A NEW MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF MUON AT FERMILAB

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New Trends in High Energy Physics 2016

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

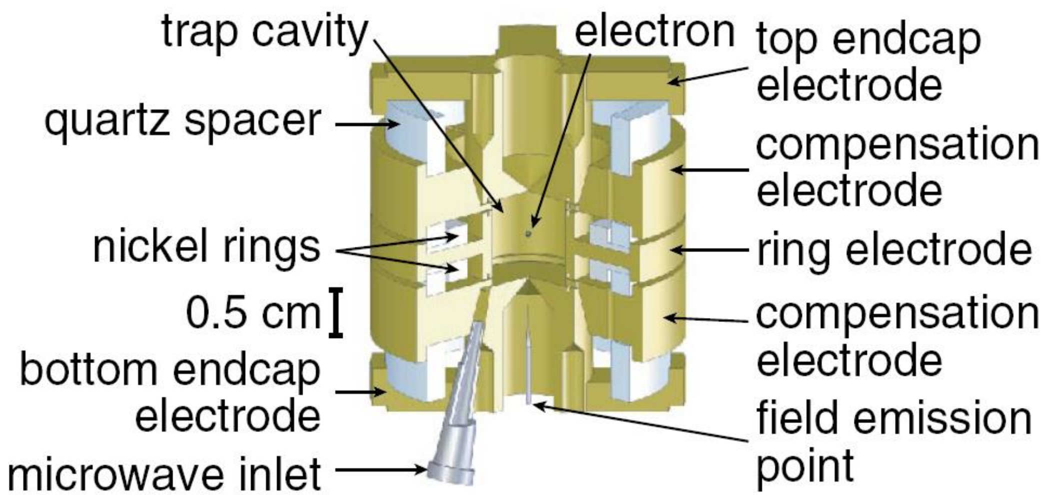
$$a \approx 10^{-3}$$

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

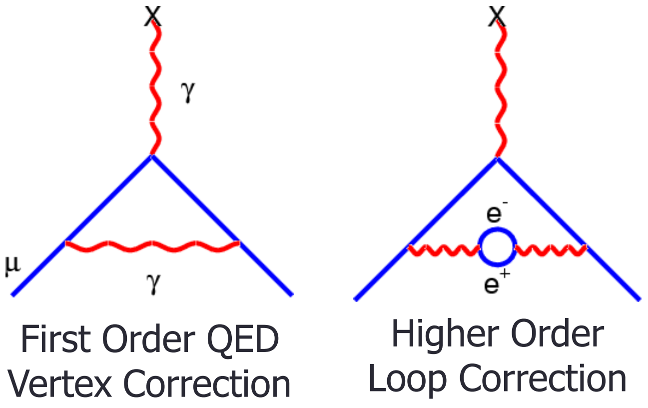
$$a_e = (115\,965\,218\,073 \pm 28) \times 10^{-14} \text{ (0.24 ppb)}$$



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.

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

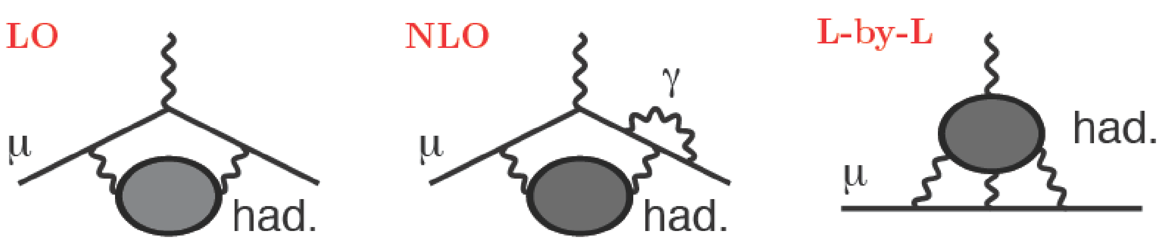
$$1{,}000{,}000 \;:\; 60 \;:\; 1.3 \;:\; \propto \left(m_\mu / m_X\right)^2$$

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

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



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

60 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):

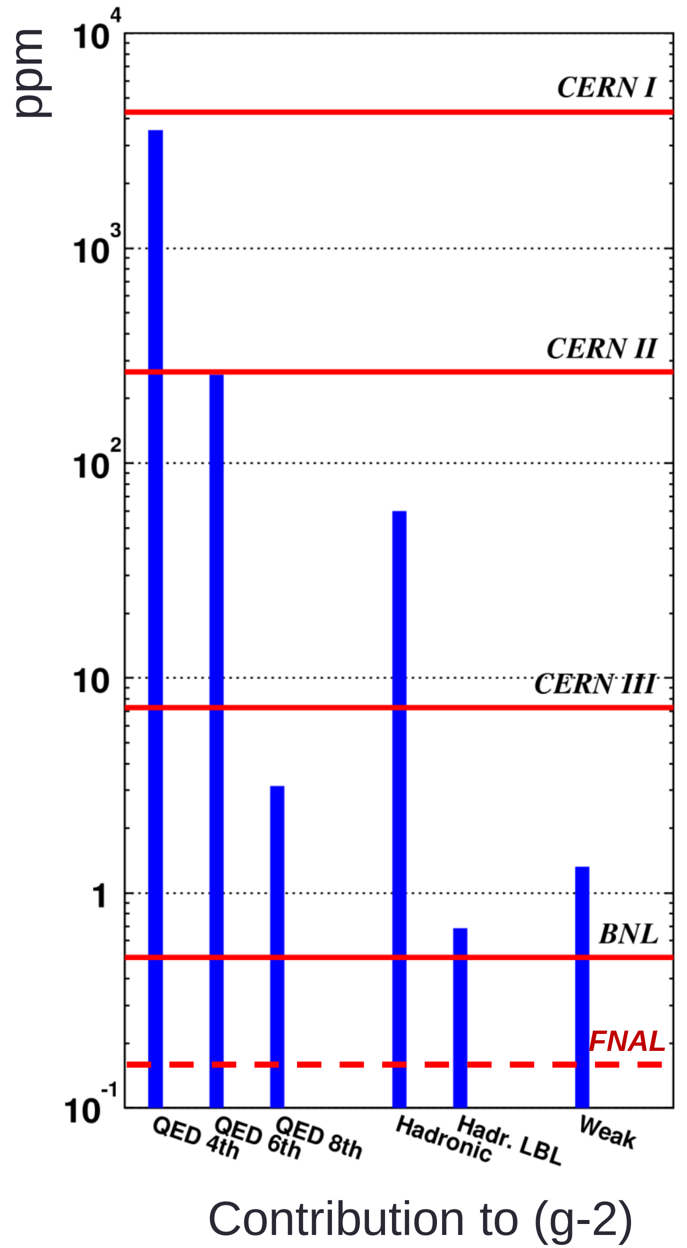
Magic γ, electric field focusing, μ^+ and μ^-, (g-2) to 7 ppm

BNL (1990-2003):

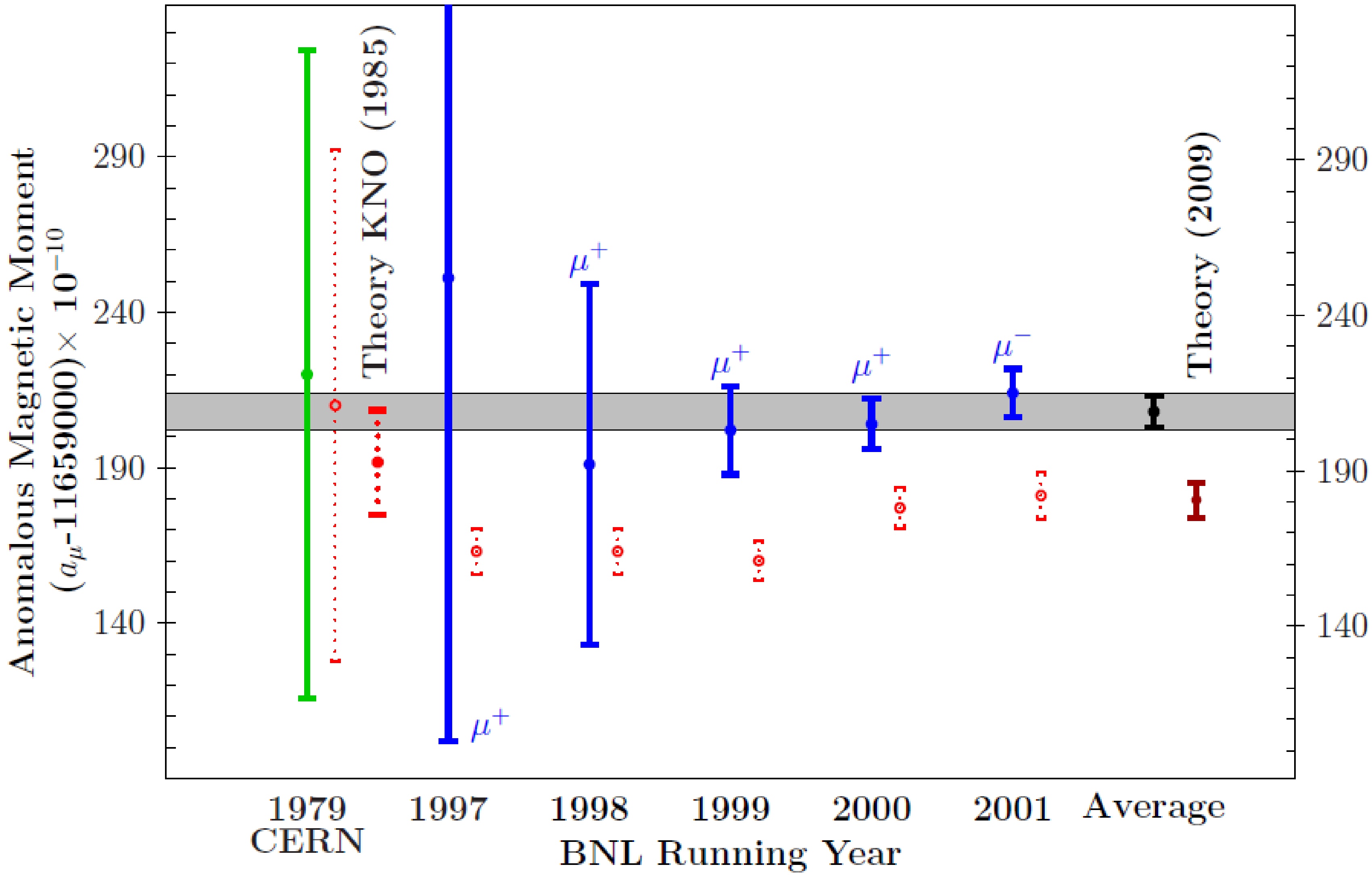
Superferric magnet, high intensity beam, muon injection, (g-2) to 0.5 ppm

FNAL (2010-?):

