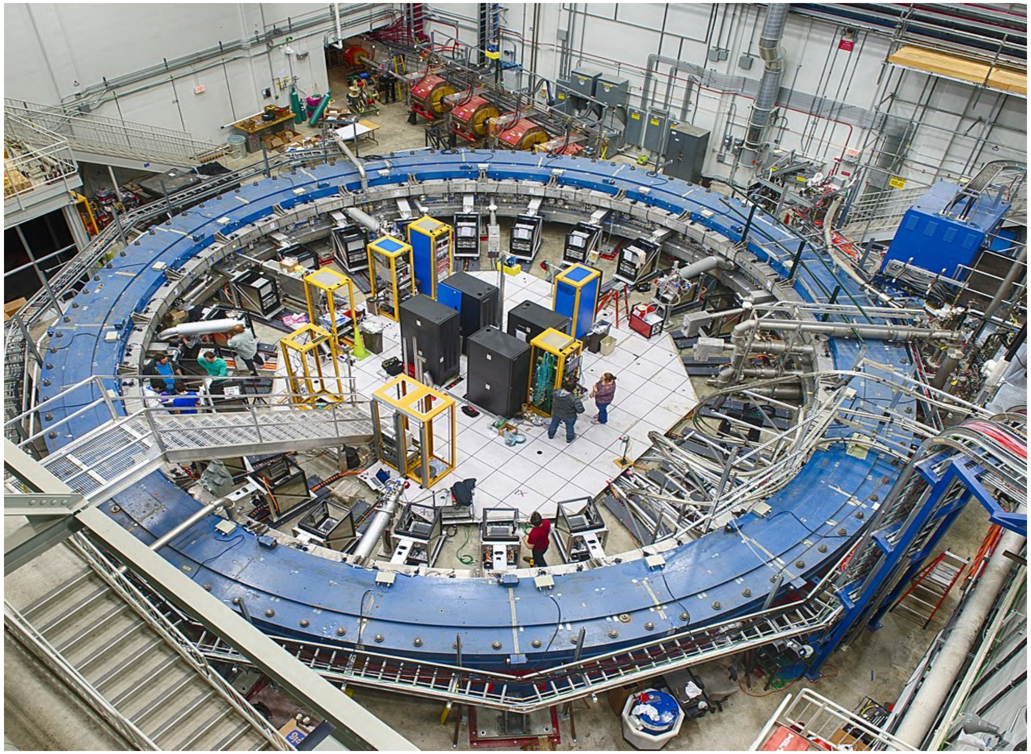
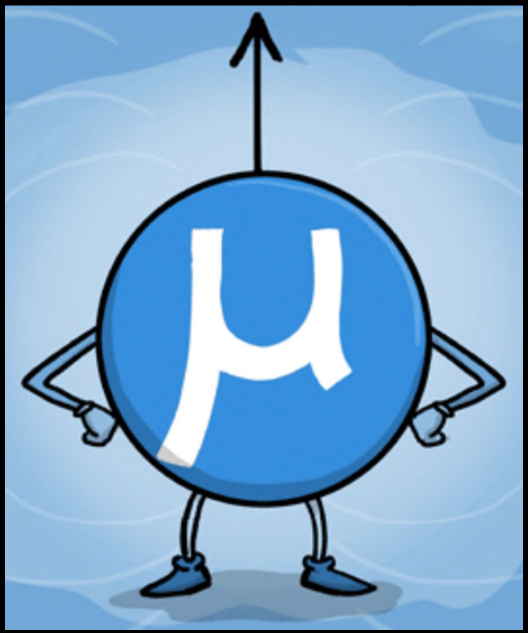
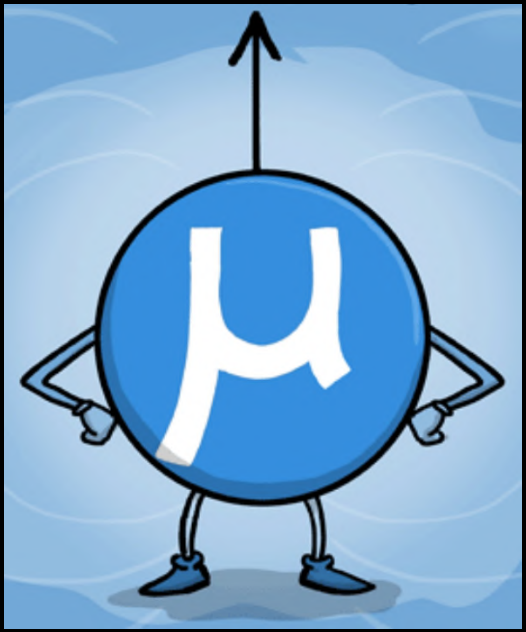
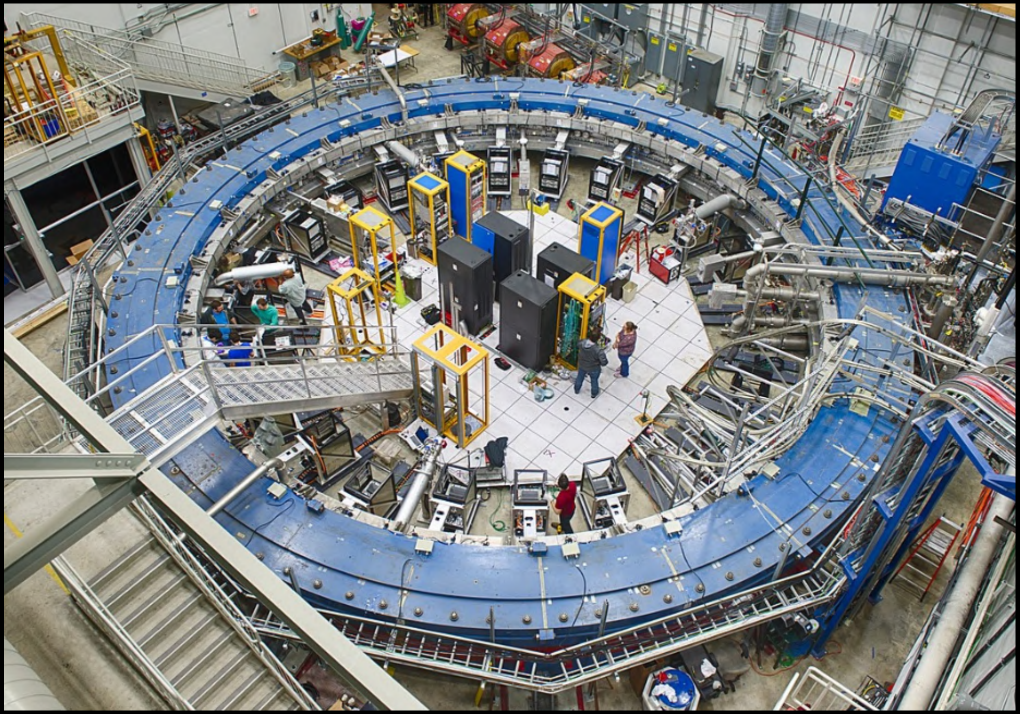


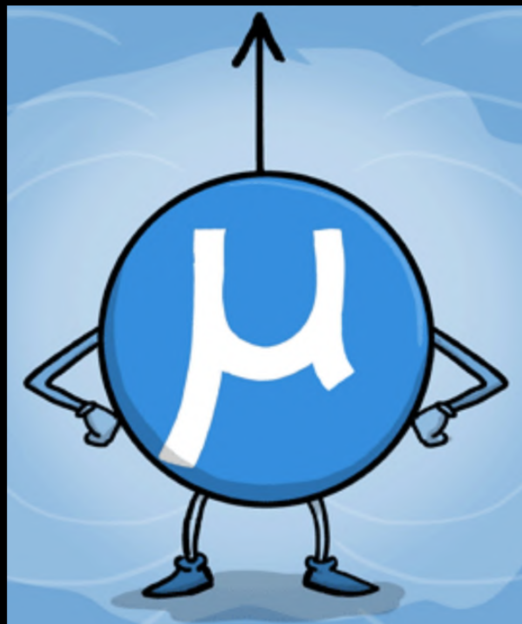
The Muon g-2 experiment

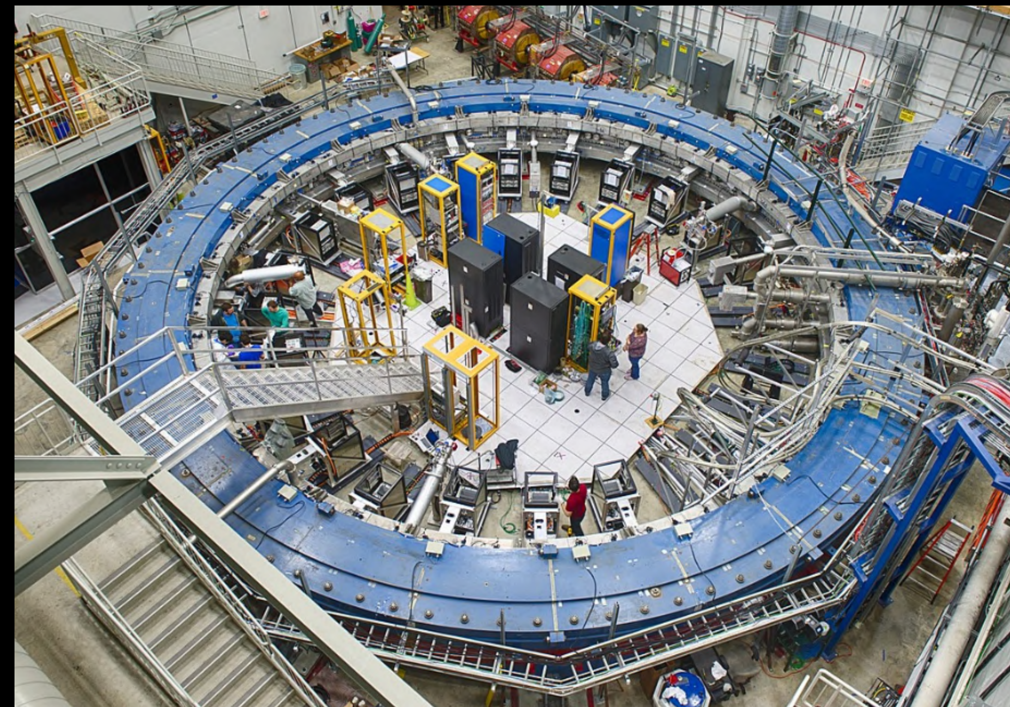
Annual Intense General Meeting
30 March 2022

Paolo Girotti | paolo.girotti@phd.unipi.it


μ

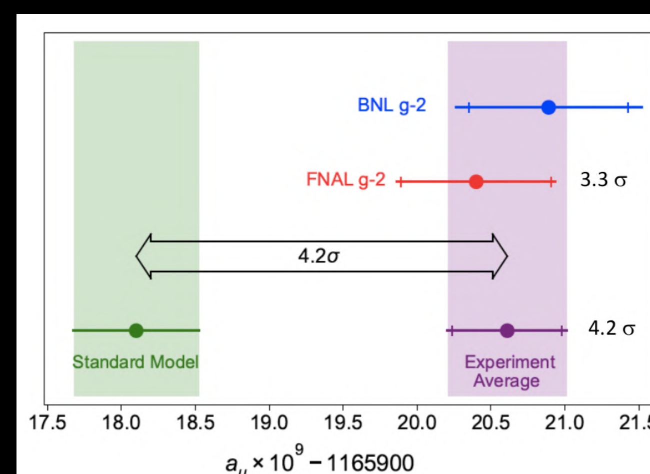

μ






7 April 2021

Experiment ≠ Theory

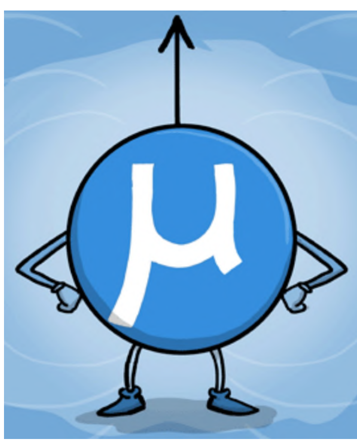


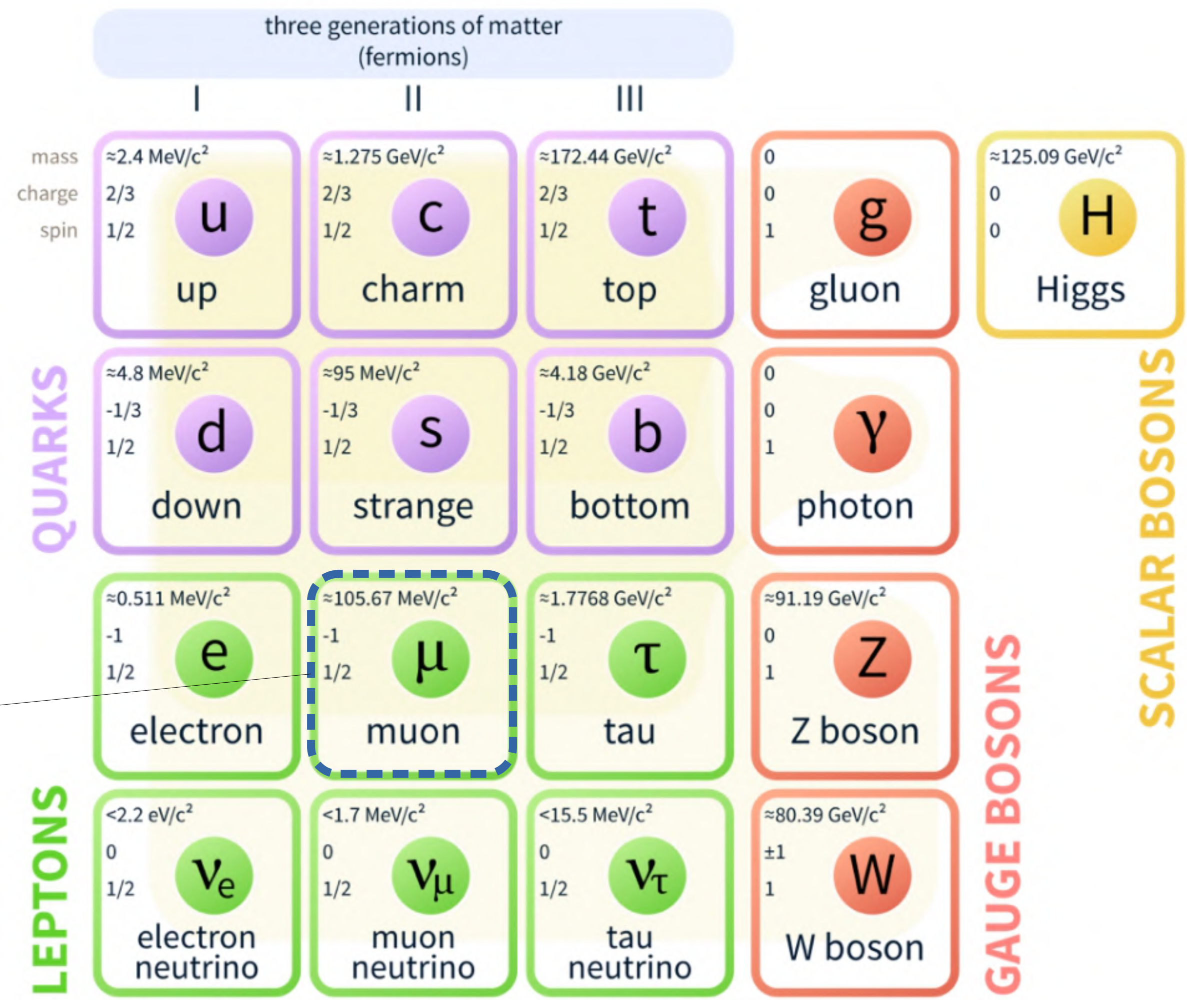
Outline

- What is the Muon g-2?
- Why is it so important?
- The Muon g-2 experiment at Fermilab
- What’s next?

The muon

- Very similar to an electron
- 200 times heavier (105 MeV/c²)
- Decays quickly (2.2 µs)
- Has a spin (½)

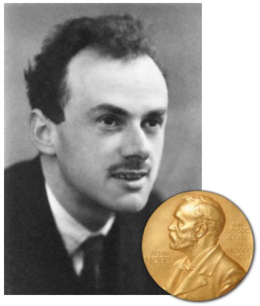




The g in g-2

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

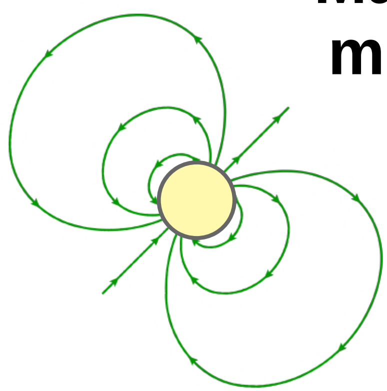
- Every charged fermion has a magnetic moment
- Depends on charge, spin, mass
- **g** is a dimensionless factor
  - Classical mechanics says it's g=1
  - Paul Dirac predicted g=2 (1928)
  - Actually, it's g=2.00233184122 (we measured it!)



The g in g-2

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

Magnetic moment



Causes the muon to precess in a magnetic field

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

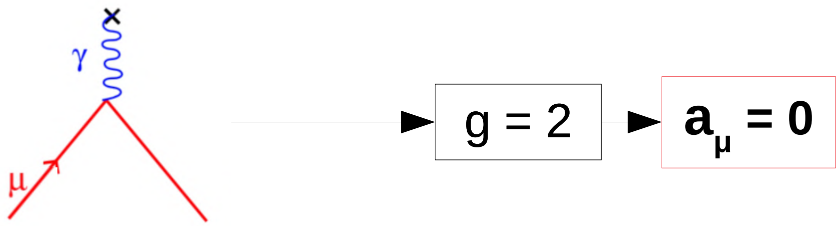
The muon anomaly

Spin

Affects the muon decay

The muon anomaly

- Deviation from 2 arise from quantum loop corrections
- The simple muon-photon interaction gives g=2



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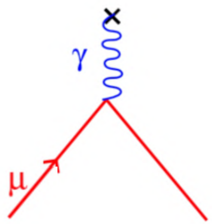
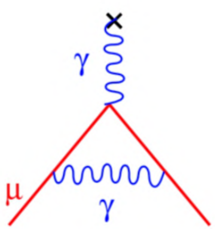


→ g = 2 → $a_\mu = 0$

- But considering corrections:



QED

$a_\mu = 0.0011658\ldots$

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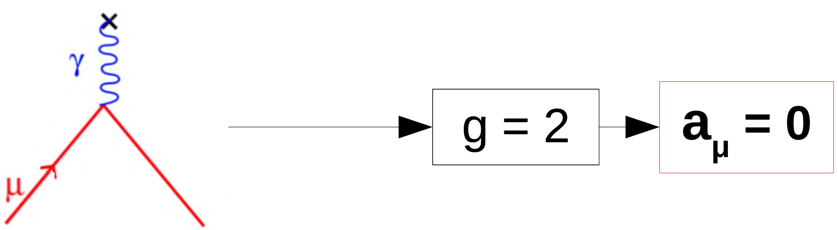

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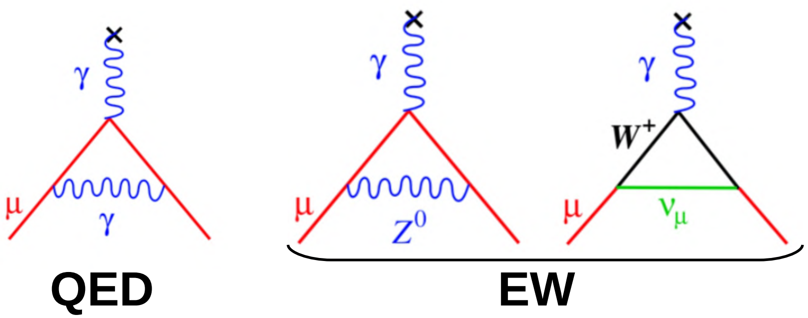

a_μ = 0.0011658… +0.000000001536...

