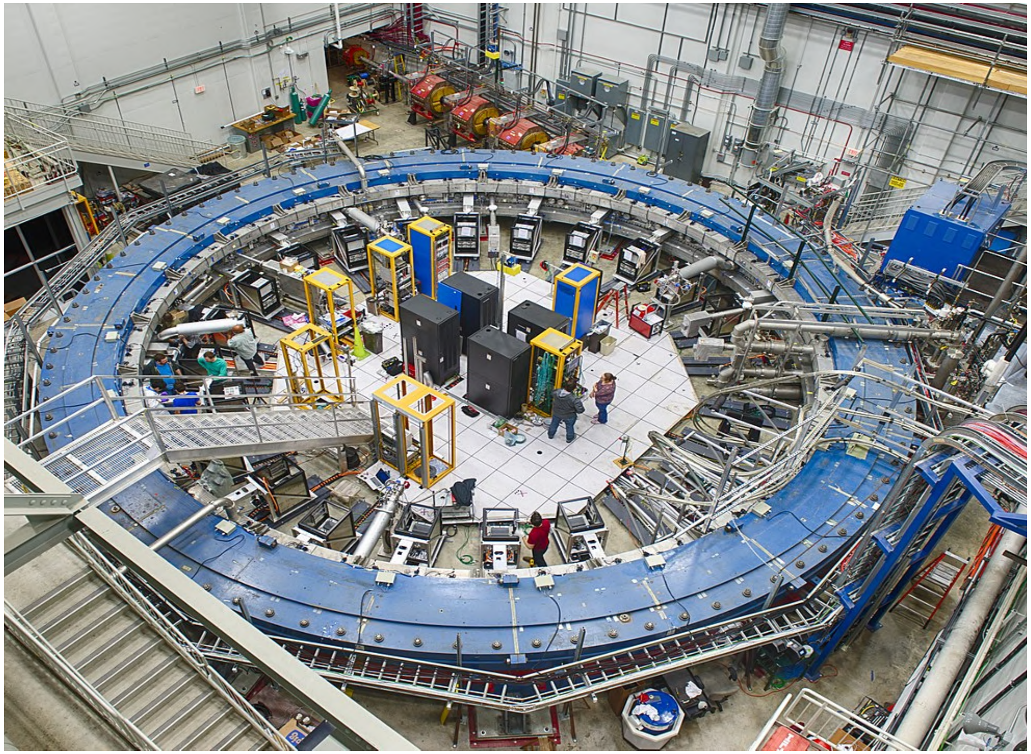
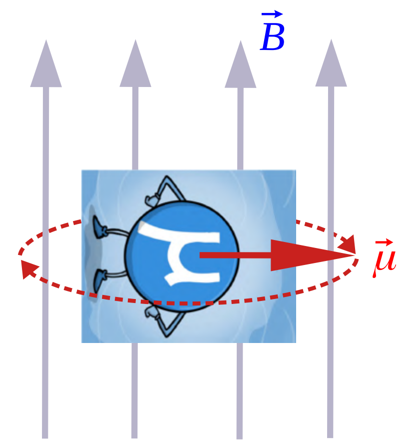


# Status of the Muon g-2 experiment

International Conference on Exotic Atoms and Related Topics
**EXA 2021**
September 14th 2021

**Paolo Girotti -** University of Pisa

# The experimental principle




$$\vec{\mu} = g\frac{q}{2m}\vec{S}$$

Spin precession frequency

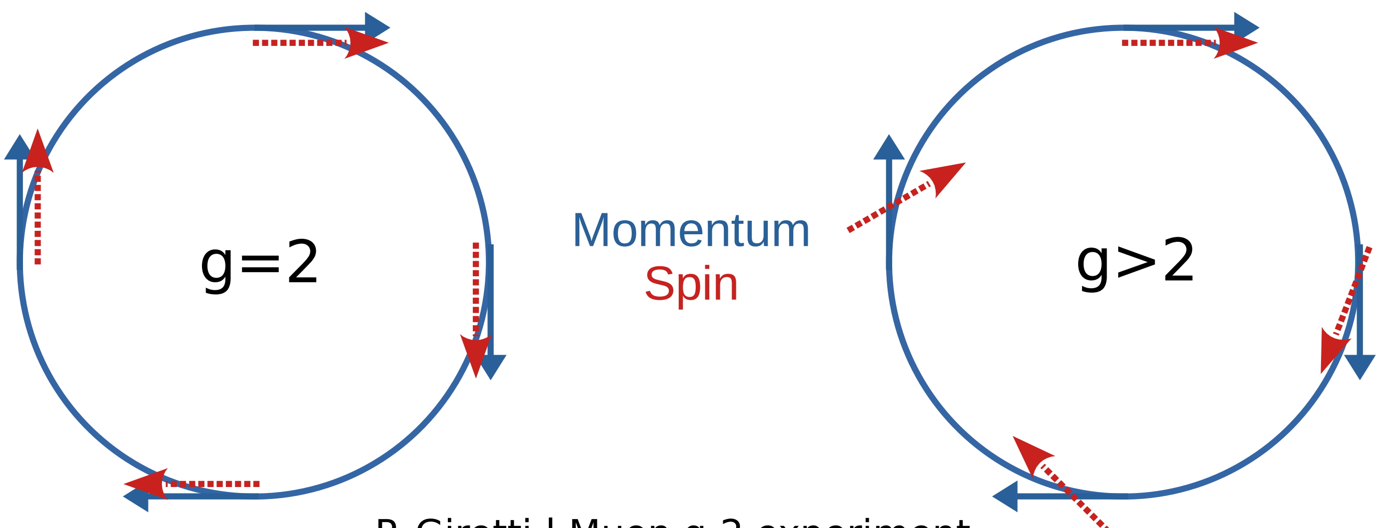
$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$$

Cyclotron frequency

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

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -a_\mu \frac{e\vec{B}}{m}$$

The muon interactions with the vacuum manifest with a difference between the spin and the momentum frequencies



# Added complexity

- Muons are naturally focused horizontally
- Vertical focusing provided by **electrostatic quadrupoles**
  - Effect on $\omega_a$ minimized by using *magic* momentum of 3.094 GeV/c
- **The beam oscillates and breathes** both horizontally and vertically
  - Beam dynamics analysis and pitch correction address these effects

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

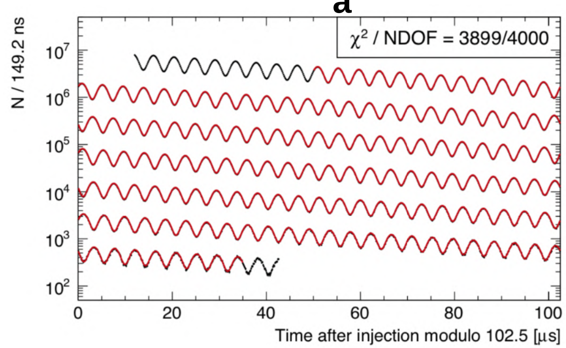
$\gamma \sim 29.3$

# Final formula

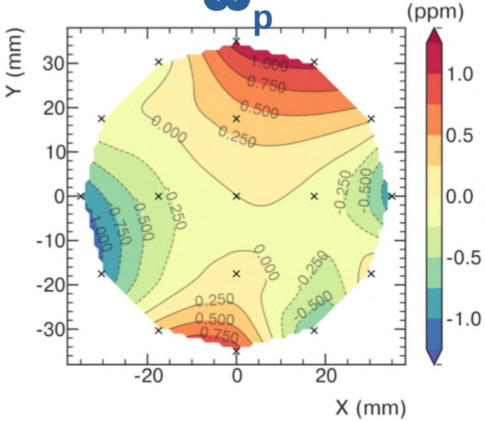
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

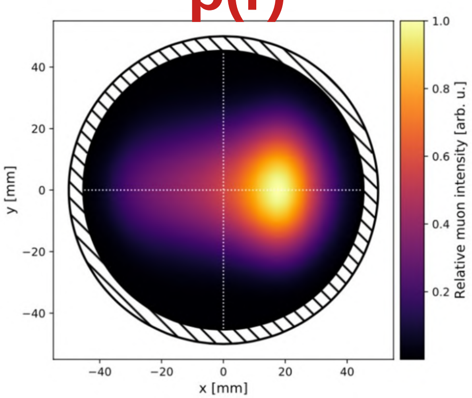
→ Constants known with high precision

**$\omega_a$**




**$\omega_p$** ⊗ **$\rho(r)$**




- **$\omega_a$**: Muon anomalous precession frequency
- **$\omega_p$**: Larmor precession frequency of protons in water (mapping B)
- **$\rho_r$**: Muon distribution in the storage ring

**Goal: measure $a_\mu$ with 140 ppb accuracy (100 stat + 100 syst)**

# How to measure g-2

Key ingredients:

- A beam of polarized muons
- A magnet to store the beam
- A way to measure the muon spin, the magnetic field and the beam through time

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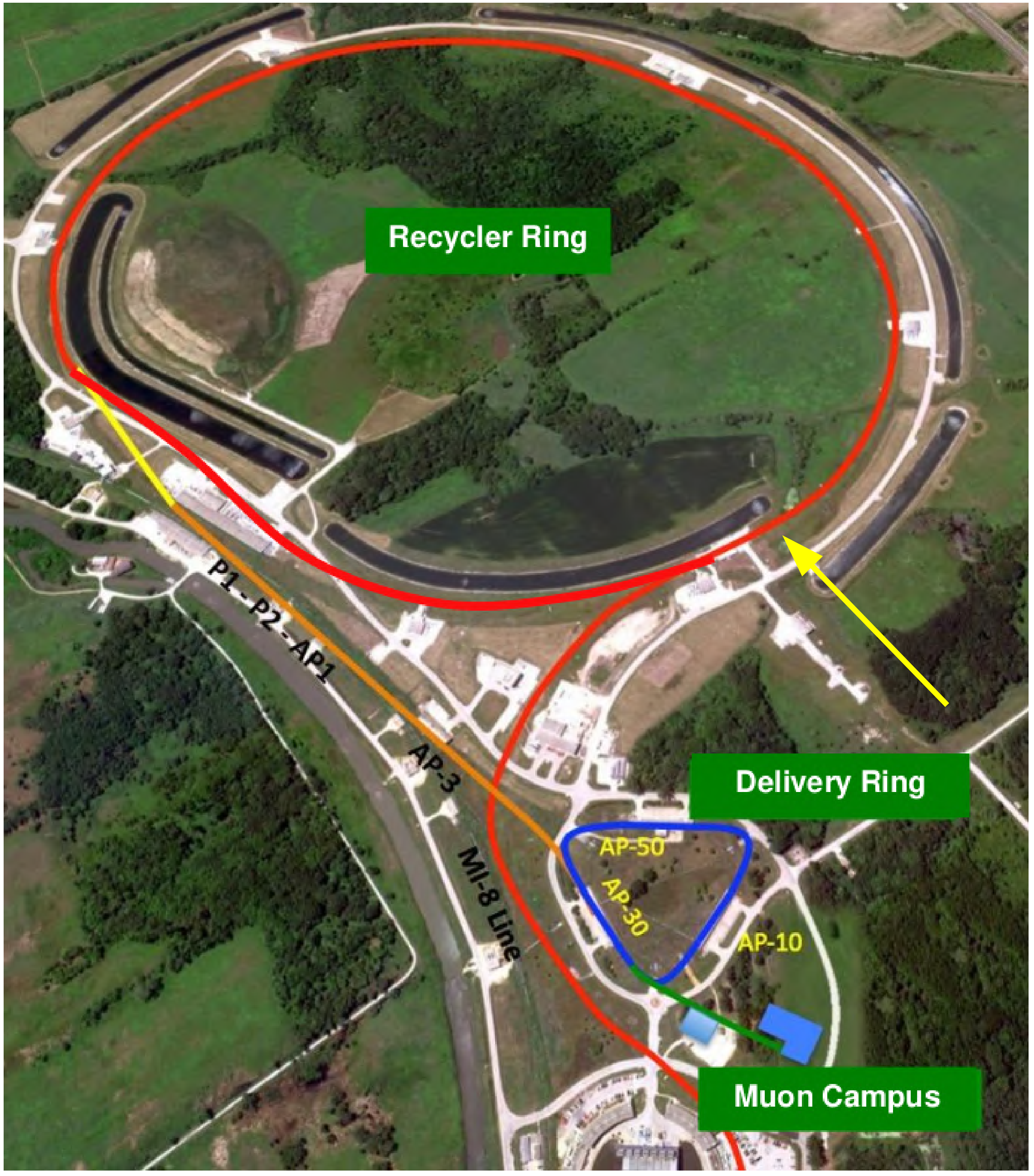
# The beam

