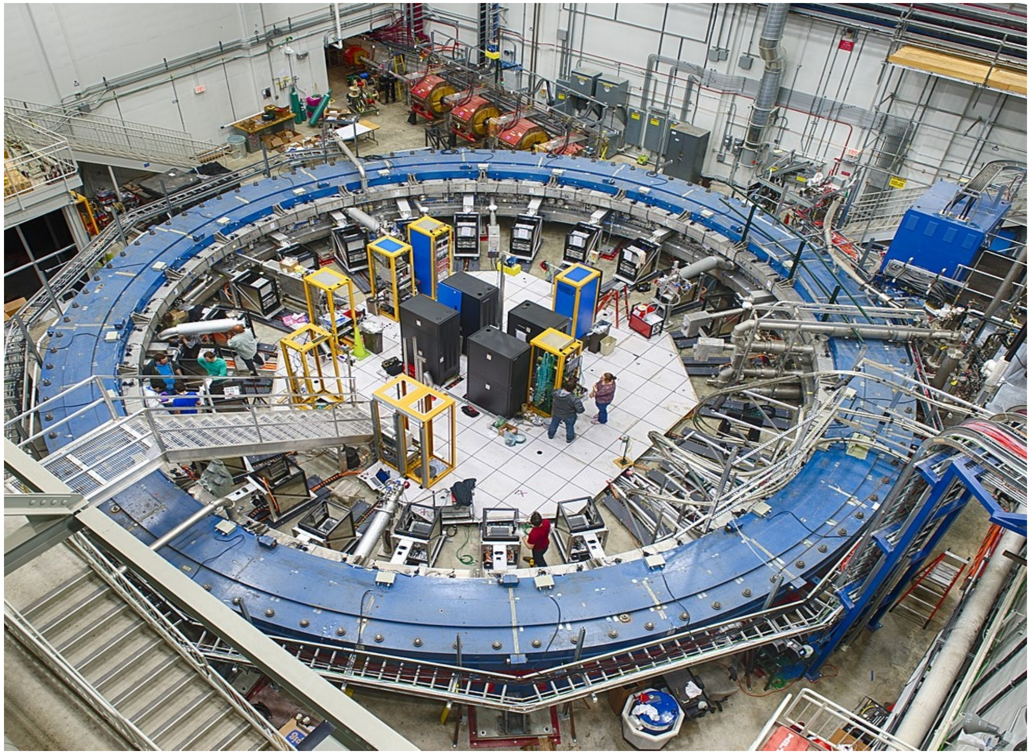
Istituto Nazionale di Fisica Nucleare



The Muon g-2 Experiment

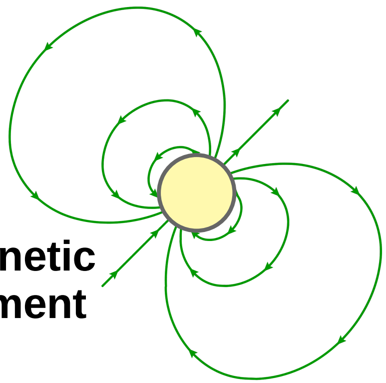
55th Annual Users Meeting
Fermilab – June 14th 2022

Paolo Girotti
on behalf of the Muon g-2 collaboration

Outline

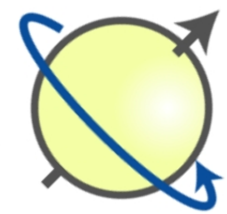
- What is g-2 and why do we care
- How do we measure g-2
- A decade of g-2 at Fermilab
- Run-1 results
- Future of g-2

The g in g-2



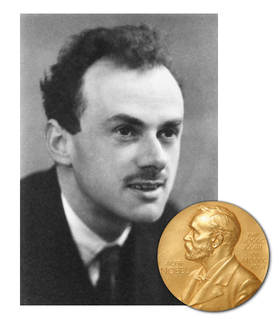
Magnetic moment

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

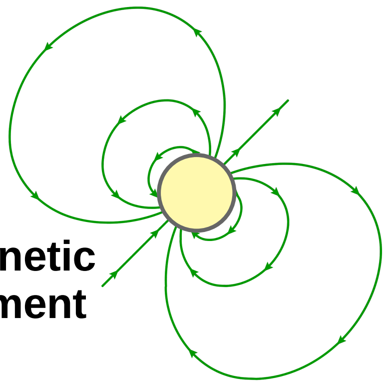


Spin

- 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)



The -2 in g-2



Magnetic moment

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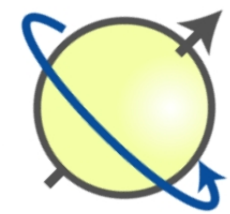
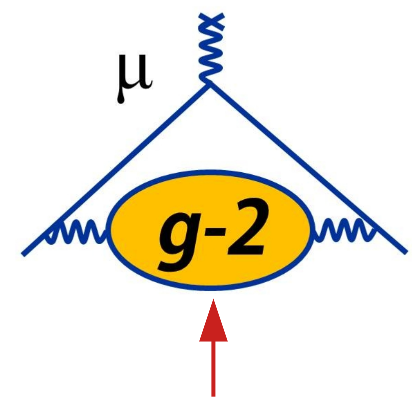


Spin

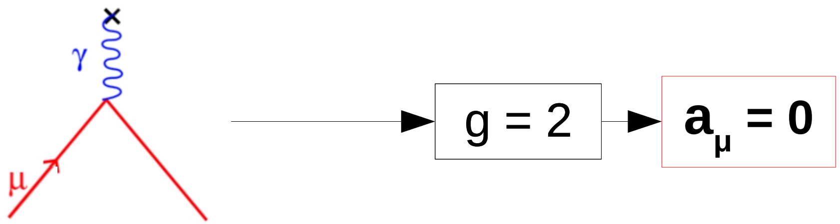
$$\boxed{a_\mu} \equiv \frac{g-2}{2}$$

- Actually, g is greater than 2!
- The discrepancy from 2 arises from quantum loop corrections in the interaction between the particle and the magnetic field
- We are interested in calculating and measuring this “anomaly”



The muon anomaly

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



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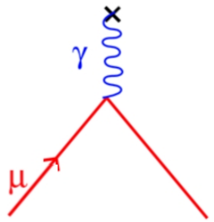
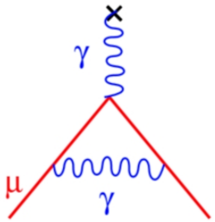


g = 2 → $\mathbf{a_\mu = 0}$

- But considering corrections:

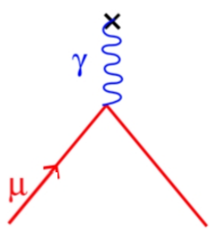


QED

$a_\mu = 0.0011658\ldots$

The muon anomaly

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



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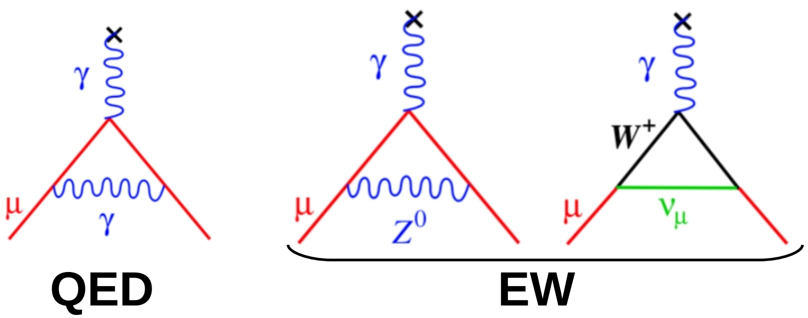
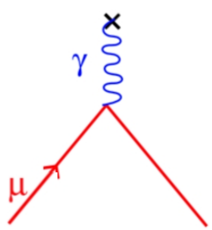


a_μ = 0.0011658… +0.000000001536...

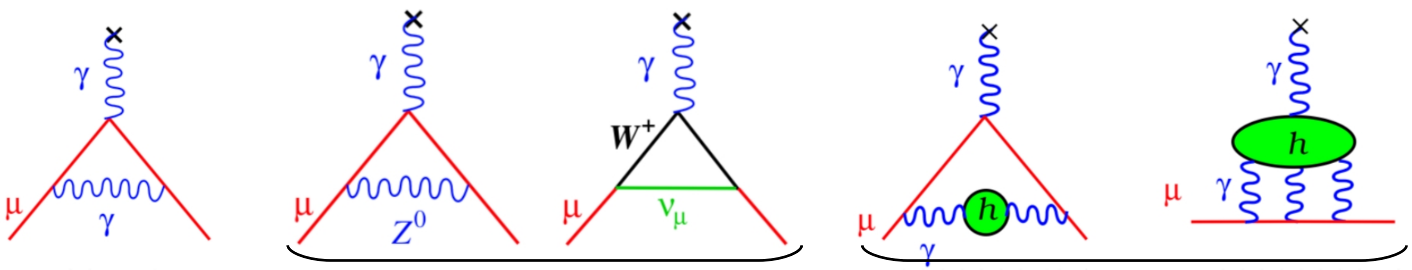
The muon anomaly

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



g = 2 → $a_\mu = 0$

- But considering corrections:

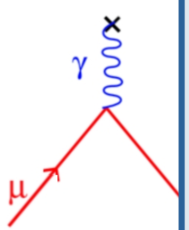


QED **EW** **QCD**

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

The muon anomaly

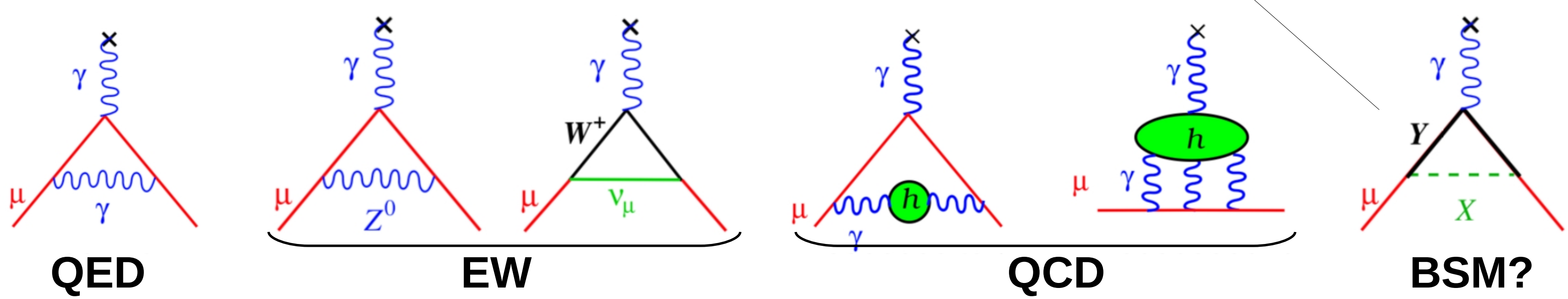
- Deviation from 2 arise from quantum loop corrections
- The si… gives g=2



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

Undiscovered particles could affect the value of g-2!