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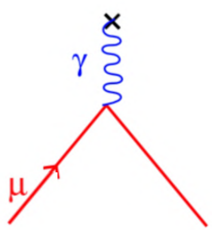

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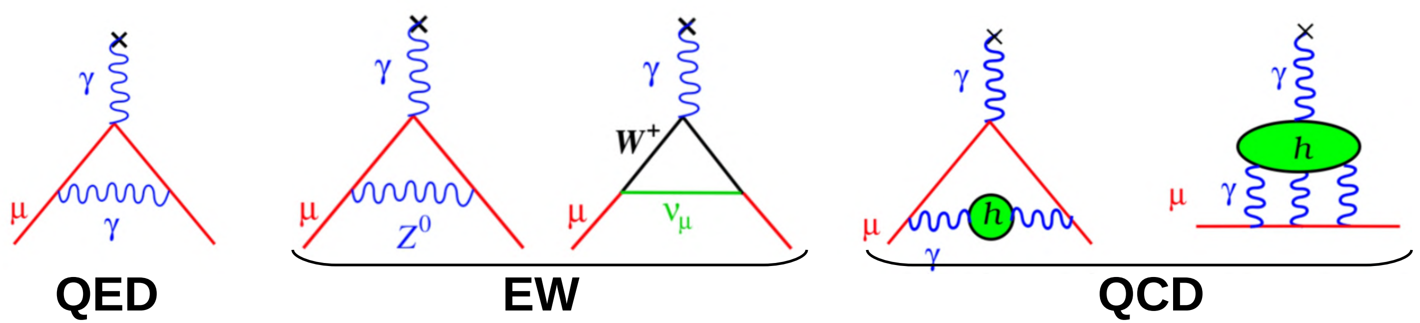

a_μ = 0.0011658… +0.000000001536... +0.000000069383…

The muon anomaly

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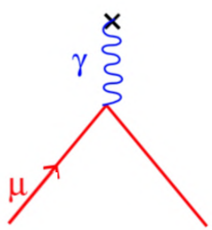

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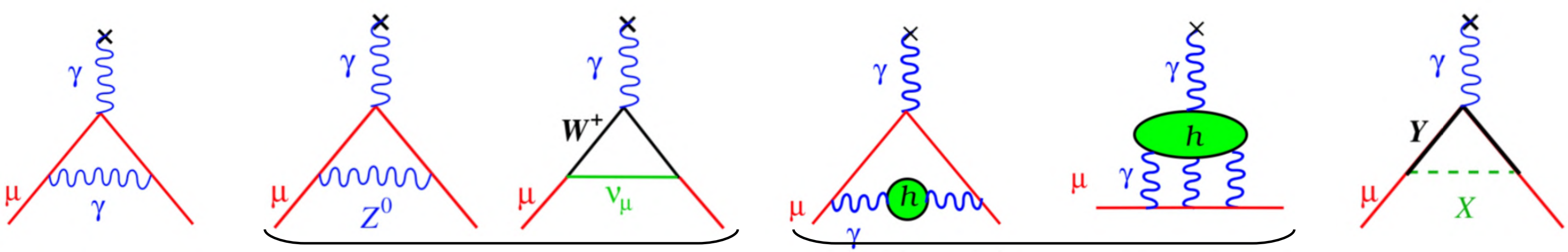
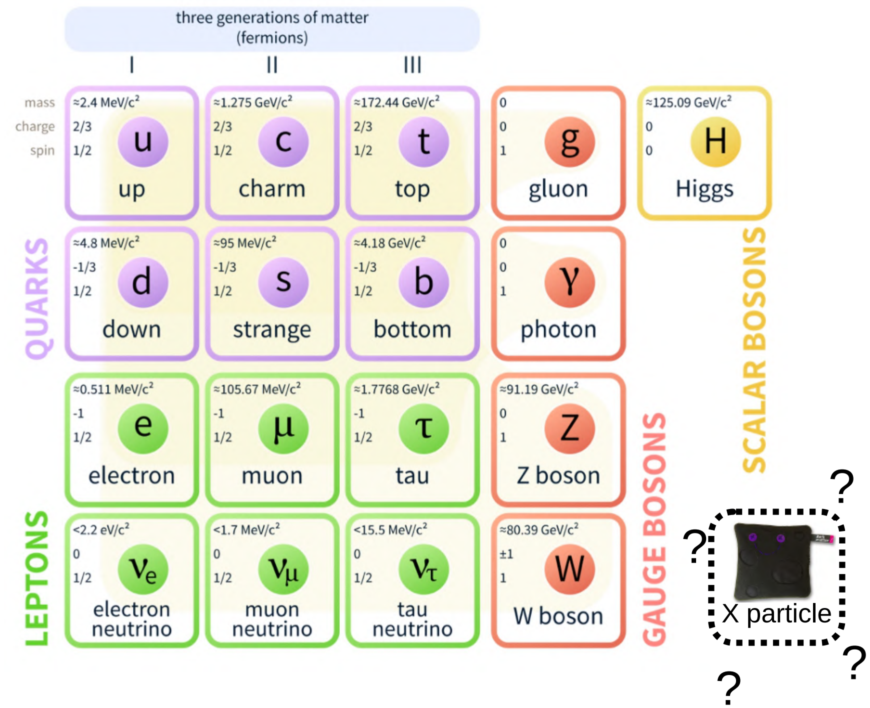


QED **EW** **QCD** **BSM?**

a_μ = 0.0011658… +0.000000001536... +0.000000069383… +?

The muon anomaly

- A precise measurement of the muon magnetic moment means:
  - A test of the Standard Model accuracy
  - A search for new physics signals (dark matter?)

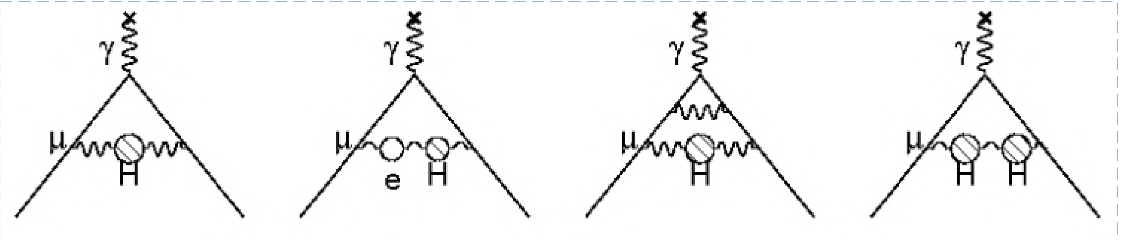


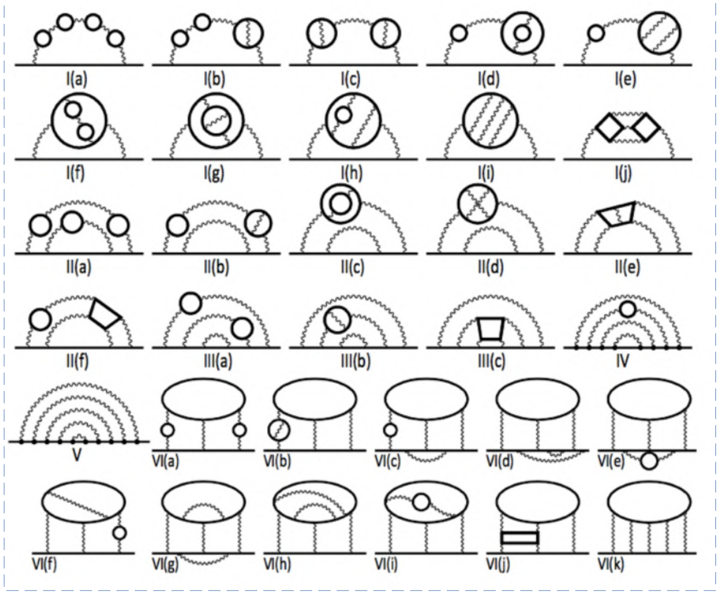
In the vacuum, the muon interacts with ALL the possible virtual particles in ALL the possible ways!

Loops and loops

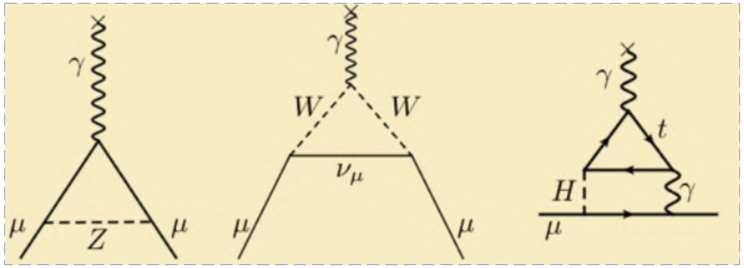
- Very difficult theory calculations
- Nature helps us a little: the more the diagram is complicated, the less it contributes
- But for the required precision we need <u>thousands</u> of them! (expecially for QED)

QCD





QED



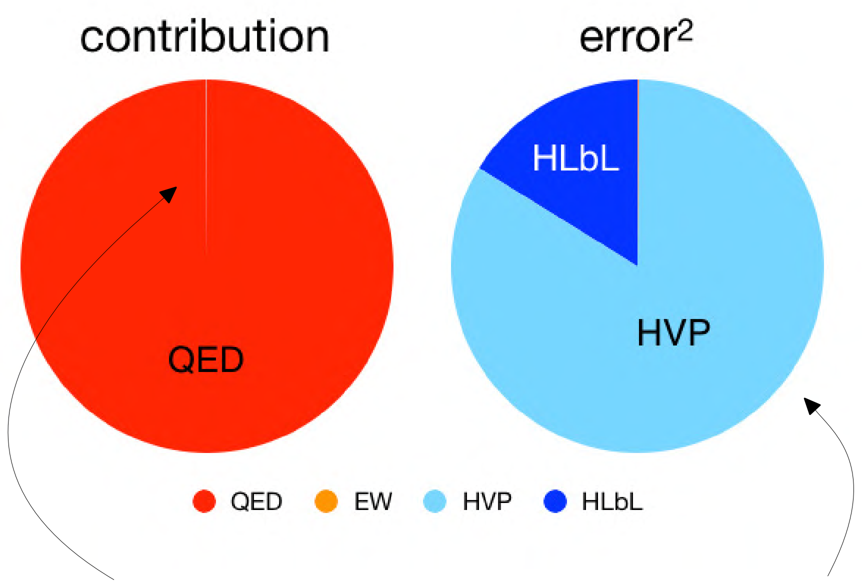
Weak

Theory

	Value ($\times 10^{-10}$) units
QED ($\gamma + \ell$)	$11\,658\,471.8951 \pm 0.0009 \pm 0.0019 \pm 0.0007 \pm 0.0077_\alpha$
HVP(lo) Davier17	692.6 ± 3.33
HLbL Glasgow	10.5 ± 2.6
EW	15.4 ± 0.1
Total SM Davier17	$11\,659\,181.7 \pm 4.2$

686 ppt !!!

Theory initiative (July 2020) 11659181.0 ± 4.3 → 370 ppb



Hadron loops account for **0.006%** of the contribution, but **99.95%** of the uncertainty!

Theory

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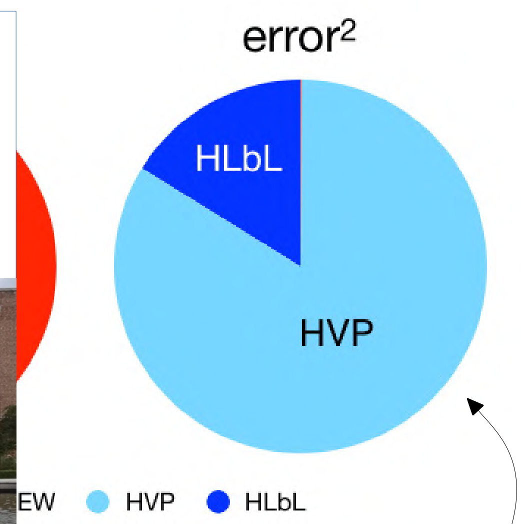
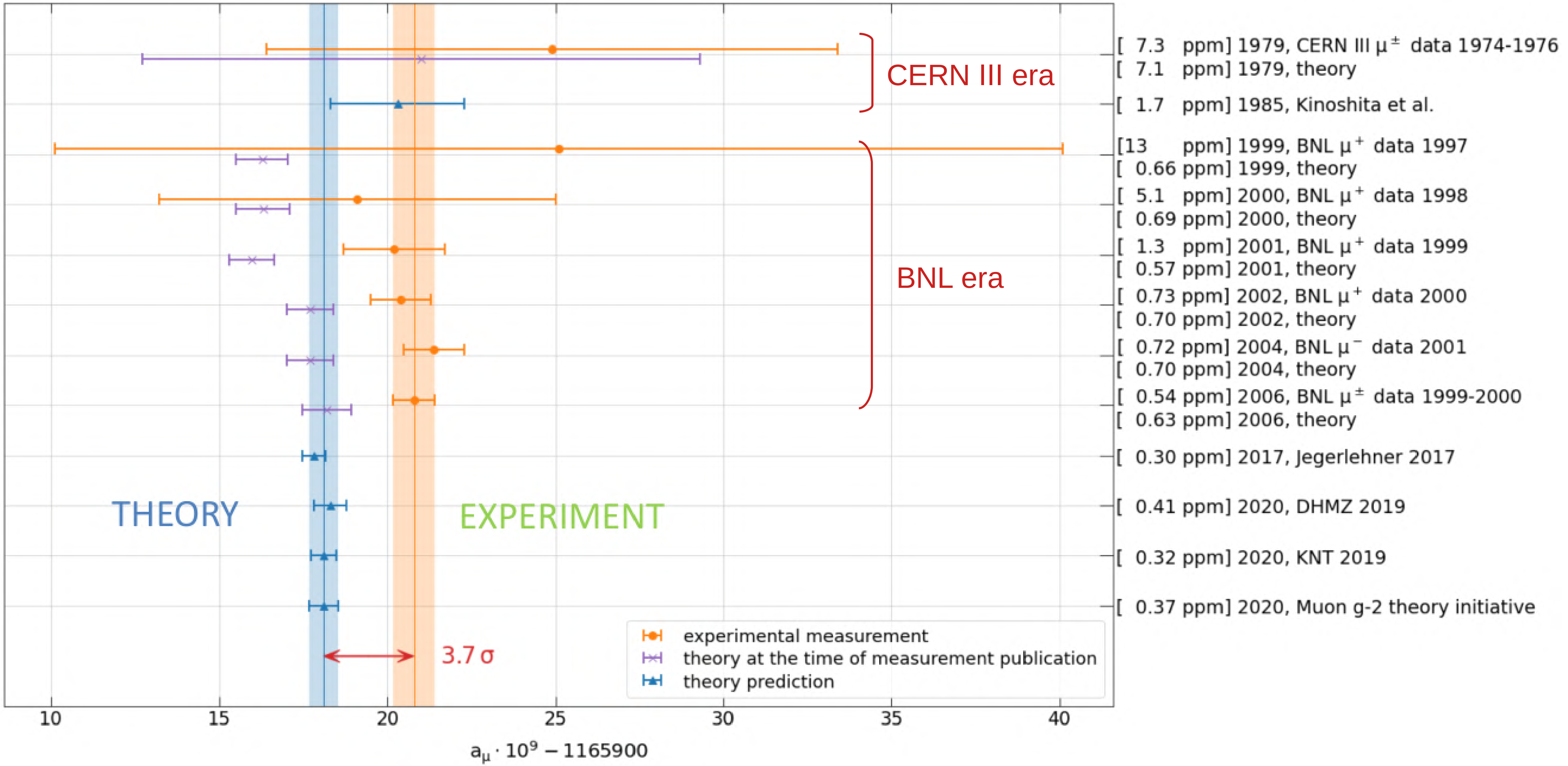
Global effort to achieve a consensus on the Standard Model prediction
https://arxiv.org/abs/2006.04822



…e contribution, but **99.95%** of the uncertainty!

History

- Century-long effort to calculate and measure g



History

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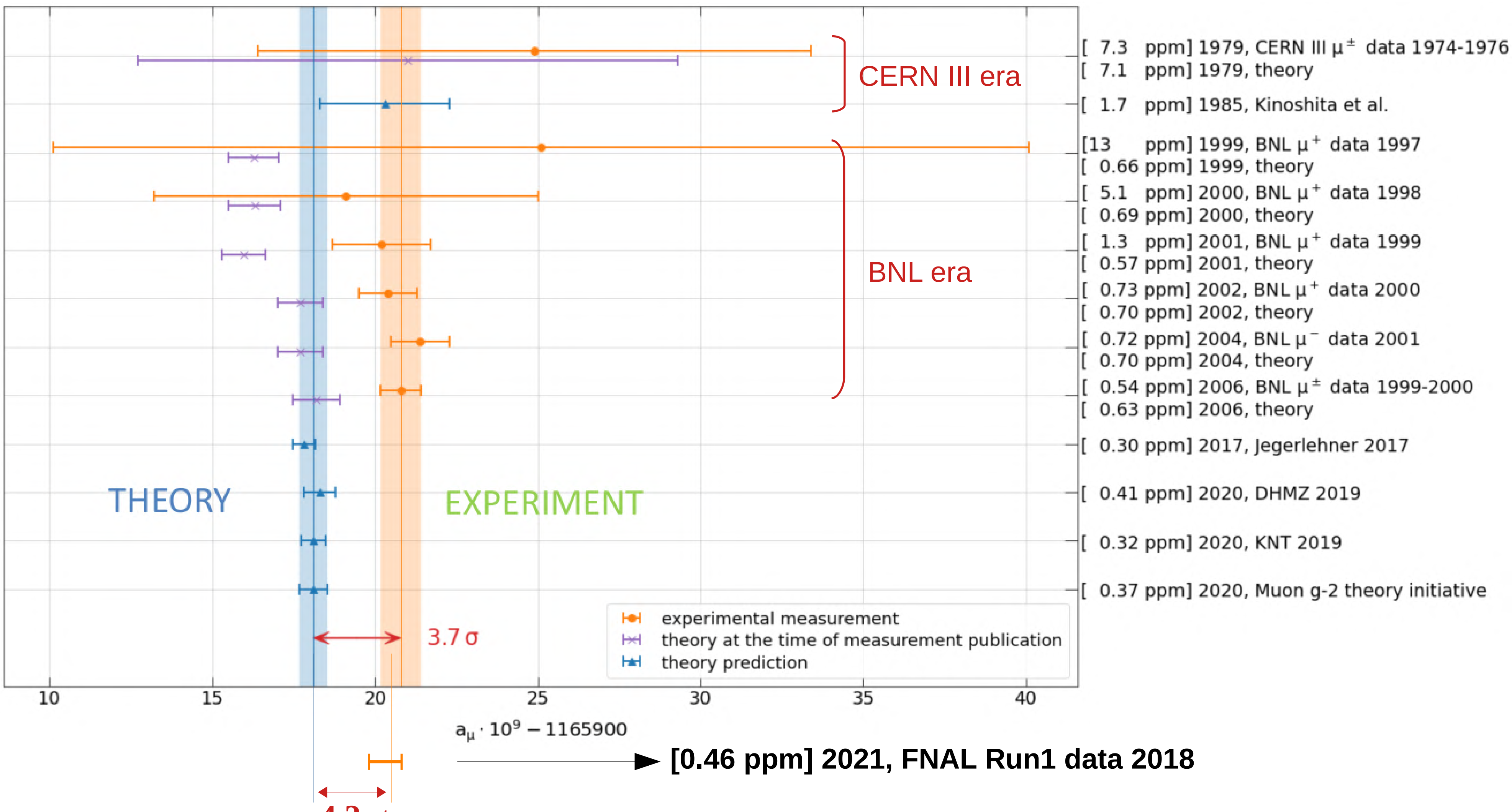
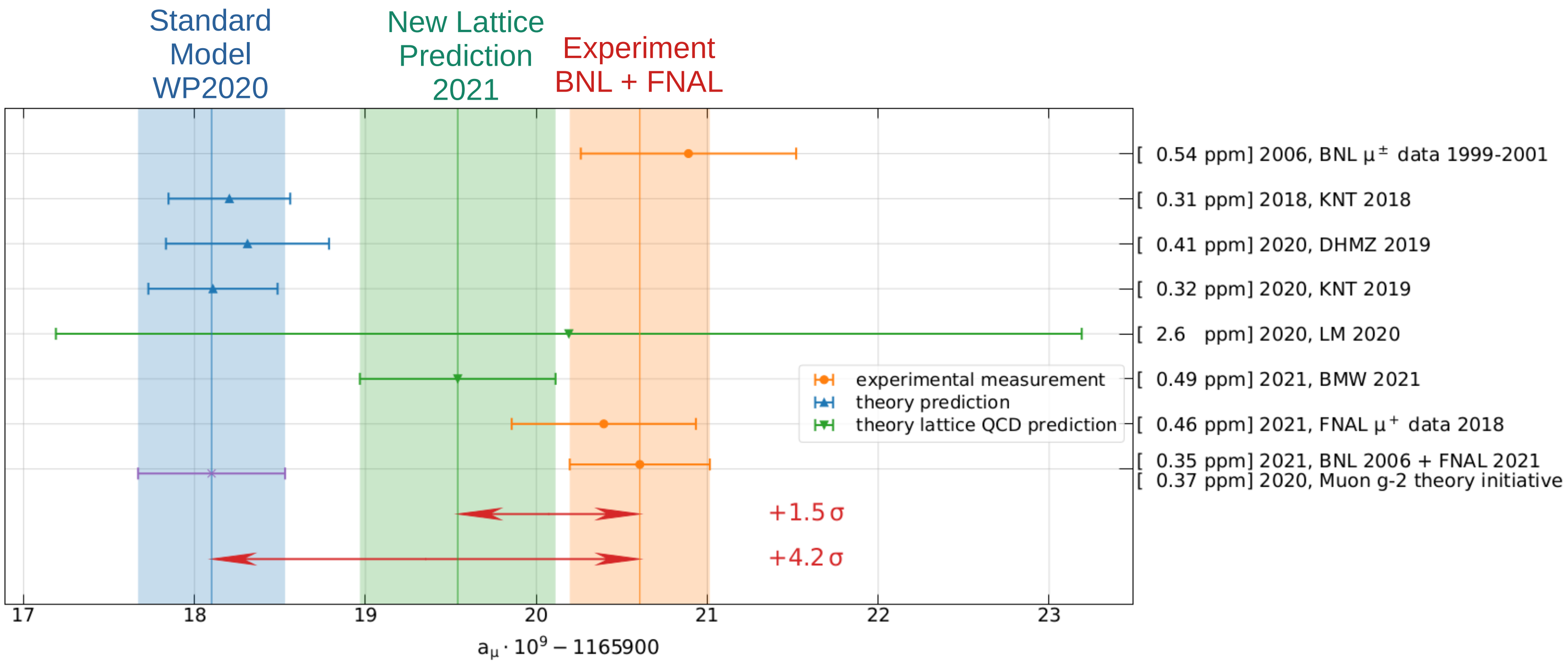


