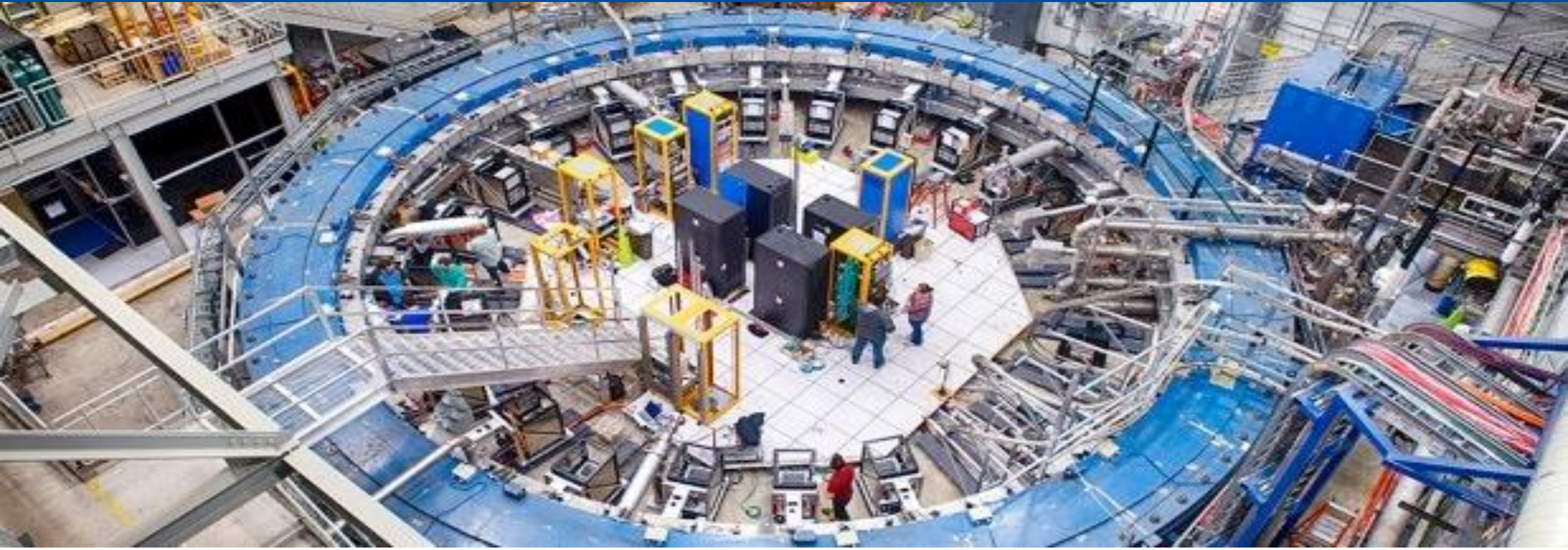


L’esperimento g-2

Carlo Gabbanini

INO-CNR e INFN sez. Pisa

per la collaborazione g-2

Moto di particella con spin in campo magnetico

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

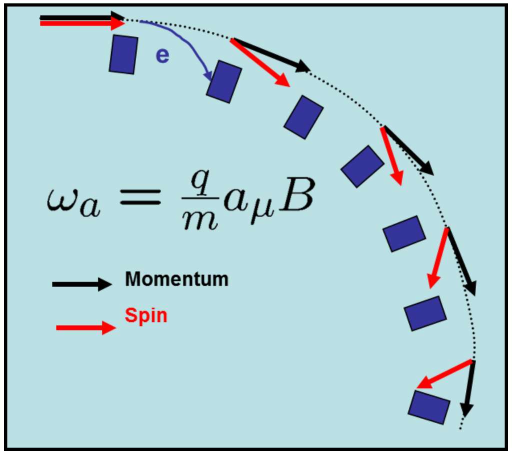
La frequenza di **Spin** relative alla frequenza di **Ciclotrone** è la “frequenza di precessione anomala” $\boldsymbol{\omega_a}$

Non dipende da γ !