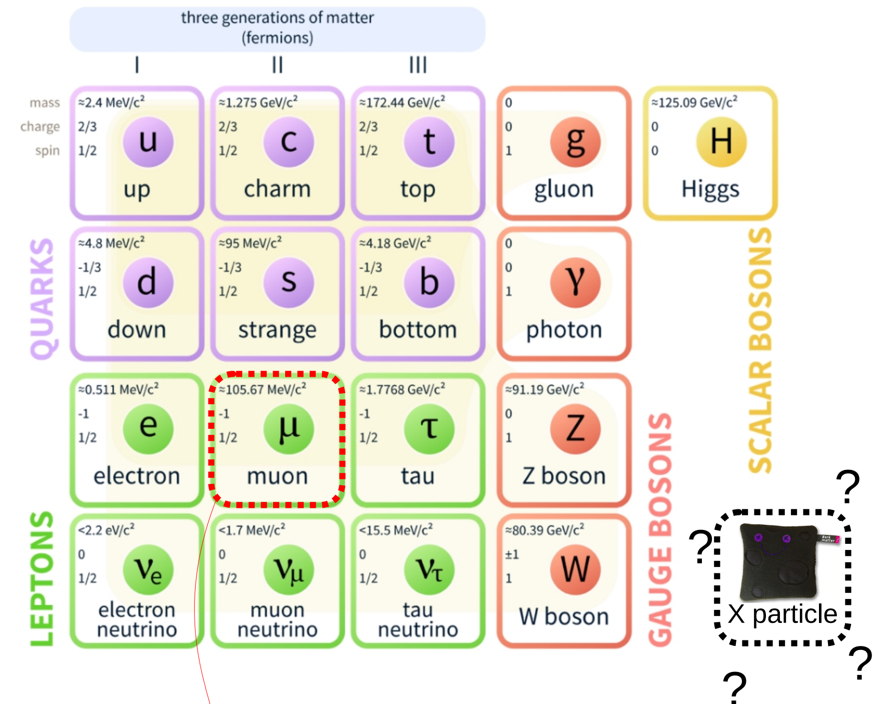
- But co…

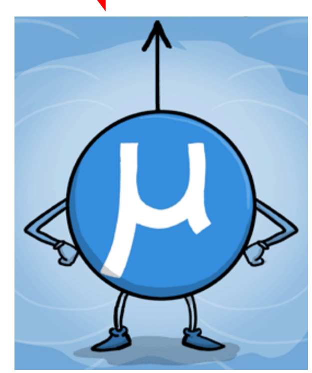


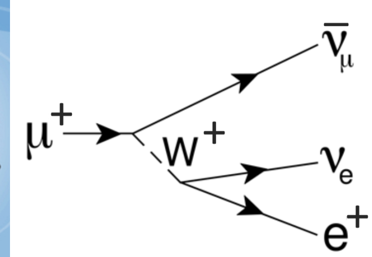
a_μ = 0.0011658… +0.000000001536... +0.000000069383… +?

Yes but why muons?

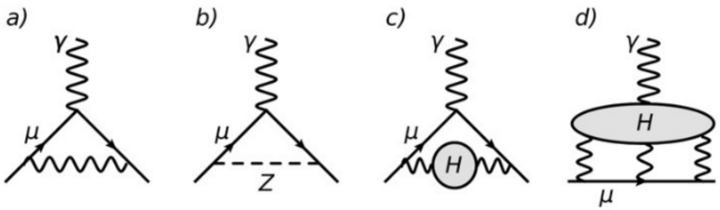
- The electron **g** is already measured and calculated with extremely high precision (2.00231930436146(56))
- The muon is 200 times heavier →40’000 times <u>more sensitive to new massive particles</u>
  - Tauons would be even better but they are very impractical
- A precise measurement of the muon magnetic moment means:
  - A test for the Standard Model
  - A search for new physics





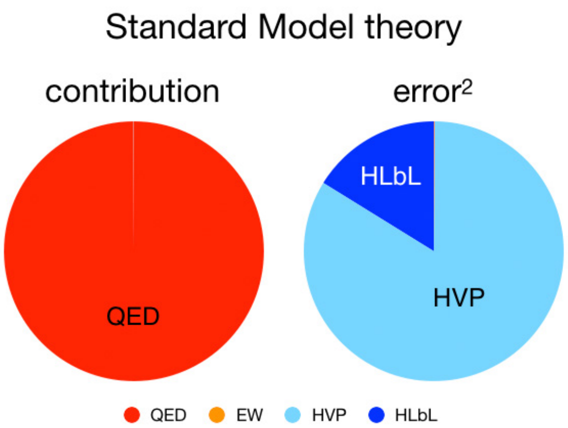


Status before 2021

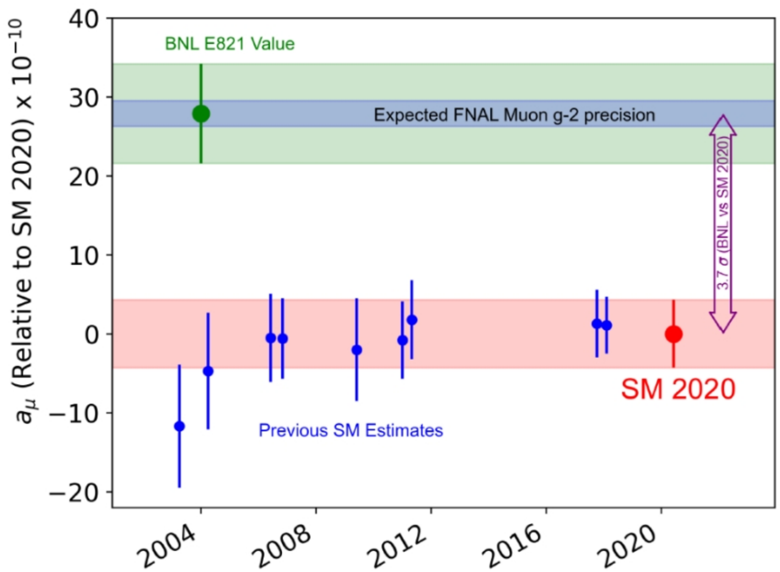


Source	Value ($a_\mu \times 10^{-11}$)	Error
a) QED	116 584 718.9	0.1
b) EW	154	1
c) HVP	6845	40
d) HLBL	92	18

Muon g-2 Theory Initiative arXiv:2006.04822

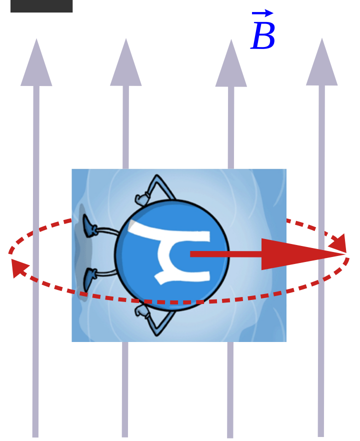


QCD loops account for:
- **0.006%** of the contribution
- **99.95%** of the uncertainty



- a_μ measured at Brookhaven National Lab (BNL, 2006), and the result differs by **3.7σ** with respect to SM prediction
- Bringing the magnet from BNL to Fermilab’s powerful accelerator beam
  - Goal: reduce the error by a factor of 4 to 140 ppb

How to measure g-2



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

Spin precession frequency

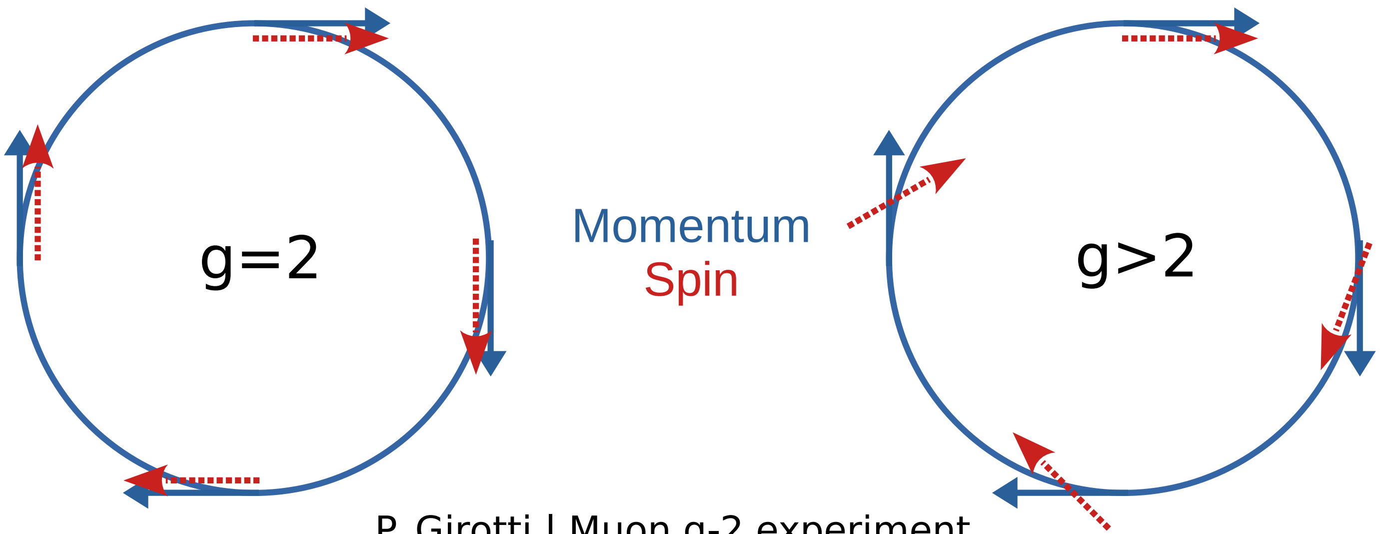
$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$$

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



Not so simple

- Experiment needs vertical focusing provided by **electrostatic quadrupoles**
  - Effect on ω_a minimized by using *magic* momentum of 3.094 GeV/c
- **The beam oscillates and breathes** both horizontally and vertically
  - Beam dynamics analysis and pitch correction address these effects
- Many **smaller effects** must be taken into account during analysis
  - Muon losses, pileup effects, decay rate, phase-acceptance, eddy currents, plate vibrations, temperature drifts, gain variations

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

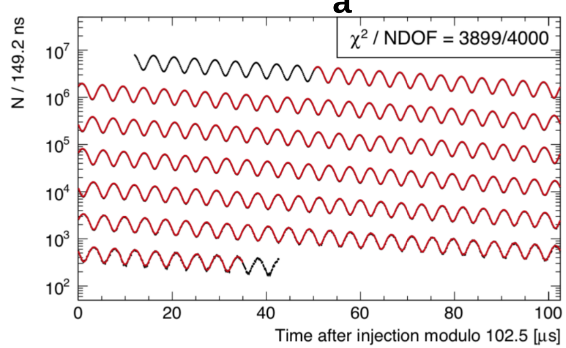
γ~29.3

Master formula

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

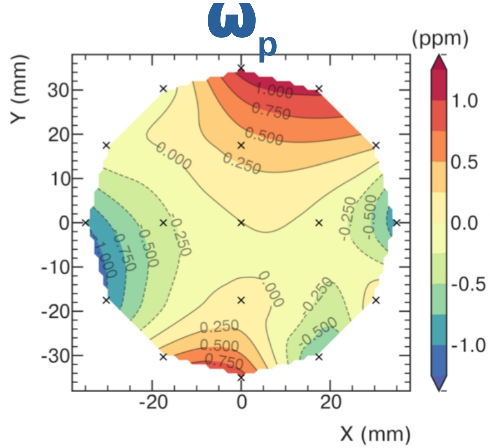
Constants known from other experiments with high precision