History

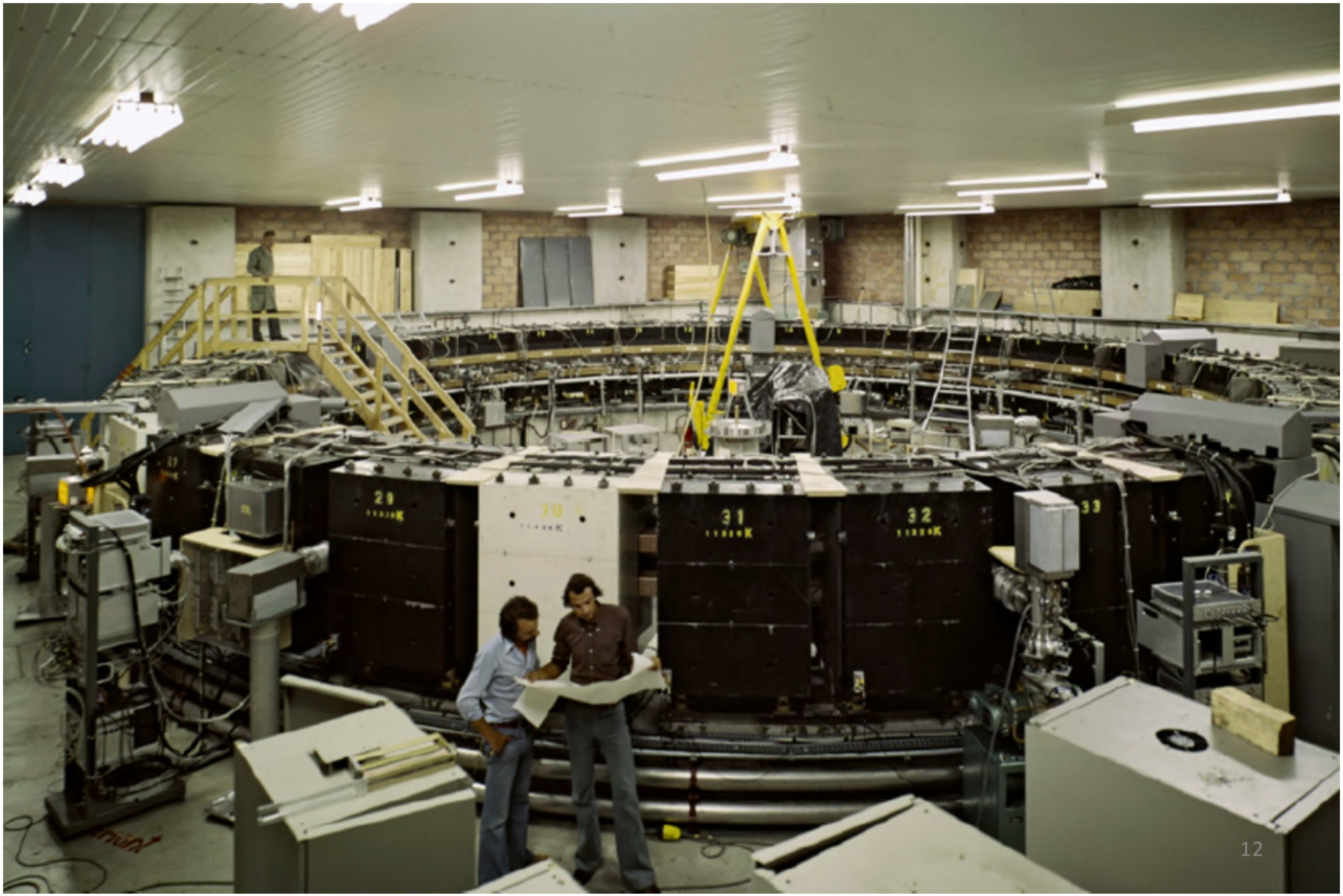
- New **Lattice QCD** estimation of the hadronic contribution
  - Ab-initio calculation, does not rely on experimental data
  - First lattice result to provide an estimate with the error comparable to the dispersive evaluations (< 1%)
  - Needs to be confirmed by other lattice communities
  - “*New g-2 puzzle*” in the theory side



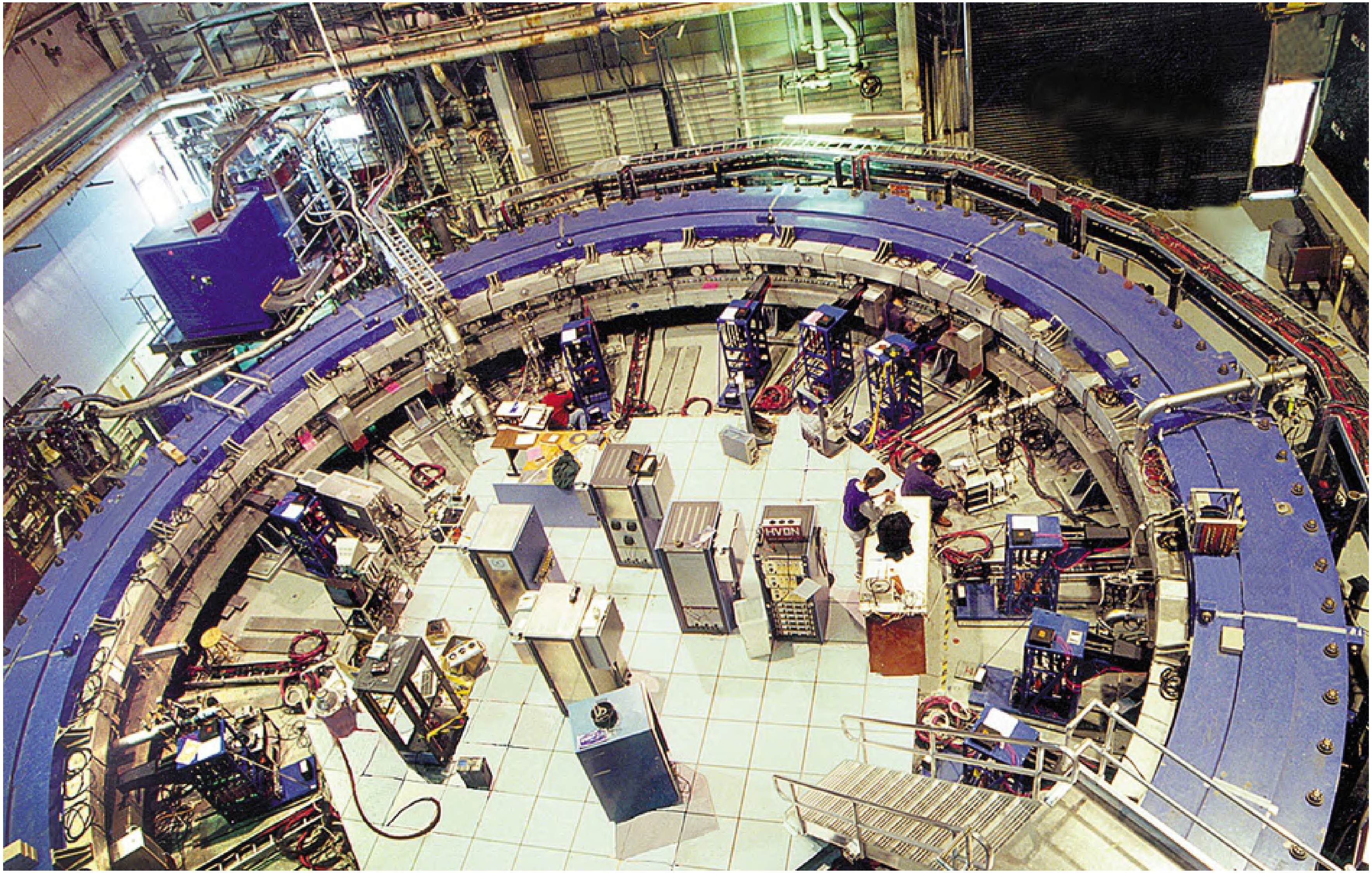
Yes but why muons?

- Leptons are the only elementary fermions that we can easily produce and store
- The electron g-2 is already measured and calculated with extremely high precision (2.00231930436146(56))
- The muon is 200 times more massive → 40’000 times more sensitive to new particles
  - Tauons would be even better but they are very impractical

CERN III (1969-1979)



BNL (1996-2006)

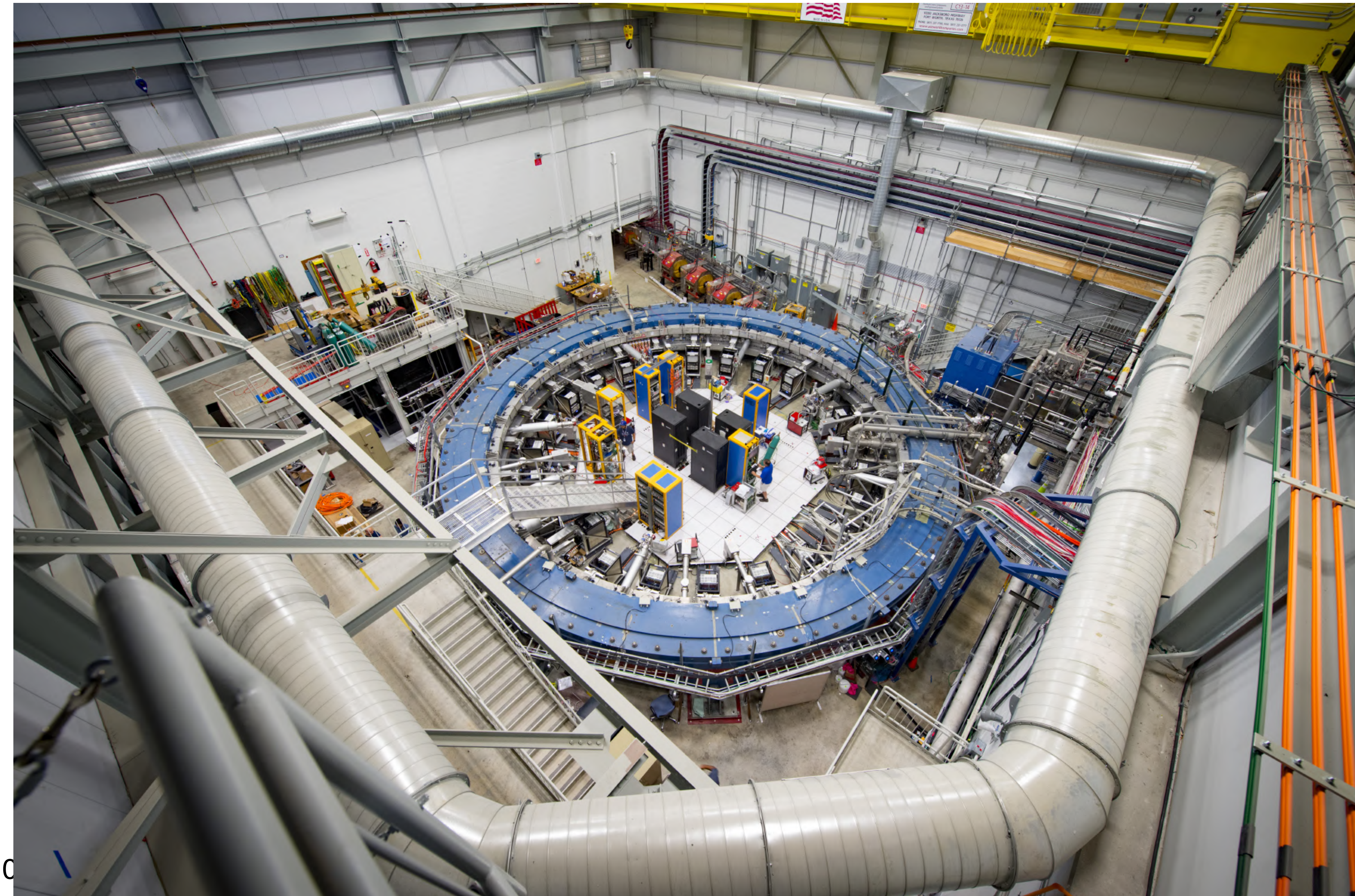


The big move

- 50 ton package shipped from Brookhaven (BNL) to Fermilab (FNAL) on the summer of 2013
- **35 days** and 5000+ km on water and land

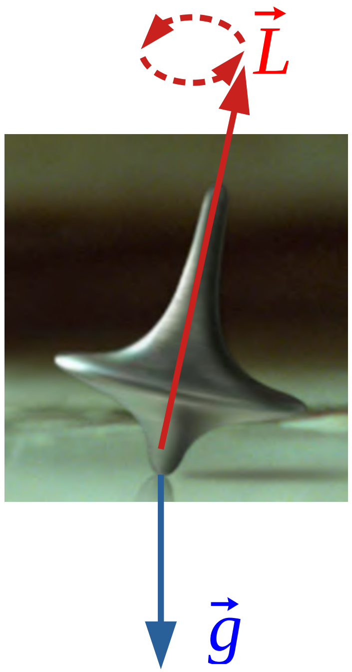
The big move

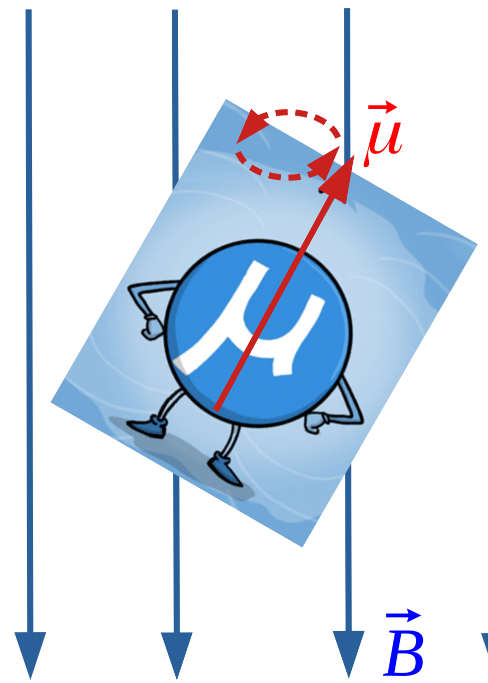
FNAL (2013-ongoing)



How to measure g-2

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





We want to measure the magnetic moment which is affected by **all** possible virtual particles

How to measure g-2

Spin precession

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

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

Cyclotron frequency

How to measure g-2

Spin precession

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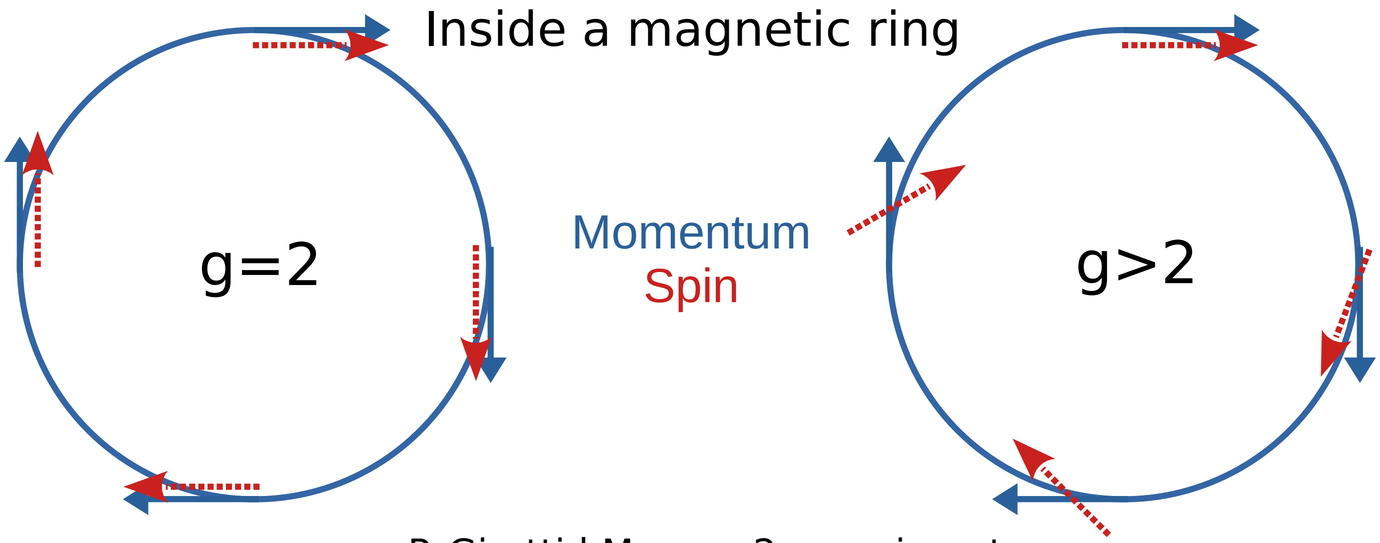
Cyclotron frequency

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

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

Inside a magnetic ring



How to measure g-2

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

Measure the spin precession and the magnetic field → get the anomalous magnetic moment

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In a real experiment, we need to keep the beam focused vertically with electric field

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

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---

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~0.00117

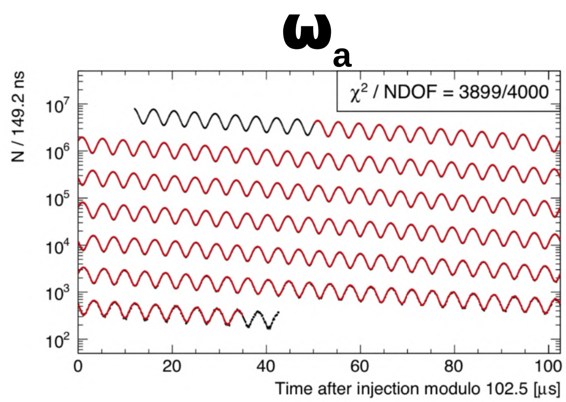
29.3

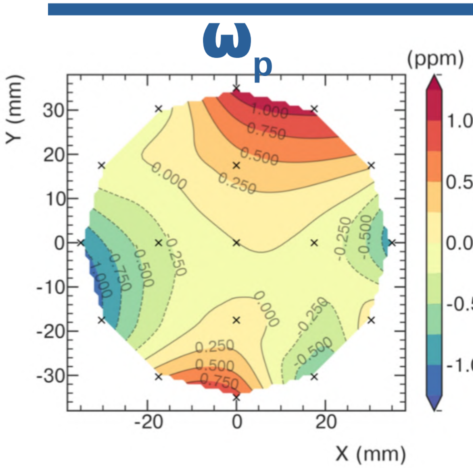
Nature gift n°1: use the magic momentum 3.094 GeV/c !

