Muon g-2 Experiments: From Fermilab to J-PARC and HIAF

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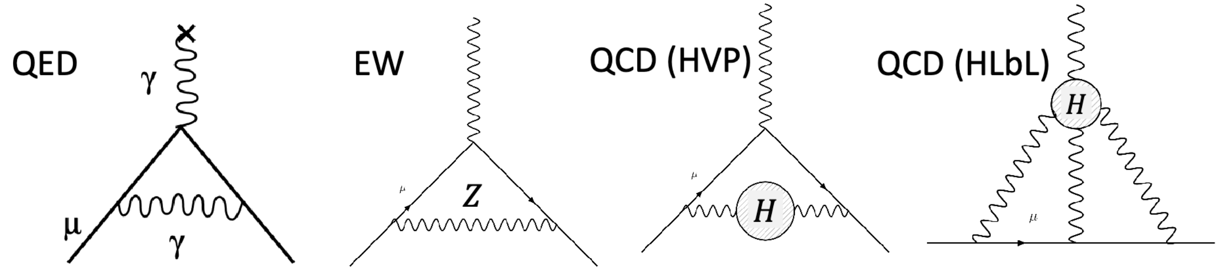
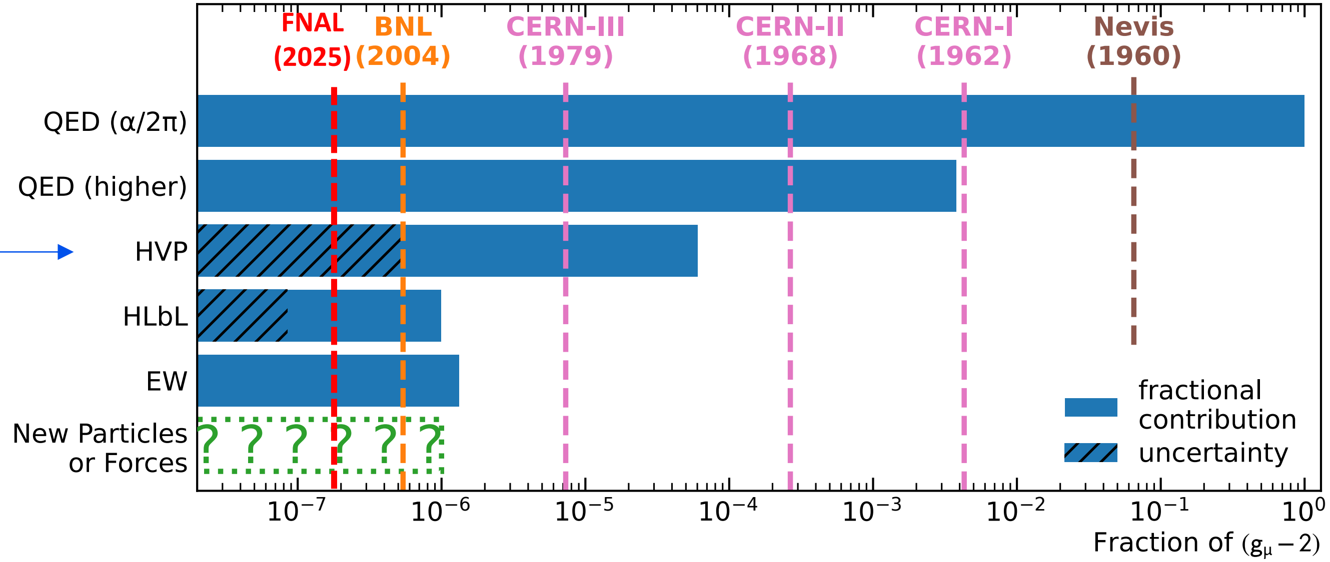
Why Muon g-2

- g: gyromagnetic ratio $\vec{\mu} = g\frac{e}{2m}\vec{S}$
- For Dirac fermion, g equals to 2.
- According to the quantum field theory, g is biased from 2. g is powerful for probing new physics and limit dark matter model.

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi} + \cdots$$



Dominant uncertainty →



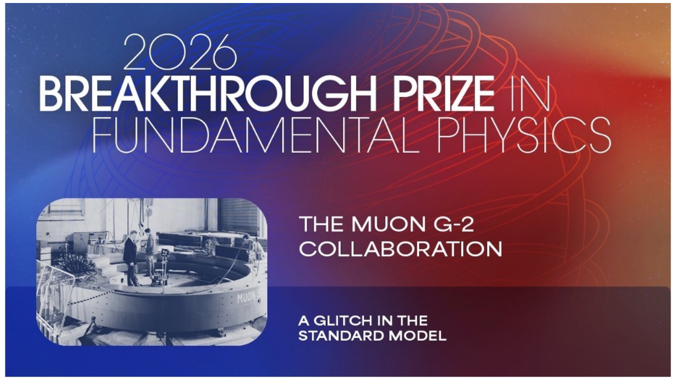
Status of Muon g-2

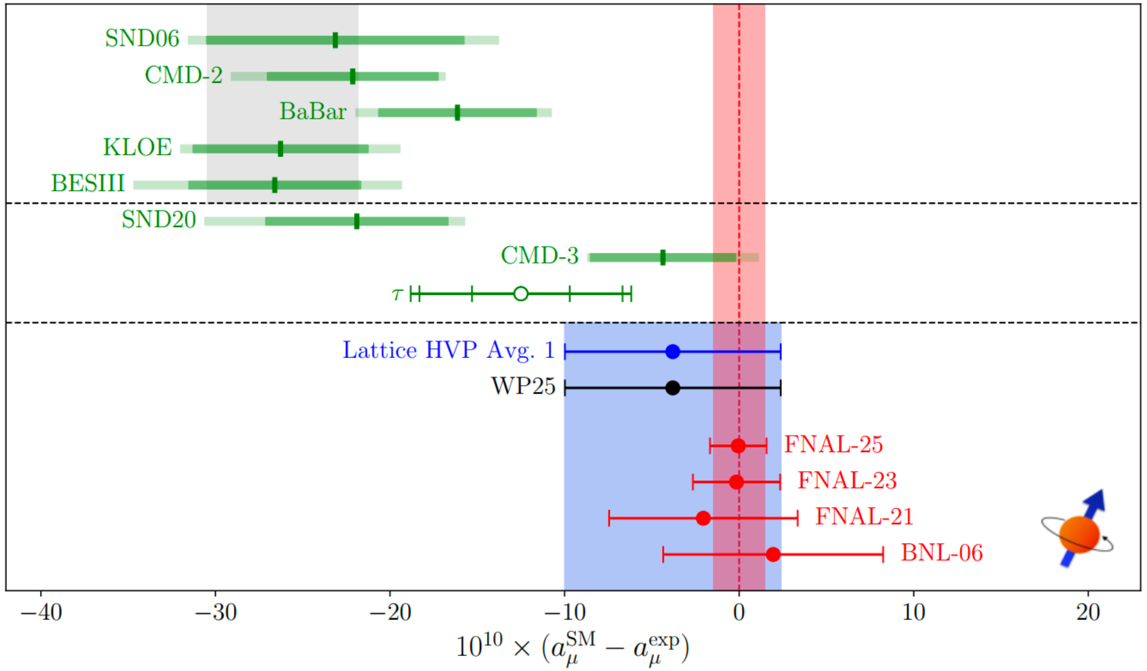
Experiment

- Consistent result, Fermilab's measurement yield 127 ppb.

Theory

- Largest uncertainty from HVP.
- Lattice QCD: consistent with experiment.
- Data driven: deviated from experiment, except for CMD-3.



