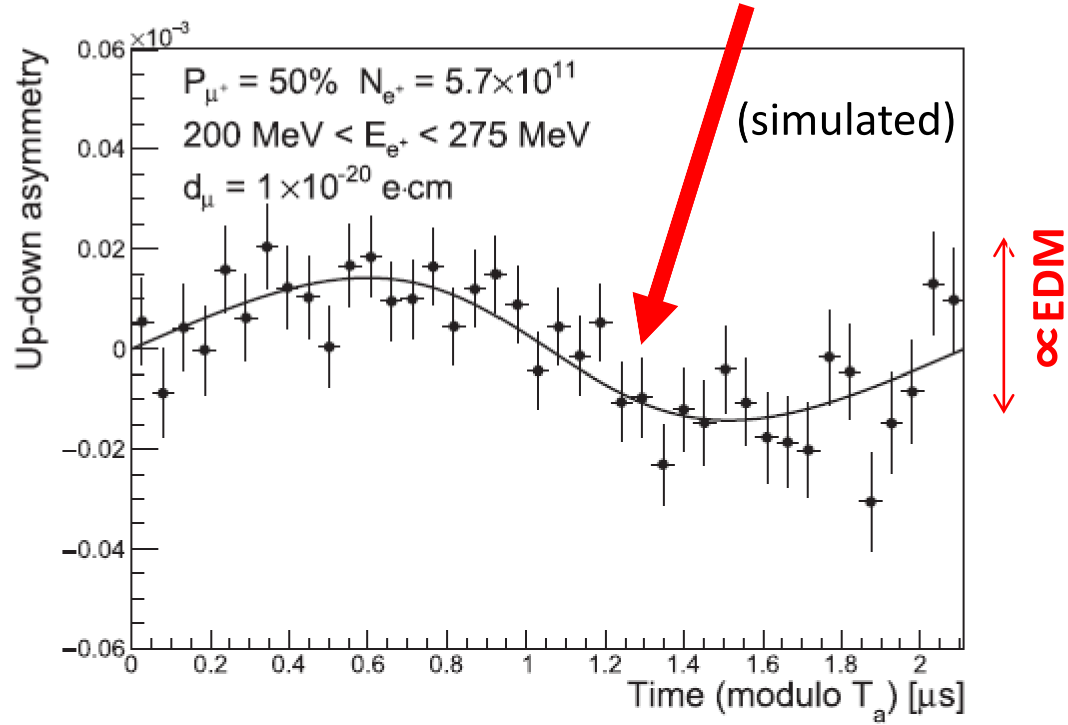
no E-field

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$

Observation

Out-of-plane (up-down) oscillation with g-2 frequency





Key

Precise detector alignment and monitor system

Expected beam intensity and statistical error

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

(from TDR)

Statistical error in 2 years run - 450 ppb (comparable to BNL)
(and $\Delta d_\mu < 10^{-21}$ e cm, x1/100)

Needs further improvement towards <200 ppb

Muon polarization recovery (0.5->0.9), improving Mu emission, ...

Our systematic error goals

in ω_a
(Precession measurement)

in ω_p
(B-field)

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56

aim at systematic error better than 100 ppb

Muon g-2/EDM@J-PARC : Status

J-PARC PAC

Letter of Intent submitted (July 2009) - 45 authors
Conceptual Design Report (Jan 2012)
Stage 1 approval as E34 (Sep 2012)
Technical Design Report (TDR) (May 2015) - 144 authors
Focused Review on TDR (Nov 15-16, 2016)
Stage 2 approval (Nov 2018)

R&D (including partial construction)

-using several competitive grants
Detector, ...
- in collaboration with other experiments
Lyman-alpha laser (muon microscope)
Magnet (Mu HFS)

Construction funding request has been submitted

from R&D to construction phase!
- We look for new collaborators

Status (collaboration)

Structure

~100 members

Spokes person : Tsutomu Mibe, KEK

Collaboration board chairman: Seonho Choi, Seoul Univ.

