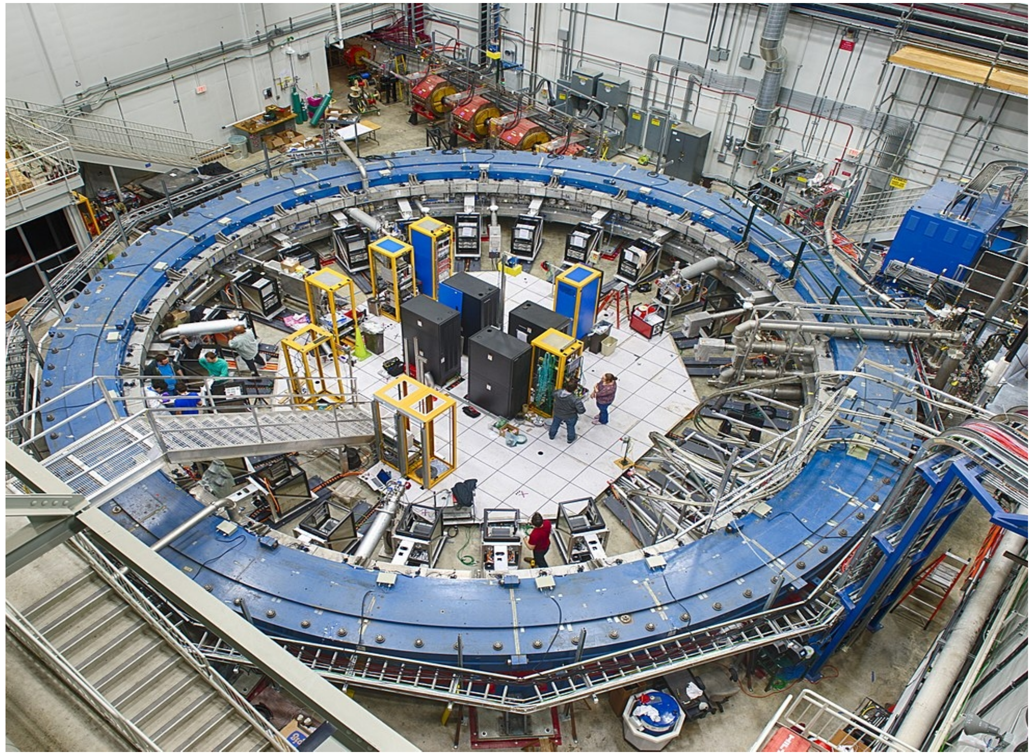
Istituto Nazionale di Fisica Nucleare



Measurement of Muon g-2

36th Les Rencontres de Physique de la Vallée d'Aoste

La Thuile | 5-11 March 2023

Paolo Girotti (INFN Pisa)

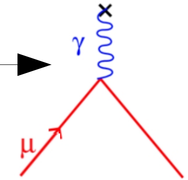
on behalf of the Muon g-2 collaboration

The Muon g-2

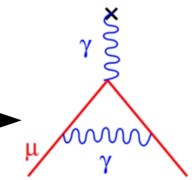
$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

$$a_\mu \equiv \frac{g-2}{2}$$

- The g-factor encodes all the possible virtual interactions between the lepton and the magnetic field
- At tree level: g=2 (a_μ=0)

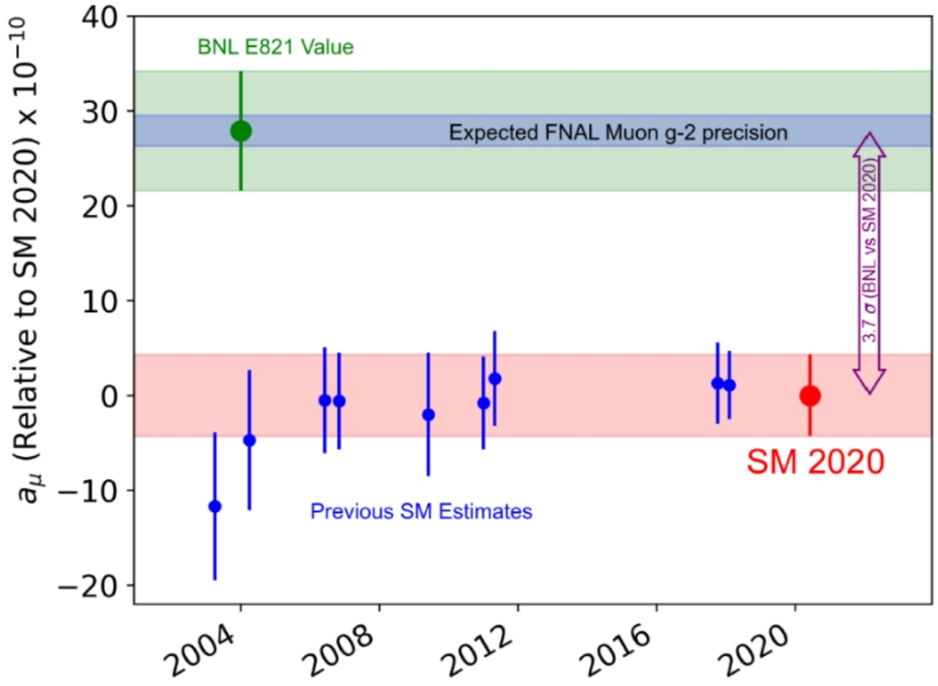


- First QED term: a_μ=0.00116



- All physics: a_μ=0.00116592061(41) [0.35 ppm]
  - (As measured by BNL + FNAL, 2021)
- Any discrepancy between experimental measurement and theoretical prediction could be a signature of virtual BSM interactions

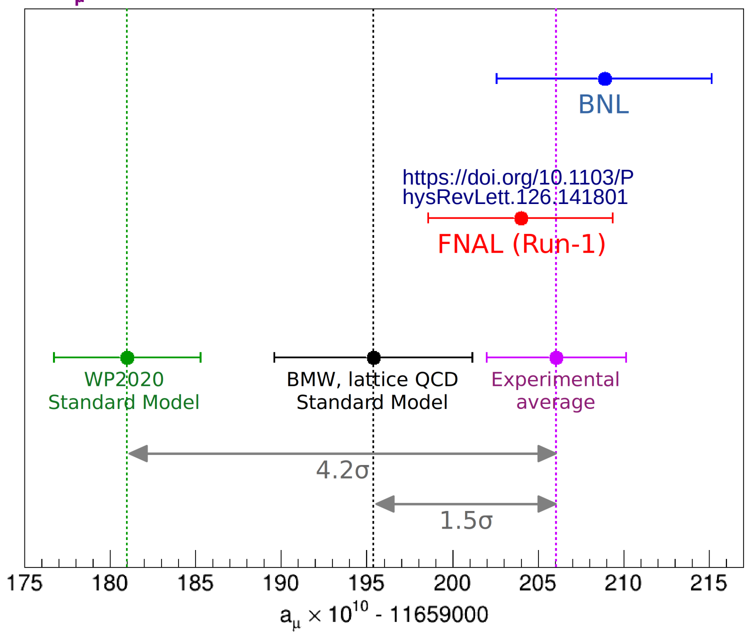
Motivation



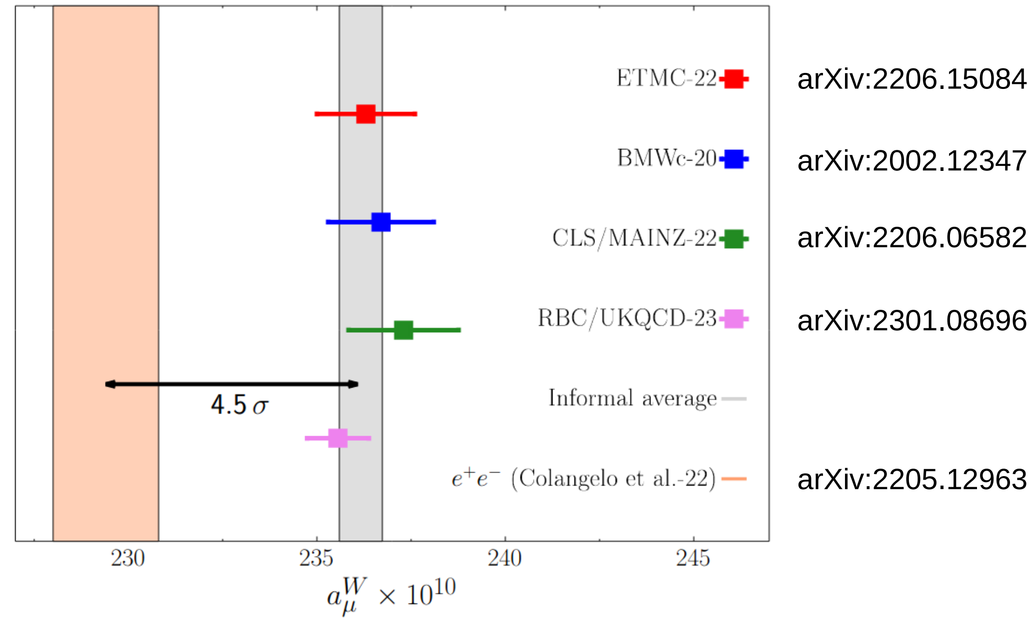
- a_μ measured at Brookhaven National Lab (BNL E821, 2006)
- a_μ (Exp) = 0.00116592089 ± 63 (540 ppb)
- a_μ (Th) = 0.00116591810 ± 43 (368 ppb)
- Discrepancy of **3.7σ**
- Fermilab Muon g-2 Experiment goal: reduce the experimental error by a factor of **4** to a final precision of 140 ppb

Current status

a_μ (Exp) = 116 592 061(41) × 10^{-11} (0.35 ppm)



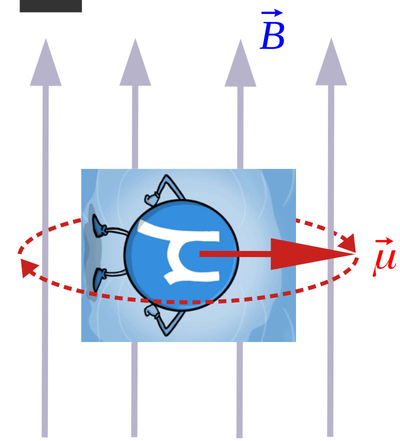
Picture from https://agenda.infn.it/event/32931/contributions/187824/



- Run-1 measurement published on 7 April 2021 (0.46 ppm)
  - Consistent with BNL (2006) measurement, increasing tension with Theory Initiative (2020) a_μ prediction to **4.2σ**
- New precise ab-initio **Lattice-QCD** calculations of the hadronic term a_μ(HVP-LO) in tension with the data-driven prediction using $\sigma(e^+e^- \to \text{hadrons})$ and the dispersion relation:

$$a_\mu^{HVP} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s} \frac{\sigma_{e^+e^- \to hadrons}(s)}{\sigma_{e^+e^- \to \mu^+\mu^-}(s)} K(s)$$

