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Muon g-2: The Experiments

Nam Tran

for the Muon $g-2$ Collaboration

FPCP 2019, Victoria BC

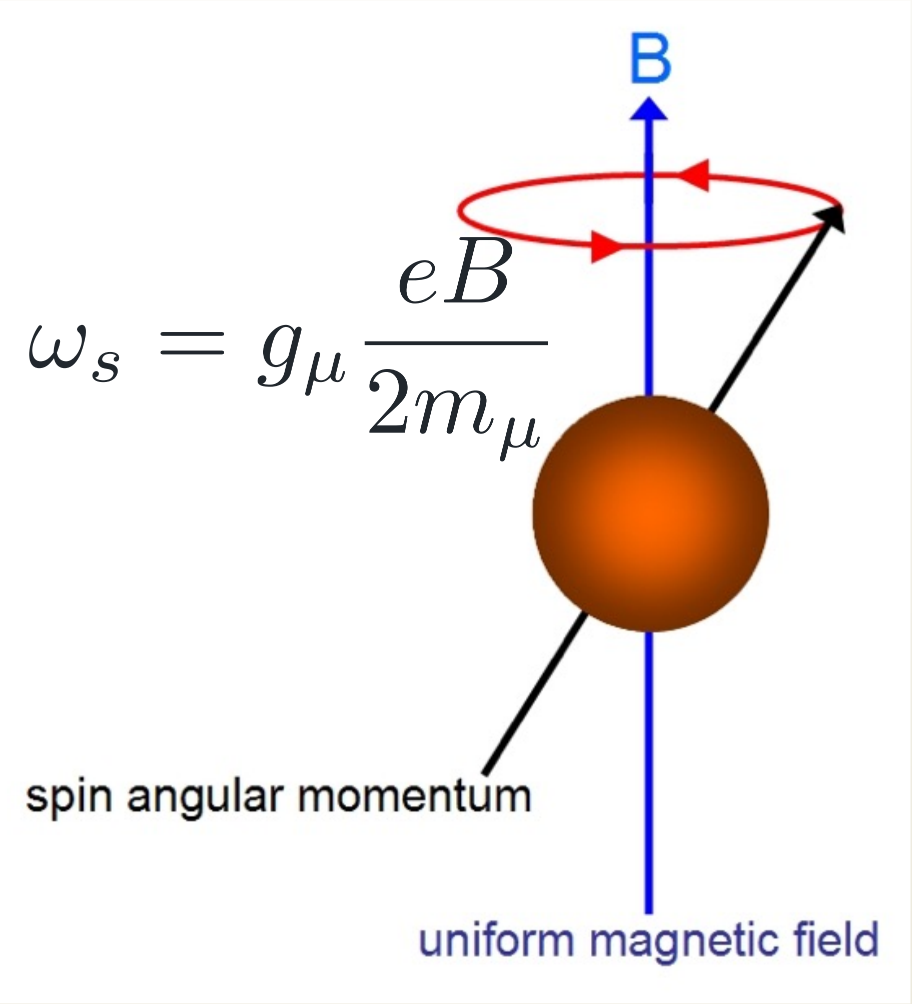
Outline

- Overview and principles of g-2 measurements
- The E989 at Fermilab
- The E34 at J-PARC
- Summary

Muon magnetic moment and the anomaly

- The muon has an intrinsic magnetic moment:

$$\vec{\mu} = g_\mu \frac{e}{2m_\mu} \vec{S}$$



- Precesses in an external magnetic field with a frequency determined by the gyromagnetic ratio g_μ
- $g_\mu = 2$ from Dirac equation for a spin-1/2 charged particle
- In reality: $g_\mu > 2$, i.e. there is an anomalous magnetic moment.
- The anomaly: $a_\mu = \frac{g_\mu - 2}{2}$

How do we measure a_μ?

- Store longitudinally polarized muons in a uniform dipole magnetic field B
- Consider difference between spin and cyclotron frequencies:

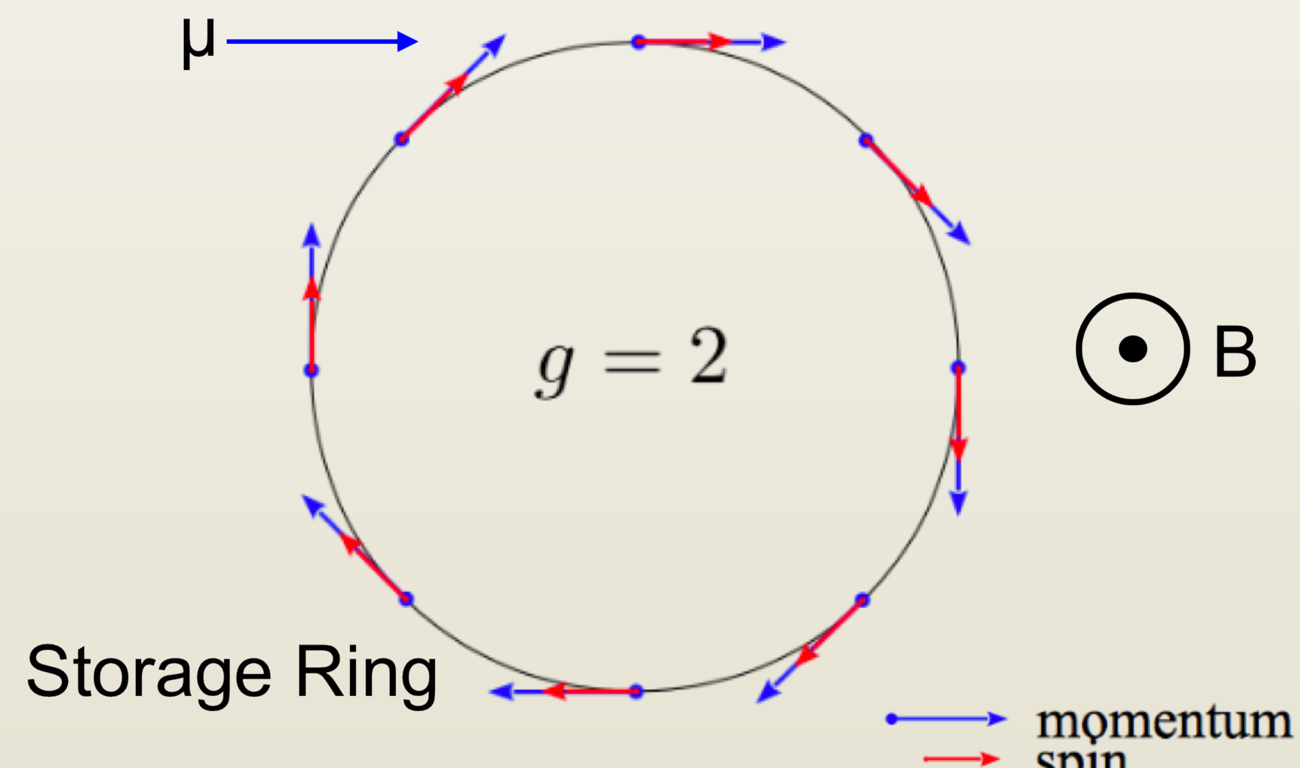
$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

$$\omega_c = \frac{eB}{\gamma m}$$

$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{m}B$$

$$\omega_a = a\frac{e}{m}B$$

- If $g_\mu = 2$: spin always aligns with momentum



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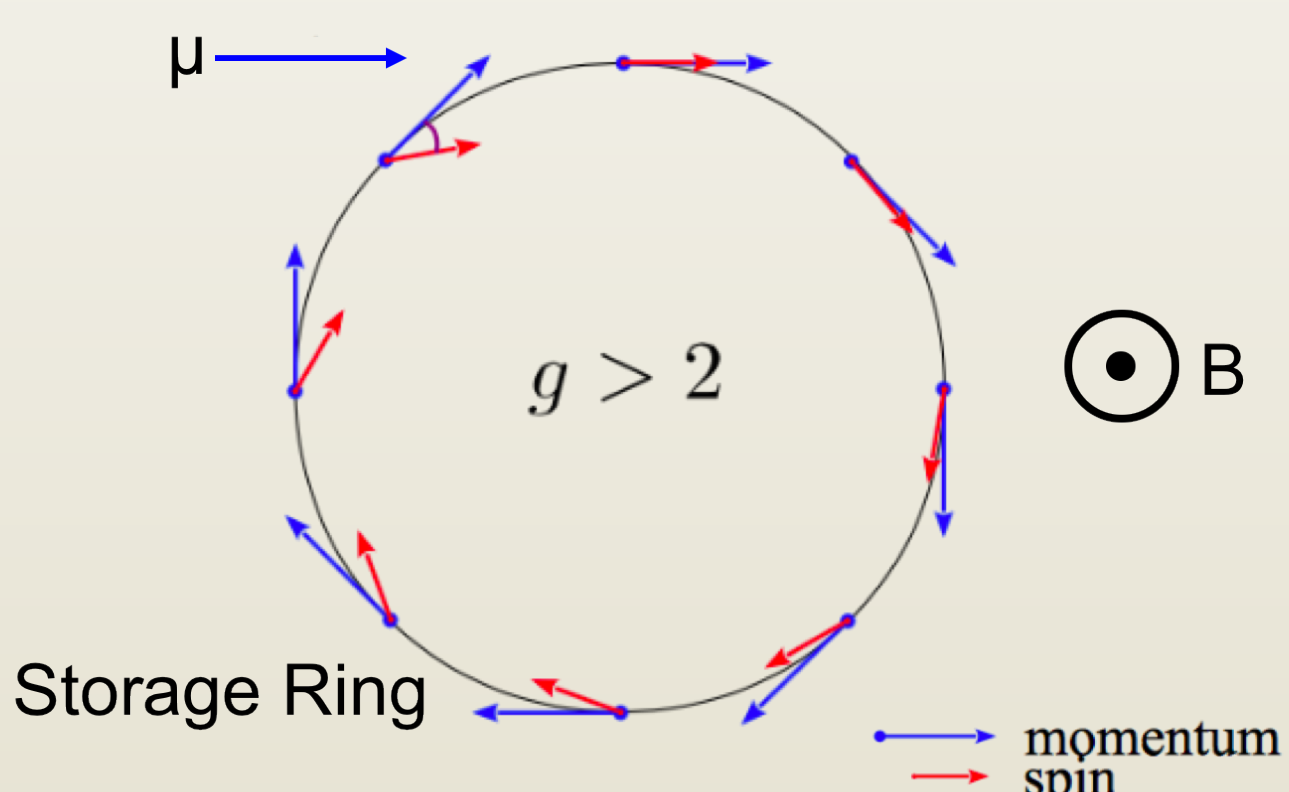
- If $g_\mu \neq 2$: spin beats against momentum, oscillating radially



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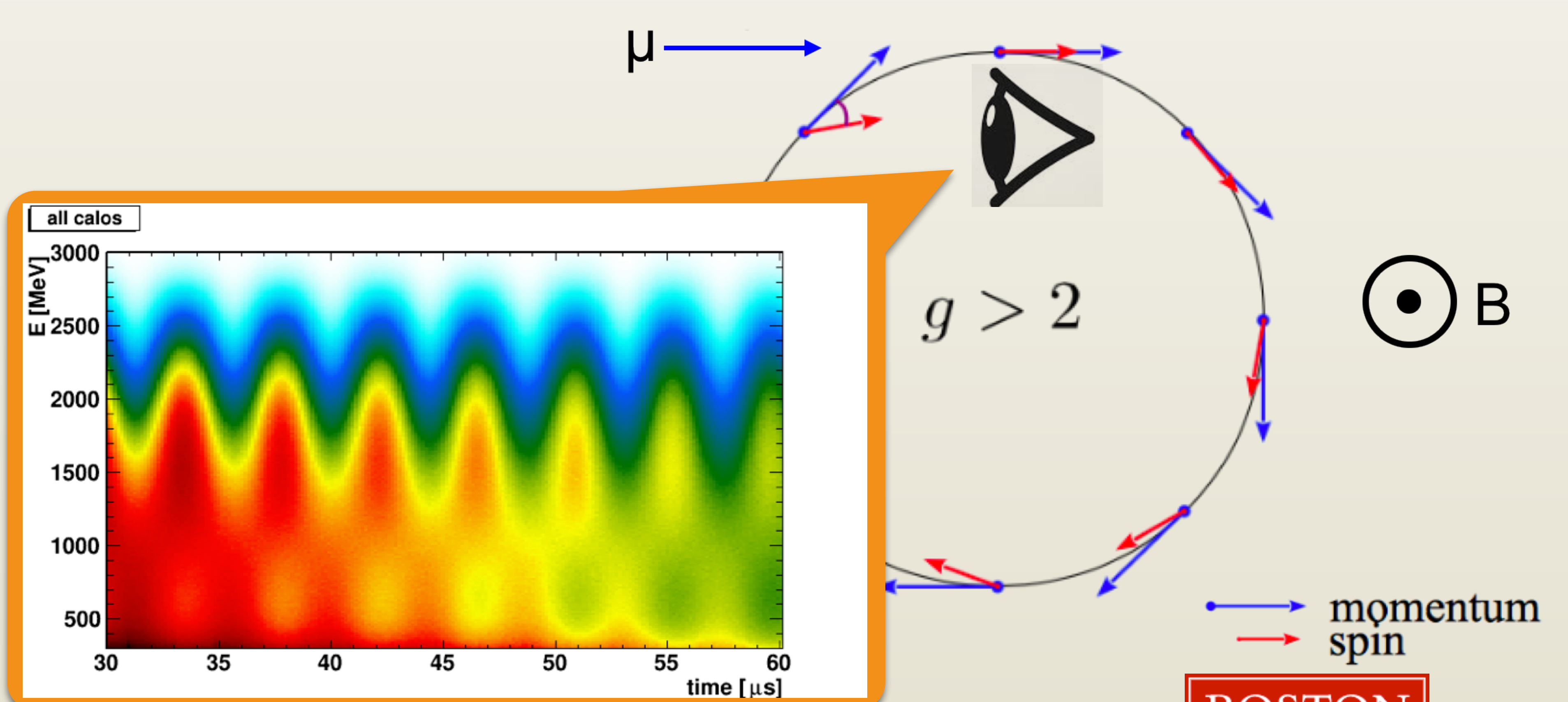
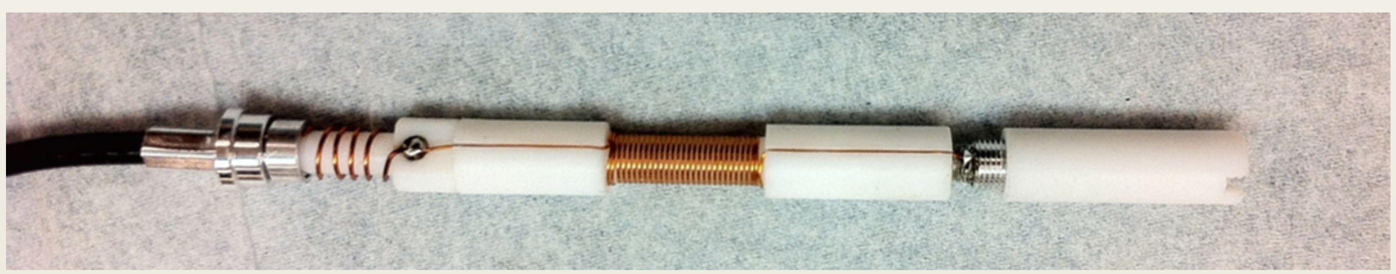
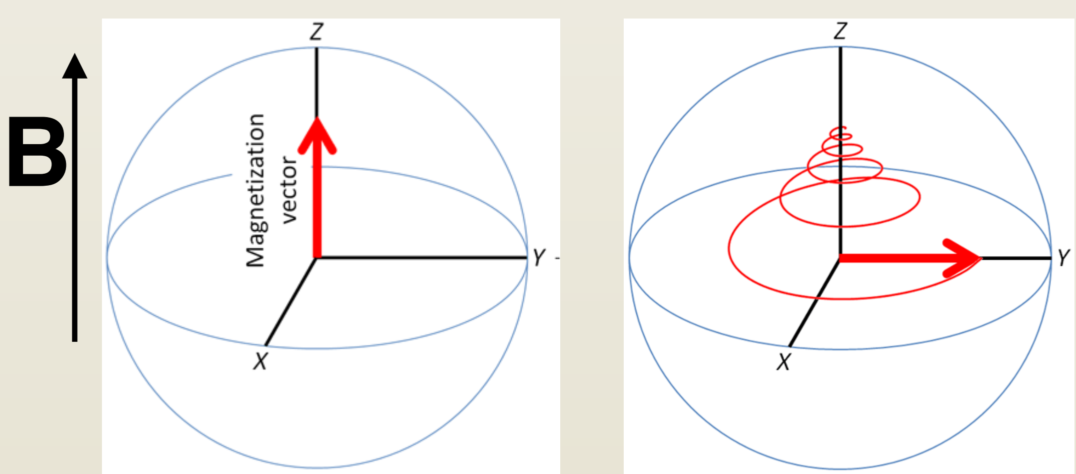
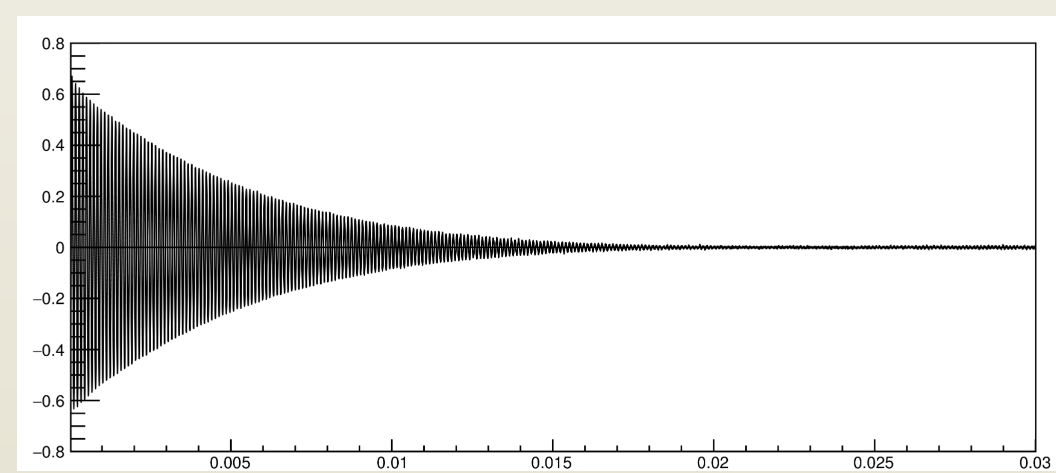


Mapping the magnetic field

- Most precise technique: NMR probes, which return B field strength in terms of precession frequency of a proton ω_p
- E.g: pulsed NMR
  - π/2 RF pulse is used to rotate a proton spin
  - detect the free induction decay using a pick up coil around the sample







Actual extraction of a_μ

- Recast ω_a:

$$\omega_a = a_\mu \frac{e}{m_\mu} B \qquad \mu_e = g_e \frac{e}{2m_e}$$

$$\omega_p = \mu_p B$$

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\mathrm{ppb}$$

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\mathrm{ppb}$$

$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\mathrm{ppt}$$

CODATA, doi:10.1103/RevModPhys.88.035009

- $\tilde{\omega}_p$: weighted average of Lamor precession frequency of a free proton in the magnetic field
  - measured using NMR probes and an absolute calibration probe

Muon g-2 experiments

- Long history of experiments

doi:10.1103/PhysRevD.73.072003

Experiment	Years	Polarity	$a_\mu \times 10^{10}$	Precision [ppm]
CERN I	1961	μ^+	11450000(220000)	4300
CERN II	1962–1968	μ^+	11661600(3100)	270
CERN III	1974–1976	μ^+	11659100(110)	10
CERN III	1975–1976	μ^-	11659360(120)	10
BNL	1997	μ^+	11659251(150)	13
BNL	1998	μ^+	11659191(59)	5
BNL	1999	μ^+	11659202(15)	1.3
BNL	2000	μ^+	11659204(9)	0.73
BNL	2001	μ^-	11659214(9)	0.72
Average			11659208.0(6.3)	0.54

