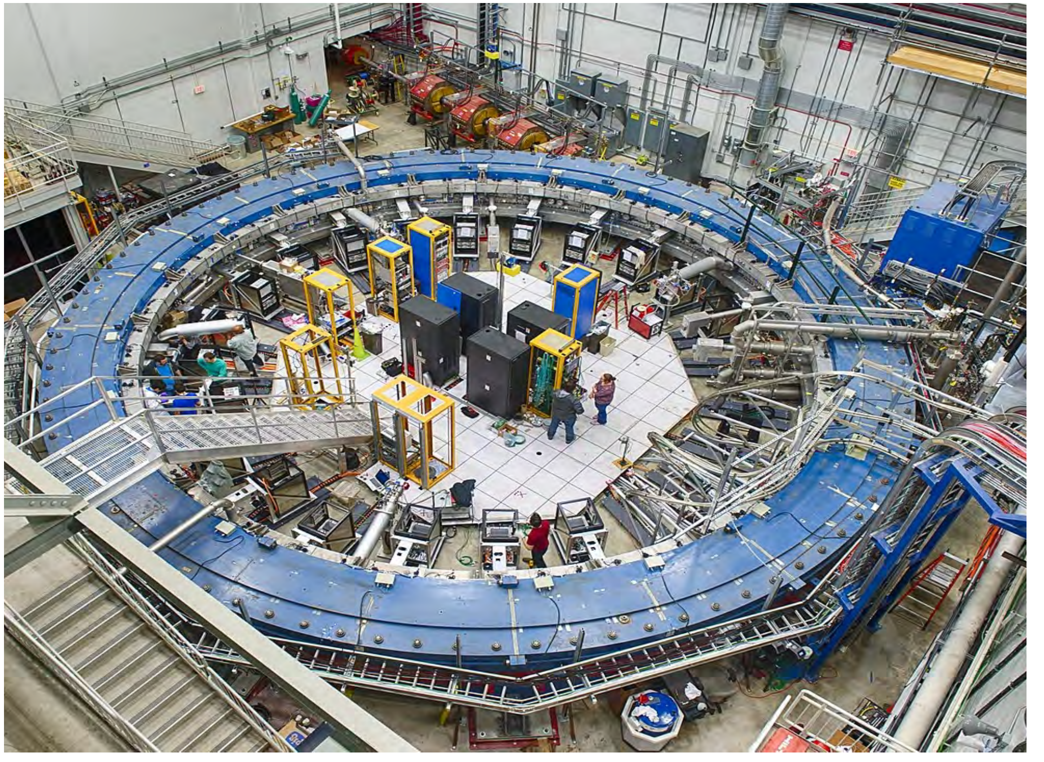
Techpub number: FERMILAB-SLIDES-23-099-V



The Muon g-2 Experiment
- in 10 minutes -

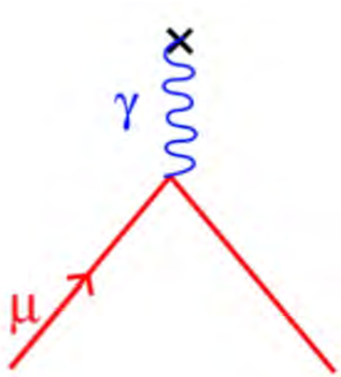
New Perspectives 2023
27 June 2023

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 <u>encodes all</u> the possible virtual interactions between the fermion and the magnetic field
  - At tree level is **g = 2**



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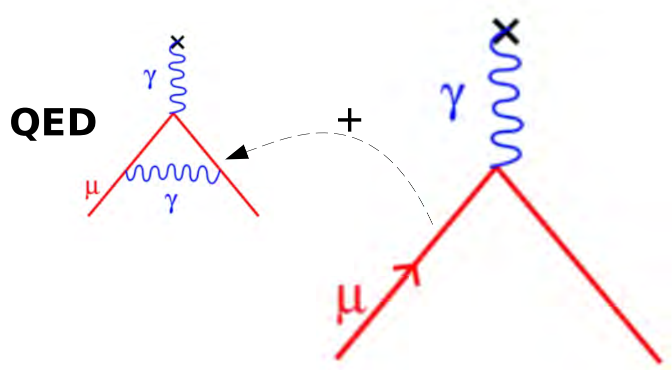
  - After counting for the virtual contributions from the entire Standard Model it becomes **g = 2.002331...**



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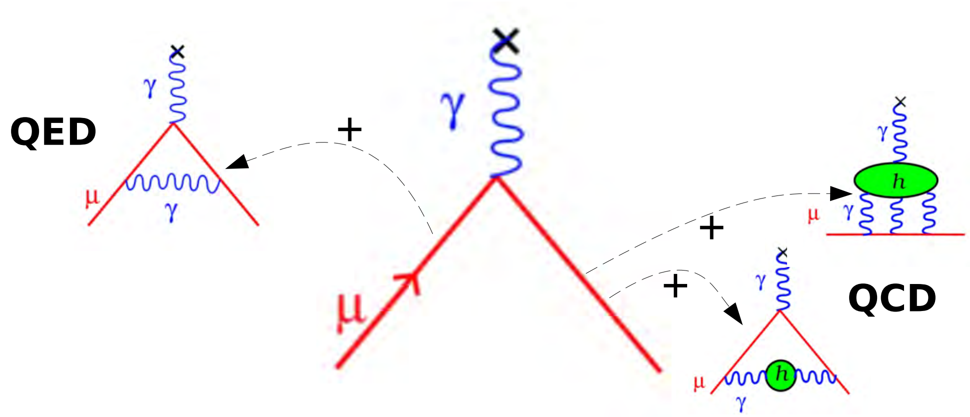

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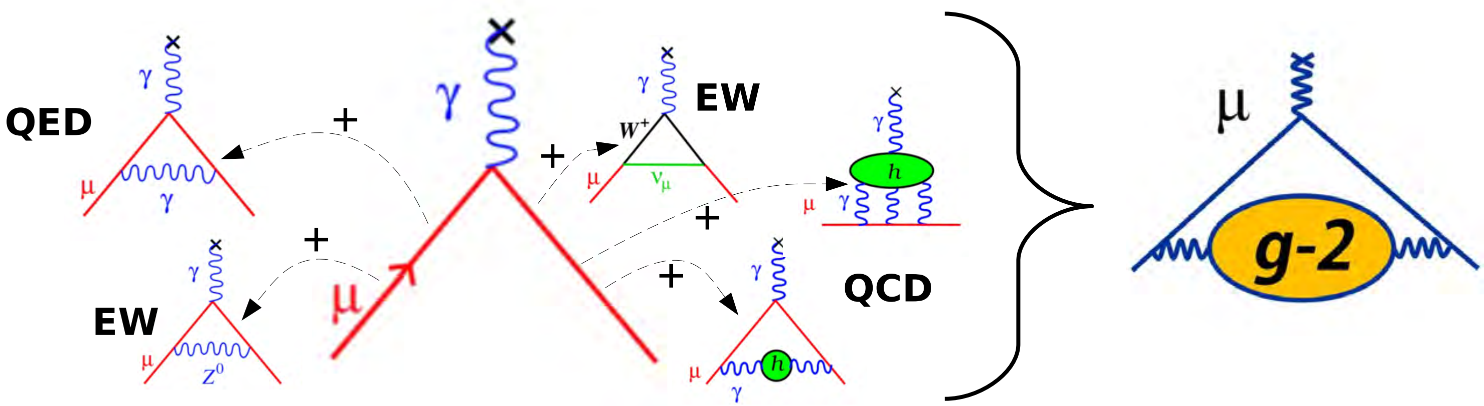
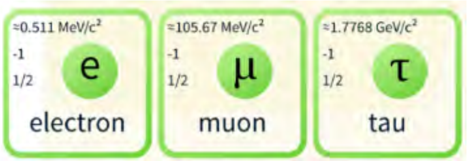


Why Muon g-2

- 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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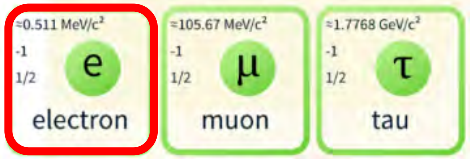

- The electron g-2 is already measured and calculated with extremely high precision → g_e = 2.00231930436146(56)

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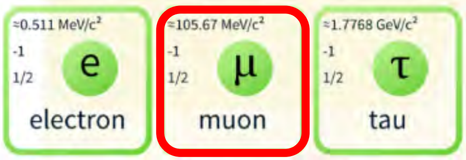