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 with high precision from other experiments





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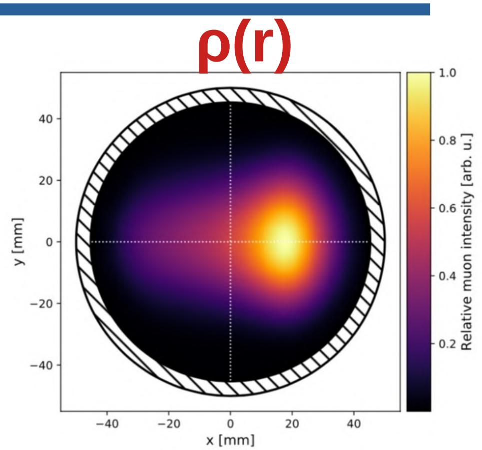

- **ω_a**: Muon anomalous precession frequency
- **ω_p**: Larmor precession frequency of protons in water (mapping B)
- **ρ_r**: Muon distribution in the storage ring

Goal: measure a_μ 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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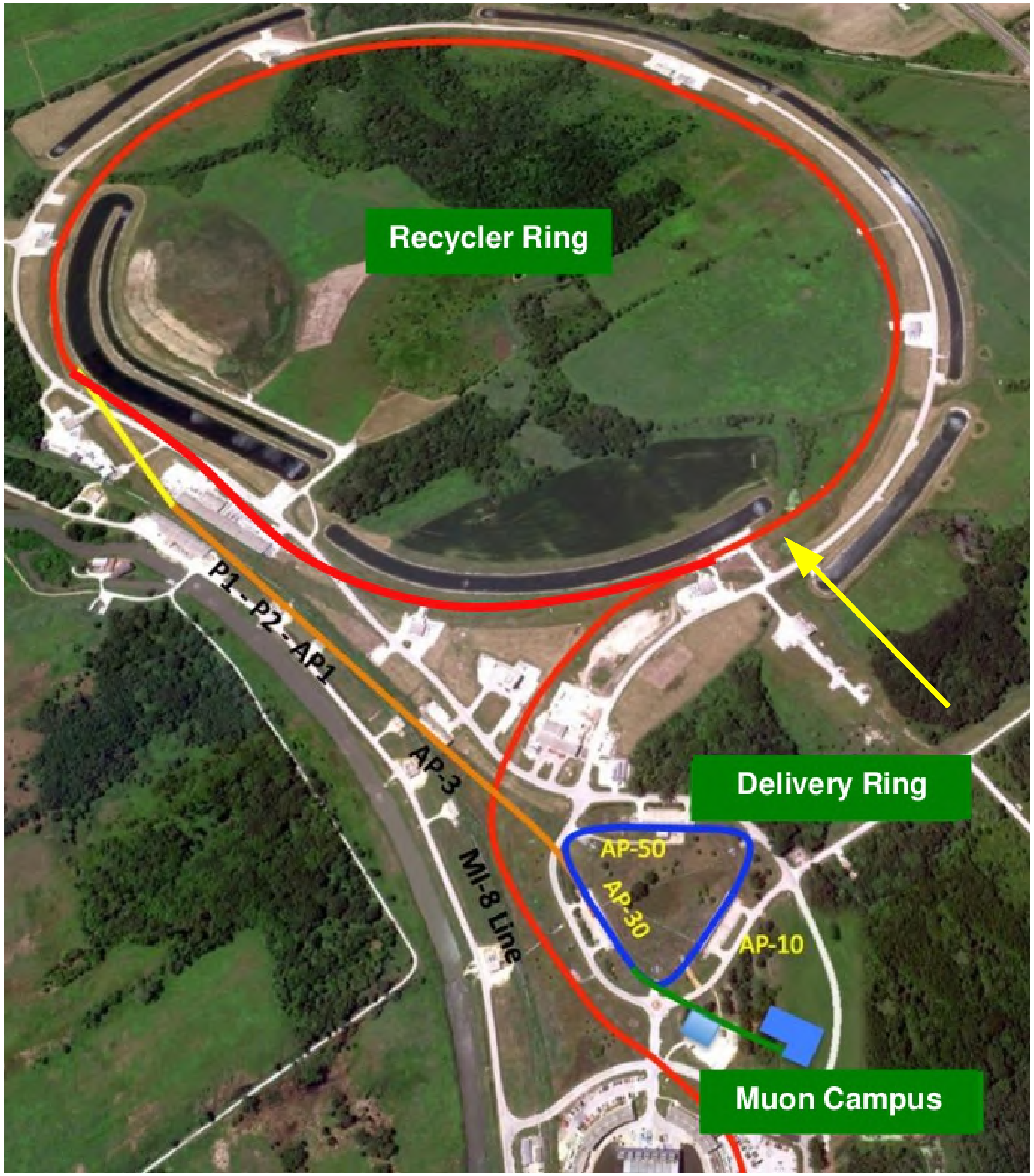
$P \to \pi^+ \to \mu^+ \to e^+$

The beam

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



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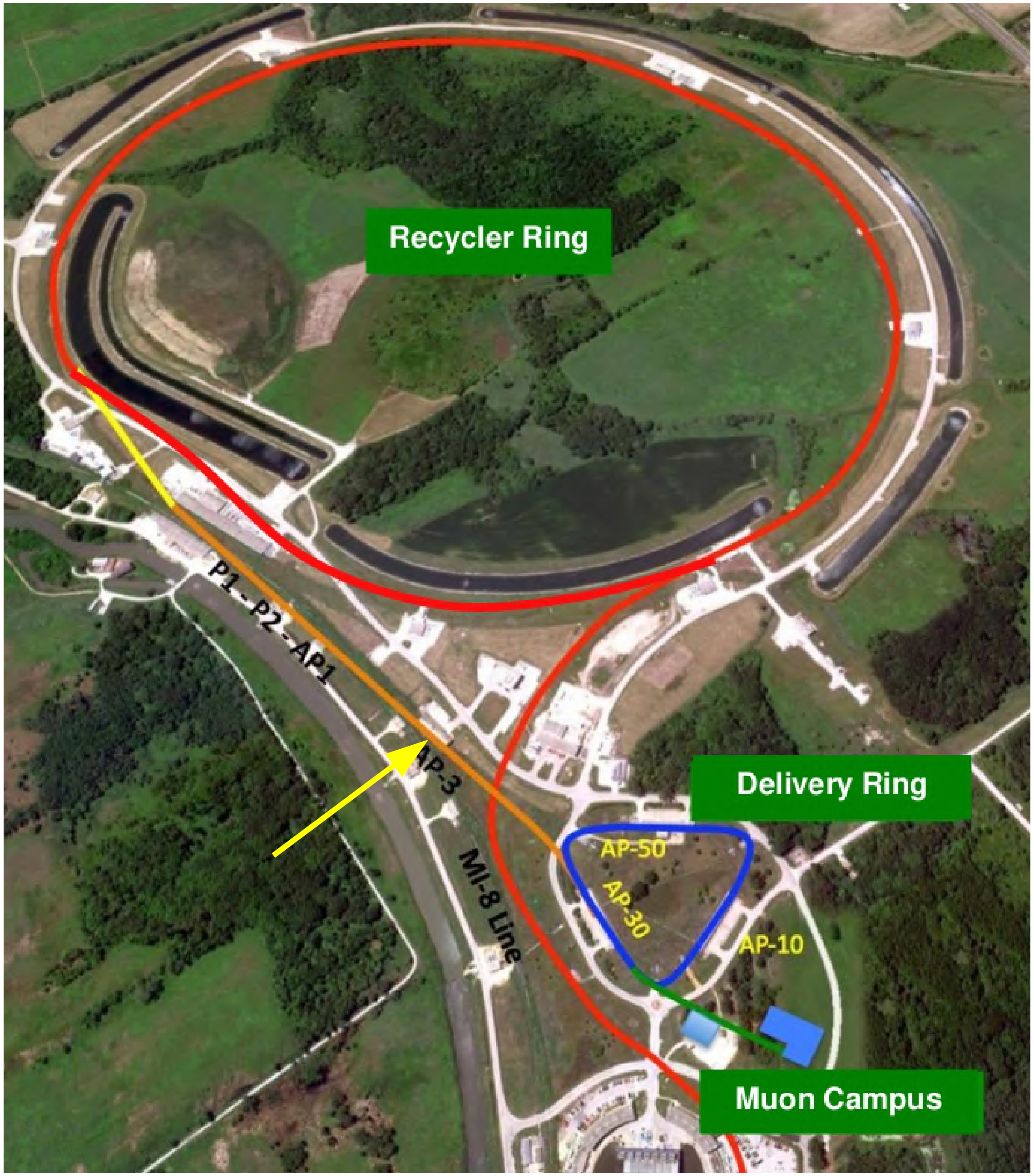

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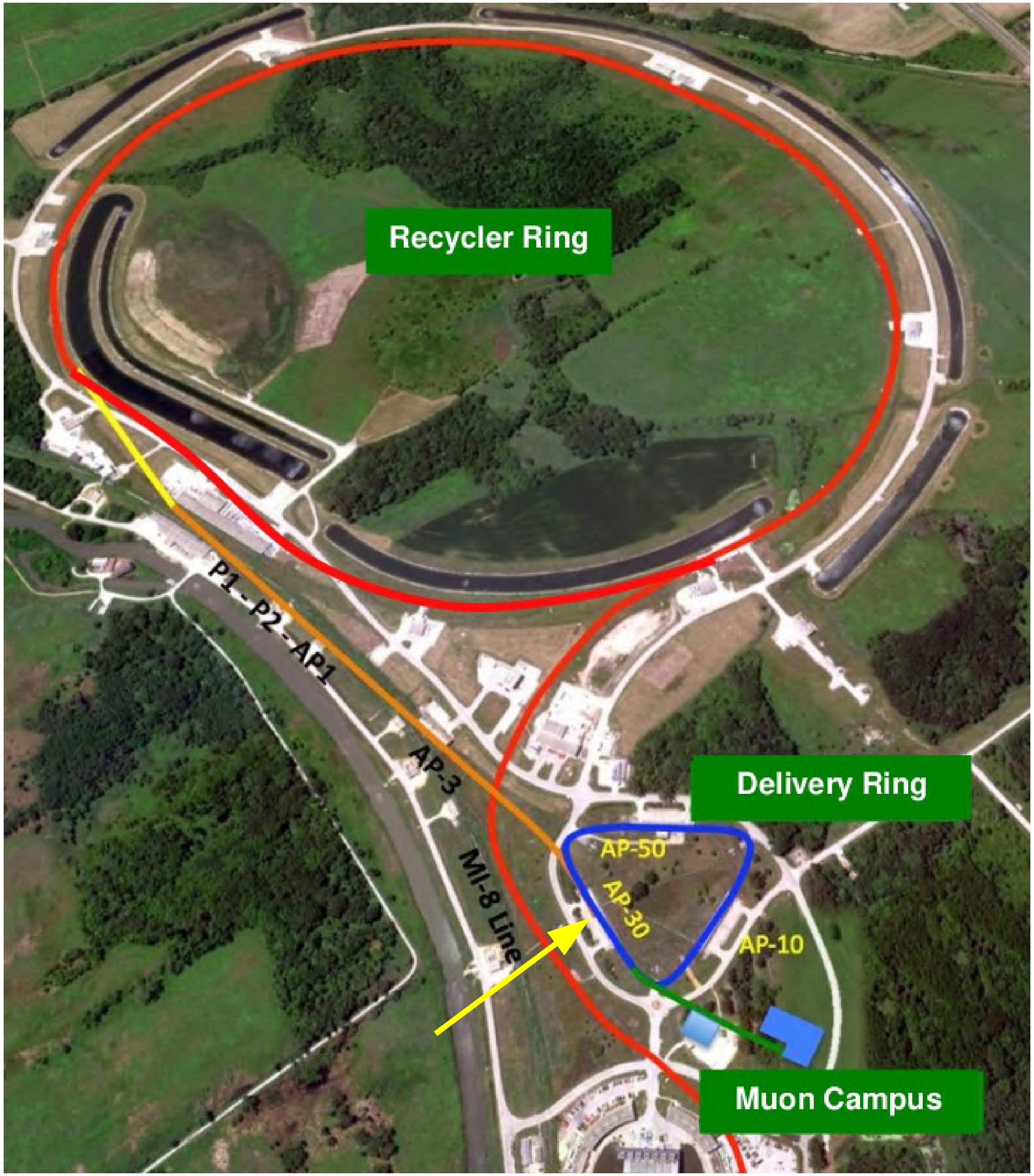

The beam

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

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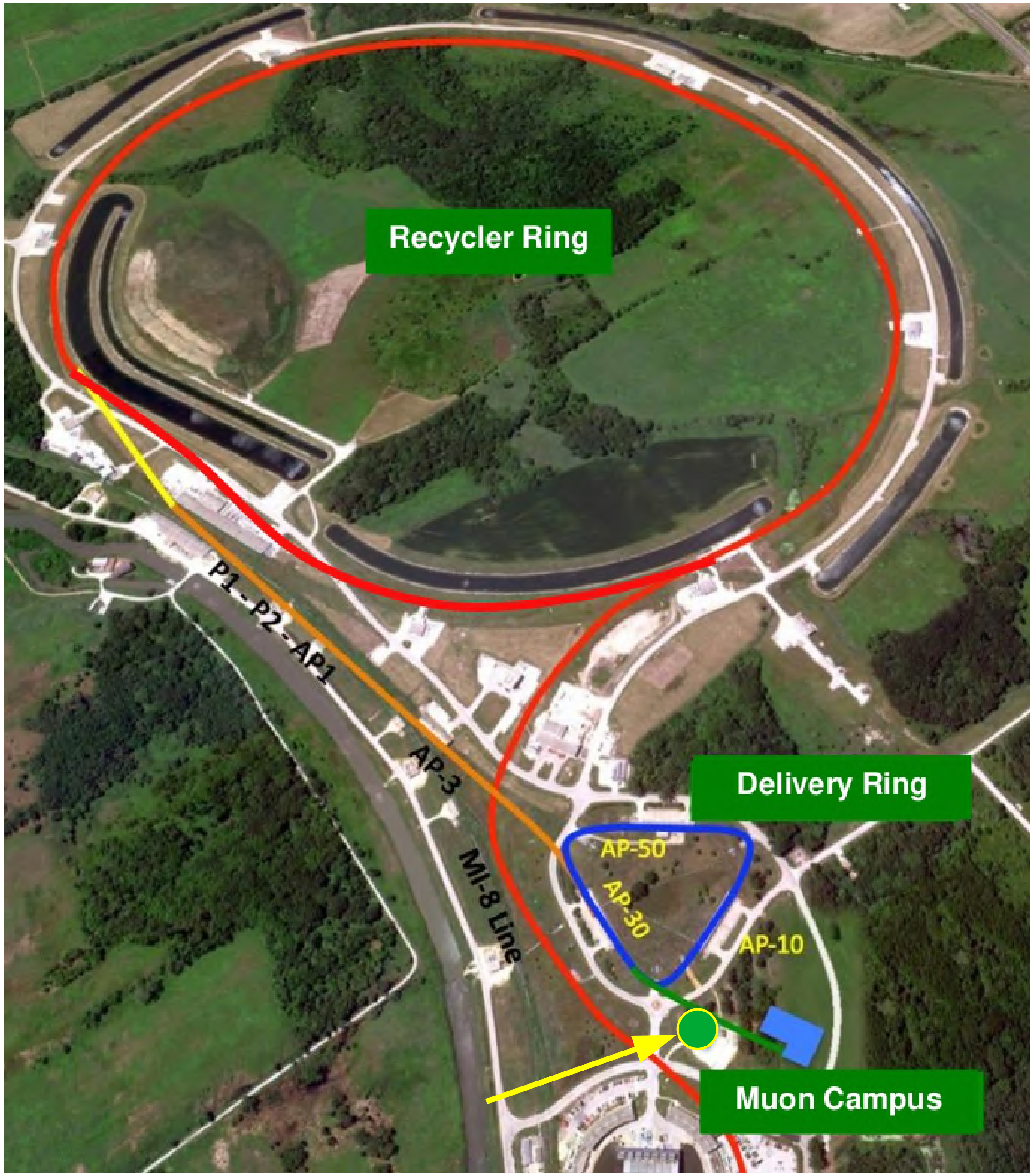
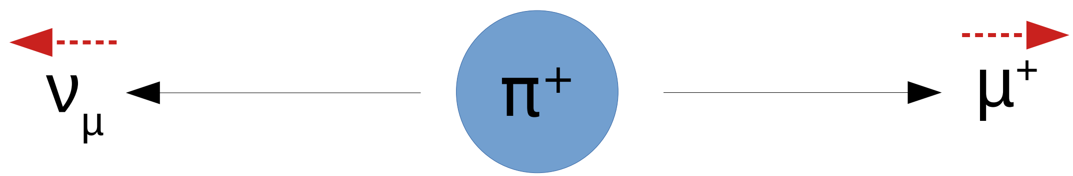
- Each bunch hits a fixed Inconel 600 target
- Pions from shower extracted and decay in delivery ring
- Muons enter g-2 ring



Pion decay

- Mass ~ 140 MeV/c2
- Lifetime ~2.6e-8 s
- Spin: 0!



Pions are boosted → muons are mostly forward/backward polarized

Nature gift n°2: high energy muons are ~97% polarized for free!

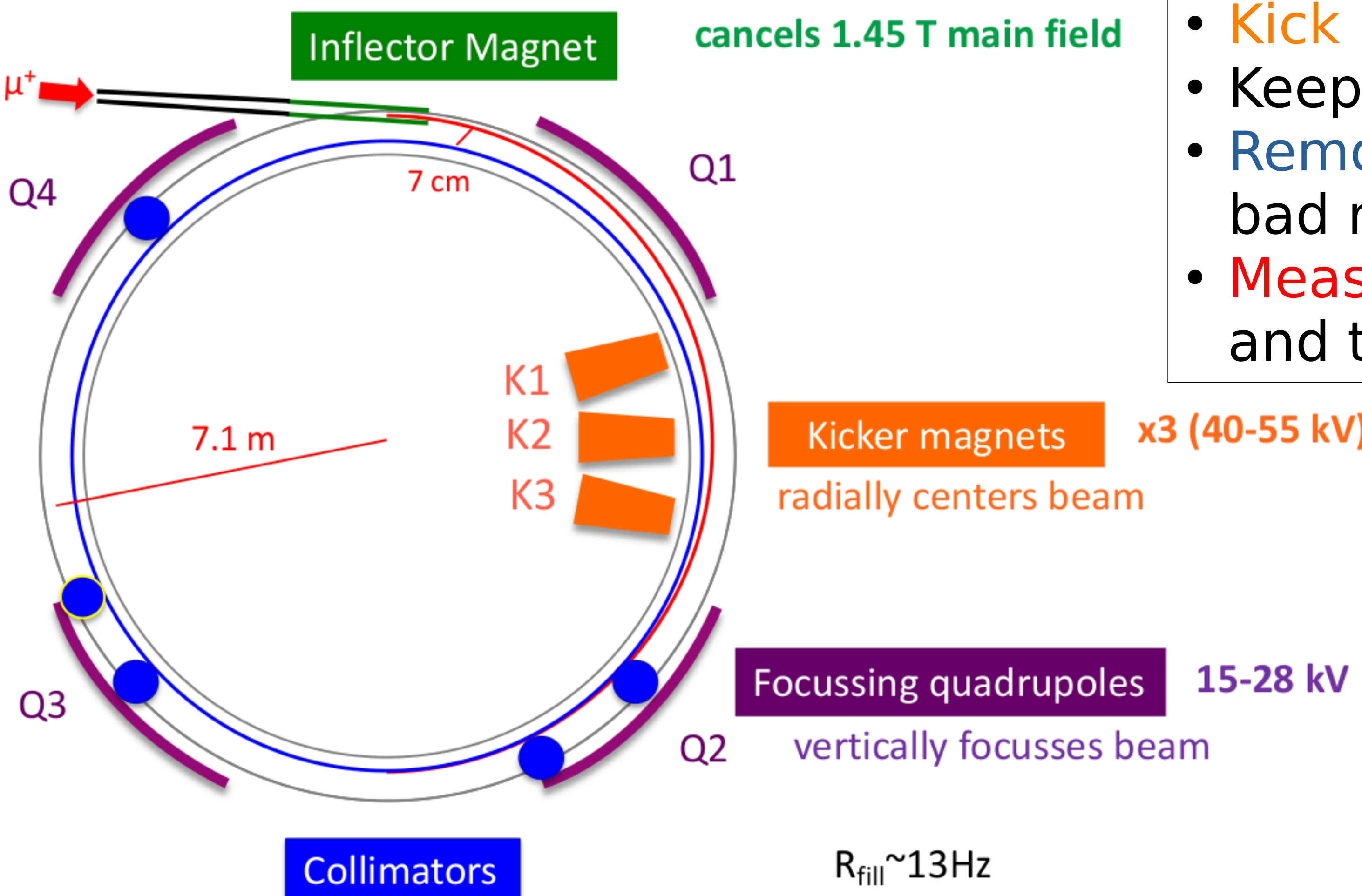
How to measure g-2

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

Storage ring

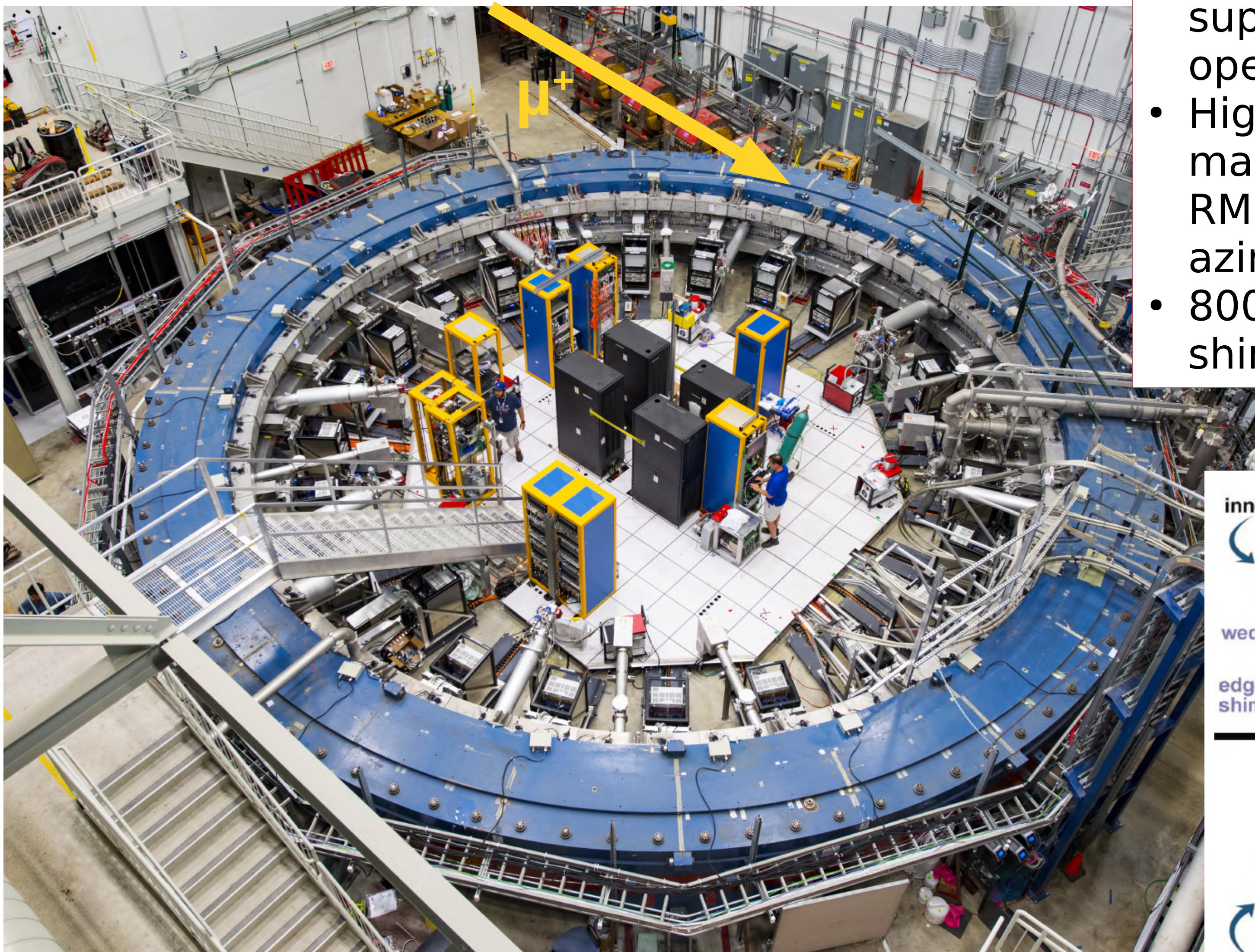
It has to:
- Inject muon beam
- Kick it into orbit
- Keep it focused
- Remove muons with bad momentum
- Measure the positrons and the field

