



# Muon $g-2$ /EDM Experiment at J-PARC and Software Techniques

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for the J-PARC E34 Collaboration

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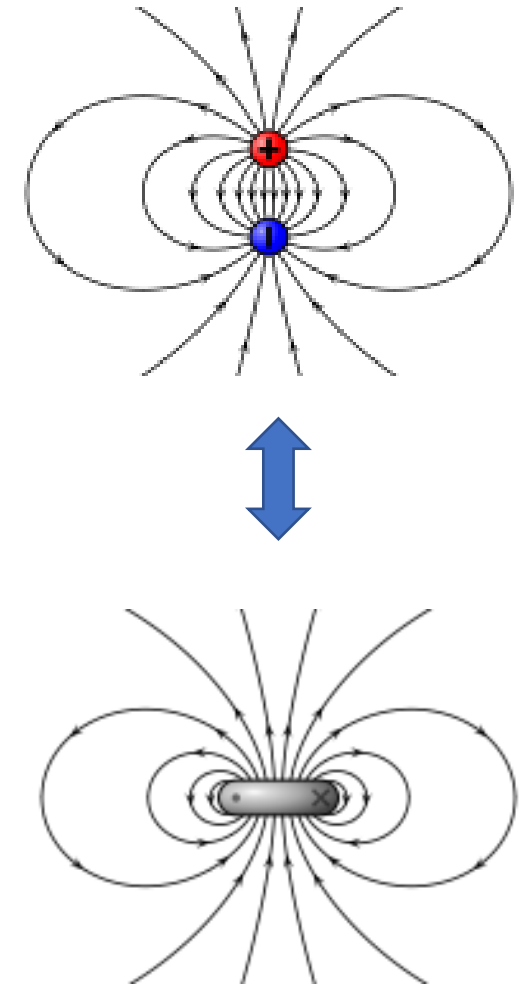
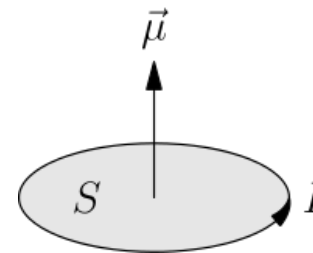
- Muon  $g-2$ 
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  - Electric dipole moment
  - Muon EDM
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- Status of J-PARC experiment

# What is $g-2$ ?

- It is a quantity formally called as an “anomalous” magnetic dipole moment.
- Let’s start reviewing the magnetic dipole moment first.

# Magnetic Dipole Moment

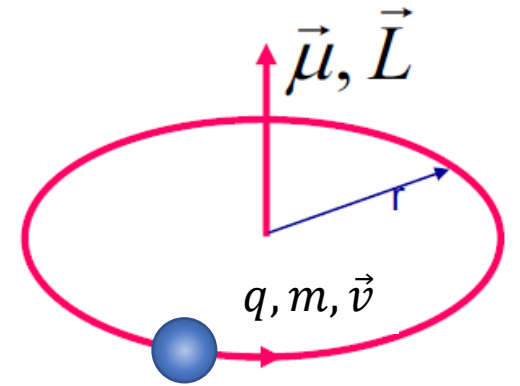
- If a magnetic monopole exists, the magnetic dipole moment of two opposite magnetic charges can be defined as  $\vec{\mu} = q_m \vec{l}$ .
  - $q_m$ : magnetic charge of each monopole
  - $\vec{l}$ : distance vector between two monopoles
- A magnetic monopole has not yet been discovered but an electric current also creates a magnetic field like the two opposite magnetic charges.
- The magnetic dipole moment of a current loop can be defined as  $|\vec{\mu}| = IS$  to be consistent with the magnetic field created by two magnetic monopoles.
  - $I$ : current
  - $S$ : area of closed loop
  - Direction is perpendicular to current



# Magnetic Moment and Angular Momentum

- If a particle with a charge of  $q$  ( $>0$ ) circulates in the radius of  $r$  with the velocity  $v$ , it can be regarded as a closed current of  $I = -\frac{qv}{2\pi r}$  and the area  $S = \pi r^2$ .
- Then, the magnetic dipole moment is  $\vec{\mu} = \frac{q\vec{r} \times \vec{v}}{2}$
- On the other hand, the angular momentum of this particle (with respect to the center of the circle) is written as  $\vec{L} = \vec{r} \times \vec{p} = m\vec{r} \times \vec{v}$ .
- Thus, the magnetic dipole moment of this system can be written as

$$\vec{\mu} = \frac{q}{2m} \vec{L}.$$



# Intrinsic Magnetic Moment

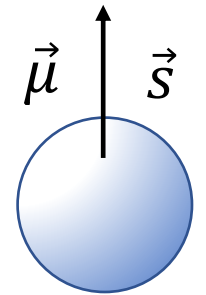
- A particle has an intrinsic angular moment, spin.
- The magnetic dipole moment also arises from the particle spin and

it is written as  $\vec{\mu} = g \left( \frac{q}{2m} \right) \vec{S}$ .

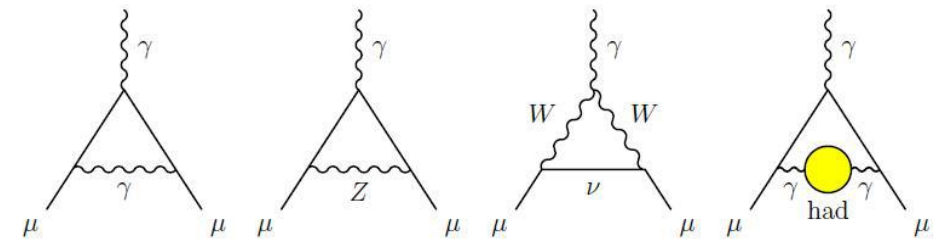
- Here,  $g$  is a so-called  $g$ -factor.
- In classical electrodynamics,  $g = 1$ .
- In quantum electrodynamics, from the Dirac equation,  $g = 2$  for a point-like, spin  $\frac{1}{2}$  particle.
- But for the existing spin  $\frac{1}{2}$  particles, we know that  $g$  is slightly larger than 2 even if it is an elementary particle due to vacuum polarization.
- The deviation of  $g$  from 2 is called as the anomalous magnetic (dipole) moment (or  $g-2$ ) and is defined as

$a = \frac{g-2}{2}$ .

- For muon,  $a_\mu = 0.00116591810(43)$  (0.37 ppm) from the Standard Model prediction according to the white paper by muon  $g-2$  theory initiative ([Phys. Rep. 887 \(2020\) 1-166](#)).



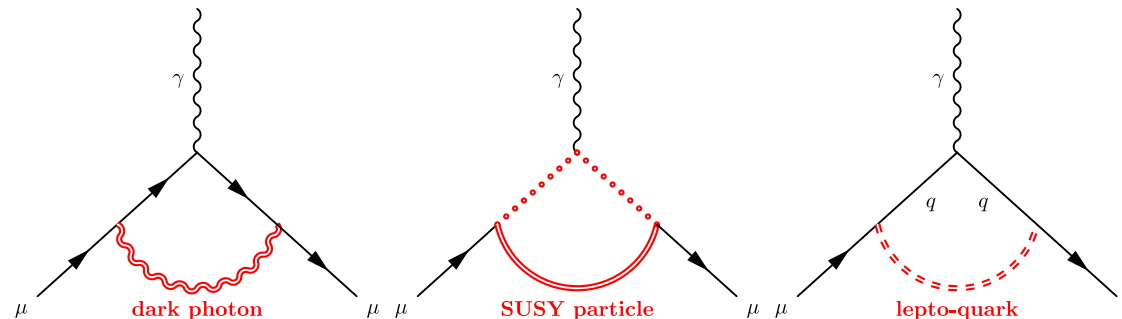
$m$ : mass  
 $q$ : charge



Example diagrams of vacuum polarization of muon

# Why is $g-2$ interesting?

- In vacuum polarization of muon, not only the Standard Model particle but other undiscovered particles can contribute.
  - They will shift the  $g-2$  value from the Standard Model prediction.



- By measuring the  $g-2$  in high precision, we may find a physics beyond the Standard Model.
- Then, how to measure it?

# Larmor Precession

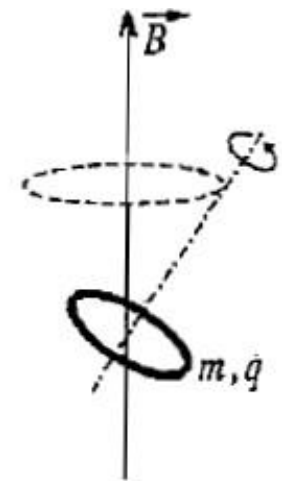
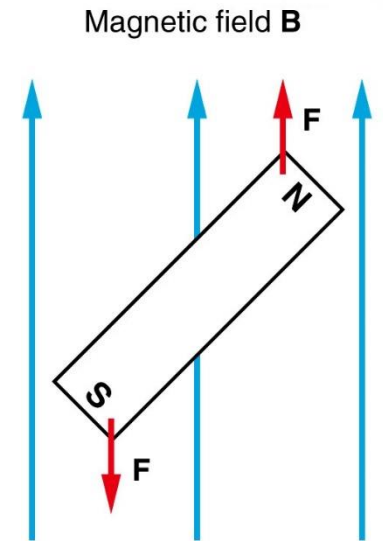
- The magnetic dipole moment feels a torque in a magnetic field like a bar magnet.

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

- The angular momentum is changed by a torque and for a circulating particle, the following equation holds.

$$\frac{d\vec{L}}{dt} = \vec{\tau} = \frac{q}{2m} \vec{L} \times \vec{B}$$

- In a uniform magnetic field, this equation leads to precession of the angular momentum with the angular velocity vector of  $\vec{\omega} = -\frac{q}{2m} \vec{B}$ .
  - This is the Larmor precession.





# Spin Precession

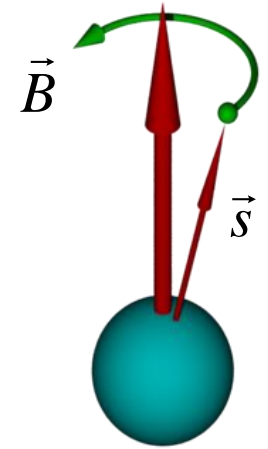
- The same equation holds for the spin of the rest particle.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} = g \frac{q}{2m} \vec{s} \times \vec{B}$$

- The angular velocity vector is  $\vec{\omega}_{s,\text{rest}} = -g \frac{q}{2m} \vec{B}$ .
  - g-factor can be obtained from this equation but it measures  $g$  rather than  $g-2$ .
- For a moving particle, this equation needs relativistic correction and the angular velocity vector is obtained as

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

- This is called the Thomas precession.
- $\gamma$  is Lorentz factor and for  $\gamma=1$ , it agrees with the Larmor precession.



# g-2 Precession

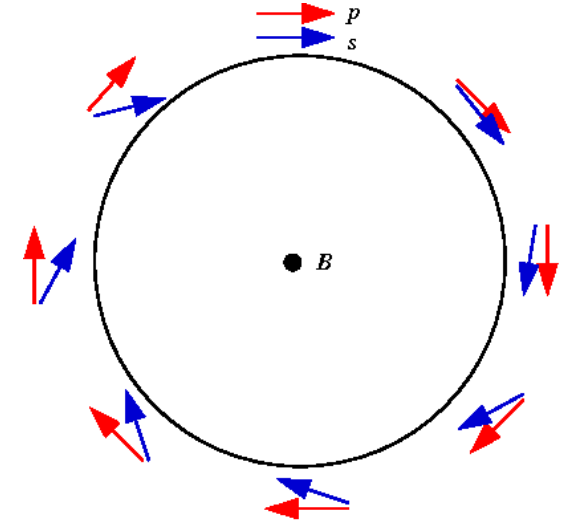
- A particle in motion rotates in the magnetic field (so-called cyclotron motion) and its angular velocity vector is

$$\vec{\omega}_c = -\frac{q}{m\gamma} \vec{B}.$$

- Then, the spin vector with respect to the particle momentum rotates by

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right) \frac{q}{m} \vec{B} = -a \frac{q}{m} \vec{B}.$$

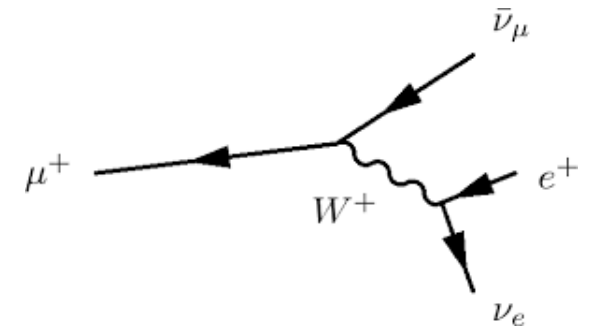
- Lorentz factor ( $\gamma$ ) is cancelled.
- Using this relation,  $a = \frac{g-2}{2}$  can be obtained rather than  $g$ .
  - Since  $g$  is close to 2 for muon,  $10^3$  times higher sensitivity is expected by measuring  $a$ .



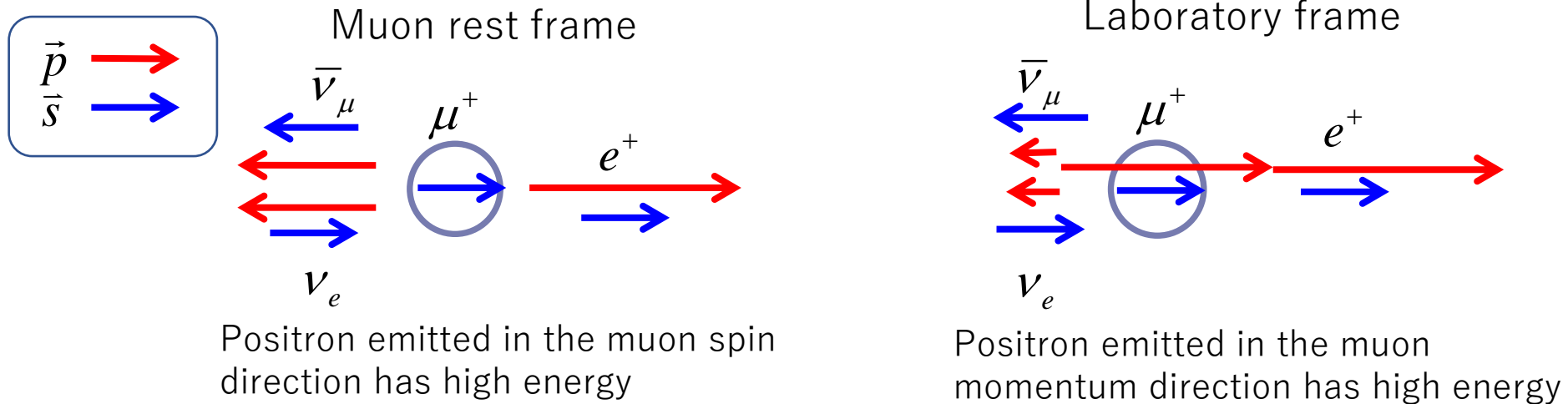
For  $g > 2$ , the spin precesses faster than the cyclotron motion.

# Muon Decay

- How to measure the muon spin direction in motion?
  1. Decay positron (electron) convey the parent muon spin information because of the weak interaction.
    - The weak interaction involves left-handed particles (or right-handed anti-particles) only.
    - If a positron is emitted in the same direction as the muon spin, it tends to be high energy.
  2. If the muon is moving in a relativistic velocity, a positron emitted in the same direction as the muon momentum has high energy.

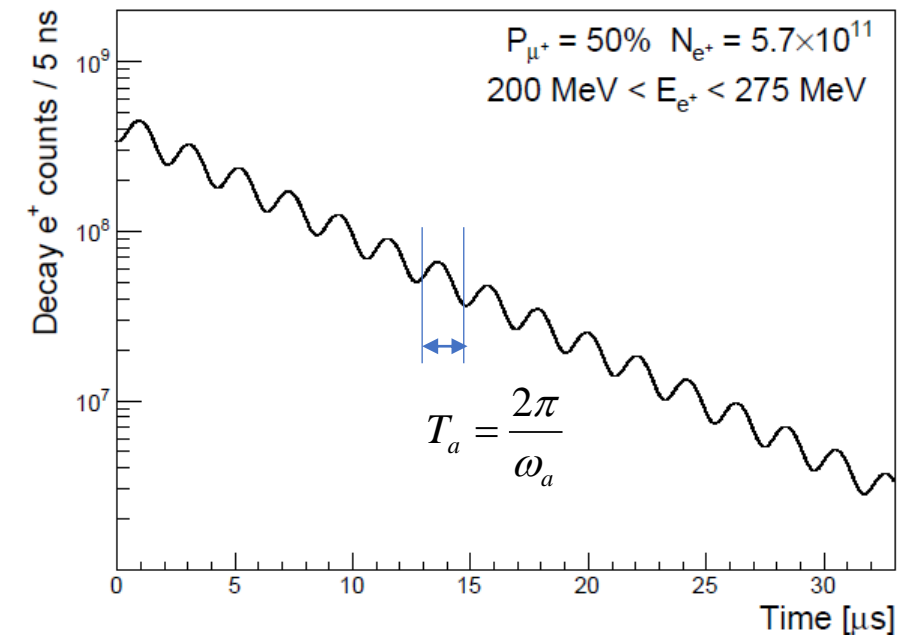
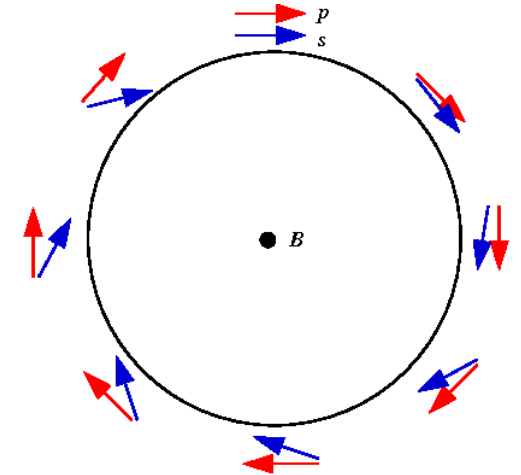


By choosing high energy (momentum) positrons, muons with their spin in the same direction as the momentum direction are selected.