- Final result from BNL

$$a_\mu(\text{Expt}) = 11659208.0(6.3) \times 10^{-10}(0.54\ \text{ppm}).$$

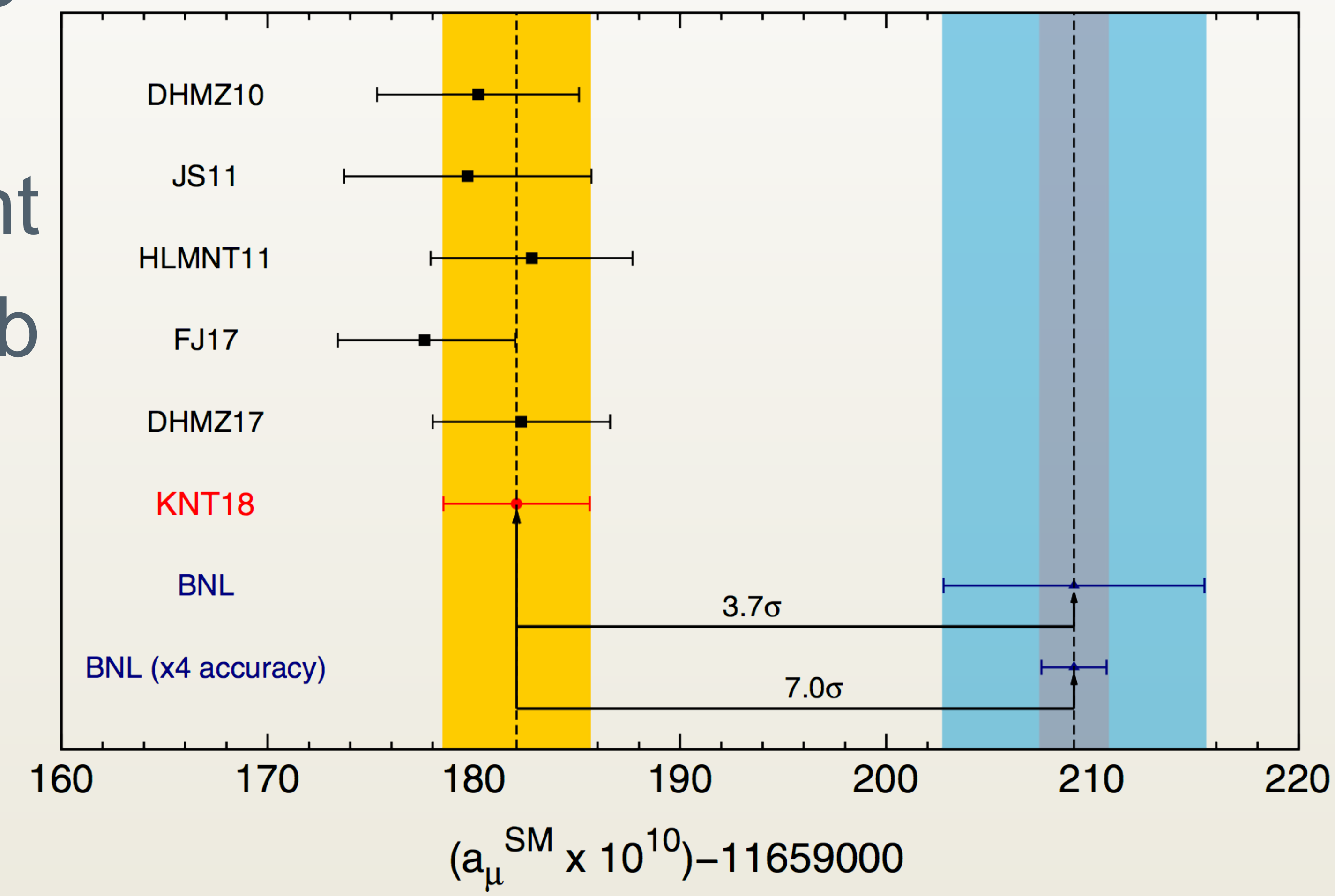
- Ongoing efforts:
  - E989 at Fermilab
  - E34 at J-PARC

Muon g-2 experiment at Fermilab - E989

- Use the same storage ring as in BNL
- Goal: 4 times improvement in precision, i.e. to 140 ppb

	E821	E989
Number of positrons	9×10^{9}	2×10^{11} (x20 BNL)
Stat. Uncertainty	480 ppb	100 ppb
Syst. Uncertainty	248 ppb	100 ppb
Total Uncertainty	540 ppb	140 ppb

Phys. Rev. D 97 (2018) 114025



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Muon beam line

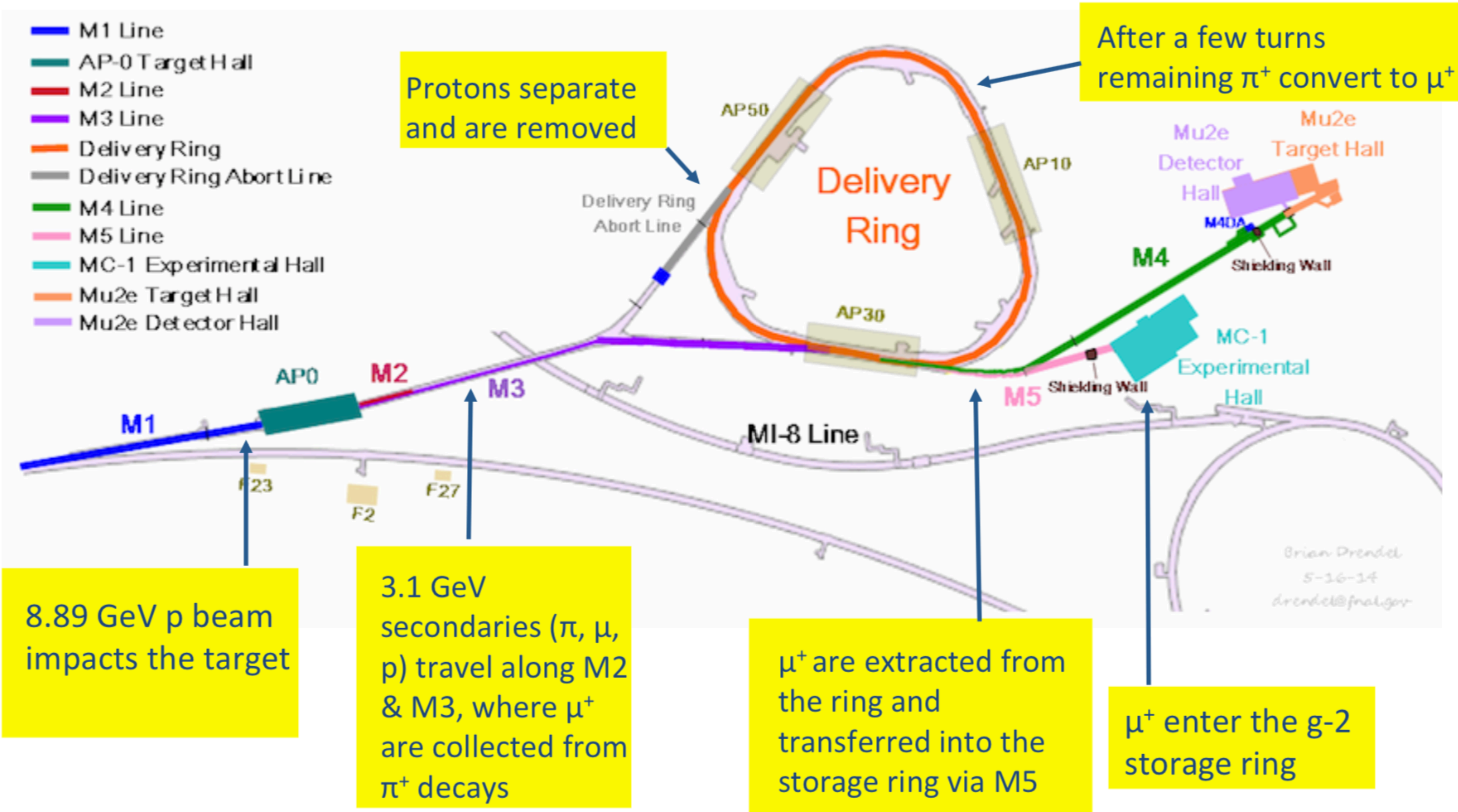
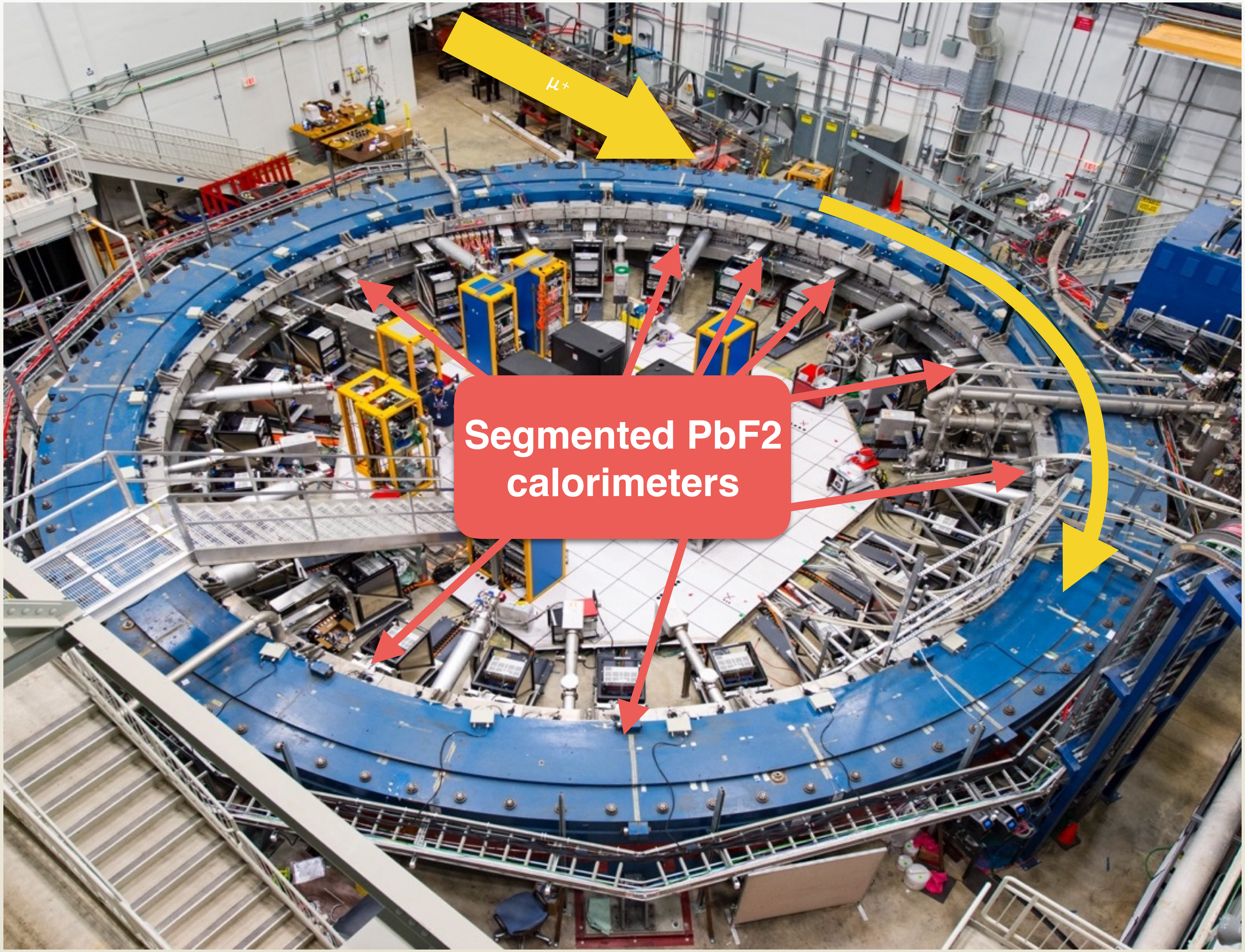


Image from D. Stratakis

Muon storage ring



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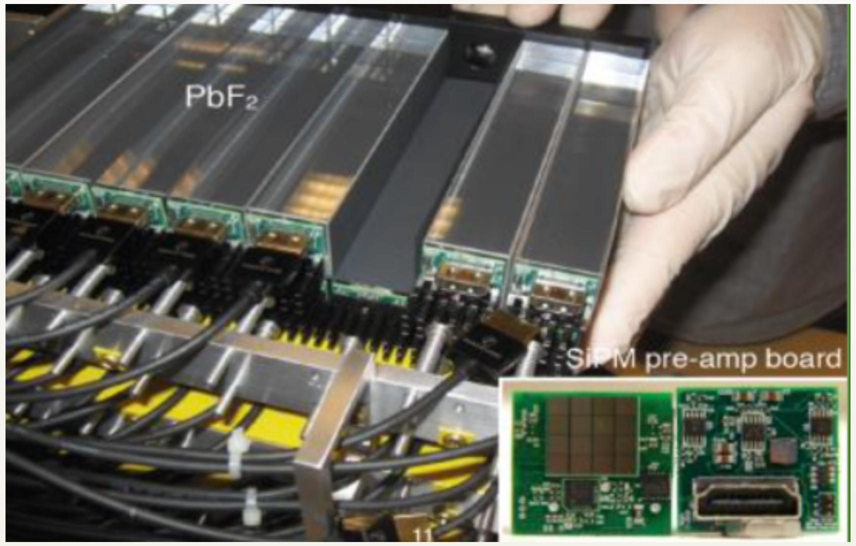
Calorimetry

- 24 PbF2 calorimeters, evenly distributed around the ring
  - 54 segments per calo
  - SiPM readout
- Detect positron from self-analyzing decay: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
  - Highest-energy e+ emitted preferentially along muon spin
  - Results in sinusoidally-oscillating arrival time of these e+ in calorimeters
- Laser system for calibration and gain correction



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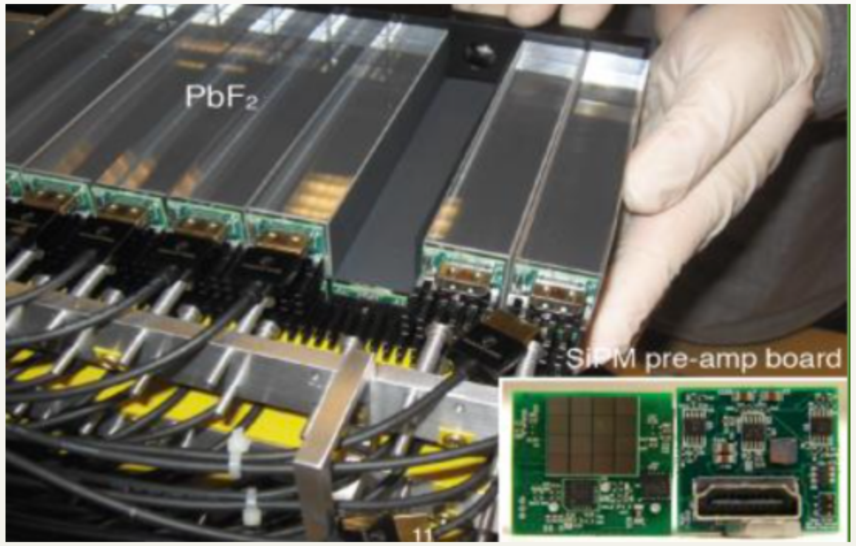