ω_a



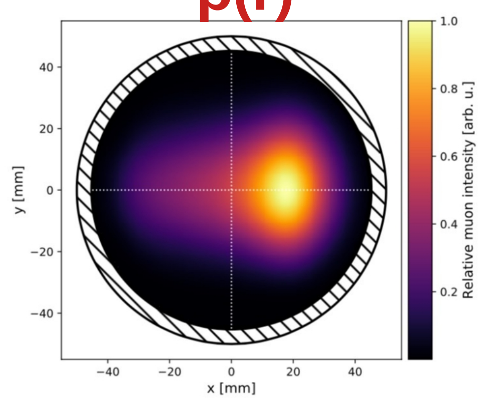
- **ω_a**: Muon anomalous precession frequency
- **ω_p**: Larmor precession frequency of protons in water (mapping B)
- **ρ_r**: Muon distribution in the storage ring

ω_p



$\otimes$

$\rho(r)$



Goal: measure a_μ with 140 ppb accuracy (100 stat + 100 syst)

How to measure g-2

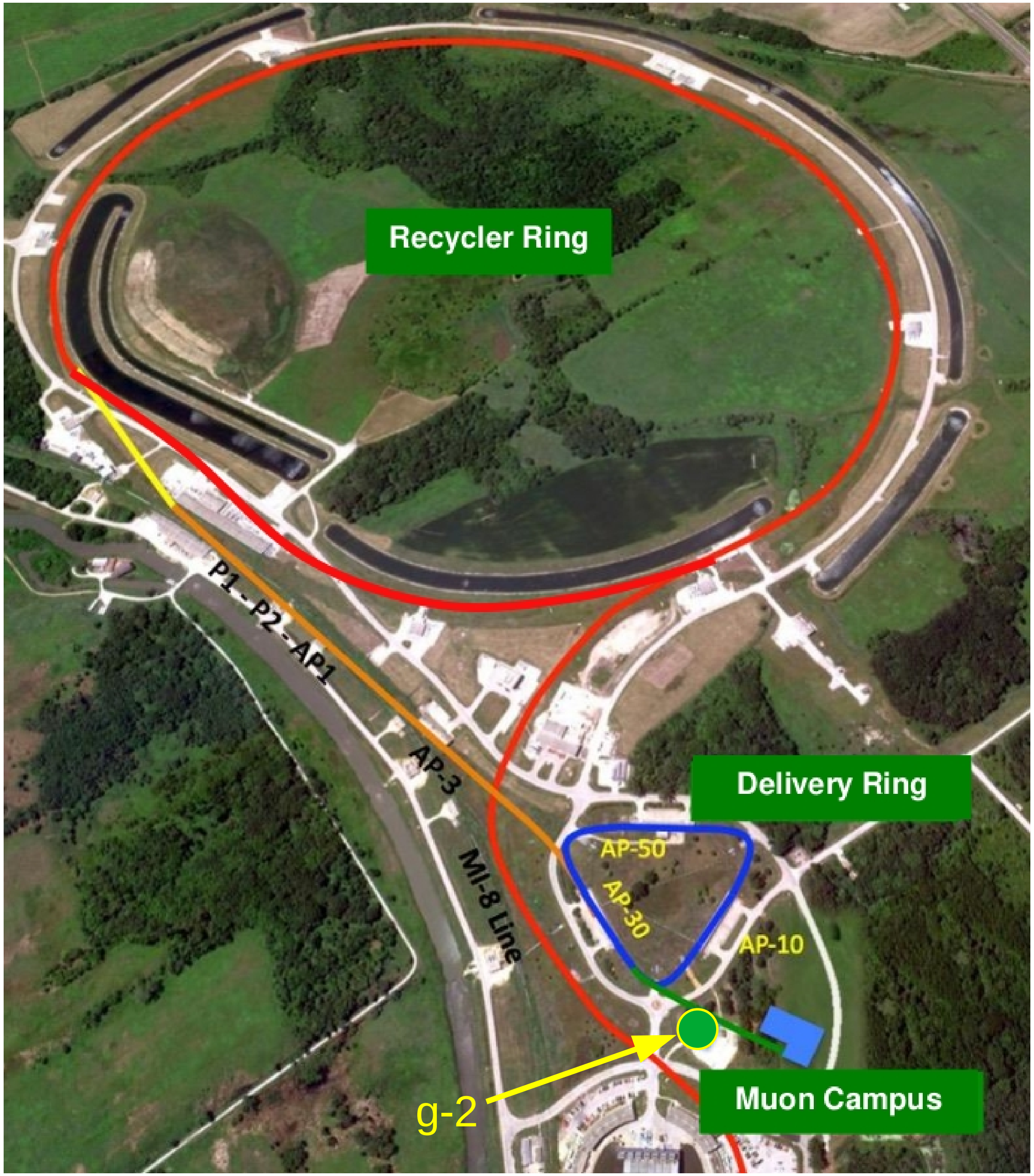
Key ingredients:

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

The beam

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

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



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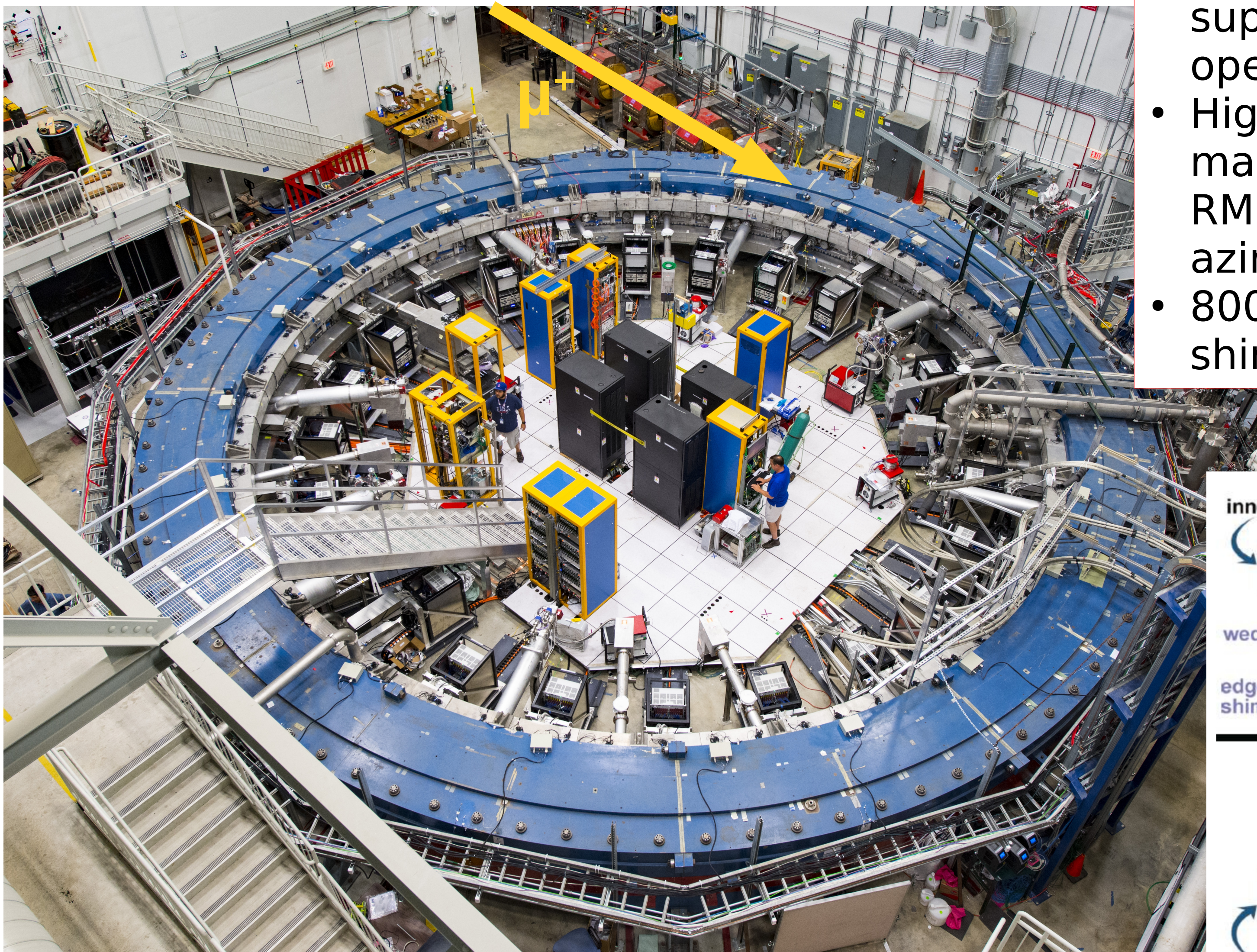
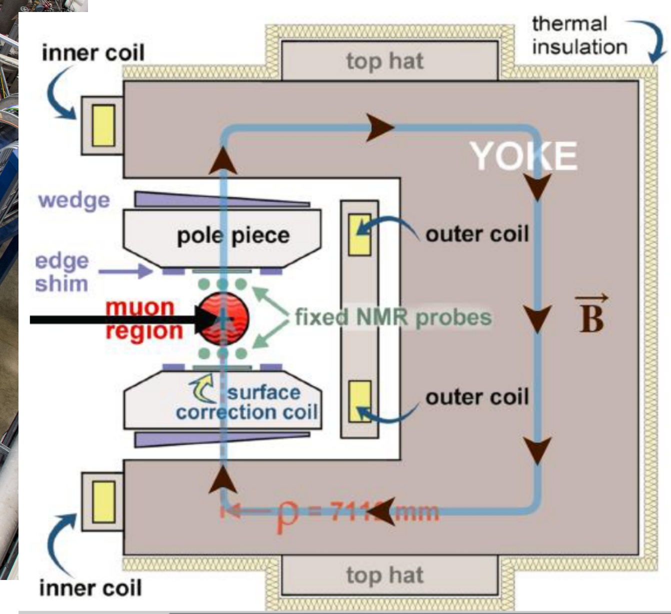
Magnet



