Measurement of muon g-2

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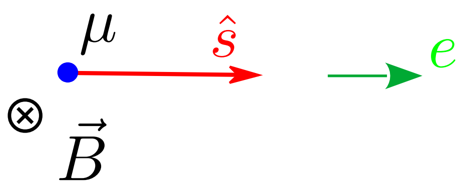
Matsue, Shimane Prefecture, Japan

a_μ measurement



$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} \qquad \vec{\tau} = \vec{\mu}\times\vec{B}$$

$$g = 2(1+a_\mu)$$

the tourque exerted by the magnetic field on the muon's magnetic moment produces a spin precession

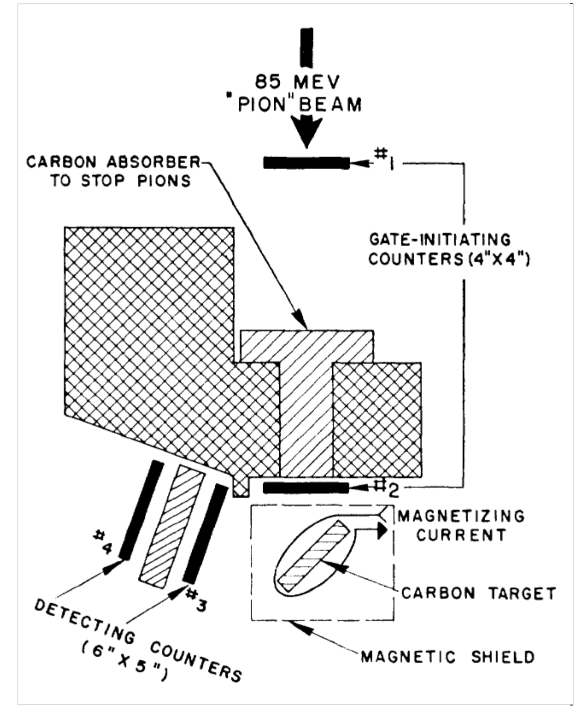
$$\omega_s = g\frac{e}{2m}B = \frac{e}{m}B(1+a_\mu)$$

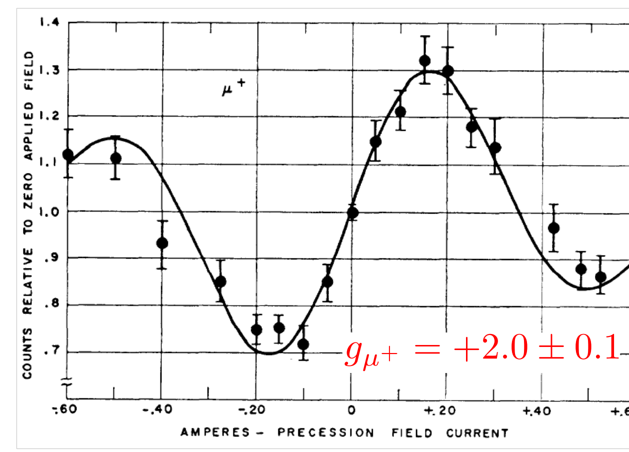
the energy and angular distributions of decay positrons are highly correlated to the muon spin direction due V-A interaction

$\Rightarrow$ a_μ is measured by detecting decay positrons from polarized muons in a known magnetic field.

$$\frac{\sigma_{a_\mu}}{a_\mu} \approx \frac{1}{a_\mu}\frac{\sigma_{\omega_s}}{\omega_s} \qquad a_\mu = \frac{\alpha}{2\pi} + \cdots \approx 0.001$$

$\frac{\sigma_{a_\mu}}{a_\mu}$	$\frac{\sigma_{\omega_s}}{\omega_s}$
1%	0.001%



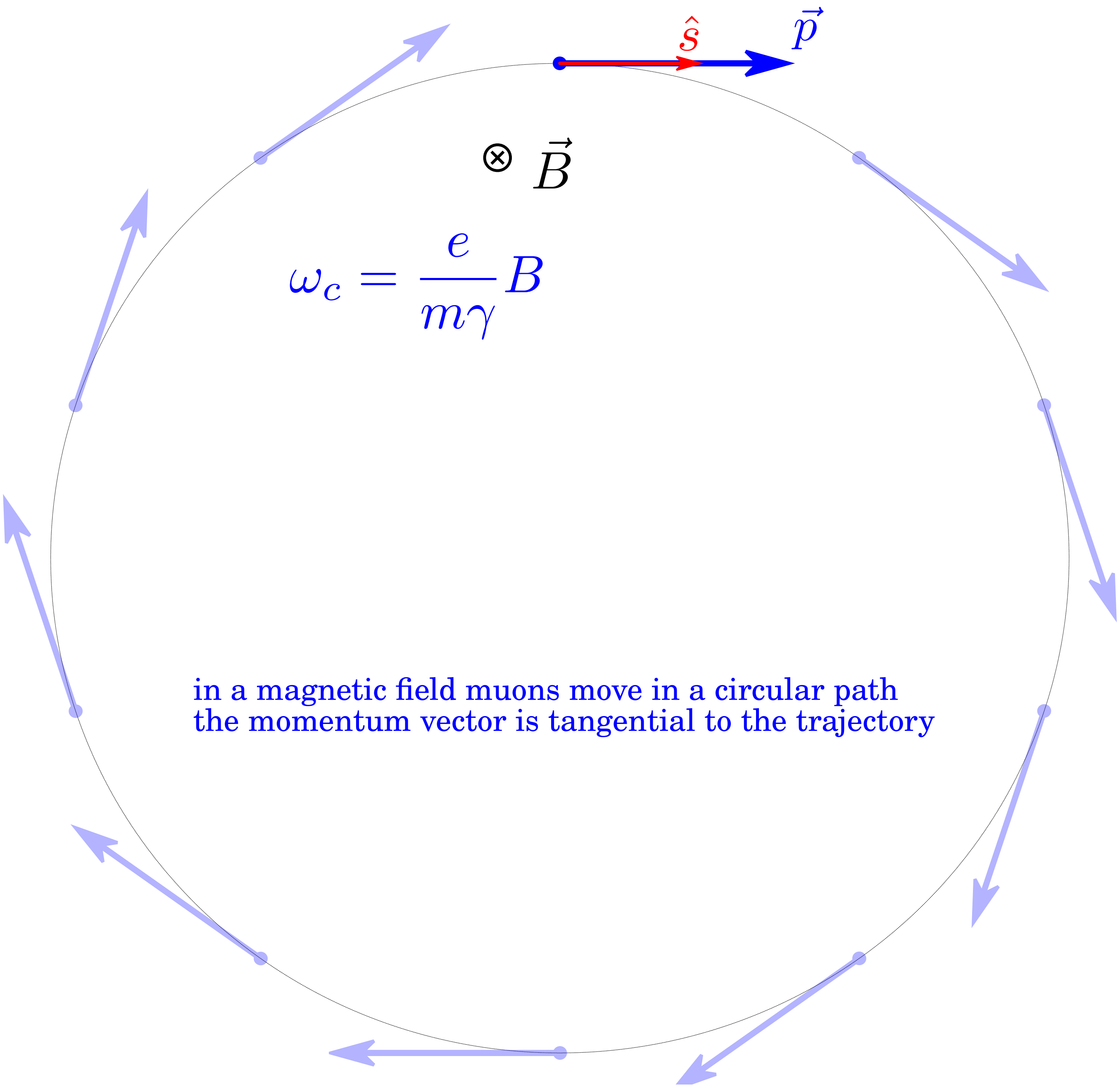


R.L. Garwin, L.M. Lederman, M. Weinrich, Phys. Rev. 105, 1415, (1957)

$$g_{\mu^+} = +2\times\left(1+0.00113^{+0.00016}_{-0.00012}\right)$$

R.L. Garwin, et al., Phys. Rev. 118, 271, (1960)

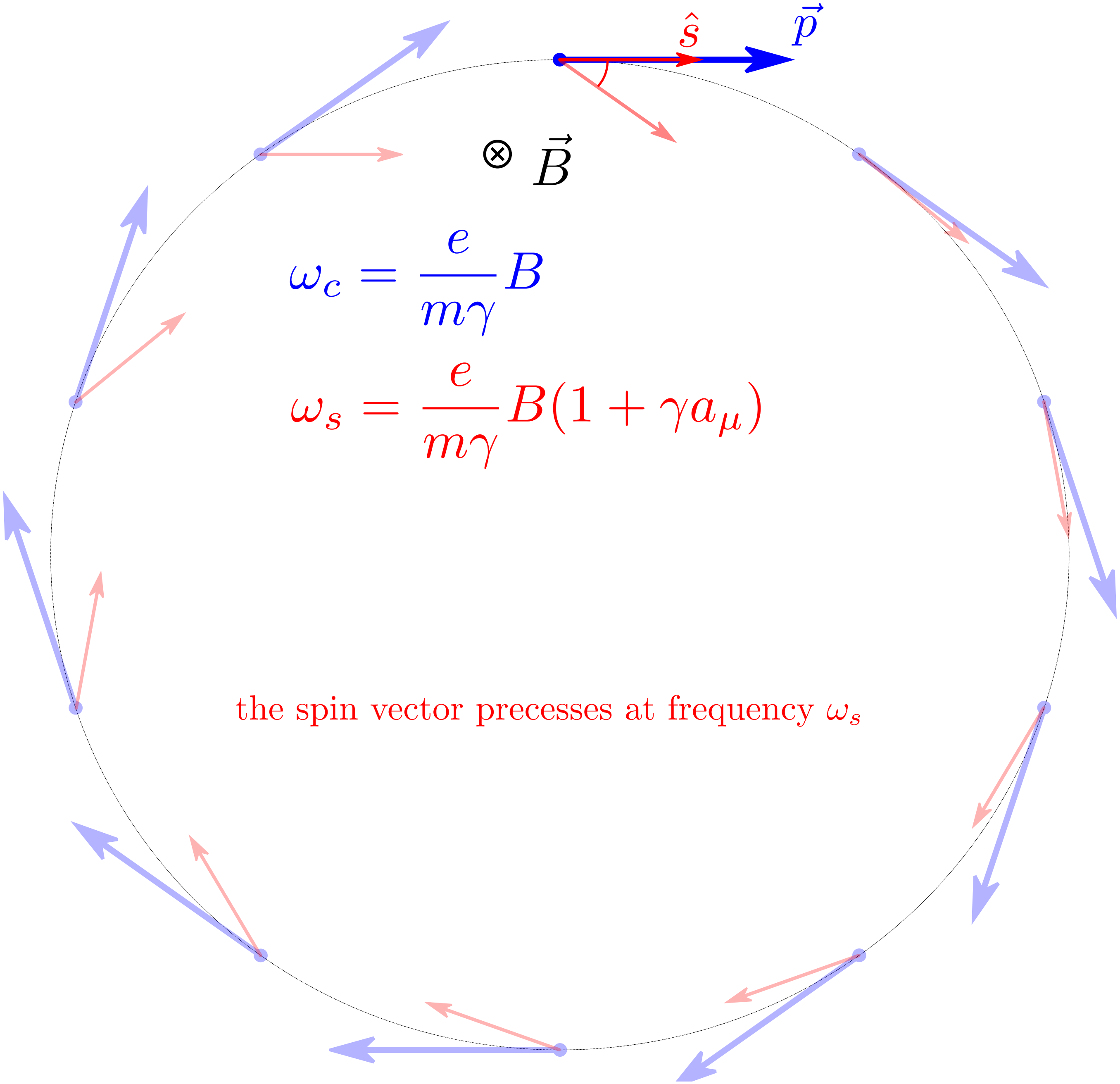
Muon g-2 experiment in a nutshell



$$\omega_c = \frac{e}{m\gamma} B$$

in a magnetic field muons move in a circular path
the momentum vector is tangential to the trajectory

