Measurement of muon g-2 at Fermilab

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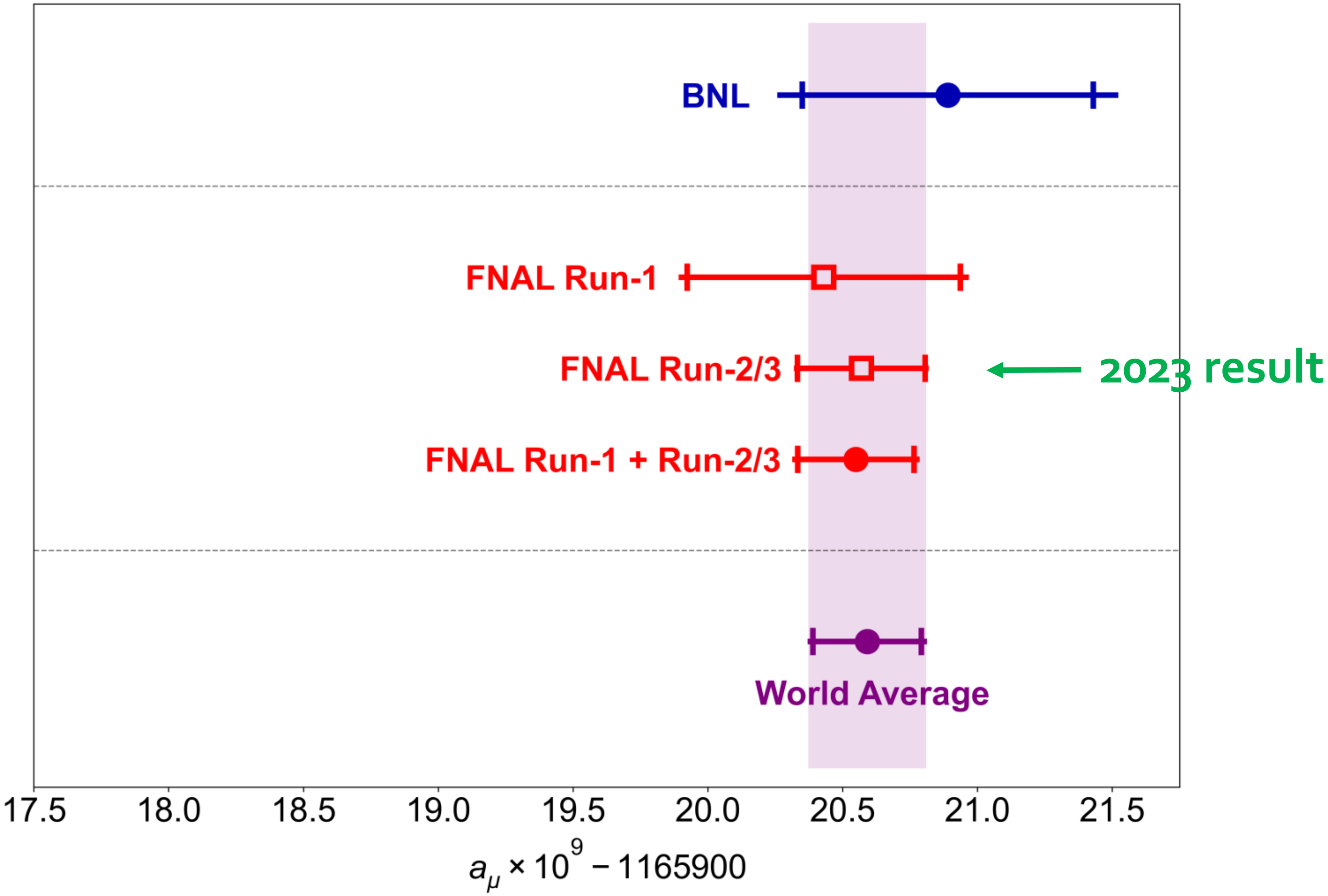
On behalf of Muon G-2 Collaboration

XXI Lomonosov Conference on Particle Physics

August 24-30, 2023
Moscow

Muon G-2 2023 result



$$a_\mu(\text{Exp}) = 0.00\ 116\ 592\ 059(22) \quad [190\ \text{ppb}]$$

Muon G-2 collaboration

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

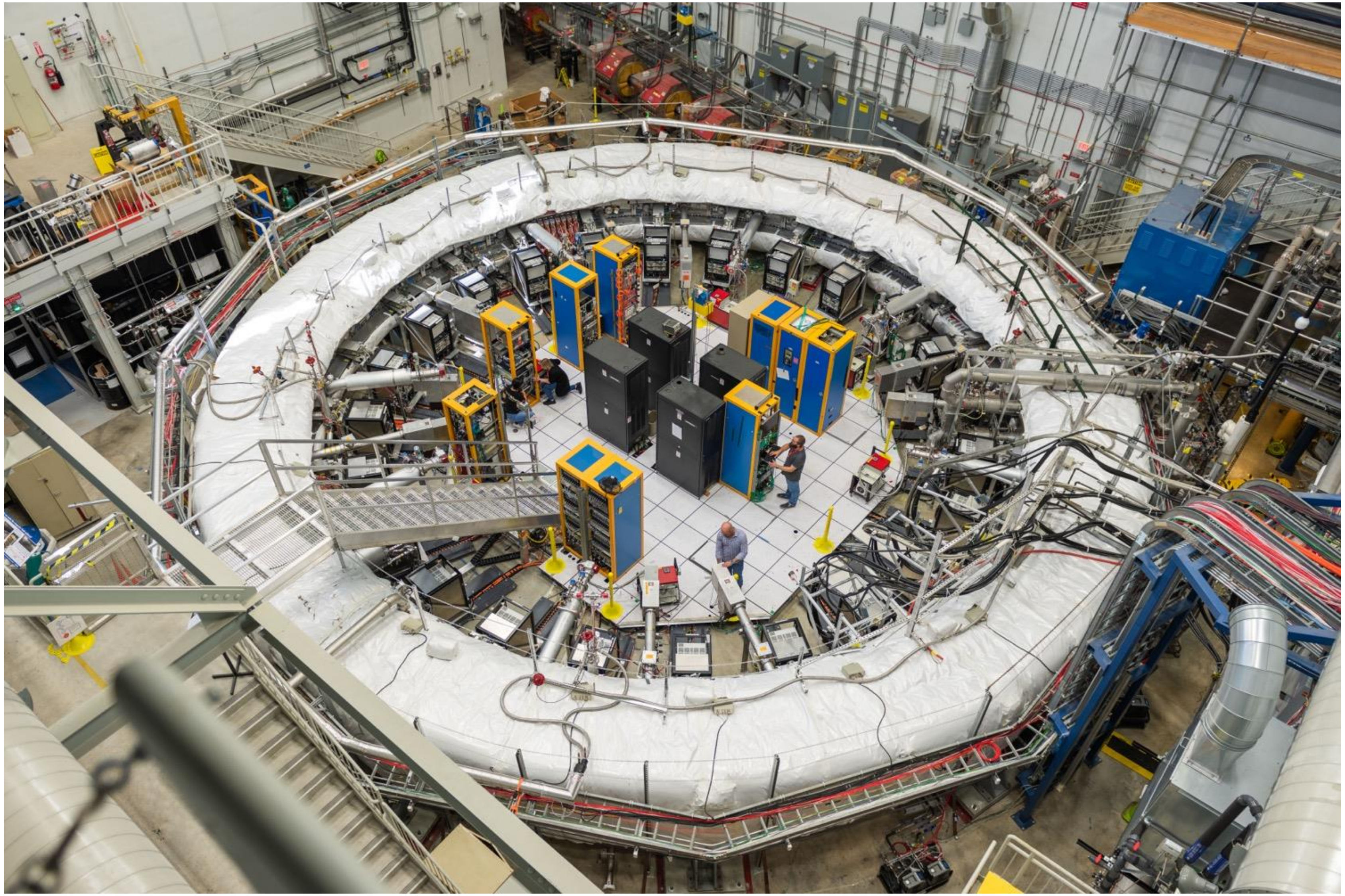
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London


Muon g-2 Collaboration Meeting @ Elba, May 2019

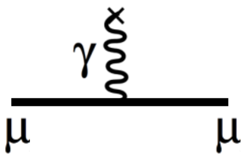
Muon G-2 Ring @FNAL



The basics

Gyromagnetic ratio g connects magnetic moment μ and spin s

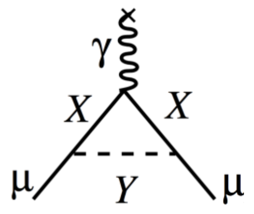
$$\vec{\mu}_S = g\frac{e}{2m}\vec{S}$$



For point-like particle $\boldsymbol{g} = \mathbf{2}$

Anomalous magnetic moment $\boldsymbol{a}$ arises in higher-orders

$$a = (g-2)/2$$



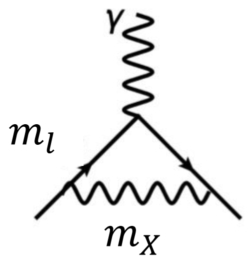
$$a_e \approx a_\mu \approx \frac{\alpha}{2\pi} \approx 10^{-3}$$ (QED dominated)

Idea of experiment: by comparing measured value of $\boldsymbol{a}$ with the theory prediction we probe extra contributions to a beyond theory expectations

$$a_\mu(strong)/a_\mu(QED) \approx 6 \times 10^{-5} \qquad a_\mu(weak)/a_\mu(QED) \approx 10^{-6}$$

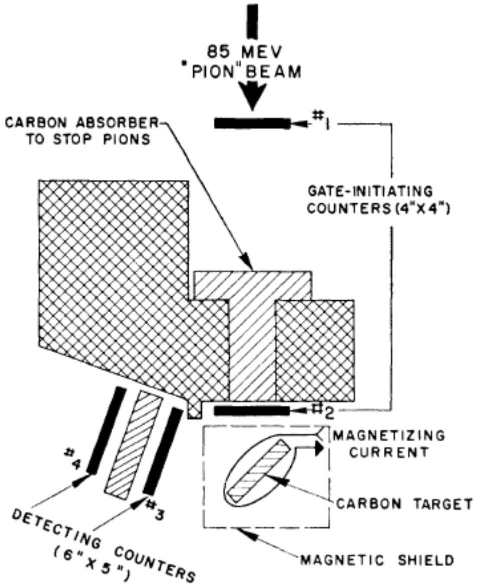
Why muon? For massive fields there is natural scaling, which enhances contribution to a_μ by $\left(m_\mu/m_e\right)^2 \sim 43000$ compared to a_e

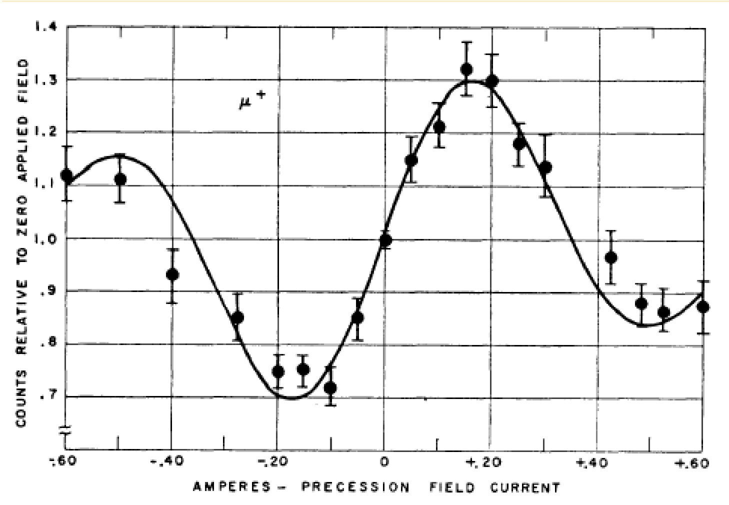
$$\Delta a \sim \left(\frac{m_l}{m_X}\right)^2$$



Generations of a_μ measurements

NEVIS (USA)





1957

$$g_\mu(\text{эксп}) \quad = 2.00\ (10)$$

$$g_\mu(\text{теория}) = 2.002\ 331\ 836\ 20\ (86)$$

WP2020

QED

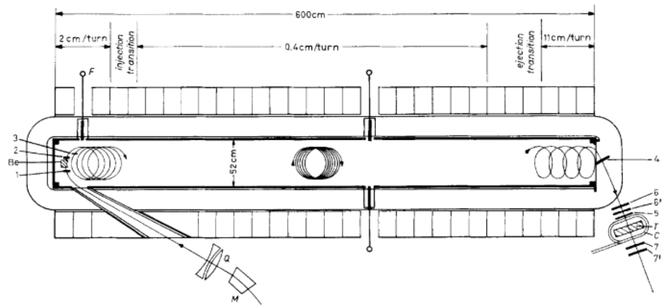
Strong

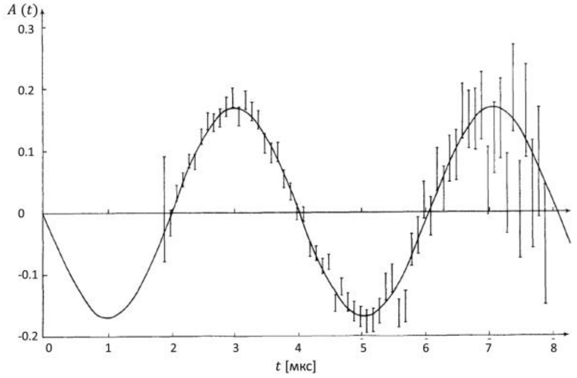
Weak

Contributions of known interactions

Generations of a_μ measurements

CERN I





1957 1965

$$g_\mu(\text{эксп}) = 2.002\ 324\ (10)$$

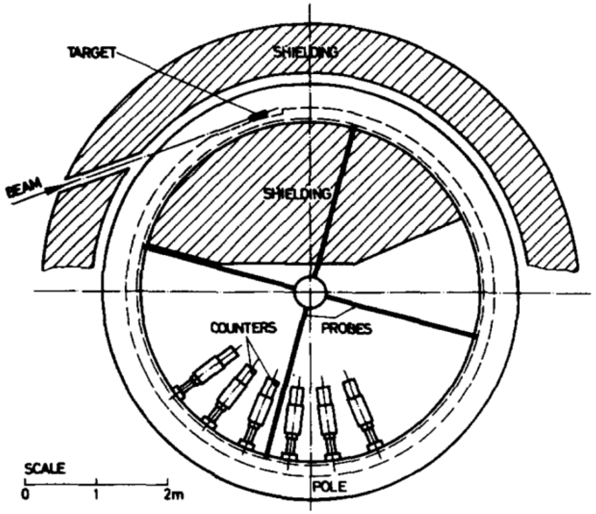
$$g_\mu(\text{теория}) = 2.002\ 331\ 836\ 20\ (86)$$ WP2020