# Measurement of g-2

- The number of high energy positrons from the decay of muons circulating in an uniform magnetic field shows a wiggle pattern with the angular frequency of  $\omega_a = \left| a_\mu \frac{e}{m} \vec{B} \right|$  as well as the exponential decay.
- If the  $|\vec{B}|$  is known,  $a_\mu$  can be calculated from this equation.
  - To measure  $a_\mu$  in high precision,  $\omega_a$  and  $|\vec{B}|$  are required to be measure precisely.



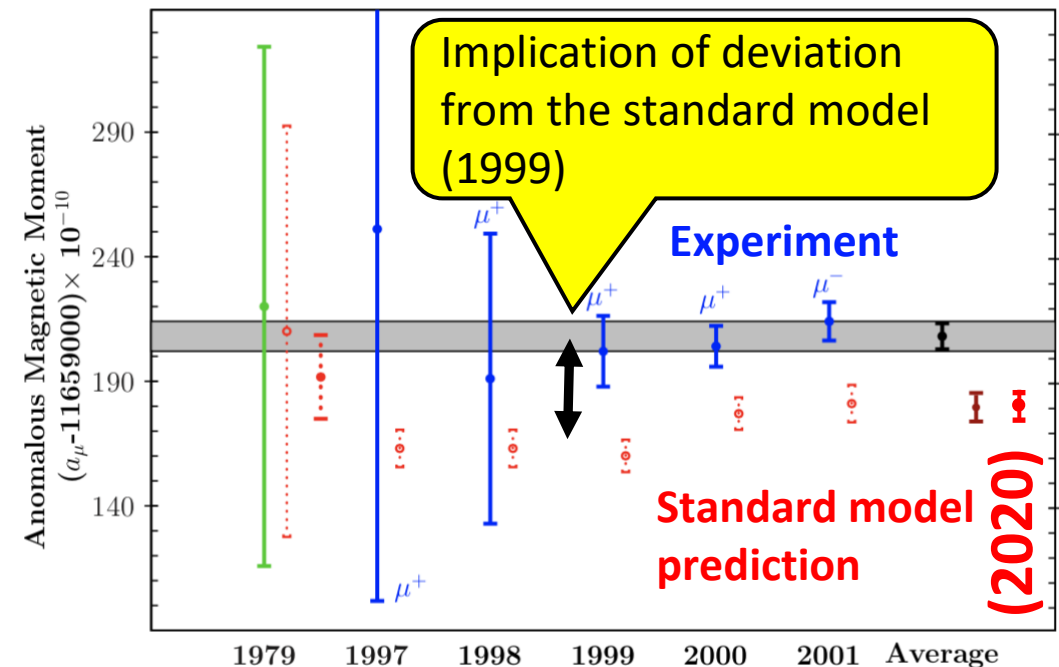
Simulated time spectrum of the number of decay positrons with  $200 < E < 275$  MeV

# Muon g-2 Anomaly

- Deviation of the muon g-2 from the SM prediction was firstly reported by the E821 experiment at Brookhaven National Laboratory (BNL) in 1999.
- The final result of the BNL experiment was published in 2006 and the measured g-2 value was  $a_{\mu} = 0.00116592080(63)$  (0.54 ppm).
  - [Phys. Rev. D 73, 072003 \(2006\)](#)
- There is  $3.7 \sigma$  deviation from the latest SM prediction in 2020.

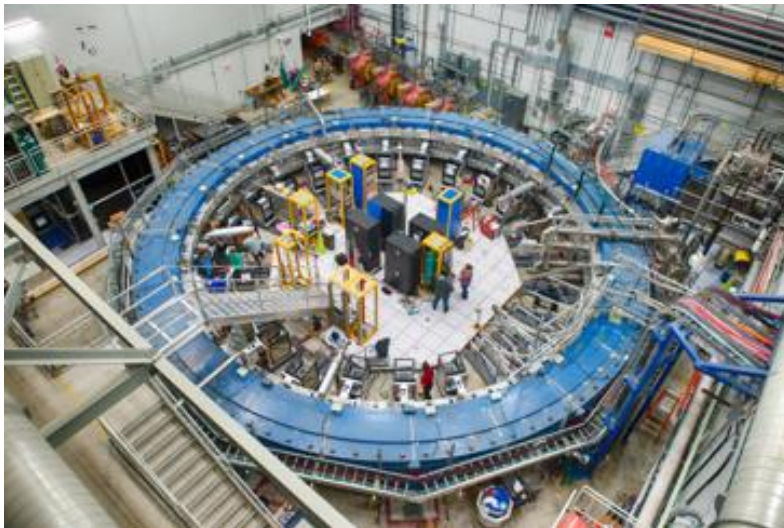


Muon storage ring of the BNL experiment

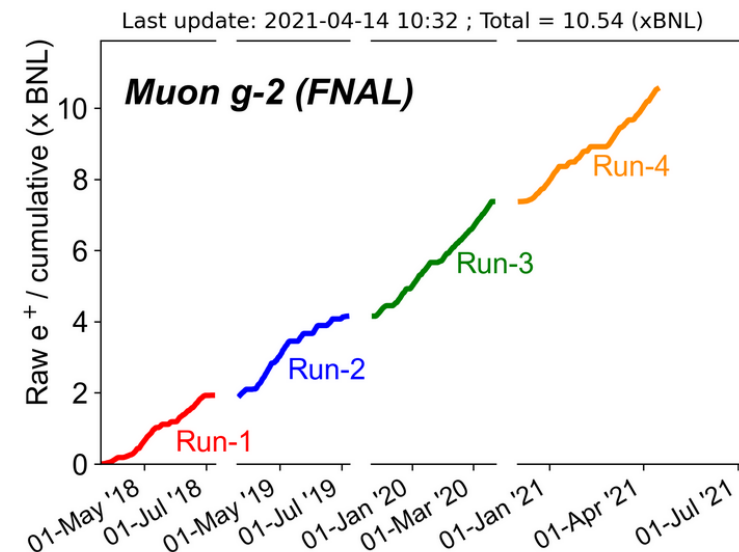


# FNAL E989 Experiment

- At Fermi National Accelerator Laboratory (FNAL), a new experiment to measure the muon  $g-2$  has been conducted using the same magnet ring at BNL while improving many sub-systems of the experiment.
- Basic experiment techniques are the same as the BNL experiment.
  - Transport 3.094 GeV/c polarized muon beam produced from pion decay
  - Store the muon beam in the magnet with 14 m diameter
  - Detect positrons from muon decay by calorimeters mainly
- They already recorded 10 times larger data than the BNL experiment.
  - Finally, 20 times larger data will be recorded and the statistical uncertainty on the muon  $g-2$  will reach 0.1 ppm.

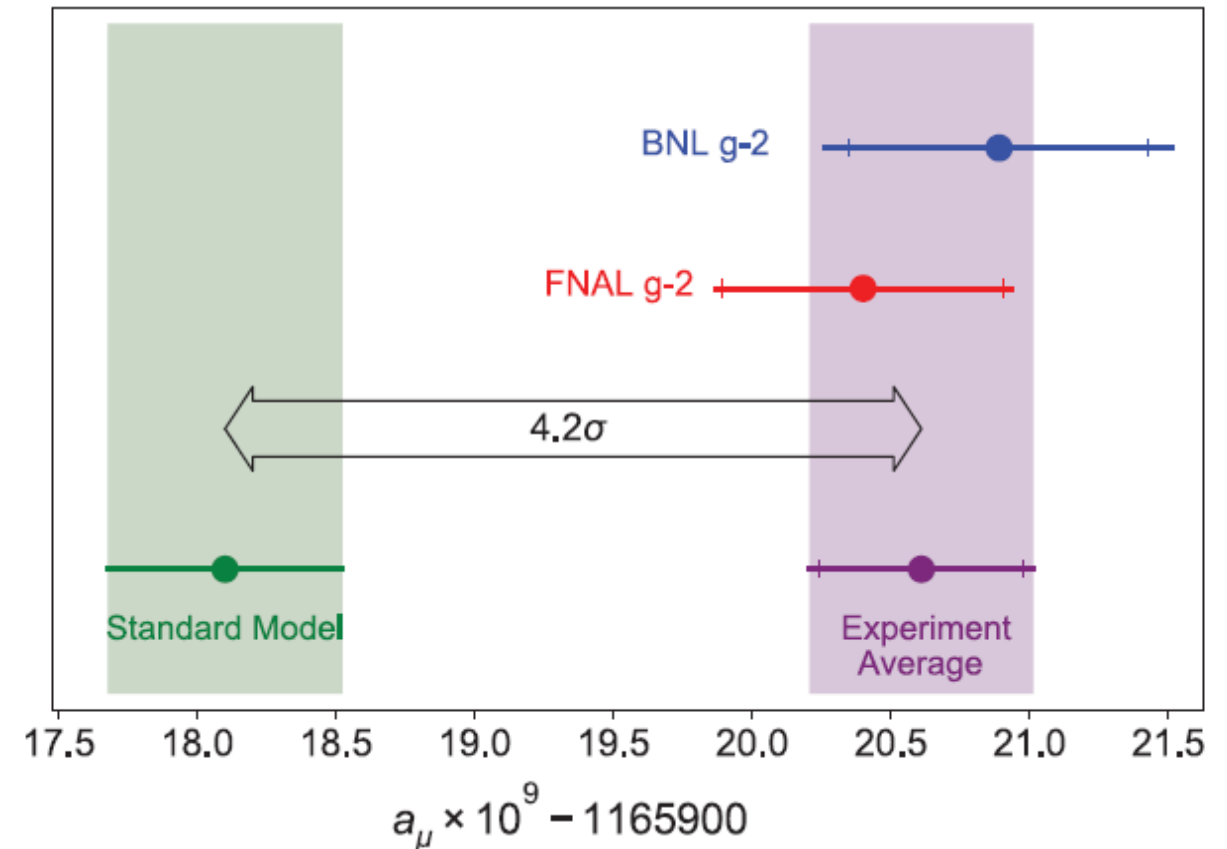


Muon storage ring @FNAL



# FNAL E989 Result

- The first result of the FNAL experiment was announced on April 7 in 2021 and the measured value was  $a_\mu = 0.00116592040(54)$  (0.46 ppm)
  - Used data statistics is equivalent with the BNL experiment.
- If the SM prediction is compared with the average of the experiment values, the deviation increases to  $4.2 \sigma$ !



[Phys. Rev. Lett. 126, 141801 \(2021\)](#)

# Muon $g-2$ /EDM Experiment at J-PARC

- What is the muon  $g-2$ /EDM experiment at J-PARC?
- What is it for?



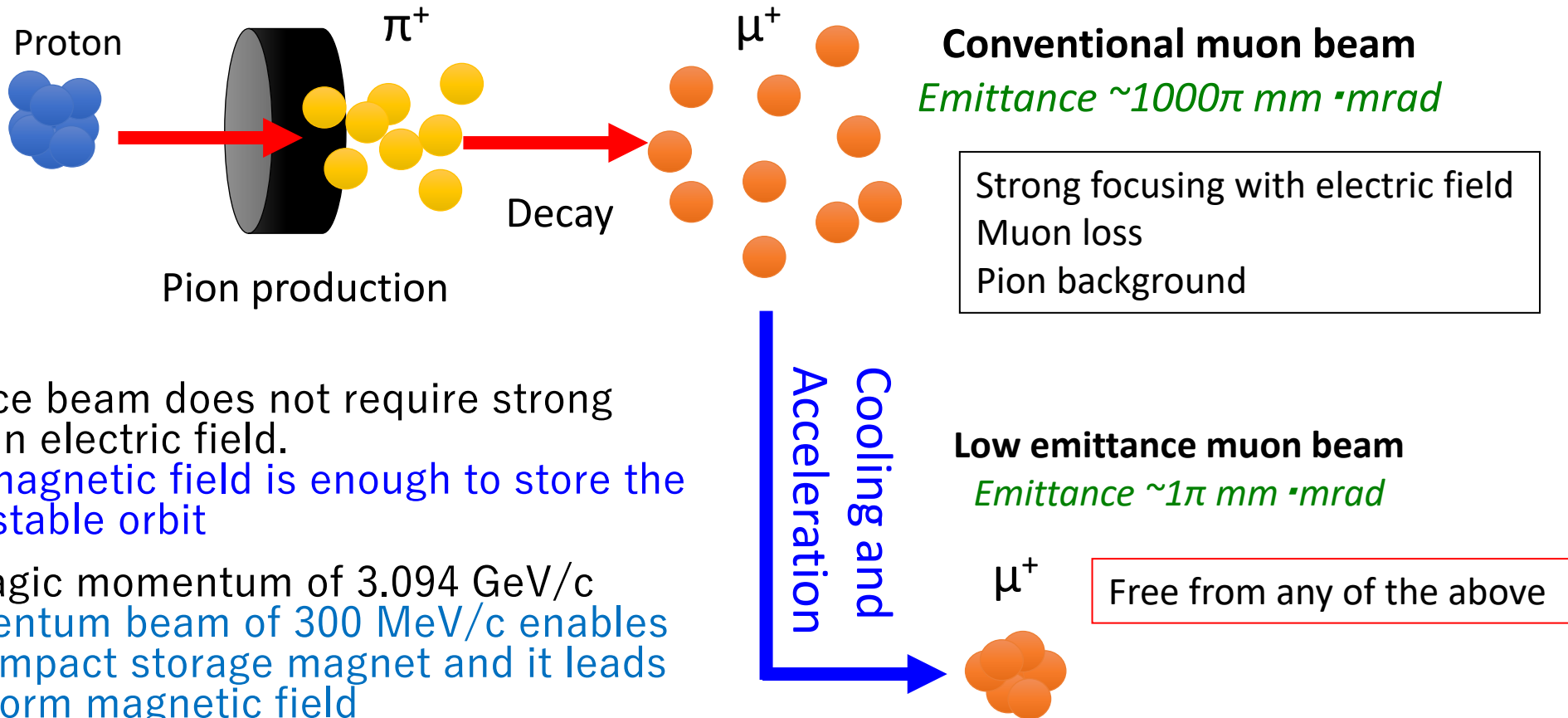
# Electric Field Contribution

- If there is an electric field, the equation of the spin precession is modified as follows.