Muon g-2 experiment in a nutshell

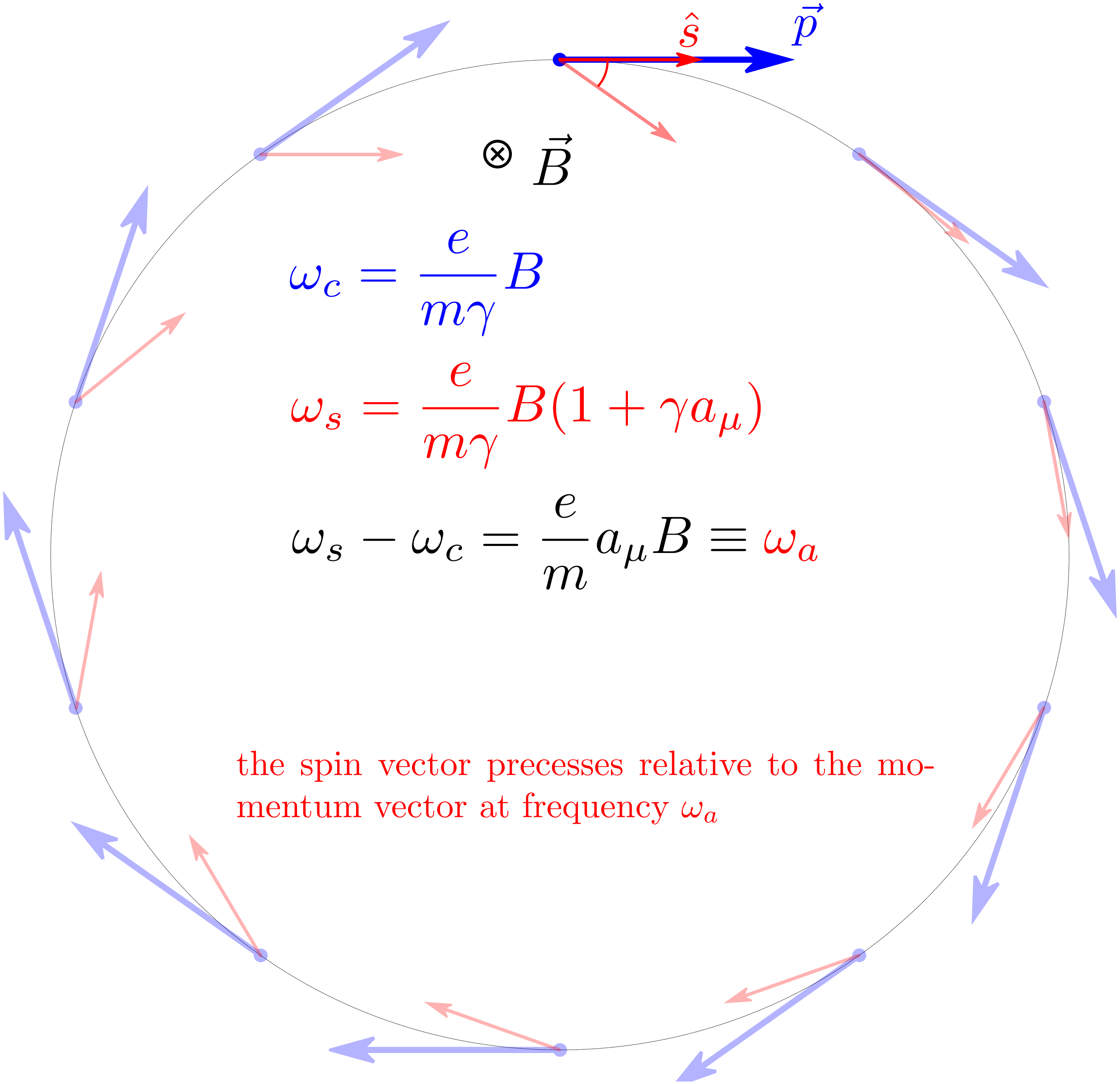


$$\omega_c = \frac{e}{m\gamma}B$$

$$\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$$

the spin vector precesses at frequency ω_s

Muon g-2 experiment in a nutshell



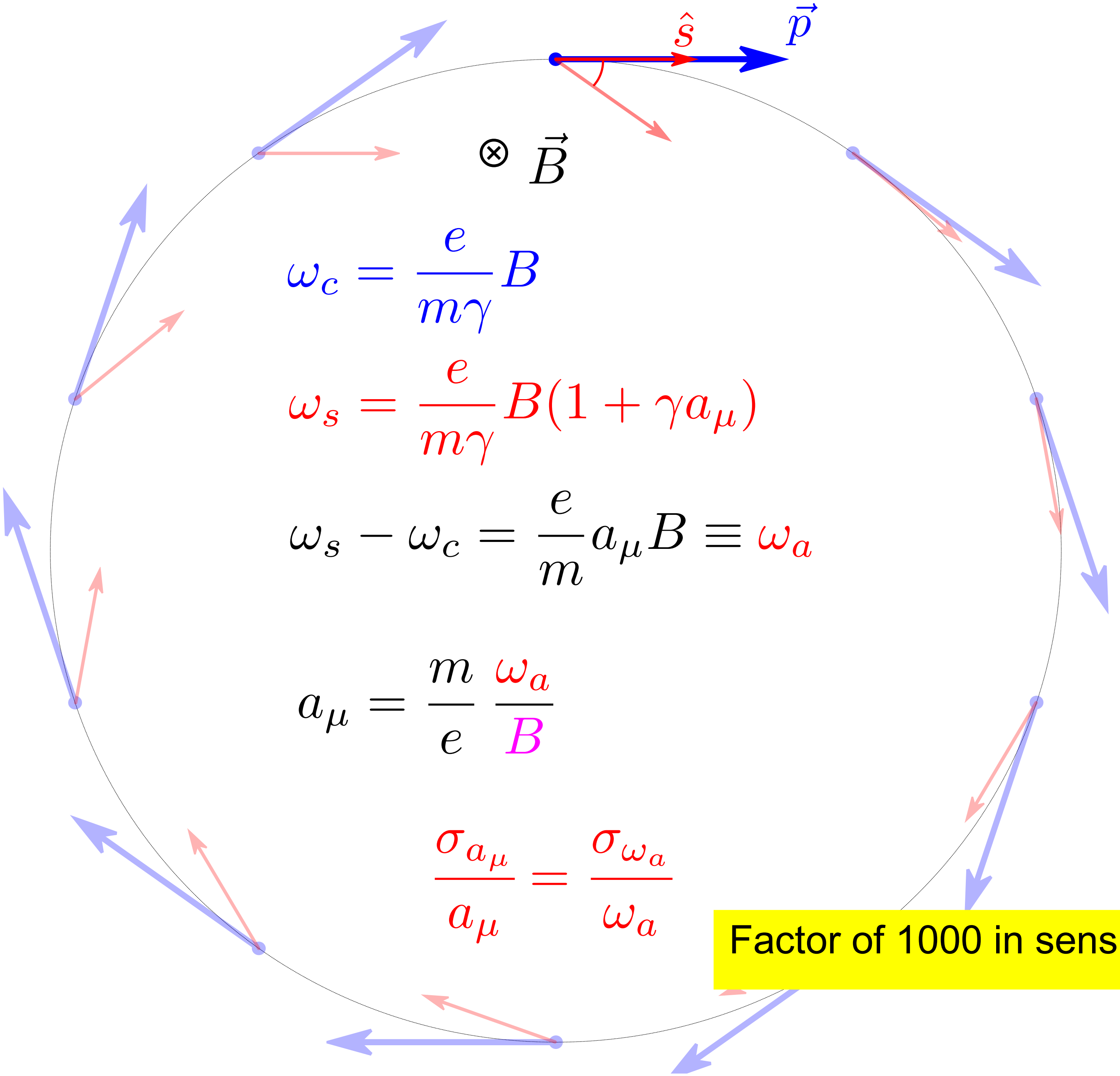
$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1+\gamma a_\mu)$$

$$\omega_s - \omega_c = \frac{e}{m} a_\mu B \equiv \omega_a$$

the spin vector precesses relative to the momentum vector at frequency ω_a

Muon g-2 experiment in a nutshell



$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

$$\omega_s - \omega_c = \frac{e}{m} a_\mu B \equiv \omega_a$$

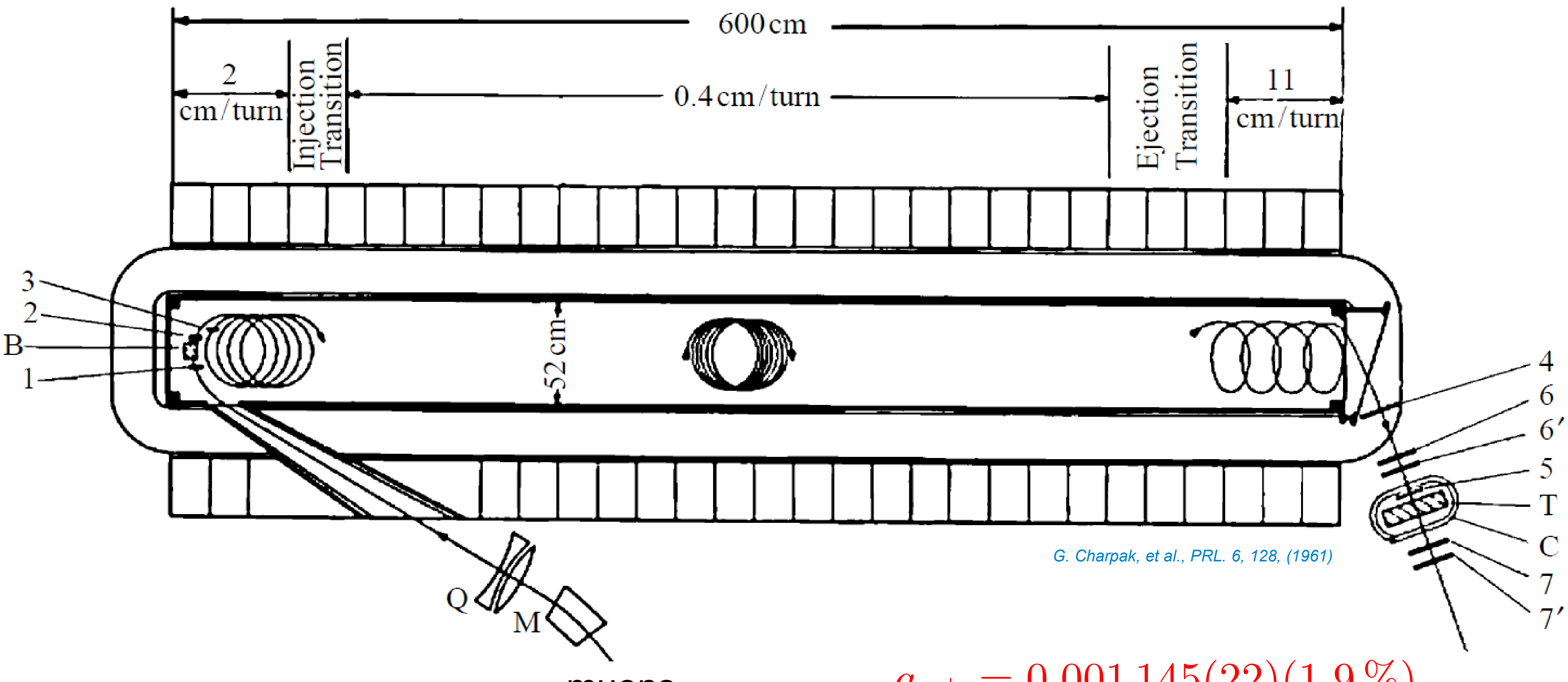
$$a_\mu = \frac{m}{e} \frac{\omega_a}{B}$$

$$\frac{\sigma_{a_\mu}}{a_\mu} = \frac{\sigma_{\omega_a}}{\omega_a}$$

Factor of 1000 in sensitivity!

