

MUON ANOMALOUS MAGNETIC MOMENT. MEASUREMENT

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BINP

Moscow International
School of Physics 2022

Поиски Новой физики

Сверхвысокие энергии

Большой адронный коллайдер
Технологический предел (сегодня
~10 ТэВ, в будущем – 100 ТэВ)



Прецизионные измерения Интенсивные пучки

Flavor physics: Новая физика проявляется в тонких эффектах при изучении свойств тяжелых известных частиц: c, b, t кварки, μ, τ лептоны, W, Z, H бозоны

Измерение
аномального
магнитного момента
мюона ($g - 2)_\mu$

Магнитный момент в классической электродинамике

Магнитный момент тесно связан с угловым моментом системы

$$\mu = IS = \frac{qv}{2\pi r} \cdot \pi r^2 = \frac{1}{2} qvr$$

$$L = mvr$$

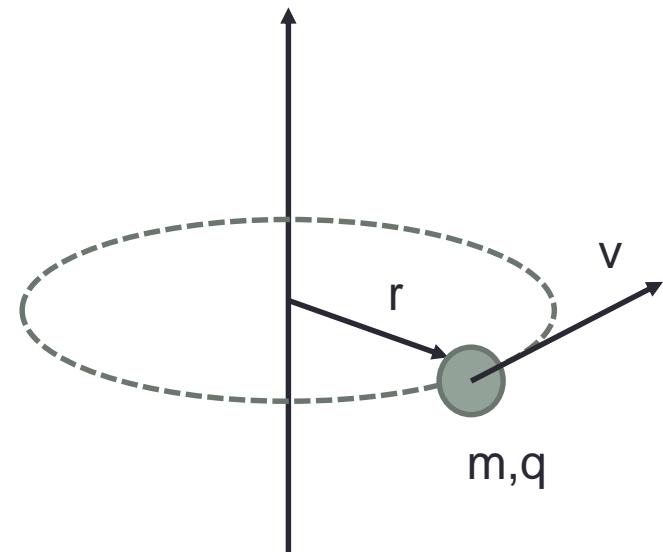
$$\vec{\mu} = \frac{q}{2m} \vec{L}$$

В квантовой механике у частицы есть спин, внутренний угловой момент.

Для частицы со спином 1/2:

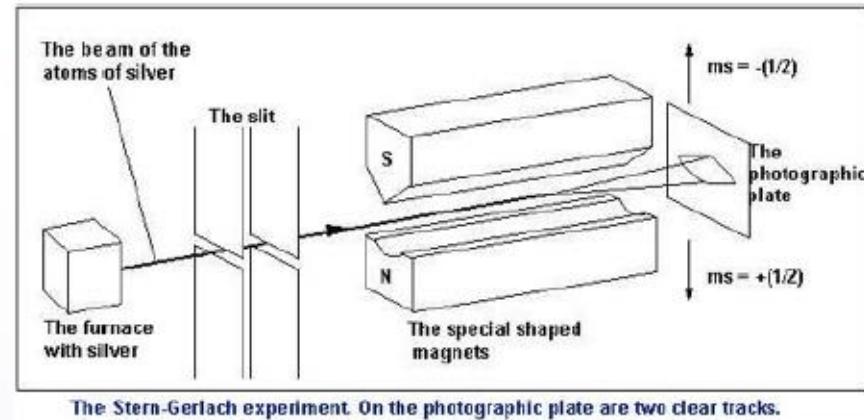
$$s = \hbar/2$$

Соответствующий магнитный момент: $\vec{\mu} = \frac{e}{2m} \vec{s}$ неправильно!



Опыт Штерна-Герлаха

- Beam of silver atoms passes through inhomogeneous magnetic field
- Result was atoms deflected either up or down
 - Later understood to be due to 2 spin states of the valence electron
- But, the magnitude of magnetic moment was wrong!



The Stern-Gerlach experiment. On the photographic plate are two clear tracks.

Gerlach and Stern,
Z. Phys. 8, 110 (1922)

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

Магнитный момент отличается от классического в g раз

Гиromагнитное отношение

Gyromagnetic factor

- The magnetic moment of the particle relates to its spin angular momentum via the **gyromagnetic factor, g**:

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

- In Dirac theory, point-like, spin $\frac{1}{2}$ particle has $g = 2$ exactly
- Experimental values: $g_e \approx 2.002$

PHYSICAL REVIEW

VOLUME 74, NUMBER 3

AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY

Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

$$g_s \approx 2(1.00119 \pm 0.00005)$$

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and 2P_1 states, In in the 2P_1 state, and Na in the 2S_1 state has been made by a measurement of the frequencies of lines in the hfs spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

Поправка Швингера

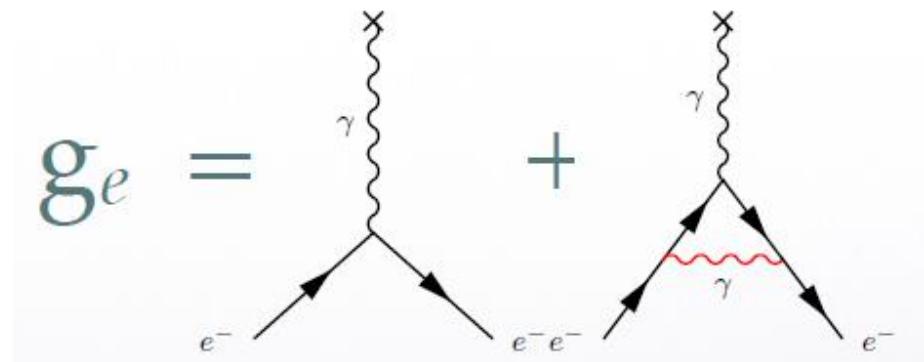
Первый триумф КЭД:

Дж.Швингер (1948), Р.Фейнман (1949)

$$\frac{g_e - 2}{2} \approx \frac{\alpha}{2\pi}, \quad \alpha = \frac{e^2}{\hbar c} \approx 1/137$$



- Швингер вычислил однопетлевую поправку к g и показал, что g немного больше 2
- На сегодняшний день такой расчет сделан до 5 петель!



Schwinger,
Phys. Rev. **73**, 416 (1948)

Anomalous magnetic moment

- The magnetic moment of the particle relates to its spin angular momentum via the **gyromagnetic factor**, g :

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

- In Dirac theory, point-like, spin $\frac{1}{2}$ particle has $g = 2$ exactly
- Experimental values:

$$\left. \begin{array}{l} g_e \approx 2.002 \\ g_\mu \approx 2.002 \\ g_p \approx 5.586 \\ g_n \approx -3.826 \end{array} \right\} \begin{array}{l} \text{point-like} \\ \text{particles} \end{array}$$
$$\left. \begin{array}{l} \\ \\ \\ \end{array} \right\} \begin{array}{l} \text{compound} \\ \text{particles} \end{array}$$

Аномальный магнитный момент: $a = (g - 2)/2$

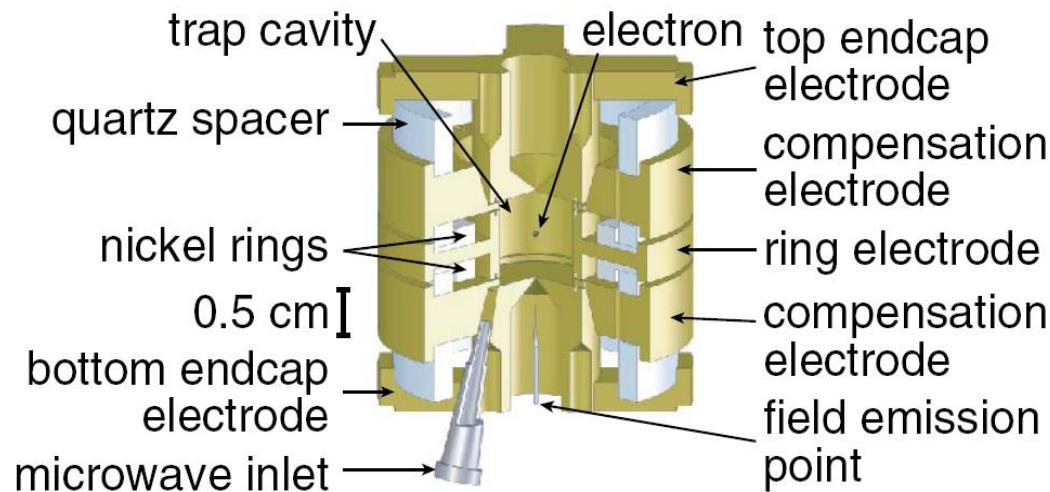
$$a \approx 10^{-3}$$

(g-2) электрона

The best precision is achieved for electrons (g-2). The value of a_e is used to get the best determination of fine-structure constant α .

D. Hanneke, S. Fogwell, G. Gabrielse, Phys.Rev.Lett. 100:120801, 2008

$$a_e = (115\,965\,218\,073 \pm 28) \times 10^{-14} \text{ (0.24 ppb)}$$



От электрона к мюону

Довольно быстро (1953,...) g-2 электрона был измерен с хорошей точностью.

Почему бы не измерить его для тяжелого близнеца электрона – мюона?

Берестецкий и др. (1956): из-за того, что мюон тяжелый, он более чувствителен к взаимодействиям высоких энергий

$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 43000$$

Concerning the Radiative Correction to the μ -Meson Magnetic Moment

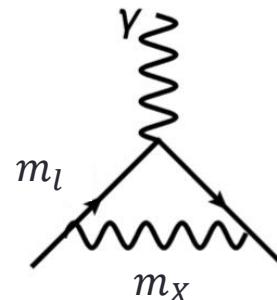
V. B. BERESTETSKII, O. N. KROKHIN

AND

A. K. KHLEBNIKOV

(Submitted to JETP editor January 7, 1956)

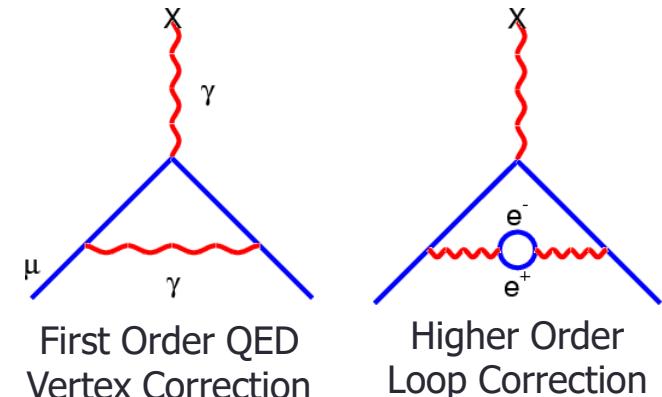
J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 788-789
(April, 1956)



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

(g-2) мюона как инструмент поиска новых взаимодействий

Все существующие в природе взаимодействия вносят вклад в аномальный магнитный момент мюона – включая те, про которые мы ничего не знаем.



Идея эксперимента: если измеренная величина a отличается от расчетной, значит в вакууме существуют какие то поля или взаимодействия, которые не учитываются современной теорией

(g-2) мюона в **40,000** раз более чувствителен к взаимодействиям за рамками Стандартной модели, чем (g-2) электрона

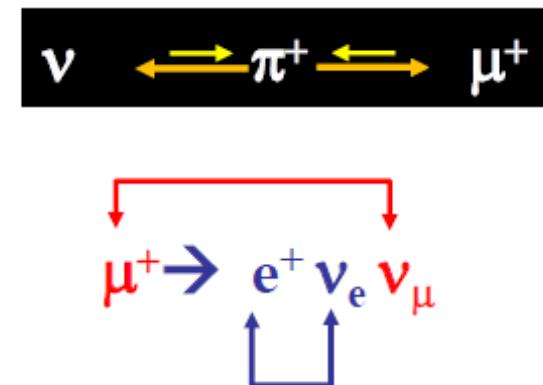
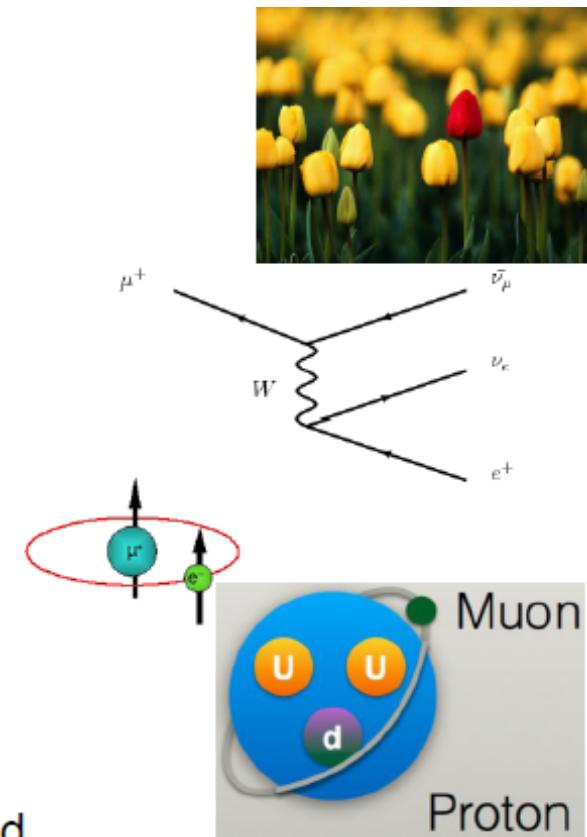
$$a_\mu = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak} + a_\mu^{New Physics}$$

$$1,000,000 : 60 : 1.3 : \propto (m_\mu/m_X)^2$$

Было бы еще интереснее использовать тау-лептоны, но их очень сложно производить и они слишком быстро распадаются...

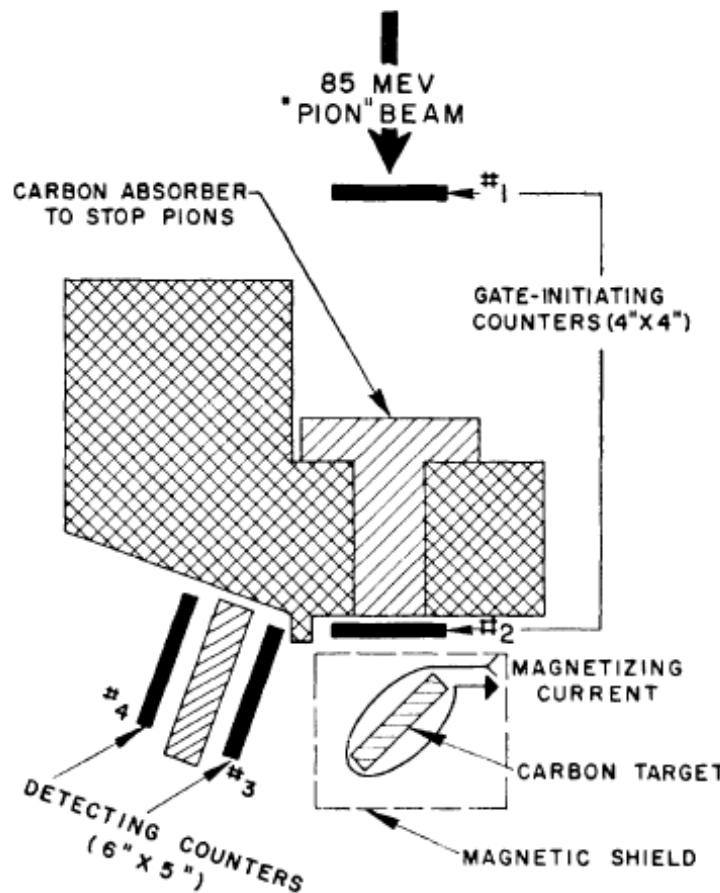
Мюон – уникальный лабораторный объект

- $m_\mu \approx 207 \times m_e$
- $(m_\mu/m_e)^2 \approx 44,000 \rightarrow$ a typical new-physics sensitivity factor
- Interacts through its electric charge and magnetic moment, and its weak charged and neutral currents (but not the strong force)
- A μ^+ can form a hydrogen-like μ^+e^- (QED) atom
- A μ^- can form a hydrogen-like μ^-A atom
- Its $\sim 2.2 \mu\text{s}$ **lifetime** is *long enough* to form beams and long(ish) lived atoms, yet *short enough* for precision decay measurements
- **PV** in the weak interaction implies it is born polarized and its decay is self analyzing
- Its “muon-ness” is conserved to a very high (perfect?) degree

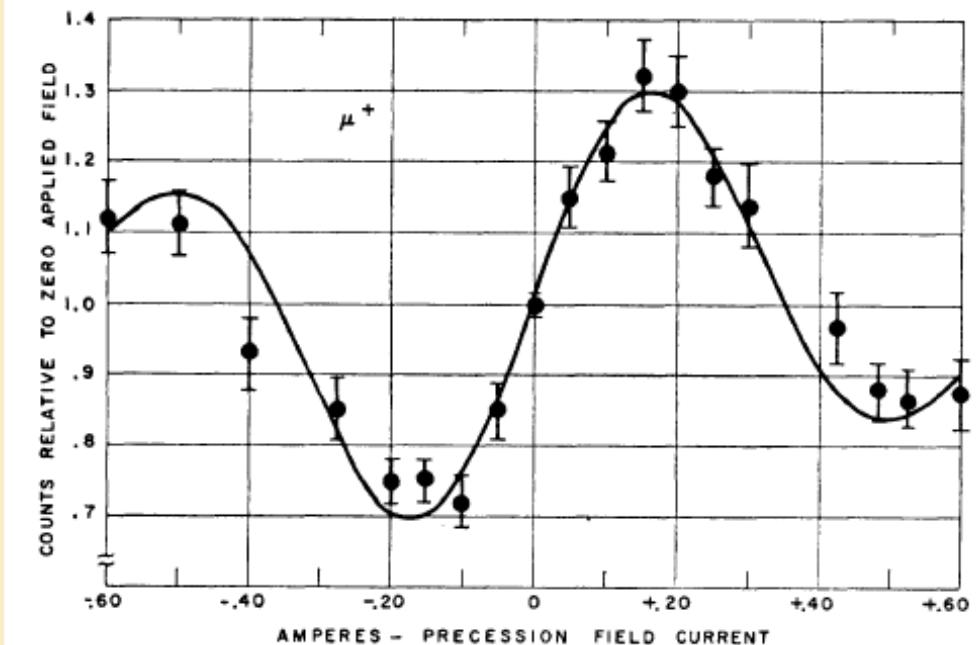


Первое измерение g_μ

1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)



Direct measurement of $g - \text{asym}$ vs field



$$g_\mu = 2.00 \pm 0.10$$

5% uncertainty

muons behave
like electrons

От покоящихся мюонов к движущимся

- Store polarized muons in the uniform magnetic field B
- Momentum rotates with cyclotron frequency:

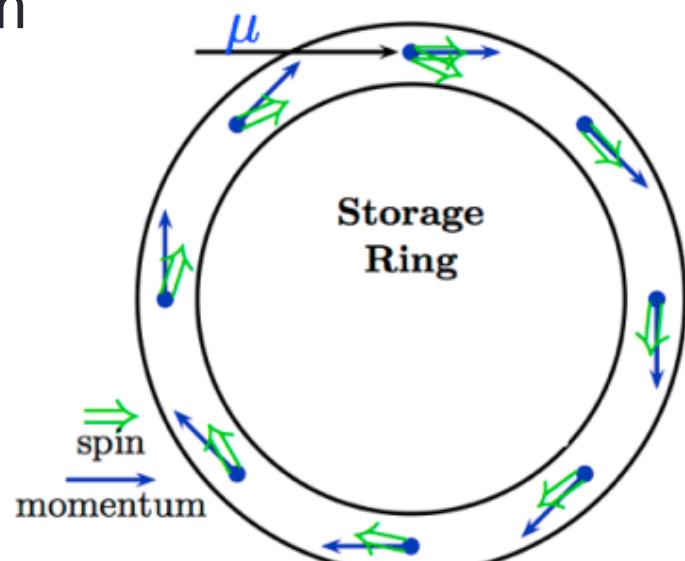
$$\omega_c = eB/\gamma mc$$

- Spin rotates with Larmor+Thomas frequency:

$$\omega_s = geB/2mc + (1 - \gamma)eB/\gamma mc$$

- Spin precesses relative to momentum with frequency ω_a :

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



$$\omega_a \quad \left. \begin{matrix} \\ B \end{matrix} \right\} \rightarrow a_\mu$$

Использование движущихся мюонов позволяет измерять прямо a_μ !