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



Muon (g-2): BNL era

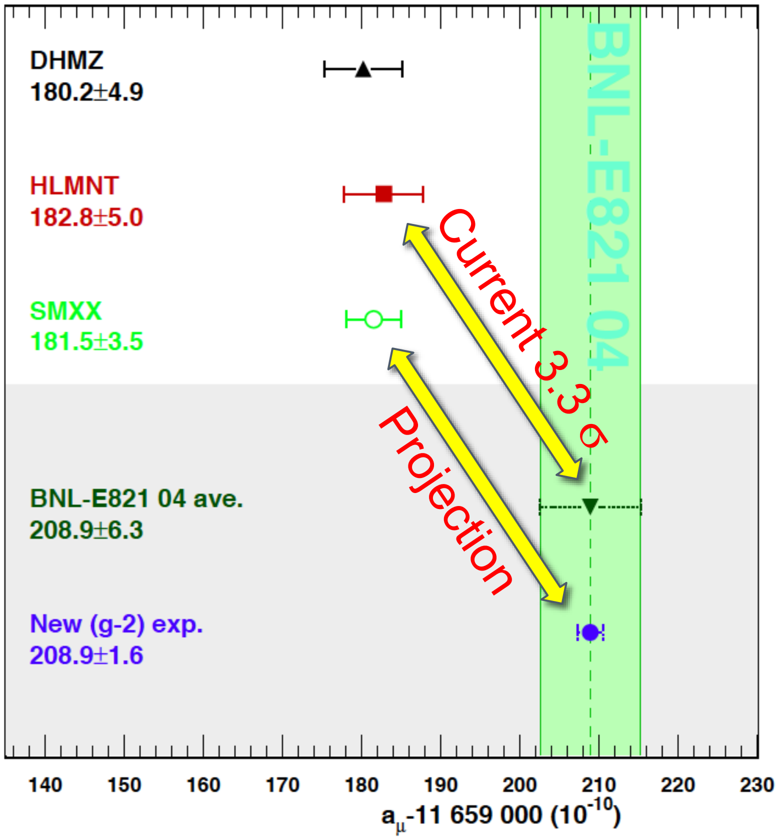


Muon (g-2) today: experiment vs theory

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

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

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



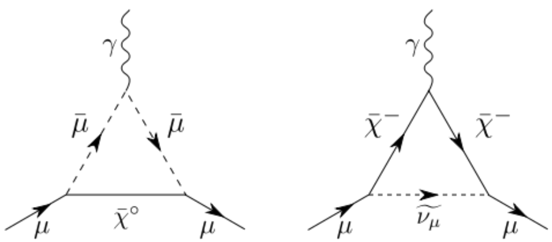
Fermilab projections:

$a_\mu(exp)$ → 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 model to describe Δa_μ? Plenty!

SUSY

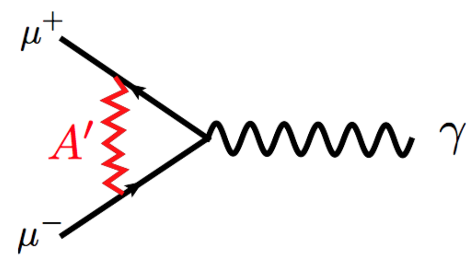


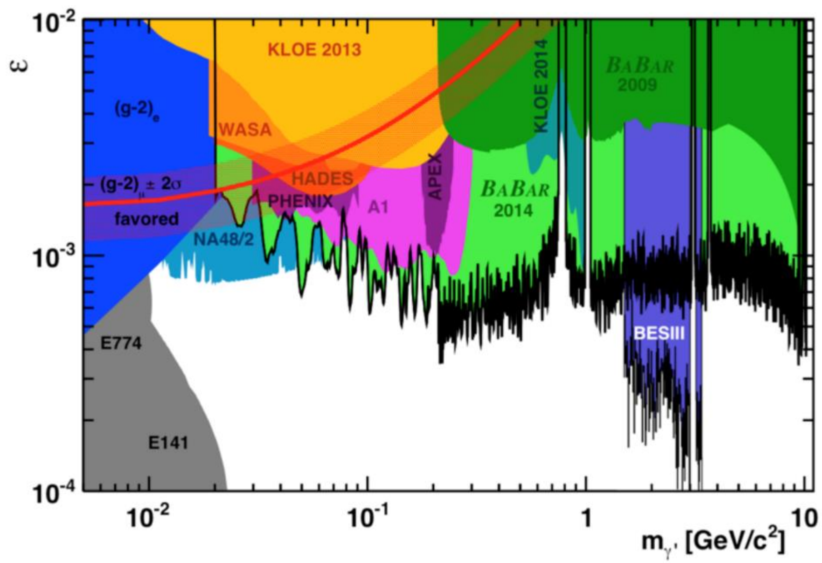
$$a_\mu(SUSY) \approx (\mathrm{sgn}\ \mu)130\times10^{-11}\tan\beta\left(\frac{100\ \mathrm{GeV}}{\widetilde{m}}\right)^2$$

Complementary to direct searches at the LHC

- Sensitive to sgn μ and tan β
- Contributions to g-2 arise from charginos and sleptons while LHC direct searches are most sensitive to squarks and gluinos

Dark photon





How to measure a_μ

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

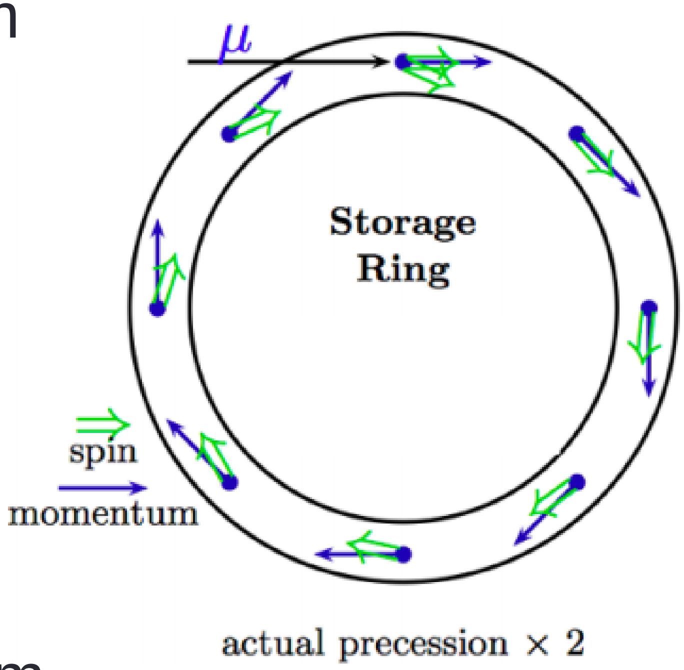
$$\omega_c = eB/\gamma mc$$

- Spin rotates with Larmor+Thomas frequency:

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

- Spin precesses relative to momentum with frequency ω_a:

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



ω_a, B → a_μ

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 $\pi \to \mu + \nu_\mu$ 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 $\mu \to e + \nu_e + \nu_\mu$, the positron is preferentially emitted in the muon spin direction

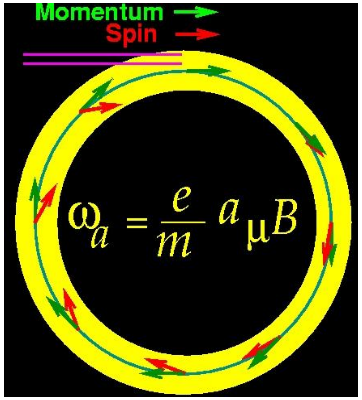
Magic γ (CERN-III)

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.

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

= 0 = 0

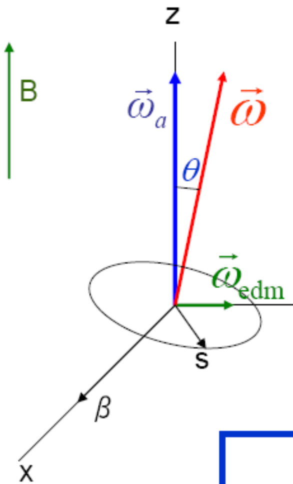


$$\gamma_{magic} = 29.3$$
$$p_{magic} = 3.09\ \mathrm{GeV}/c$$

Contribution from potential EDM (more later)

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

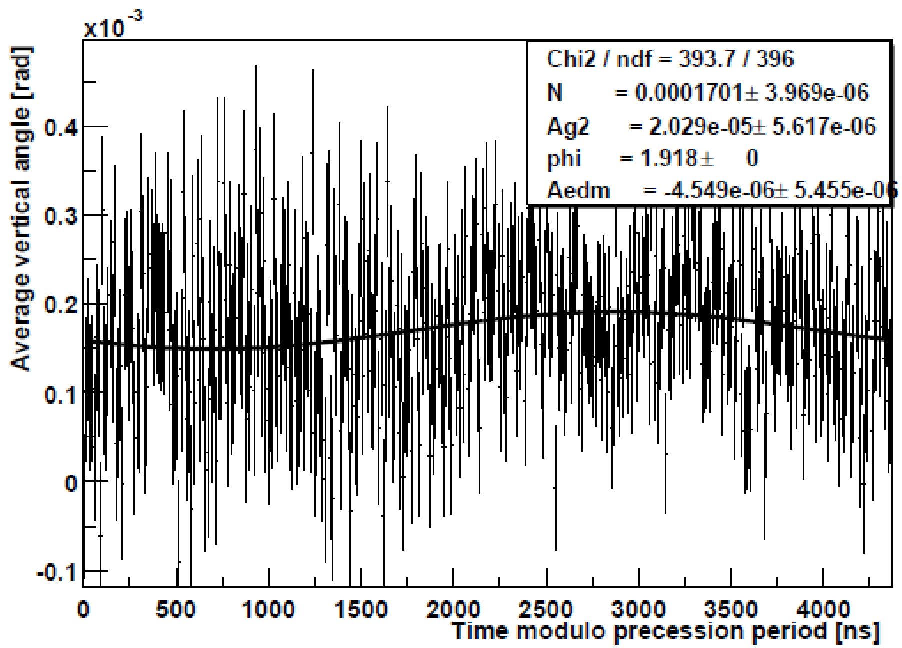
Effect of EDM



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

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

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



Non-zero EDM presents itself as up-down oscillations

BNL limit: $|d_\mu| \leq 1.8\times10^{-19}\ e\cdot cm\ (95\%)$

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

But we assume $|d_\mu| \leq 3.2\times10^{-25}\ e\cdot cm$ from $|d_e|$ limit.

FNAL should improve BNL limit by factor of ~100.