1st CERN muon g-2 experiment 1958-1962

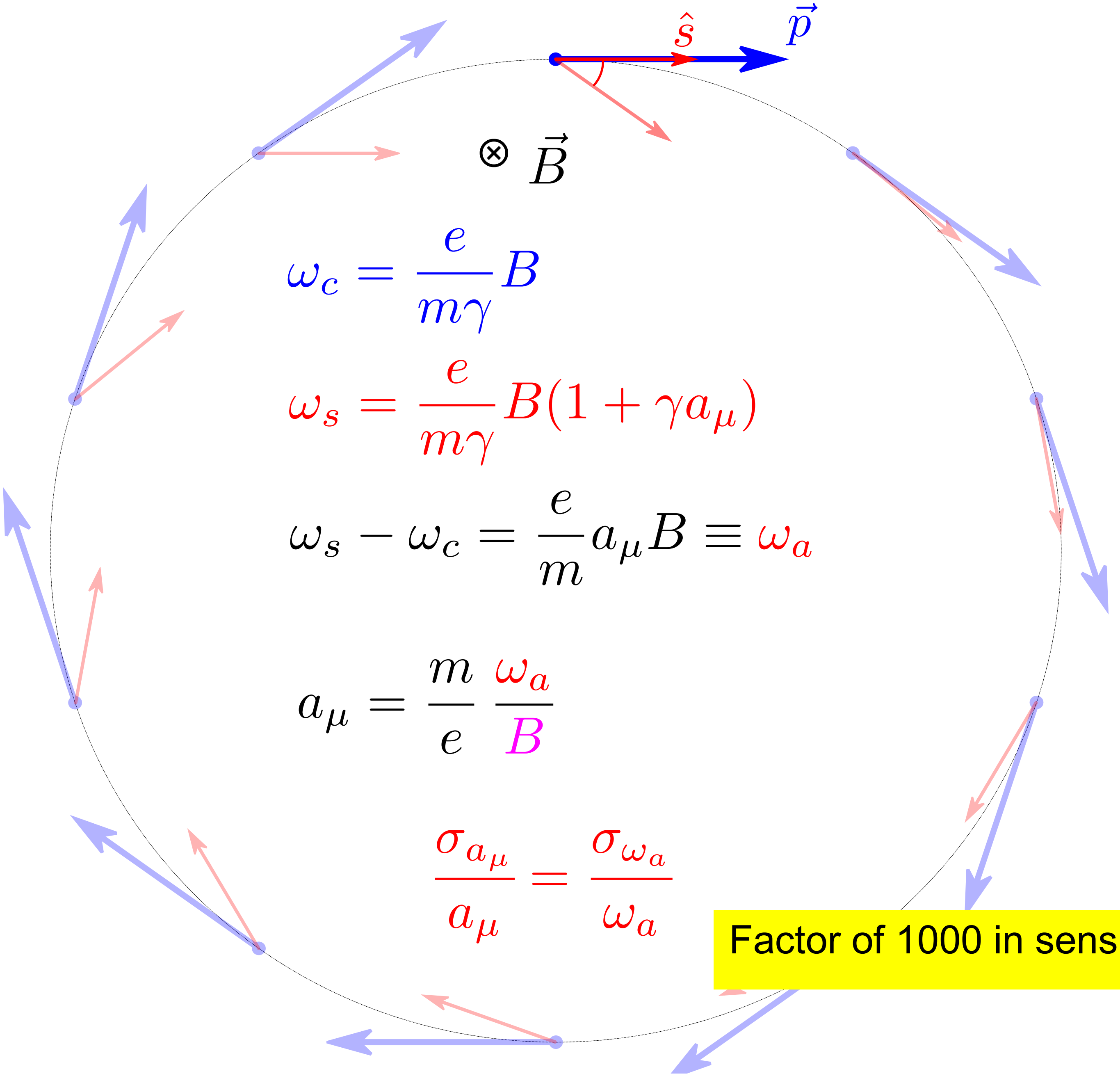
6-m-long 52-cm-wide 14-cm-gap bending magnet, B=1.5 T.
440 turns during τ=2.2 μs. Muon step size from 0.4cm to 11 cm.
Time t spent inside the magnet was determined by by coincidence in counters 123 at input, and counters 466'5$\bar{7}$ at the output. t=2-8 μs depending on the location of the orbit center on the varying gradient field.



G. Charpak, et al., PRL. 6, 128, (1961)

$$a_{\mu^+} = 0.001\,145(22)(1.9\,\%)$$

Muon g-2 experiment in a nutshell



$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

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$$a_\mu = \frac{m}{e} \frac{\omega_a}{B}$$

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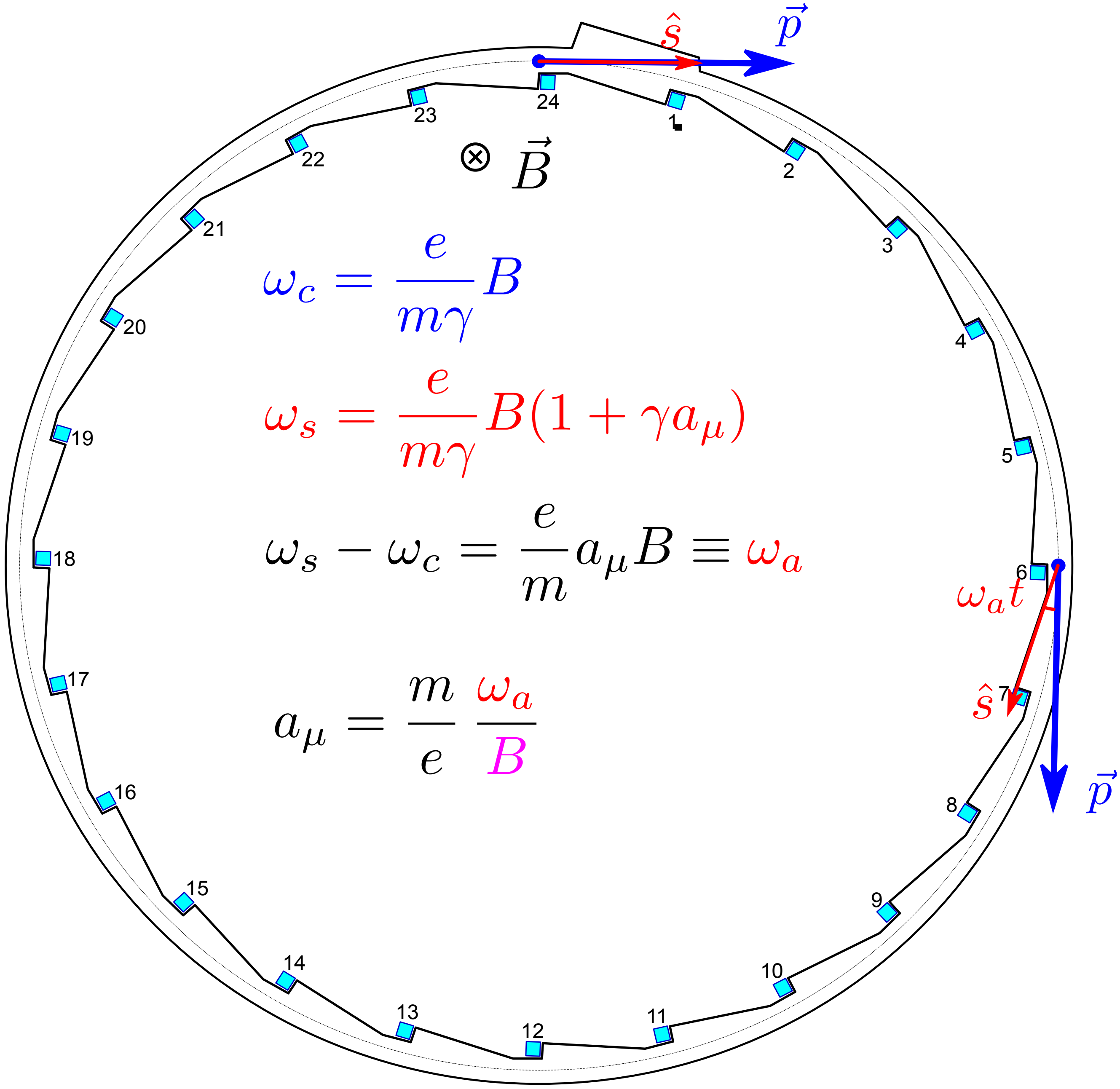
Factor of 1000 in sensitivity!

Muon g-2 experiment in a nutshell



$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

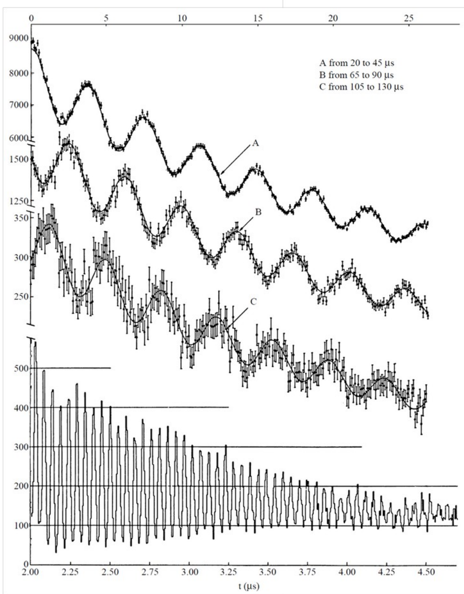
$$\omega_s - \omega_c = \frac{e}{m} a_\mu B \equiv \omega_a$$