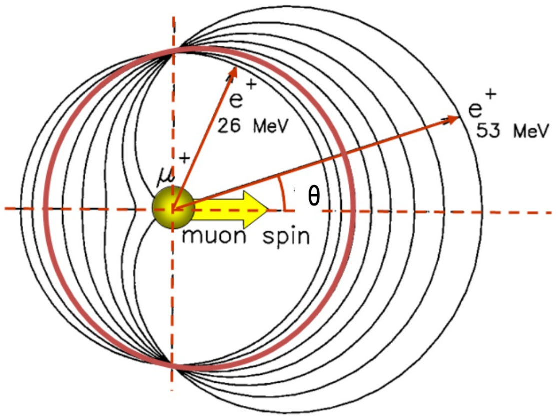


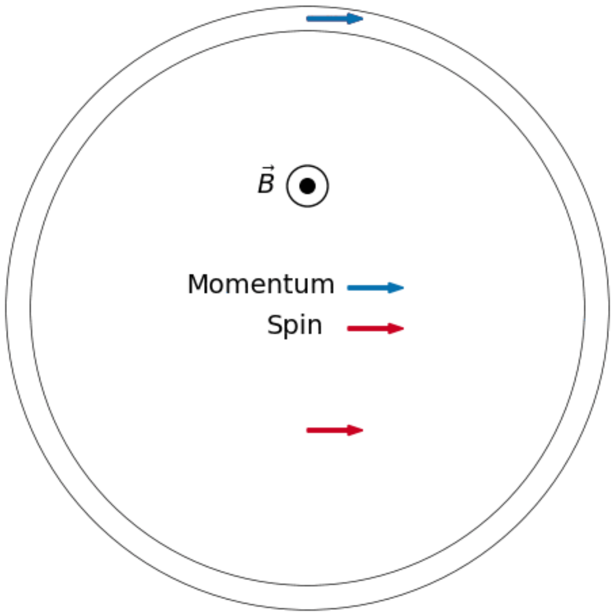
Measurement of g-2

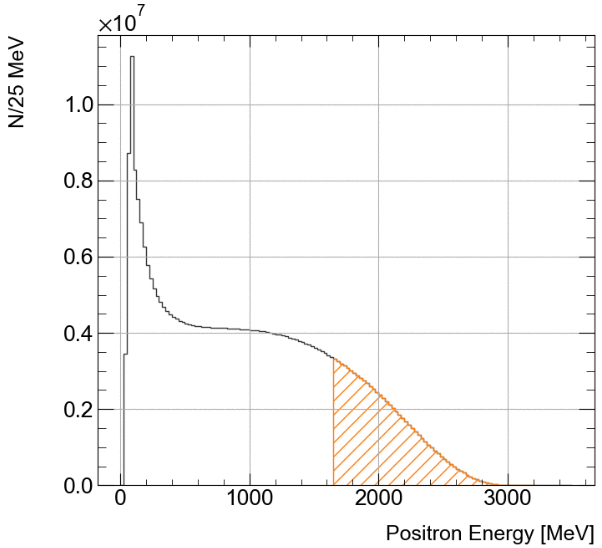
In magnetic field:

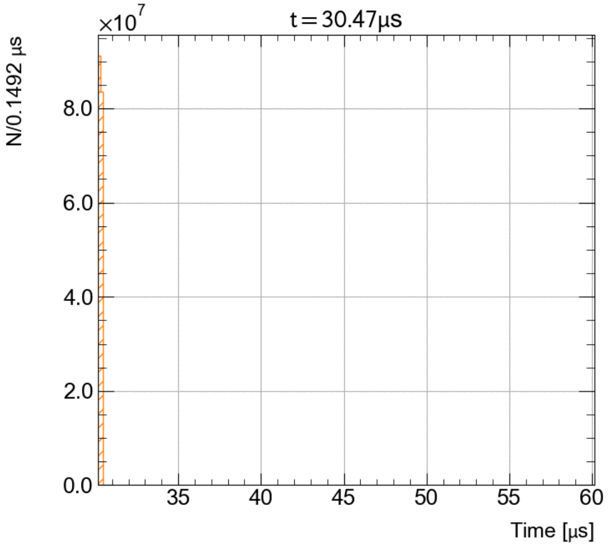
- $\omega_s = \frac{qB}{m}\left[\frac{g_\mu}{2} - \frac{\gamma-1}{\gamma}\right] = \frac{qB}{m}\left[a_\mu + \frac{1}{\gamma}\right]$
- $\omega_c = \frac{qB}{\gamma m}$
- $\omega_a = \omega_s - \omega_c = \frac{qB}{m} a_\mu$

- Decay e^+ tend to be in the spin direction.
- In storage ring, this will be reflected by the energy of decay e^+ .









Measurement of g-2

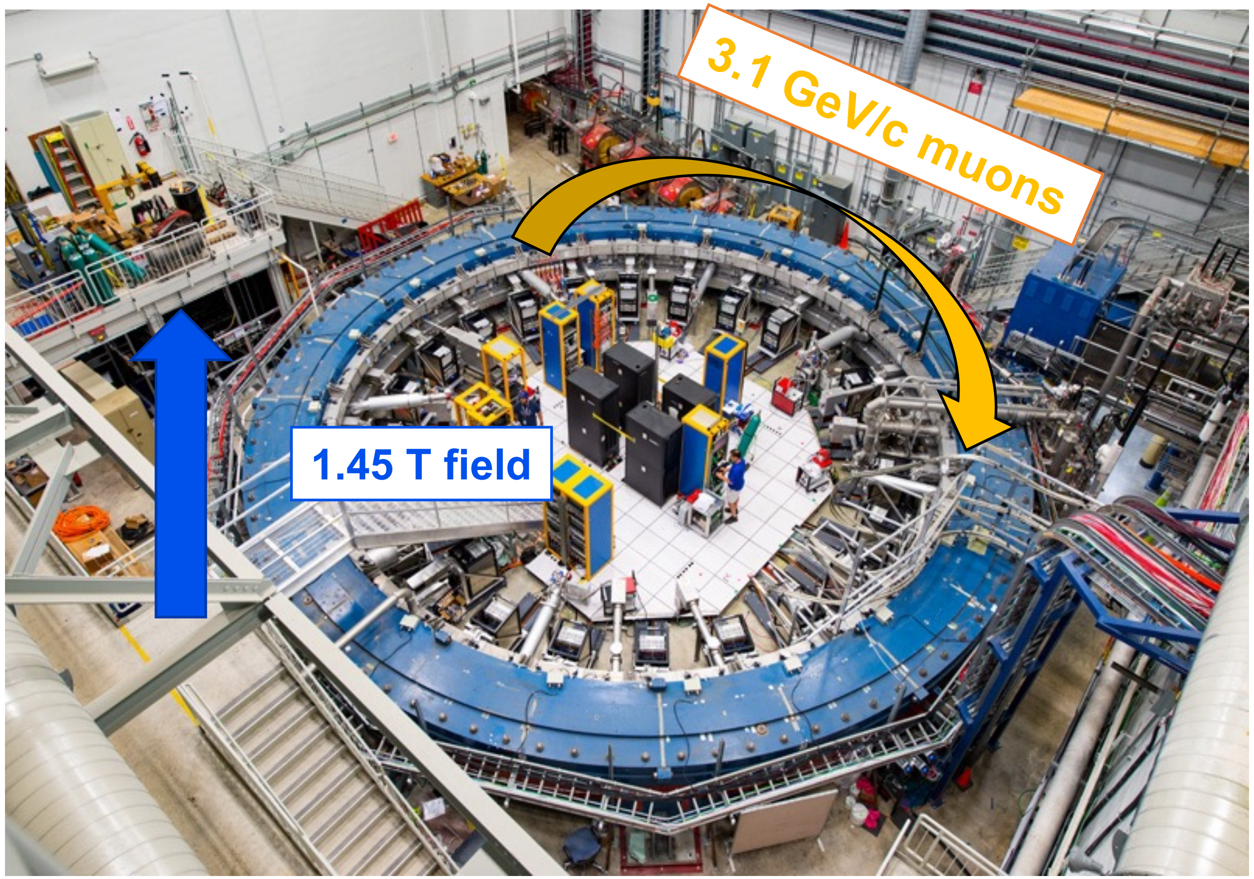
- Consider electric field and non-perpendicular of $\vec{p}$ and $\vec{B}$:

$$\vec{\omega}_a = -\frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

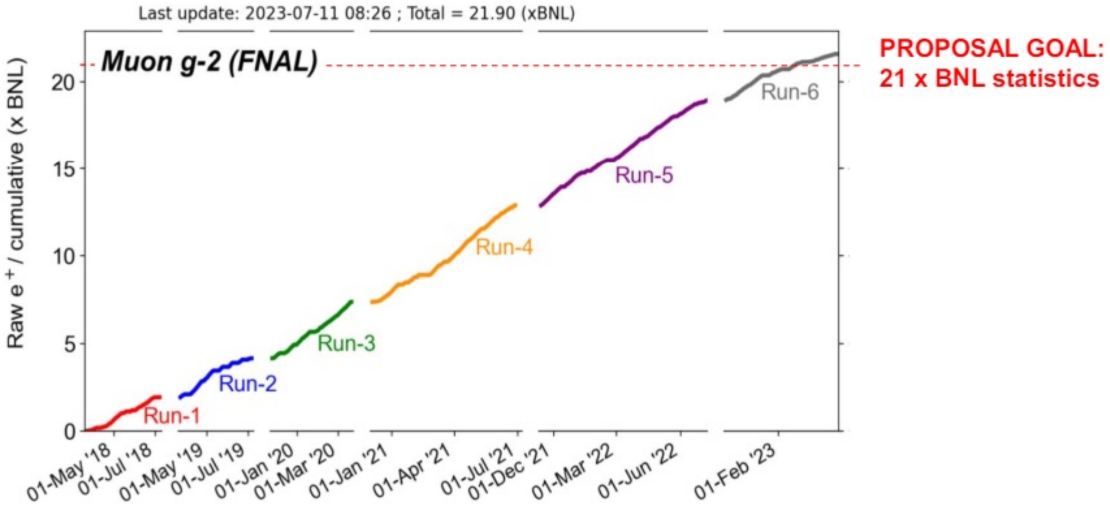
At magic moment $\gamma \approx 29.3$, or $p = 3.1\ \mathrm{GeV/c}$, the electric field term vanish.

- In reality, the muon beam has momentum spread, we still need to consider the electric field correction.
- Precise measurement of muon vertical betatron oscillation and momentum distribution is needed.

