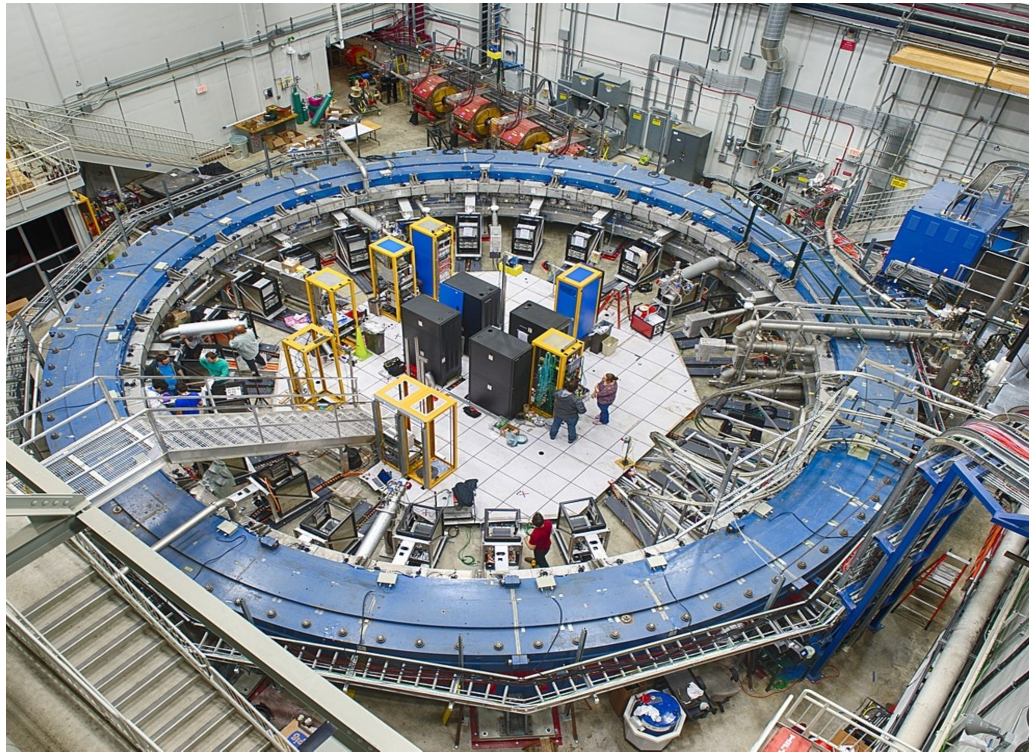
Techpub number: FERMILAB-SLIDES-23-099-V



INFN
Istituto Nazionale di Fisica Nucleare

μ g-2
Fermilab

# The Muon g-2 Experiment
## - in 10 minutes -

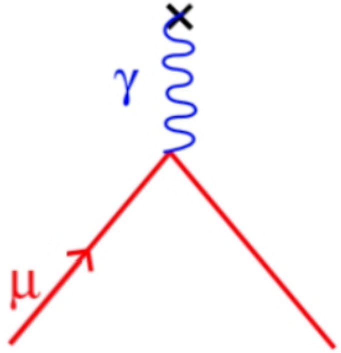
New Perspectives 2023
27 June 2023

**Paolo Girotti (INFN Pisa)**
on behalf of the g-2 collaboration

# What is g-2

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

- **g** is a dimensionless factor which encodes all the possible virtual interactions between the fermion and the magnetic field
  - At tree level is **g = 2**



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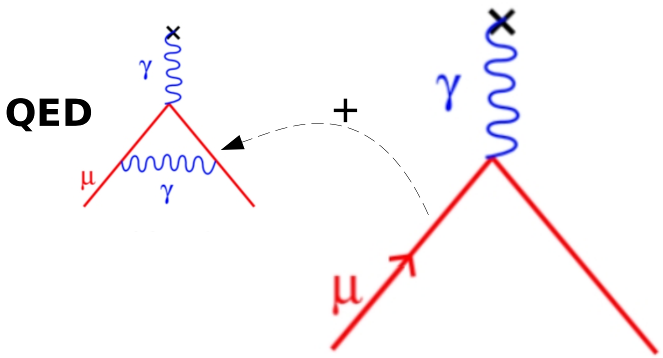
  - After counting for the virtual contributions from the entire Standard Model it becomes **g = 2.002331...**



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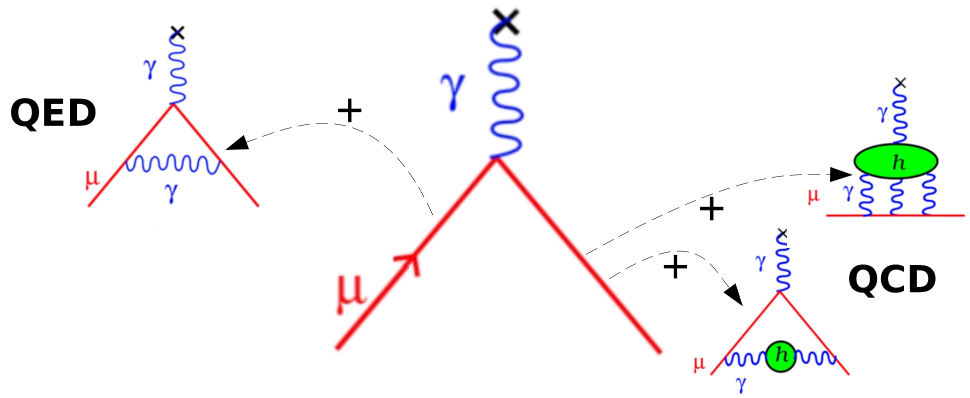

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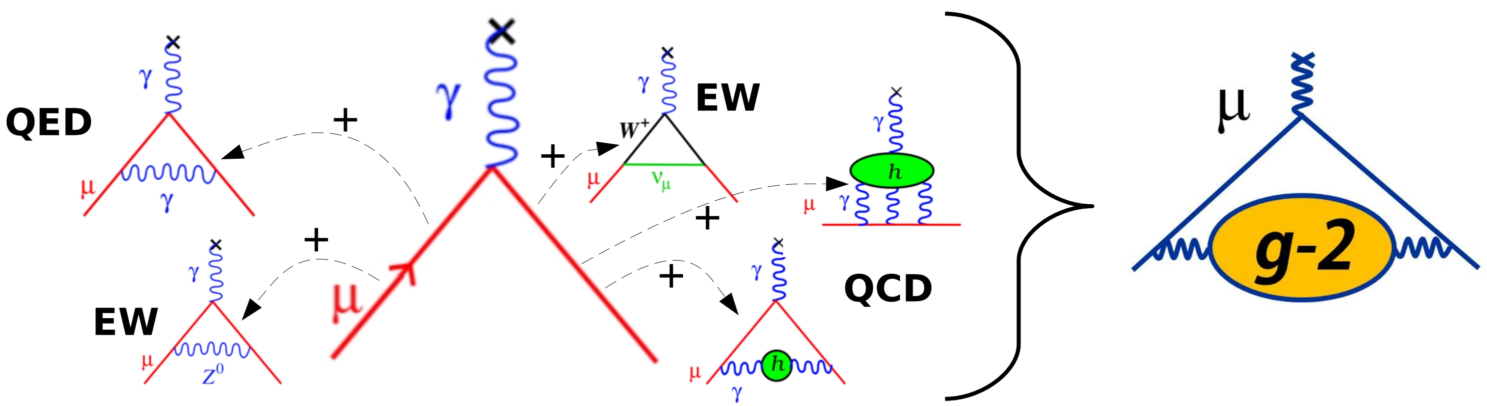
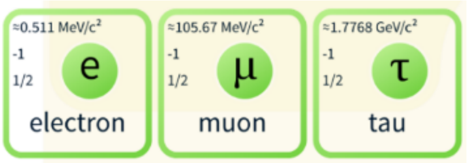


# Why Muon g-2

- Any **discrepancy** between experimental measurement and theoretical prediction could be a hint of **new physics**
- Leptons are the only elementary fermions that we can easily produce and store



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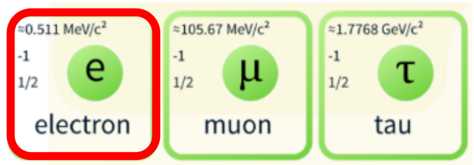


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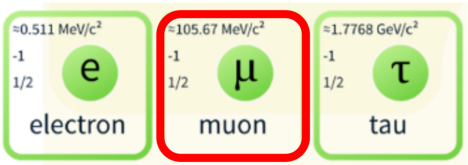


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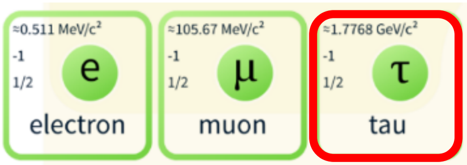