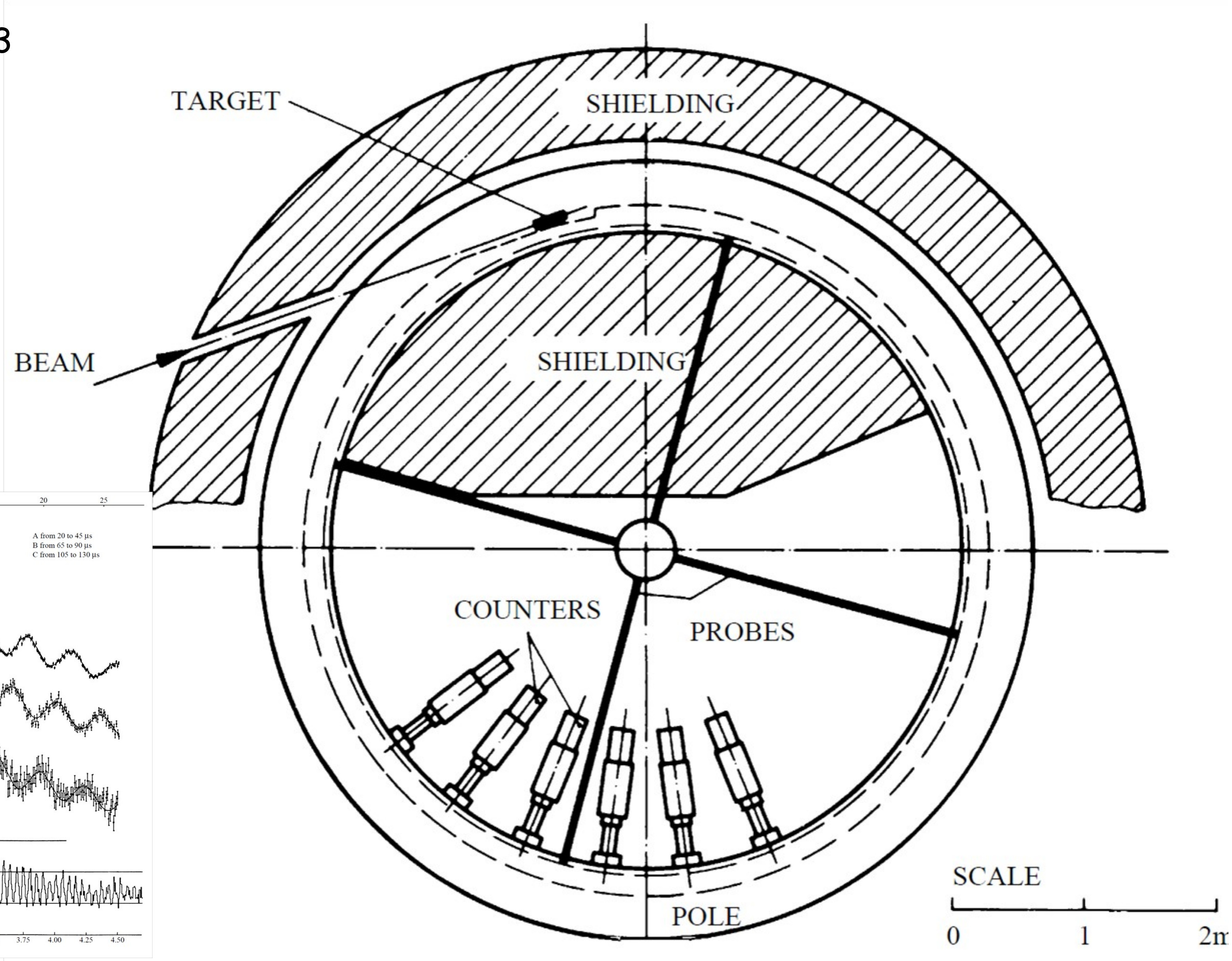
$$a_\mu = \frac{m}{e} \frac{\omega_a}{B}$$

1st muon storage ring at CERN, 1962-1968

features:

- weak focusing ring, n=0.13
- B=1,.711 T
- orbit diameter: 5m
- aperture: 4cm x 8 cm
- beam: 10.5 GeV protons
- injection time: 10 ns
- rotation time: 50 ns
- stored muons:
  p=1.28 GeV/c
- γ = 12, t_μ=27 μs





problems:

- high background
- low muon polarization

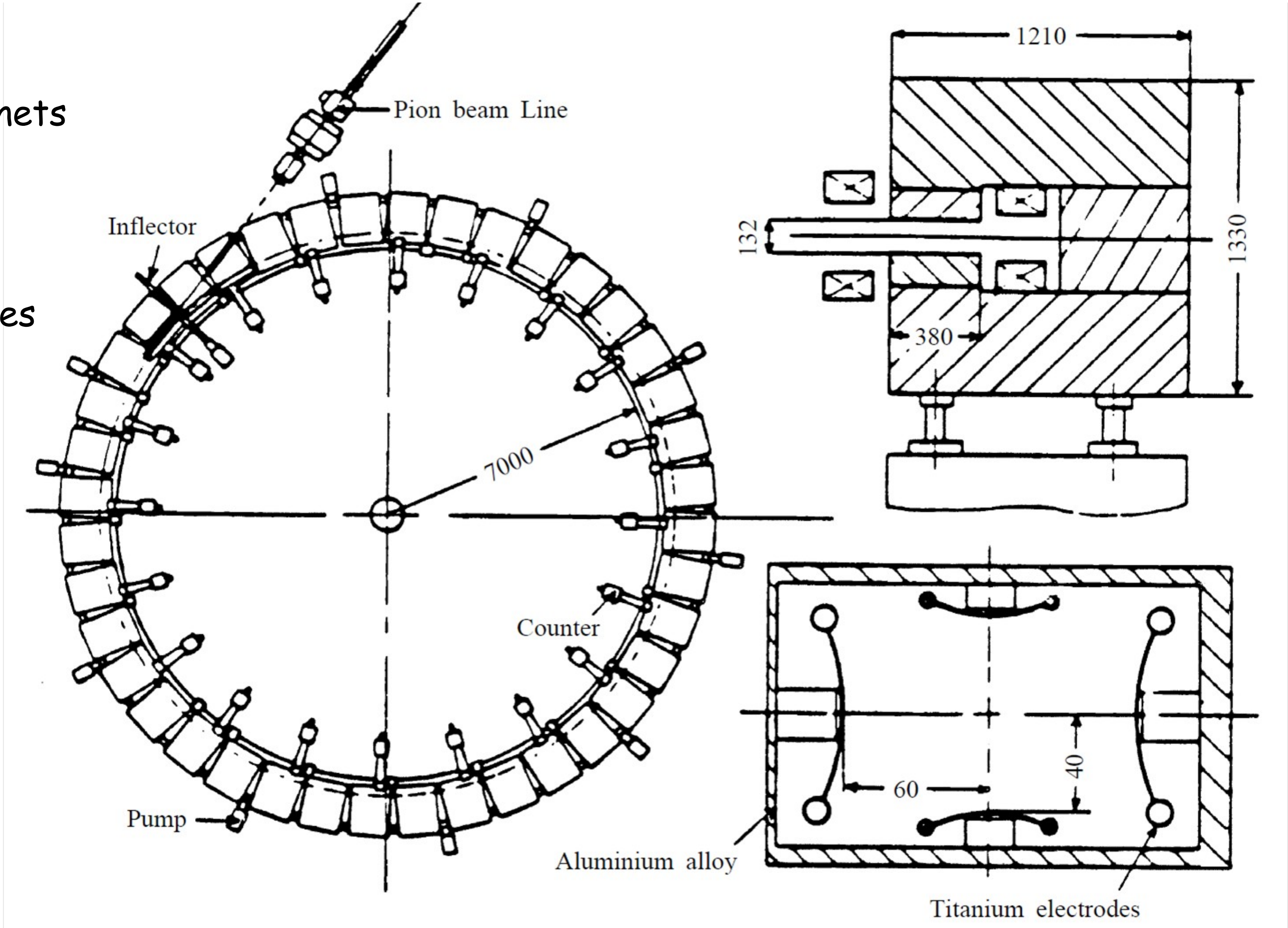
$$a_\mu = 0.001\,166\,16(31)(265\,\text{ppm})$$

J. Bailey, et al., Phys. Lett. 28B, 287 (1968)

2nd muon storage ring at CERN, 1969-1976

features:

- 40 C-shaped bending magnets
- pole: 38-cm x 14 cm (width x gap)
- field in each magnet stabilized with NMR probes
- pion injection!
- electric quadrupoles for vertical focusing
- magic-momentum concept



$$\frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s}_{\perp}\cdot\left[a_\mu\hat{\beta}\times\vec{B} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\beta\vec{\mathcal{E}}\right]$$

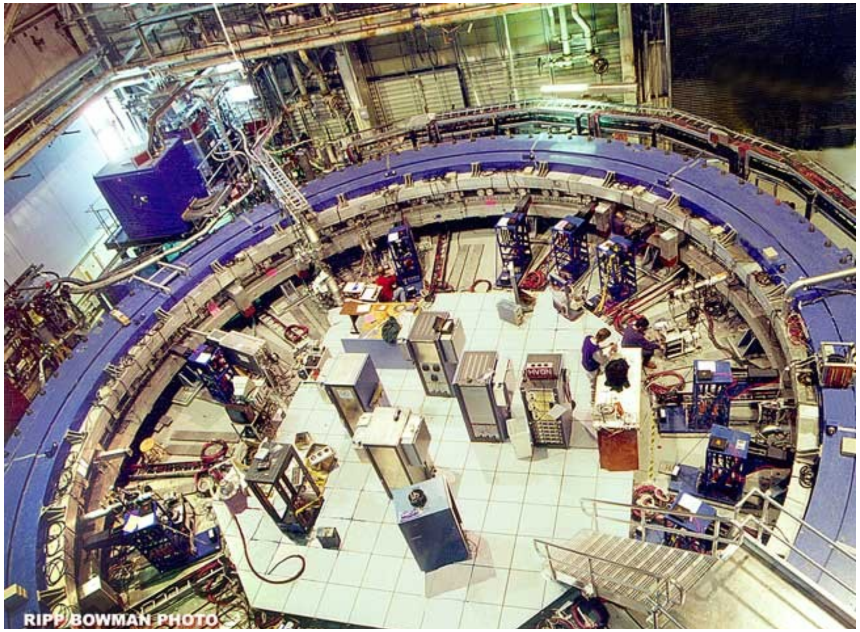
$\rightarrow 0$ at $\gamma = 29.304$ $(p_\mu = 3.09\ \mathrm{GeV/c})$

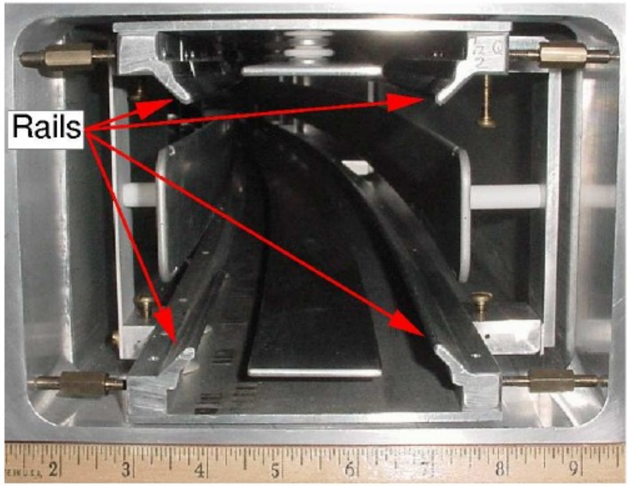
"magic" momentum

$$a_\mu = 0.001\,165\,924(8.5)(7\,\mathrm{ppm})$$

J. Bailey, et al., Nucl. Phys. B150, 1 (1979)

Brookhaven storage ring (1984-2001)





(a) Vacuum chamber cross section

(b) Trolley

$$a_\mu = 0.001\,165\,920\,8(6.3)(0.54\,\text{ppm})$$

G.W. Bennett, et al., PRD. 73, 072003, (2006)

Long list of innovations beyond CERN III

- Continuous superconducting magnet having high field uniformity
- Superconducting DC Inflector (designed and built by KEK, Japan) to get muons through the back yoke.
- High voltage, fast, non-ferric kickers to shift muons onto design orbit in first cycle – enabled muon injection
- Flux in 12 bunches from the AGS
- Long enough beamline to operate with pion or muon injection
- Thin quadrupoles and scalloped vacuum vessels minimize preshower
- In situ, field measurements with NMR trolley
- Continuous NMR monitoring and <0.1 ppm absolute calibration
- Pb/Scifi calorimeters, hodoscopes, and a traceback wire chambers

E989 timeline: proposal submition

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

E989 Proposal

The New (g – 2) Experiment:

A Proposal to Measure the Muon Anomalous

Magnetic Moment to ±0.14 ppm Precision

Request: 4×10^{20} protons on target in 6 of

20 Booster batches during 15 Hz operation

February 9, 2009

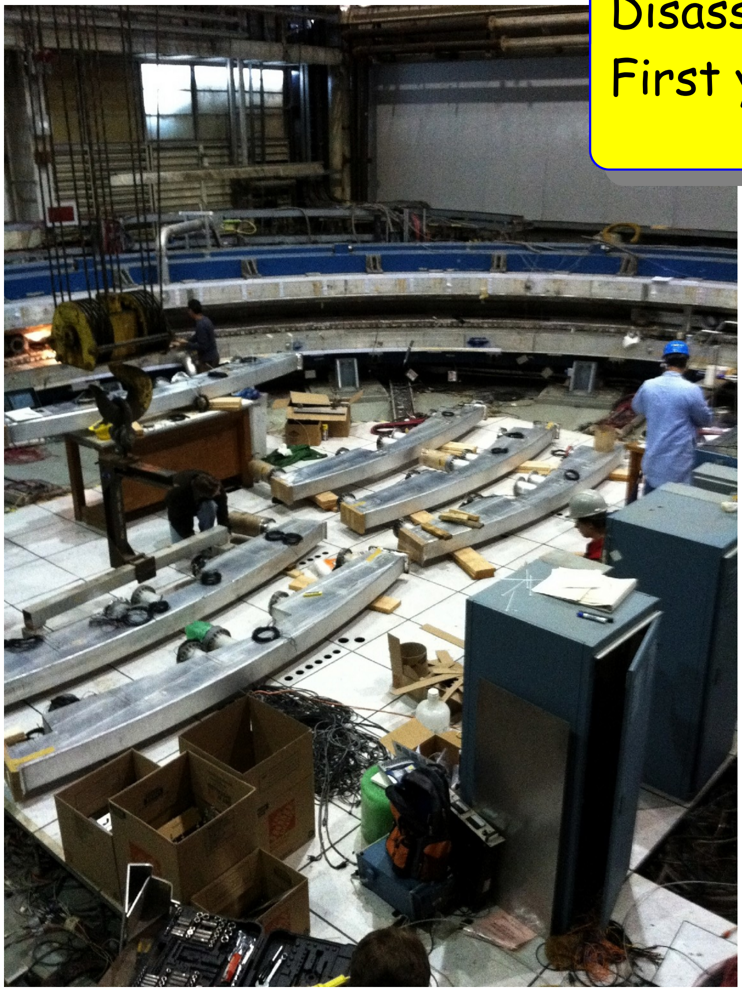
Contactpersons: David W. Hertzog (hertzog@illinois.edu, 217-333-3988)

B. Lee Roberts (roberts@bu.edu, 617-353-2187)

Disassembly of g-2 storage ring at BNL

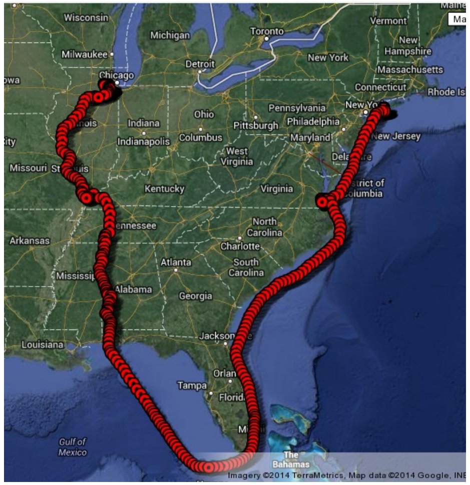
2009 | 2010 | 2011 | **2012** | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

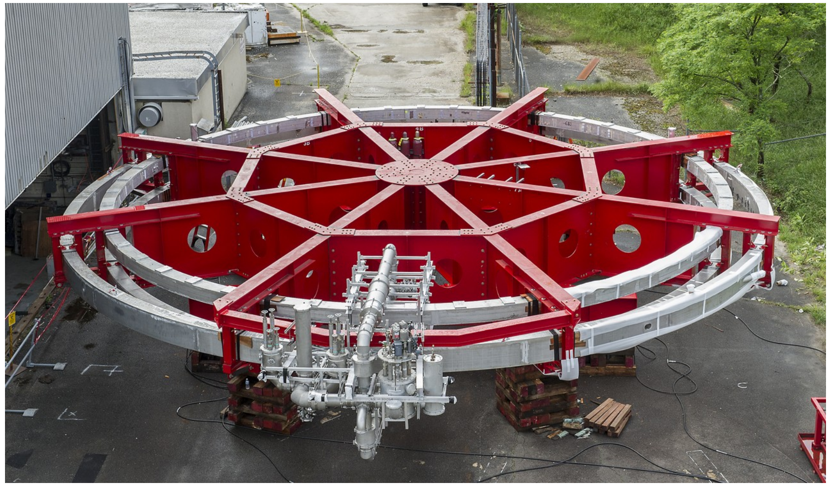
Disassembly of g-2 storage ring started
First yoke piece removed (Sept.)



transportation of coils from BNL to Fermilab

2009 | 2010 | 2011 | 2012 | **2013** | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021





more photos and info: http://muon-g-2.fnal.gov/bigmove

Ring reassembly at Fermilab

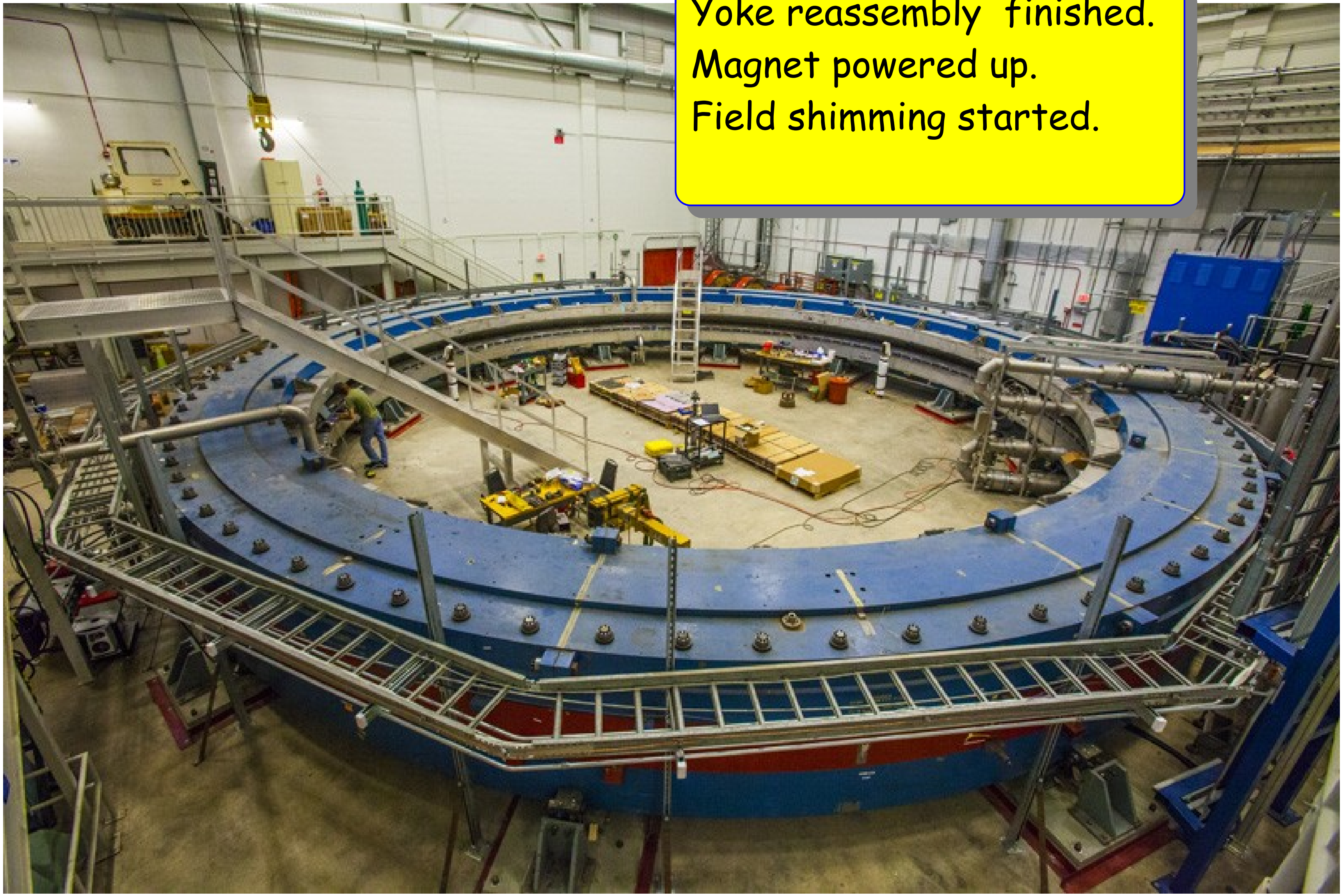
2009 | 2010 | 2011 | 2012 | 2013 | **2014** | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

June 23, 2014. Bottom yoke. Reassembly progresses well. Superconducting coils will be moved into the experimental hall end of July 2014

g-2 storage magnet reassembled at FNAL

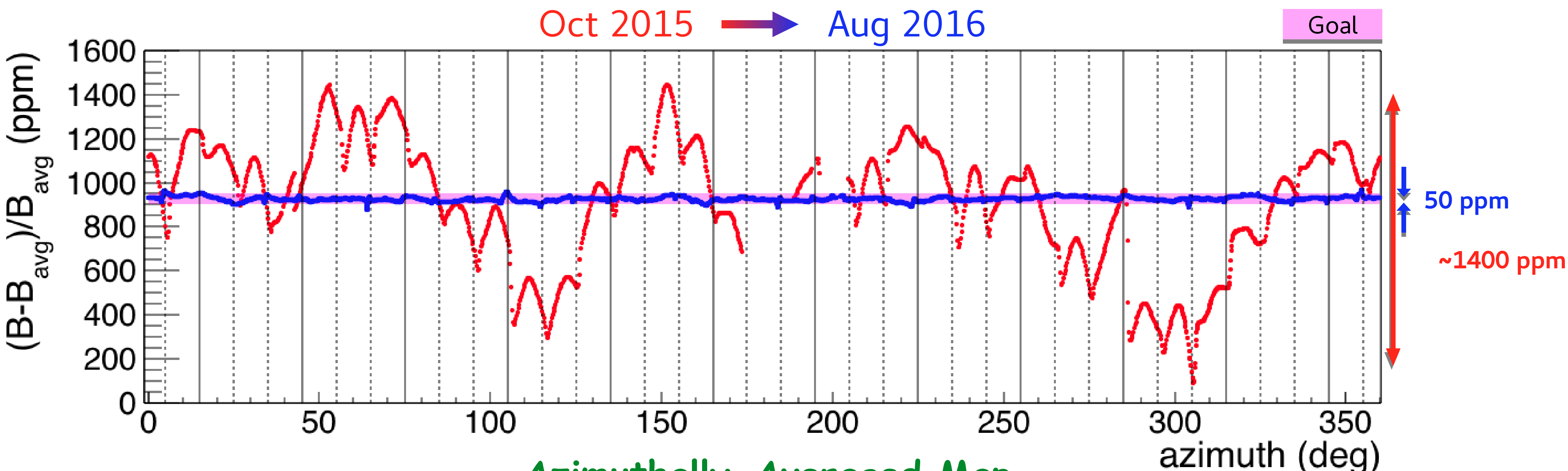
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | **2015** | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

Yoke reassembly finished.
Magnet powered up.
Field shimming started.