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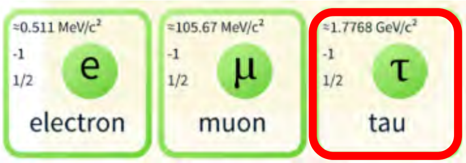

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- The muon is 200 times more massive → 40’000 times more sensitive to new massive particles
- The tau would be even better, but it’s impractical

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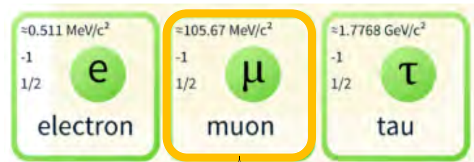
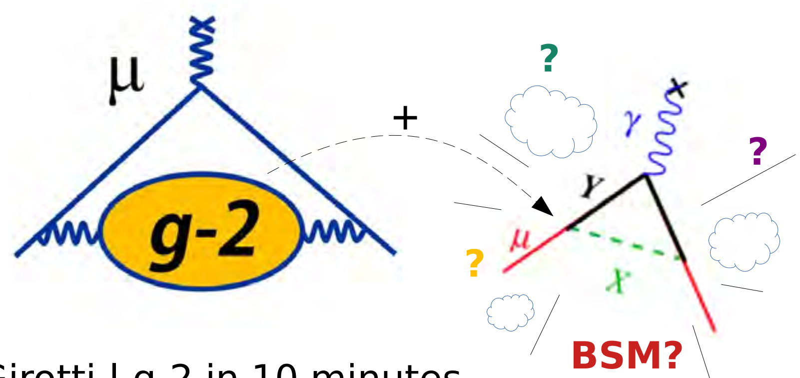


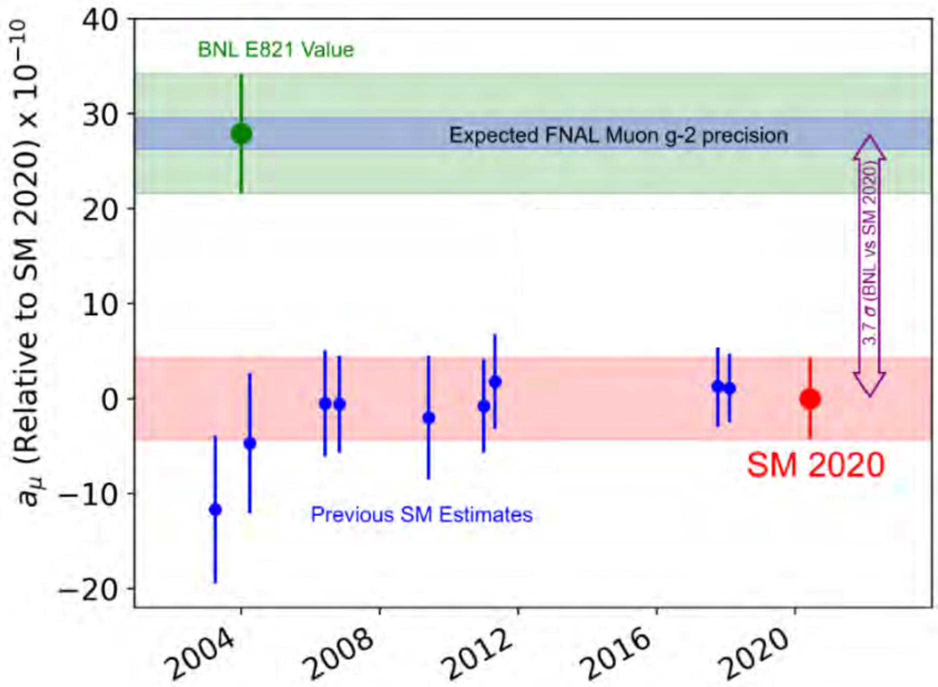
- The electro … ted with extremely … 6(56)
- The muon … es more sensitive t…
- The tau wo…

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



Is there a hint?

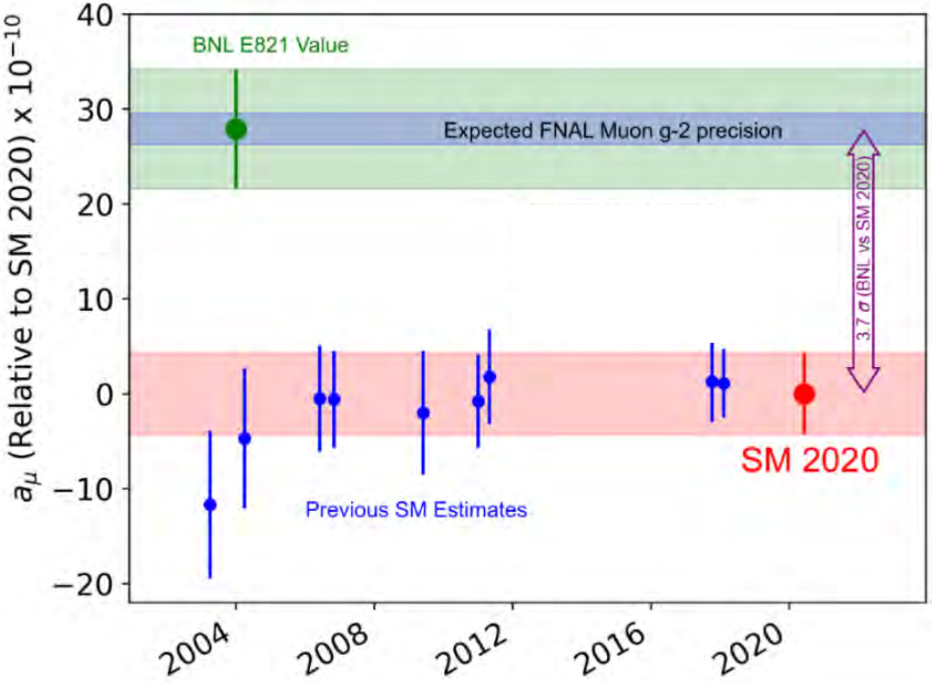
Before 2021



- 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?

Before 2021



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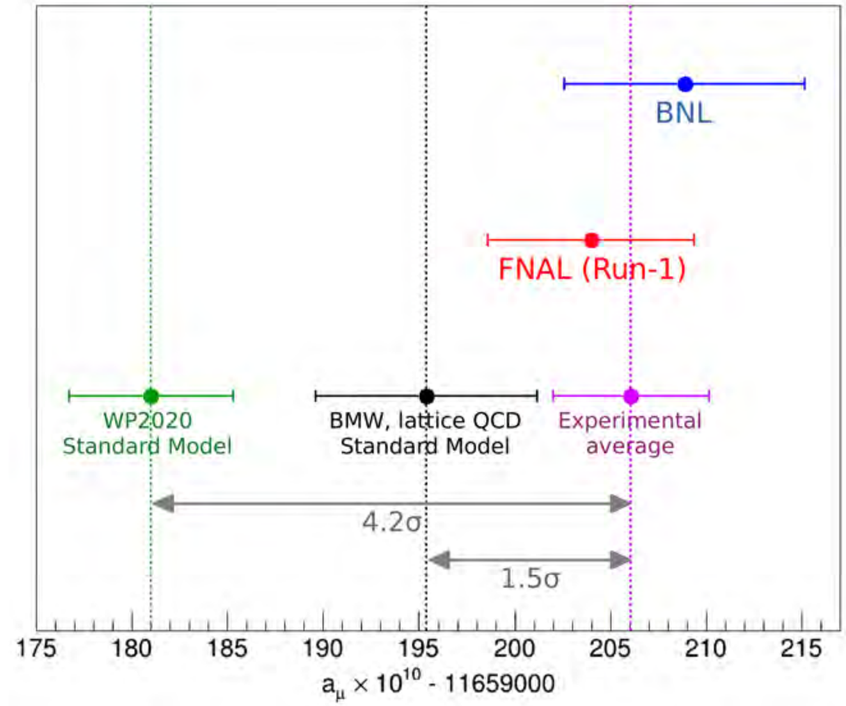
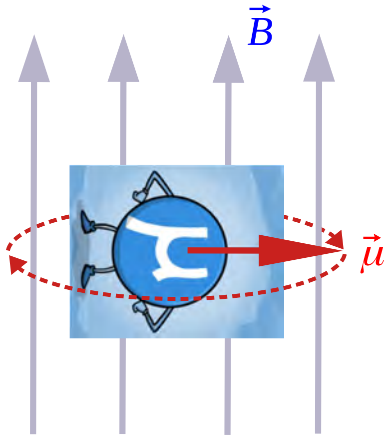
2021 - Now