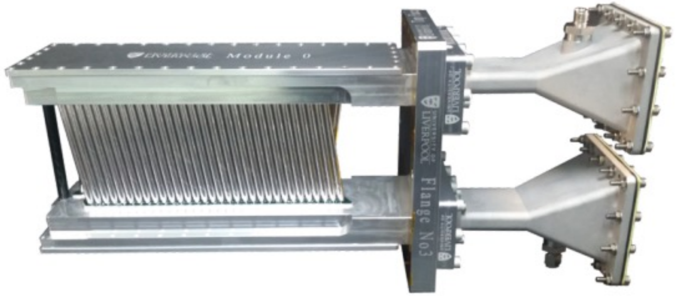
Fermilab Muon g-2 Experiment



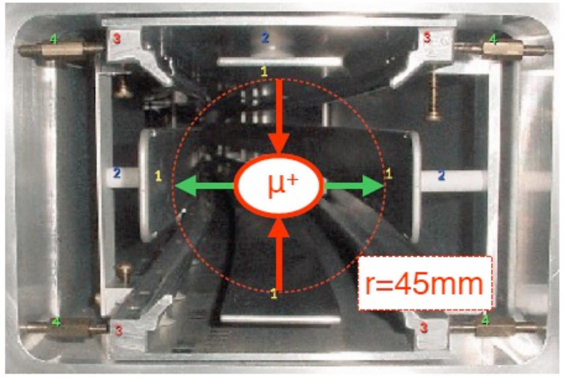
$$a_\mu(\text{Run-1-6}) = 116\,592\,0705(148) \times 10^{-12} \quad (127\,\text{ppb})$$



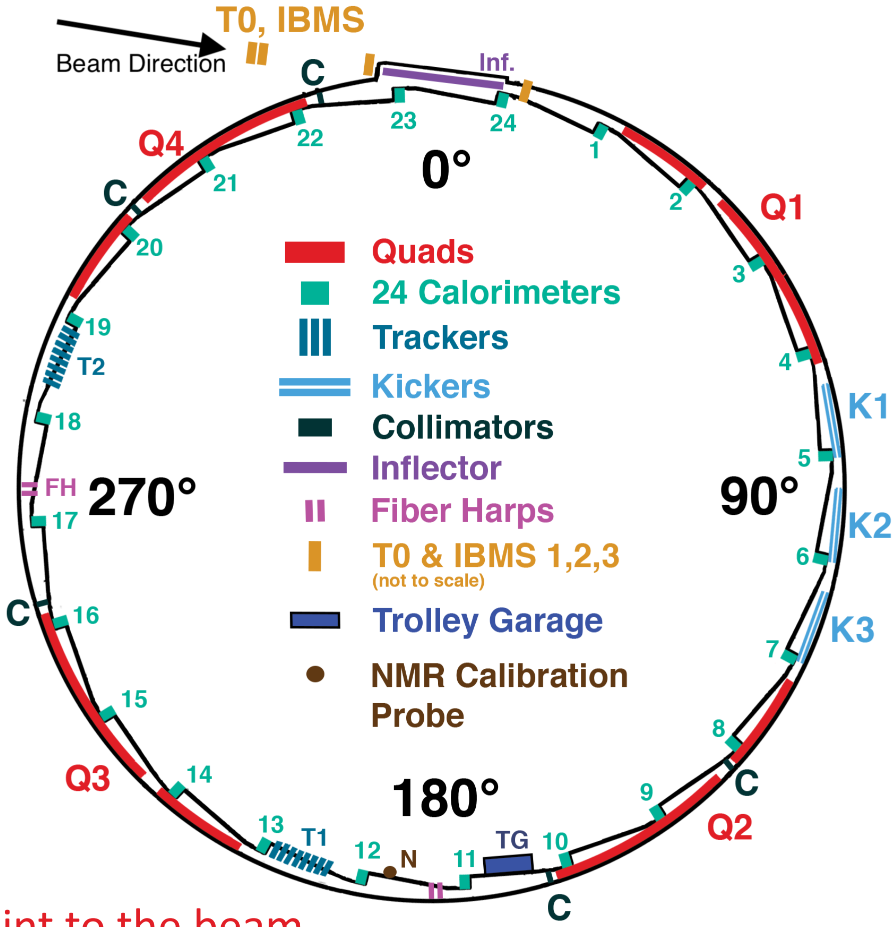
The Storage Ring

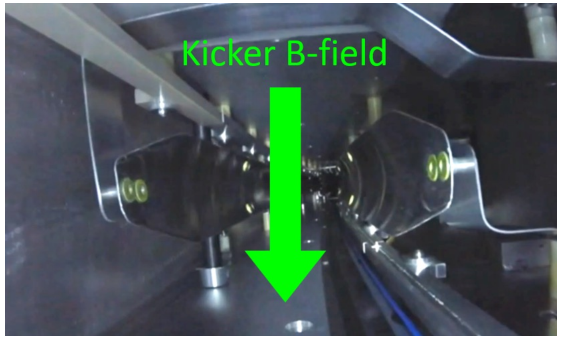


Tracker: Measure the beam position

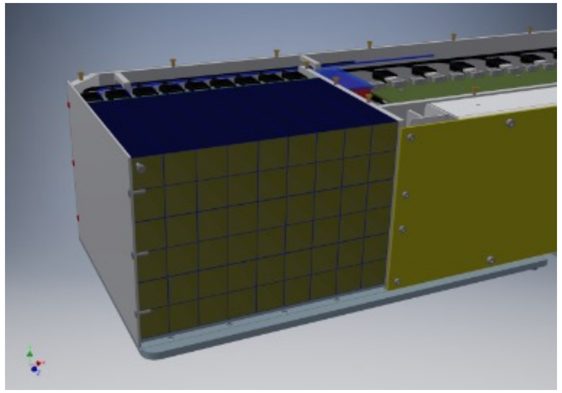


Electric quads: Provide vertical constraint to the beam





Kicker: “kick” the beam to ideal orbit

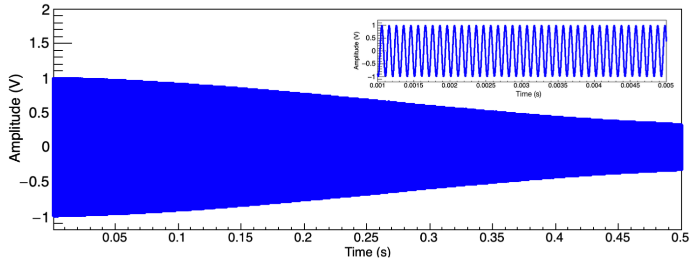


Calorimeters: reconstruct the decay e^+

Measurement Principle

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$\mathcal{R}'_\mu$



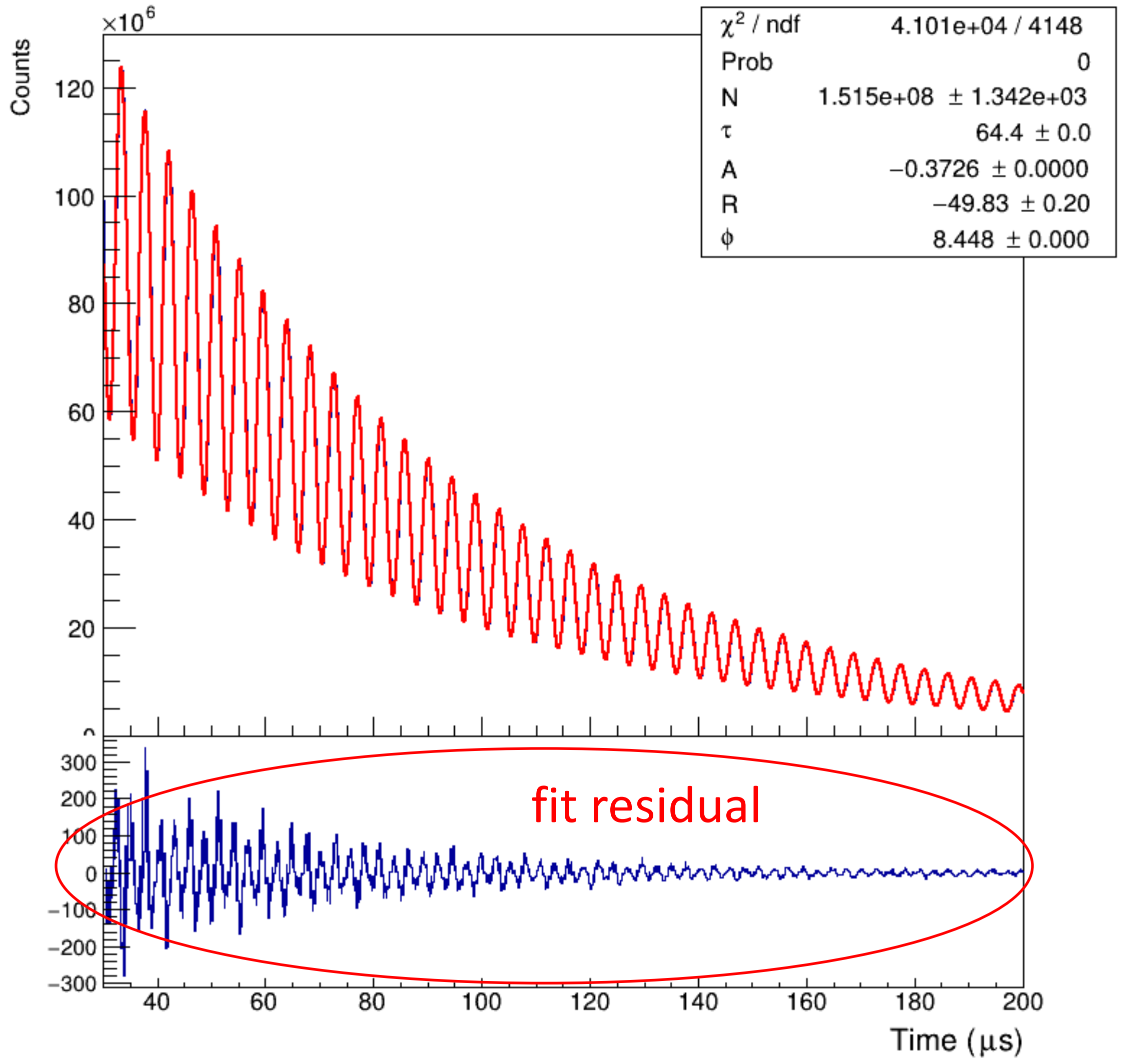
Magnetic field is measured by NMR probe.