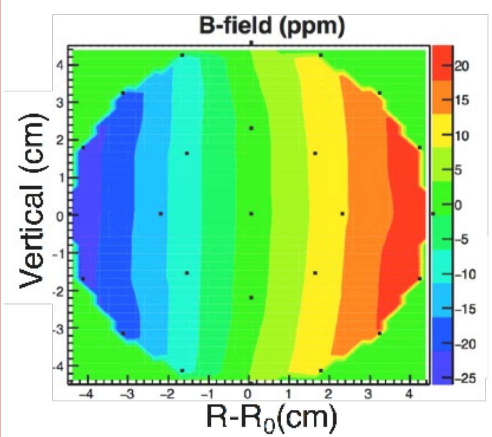


Rough Shimming Results

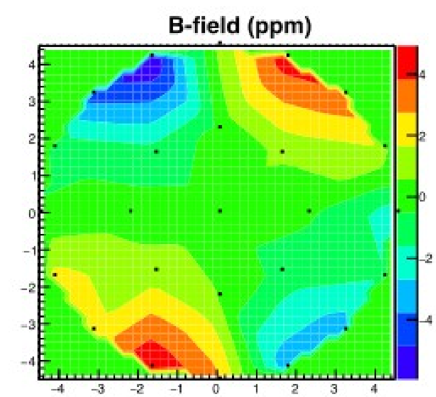
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | **2016** | 2017 | 2018 | 2019 | 2020 | 2021



Azimuthally-Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

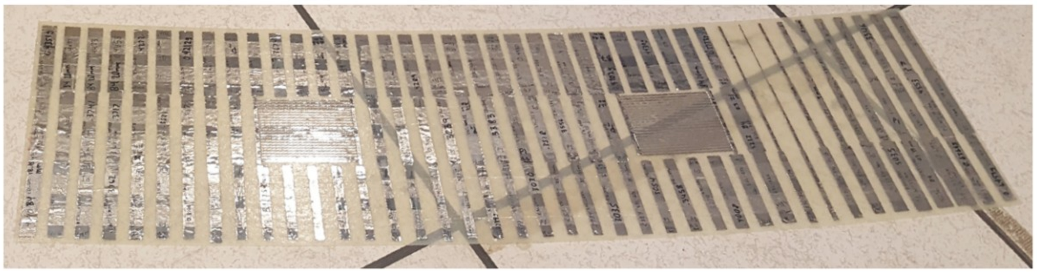
D. Flay

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

Rough Shimming – lamination shims

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | **2016** | 2017 | 2018 | 2019 | 2020 | 2021

- Lamination shims: small pieces of iron foil
- Predict foil mass required to make local adjustments of the B-field
- 8500 foils installed in total



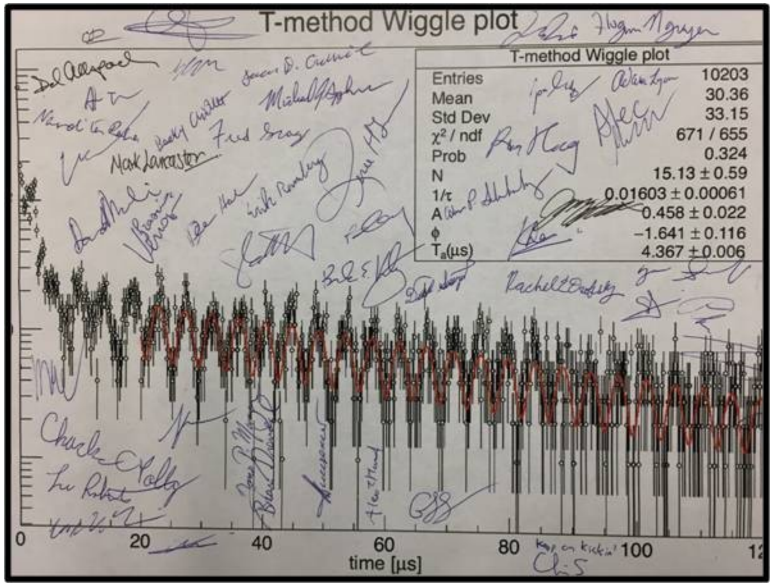
foils sorted by mass

laminations affixed to the pole surfaces

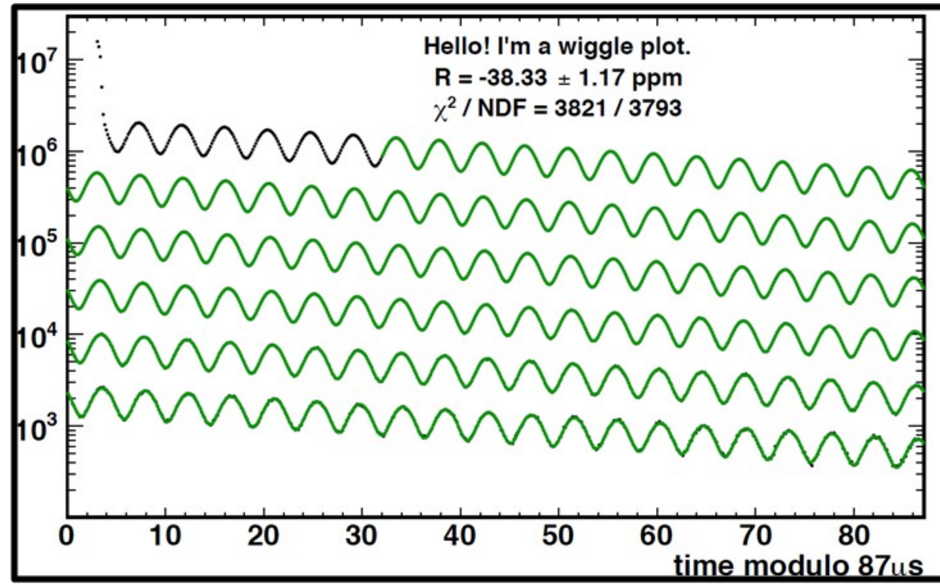
First physics run - 2018

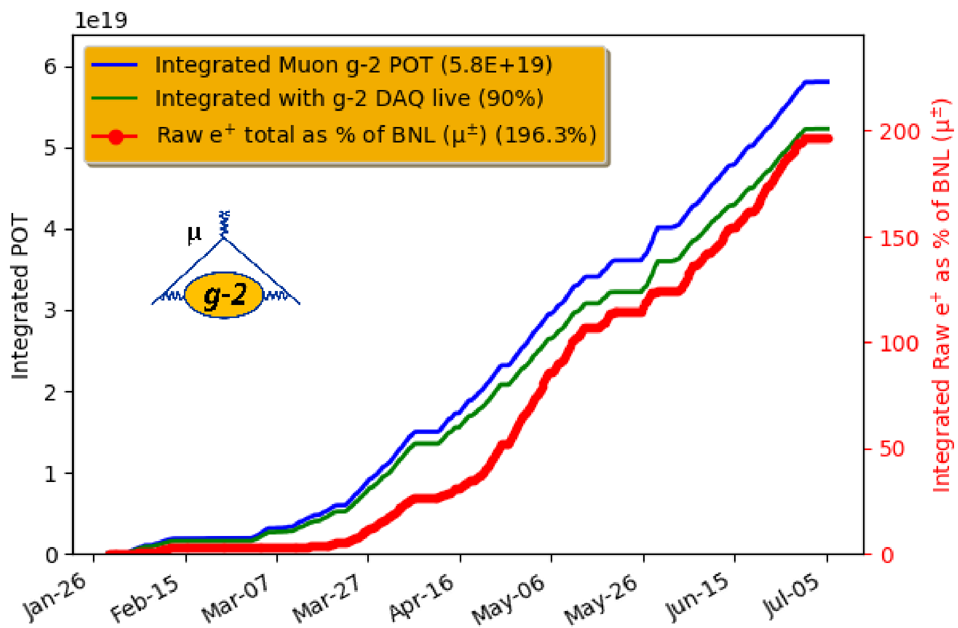
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** | 2019 | 2020 | 2021

2017- commissioning



2018 - production



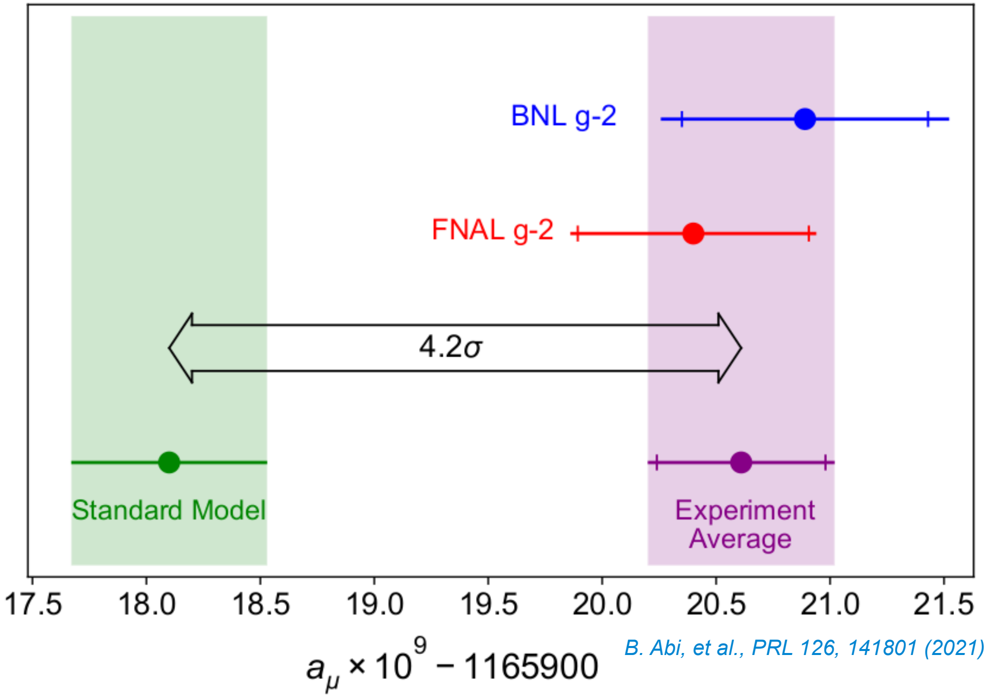


Run 1 finished in July. Almost twice the BNL statistics of raw data collected.