How to measure g-2



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

Spin precession frequency

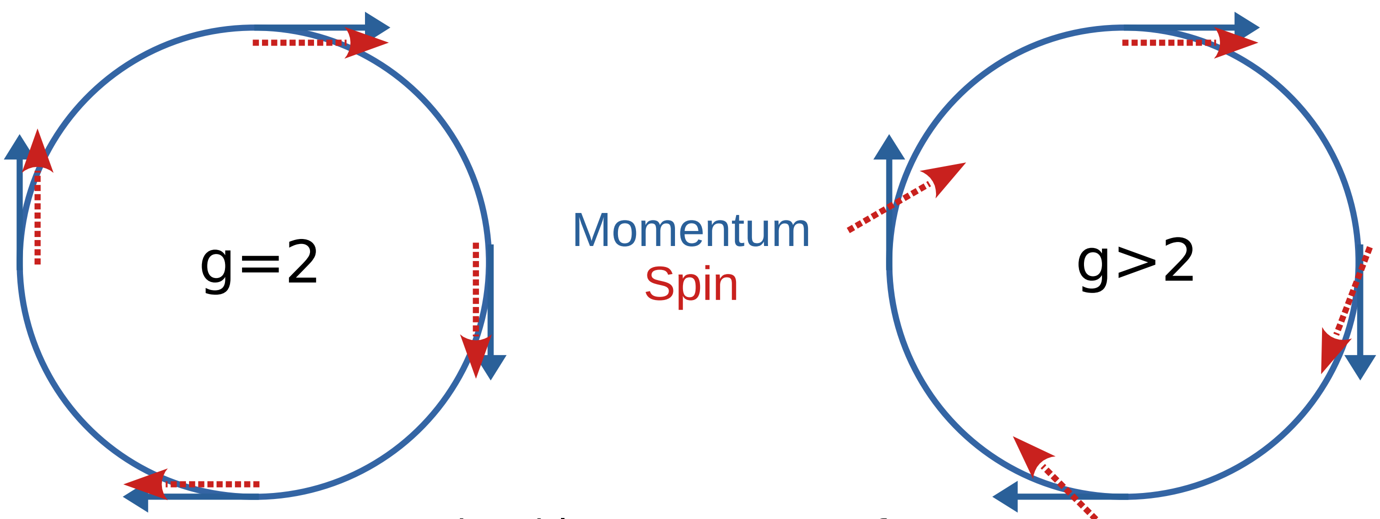
$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$$

Cyclotron frequency

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

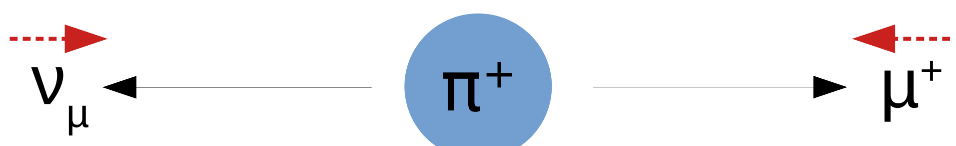
$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -a_\mu\frac{e\vec{B}}{m}$$

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

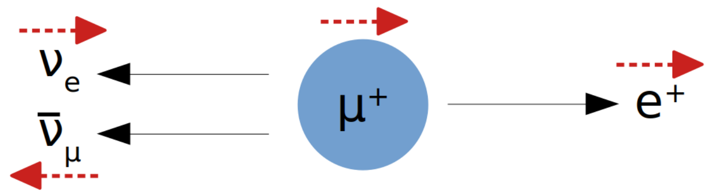


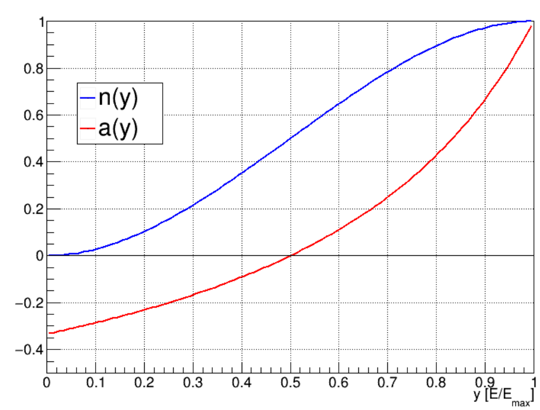
Two **gifts** from nature

- Pions have spin 0 and decay in a muon and a neutrino (~99.99%)
- Parity violation dictates that the muon has left helicity
- Boosted beam → high energy muons are **highly polarized**

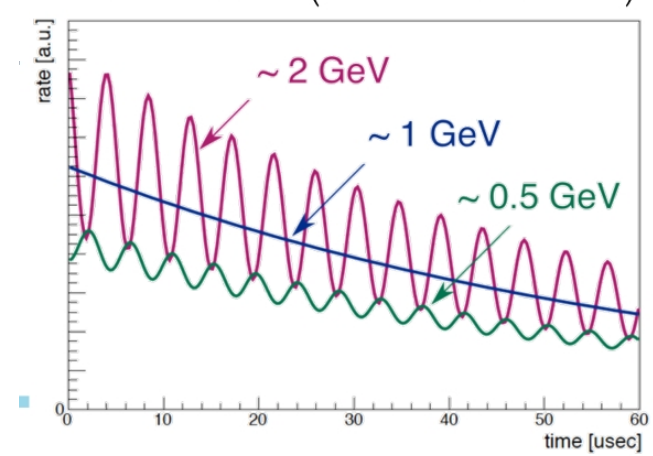


- Parity violation in the muon decay dictates that high energy positrons are emitted preferably in the direction of muon spin
- The decay **asymmetry** is observed in the lab frame as an oscillation of the positron count over time





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

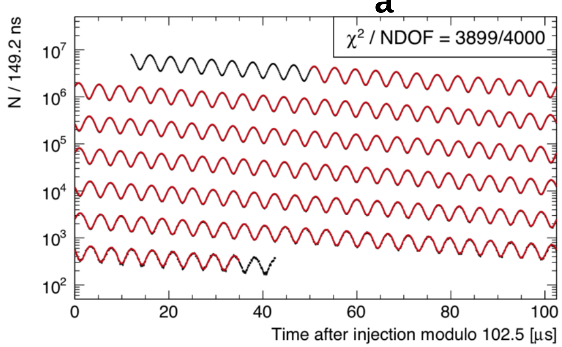


Master formula

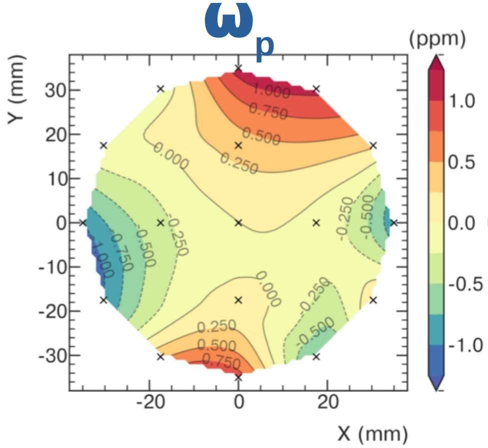
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Constants known from other experiments with high precision (25 ppb)

ω_a

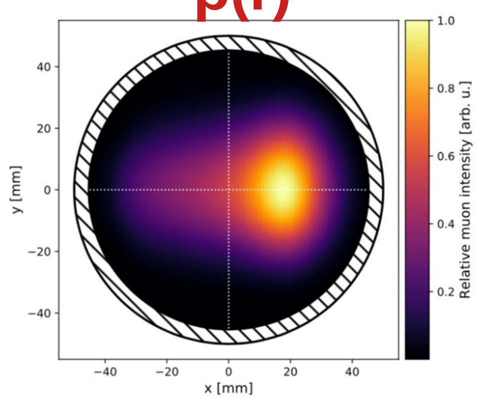


ω_p



$\otimes$

$\rho(r)$



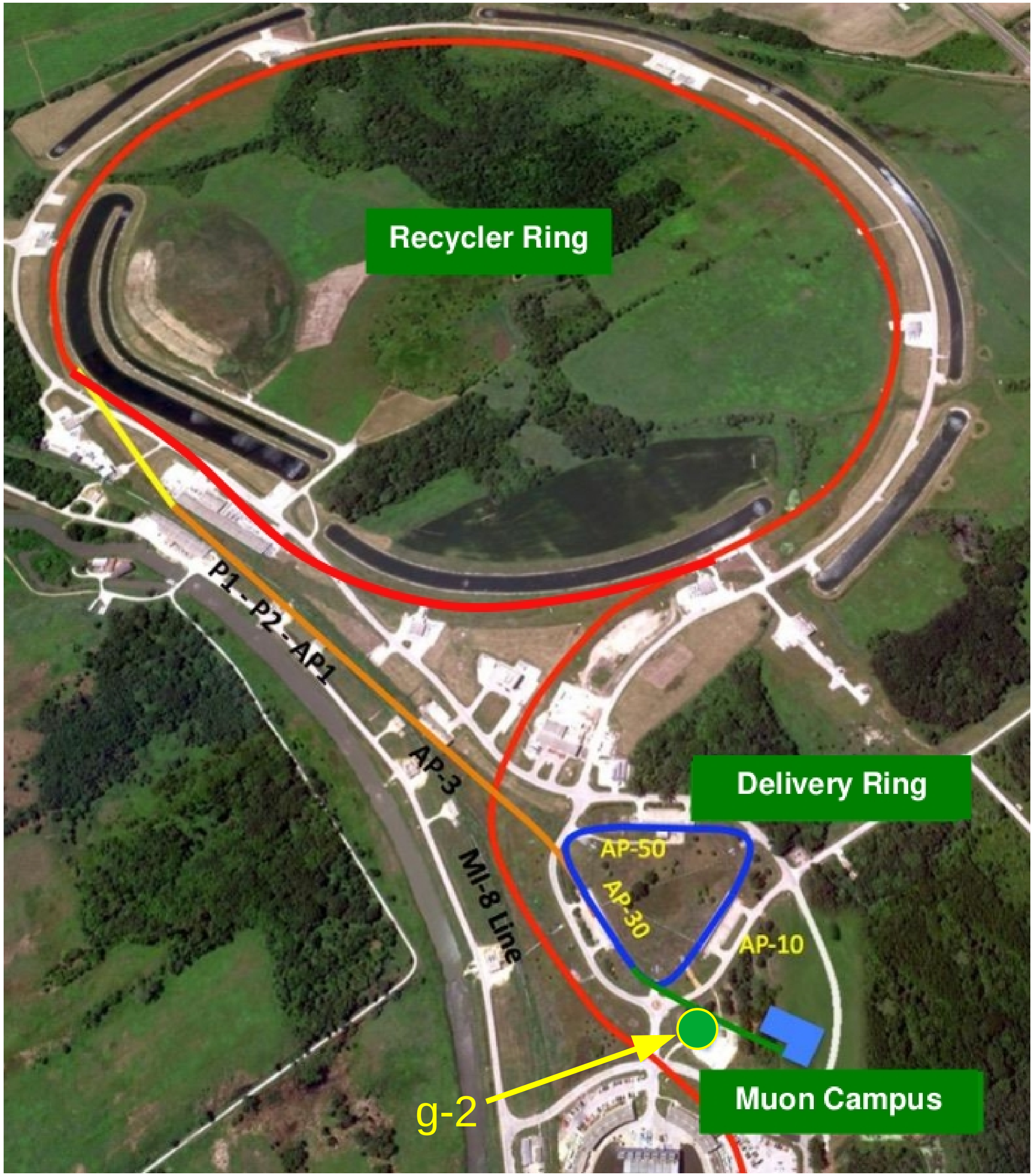
Three key measurements:

- **ω_a**: Muon anomalous precession frequency
- **ω_p**: Larmor precession frequency of protons in water (B field)
- **ρ_r**: Muon distribution in the storage ring

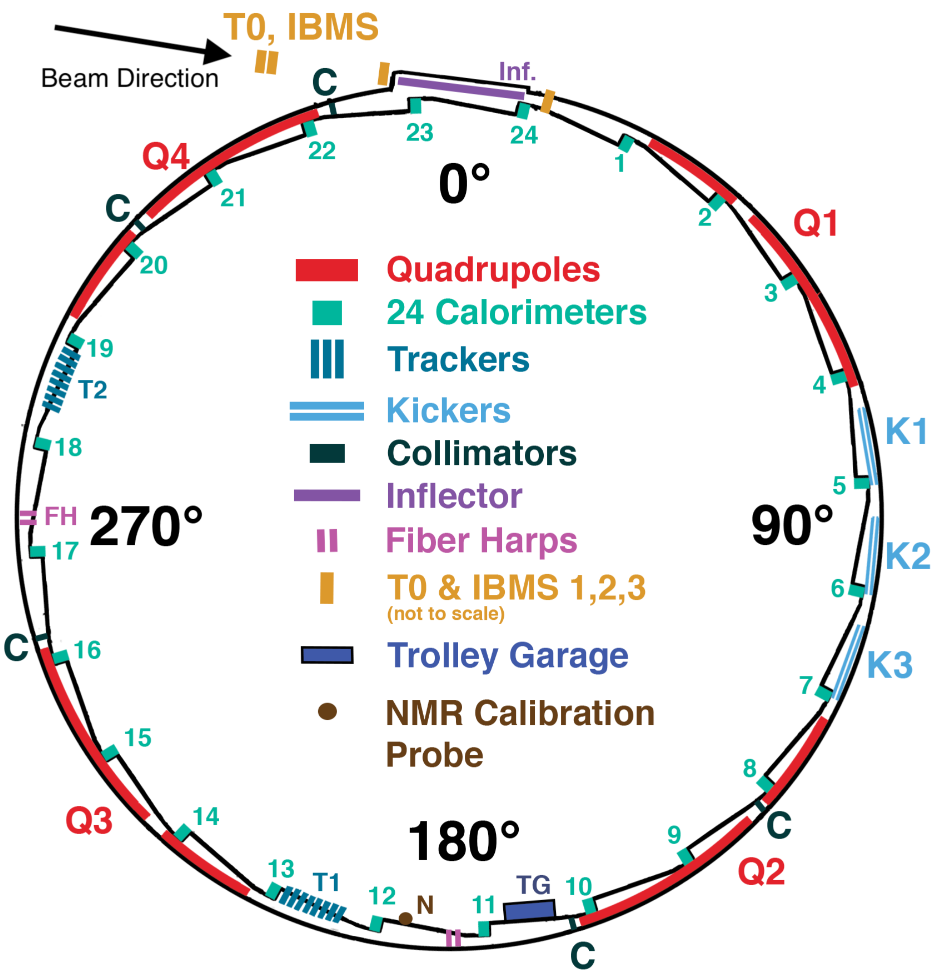
Muon source

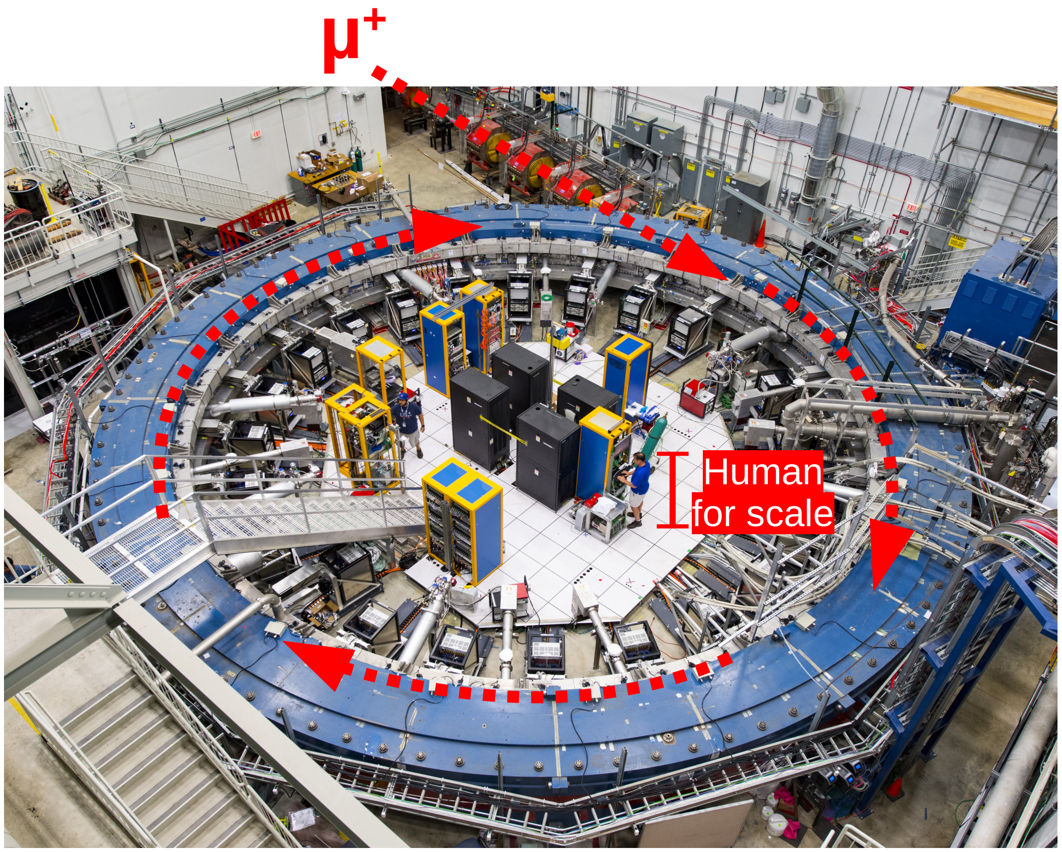
$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

- 16 bunches of 10^{12} protons @8 GeV get boosted and delivered via the recycler ring every 1.4 seconds
- Each bunch hits a fixed Inconel® 600 target
- Positive pions from shower extracted and decay in delivery ring
- Pure and polarized muon beam enters g-2 ring