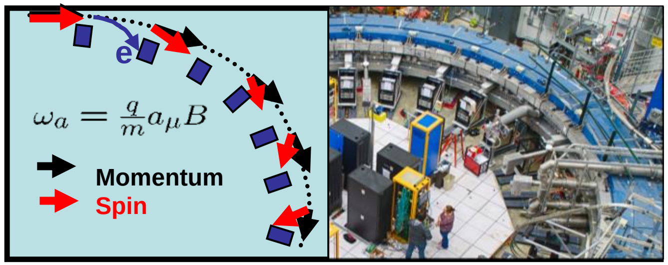
Proportionale a g - 2 e ***B*** !

$$\omega_a = \omega_S - \omega_C$$

$$= \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$



Measurement of Muon g-2



Determine difference between spin precession and cyclotron motion for a muon moving in a magnetic field:

The expression including E-field focusing and possible EDM

Get a_μ

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

Magic γ

EDM

Measure these

$$\vec{\omega}_{net} = \vec{\omega}_a + \vec{\omega}_{EDM}$$

Muon g-2 experiment at FNAL

- Improved measurement of the μ anomalous magnetic moment: $a_\mu = (g_\mu - 2)/2$
- Best previous measurement BNL-E821 (1997-2001)
  0.54 ppm

$$a_\mu^{\text{exp}} = (11\,659\,208.9(5.4)_{\text{stat}}(3.3)_{\text{syst}}(6.3)_{\text{tot}}) \times 10^{-10}$$

G. W. Bennett et al.,
PRL 92, 161802 (2004).
L. Roberts, Chinese Phys. C 34, 741 (2010).

  - **Error statistics limited**
  - **Difference wrt. SM ~ 3σ (theory error ~ 5 x 10^{-10})**
  - $a_\mu(SM) = a_\mu(QED)+a_\mu(Weak)+a_\mu(HVP)+a_\mu(Had\ HO)+a_\mu(HLbL)$

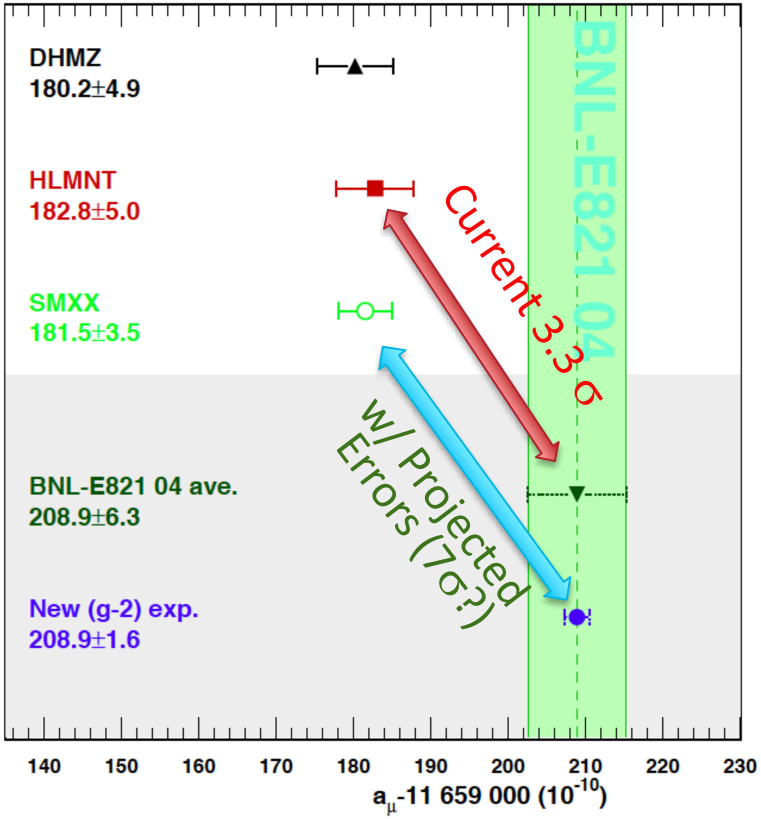
- **Goal of new FNAL experiment (E989) (x4 better)**
  - σ_{tot} **= (1.2 stat. ⊕ 1.3 syst.) x 10^{-10} = 1.6 x 10^{-10}**
- **Assuming same central values (exp. & theory):**

  exp. Difference - SM: ~ 5 (7) σ if no (x2) improvement in theoretical determination

a_μ(New Physics) ≡ a_μ(Expt) – a_μ(SM)