- 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_μ 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

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

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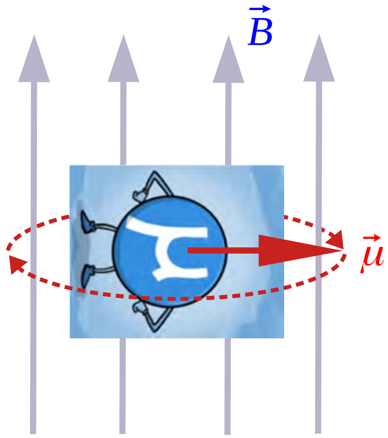

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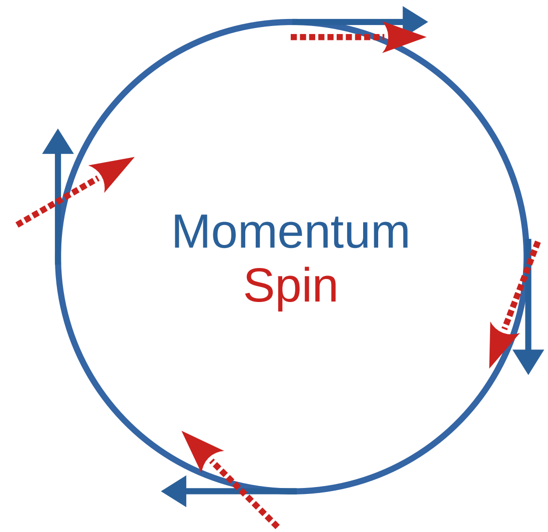
- If we do the difference we get…

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

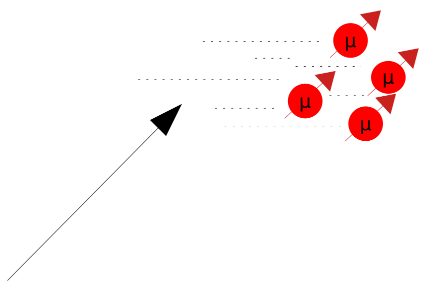
- The “anomalous” precession frequency of the muon is proportional to the g-2 and to the magnetic field strength
- Virtual particles make this happen!
- Measure $\boldsymbol{\omega_a}$ and $\mathbf{B}$ → obtain $\mathbf{a_\mu}$

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



Let’s build a g-2 experiment

Polarized muons



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

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

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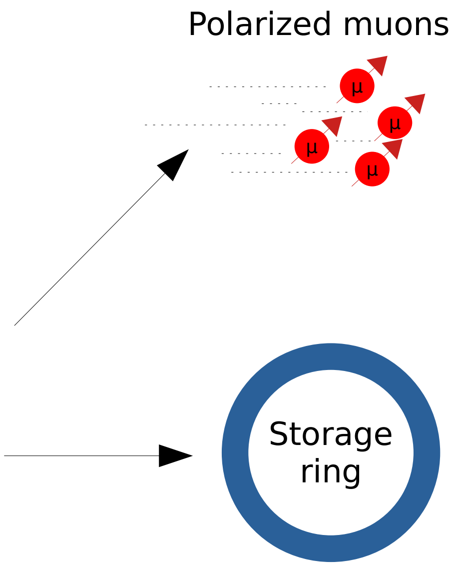

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- Inject beam into a continuous magnet
- Store the muons until they all decay
- Keep the beam focused and centered

Let's build a g-2 experiment

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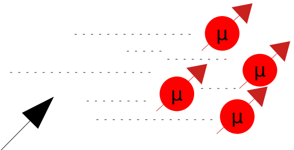

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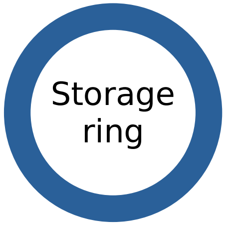

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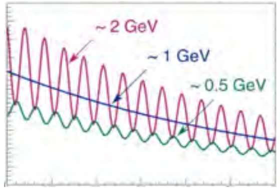
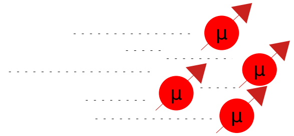
Measure ω_a, B

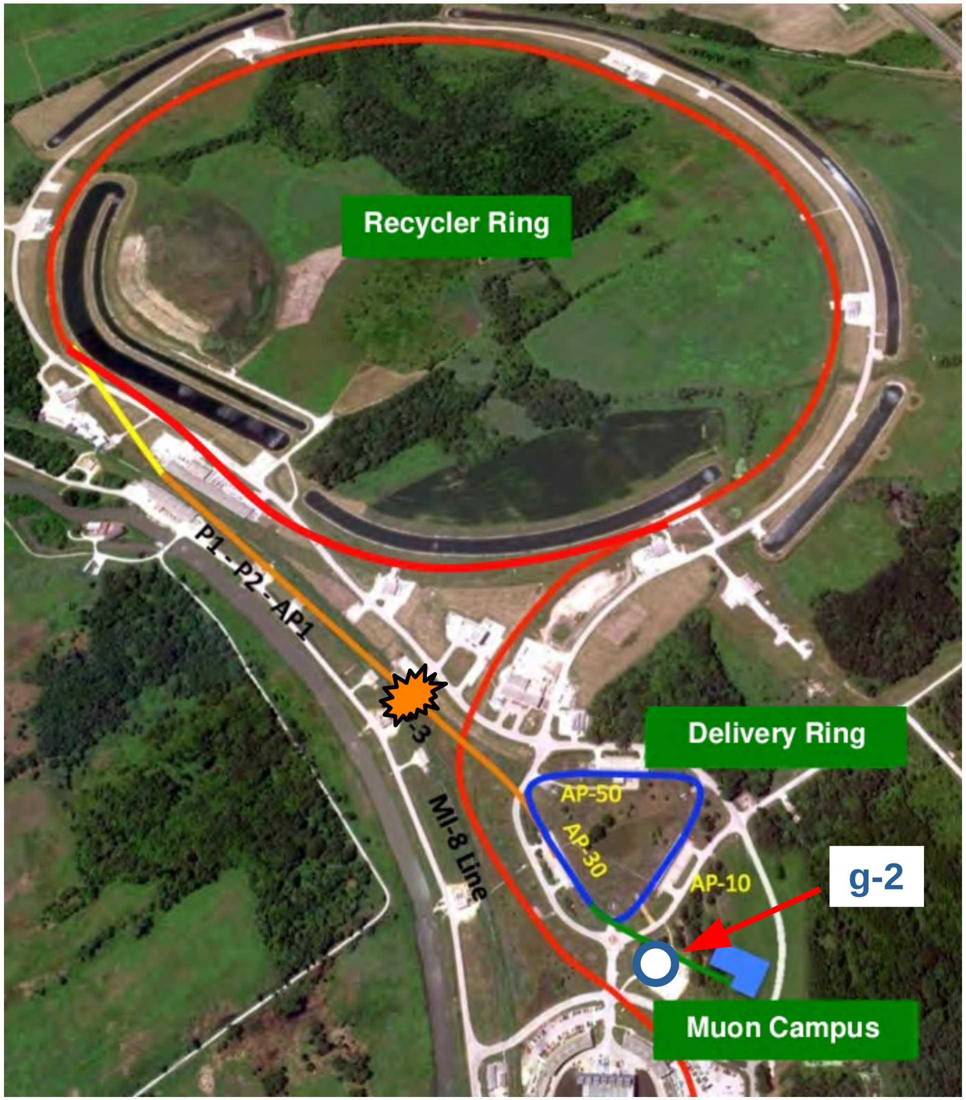


- Detect all the decay positrons
- Measure the magnetic field
- Measure the beam distribution