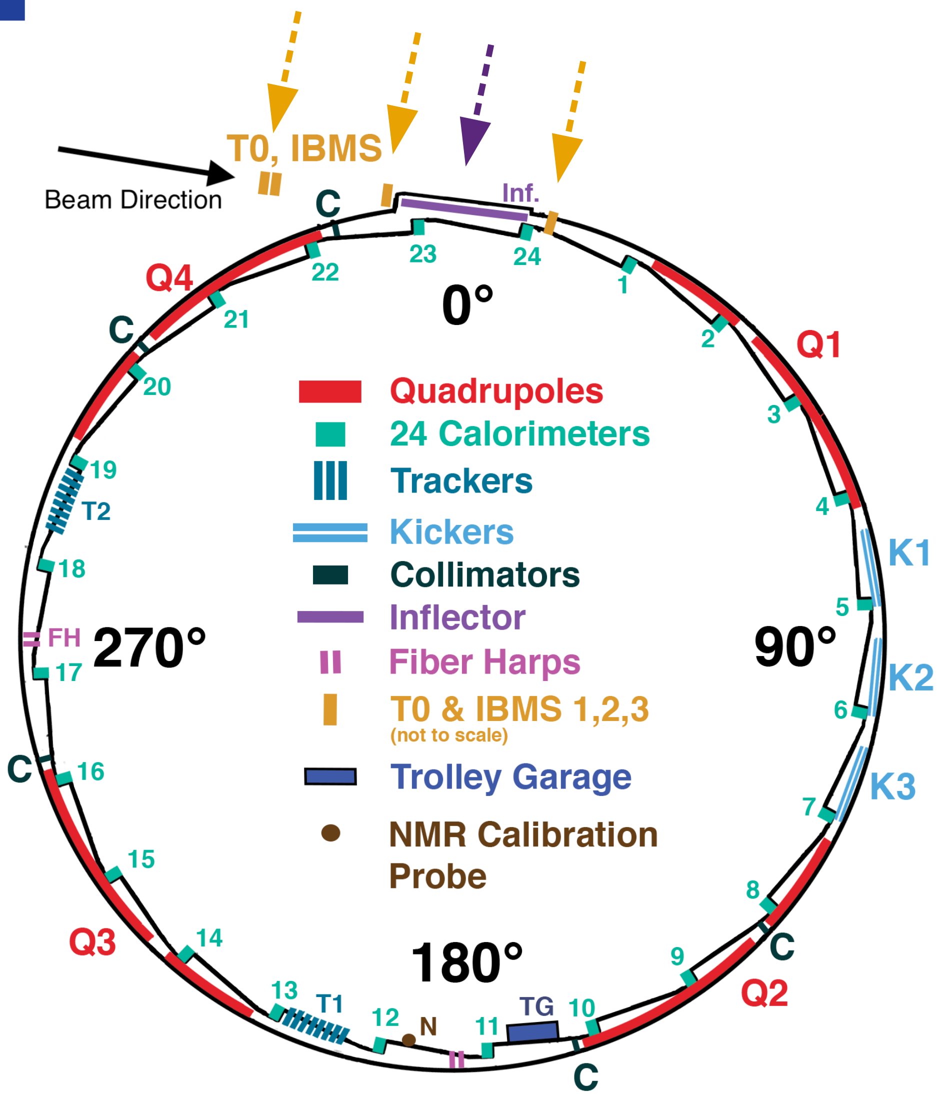
Muon g-2 Experiment



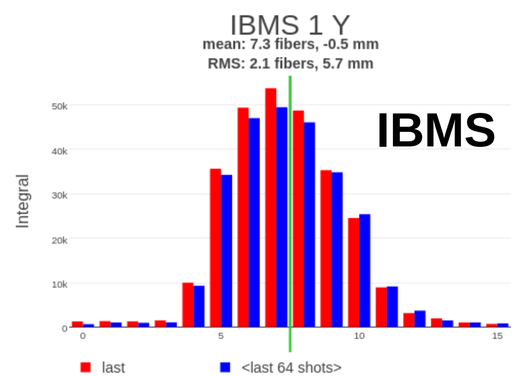


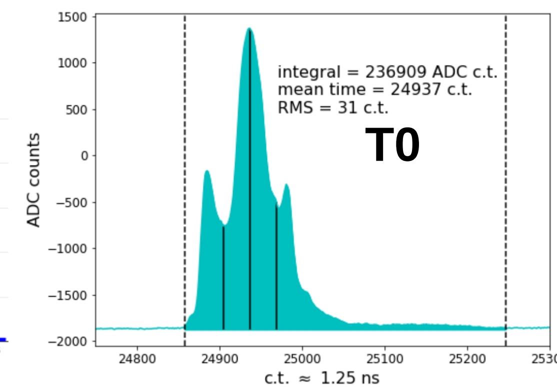
MC-1 building @Fermilab

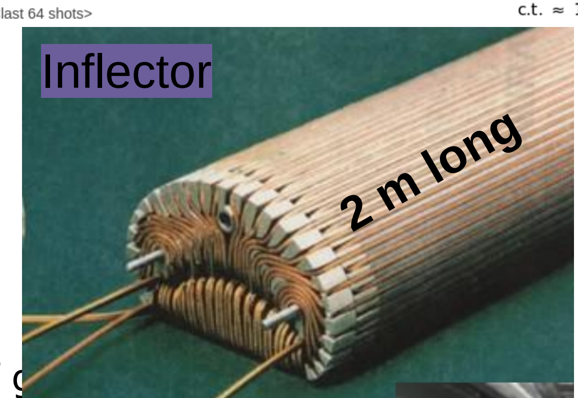
Beam injection



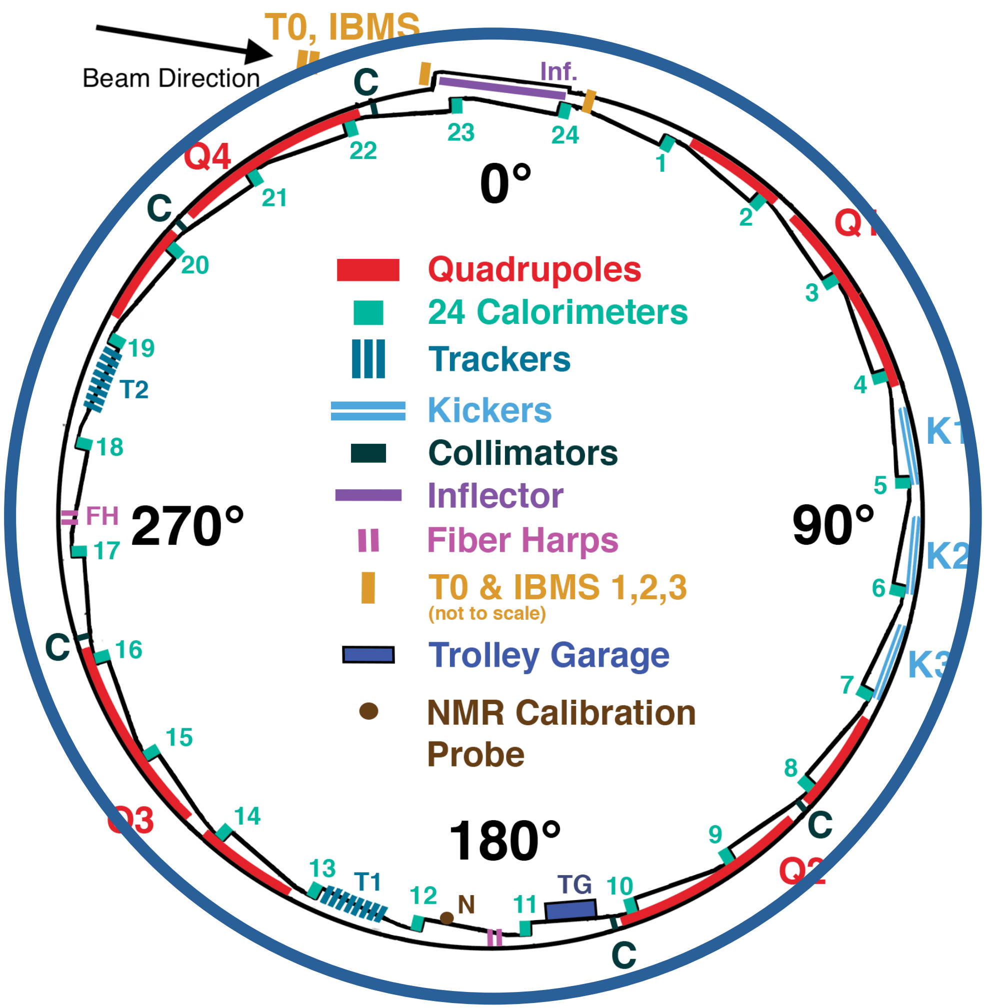
- 3 **IBMS** (Inflector Beam Monitor System) detectors with scintillating X-Y fiber planes for beam profile measurement
- 1 **T0** scintillator detector for time synchronization and beam time profile measurement
- Superconducting **inflector** to cancel the magnetic field for beam injection, ~8 cm offset from nominal orbit



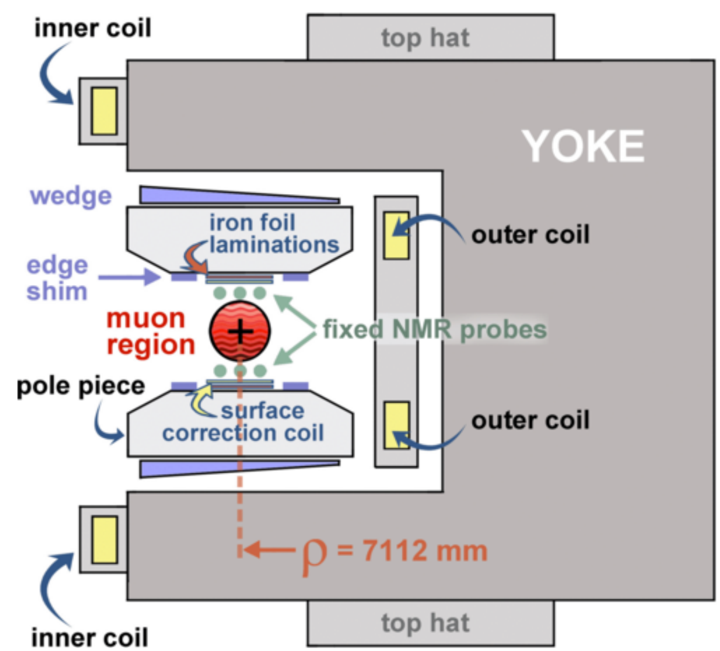




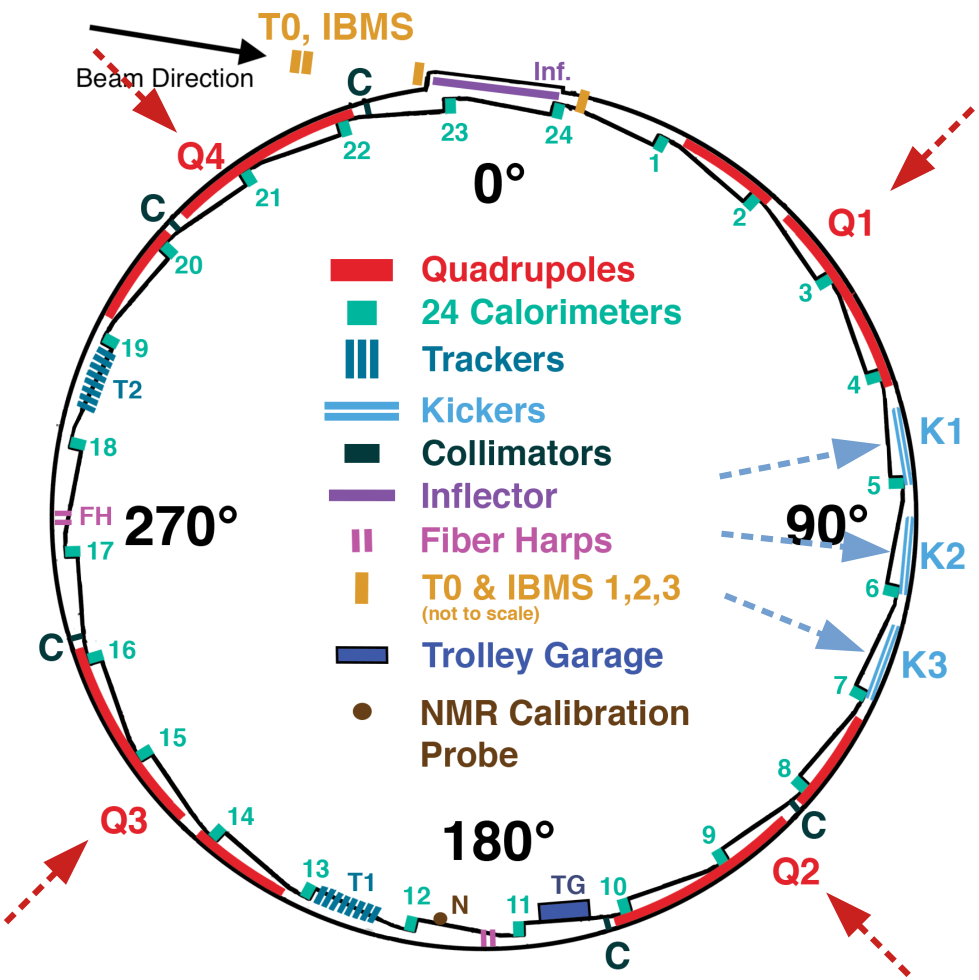
Magnet



- Superconductive **magnet** cooled at ~5 K with LHe
- 7.112 m radius C-shaped with highly **uniform 1.45 T** vertical magnetic field in the storage region
- Shimmed passively with iron foils and actively stabilized with correction coils to achieve better than 14 ppm RMS field homogeneity across the full azimuth



Beam storage

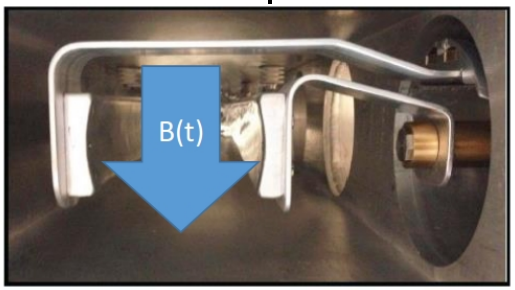


- 3 fast magnetic **kickers** to reach nominal orbit after first ¼ turn. Operated at ~4 kA current for ~200 ns
- 8 aluminum electrostatic **quadrupoles** at 13.8 kV to provide weak vertical focus
- The effect of electric field on the muon precession is minimized thanks to the <u>magic</u> beam momentum of 3.094 GeV/c