Goal of the new E989 experiment

- Reduce the experimental error bar in a_μ by a factor 4
- Resolve the long-standing E821 *g*-2 discrepancy



$\delta\omega_a$(statistics) at 100 ppb level

~ 1.5 x 10^{11} events in the final fit

Multiple independent blind analyses

Multiple sorting and fitting methods

Net Systematics error to 100 ppb (x 3 improvement)

Leading issues

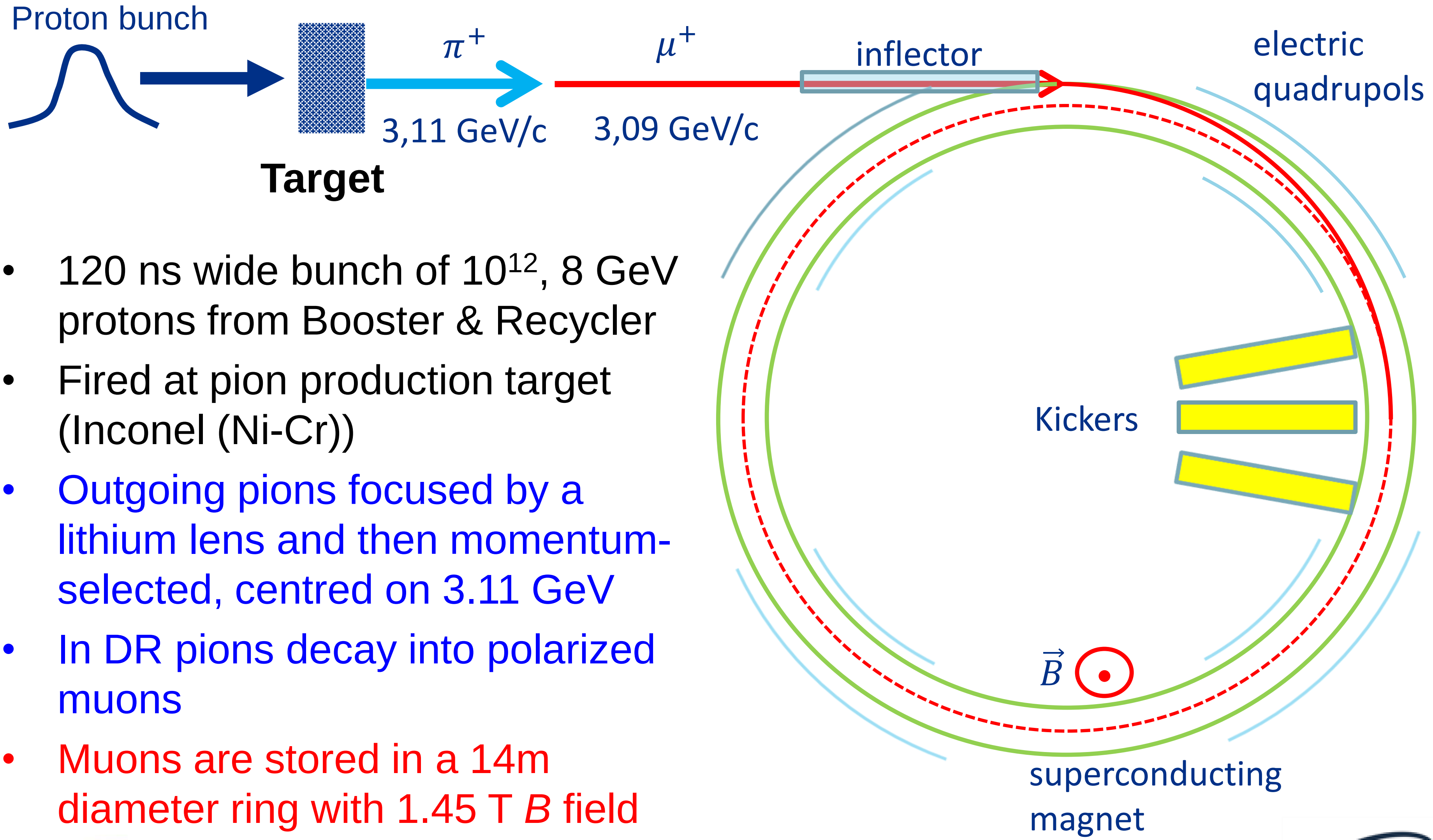
Pileup

Gain (energy scale) stability

Muon losses

The Big Move of the Ring (2013)