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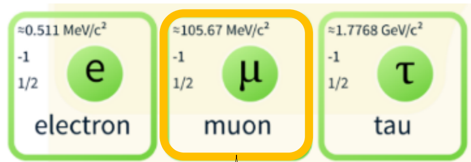
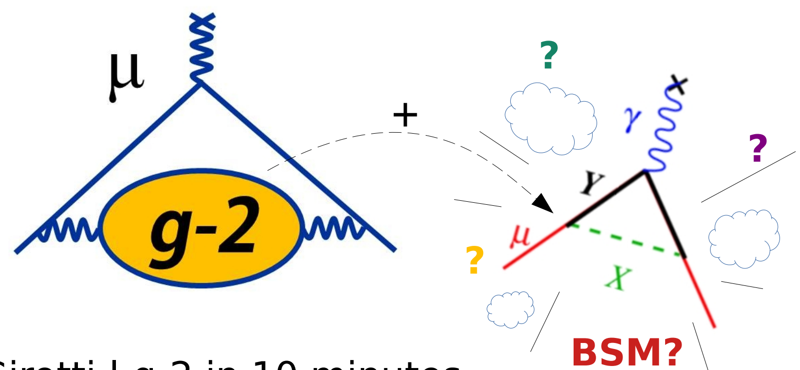


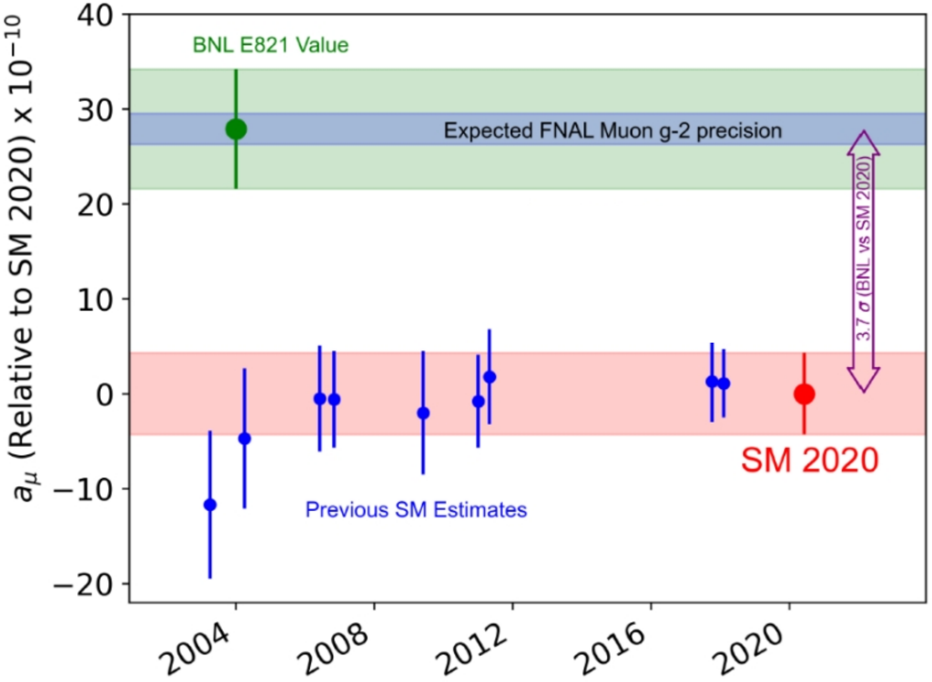

- The electr ... ted with extremely ... 6(56)
- The muon ... es more sensitive t...
- The tau would be even ... impractical

The muon is our golden ticket to explore the unknown...
Just measure it very precisely!



# Is there a hint?

## Before 2021




- BNL E821 Experiment (2006) and Standard Model theory (2020) were different by **3.7σ**
- Fermilab E989 Experiment goal: improve the experimental precision by a factor of **4** to 140 ppb

# Is there a hint?

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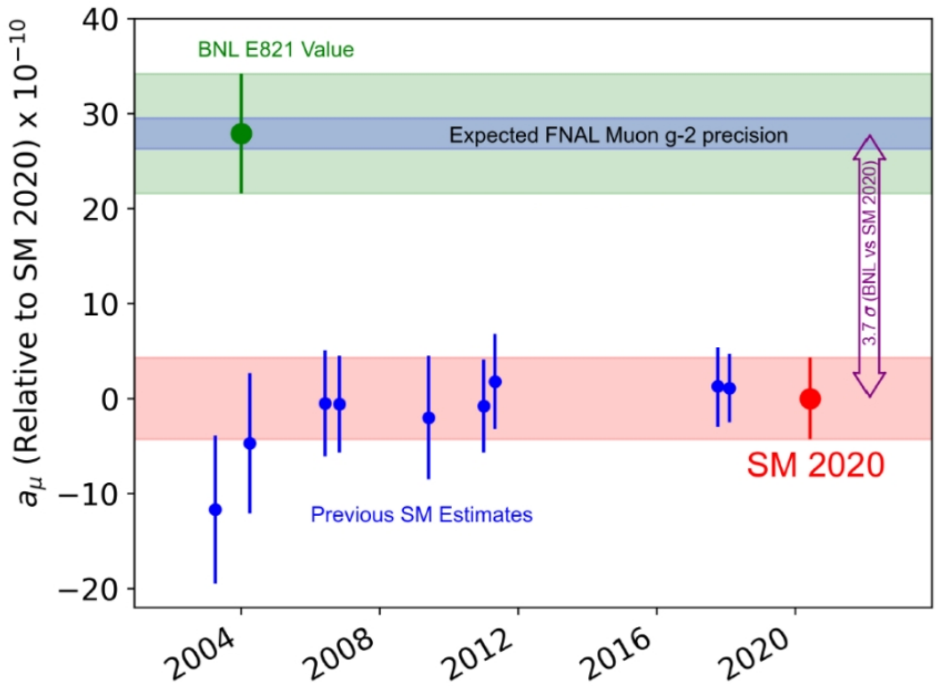


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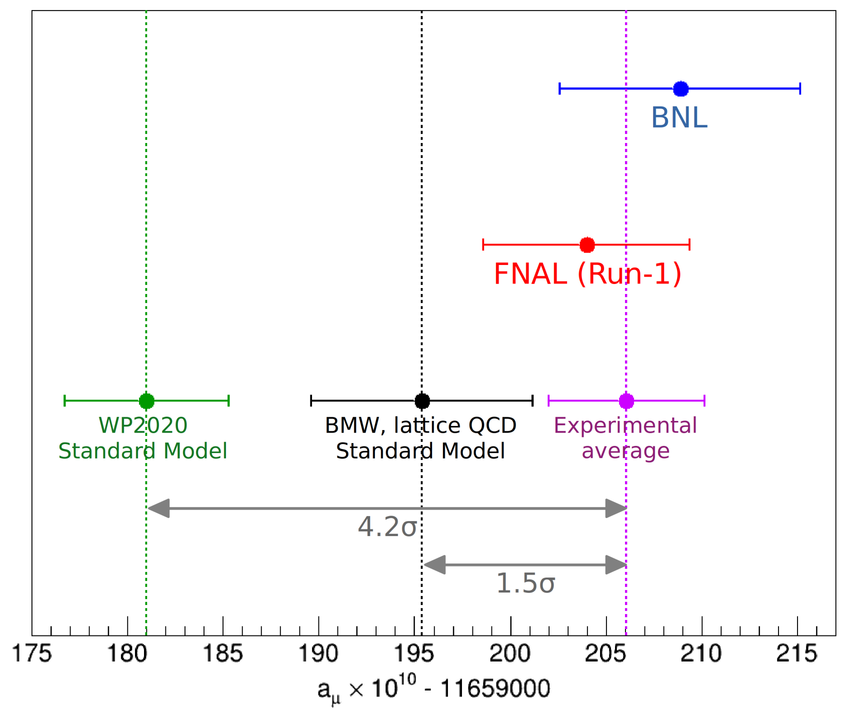
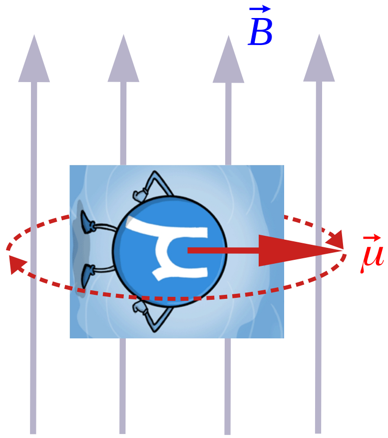
## 2021 - Now




- Fermilab Run-1 result published in 2021 with 460 ppb precision → Discrepancy increased to **4.2σ** !
- New precise **Lattice-QCD** calculations of the hadronic contribution to $a_\mu$ in tension with the data-driven SM prediction → a new g-2 puzzle !

# How to measure g-2

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




- In a magnetic storage ring, the muon spin precesses slightly faster than the cyclotron frequency

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

- If we do the difference we get...