$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

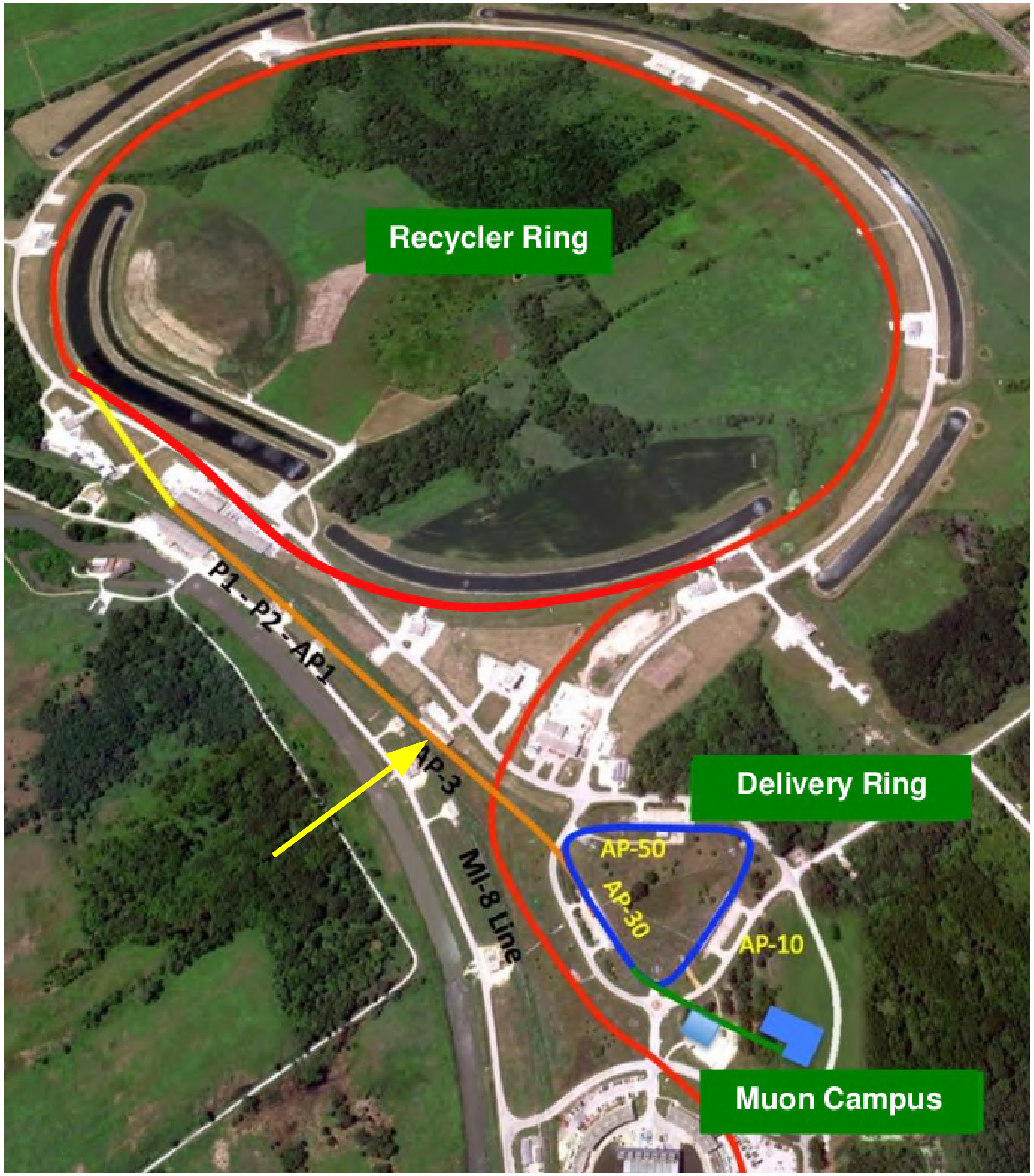
- 16 bunches of $10^{12}$ protons @8 GeV get boosted and handled by the recycler ring



# The beam

$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

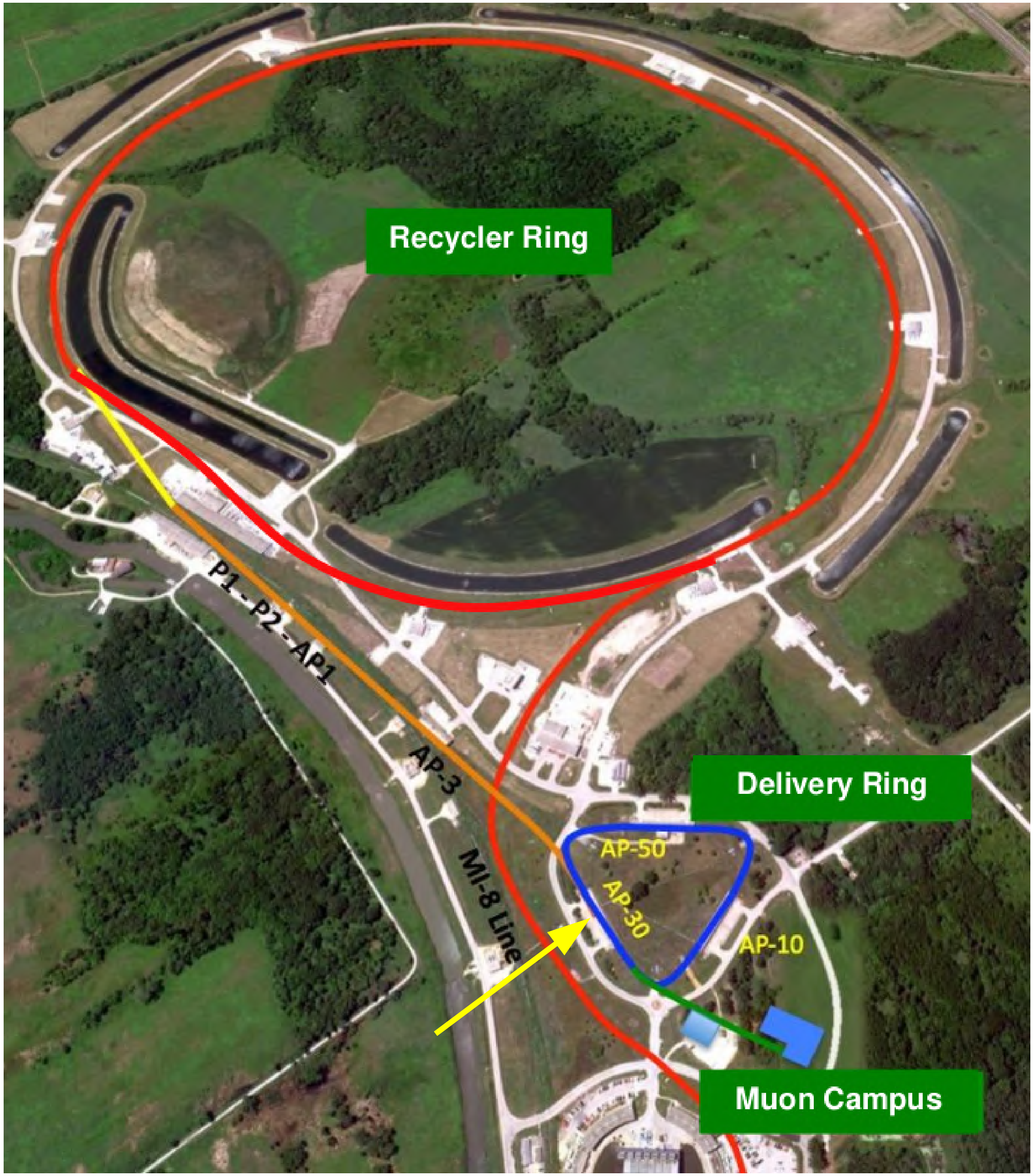
- 16 bunches of $10^{12}$ protons @8 GeV get boosted and handled by the recycler ring
- Each bunch hits a fixed Inconel 600 target



# The beam

$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

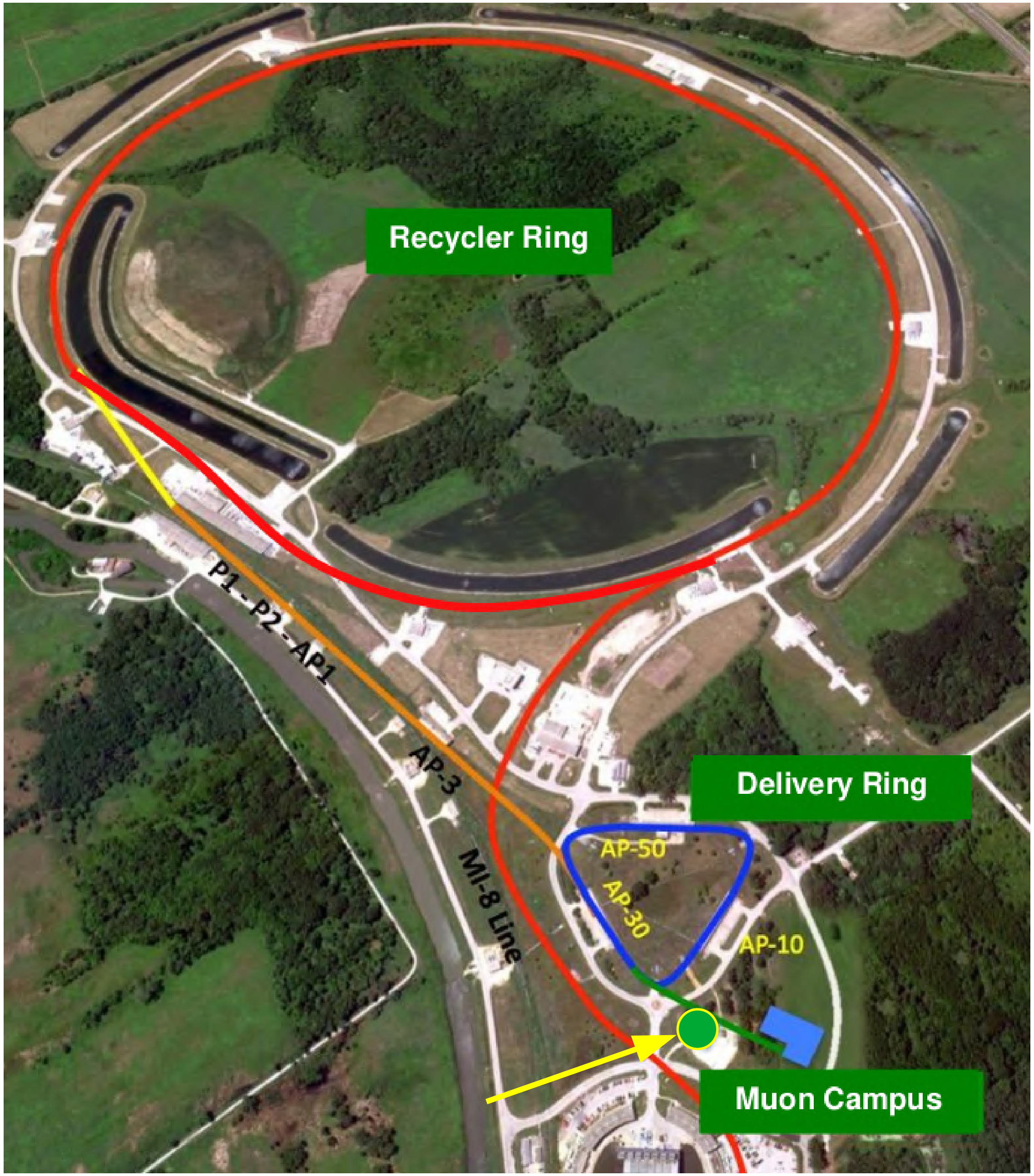
- 16 bunches of $10^{12}$ protons @8 GeV get boosted and handled by the recycler ring
- Each bunch hits a fixed Inconel 600 target
- Pions from shower extracted and decay in delivery ring