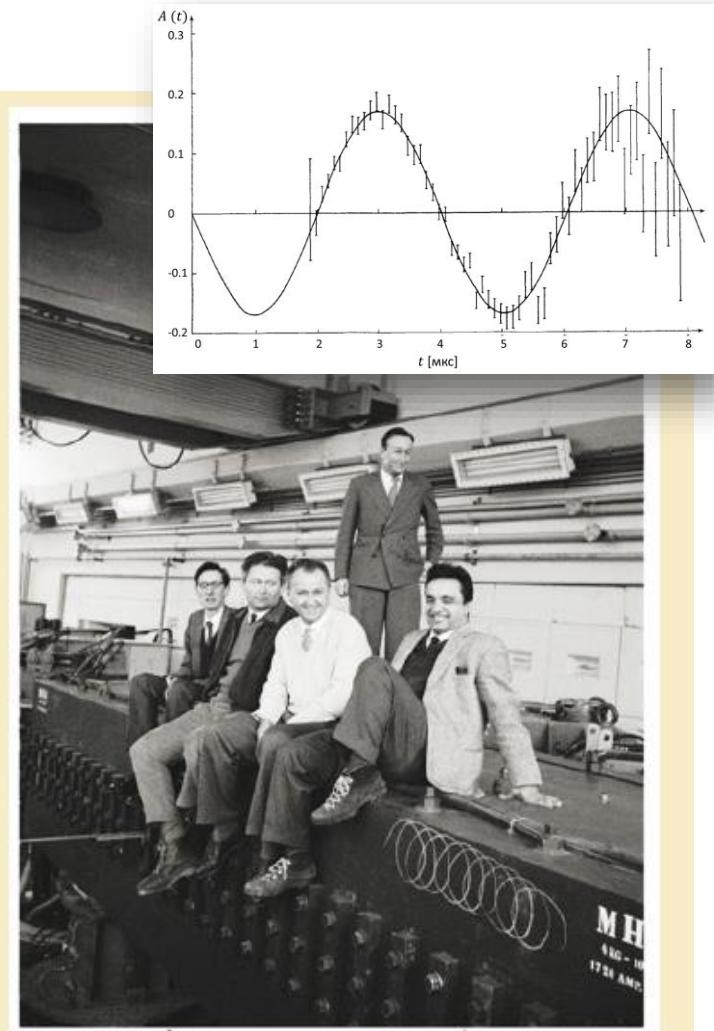
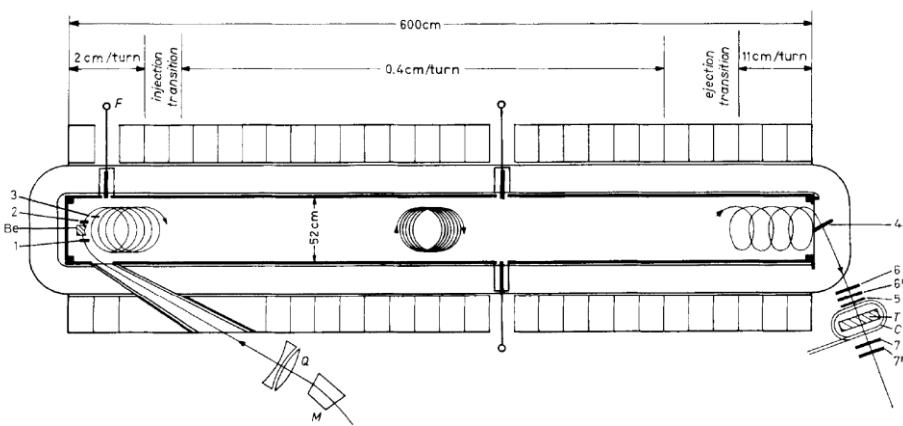
CERN-1 (1958-1962)

**Such experiments continued at Nevis
and CERN until 1965**

Best measurement CERN I (1965)

$$a_\mu = 0.001\ 162(5) \ (\pm 4300 \text{ ppm})$$

**Just like the electron!
Sensitive to 2nd order QED**



The first CERN g-2 team: Sens, Charpak, Muller,
Farley, Zichichi (CERN/1959)

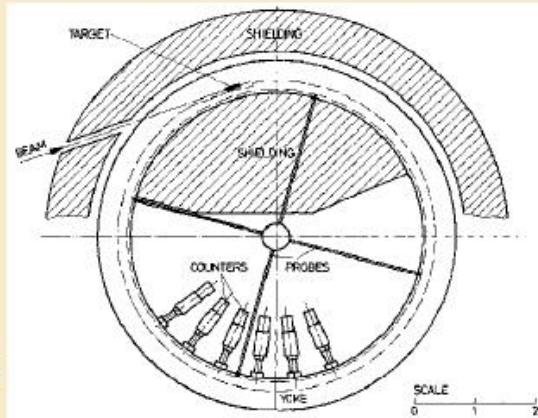
CERN-II (1962-1968)



$$p_\pi = 1.27 \text{ GeV}/c$$

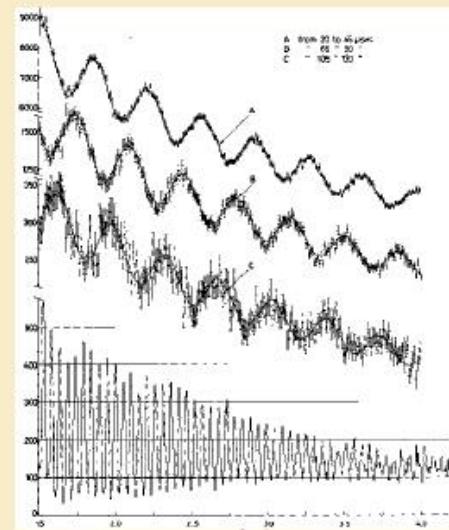
$$B = 1.7 \text{ T}$$

**Electrons go
inward to detectors**



$$a_\mu = 0.001\ 166\ 16(31), \pm 270 \text{ ppm}$$

Sensitive to 3rd order QED and light-by-light scattering



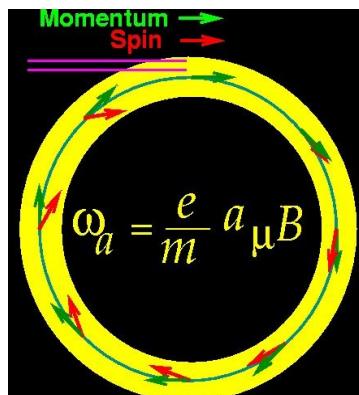
130 μ s of wiggles

Magic γ (CERN-III)

Anomalous magnetic moment is independent of γ . The larger γ , the longer muon lifetime, the more g-2 circles observed – **good!** But there is a problem: particles are not stored in the uniform magnetic field.

Solution: introduce gradient with electric field to build a trap.

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



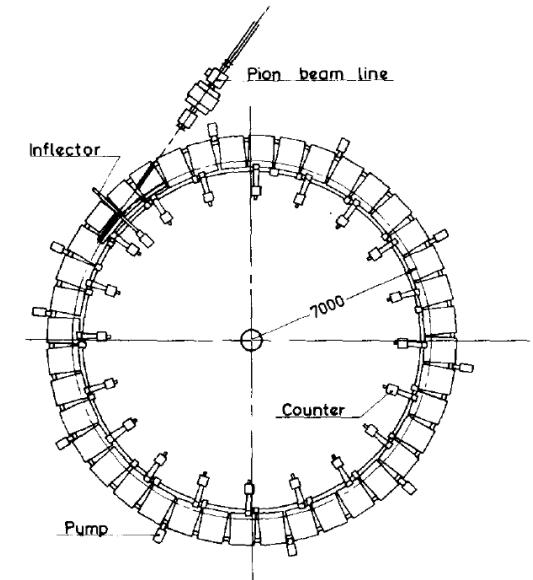
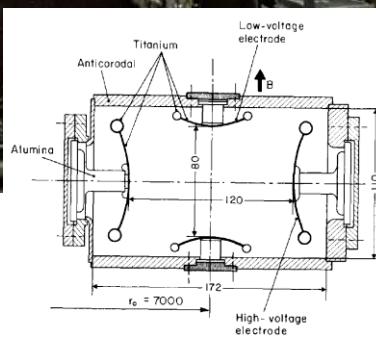
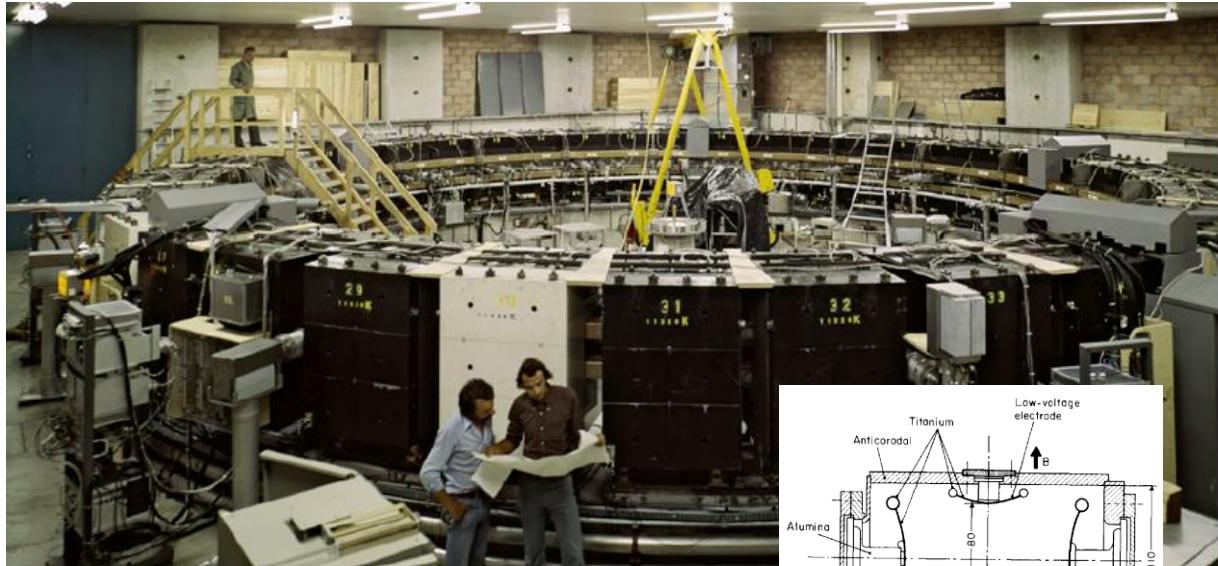
$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09 \text{ GeV/c}$$

Contribution from potential EDM

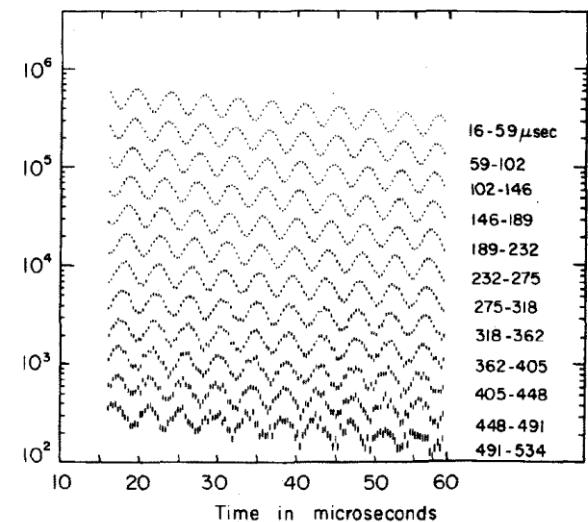
Magic γ completely determines the size of the CERN-type experiment.

CERN-III (1969-1976)

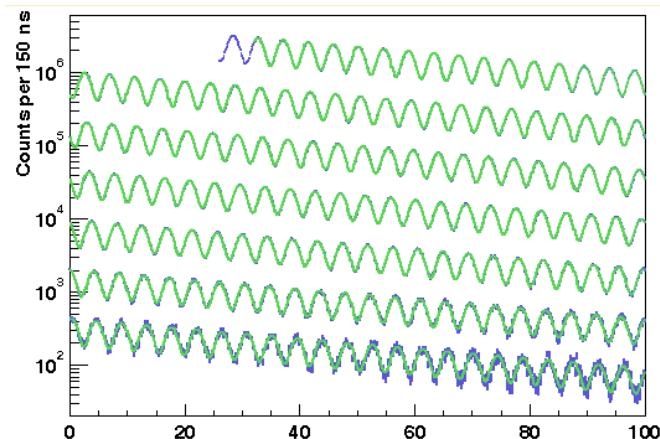
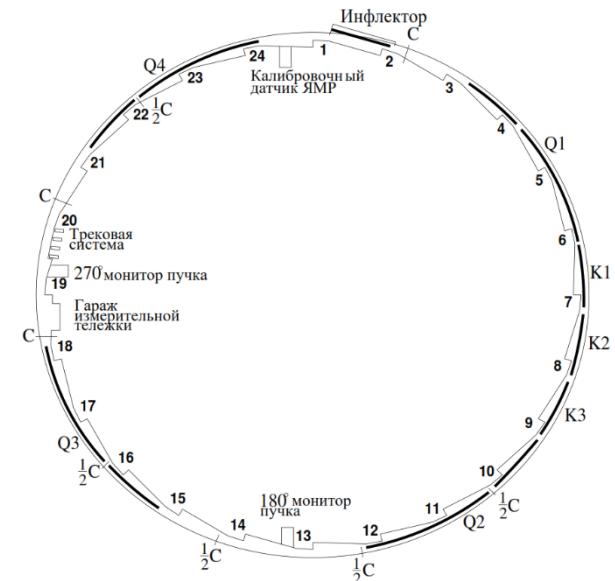


$$a_\mu = 0.001\,165\,924(8.5), \pm 7 \text{ ppm}$$

Sensitive to hadronic contribution



BNL (1997-2001)



$$a_\mu = 0.001\ 165\ 920\ 89(54)_{stat}(33)_{sys}, \pm 0.54 \text{ ppm}$$

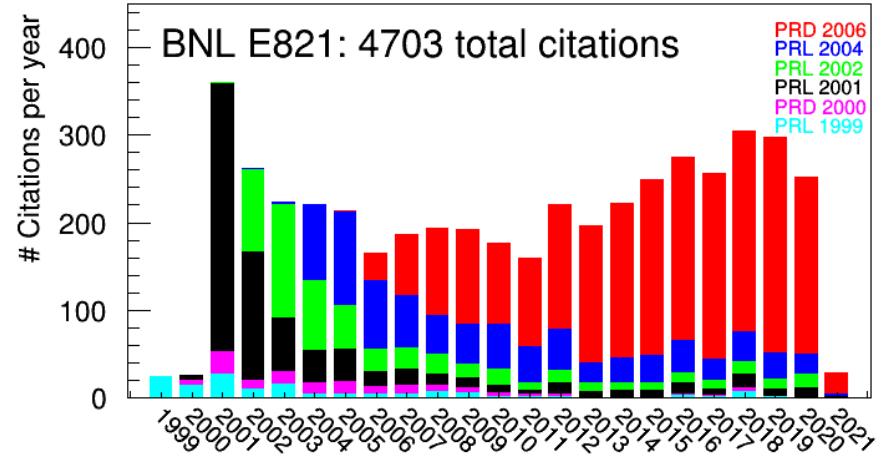
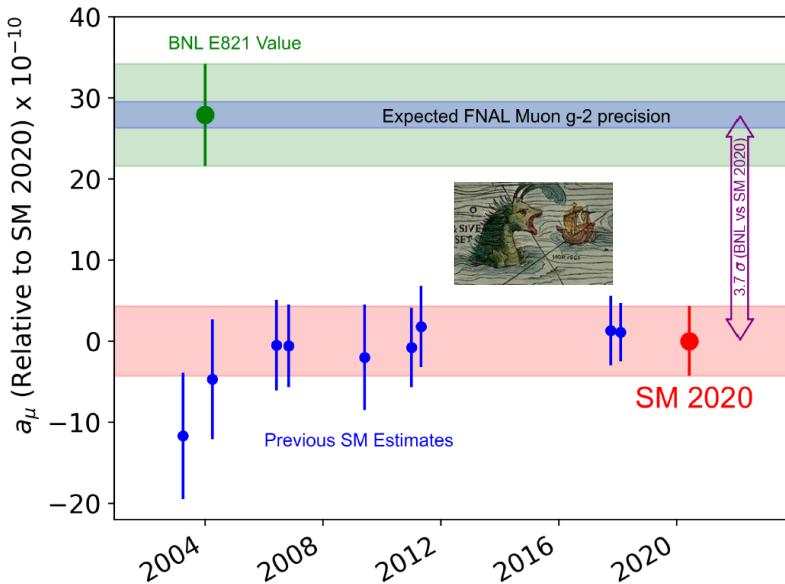
Sensitive to all SM fields

$$a_\mu = 116\ 592\ 089(54)_{stat}(33)_{sys} \times 10^{-11} \quad 1 \text{ ppm} \equiv 117 \times 10^{-11}$$

После измерения в БНЛ

- a_μ last measured 20 years ago at Brookhaven National Lab (BNL) where an interesting 2.7σ hint of new physics was discovered
 - Has grown to 3.7σ with improvements in theory

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



- The difference has intrigued physicists for years
 - Difference is $\sim 27 \times 10^{-10}$ in a_μ

Постановка эксперимента

$$a_\mu = \frac{g - 2}{2} \propto \frac{\omega_a}{B}$$

измеряем

Поляризованный
пучок мюонов



Прецессия в
однородном
магнитном поле



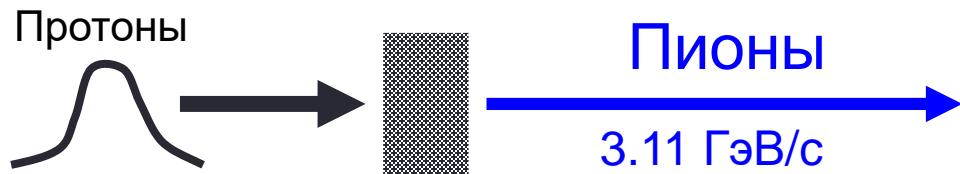
Измерение
направления спина
в момент распада

Поляризованные мюоны рождаются при
распаде пиона $\pi \rightarrow \mu + \nu_\mu$

Мюоны захватываются в накопительное кольцо
с очень однородным магнитным полем.

Направление спина измеряется в момент
распада мюона $\mu \rightarrow e + \nu_e + \bar{\nu}_\mu$
по анизотропии рожденных электронов

Muon g-2: Генерация мюонов



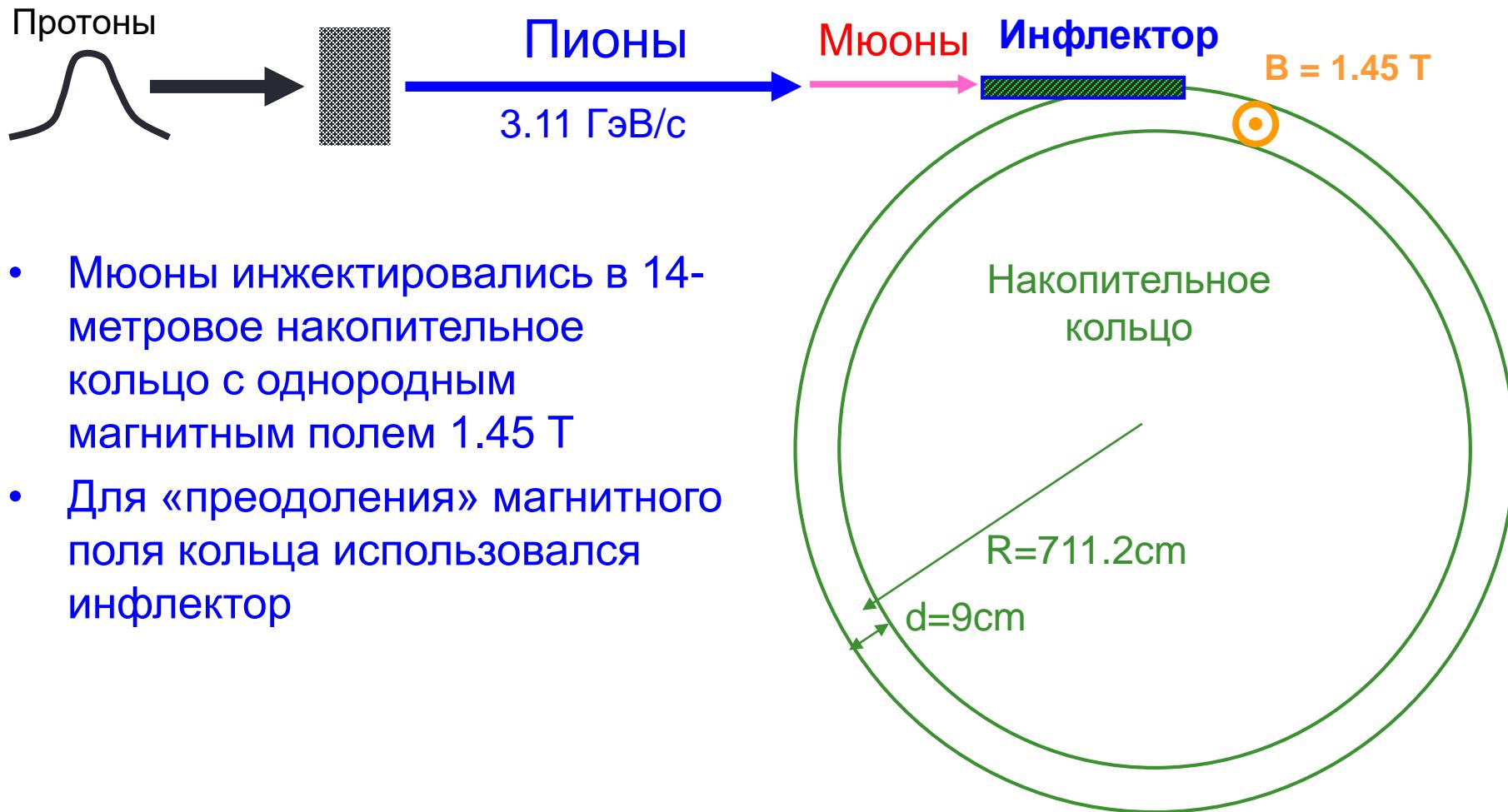
- Протоны направляются на мишень.
- Отбираются пионы с энергией около 3.11 ГэВ и направляются в длинный распадный канал

Muon g-2: Генерация мюонов

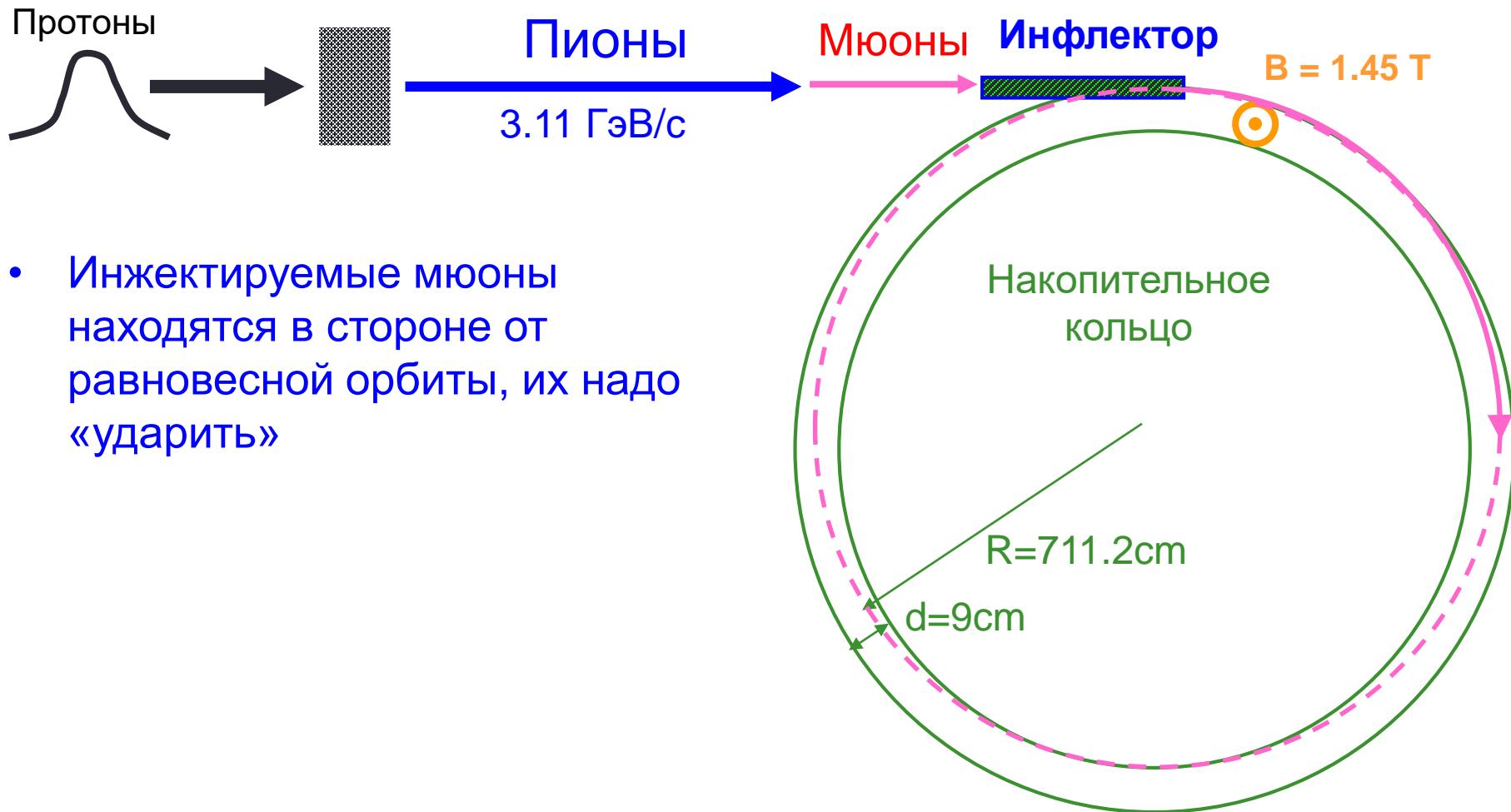


- Отбирая мюоны, вылетевшие при распаде пиона вперед, получается пучок с поляризацией 95%
- Отбирались мюоны с энергией около 3.09 ГэВ (“magic γ”)