electric field | pitch | beam dynamic correction

$$\mathcal{R}'_\mu = \frac{\omega_a^m \left(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}\right)}{\langle \omega'_p(T_r) \times M \rangle \left(1 + B_k + B_q\right)}$$

Field map convoluted by muon distribution | transient field correction

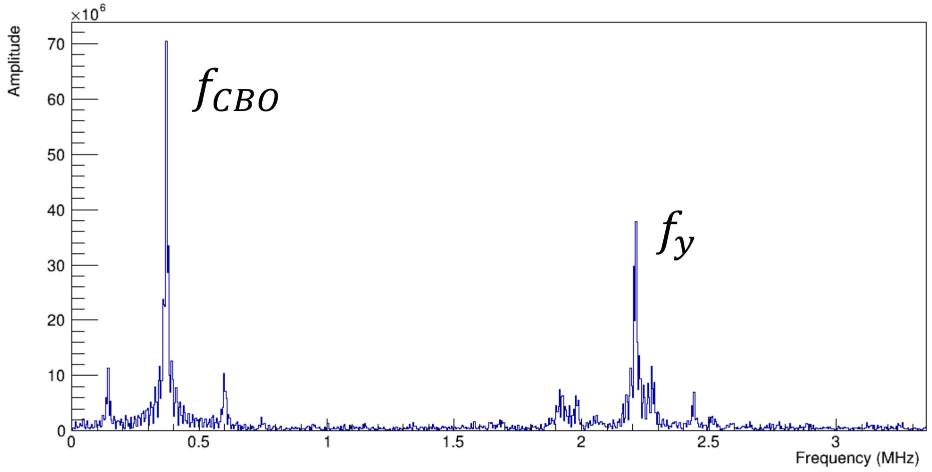
ω_a Analysis



- Fit with 5-parameter function:

$$f(t) = Ne^{-t/\tau}\times[1 + A\cos(\omega_a t - \phi)]$$

- 5-parameter is not enough.
- Oscillation in the fit residual.



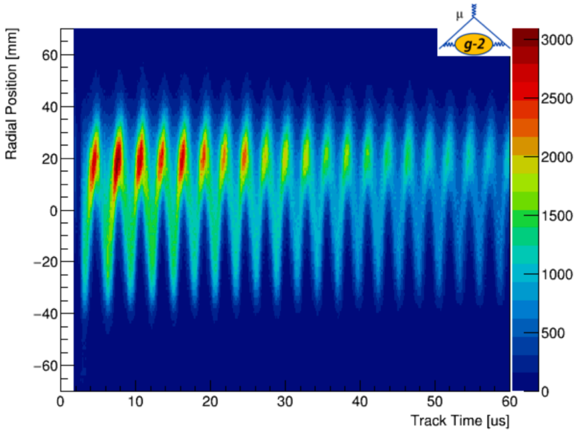
FFT of residual

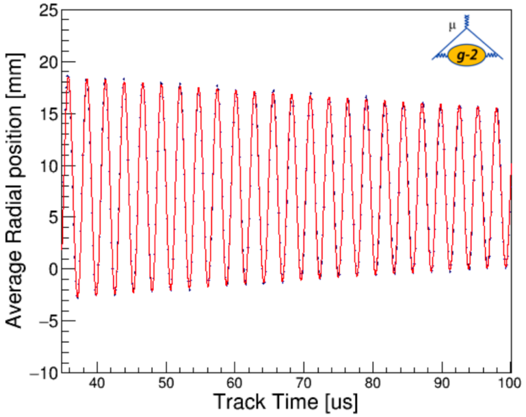
ω_a Analysis

Oscillation mode	frequency	Aliased frequency
X position (CBO)	f_x	$f_c - f_x$
X width (2CBO)	$2f_x$	$2f_c - 2f_x$
Y position (y)	f_y	f_y
Y width (VW)	$2f_y$	$f_c - 2f_y$

- Decoherence:

Spread of muon momentum cause spread of ω_{CBO}
-> Distribution of ϕ_{CBO} becomes uniform as time goes on.



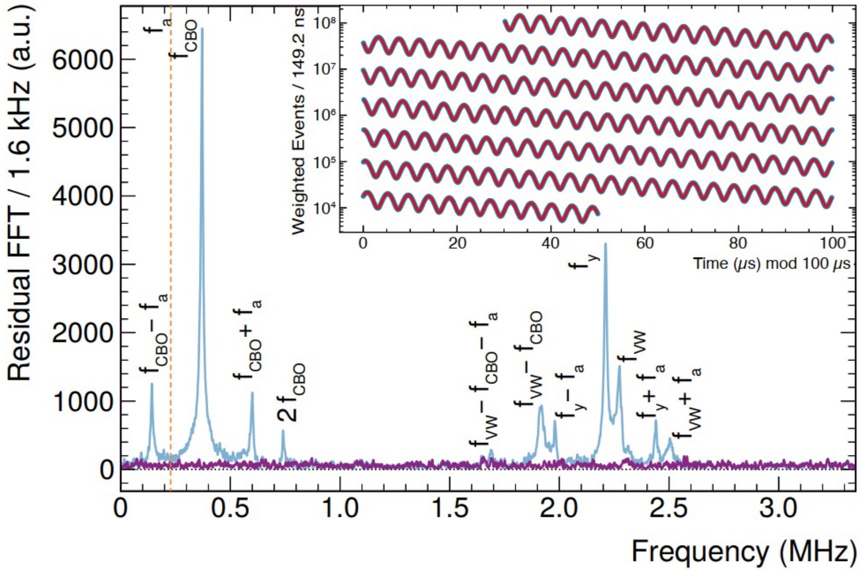


$$f(t) = Ne^{-t/\tau}\times\{1 + A\cos[\omega_a t + \phi]\}$$

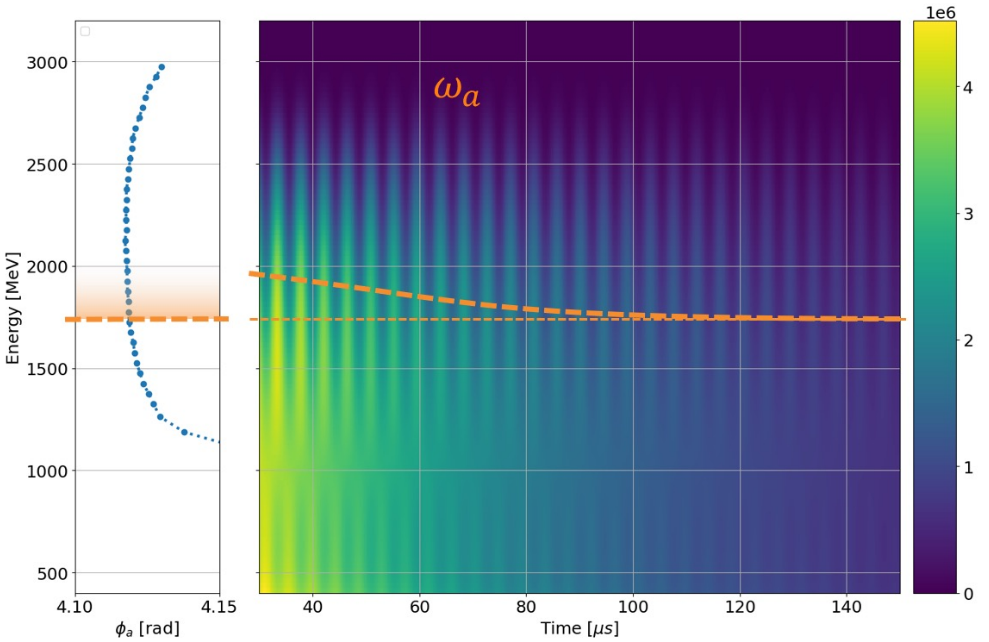
$$f(t) = N\,\boldsymbol{\eta_N(t)}\,e^{-t/\tau}\times\{1 + A\,\boldsymbol{\eta_A(t)}\cos[\omega_a t - \phi + \boldsymbol{\eta_\phi(t)}]\}$$