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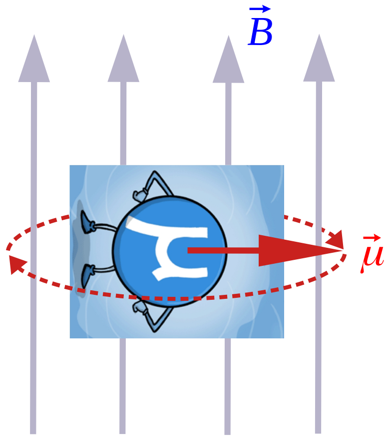


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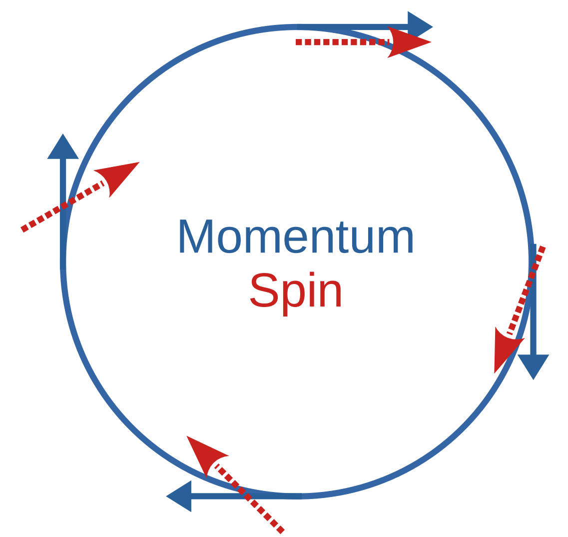
- If we do the difference we get…

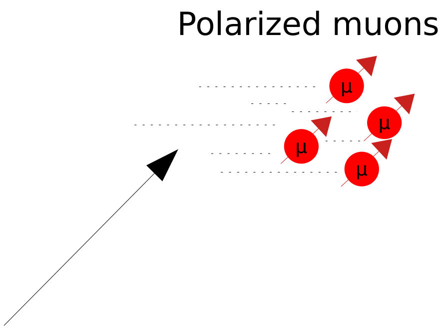
$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -a_\mu \frac{e\vec{B}}{m}$$

- The “anomalous” precession frequency of the muon is proportional to the g-2 and to the magnetic field strength
- Virtual particles make this happen!
- Measure $\boldsymbol{\omega}_a$ and **B** → obtain $\mathbf{a}_\mu$

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



# Let's build a g-2 experiment

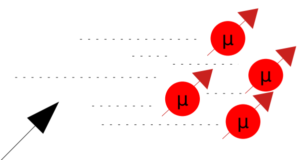



- Produce muons artificially
- Very pure and polarized beam
- Luminosity as high as possible

$$a_\mu = \frac{m_\mu}{e} \frac{\vec{\omega_a}}{\vec{B}}$$

# Let's build a g-2 experiment

Polarized muons

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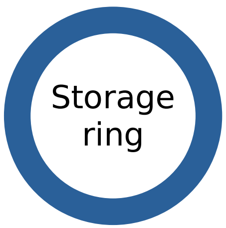


- Produce muons artificially
- Very pure and polarized beam
- Luminosity as high as possible

- Inject beam into a continuous magnet
- Store the muons until they all decay
- Keep the beam focused and centered

# Let’s build a g-2 experiment

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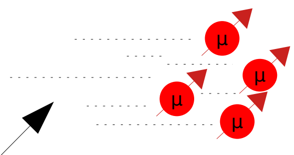
Polarized muons

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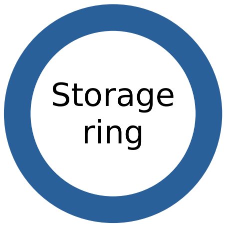


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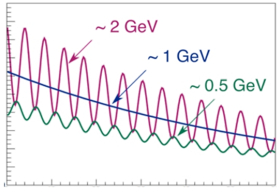
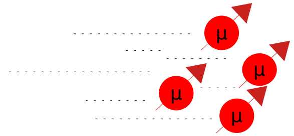
Measure $\omega_a$, B



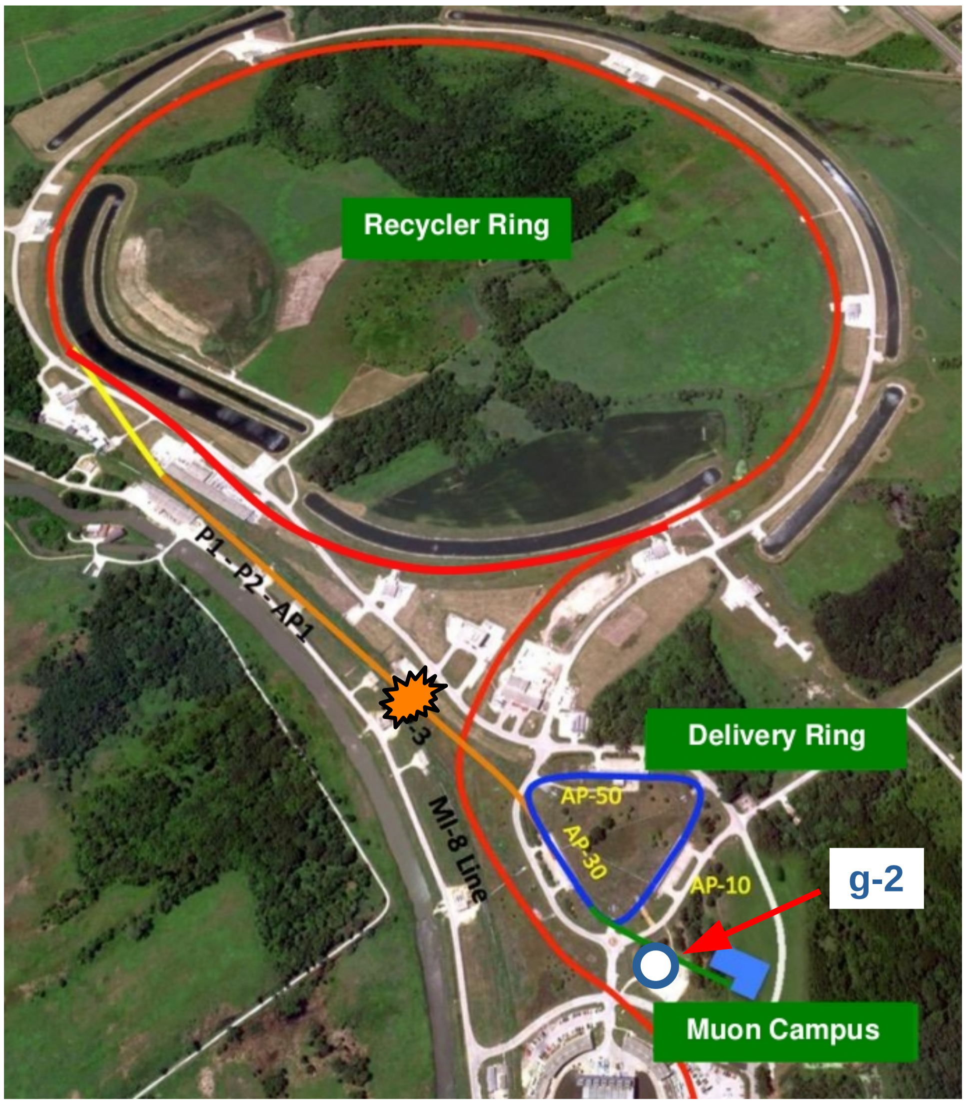

- Detect all the decay positrons
- Measure the magnetic field
- Measure the beam distribution