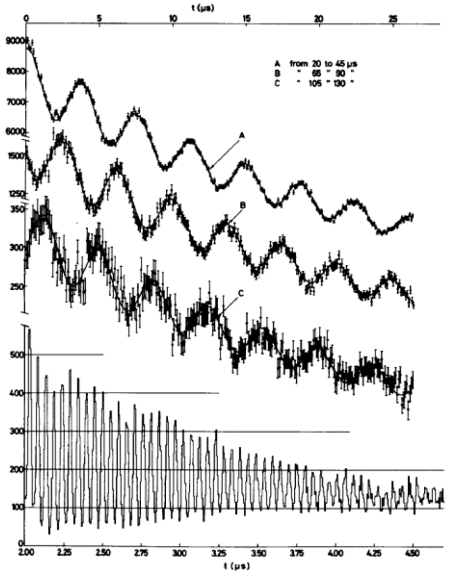
QED
Strong
Weak

Contributions of known interactions

Generations of a_μ measurements

CERN II





1957
1965
1968

$$g_\mu(\text{эксп}) = 2.002\ 332\ 32\ (62)$$

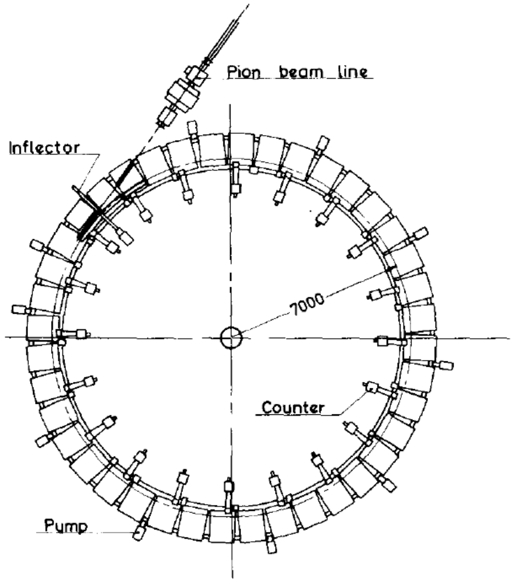
$$g_\mu(\text{теория}) = 2.002\ 331\ 836\ 20\ (86)$$ WP2020

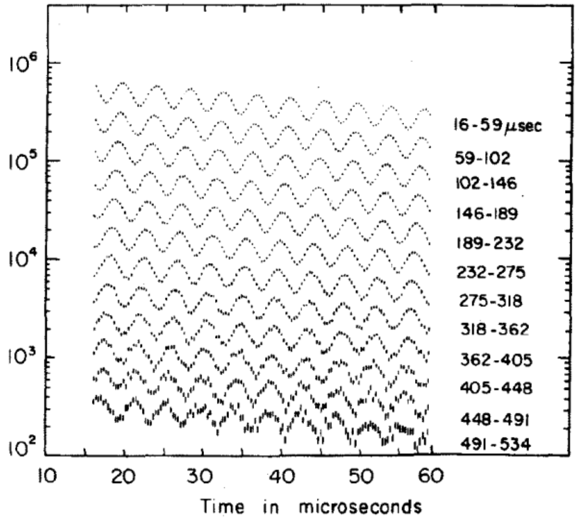
QED
Strong
Weak

Contributions of known interactions

Generations of a_μ measurements

CERN III





1957
1965
1968
1976

"CERN-III-type experiments"

$$g_\mu(\text{эксп}) = 2.002\,331\,848\,(17)$$

$$g_\mu(\text{теория}) = 2.002\,331\,836\,20\,(86)$$

WP2020

QED

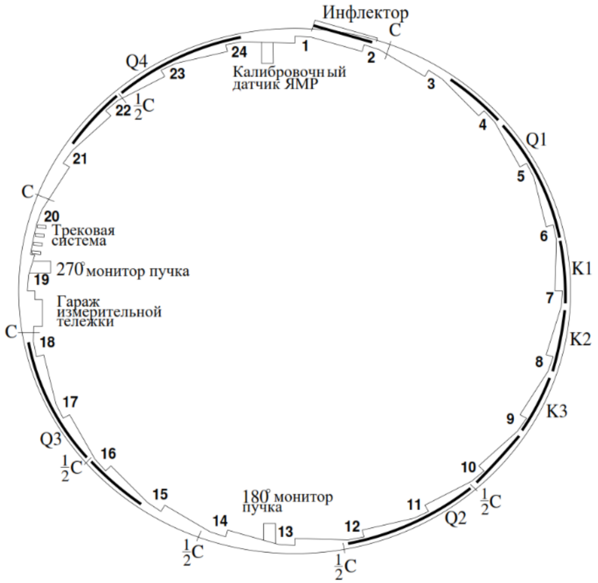
Strong

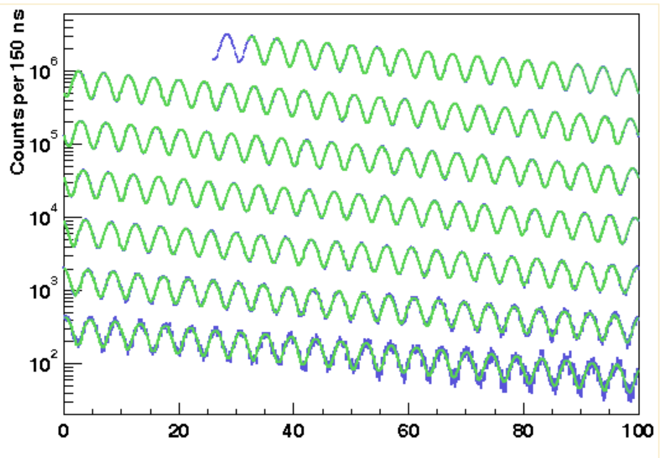
Weak

Contributions of known interactions

Generations of a_μ measurements

BNL (USA)





1957 1965 1968 1976 2006

$$g_\mu(\text{эксп}) = 2.002\,331\,841\,78\,(126)$$

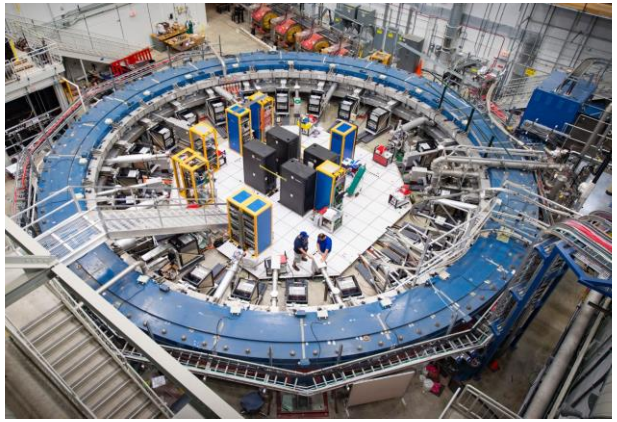
$$g_\mu(\text{теория}) = 2.002\,331\,836\,20\,(86)$$ WP2020

QED
Strong
Weak

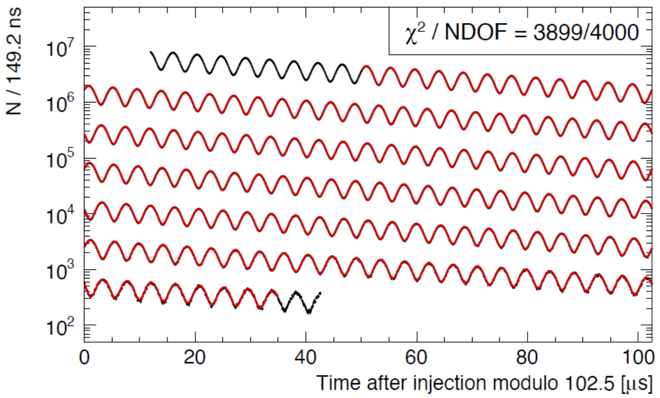
Contributions of known interactions

Generations of a_μ measurements

FNAL Run 1 (USA)



Run 1d



$$g_\mu(\text{эксп}) \quad = 2.002\,331\,841\,22\,(82)$$

$$g_\mu(\text{теория}) = 2.002\,331\,836\,20\,(86)$$ WP2020

QED

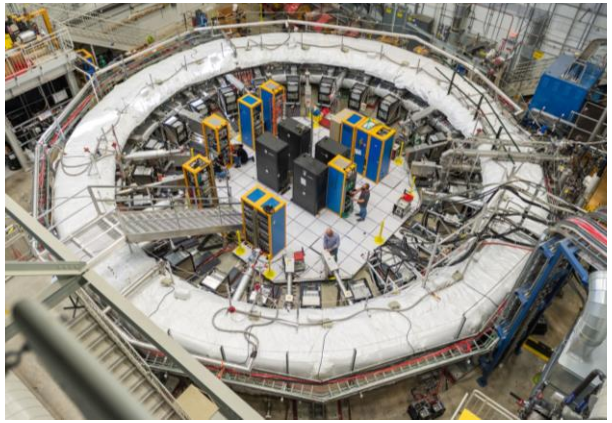
Strong

Weak

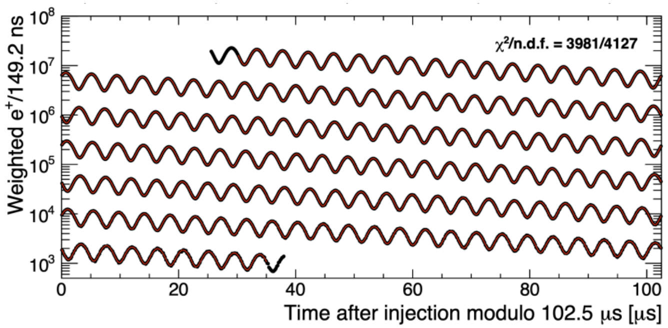
Contributions of known interactions

Generations of a_μ measurements

FNAL Run 2-3 (USA)



Run 3a



$$g_\mu(\text{эксп}) \quad = 2.002\ 331\ 841\ 10\ (48)$$

$$g_\mu(\text{теория}) = 2.002\ 331\ 836\ 20\ (86)$$ WP2020

QED
Strong
Weak

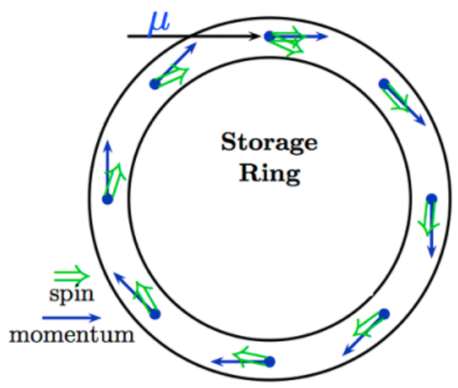
Contributions of known interactions

Principles of CERN-III type measurement

1. Spin precesses relative to momentum with frequency ω_a proportional directly to a_μ

$$\omega_a = \omega_s - \omega_c = a_\mu eB/mc$$

$$a_\mu = \frac{mc}{e}\frac{\omega_a}{B}$$



Muons are stored in a storage ring
ω_a and B are measured

Need focusing!