# The beam

$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

- 16 bunches of $10^{12}$ protons @8 GeV get boosted and handled by the recycler ring
- Each bunch hits a fixed Inconel 600 target
- Pions from shower extracted and decay in delivery ring
- Muons enter g-2 ring



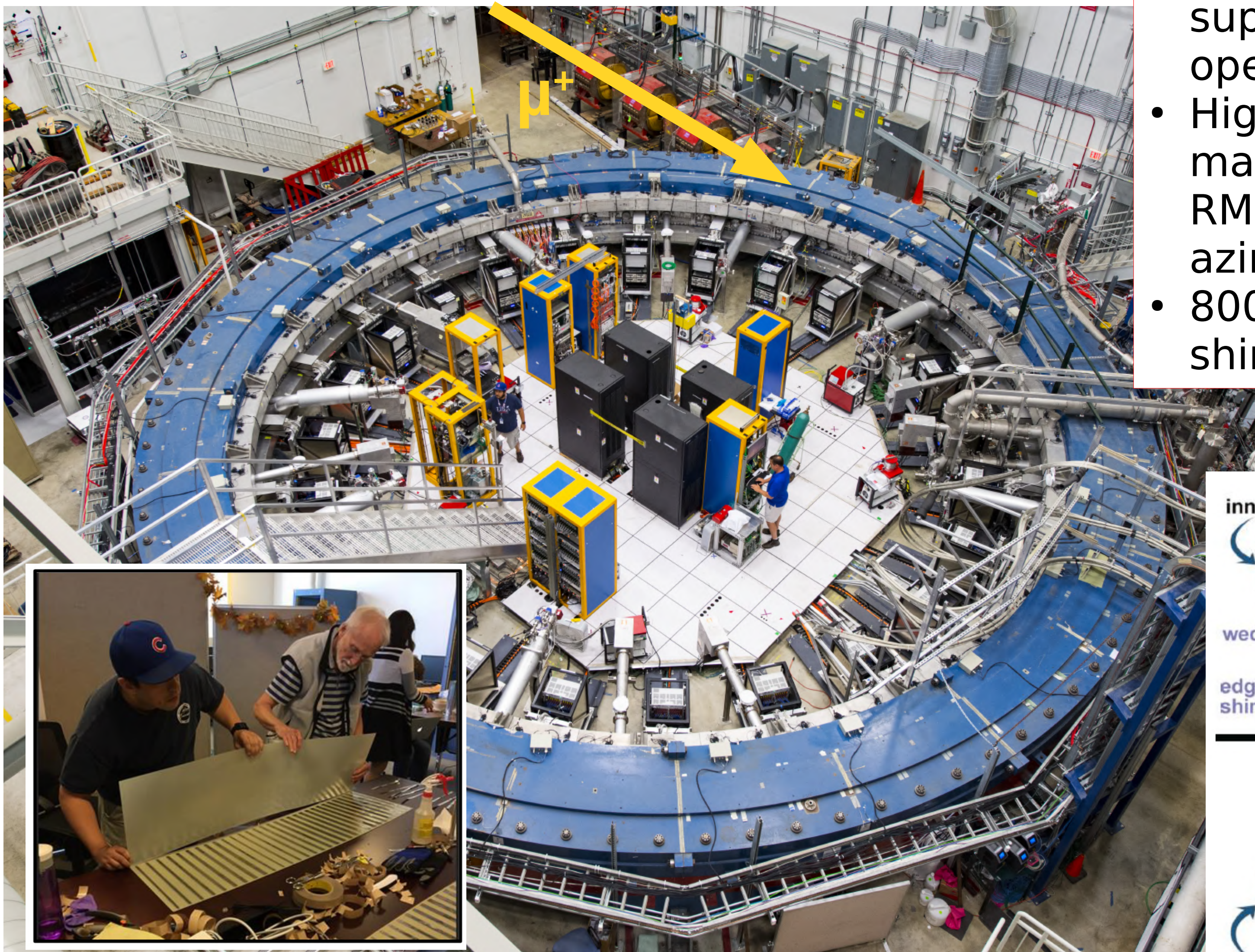
# How to measure g-2

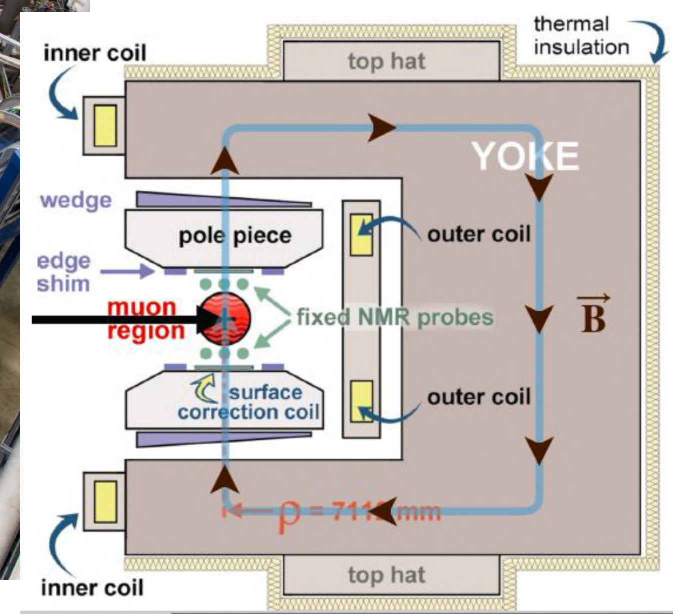
Key ingredients:

- A beam of polarized muons
- **A magnet to store the beam**
- A way to measure the muon spin, the magnetic field and the beam through time

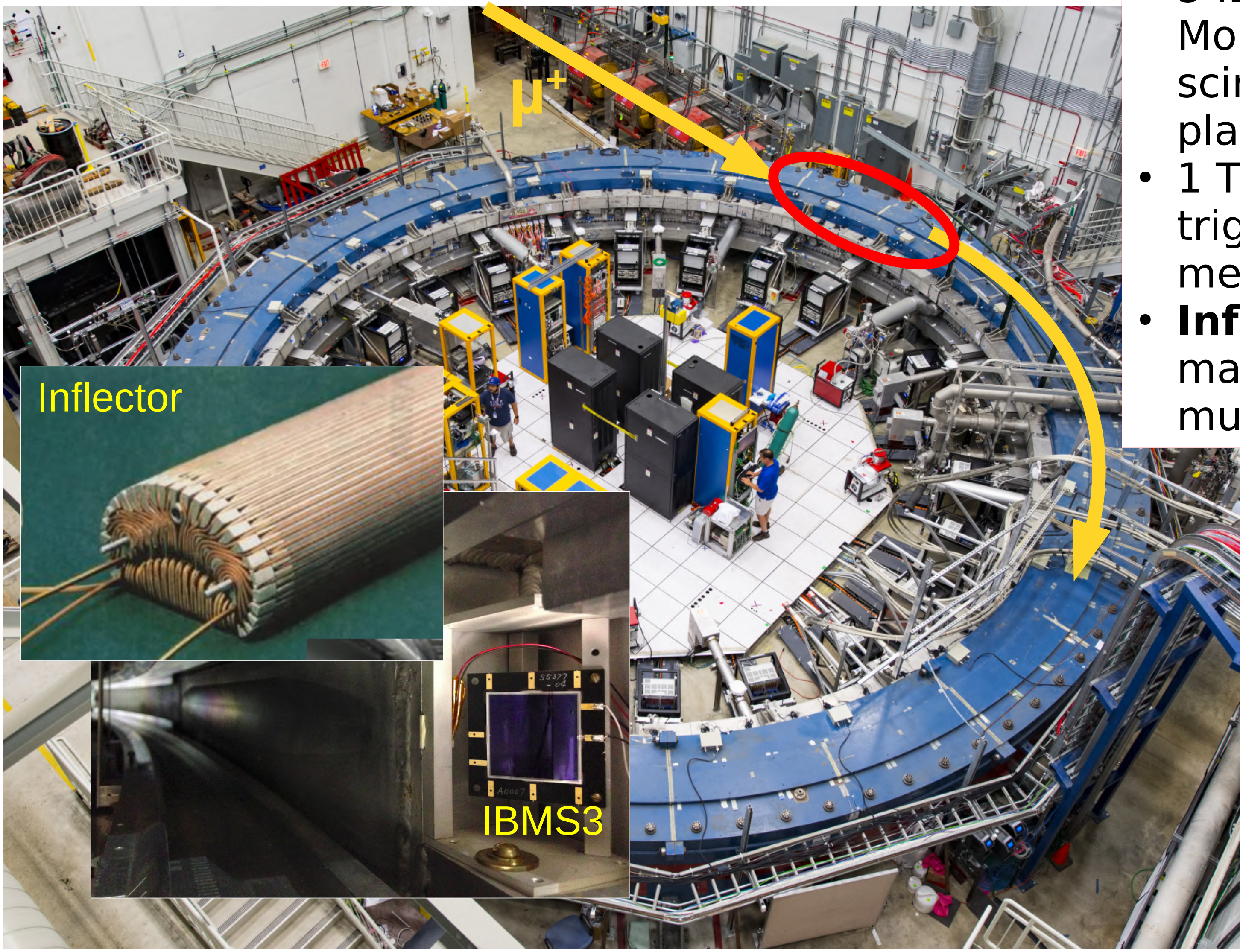
# Magnet

- 7.112 m radius C-shaped superconducting magnet operating at ~5 K
- Highly **uniform 1.45 T** magnetic field (14 ppm RMS across the full azimuth)
- 8000 iron foils for precise shimming