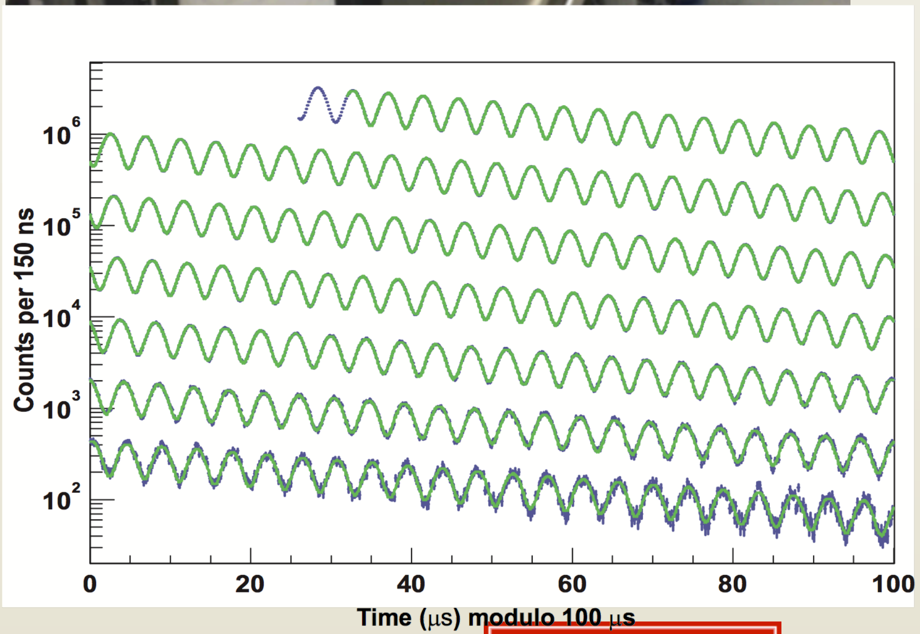

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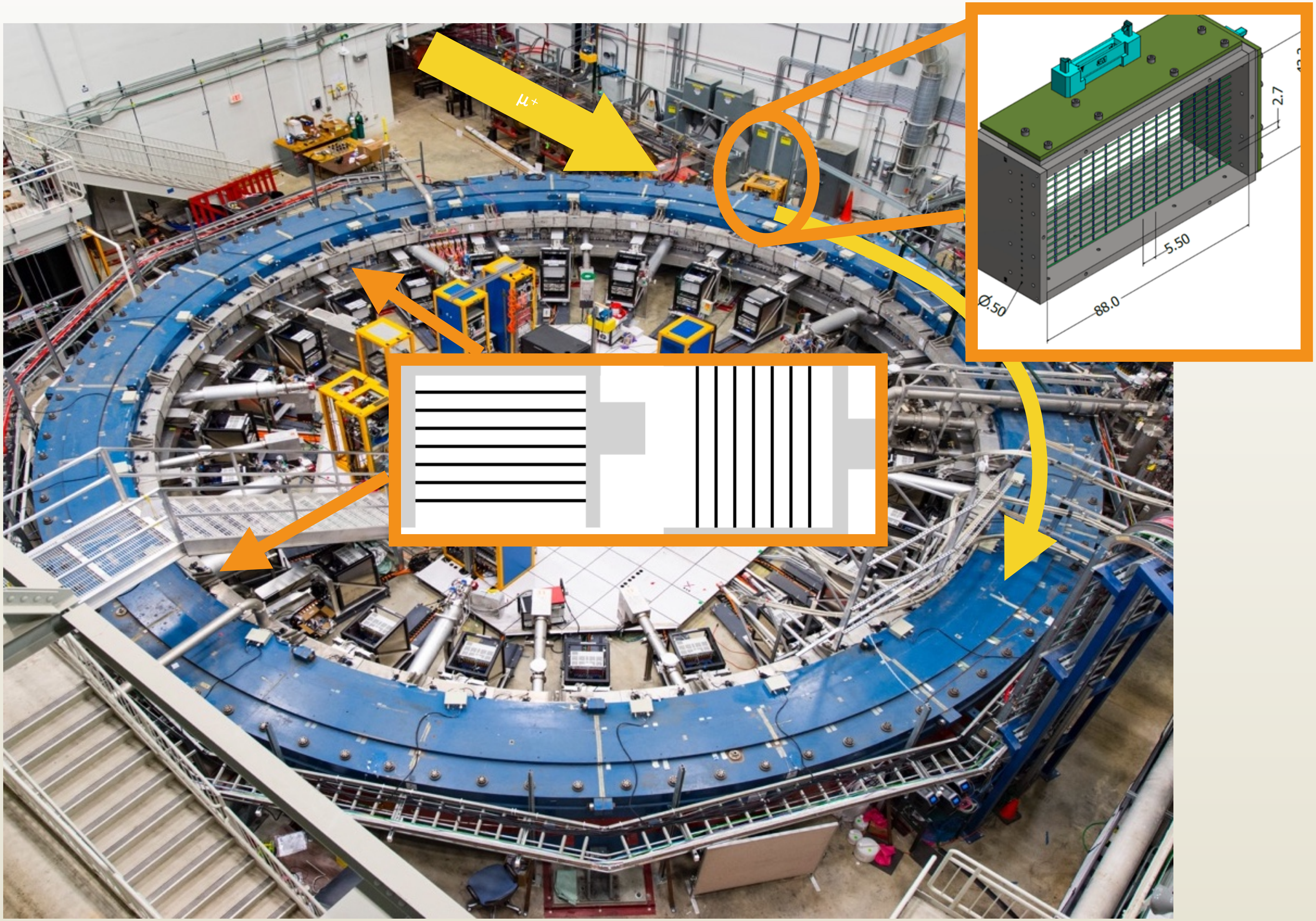
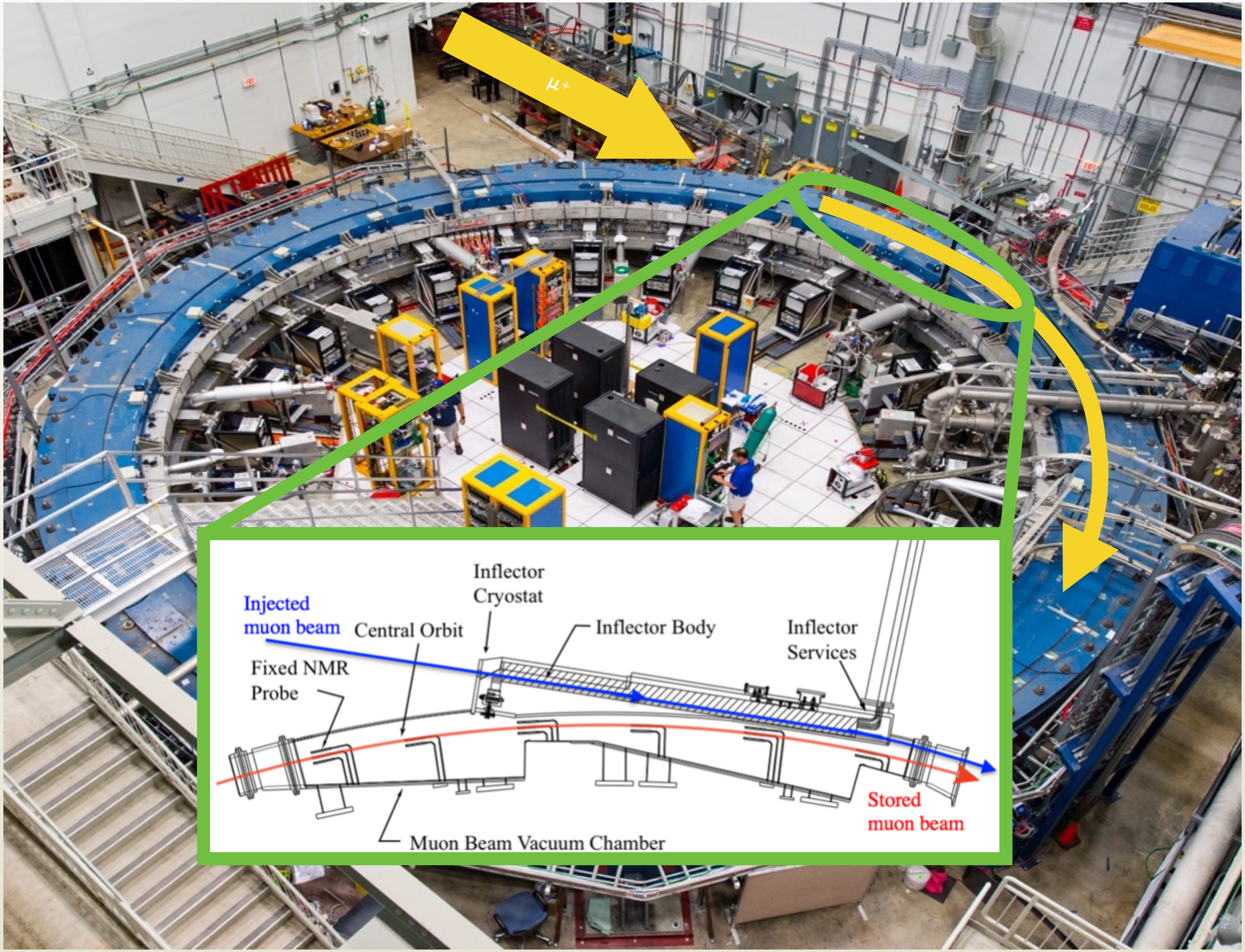
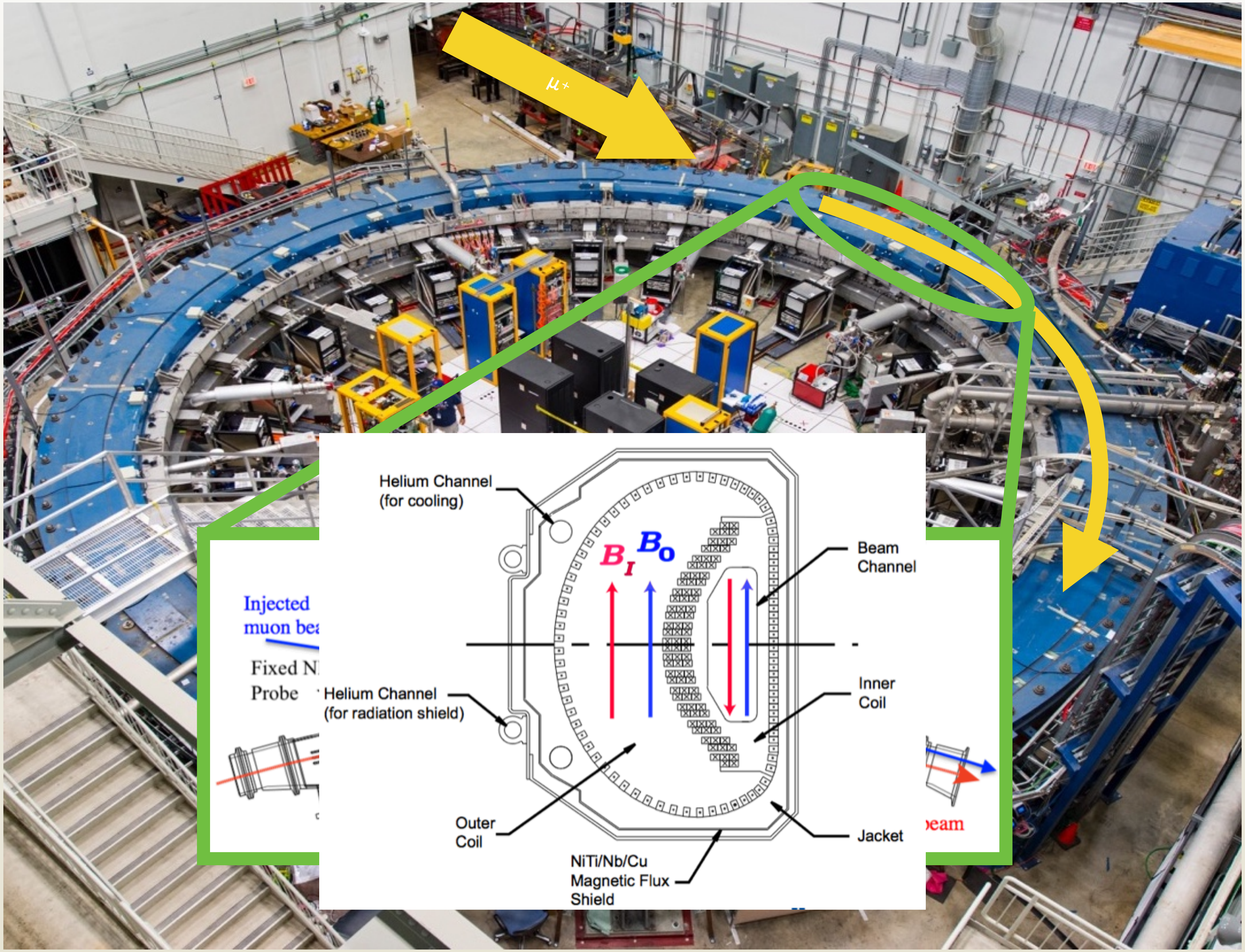
Beam profile monitors



Inflector


μ+
Inflector
Cryostat
Injected
muon beam
Central Orbit
Inflector Body
Inflector
Services
Fixed NMR
Probe
Stored
muon beam
Muon Beam Vacuum Chamber

Inflector



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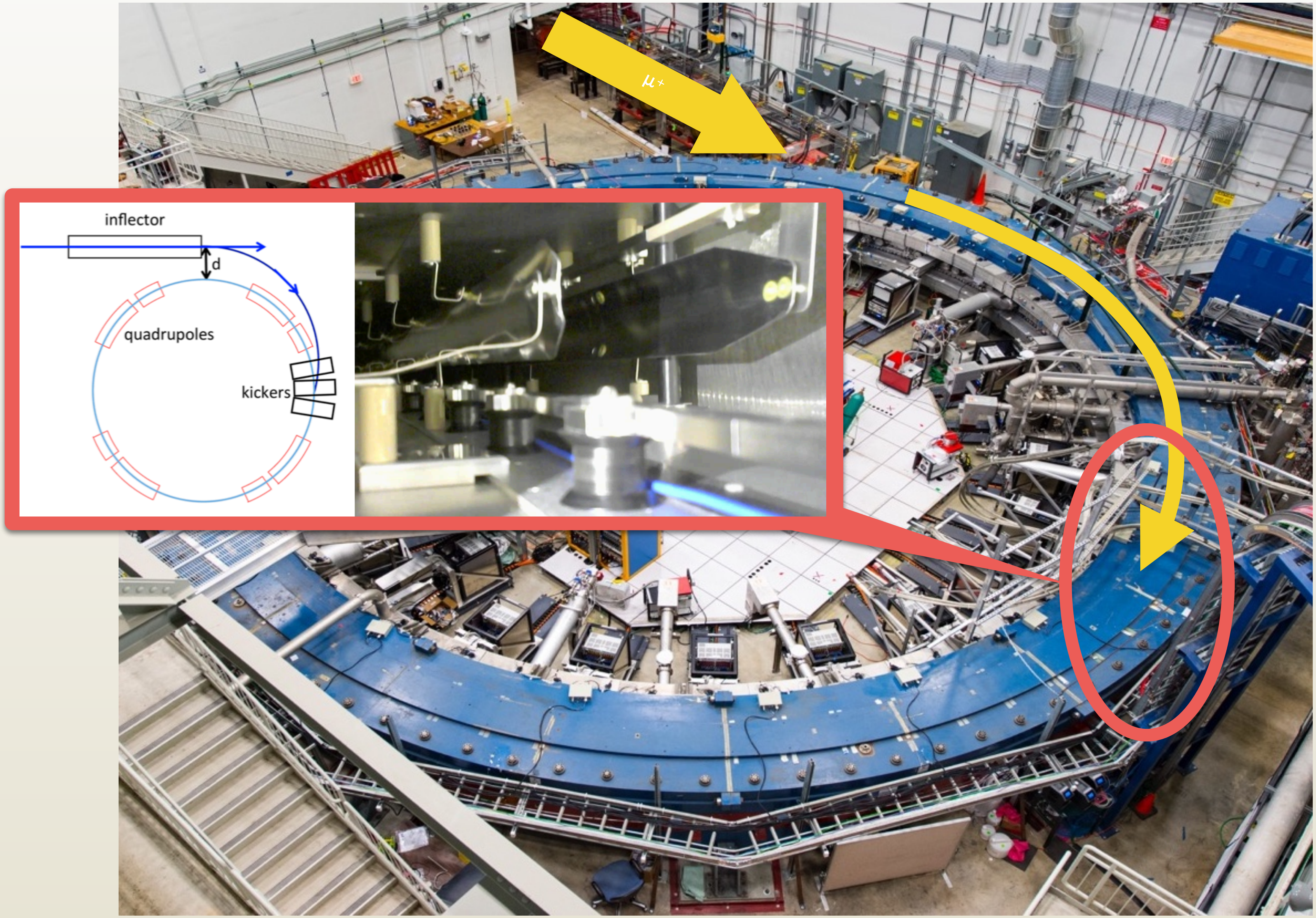
Magnetic kicker



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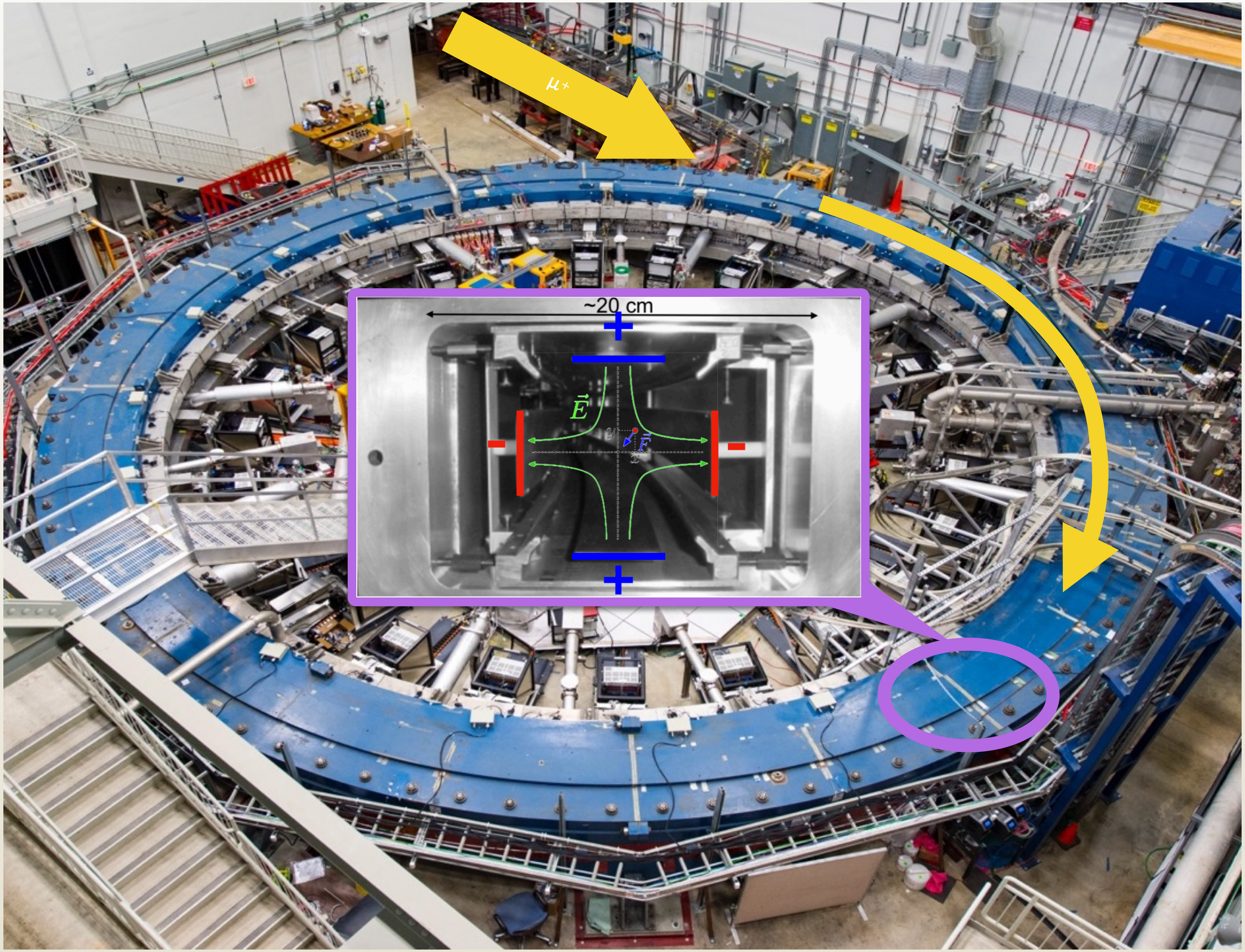
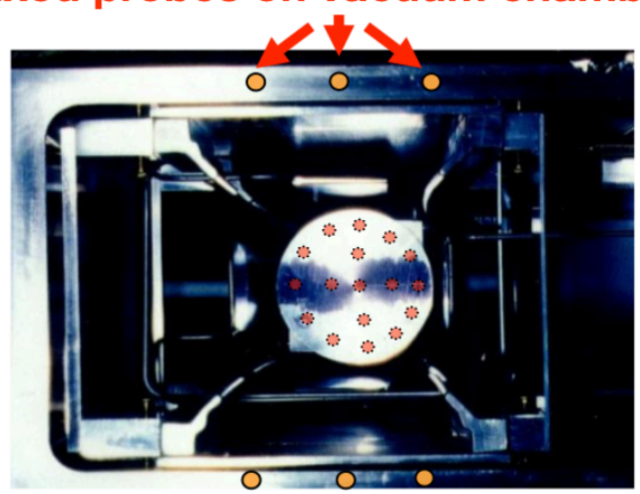
Eletrostatic quadrupole focusing



Mapping the magnetic field

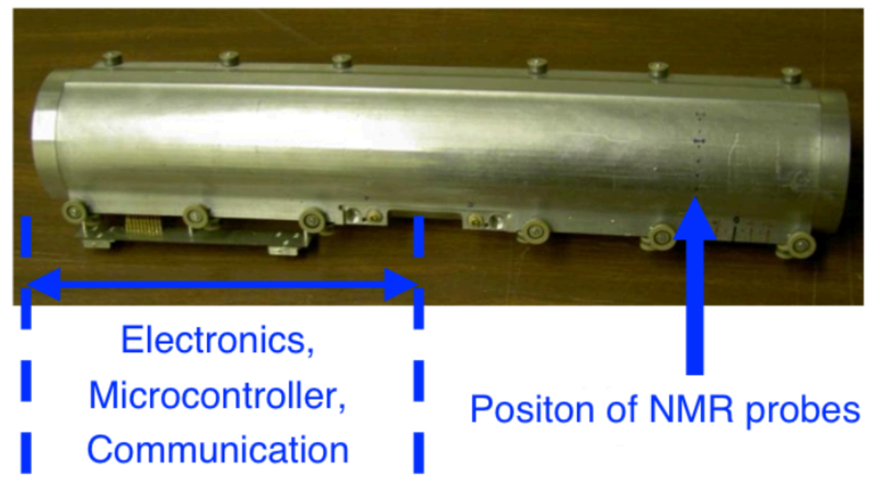
- Map the magnetic field inside the ring every 3 days
- Fixed probes for continuously monitoring