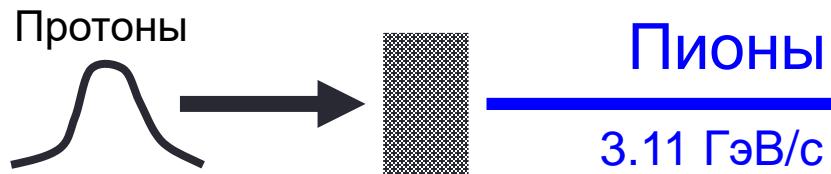
Muon g-2: Захват мюонов



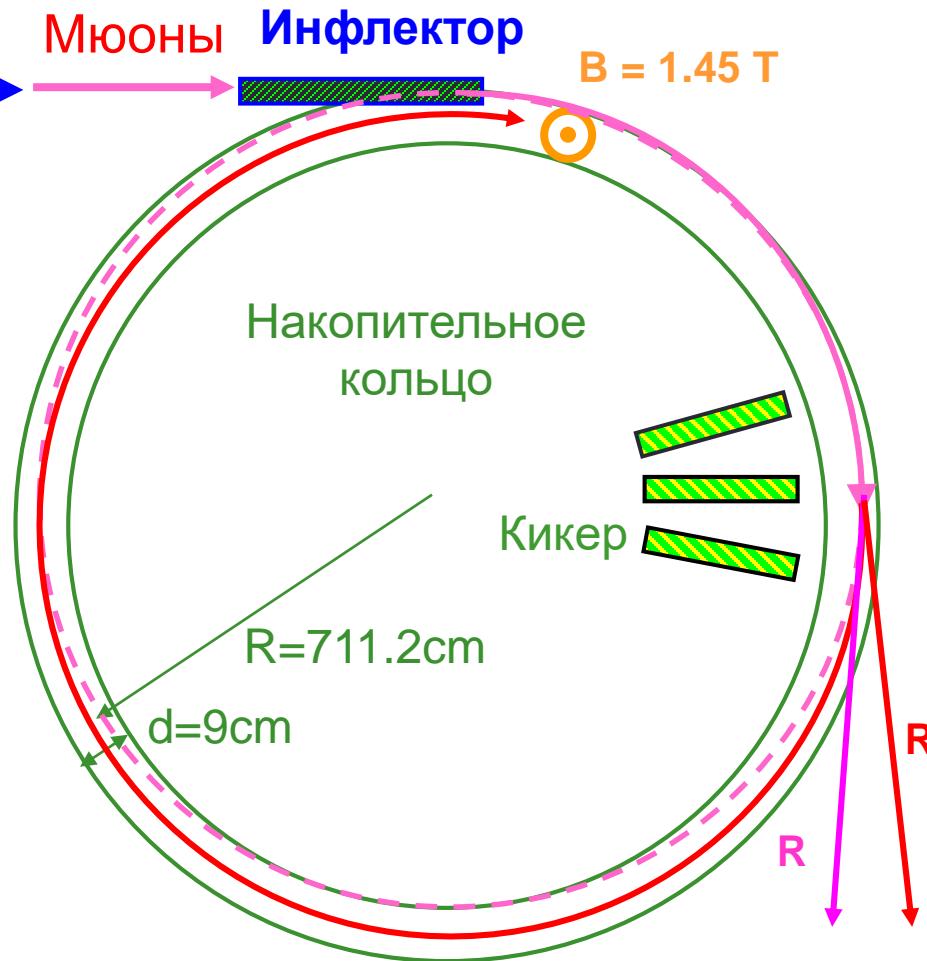
Muon g-2: Захват мюонов



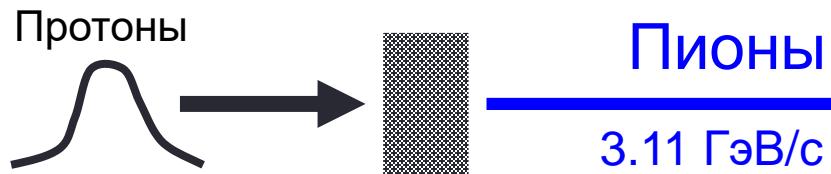
Muon g-2: Захват мюонов



- Инжектируемые мюоны находятся в стороне от равновесной орбиты, их надо «ударить»
- Для «удара» использовался импульсный магнит (кикер)



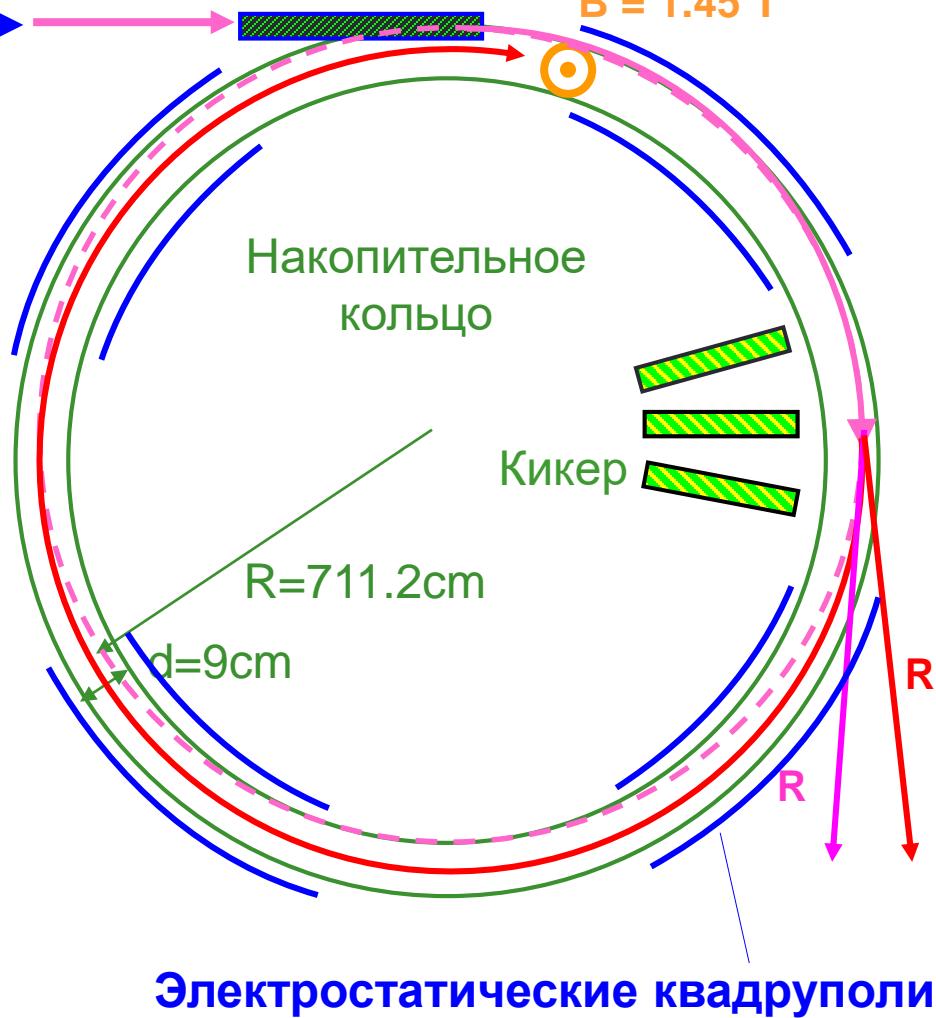
Muon g-2: Удержание мюонов



Мюоны **Инфлектор**

$B = 1.45 \text{ Т}$

- Для удержания мюонов на орбите использовалась вертикальная фокусировка с помощью электростатических квадрупольей
- Это не приводило к искажению частоты прецессии, т.к. использовались мюоны с “magic γ”



New measurement at FNAL

New CERN-type measurement E989 at Fermilab

Goal: 4x improvement over BNL

- 21x more statistics
- 2.8x reduction in systematics

BNL

$$\left. \begin{array}{l} \sigma_{stat} = \pm 0.46 \text{ ppm} \\ \sigma_{syst} = \pm 0.28 \text{ ppm} \end{array} \right\} \sigma = \pm 0.54 \text{ ppm}$$

Fermilab

$$\left. \begin{array}{l} \sigma_{stat} = \pm 0.10 \text{ ppm} \\ \sigma_{syst} = \pm 0.10 \text{ ppm} \end{array} \right\} \sigma = \pm 0.14 \text{ ppm}$$

How?

- Better muon beam
- More uniform storage ring, better field measurement
- Improvements in detection of decay electrons and data analysis

Muon g-2

>200 collaborators
35 Institutions
7 countries

Many experts
from BNL E821



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



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



Ways to improve precision

Conceptually, measurement at Fermilab is similar to measurement at Brookhaven,
but there improvements in every department

ω_p systematics (ppb)

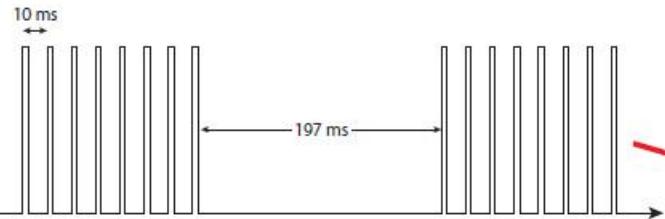
| Contribution | BNL | FNAL |
|----------------------|------------|-----------|
| Absolute calibration | 50 | 35 |
| Trolley measurements | 100 | 50 |
| Fixed probes | 70 | 30 |
| Muon distribution | 30 | 10 |
| Total | 170 | 70 |

ω_a systematics (ppb)

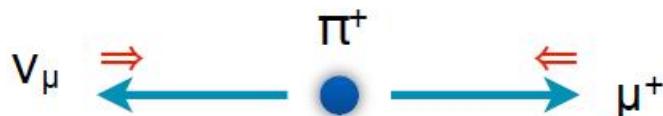
| Contribution | BNL | FNAL |
|--------------|------------|-----------|
| Gain changes | 120 | 20 |
| Pileup | 80 | 40 |
| Lost muons | 90 | 20 |
| CBO | 70 | 30 |
| E and pitch | 50 | 30 |
| Total | 180 | 70 |

Goal: $\Delta a_\mu = 0.14 \text{ ppm}$ (0.1 ppm statistics and 0.1 ppm systematics)

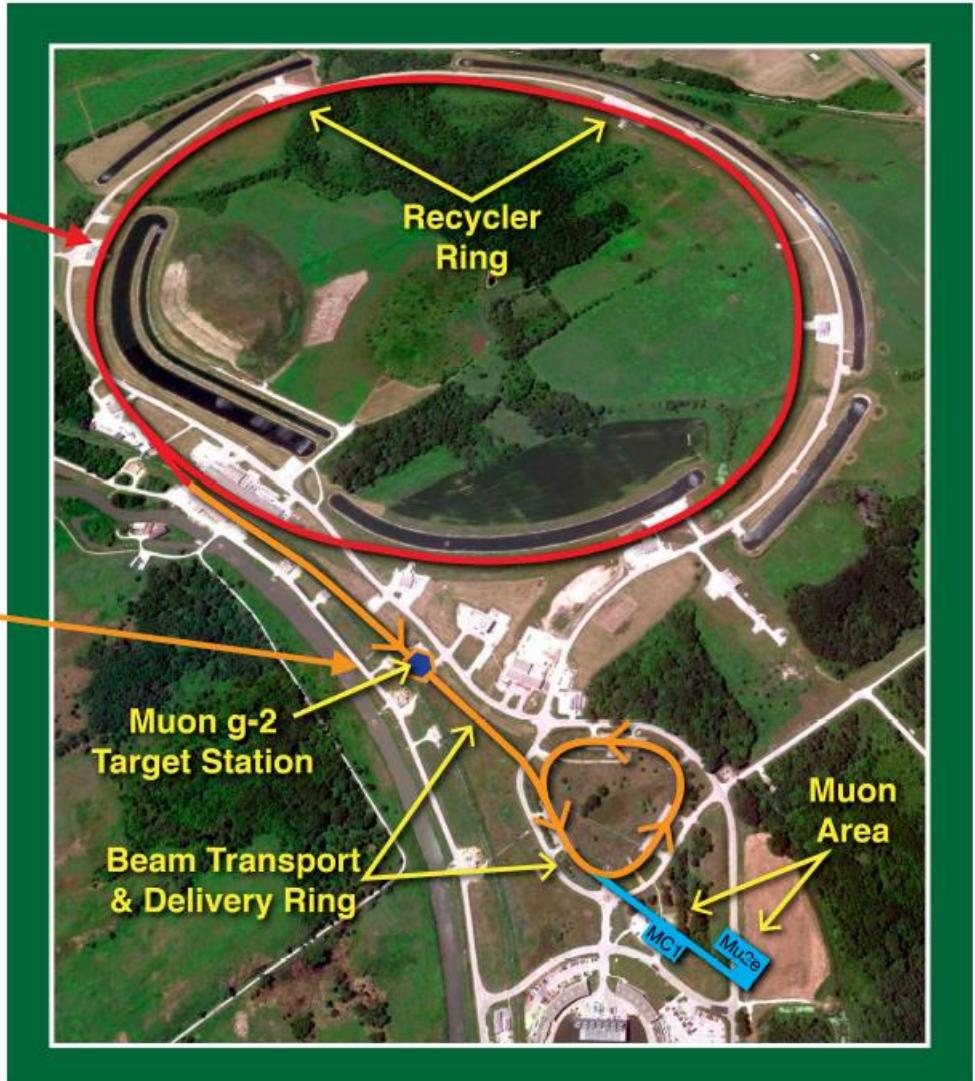
Генерация мюонов



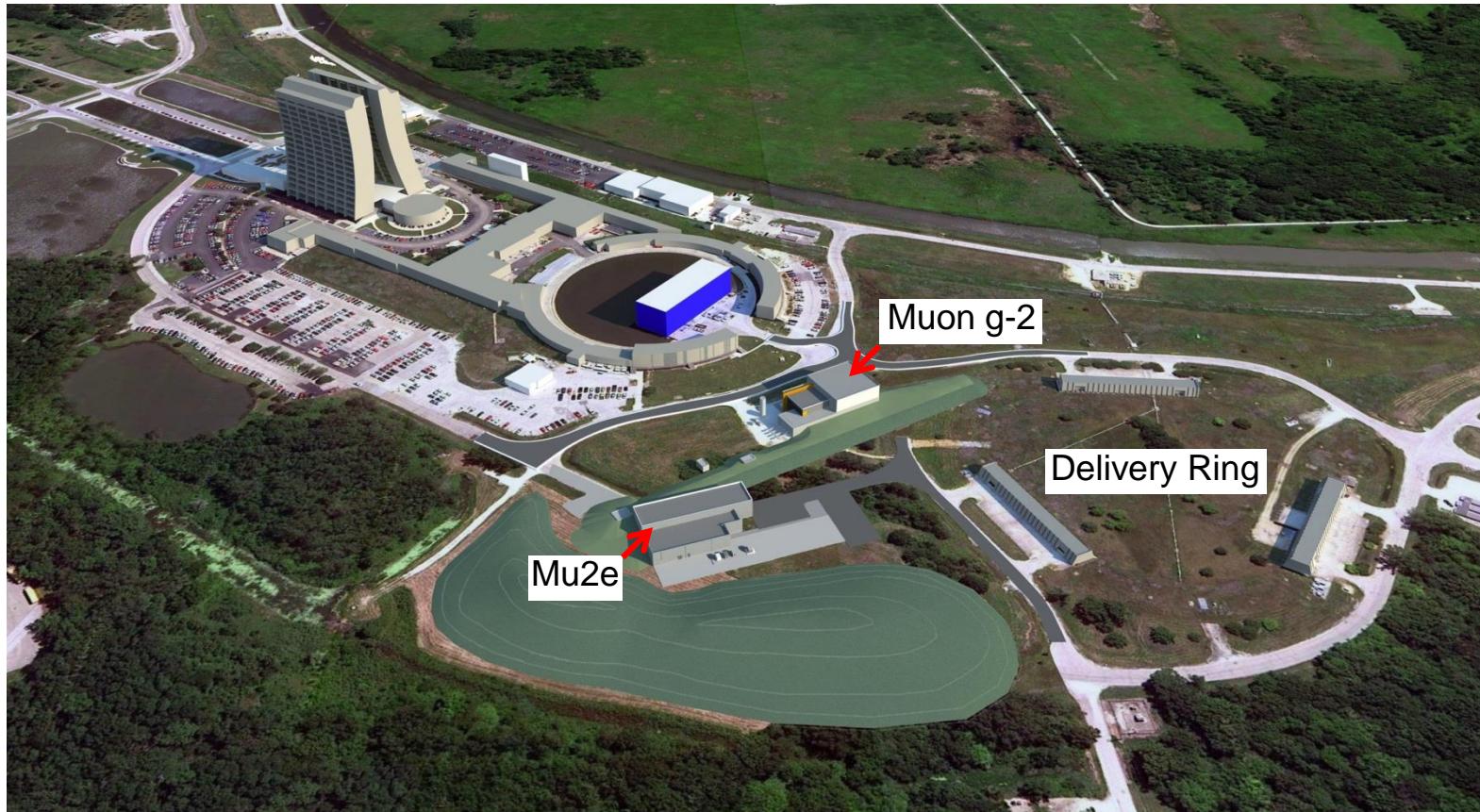
4 Booster batchs → 16 muon fills
• 1.4 sec repetition rate



Select ~3.1 GeV π^+ (magic p)
• Parity violation → 95% polarized muons



Muon Campus ($g-2 + \text{Mu}2e$): the plan



Muon Campus: today

G-2



Mu2e

G-2



Moving the ring to Fermilab

In order to save \$, the most expensive piece from the BNL experiment – the storage ring itself, is reused. The steel, pole pieces etc. are disassembled and moved by trucks. But there are three coils inside the cryostats... - 15 m diameter, they cannot be broken in pieces, flexed > 3 mm



Moved in 2013 by truck and the sea

5000 km journey



Arriving at Fermilab



RING

FIELD

PRECESSION

muons

Inflector

QUADS

S

L

24 Calorimeter stations located all around the ring

NMR probes and electronics located all around the ring

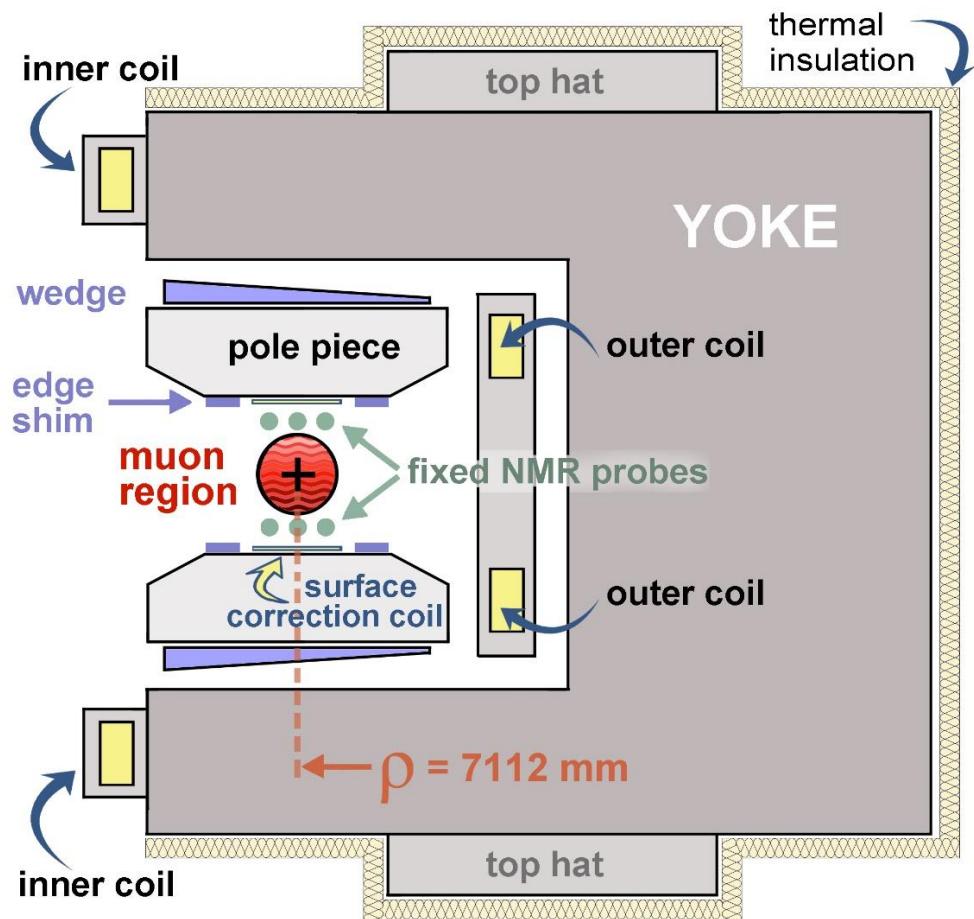
Kicker

Reaching ultra-uniform field

C-shaped design with 1.45 T dipole field between poles

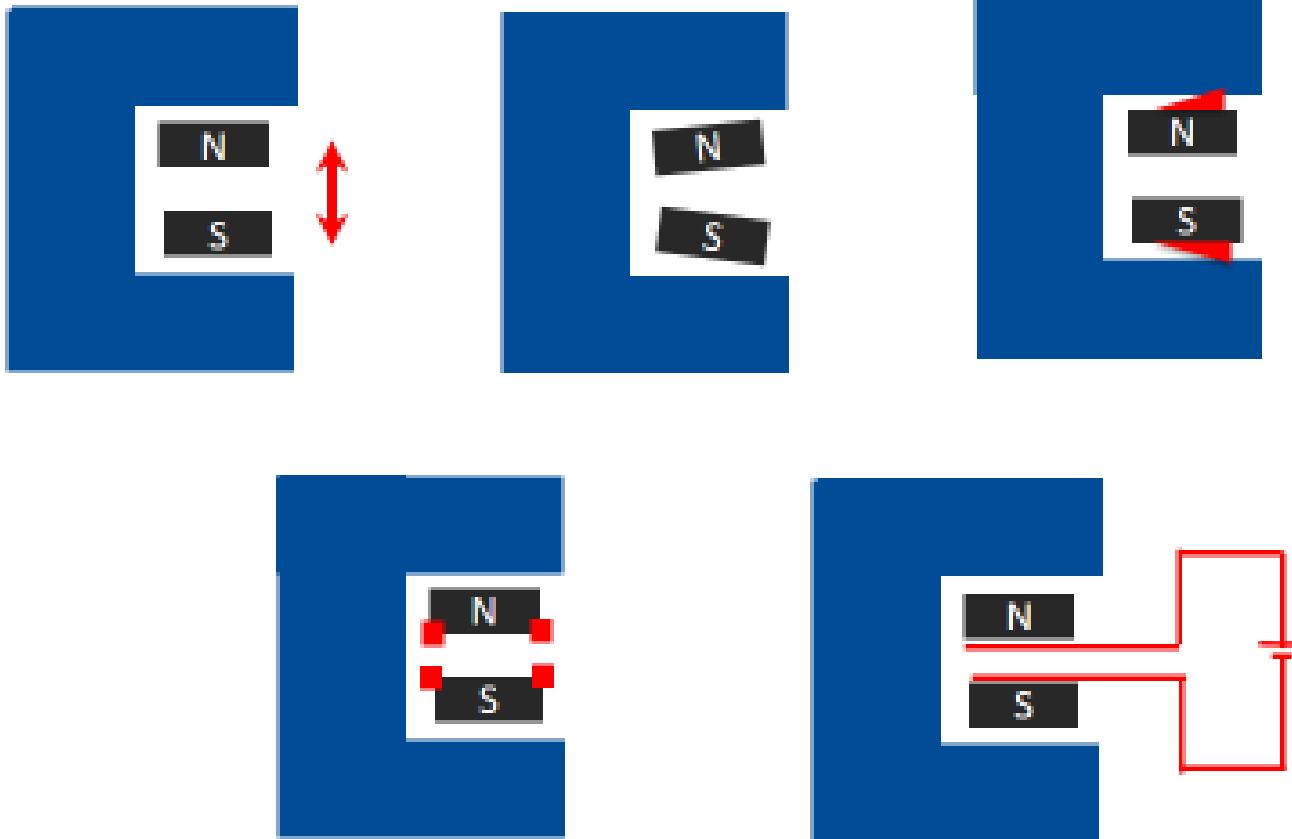
Many “knobs” to shim the field:

- 72 pole pieces
- 864 wedge shims
- 48 iron top hats
- 144 edge shims
- 8000 surface iron foils
- 100 active surface coils

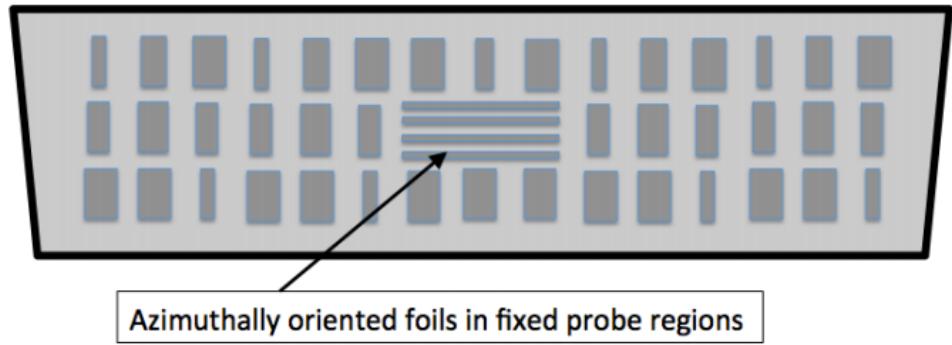


g-2 Magnet in Cross Section

Shimming



Shimming continues...



Azimuthally oriented foils in fixed probe regions



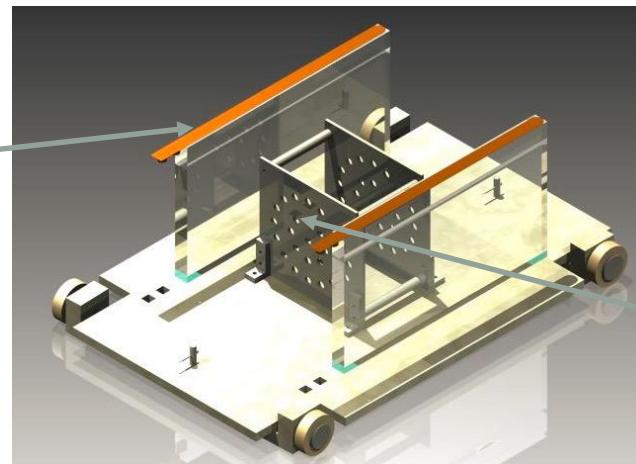
Rough shimming: Oct.2015-Aug.2016



Rough shimming is performed using shimming cart, before installation of vacuum chambers

Goal: 50 ppm uniformity

Laser tracker

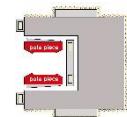
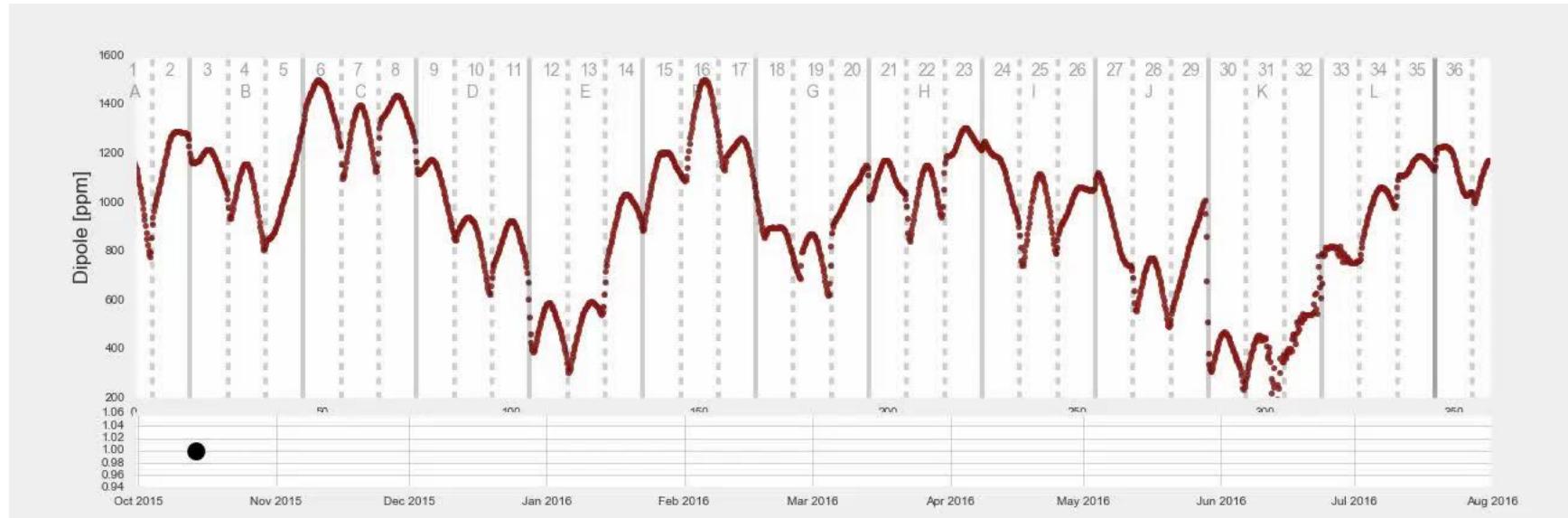


4 corner-cube retroreflectors

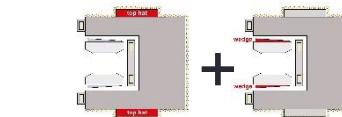
4 capacitive gap sensors

25 NMR probes

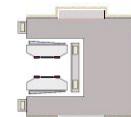
Shimming history



Poles



Top hats & wedges

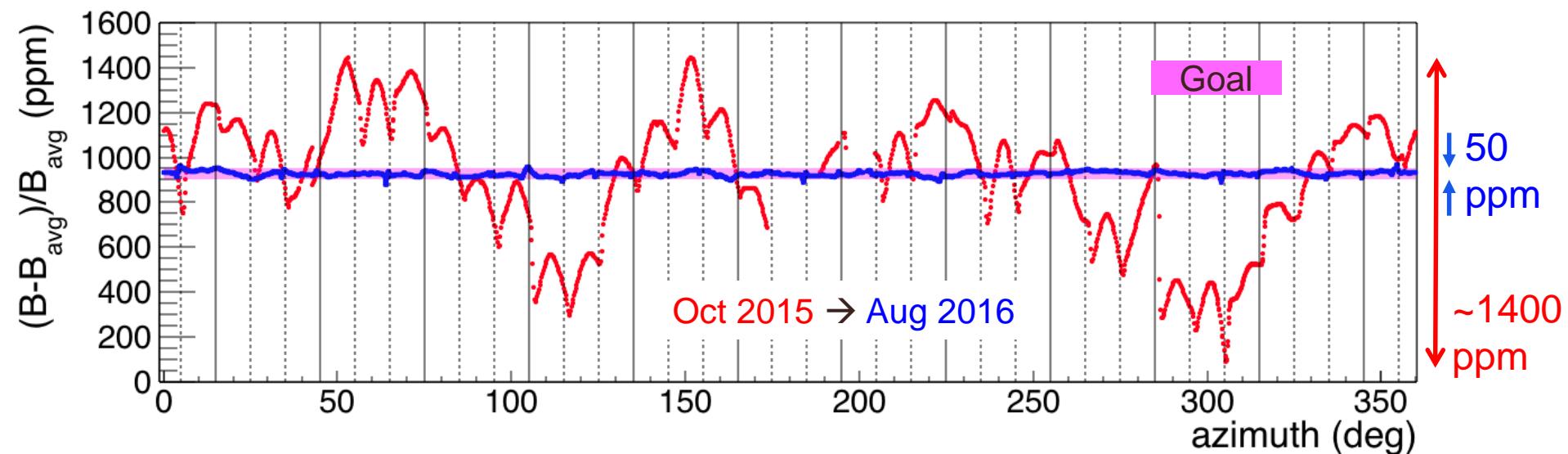


Surface foils

← Surface foils

Rough shimming results

- August 2016: completed addition of surface foils & achieved 50 ppm goal for rough shimming:



| | RMS (ppm) | p-p (ppm) |
|----------------------|-----------|-----------|
| FNAL (Rough shimmed) | 10 | 75 |
| BNL (Typical scan) | 30 | 230 |

Измерение a_μ

$$\omega_a = a_\mu eB/mc$$

$\omega_p = a_p eB/mc$

Измеряется в Фермилаб

Измерено в других экспериментах

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

ω_a : the muon spin precession frequency

$\tilde{\omega}'_p(T_r)$: precession of protons in water sample mapping the field and weighted by the muon distribution

Goal: 140 ppb =
100 ppb (stat) \oplus 100 ppb (syst)

$\tilde{\omega}'_p(T)$ Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1 ppb/ $^{\circ}\text{C}$.
[Metrologia 13, 179 \(1977\)](#), [Metrologia 51, 54 \(2014\)](#), [Metrologia 20, 81 \(1984\)](#)

$\frac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb accuracy at $T = 34.7^{\circ}\text{C}$
[Metrologia 13, 179 \(1977\)](#)

$\frac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)
[Rev. Mod. Phys. 88 035009 \(2016\)](#)

$\frac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting
[Phys. Rev. Lett. 82, 711 \(1999\)](#)

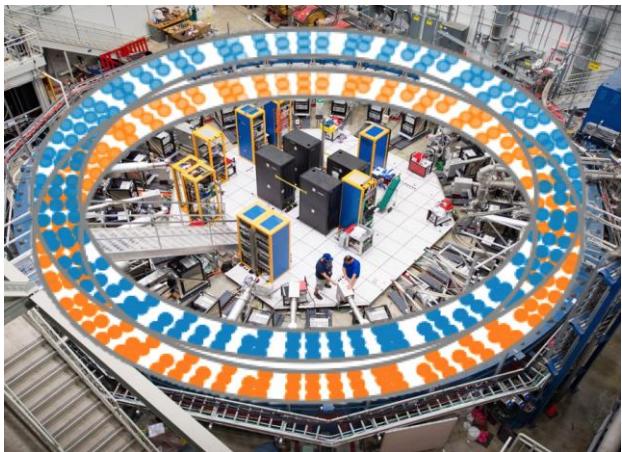
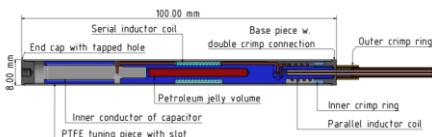
$\frac{g_e}{2}$ Measured to 0.28 ppt
[Phys. Rev. A 83, 052122 \(2011\)](#)

All < 22 ppb

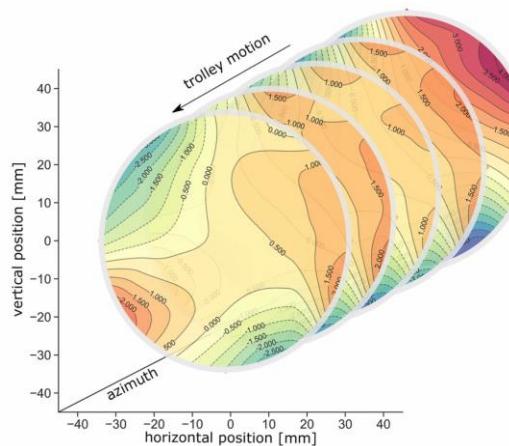
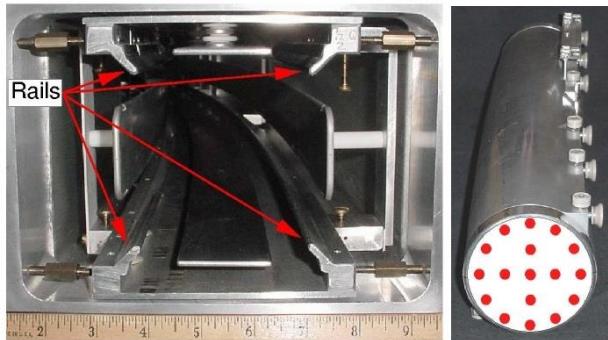
Измерение ω_p

Use NMR to find B-field in terms of proton precession frequency ω_p (comagnetometer)

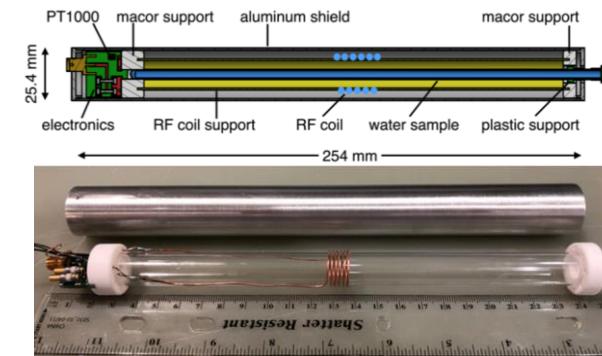
378 fixed probes
monitor 24/7



NMR trolley maps
field every 3 days



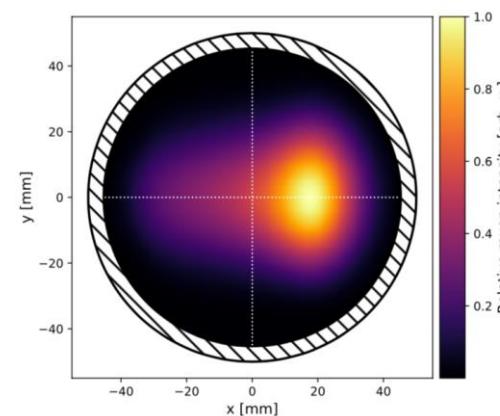
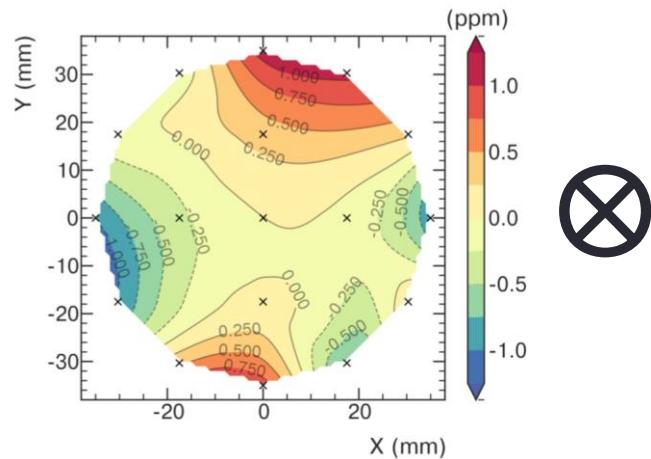
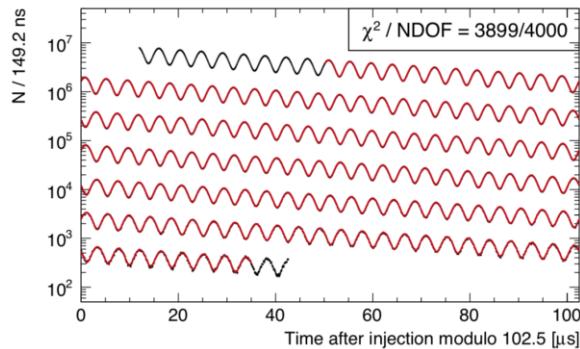
Trolley cross-calibrated
to absolute probes



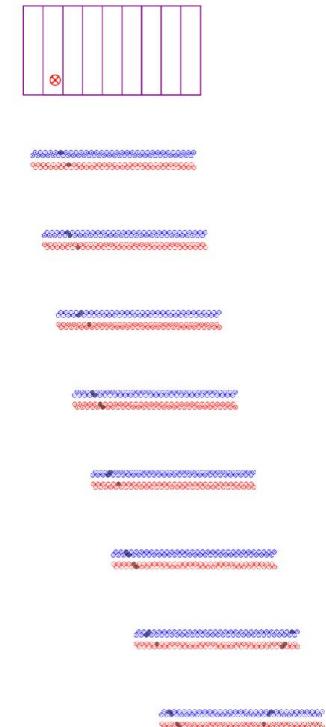
Absolute probes all cross-
calibrated at ANL test magnet

Мюонный ансамбль

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$

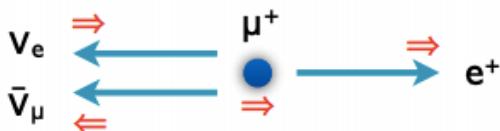
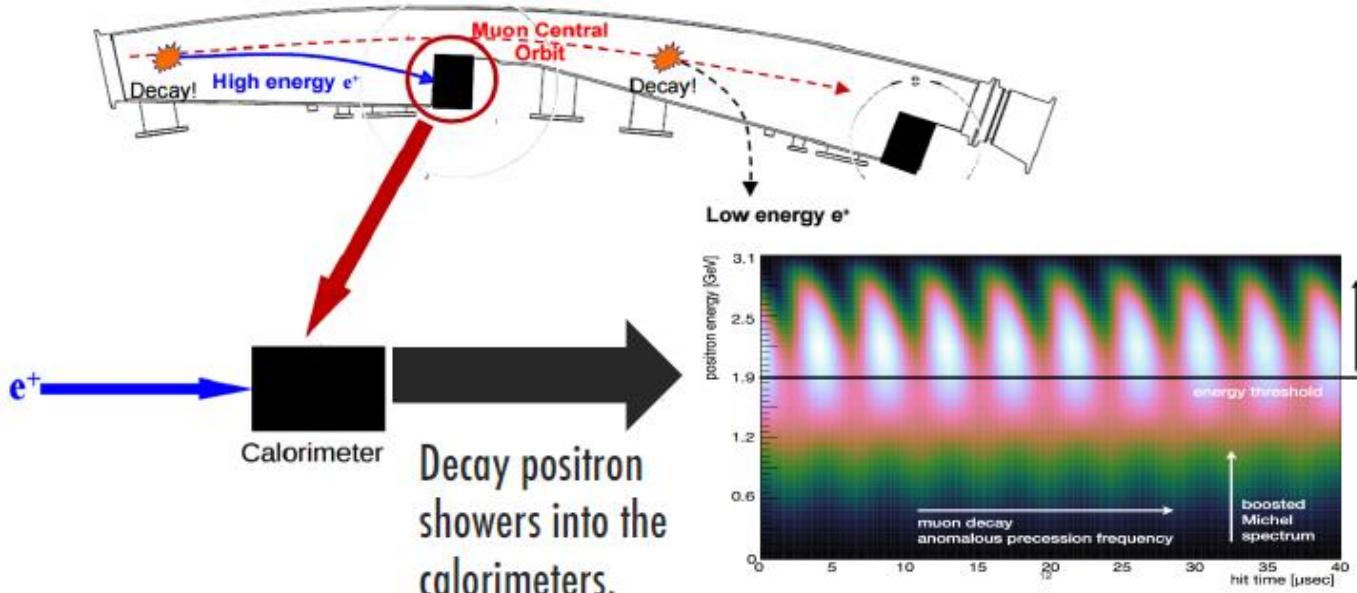


*All plots actual Run 1 data

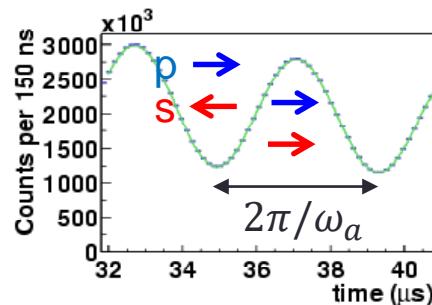


- *In vacuo* straw trackers tell us the spatial distribution and many other muon beam properties (CBO, p-dist)