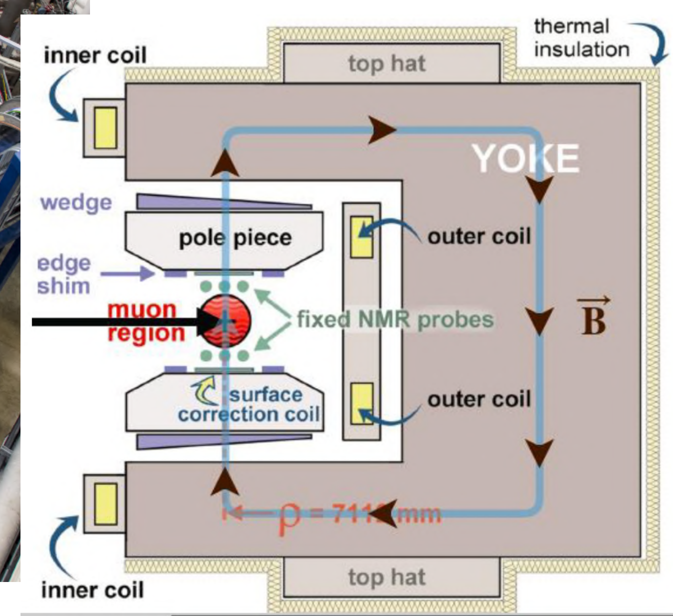


R_{fill}~13Hz
N_{μ}/fill (TDR)~ 10^4
N_{μ}/sec(TDR)~ $1.3x10^5$
$N_{e+\ E>1.8\ GeV}$/fill (TDR)~ 10^3

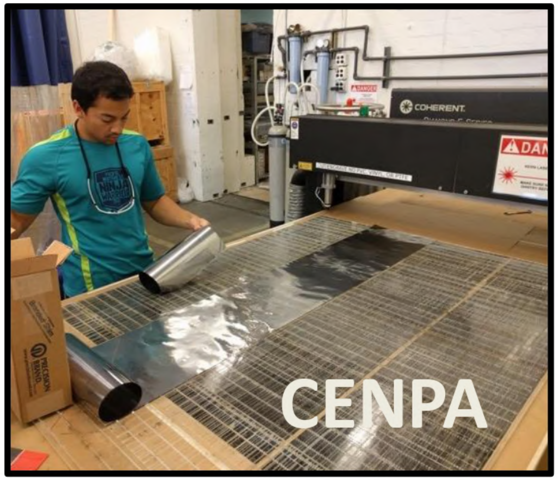
Magnet

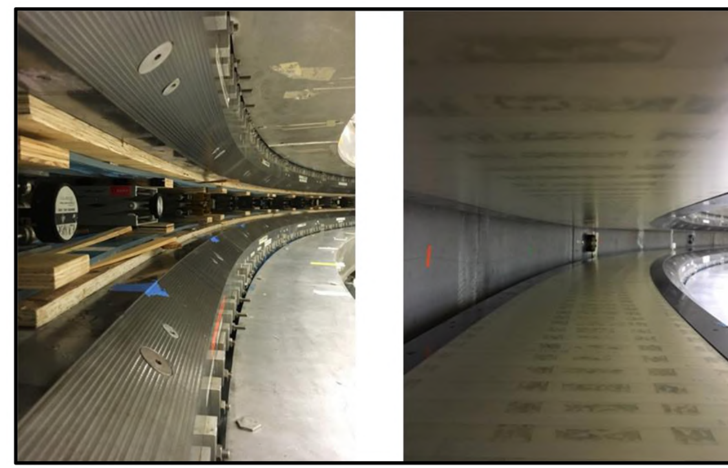
- 7.112 m radius C-shaped superconducting magnet operating at ~5 K
- Highly **uniform 1.45 T** magnetic field (14 ppm RMS across the full azimuth)
- 8000 iron foils for precise shimming

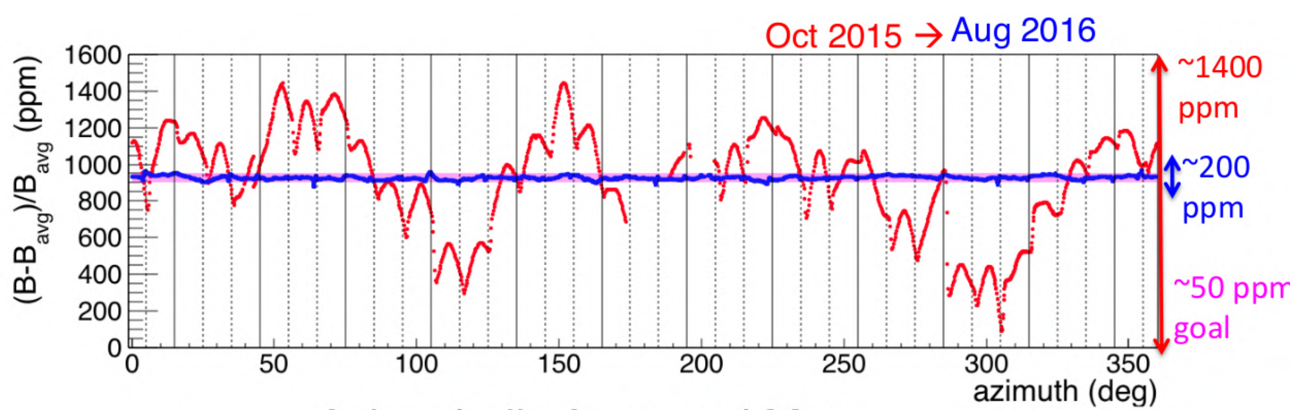




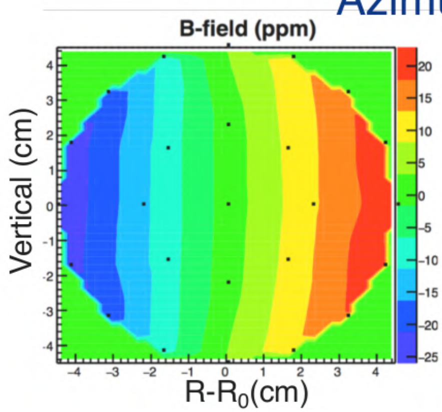
Magnet





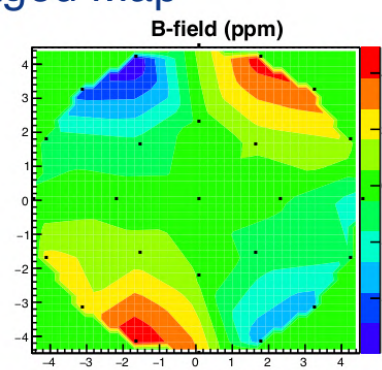


Azimuthally Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

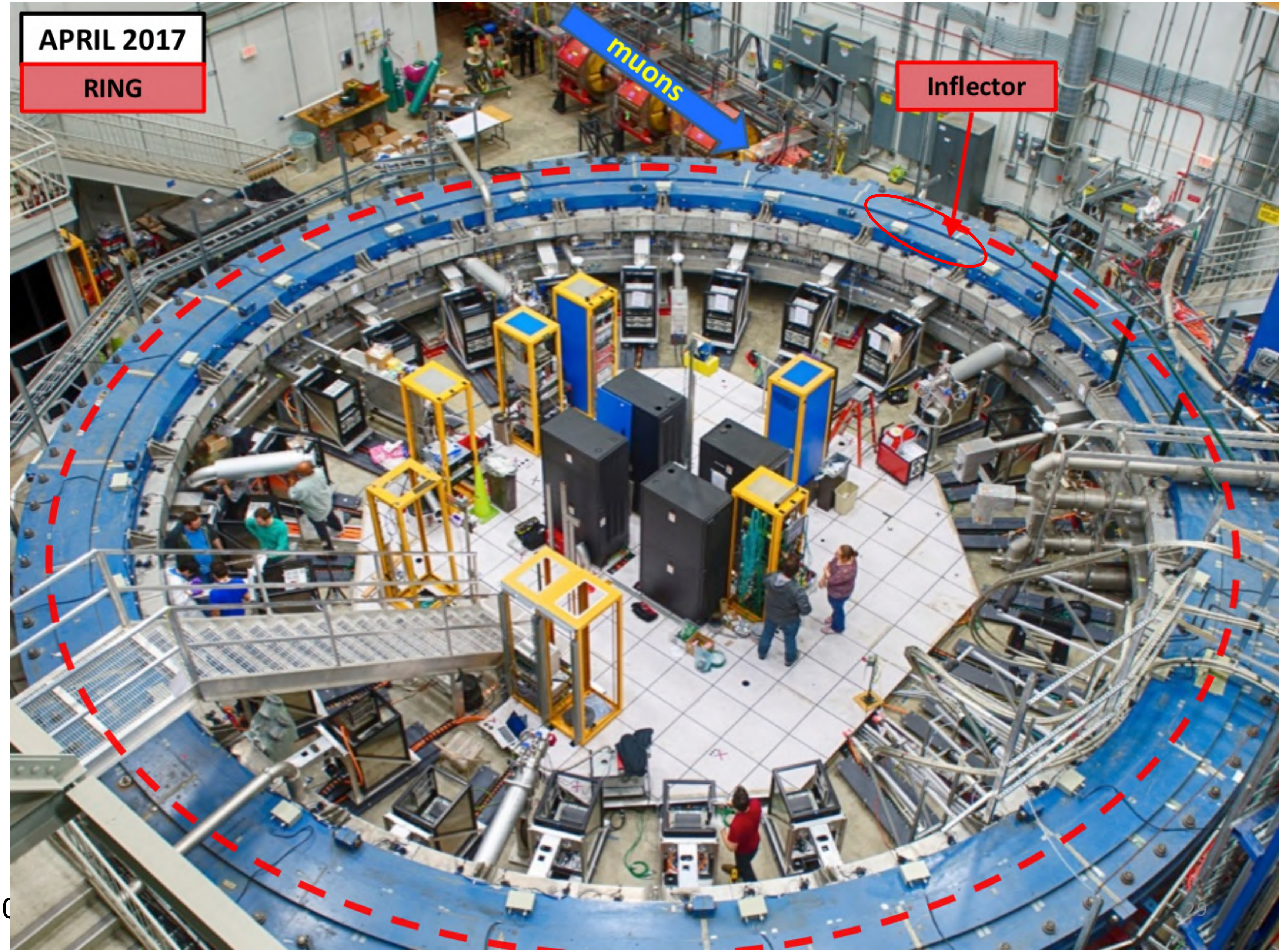
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