How to

Polarized muons





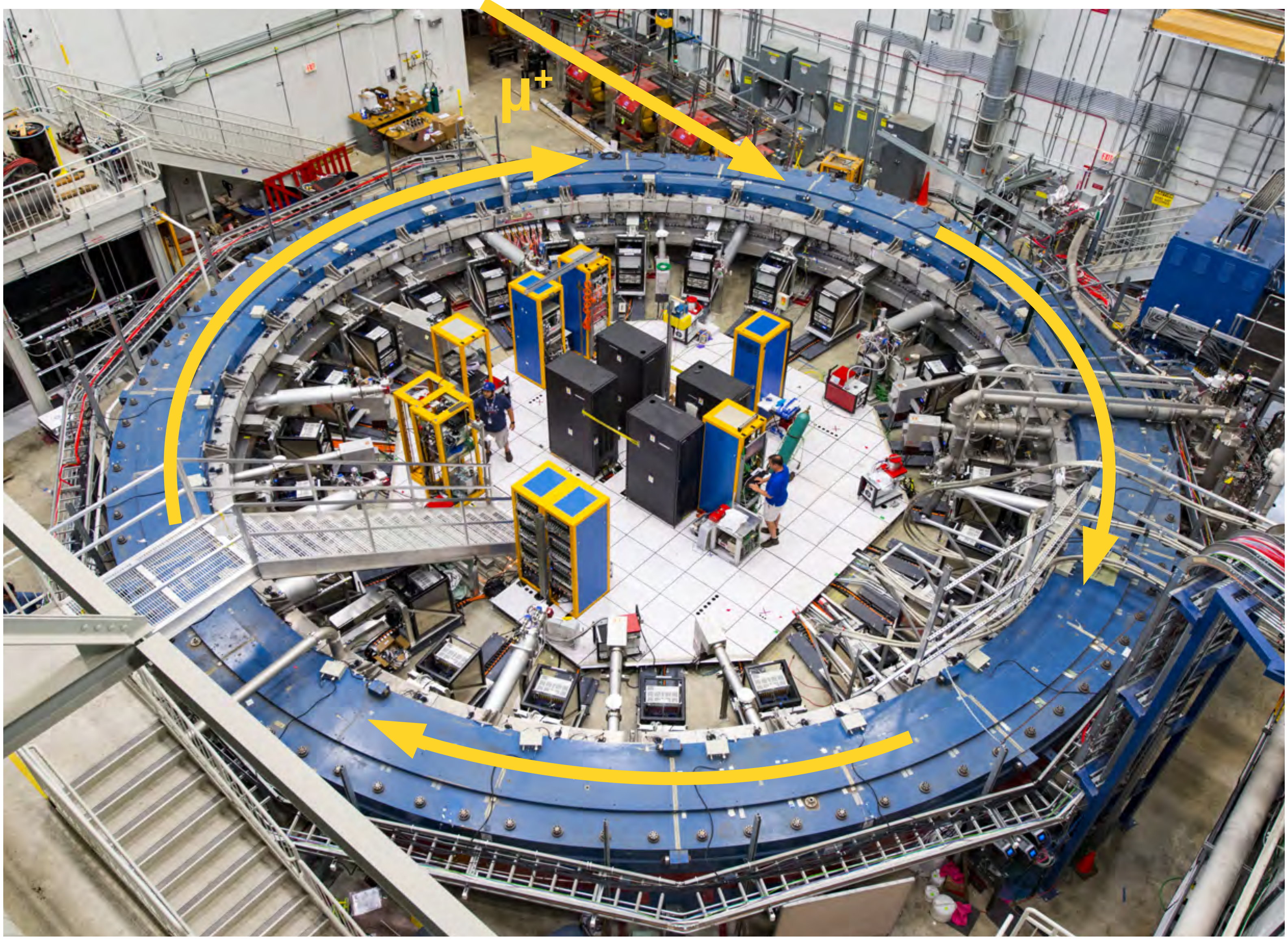
$p \rightarrow \pi^+ \rightarrow \mu^+$

- 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

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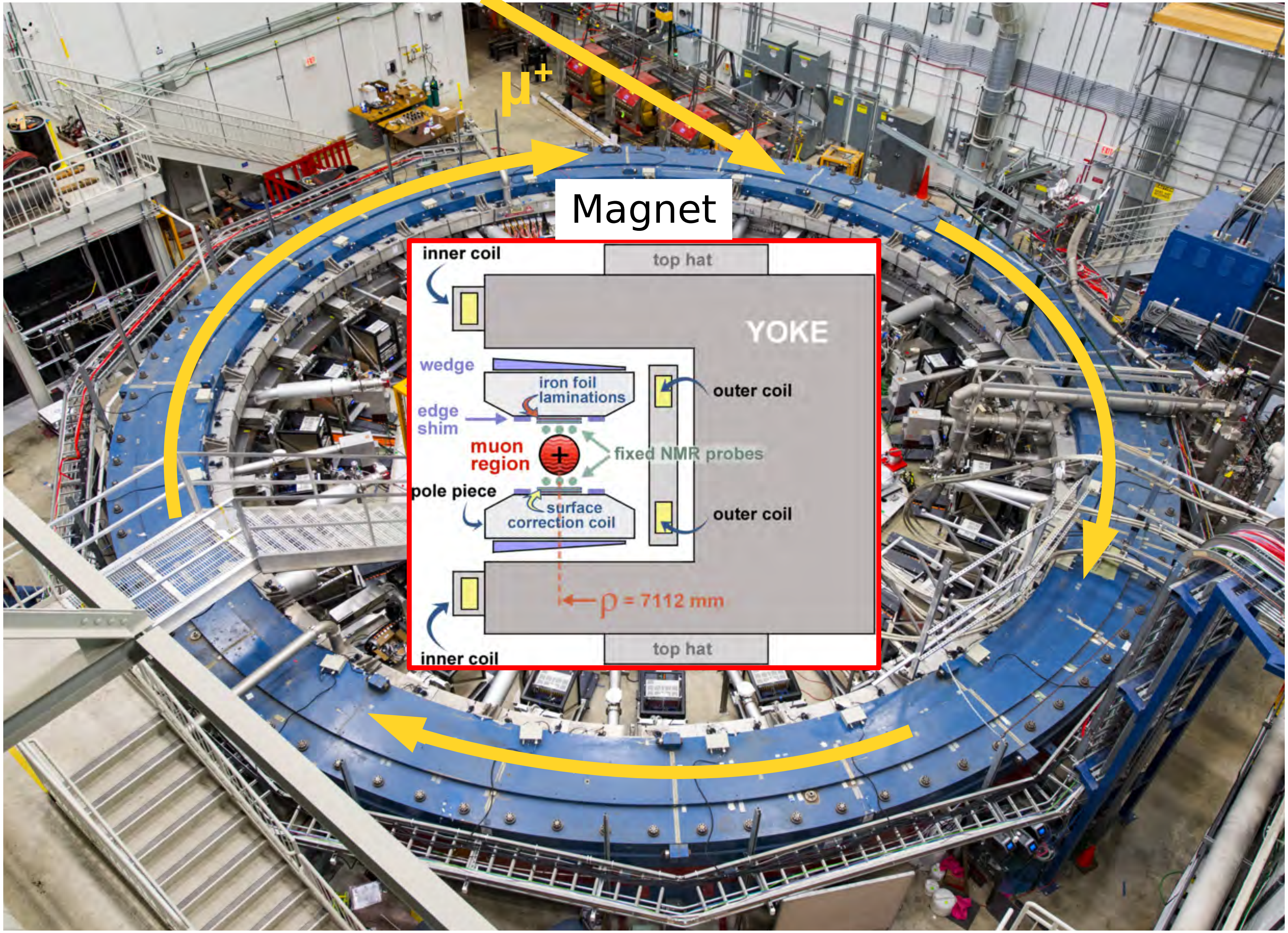