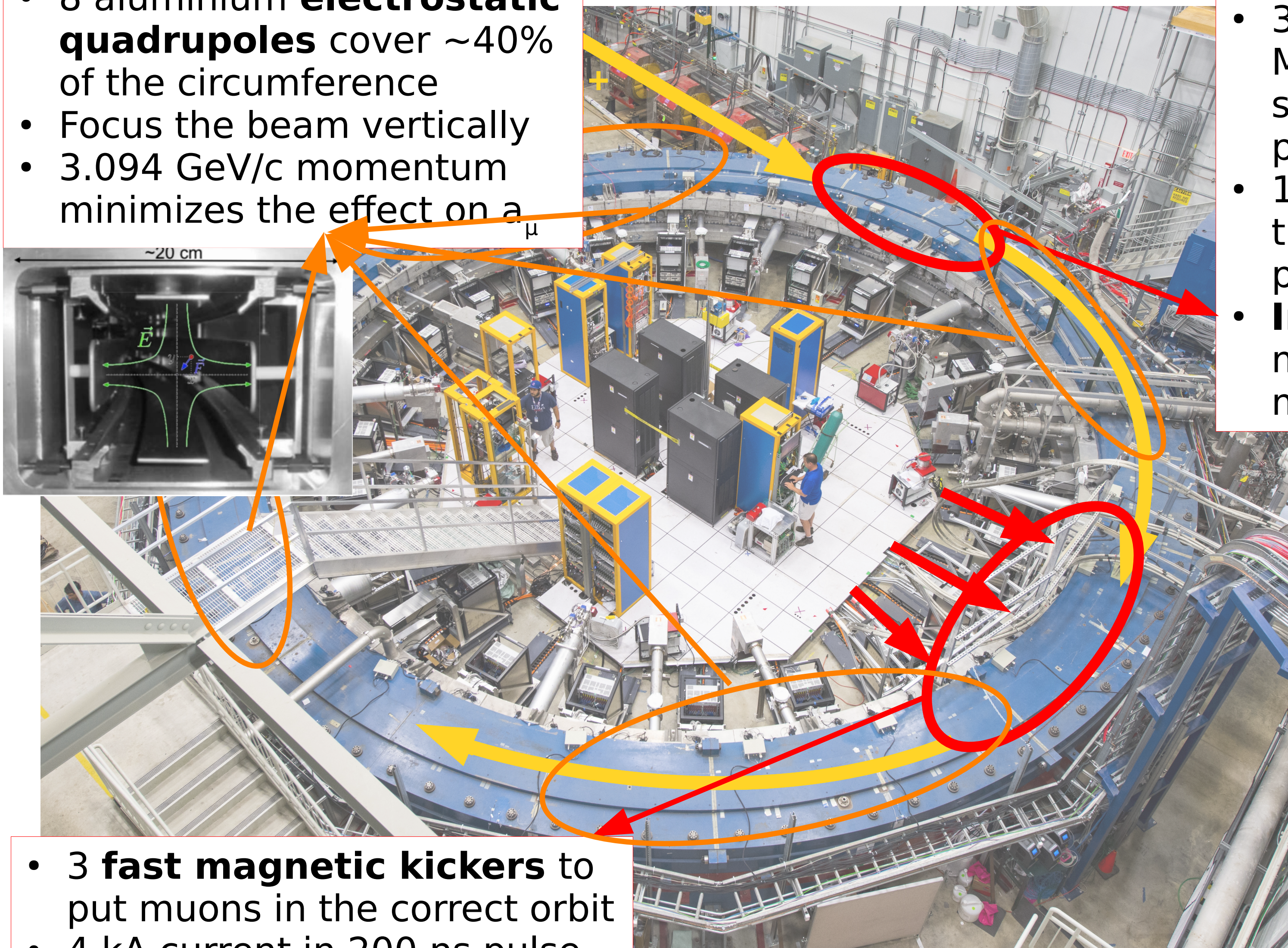
- 7.112 m radius C-shaped superconducting magnet operating at ~5 K
- Highly **uniform 1.45 T** magnetic field (14 ppm RMS across the full azimuth)
- 8000 iron foils for precise shimming

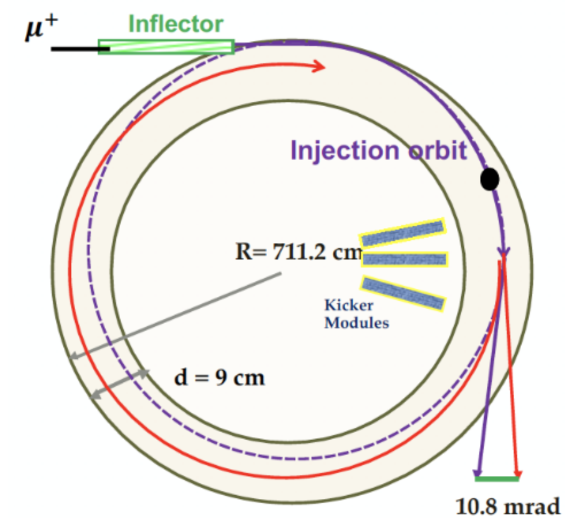


Beam storage

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

- 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





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

How to measure g-2

Key ingredients:

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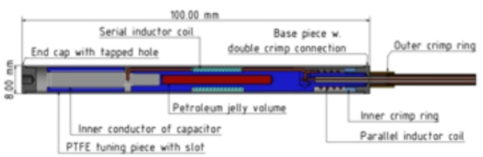
- **A way to measure the magnetic field, the beam position, and the muon spin through time**

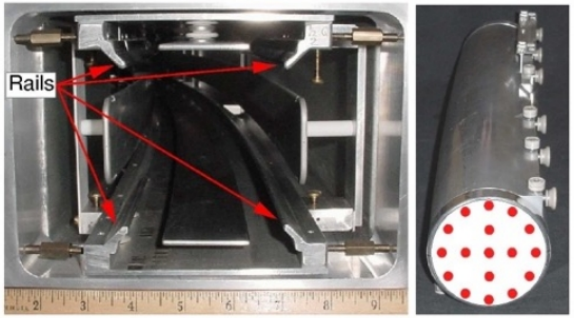
Measuring the field

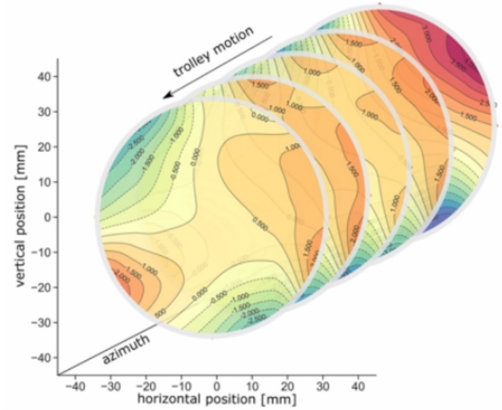
- Need to determine **B at < 100 ppb** to determine a_μ
  - Use NMR to assess B-field in terms of proton precession frequency ω_p

378 fixed probes continuous monitoring

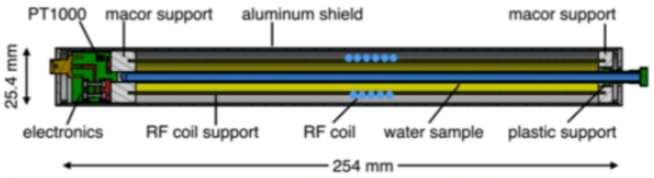


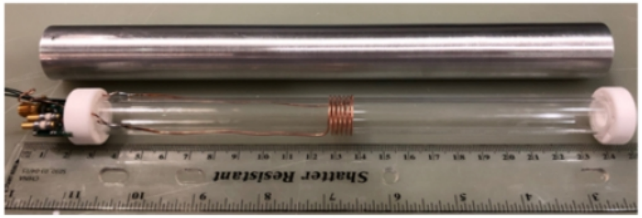
17 probes on a trolley to 3D map every ~3 days





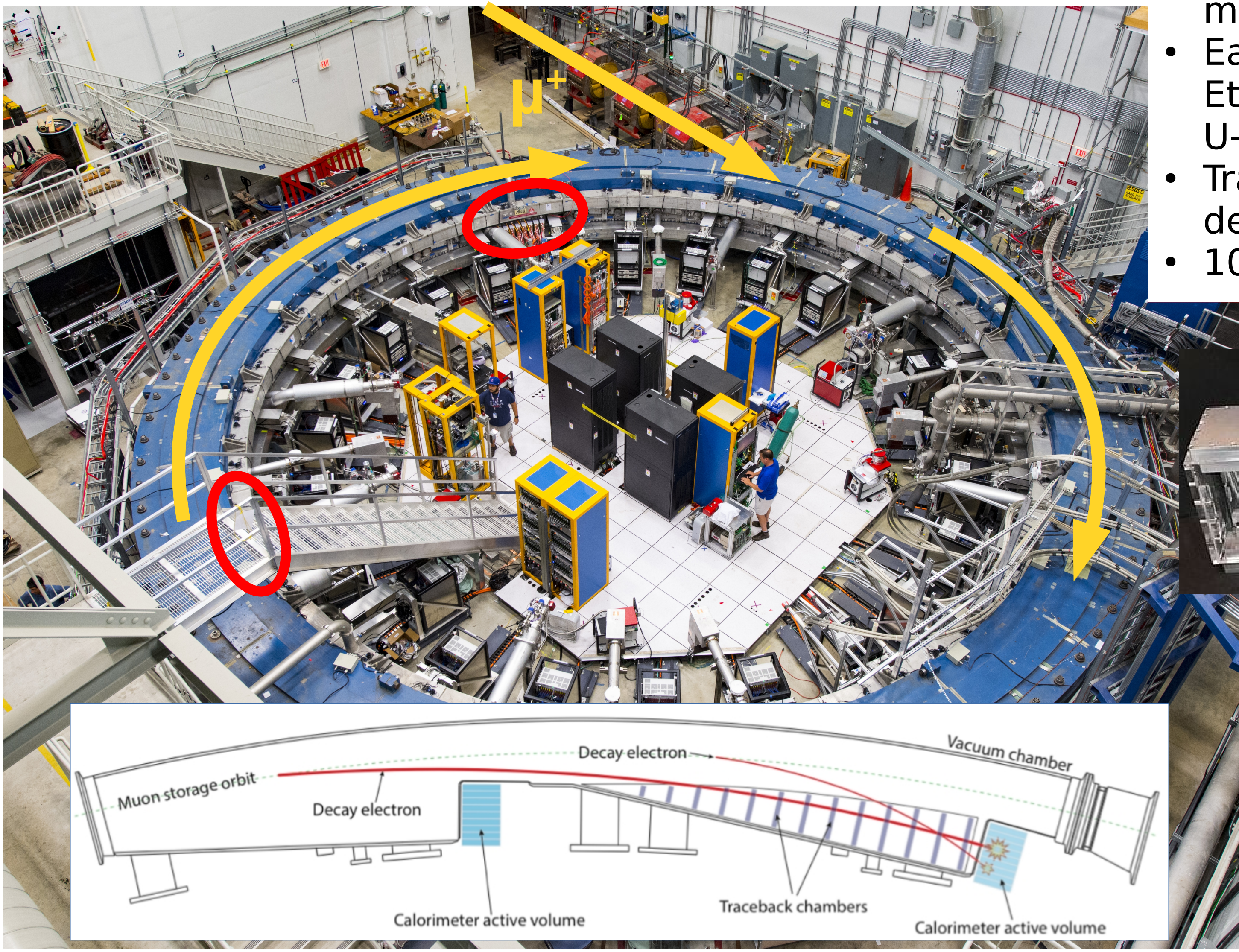
Trolley cross-calibrated to absolute probes