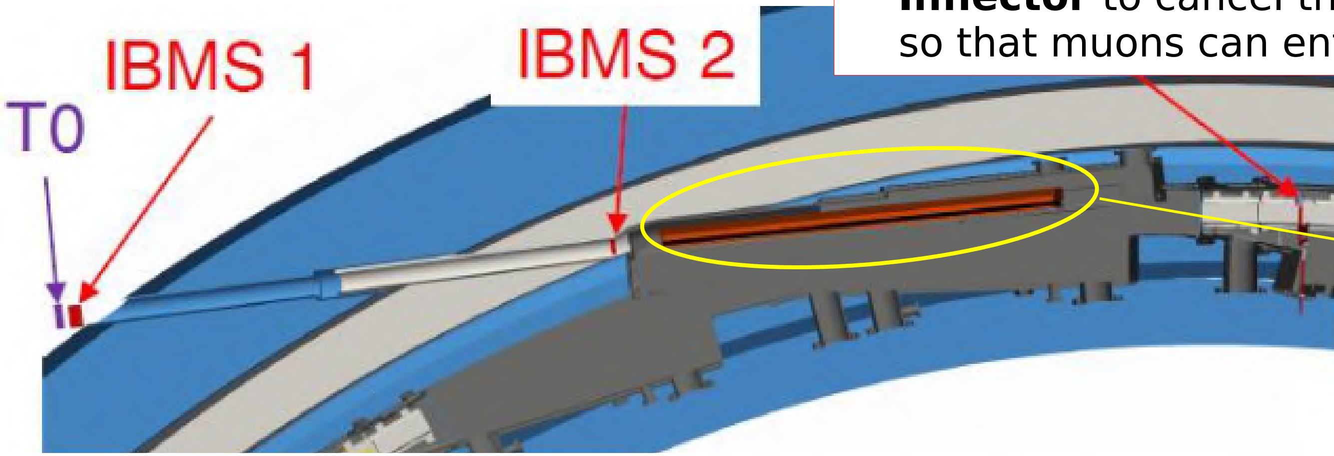
Aug 2016

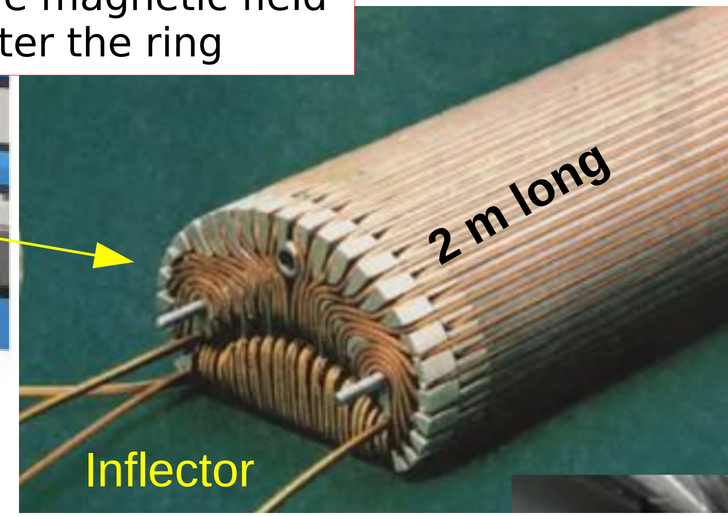
Inflector

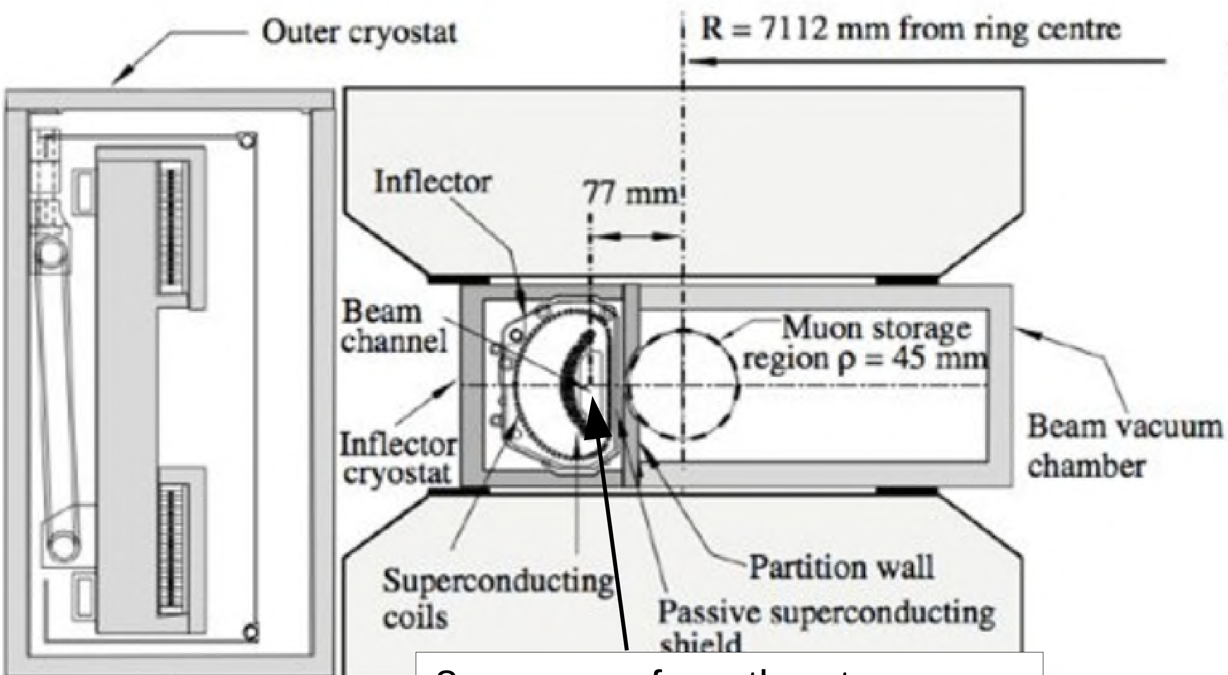


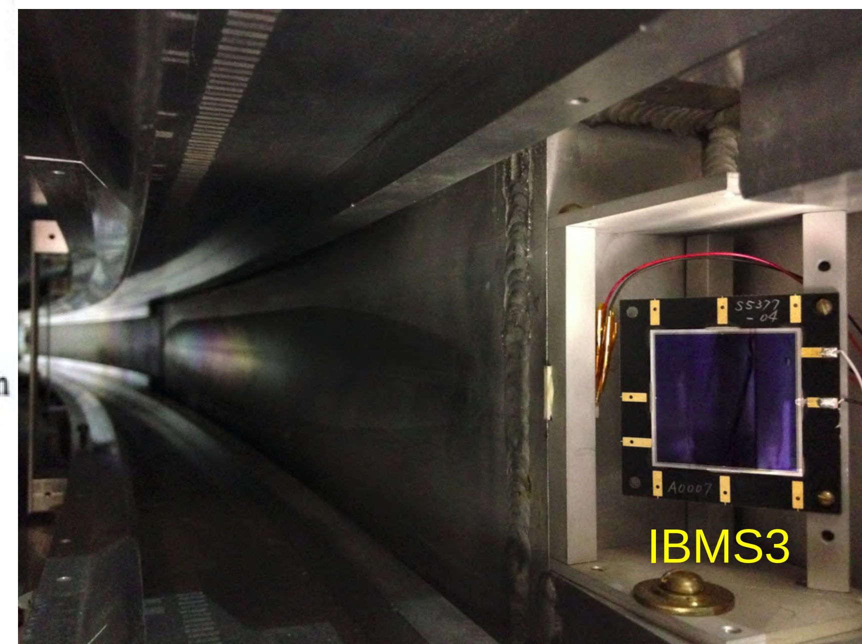
Inflector

- 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





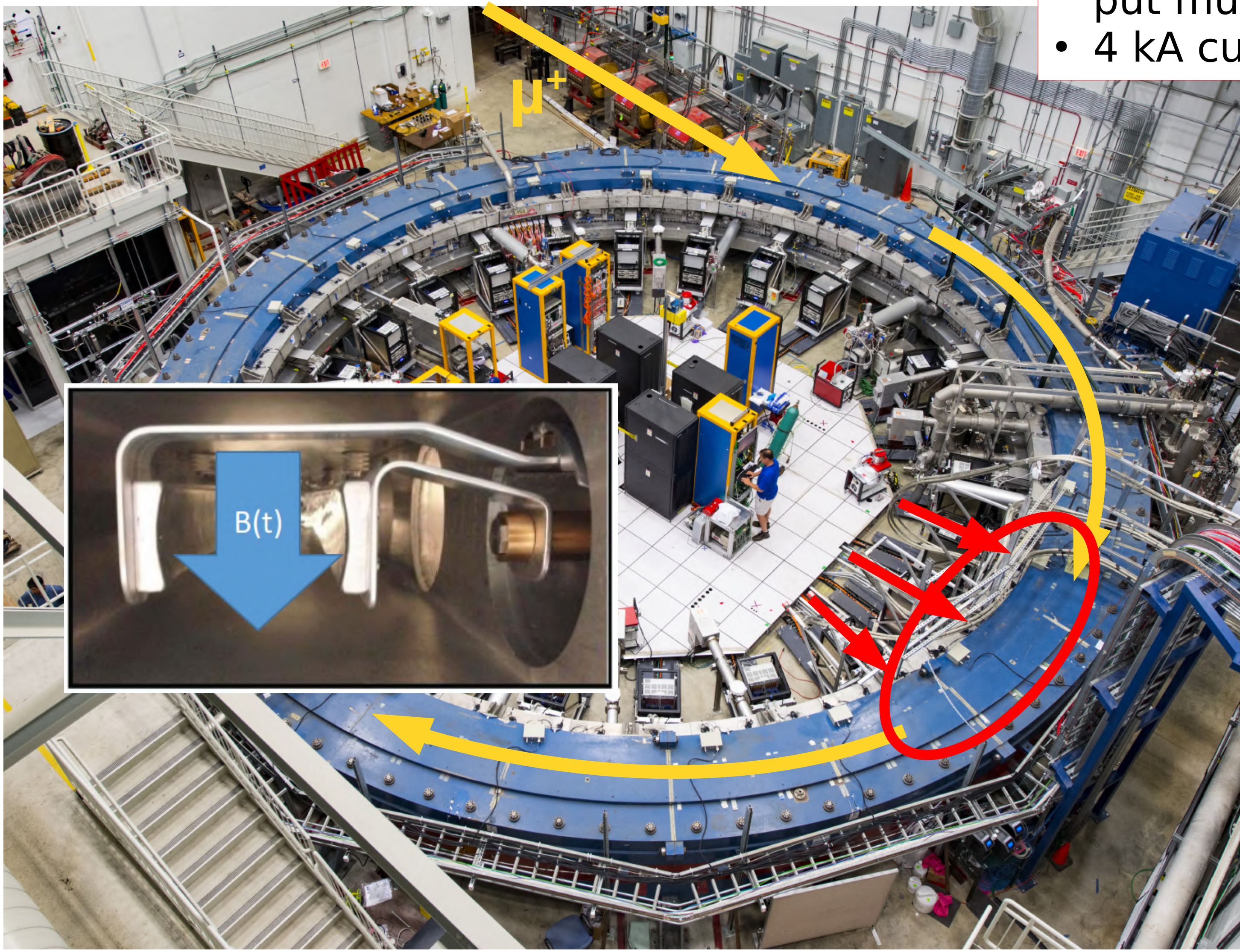


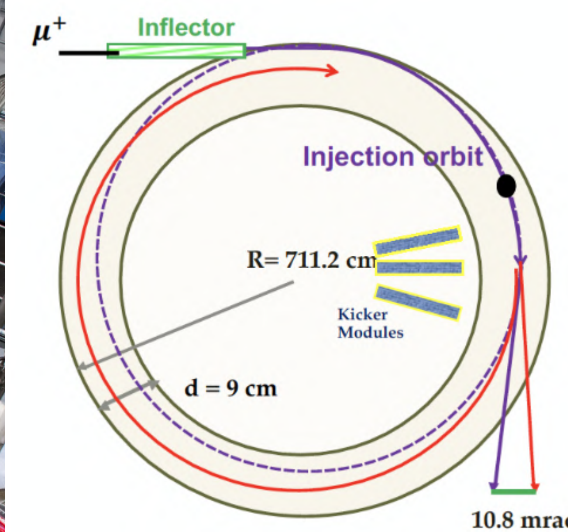


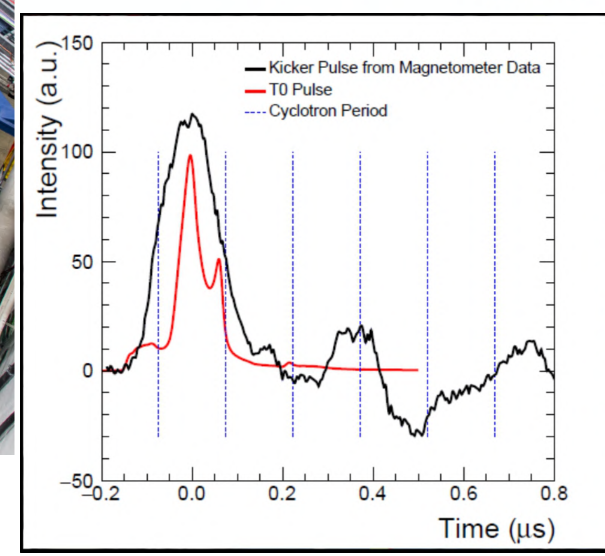
8 cm away from the storage region in order to not interfere with circulating muons

Kicker

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

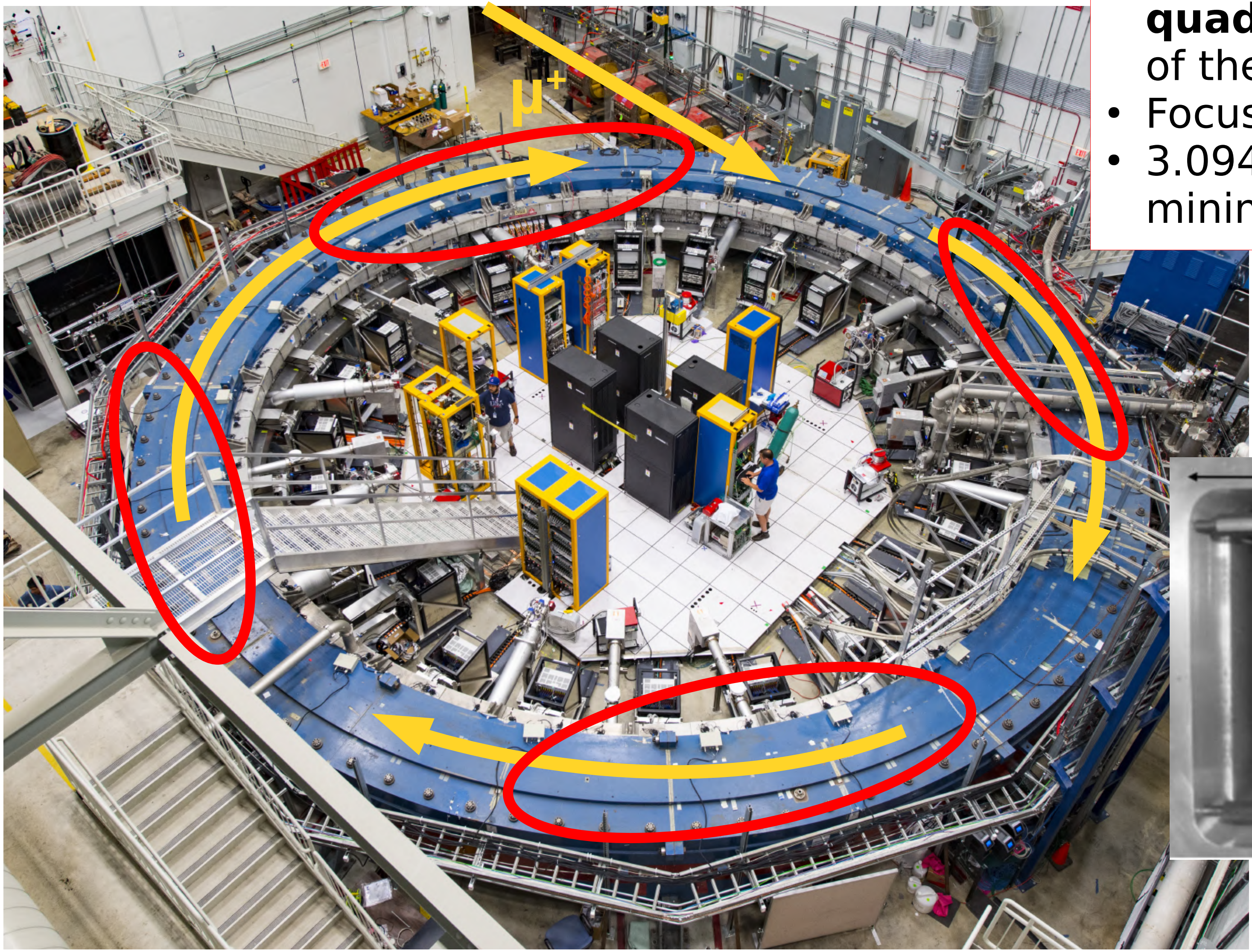


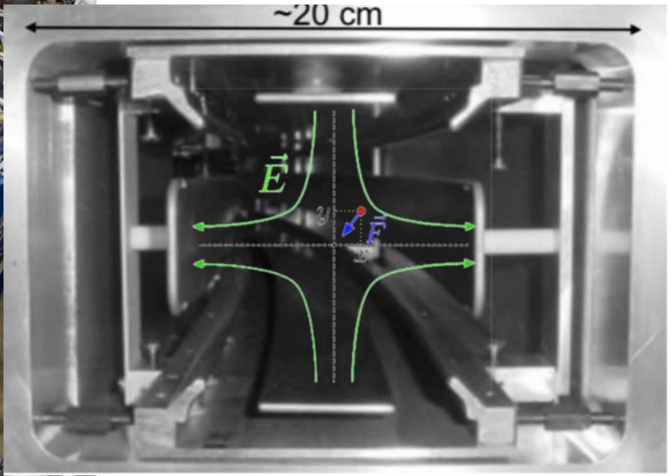




Quadrupoles

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





How to measure g-2

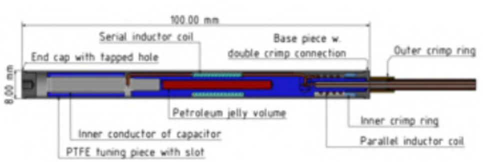
Key ingredients:

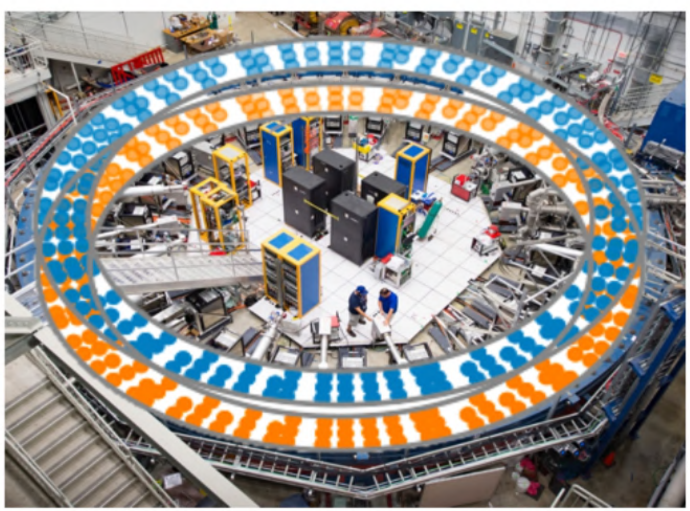
- A beam of polarized muons
- A magnet to store the beam
- **A way to measure the muon spin, the magnetic field and the beam through time**

Measuring the field

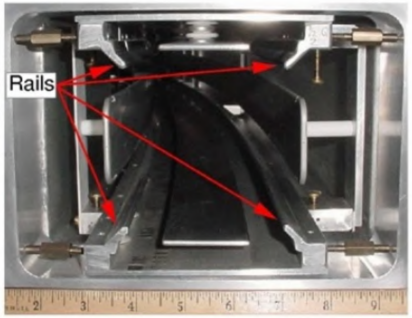
- Need to determine **B at < 100 ppb** to determine a_μ
  - Use NMR to assess B-field in terms of proton precession frequency ω_p

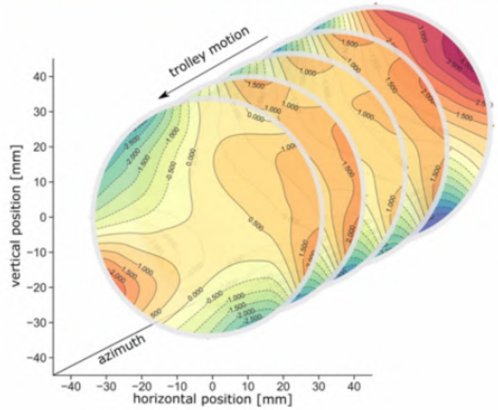
378 fixed probes continuous monitoring



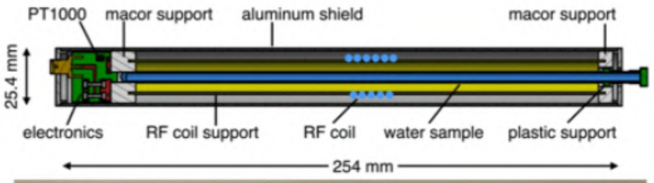


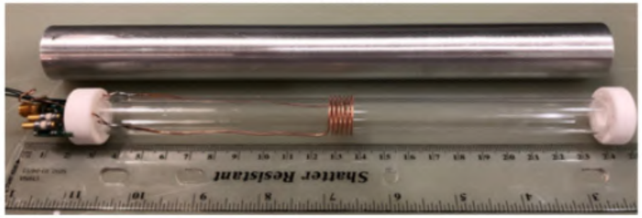
17 probes on a trolley to 3D map every ~3 days





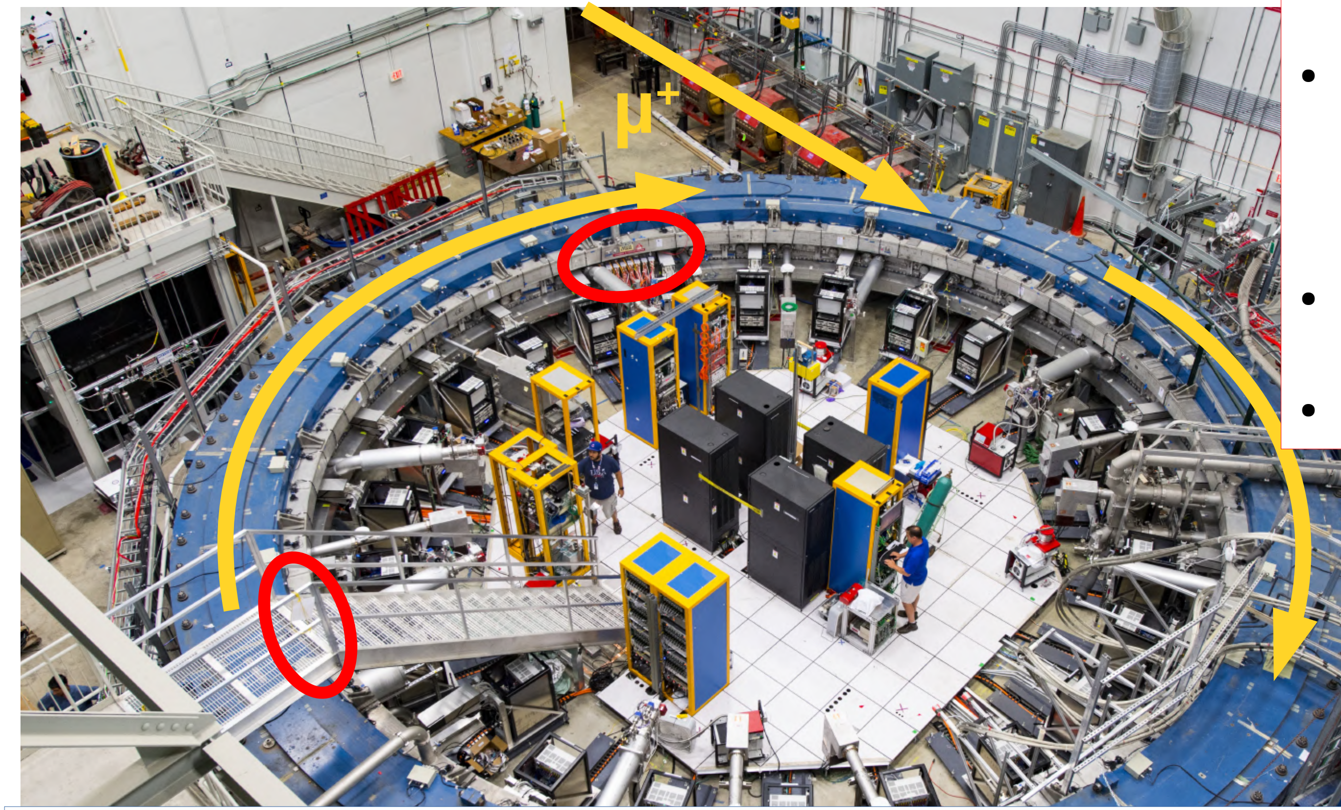
Trolley cross-calibrated to absolute probes

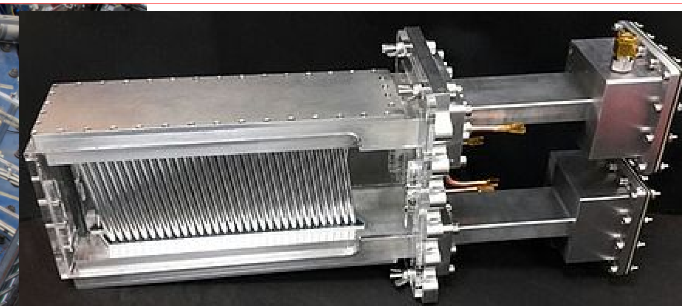


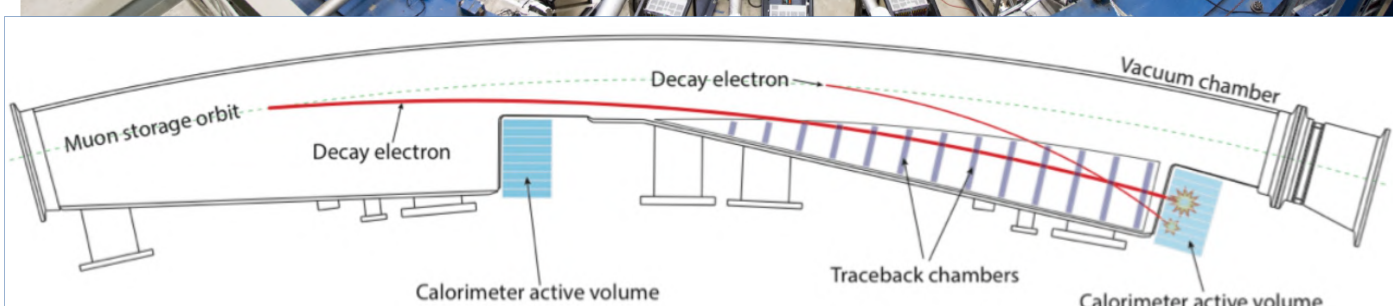


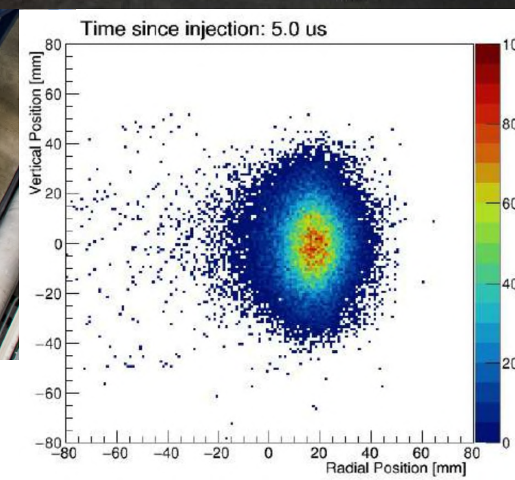
Measuring the beam

- 2 tracker stations with 8 modules each
- Each module has 128 Argon-Ethane filled straw tube in a U-V plane configuration → 2000+ channels
- Traceback positrons to their decay point
- 100 μm hit resolution