# How to

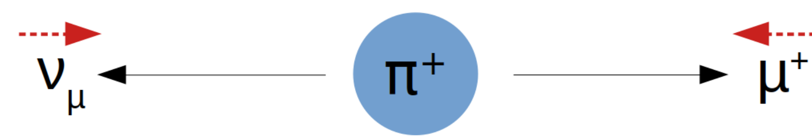
Polarized muons




$$p \rightarrow \pi^+ \rightarrow \mu^+$$



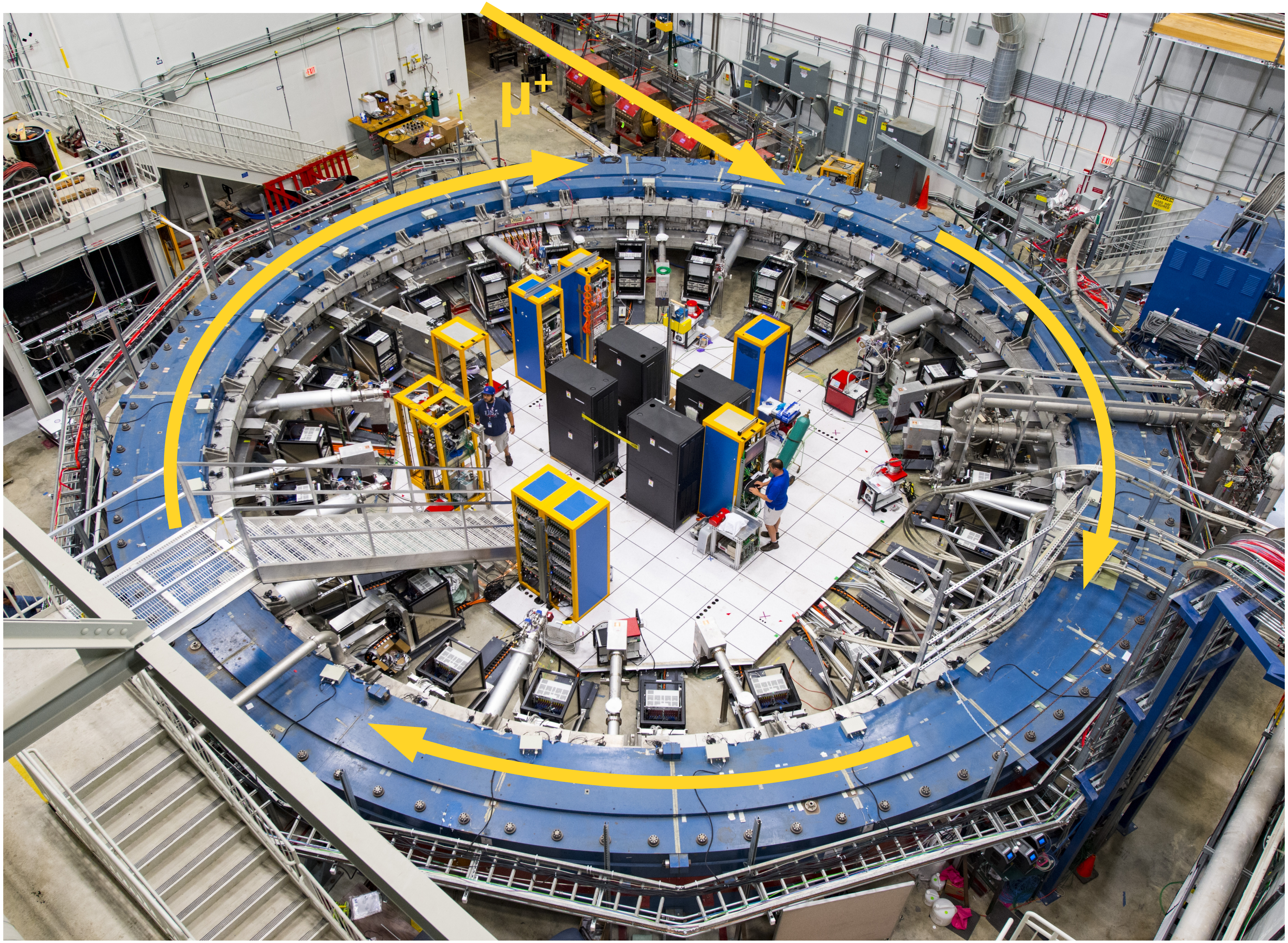

- 16 bunches of $10^{12}$ protons boosted @8 GeV to recycler ring and sent toward a fixed target
- Positive pions are extracted from the interaction with target
- Four turns in the delivery ring to separate remaining protons and let pions fully decay into muons
- High energy muons are naturally polarized