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

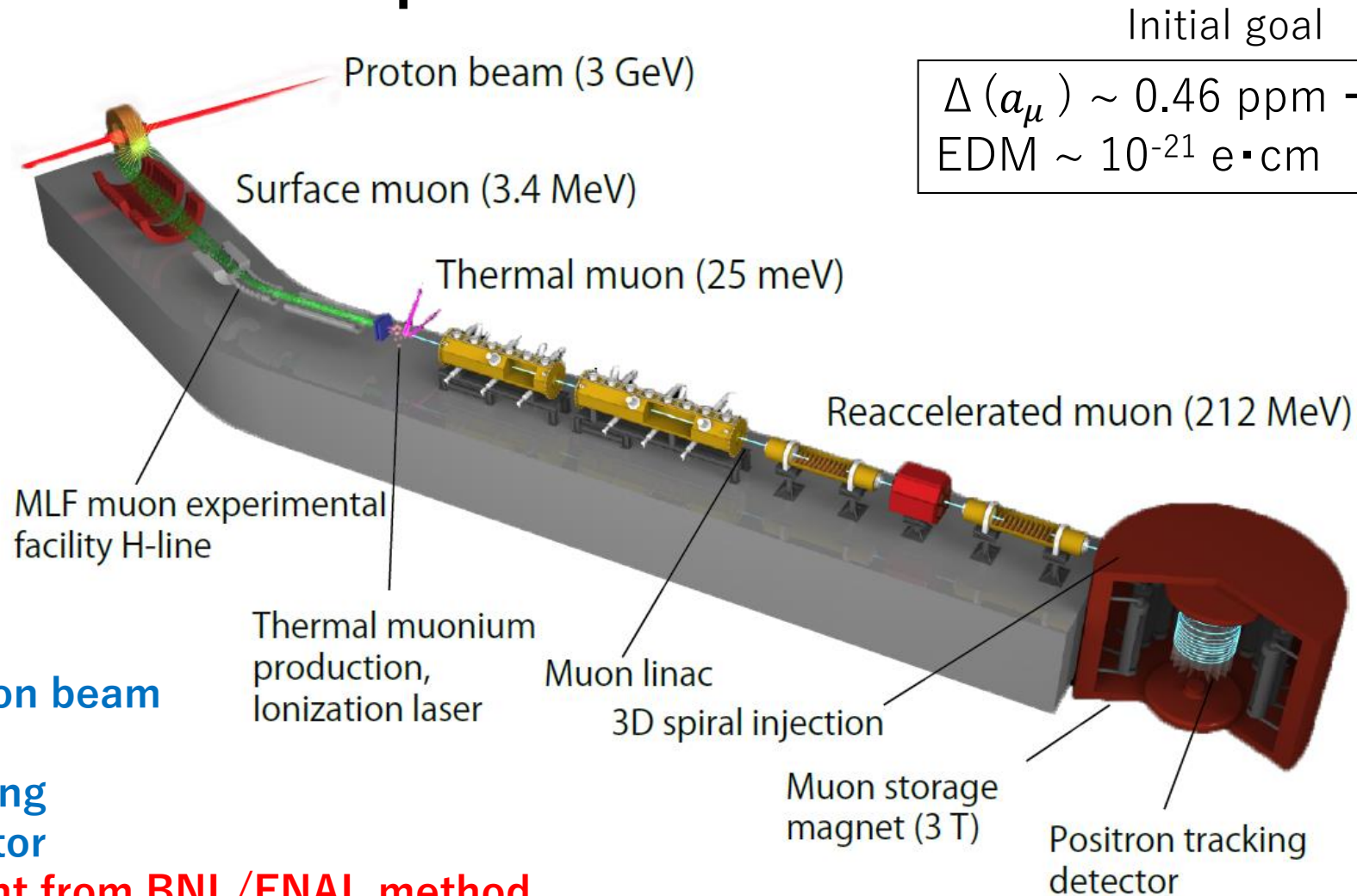
- In the BNL and FNAL experiments, use of focusing electric field is necessary to store the muon beam in the stable orbit.
- To remove a contribution from the electric field, the muon momentum is chosen to satisfy  $a_{\mu} - \frac{1}{\gamma^2 - 1} = 0$ .
  - It corresponds to  $p=3.094$  GeV/c and is called as the magic momentum.
- In the J-PARC experiment, instead of using the magic momentum, the electric field itself is eliminated ( $\vec{E} = 0$ ).
  - How is it possible?

# Low Emittance Muon Beam



- Low emittance beam does not require strong focusing by an electric field.  
→ Gradient magnetic field is enough to store the beam in the stable orbit
- Free from magic momentum of 3.094 GeV/c  
→ Low momentum beam of 300 MeV/c enables use of the compact storage magnet and it leads to highly uniform magnetic field  
→ It also enables the tracking detector with 100% acceptance

# J-PARC E34 Experiment



| Initial goal                                       | Final goal                    |
|--|-------------------------------|
| $\Delta(a_\mu) \sim 0.46 \text{ ppm}$              | $\rightarrow 0.1 \text{ ppm}$ |
| $\text{EDM} \sim 10^{-21} \text{ e}\cdot\text{cm}$ |                               |

## Features

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

# Comparison of Experiment Parameters

**Table 1.** Comparison of BNL-E821, FNAL-E989, and our experiment.

J-PARC Experiment

|                           | BNL-E821                     | Fermilab-E989        | Our experiment                |                   |
|---------------------------|------------------------------|----------------------|-------------------------------|-------------------|
| Muon momentum             | 3.09 GeV/c                   |                      | 300 MeV/c                     |                   |
| Lorentz $\gamma$          | 29.3                         |                      | 3                             |                   |
| Polarization              | 100%                         | cyclotron radius:    | 50%                           | cyclotron radius: |
| Storage field             | $B = 1.45$ T                 | 7.1 m                | $B = 3.0$ T                   | 333 mm            |
| Focusing field            | Electric quadrupole          |                      | Very weak magnetic            |                   |
| Cyclotron period          | 149 ns                       |                      | 7.4 ns                        |                   |
| Spin precession period    | 4.37 $\mu$ s                 |                      | 2.11 $\mu$ s                  |                   |
| Number of detected $e^+$  | $5.0 \times 10^9$            | $1.6 \times 10^{11}$ | $5.7 \times 10^{11}$          |                   |
| Number of detected $e^-$  | $3.6 \times 10^9$            | –                    | –                             |                   |
| $a_\mu$ precision (stat.) | 460 ppb                      | 100 ppb              | 450 ppb                       |                   |
| (syst.)                   | 280 ppb                      | 100 ppb              | <70 ppb                       |                   |
| EDM precision (stat.)     | $0.2 \times 10^{-19}$ e · cm | –                    | $1.5 \times 10^{-21}$ e · cm  |                   |
| (syst.)                   | $0.9 \times 10^{-19}$ e · cm | –                    | $0.36 \times 10^{-21}$ e · cm |                   |

[PTEP 2019 \(2019\), 053C02](#)

# J-PARC Facility



Located at Ibaraki prefecture  
in Japan



# Muon Facility at J-PARC

## S-line

- surface  $\mu^+$
- dedicated to  $\mu$  SR
- S1 area is available
- S2 is under construction
- S3/S4 are planned

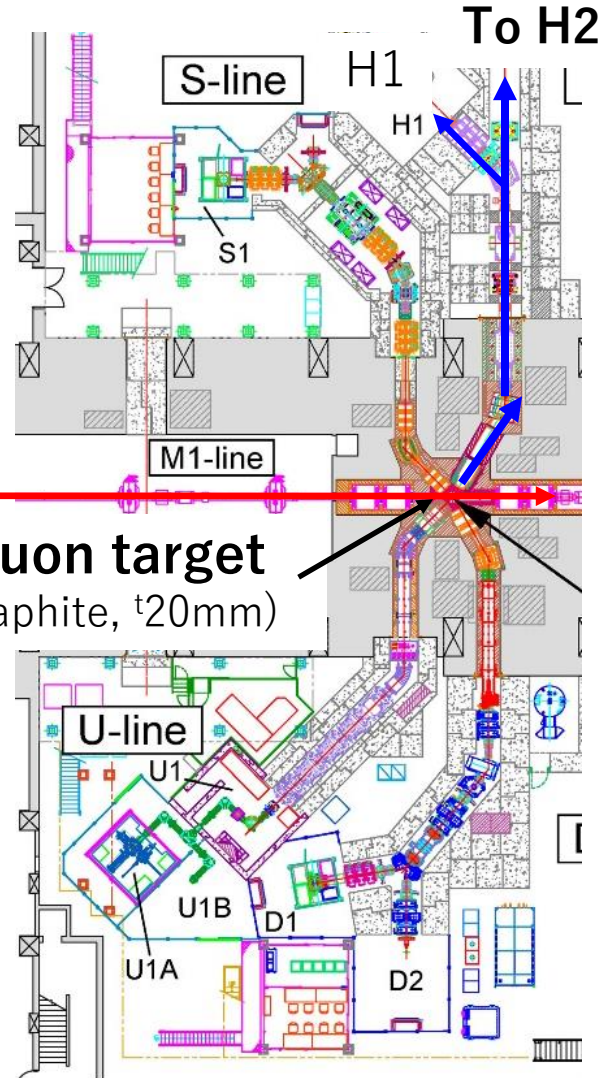
3GeV proton from RCS

$2 \times 10^{15}$  /s @1MW

## U-line

- ultra slow  $\mu^+$
- U1A for nm- $\mu$  SR
- U1B for  $\mu$  microscopy
- under commissioning

**Muon target**  
(graphite,  $t=20$ mm)



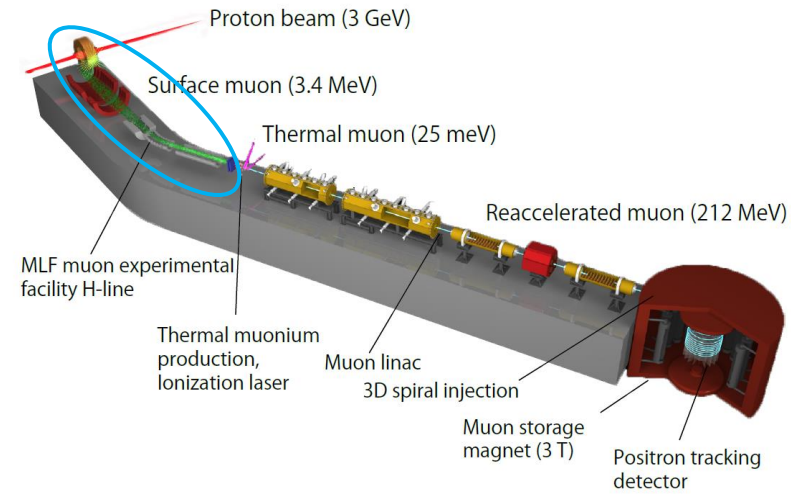
## H-line

- **surface  $\mu^+$  ( $>10^8 \mu^+$ /s), decay  $\mu^+/\mu^-, e^-$**
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2 for  $g-2$ /EDM & transmission muon microscopy**
- **under construction**

## D-line

- decay  $\mu^+/\mu^-$ , surface  $\mu^+$
- D1 area for  $\mu$  SR
- D2 for variety of science

# H-line Construction



to g-2/EDM area  
 H line

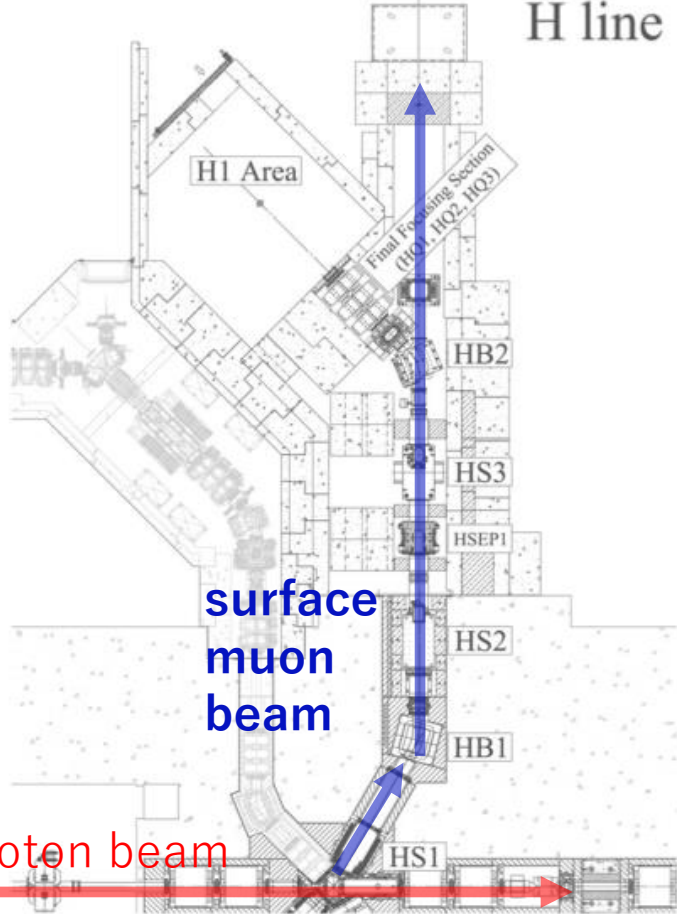
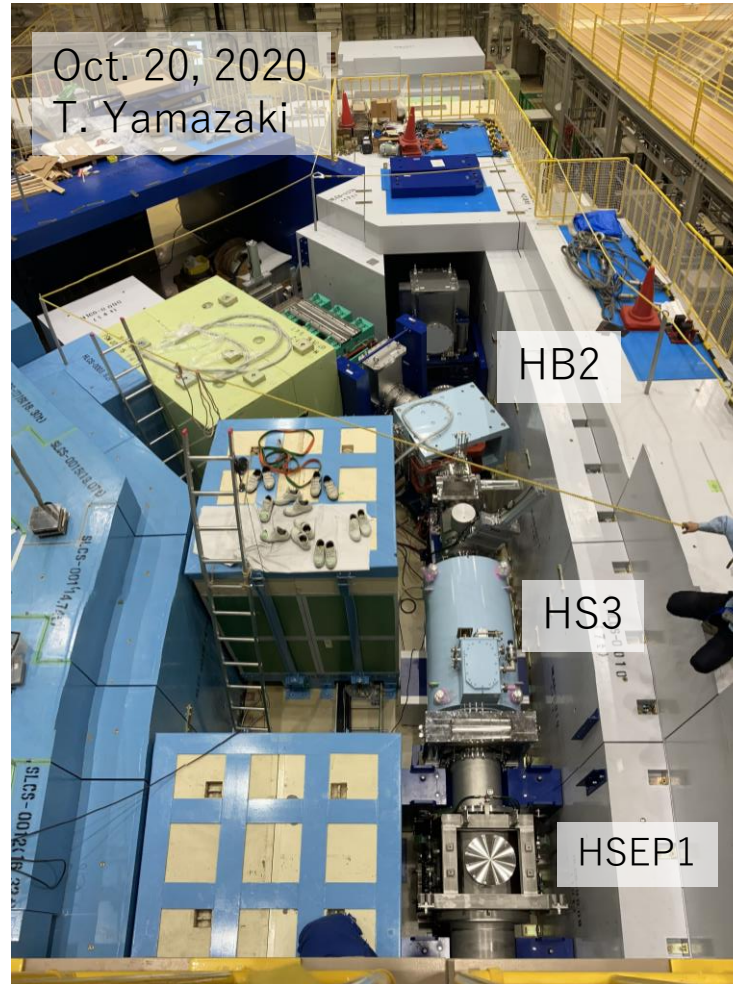


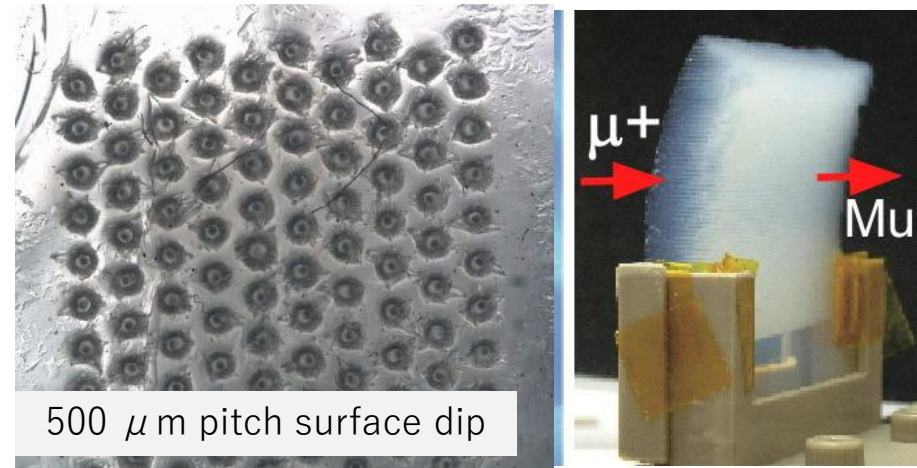
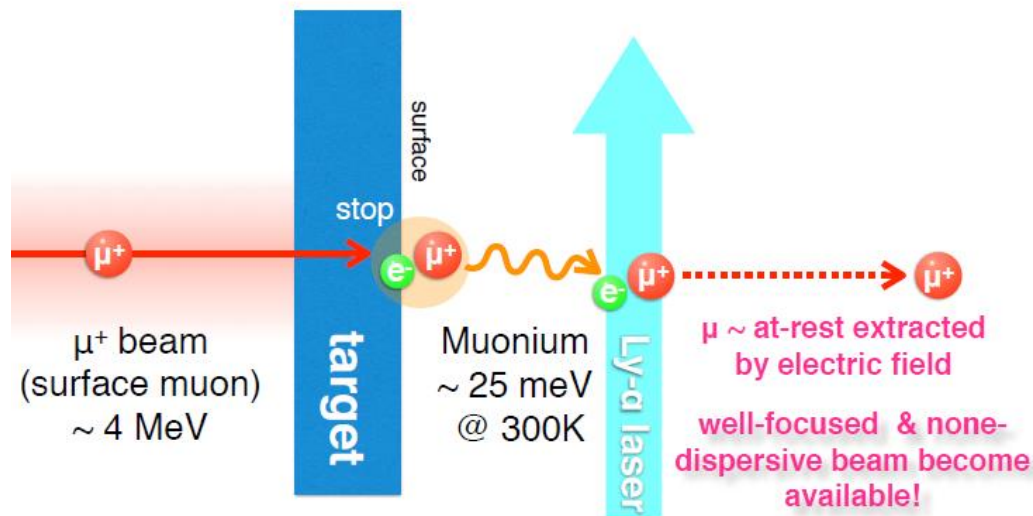
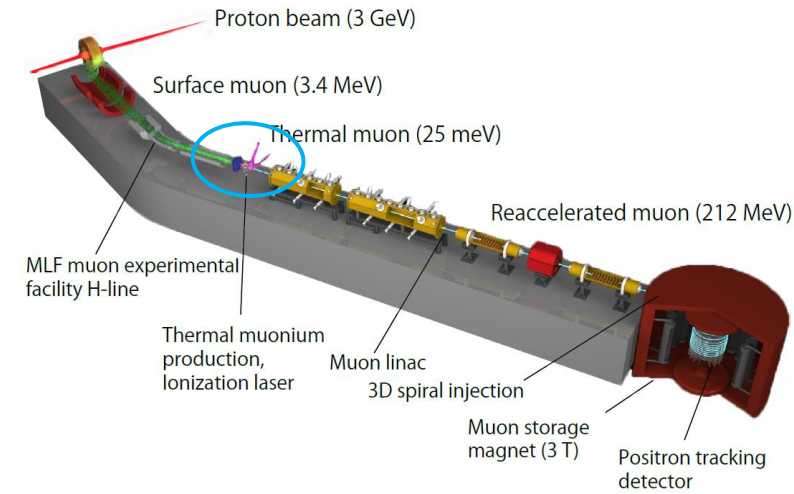
Fig. 2. The H-line layout.