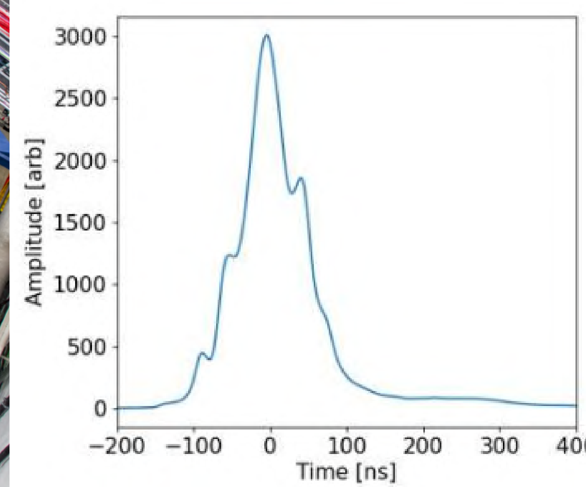


# Beam injection

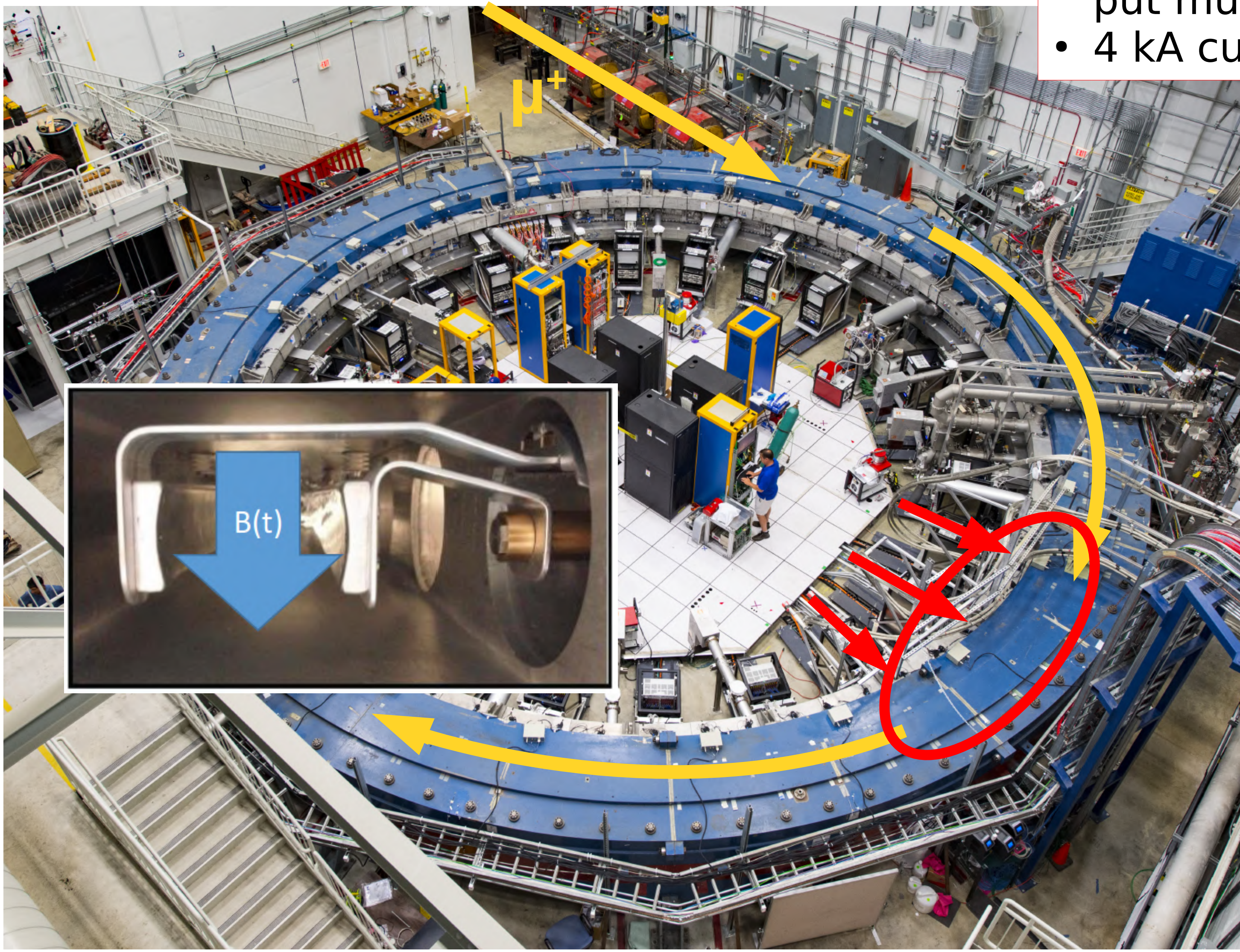


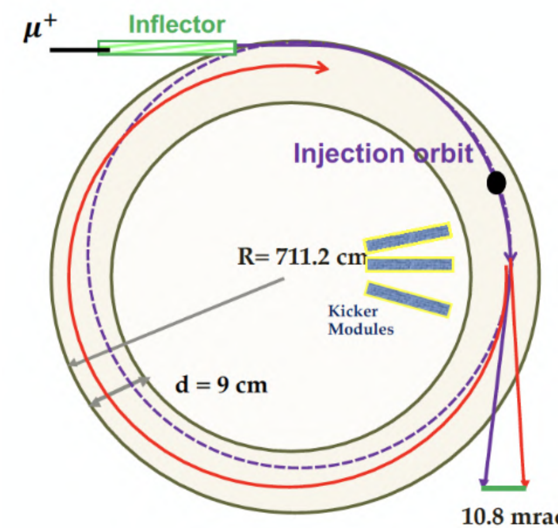

- 3 IBMS (Inflector Beam Monitor System) with scintillating X and Y fiber planes
- 1 T0 detector for triggering and time profile measurement
- **Inflector** to cancel the magnetic field so that muons can enter the ring

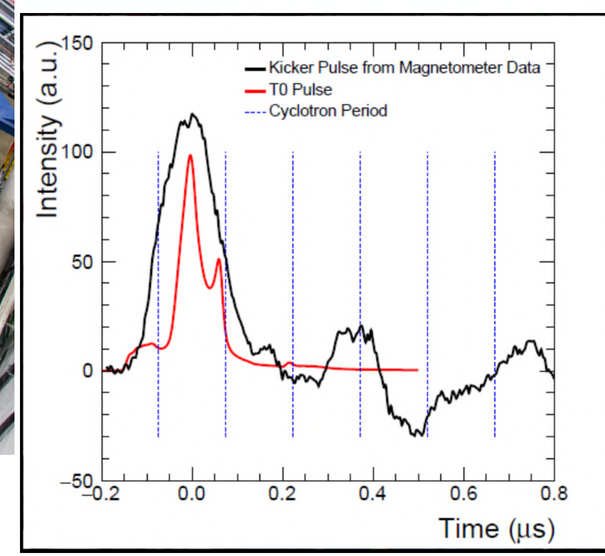


# Kicker

- 3 **fast magnetic kickers** to put muons in the correct orbit
- 4 kA current in 200 ns pulse

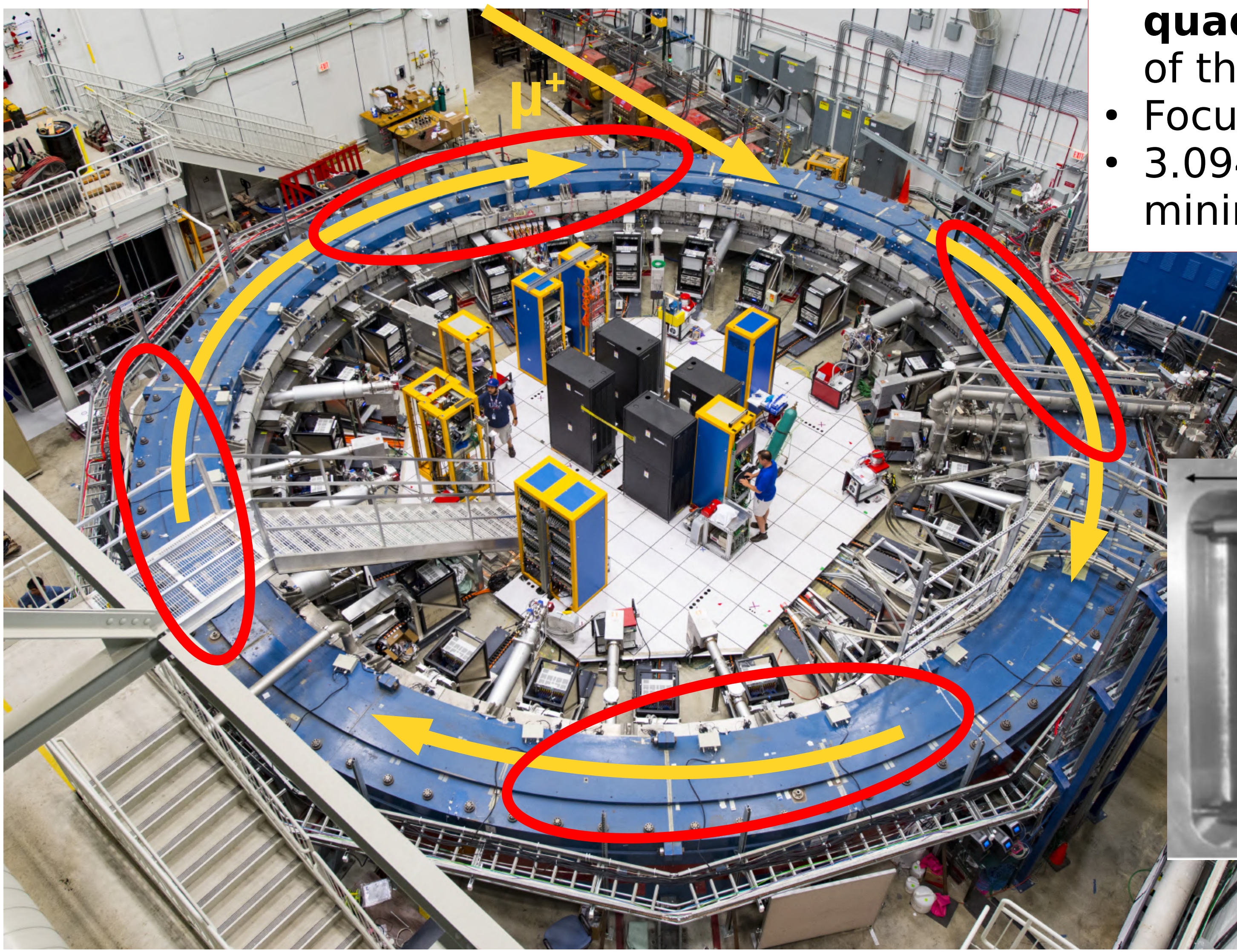


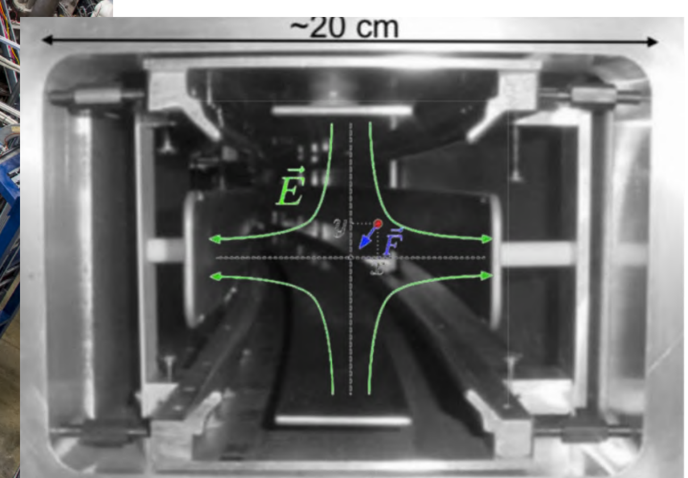



# Quadrupoles

- 8 aluminium **electrostatic quadrupoles** cover ~40% of the circumference
- Focus the beam vertically
- 3.094 GeV/c momentum minimizes the effect on $a_\mu$