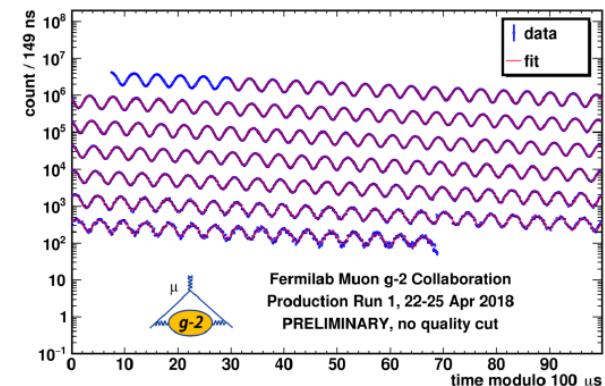
Measuring ω_a



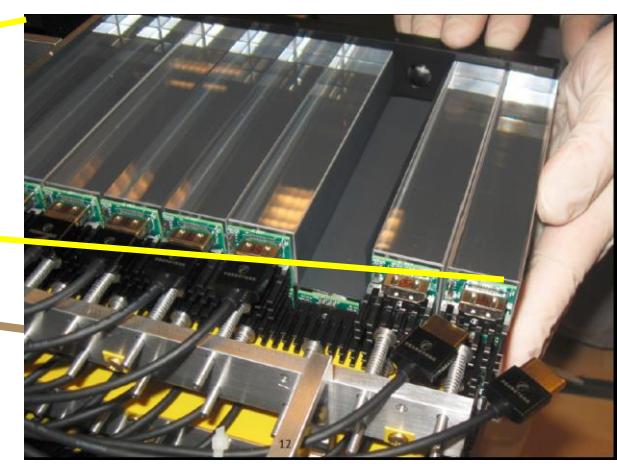
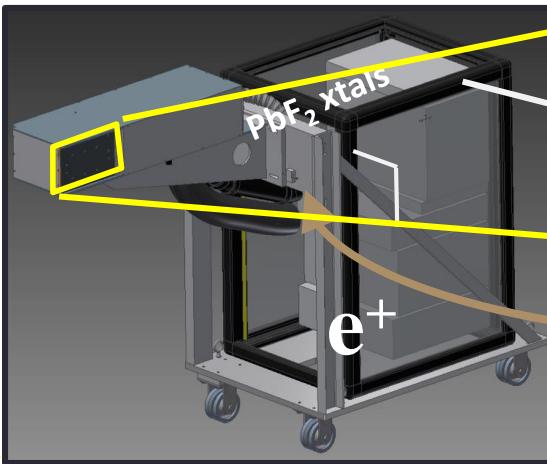
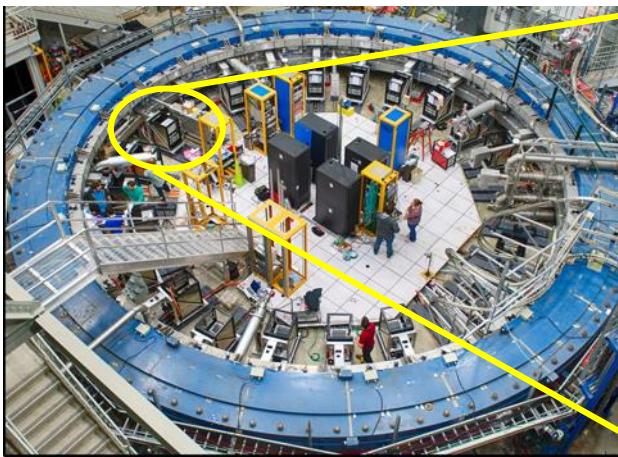
Энергия позитрона
коррелирует со спином



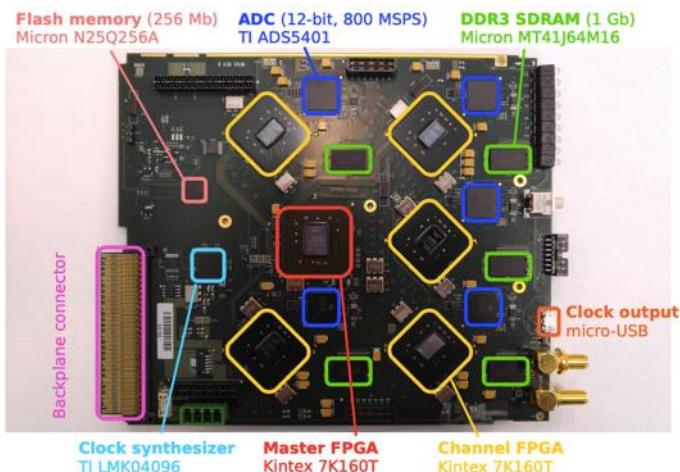
$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \cos(\omega t + \varphi)]$$



Калориметры



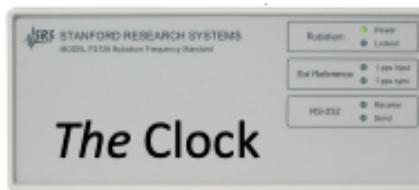
9x6 array of PbF_2 crystals at 24 locations on the inside of the ring (54 segments at FNAL, 1 segment at BNL)



800 MSPS WFDs with 128 MB memory (400 MSPS w/64kB mem at BNL)



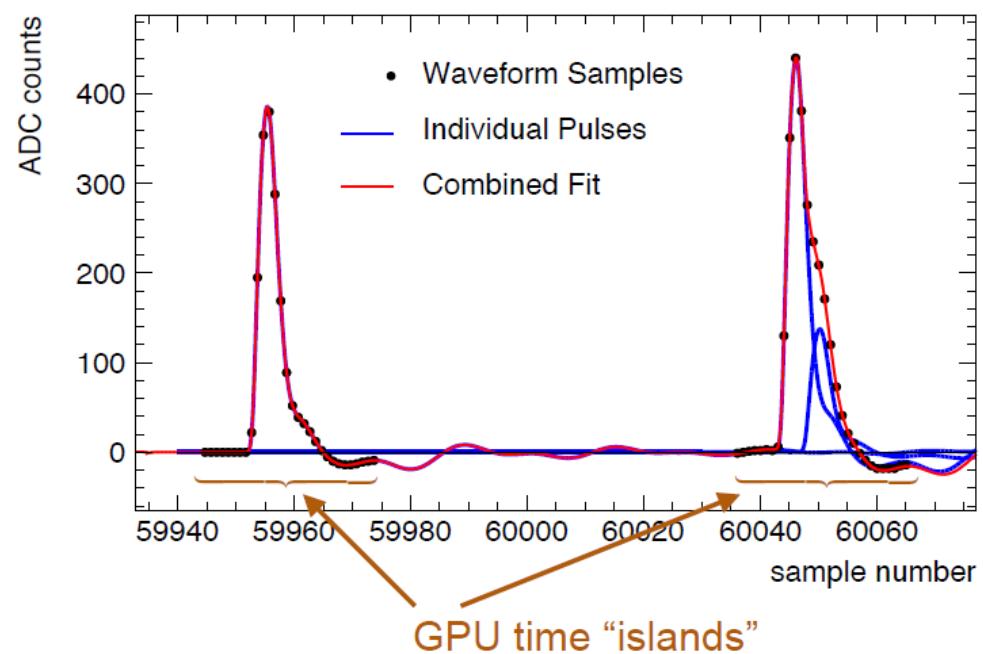
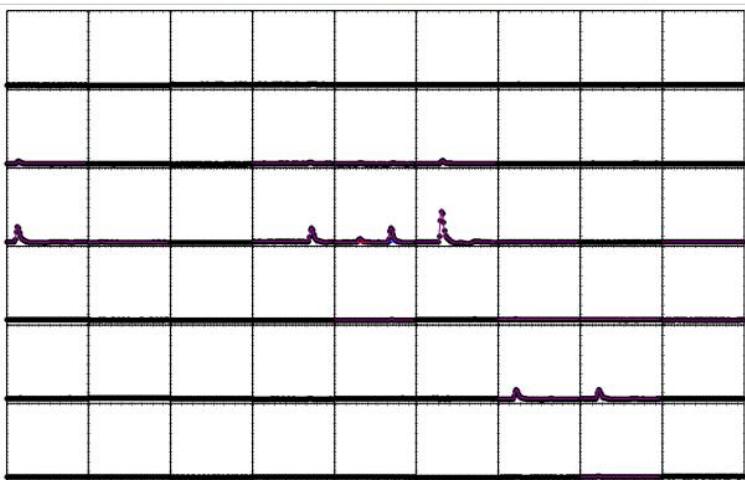
GPU based DAQ(18 GB/s at FNAL, 1 MB/s at BNL)



- 10 MHz GPS disciplined Rubidium clock with ~1ppt Allan variance

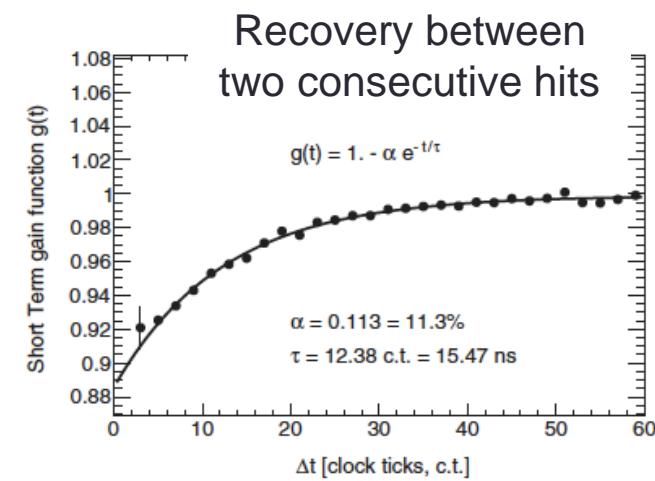
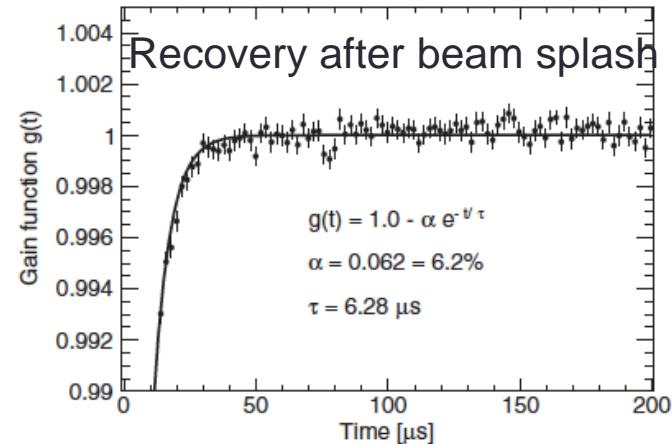
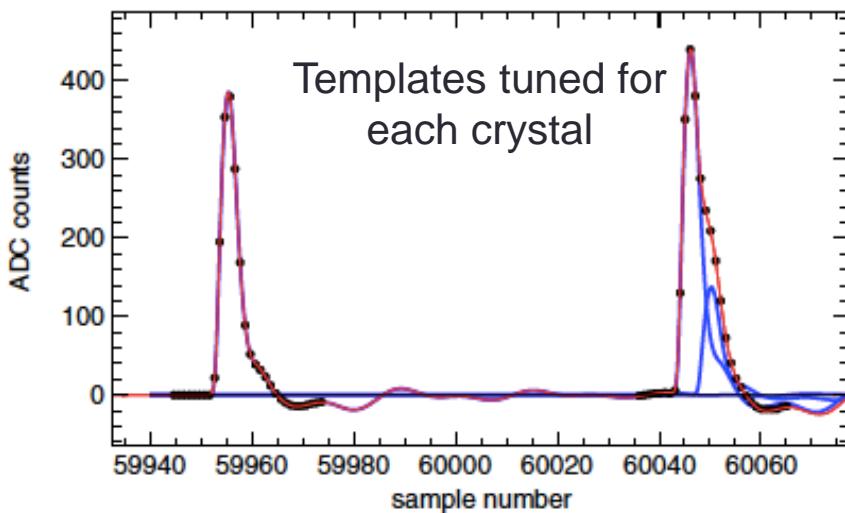
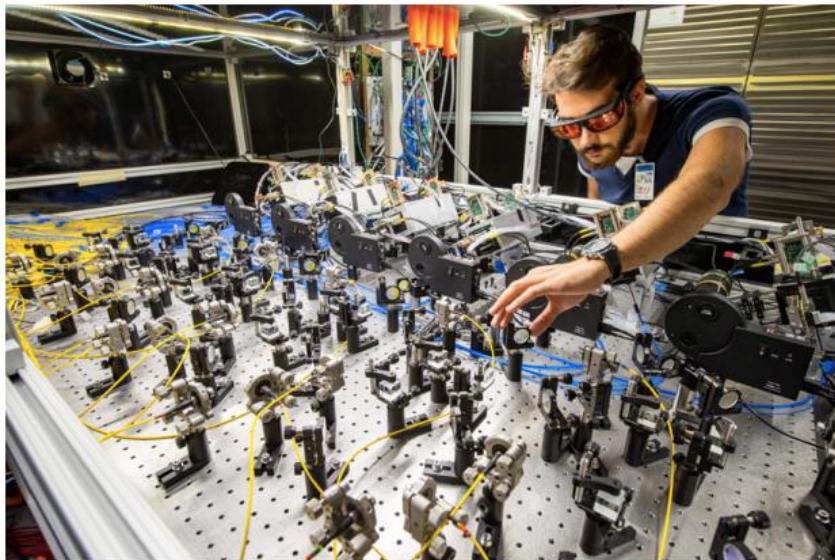
Реконструкция данных

Waveform slices from 9 x 6 PbF₂ array



Система лазерной калибровки

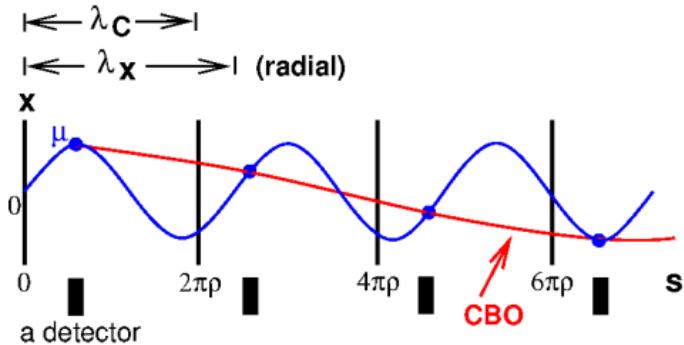
Highly tunable, precise laser system sends pulses to all crystals



Pileup and gain systematics reduced from 180 ppb at BNL to 41 ppb

Динамика пучка

Когерентные бетатронные колебания



Beam moves and “breathes” as a whole with observed frequency

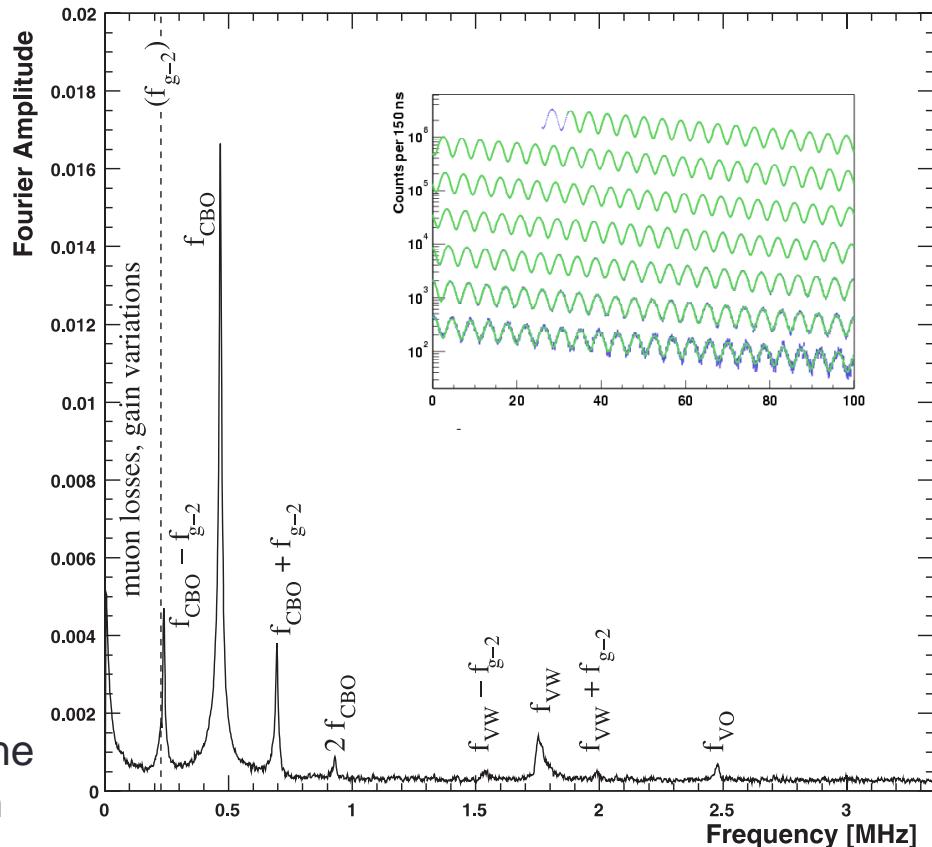
$$\omega_{CBO} = \left(1 - \sqrt{1 - n}\right) \omega_c$$

Detector acceptance and the electron flight time depends on the position of decay and electron energy. Therefore in:

$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \cos(\omega t + \varphi)]$$

N_0 , A and φ oscillate with ω_{CBO} :

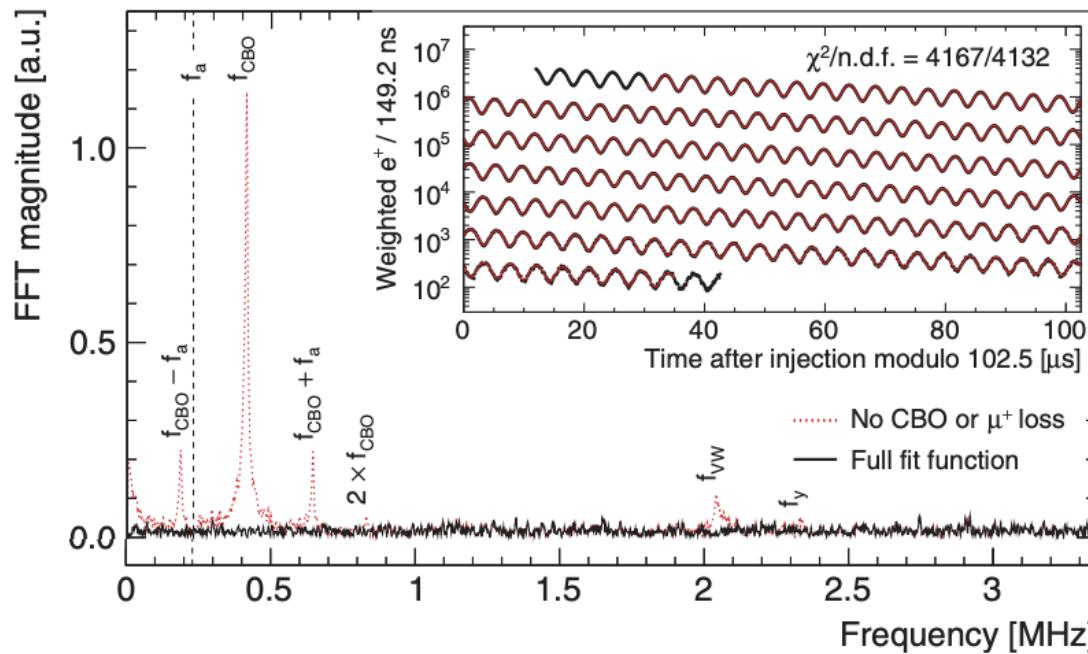
$$A(t) = A_0 [1 + a e^{-t/\tau_{CBO}} \cos(\omega_{CBO} t + \varphi_1)]$$



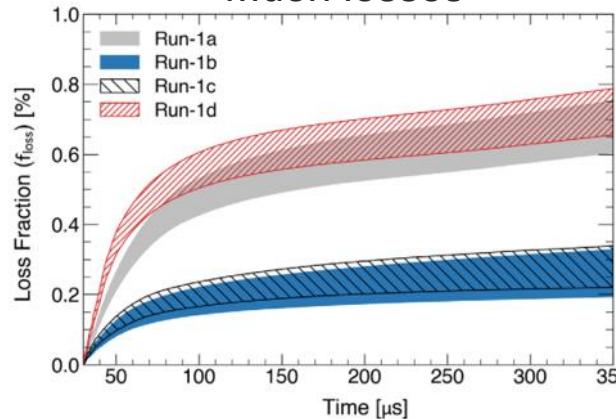
Фурье-спектр того, что осталось после 5-параметрической подгонки

Учет динамики пучка

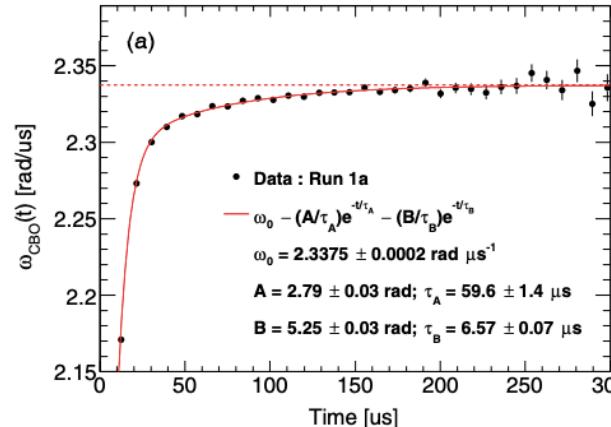
22 parameter fit



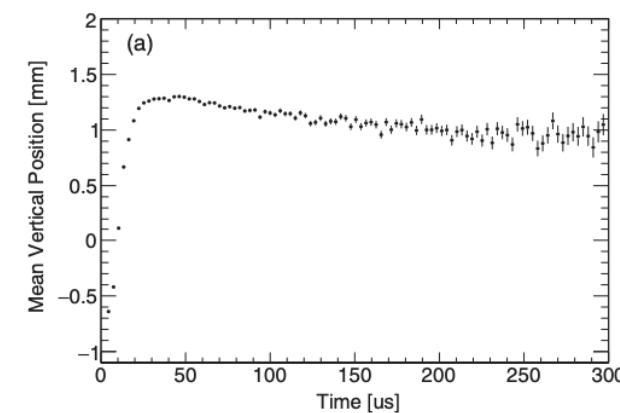
Muon losses



Mean horizontal motion



Mean vertical motion



$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\tau_{\mu}} \cdot$$

$$[1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a^m t + \phi_0 \cdot \phi_x(t))]$$

$$N_x(t) = 1 + e^{-1t/\tau_{\text{CBO}}} A_{N,x,1,1} \cos(1\omega_{\text{CBO}}t + \phi_{N,x,1,1}) + e^{-2t/\tau_{\text{CBO}}} A_{N,x,2,2} \cos(2\omega_{\text{CBO}}t + \phi_{N,x,2,2}),$$

$$N_y(t) = 1 + e^{-1t/\tau_y} A_{N,y,1,1} \cos(1\omega_y t + \phi_{N,y,1,1}) + e^{-2t/\tau_y} A_{N,y,2,2} \cos(2\omega_{\text{VW}} t + \phi_{N,y,2,2}),$$

$$A_x(t) = 1 + e^{-1t/\tau_{\text{CBO}}} A_{A,x,1,1} \cos(1\omega_{\text{CBO}}t + \phi_{A,x,1,1}),$$

$$\phi_x(t) = 1 + e^{-1t/\tau_{\text{CBO}}} A_{\phi,x,1,1} \cos(1\omega_{\text{CBO}}t + \phi_{\phi,x,1,1}).$$

Поправки

$$\frac{\omega_a}{\tilde{\omega}_p} = \frac{f_{\text{clock}} \omega_a (1 + C_e + C_p + C_{\text{ml}} + C_{\text{pa}})}{(1 + B_{\text{QT}} + B_{\text{Eddy}}) f_{\text{field}} \omega_p \otimes \rho(\mathbf{r})}$$

Field transients Field calibration

E-field & pitch corrections Muon loss & phase acceptance corrections

- Every one of these terms has been studied in extraordinary detail. How much?