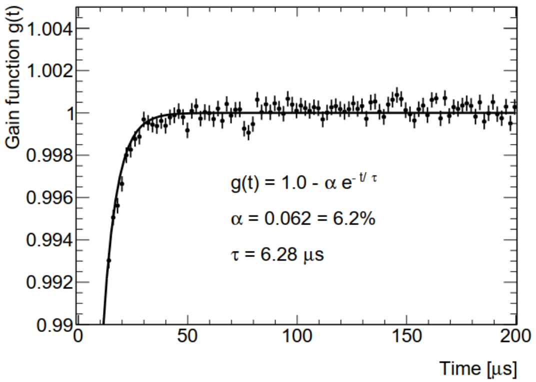
$$\boldsymbol{\eta_N(t)} = \eta_{CBO}(t)\cdot\eta_{2CBO}(t)\cdot\eta_{VW}(t)\cdot\eta_y(t)$$

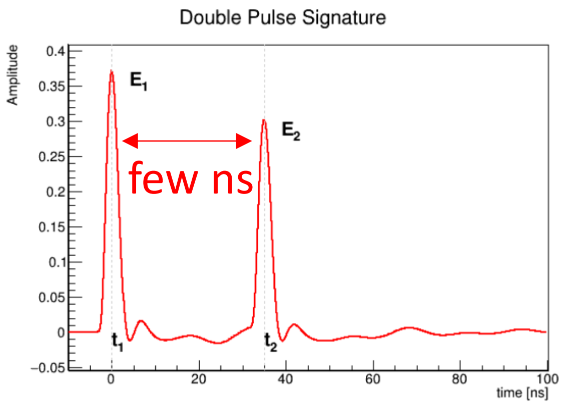
$$\eta_{CBO}(t) = \left[1 + A_{CBO}\,e^{-t/\tau_{CBO}}\cos\left(\omega_{CBO}t + \phi_{CBO}\right)\right]$$



Gain Related Systematics

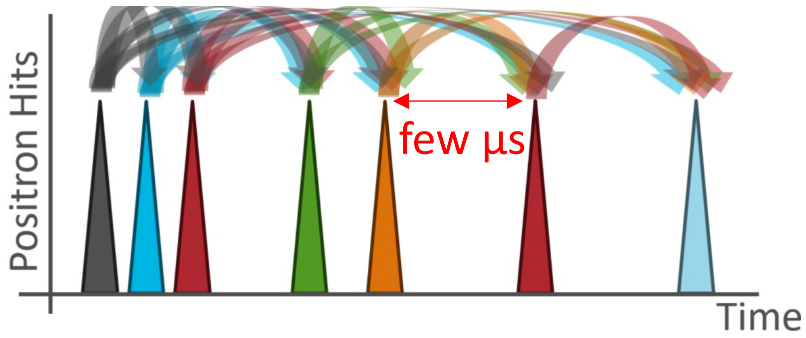






In fill gain: detector recovers from initial splash.

Short-term double pulse: recharge of SiPM after avalanche.



Intermedia term double pulse: small amplitude but has phase shift with g-2 oscillation, causing larger bias.

- In 5-parameter function:

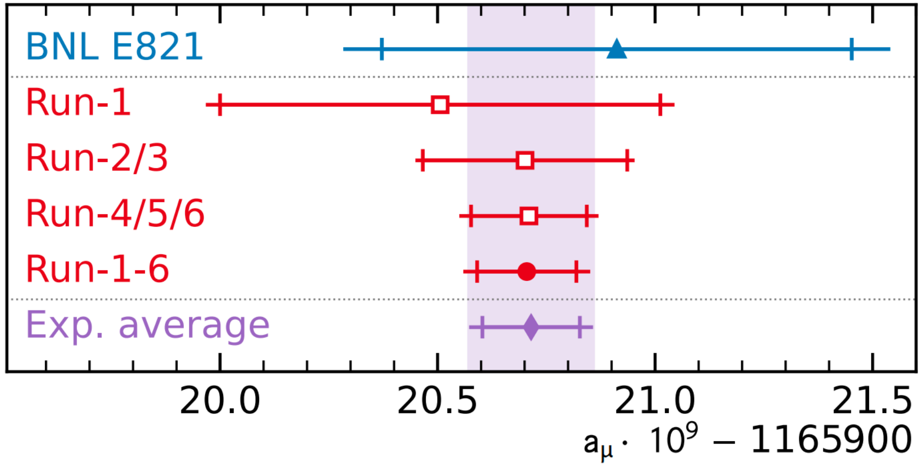
$$f(t) = Ne^{-t/\tau}\times[1 + A\cos(\omega_a t - \phi)]$$

ϕ is dependent with energy.

- Gain change causes $E(t)$, the correlation of ϕ and E further cause $\phi(t)$

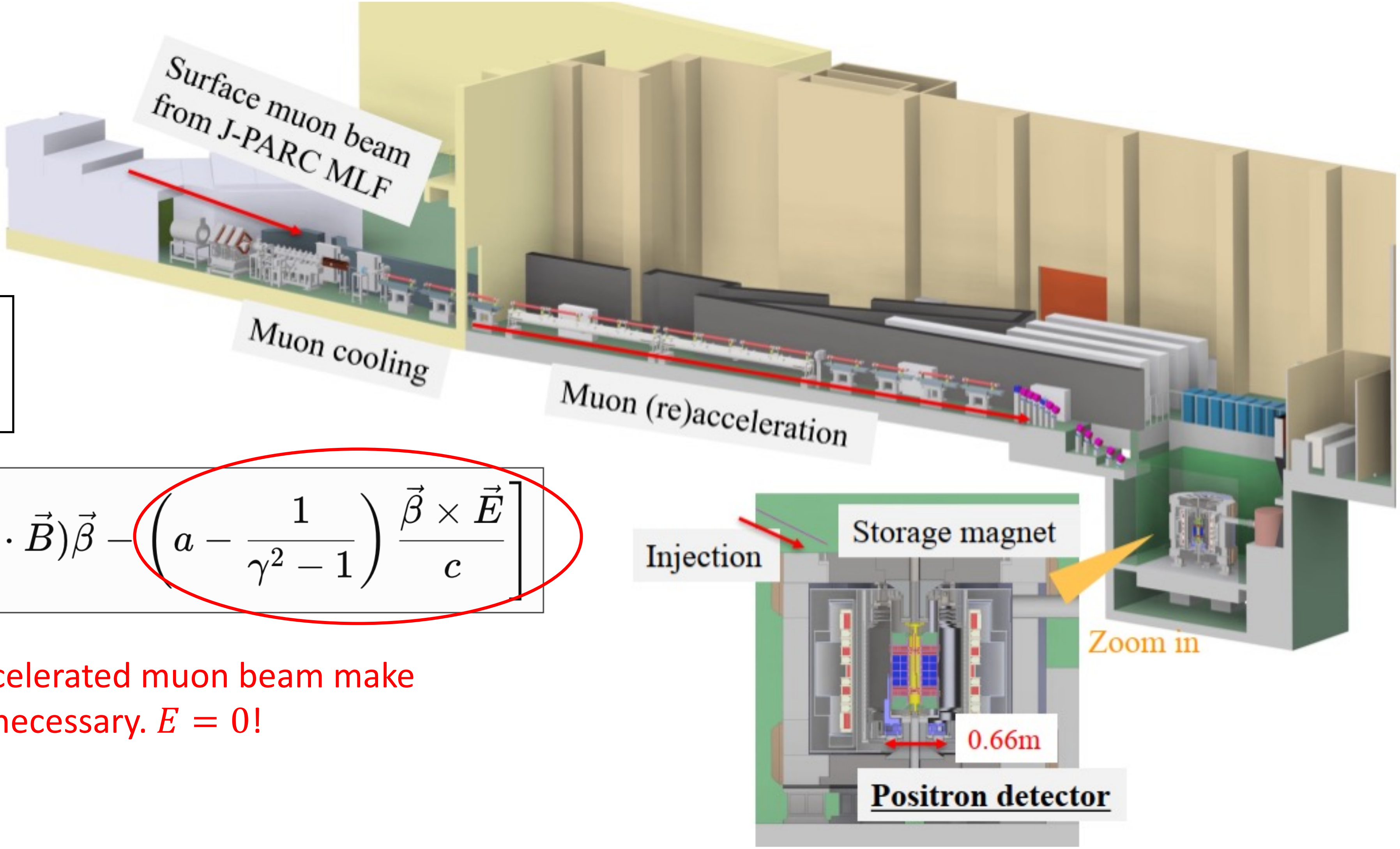
Uncertainties

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	114
ω_a^m (systematic)	$\cdots$	30
C_e	347	27
C_p	175	9
C_{pa}	-33	15
C_{dd}	26	27
C_{ml}	0	2
$\langle \omega_p' \times M \rangle$ (mapping, tracking)	$\cdots$	34
$\langle \omega_p' \times M \rangle$ (calibration)	$\cdots$	34
B_k	-37	22
B_q	-21	20
μ_p'/μ_B	$\cdots$	4
m_μ/m_e	$\cdots$	22
Total systematic for $\mathcal{R}_\mu'$	$\cdots$	76
Total for a_μ	572	139