2. Effect of electric field is cancels out for muons of "magic" momentum

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

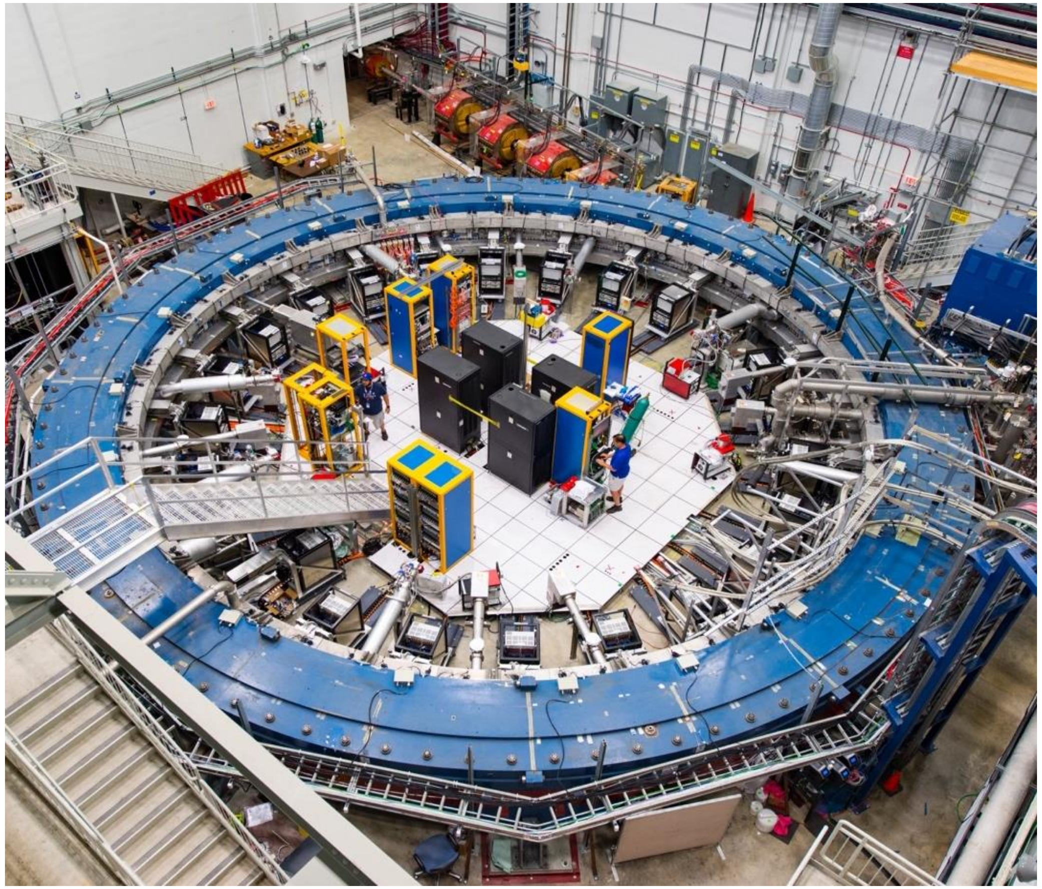
zero for $\gamma_\mu = 29.3$

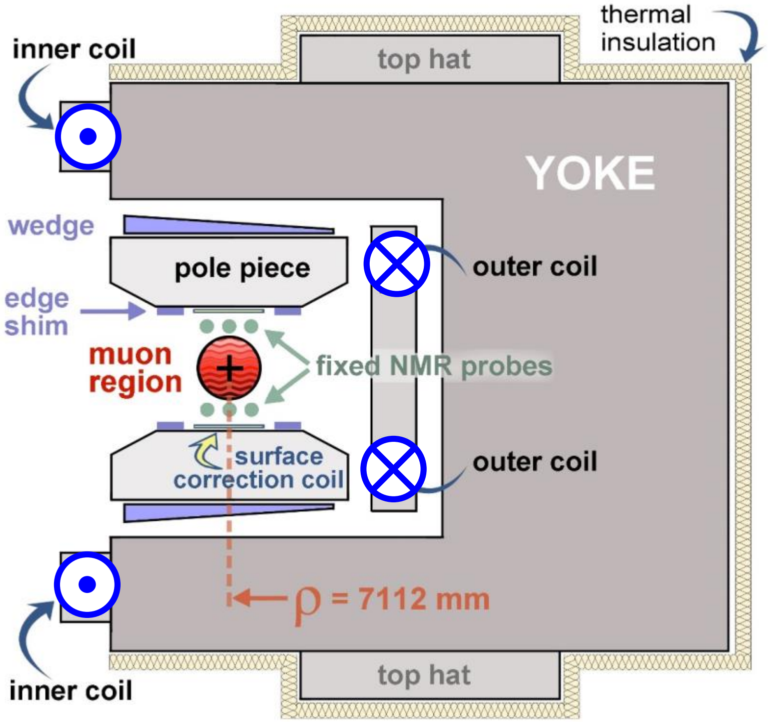
Muons with $p = 3.09$ GeV/c are used

Focusing with electrostatic quadrupoles

The ring magnet

The storage ring is a 14 m diameter, 1.45 T C-shaped magnet

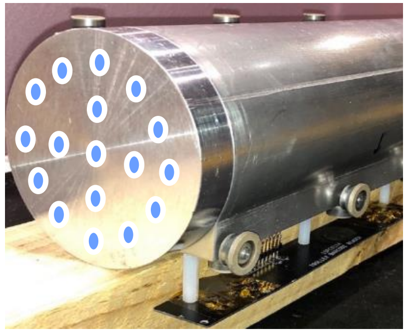




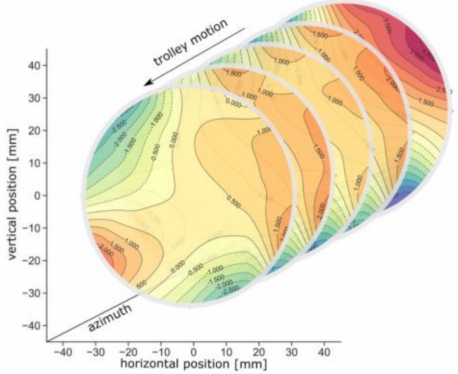
B field is measured in terms of proton NMR frequency ω_p

Monitoring B field

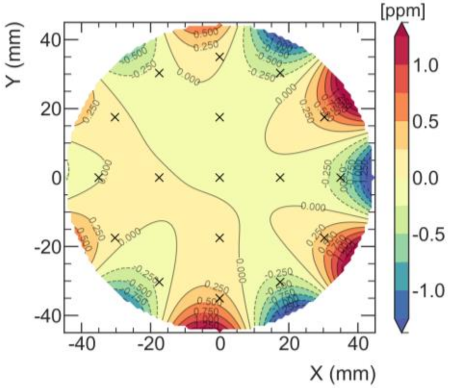
- In-vacuum NMR trolley **maps field every ~3 days**



17 petroleum jelly NMR probes



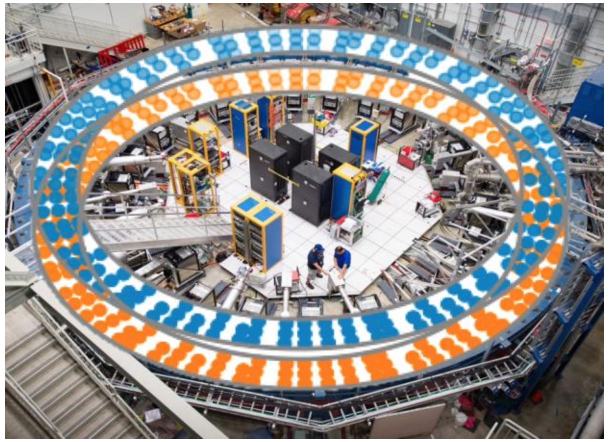
2D field maps (~8000 points)

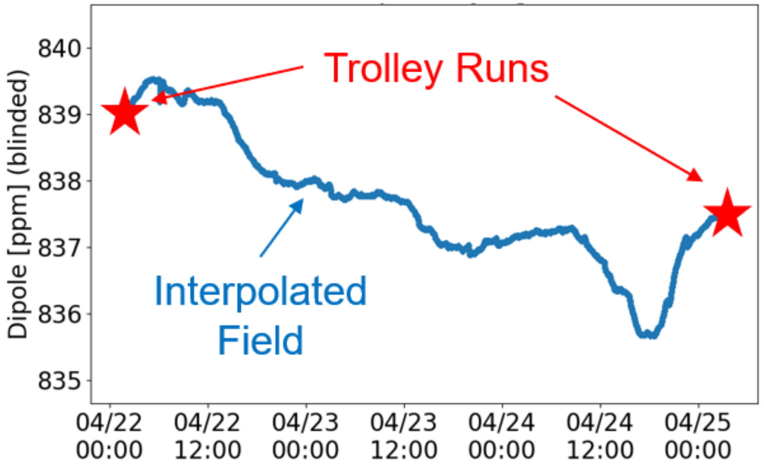


Azimuthally-Averaged **Variation < 1 ppm**

- **378 fixed probes** monitor field during muon storage at 72 locations

Fixed probes above/below muon storage region

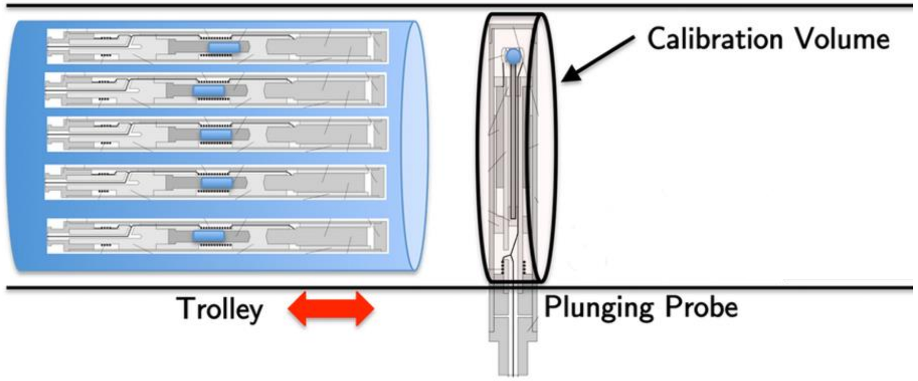


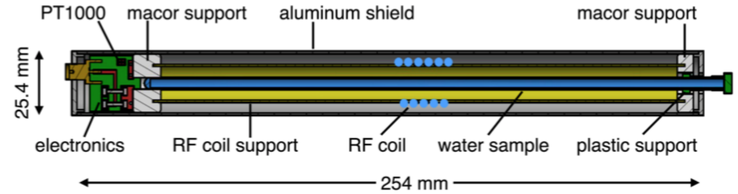


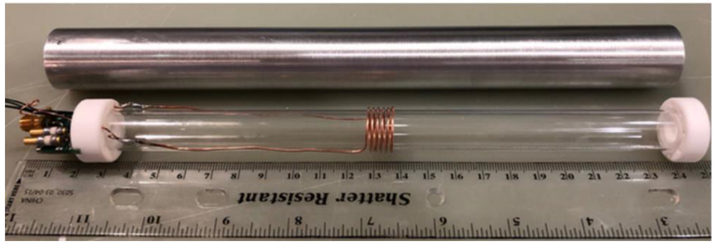
Field map is convoluted with muon spatial distribution to get an average field

Absolute calibration

- Cross-calibrate using a cylindrical **plunging H_2O probe** which repeatedly **changes places with trolley (petroleum jelly probes)**







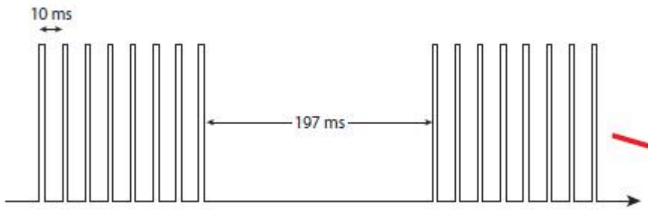
- This probe is **checked against a spherical probe** using an MRI magnet at ANL
- Both also cross-checked against a **^{3}He probe** (different systematics)

$$\Delta B/B \approx 5 \cdot 10^{-8}$$

H_2O Probe

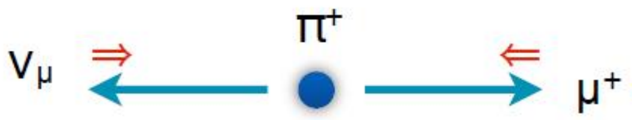
^{3}He Probe

Generation of muons



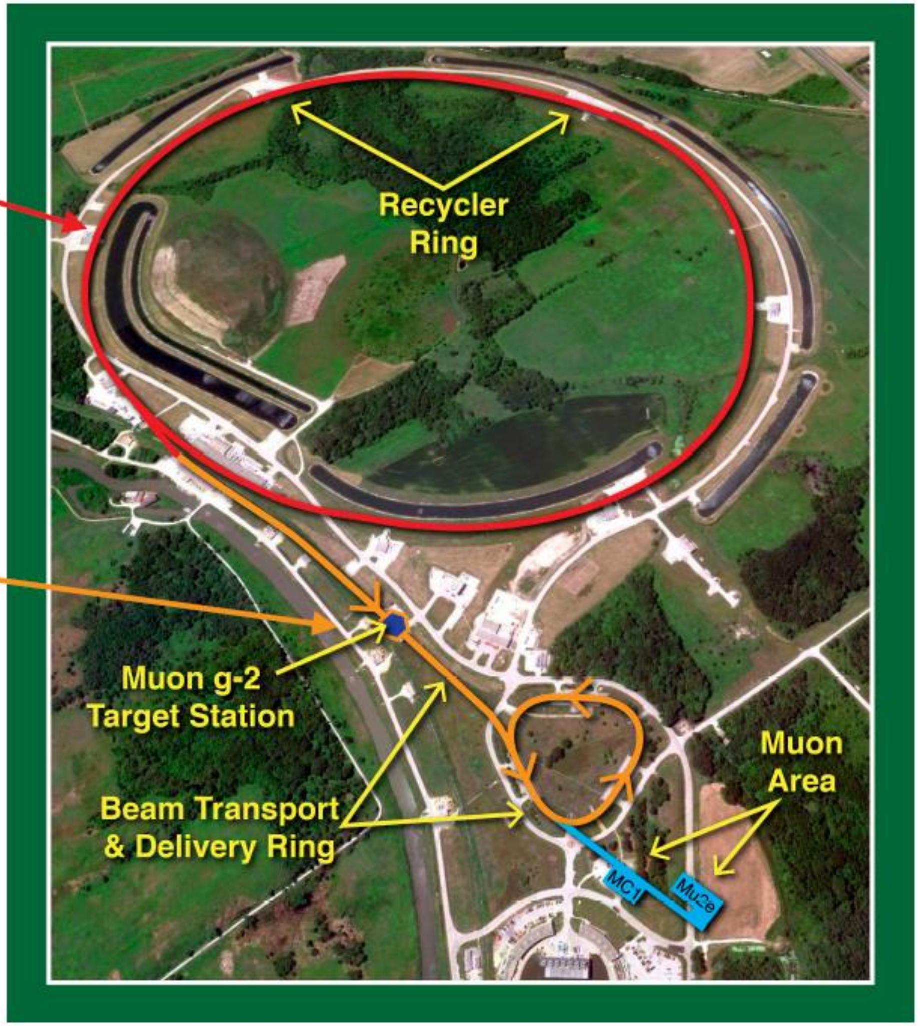
4 Booster batchs → 16 muon fills

- 1.4 sec repetition rate



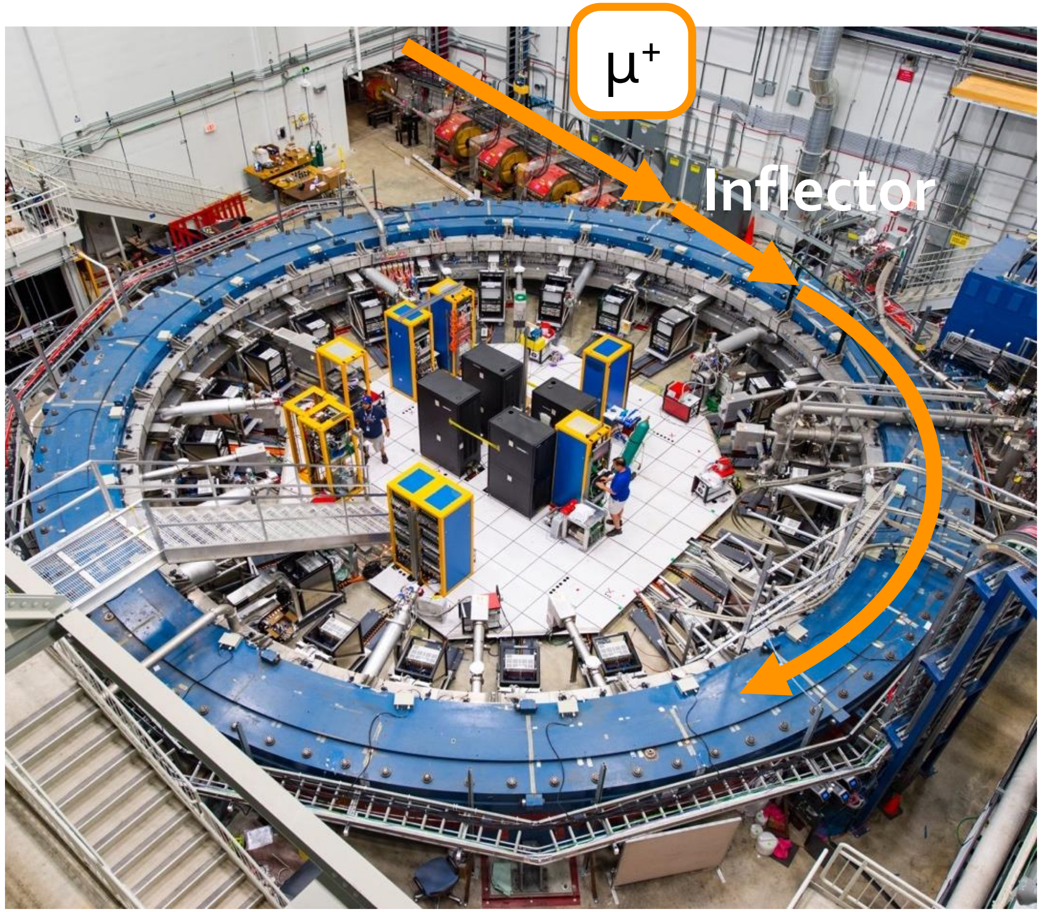
Select ~3.1 GeV π^+ (magic p)