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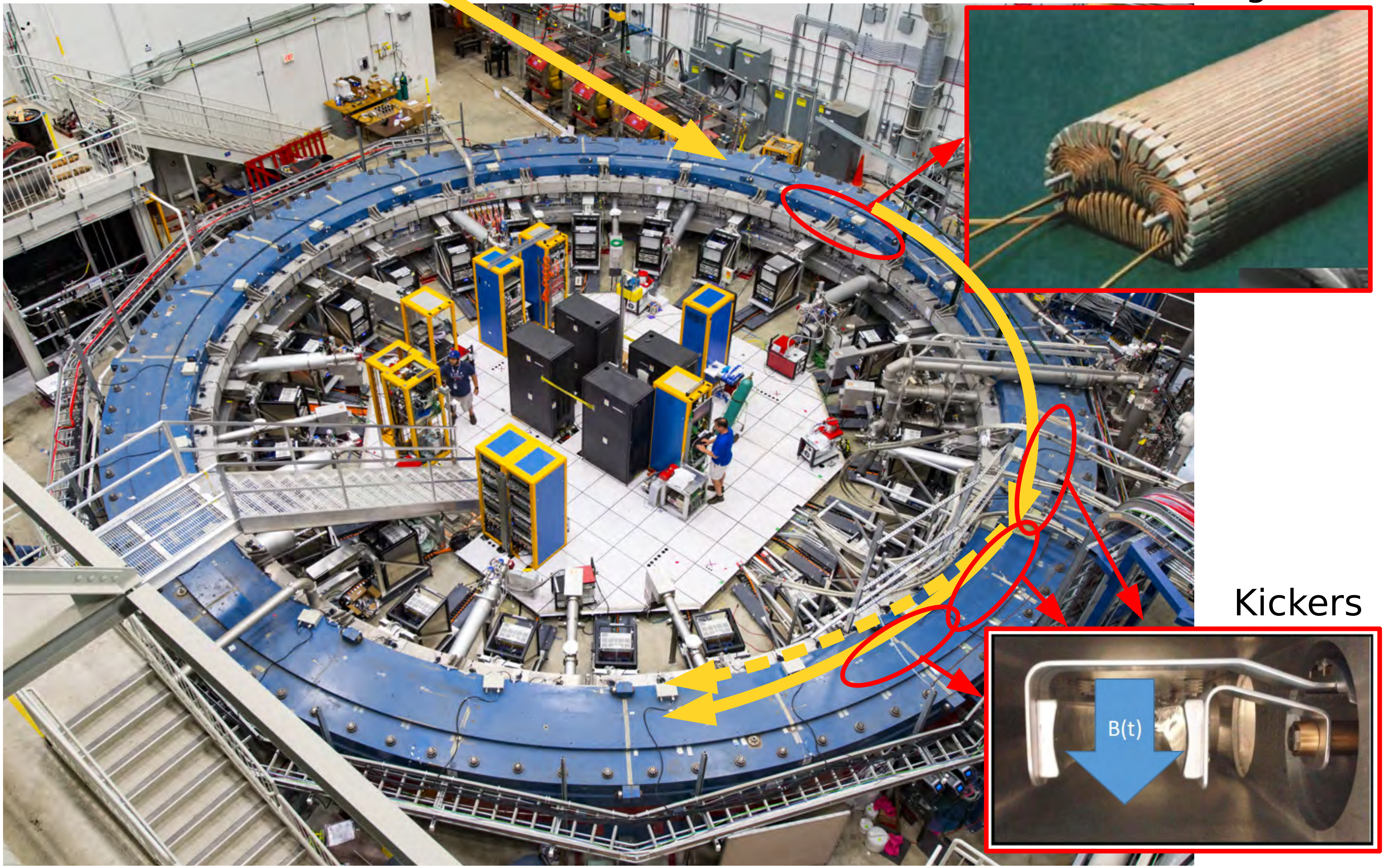

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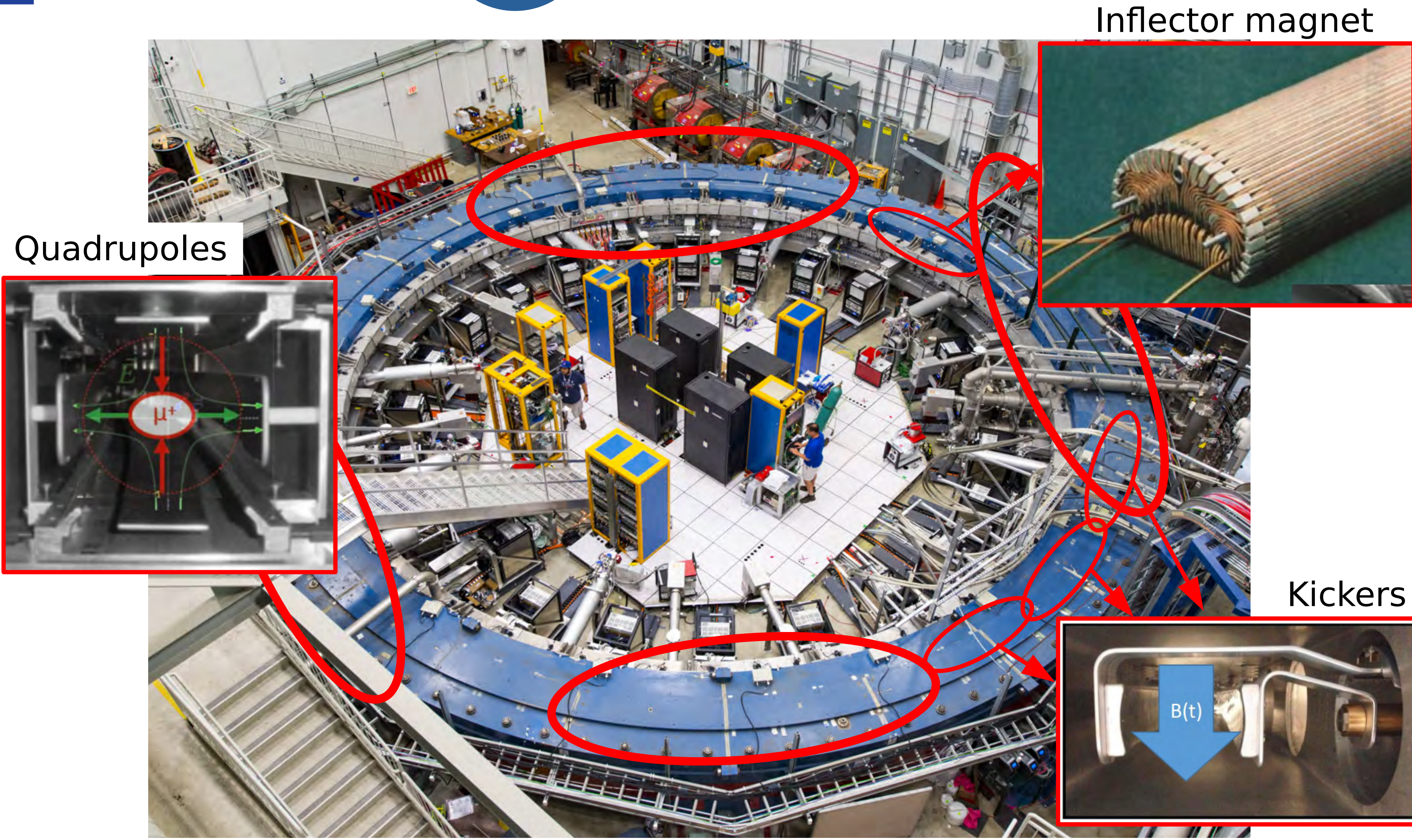

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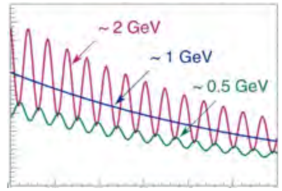