Collaboration meetings (every half year)

To share/discuss global matters and progress from each subgroup

18th Meeting, Seoul, Jun 2019

PTEP

Prog. Theor. Exp. Phys. **2019**, 053C02 (22 pages)
DOI: 10.1093/ptep/ptz030

A new approach for measuring the muon anomalous magnetic moment and electric dipole moment

M. Abe[1], S. Bae[2,3], G. Beer[4], G. Bunce[5], H. Choi[2,3], S. Choi[2,3], M. Chung[6], W. da Silva[7], S. Eidelman[8,9,10], M. Finger[11], Y. Fukao[1], T. Fukuyama[12], S. Haciomeroglu[13], K. Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma[18], H. Ikeda[19], M. Ikeno[1], K. Inami[17], K. Ishida[20], T. Itahashi[21], M. Iwasaki[20], Y. Iwashita[22], Y. Iwata[23], R. Kadono[1], S. Kamal[24], T. Kamitani[1], S. Kanda[20], F. Kapusta[7], K. Kawagoe[25], N. Kawamura[1], B. Kim[2,3], Y. Kim[26], T. Kishishita[1], R. Kitamura[14], H. Ko[2,3], T. Kohriki[1], Y. Kondo[14], T. Kume[1], M. J. Lee[13], S. Lee[13], W. Lee[27], G. M. Marshall[28], Y. Matsuda[29], T. Mibe[1,30], Y. Miyake[1], T. Murakami[1], K. Nagamine[1], H. Nakayama[1], S. Nishimura[1], D. Nomura[1], T. Ogitsu[1], S. Ohsawa[1], K. Oide[1], Y. Oishi[1], S. Okada[20], A. Olin[4,28], Z. Omarov[26], M. Otani[1], G. Razuvaev[8,9], A. Rehman[30], N. Saito[1,31], N. F. Saito[20], K. Sasaki[1], O. Sasaki[1], N. Sato[1], Y. Sato[1], Y. K. Semertzidis[26], H. Sendai[1], Y. Shatunov[32], K. Shimomura[1], M. Shoji[1], B. Shwartz[9,32], P. Strasser[1], Y. Sue[17], T. Suehara[25], C. Sung[6], K. Suzuki[17], T. Takatomi[1], M. Tanaka[1], J. Tojo[25], Y. Tsutsumi[25], T. Uchida[1], K. Ueno[1], S. Wada[20], E. Won[27], H. Yamaguchi[1], T. Yamanaka[25], A. Yamamoto[1], T. Yamazaki[1], H. Yasuda[33], M. Yoshida[1], and T. Yoshioka[25,*]

[1] *High Energy Accelerator Research Organization (KEK), Ibaraki 319-1106, Japan*
[2] *Seoul National University, Seoul 08826, Republic of Korea*
[3] *Institute for Nuclear and Particle Astrophysics, Seoul 08826, Republic of Korea*
[4] *University of Victoria, British Columbia V8W 2Y2, Canada*
[5] *Retired*
[6] *Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Republic of Korea*
[7] *LPNHE (CNRS/IN2P3/UPMC/UDD), Paris 75005, France*
[8] *Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[9] *Novosibirsk State University, Novosibirsk 630090, Russia*
[10] *Lebedev Physical Institute RAS, Moscow 119333, Russia*
[11] *Charles University, Prague 11000, Czech Republic*
[12] *Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*
[13] *Institute for Basic Science (IBS), Daejeon 34126, Republic of Korea*
[14] *Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan*
[15] *Niigata University, Niigata 950-2181, Japan*
[16] *Tokyo Institute of Technology, Tokyo 152-8550, Japan*
[17] *Nagoya University, Aichi 464-8601, Japan*
[18] *Ibaraki University, Ibaraki 310-8502, Japan*
[19] *Japan Aerospace Exploration Agency (JAXA), Tokyo 229-8510, Japan*
[20] *RIKEN, Saitama 351-0198, Japan*
[21] *Graduate School / School of Science, Osaka University, Osaka 560-0043, Japan*
[22] *Institute for Chemical Research (ICR), Kyoto University, Kyoto 611-0011, Japan*
[23] *National Institute of Radiological Sciences (NIRS), Chiba 263-0024, Japan*
[24] *University of British Columbia, British Columbia V6T 1Z4, Canada*
[25] *Kyushu University, Fukuoka 819-0395, Japan*