New measurement at FNAL

New CERN-type measurement E989 is in preparation at Fermilab with the goal of 4x improvement over BNL

- 21x more statistics
- 2.8x reduction in systematics

How? →

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

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**

Muon G-2 collaboration

USA Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

England
University College London

Liverpool

Oxford

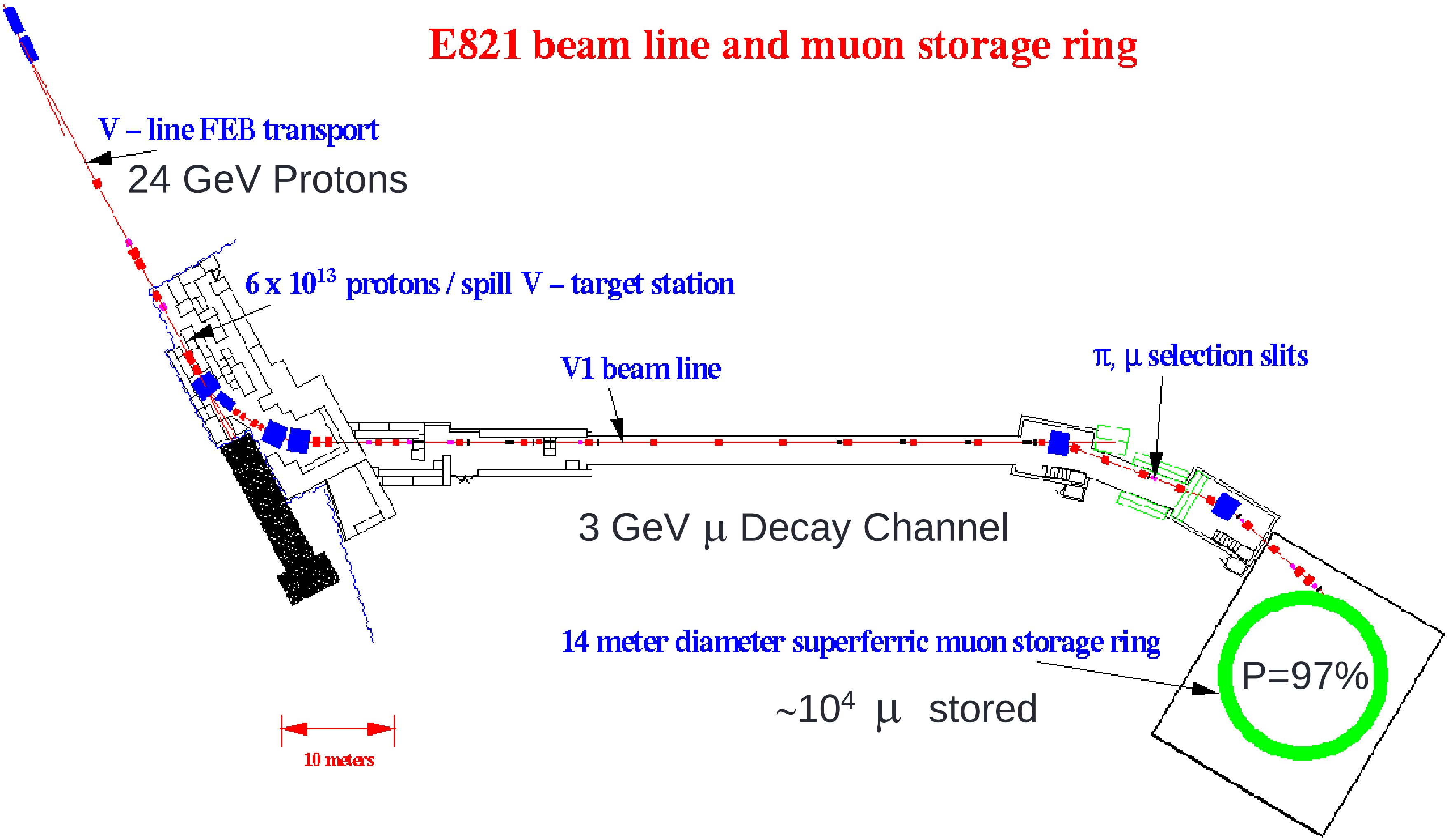
Korea
KAIST

Co-Spokespersons:
D.W. Hertzog
B.L. Roberts

Project Manager:
C. Polly

33 institutions
150 members

Layout of BNL experiment (1997-2001)



Layout of FNAL experiment

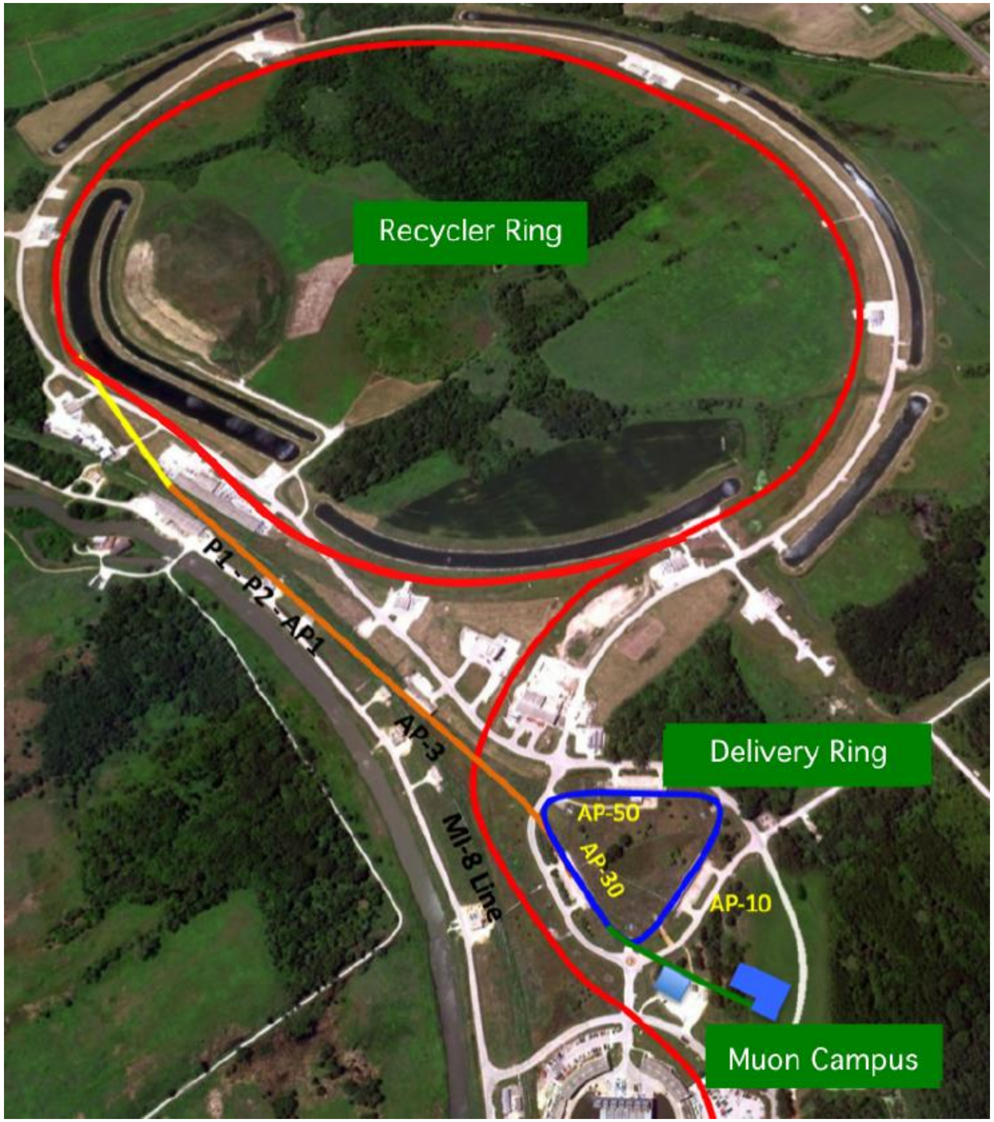
- 8 GeV/c protons from the Booster are rebunched in Recycler Ring
- Transfer line and Delivery Ring (part of old $\bar{p}$ source) make ~2 km decay line. No hadron background!

20 times more statistics!

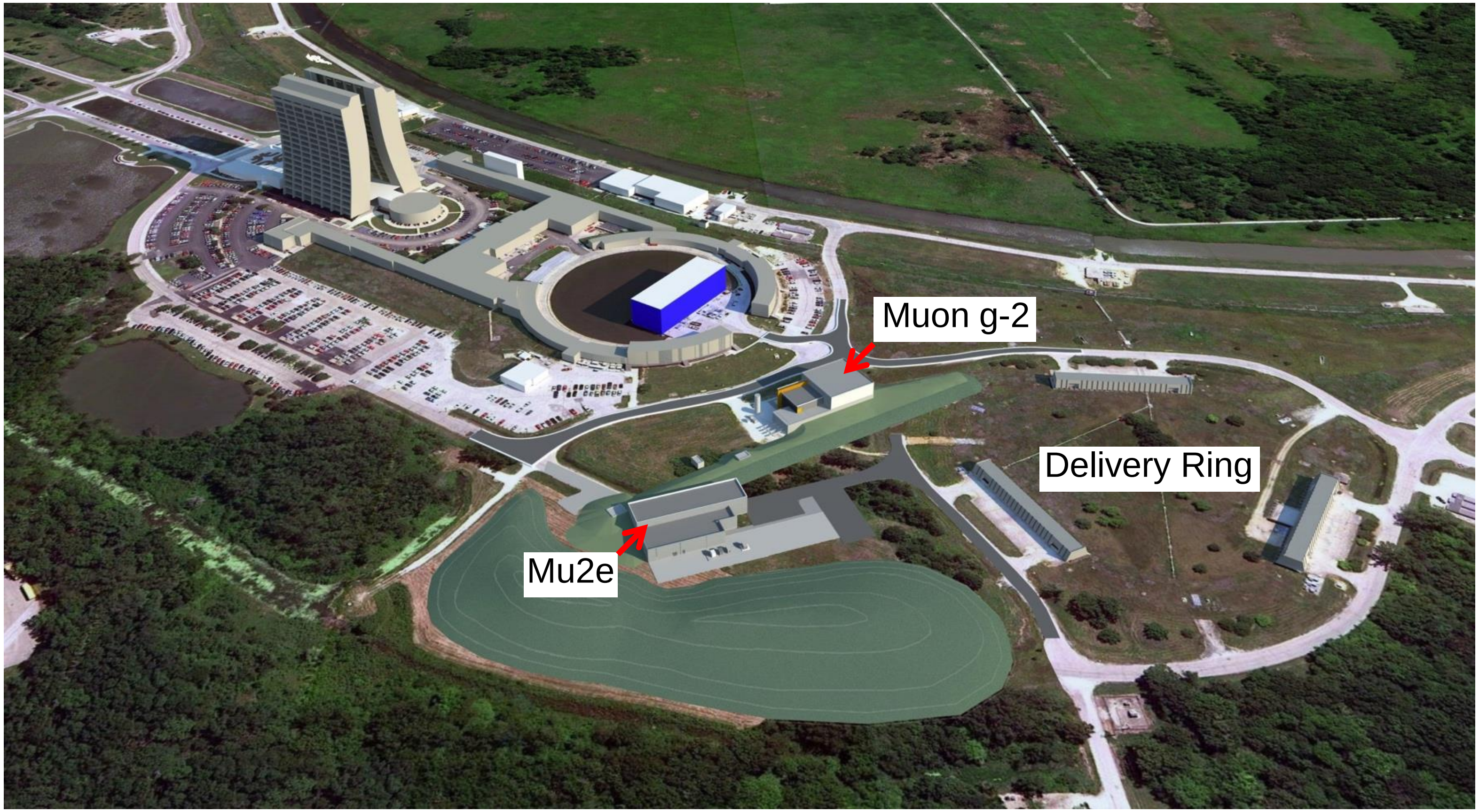
The effective beam power is smaller at FNAL by x4.