- Construction of H-line already started.
- The minimum construction of the upstream part of H-line (H1 area) has finished and it is ready to start beam commissioning.

# Muon Source

- Surface muon beam is used as the source of our experiment.
  - Monochromatic and  $\sim 100\%$  polarized beam
- Muon beam is stopped at target and muonium (bound state of  $e^-$  and  $\mu^+$ ) is produced.
  - Laser-ablated silica aerogel is used for muonium production target.
- An electron is stripped from a muonium by laser and thermal muon beam is produced.

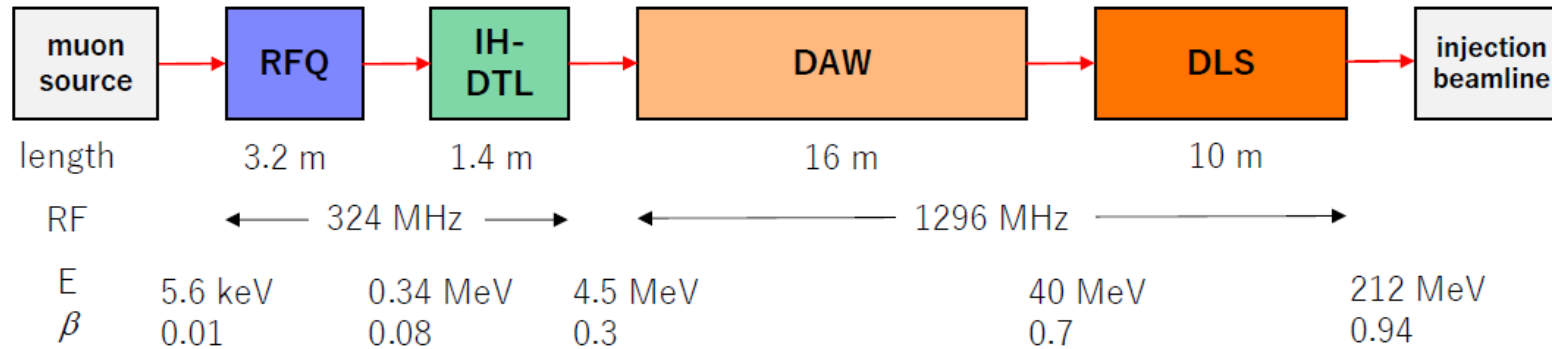


laser-ablated silica aerogel

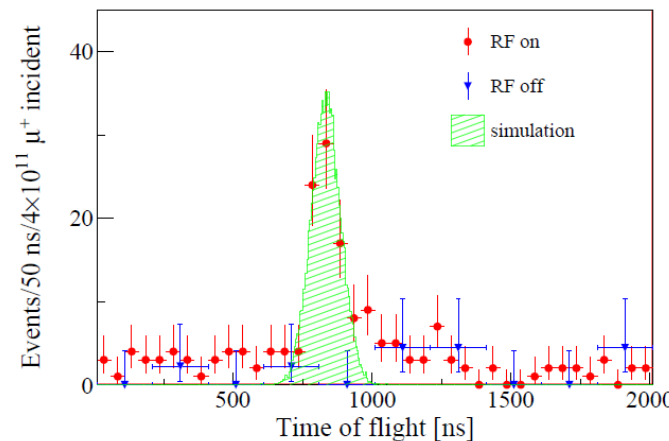


# Muon Acceleration

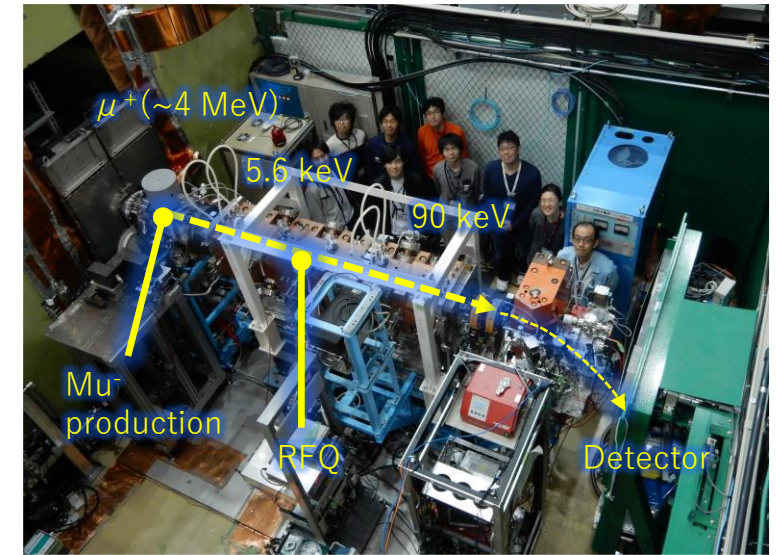
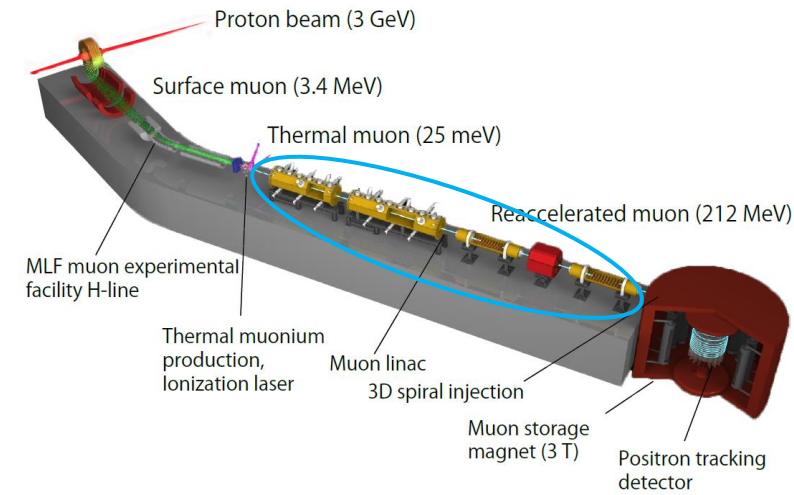
- Cooled muon beam is accelerated to  $p=300$  MeV/c in LINAC.



Recent achievement is acceleration of muon (negative muonium ion, to be precise) with RFQ for the first time in the world.



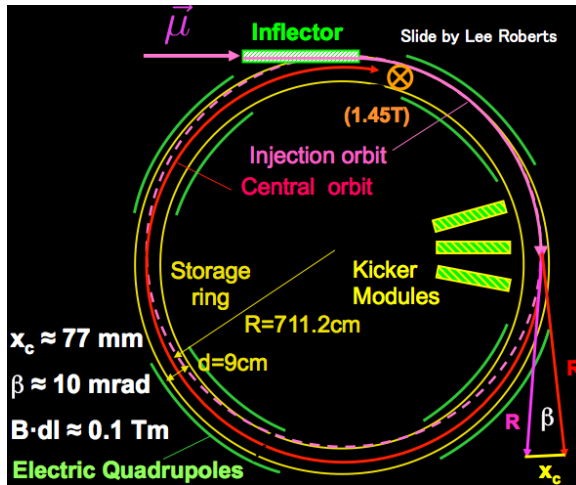
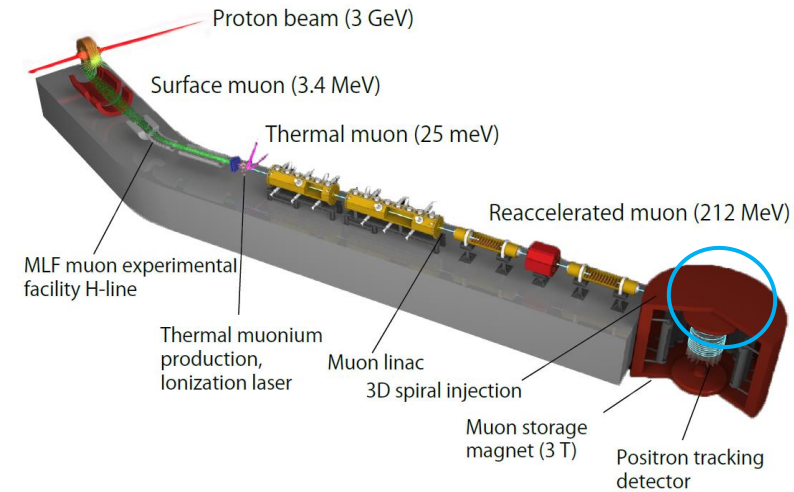
Signal indicating the arrival of Mu- when RF was on ([Phys. Rev. Accel. Beams 21, 050101 \(2018\)](#))



J-PARC MLF D2-line

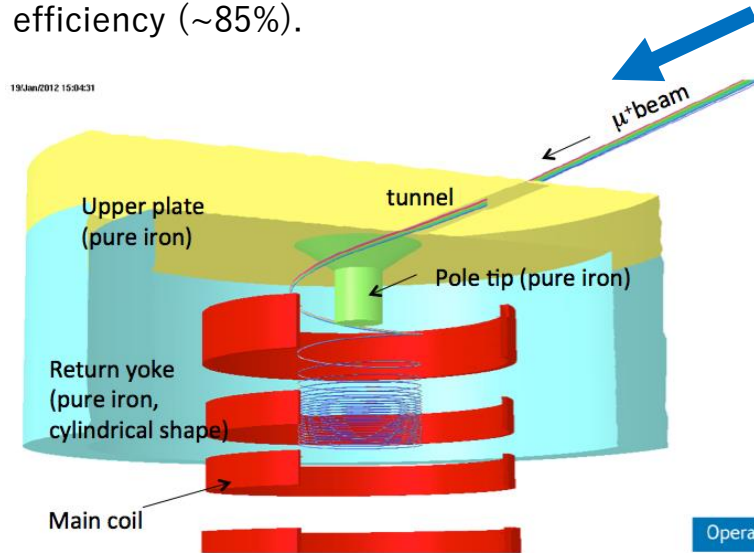
# Spiral Injection

- Usually, the beam is injected to the storage magnet horizontally as so in BNL and FNAL experiments.
- However, our storage magnet is too small (cyclotron radius is 333 mm) to inject in the same way.
  - Unrealistically high kicker magnetic field is needed to reflect beam direction instantaneously.
- To overcome this challenge, vertical spiral injection scheme was developed.
  - There is another advantage of high injection efficiency (~85%).

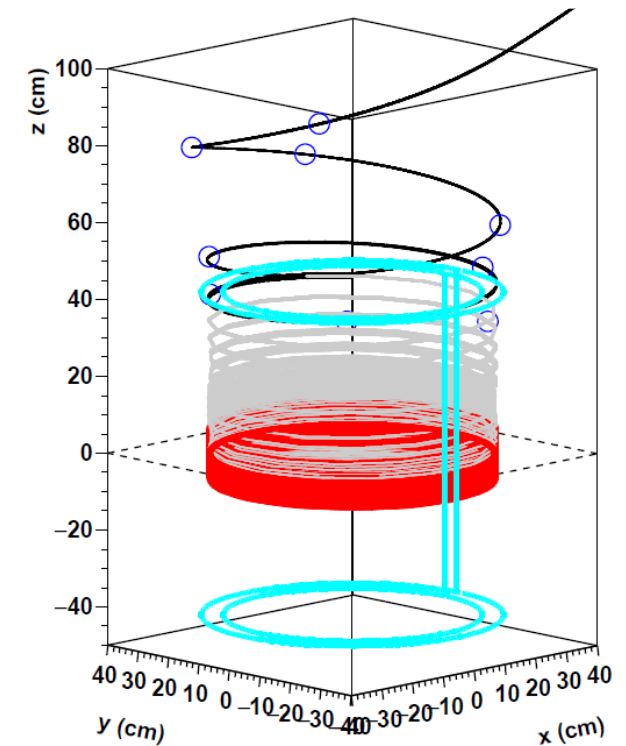


Injection scheme of the BNL and FNAL experiments

July 19, 2021



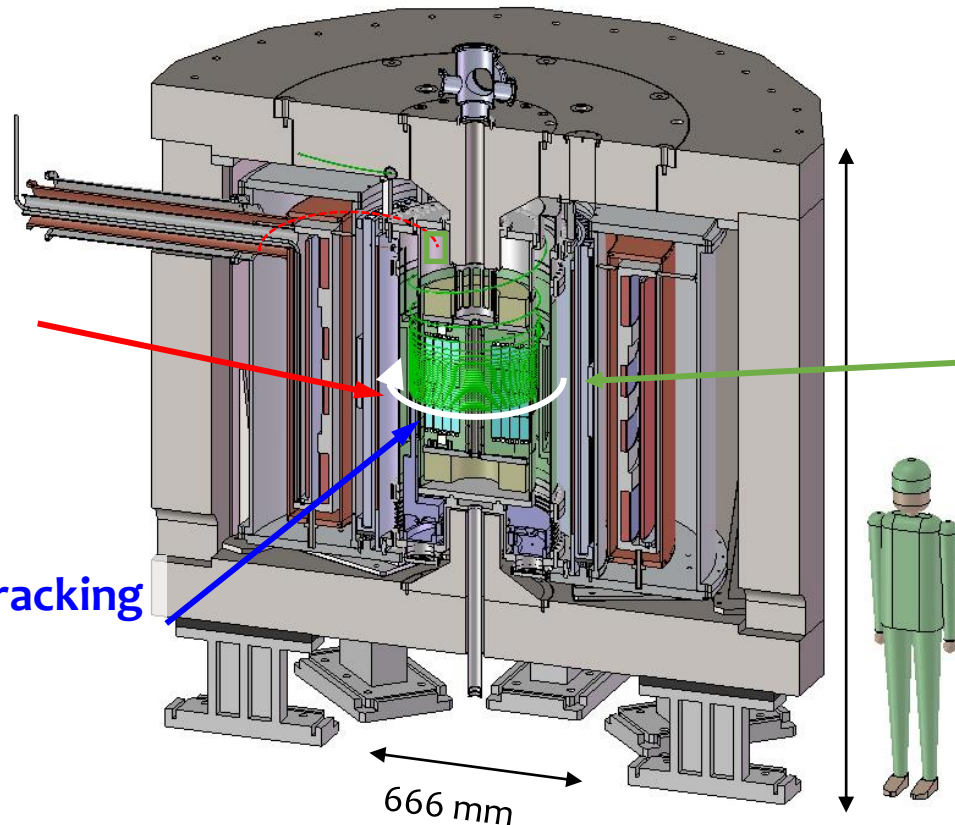
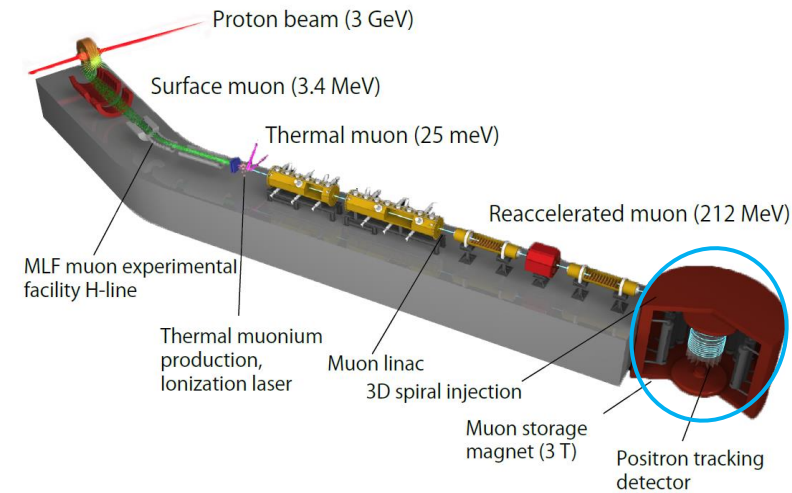
Injection scheme of the J-PARC experiment



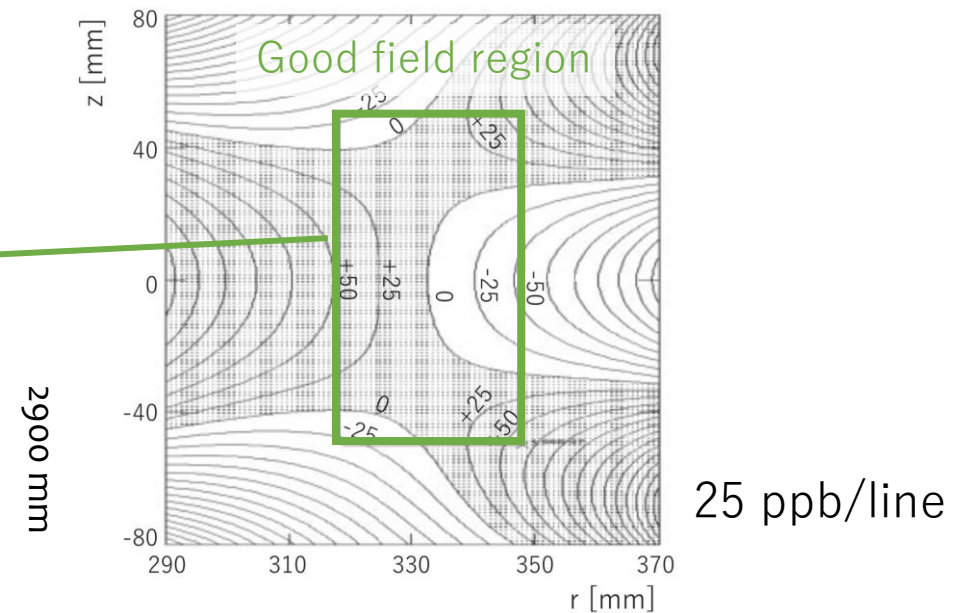
Simulation of muon injection

# Storage Magnet

- 3 T MRI-type solenoid magnet will be used.
  - Weak focusing magnetic field is also applied to keep muon beam size.