Fixed probes on vacuum chambers



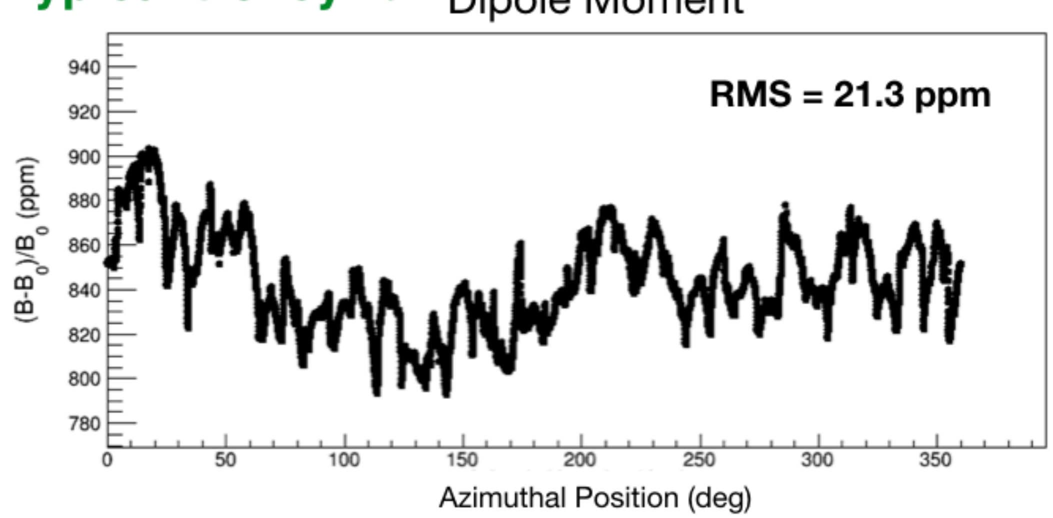
- Measure field while muons are in ring – 378 probes **outside** storage region

Trolley matrix of 17 NMR probes

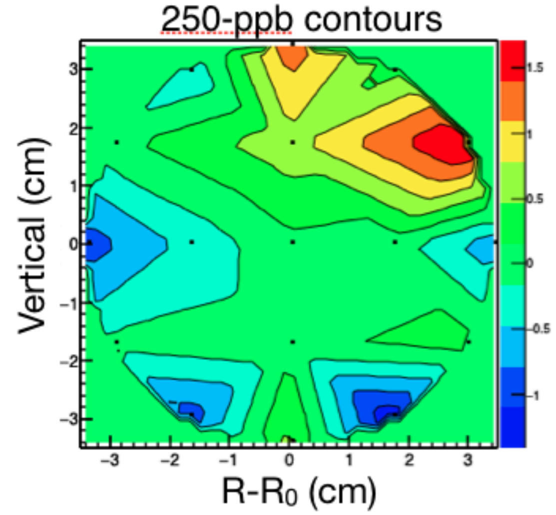


- Measure field in storage region during **specialized runs** when **muons are not being stored**

Typical trolley run



Azimuthal average
250-ppb contours



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Real world considerations

- Real muon beam has a small vertical component
- Need vertical electric field to focus the beam

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

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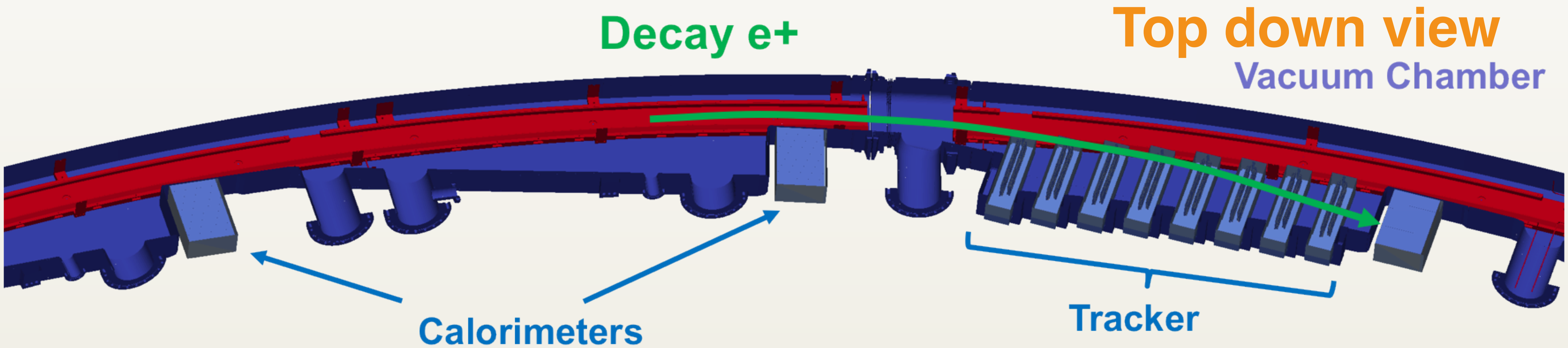
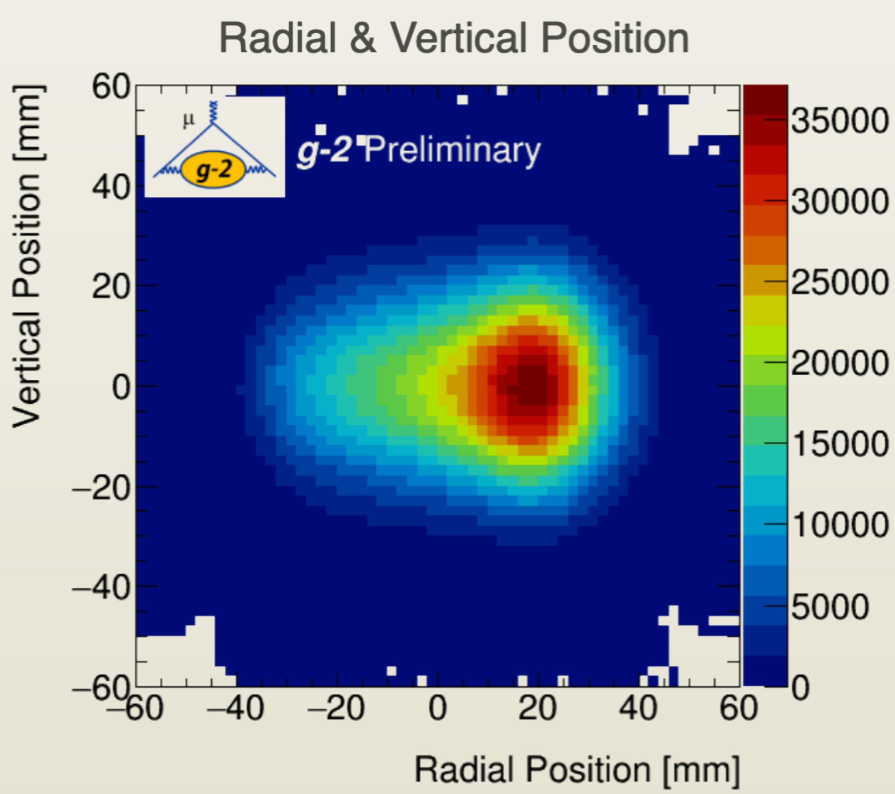
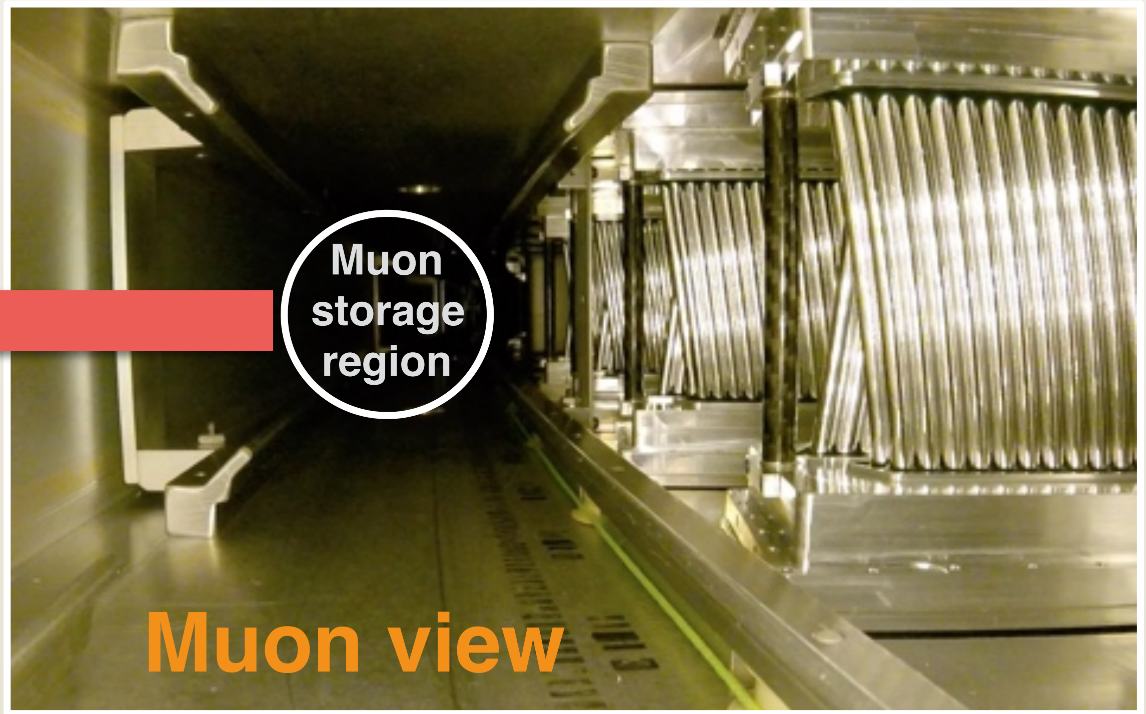
- Choose γ = 29.304 (p = 3.09 GeV, a.k.a magic momentum)
  - but not all muons are at magic momentum (Δp = 0.5 %), i.e. the term is not completely vanished
- Vertical motion of the beam can be corrected for by measuring beam profile
  - using scintillating fiber tracker (destructive), and straw tube trackers (non-destructive)

Beam profile measurement

- Two tracker stations for monitoring

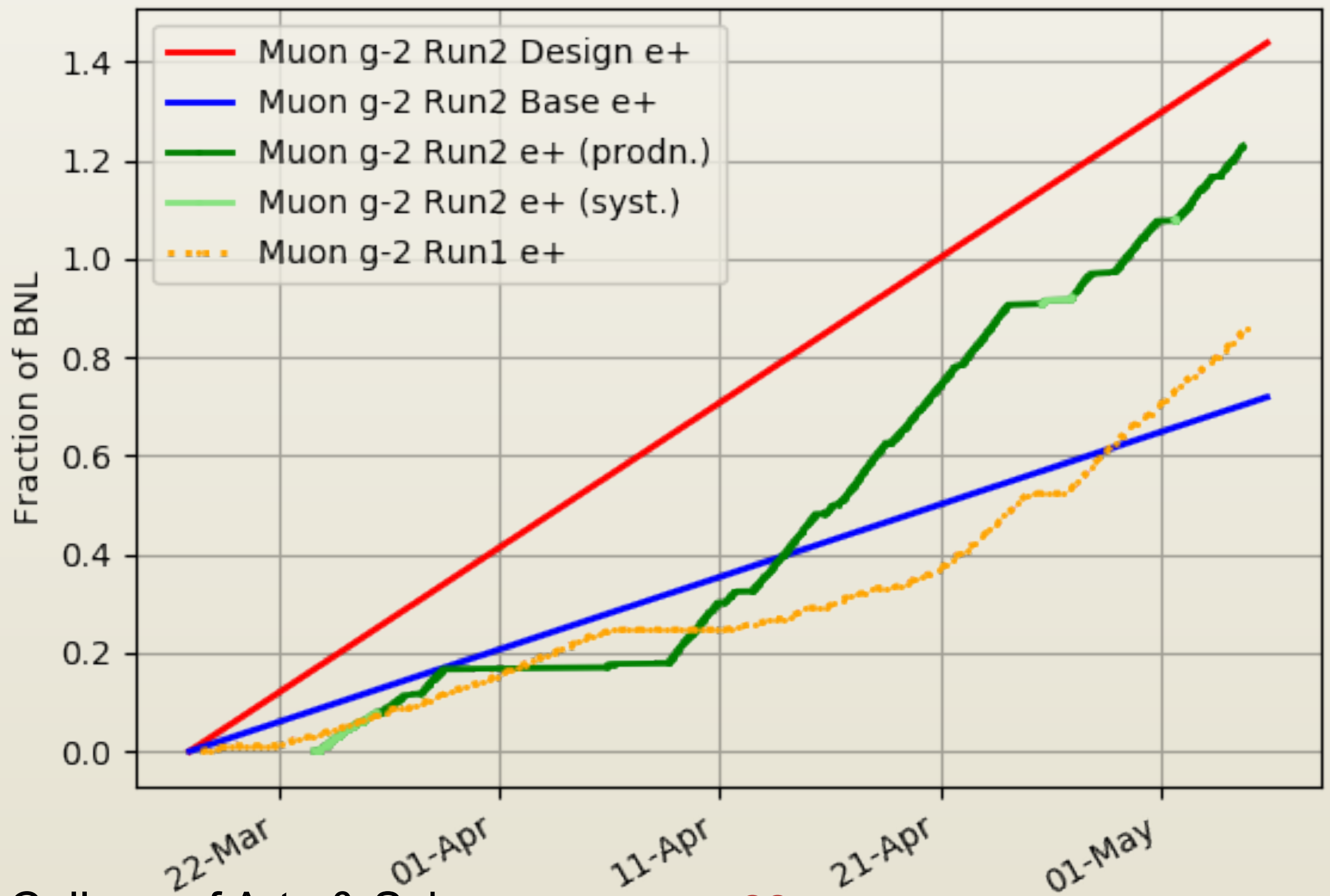






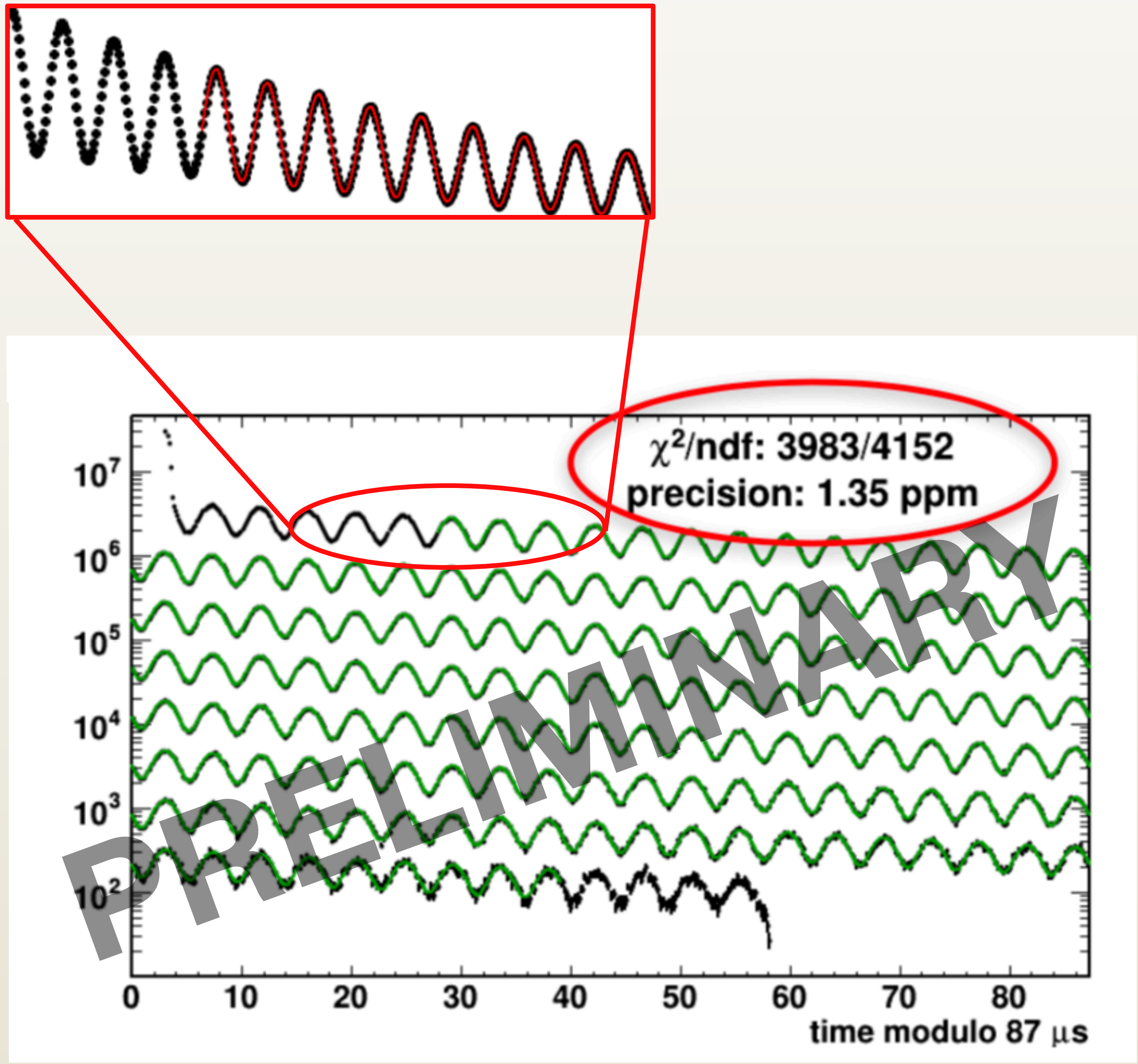
Data taking progress

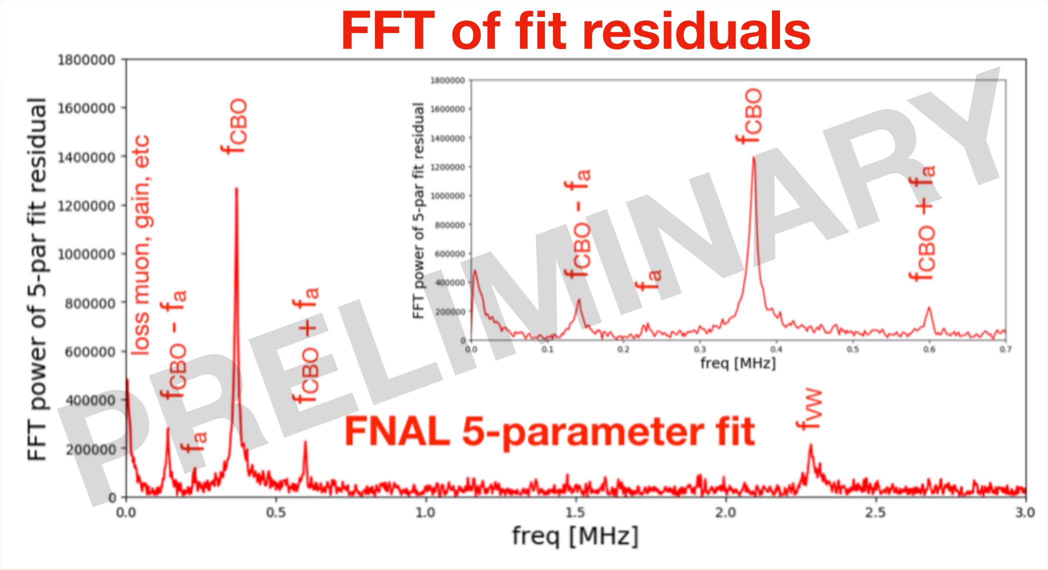
- Finished first physics run, Run 1, in July 2018
  - Field uniformity 2x better than BNL
  - 1.75×10^{10} positrons collected, ~ 2x BNL stats
    - 1.4x BNL after data quality cut, $\delta\omega_a$(stat) ~ 350 ppb
    - analysis in progress
- Half way through the Run 2
  - Improvements: muon flux, kicker strength, overall stability, …