- Systematics comparable with statistical uncertainty. No dominant systematics source.
- How to improve?
  - Precise beam control
  - Use tracker instead of calorimeter
  - Better magnetic field measurement

J-PARC Muon g-2 Experiment



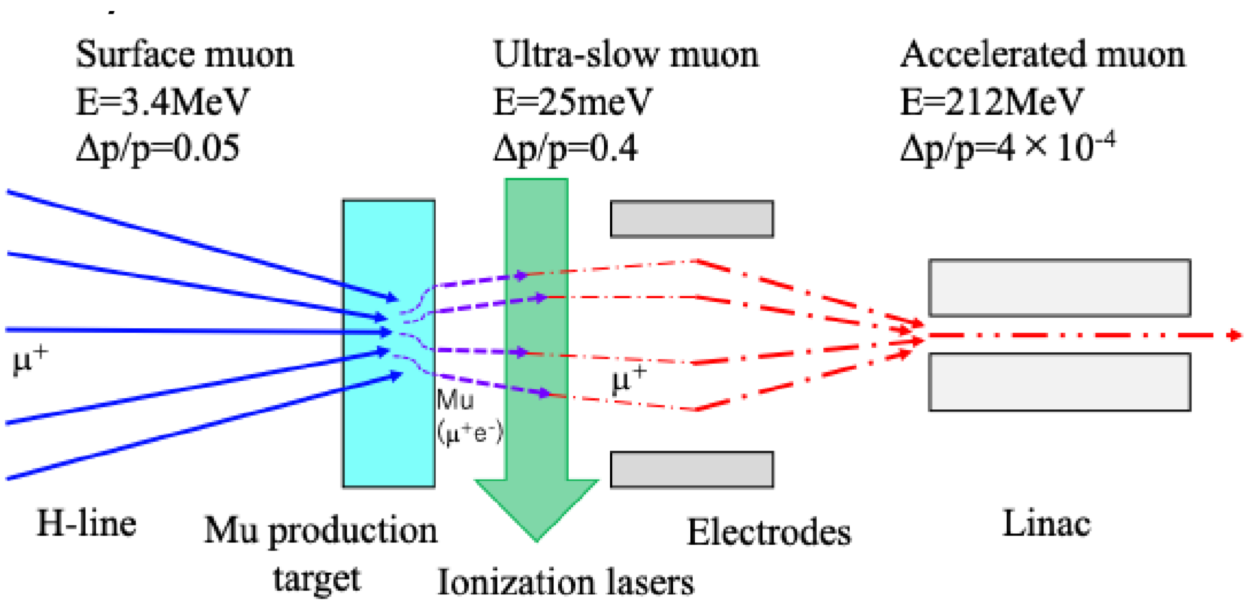
- Momentum: 300 MeV/c
- Magnetic field: 3 T
- Radius: 0.33 m

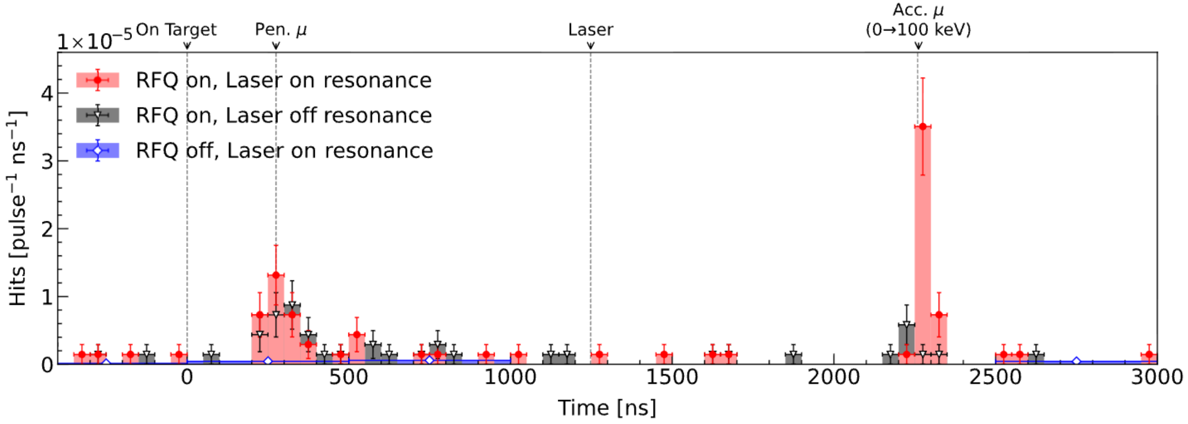
$$\vec{\omega}_a = -\frac{q}{m}\left[a\vec{B} - \frac{a\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

High stability of the reaccelerated muon beam make electric field focusing unnecessary. $E = 0$!

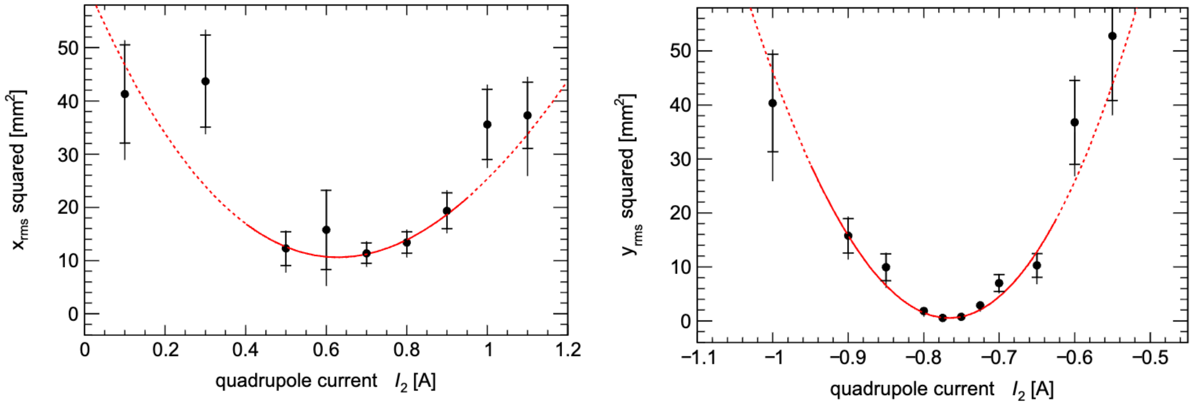
Muon Source

Physical Review Letters 134, 245001 (2025)





Improvement on both momentum spread and emittance



$\varepsilon_x = 0.85 \pm 0.25^{+0.22}_{-0.13}\,\pi$ $\quad \varepsilon_y = 0.32 \pm 0.03^{+0.05}_{-0.02}\,\pi$ mm · mrad