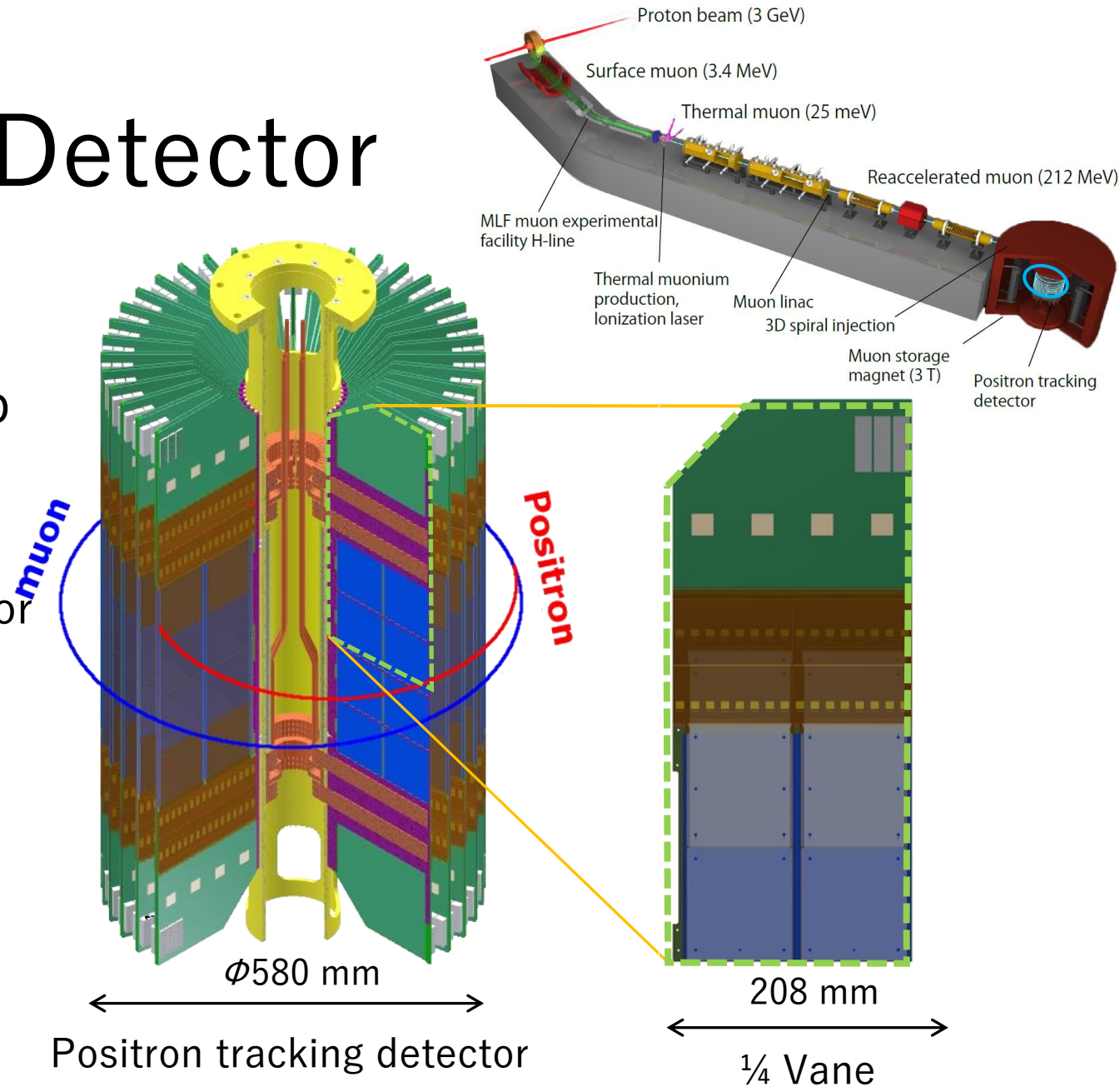
Calculated average field uniformity



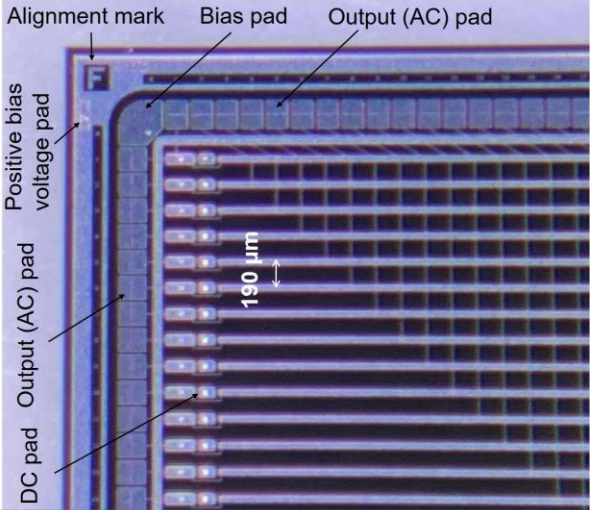
In good storage volume, field uniformity is better than 100 ppb.

# Positron Tracking Detector

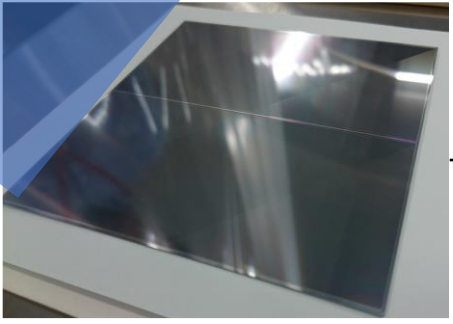
- Positrons from decay of stored muon beam are detected by the detector consisting of silicon strip sensors installed in the storage magnet.
  - Positron tracks are reconstructed from hits in radially arranged detector modules called “vanes”.
  - There are 40 vanes in total.
- Each vane has silicon strip sensors in both sides with their strip directions orthogonal each other.



# Detector Components

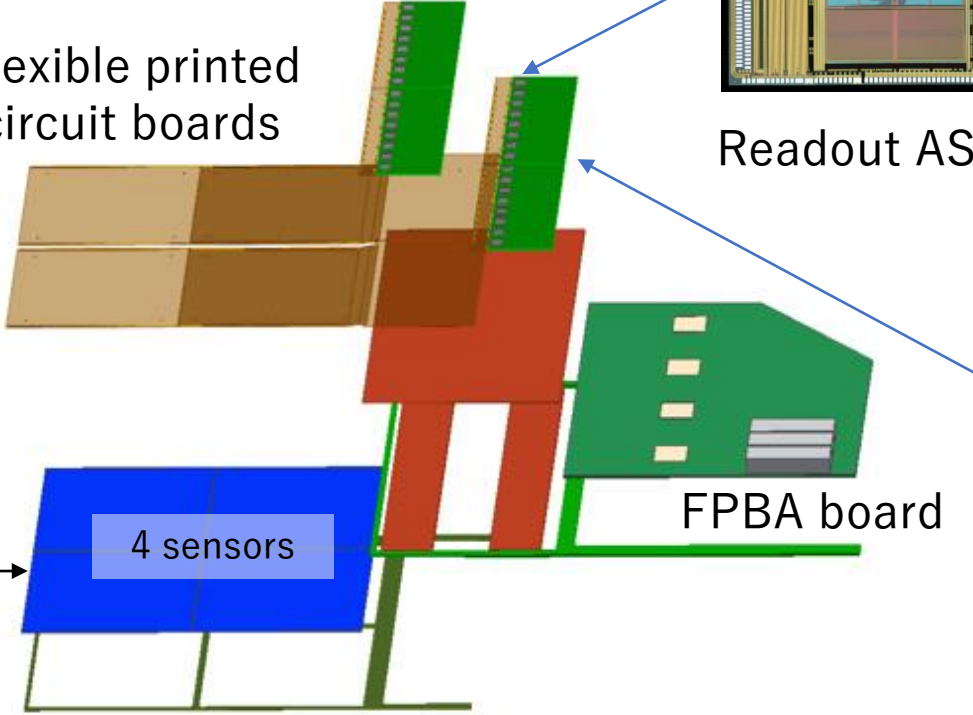


| Specification      |
|--------------------|
| 98.77 × 98.77 mm   |
| 190 μm pitch strip |
| 512 × 2 strip      |

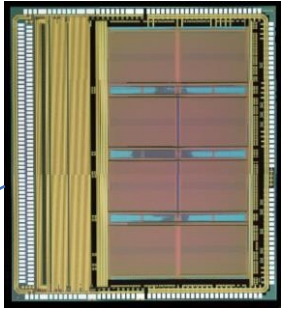


Silicon strip sensor

Flexible printed circuit boards

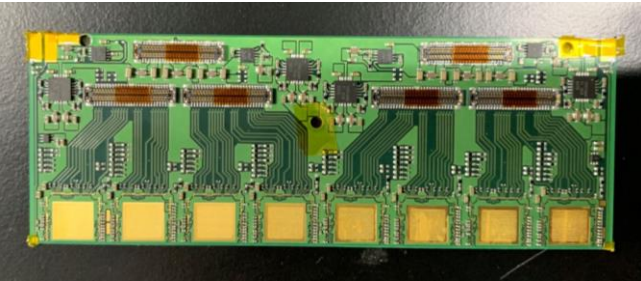


1/4 vane structure



Readout ASIC

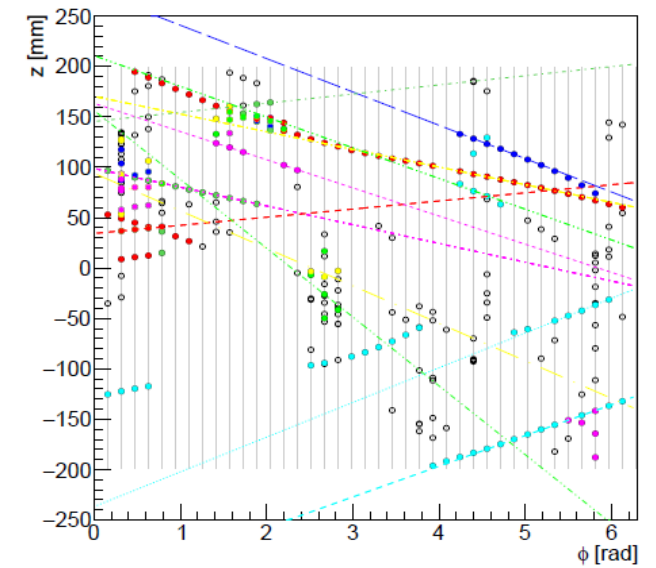
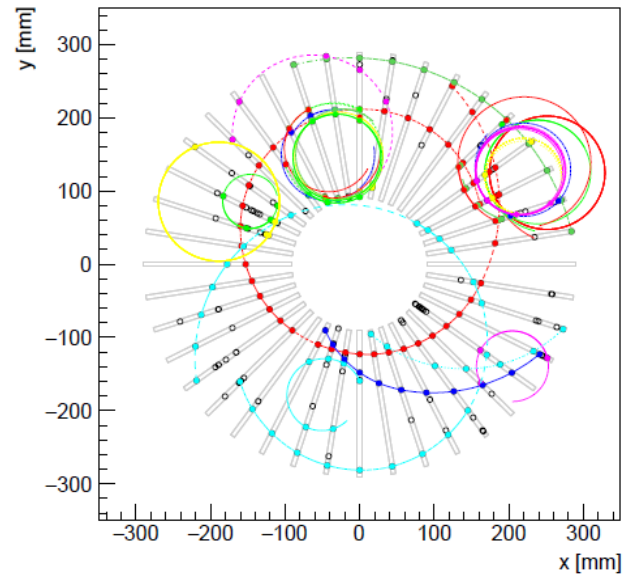
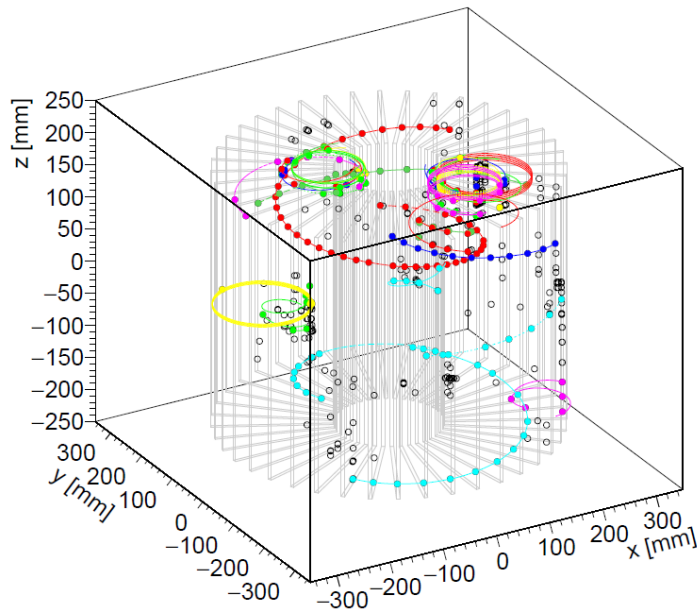
| Specifications                |
|-------------------------------|
| >4 MIP range                  |
| 1600 e <sup>-</sup> ENC@30 pF |
| 128 ch/chip                   |
| 8096 memory buffer/ch         |
| 5 ns sampling                 |



ASIC boards

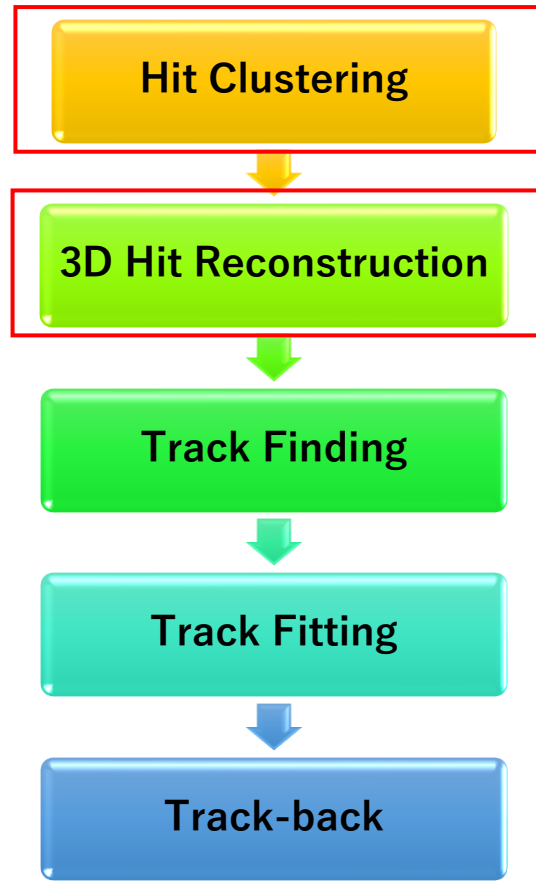
# Positron Track Reconstruction

- The challenge of software in the experiment is reconstruction of positron tracks in the condition that the rate of muon decays changes by a factor of 150 from the beginning of the data taking to the end.
  - The expected highest muon decay rate is 30 per time stamp of the detector (5 ns).
- The stable tracking efficiency during the data taking period is required not to bias the measurement of  $\omega_{\mu}$ .