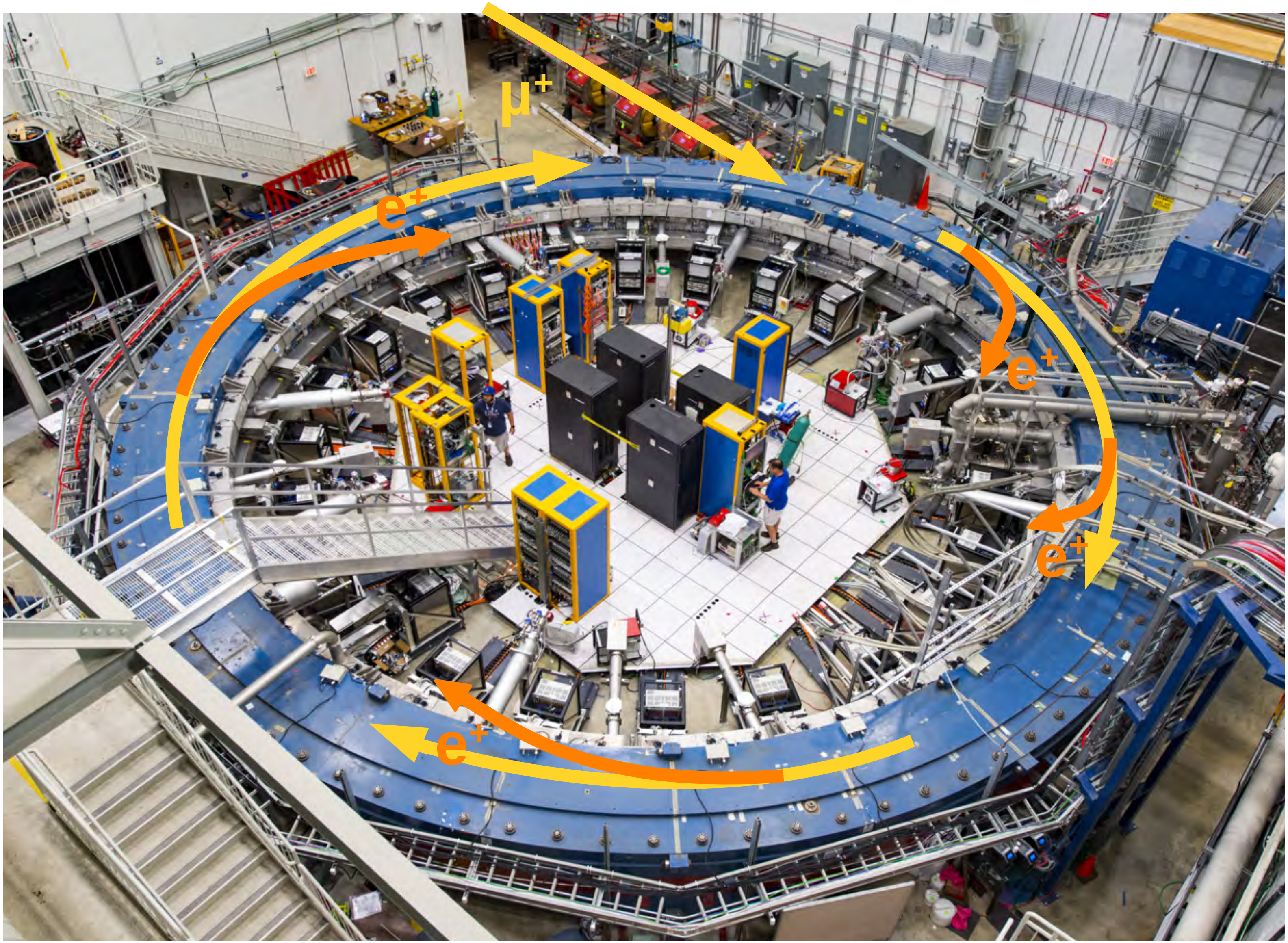

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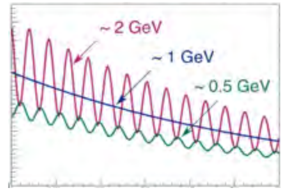
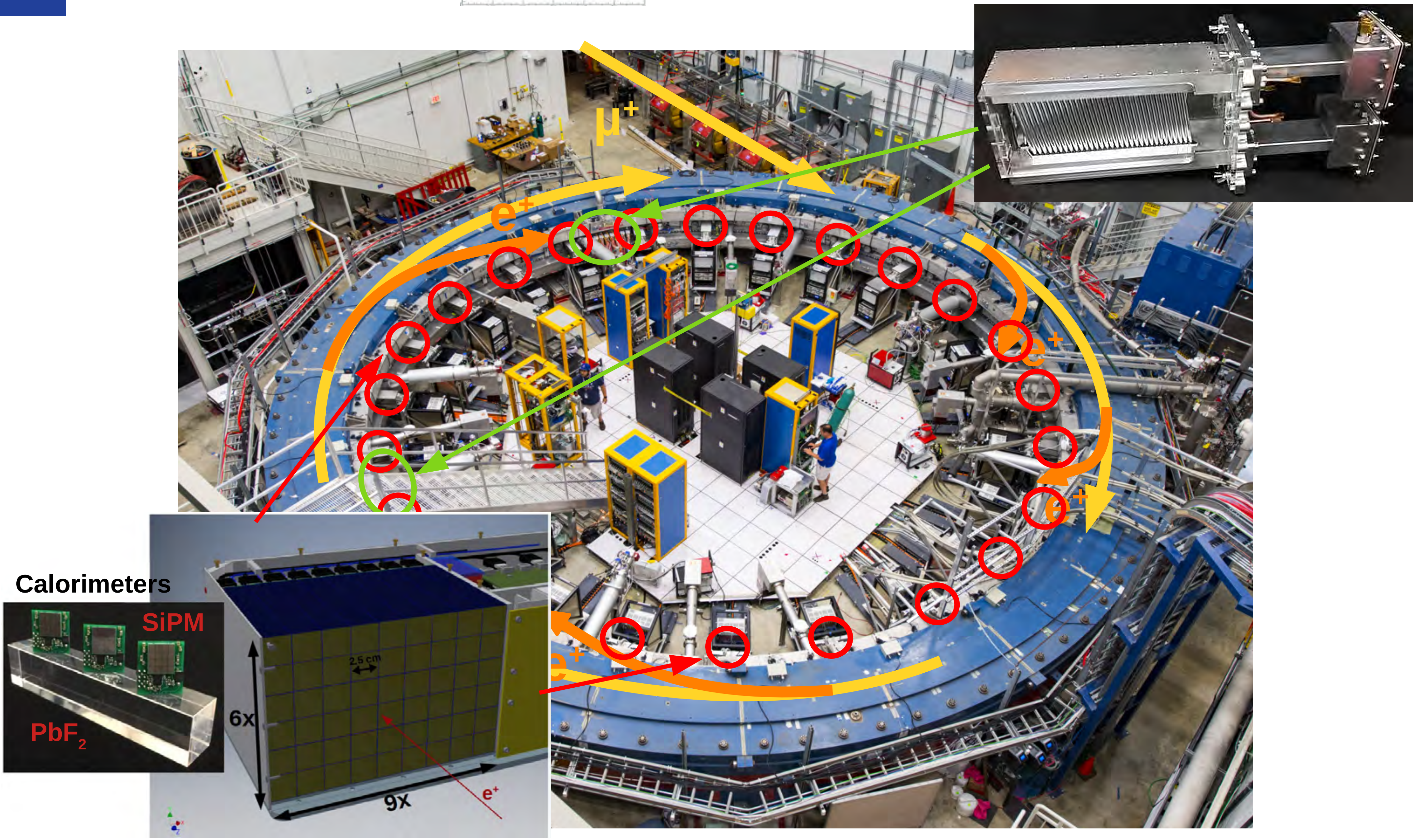


Tracker modules



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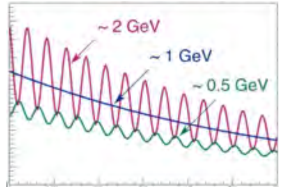