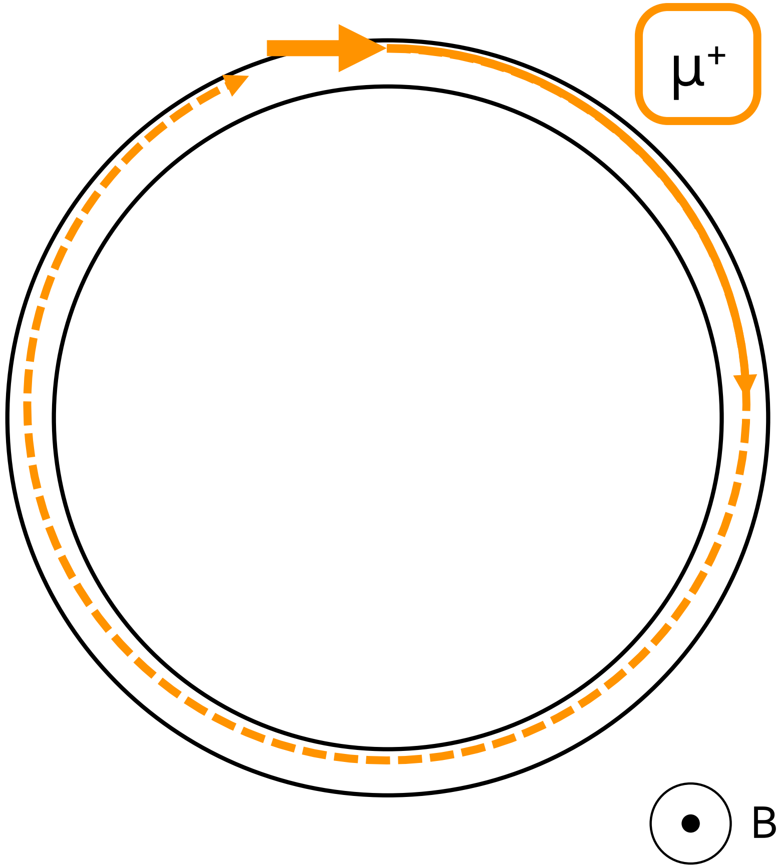
- Parity violation → 95% polarized muons



Injection of muons

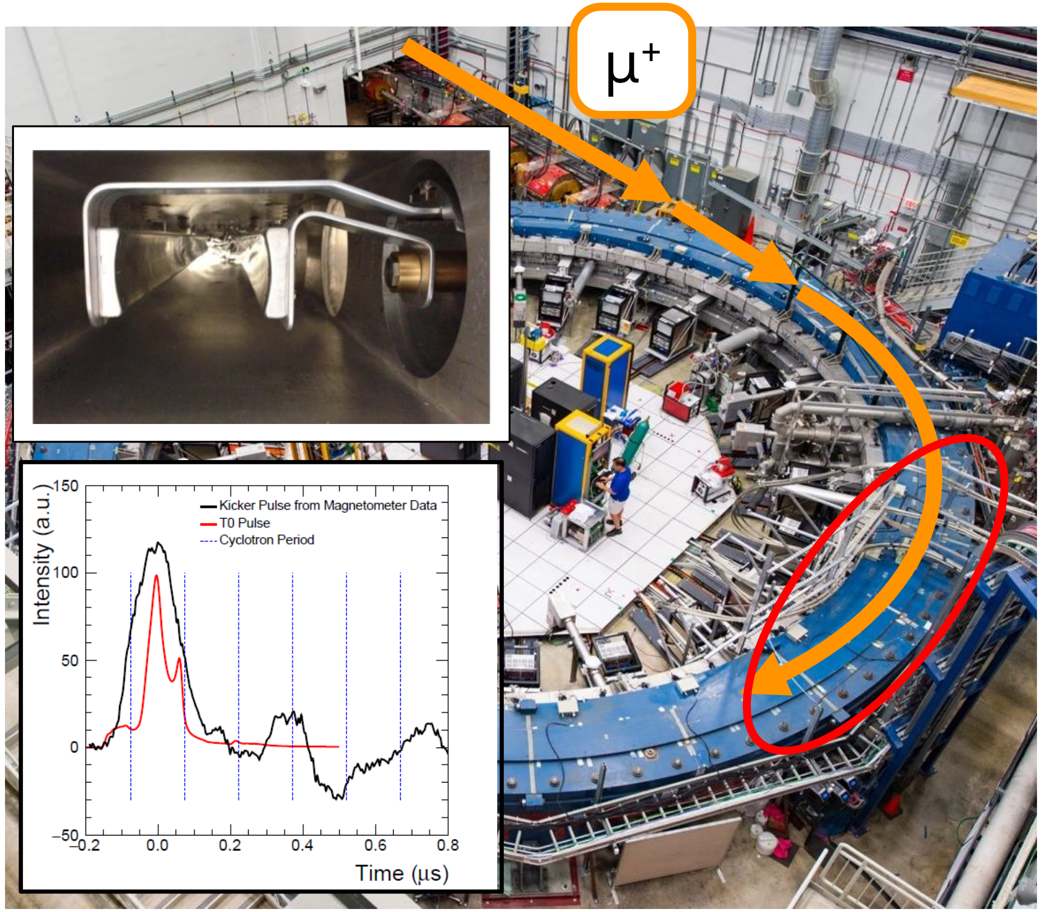
Muons are injected into the storage ring with uniform field. After one turn they hit the wall, unless…

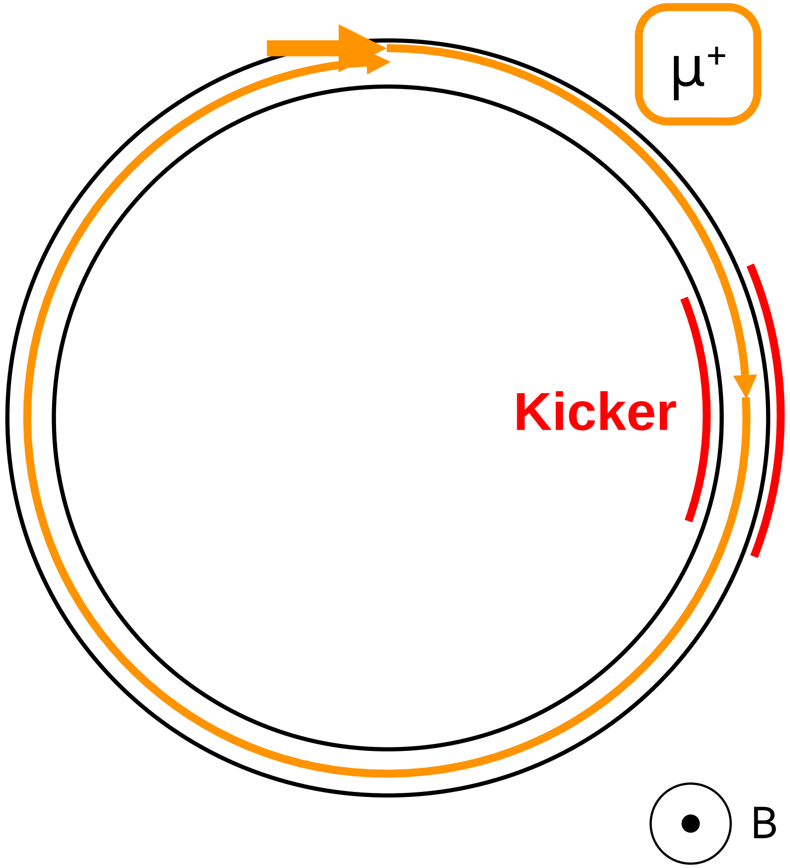




Kicker

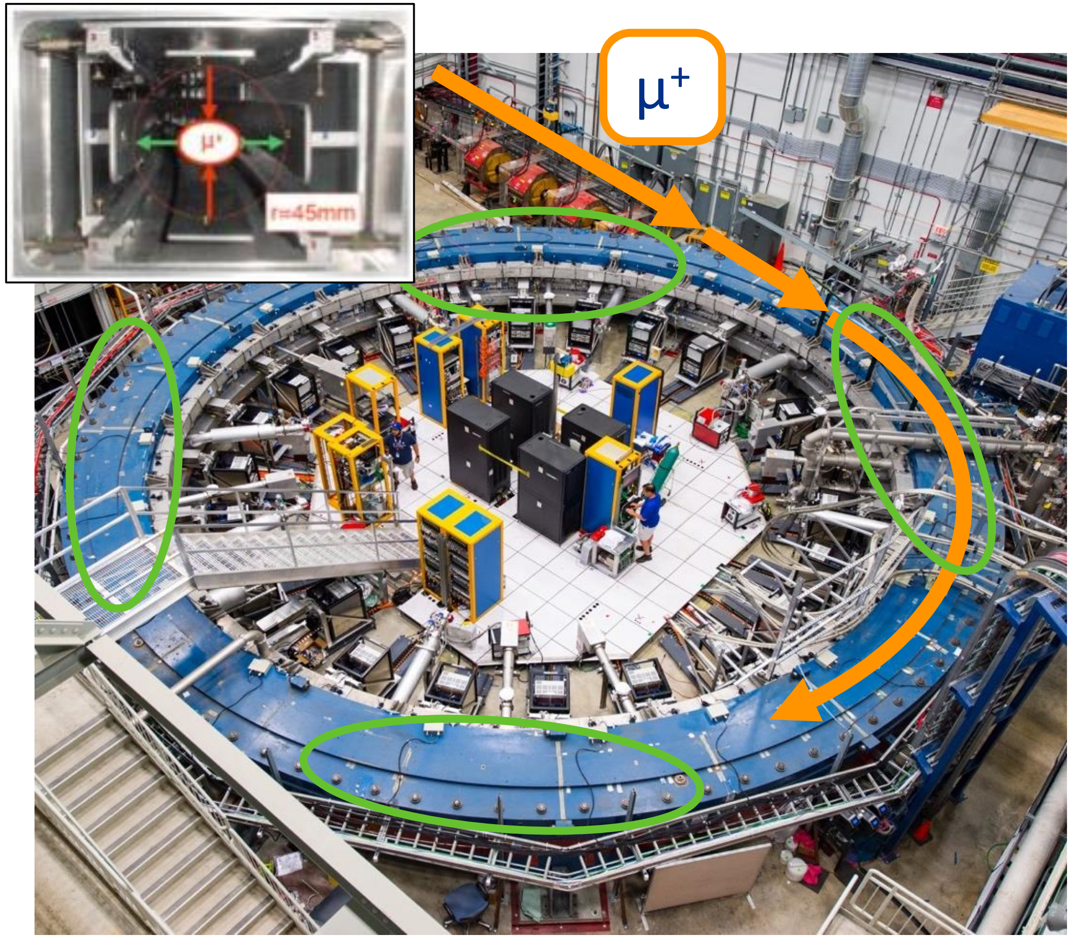
Fast kicker magnet briefly reduces field at 90° and puts beam to standard orbit