ω_a in Run 1

$$N(t) = N_0 e^{-t/\tau}\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$$





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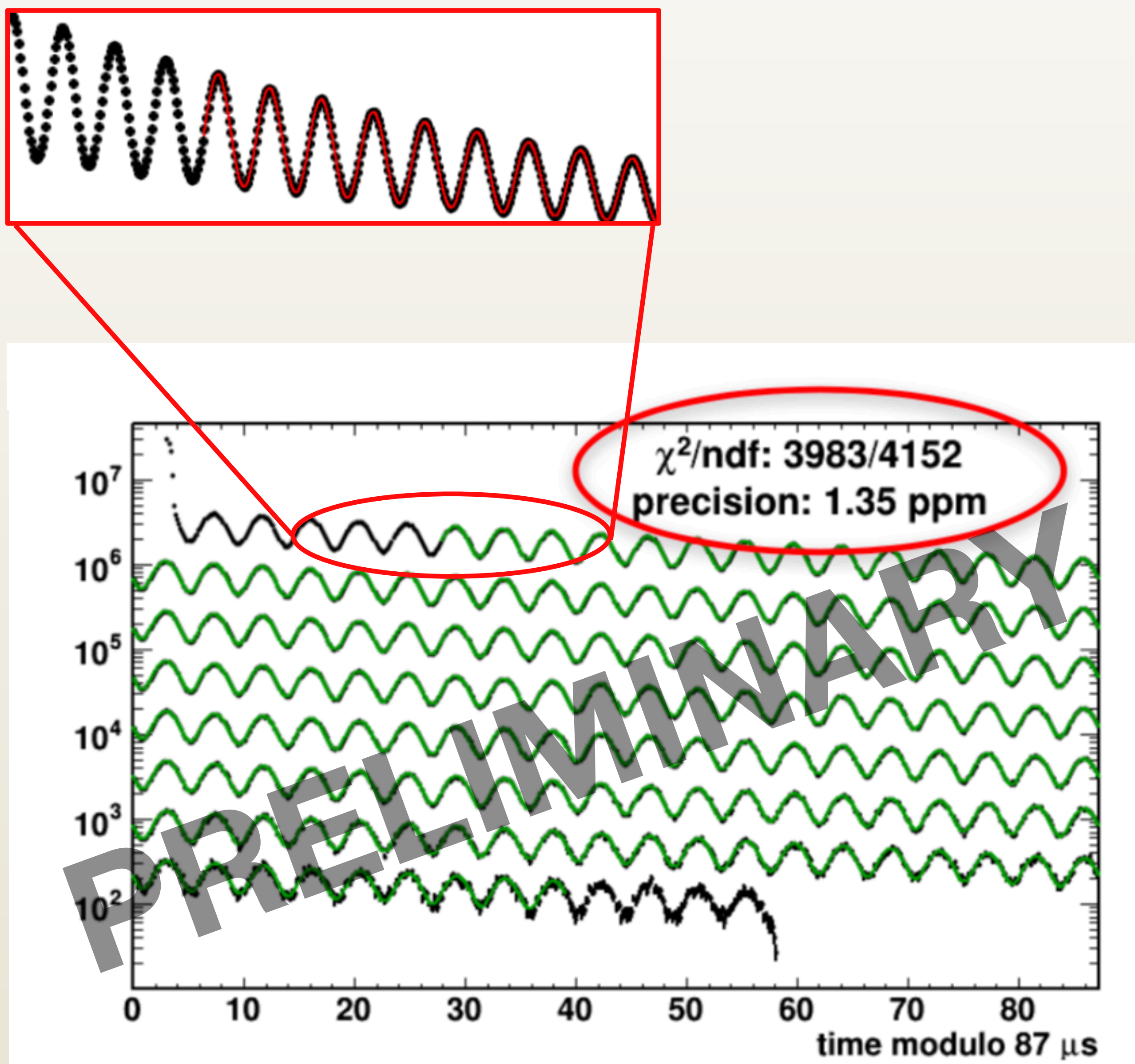
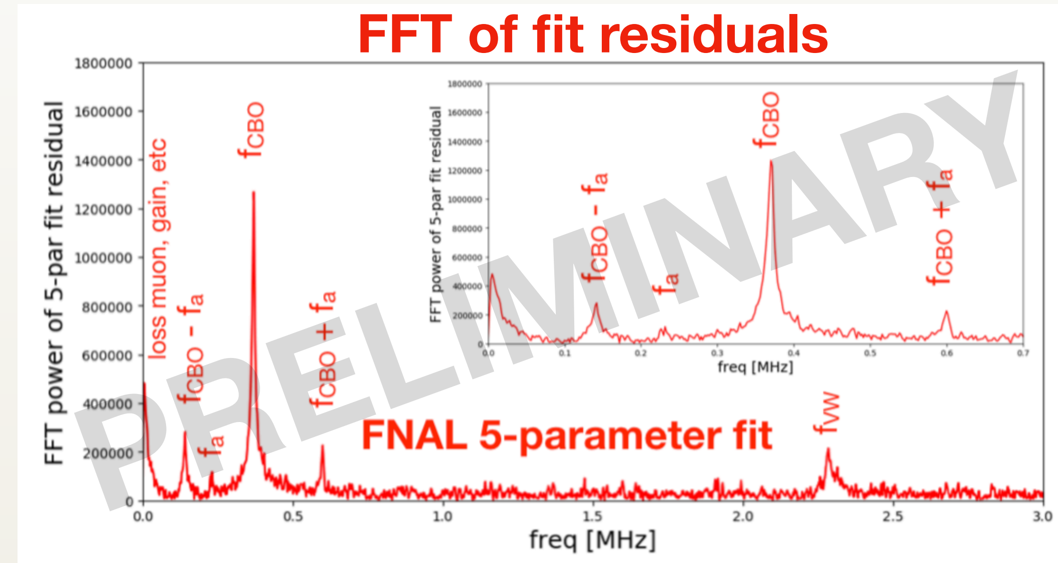
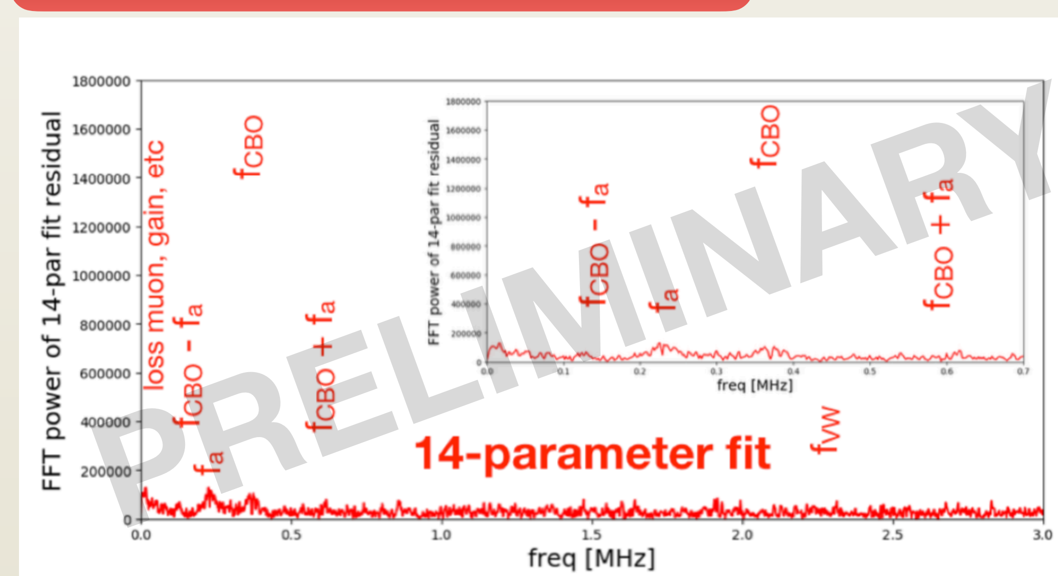




Big improvements when accounting for CBO, lost muons,…



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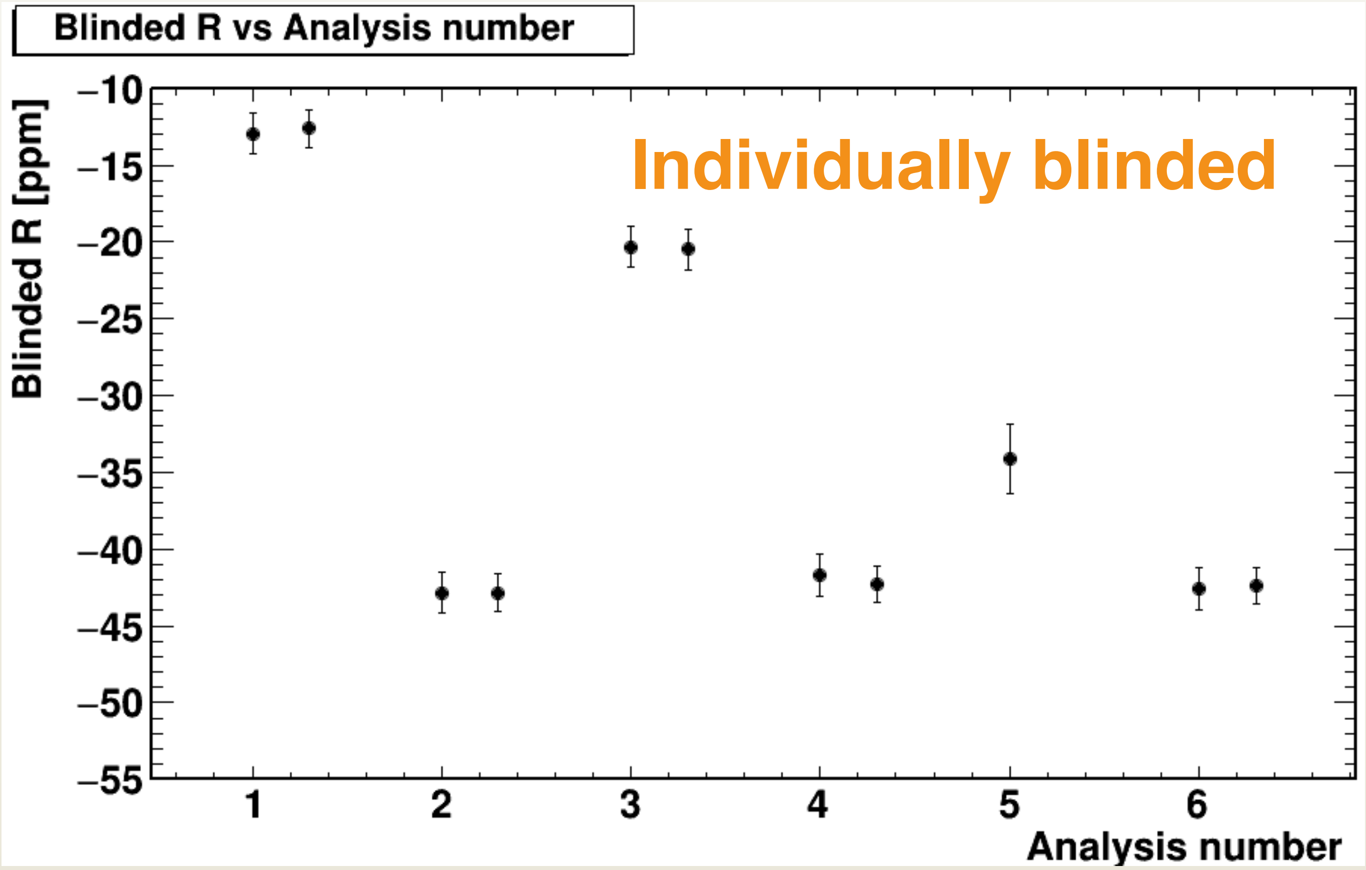
Relative unblinding test

- Two fold blindings:
  - Global clock tuned to (1 ± 25 ppm) × 40 MHz
  - Individual analyzer has another 25 ppm random offset



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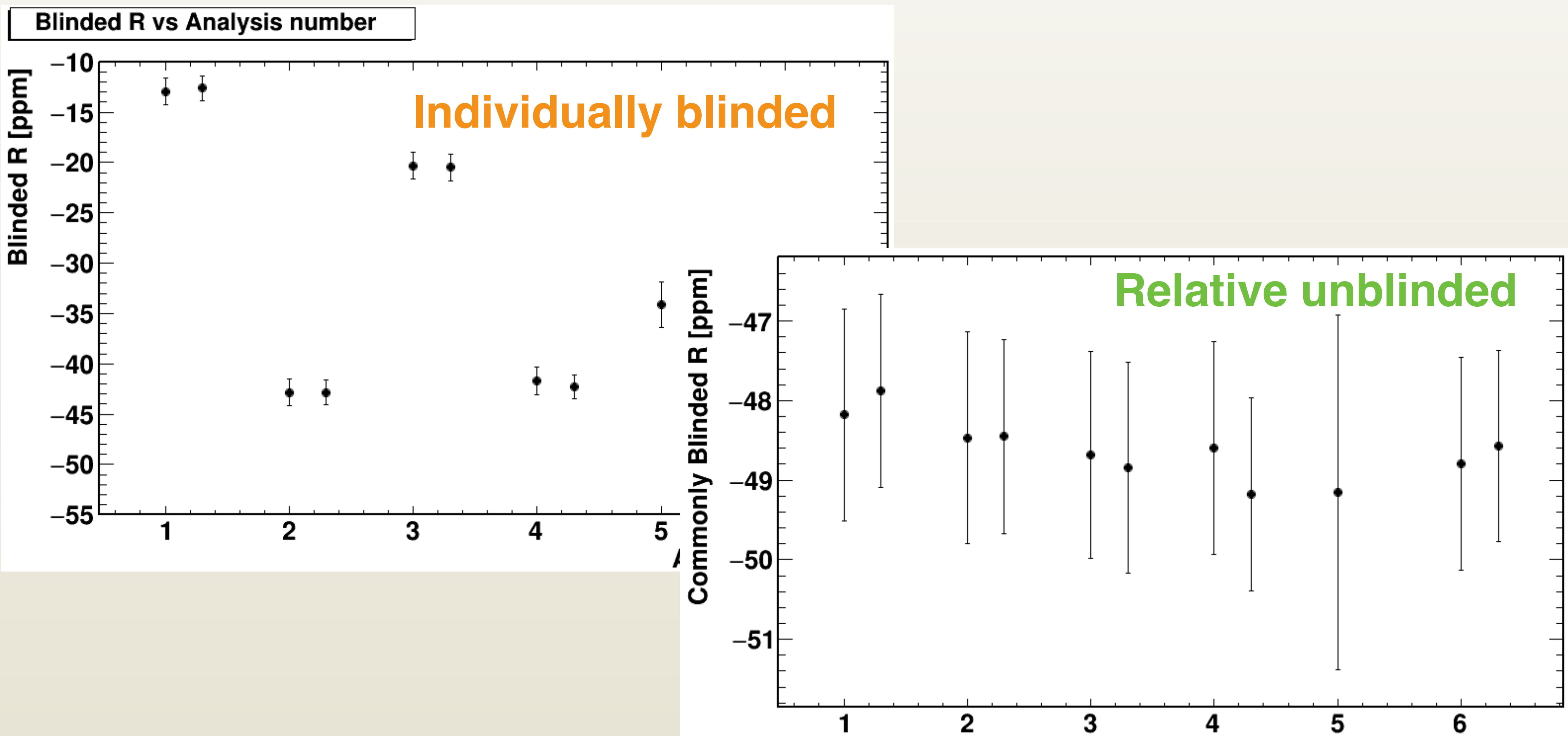