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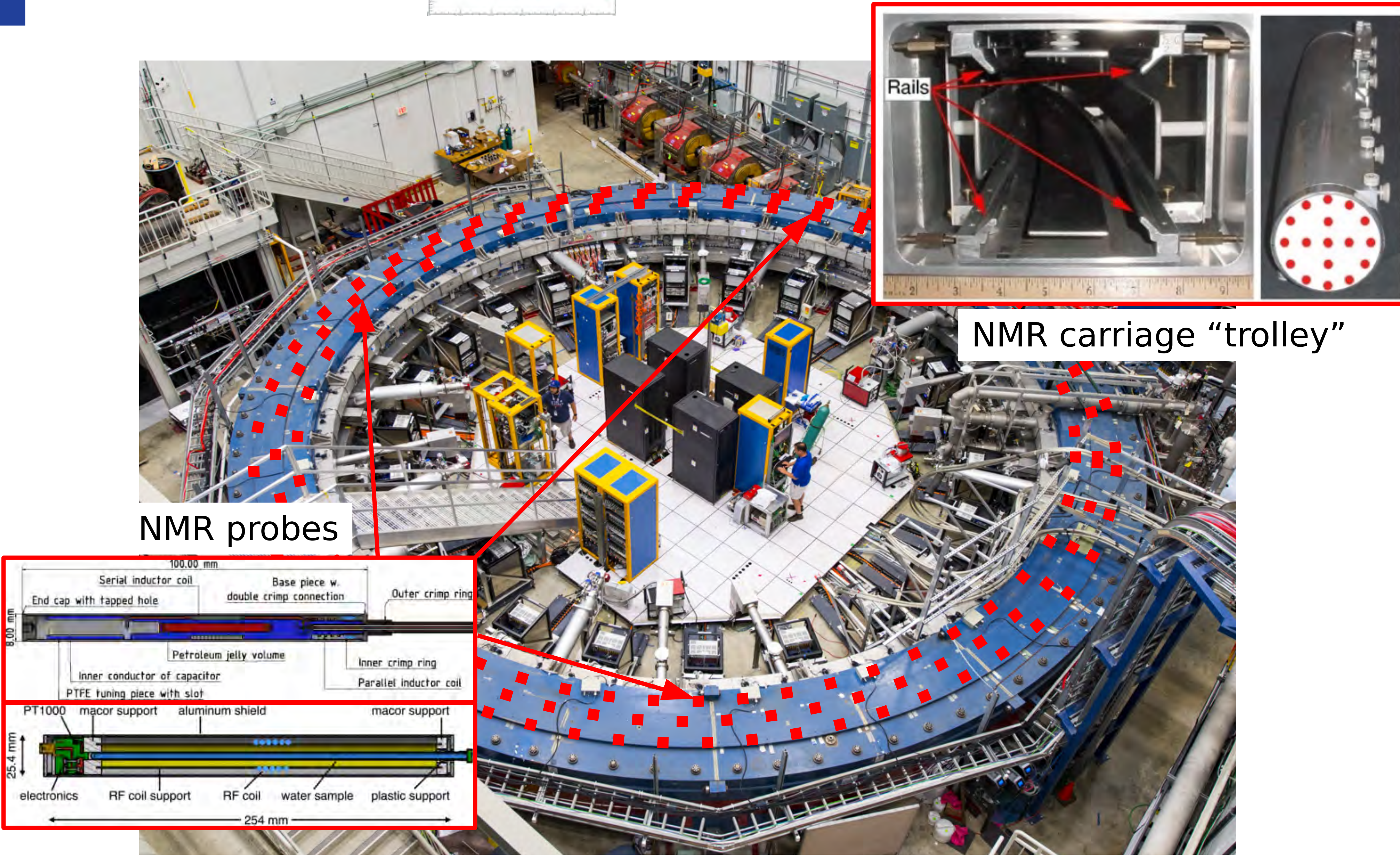
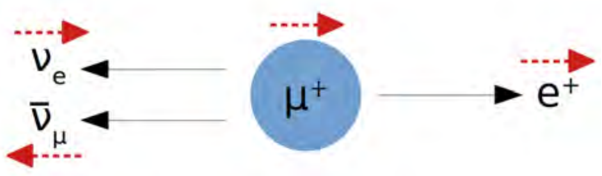
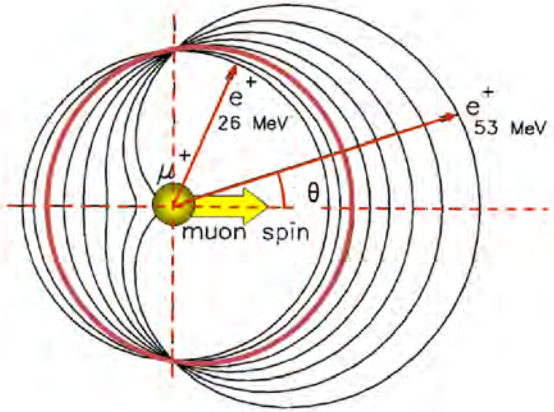


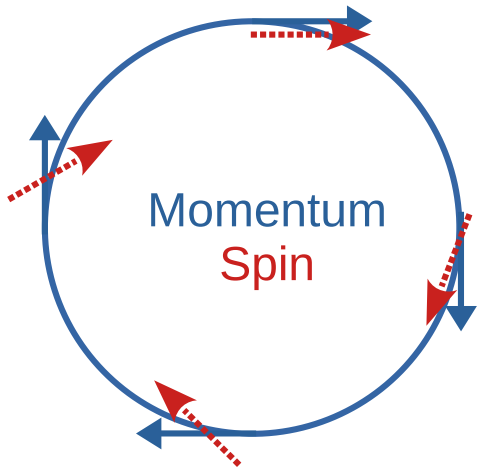
How to measure ω_a



Muon decays in a
positron and 2 neutrinos



Parity violation → positrons in CM preferably in the direction of the muon spin



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

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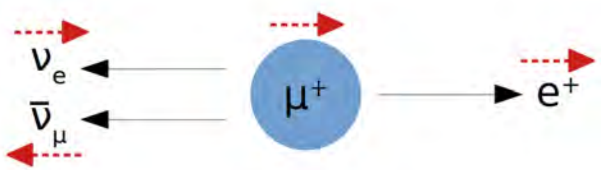

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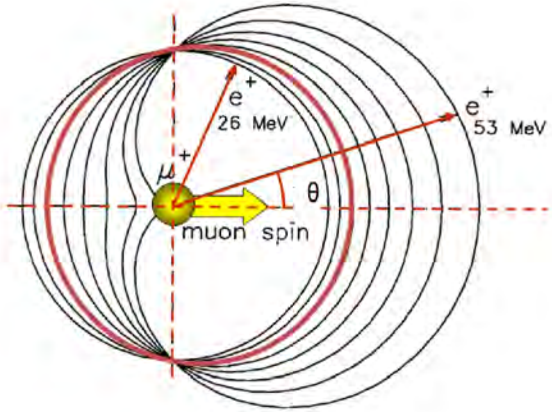

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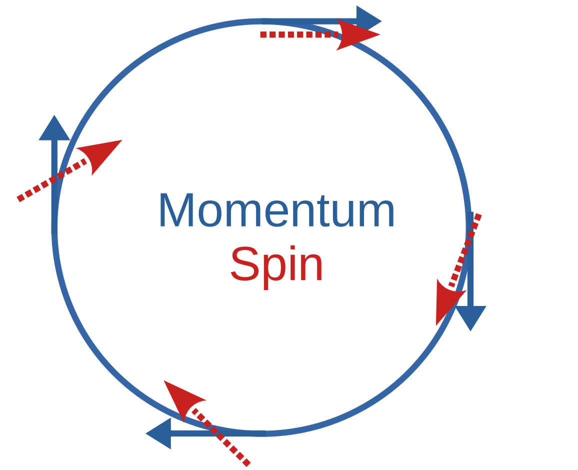

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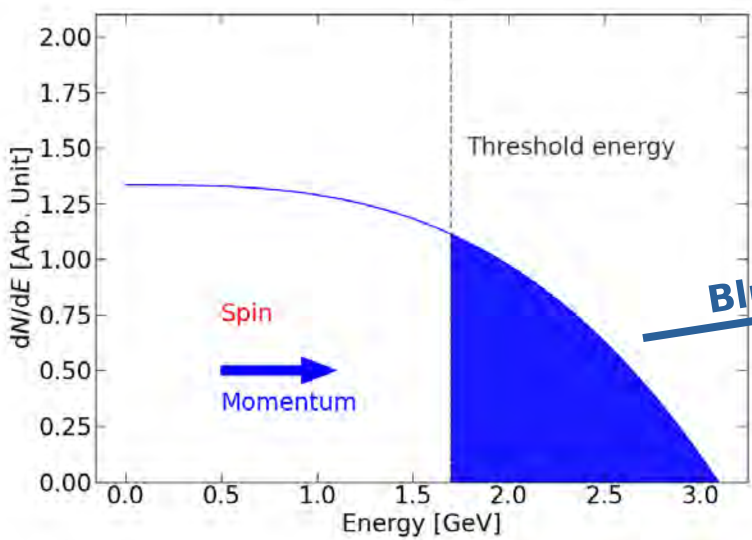
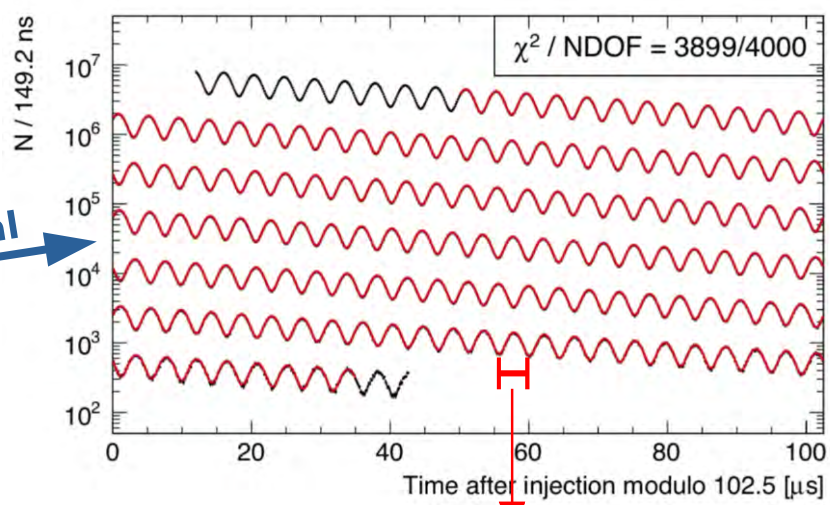


Blue integral



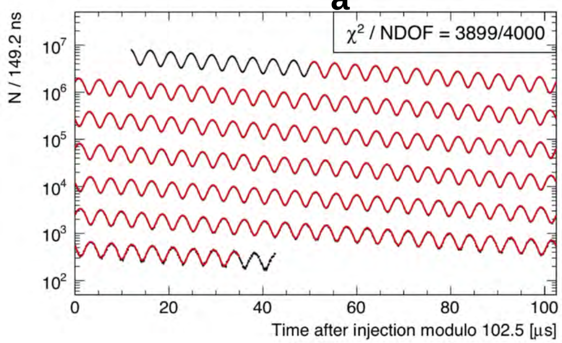
g-2 frequency!