First physics result - 2021

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\ \mathrm{ppm}),$$
$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\ \mathrm{ppm}).$$

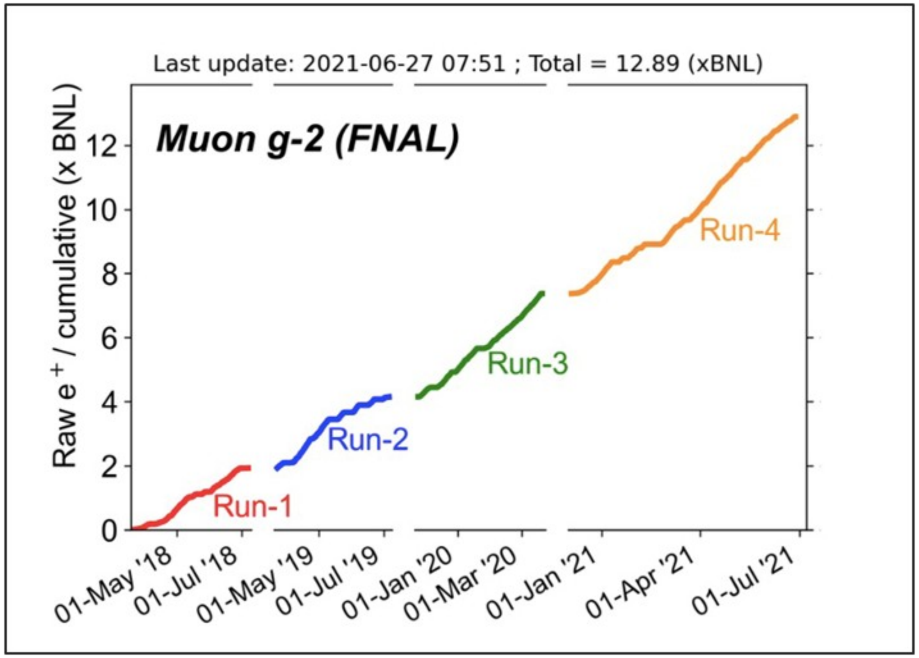


B. Abi, et al., PRL 126, 141801 (2021)

From top to bottom: Experimental values of a_μ from BNL E821, FNAL E989 Run-1, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value for the Standard Model is also shown.

$$a_\mu(\mathrm{FNAL}) - a_\mu(\mathrm{SM}) = (230 \pm 69) \times 10^{-11}\ (3.3\sigma)$$
$$a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}\ (4.2\sigma)$$

Present and future - FNAL



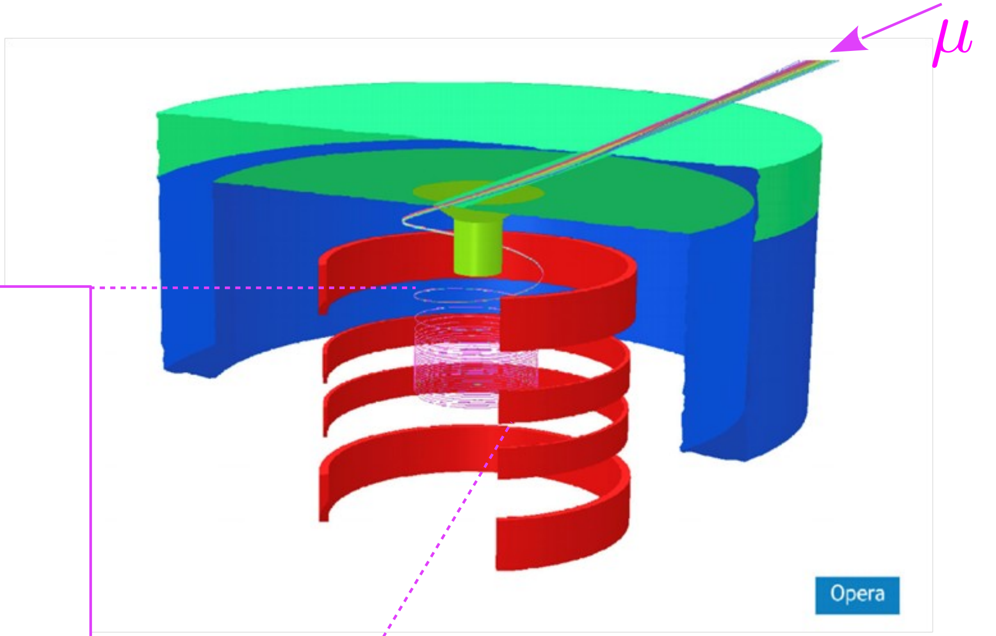
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7°)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

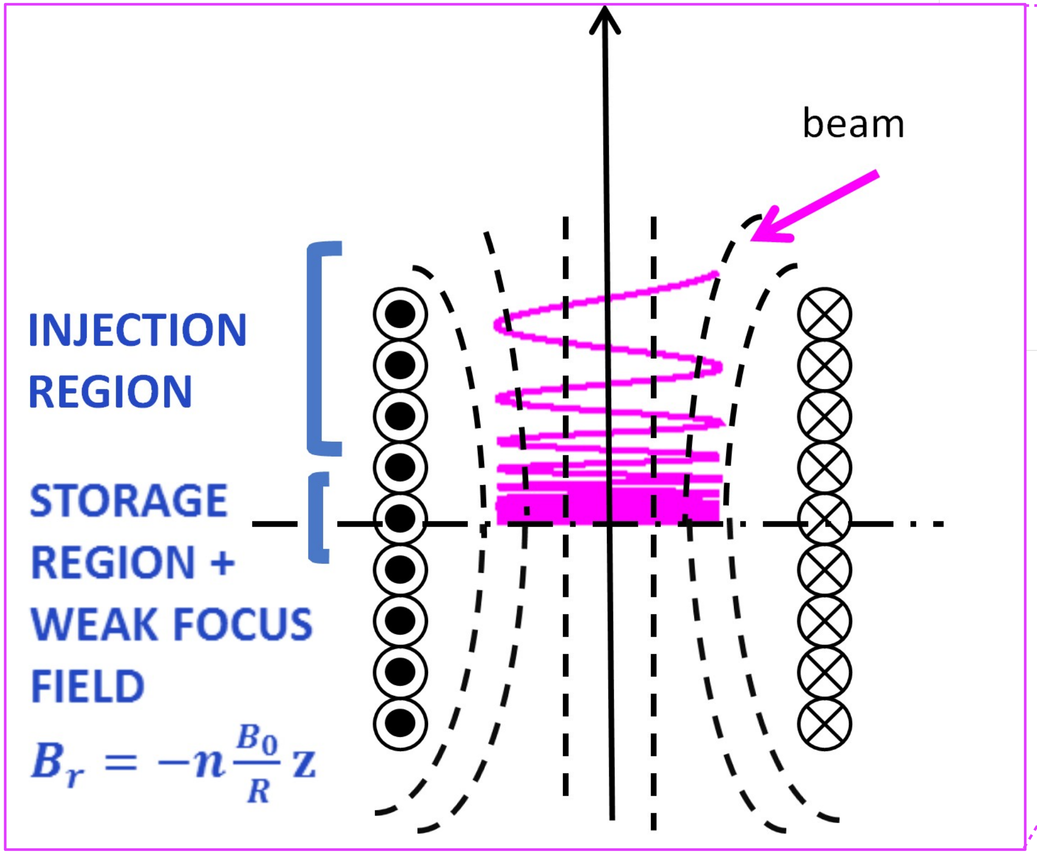
B. Abi, et al., PRL 126, 141801 (2021)

- Run 1 Result published (0.46 ppm). Statistically limited.
- Improvements implemented to reduce uncertainties to 100 ppb syst, 100 ppb stat
  - Damaged quadrupole resistors replaced
  - Mid-Run 3 kickers to full strength
  - Electric field improvements under study
  - Improved magnet temperature stability (reduces field tracking systematics)
  - Improved transient fields mapping
- Published 6%, collected >50% of goal
- Additional long Run 5 is starting

Muon g-2 at J-PARC

- MRI-type solenoid storage ring
- Very weak magnetic focusing ($n \sim 10^{-4}$)
- Vertical beam injection



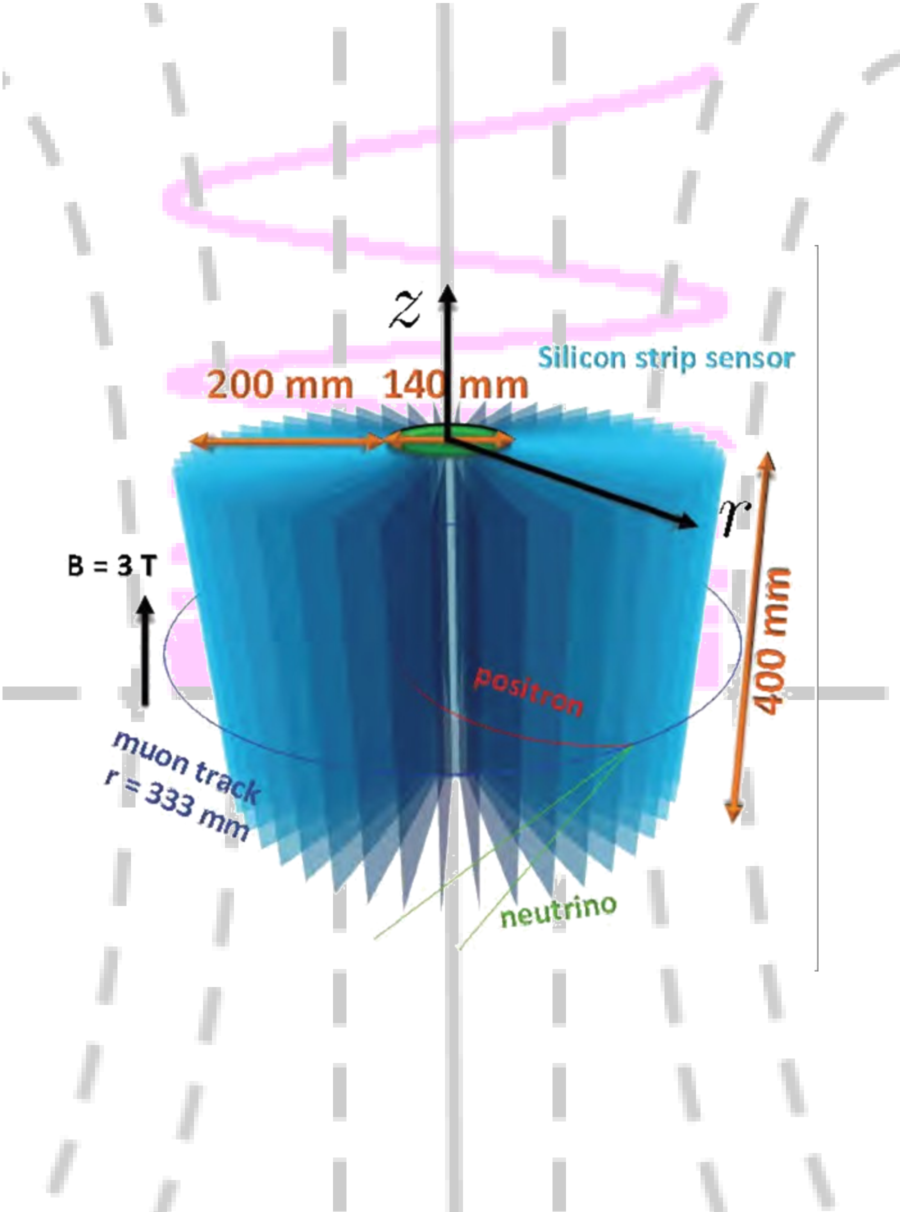


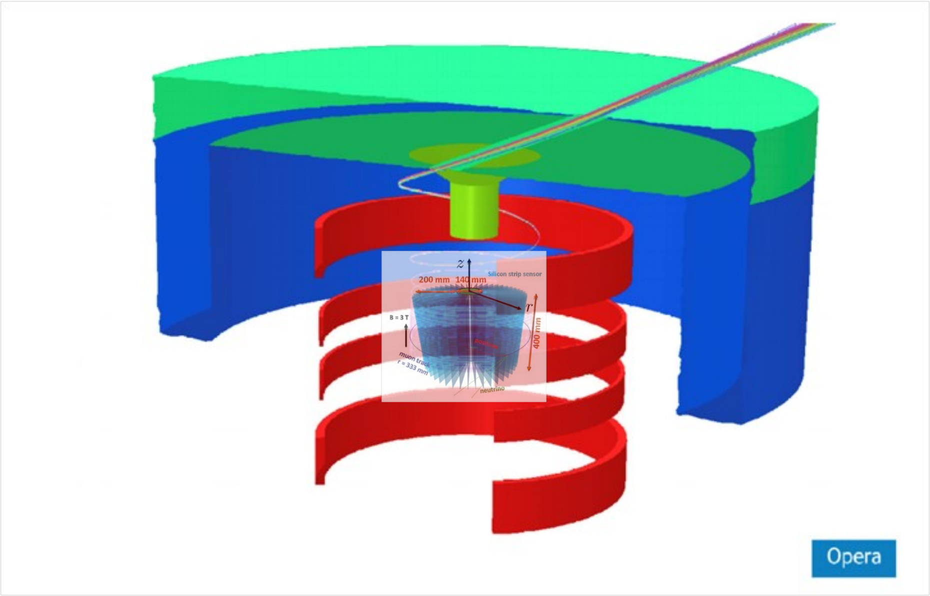
Storage region
- Field strength : 3 T
- Homogeneity: <1 ppm locally
- radius: 33.3 cm
- height: ±5 cm