Need to recover factor ~80:

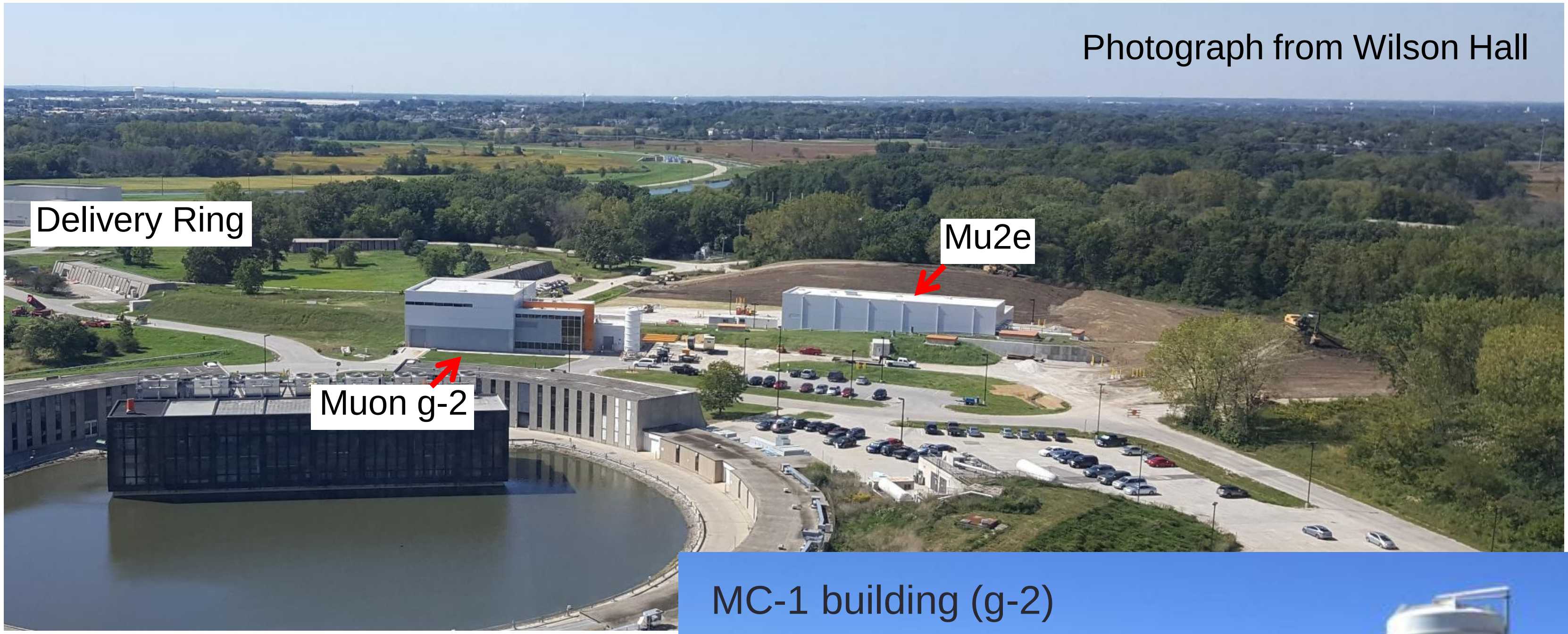
- more efficient collection and transmission
- longer decay line
- longer running time
- more efficient data analysis



Muon Campus (g-2 + Mu2e): the plan



Muon Campus: today



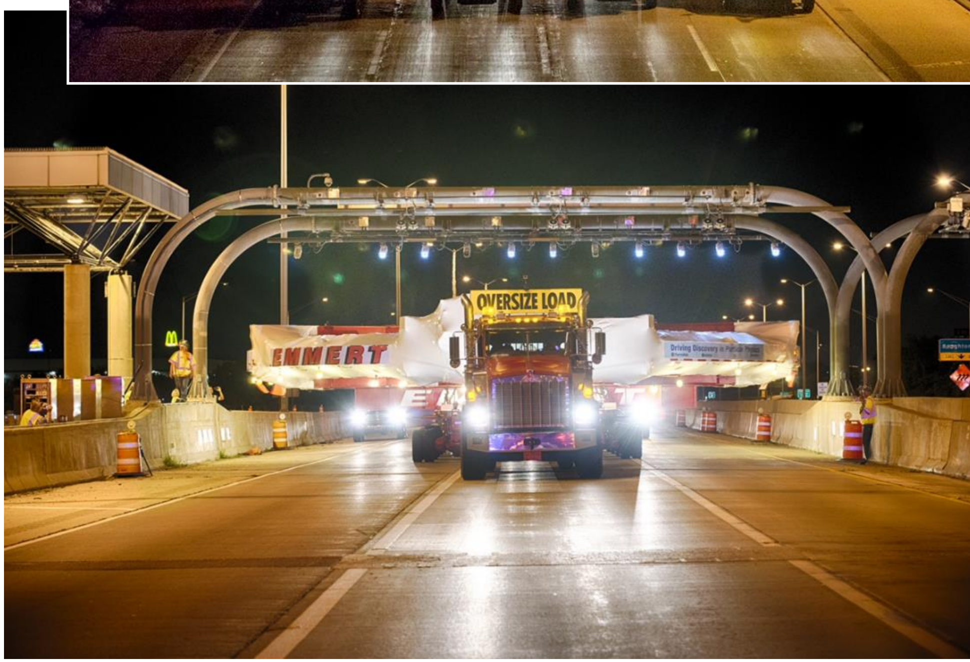
- g-2 building (MC-1) is fully operational
- Mu2e building is under construction

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

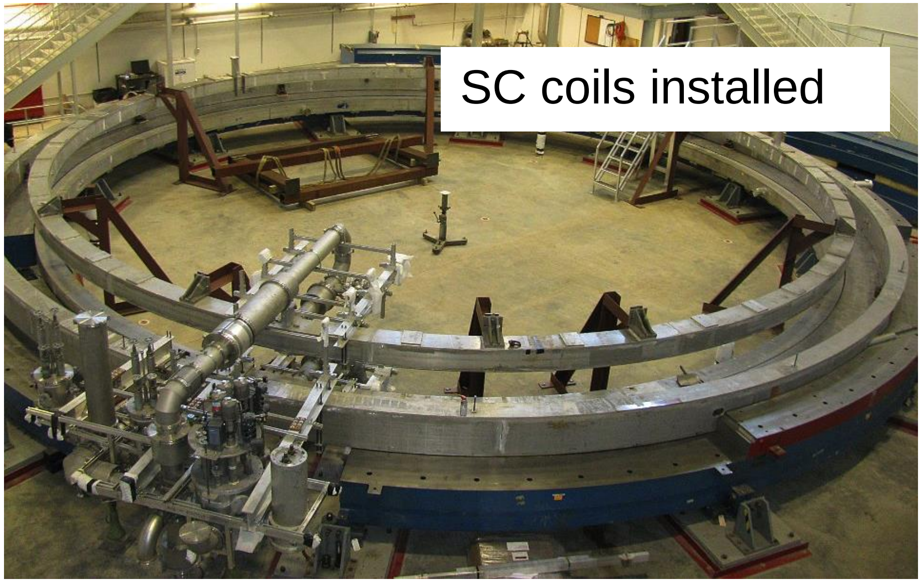
Moved in 2013 by truck and the sea

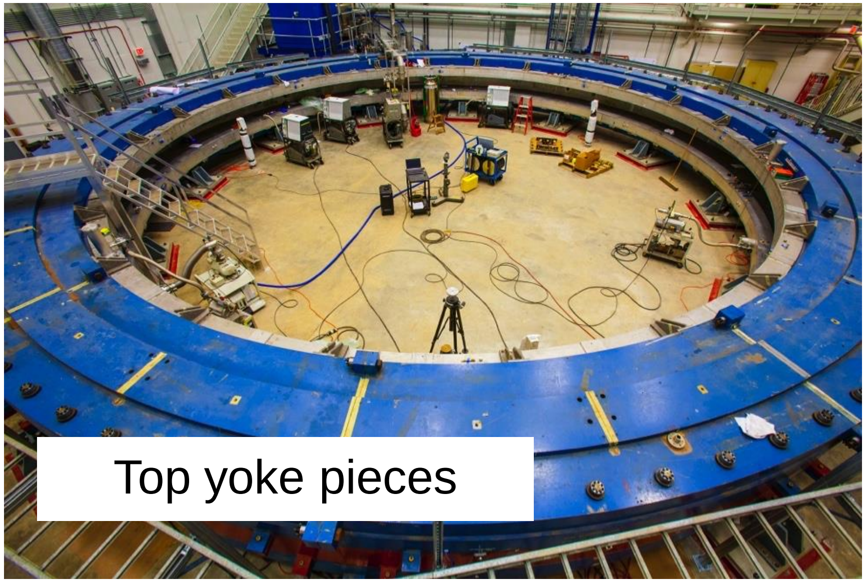
5000 km journey



Arriving at Fermilab

Reassembly of the ring (2014-2015)





