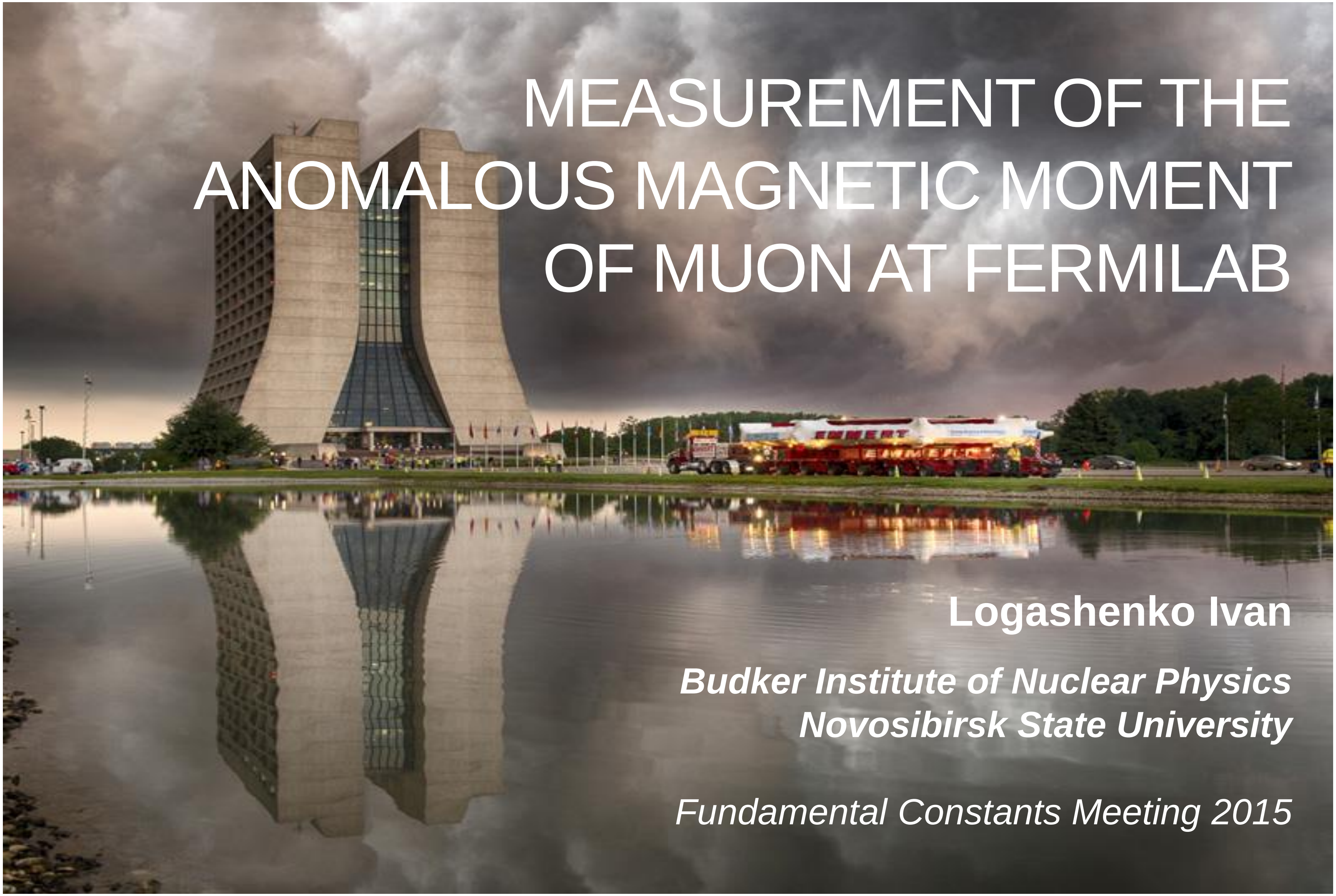


MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF MUON AT FERMILAB

Logashenko Ivan

Budker Institute of Nuclear Physics
Novosibirsk State University

Fundamental Constants Meeting 2015

The g-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 ½ particle has $g = 2$ exactly
- Experimental values:

$$\left.\begin{aligned} g_e &\approx 2.002 \\ g_\mu &\approx 2.002 \end{aligned}\right\} \text{point-like particles}$$

$$\left.\begin{aligned} g_p &\approx 5.586 \\ g_n &\approx -3.826 \end{aligned}\right\} \text{compound particles}$$

Anomalous magnetic moment: $a = (g-2)/2$

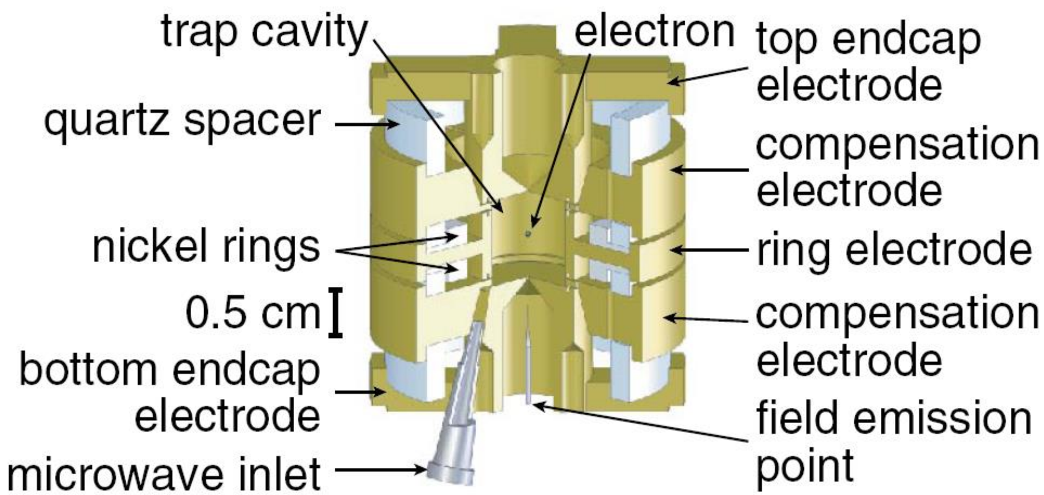
$$a \approx 10^{-3}$$

Electron (g-2)

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

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

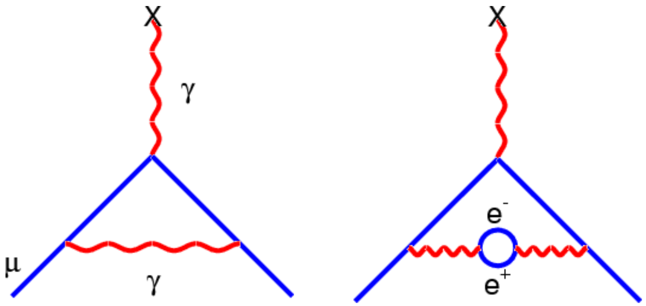


Talk by Elise Novitski on Tuesday

Muon (g-2) as the probe of vacuum

The value of g is modified by quantum field fluctuations, resulting in *anomalous magnetic moment*:

$$a_\mu = \frac{g-2}{2} \approx \frac{\alpha}{2\pi} \approx \frac{1}{800}$$



G-2 probes structure of the vacuum. Higher precision means shorter distances and higher energies. All virtual fields contribute to (g-2).

Muon (g-2) is 40,000 times more sensitive to non-QED fields than electron (g-2), providing more sensitive probe for New Physics.

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

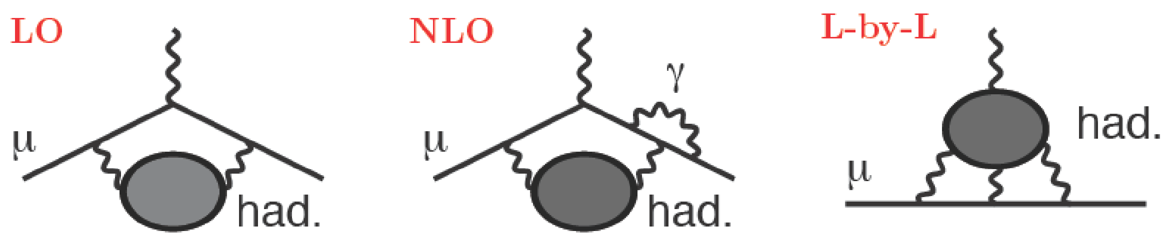
$$1{,}000{,}000 \quad : \quad 60 \quad : \quad 1.3 \quad : \quad \propto \left(m_\mu / m_X\right)^2$$

Taus are even better! But they are too short lived and too difficult to produce…

The SM value of a_μ: today

- QED: Kinoshita et al., 2012: up to 5 loops (12672 diagrams). 0.7 ppb
- EW: 2 loops, now Higgs mass is known. 9 ppb
- Hadronic

$$a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{had,VP\ LO}} + a_\mu^{\mathrm{had,VP\ NLO}} + a_\mu^{\mathrm{had,Light-by-Light}}$$



370 ppb 10 ppb 220 ppb

LBL: model-dependent calculations; improvement is expected from lattice calculations

HVP: the value is based on the hadronic cross-section e^+e^- data; there are effort to get it via lattice calculations.