Systematics (numerator)

| Source | Uncertainty |
|------------------------|-------------|
| Frequency Standard | 1 ppt |
| Frequency Synthesizers | 0.1 ppb |
| Digitization Frequency | 2 ppb |
| Total Systematic | 2 ppb |

| 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 |

| $R(\omega_a)$ 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 |

*Run 1 ω_a data analyzed in four subsets

| | 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 |

| 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 |

| | 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 |



Systematics (denominator)

| | |
|--------------------------------|------------------|
| 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 |

| 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 |

| 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 |

| 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 |

Run-1 Estimate:
 $B_k = -27.4 \pm 37 \text{ ppb}$

| Dataset | correction [ppb] | | | | uncertainty [ppb] | | | |
|-----------------------------|------------------|-------------|------------|-------------|-------------------|-------------|-------------|-------------|
| | 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 |

Early-to-late systematics

$$\cos(W_a t + f)$$

Leading systematics come from time dependence in the phase

Taylor expansion: $f(t) = f_0 + at + bt^2 \dots \gg f_0 + at$

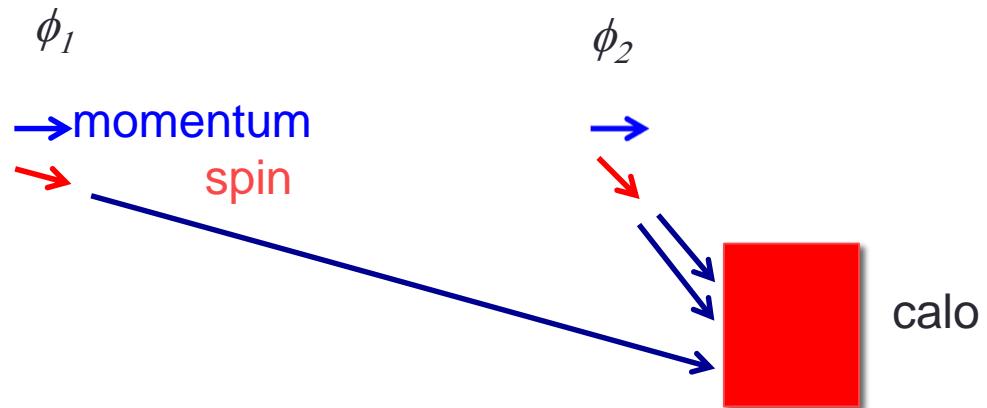
$$\cos(W_a t + f(t)) \gg \cos((W_a + a)t + f_0)$$

Things that change “**early to late**” in the fill typically lead to a time dependence in the phase of the accepted sample that directly biases the extracted value of ω_a

Systematics

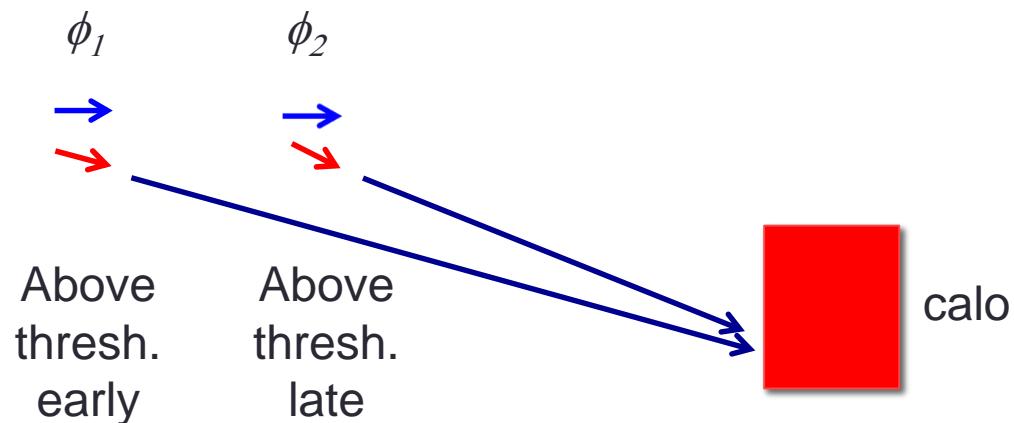
Pileup: two low energy positrons fake a high energy positron
 (happens early, not late)

$$\begin{aligned}\phi_{\text{early}} &\sim \phi_1 + \phi_2 \\ \phi_{\text{late}} &\sim \phi_1\end{aligned}$$



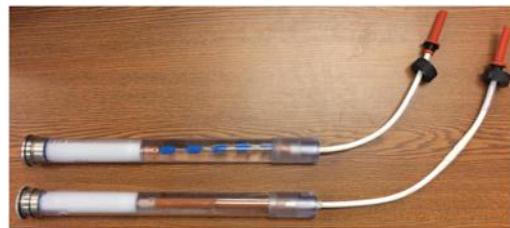
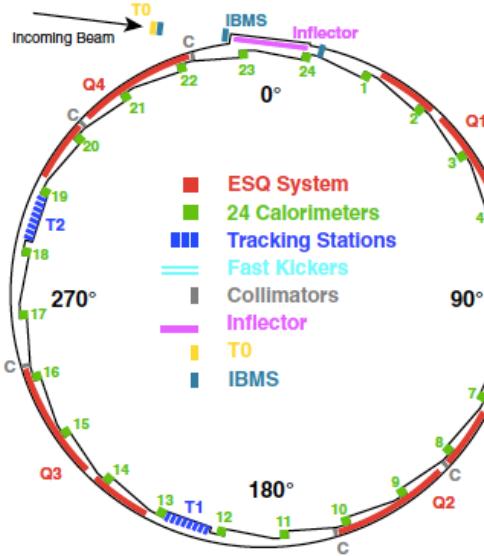
Gain change:
 example: saturation (happens early, not late)

$$\begin{aligned}\phi_{\text{early}} &\sim \phi_1 \\ \phi_{\text{late}} &\sim \phi_2\end{aligned}$$

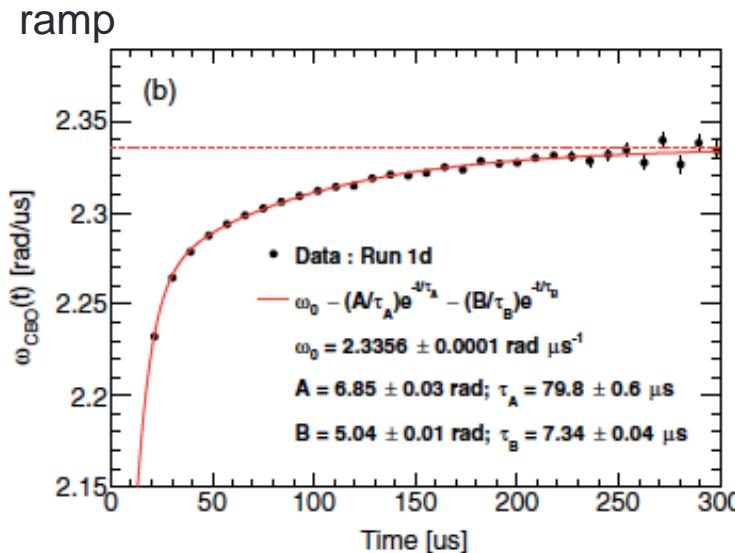
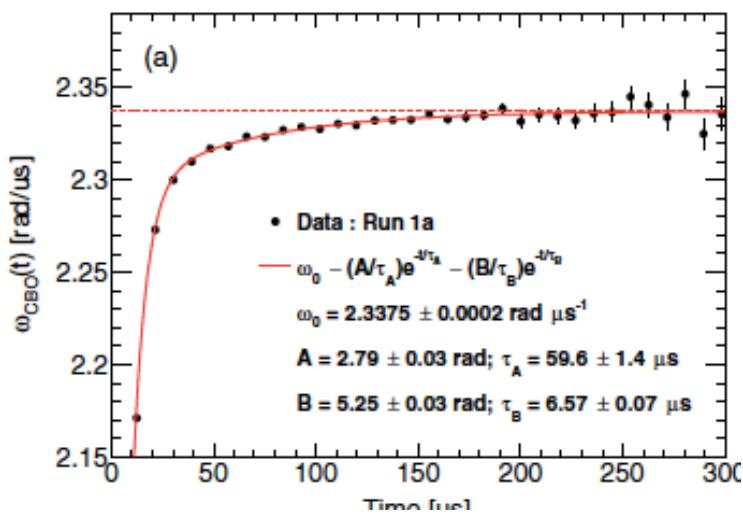
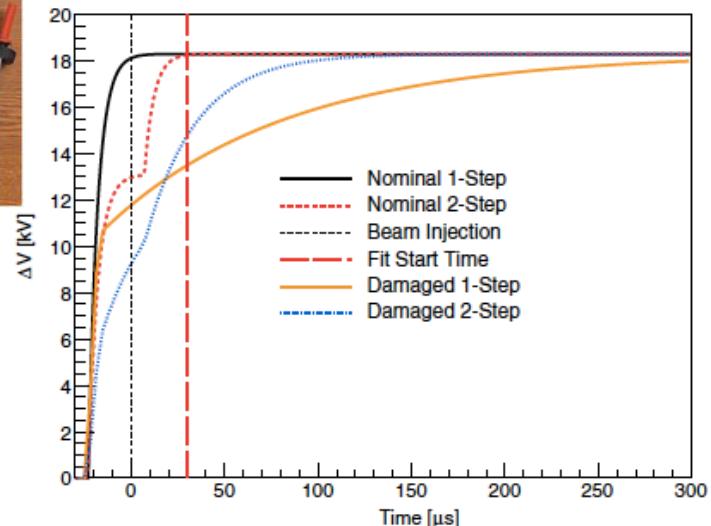


Система лазерной калибровки, алгоритмы реконструкции, возможности DAQ
 позволили учесть оба эффекта с необходимой точностью

Residual systematics from beam motion



Towards the end of the run, a few HV feedthrough resistors broke, changing the RC time constant of the ramp



So the beam is moving early-to-late in the fill

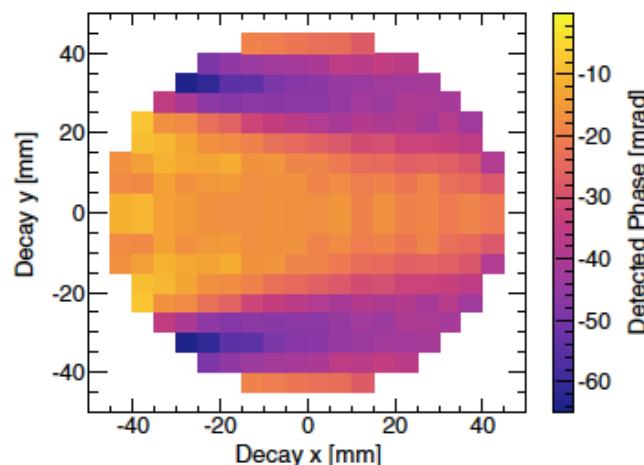
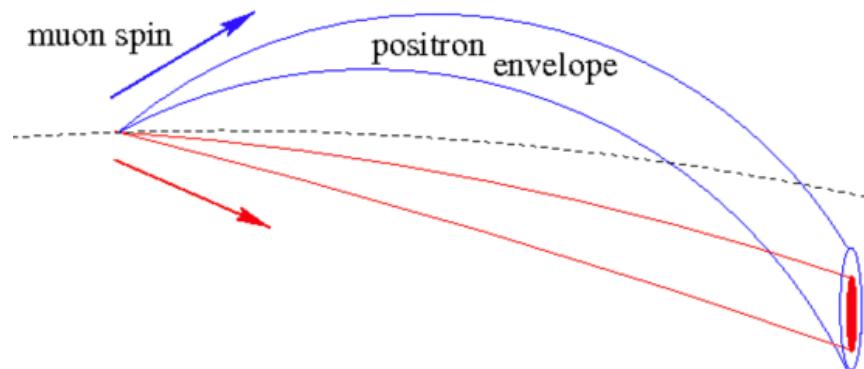
Phase coupling to acceptance

$$\cos(W_a t + f)$$

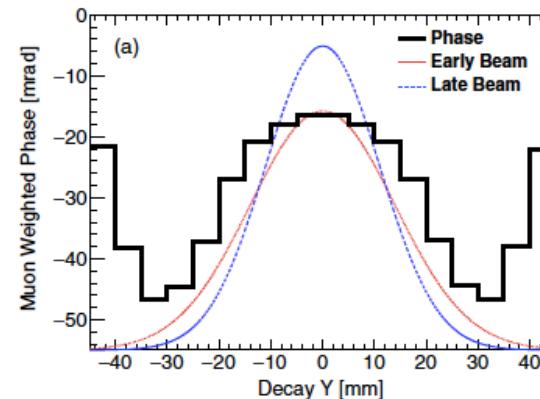
Phase between the muon spin and momentum

Phase advance between decay time and detection time due to path length

If the beam is moving, this phase advance is changing



Vertical decay position

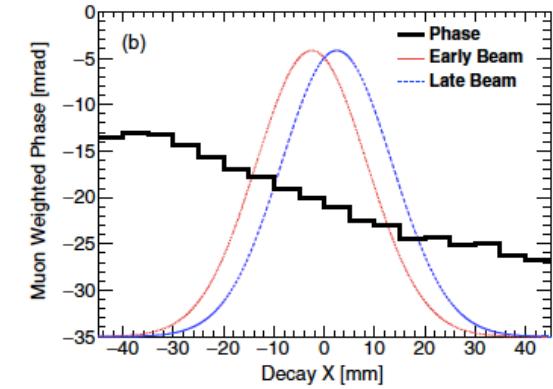


Phase at calorimeter depending on muon decay point

For final run period:

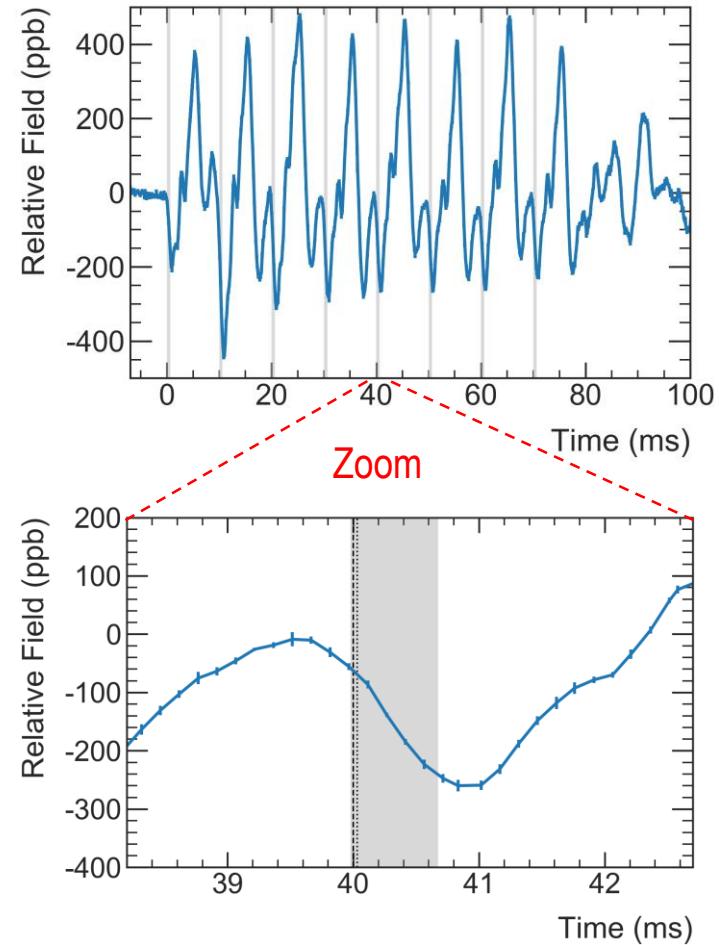
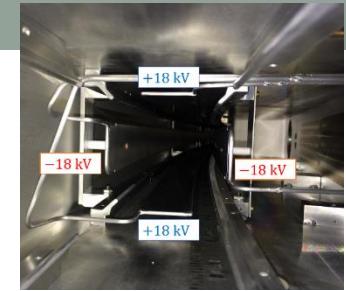
$$\frac{\Delta \omega_a}{\omega_a} = -164 \pm 80 \text{ ppb}$$

Horizontal decay position

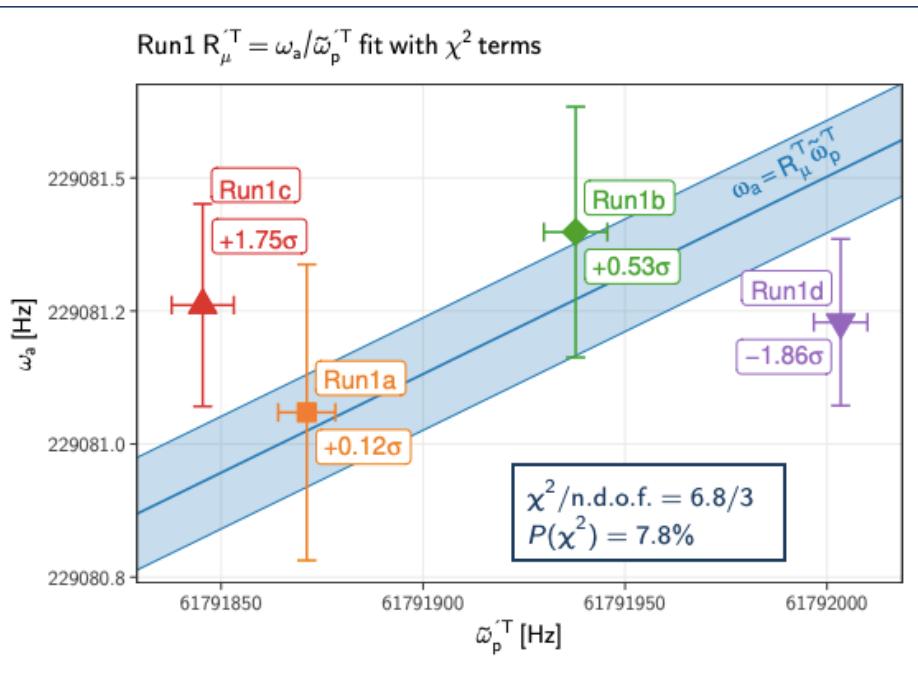


B_q – Quad transients

- Recall, E- field keeps muons vertically confined
- Quads pulsed → induces mech. vibrations → oscillating conductor perturbs B field
 - Deliver 8 muon bunches with 10 ms spacing → close to 100 Hz natural resonance
- Had to build special NMR probes to map the effect
 - Long process to make measurements
- Overall correction is 17 ppb
 - Only matters in window when muons are present, averaged over 8 bunches, averaged over 43% of ring with quad coverage
- 92 ppb uncertainty is dominated by not having a complete map
 - Analysis of more complete map is underway
 - Expect uncertainty to be reduced x2-3 for Run 2 and beyond



Run 1 summary



| Quantity | Correction Terms | 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 |
| $\mu'_p(34.7^\circ)/\mu_e$ | – | 10 |
| m_μ/m_e | – | 22 |
| $g_e/2$ | – | 0 |
| Total systematic | – | 157 |
| Total fundamental factors | – | 25 |
| Totals | 544 | 462 |

4 под-сезона, набранные в разных условиях

- 462 ppb overall error
 - 434 ppb statistical
 - 157 ppb systematic (0.5 BNL)
 - 25 ppb CODATA inputs

Слепой анализ

$$\frac{\omega_a}{\tilde{\omega}_p} = \frac{f_{\text{clock}} \omega_a (1 + C_e + C_p + C_{\text{ml}} + C_{\text{pa}})}{(1 + B_{\text{QT}} + B_{\text{Eddy}}) f_{\text{field}} \omega_p \otimes \rho(\mathbf{r})}$$

- f_{clock} is the frequency that our clock ticks
 - Precision timepiece, stable at ppt level
- Throughout the entire analysis the clock frequency is kept secret from all collaborators
 - Joe Lykken and Greg Bock (FNAL Directorate) stop in each week to check on the clock
 - Secret envelopes kept until physics analysis is complete and ready to be revealed (Feb 25)