Magnet reached the full power in September 2015

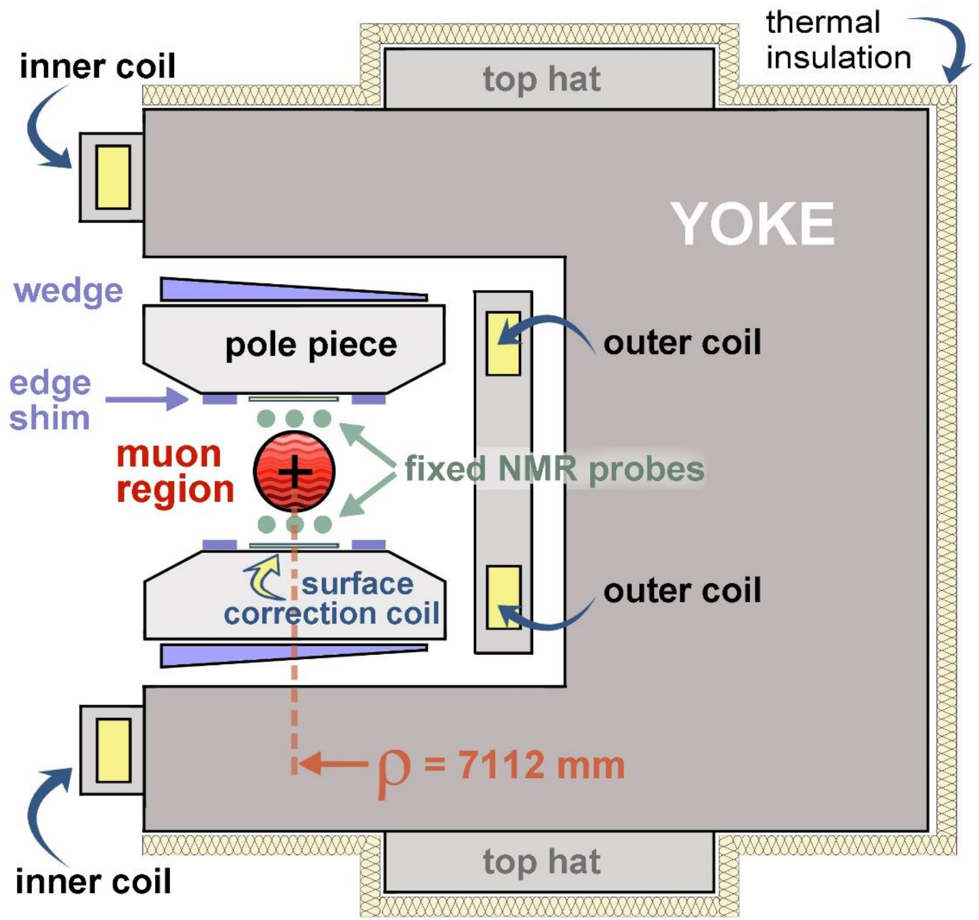
To the shimming…

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

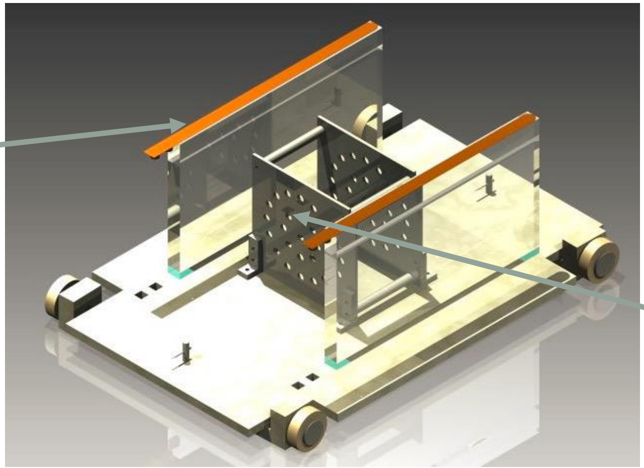
Rough shimming: Oct.2015-Aug.2016

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

Goal: 50 ppm uniformity

Laser tracker

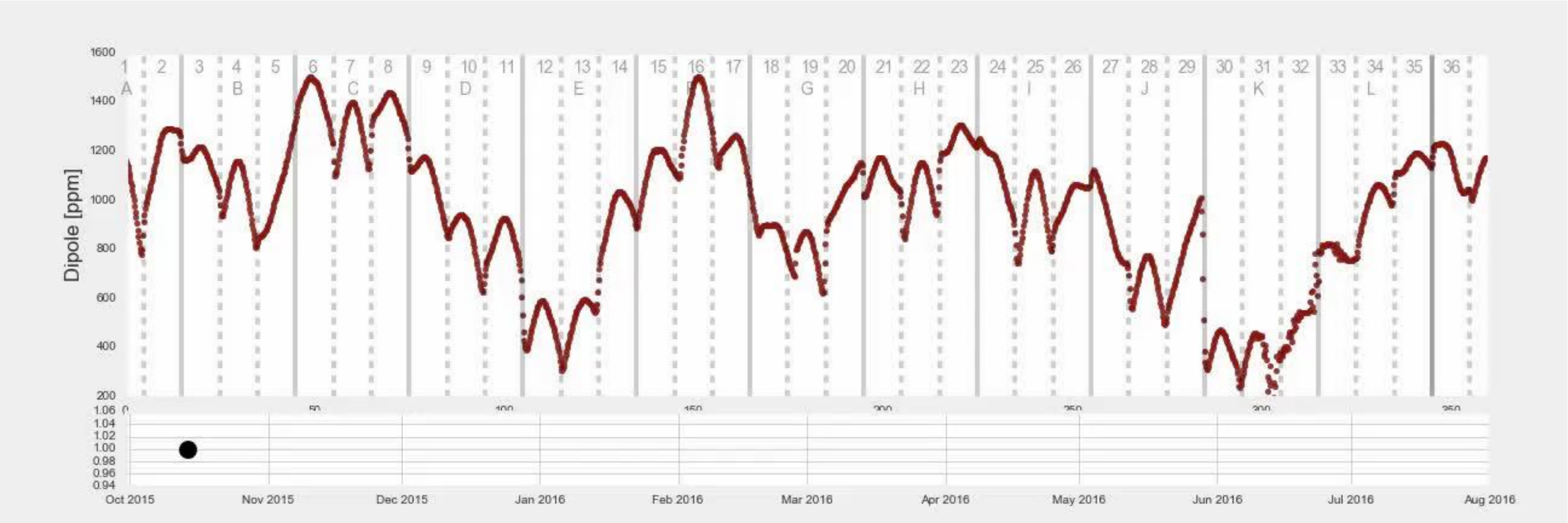
4 corner-cube retroreflectors

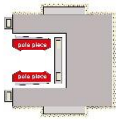


4 capacitive gap sensors

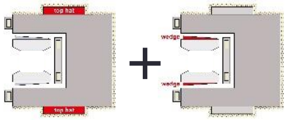
25 NMR probes

Shimming history

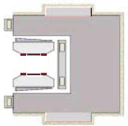




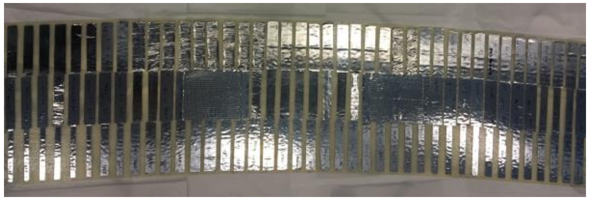
Poles



Top hats & wedges



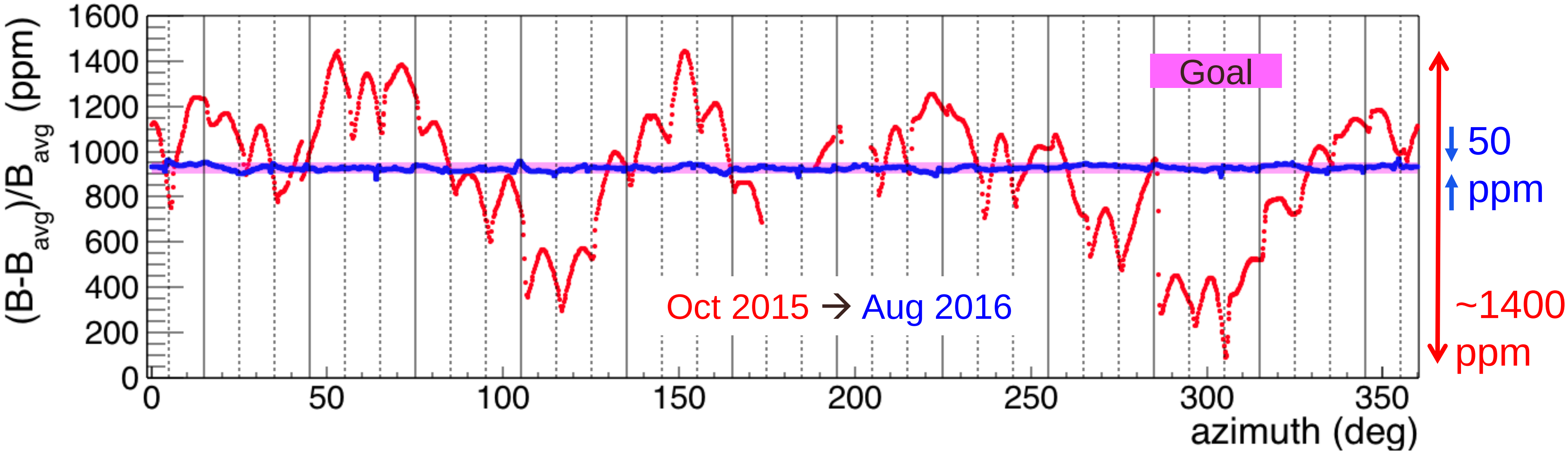
Surface foils



← 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

Measuring ω_a (T-method)

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

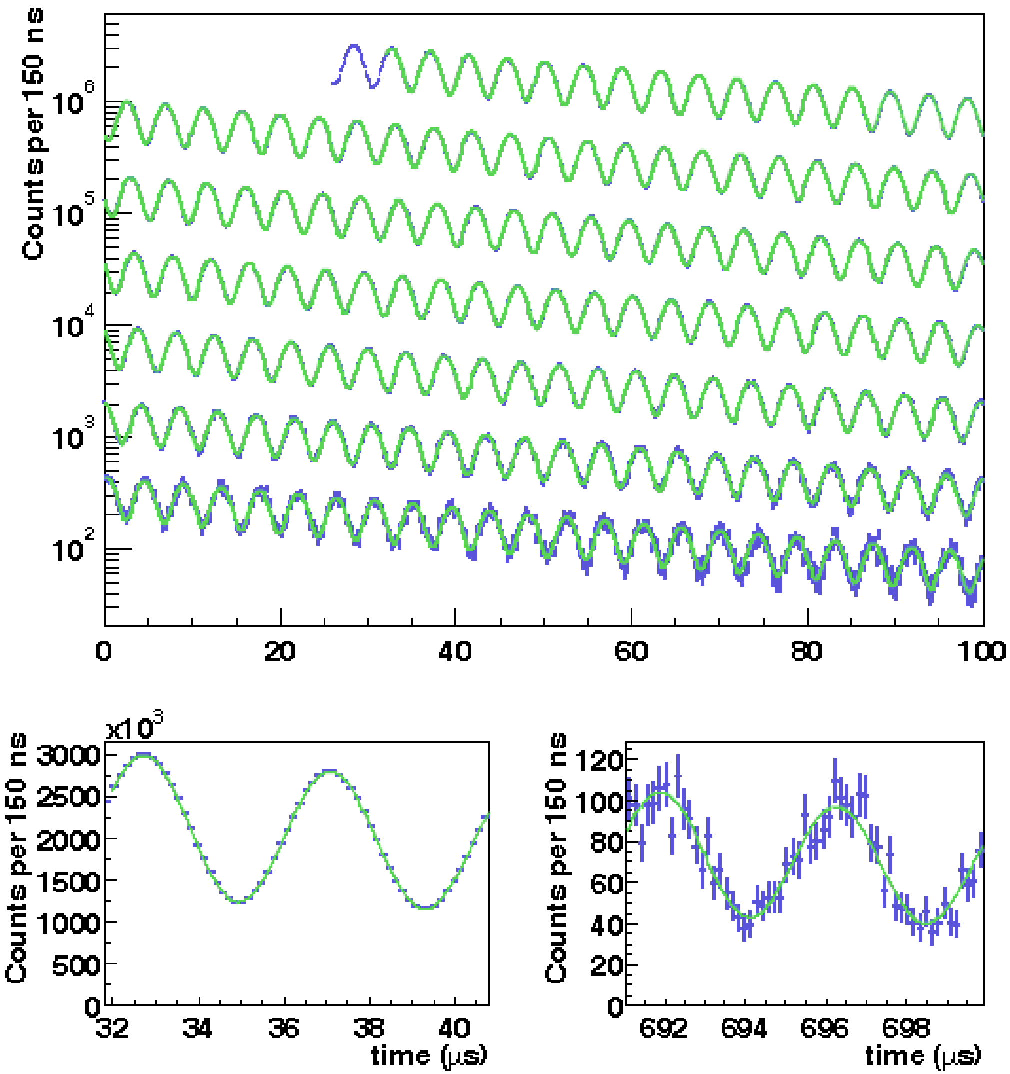
Number of forward decay electrons in CM frame correlates to spin direction