New experiment at FNAL: 140 ppb

40 years of muon (g-2)

CERN I (1958-1962):

First measurement, (g-2) to 0.4%

CERN II (1962-1968):

First muon storage ring, magnetic focusing, (g-2) to 270 ppm

CERN III (1969-1976):

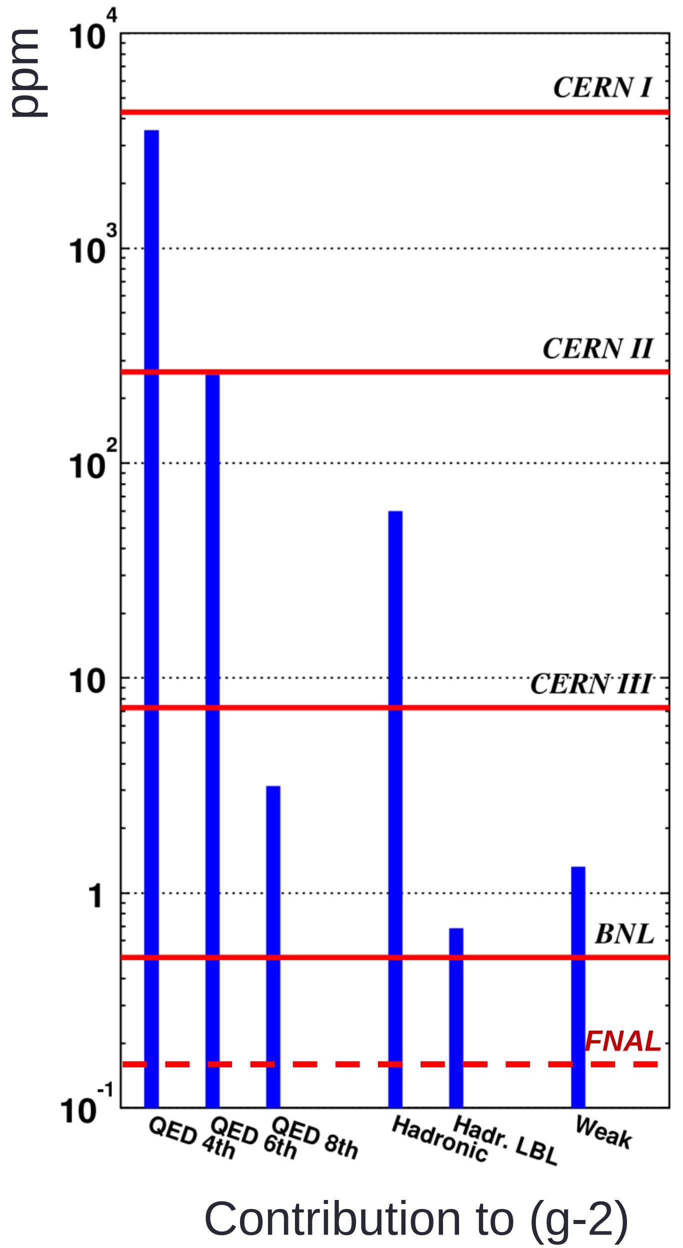
Magic γ, electric field focusing, μ^+ and μ^-, (g-2) to 7 ppm

BNL (1990-2003):

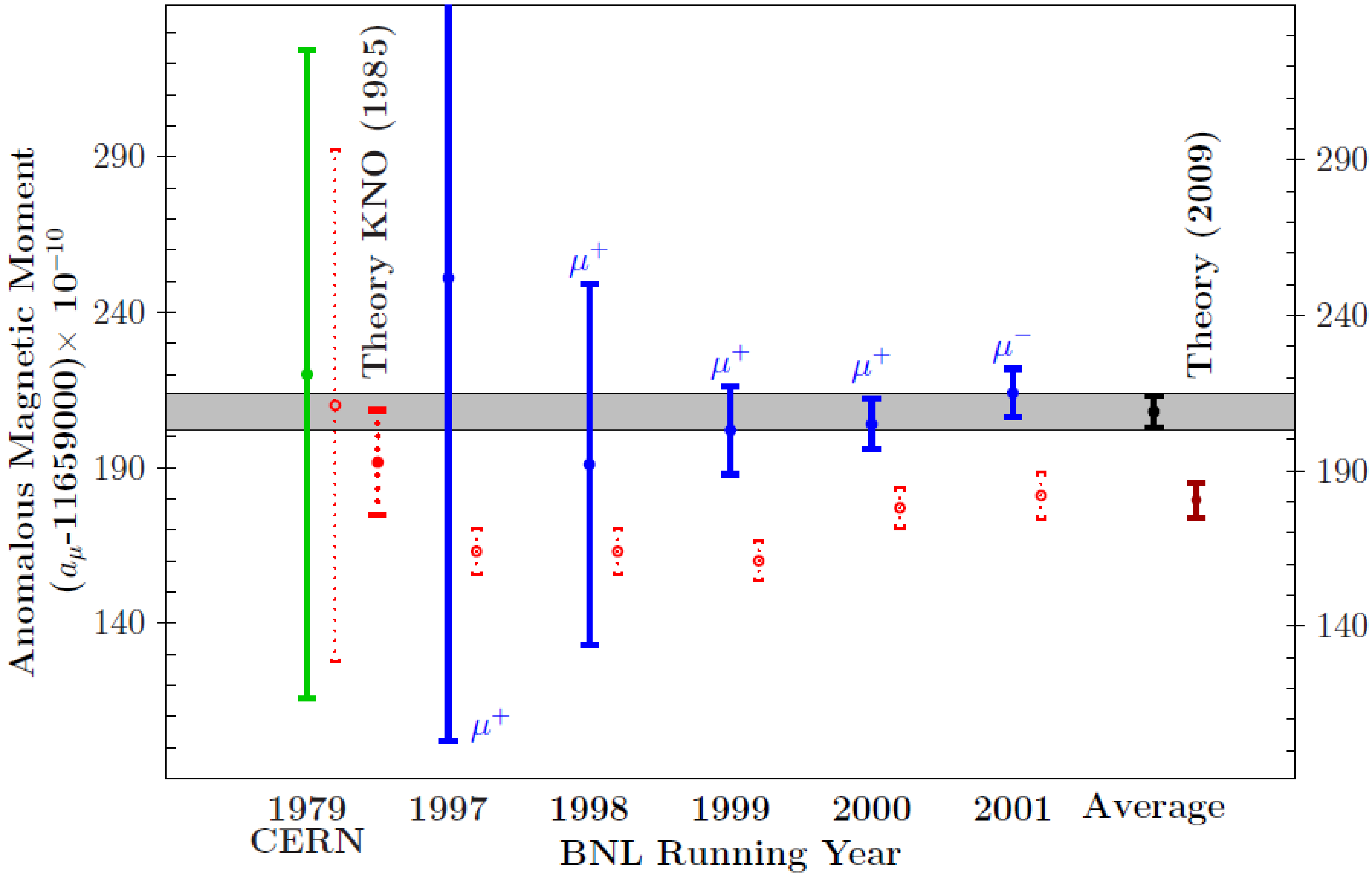
Superferric magnet, high intensity beam, muon injection, (g-2) to 0.5 ppm

FNAL (2016-?):

Improvements in all aspects, Q-method, (g-2) to 0.14 ppm



Muon (g-2): BNL era

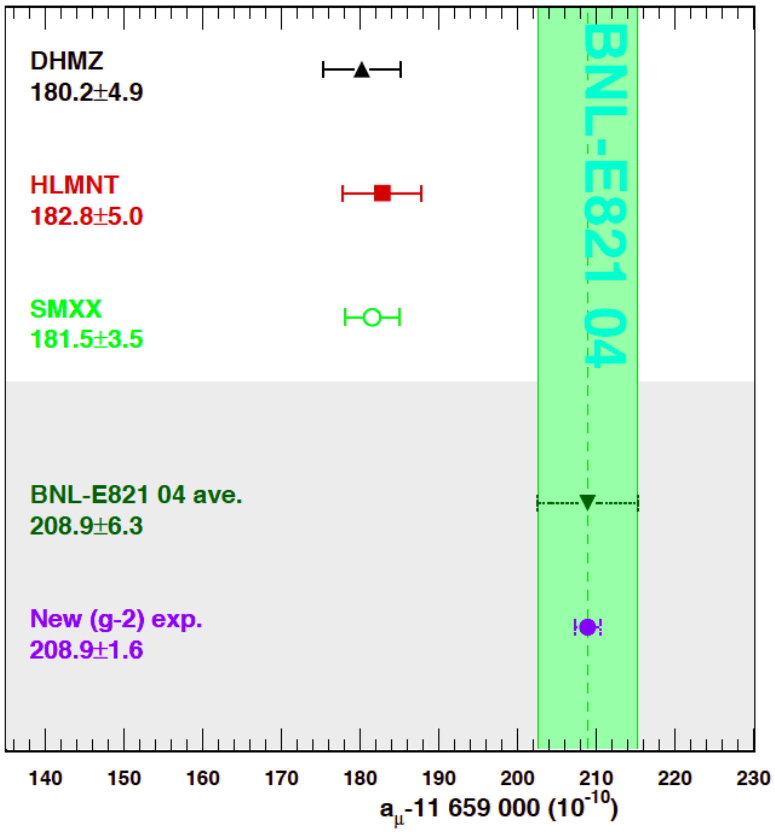


Muon (g-2): experiment vs theory

$a_\mu(exp) = 1\ 165\ 920\ 89\ (63) \times 10^{-11}$ (0.54 ppm)

$a_\mu(th) \quad = 1\ 165\ 918\ 02\ (49) \times 10^{-11}$ (0.42 ppm)

$$\Delta a_\mu(exp - th) = \underbrace{(260 \div 287) \pm 80 \times 10^{-11}}_{3.3 \div 3.6\ \sigma}$$



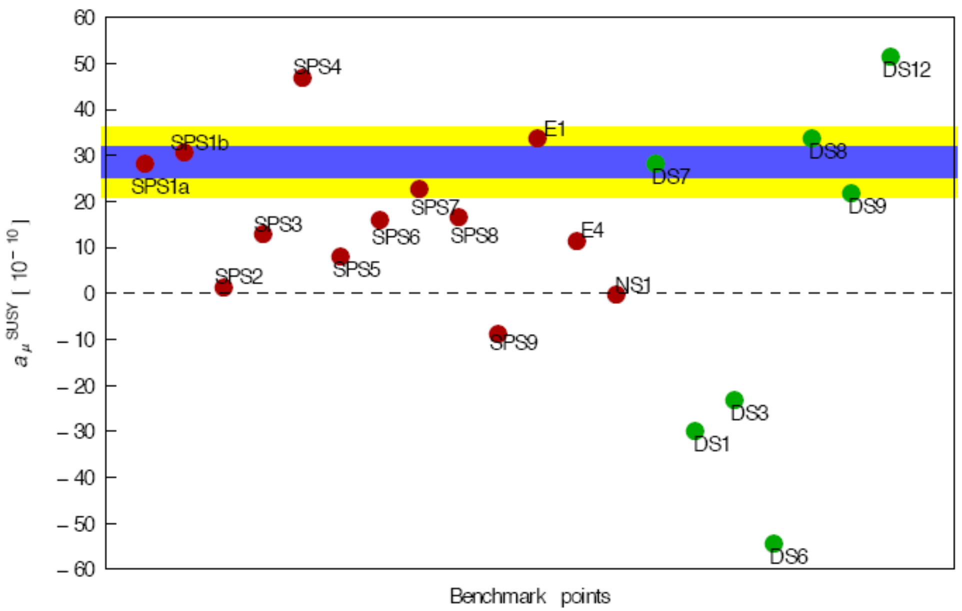
Fermilab projections:

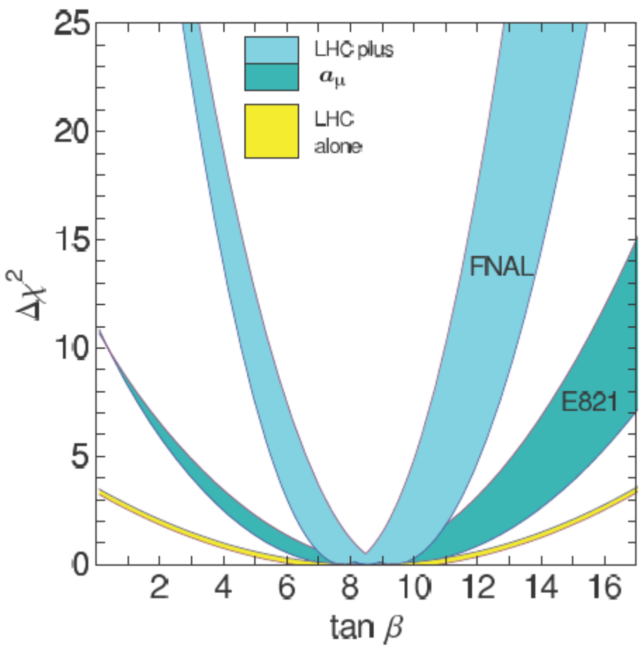
$a_\mu(exp)$ → to 0.14 ppm
$a_\mu(th)$ → to 0.30 ppm

$\Delta a_\mu(exp - th) \rightarrow$ to $\pm 40 \times 10^{-11}$

Is there New Physics to explain Δa_μ?

The value of Δa_μ is unexpectedly large – same order of magnitude as electroweak contribution. Are there models to explain such large contribution? Plenty!





The value of muon (g-2) is a powerful "model selector" and in many scenarios is complementary to LHC.

Experimental technique since CERN-II

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

Polarized muons

Make a pion beam, then select highest energy muons from parity violating $\pi \rightarrow \mu + \nu_\mu$ decay

Precession in uniform B-field

Storage ring with ultra-precise dipole B-field. Allow muons to precess through as many g-2 cycles as possible.

Measure muon spin direction vs time

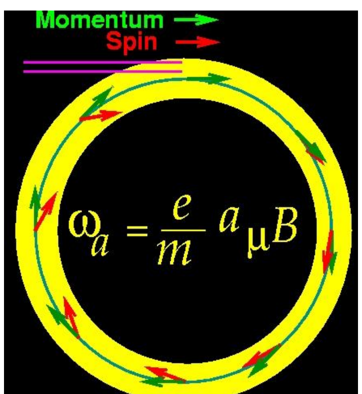
In parity violating decay $\mu \rightarrow e + \nu_e + \nu_\mu$, the positron is preferentially emitted in the muon spin direction

Magic γ

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.

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}}_{=0} + \underbrace{\cancel{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}}_{=0}\right]$$



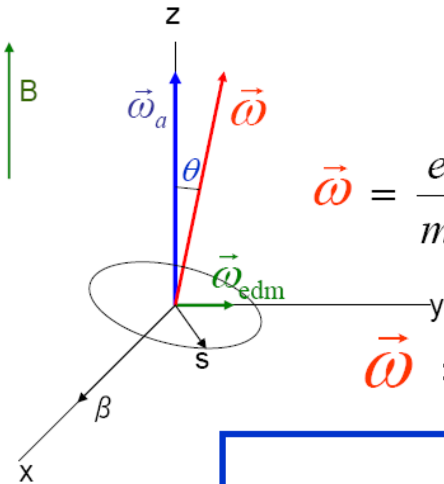
$$\gamma_{\text{magic}} = 29.3$$

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

Contribution from potential EDM (more later)

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

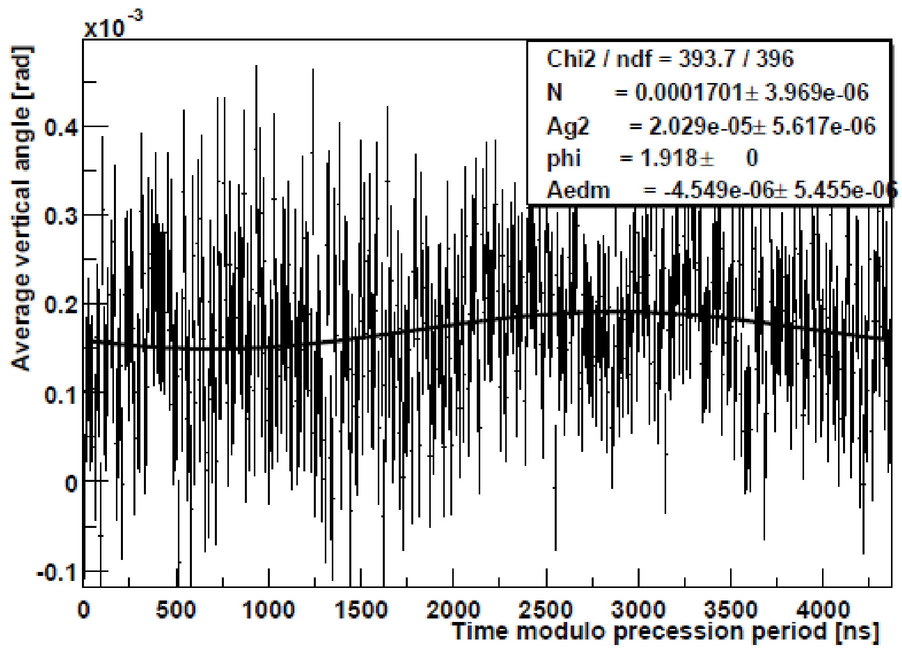
Effect of EDM



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\rm edm}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$



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 $\Delta a_\mu = 1.6\ ppm$.

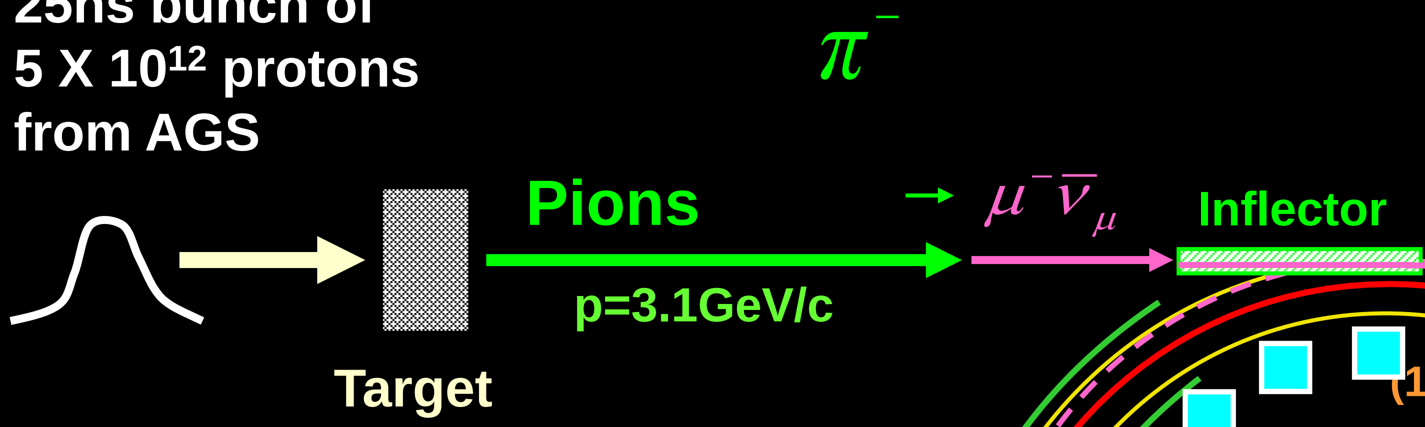
But we assume $|d_\mu| \leq 3.2 \times 10^{-25}\ e \cdot cm$ from $|d_e|$ limit.

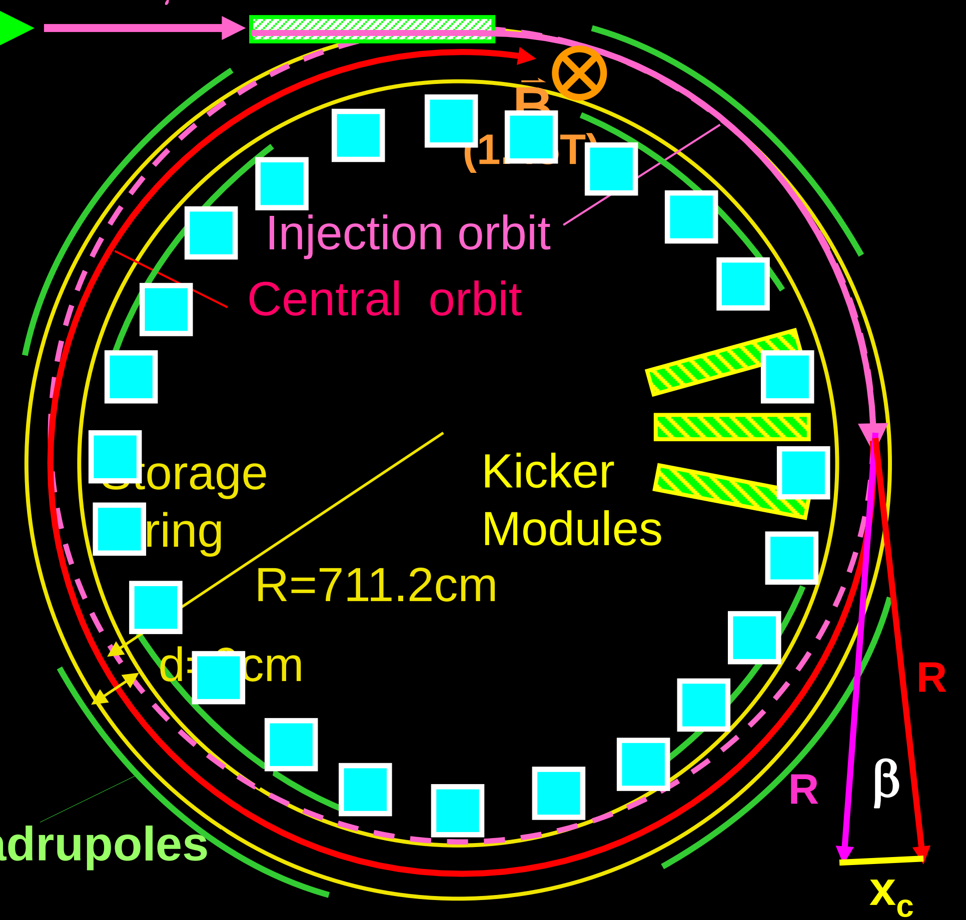
FNAL should improve BNL limit by factor of ~100.