# How to measure g-2

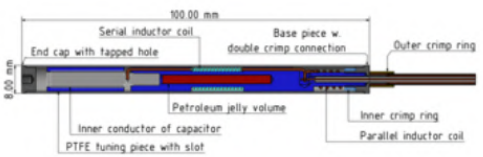
Key ingredients:

- A beam of polarized muons
- A magnet to store the beam
- **A way to measure the muon spin, the magnetic field and the beam through time**

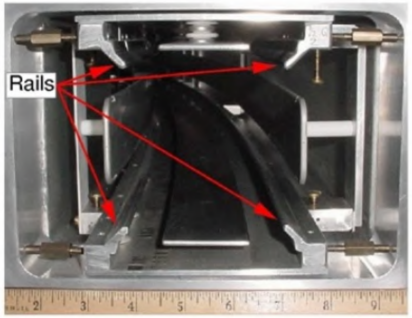
# Measuring the field

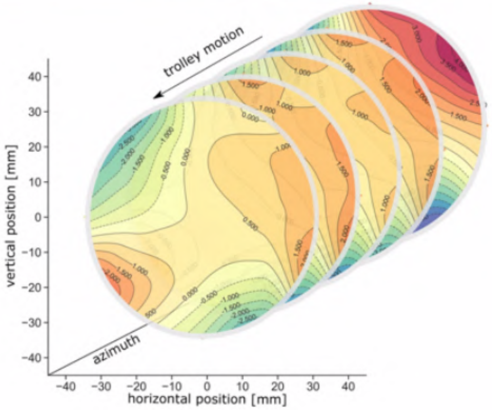
- Need to determine **B at < 100 ppb** to determine $a_\mu$
  - Use NMR to assess B-field in terms of proton precession frequency $\omega_p$

378 fixed probes continuous monitoring

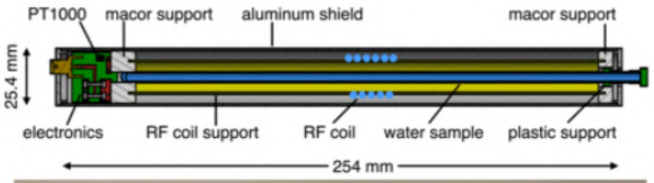


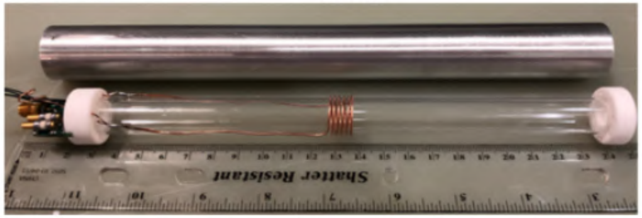

17 probes on a trolley to 3D map every ~3 days



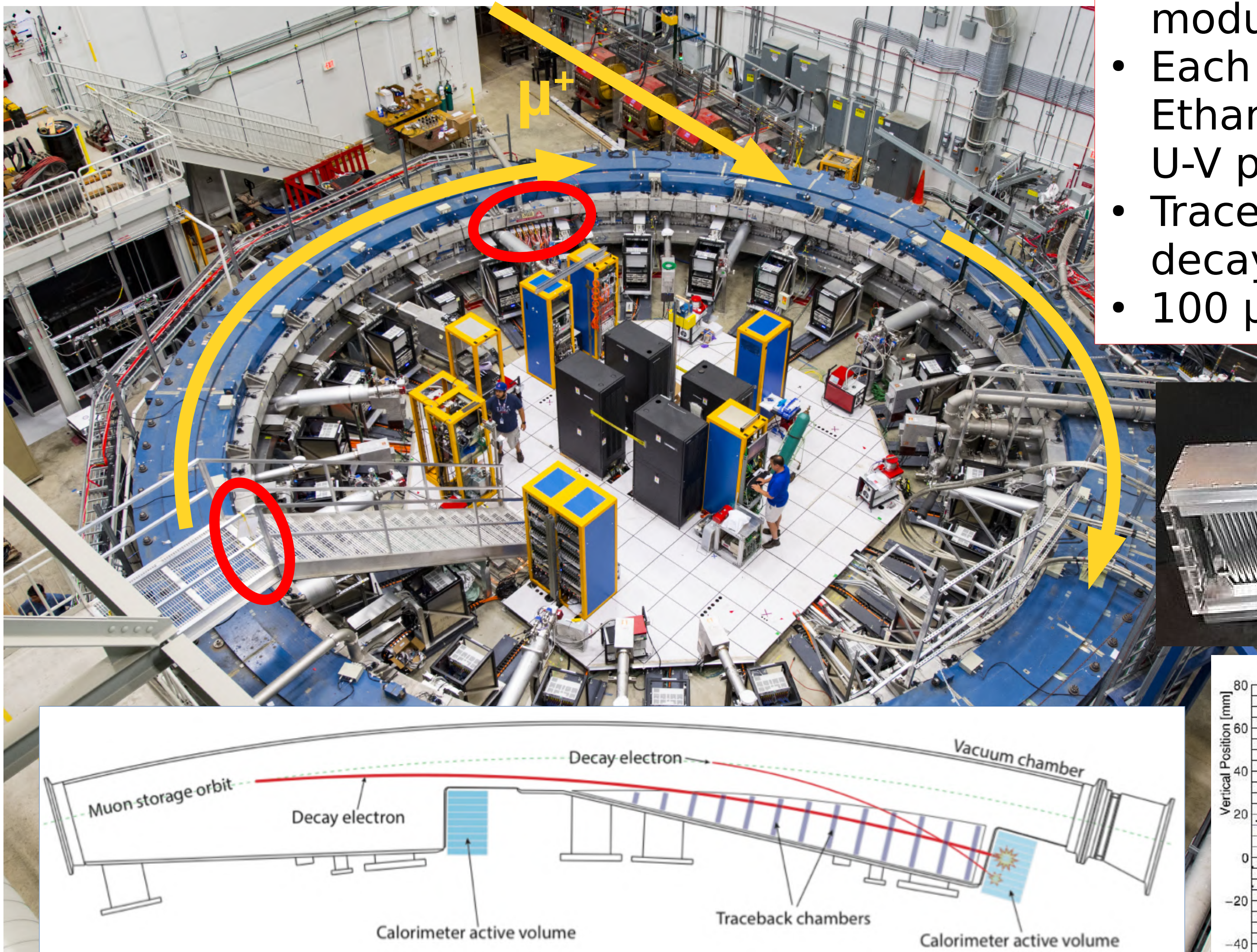

Trolley cross-calibrated to absolute probes

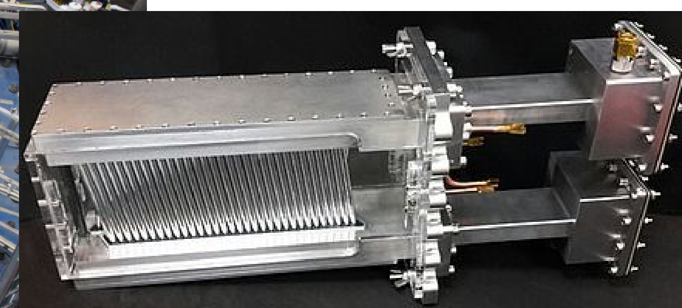


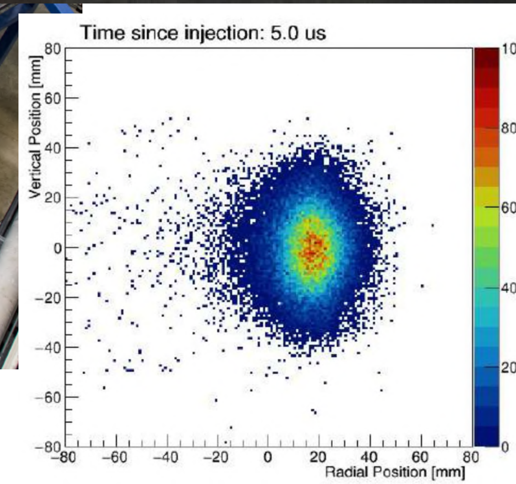



# Measuring the beam

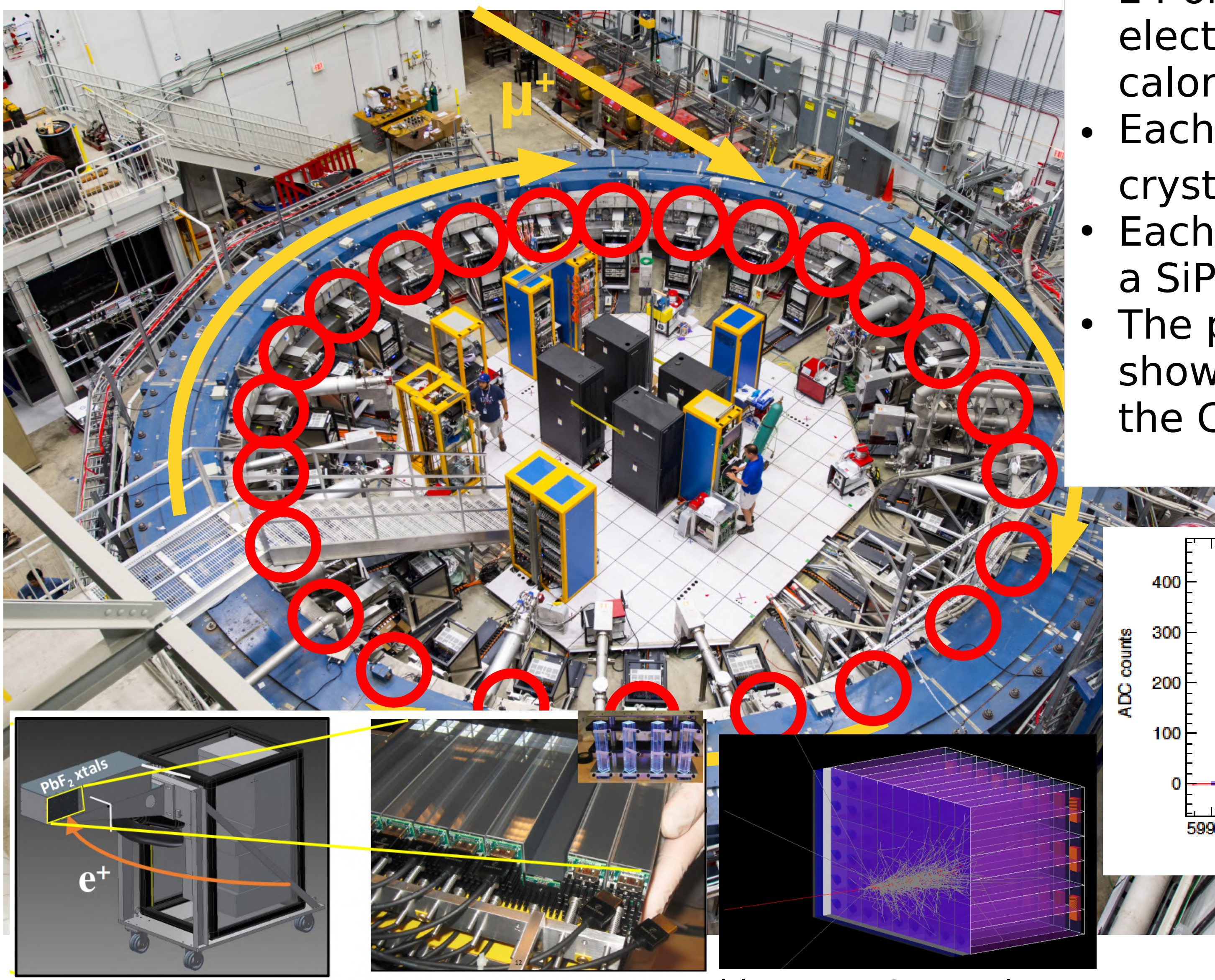
- 2 tracker stations with 8 modules each
- Each module has 128 Argon-Ethane filled straw tube in a U-V plane configuration
- Traceback positrons to their decay point
- 100 μm hit resolution