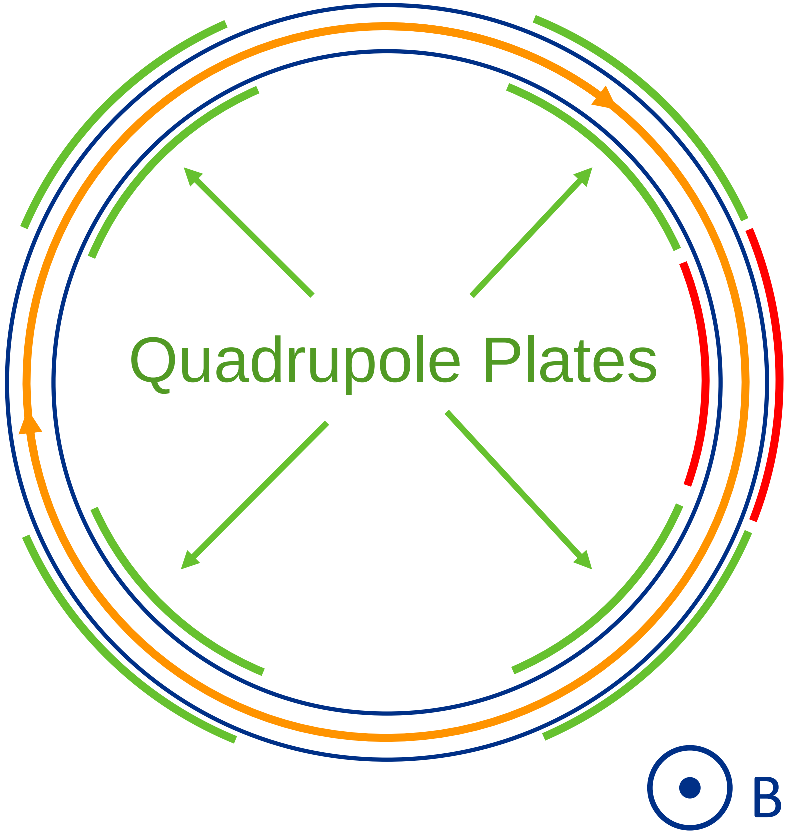




Quads

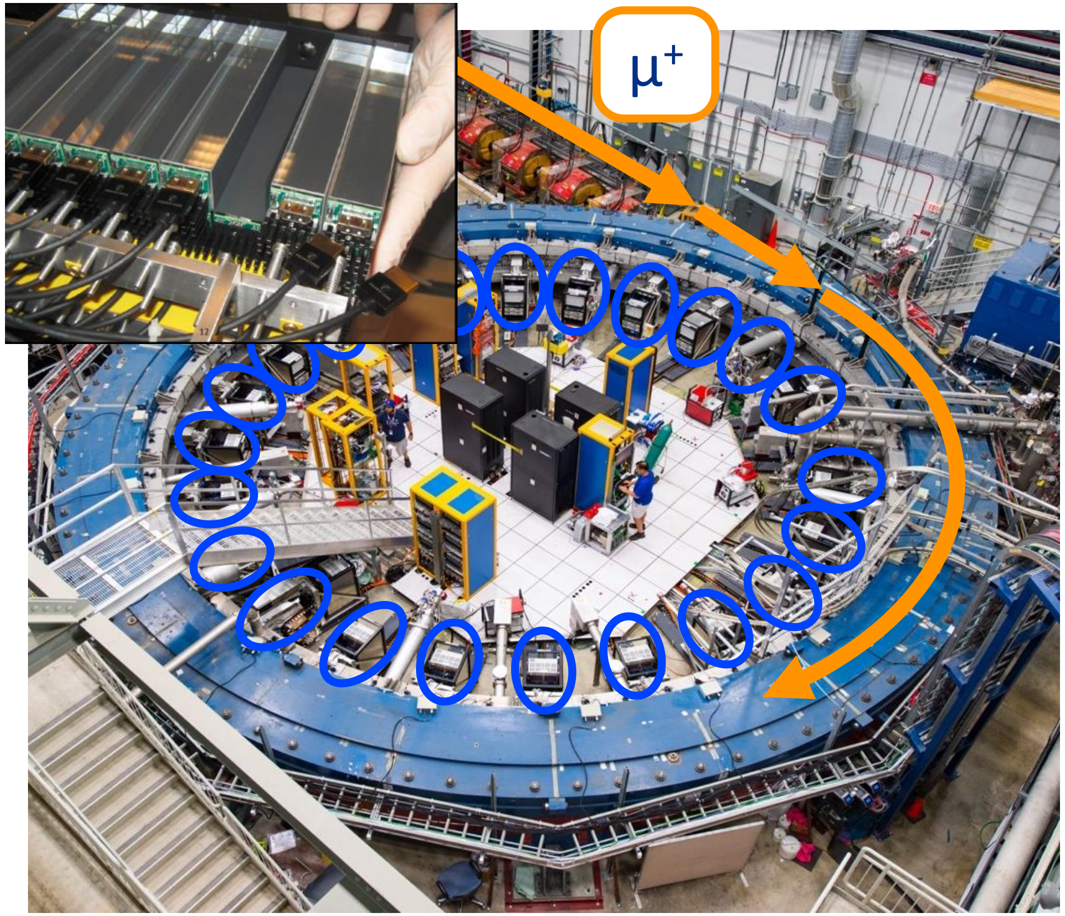
- Electrostatic quadrupoles vertically contain the beam

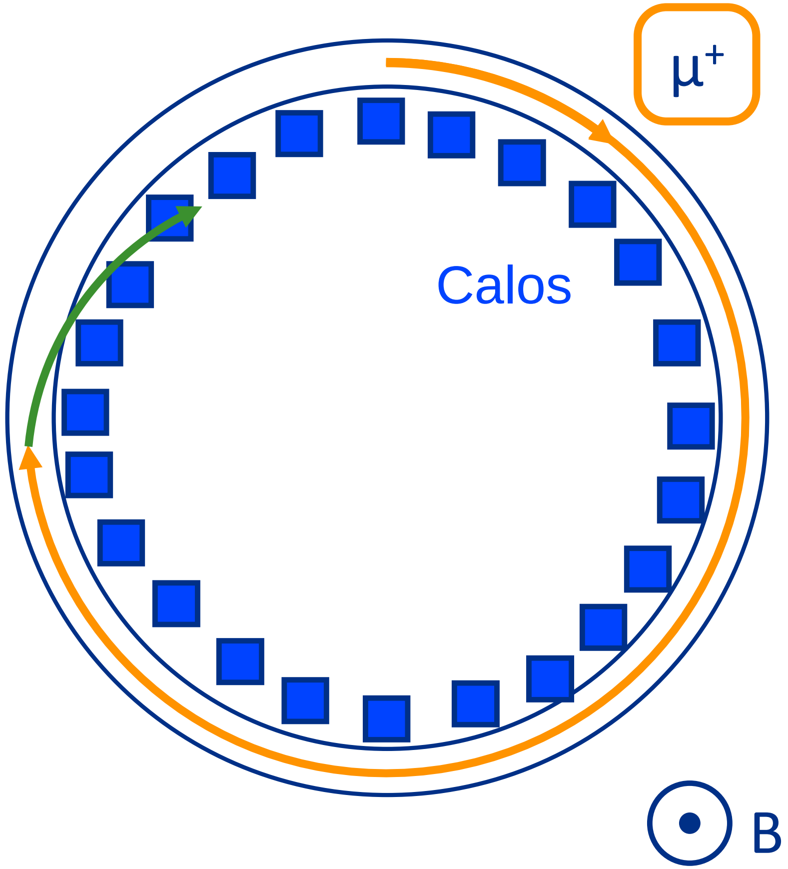




Calorimeters

- Time & energy of decay e^+ are measured by **24 calorimeters**

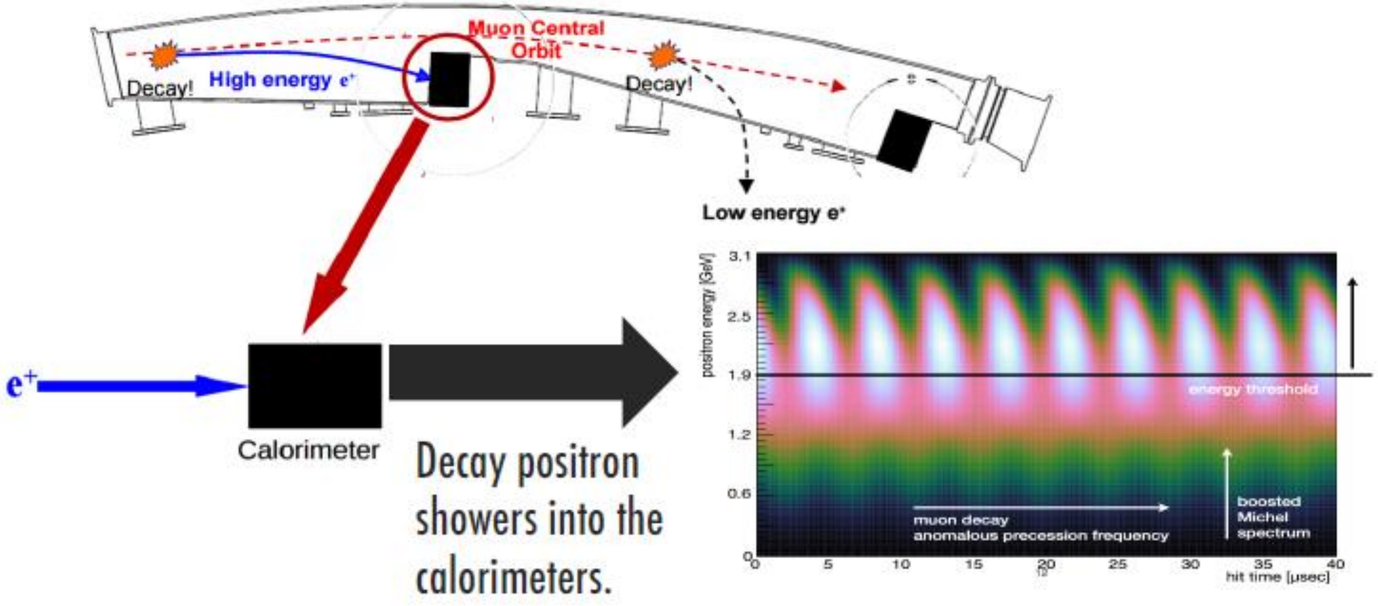




Each calorimeter: array of 9x6 PbF_2 crystals (2.5 x 2.5 cm^2 x 14 cm, $15X_0$), readout by SiPMs

Measuring ω_a

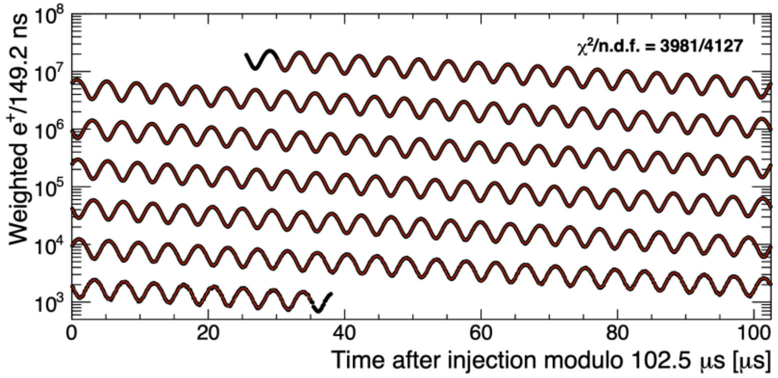
The energy distribution of positrons depends on spin direction, thus number of high energy positrons is modulated by precession frequency



Counting rate of high energy positrons

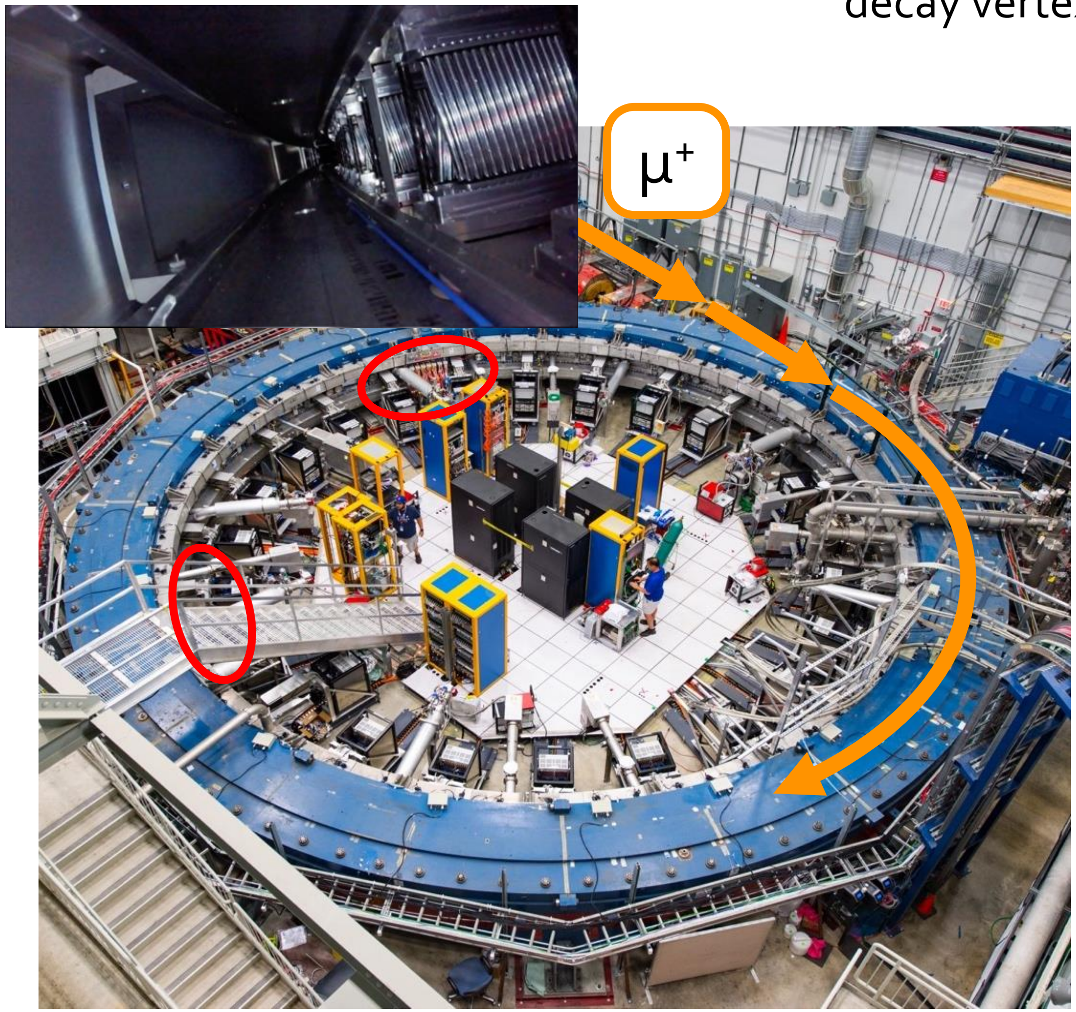
"Wiggle plot"

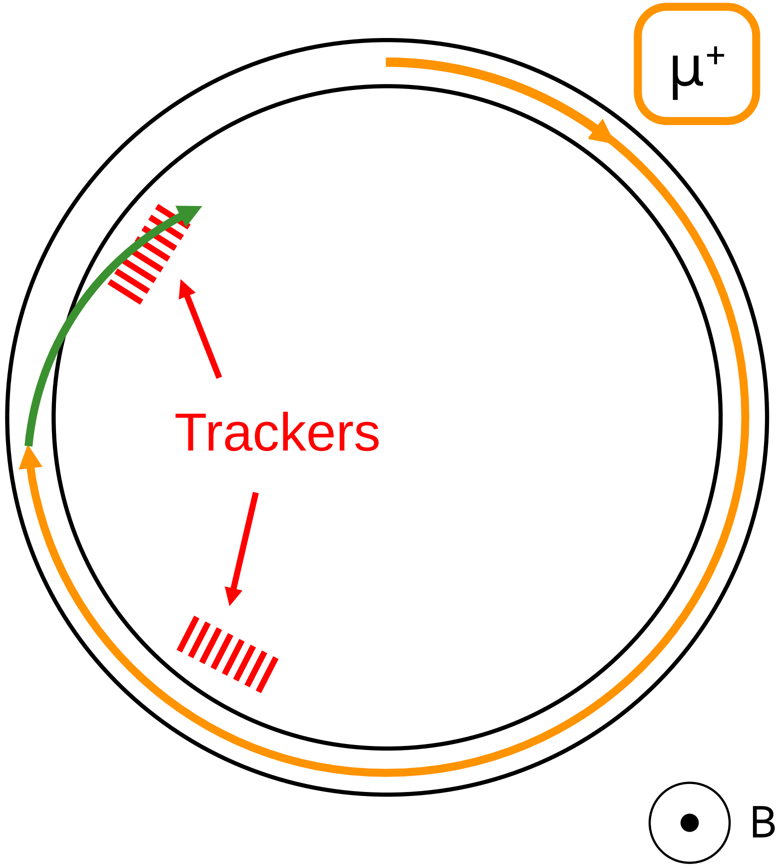
$$dN(e^+ > 1\ \text{GeV})/dt$$



Trackers

Two trackers allow to see muon beam dynamics in real time by reconstruction of muon decay vertex