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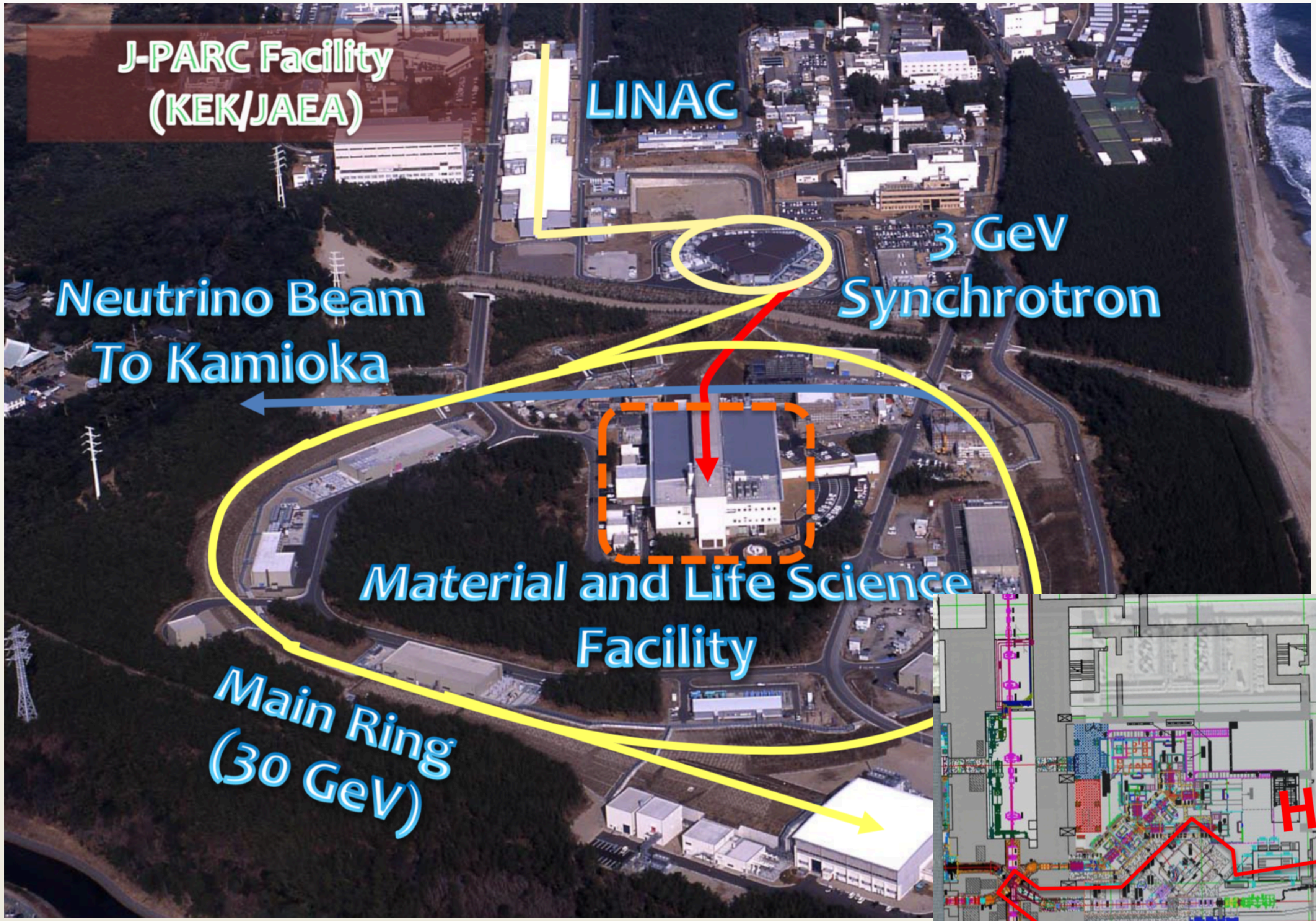
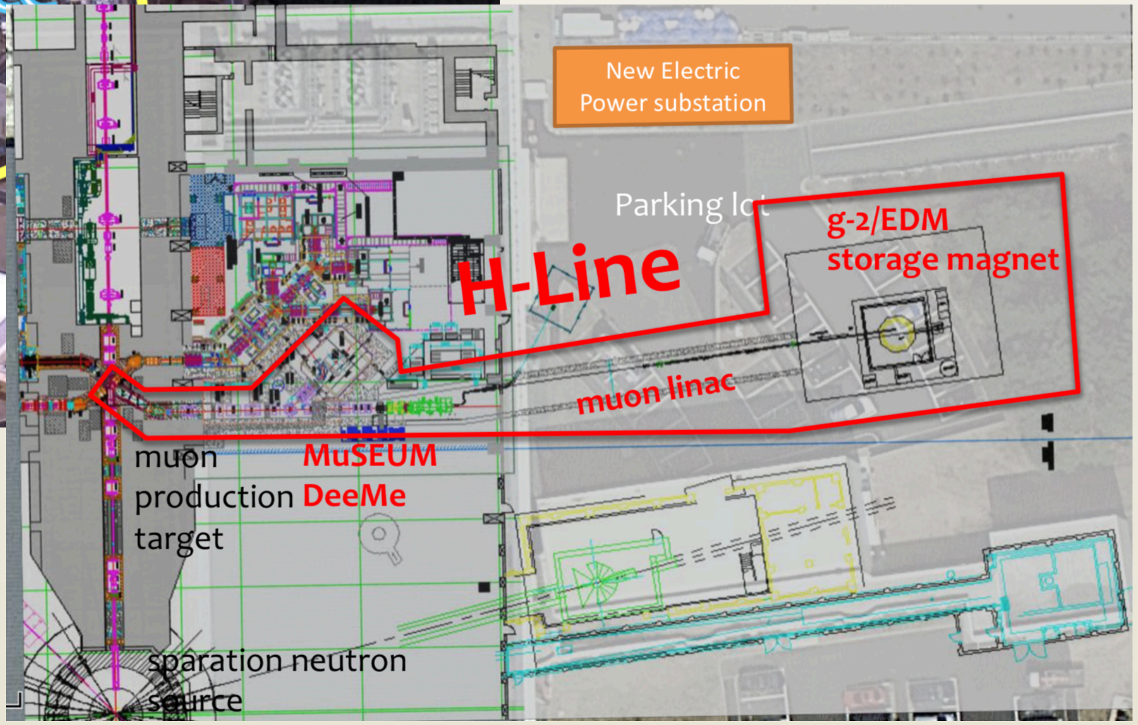
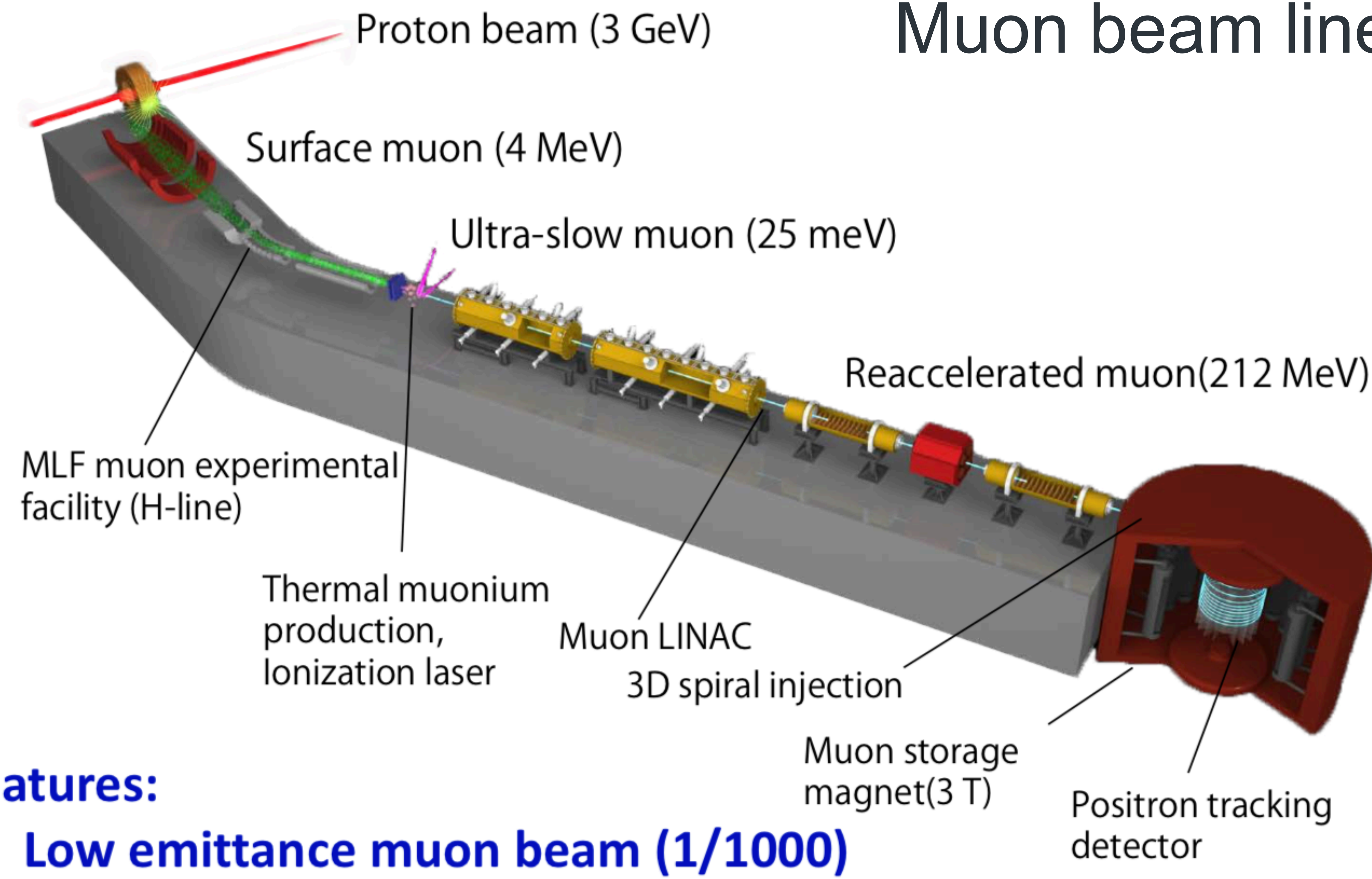
Muon g-2 at J-PARC (E34)





Most figures and numbers are from arXiv:1901.03047 and T. Mibe's slides

Muon beam line

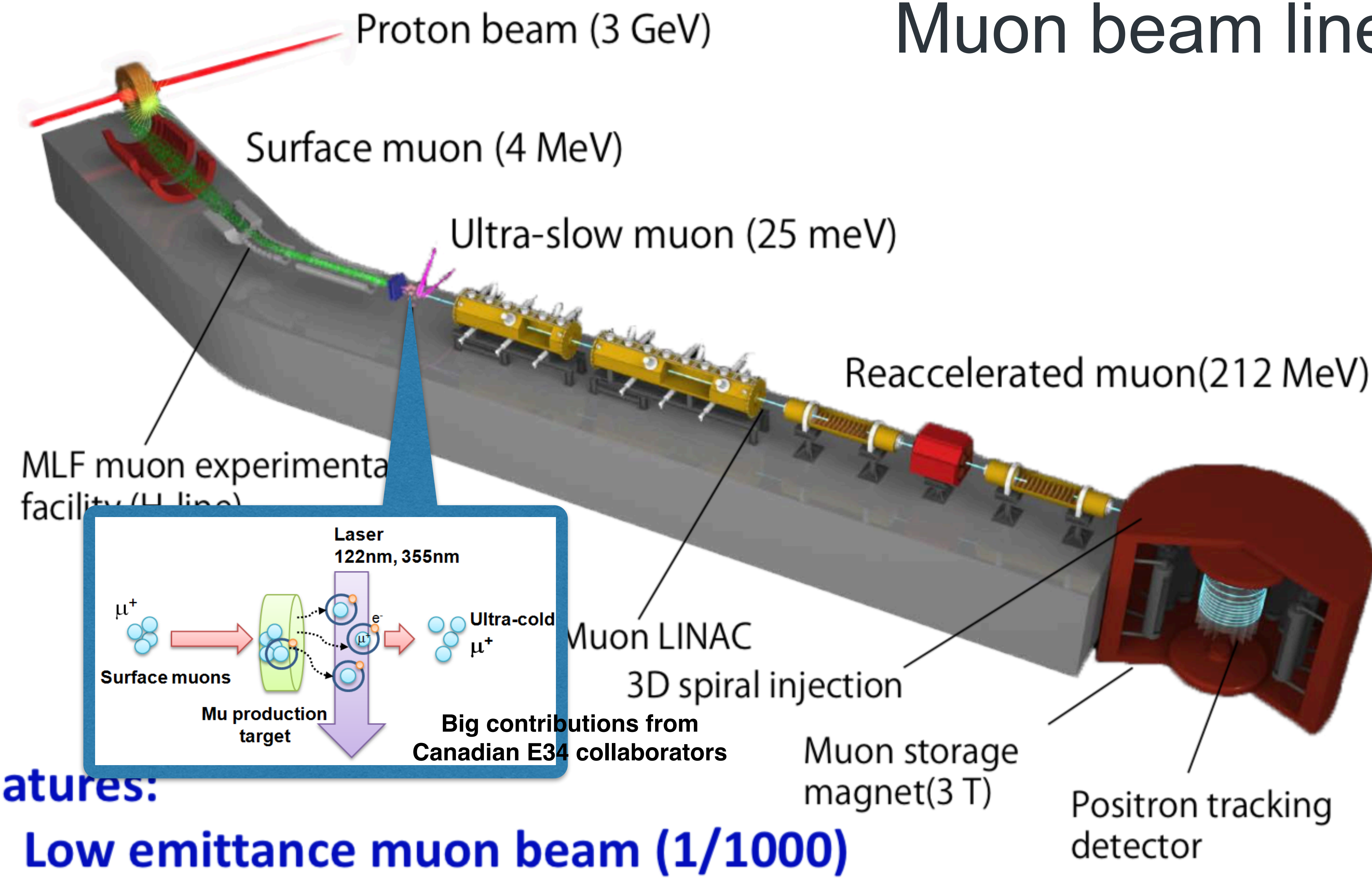


Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**

From T. Mibe-san

Muon beam line



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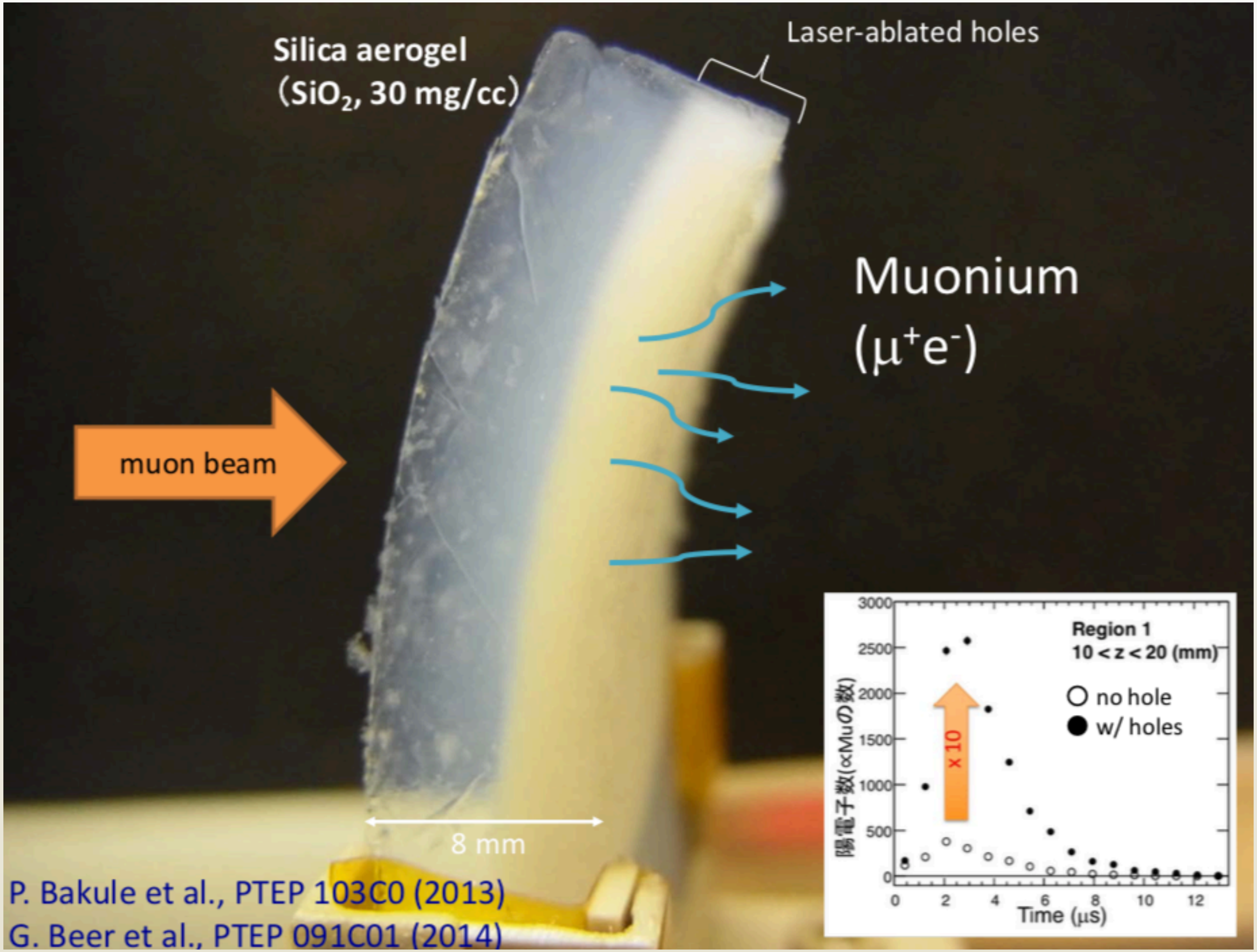
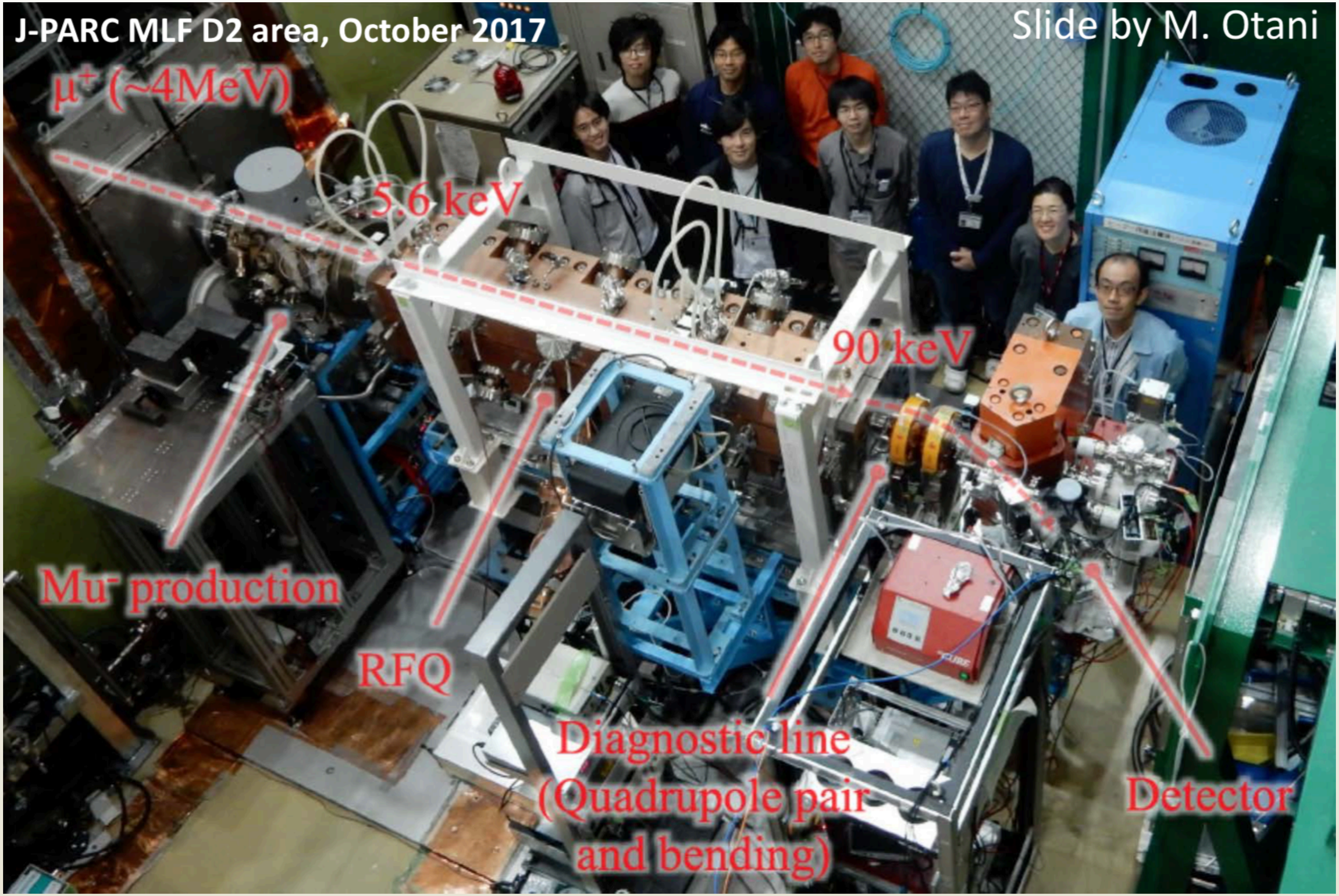
From T. Mibe-san

Muonium production



Demonstration of muon reacceleration



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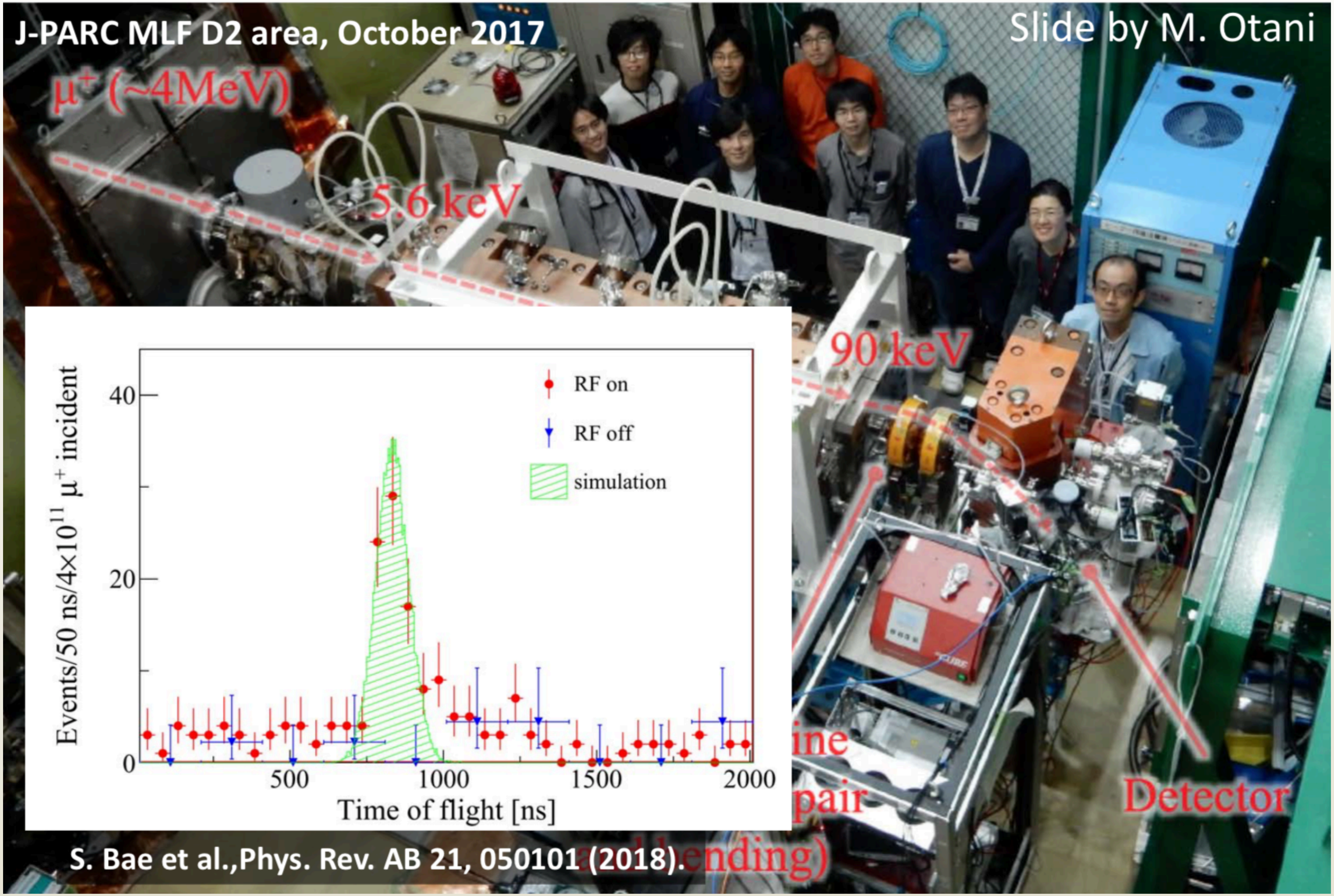