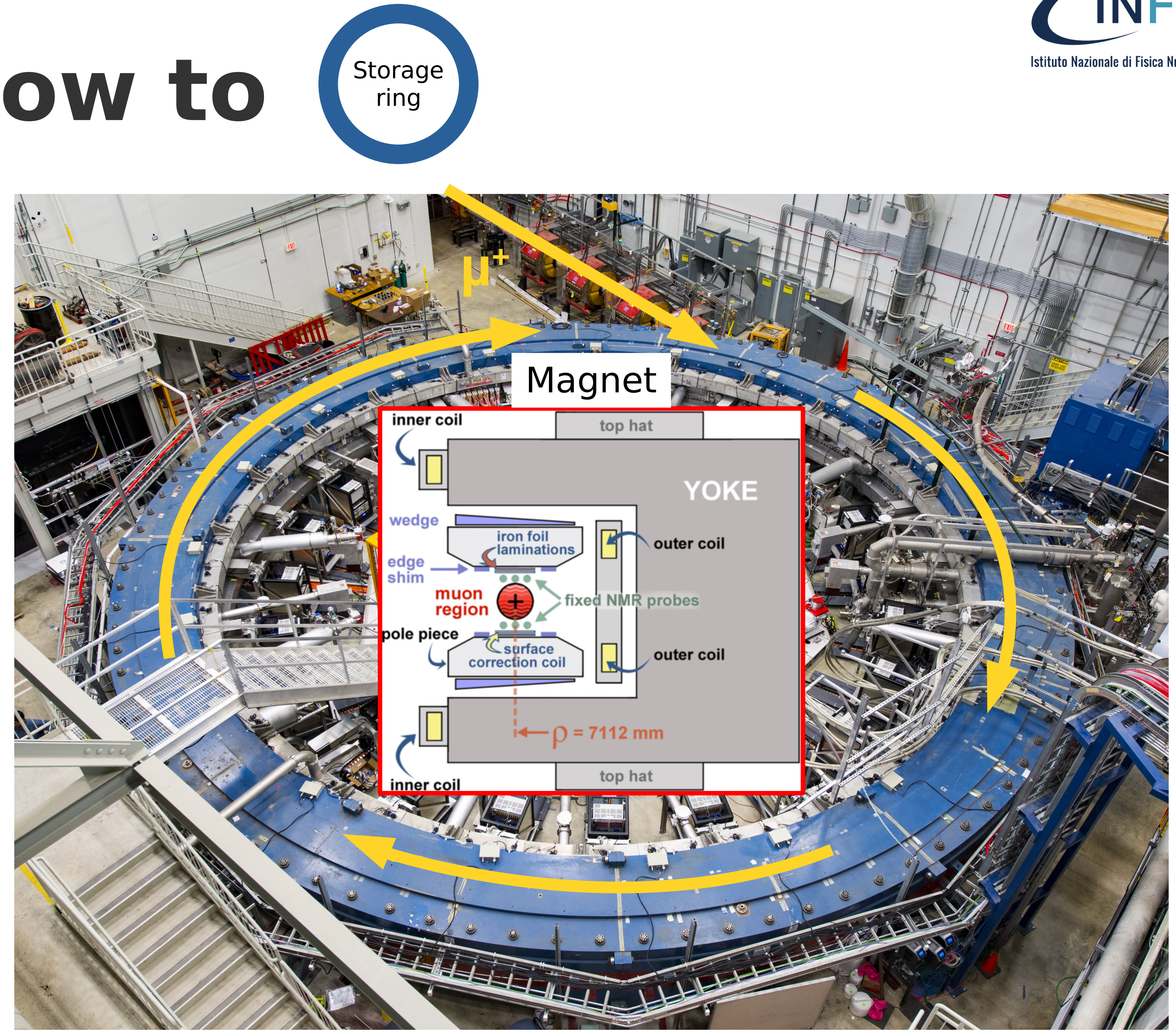

- Muons enter the g-2 ring

# How to

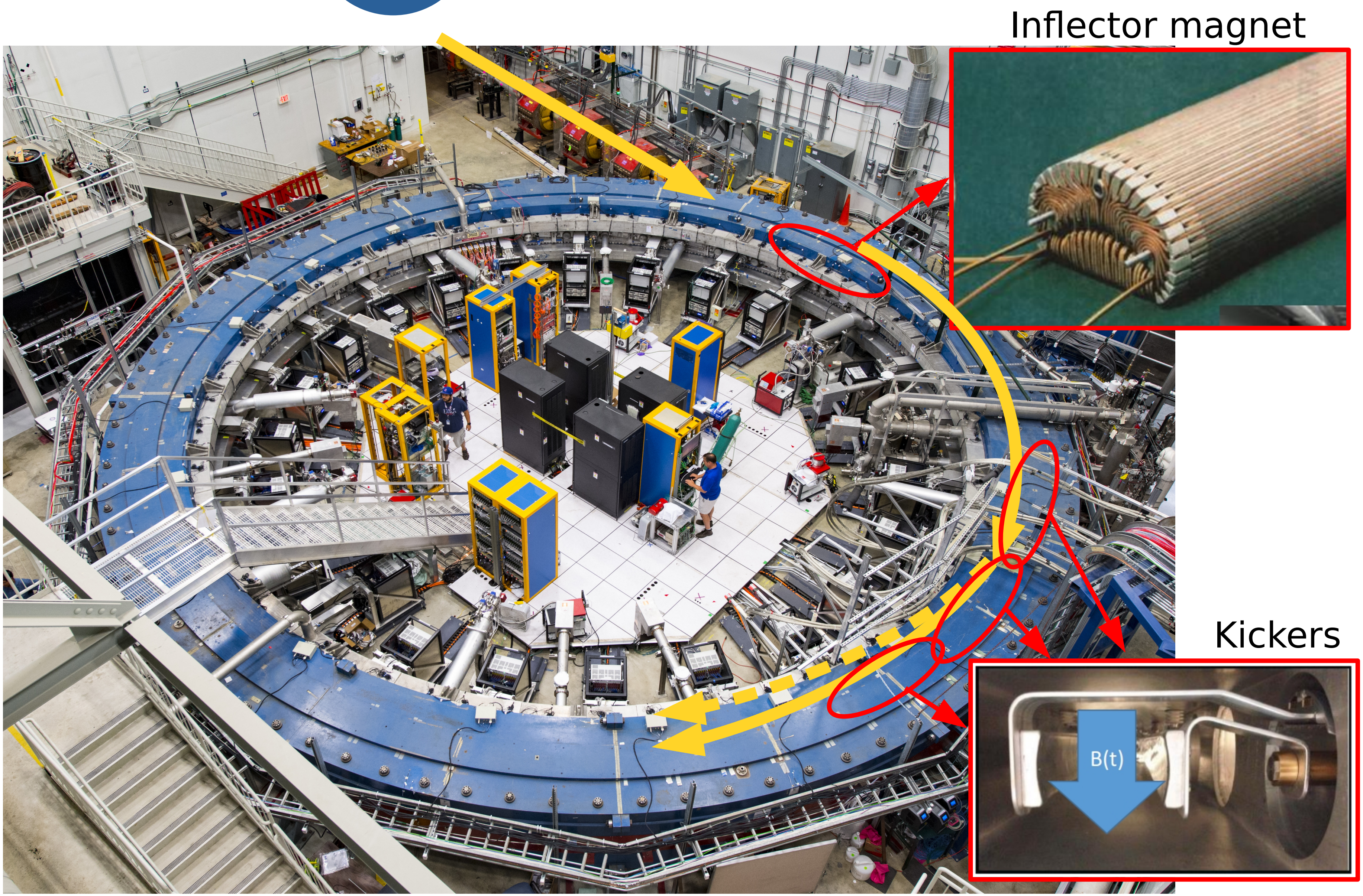
Storage ring



# How to


Storage
ring
μ+
Magnet
inner coil
top hat
YOKE
wedge
iron foil
laminations
outer coil
edge
shim
muon
region
fixed NMR probes
pole piece
surface
correction coil
outer coil
ρ = 7112 mm
inner coil
top hat

# How to Storage ring



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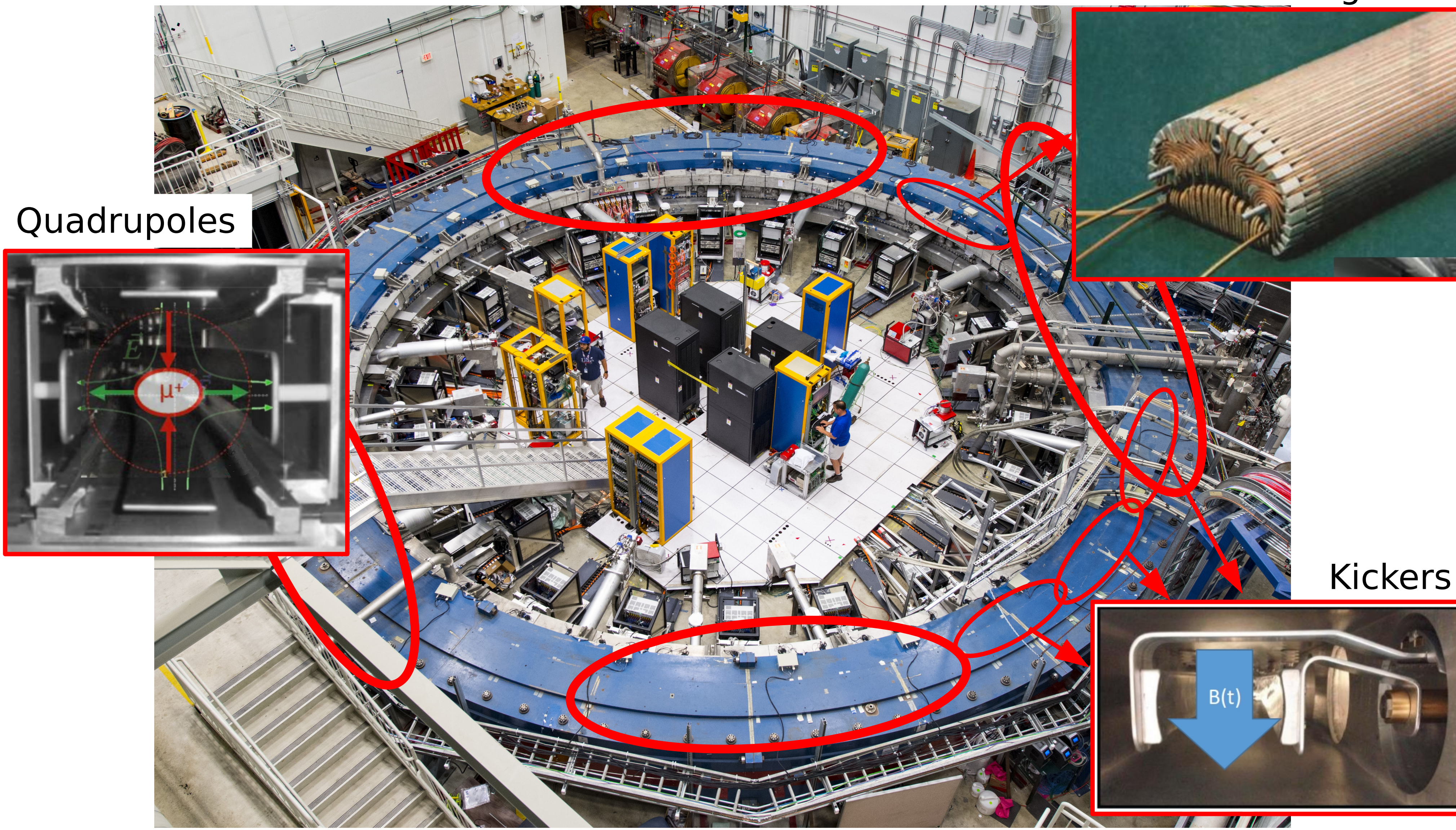

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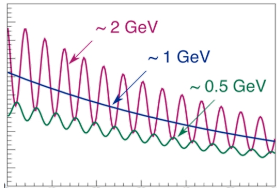