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

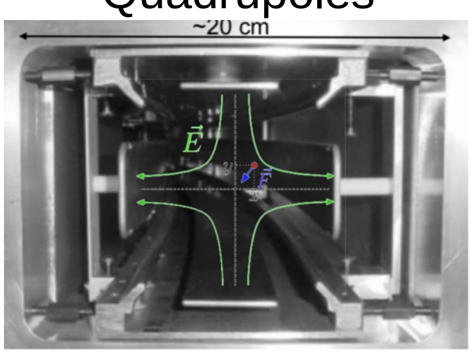
= 0

Kicker plates

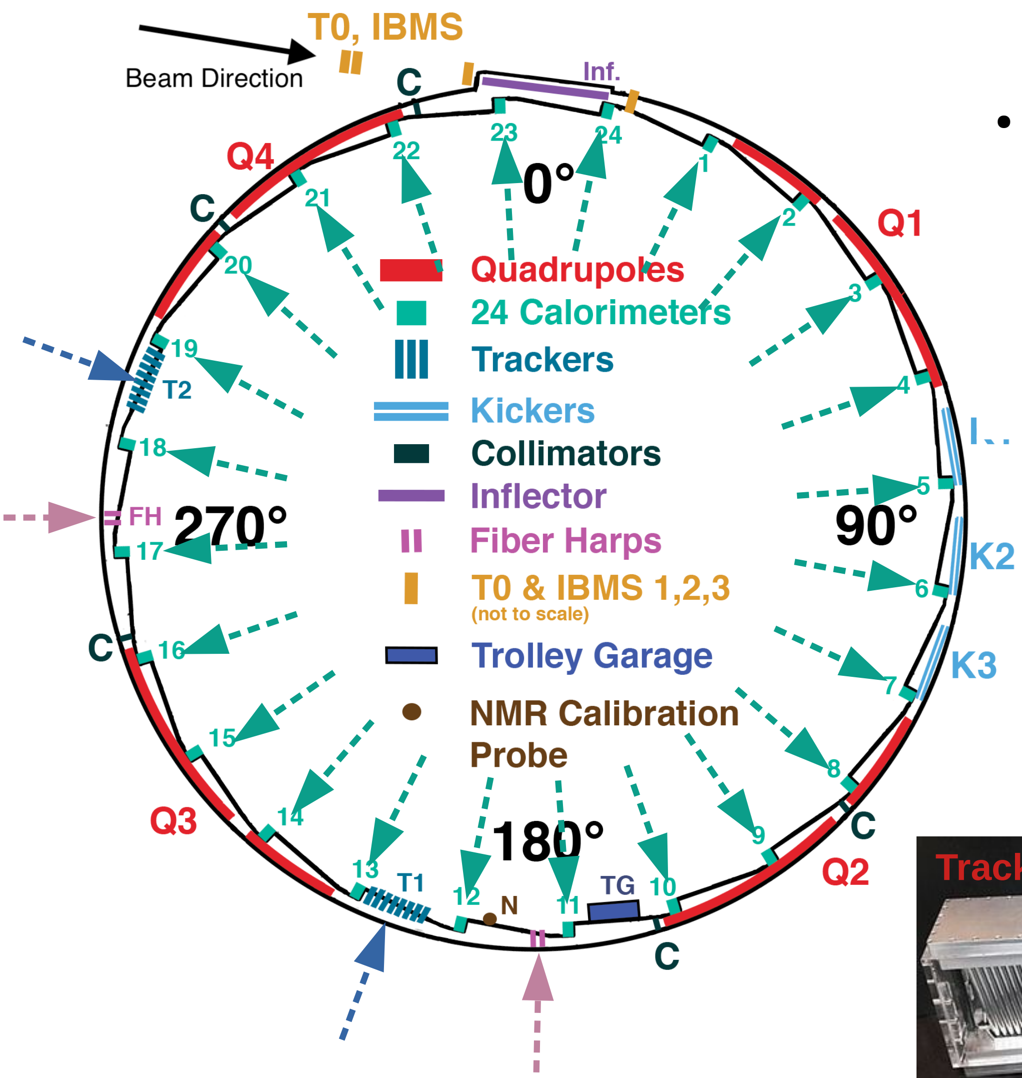


https://doi.org/10.1016/j.nima.2021.165597

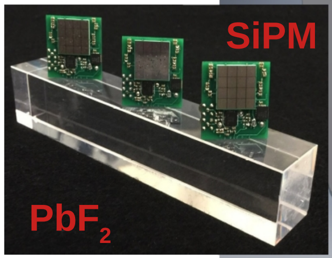
Quadrupoles

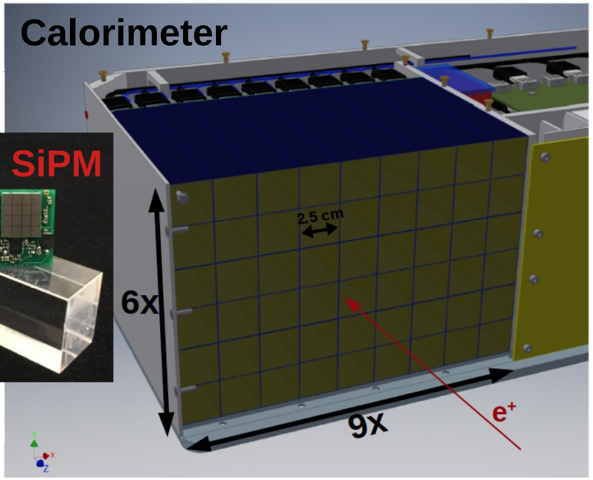


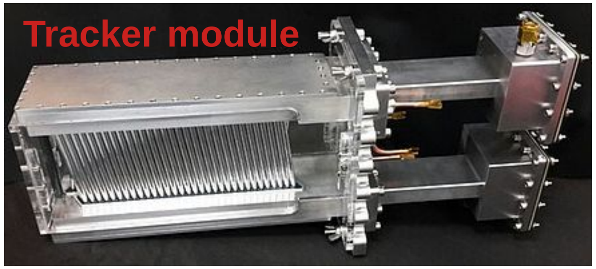
Detectors



- 24 electromagnetic **calorimeters** for positron energy and time measurement
  - Each calorimeter is a 9x6 matrix of PbF_2 crystals coupled with 144 mm^2 SiPMs
- 2 **tracker** stations extrapolating decay vertex location for measuring beam movements
  - Each tracker is composed of 8 modules with 64+64 Argon-Ethane straw tubes arranged as U-V planes



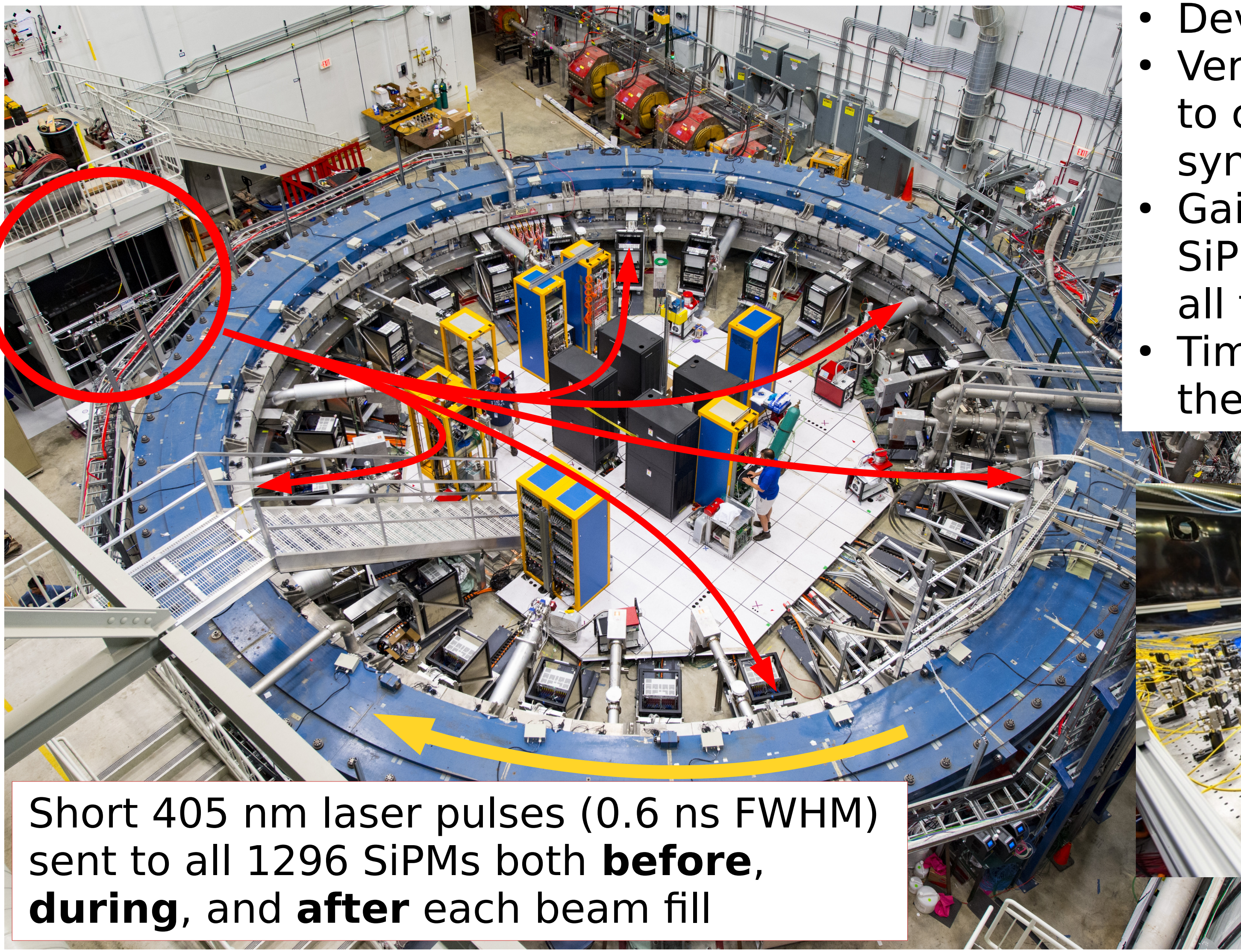




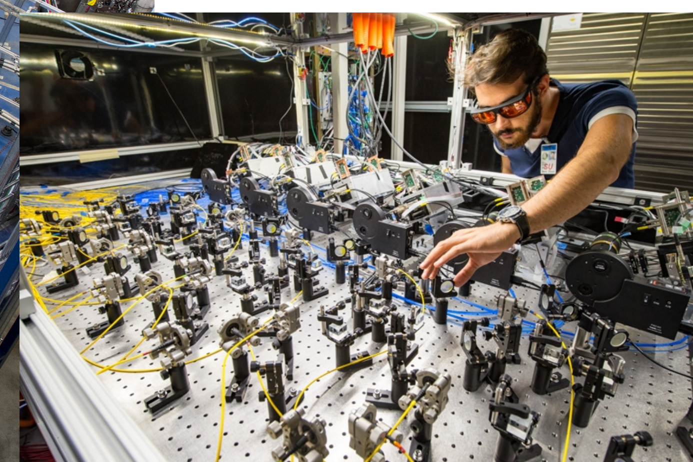
Laser Calibration System

https://doi.org/10.1088/1748-0221/14/11/P11025

- Developed by INFN-INO
- Very stable laser system to calibrate and synchronize the detectors
- Gain calibration of the SiPMs at the 10^{-4} level at all timescales
- Time synchronization at the ~50 ps level



Short 405 nm laser pulses (0.6 ns FWHM) sent to all 1296 SiPMs both **before**, **during**, and **after** each beam fill