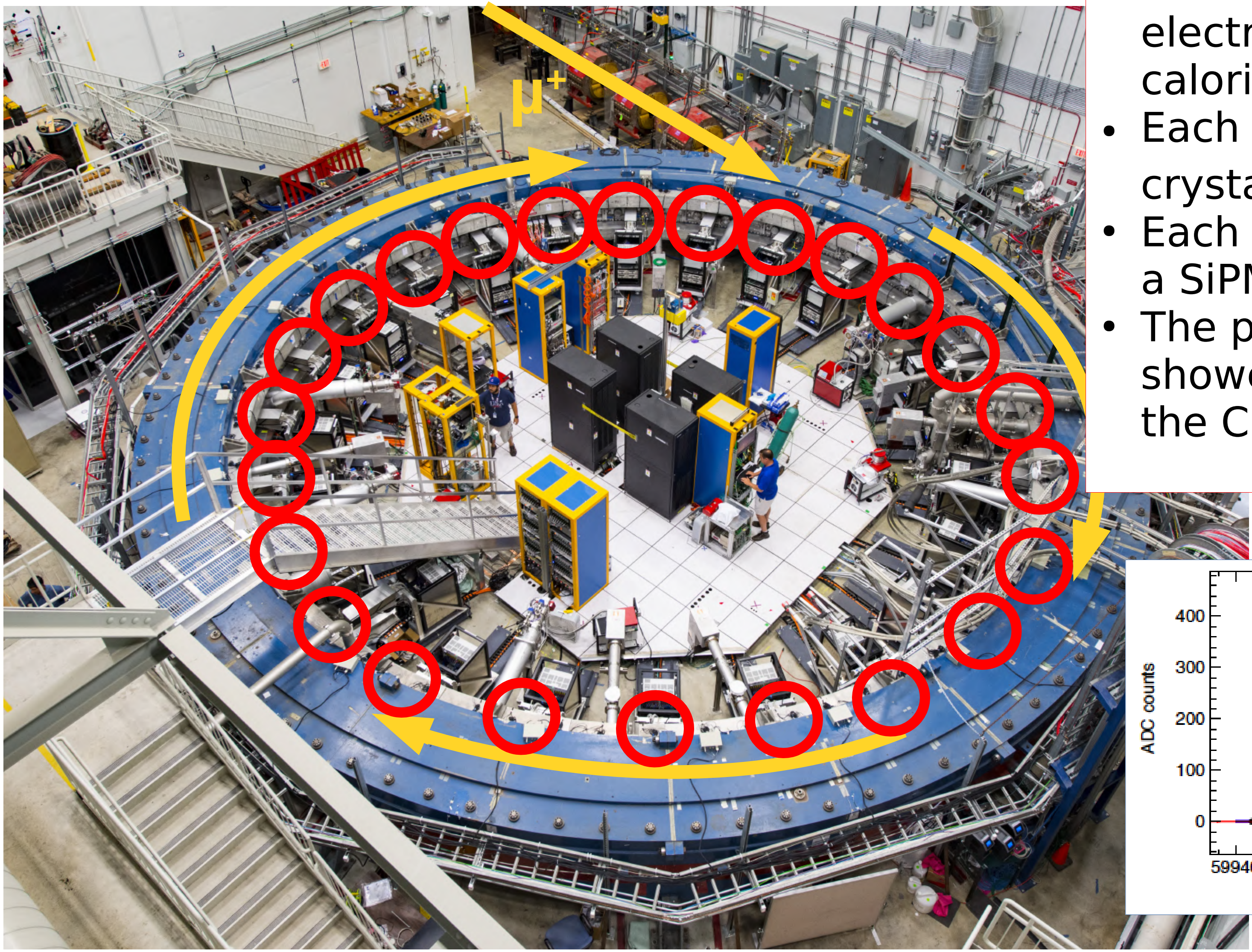




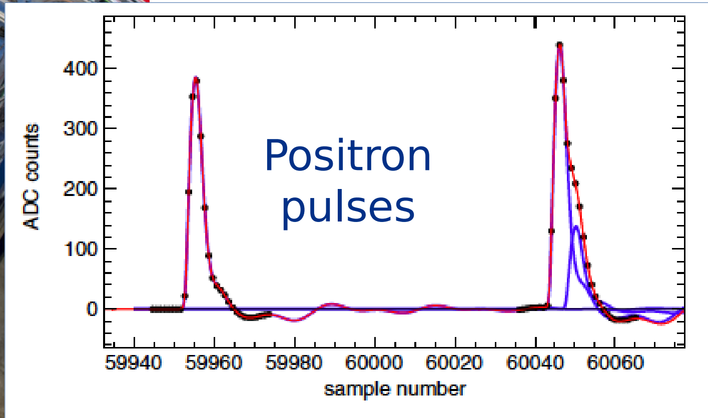




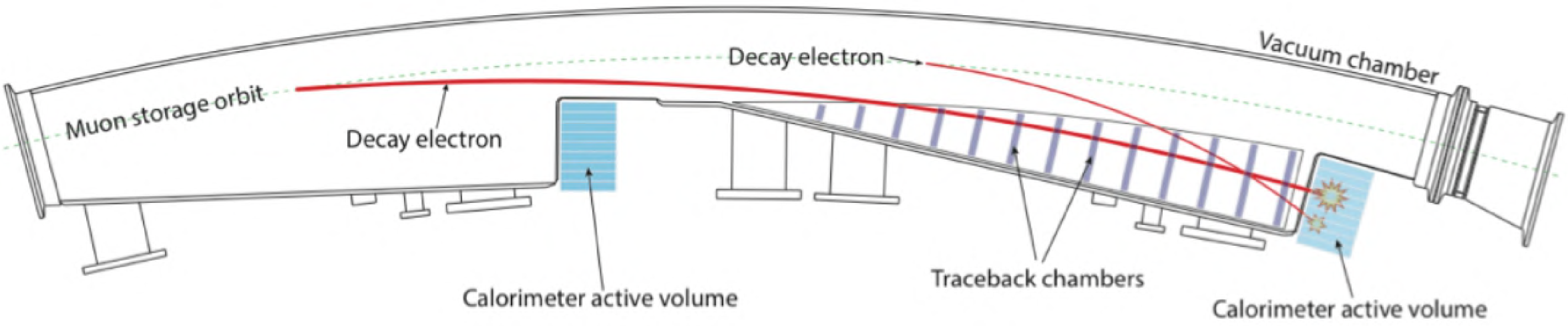
Measuring the positrons

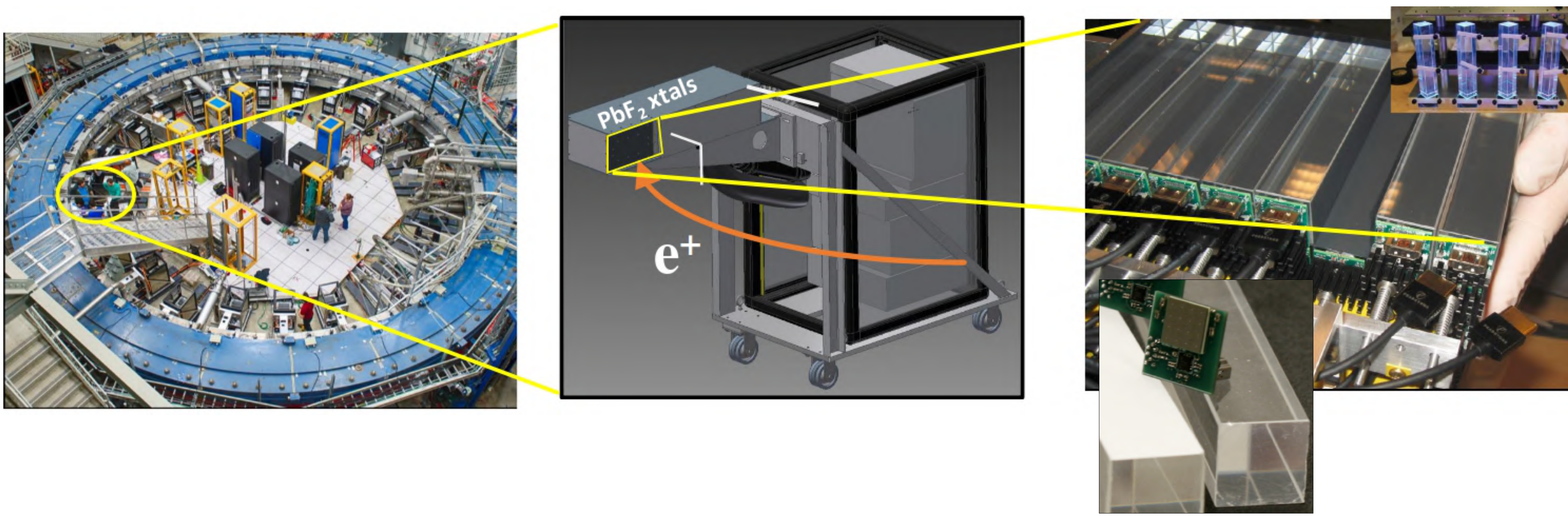


- 24 omogeneous electromagnetic calorimeters along the ring
- Each is a 9 x 6 array of PbF_2 crystals 2.5 x 2.5 x 14 cm
- Each crystal is coupled with a SiPM digitized at 800 MHz
- The positrons produce an EM shower and the SiPMs collect the Cherenkov light



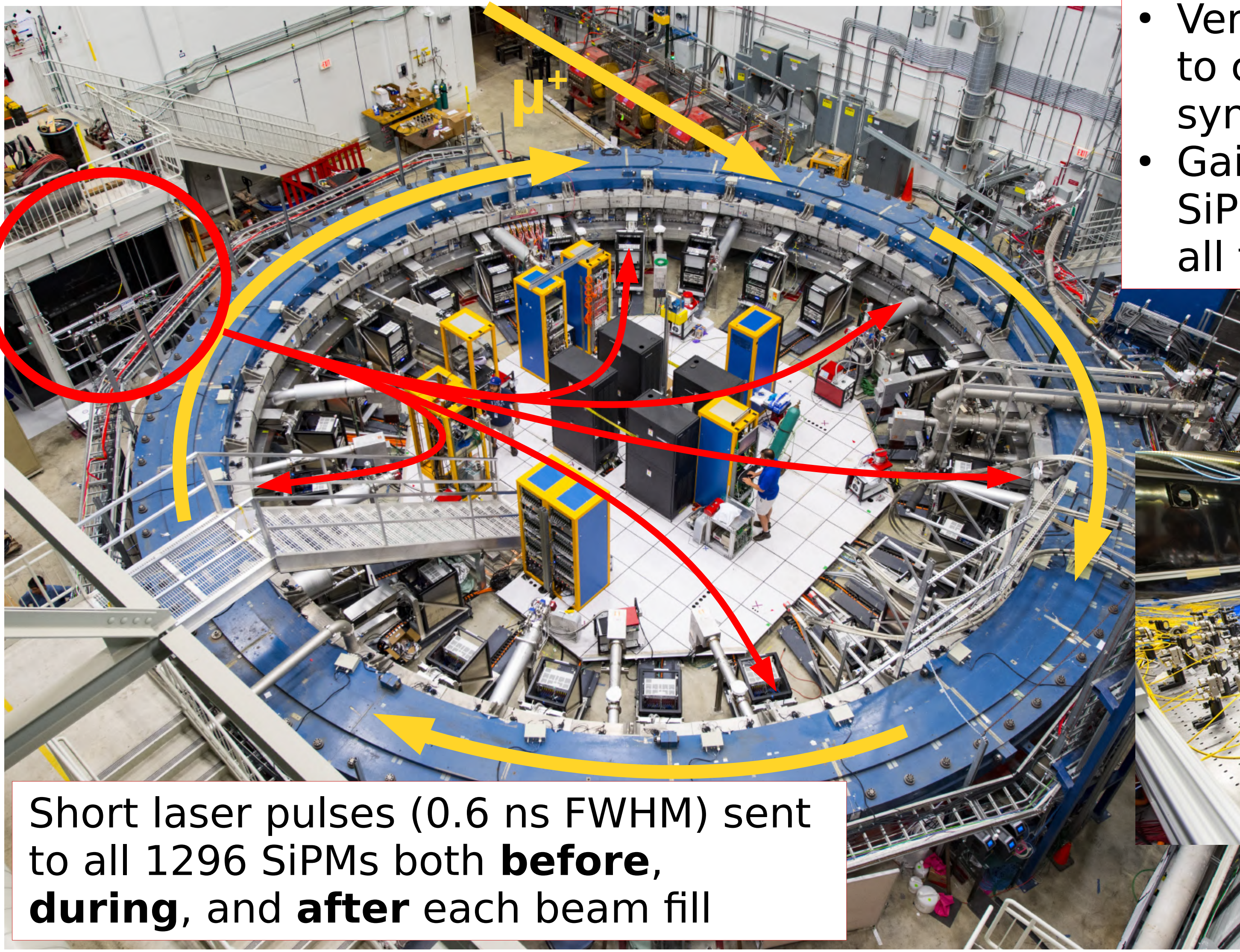
Calorimeters



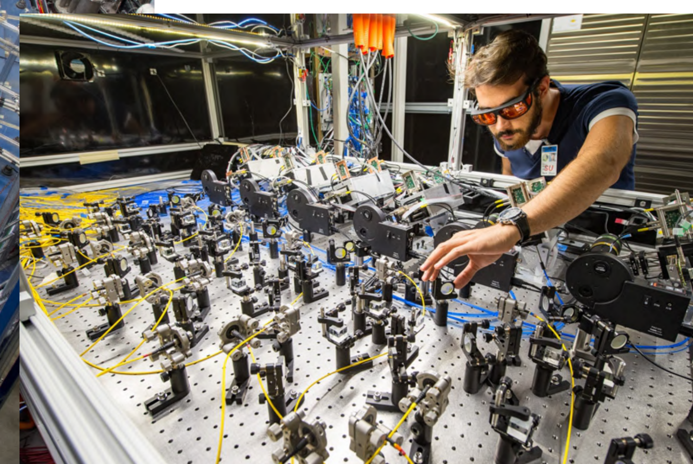


Laser Calibration System

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



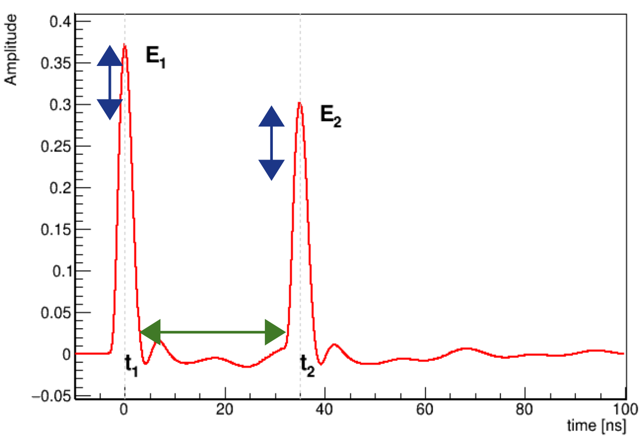
Short laser pulses (0.6 ns FWHM) sent to all 1296 SiPMs both **before**, **during**, and **after** each beam fill

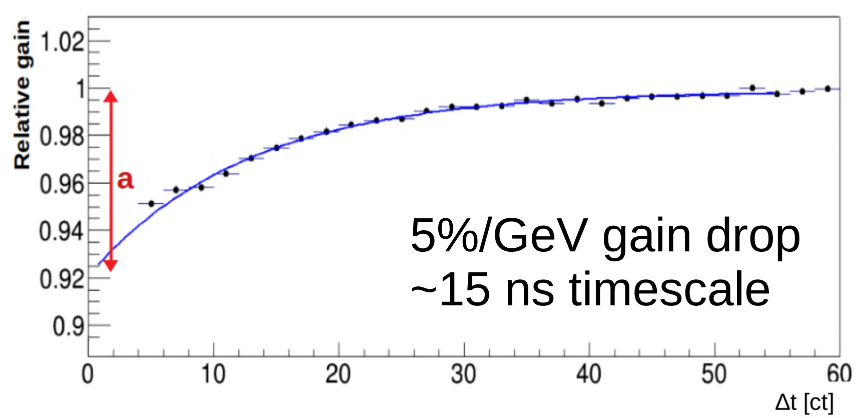


Laser corrections

- **Time corrections**
  - Synchronization pulse before each injection to align the SiPMs readouts with ~50 ps precision
- **Gain corrections**
  - Any gain variation within the beam lifetime (700 µs of beam storage) induces a direct bias to the ω_a measurement
  - Systematic error < 20 ppb thanks to this system

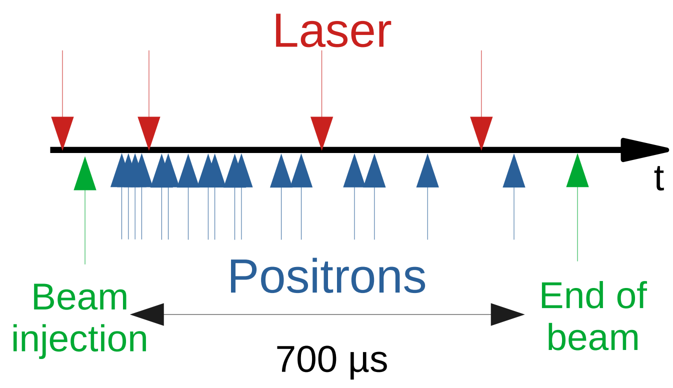
- Charge depletion of the SiPMs pixels take ~15 ns to recover after a positron signal

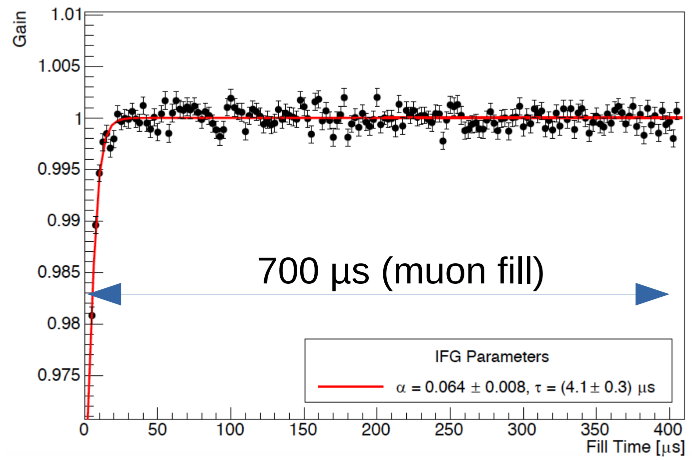




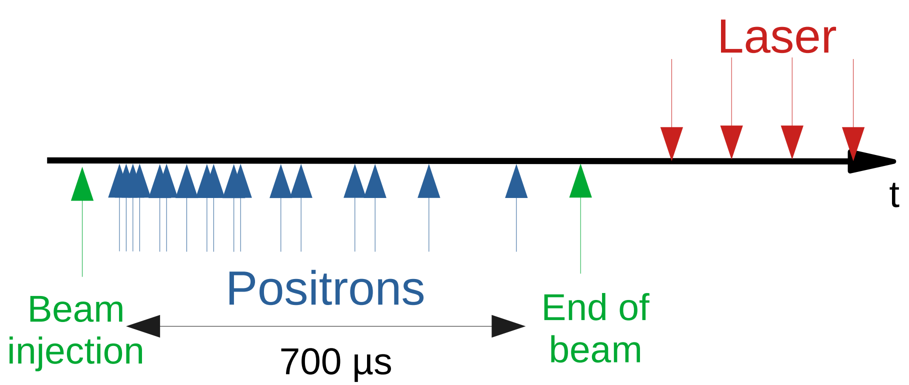
Laser corrections

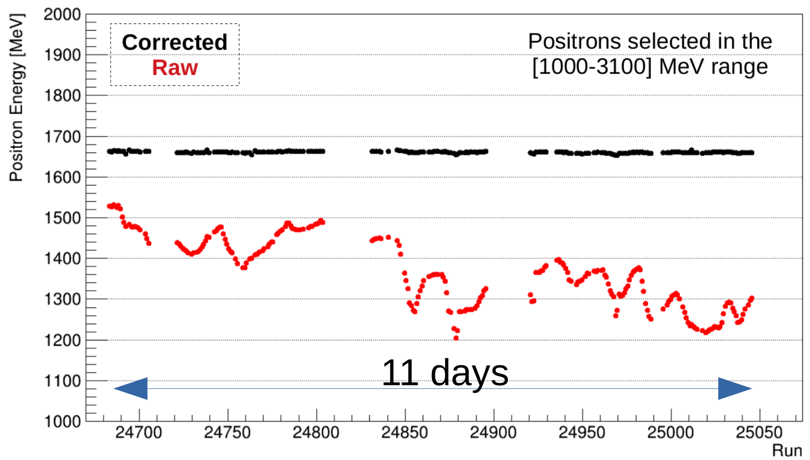
- Gain drop induced by the energetic "splash" of particles at beam injection. SiPM high voltage takes some microseconds to recover





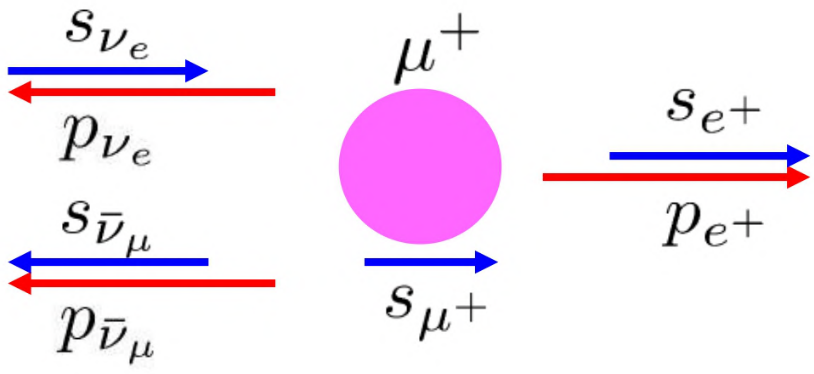
- Long-term SiPM fluctuations due to temperature variations





Measuring the positrons

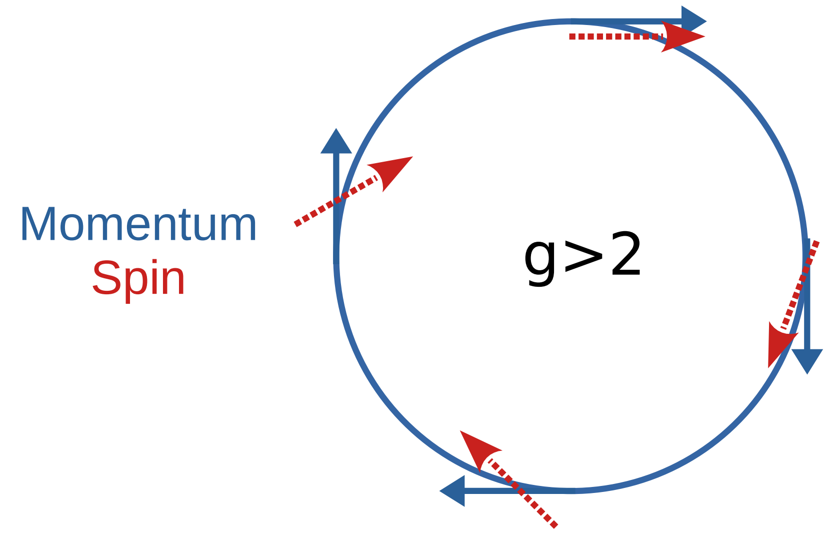
- Mass: 105 MeV/c^2
- Lifetime: 2.2 µs
- Spin: ½



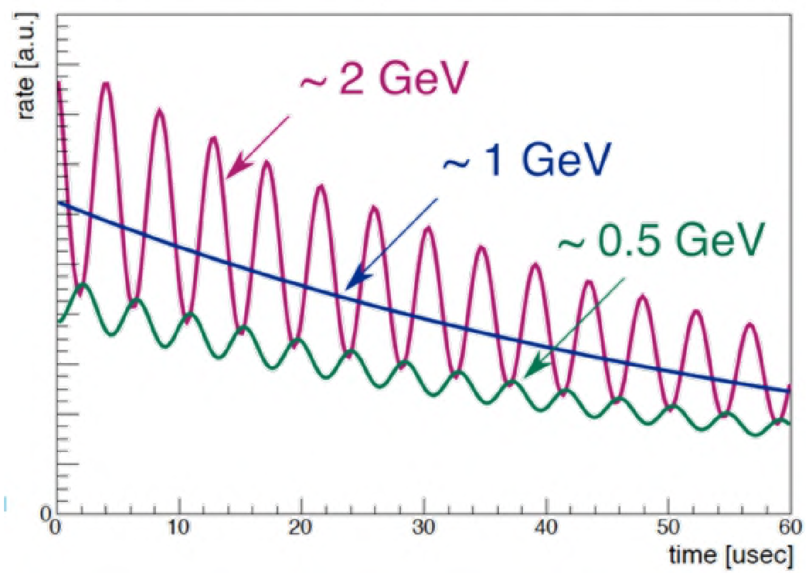
- The muon decays into a positron and two neutrinos
- Parity violation enhances probability of right-handed positrons
- Nature gift n°3: high energy positrons are emitted in the direction of the muon spin!