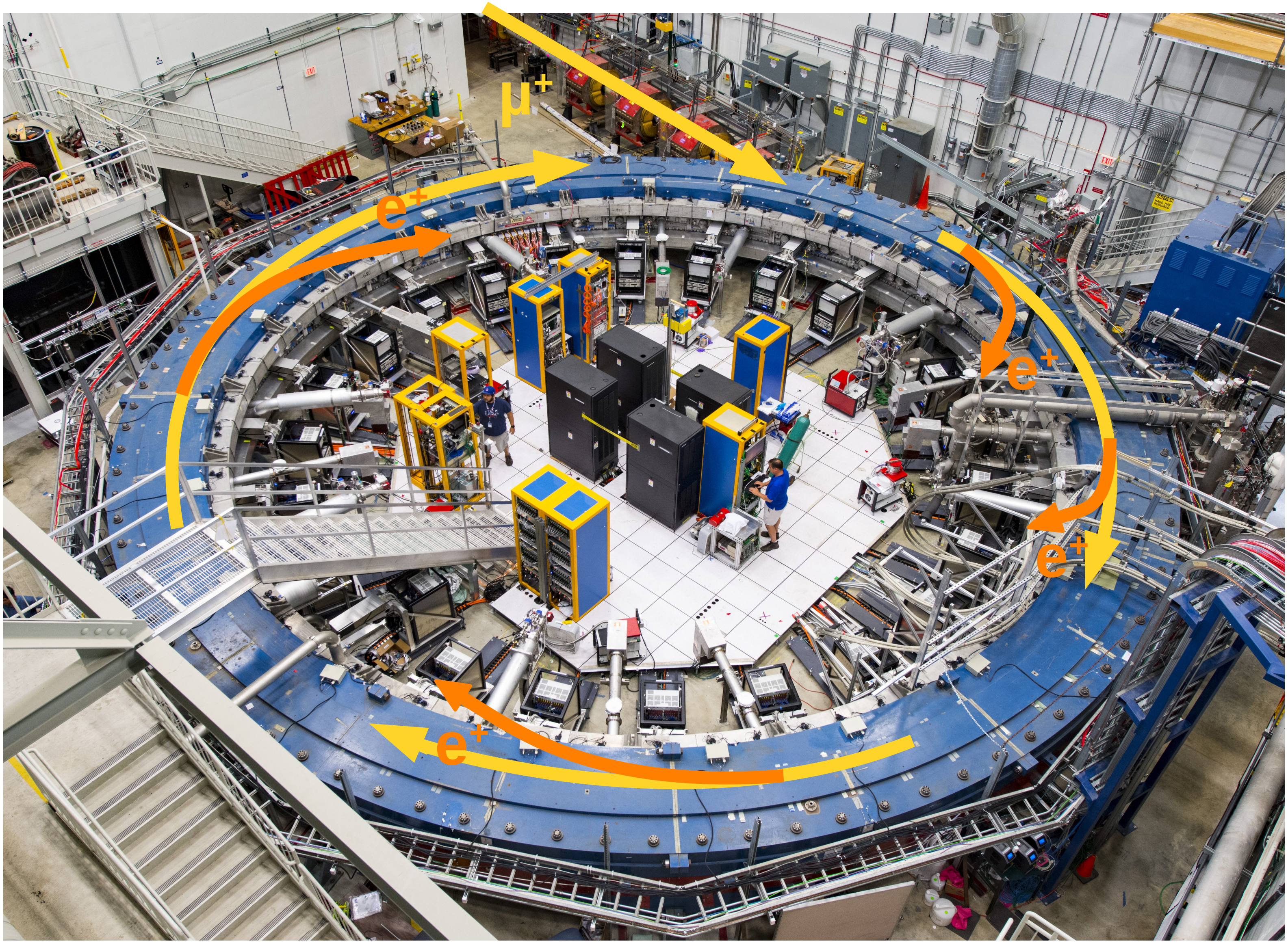

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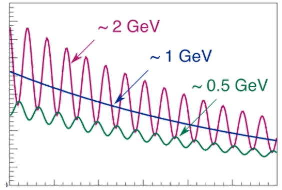
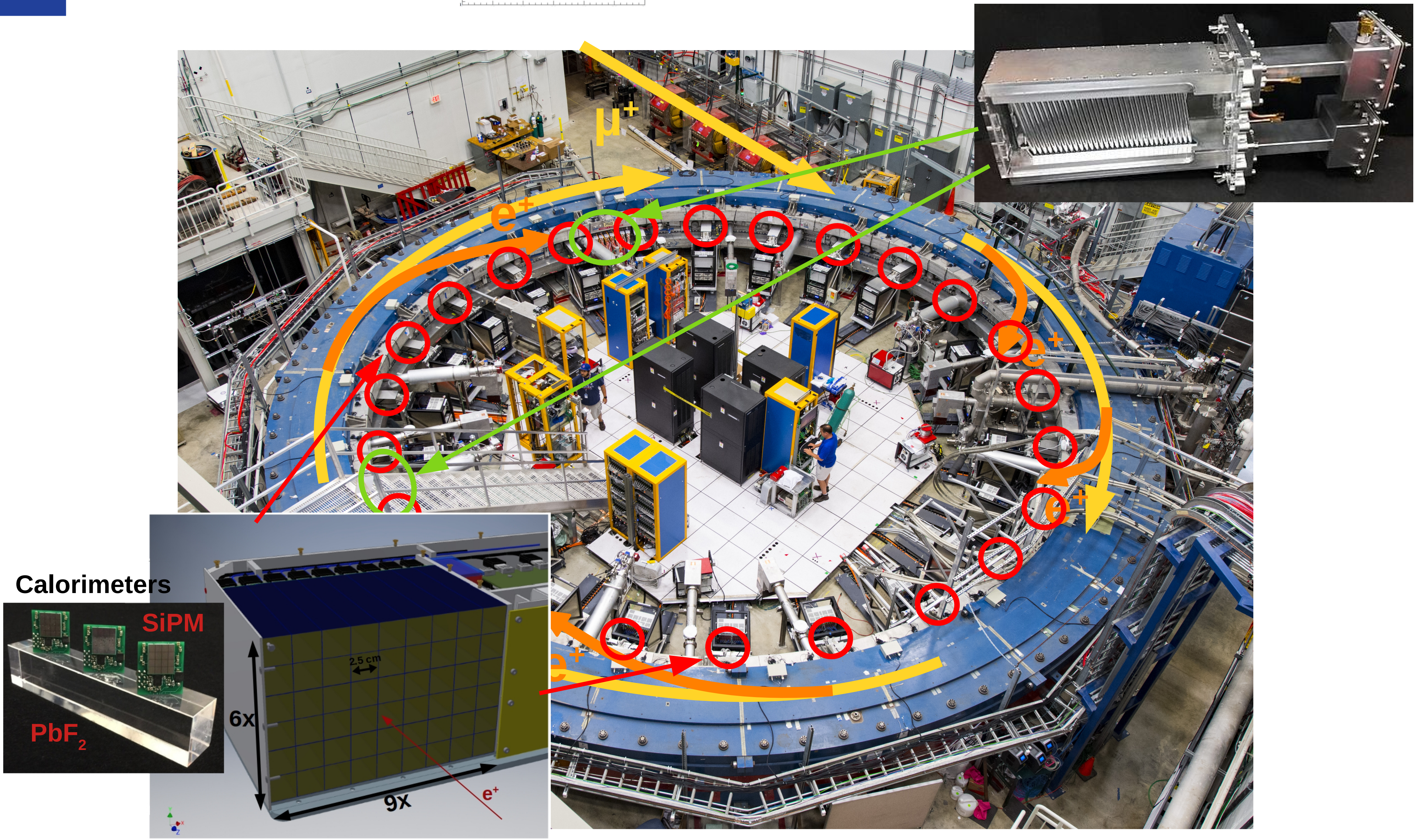



**Tracker modules**

**Calorimeters**



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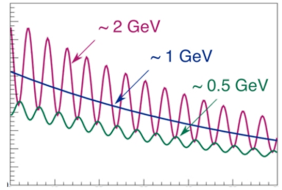
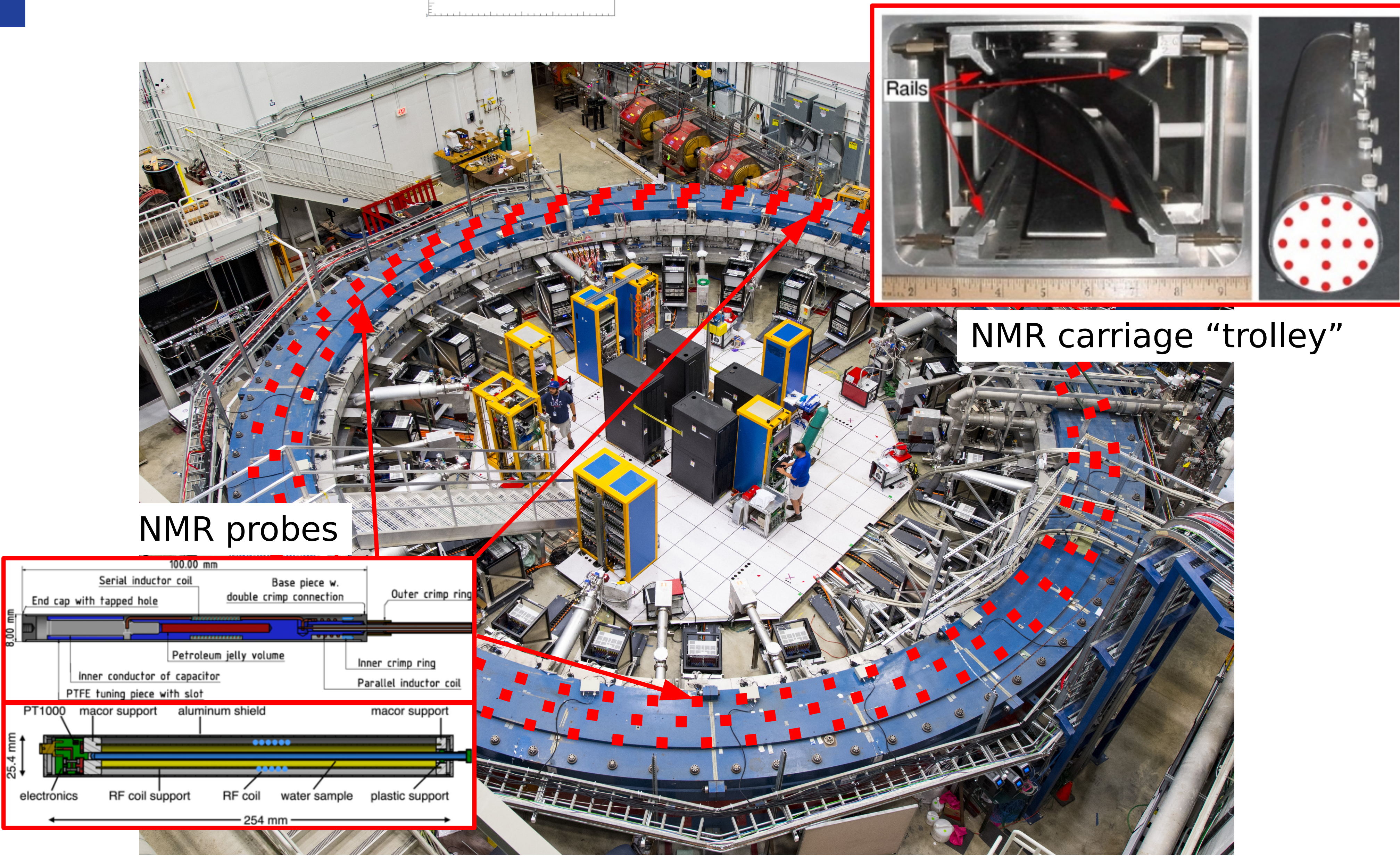
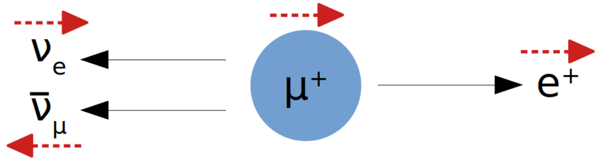