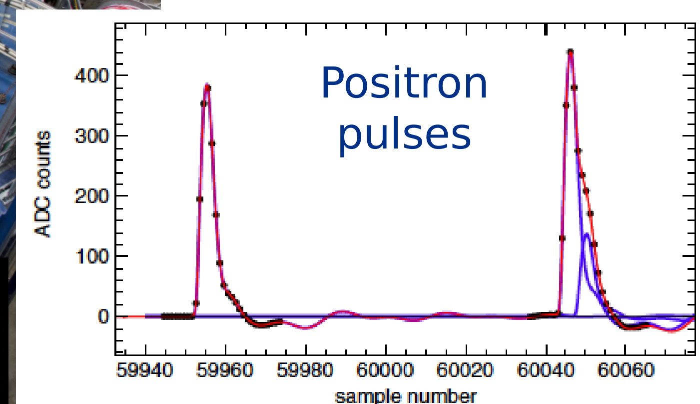





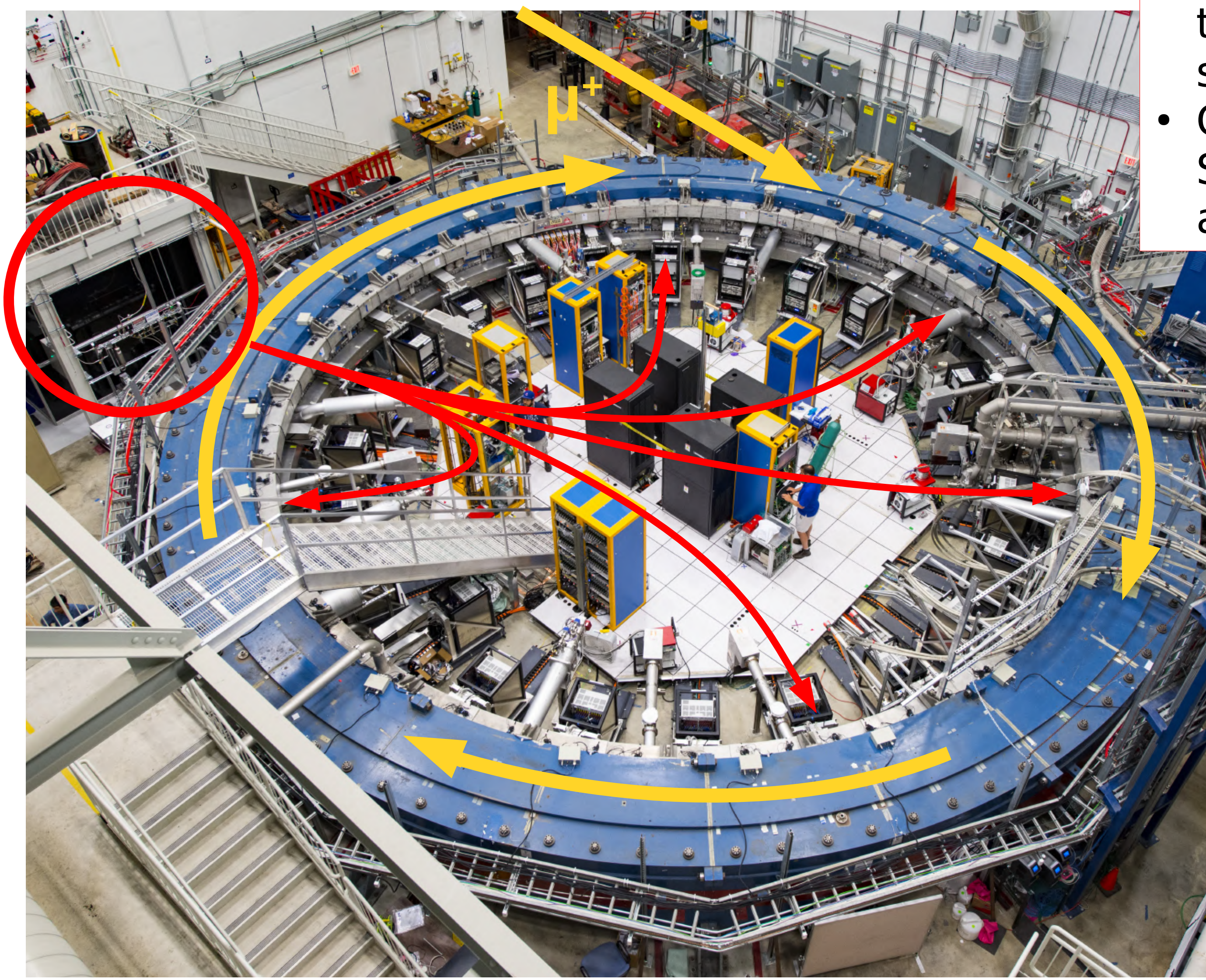
# Measuring the positrons



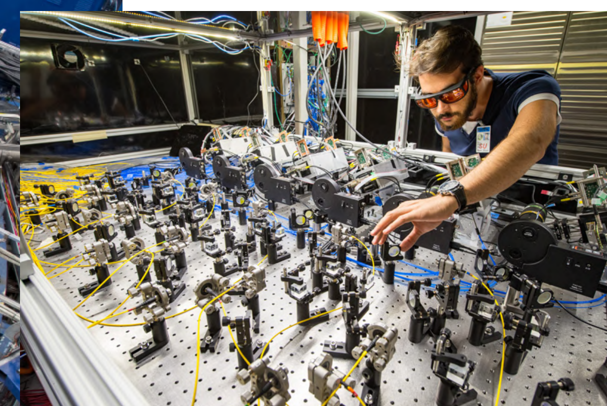

- 24 omogeneous electromagnetic calorimeters along the ring
- Each is a 9 x 6 array of $PbF_2$ crystals 2.5 x 2.5 x 14 cm
- Each crystal is coupled with a SiPM digitized at 800 MHz
- The positrons produce an EM shower and the SiPMs collect the Cherenkov light

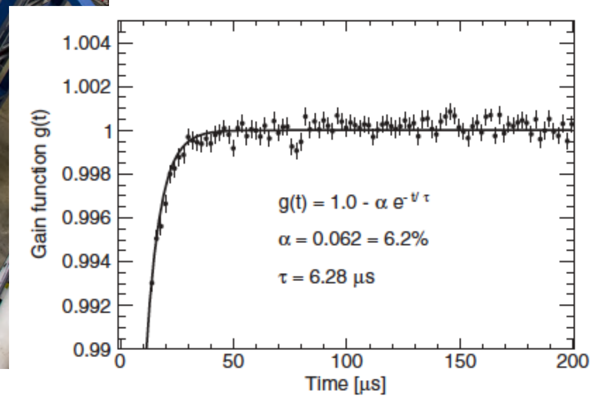


# Laser Calibration System



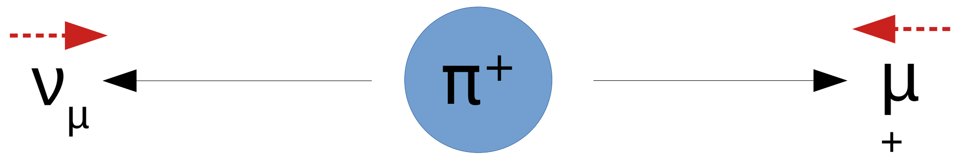

- Very stable laser system to calibrate and synchronize the detectors
- Gain calibration of the SiPMs at the $10^{-4}$ level at all timescales



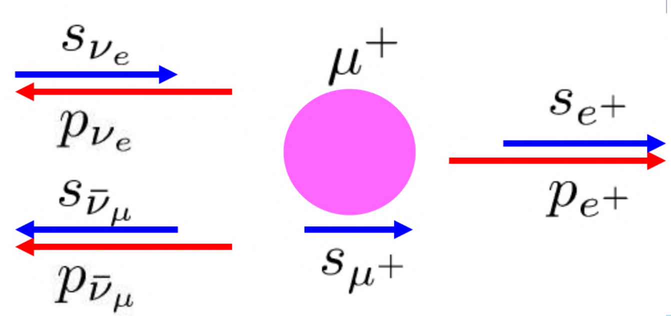


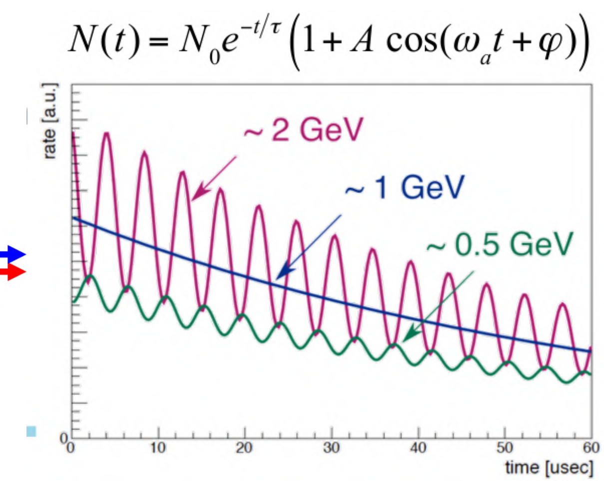
# Two gifts from nature

- Pions have no spin and decay in a muon and a neutrino
  - Parity violation dictates that the muon has left elicity
  - Since beam is boosted, higher energy muons are **highly polarized** (~97%)




- Muon decays in a positron and two neutrinos
- Parity violation dictates that high energy positrons are emitted preferably in the direction of muon spin
- The decay **asymmetry** is observed as an oscillation of the positron count over time



# The final formula

Muon loss & phase-acceptance corrections

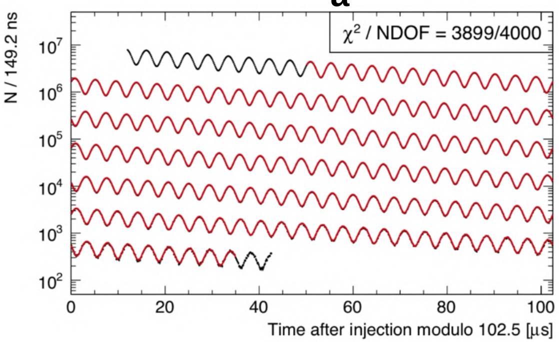
E-field & pitch corrections

Blinding

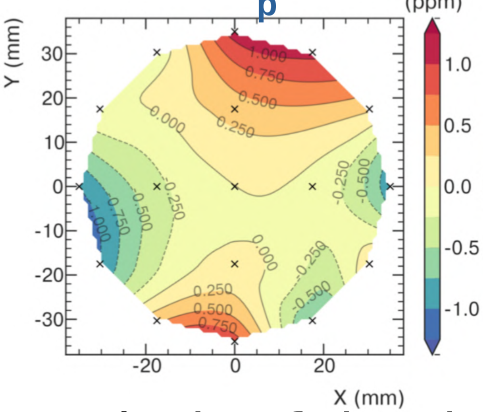
$$\frac{\omega_a}{\tilde{\omega}_p} = \left( \frac{f_{clock}\,\omega_a\,(1 + C_e + C_p + C_{ml} + C_{pa})}{(1 + B_q + B_k)\; f_{field}\,\omega_p \otimes \rho(\mathbf{r})} \right) =$$