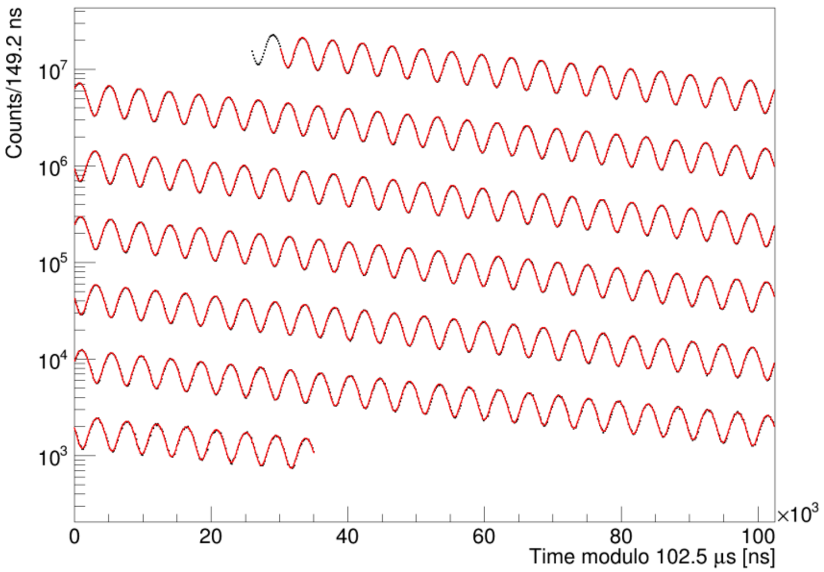


5-par fit

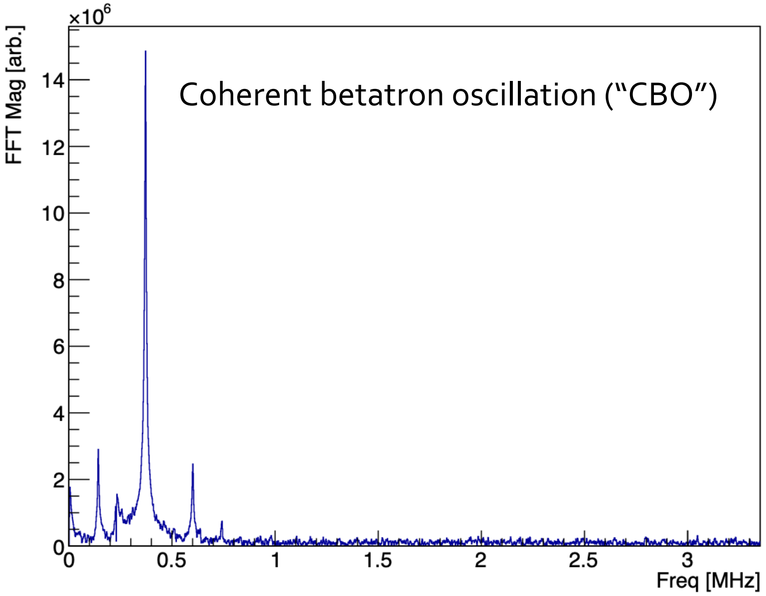
Simple model: exponential decay and precession

$$N(t) = \boldsymbol{N_0} e^{(-t/\boldsymbol{\tau})}[1 + \boldsymbol{A}\cos(\boldsymbol{\omega_a} t - \boldsymbol{\phi})]$$

χ^2/ndf = 51530/4150



Fourier transform of residuals



Realistic model must account for **detector effects**, **beam oscillations** that couple to acceptance, and **lost muons** that disrupt pure exponential

Full fit function

Fit function is extended to cover all extra effects

$$N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

⬇

$$f(t) = N_0 e^{-t/\tau}\,\Lambda(t)\,N_{cbo}(t)\,N_{2cbo}(t)\,(1 + A_{cbo}(t) cos(\omega_a t + \phi_{cbo}(t))$$

- Muons that are lost from storage ring before they decay:

$$\Lambda(t) = 1 - \boldsymbol{\kappa_{loss}} \int_{t_0}^{t} L(t')e^{(t'/\tau)}dt'$$

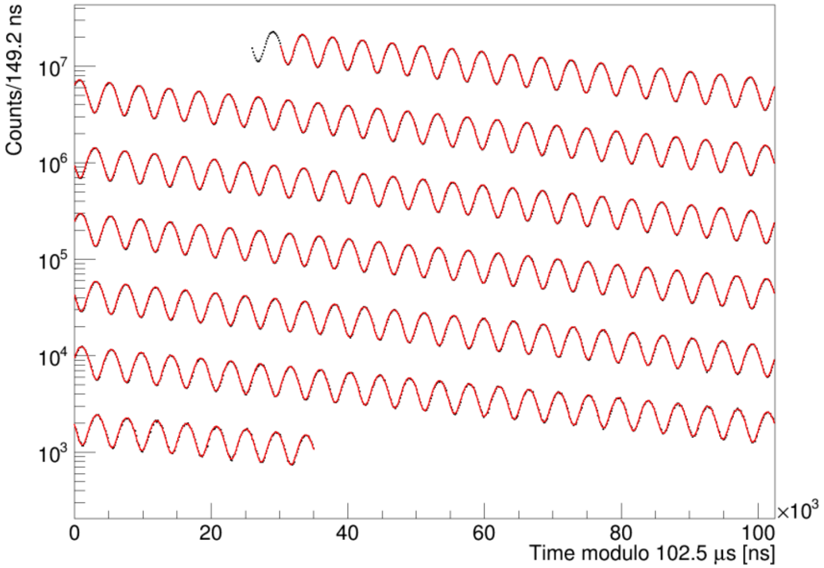
- Beam oscillations that modulate decay rate:

e.g. $N_{cbo}(t) = (1 + \boldsymbol{A_{cbo-N}} \cdot e^{-t/\boldsymbol{\tau_{cbo}}} \cdot \cos(\omega_{cbo}(t) \cdot t + \boldsymbol{\phi_{cbo-N}}))$

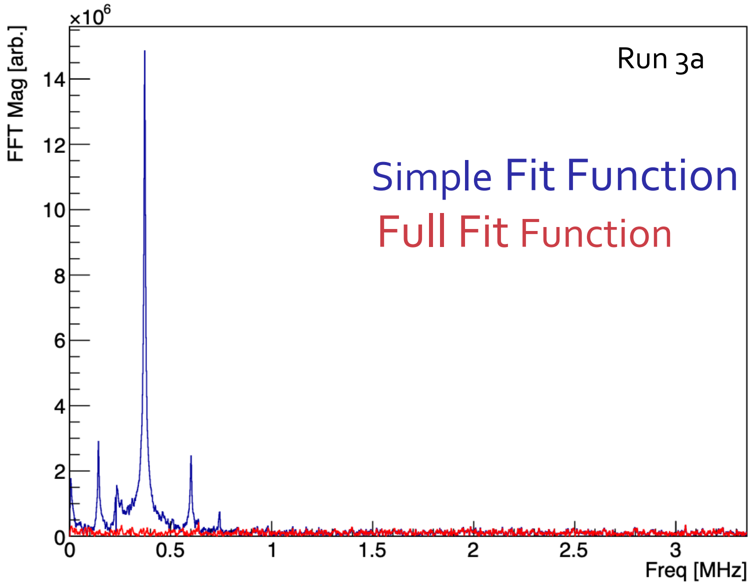
Full fit

Realistic model allows to reach good fit quality.
These effect are important! ω_a shifts by 1-2 ppm.

χ^2/ndf = 4086/4138



Fourier transform of residuals



Must check for potential early-to-late effects

Obtaining a_μ

Corrections due to beam dynamics

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

Measured Values

Corrections due to transient magnetic fields

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

Metrological constants known to ~25 ppb

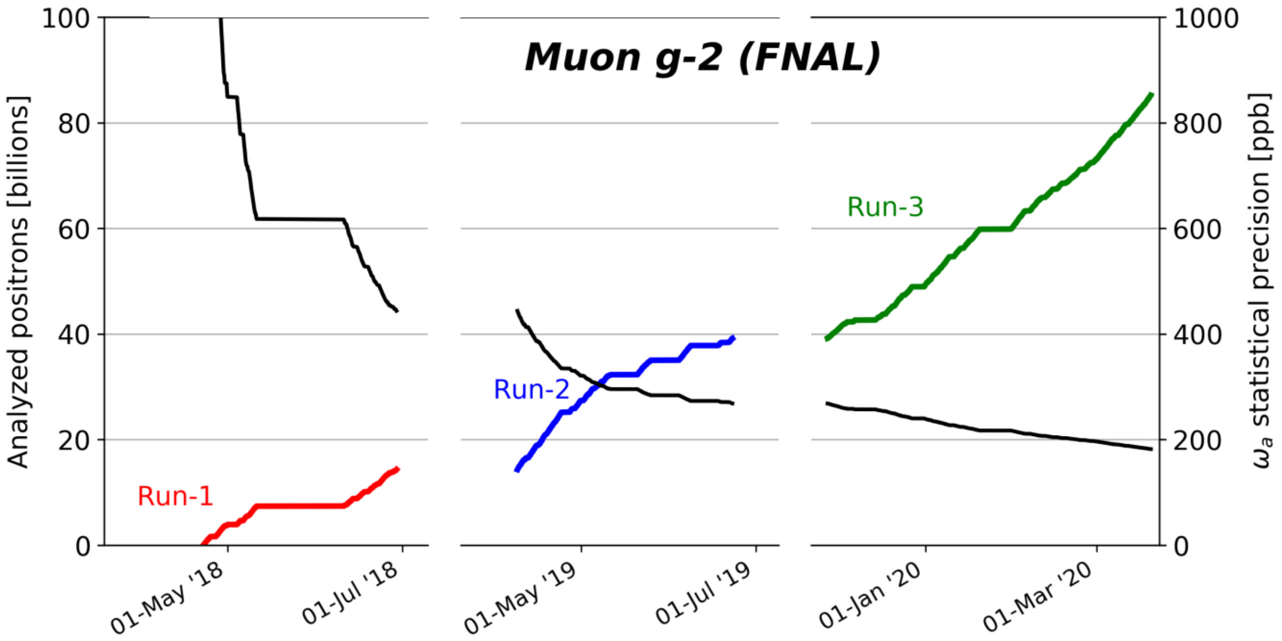
Total correction is about 622 ppb

Run-1 vs Run-2/3

Statistics

Weighted e⁺ in our final fit after quality control

E > 1 GeV
t > 30 us



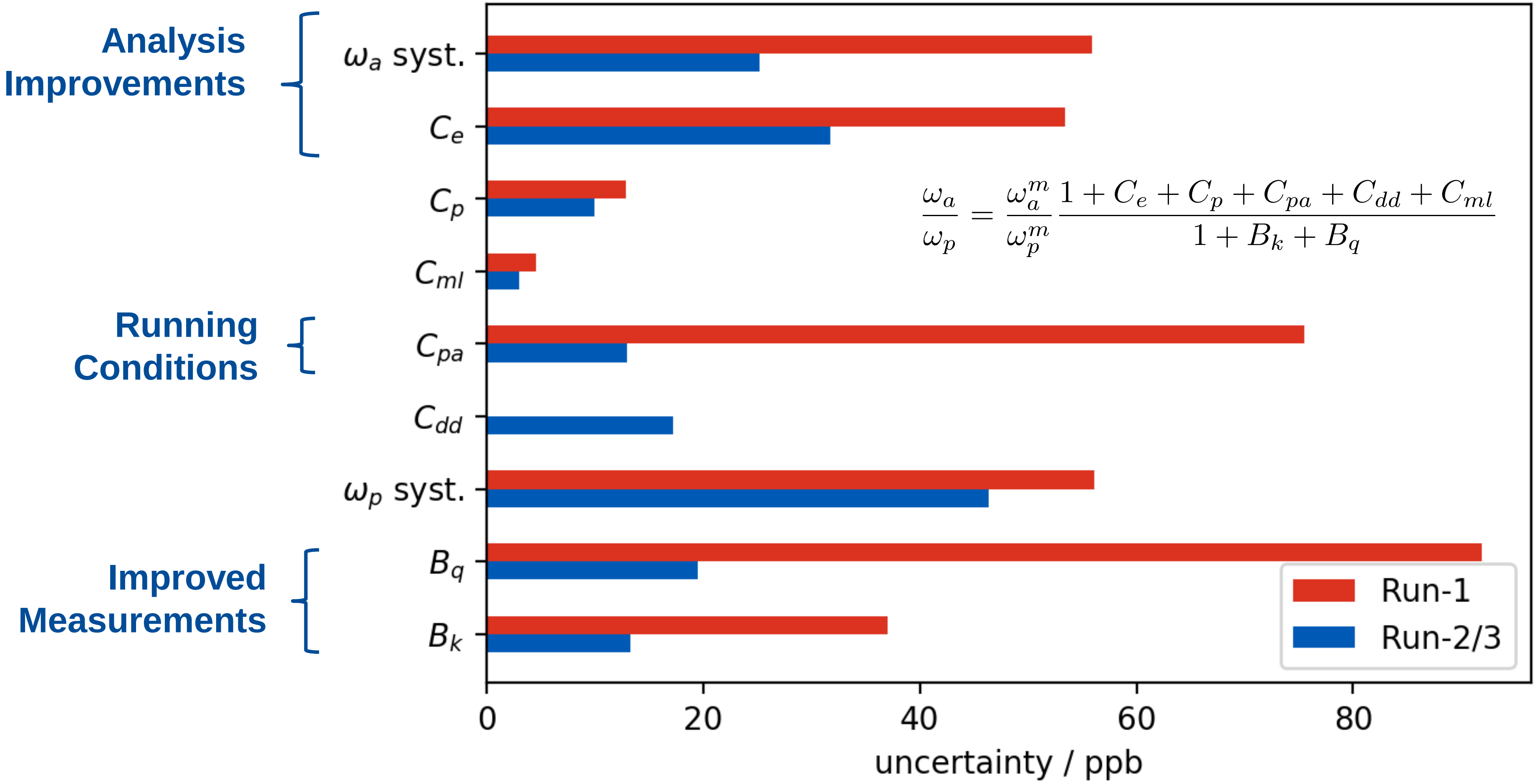
- **Factor 4.7** more data in Run-2/3 than Run-1