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

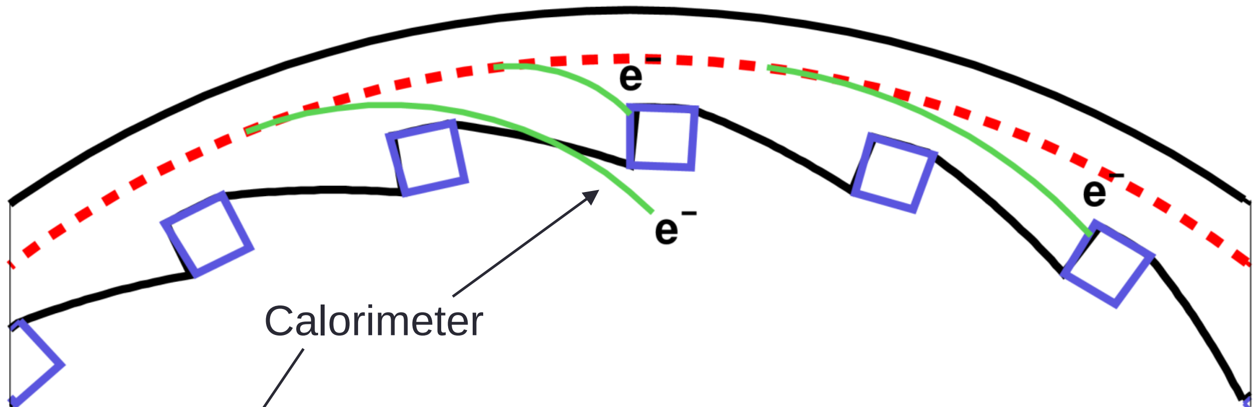
$$N(t) = N_0 e^{-t/\gamma\tau}[1 + A\cos(\omega t + \varphi)]$$

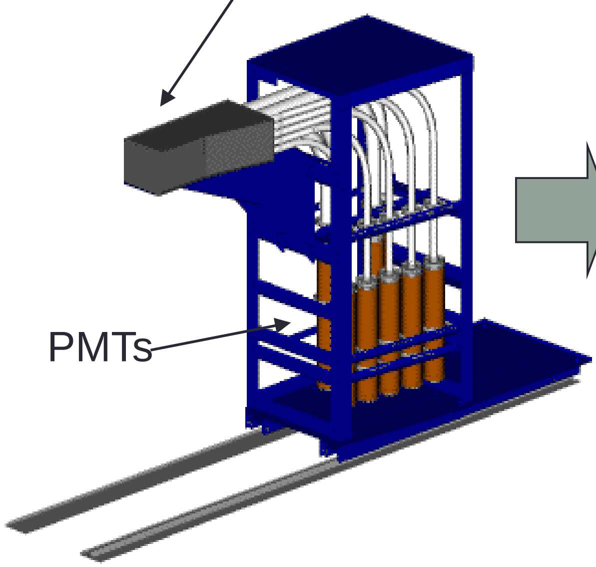
Simple 5-parameter fit! In real life, it is not that simple:

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

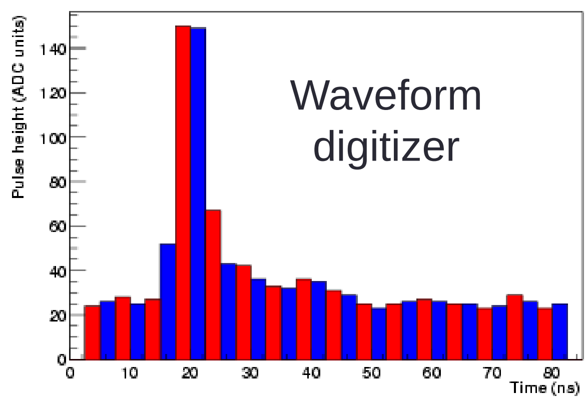


Measuring ω_a at BNL

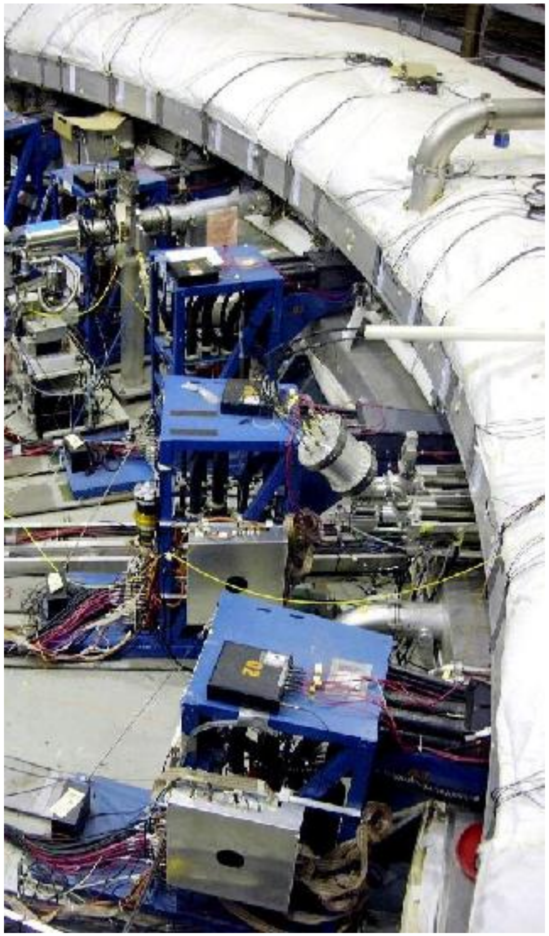




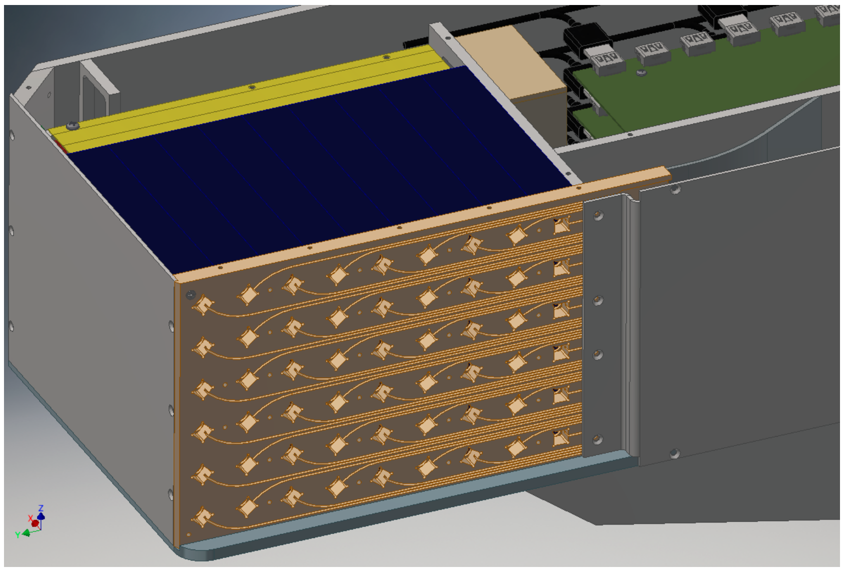
24 calorimeters around the ring

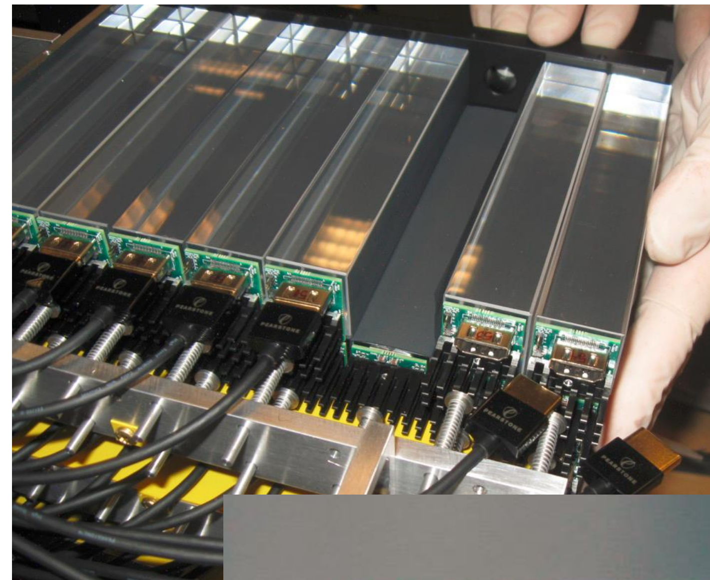


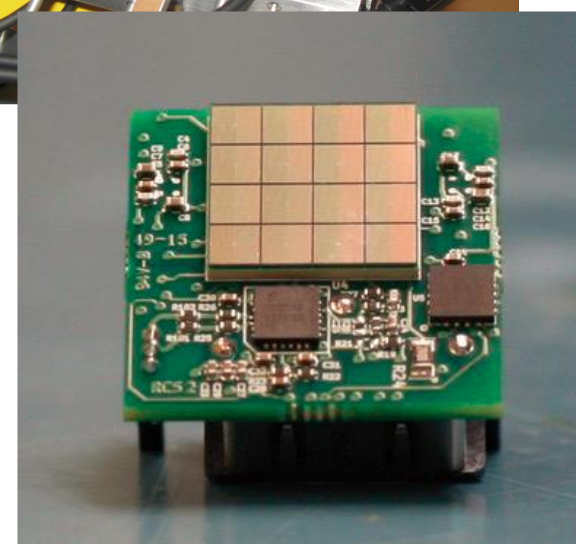
Offline reconstruction of energy and time



FNAL calorimeters



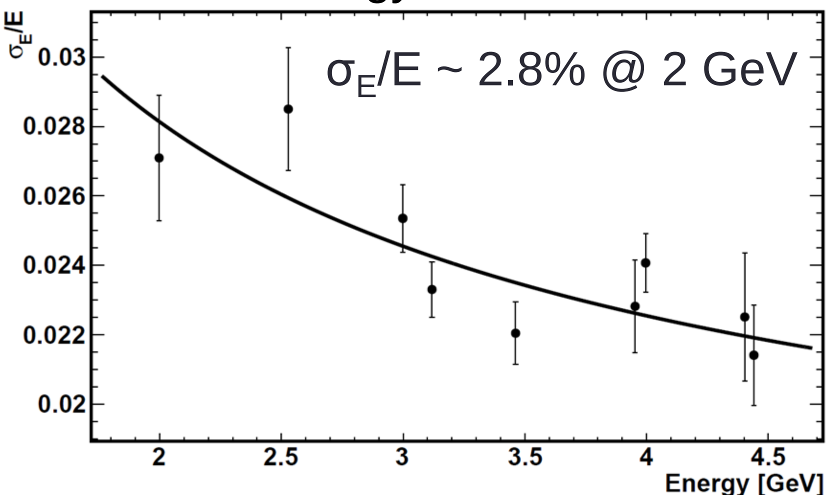




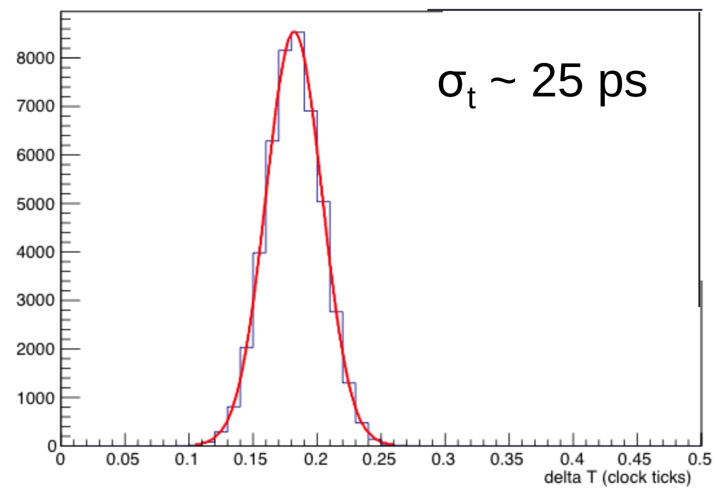
- 24 calorimeters: each is array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels)
- Advanced laser calibration system