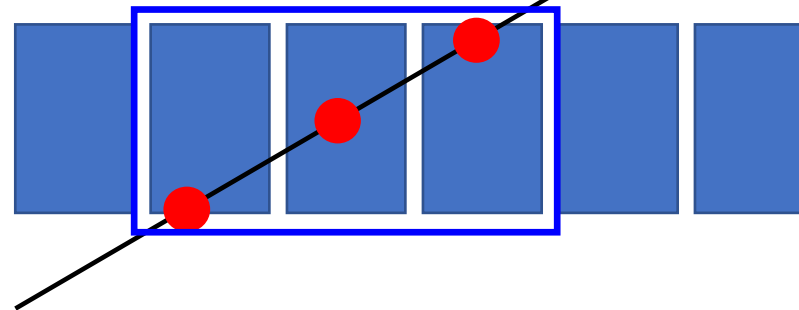


Simulated positron hits and reconstructed tracks with 25 positrons

# Track Reconstruction Procedures



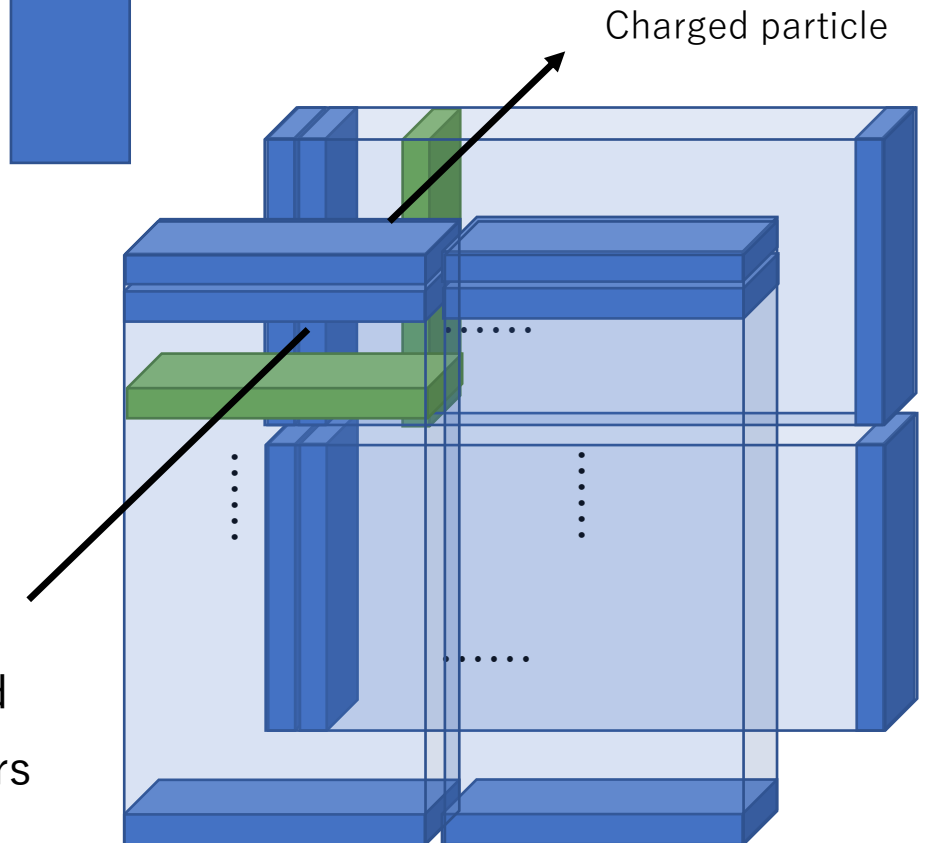
Cross-section of sensor



Charged particle

For a particle passing through several strips, neighboring hits with the same time stamp are clustered to one hit.

3-dimensional position of charged particles are reconstructed by combining two silicon strip sensors whose strip directions are orthogonal each other.



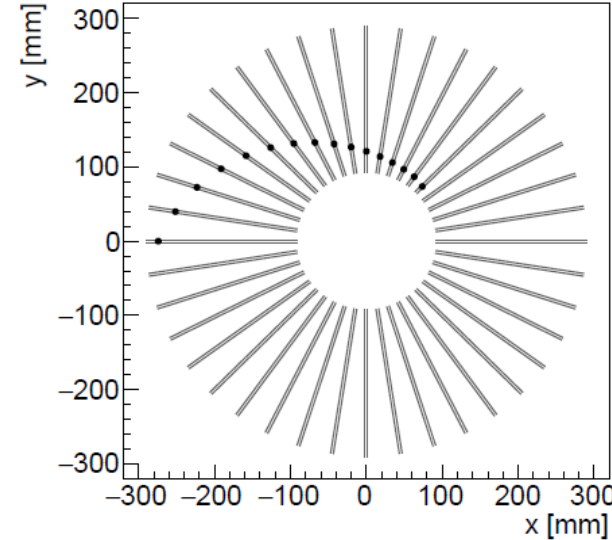
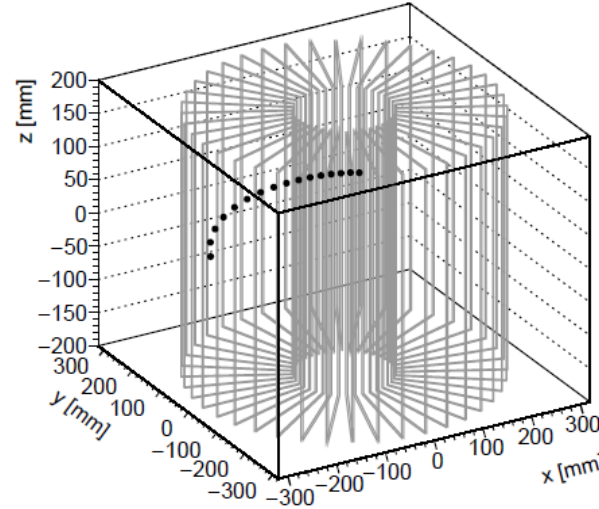
Charged particle

# Track Finding (1)

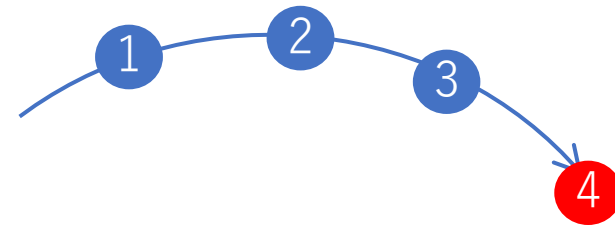
- Track candidates are searched from the reconstructed 3D hits.
- If the collection of the reconstructed hits is simple, it will be enough to search for hits included in a track candidate one by one assuming a helix orbit.

$$\begin{cases} x(t) = x_0 + r\cos(kt + \varphi) \\ y(t) = y_0 + r\sin(kt + \varphi) \\ z(t) = z_0 + v_z t \end{cases}$$

- 3 hits are selected (randomly) first and the next hit is searched for, which is consistent with the initial 3 hits.
- This calculation complexity to decide the initial 3-hit combination (called as “seeds”) is  $\mathcal{O}(N_{\text{hits}}^3)$ .



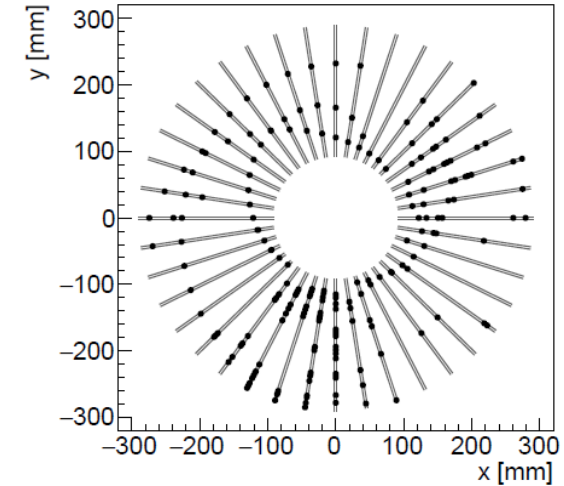
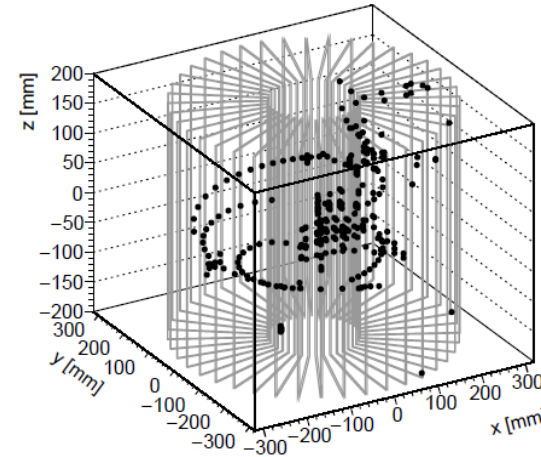
Example of single-track event display



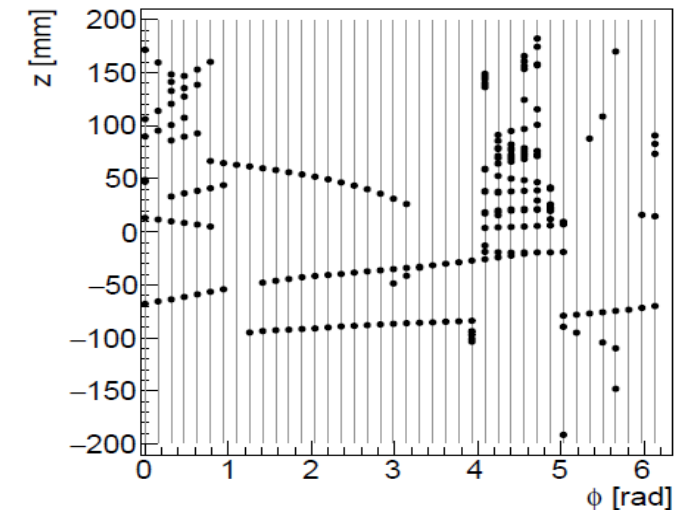


# Track Finding (2)

- When the number of pile-up tracks in the same time window becomes larger, this algorithm takes too long time in computation.
- More effective algorithms are needed to find track candidates in a dense hit condition.
- We use a feature that our signal tracks tend to leave hits in a straight line when it is viewed in  $z-\phi$  plane.
  - This is because in a particle travels with almost constant velocity in the vertical direction and the center of the circular motion is close to the detector center.



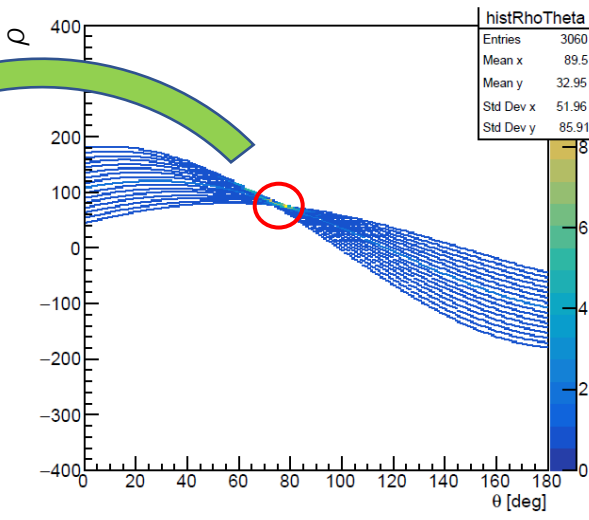
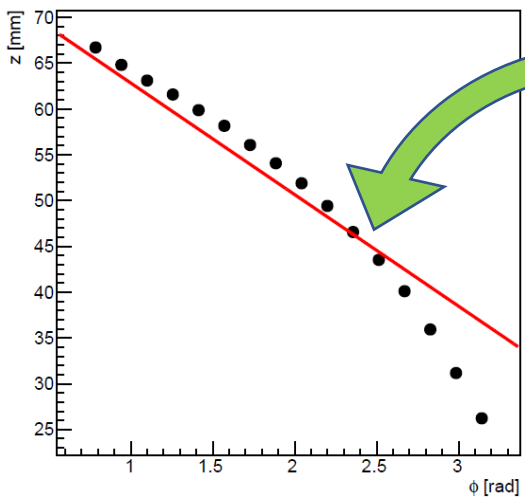
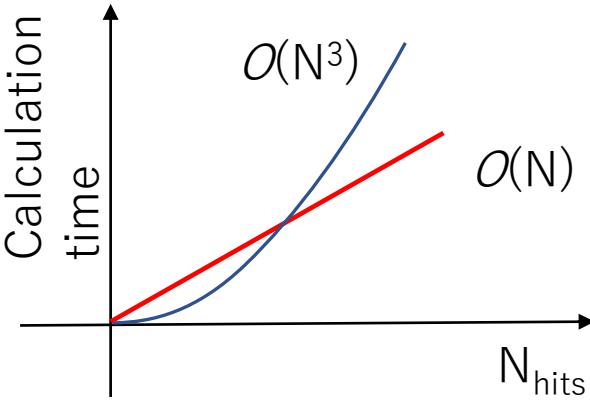
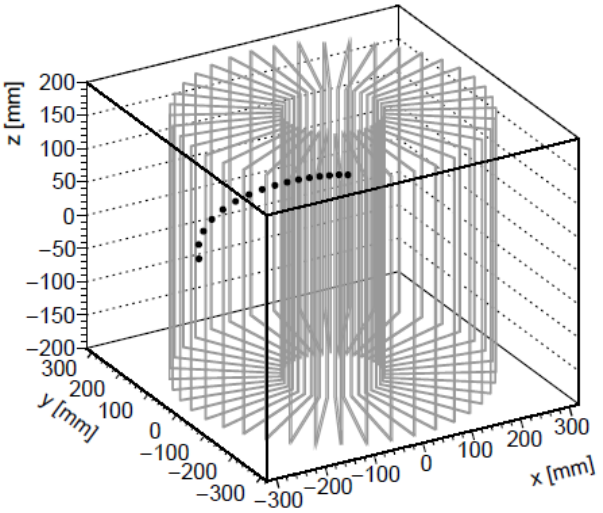
Example of multi-track event display



Hit positions projected onto  $z-\phi$  plane

# Hough Transform

- There is a smart algorithm to find a straight line in 2-D plane called “Hough Transform”.
  - Consider the transformation of a point in  $(z, \phi)$  plane to a sinusoidal curve in  $(\rho, \theta)$  plane using the following formula.
 
$$\rho = \phi \cos \theta + z \sin \theta$$
  - If several hits are on the same line in  $(z, \phi)$  plane, there is a crossing point between curves in  $(\rho, \theta)$  plane.
  - Assume this point is  $(\rho_0, \theta_0)$ , then the line in  $(z, \phi)$  plane is  $z(\phi) = -\phi \cot \theta_0 + \frac{\rho_0}{\sin \theta}$ .
  - Then, hits close to this line are expected to be hits from the same track.
- Initial calculation becomes complicated but the computation complexity is  $O(N_{\text{hits}})$ .



# Track Fitting

- After finding track candidates, their momentum are obtained by “track fitting”.
- If a magnetic field is uniform and track momentum is constant, its orbit can be regarded as a helix simply.
  - Momentum assuming such a simple condition is already obtained at the stage of track finding.
- However, in practice, the magnetic field is not uniform and track momentum changes in time due to material effect (energy loss, multiple scattering etc.).
  - Measured values also include errors and/or noises.
- To treat such a problem, “Kalman filter” is widely used.