Dataset	Statistical Error [ppb]
Run-1	434
Run-2/3	201
Run-1 + Run-2/3	185

Improvement by factor 2.2

Run-1 vs Run-2/3

Systematics

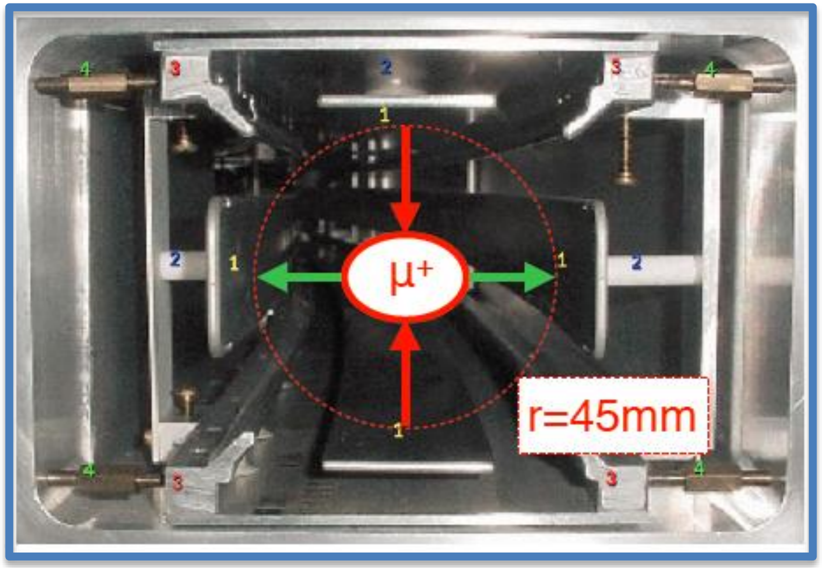


Overall improvement by factor 2.2

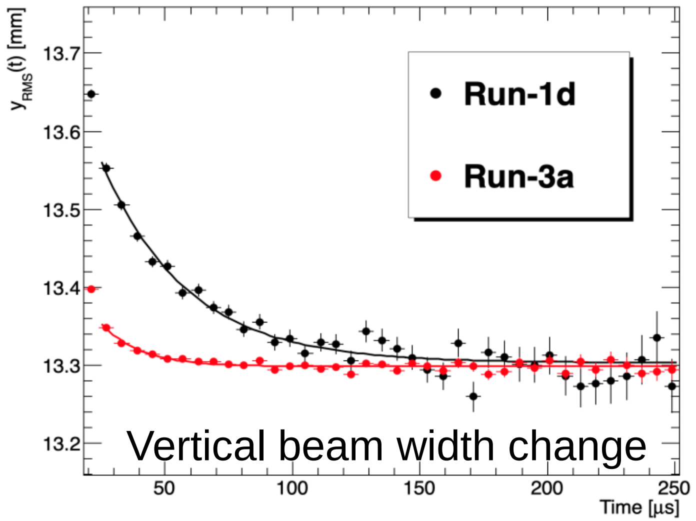
Improvements

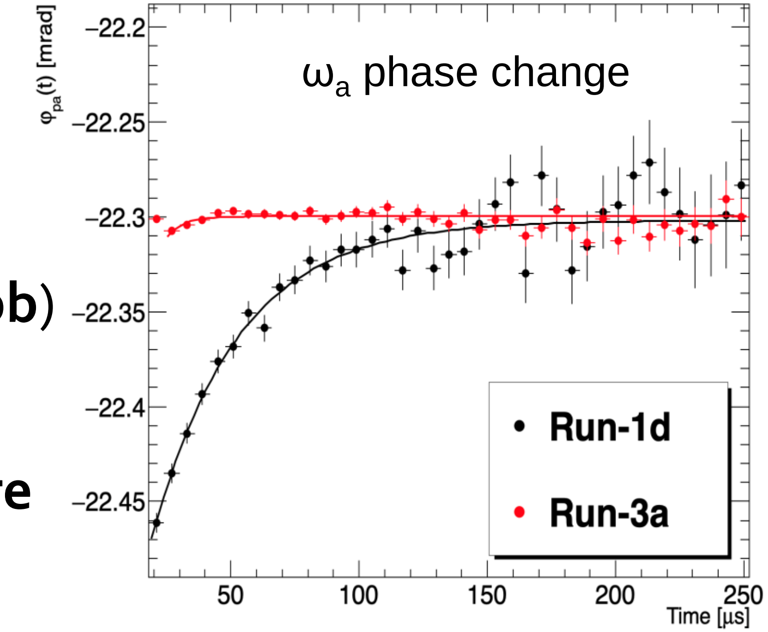
C_{pa}

- Run-1 had **damaged resistors** in 2/32 quad plates leading to **unstable beam storage**
- Resistors **replaced before Run-2**



- C_{pa} uncertainty is reduced (**75 ppb → 13 ppb**) thanks to a more stable beam
- Beam **oscillation frequencies** are also **more stable**

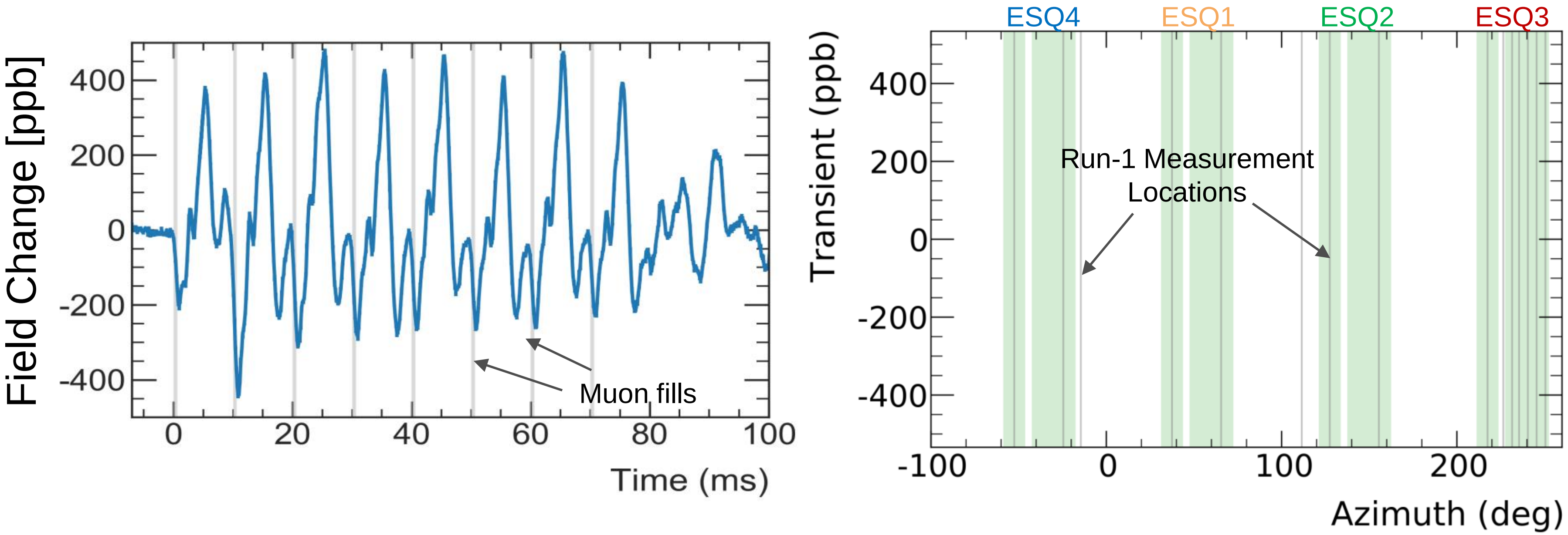




Improvements

B_q

- Pulsing **quads vibrate ⇒ oscillating magnetic fields**
- Measured with a **new NMR probe** housed in insulator



- For Run-1 analysis, we had **limited measurement positions**
- Largest Run-1 systematic: **92 ppb**
- For Run-2/3 the field was fully mapped and uncertainty is reduced to **20 ppb**

Other Improvements

- **Running conditions:**
  - Improved cooling of the hall and added insulation of the magnet which made the magnetic field more stable
  - Improved kicker strength which made the orbit more centered and reduced the E-field correction
- **Improved measurements:**
  - Reduced vibration noise for kicker transient field measurement
- **Analysis improvements:**
  - Improved treatment of the pileup for ω_a analysis
  - Improved analysis of E-field correction including correlations between momentum & time of injection.

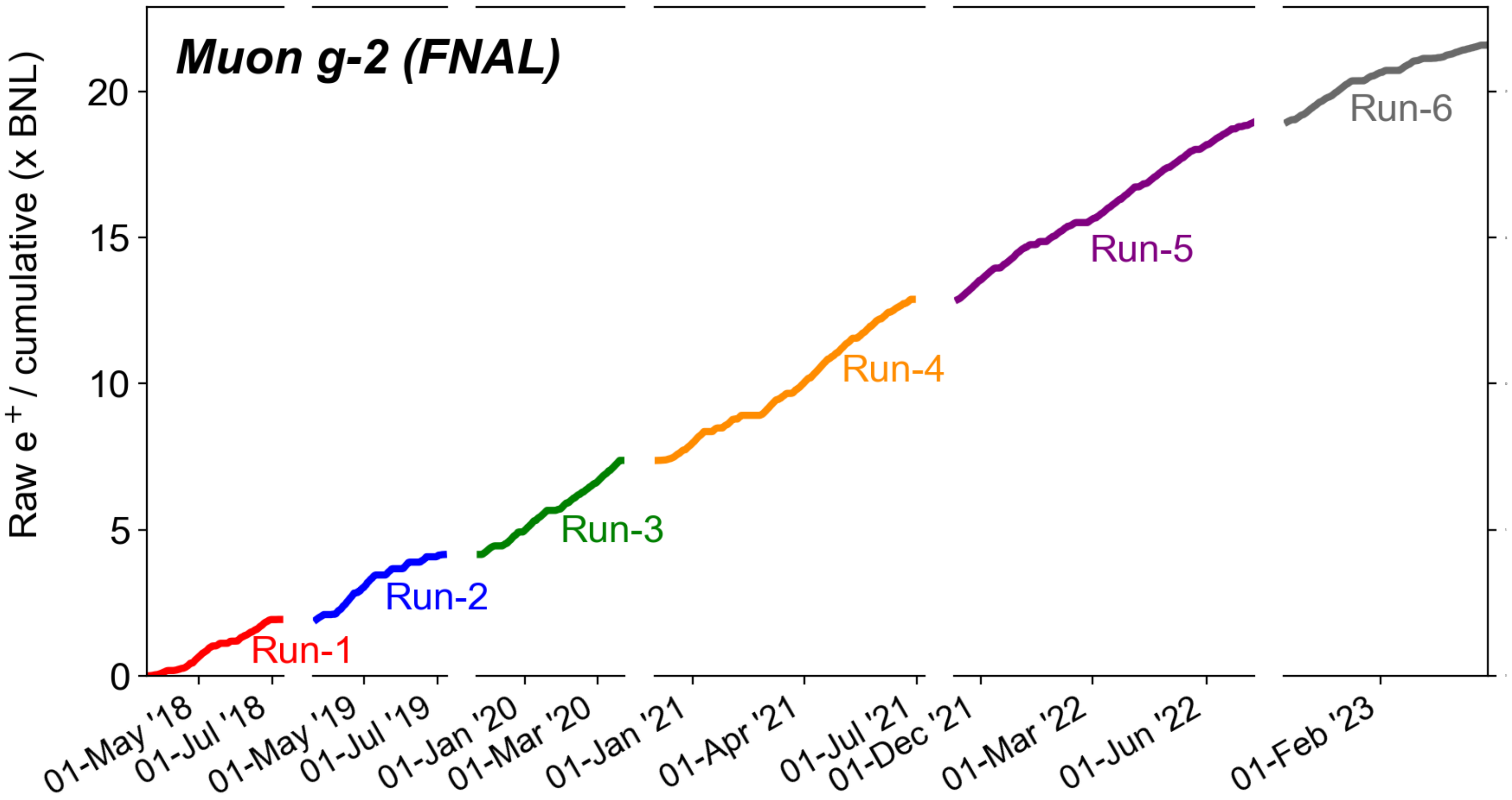
Final error table

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}}\langle\omega'_p(\vec{r}) \times M(\vec{r})\rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7°)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

The Run-2/3 result is statistically dominated

70 ppb systematic uncertainty surpasses the proposal goal of 100 ppb!