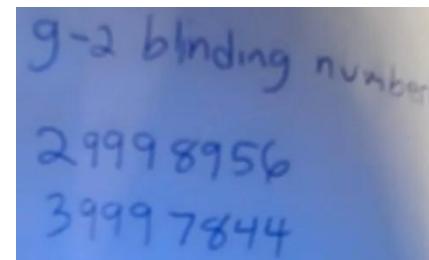
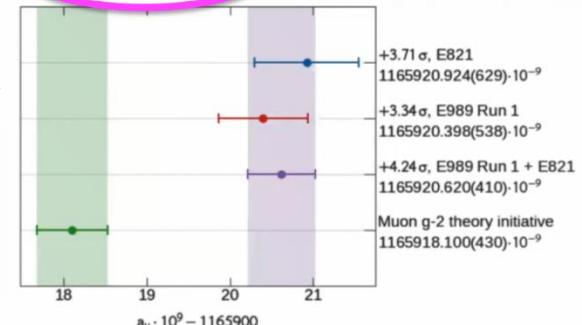
Gathered on Feb 25, 2001 to unblind



gm2-run1-comb.ipynb gm2-run1-elab.ipynb gm2-run1-check.ipynb gm2-omega-a-aug

E989 Run 1 unblinding

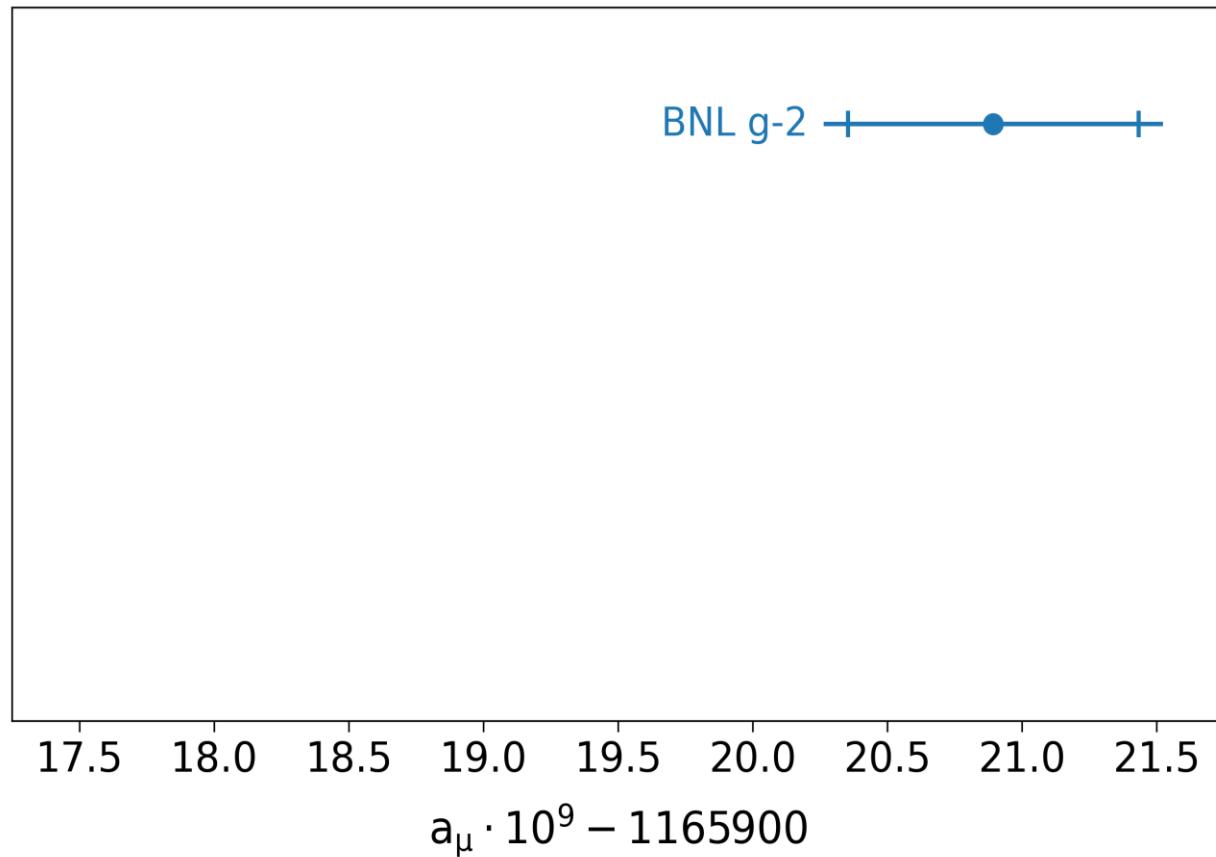
```
[154]: 1 ## using f_blind != 40e6 Hz
2 ## - fake_offset is disregarded
3 ## - the blinding is removed
4 ## - the watermark is removed
5 ## - the MW blind central value: plot_mu_a_mu(f_blind=39997844)
6 ## - the plot_result(f_blind=39997844)
a_MW_E989 = 1165920.398(538)e-9
```



Same numbers!

Run 1 result

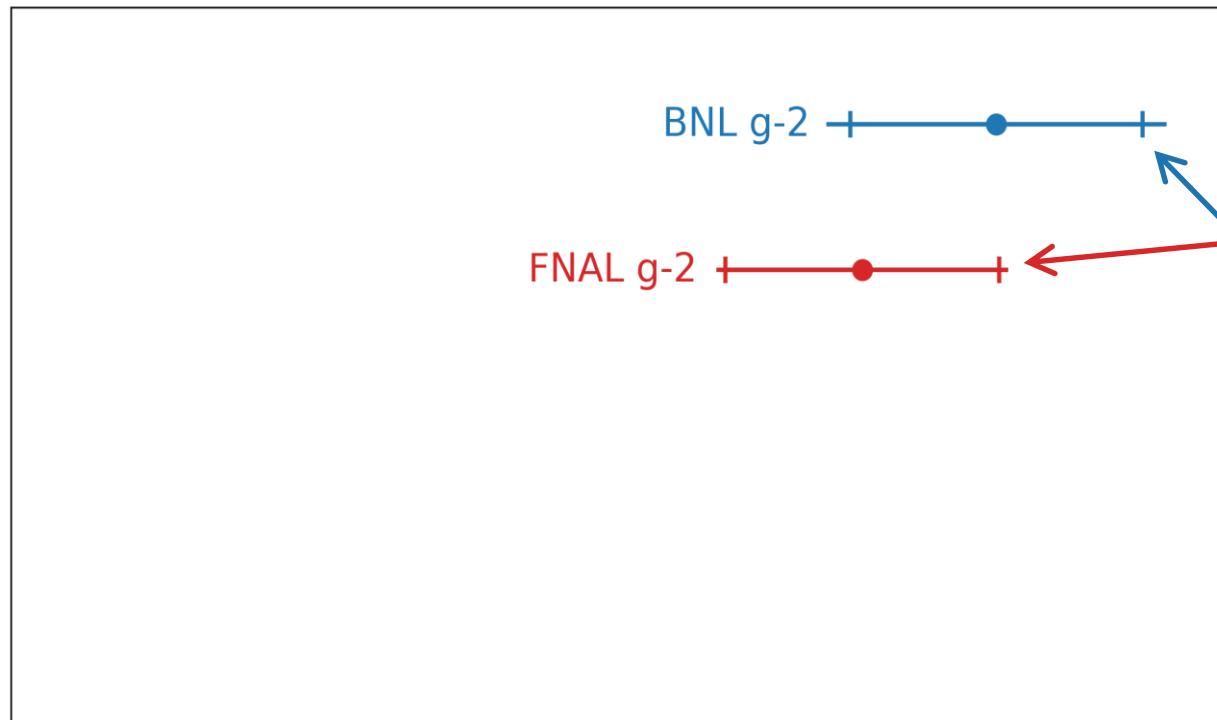
$$a_\mu(\text{BNL}) = 0.00116592089(63) \rightarrow 540 \text{ ppb}$$



- We found nothing that would change BNL result
 - Larger collaboration
 - Higher purity beam
 - More advanced instrumentation
 - More powerful simulations

Run 1 result

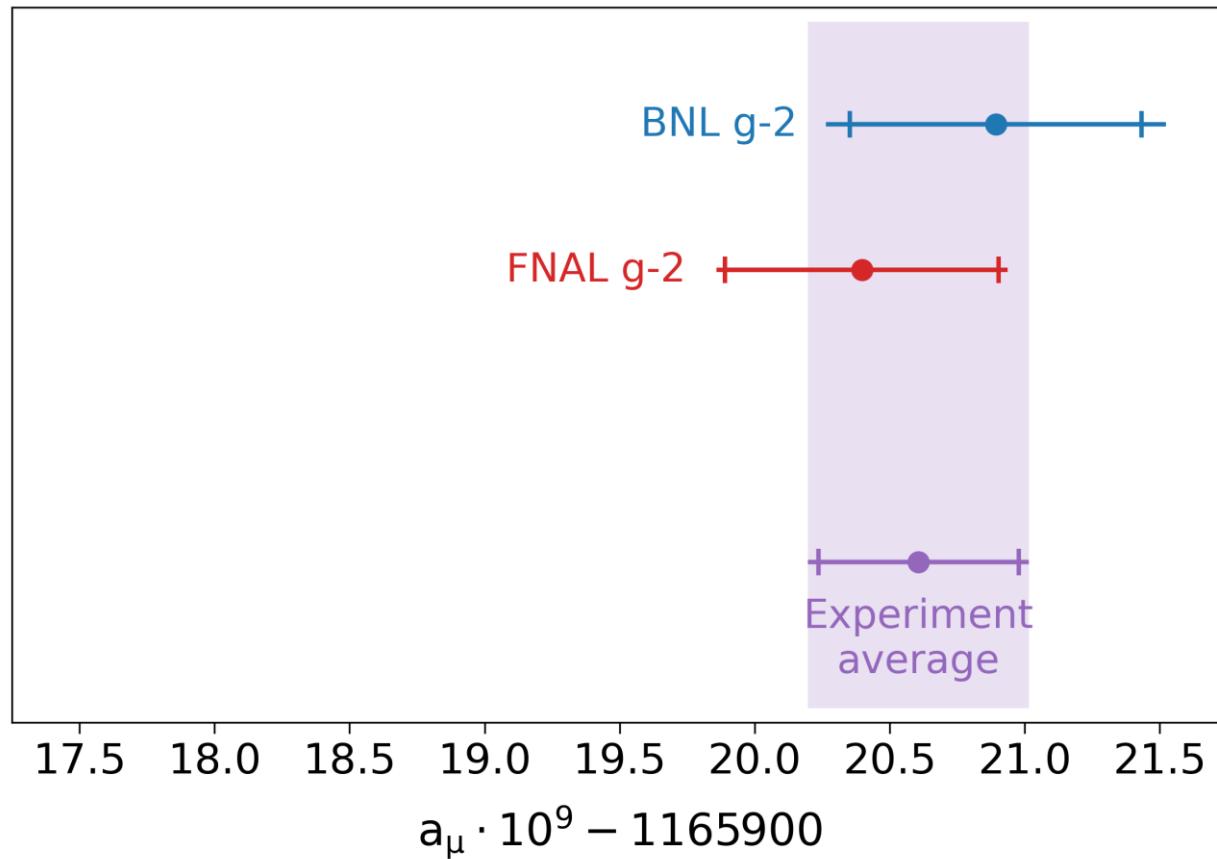
$$a_{\mu}(\text{FNAL g-2; Run 1}) = 0.00116592040(54) \rightarrow 463 \text{ ppb}$$



- 15% smaller error than BNL
- Both experiments dominated by statistical error
- Good agreement → safe to combine

Experimental combination

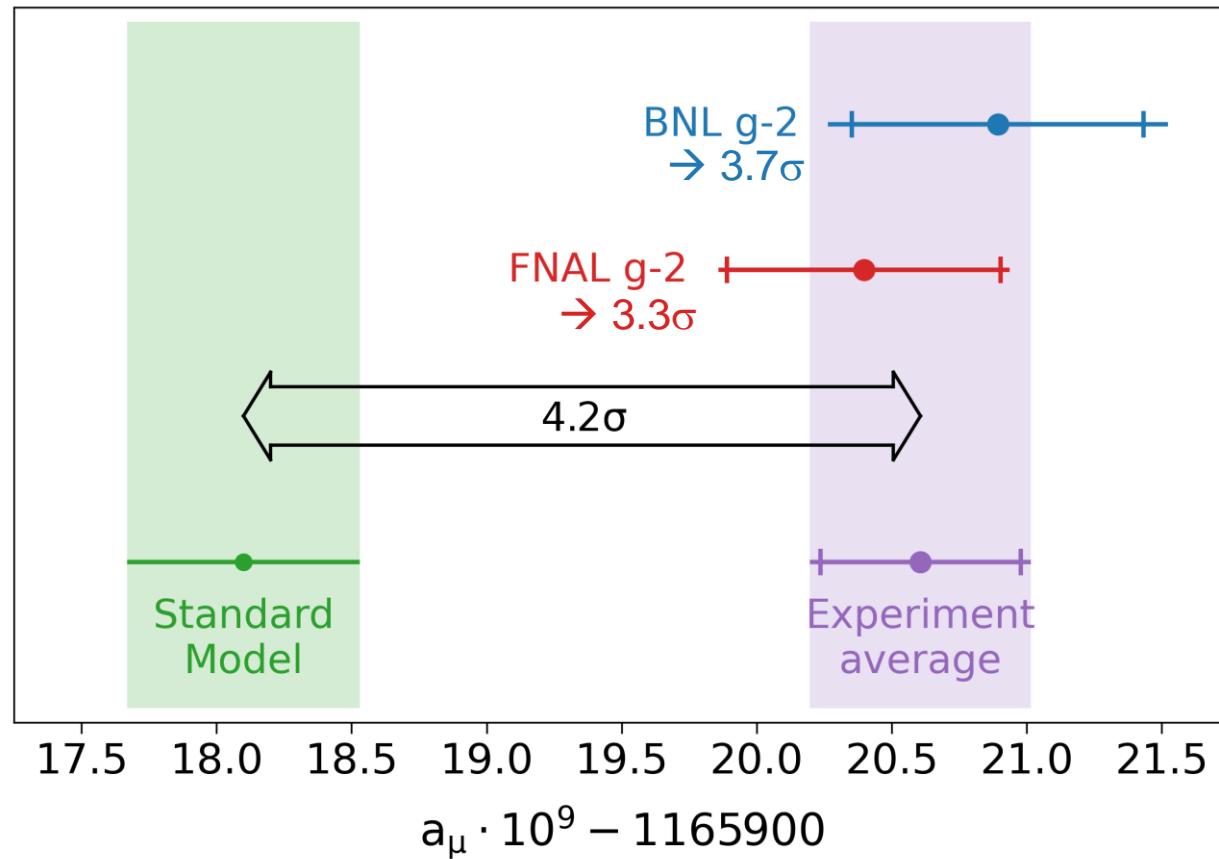
$$a_{\mu}(\text{Exp}) = 0.00116592061(41) \rightarrow 350 \text{ ppb}$$



- 15% smaller error than BNL
- Both experiments dominated by statistical error
- Good agreement → safe to combine

Comparison to SM prediction

$$a_\mu(\text{SM}) = 0.00116591810(43) \rightarrow 368 \text{ ppb}$$



- Individual tension with SM
 - BNL: 3.7σ
 - FNAL: 3.3σ

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 0.00000000251(59) \rightarrow 4.2\sigma$$

The results heard round the world!

- Worldwide press coverage
 - Over 3000 media outlets covered the story
 - Total estimated media reach of those outlets
> 6 billion people! (Pop. Earth 7.7 billion)

The New York Times

"All the News That's Fit to Print"

VOL. CLXX..... No. 59,022 © 2021 The New York Times Company NEW YORK, THURSDAY, APRIL 8, 2021 \$3.00

Biden Tax Plan Aims to Curtail Contagious Variant Is Fueling Surge in Infections Across the U.S.

Some states where new cases of the coronavirus are rising have been hit hard by the B.1.1.7 variant. Page A6.

reached a record high, the Islamic State has trumpeted these battlefield wins to project an image of strength and inspire its supporters.

Continued on Page A18

researchers. "As an organization more broadly, ISIS is hurting," said Col-

Continued on Page A11

the pandemic. The effort — a \$2.1 billion fund in the state budget — is by far the biggest of its kind in the country and a sign of the budget deal that was reached on Tuesday, was one of the most contentious points of debate during

Continued on Page A16

in Europe, the safety concerns have delayed inoculations, sunk confidence in the shot and created

Continued on Page A9

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

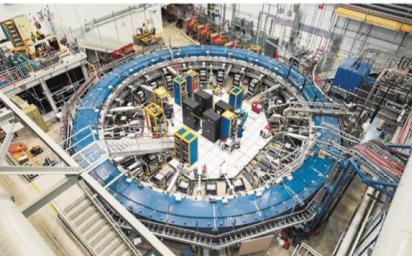
Evidence is mounting that a tiny subatomic particle seems to break the rules of physics. Last week, physicists announced on Wednesday, a finding that would overturn and reshape our view of our understanding of the universe.

The result, physicists say suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that we have known little or nothing about.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermilab Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working on this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but with 200 times the intrinsic element of the cosmos. Dr. Polly and his colleagues — an international team of physicists from seven countries — found that muons do not behave as predicted by the Standard Model, the reigning theory of particle physics.

The aberrant behavior poses a firm challenge to the bedrock theory of physics, the Standard Model, a suite of equations that enumerates the fundamental



REED HAMILTER/ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

particles in the universe (17 at last count) and how they interact.

"This is strong evidence that the muon is sending us some sort of signal that is not in the best theory," said Renee Fatemi, a physicist at the University of Kentucky.

Continued on Page A19

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

PINEDALE, Wyo. — Kenny Tamm and his team can't wait for cases from mountain hikers. There was the woman who got tired and did not feel like finishing her hike; the couple who got lost in a snow blizzard; the base jumper, misjudging his leap from a treacherous granite cliff face, who — equipped with snowmobiles — buried up to his neck in an avalanche.

All of them were pulled off Ms. Tam's trail by the Search and Rescue crew from the rugged Wind River mountain range in the last month, which is a small pocket of western Wyoming. And all of them, these rescuers said, were really unprepared for the brutal backcountry in which they were traveling.

"It is super frumming," said Mr. Tamm, the 36-year-old Search and Rescue crew from the rugged Wind River mountain range in the last month, which is a small pocket of western Wyoming. And all of them, these rescuers said, were really unprepared for the brutal backcountry in which they were traveling.



MAX WHITAKER FOR THE NEW YORK TIMES

A trail in the Wind River Range in western Wyoming.

These heroes of inexperienced adventurers explore the treacherous terrain of the backcountry, many of whom call it home. They have strayed off the beaten path, blazed new routes for national parks and the public lands around them. But as

Continued on Page A17

PHYSICAL REVIEW LETTERS

Published week ending 9 APRIL 2021

PRD 126 (14), 140501-1-149001, 9 April 2021 (242 pages)

BNL g-2

FNAL g-2

Standard Model

Experiment Average

4.2 σ

14

Published by American Physical Society

APS physics

Volume 126, Number 14



Fermilab

Four articles on arXiv and published in Phys Rev

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

PRAB

Beam dynamics

T. Albahri,³⁰ A. Anastasi¹⁰, K. Badgley,⁷ S. Baefler,^{36, a} I. Bailey,^{17, b} V. A. Baranov,¹⁵ E. Barlas-Yucel,²⁸
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 J. D. Crnkovic,³⁴ S. Dabda,¹¹
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Magnetic Field Measurement and Analysis for the Muon $g - 2$ Experiment at Fermilab

T. Albahri,³⁹ A. Anastasi,^{11, a} K. Badgley,⁷ S. Baefler,^{47, b} I. Bailey,^{19, c} V. A. Baranov,¹⁷ E. Barlas-Yucel,³⁷
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 C. Gabbanini,^{11, 14} M. D. Gala,¹¹ K. L. Giovanetti,¹⁵ P. G. S. Haciomeroglu,⁵ T. Haider,¹¹ D. W. Hertzog,⁴⁸ G. Heske,¹¹ M. Iacobacci,^{10, 31} M. Incaglia,¹¹
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 R. N. Pilato,^{11, 32} K. T. Pitts,¹¹ N. Raha,¹¹ S. Ramachandran,¹¹ C. Schlesier,³⁷ A. Schreder,¹¹ M. Sorbara,^{12, 33} D. Stöckinger,²⁸
 G. Sweetmore,⁴⁰ D. A. Sweigart,⁶ K. Thomson,³⁹ V. Tishchenko,¹¹ T. Walton,⁷

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g - 2$ experiment

T. Albahri,³⁹ A. Anastasi,^{11, a} A. Anisenkov,^{4, b} K. Badgley,⁷ S. Baefler,^{47, c} I. Bailey,^{19, d} V. A. Baranov,¹⁷
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 P. Di Leo,¹⁰ G. Di Sciascio,¹² R. Farooq,⁴² R. Fatemi,³⁸ C. Ferraro,^{48, 22} N. Froemming,^{48, 22} J. Fry,^{47, c} L. K. Gibbons,⁶ A. Gioiosa,^{29, 11} S. Grant,³⁶ F. Gray,²⁴ S. Hacioğlu,¹¹ A. Herrod,^{39, d} D. W. Hertzog,⁴⁸ R. Hong,^{1, 38} M. Iacobacci,^{10, 31} M. Kawanou,⁴¹ L. Kelton,³⁸ A. Kuchibhotla,³⁷ N. A. Kuchiniskiy,¹⁵ B. Kiburg,⁷ M. Li,^{26, 1, e} D. Li,^{26, g} L. Li,^{26, e} I. Lyon,⁷ B. MacCoy,⁴⁸ R. M. Miozzoli,¹² W. M. Morse,³ J. M. G. M. Piacentino,^{29, 12} R. N. Pilato,^{11, 32} J. Price,³⁹ B. Quinn,⁴³ N. Raha,¹¹ S. L. Santi,^{35, 8} C. Schlesier,³⁷ A. Schreder,¹¹ M. Sorbara,^{12, 33} D. Stöckinger,²⁸ G. Sweetmore,⁴⁰ D. A. Sweigart,⁶ K. Thomson,³⁹ V. Tishchenko,¹¹ T. Walton,⁷