Storing muons



Proton bunch

π^+

3,11 GeV/c

μ^+

3,09 GeV/c

inflector

electric quadrupols

Target

Kickers

$\vec{B}$

superconducting magnet

- 120 ns wide bunch of 10^{12}, 8 GeV protons from Booster & Recycler
- Fired at pion production target (Inconel (Ni-Cr))
- Outgoing pions focused by a lithium lens and then momentum-selected, centred on 3.11 GeV
- In DR pions decay into polarized muons
- Muons are stored in a 14m diameter ring with 1.45 T *B* field

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

Si può scrivere come:

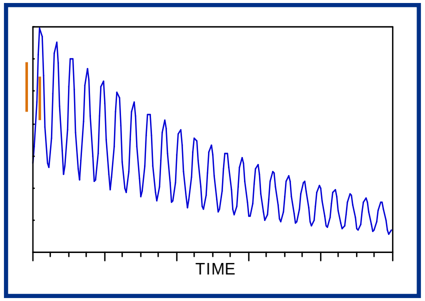
$$a_\mu = \frac{\omega_a/\omega_p}{\lambda - \omega_a/\omega_p}$$

$\lambda = \mu_\mu/\mu_p$
da struttura iperfine del muonio
120 ppb

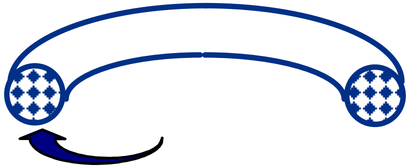
rapporto di frequenze

Two “blinded” frequency measurements are made. The ratio gives $a_\mu \equiv (g-2)/2$

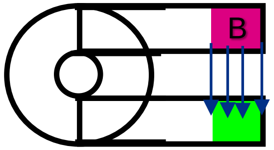
(1) Precession frequency
    (1) Calorimeters



(2) Muon distribution
    (2) Trackers & Models



(3) Magnetic field
    (3) proton pNMR

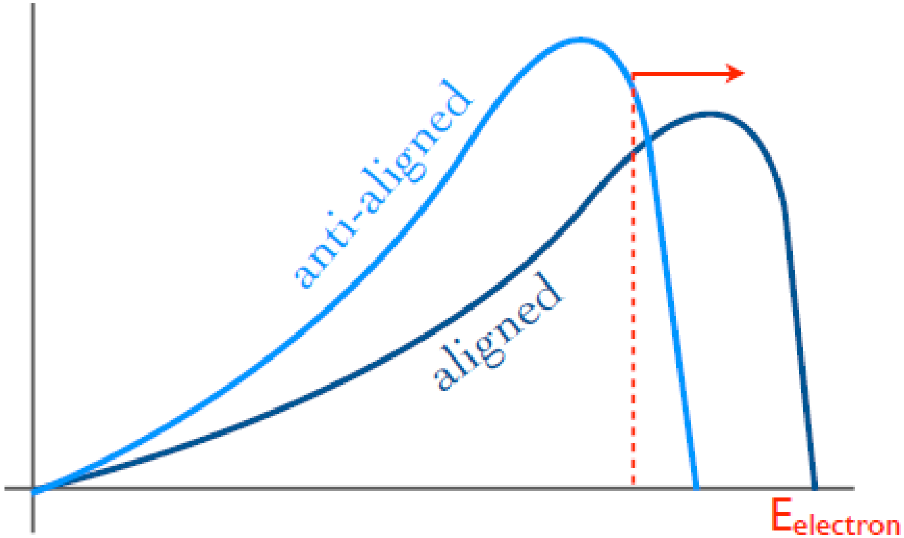


$$\boxed{(g-2) \propto \frac{(1)}{\langle \int (2)(3) \rangle}}$$

How do we get each of these?