Calorimeter performance

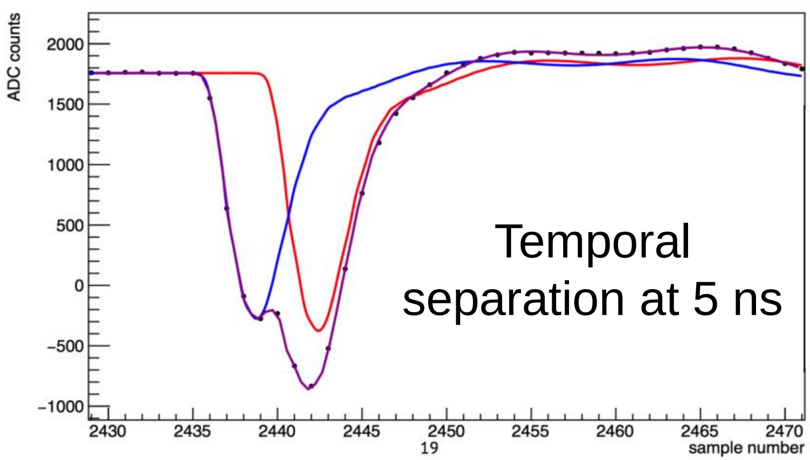
Energy Resolution



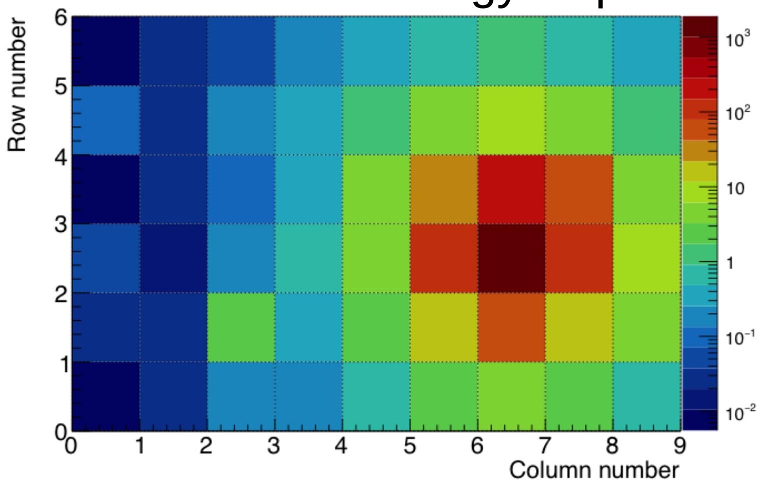
Timing Resolution



Electron pile-up



Position from Energy Deposit



[NIM A 783 (2015), pp 12–21]

Pileup at FNAL

Overlapping of two decay electrons (pileup) introduces significant early-to-late effect

Was dealt at BNL by statistical reconstruction and subtraction of the integrated pileup effect

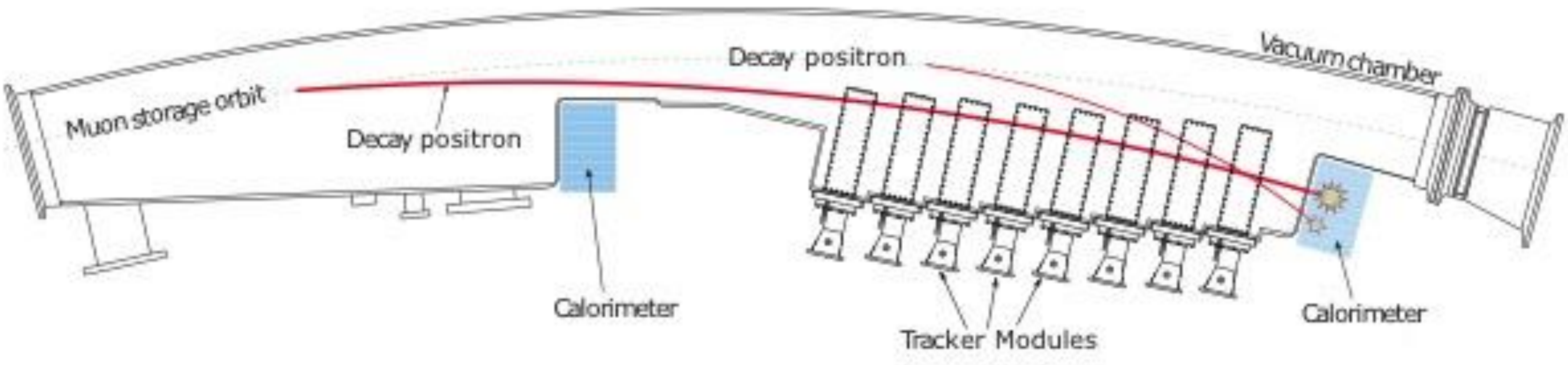
Numerous improvements @FNAL:

1. Instantaneous rate stays the same – the size of the effect does not increase
2. Segmented calorimeter allows to reduce pileup
3. Continuous digitization without energy threshold is important for accurate reconstruction and subtraction of pileup effect
4. **New analysis technique: 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

Tracker system (traceback)

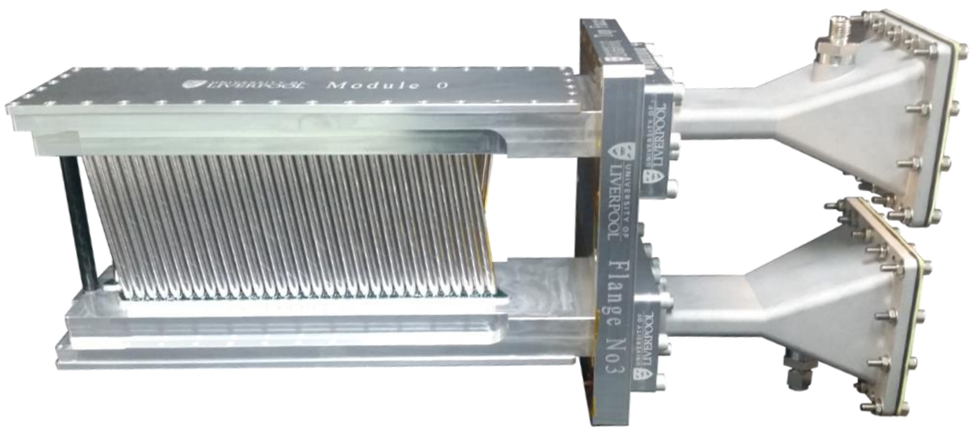


Low-mass trackers are installed in 3 locations around the ring to measure muon decay position with ~1 mm precision

BNL: one station, outside of vacuum, limited performance
FNAL: 3 stations, inside the vacuum

Each tracker:

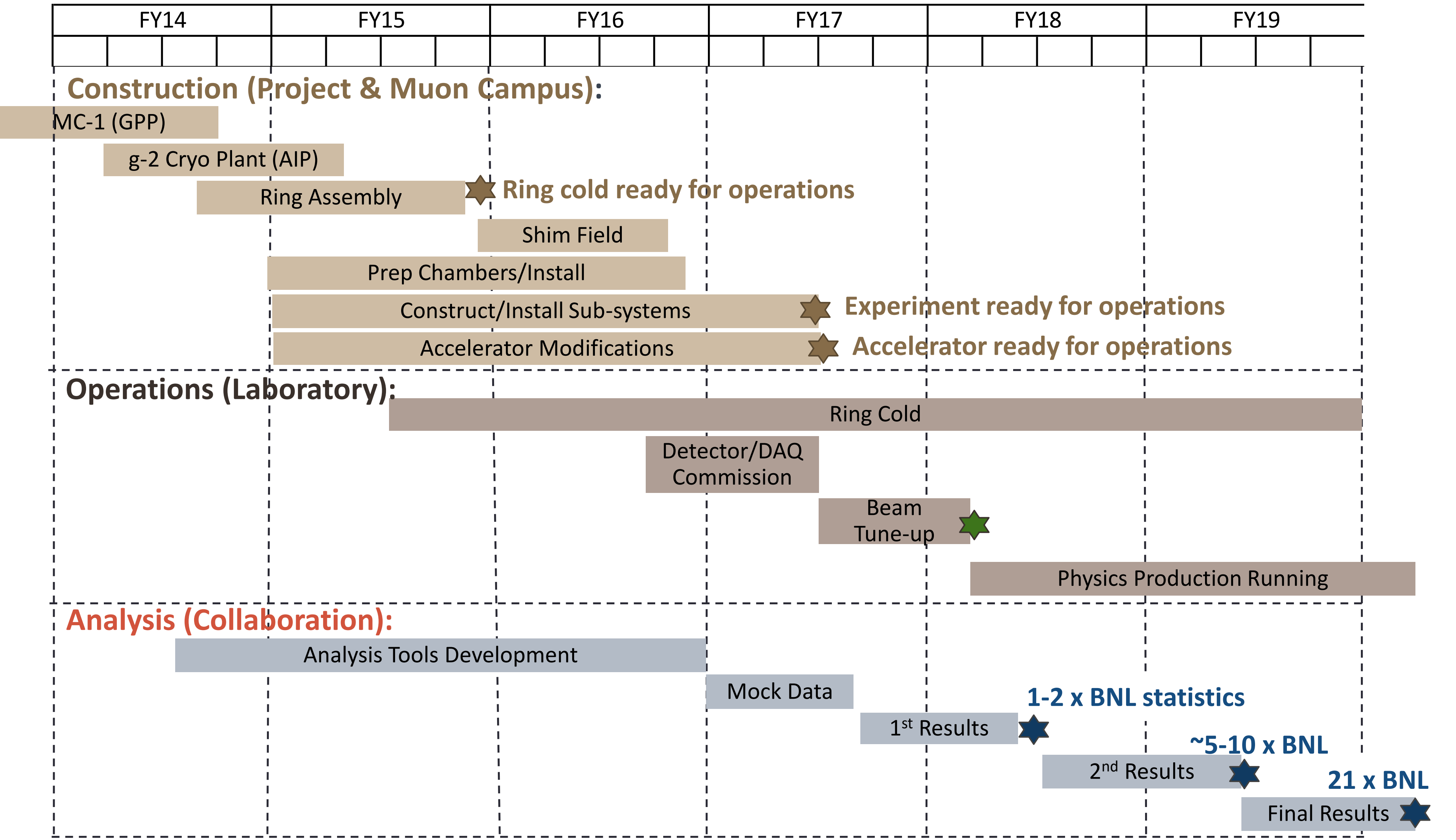
- 8 modules
- 4 layers per module, 128 straws per module