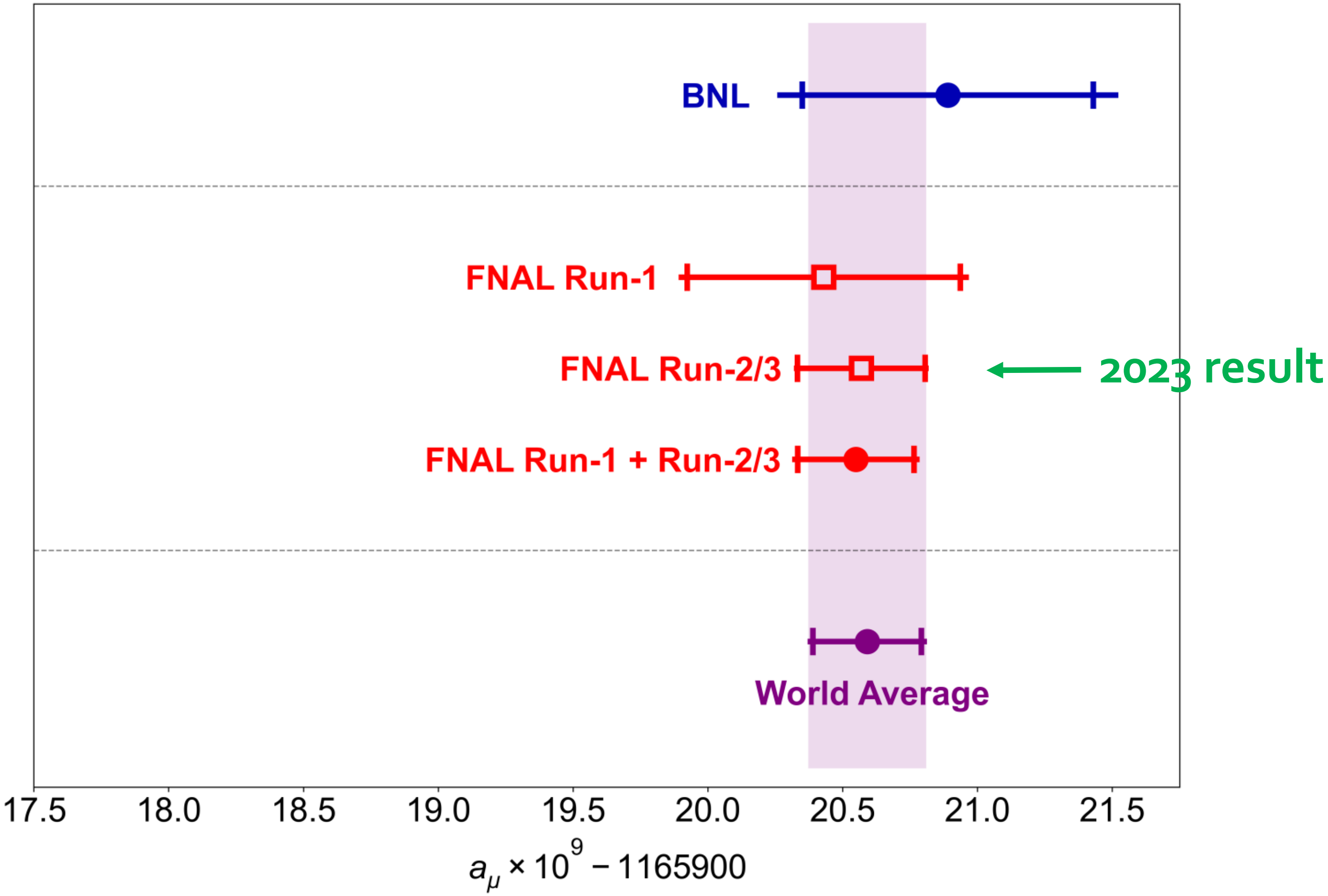
Total collected statistics



21.9 BNL datasets have been collected in FNAL (proposal – 21 BNL)

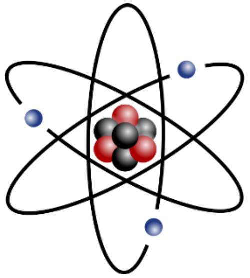
Run 4/5/6 statistics is x3 Run-1/2/3

Muon G-2 2023 result

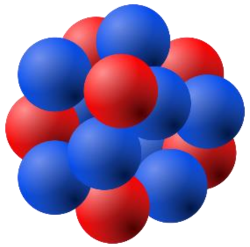


What about theory?

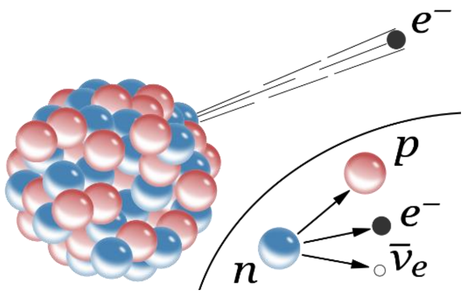
SM prediction for a_μ



Electromagnetic interactions



Strong interactions



Weak interactions

$0.001\ 165\ 847\ 19\ (0.1)$

$0.000\ 000\ 069\ 37\ (43)$

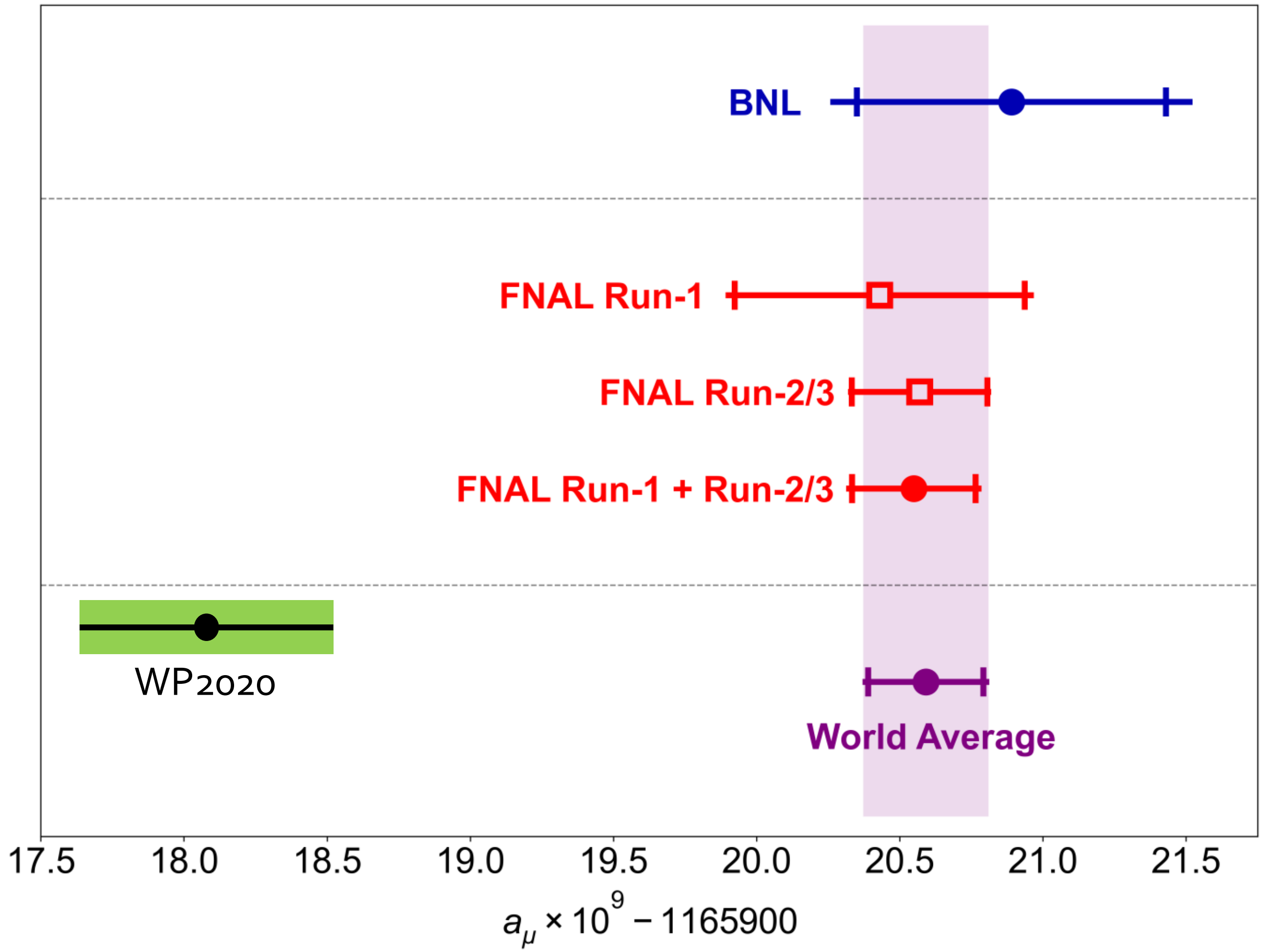
$0.000\ 000\ 001\ 54\ (1)$

$$a_\mu = 0.001\ 165\ 918\ 10\ (43)$$

The uncertainty is dominated by contribution of strong interactions

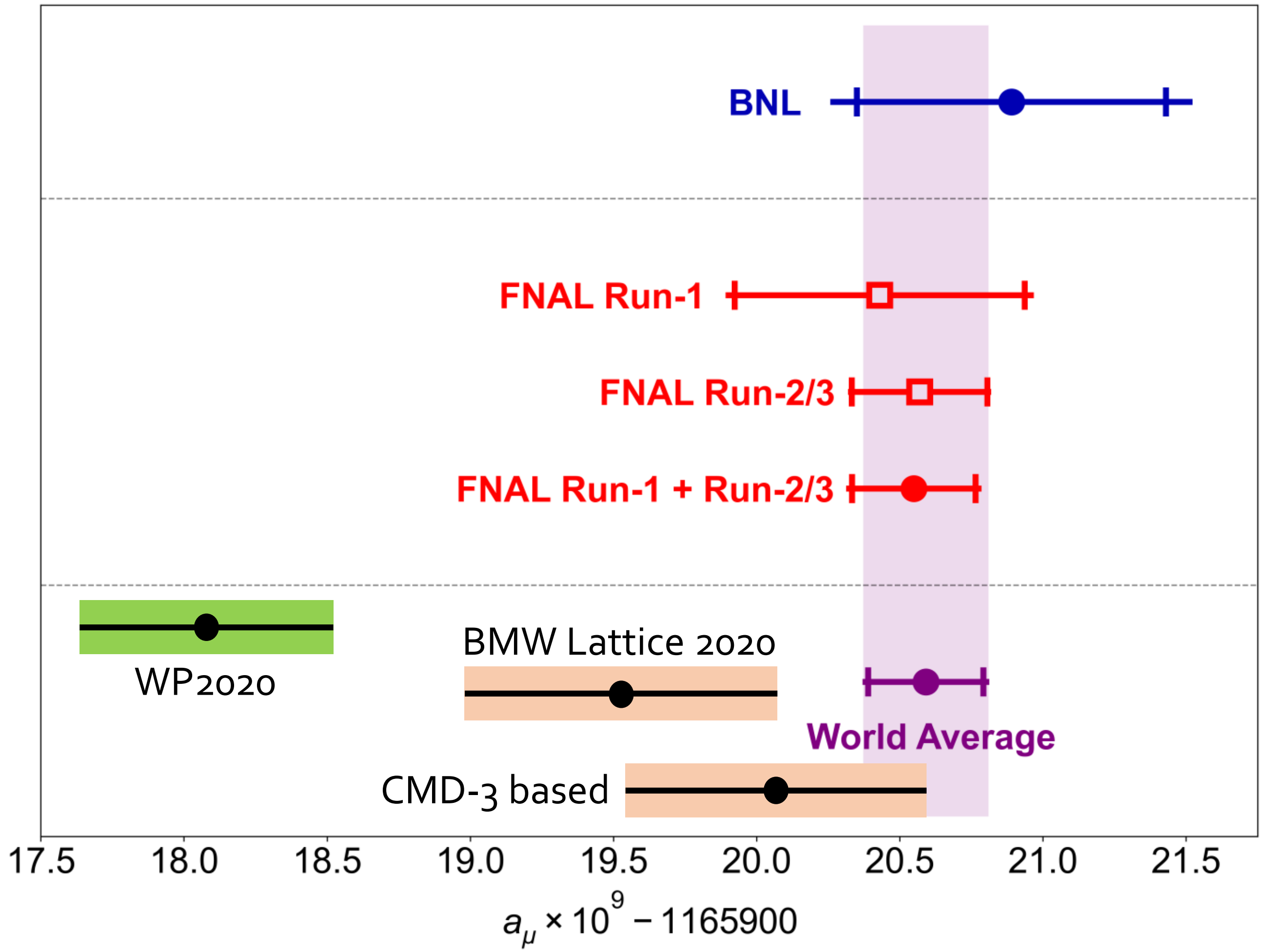
Dispersive approach: $a_\mu(Had; LO) = \int \sigma_{e^+e^- \to hadrons}(s)\ K(s)\ ds$

Experiment vs SM prediction



At the moment, the SM prediction for a_μ is unclear (due to hadronic contribution)
CMD-3 measurement will be discussed in the next talk by G.Fedotovich

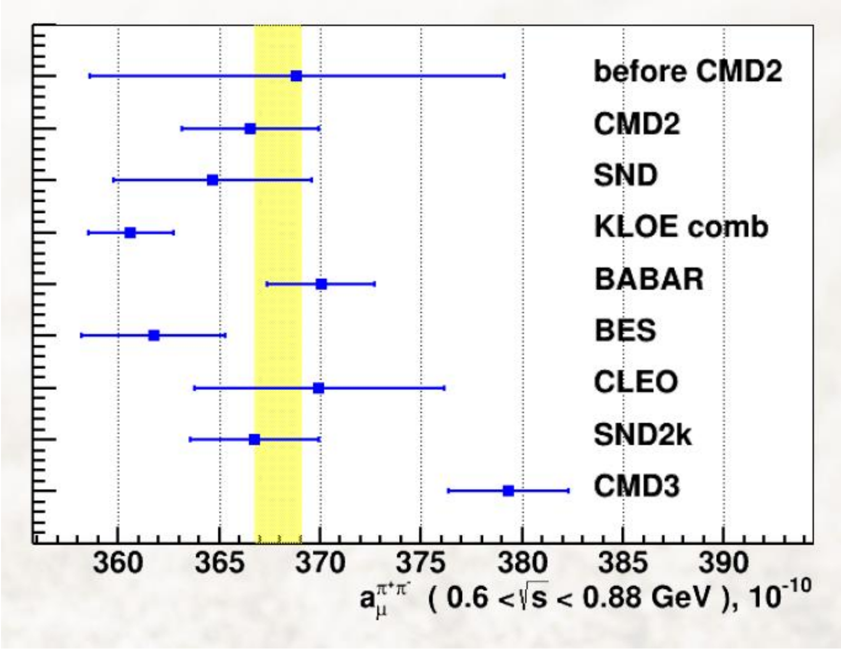
Experiment vs SM prediction



At the moment, the SM prediction for a_μ is unclear (due to hadronic contribution)
CMD-3 measurement will be discussed in the next talk by G.Fedotovich

Prospects for SM prediction

1. There are a lot of efforts to understand discrepancies in existing data
2. There will be additional high-statistics results on hadron cross sections from VEPP-2000 experiments (CMD-3, SND)
3. There will be new results from B-factories on hadron cross section (BaBar, Belle-II)
4. There is dedicated experiment, Muone, being prepared at CERN to measure hadronic contribution via $e\mu$ scattering
5. There is fast progress in lattice calculations



Hadronic contribution from 2π based on data from various experiments

There are discrepancies between hadron data from various experiments well beyond estimated systematic errors

There are good chances to improve precision of SM prediction in coming years

Conclusion

- We've determined a_μ to an unprecedented **203 ppb** precision
- New result is in **excellent agreement** with **Run-1 & BNL**
- Systematic uncertainty of **70 ppb** surpassed the design goal
- The data taking is finished; about **3 times more data** are to be analyzed
- The status of SM prediction is unclear; with amount of world-wide dedicated efforts, expect improvement in theory in coming years