Experimental Technique in BNL

25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B \cdot dl \approx 0.1$ Tm





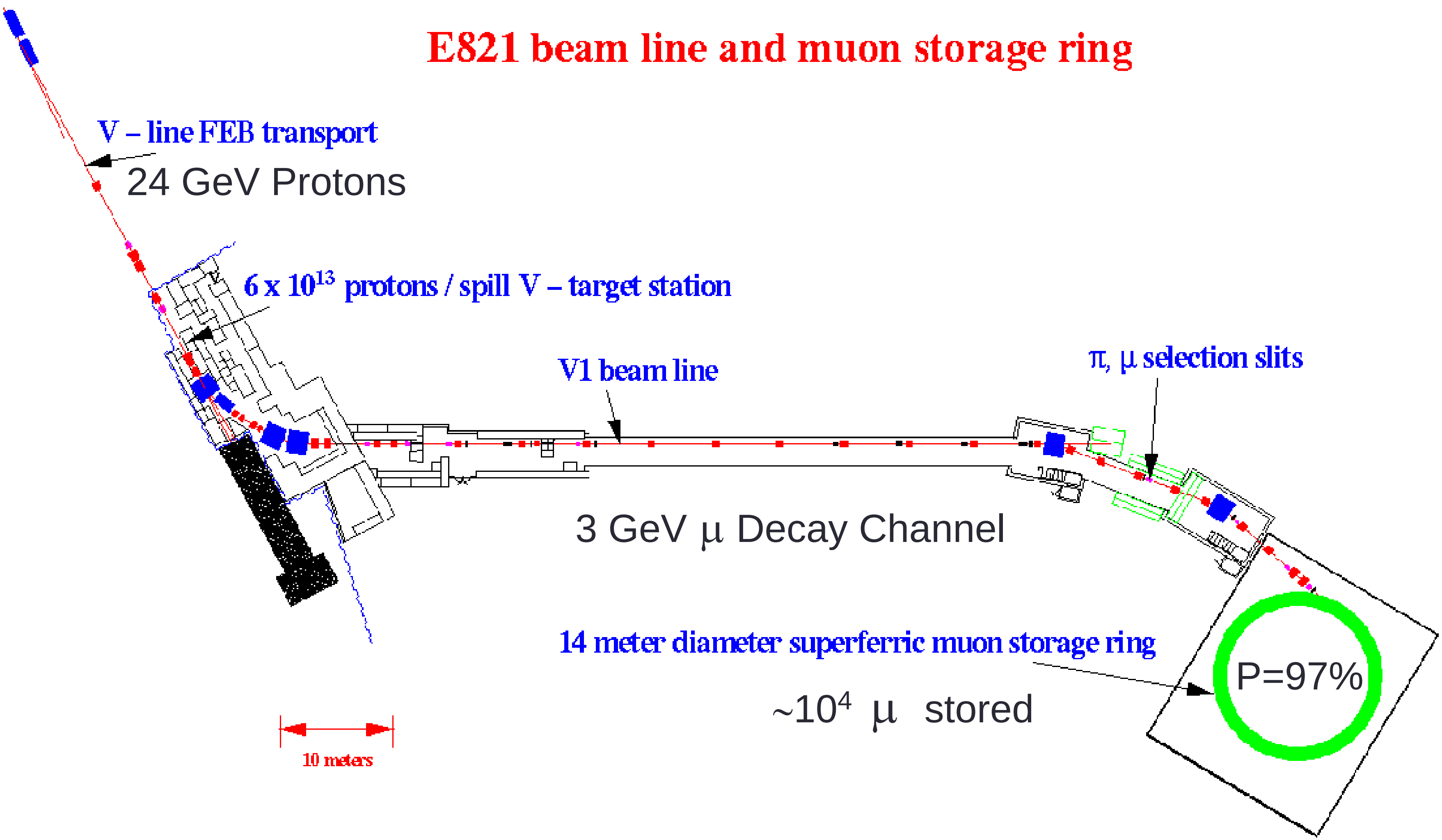
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

Courtesy of B.L.Roberts

Logashenko
Ivan

Layout of BNL experiment (1997-2001)

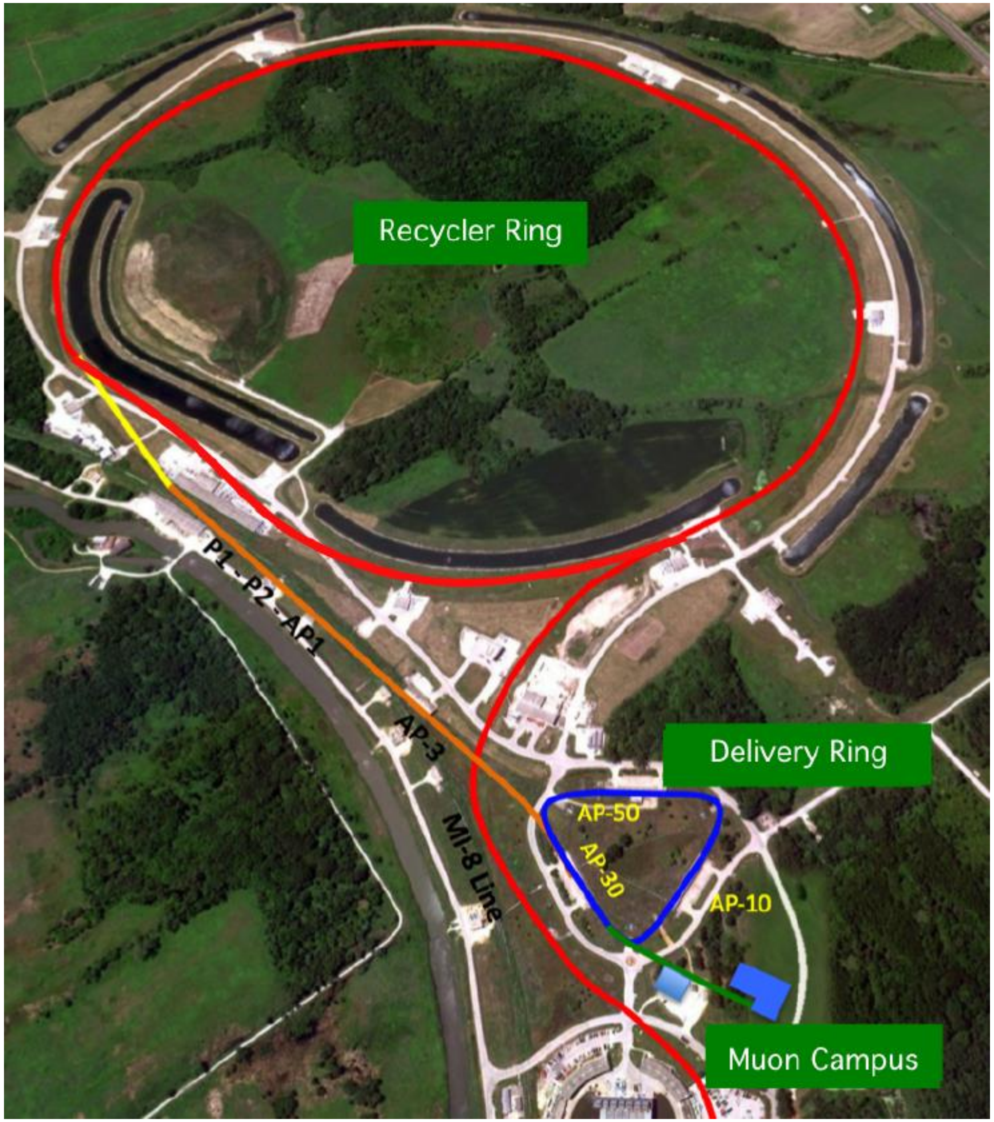


Layout of FNAL experiment

- 8 GeV/c protons from the Booster are rebunched in Recycler Ring
- Transfer line and Delivery Ring (part of old $\bar{p}$ source) make ~2 km decay line. No pion background!