Injection region
- Br x Bz > 0
- Br changes smoothly along the beam orbit

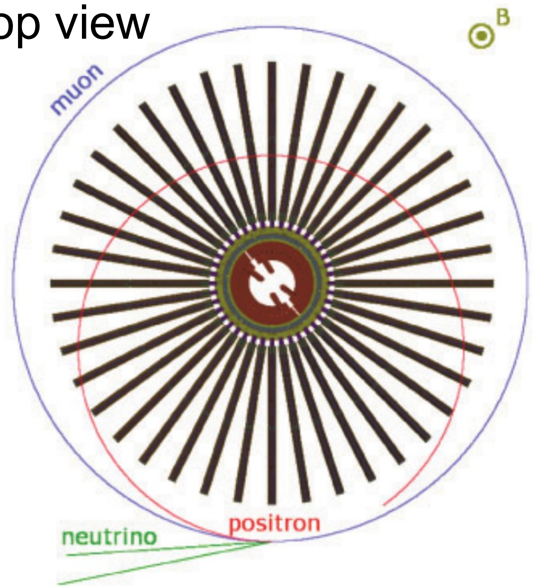
Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

Muon g-2 at J-PARC: detector



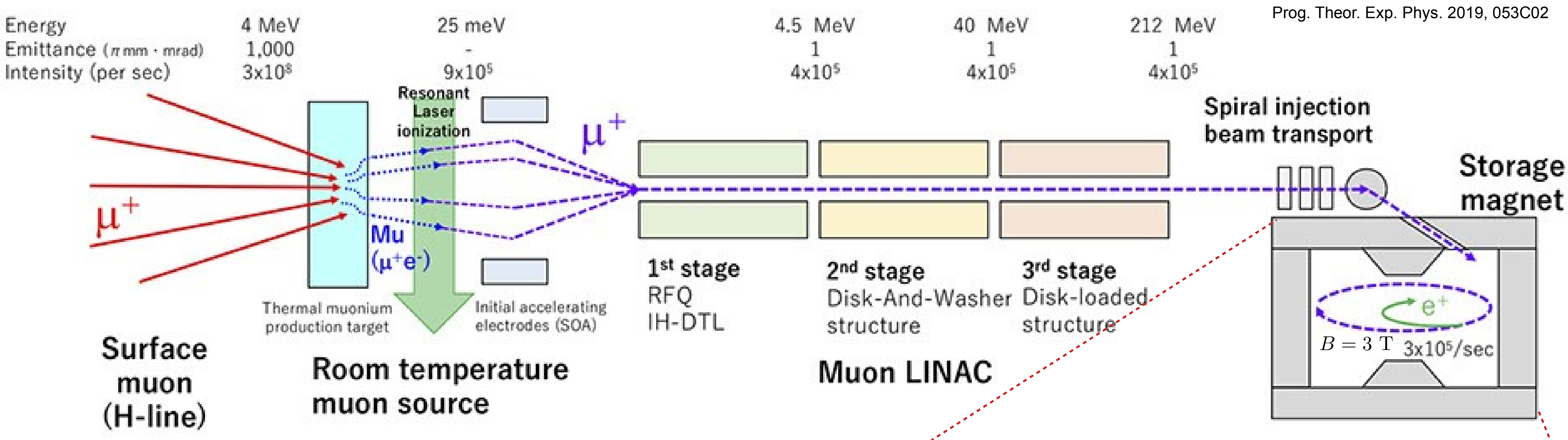


Top view

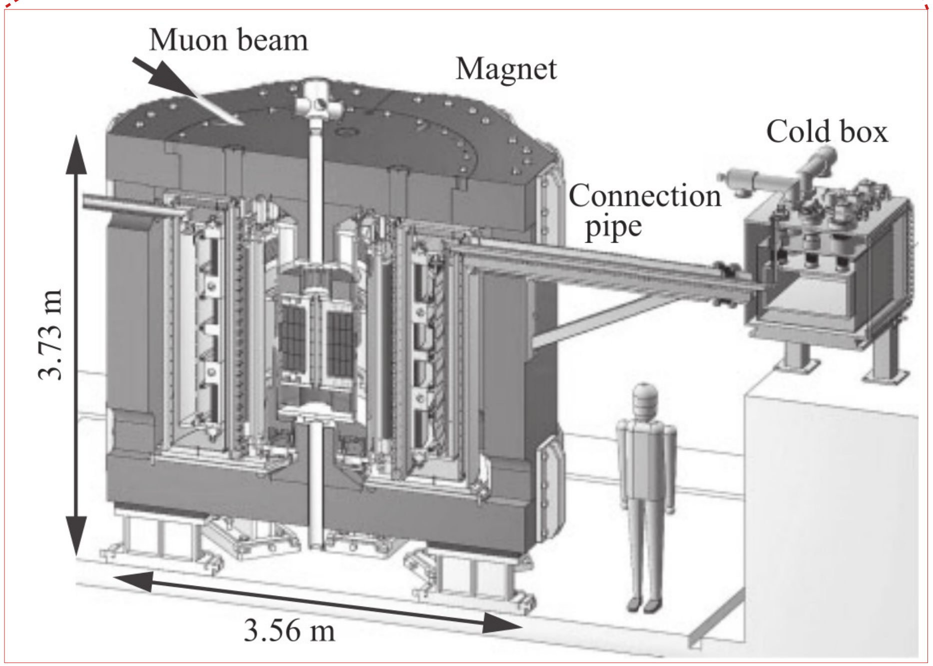


Extracted from talks by K. Ishida (RIKEN) and K. Sasaki (KEK)

Muon g-2 at J-PARC: muon source



The very weak magnetic focusing of the storage ring requires a muon beam with low emittance, which will be realized using a state-of-the art muon source.



Comparison of experiments

	BNL-E821	Fermilab-E989	J-PARC
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	96 %	98 %	50
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	electrostatic quadrupoles		very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.4 μs		2.1 ns
Storage radius	7.1 m		0.3 m
Detector	calorimeters		tracking
Stat. uncertainty on a_μ	460 ppb	100 ppb*)	450 ppb*)
Syst. uncertainty on a_μ	280 ppb	100 ppb*)	70 ppb*)
Total uncertainty on a_μ	540 ppb	140 ppb*)	455 ppb*)

*) goal

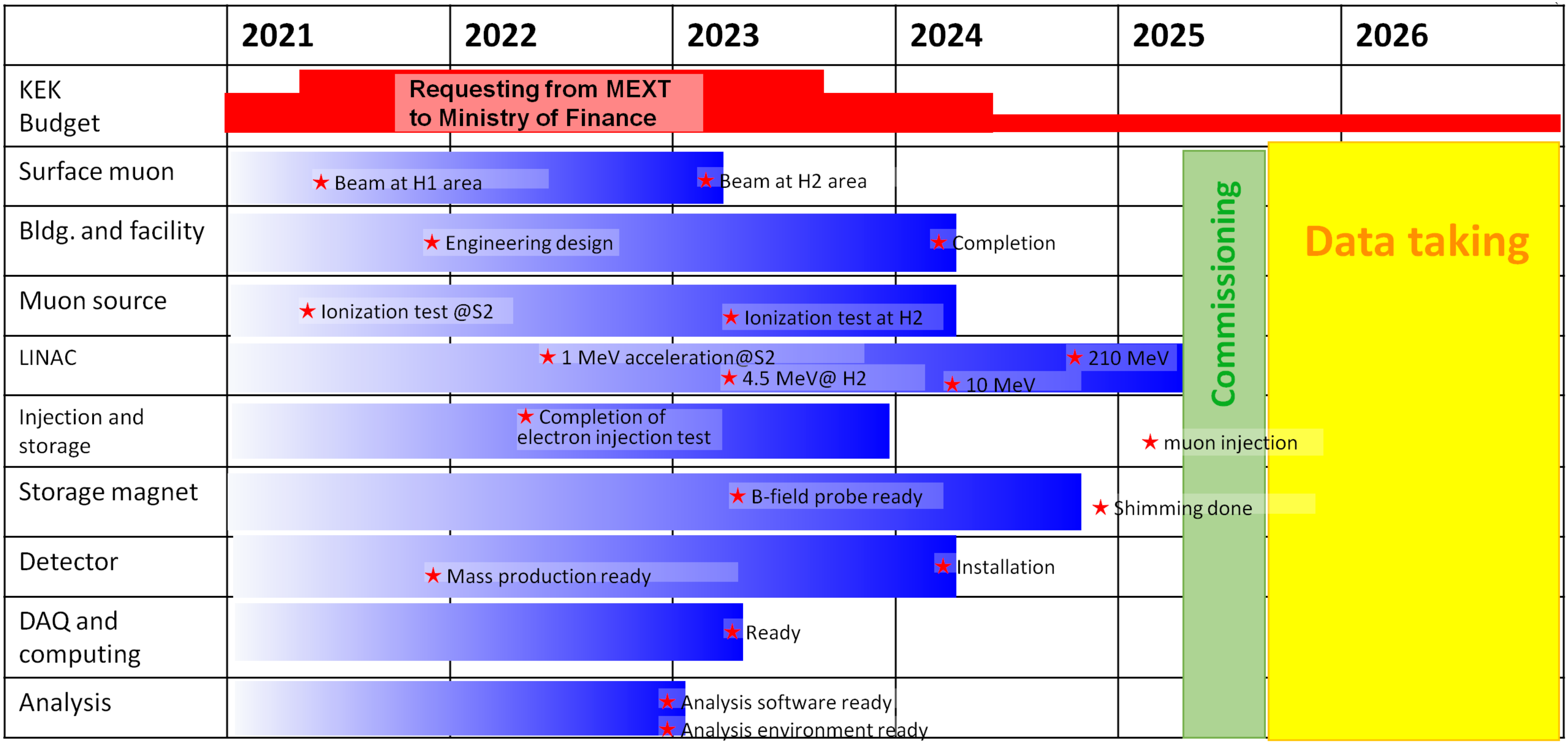
$$\frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s}_\perp \cdot \left[a_\mu \hat{\beta}\times\vec{B} + \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{\to 0 \text{ at } \gamma = 29.304\ (p_\mu = 3.09\ \mathrm{GeV/c})}\beta\vec{\mathcal{E}}\right]$$

(BNL and FNAL)

In J-PARC experiment, the electric field eliminated, $\vec{\mathcal{E}} = 0$

The J-PARC experiment will have different systematic uncertainties.

Present and future - J-PARC



Source: Takashi Yamanaka (Kyushu University), FCCP 2021