Measuring ω_a

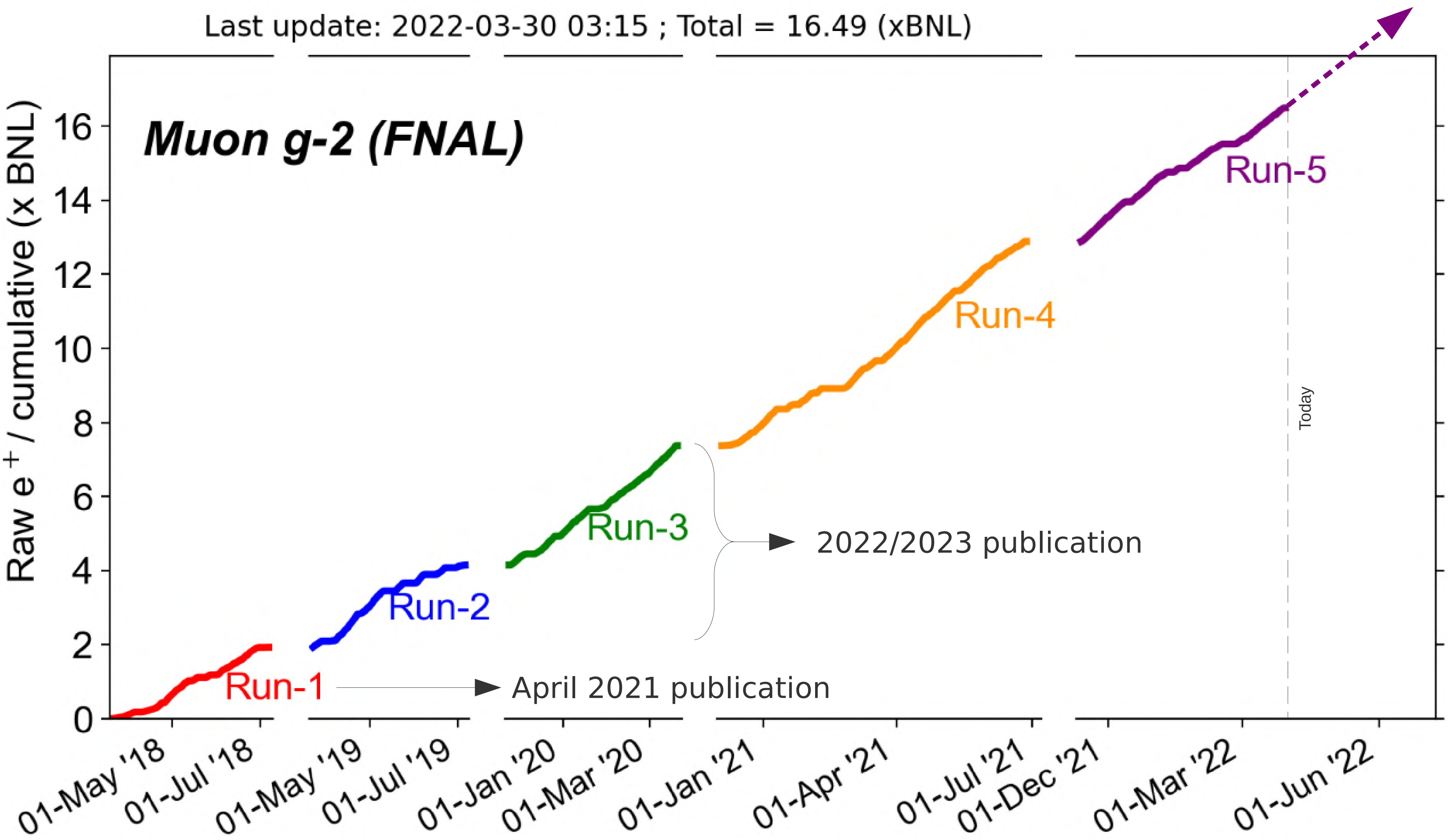
- This decay **asymmetry** is observed as an oscillation of the positron count over time
- The frequency of the oscillation is ω_a
- High energy positrons (2-3 GeV) have the highest oscillation amplitude
- Goal: collect as many positrons as possible with the calorimeters and fit the *wiggle plot* to obtain the oscillation frequency with **100 ppb** precision (stat+syst)



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



Data acquisition



Data reconstruction

- Raw data stored on tapes (Currently more than 5 PB)
- Each file is ~5 seconds of data taking (> 3 million files)
- Data is trasformed (reconstructed) from raw detector signals into an usable form file by file

- This would take millennia on a single computer → we use the GRID 😍
  - Jobs can run in parallel on thousands of CPUs
- The final .root files can be used by individual analyzers for fits and physics studies

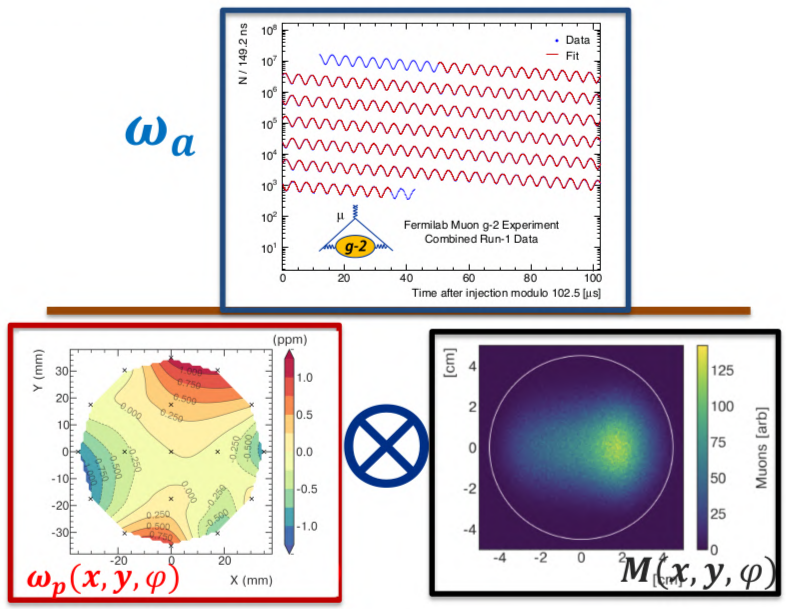
Data analysis

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

Constants known with high precision from other experiments

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

- Very complicated analysis with many correction parameters
- More than 2 years to complete Run 1 evaluation
  - Must publish first result with high confidence
- Run 2/3 analysis is in progress



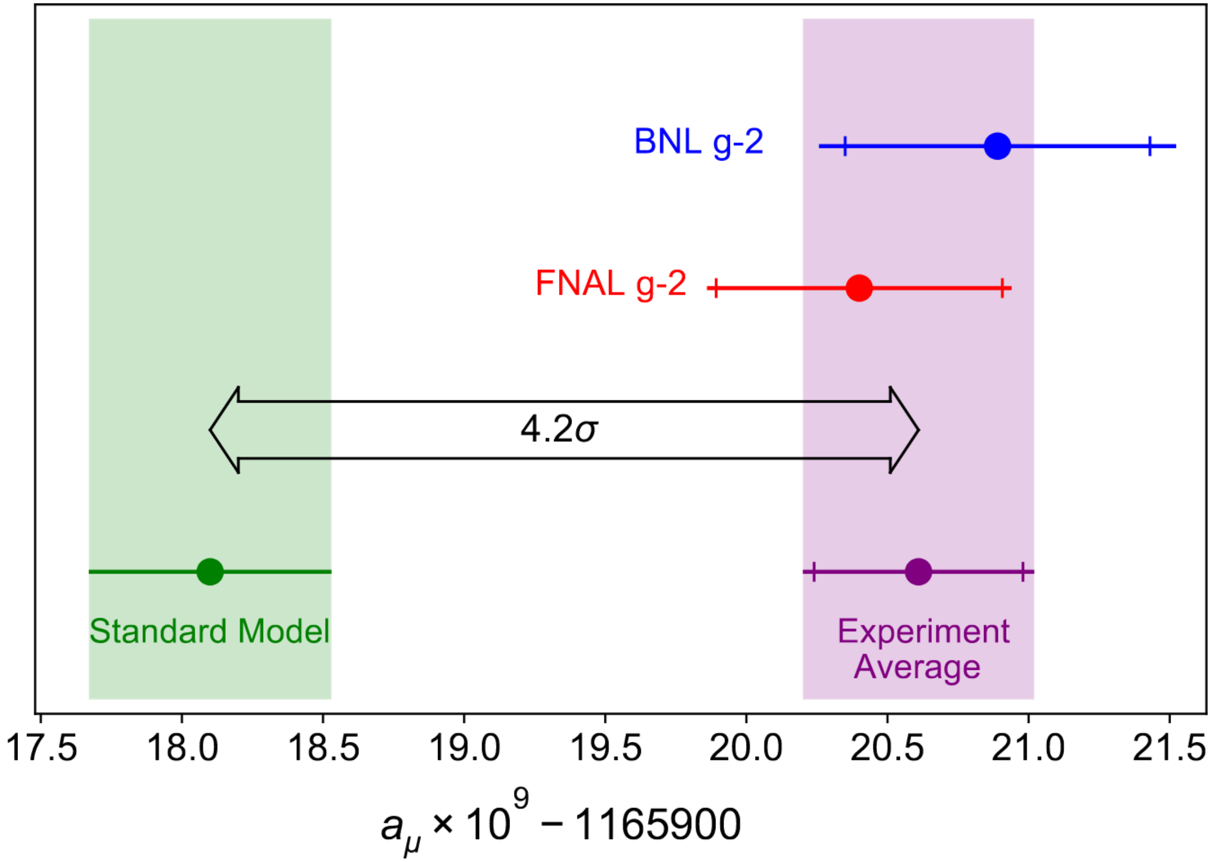
Run 1 release

- 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

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi *et al.* (Muon $g-2$ Collaboration)
Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

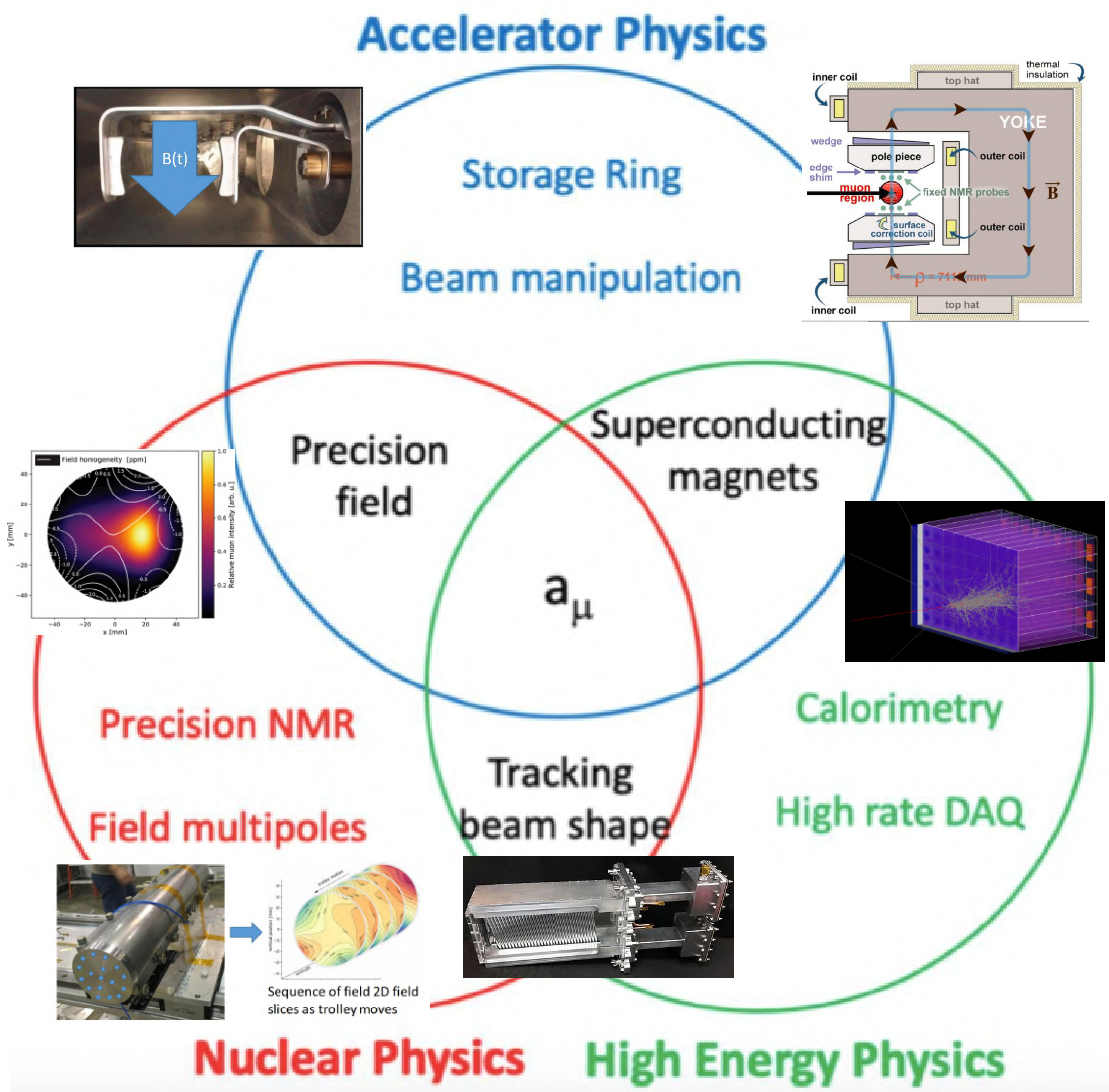


Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle$	–	56
B_q	-17	92
B_k	-27	37
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462

434 ppb stat ⊕ 157 ppb syst error

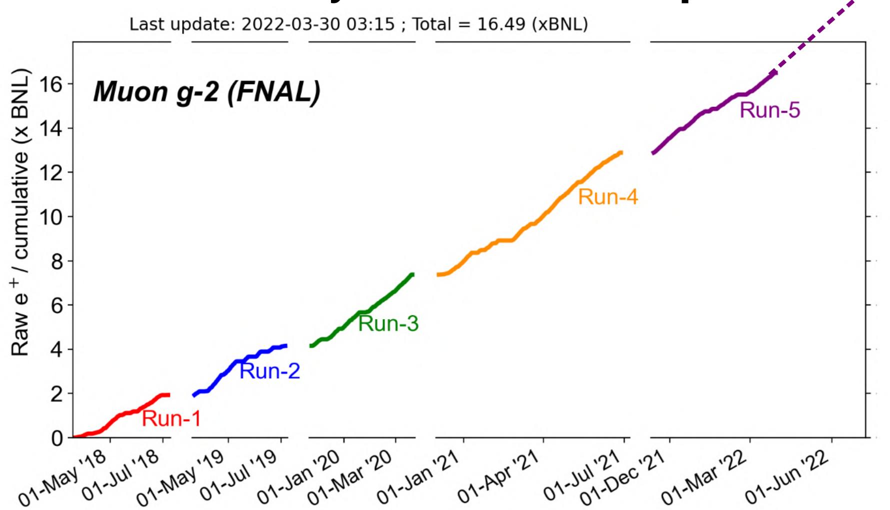
Summing up...

- Truly interdisciplinary experiment
- Touches almost every aspect of particle physics
- Many engineering challenges
- Exciting and encouraging result from Run1
- Run 2/3 analysis ongoing to reduce error by factor 2

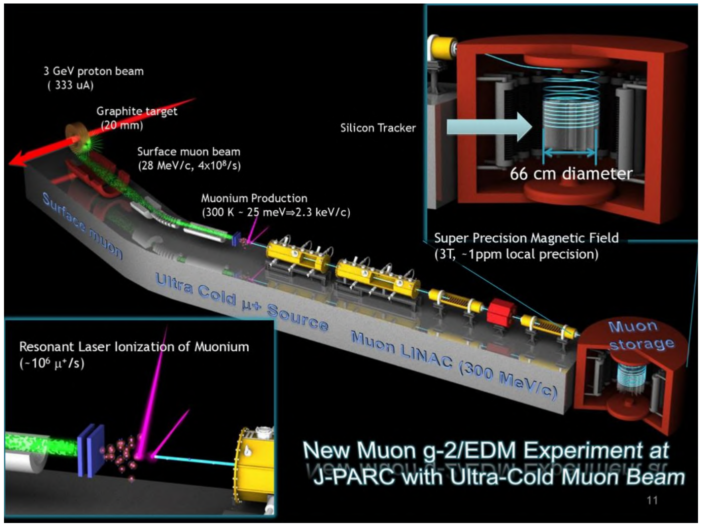


What's next

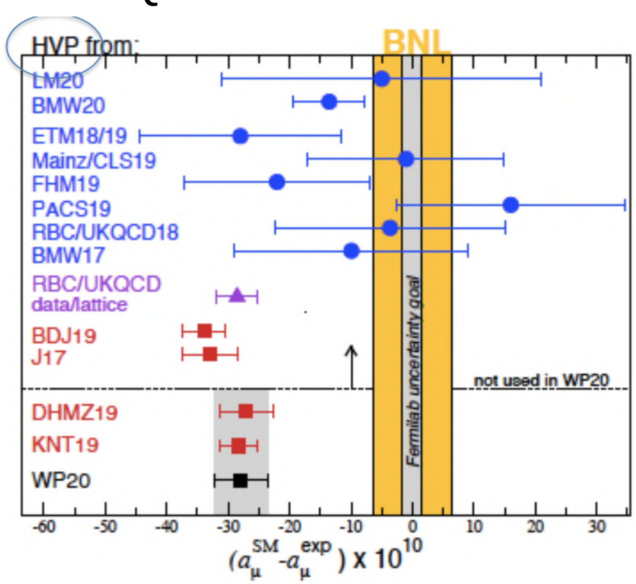
Run 2-5 analysis, Run 6 with **μ-** data



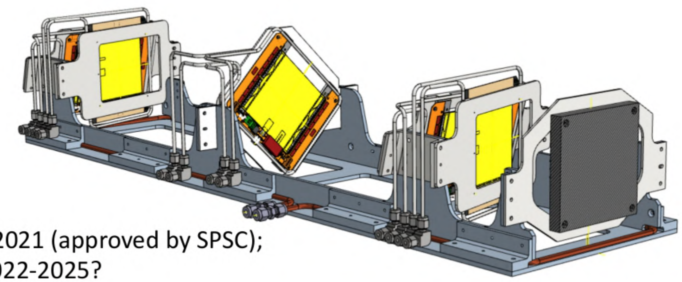
Muon g-2 experiment at J-PARC



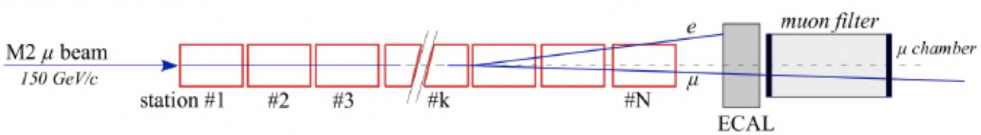
New QCD Lattice calculations



MuonE experiment at CERN



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



Useful links

- Contact me at paolo.girotti@phd.unipi.it !
- Release papers:
  - Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm https://doi.org/10.1103/PhysRevLett.126.141801 (2021)
  - Measurement of the anomalous precession frequency of the muon in the Fermilab Muon g-2 Experiment https://doi.org/10.1103/PhysRevD.103.072002 (2021)
  - Magnetic-field measurement and analysis for the Muon g-2 Experiment at Fermilab https://doi.org/10.1103/PhysRevA.103.042208 (2021)
  - Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab https://doi.org/10.1103/PhysRevAccelBeams.24.044002 (2021)
- Muon g-2 website https://muon-g-2.fnal.gov/
- MUSE website http://muse.lnf.infn.it/
- Press release of 7 April 2021 https://www.youtube.com/watch?v=81PfYnpuOPA