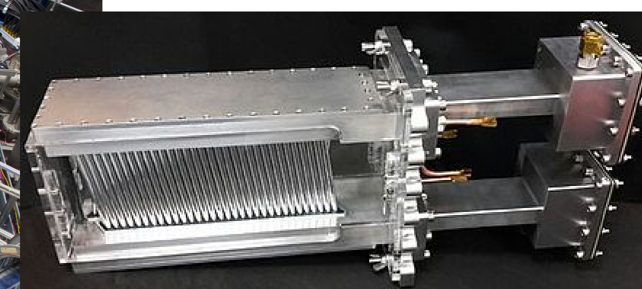


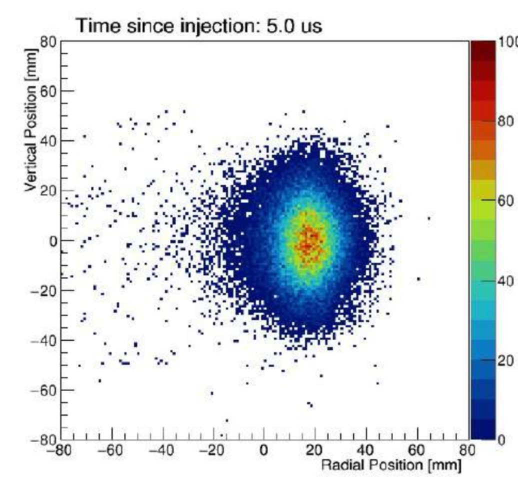


Measuring the beam

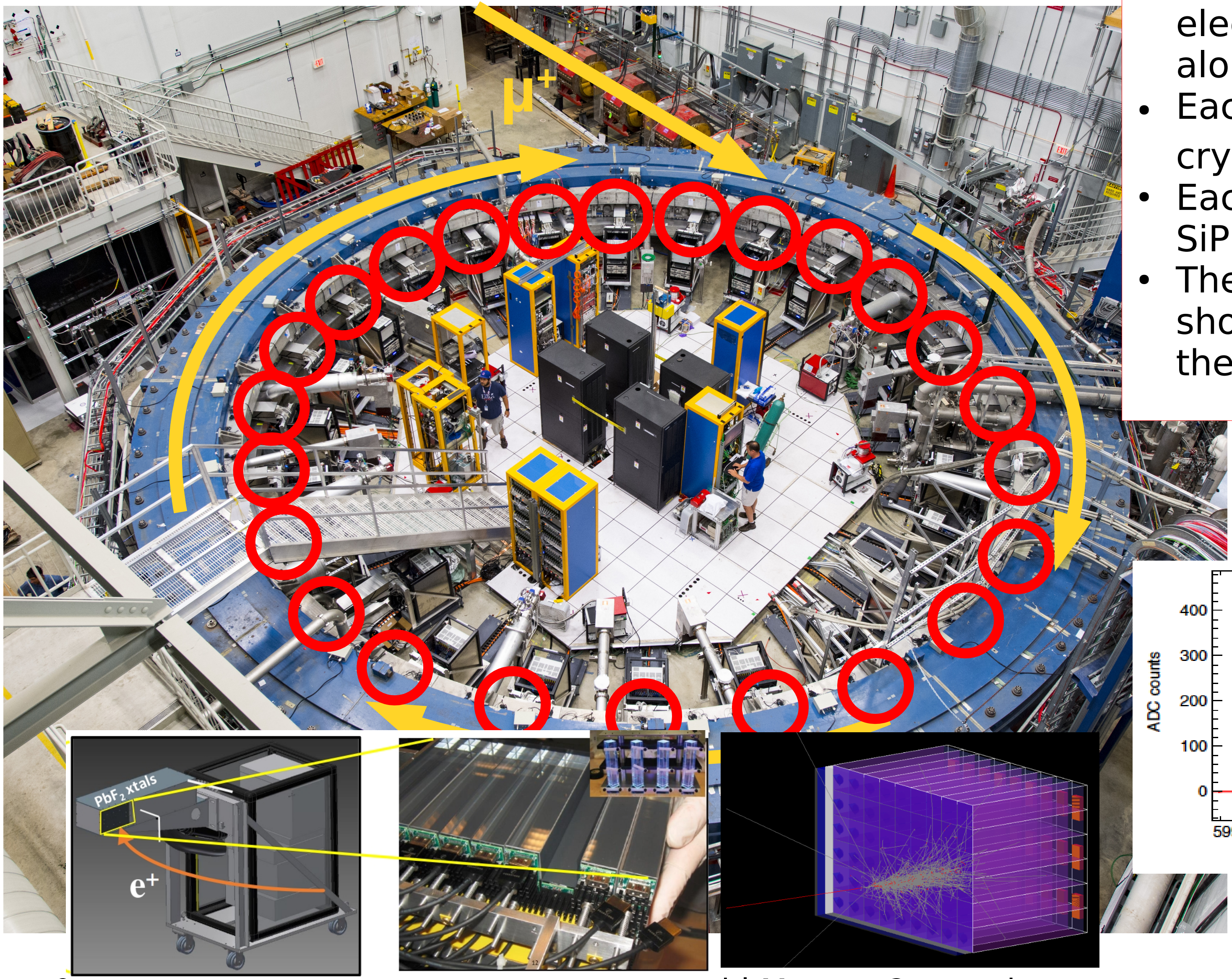
- 2 tracker stations with 8 modules each
- Each module has 128 Argon-Ethane filled straw tube in a U-V plane configuration
- Traceback positrons to their decay point
- 100 µm hit resolution



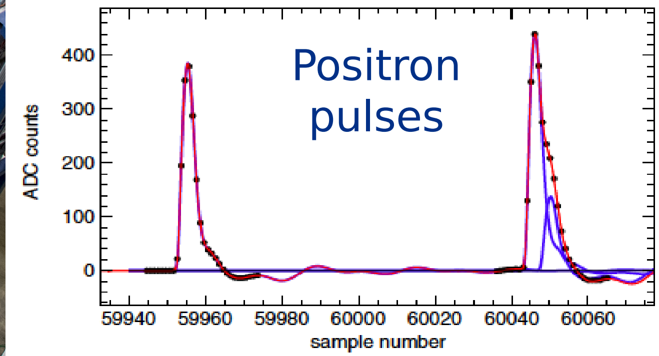




Measuring the positrons

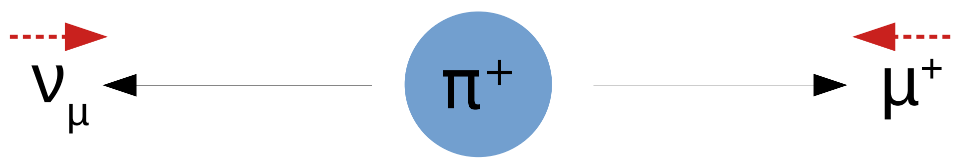


- 24 omogeneous electromagnetic calorimeters along the ring
- Each is a 9 x 6 array of PbF_2 crystals 2.5 x 2.5 x 14 cm
- Each crystal is coupled with a SiPM digitized at 800 MHz
- The positrons produce an EM shower and the SiPMs collect the Cherenkov light

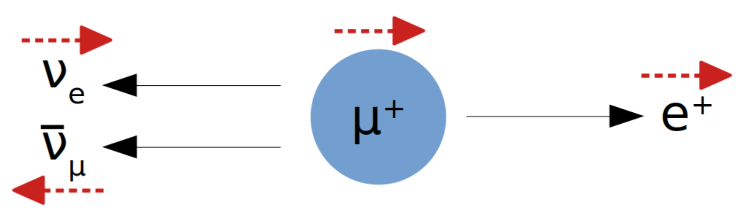


Two **gifts** from nature

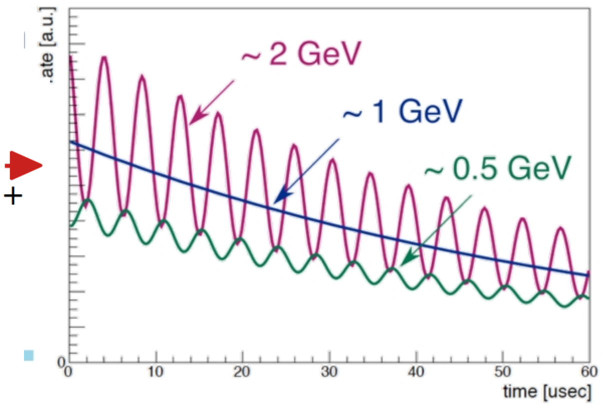
- Pions have no spin and decay in a muon and a neutrino
  - Parity violation dictates that the muon has left elicity
  - Since beam is boosted, higher energy muons are **highly polarized** (~97%)



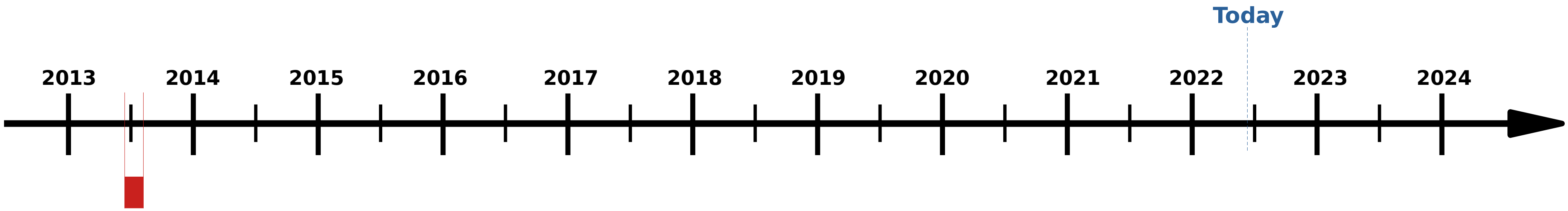
- Muon decays in a positron and two neutrinos
- Parity violation dictates that high energy positrons are emitted preferably in the direction of muon spin
- The decay **asymmetry** is observed as an oscillation of the positron count over time