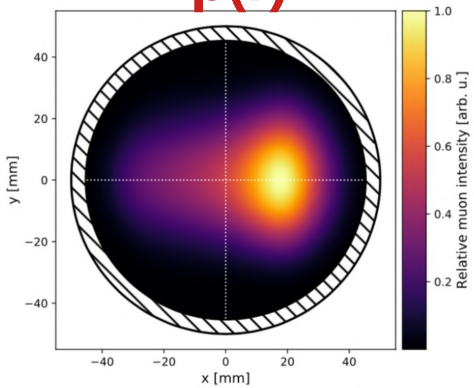
Field transients    Field calibration

$\omega_a$




$\omega_p$ ⊗ $\rho(r)$




- 2.5 years of complex and extensive analysis of the data since the acquisition to the public release
- Two new effects from the field transients and the phase-acceptance discovered and calculated
- Systematics calculated with excruciating detail to the **ppb level**

# 2.5 years of analysis

| | |
|---|---|
| run-1 (substructure) | 77.4 ppb |
| azimuthal shape* | 7.6 ppb |
| skin depth | 12.6 ppb |
| frequency extraction (0.4/1ms) | 4.6 ppb |
| Q3L: fit, position | 1.5 ppb |
| repeatability | 13.3 ppb |
| drift | 10.2 ppb |
| radial dependency | 4.4 ppb |
| $2^{nd}$ 8-pulses | 14.0 ppb |
| **total** −15.0 ppb | 81.7 ppb |

| PROBE | Calibration Coefficients Value (Hz) | Stat (Hz) | Syst (Hz) |
|---|---|---|---|
| 1 | 90.81 | 0.38 | 2.02 |
| 2 | 84.21 | 0.65 | 1.18 |
| 3 | 95.02 | 0.53 | 2.19 |
| 4 | 86.03 | 0.25 | 1.28 |
| 5 | 92.96 | 0.51 | 1.10 |
| 6 | 106.24 | 0.46 | 1.35 |
| 7 | 116.64 | 0.96 | 1.61 |
| 8 | 76.39 | 0.60 | 1.21 |
| 9 | 83.52 | 0.23 | 1.64 |
| 10 | 24.06 | 1.39 | 1.26 |
| 11 | 177.55 | 0.22 | 1.99 |
| 12 | 110.85 | 0.44 | 1.73 |
| 13 | 122.89 | 2.08 | 1.93 |
| 14 | 77.11 | 0.53 | 1.88 |
| 15 | 74.82 | 1.06 | 1.59 |
| 16 | 20.35 | 0.44 | 2.94 |
| 17 | 172.12 | 1.23 | 1.96 |
| AVG | | 0.70 | 1.70 |

| Source | Uncertainty |
|---|---|
| Frequency Standard | 1 ppt |
| Frequency Synthesizers | 0.1 ppb |
| Digitization Frequency | 2 ppb |
| Total Systematic | 2 ppb |

$f_{clock}$

| $R(\omega_a)$ with detailed systematics categories [ppb] | | | | |
|---|---|---|---|---|
| Total systematic uncertainty | 65.2 | 70.5 | 54.0 | 48.8 |
| Time randomization | 14.8 | 11.7 | 9.2 | 6.9 |
| Time correction | 3.9 | 1.2 | 1.1 | 1.0 |
| Gain | 12.4 | 9.4 | 8.9 | 4.8 |
| Pileup | 39.1 | 41.7 | 35.2 | 30.9 |
| Pileup artificial dead time | 3.0 | 3.0 | 3.0 | 3.0 |
| Muon loss | 2.2 | 1.9 | 5.2 | 2.4 |
| CBO | 42.0 | 49.5 | 31.5 | 35.2 |
| Ad-hoc correction | 21.1 | 21.1 | 22.1 | 10.3 |

$\omega_a$

| | 1a | 1b | 1c | 1d |
|---|---|---|---|---|
| $C_e$ (ppb) | 471 | 464 | 534 | 475 |
| Statistical uncertainty | 0.4 | 0.5 | 0.4 | 0.2 |
| Fourier method | 8.4 | 13.4 | 14.4 | 3.9 |
| Momentum-time correlation | 52 | 52 | 52 | 52 |
| Quad alignment/voltage | 6.4 | 6.4 | 6.4 | 6.4 |
| Field index | 1.7 | 1.5 | 1.7 | 4.0 |
| Systematic uncertainty | 53 | 54 | 54 | 53 |

$C_e$

| | 1a | 1b | 1c | 1d |
|---|---|---|---|---|
| $C_p$ (ppb) | 176 | 199 | 191 | 166 |
| Statistical uncertainty | <0.1 | <0.1 | <0.1 | <0.1 |
| Tracker alignment/reco. | 11.0 | 12.3 | 12.0 | 10.7 |
| Tracker res. & acc. removal | 3.3 | 3.9 | 3.7 | 3.0 |
| Azimuthal avg. & calo. acc. | 1.0 | 1.3 | 2.2 | 1.1 |
| Amplitude fit | 1.2 | 0.4 | 1.0 | 2.9 |
| Quad alignment/voltage | 4.4 | 4.4 | 4.4 | 4.4 |
| Systematic uncertainty | 12.4 | 13.7 | 13.6 | 12.3 |

$C_p$

| Data Set | Run-1a | Run-1b | Run-1c | Run-1d |
|---|---|---|---|---|
| $C_{ml}$ | -14 | -3 | -7 | -17 |
| Phase-momentum | 2 | 0 | 1 | 3 |
| Form of $l(t)$ | 2 | 0 | 1 | 1 |
| $f_{loss}$ function | 2 | 1 | 2 | 2 |
| Linear sum ($\sigma_{C_{ml}}$) | 6 | 2 | 4 | 6 |

$C_{ml}$

| Data Set | Run-1a | Run-1b | Run-1c | Run-1d |
|---|---|---|---|---|
| $C_{pa}$ | -184 | -165 | -117 | -164 |
| Stat. uncertainty | 23 | 20 | 15 | 14 |
| Tracker & CBO | 73 | 43 | 41 | 44 |
| Phase maps | 52 | 49 | 35 | 46 |
| Beam dynamics | 27 | 30 | 22 | 45 |
| Total uncertainty | 96 | 74 | 60 | 80 |

$C_{pa}$

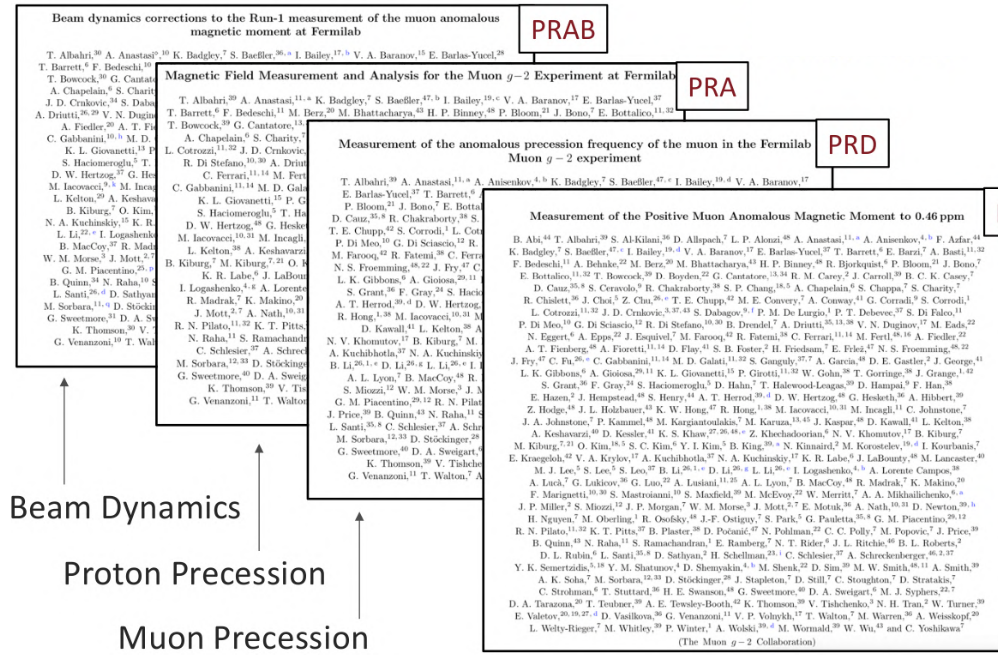
| Quantity | Symbol | Value | Unit |
|---|---|---|---|
| Diamagnetic Shielding T dep | $(1/\sigma)d\sigma/dT$ | -10.36(30) | ppb/°C |
| Bulk Susceptibility | $\delta_b$ | -1504.6 ± 4.9 | ppb |
| Material Perturbation | $\delta_s$ | 15.2 ± 13.3 | ppb |
| Paramagnetic Impurities | $\delta_p$ | 0 ± 2 | ppb |
| Radiation Damping | $\delta_{RD}$ | 0 ± 3 | ppb |
| Proton Dipolar Fields | $\delta_d$ | 0 ± 2.3 | ppb |

| Source | Uncertainty (ppb) |
|---|---|
| Temperature | 15 – 28 |
| Configuration | 22 |
| Trolley | 25 |
| Fixed Probe Production | <1 |
| Fixed Probe Baseline | 8 |
| Tracking Drift | 22 – 43 |
| Total | 43 – 62 |