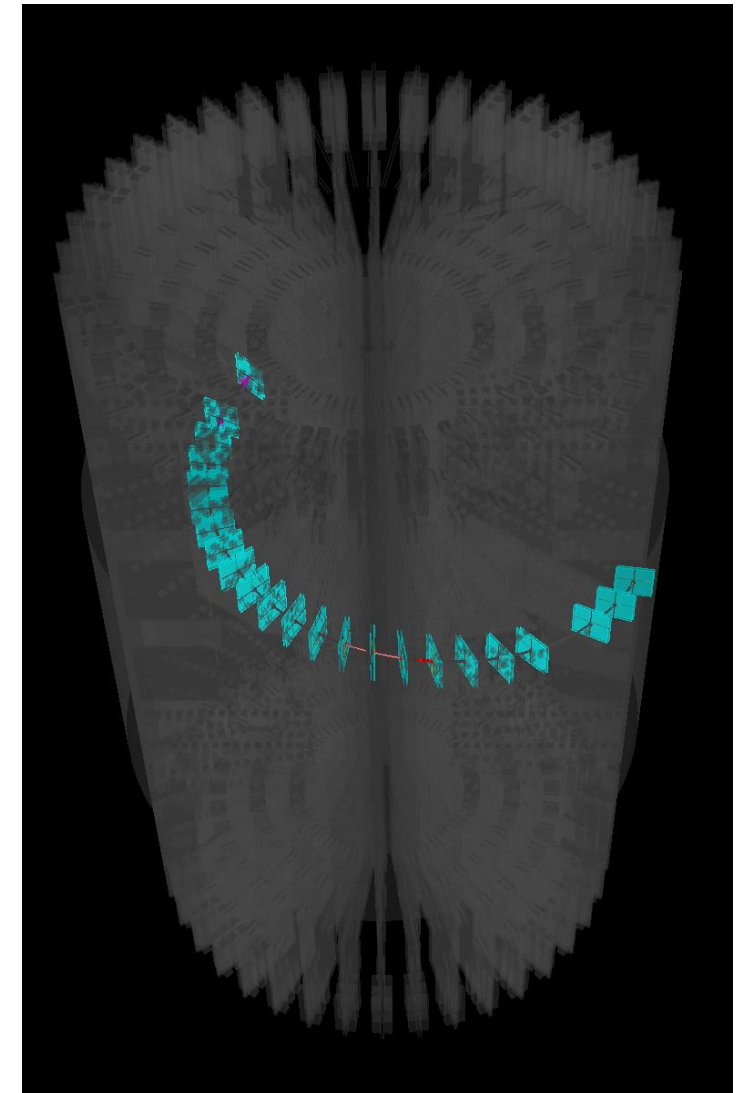
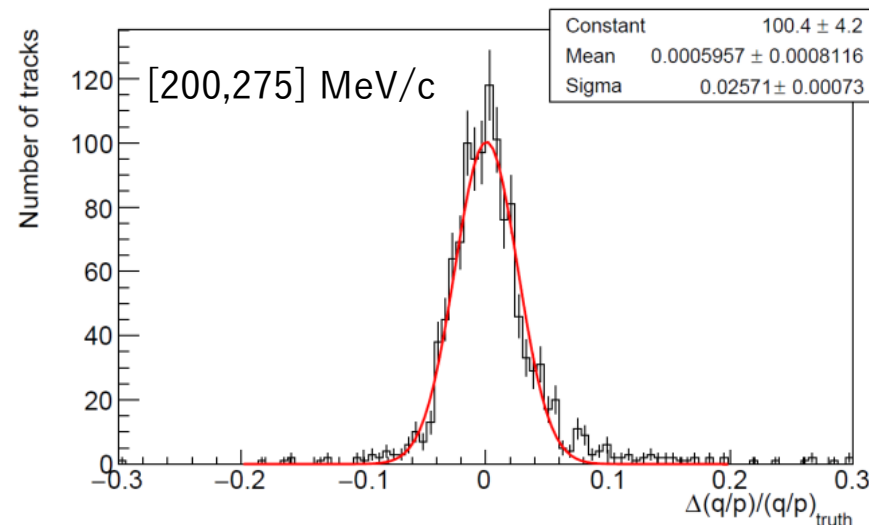
# Kalman Filter

- In Kalman filter, the state vector ( $\vec{x}$ ) of a track is defined at each measurement.
  - For planar sensor measurement, 5-parameter expression (momentum, the position and direction fixed to the plane) is enough.
- The state at the site  $k$  ( $\vec{x}_k$ ) is assumed to be predicted using the state at  $k-1$  ( $\vec{x}_{k-1}$ ),
$$\vec{x}_k = f_{k-1}(\vec{x}_{k-1}) + \vec{w}_{k-1}.$$
  - $f_{k-1}$  is the track propagator from the site  $k-1$  to the site  $k$ .
  - $\vec{w}_{k-1}$  is the random variable at the site  $k-1$  caused by multiple scattering.
- Kalman filter performs prediction, filtering, smoothing using the all measured states and improves the estimates of each state.
  - Prediction: prediction a new state vector at next site based on the observation made so far (future)
  - Filtering: update the predicted state vector of the current site after adding this site (present)
  - Smoothing: improve the filtered state vector by using all the observations made so far (past)
- One need to prepare such a machinery but it is not so easy to do it from scratch.

# GENFIT2

- In practice, we use Kalman filter implemented in GENFIT2, which is an experiment-independent modular framework for track fitting.
  - <https://arxiv.org/abs/1902.04405>
  - Magnetic field map, material distribution can be provided.
  - Typical sensor measurements are pre-defined.

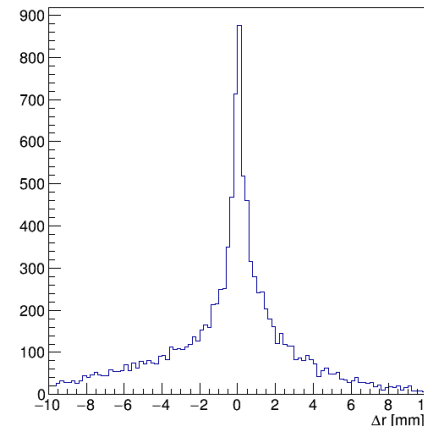
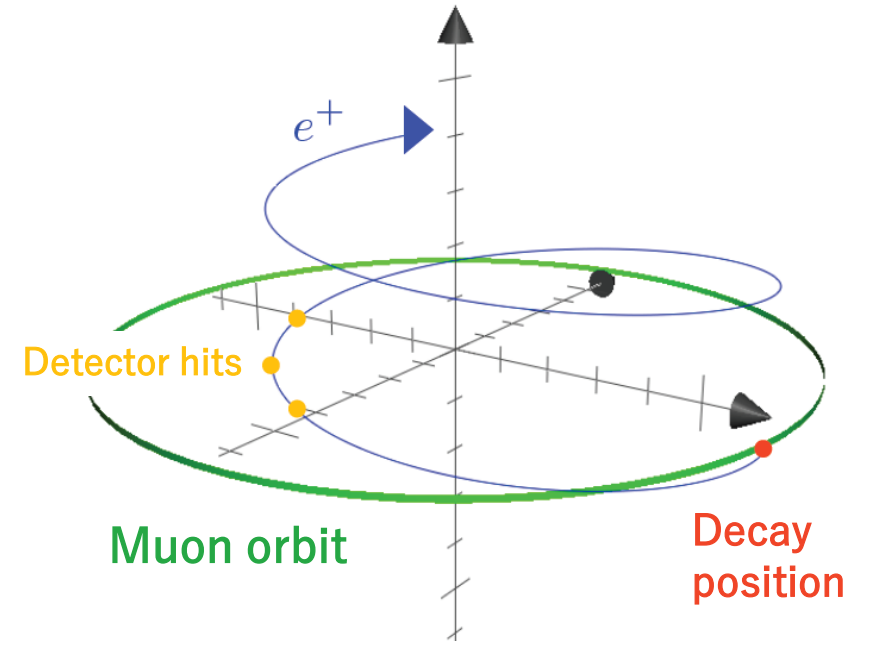
Kalman filter in GENFIT2 is applied to our detector simulation and  $\sim 3\%$  momentum resolution is obtained for tracks with  $[200,275]$  MeV/c in 3 T magnetic field.



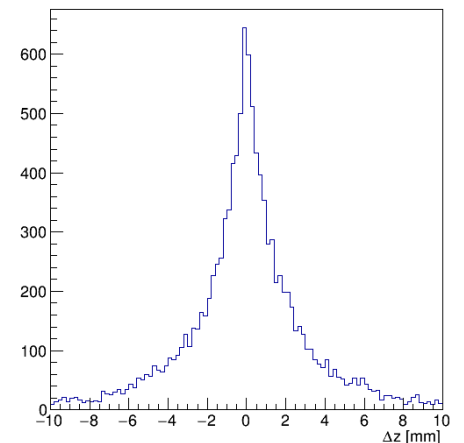
Event display of our detector drawn by GENFIT2

# Track Back

- Finally, to determine the muon decay position reconstructed positron tracks are extrapolated to the muon orbit and the closest point of approach is assumed to be the decay position.
  - In practice, the muon orbit is not a circle but has a width and it is also taken into an account.
- Decay time is calculated using time stamps of each detector hit and considering time-of-flight.



Radial direction

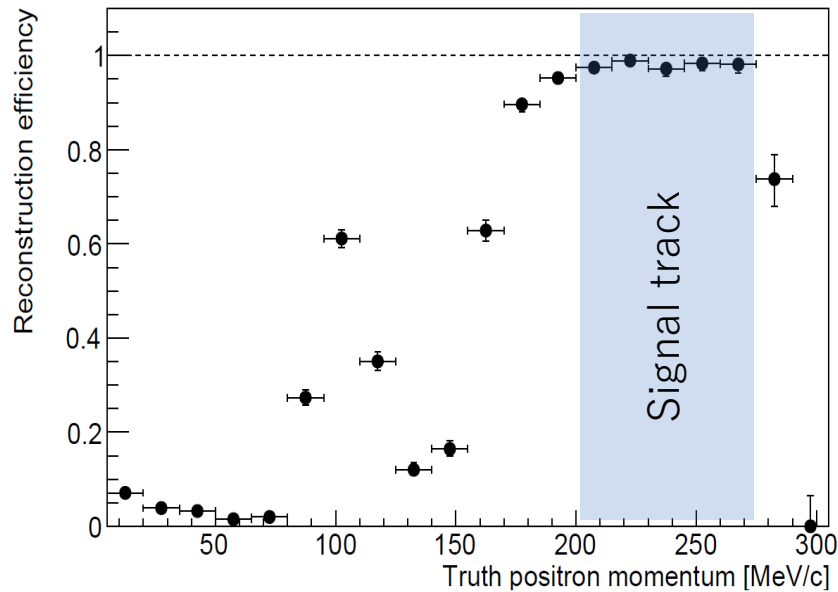


Vertical direction

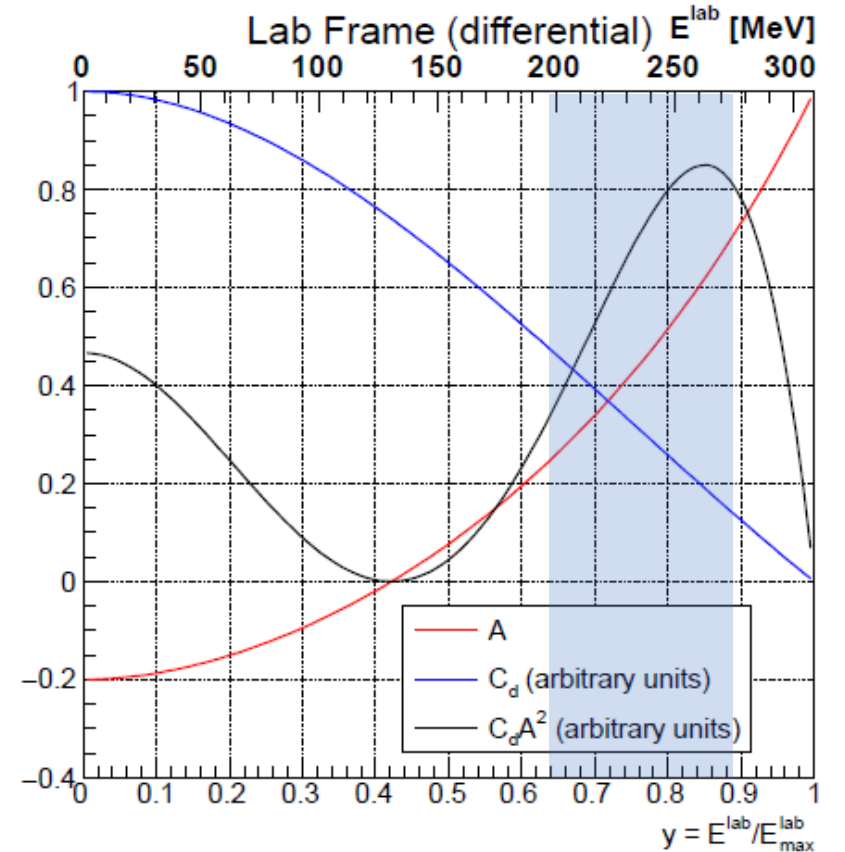
Decay position resolution

# Track Reconstruction Efficiency

- The whole track reconstruction is evaluated.
- In the signal momentum of [200,275] MeV/c, efficiency >95% is estimated.
  - The analyzing power is the highest in this momentum range.



Simulated track reconstruction efficiency for single-track events



Sensitivity of  $\omega_a$  as a function of decay positron energy in the laboratory frame

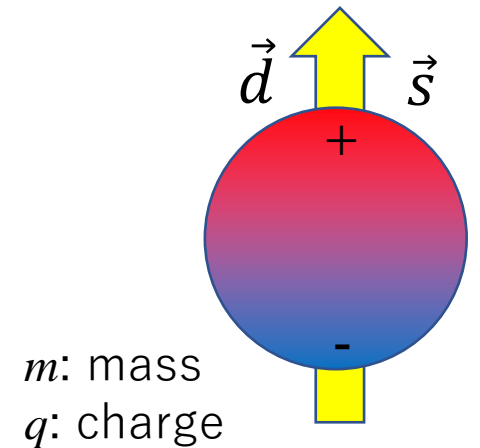
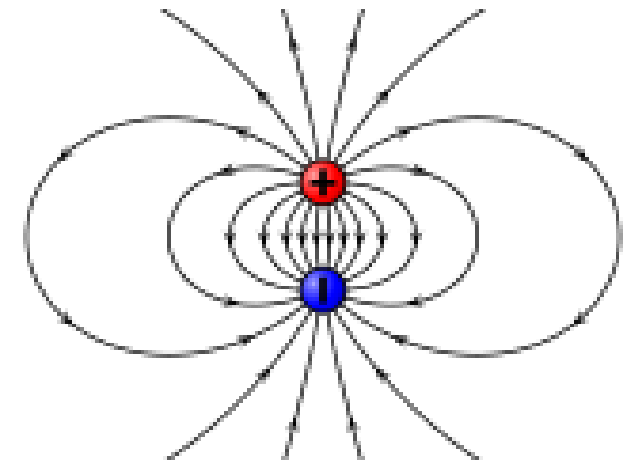
# What is EDM?

- It is an acronym of the electric dipole moment.
  - Similar quantity to the magnetic dipole moment.
- Let's start reviewing why its measurement is important.



# Electric Dipole Moment

- Two opposite electric charges separate by  $l$  creates an electric dipole moment of  $\vec{d} = ql\vec{l}$ .
- A single particle can have an electric dipole moment intrinsically.
- Such an EDM has not yet been measured in any elementary particle but it is believed to be linear to the spin direction and is expressed as  $\vec{d} = \eta \frac{q}{2mc} \vec{s}$ .
- Here,  $\eta$  is a coefficient for EDM analogy with g-factor of the magnetic dipole moment.
- The SM prediction for the muon EDM is  $\sim 2 \times 10^{-38} \text{ e} \cdot \text{cm}$ .
- The current experimental limit is  $|d| < 1.8 \times 10^{-19} \text{ e} \cdot \text{cm}$  by the BNL experiment.
- The J-PARC experiment aims to measure up to  $10^{-21} \text{ e} \cdot \text{cm}$  but it is still by far larger than the SM prediction
- However, if there is a new physics, it might be in our reach.



# T-Violation

- The Hamiltonian of the magnetic/electric dipole moment in an electromagnetic field can be written as

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

- Transformation properties

|     | $\vec{E}$ | $\vec{B}$ | $\vec{\mu}$ or $\vec{d}$ |
|-----|-----------|-----------|--------------------------|
| $P$ | -         | +         | +                        |
| $C$ | -         | -         | -                        |
| $T$ | +         | -         | -                        |

→  $\vec{\mu} \cdot \vec{B}$  conserves C, P, T, while  $\vec{d} \cdot \vec{E}$  violates P and T symmetry.

- Assuming CPT conservation, T-violation means CP-violation as well, which has not yet been discovered in the lepton sector.
  - The existence of the measurable EDM might solve the matter-antimatter asymmetry.

# EDM Measurement

- If a particle is in rest, we can measure the EDM by an electric field like the magnetic moment in a magnetic field.