20 times more statistics!:

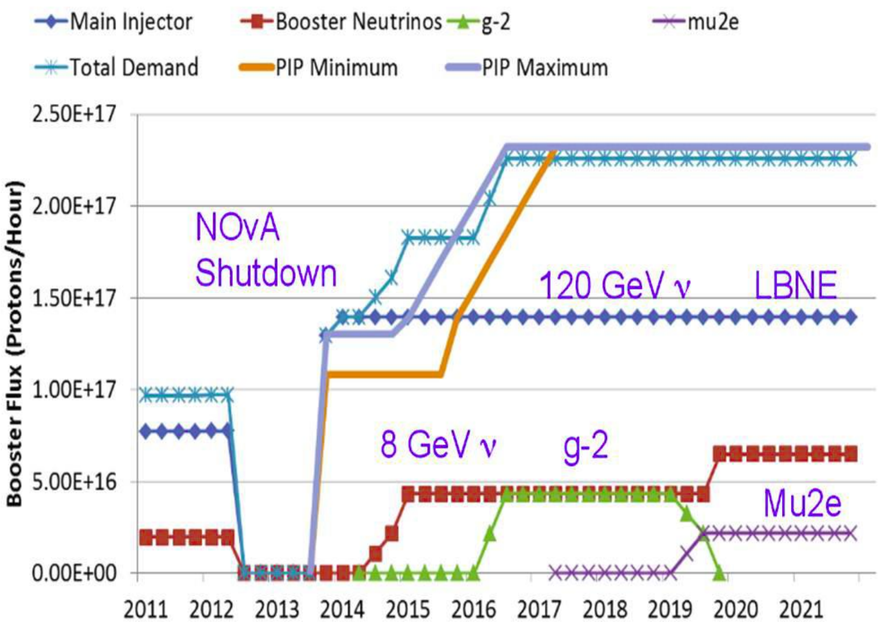
Running time	1.5-2 years
Stored muons	$> 2 \cdot 10^{12}$
Detected decay electrons with $E > 1.8$ GeV	$> 1.6 \cdot 10^{11}$
Protons on target	$3 \cdot 10^{20}$



Status of FNAL experiment

- **2013**: the muon storage ring was moved BNL to Fermilab
- **2014**: construction of the experimental hall (brand new building) is finished; the ring is in the building and is being equipped.
- **2015**: plan to power on the ring to the full field and start shimming
- **2016**: construct and install detectors and other equipments
- **2017-2018**: data taking

TDR is available in arXiv



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,… are disassembled and moved by trucks. But there are three coils…

**Continuously wound coils,
can't break into pieces,
can't flex > 3mm**

~15 m diameter, 4 lanes on the highway

**~ $2M to move.
10x more, ~$30M, to build them anew!**

Yes, we can move it!

Fancy trailer: 8 axels, 64 tires

Auto-leveling
Height control
Independent steering

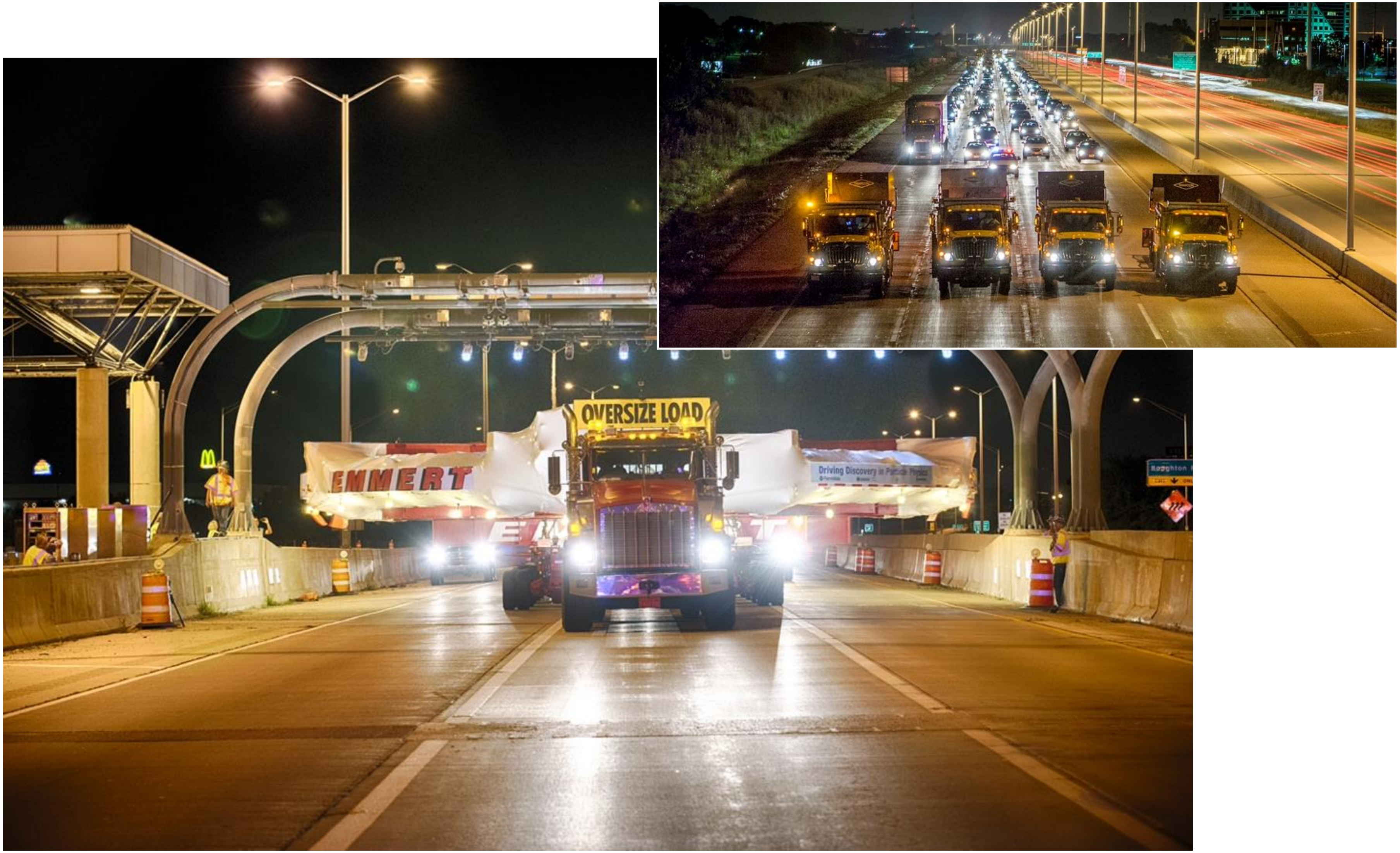
Miss Katie

5000 km journey: June 25 – July 20

Tennessee-Tombigbee Waterway
Mississippi,
Illinois and
Des Plaines rivers.