~ 2 GeV
~ 1 GeV
~ 0.5 GeV

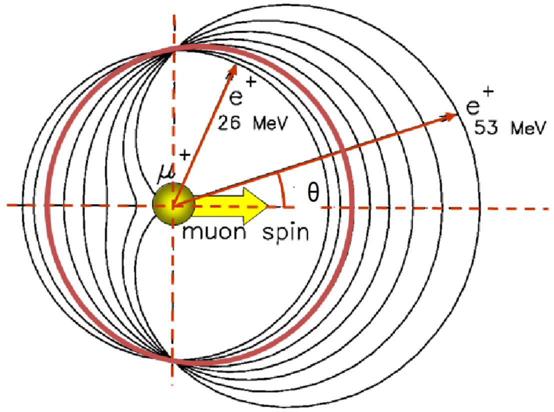



Rails
NMR carriage “trolley”
NMR probes
100.00 mm
Serial inductor coil
End cap with tapped hole
Base piece w. double crimp connection
Outer crimp ring
8.00 mm
Petroleum jelly volume
Inner crimp ring
Inner conductor of capacitor
Parallel inductor coil
PTFE tuning piece with slot
PT1000
macor support
aluminum shield
macor support
25.4 mm
electronics
RF coil support
RF coil
water sample
plastic support
254 mm

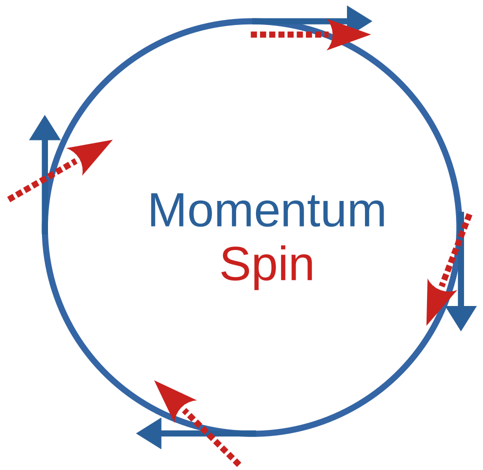
# How to measure $\omega_a$




Muon decays in a
<u>positron</u> and 2 neutrinos

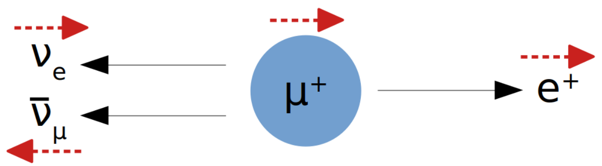



Parity violation → positrons
in CM preferably in the
<u>direction of the muon spin</u>




Spin precession → the energy
spectrum in the lab frame
**oscillates** through time

# How to measure $\omega_a$

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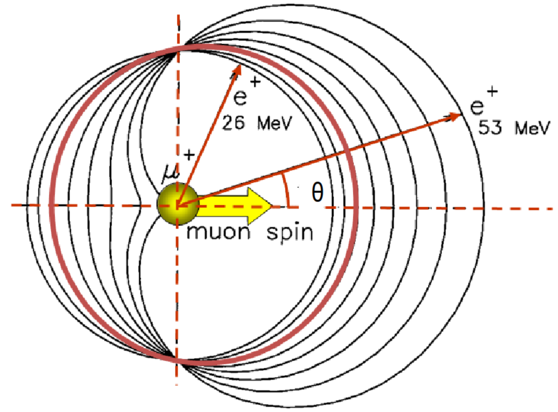


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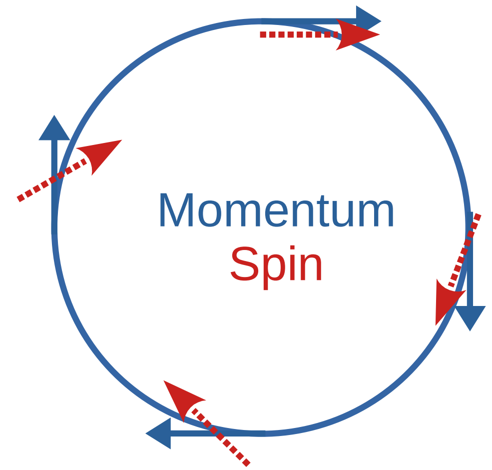


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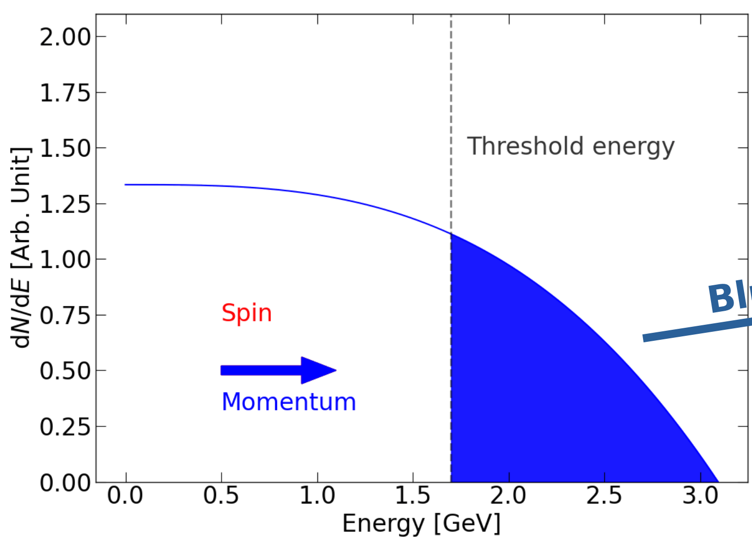
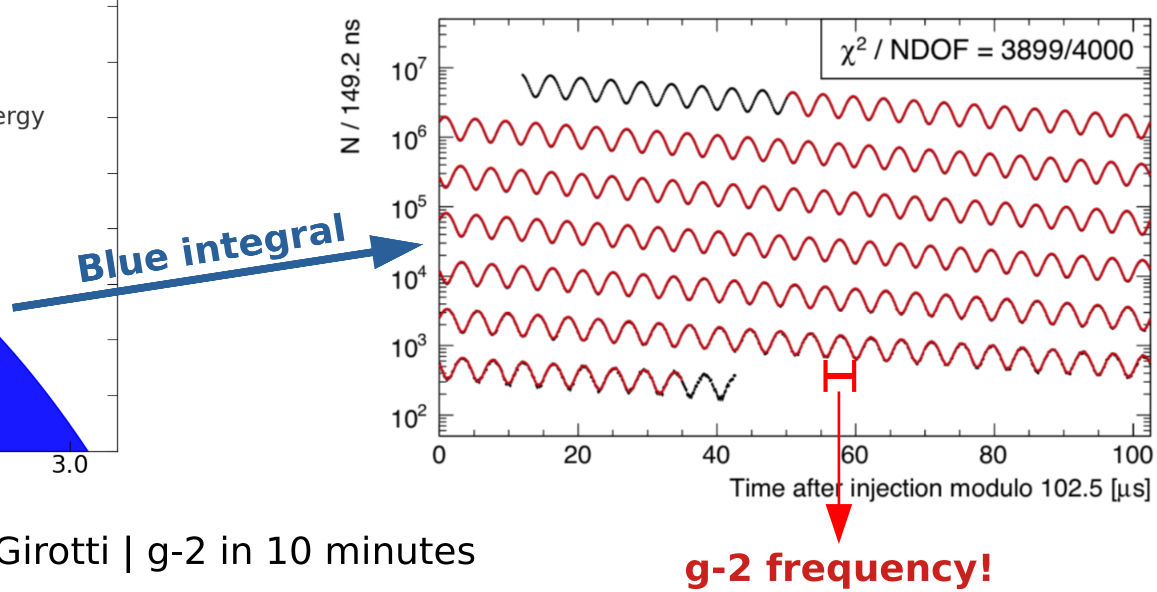