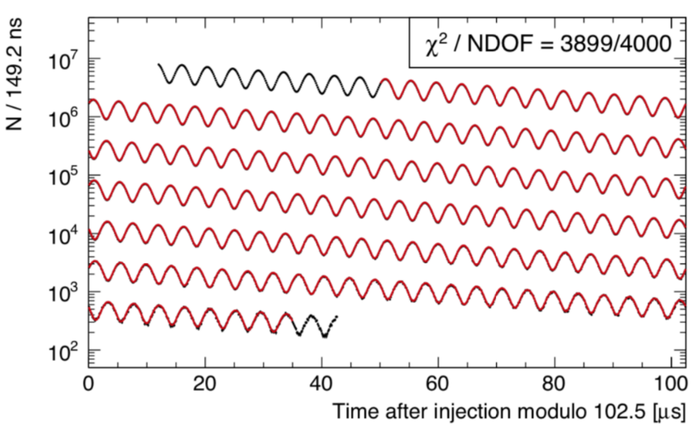


Master formula

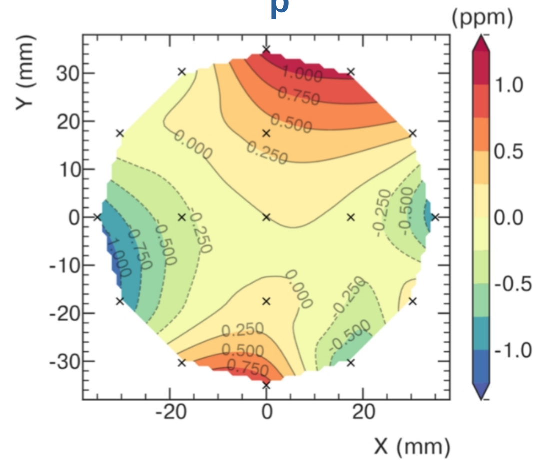
$$a_\mu \propto \frac{f_{clock}\,\underline{\omega_a^m}\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle \underline{\omega'_p(x,y,\phi)} \times \underline{M(x,y,\phi)} \rangle\,(1 + B_k + B_q)}$$

- f_clock: hardware blinding of the calorimeter digitizer clock
- f_calib: absolute magnetic field calibration

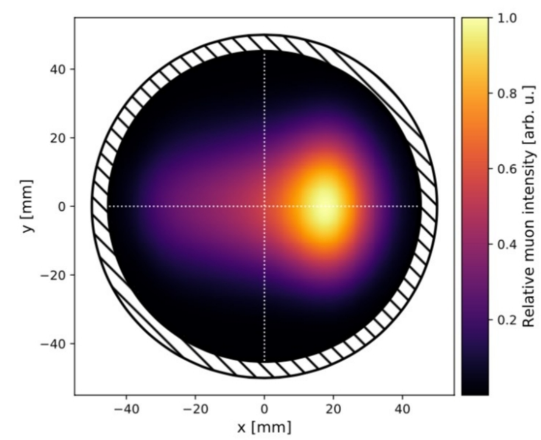
ω_a



ω_p

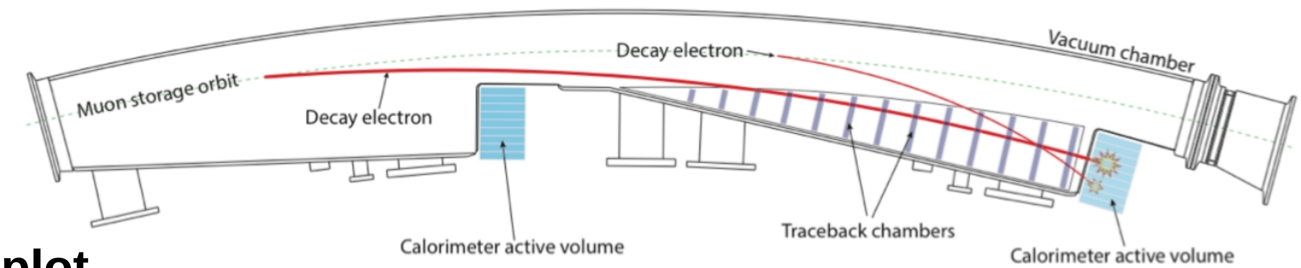


ρ(r)

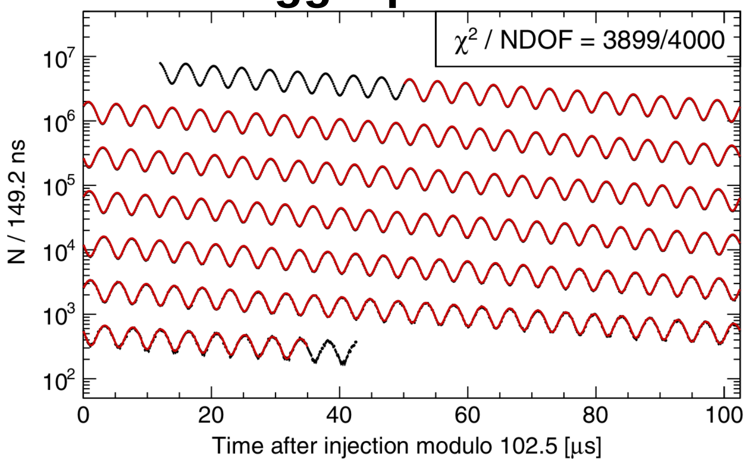


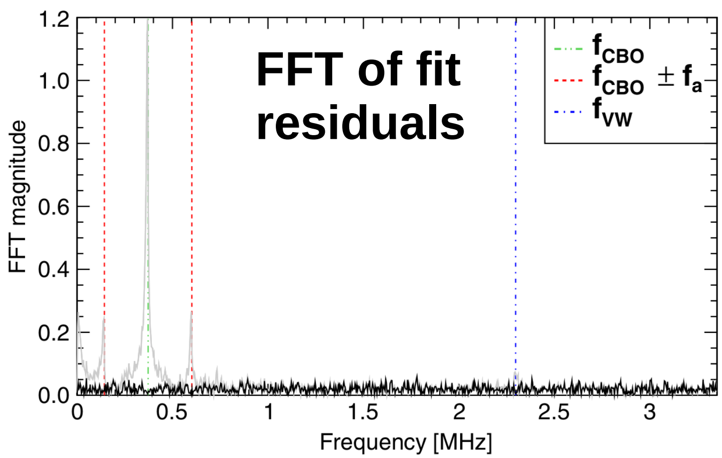
Measuring ω_a

https://doi.org/10.1103/PhysRevD.103.072002



Run-1 wiggle plot





- Positrons above 1 GeV are counted vs time and weighted by their asymmetry A(E)
- Histogram fitted with 27-parameter function
  - Muon precession and beam oscillations
- 7 independent blinded analyses to extract the muon anomalous precession frequency ω_a

$$N(t) = Ne^{-t/\tau_\mu}\left[1 + A\cdot\cos(\omega_a t - \phi + \phi_{BO}(t))\right]\cdot$$

$$\cdot\left(1 + A_{CBO}\cos(\omega_{CBO}t - \phi_{CBO})e^{-\frac{t}{\tau_{CBO}}}\right)\cdot$$ → Horizontal betatron oscillation

$$\cdot\left(1 + A_{VW}\cos(\omega_{VW}t - \phi_{VW})e^{-\frac{t}{\tau_{VW}}}\right)\cdot$$ → Vertical waist

$$\cdot\left(1 + A_{2CBO}\cos(\omega_{2CBO}t - \phi_{2CBO})e^{-\frac{t}{\tau_{2CBO}}}\right)\cdot$$ → Horizontal breathing

$$\cdot\left(1 + A_y\cos(\omega_y t - \phi_y)e^{-\frac{t}{\tau_y}}\right)\cdot$$ → Vertical oscillation

$$\cdot\left(1 - k_{LM}\int_0^t L(t')e^{t'/\tau_\mu}dt'\right)\cdot$$ → Lost muons

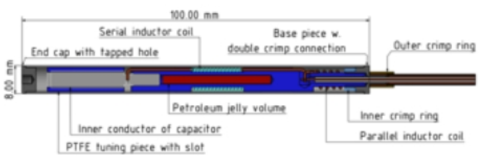
$$\cdot\left(1 + \left[A_+\cos(\omega_+(t)t - \phi_+) + A_-\cos(\omega_-(t)t - \phi_-)\right]e^{-\frac{t}{\tau_{CBOVW}}}\right)$$

Measuring the field

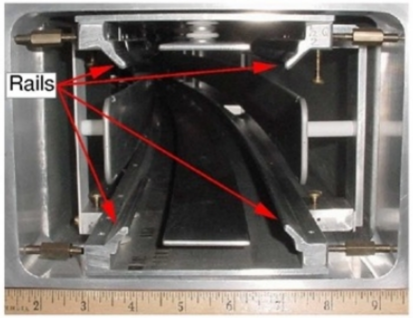
https://doi.org/10.1103/PhysRevA.103.042208

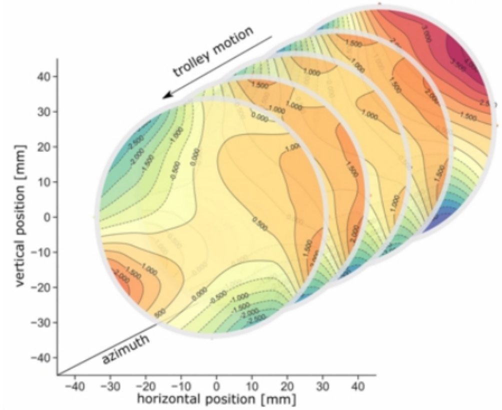
- Field intensity measured with Nuclear Magnetic Resonance (NMR) probes in terms of proton precession frequency ω_p
- Continuously monitored around the storage region and periodically measured inside the storage region

378 fixed probes continuous monitoring

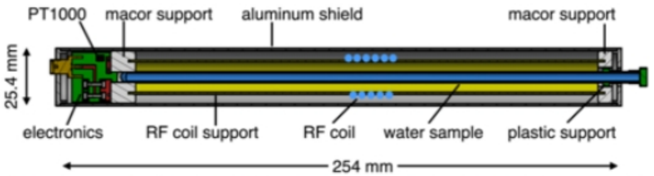


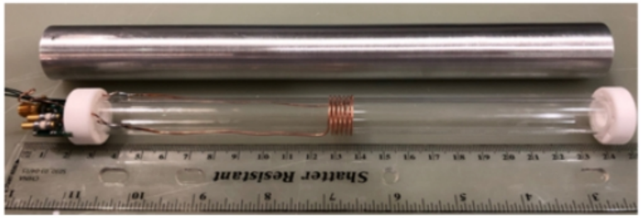
17 probes on a trolley to 3D map every ~3 days





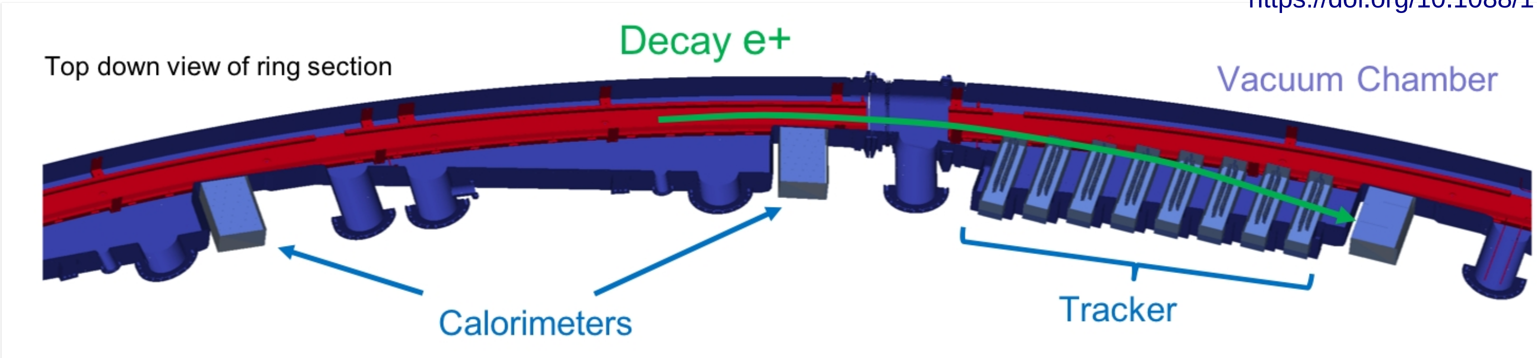
Trolley cross-calibrated to absolute probes