Final formula

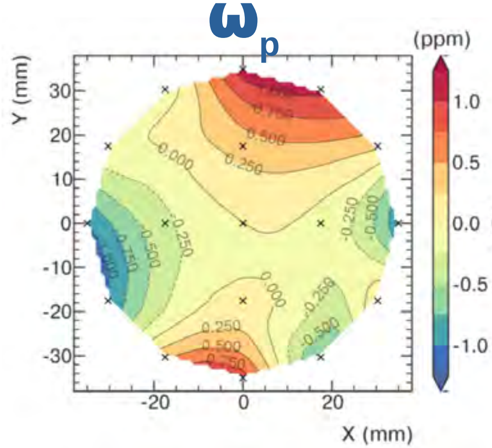
$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

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

ω_a

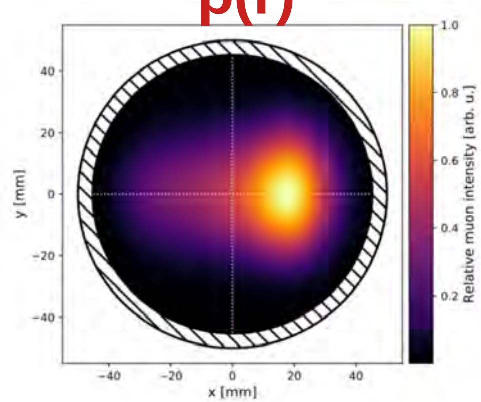


ω_p



$\otimes$

$\rho(r)$



Three measurements:

- **ω_a**: Muon anomalous precession frequency
- **ω_p**: Larmor precession frequency of protons (B field)
- **ρ_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

ω_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}

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

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

	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

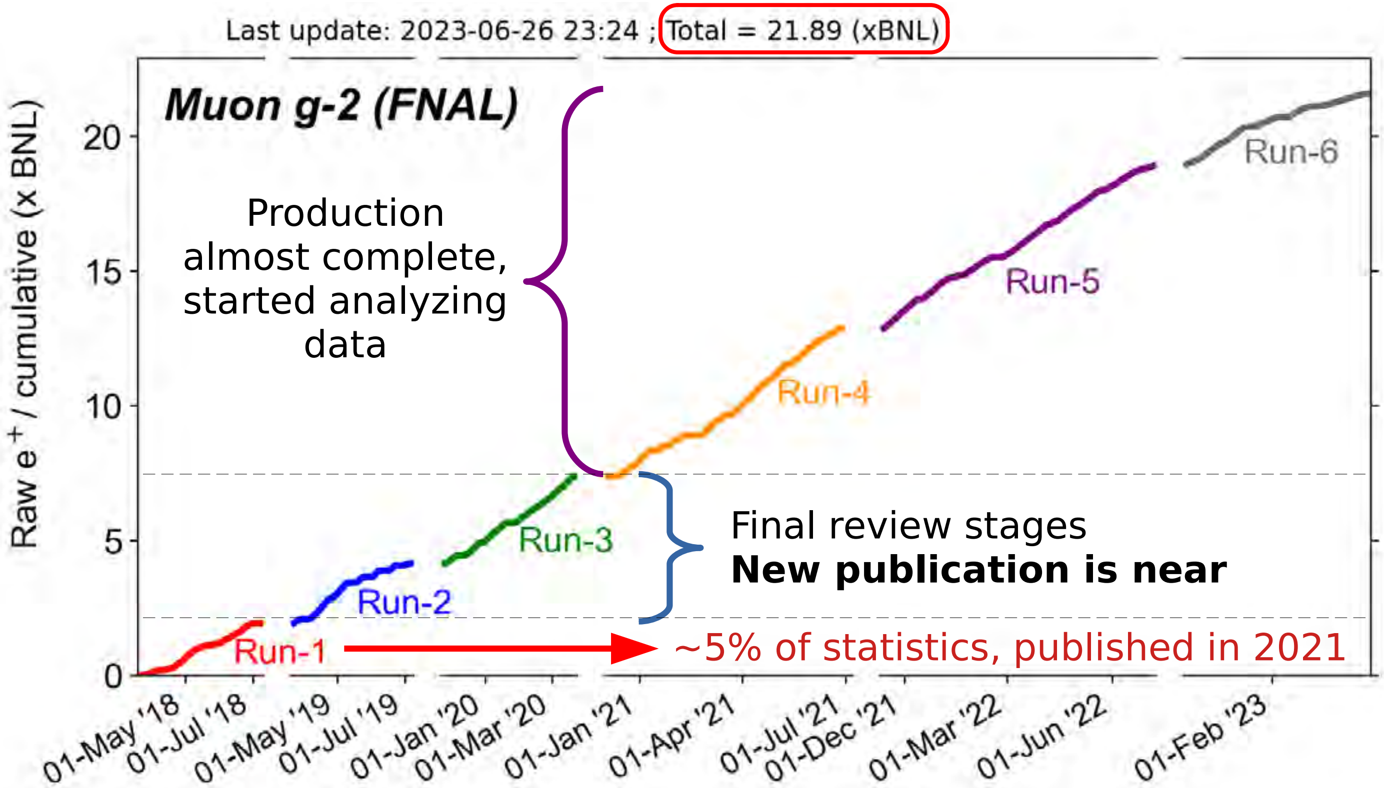
run-1 (substructure)	77.4 ppb
azimuthal shape*	7.6 ppb
skin depth	12.6 ppb
frequency extraction (0.4/1ms)	4.6 ppb
Q3L: fit, position	1.5 ppb
repeatability	13.3 ppb
drift	10.2 ppb
radial dependency	4.4 ppb
2^{nd} 8-pulses	14.0 ppb
total −15.0 ppb	81.7 ppb

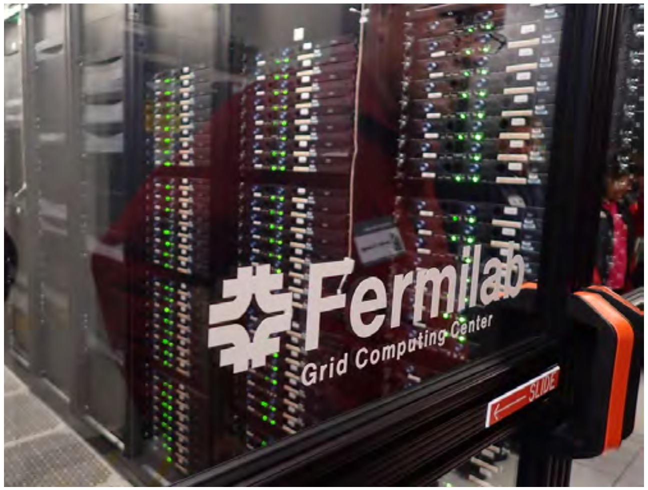
Run-1 uncertainty table

Quantity	Correction [ppb]	Uncertainty [ppb]
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 lot of data

- More than **7 PB** of raw data have been accumulated in 6 years of data taking
- All the detected $\sim 10^{11}$ positrons are reconstructed and carefully calibrated in time and energy
- $\sim 3 \times 10^7$ 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 out as soon as analysis review is complete. Stay tuned!

Thank you for listening!