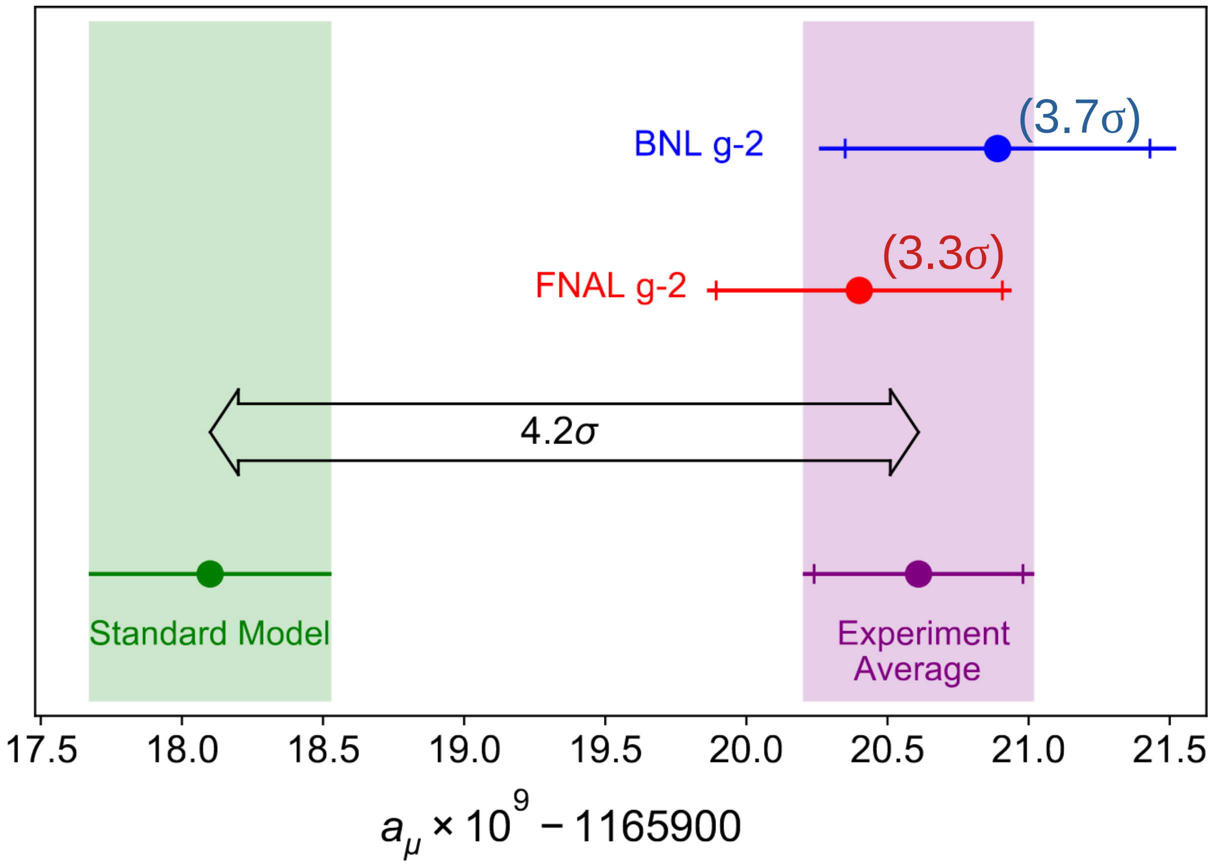
| | correction [ppb] | | | | uncertainty [ppb] | | | |
|---|---|---|---|---|---|---|---|---|
| Dataset | 1a | 1b | 1c | 1d | 1a | 1b | 1c | 1d |
| 1. Tracker and calo effects | - | - | - | - | 9.2 | 13.3 | 15.6 | 19.7 |
| 2. COD effects | 1.6 | 1.5 | 1.7 | 1.4 | 5.2 | 4.7 | 5.2 | 4.9 |
| 3. In-fill time effects | -1.9 | -2.3 | -1.2 | -4.1 | - | - | - | - |
| Total | -0.3 | -0.8 | 0.5 | -2.7 | 10.6 | 14.1 | 16.5 | 20.3 |

# Run 1 release

- Data unblinded on 25 February 2021 on a zoom session with 170+ collaborators
- Publicly released on 7 April 2021
- 4 papers released at the same time (PRL, PRD, PRA, PRAB)




# Run 1 release




| Quantity | Correction Terms (ppb) | Uncertainty (ppb) |
|---|---|---|
| $\omega_a^m$ (statistical) | – | 434 |
| $\omega_a^m$ (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 |
| $m_\mu/m_e$ | – | 22 |
| $g_e/2$ | – | 0 |
| Total systematic | – | 157 |
| Total fundamental factors | – | 25 |
| Totals | 544 | 462 |

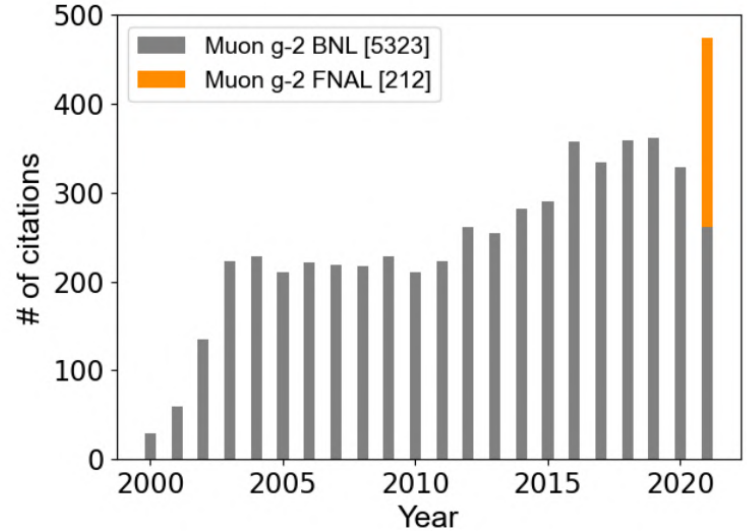
**$a_\mu$ (Th) = 116 591 810(43) × $10^{-11}$ (0.37 ppm)**

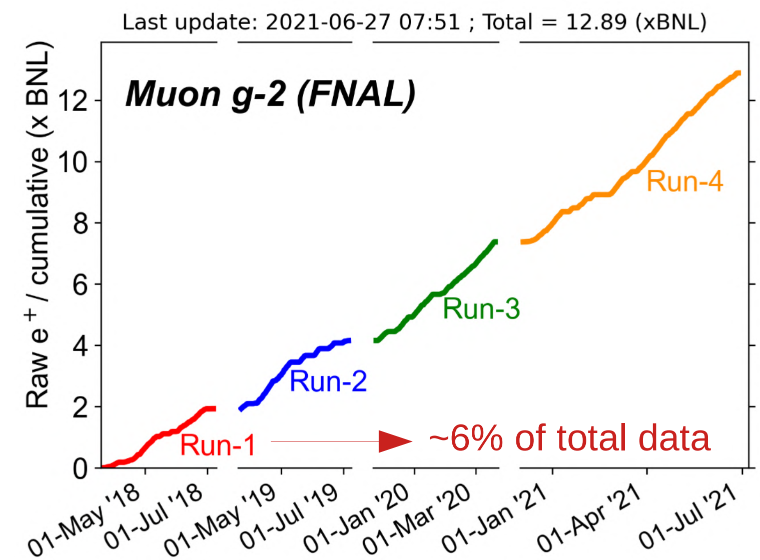
**$a_\mu$ (FNAL) = 116 592 040(54) × $10^{-11}$ (0.46 ppm)**

**$a_\mu$ (Exp) = 116 592 061(41) × $10^{-11}$ (0.35 ppm)**

# Summing up...

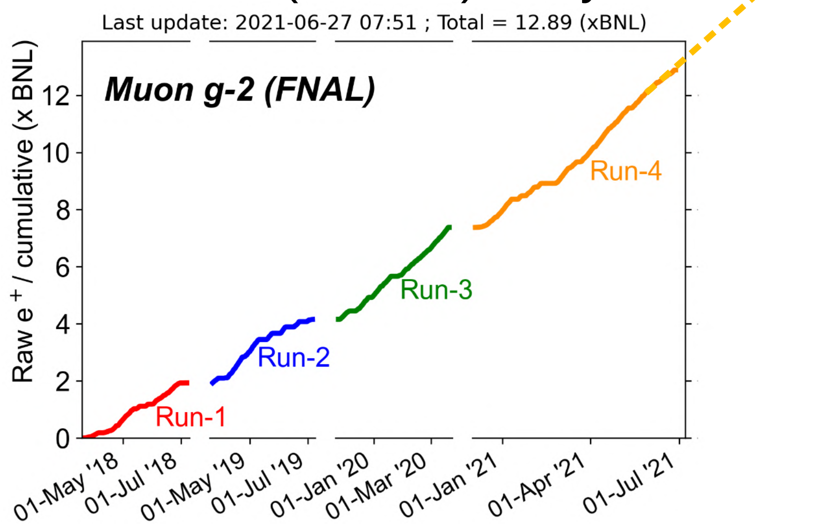
- Truly interdisciplinary experiment, touching many aspects of particle physics
- The analysis of Run-1 data produced a result with 460 ppb precision
- **FNAL confirms BNL**
- A lot more data to be analyzed. Run 2-3 result coming in 1-2 years, with a factor 2 improvement – still statistically limited
- Run 4 concluded this June, Run 5 starting soon



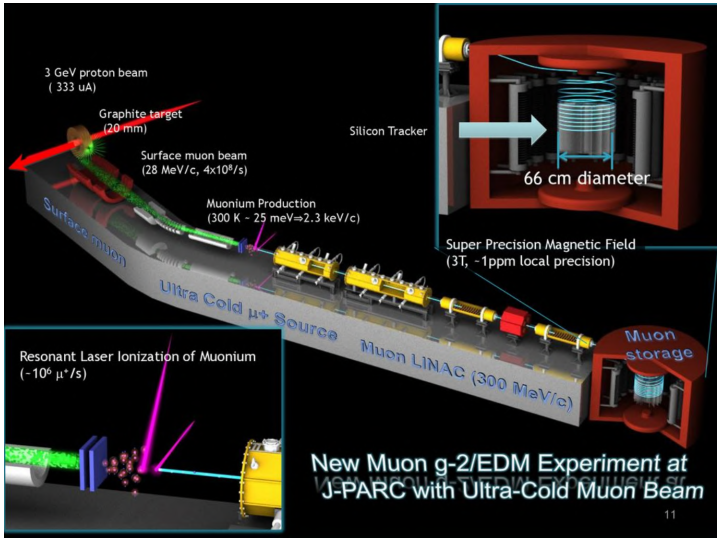



# What's next

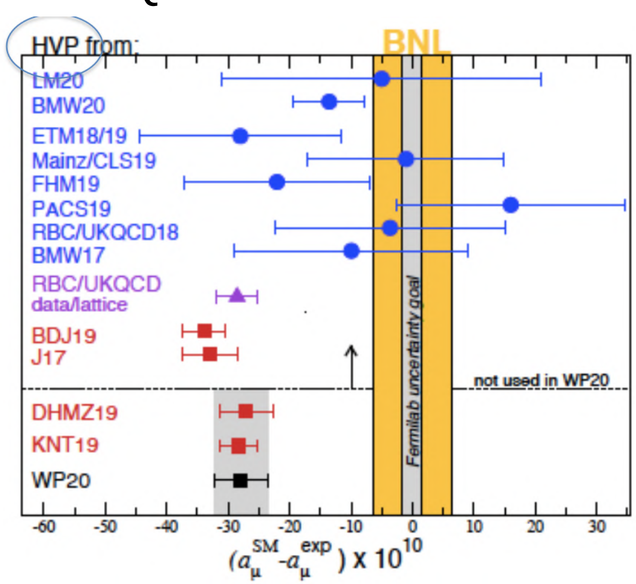
## Run2-4 (and 5-6) analysis



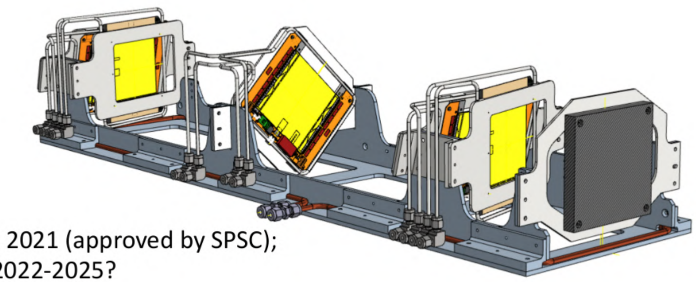

## Muon g-2 experiment at J-PARC




## New QCD Lattice calculations




## MuonE experiment at CERN



Test RUN 2021 (approved by SPSC);
Full run 2022-2025?