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

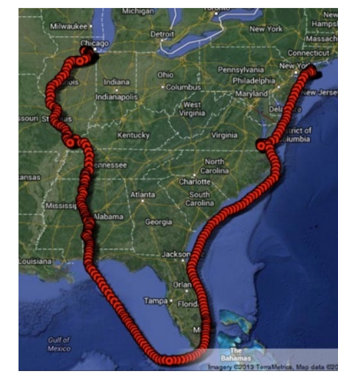


Timeline

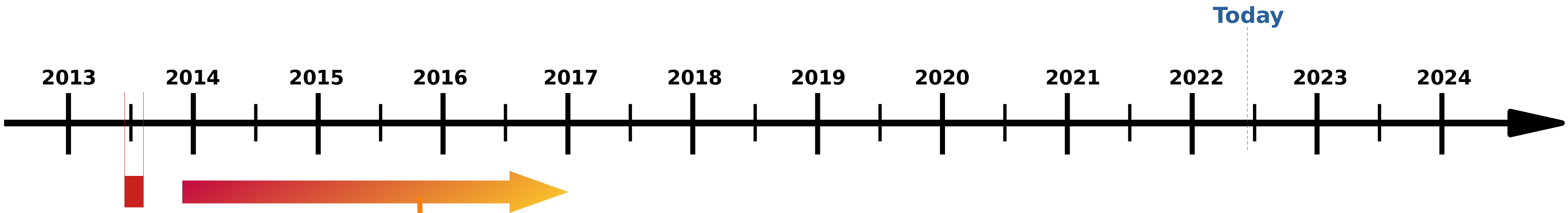


The big move

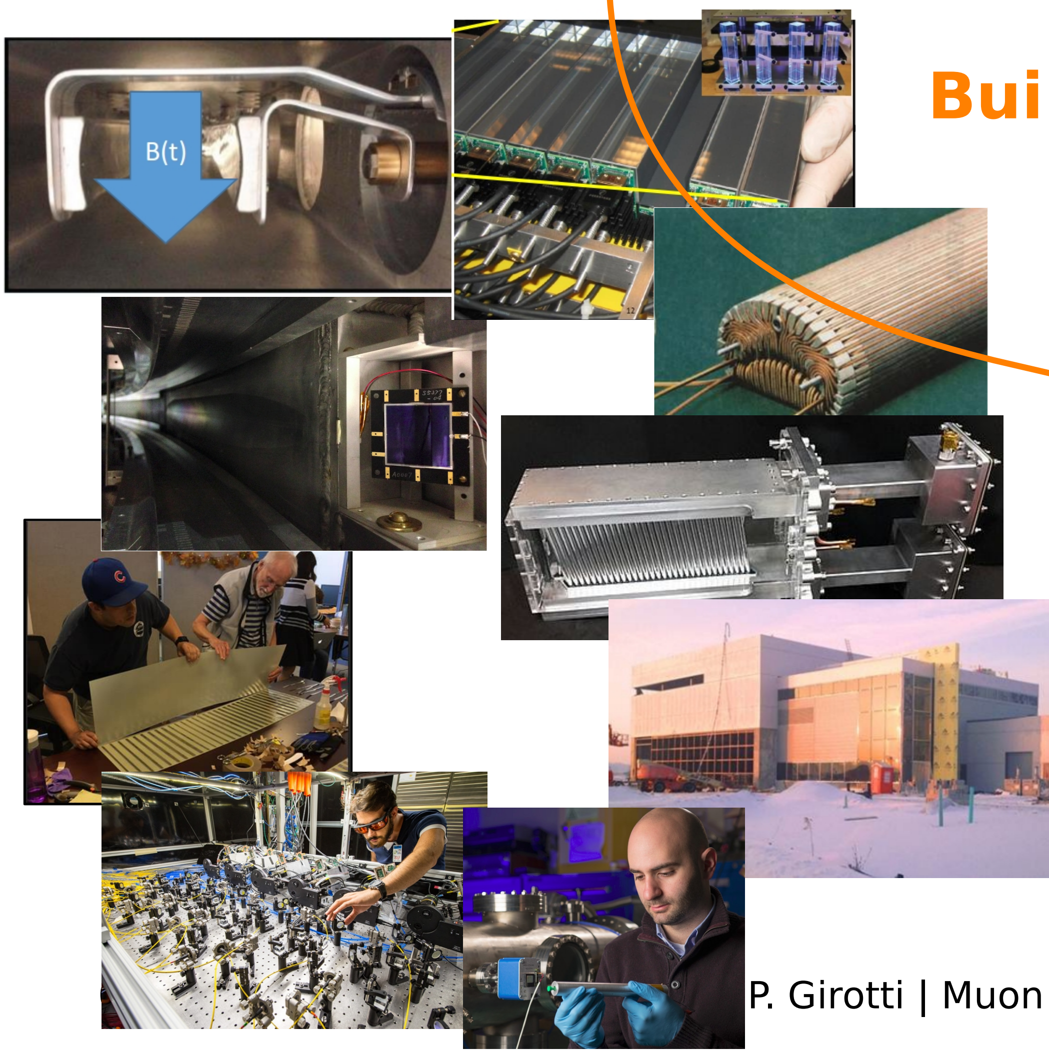
- 45 ton structure
- From Brookhaven to Fermilab
- 35 days, 3200 miles