Lemont, IL - safely ashore

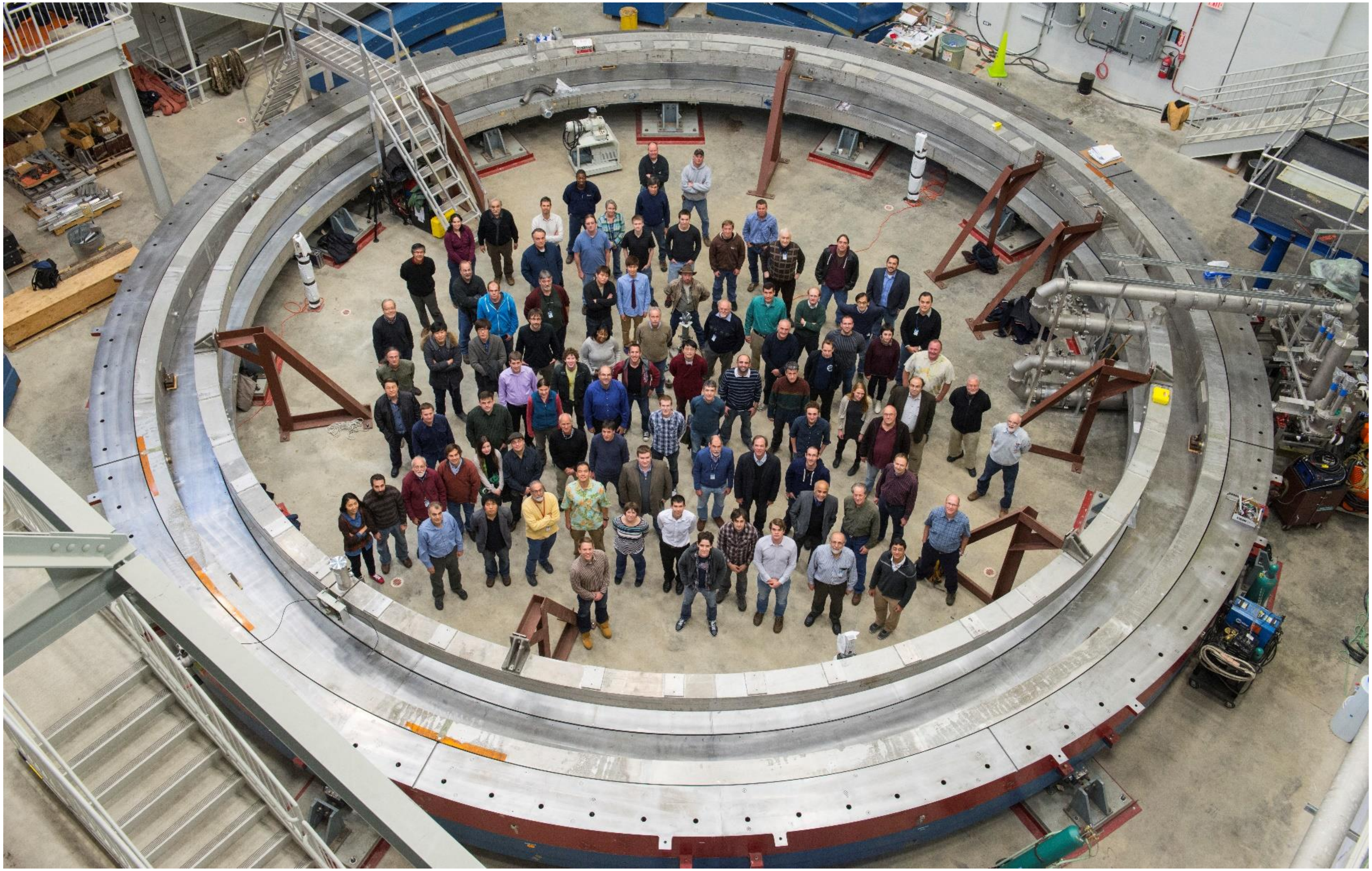
Moving at night to Fermilab



Arriving at Fermilab

Celebration

G-2 ring at Fermilab: November 2014



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**

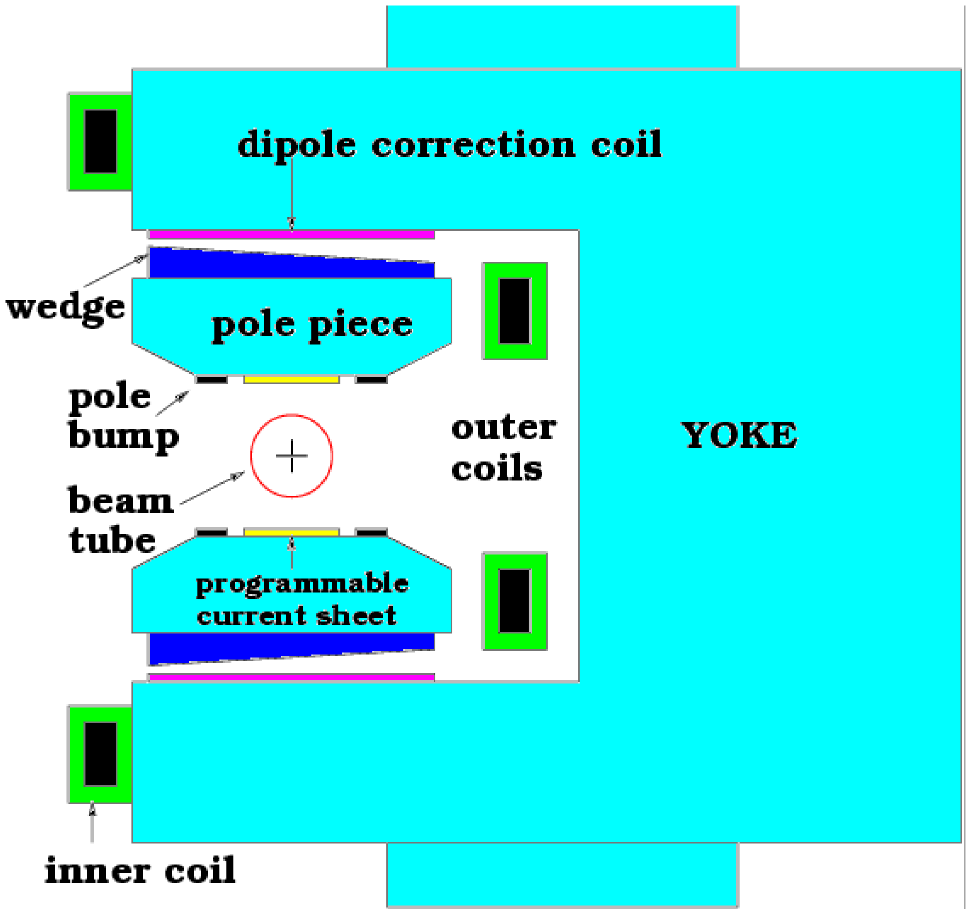
ω_a systematics (ppb)

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**

Improving ω_p

Field is measured in terms of the free proton NMR frequency (ω_p)

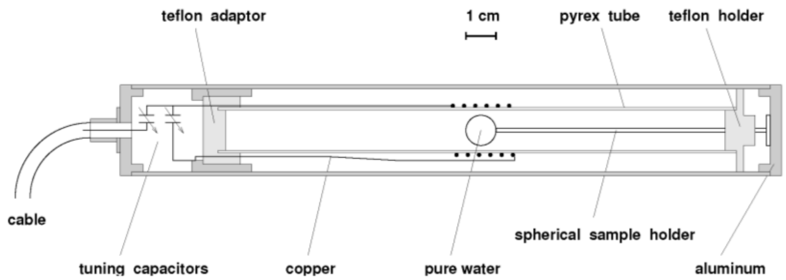
- Absolute calibration from spherical water probe
  - Will be improved
- Field inside the vacuum chamber measured using 17 probes mounted on a “trolley”
  - Better probes, better positioning, more frequent
- Constant monitoring of the field (and stabilization via feedback) using 378 fixed probes
  - Twice number of probes, better temperature control



Absolute calibration

The absolute calibration is done with special spherical pure water NMR probe

This same probe was calibrated in LANL E1054 (muonium experiment) to 34 ppb.



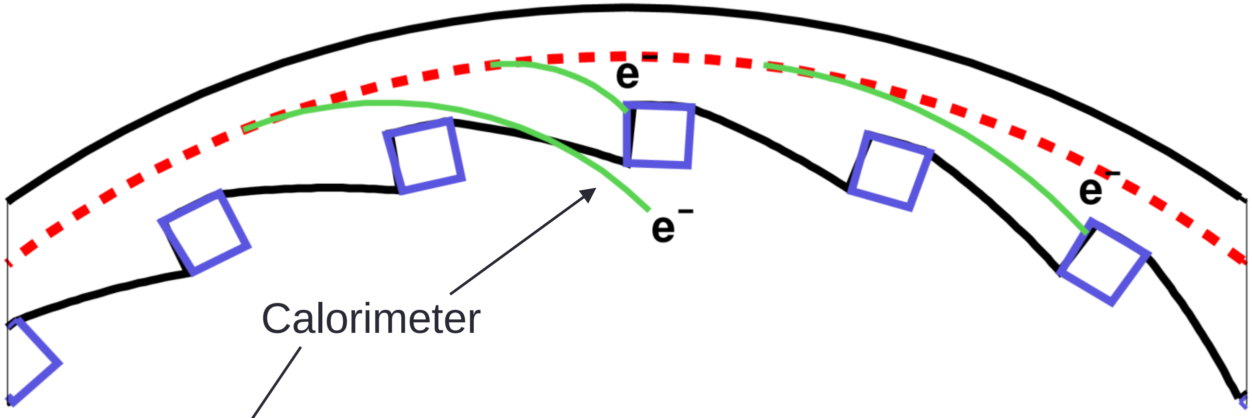
The NMR frequency in water differs from ω_p: $\omega_{probe} = (1-\delta)\cdot\omega_p$

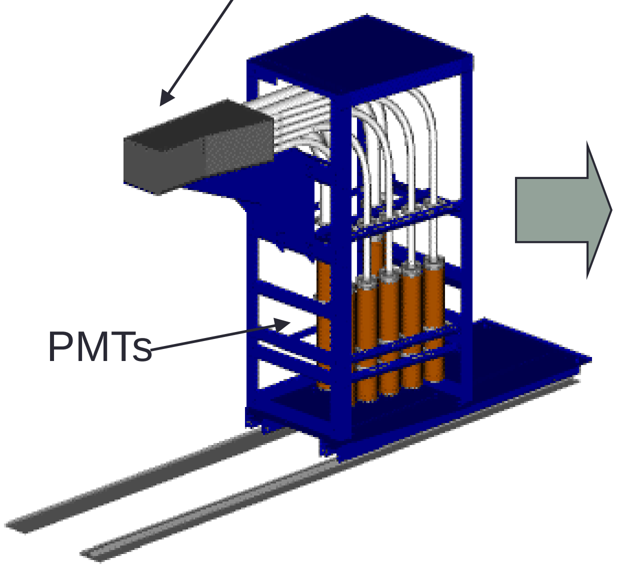
Correction $\delta \approx 26$ ppm, but it is well known to few ppb

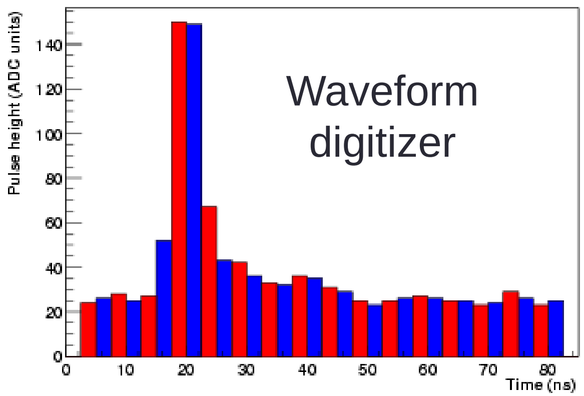
FNAL improvements:

- Build the new absolute calibration probe with the same technology
- Perform independent calibration of the probe
- Improve temperature and position controls, which improves the whole calibration chain: absolute probe → plunging probe → trolley probes
- There is effort to build ^{3}He probe

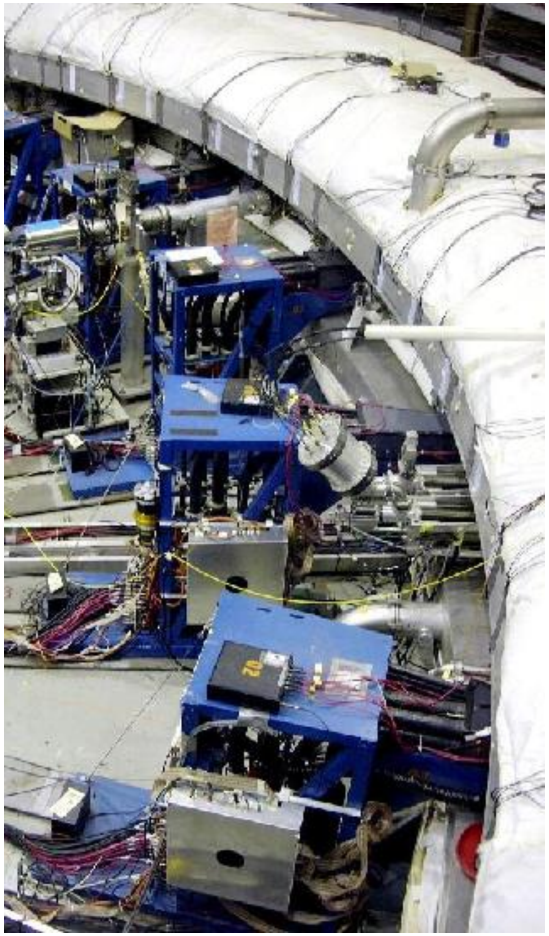
Measuring ω_a







Offline reconstruction of energy and time



Measuring ω_a (T-method)

High energy electrons in LAB frame correlate to forward decay electrons in CM frame