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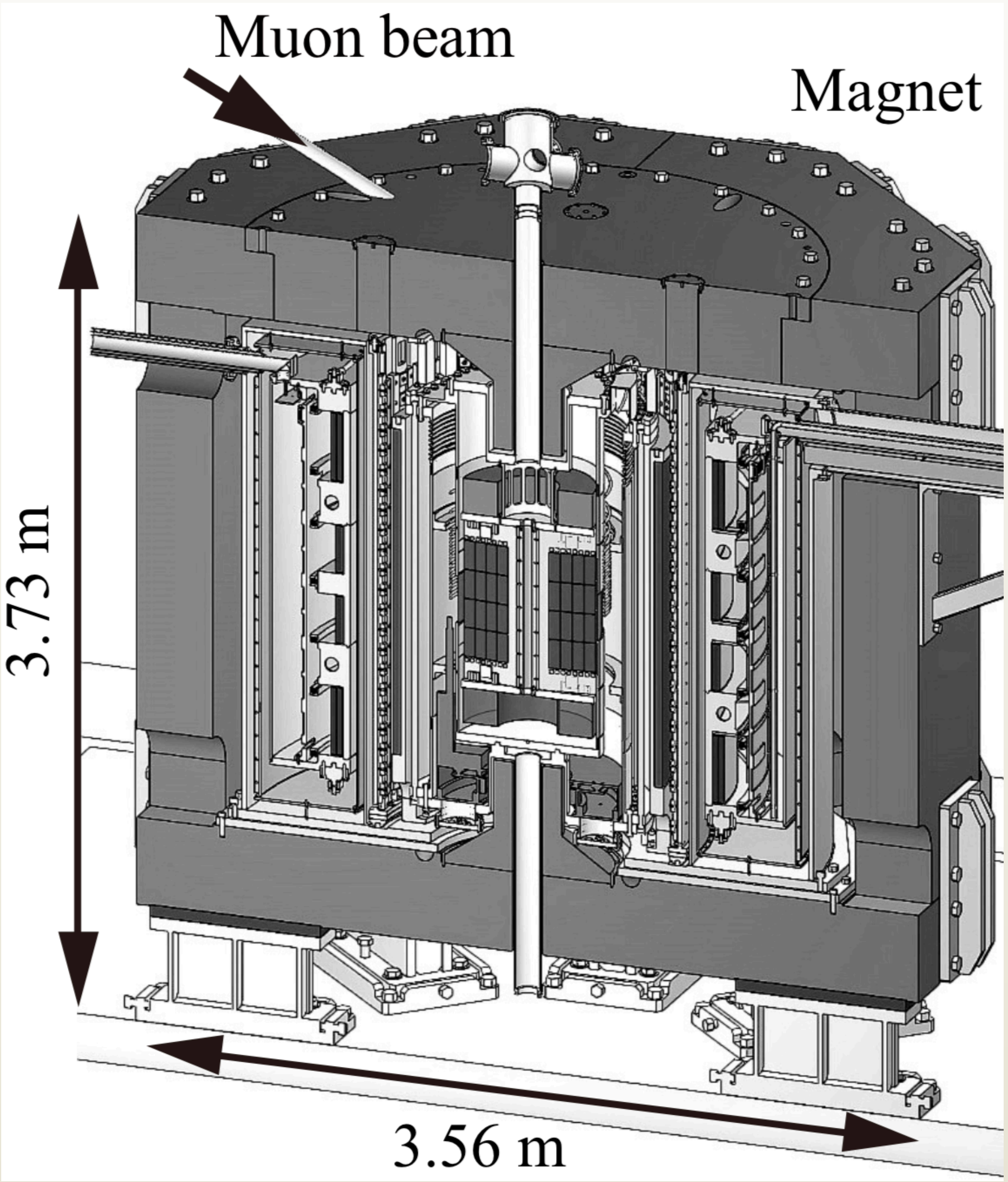
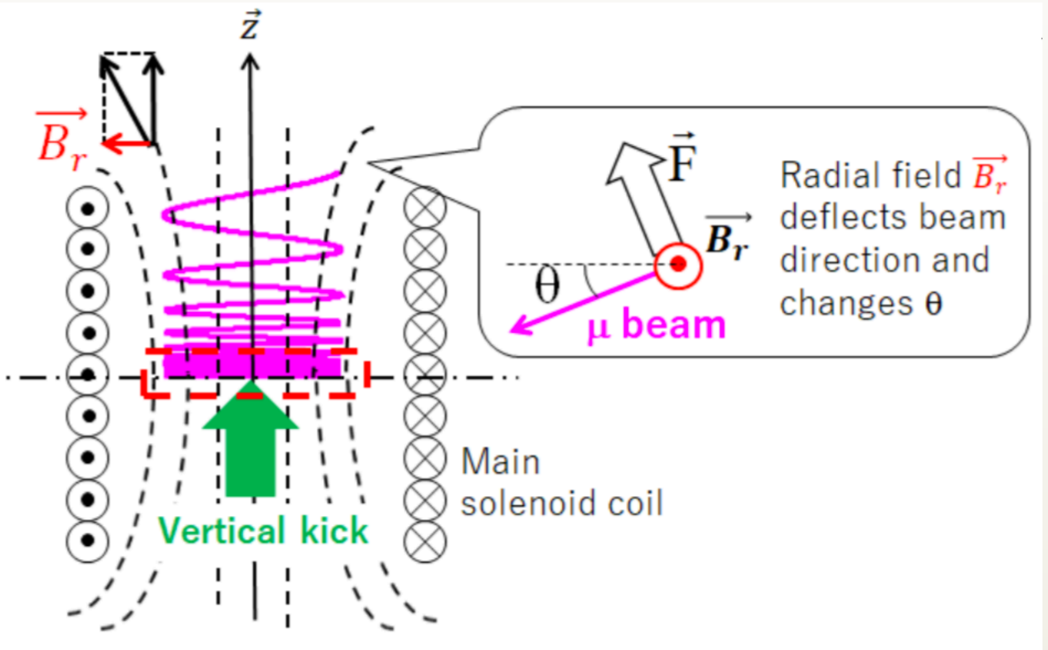
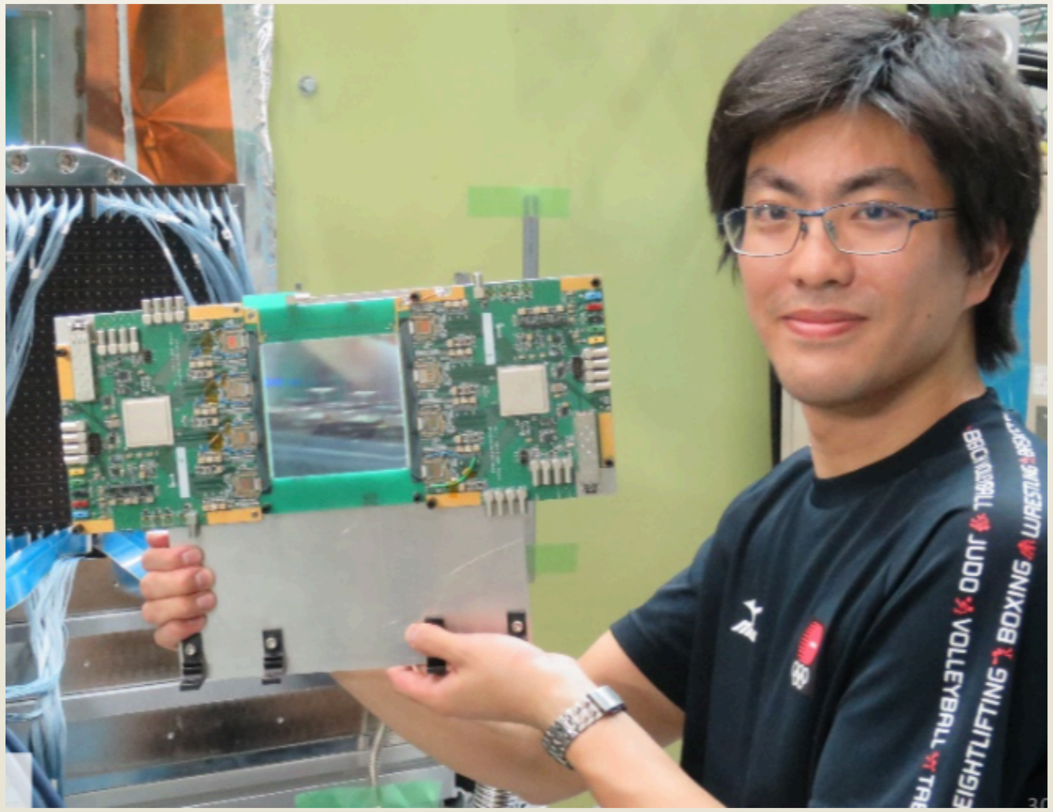
Muon storage region and positron detectors







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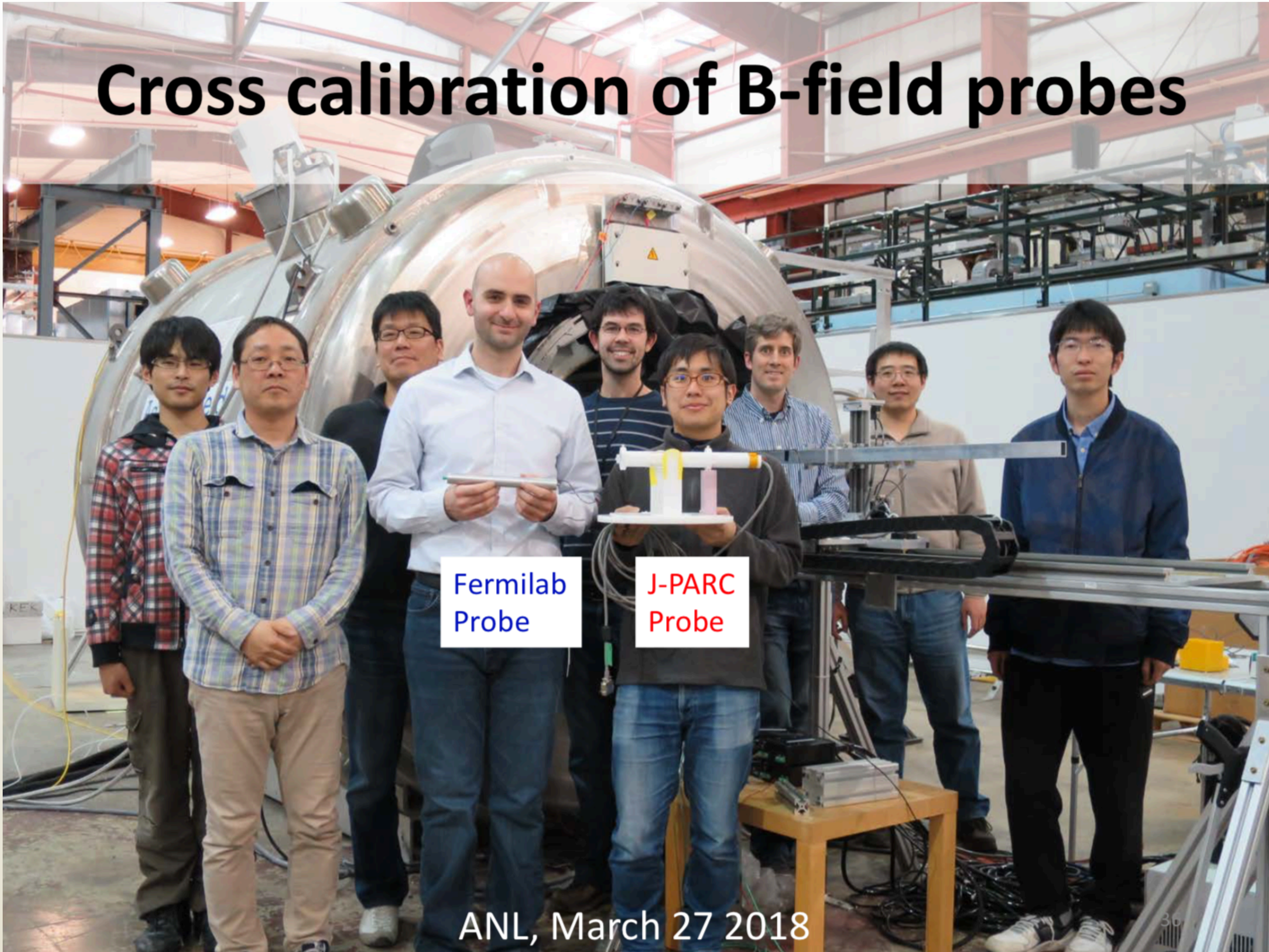
Cross calibration of B-field probes



Outlook

- Moving from R&D to construction phase
- Construction of H-line
- Further demonstration of reacceleration to 1 MeV

Comparing the two g-2 experiments

Parameter	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/c)
Polarization	P_{max} = 50-90% (spin reversal possible)	$P \approx 97\%$ (no spin reversal)
Magnet	MRI-like solenoid ($r_{storage}$ = 33 cm)	Storage ring ($r_{storage}$ = 7 m)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Injection	Spiral + kicker (~90% efficiency)	Inflector + kicker (~5% efficiency)
Positron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	450 ppb	140 ppb

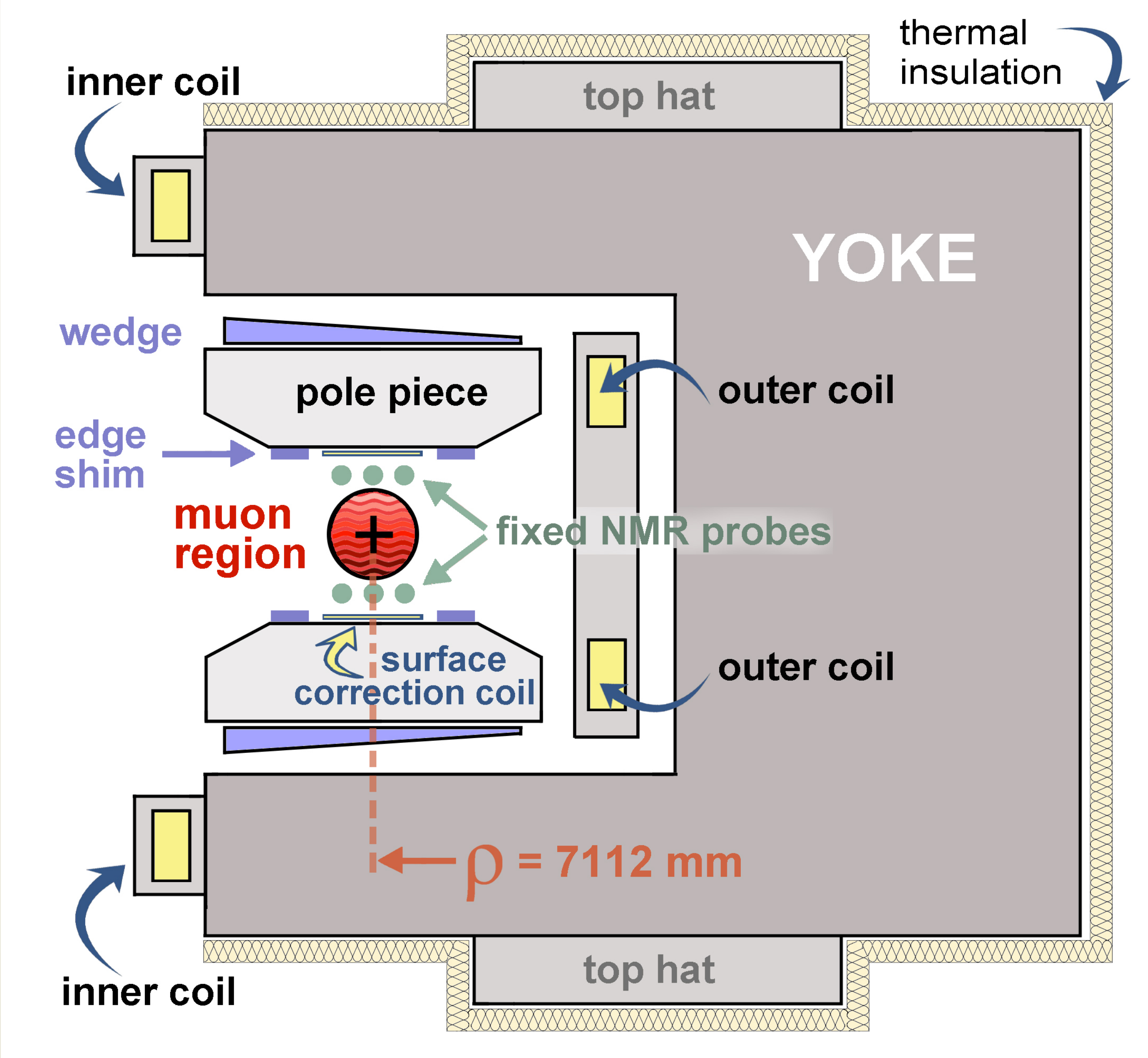
Summary

- Multiple experimental efforts on muon g-2
- E989 at Fermilab is going to have first result soon
  - And on the second run
- E34 at J-PARC is making good progress
  - Completely new approach, excellent crosschecks
- Interesting time ahead!

Thanks!