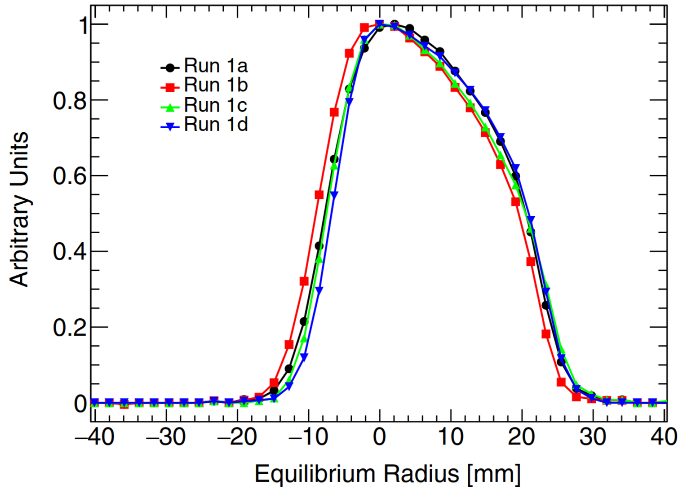


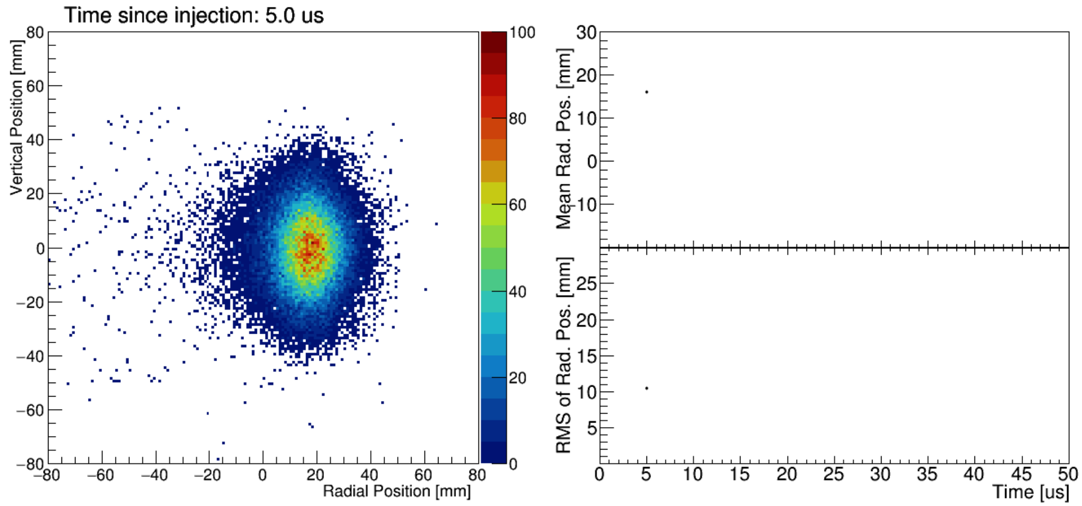
Measuring the beam

https://doi.org/10.1088/1748-0221/17/02/P02035



- Trackers at 180° and 270° reconstruct the positron trajectory to extrapolate the decay vertex in the storage region
- Muon distribution maps extrapolated to the entire ring azimuth with Geant4 simulation (gm2ringsim)
- Calorimeter hit energy matching to perform particle identification



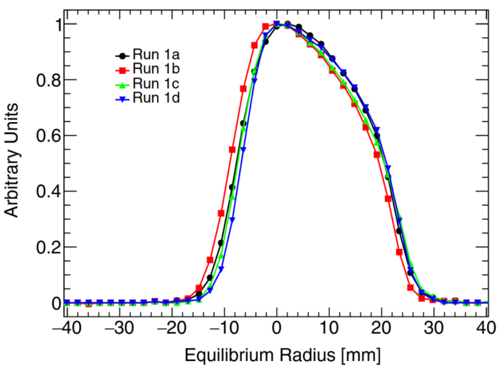


Master formula

https://doi.org/10.1103/PhysRevAccelBeams.24.044002

$$a_\mu \propto \frac{f_{clock}\, \omega_a^m \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{calib} \left\langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_k + B_q\right)}$$

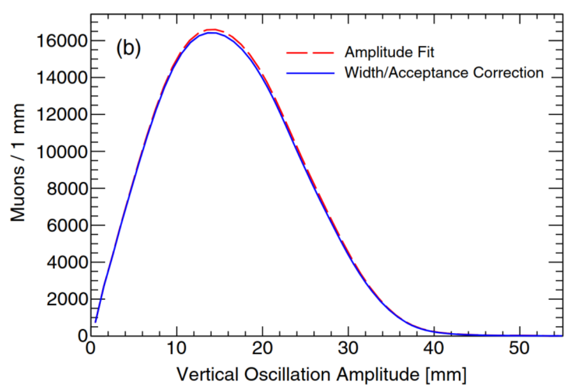
$$C_e \approx 2n(1-n)\beta_0 \frac{\langle x_e^2 \rangle}{R_0^2}$$

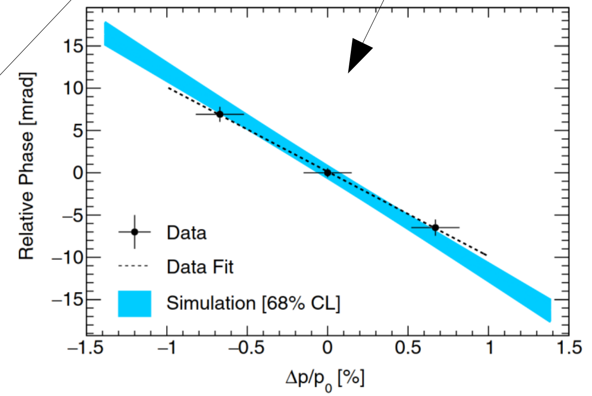


Electric field correction

Pitch correction

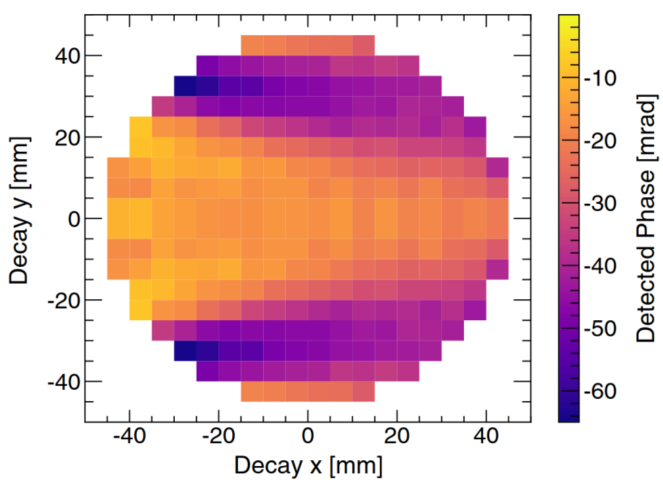
$$C_p \approx \frac{n}{4} \frac{\langle A_y^2 \rangle}{R_0^2}$$





Lost muons momentum correlation

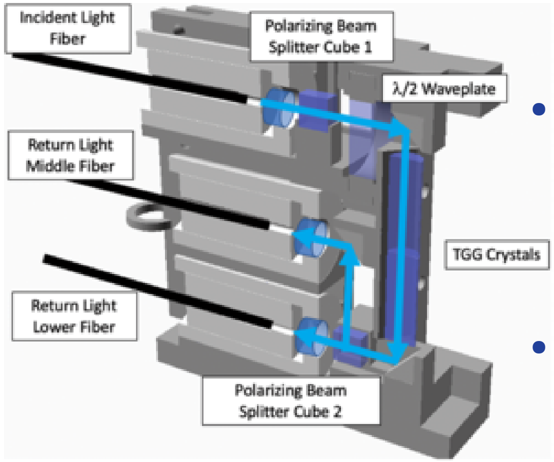
Phase-acceptance correction



Master formula

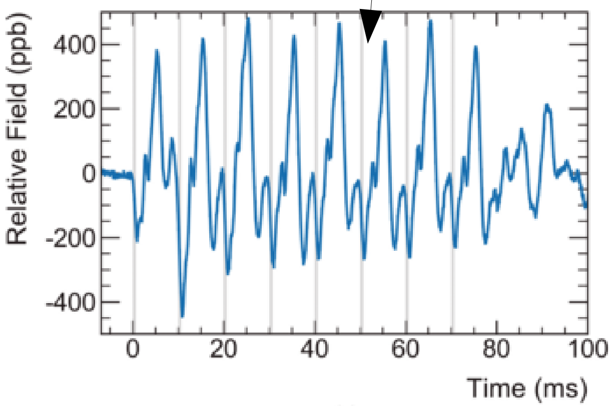
https://doi.org/10.1103/PhysRevA.103.042208

$$a_\mu \propto \frac{f_{clock}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

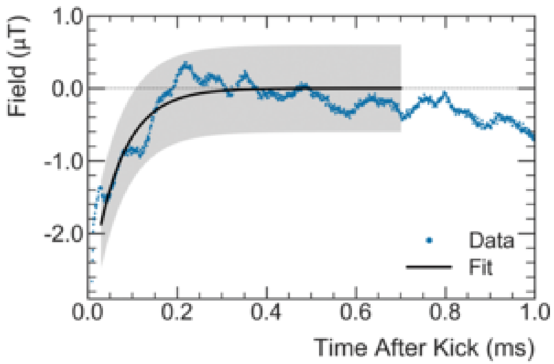


(a)

- Millisecond-long eddy currents induced by the kicker pulse
- Measured with dedicated Faraday magnetometers

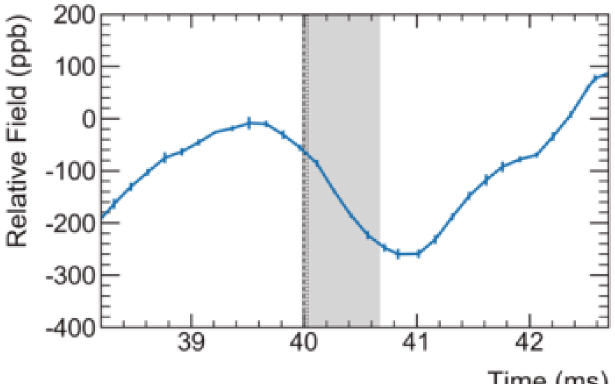


(a)