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} = \eta \frac{q}{2mc} \vec{s} \times \vec{E}$$

- However, our muon beam are moving.
  - Moreover, this method is not applicable for a charged particle.
- Moving charged particle feels an electric field from a magnetic field according to the Lorentz transformation.
  - We can see the interaction between EDM and a magnetic field.

$$\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B}) = \eta \frac{q}{2m} \vec{s} \times (\vec{\beta} \times \vec{B})$$

# Angular Velocity Vector Tilt

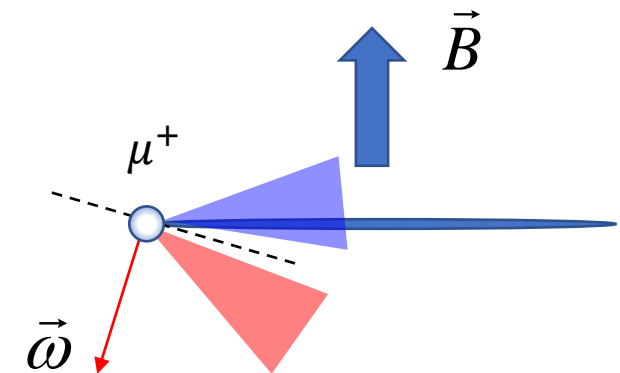
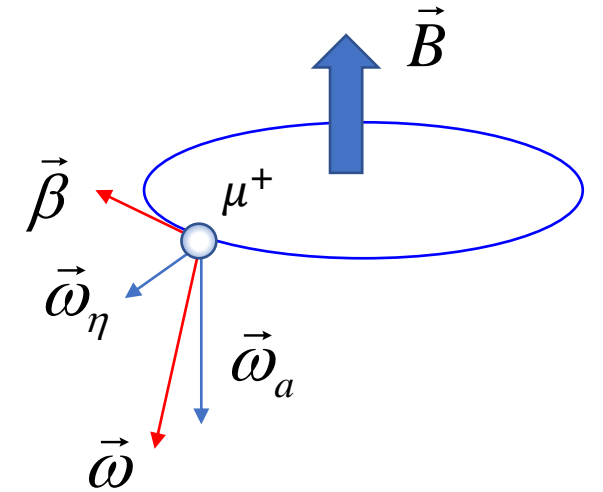
- Since there is a contribution of the magnetic dipole moment, the combined angular velocity vector with respect to the momentum direction is

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = -a \frac{q}{m} \vec{B} - \eta \frac{q}{2m} (\vec{\beta} \times \vec{B})$$

- $\omega_\eta / \omega_a$  (with  $d_\mu = 10^{-21} \text{ e} \cdot \text{cm}$ ) is about  $10^{-5}$
- Too small to see a  $\omega_\eta$  contribution ( $\sim 10^{-10}$ ) in  $\omega$
- But the tilt of angular velocity vector is visible ( $\sim 10^{-5}$  rad).

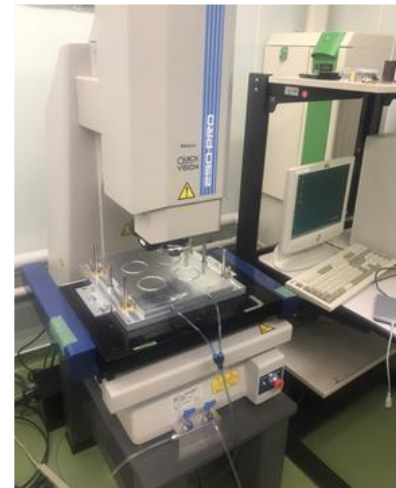
$$\tan \delta = \frac{\omega_\eta}{\omega_a} = \frac{\eta \beta}{2a}$$

- The tilt of the angular velocity vector is observed as an asymmetry between up-going and down-going decay positrons.

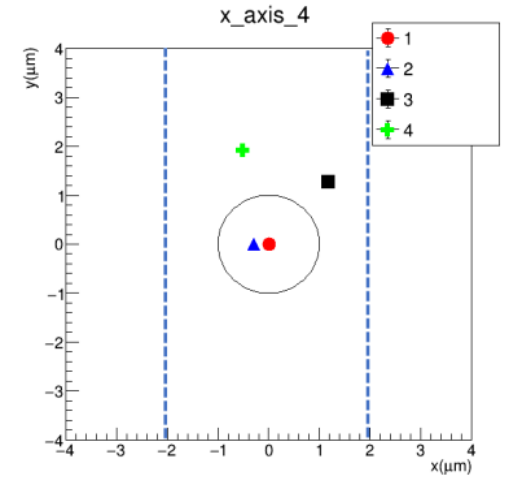


# Detector Alignment

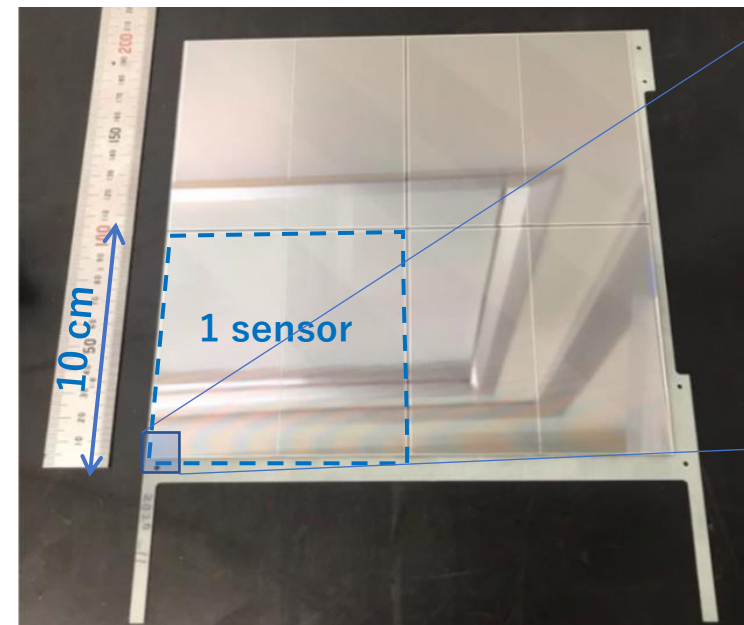
- To achieve  $10^{-21}$  e · cm sensitivity of the EDM, sensors on the detector need to be positioned in the precision of  $1 \mu\text{m}$ .
- Detector assembly aiming at the accuracy of  $1 \mu\text{m}$  in sensor plane is being developed.
  - Sensor assembly with the position deviation less than  $3 \mu\text{m}$  was achieved so far.
- A way to measure sensor positions using positron tracks is also being developed.



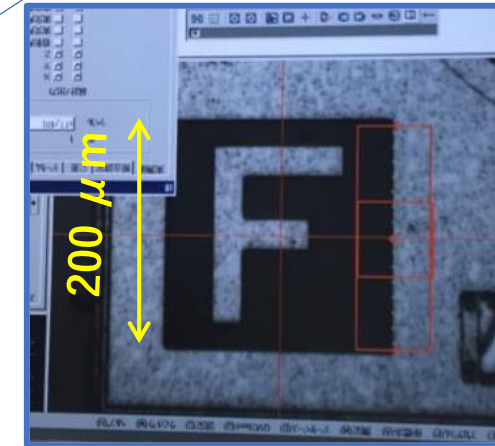
Sensor assembly using a coordinate measuring machine (CMM)



Example of the deviation from the target position after sensor gluing



4 sensors glued on frame



Sensor position is aligned measuring positions of marks on each corner of sensors with a CMM.

# Experiment Status

- Revised version of technical design report (TDR) was submitted to review committee in December 2017.
- Summary paper of TDR was published by PTEP in 2019
  - [PTEP 2019 \(2019\), 053C02](#)
- KEK-SAC endorsed the experiment for the near-term priority in 2019.
- KEK prepared for a function request to Japanese government (MEXT) in 2020.
- The experiment was funded by Specially Promoted Research by JSPS from 2020.

116 members from Canada, China, Czech, France, India, Japan, Korea, Russia, USA



Domestic institutes : Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.  
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC



19th Collaboration Meeting in Dec. 2019@J-PARC

# Schedule and Milestones

Data taking

First result

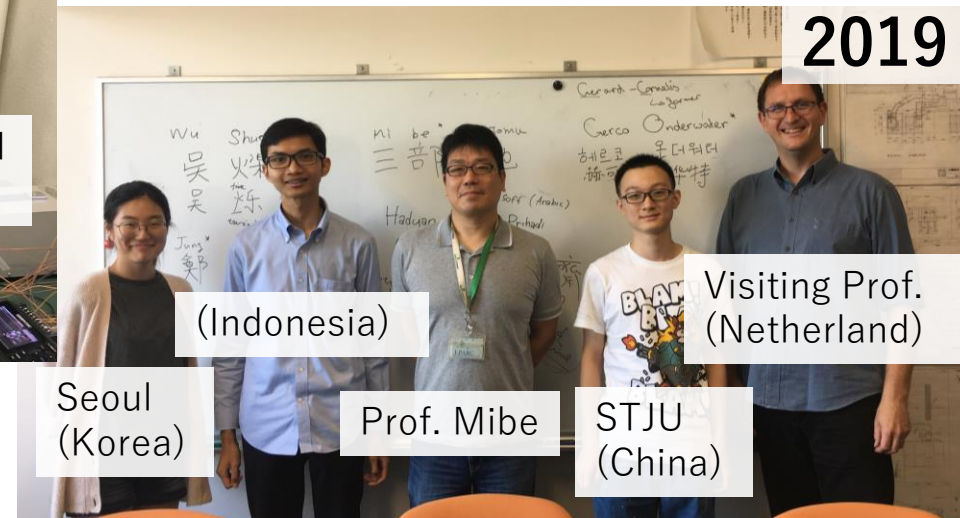
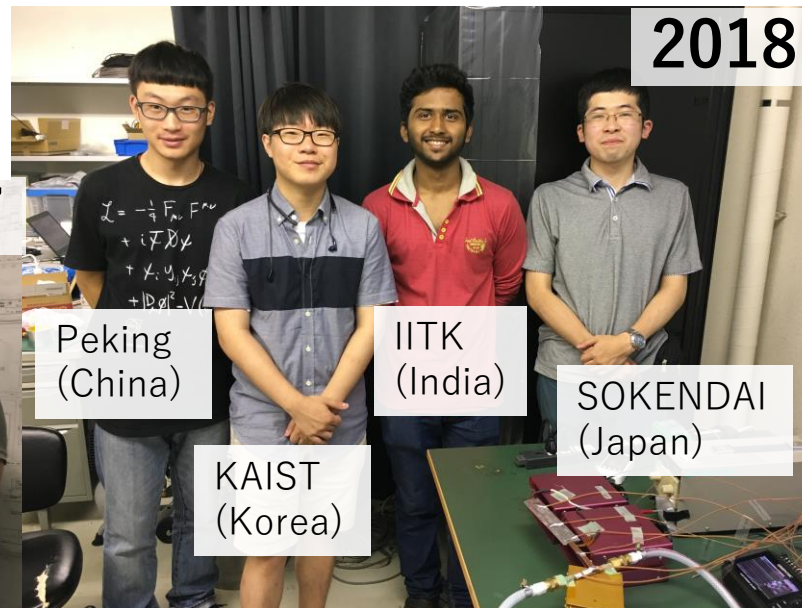
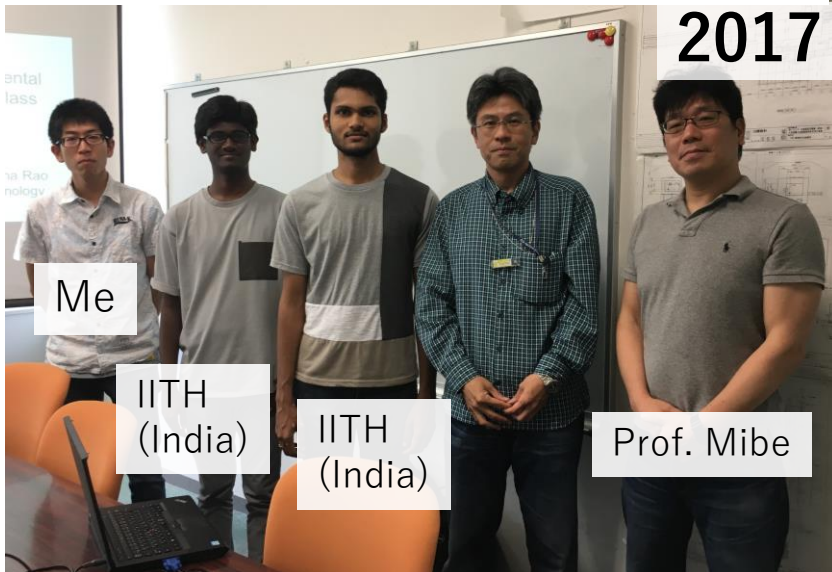
|                       | 2021  | 2022 | 2023  | 2024                  | 2025             | 2026 |
|-----------------------|---|------|---|-----------------------|------------------|------|
| KEK Budget            | Requesting from MEXT to Ministry of Finance |      |   |                       |                  |      |
| Surface muon          | ★ Beam at H1 area                           |      | ★ Beam at H2 area   |                       |                  |      |
| Bldg. and facility    |   |      |   | ★ Completion          |                  |      |
| Muon source           | ★ Ionization test @S2                       |      | ★ Ionization test at H2                                   |                       |                  |      |
| LINAC                 | ★ 1 MeV acceleration@S2                     |      | ★ 4.5 MeV@ H2   | ★ 210 MeV<br>★ 10 MeV |                  |      |
| Injection and storage | ★ Completion of electron injection test     |      |   |                       | ★ muon injection |      |
| Storage magnet        |   |      | ★ B-field probe ready                                     | ★ Shimming done       |                  |      |
| Detector              | ★ Mass production ready                     |      |   | ★ Installation        |                  |      |
| DAQ and computing     |   |      | ★ Ready   |                       |                  |      |
| Analysis              |   |      | ★ Analysis software ready<br>★ Analysis environment ready |                       |                  |      |

Commissioning

Data taking

# International Exchange

- The experiment has been accepted summer students as SOKENDAI KEK Tsukuba/J-PARC summer student program.





# g-2 School in Mainz (Virtual)

**NEW DATE**  
AUG. 29 TO SEPT. 03, 2021  
— MAINZ, ERBACHER HOF  
**VIRTUAL**

INTERNATIONAL PHYSICS SCHOOL  
**MUON DIPOLE MOMENTS AND HADRONIC EFFECTS**

[https://indico.mitp.uni-mainz.de/e/g-2\\_school](https://indico.mitp.uni-mainz.de/e/g-2_school)

**TOPICS AND SPEAKERS**

- Muon Magnetic Moment Experiment Graziano Venanzoni (INFN Pisa, Italy)
- Muon Magnetic Moment Theory Daisuke Nomura (KEK, Japan)
- Hadronic Light-by-Light Phenomenology Bastian Kubis (Bonn, Germany)
- Data Input to Hadronic Vacuum Polarization Erika de Lucia (Frascati, Italy)
- Data Input to Hadronic Light-by-Light Christoph Redmer (Mainz, Germany)
- Particle Detectors Wolfgang Kühn (Gießen, Germany)
- Lattice QCD Theory Marina Marinkovic (Dublin, Ireland), L.b.c.
- New Physics Contributions to g-2 Sijetlana Fajfer (Ljubljana, Slovenia)
- Atomic Physics Precision Experiments Klaus Blaum (MPI Heidelberg, Germany)
- Exercise Session Lena Heijmanskjöld (JGU Mainz, Germany)

**SCIENTIFIC ORGANIZERS**

- Achim Denig (JGU Mainz, Germany)
- Simon Edelman (BINP, Russia)
- Tsutomu Mibe (KEK Tsukuba, Japan)
- Boris Shwartz (BINP, Russia)

**SCIENTIFIC SECRETARY**

- Lena Heijmanskjöld (JGU Mainz, Germany)

**SCHOOL SECRETARY**

- Susanne Fischer (JGU Mainz, Germany)

- There will be lectures by the world experts related to the muon g-2.
- Please register!
  - <https://indico.mitp.uni-mainz.de/event/208/>

## Tentative schedule

### International Physics School on Muon Dipole Moments and Hadronic Effects

August 30 – September 2, 2021

|                      | Monday   | Tuesday  | Wednesday   | Thursday  |
|----------------------|--|--|---|---|
| 14:00 – 15:25 (CEST) | <b>Lecture 1</b><br>g-2 Exp.<br>Graziano Venanzoni | <b>Lecture 3</b><br>HLbL Theory<br>Bastian Kubis | <b>Lecture 5</b><br>HLbL Exp.<br>Christoph Redmer   | <b>Lecture 7</b><br>LatticeQCD<br>Marina Marinkovic |
| 10 min coffee break  |  |  |   |   |
| 15:35 – 17:00 (CEST) | <b>Lecture 2</b><br>g-2 Theory<br>Daisuke Nomura   | <b>Lecture 4</b><br>HVP Exp.<br>Ivan Logashenko  | <b>Lecture 6</b><br>Atomic Prec.Exp.<br>Klaus Blaum | <b>Lecture 8</b><br>BSM<br>Sijetlana Fajfer         |
|                      |  |  |   | <b>Virtual farewell party</b>                       |

# Summary

- In the J-PARC E34 experiment, measurement of muon  $g-2$  and EDM is planned with a method different from the other experiments.
  - Use of reaccelerated thermal muon beam enables focusing the muon beam without an electric field.
  - By using the muon beam with 10 times lower momentum than the other experiments, the storage region can be smaller and highly uniform magnetic field becomes possible.
  - Final goals are 0.1 ppm for muon  $g-2$  and  $10^{-21}$  e · cm for muon EDM.
- For track reconstruction in the detector, similar techniques used in collider experiments are also used.