1/200, 1/400 of surface muon beam respectively

Magnet and Detector

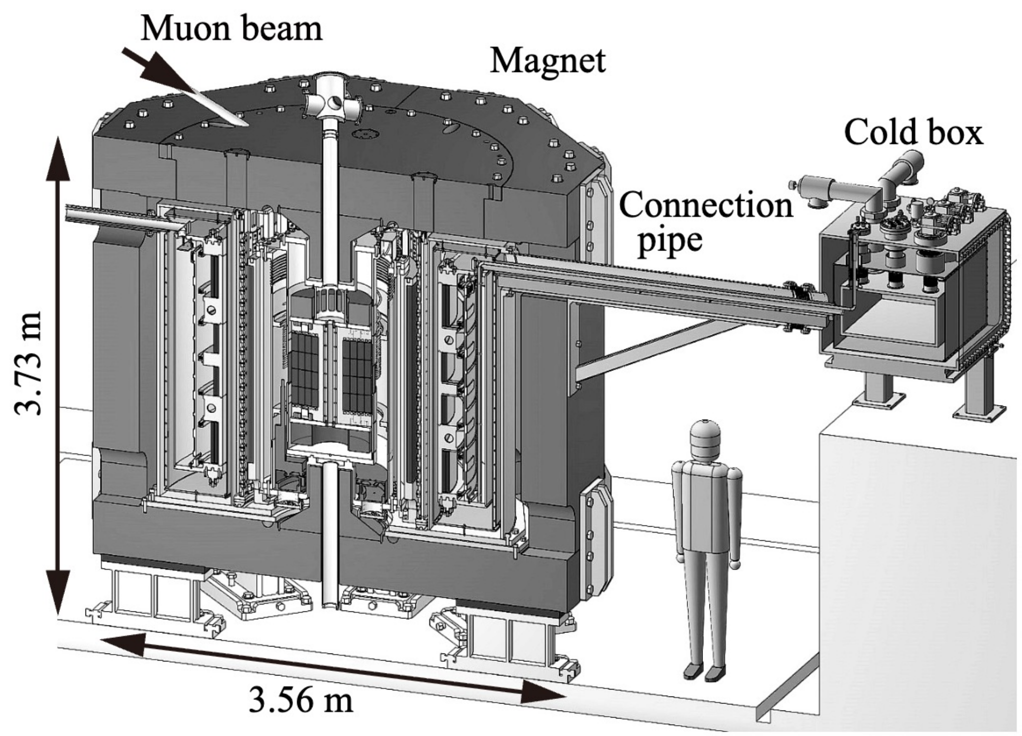
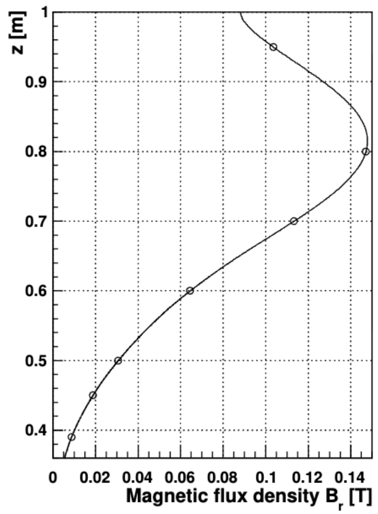
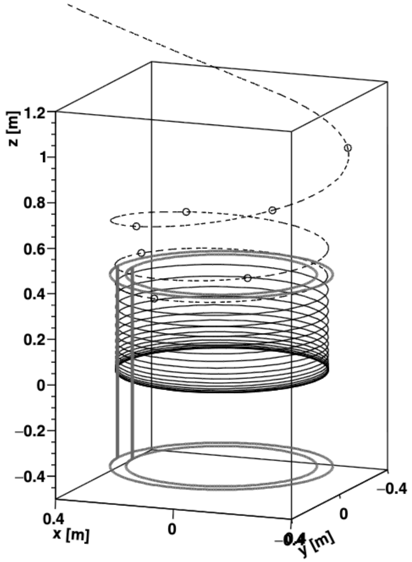


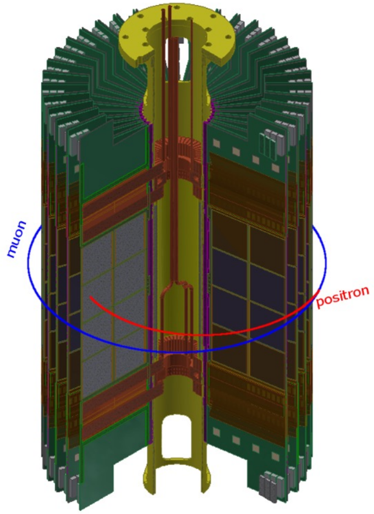
Fig. 8 Overview of the muon storage magnet.

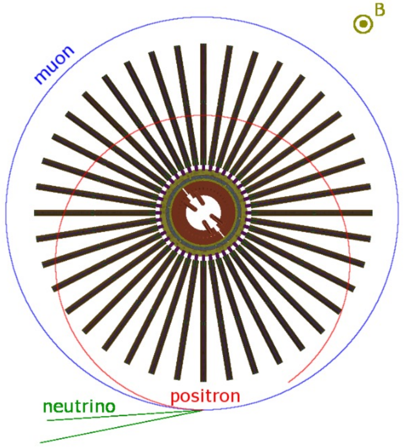
Compact magnet, better field control.





3D injection scheme, use fringe field and kicker to store the muons.

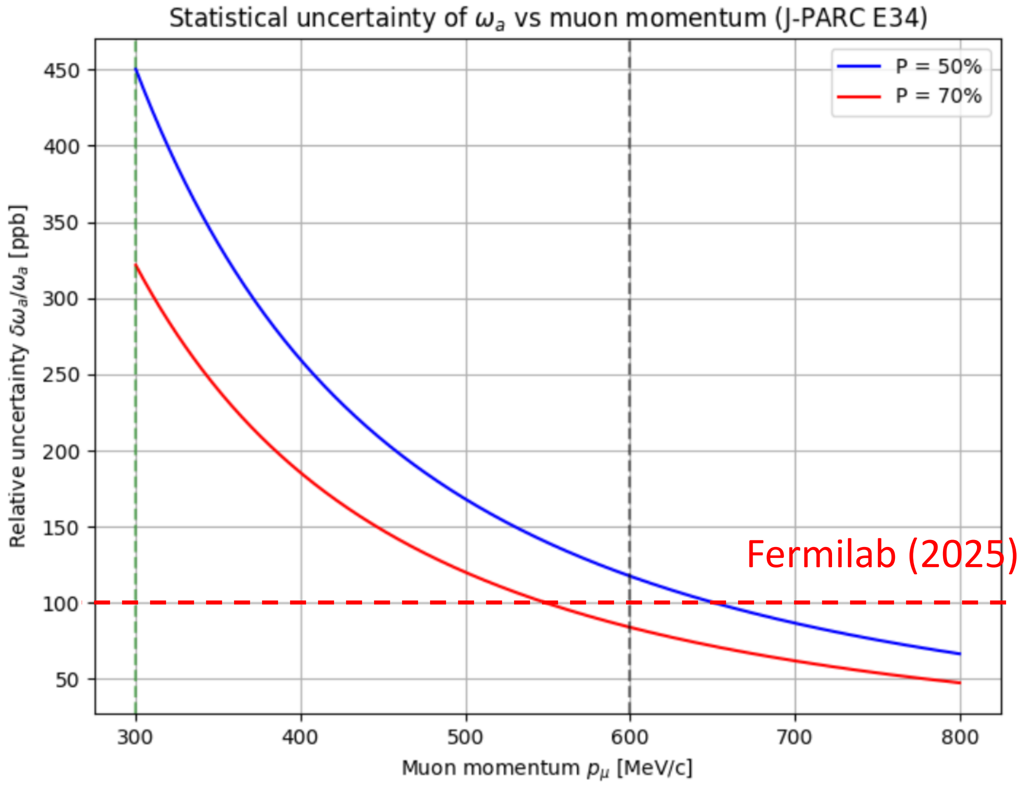




- Tracker detectors to reconstruct decay positrons. Better pileup control, no gain related systematics.