PRA Proton precession

PRD Muon precession

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

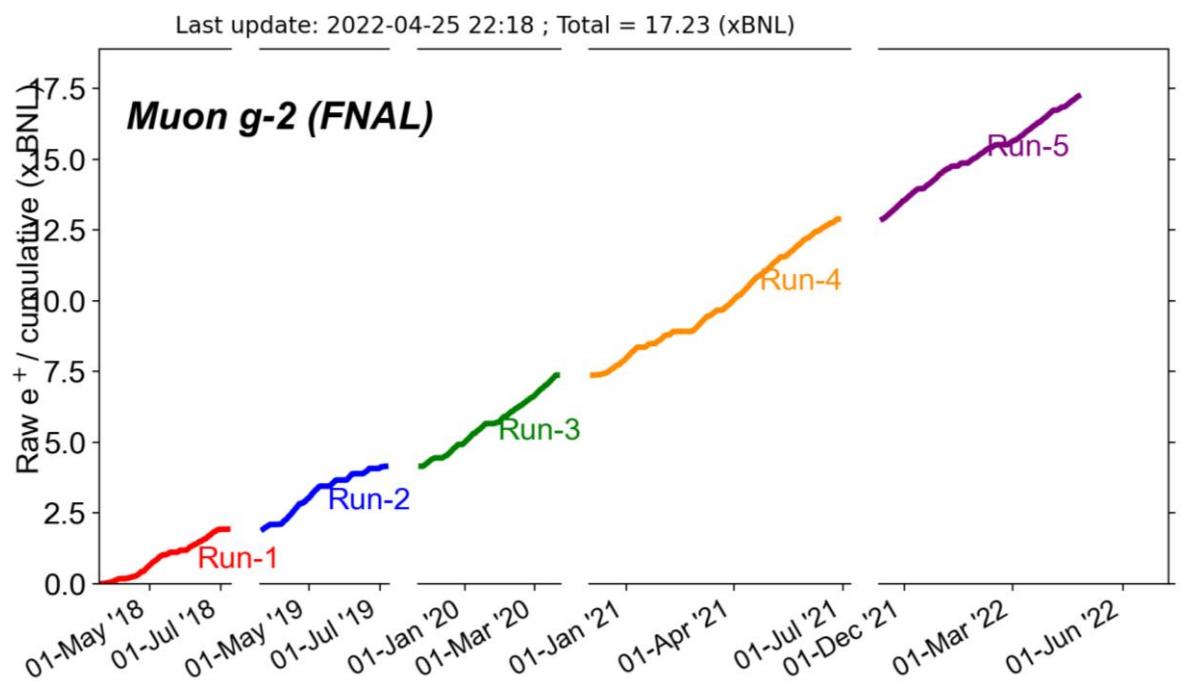
B. Abi,⁴⁴ T. Albahri,³⁹ S. Al-Kilani,³⁶ D. Allspach,⁷ L. P. Alzonij,⁴⁸ A. Anastasi,^{11, a} A. Anisenkov,^{4, b} F. Azfar,⁴⁴ K. Badgley,⁷ S. Baefler,^{47, c} I. Bailey,^{19, d} V. A. Baranov,¹⁷ E. Barlas-Yucel,³⁷ T. Barrett,⁶ E. Barzi,⁷ A. Basti,^{11, 32} F. Bedeschi,¹¹ A. Behnke,²² M. Berz,²⁰ M. Bhattacharya,⁴³ H. P. Binney,⁴⁸ R. Bjorkquist,⁶ P. Bloom,²¹ J. Bono,⁷ E. Bottalico,^{11, 32} T. Bowcock,³⁹ D. Boyden,²² G. Cantatore,^{13, 34} R. M. Carey,² J. Carroll,³⁹ B. C. K. Casey,⁷ D. Cauz,^{35, 8} S. Ceravolo,⁹ R. Chakraborty,³⁸ S. P. Chang,^{18, 5} A. Chapelain,⁶ S. Chappa,⁷ S. Charity,⁷ R. Chislett,³⁶ J. Choi,⁵ Z. Chu,^{26, e} T. E. Chupp,⁴² M. E. Convery,⁷ A. Conway,⁴¹ G. Corradi,⁹ S. Corradi,¹ L. Cotrozzi,^{11, 32} J. D. Crnkovic,^{3, 37, 43} S. Dabagov,^{9, f} P. M. De Lurgio,¹ P. T. Debevec,³⁷ S. Di Falco,¹¹ P. Di Leo,¹⁰ G. Di Sciascio,¹² R. Di Stefano,^{10, 30} B. Drendel,⁷ A. Driutti,^{35, 13, 38} V. N. Duginov,¹⁷ M. Eads,²² N. Eggert,⁶ A. Epps,²² J. Esquivel,⁷ M. Farooq,⁴² R. Fatemi,³⁸ C. Ferrari,^{11, 14} M. Fert,^{48, 16} A. Fiedler,²² A. T. Fienberg,⁴⁸ A. Fioretti,^{11, 14} D. Flay,⁴¹ S. B. Foster,² H. Friedsam,⁷ E. Frelez,⁴⁷ N. S. Froemming,^{48, 22} J. Fry,⁴⁷ C. Fu,^{26, e} C. Gabbanini,^{11, 14} M. D. Galati,^{11, 32} S. Ganguly,^{37, 7} A. Garcia,⁴⁸ D. E. Gastler,² J. George,⁴¹ L. K. Gibbons,⁶ A. Gioiosa,^{29, 11} K. L. Giovanetti,¹⁵ P. Girotti,^{11, 32} W. Gohn,³⁸ T. Gorringe,³⁸ J. Grange,^{1, 42} S. Grant,³⁶ F. Gray,²⁴ S. Haciomeroglu,⁵ D. Hahn,⁷ T. Halewood-Leagues,³⁹ D. Hampai,⁹ F. Han,³⁸ E. Hazen,² J. Hempstead,⁴⁸ S. Henry,⁴⁴ A. T. Herrod,^{39, d} D. W. Hertzog,⁴⁸ G. Heske,³⁶ A. Hibbert,³⁹ Z. Hodge,⁴⁸ J. L. Holzbauer,⁴³ K. W. Hong,⁴⁷ R. Hong,^{1, 38} M. Iacobacci,^{10, 31} M. Incaglia,¹¹ C. Johnstone,⁷ J. A. Johnstone,⁷ P. Kammler,⁴⁸ M. Kargianoulakis,⁷ M. Karuza,^{13, 45} J. Kaspar,⁴⁸ D. Kawall,⁴¹ L. Kelton,³⁸ A. Keshavarzi,⁷ D. Kessler,⁴¹ K. S. Khaw,^{27, 26, 48, e} Z. Khechadoorian,⁶ N. V. Khoumoutov,¹⁷ B. Kiburg,⁷ M. Kiburg,⁷ O. Kim,^{18, 5} S. C. Kim,⁶ Y. I. Kim,⁵ B. King,^{39, a} N. Kinnaird,² M. Korostelev,^{19, d} I. Kourbanis,⁷ E. Kraegeloh,⁴² V. A. Krylov,¹⁷ A. Kuchibhotla,³⁷ N. A. Kuchiniskiy,¹⁷ K. R. Labe,⁶ J. LaBounty,⁴⁸ M. Lancaster,⁴⁰ M. J. Lee,⁵ S. Lee,⁵ S. Leo,³⁷ B. Li,^{26, 1, e} D. Li,^{26, g} L. Li,^{26, e} I. Logashenko,⁶ A. Lorente Campos,³⁸ A. Luci,⁷ G. Lukicov,³⁶ G. Luo,²² A. Lusiani,^{11, 25} A. Lyon,⁷ B. MacCoy,⁴⁸ R. Madrak,⁷ K. Makino,²⁰ F. Marignetti,^{10, 30} S. Mastroiani,¹⁰ S. Maxfield,³⁹ M. McEvoy,²² W. Merritt,⁷ A. A. Mikhailichenko,^{6, a} J. P. Miller,² S. Miozzoli,¹² J. P. Morgan,⁷ W. M. Morse,³ J. Mott,^{2, 7} E. Motuk,³⁶ A. Nath,^{10, 31} D. Newton,^{39, h} H. Nguyen,⁷ M. Oberling,¹ R. Osofsky,⁴⁸ J.-F. Ostiguy,⁷ S. Park,⁵ G. Pauleta,^{35, 8} G. M. Piacentino,^{29, 12} R. N. Pilato,^{11, 32} K. T. Pitts,³⁷ B. Plaster,³⁸ D. Počanic,⁴⁷ N. Pohlman,²² C. C. Polley,⁷ M. Popovic,⁷ J. Price,³⁹ B. Quinn,⁴³ N. Raha,¹¹ S. Ramachandran,¹ E. Ramberg,⁷ N. T. Rider,⁶ J. L. Ritchie,⁴⁶ B. L. Roberts,² D. L. Rubin,⁶ L. Santi,^{35, 8} D. Sathyam,² H. Schellman,^{23, 1} C. Schlesier,³⁷ A. Schreckenberger,^{46, 2, 37} Y. K. Semertzidis,^{5, 18} Y. M. Shatunov,⁴ D. Shemyakin,^{4, b} M. Shenk,²² D. Sim,³⁹ M. W. Smith,^{48, 11} A. Smith,³⁹ A. K. Soha,⁷ M. Sorbara,^{12, 33} D. Stöckinger,²⁸ J. Stapleton,⁷ D. Still,⁷ C. Stoughton,⁷ D. Stratakis,⁷ C. Strohman,⁶ T. Stuttard,³⁶ H. E. Swanson,⁴⁸ G. Sweetmore,⁴⁰ D. A. Sweigart,⁶ M. J. Syphers,^{22, 7} D. Tarazona,²⁰ T. Teubner,³⁹ A. E. Tewsley-Booth,⁴² K. Thomson,³⁹ V. Tishchenko,³ N. H. Tran,² W. Turner,³⁹ E. Valetov,^{20, 19, 27, d} D. Vasilkova,³⁶ G. Venanzoni,¹¹ V. P. Volnykh,¹⁷ T. Walton,⁷ M. Warren,³⁶ A. Weisskopf,²⁰ L. Welty-Rieger,⁷ M. Whitley,³⁹ P. Winter,¹ A. Wolski,^{39, d} M. Wormald,³⁹ W. Wu,⁴³ and C. Yoshikawa⁷

(The Muon $g - 2$ Collaboration)

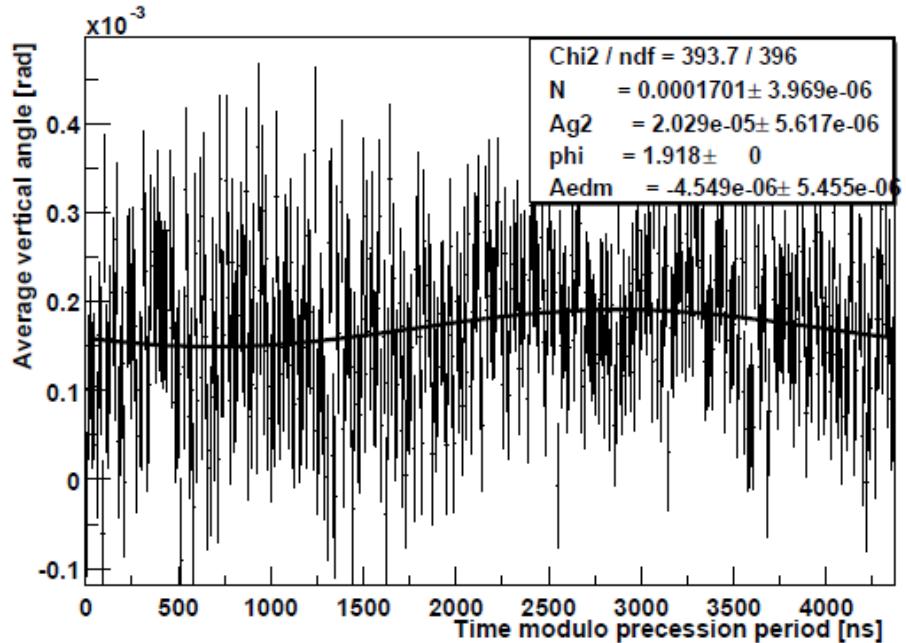
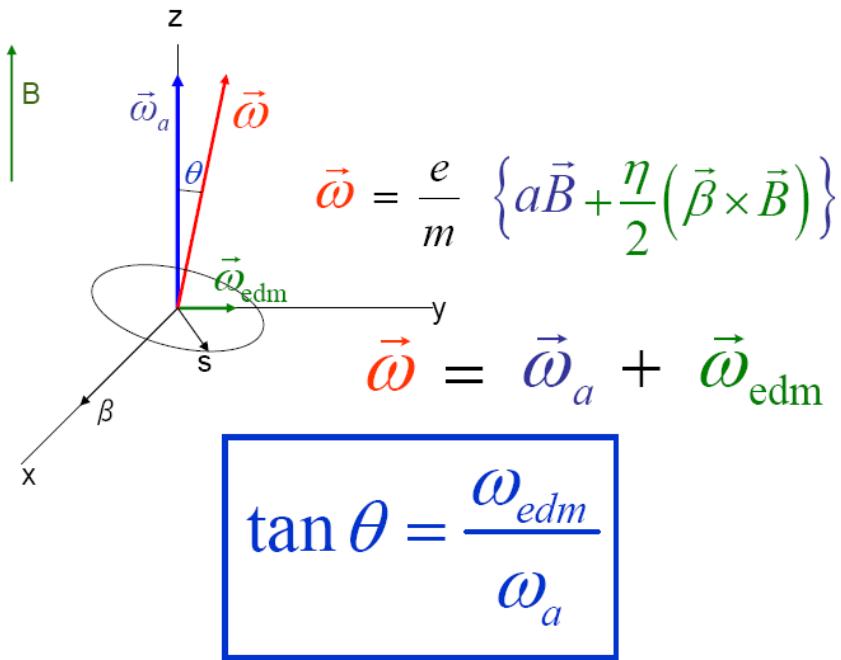


ЭТО ТОЛЬКО ПЕРВЫЙ СЕЗОН!

- RUN1 is only 6% of the final dataset ... with 4 configurations.
- Recently surpassed 17 BNL data sets.
- Runs 2, 3 has ~1 data-taking configuration with higher kick setting
- Run 4 (now) has the best kicker setting (met TDR) !



Effect of EDM



Non-zero EDM presents itself as up-down oscillations

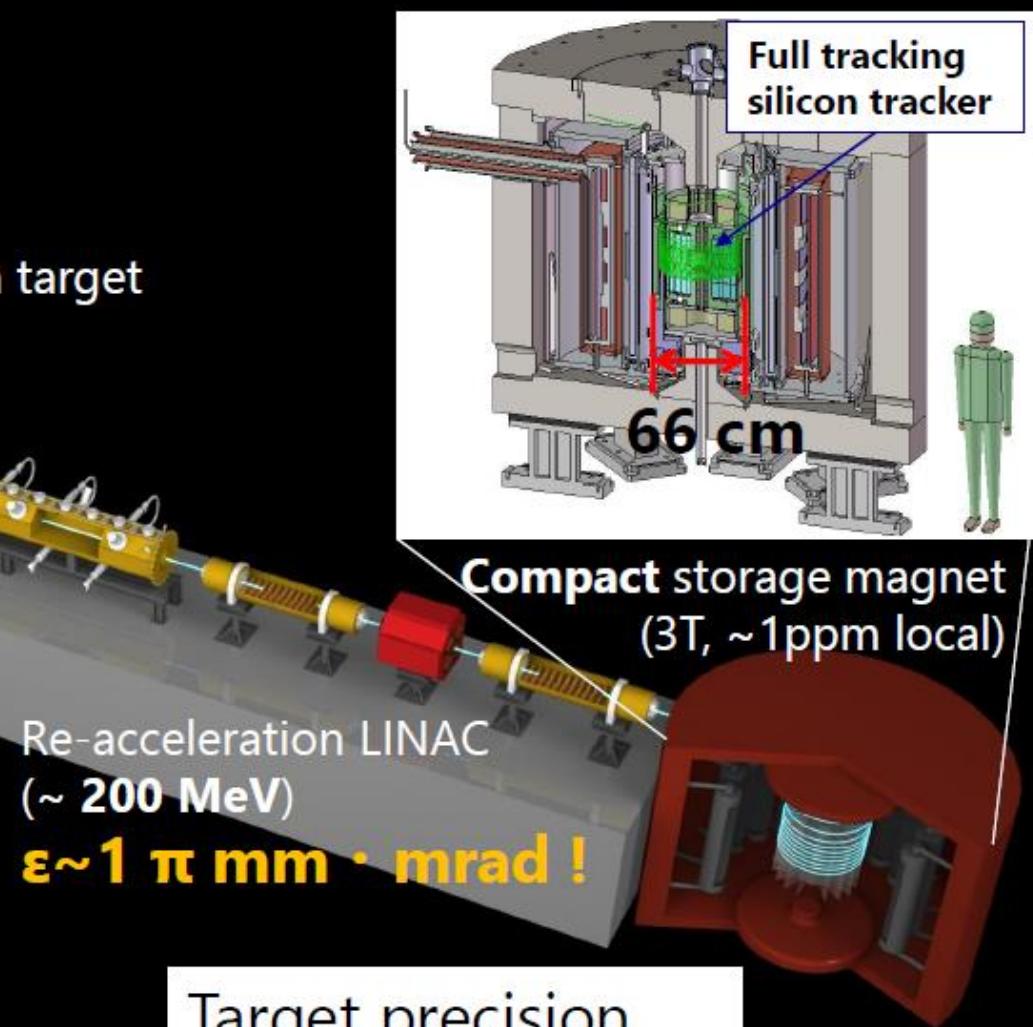
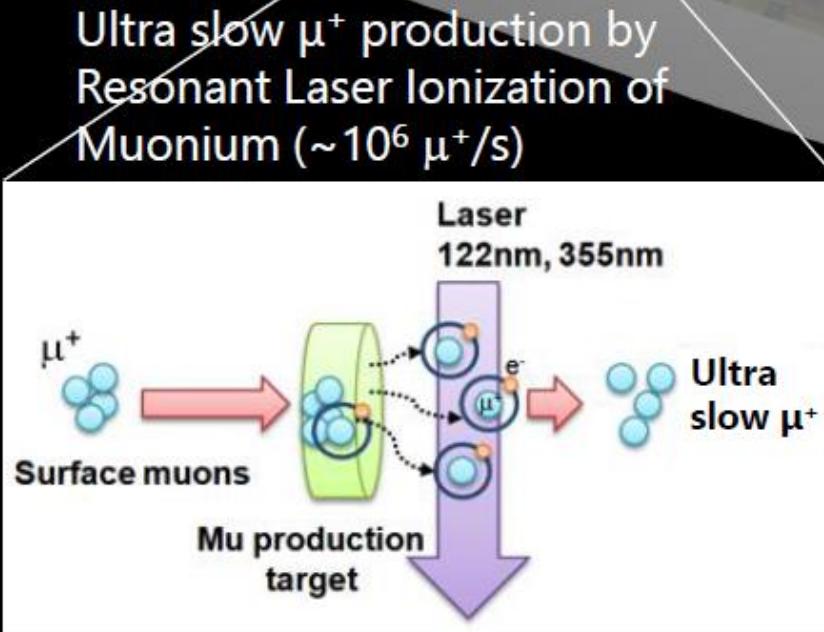
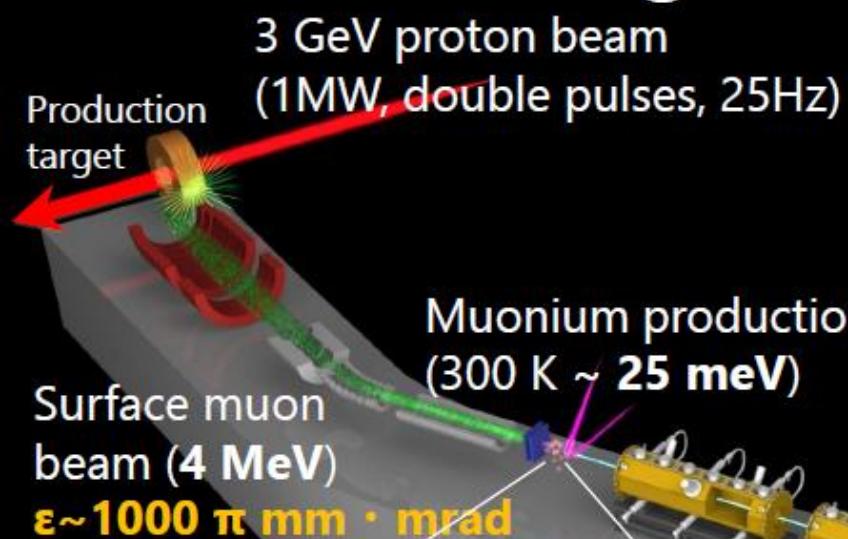
BNL limit: $|d_\mu| \leq 1.8 \times 10^{-19} e \cdot cm$ (95%)

EDM at this level corresponds to $\Delta a_\mu = 1.6 \text{ ppm}$.

But we assume $|d_\mu| \leq 3.2 \times 10^{-25} e \cdot cm$ from $|d_e|$ limit.

FNAL should improve BNL limit by factor of ~100.

J-PARC $g-2$ experiment (E34)



Target precision
 $\Delta(g-2) = 0.1 \text{ ppm}$
 $\Delta\text{EDM} = 10^{-21} \text{ e} \cdot \text{cm}$

Comparison of Experiment Parameters

Table 1. Comparison of BNL-E821, FNAL-E989, and our experiment.

| | BNL-E821 | Fermilab-E989 | Our experiment | J-PARC E34 |
|---------------------------|---|----------------------|--|---------------------------------------|
| Muon momentum | | 3.09 GeV/c | 300 MeV/c | |
| Lorentz γ | | 29.3 | 3 | |
| Polarization | Radius of cyclotron motion: 7.1 m | 100% | 50% | Radius of cyclotron motion: 333 mm |
| Storage field | | $B = 1.45$ T | $B = 3.0$ T | |
| Focusing field | | Electric quadrupole | Very weak magnetic | |
| Cyclotron period | | 149 ns | 7.4 ns | |
| Spin precession period | | 4.37 μ s | 2.11 μ s | |
| Number of detected e^+ | 5.0×10^9 | 1.6×10^{11} | 5.7×10^{11} | |
| Number of detected e^- | 3.6×10^9 | – | – | |
| a_μ precision (stat.) | 460 ppb | 100 ppb | 450 ppb | |
| (syst.) | 280 ppb | 100 ppb | <70 ppb | |
| EDM precision (stat.) | $0.2 \times 10^{-19} e \cdot \text{cm}$ | – | $1.5 \times 10^{-21} e \cdot \text{cm}$ | |
| (syst.) | $0.9 \times 10^{-19} e \cdot \text{cm}$ | – | $0.36 \times 10^{-21} e \cdot \text{cm}$ | |

[PTEP 2019 \(2019\), 053C02](#)

From talk **Muon g-2/EDM Experiment at J-PARC** by Takashi Yamanaka at g-2 meeting

Schedule

- Construction of experimental components is ongoing aiming at the start of the experiment in 2027 JFY.

| JFY | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | |
|---|------|---|------|------|------|------|--|---|
| H2 area | |  | | | | |  |  |
| H-line experimental building | | | | | | |  | |
| Muon Source, LINAC, injection, storage magnet, detector | | | | | | |  | |
| Grant-in-Aids | | | | | | | | |

From talk **Muon g-2/EDM Experiment at J-PARC** by Takashi Yamanaka at g-2 meeting

On a theoretical side...

Интересно не само значение аномального момента мюона, а его
отличие от предсказания Стандартной модели

$$\Delta a_\mu(\text{New Physics}) = a_\mu(\text{exp}) - a_\mu(\text{SM})$$

Вычисление a_μ в Стандартной модели:

$$a_\mu = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

Расчет $a_\mu(\text{SM})$ не менее важен, чем измерение $a_\mu(\text{exp})!$

Итак:

- Эксперимент в Фермилаб подтвердил результаты предыдущего измерения в БНЛ аномального магнитного момента мюона
- На сегодняшний день наблюдается интригующая разница 4σ между измеренных значением ($g-2$) мюона и его предсказанием в рамках Стандартной Модели
- Эксперимент в Фермилаб продолжается. Уже набраны данные для улучшения точности приблизительно в 4 раза

Про предсказание Стандартной Модели – на следующей лекции...