(b)

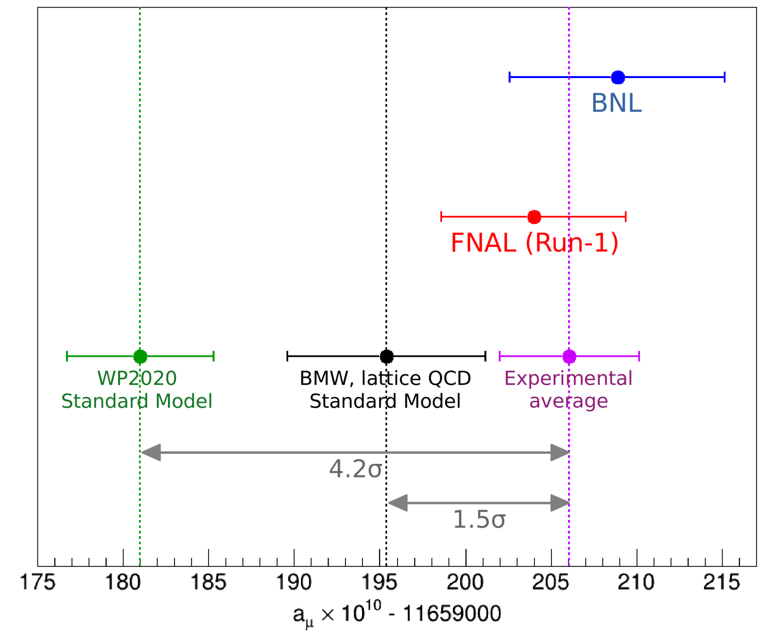
- Low-frequency oscillations of the electrostatic quadrupole plates
- Measured with dedicated probes



(b)

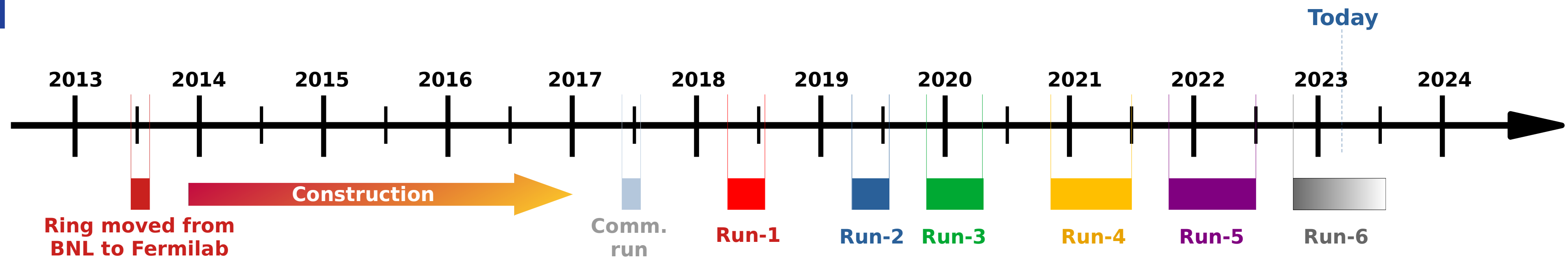
Run-1 result

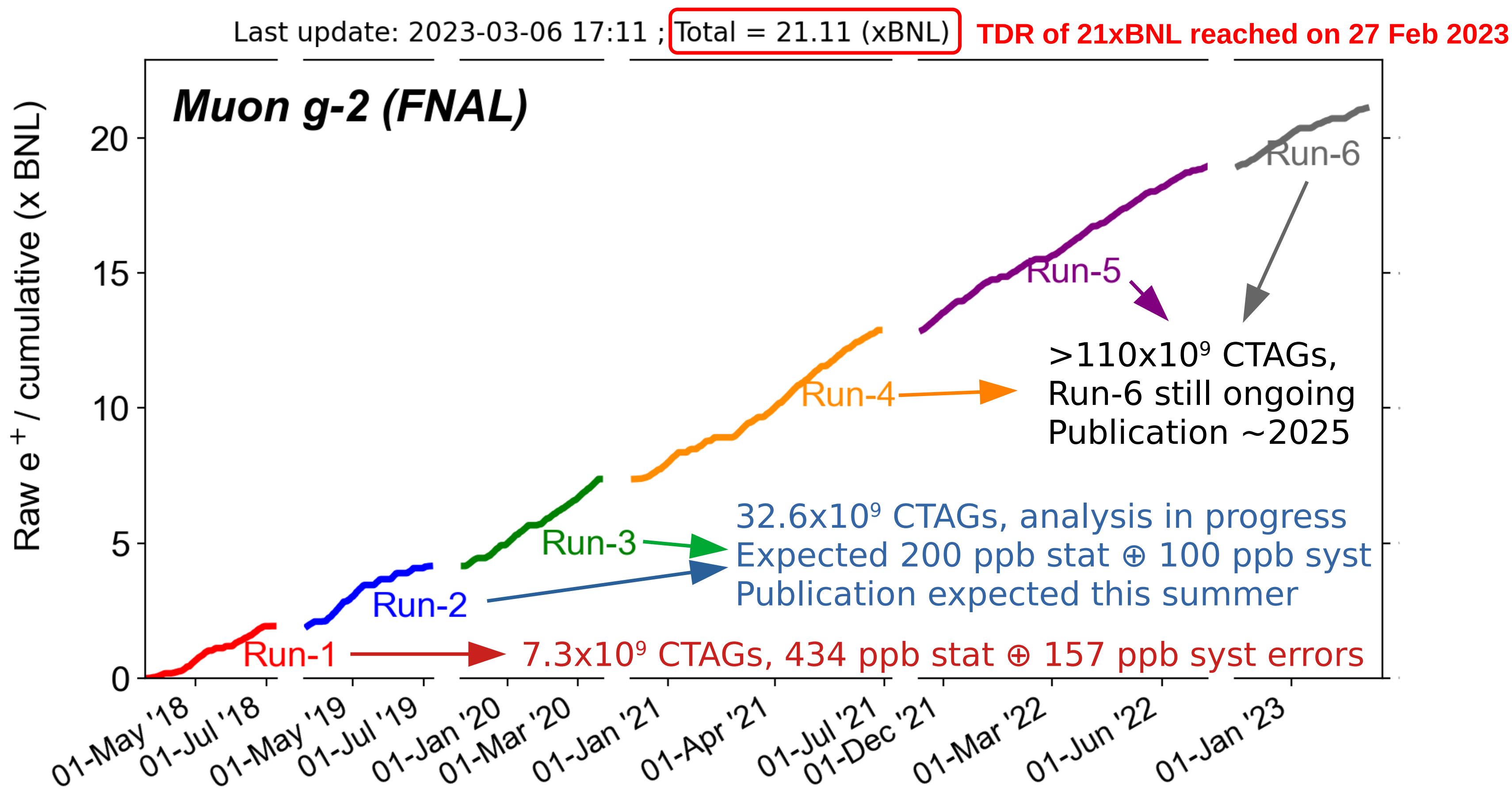
Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a (statistical)	-	434
ω_a (systematic)	-	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi)\cdot M(x,y,\phi)\rangle$	-	56
B_q	-17	92
B_k	-27	37
μ'_p/μ_e	-	10
m_μ/m_e	-	22
g_e	-	0
Total systematic	-	157
Total external factors	-	25
Total	544	462



a_μ (FNAL) = 116 592 040(54) × 10^{-11} (0.46 ppm)
a_μ (Exp) = 116 592 061(41) × 10^{-11} (0.35 ppm)

Where we are now



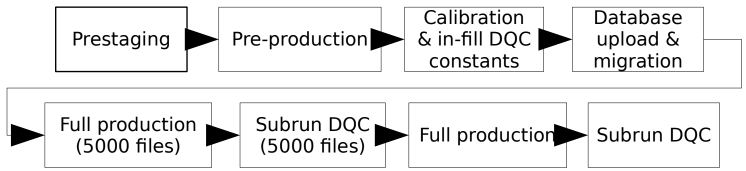


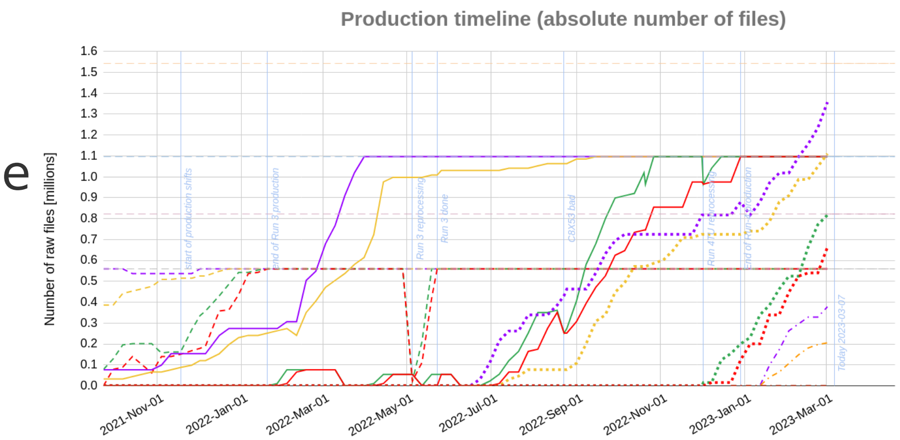
Data production

https://doi.org/10.22323/1.414.0228

- Non-trivial task to produce and handle more than **7 PB** of raw data (~4.5 million files)
- All the collected data contributes to the measurement and must be reconstructed
- Multi-step parallel production workflow involving continuously staging data from tape to disk, running ~5k jobs on grid, extracting gain calibrations, performing validation and DQC selection. Collaboration participates in offline-production shifts
- Production speed improved by factor 2 from Run-2 to Run-3 and then by another factor 2 from Run-3 to Run-4/5
- Run-6 is now being pre-produced in real time

Dataset	N° of files	Prod. time [days]	Rate [files/day]
Run-2	267152	129	2071
Run-3	538622	122	4415
Run-4	992005	111	8937





Current analyses

- **Run-1** published 7 April 2021
- **Run-2/3** analysis being finalized → publication this summer
  - 4x the statistics wrt Run-1 → expected 200 ppb stat error
  - Many hardware upgrades
    - A/C system installed in experimental hall, magnet insulating blanket
    - Kicker system improved and achieved design kick toward the end of Run-3
  - Several reconstruction and analysis improvements to reduce systematic uncertainties
  - Expected 100 ppb syst error
- **Run-4/5/6** being reconstructed → publication year 2025
  - Run-6 still ongoing
  - 4x the statistics of Run-2/3 → expected 100 ppb stat error
  - New Quad-RF system to reduce betatron oscillations
  - On track to achieve the final goal of 140 ppb

Summary

- The Muon g-2 Experiment is a precision experiment involving many aspect of physics and engineering
- Very successful Run-1 publication at 460 ppb which confirmed BNL measurement
- Ever-improving hardware conditions and analysis techniques from Run-2 onward
- New publication with 2x precision is imminent
- On track to achieve final goal of 140 ppb
- New tensions on the theory side for hadronic contributions to a_μ
- 75 years of g-2 physics and it's still a hot topic

Thank you for listening!