High Sensitivity Scheme

$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$



arXiv:2512.20335

Muon source: Polarization 50% -> 70%

LINAC: 300 MeV/c -> 600 MeV/c

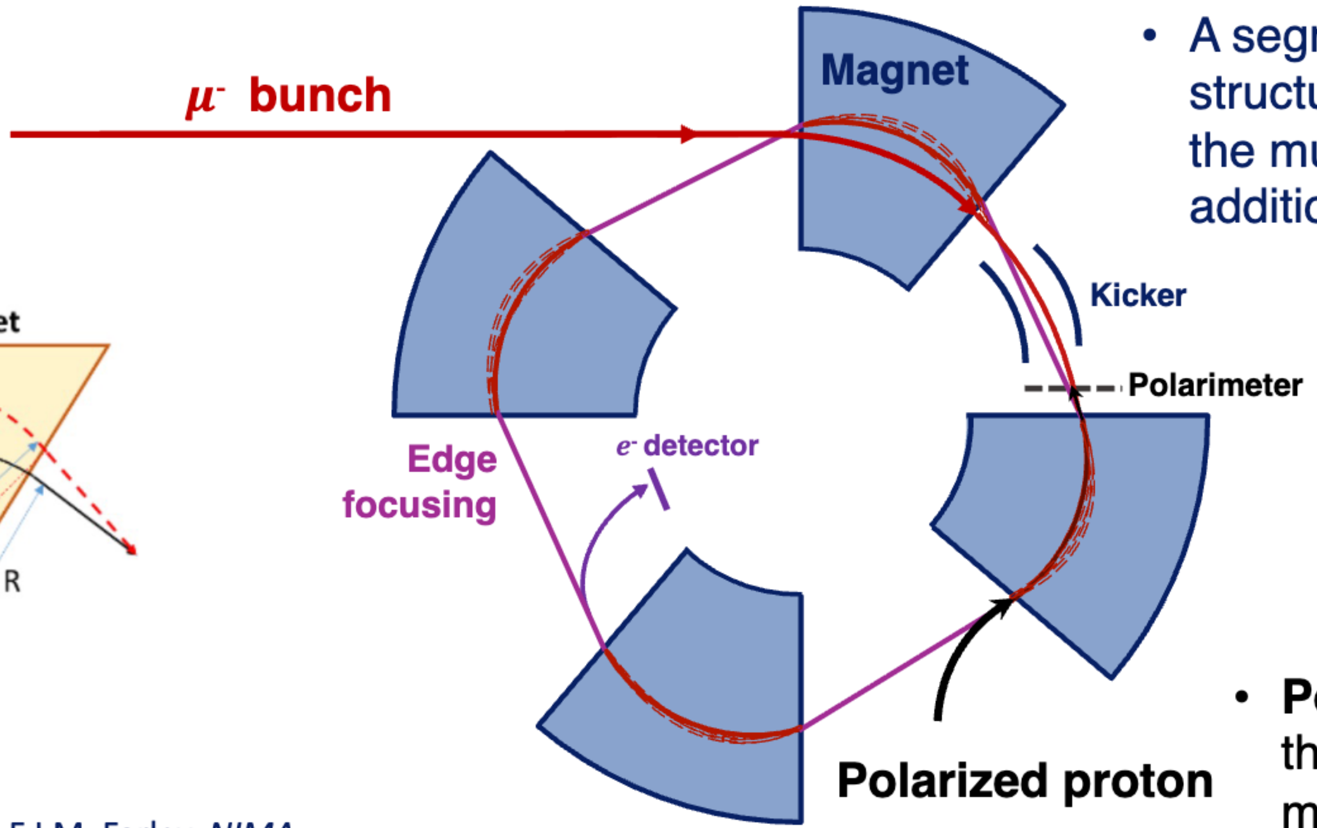
Magnet: 3T -> 6T

Statistical uncertainty: 450ppb -> 70 ppb

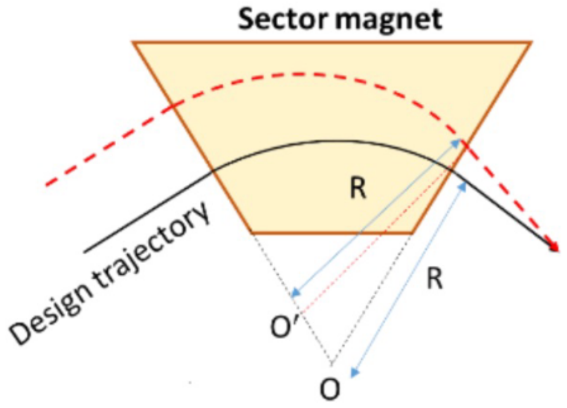
Through these improvement, J-PARC muon g-2 precision can reach ~0.1 ppm and surpass Fermilab's result!

Feasibility study ongoing, will be the future focus of the collaboration.

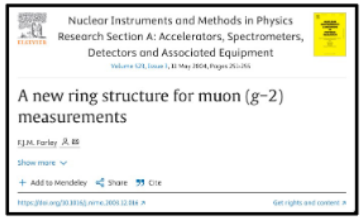
Future g-2 Experiment: CANTON-μ



- A segmented **sector magnet** structure with fringe fields to focus the muons, removing the need for additional E field focusing.



- **Polarized protons** experience the same magnetic field as the muons for a direct calibration of the magnetic field.


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

A new ring structure for muon (g−2) measurements

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Sensitivity Comparison

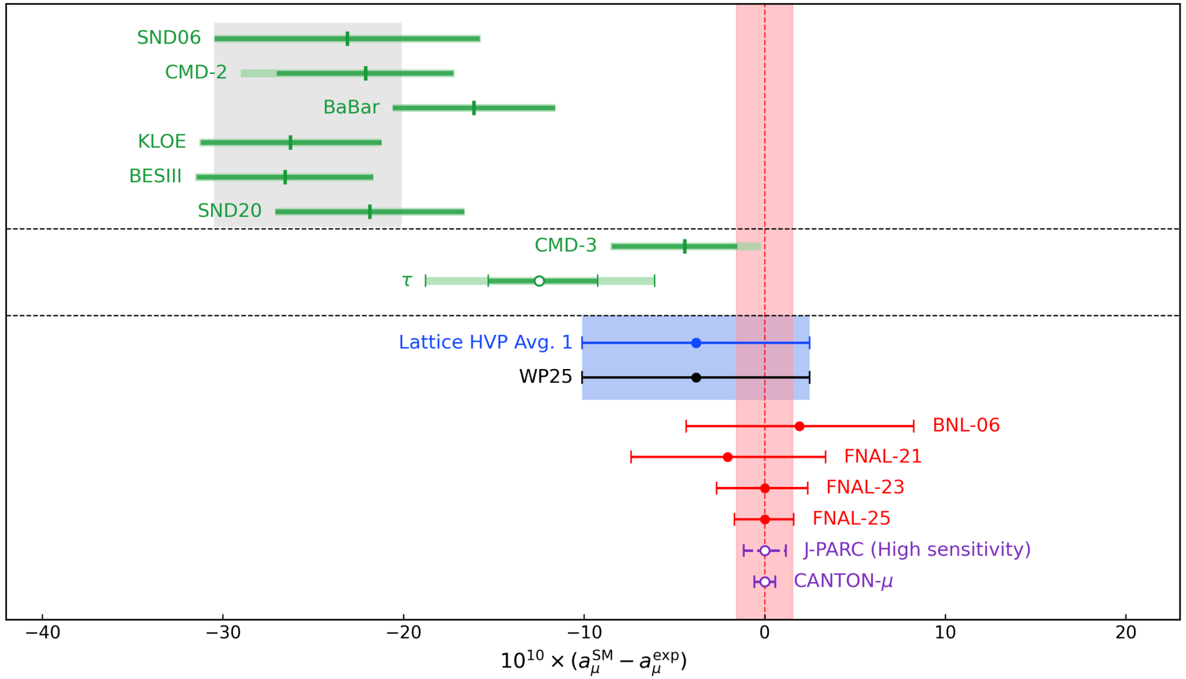
$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau P}\sqrt{\frac{2}{NA^2}}$$

	FNAL	J-PARC	HIAF	HIAF-U
γ	30	**3**	20 – 40 (2-4 GeV)	150 (15 GeV)
B	1.5 T	3 T	3 T or higher	6 – 15 T?
P	100%	50%	100%	100%
N required to achieve the same precision in $\Delta\omega_a/\omega_a$	$\boldsymbol{N}$	100 $\boldsymbol{N}$	$\boldsymbol{N/4}$	$\boldsymbol{N/500}$

- Higher momentum and field release the statistics requirement.
- Aim for 0.05 ppm precision, two folds better than Fermilab’s result.

Summary and Outlook

- From CERN to BNL and Fermilab, increasingly precise muon g−2 measurements have provided a powerful probe of physics beyond the Standard Model.
- What's next?
  - J-PARC: 2030s
  - CANTON-μ: future
  - MUonE: 2030s
  - More $e^{-}e^{+}$ collision experiments
  - More precise lattice QCD result
  - …
- The story of muon g-2 goes on!



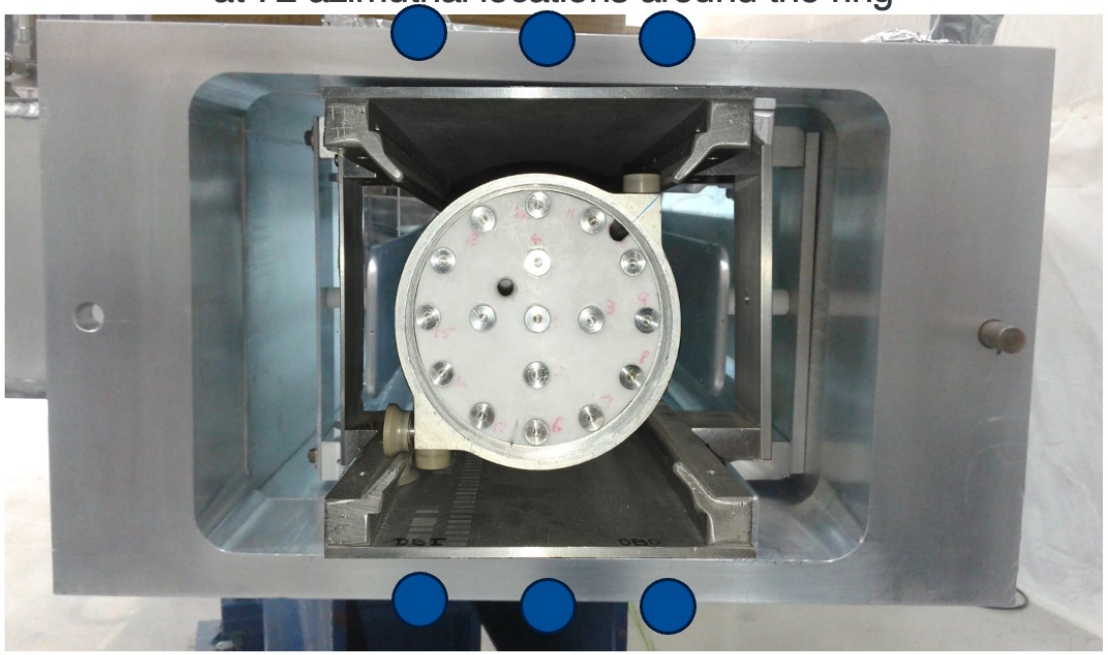
Thank you!

Back up

B Field Measurement

Field Monitor: Fix installed NMR probes

at 72 azimuthal locations around the ring



Trolley: Field Mapper