Magnet design

- B = 1.45 T (~5200 A)
  - Power supply with feedback to fine-tune field in real time
- 12 C-shaped yokes
  - 3 upper and 3 lower poles per yoke
  - 72 total poles
- Field shape: determined by positioning of pole pieces, wedge-shaped pieces of steel, programmable surface coils



g-2 Magnet in Cross Section

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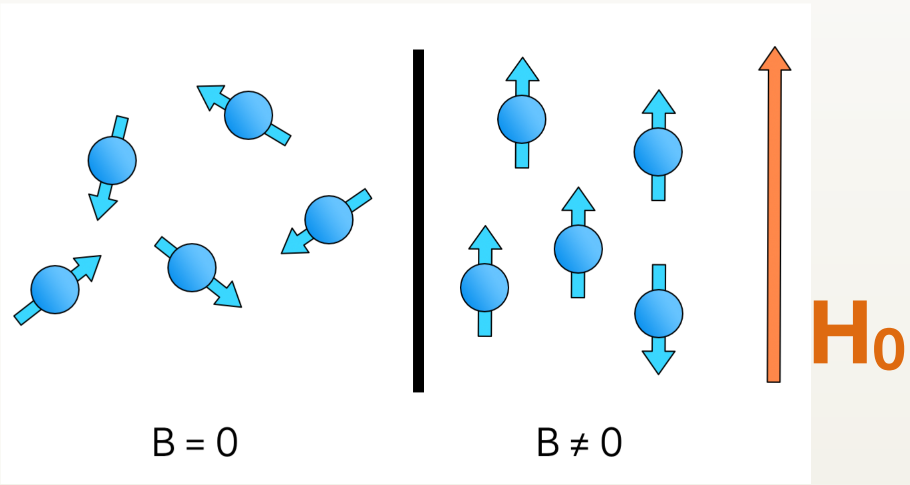

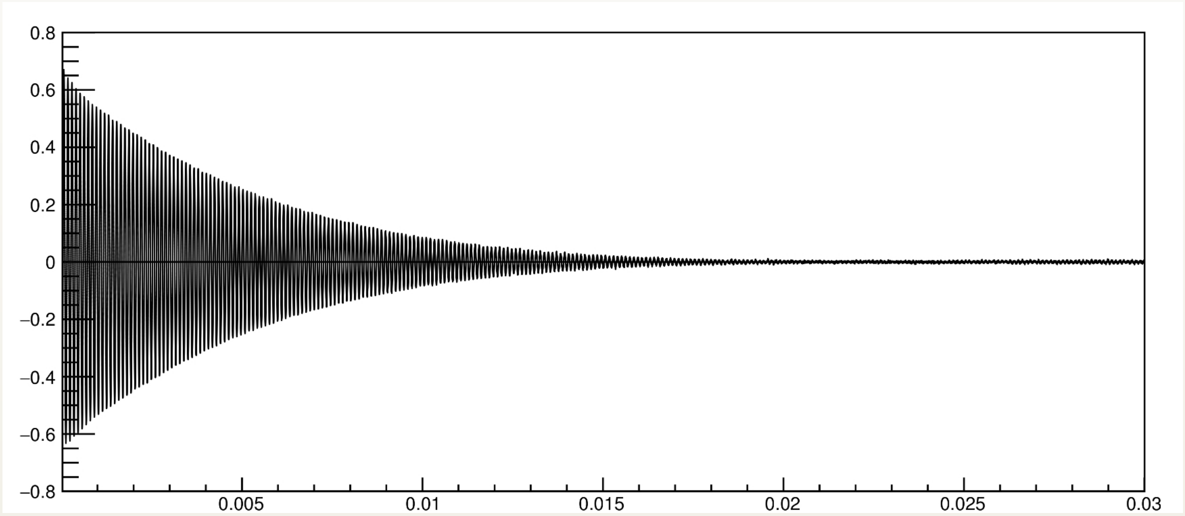

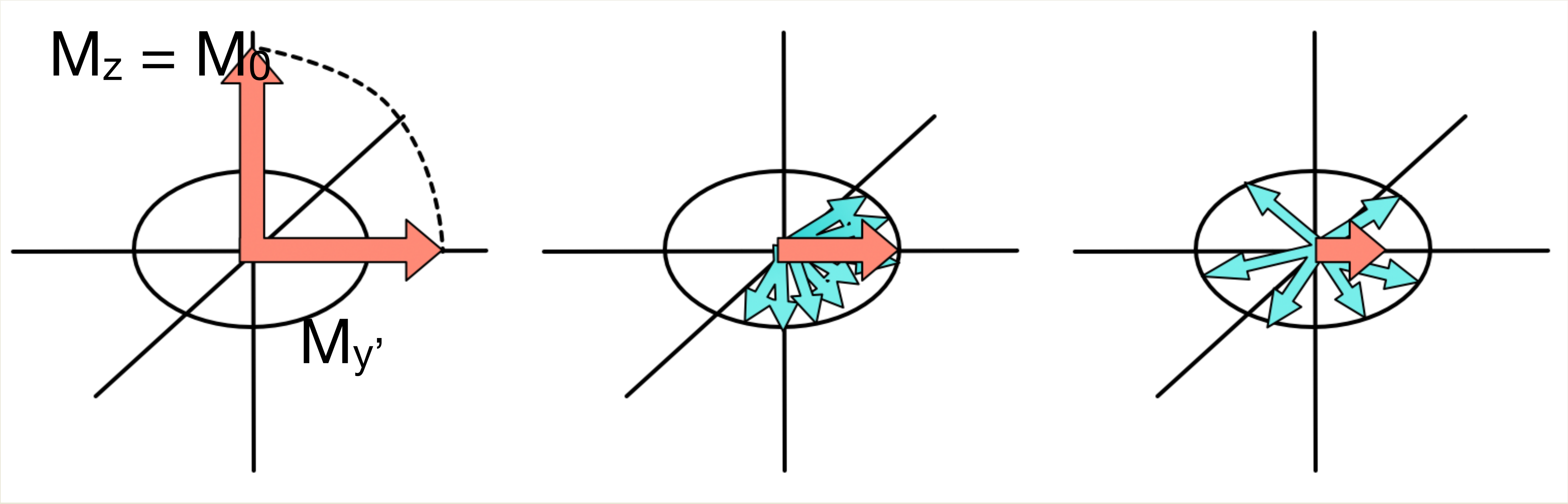

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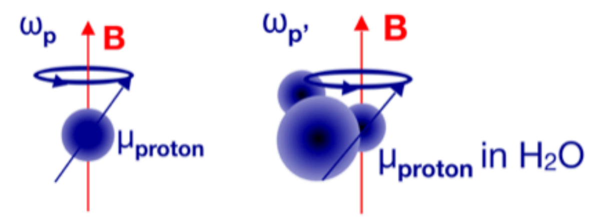
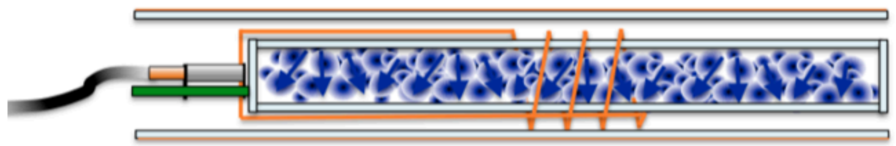
D. Flay

Run 1 Analysis Status: ω_p — Field Calibration

- In the experiment, need to extract ω_p; however, don't have free protons
  - Need a calibration
- Field at the proton differs from the applied field





$$\omega_p^{\mathrm{meas}} = \omega_p^{\mathrm{free}}\left[1 - \sigma\left(\mathrm{H_2O}, T\right) - \left(\varepsilon - \frac{4\pi}{3}\right)\chi\left(\mathrm{H_2O}, T\right) - \delta_m\right]$$

Protons in H_2O molecules, diamagnetism of electrons screens protons => local B changes

- **Known to 2.5 ppb**

Magnetic susceptibility of water gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (sphere), 2π (cylinder) when probe is perpendicular to B
- **Known to 5 ppb**

Magnetization of probe materials perturbs the field at site of protons

- **Measured to 6.5 ppb**

Goal: Determine total correction to ≤ 35 ppb accuracy

These are **static** corrections; need to worry about **dynamic** ones too (radiation damping, RF coil inhomogeneity, time dependence of gradients, …)

Run 1 Analysis Status: ω_p — Field Calibration

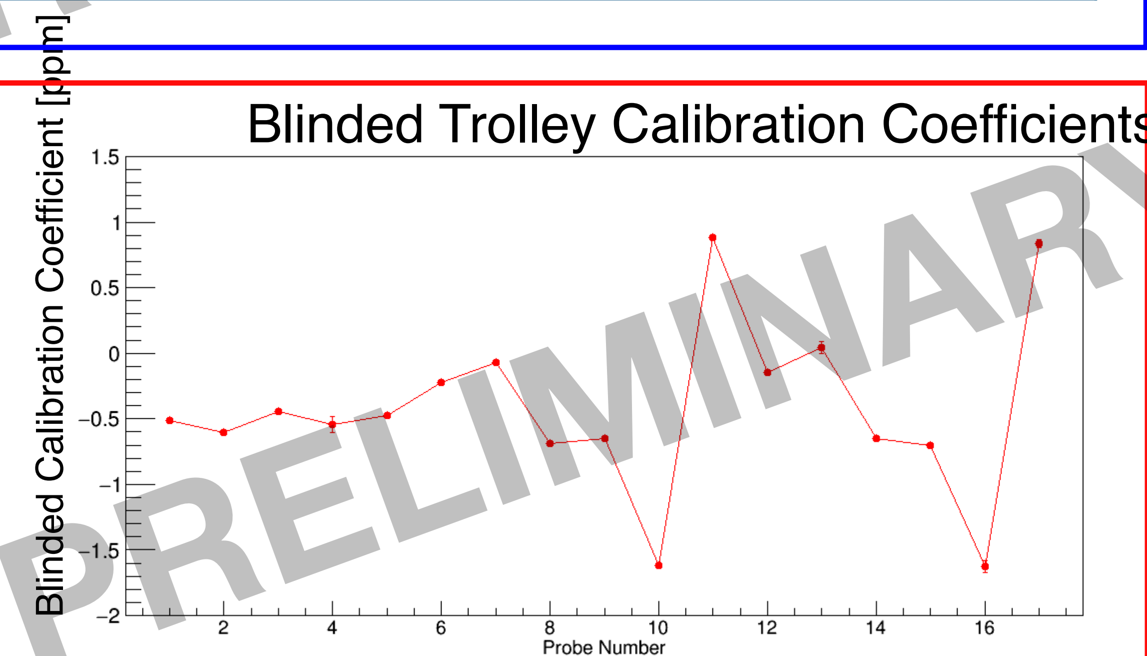
Plunging Probe

- Achieved **small perturbation of plunging probe** ~ (-5.0 ± 6.5) ppb
- Quantified uncertainties on plunging probe material, dynamic effects — **under budget of 35 ppb**

Plunging Probe Uncertainties	
Effect	**Uncertainty**
Probe Perturbation to Field (includes	6.5
Radiation Damping	20
Proton Dipolar Field	2
Oxygen Contamination of Water	< 1
TOTAL	**21**

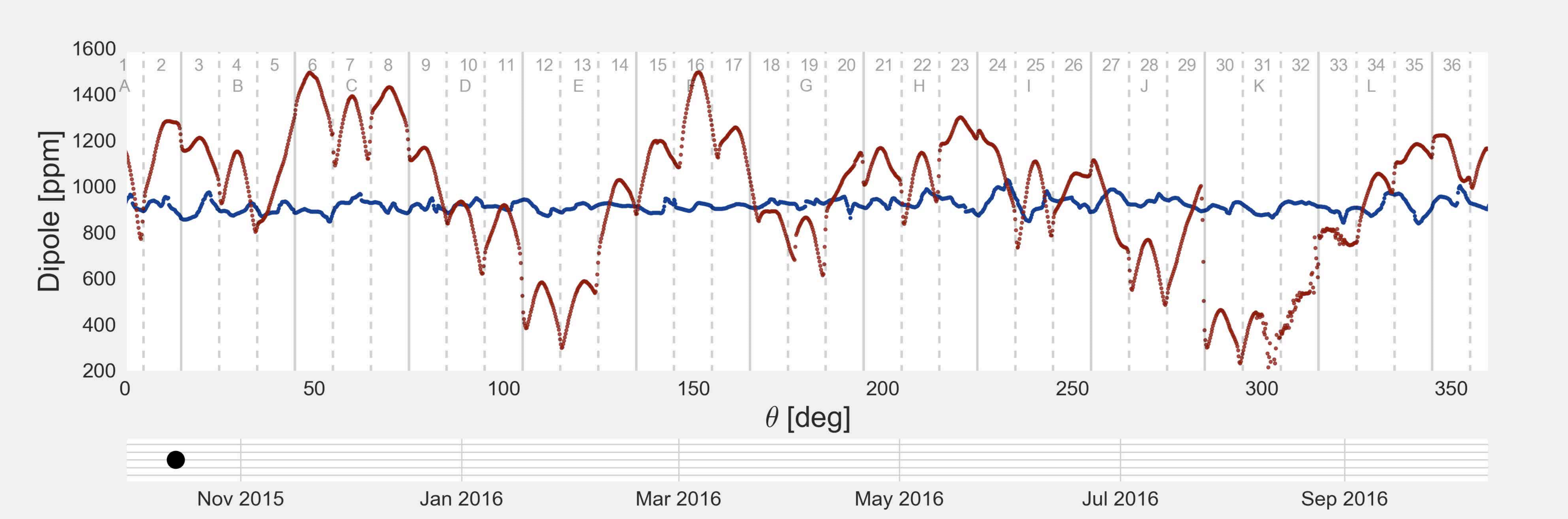
Trolley Calibration

- **Calibration of trolley probes under control**
- Factor of ≥ 2 improvement on uncertainties for nearly all probes compared to E821
- Uncertainty is ~ 26 ppb on average per probe — **under budget of 30 ppb**



Magnetic field uniformity

- Shimming 1.45 T field



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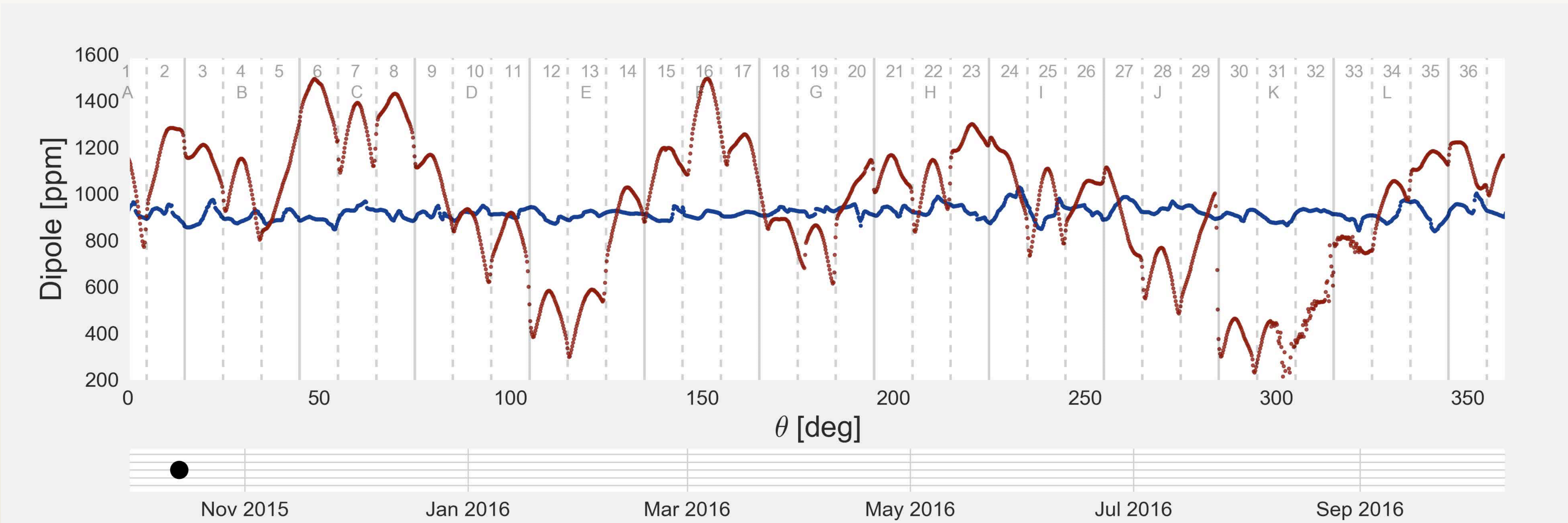
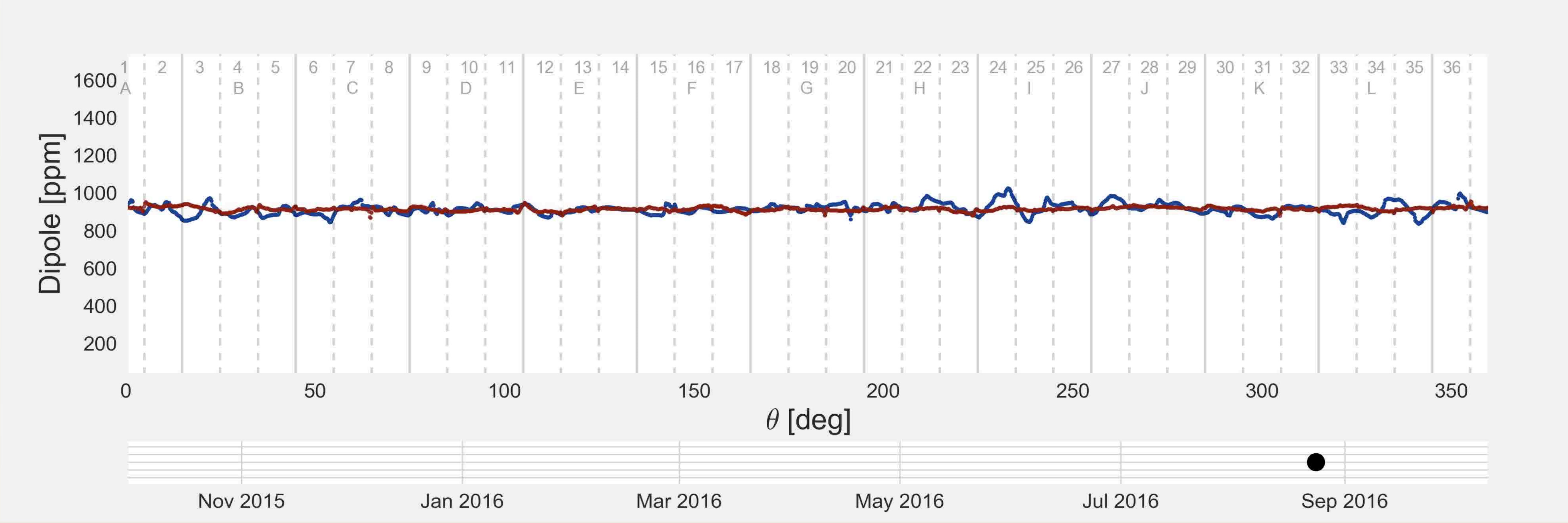
Magnetic field uniformity

- Shimming 1.45 T field



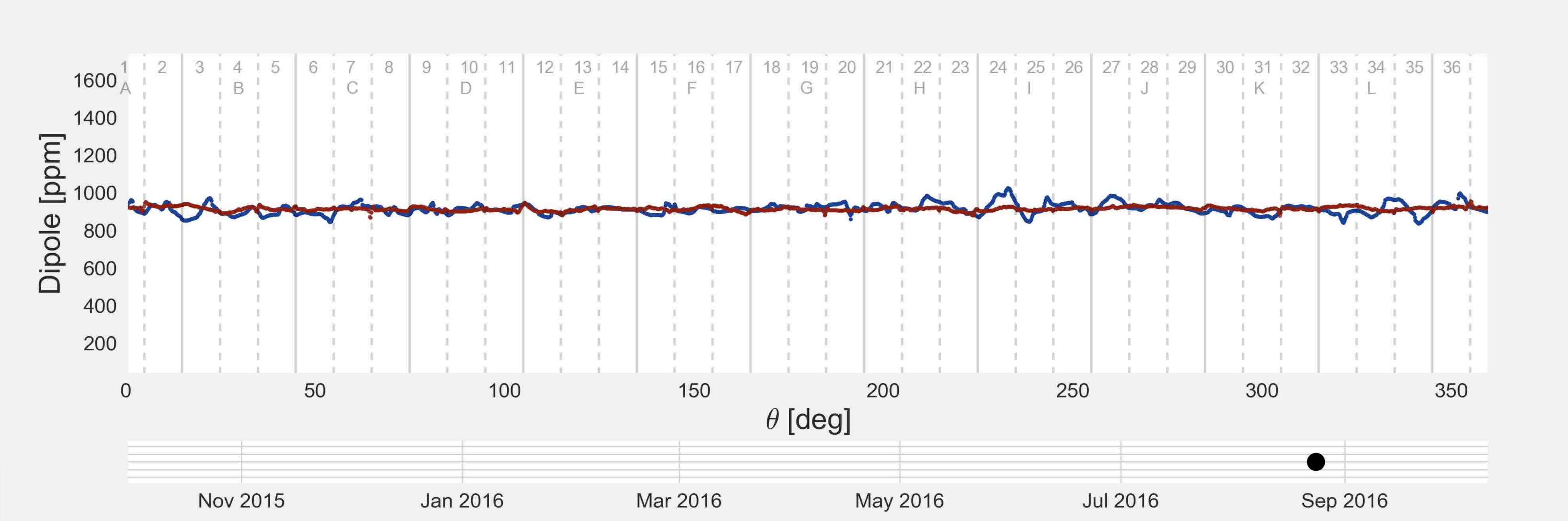
Magnetic field uniformity

- Shimming 1.45 T field



Magnetic field uniformity

- Shimming 1.45 T field



Magnetic field uniformity

- Shimming 1.45 T field