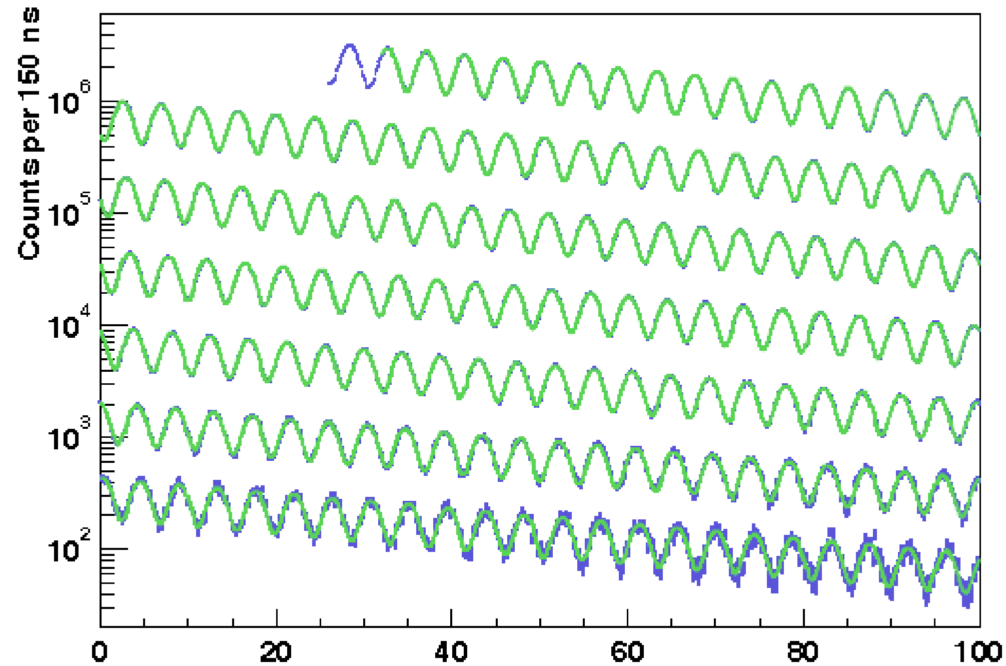
Number of forward decay electrons in CM frame correlates to spin direction

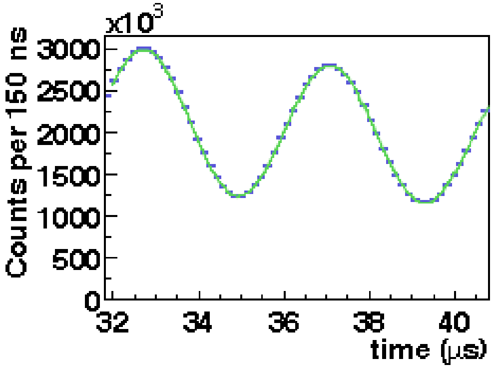
So: count electrons with $E > E_{thr}$

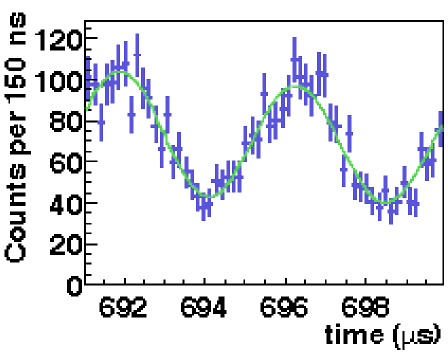
$$N(t) = N_0 e^{-t/\gamma\tau}[1 + A\cos(\omega t + \varphi)]$$

Simple 5-parameter fit! In real life, it is not that simple:

gain changes, pileup, coherent betatron oscillations (CBO), muon losses, …

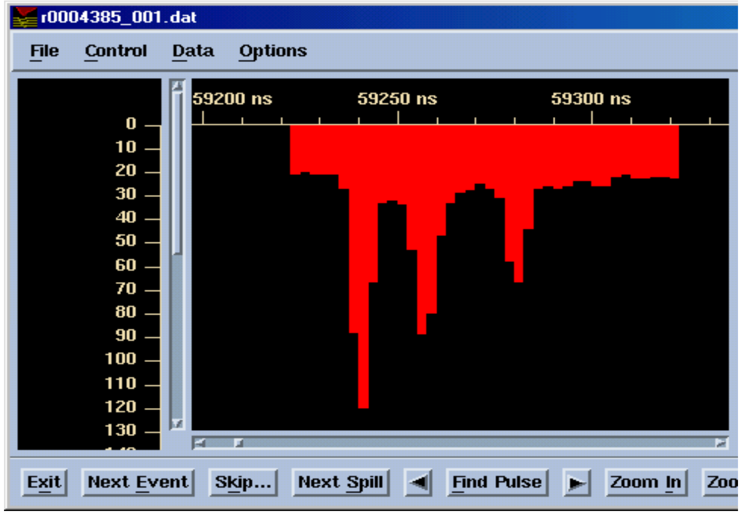


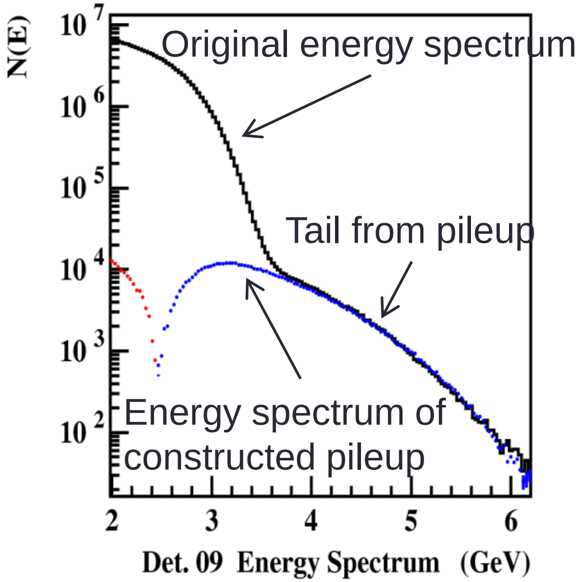




Pileup at BNL

Electrons detected within 3-5 ns are reconstructed as one electron. These “pileup” electrons “carry” $2\omega_a$. The relative amount of pileup electrons is ~1% after injection and then going down $\sim \exp(-t/\gamma\tau)$. If unaccouned for, this leads to early-to-late shift in ω_a.





Using electrons, detected on the “tail” of previous electron (but outside 3-5 ns window), we can statistically predict and subtract pileup contribution with 5-10% accuracy.

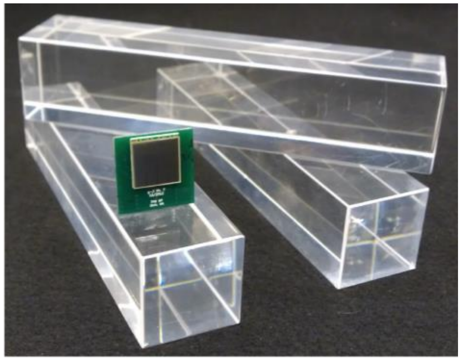
Pileup at FNAL

1. Reduce the rate

   Number of protons per fill (injection): 5 Tp/fill @ BNL, 1 Tp/fill @FNAL
   Muon production efficiency (μ/p) is 5-6 times better @FNAL
   Average rate is higher @FNAL, but instantaneous rate stays the same

2. Segmented PbF_2 calorimeter

   Smaller pileup rate per channel (crystal)



3. Continuous digitization

   No energy threshold is important for accurate "reconstruction" of pileup

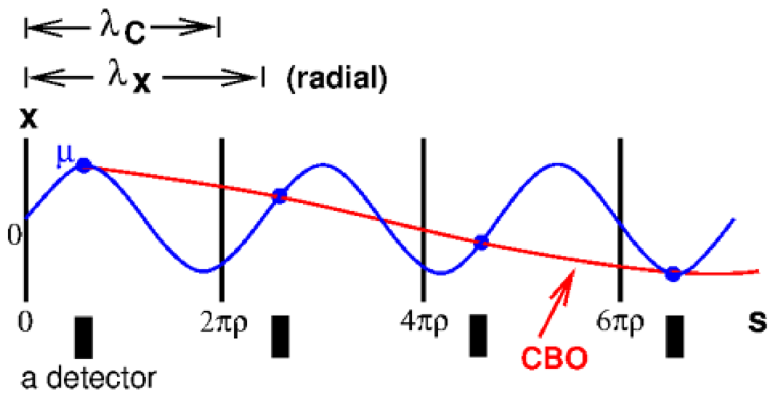
4. **Q-method**

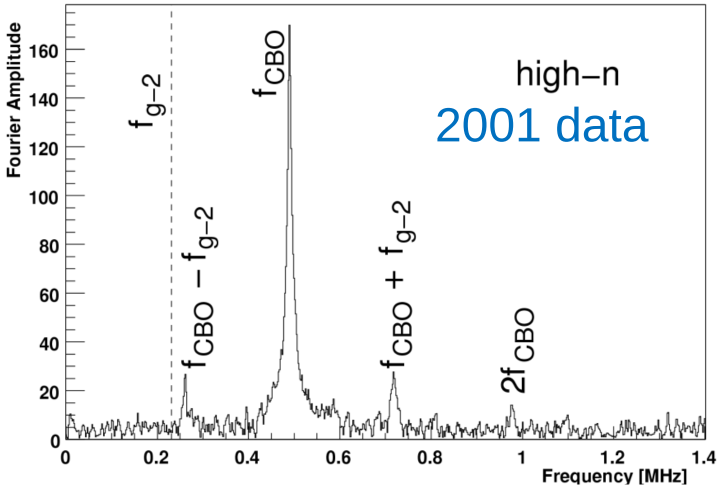
   Do not count electrons, but measure total deposited energy vs time.
   Equivalent to measurement of number of electrons, weighted by energy.