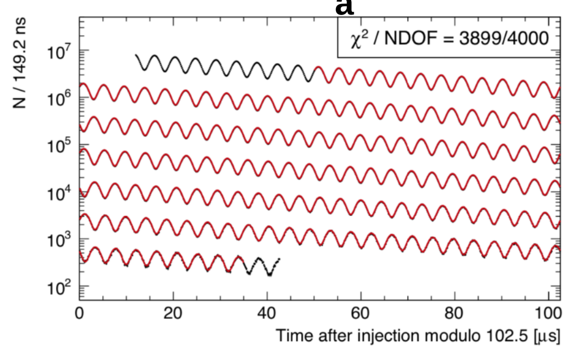



# Final formula

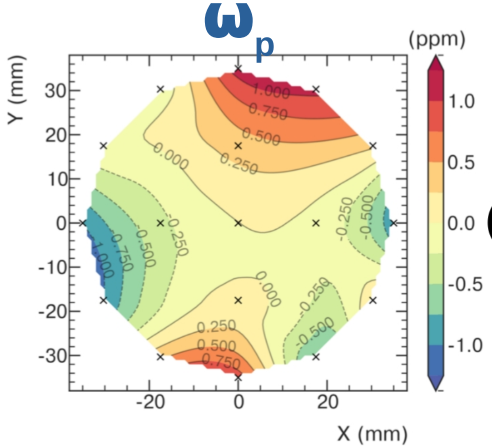
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

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

**$\omega_a$**

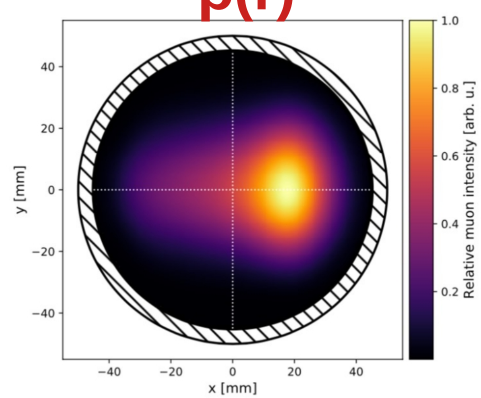



**$\omega_p$**




$\otimes$

**$\rho(r)$**




**Three measurements:**

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

# Painstaking detail

- Many analysis teams performing the same measurements independently
- Many cross-checks and validation routines
- Every systematic effect to be studied at **ppb** level → that's 0.0000001% !

| 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 |

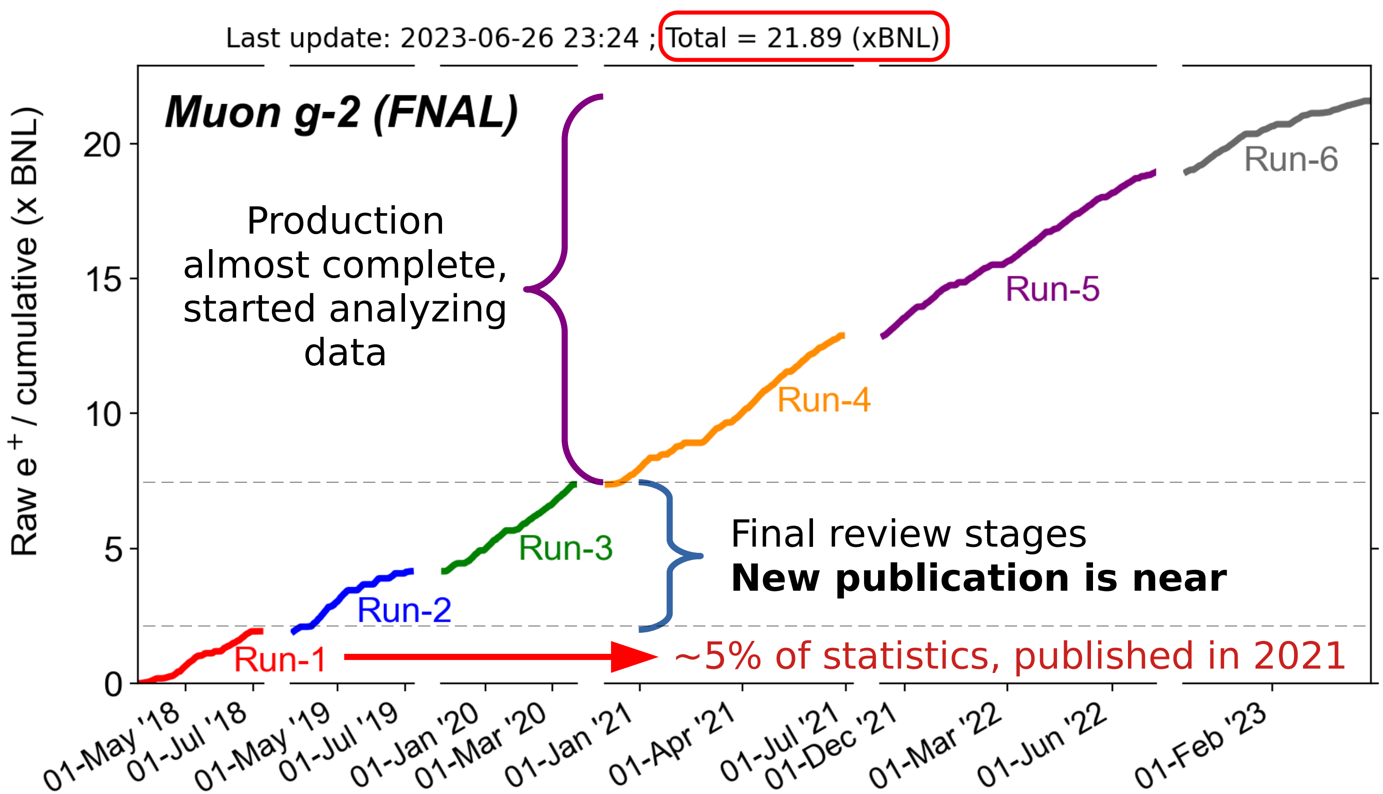
| | |
|---|---|
| run-1 (substructure) | 77.4 ppb |
| azimuthal shape* | 7.6 ppb |
| skin depth | 12.6 ppb |
| frequency extraction (0.4/1ms) | 4.6 ppb |
| Q3L: fit, position | 1.5 ppb |
| repeatability | 13.3 ppb |
| drift | 10.2 ppb |
| radial dependency | 4.4 ppb |
| $2^{nd}$ 8-pulses | 14.0 ppb |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

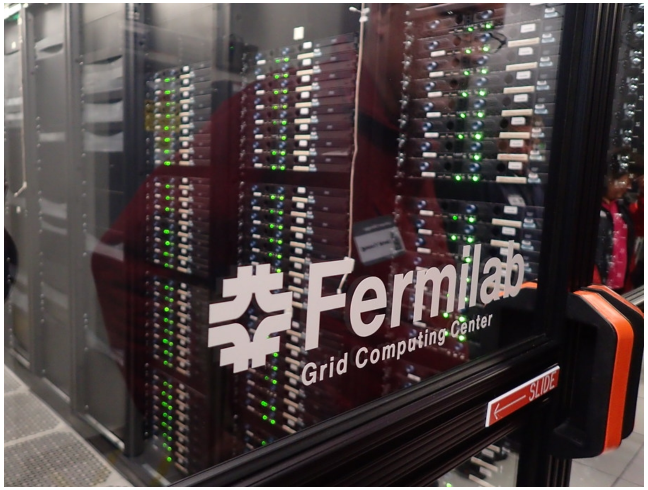
## Run-1 uncertainty table

| Quantity | Correction [ppb] | Uncertainty [ppb] |
|---|---|---|
| $\omega_a$ (statistical) | - | 434 |
| $\omega_a$ (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 |
| $\mu'_p/\mu_e$ | - | 10 |
| $m_\mu/m_e$ | - | 22 |
| $g_e$ | - | 0 |
| Total systematic | - | 157 |
| Total external factors | - | 25 |
| Total | 544 | 462 |

# A lot of data

- More than **7 PB** of raw data have been accumulated in 6 years of data taking
- All the detected ~$10^{11}$ positrons are reconstructed and carefully calibrated in time and energy
- ~$3x10^7$ cpu-hours of Grid production every year + simulation



# Takeaways

- The Muon g-2 is a fashinating topic that touches a large portion of modern physics
- Impossible to cover all aspects of g-2 in 10 minutes
  → I hope I sparked a bit of curiosity
- Possible hints of new physics could come via extreme precision measurements
- New tensions are arising on the theory side too
- New publication at ~220 ppb coming as soon as analysis review is complete. Stay tuned!

**Thank you for listening!**