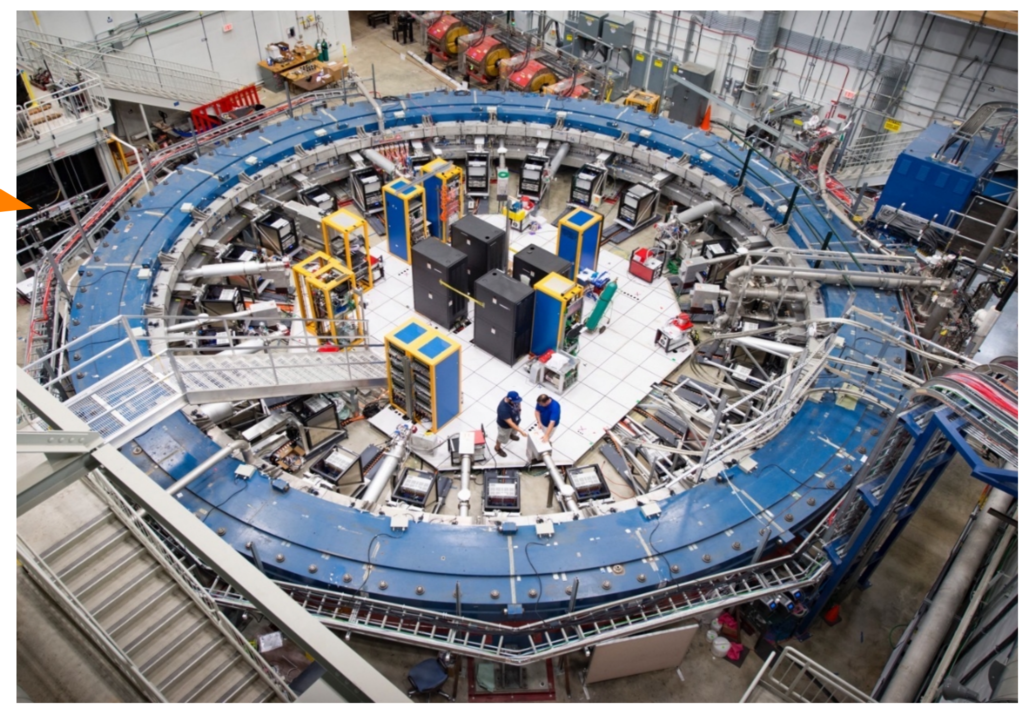


Timeline

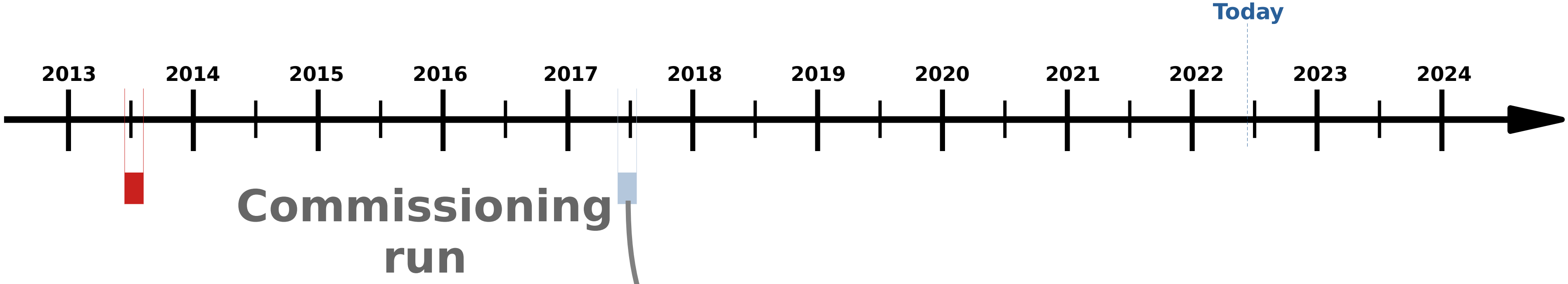


Building the experiment

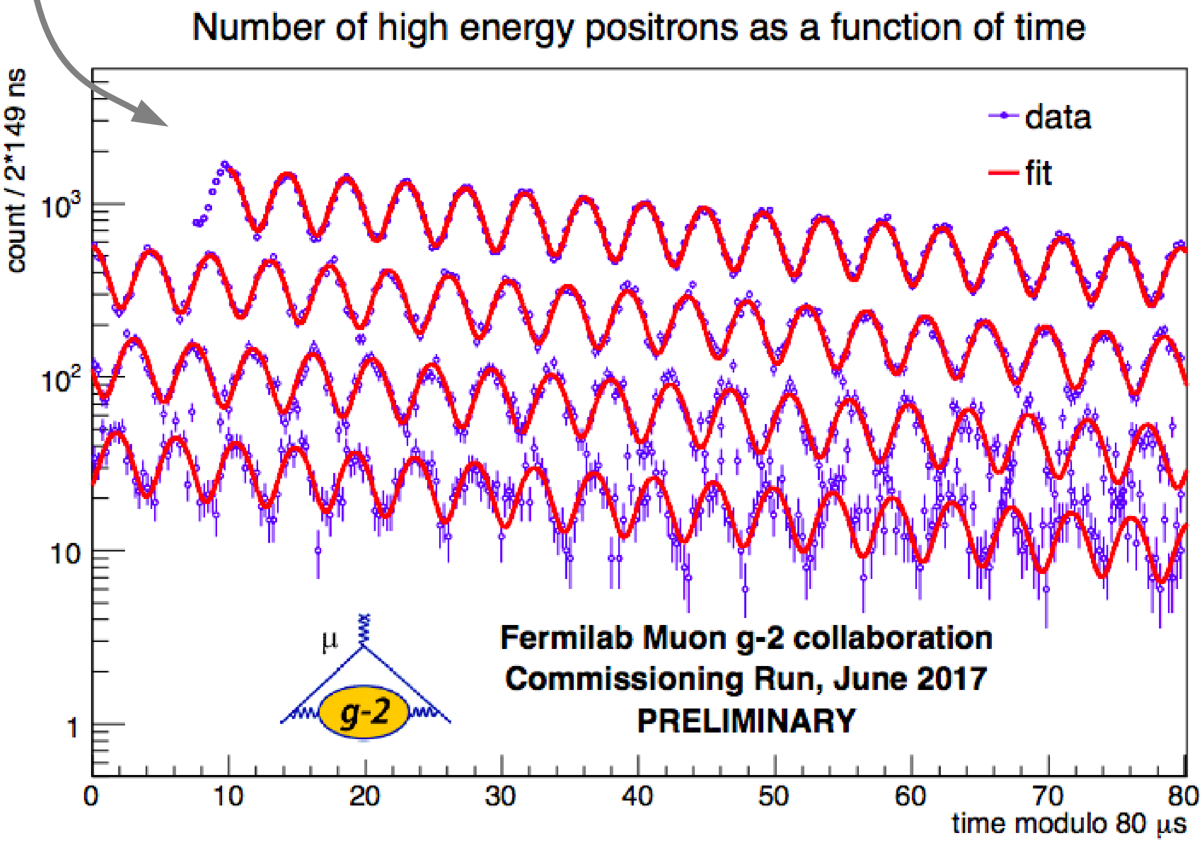




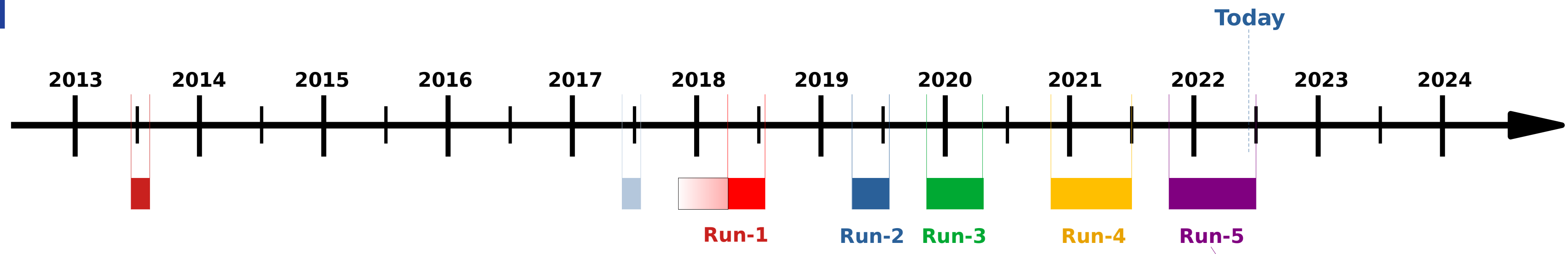
Timeline



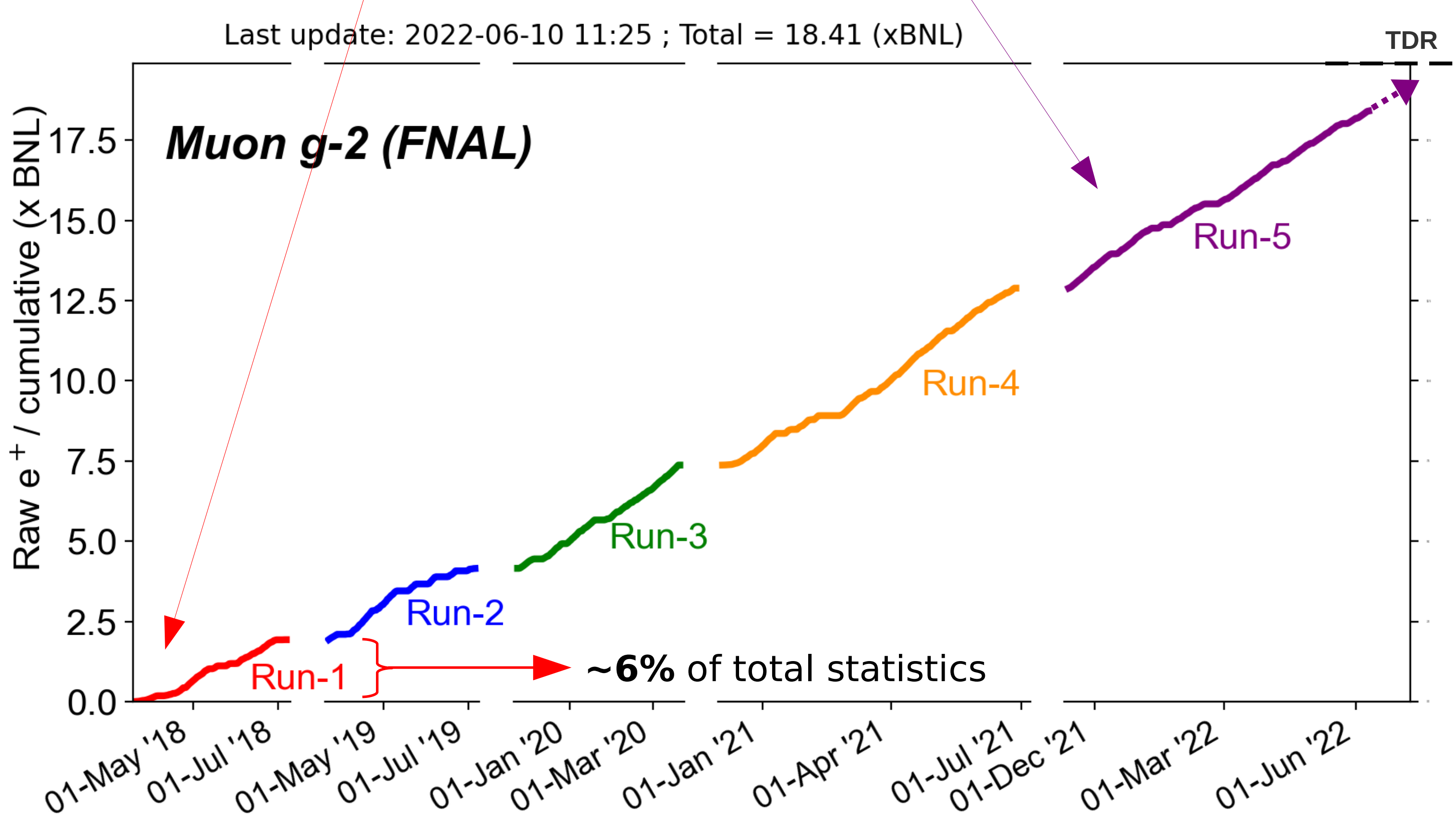
- Two weeks of data taking in June 2017
- Incredible effort to achieve this first result
- The analysis framework was being developed
- Many improvements and tuning still needed for the first physics run



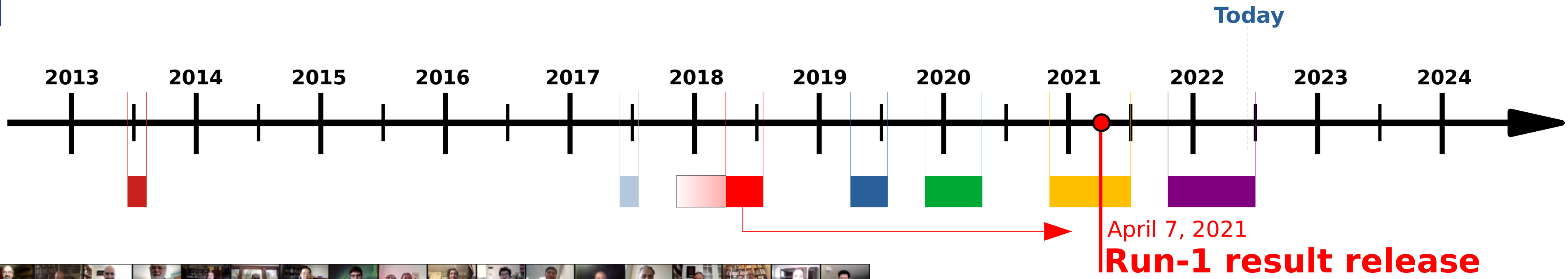
Timeline



- Many improvements from one Run to the next
- Managed to push through Covid isolations with fully remote shifts
- On track to reach design statistics
- A lot of data to analyze

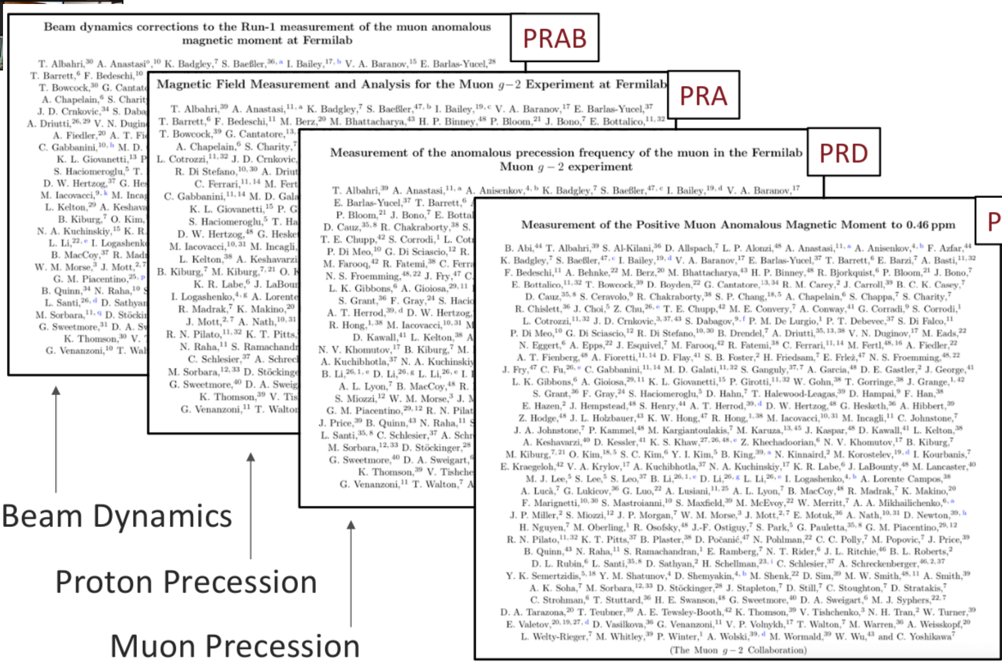


Timeline



>3000 media outlets talked about us

More than 1000 citations already



Beam Dynamics

Proton Precession

Muon Precession

2.5 years of analysis

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

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
2nd 8-pulses	14.0 ppb
total −15.0 ppb	81.7 ppb

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

	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

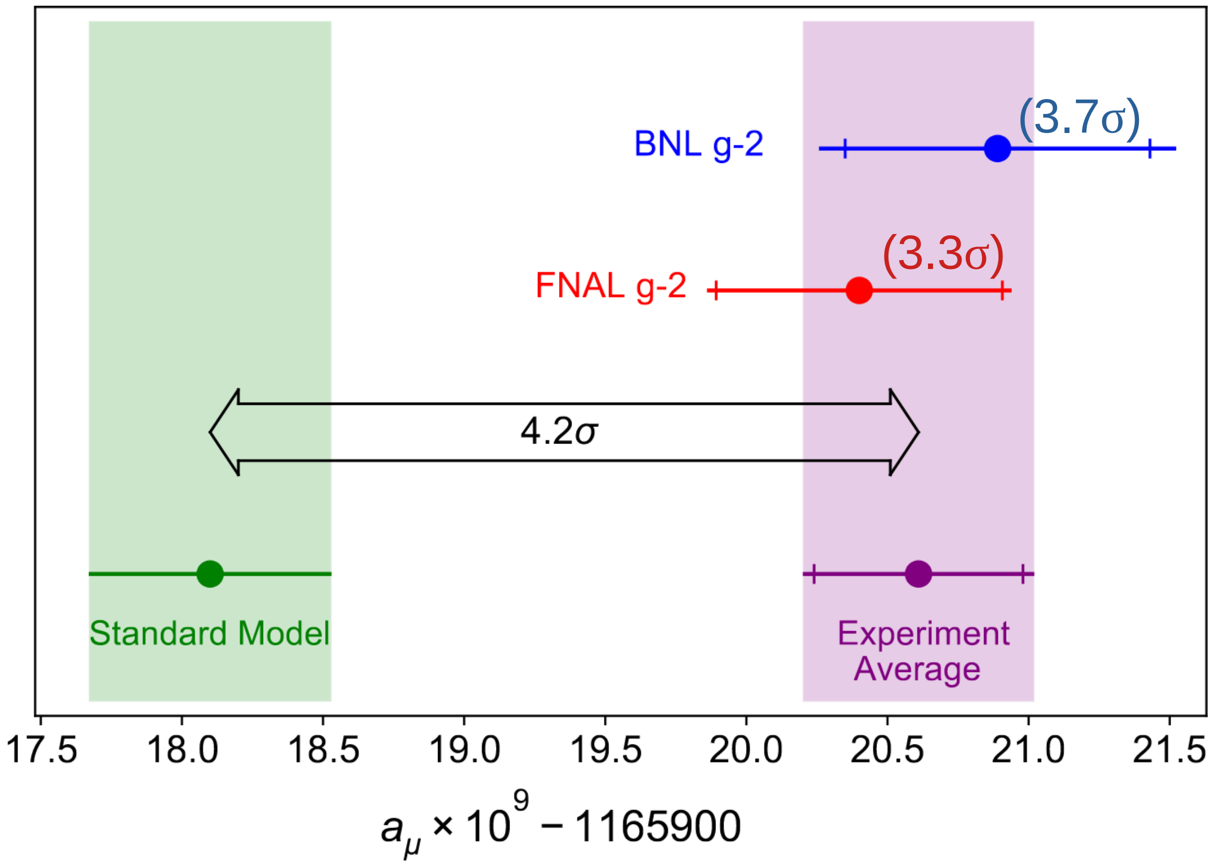
C_{pa}

Quantity	Symbol	Value	Unit
Diamagnetic Shielding T dep	(1/σ)dσ/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