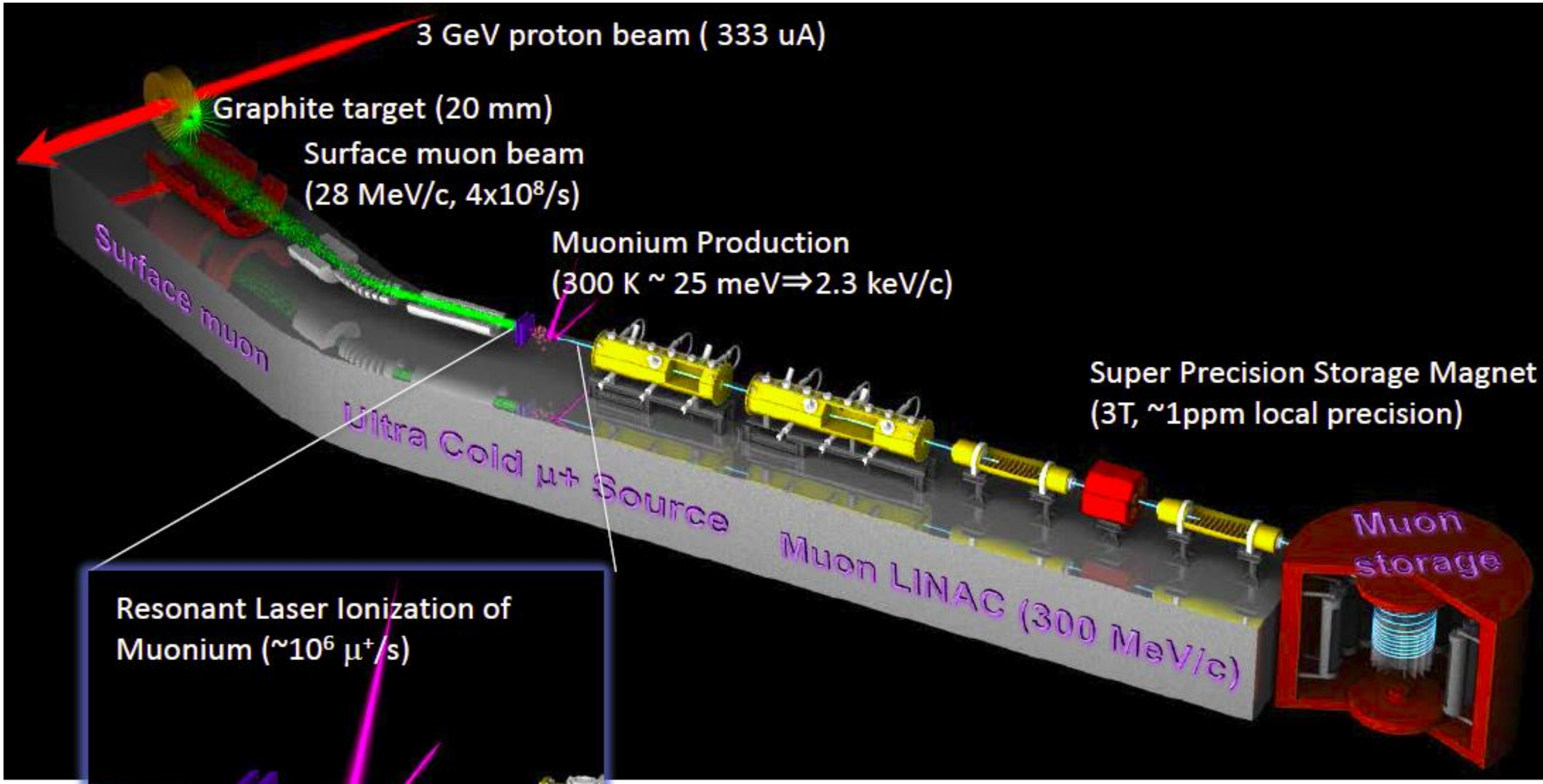
Why we need trackers?

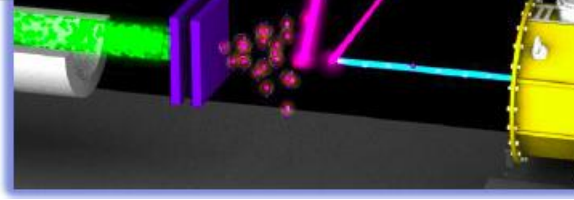
- Measurement of the muon distribution
  - to calculate average magnetic field, seen by muons
- Study of the beam dynamics
  - to calculate the pitch correction (effect of betatron motion)
  - to calculate the electric field correction (residual effect due to momentum dispersion around magic γ)
- Measurement of the muon EDM
  - by measuring vertical pitch of decay electrons
- Various systematics studies
  - pileup
  - lost muons
  - effect of coherent betatron oscillations

Project timeline



Alternative (g-2) project @J-PARC





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

- use ultra cold muon beam – no need for “magic” p

4

On a theoretical side…

$$\Delta a_\mu = a_\mu(exp) - a_\mu(SM)$$

New experiment at FNAL

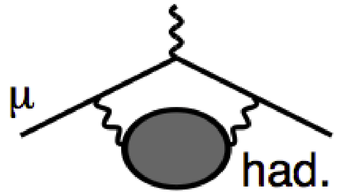
Possible new experiment at J-PARC

Two largest uncertainties:

- lowest order hadronic contribution $a_\mu(had; LO)$
- light-by-light hadronic contribution $a_\mu(had; LbL)$

Extensive world-wide effort, both in experiment and in theory

$$a_\mu^{\mathrm{had,LO}} = \frac{m_\mu^2}{12\pi^3} \int_{s_{\mathrm{th}}}^{\infty} ds \, \frac{1}{s} \hat{K}(s) \sigma_{\mathrm{had}}(s)$$



Calculation of $a_\mu(had; LO)$ depends on measurement of $e^+e^- \rightarrow hadrons$ at $\sqrt{s} \lesssim 2$ GeV – experimental problem!

Expectations for the hadronic contribution

Now

New $a_\mu(exp)$

2010 FNAL experiment 2020

Precise data $e^+e^- \to hadrons$ from VEPP-2M (Novosibirsk)

Precise ISR data $e^+e^- \to \gamma + hadrons$ from BABAR and KLOE (there is some tension)

Lattice calculations started

VEPP-2000
Lattice calculations

Precise and high statistics e^+e^- data from VEPP-2000 (Novosibirsk)

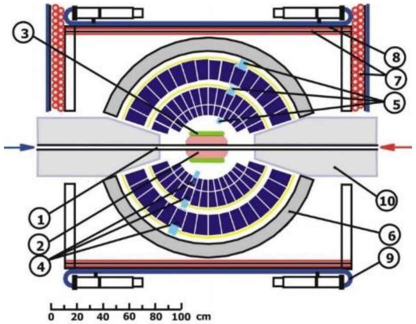
Precise ISR data from BABAR, KLOE, KLOE-2 and BES-III

Precise lattice calculations

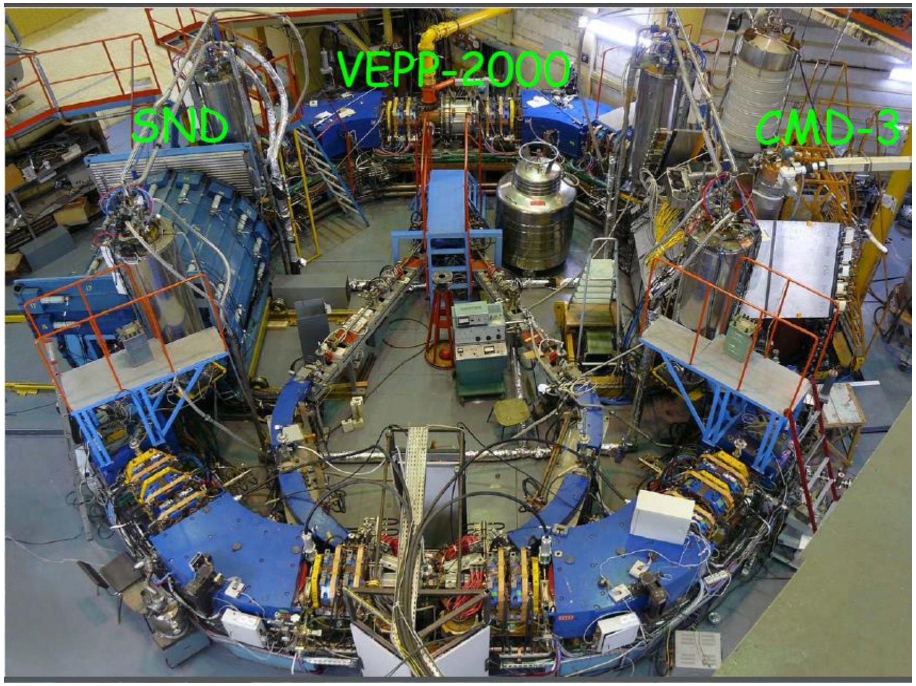
We expect very significant progress on $a_\mu(had)$ by the release of the result of the new FNAL measurement.

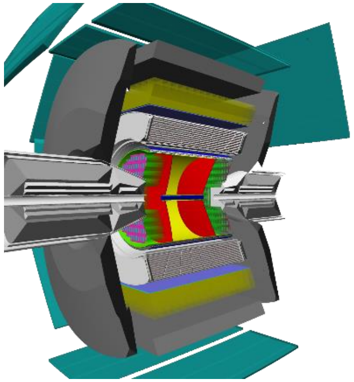
Lattice calculations are very important – completely independent approach, from the first principles.

VEPP-2000 (BINP, Novosibirsk)



SND





CMD-3

VEPP-2000 - e^+e^- collider at Budker Institute of Nuclear Physics (Novosibirsk).

C.m. energy range is 0.32-2.0 GeV; Design $L = 10^{32} 1/cm^2 s$ @ $\sqrt{s} = 2$ GeV

Collected first set of data in the whole energy range in 2011-2013 (few times the VEPP-2M statistics, similar to ISR statistics)

2013-2016 – installation of the new e^+ source, now in commissioning

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 predicted within the Standard Model.

The new experiment to measure (g-2) of muon is under preparation at FNAL. The expected uncertainty is 140 ppb - 4 times better compare to BNL.

The construction is nearly finished, the data taking will start by the end of 2017, the BNL-precision statistics by the middle 2018.

There is concurrent world-wide effort to improve the precision of the Standard Model calculation.

Stay tuned…