   Was not done at BNL – requires extreme gain stability, low "flash", new electronics

   Pileup contribution vanishes! (but there are other systematics which become worse…)

Coherent Betatron Oscillations (CBO)





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

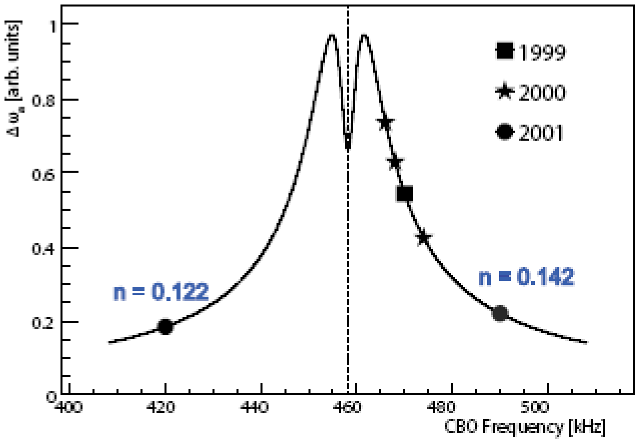
$$\omega_{CBO} = \left(1 - \sqrt{1-n}\right)\omega_C$$

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}:

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



Relative amount of CBO syst.error @BNL

CBO @FNAL

1. New quadrupoles with higher maximum voltage

   Plan to run with $n = 0.18$ – much higher than in BNL

2. New kicker

   Inject muon beam closer to normal orbit, thus reducing CBO amplitude

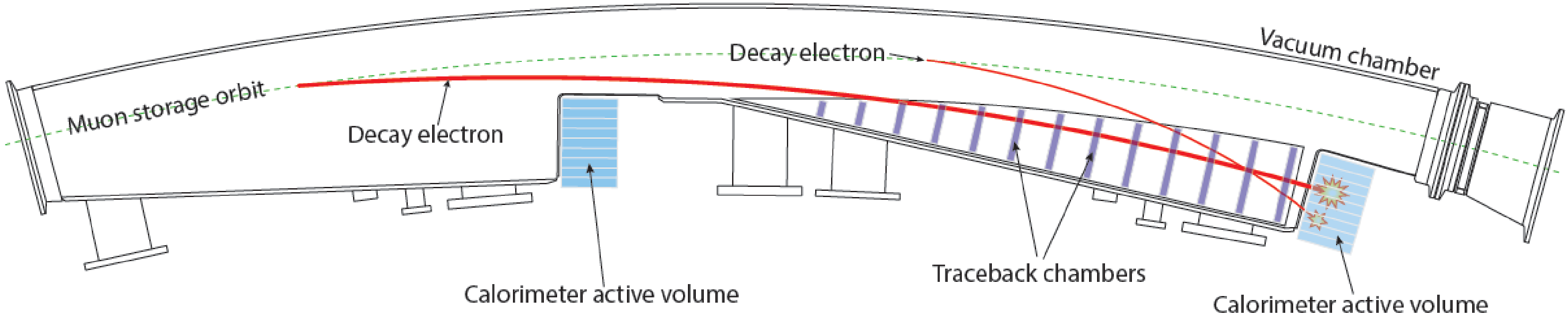
3. Running only with μ^+

   That allows for longer and more stable quads operation

Higher HV also helps to reduce muons losses. Muons are preferably lost from the outer edge of beam. These muons carry different polarization, which leads to early-to-late shift in ω_a.

Beam is shifted for few mks after injection to depopulate outer edge of the beam (scraping). $n = 0.18$ is particulary “resonance-free” mode of operation – fewer lost muons after scraping.

Tracker system (traceback)



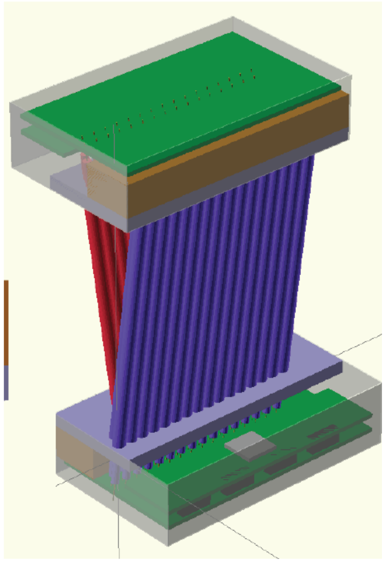
Low-mass trackers are installed in 2 locations around the ring to measure muon decay position with ~1 mm precision several meters away

BNL: one station, outside of vacuum, limited performance

FNAL: inside the vacuum

Tracker is needed for:

- measurement of the beam profile
- Study of lost muons
- calculating pitch correction
- study of pileup
- EDM measurement



From ω_a/ω_p to a_μ (1)

How to extract a_μ from the frequencies we measure?

$$\left.\begin{aligned} \omega_a &= \frac{e}{m_\mu} a_\mu B \\ \hbar\omega_p &= 2\mu_p B \\ \mu_e &= g_e \frac{e\hbar}{4m_e} \end{aligned}\right\} \rightarrow a_\mu = \frac{\omega_a}{\omega_p} \cdot \frac{g_e}{2} \cdot \frac{\mu_p}{\mu_e} \cdot \frac{m_\mu}{m_e}$$

measured in experiment, 140 ppb

0.28 ppt 8.1 ppb 25 ppb

But there is a catch: m_μ/m_e is obtained from hyperfine structure of muonium using SM prediction:

$$\Delta\nu_{Mu}(SM) = \frac{16}{3} c R_\infty \alpha^2 \frac{m_e}{m_\mu}\left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \text{HO terms} = \Delta\nu_{Mu}(exp.)$$

If there is beyond-the-SM contribution to a_μ, it will affect m_μ/m_e as well – should be taken into account.

From ω_a/ω_p to a_μ (2)

Less theory-dependent approach:

measured in experiment, 140 ppb

$$\left.\begin{aligned} a_\mu &= \frac{\omega_a}{\omega_p}\cdot\frac{g_e}{2}\cdot\frac{\mu_p}{\mu_e}\cdot\frac{m_\mu}{m_e} \\ \frac{m_\mu}{m_e} &= \frac{g_\mu}{g_e}\cdot\frac{\mu_e}{\mu_\mu} \end{aligned}\right\} \rightarrow a_\mu = \frac{\omega_a}{\omega_p}\cdot\frac{\mu_p}{\mu_\mu}\cdot(1+a_\mu) = \frac{\omega_a/\omega_p}{\mu_p/\mu_\mu - \omega_a/\omega_p}$$

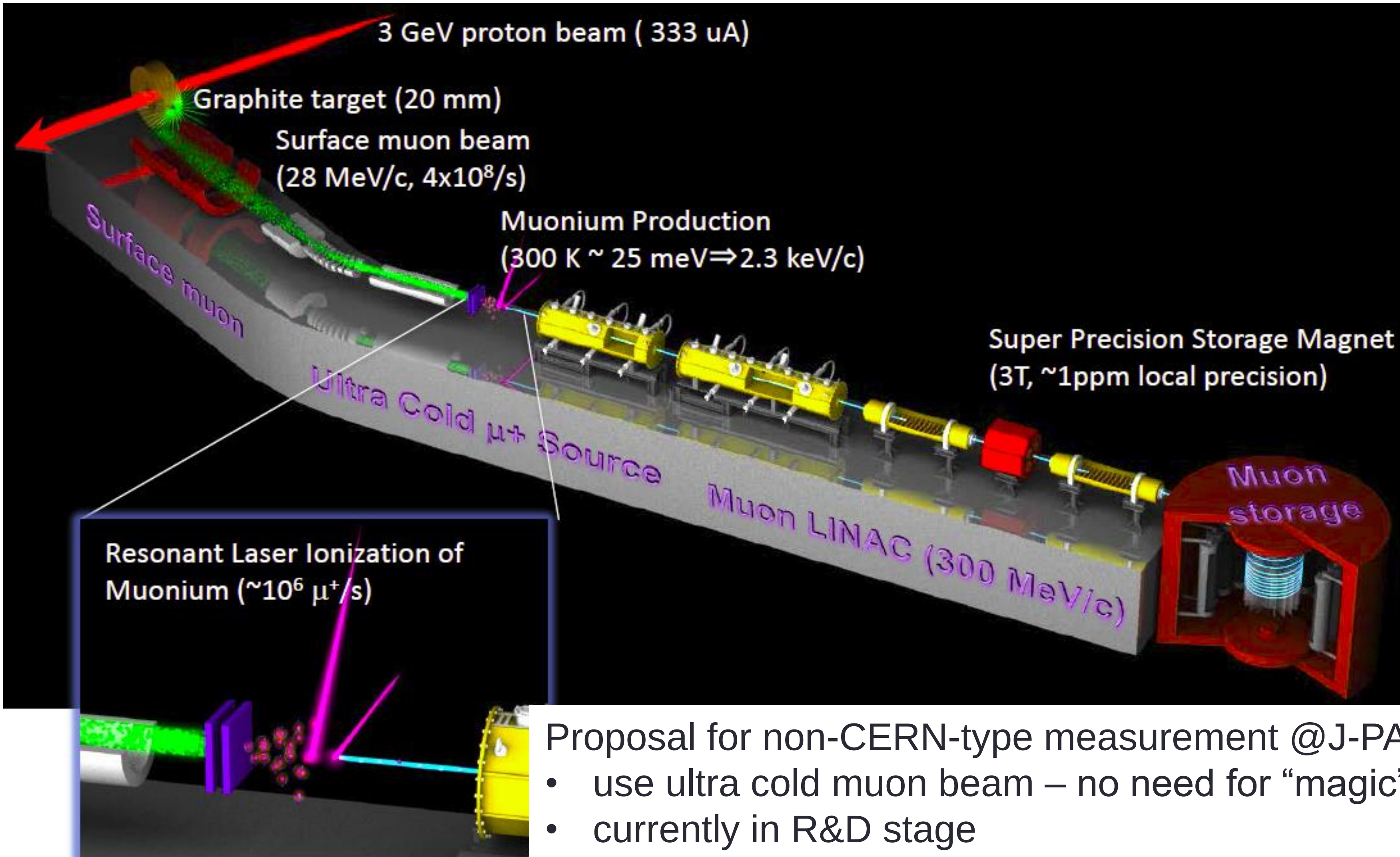
120 ppb

μ_p/μ_μ was measured in Los Alamos muonium experiment to 120 ppb.

BNL experiment used this approach, but for the Fermilab experiment better precision would be helpful.

There is proposal to do the new muonium measurement at J-PARC.

Alternative (g-2) project @J-PARC



Proposal for non-CERN-type measurement @J-PARC:

- use ultra cold muon beam – no need for “magic” p
- currently in R&D stage

Conclusion

There is well-known $3 \div 4\sigma$ discrepancy between the values of anomalous magnetic moment of muon, measured at Brookhaven (1997-2001) and expected within Standard Model.

The new experiment to measure (g-2) of muon is under preparation at FERMILAB.

The expected uncertainty is 140 ppb (4 times better compare to BNL)

The ring is expected to be powered in 2015, the data taking should start in 2017.

Stay tuned…