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 result



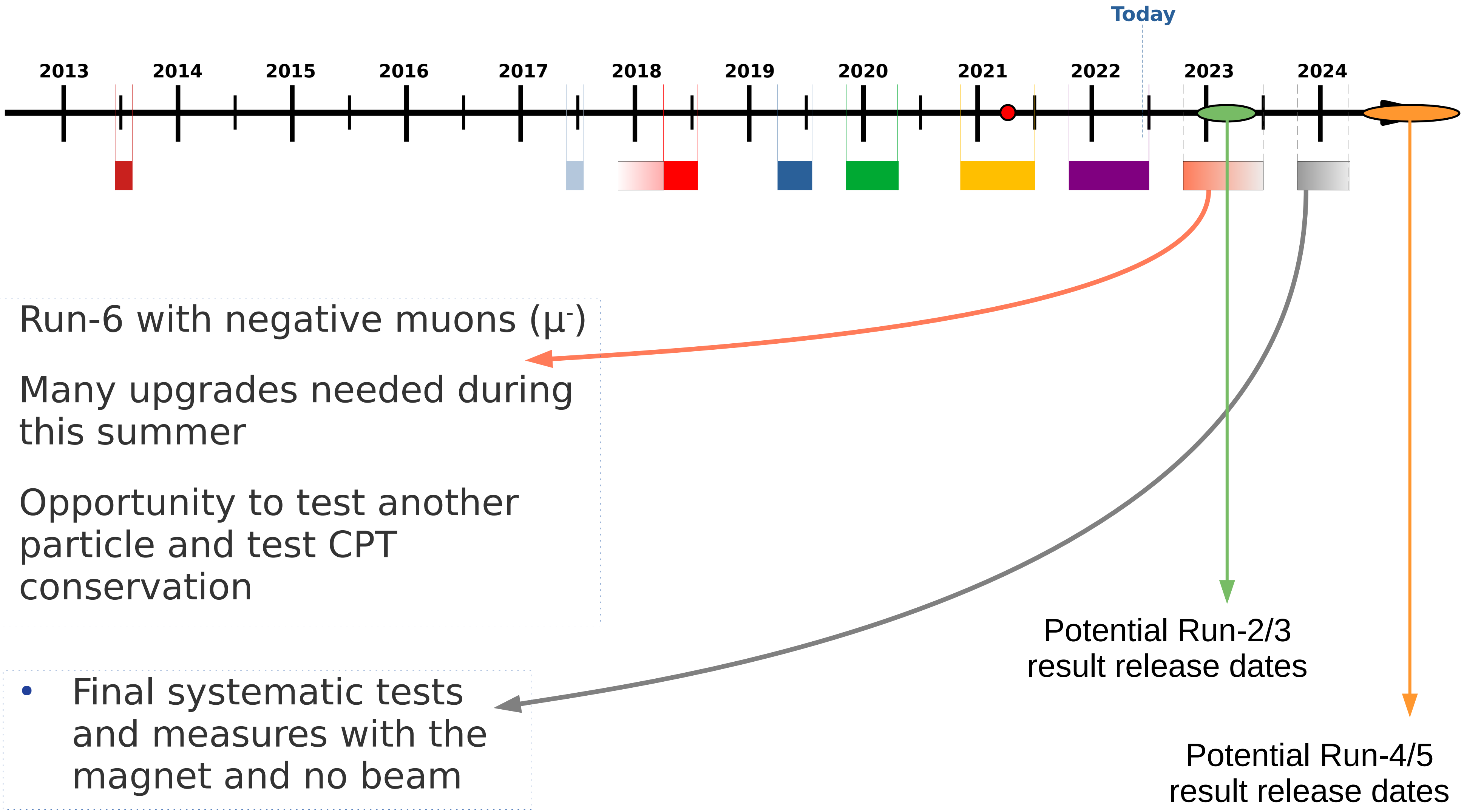
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7°)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	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)

a_μ (Th) = 116 591 810(43) × 10^{-11} (0.37 ppm)

Timeline

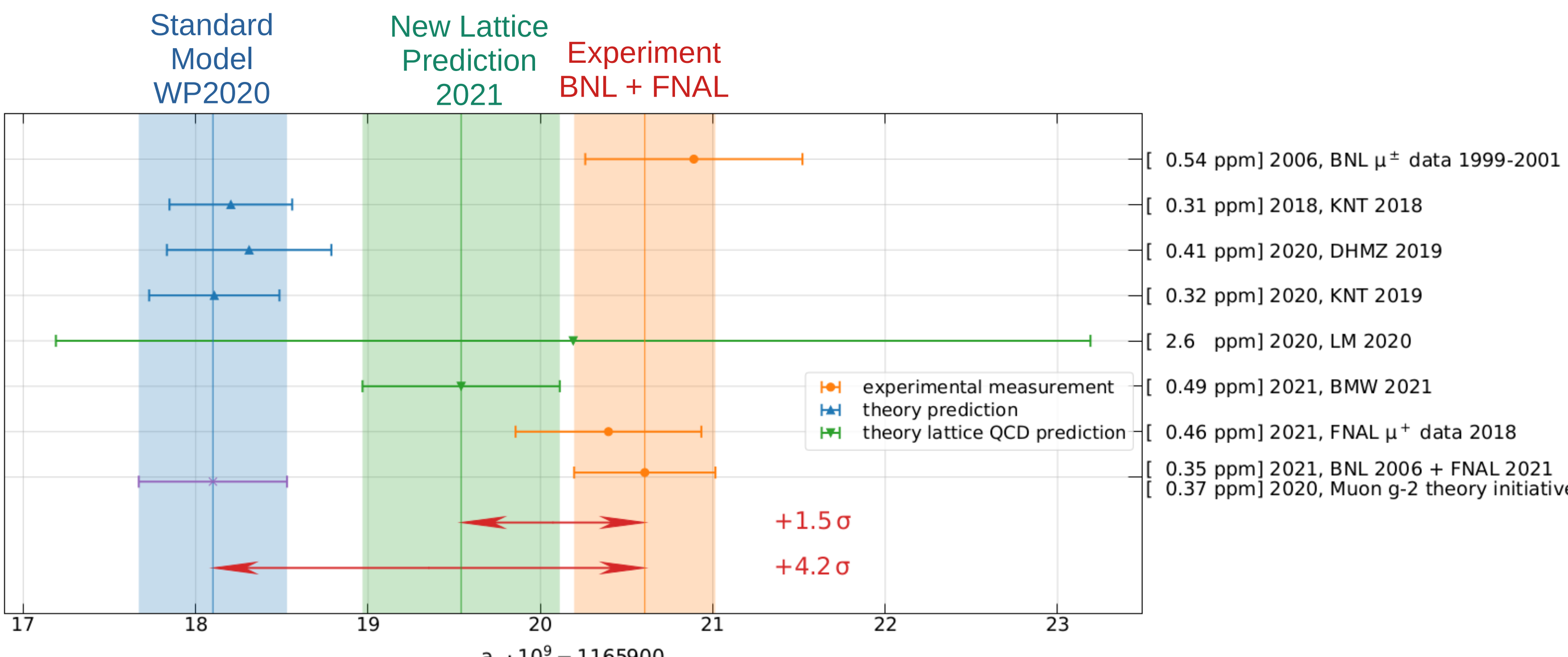


- Run-6 with negative muons (μ^-)
- Many upgrades needed during this summer
- Opportunity to test another particle and test CPT conservation

- Final systematic tests and measures with the magnet and no beam

Future of g-2

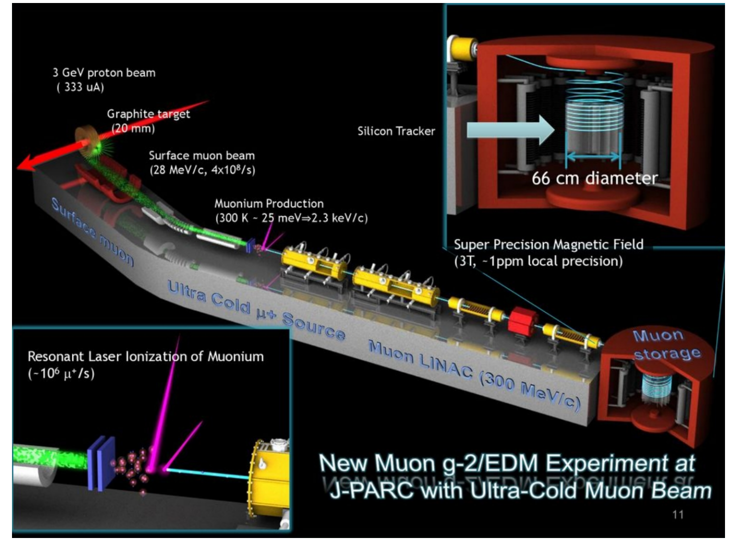
- New **Lattice QCD** estimation of the hadronic contribution
  - Ab-initio calculation, does not rely on experimental data
  - First lattice result to provide an estimate with the error comparable to the dispersive evaluations (< 1%)
  - Needs to be confirmed by other lattice communities
  - "*New g-2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



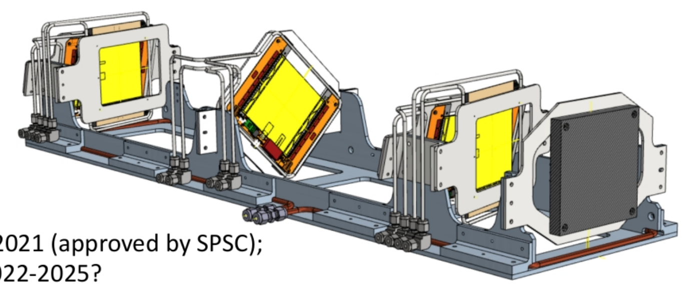
Future of g-2

- New independent method to measure g-2
- Re-accelerated muons at low energy
- Compact, low emittance, high acceptance
- Cross-checking the BNL/FNAL experiments

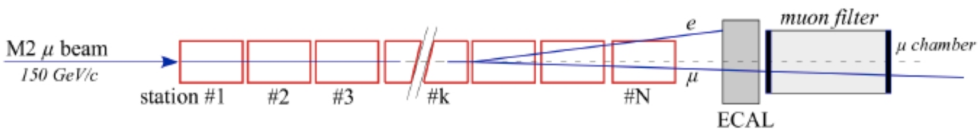
Muon g-2 experiment at J-PARC



MuonE experiment at CERN



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



- Alternative measurement of hadronic loops (HVP) for a_μ
- Scattering experiment with 150 GeV muons
- Cross-checking the SM prediction

Summary

- The Muon g-2 Experiment measures a fundamental property of the muon with extreme precision
- Run-1 result confirmed and increased the discrepancy with the Standard Model prediction
- A lot of data is being analyzed, on track to reach 140 ppb
- Run-6 with μ- will enable new physics tests
- Exciting times, cracks in the Standard Model seem to be appearing in multiple experiments
- Many follow-up experiments are planned, and improvement efforts in theory are under way

Thank you for the attention

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