First Collaboration Paper!

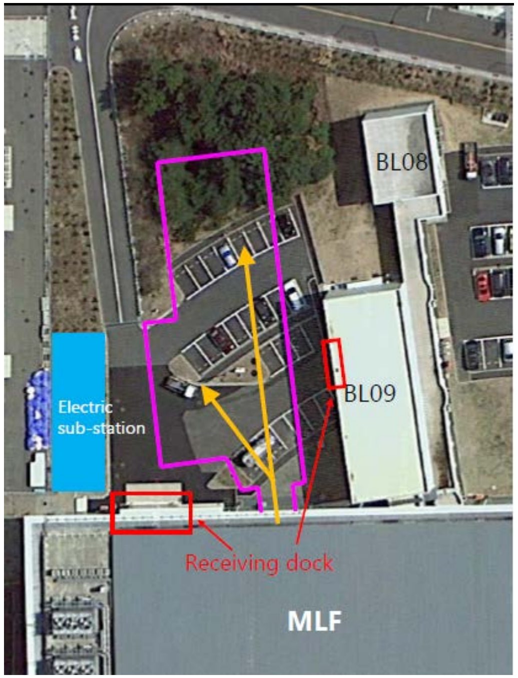
M. Abe et al., PTEP 2019,053C02 (May 2019) - 96 authors

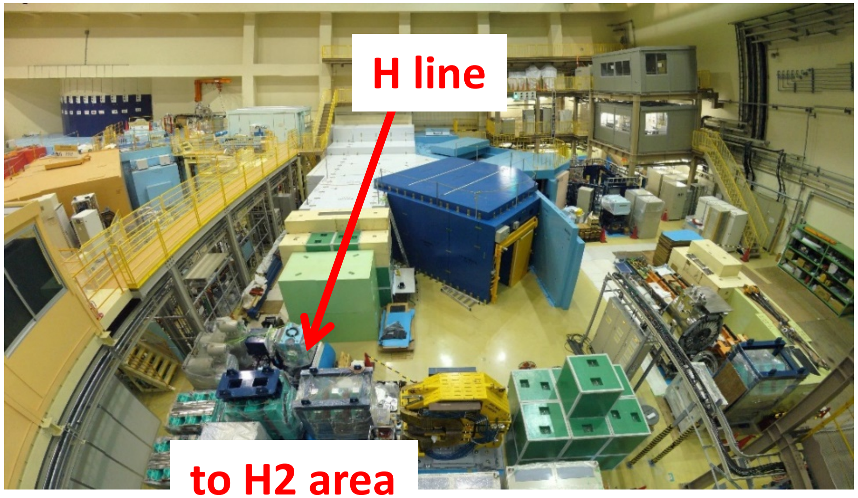
"A New approach for Measuring the Muon Anomalous Magnetic Moment and Electron Dipole Moment"

Status (Construction/Run Schedule)

H-line first muon beam expected next year.
Electric power station under construction.
Building extension is being designed.

Intended schedule
2019 Funding request from KEK to MEXT
2020-2023 Construction
2023 Commissioning
2024-2026 Data Run





Summary

We aim to measure muon g-2 and EDM
with accelerated low emittance muon beam at J-PARC.

An independent measurement to BNL/FNAL

R&D phase is ending.
Construction phase is starting.

Further information

http://g-2.kek.jp