How it works: ω_a

- Inject polarized muons into the ring
- Observe decay electrons
  - Count electrons above energy threshold (1.9 GeV optimal)



Harder electron spectrum when spin is aligned with momentum

«wiggle plot»

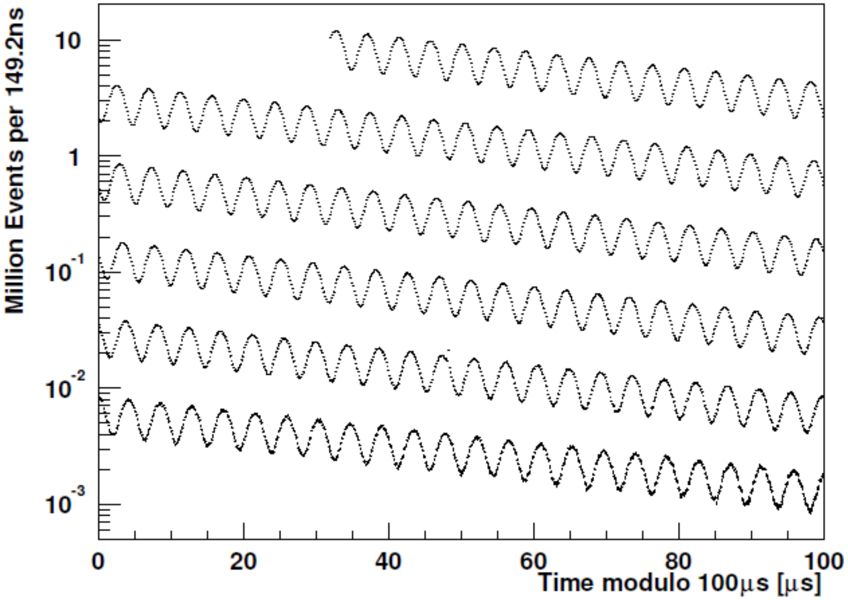
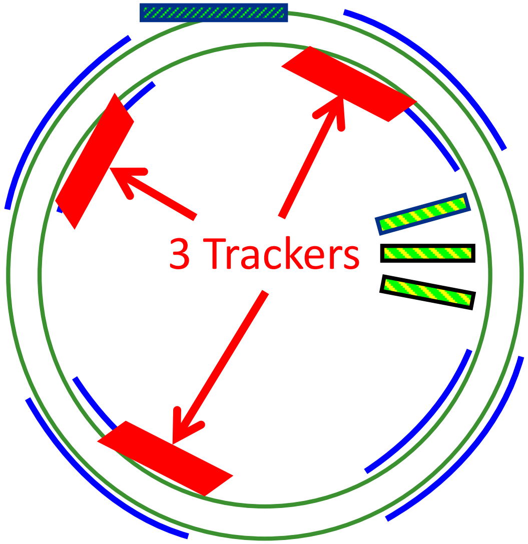


Figure 2: Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 μs [9].

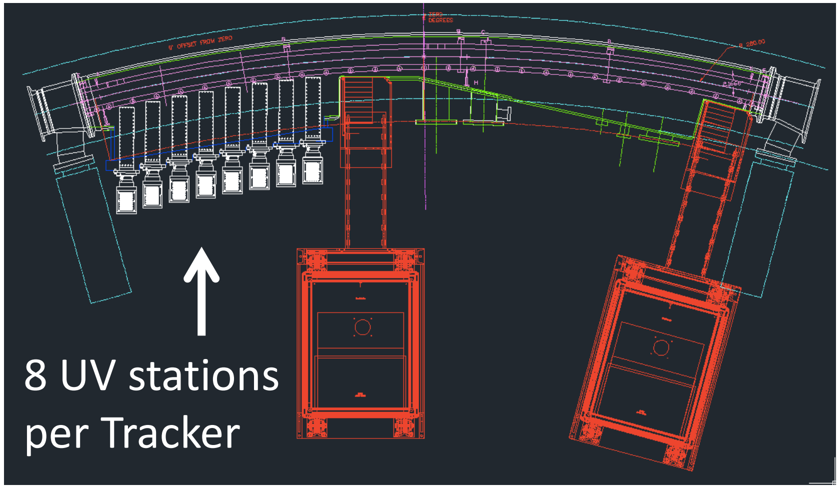
$$N(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left[1 + A\cos(\omega_a t + \phi)\right]$$

How it works: muon distribution

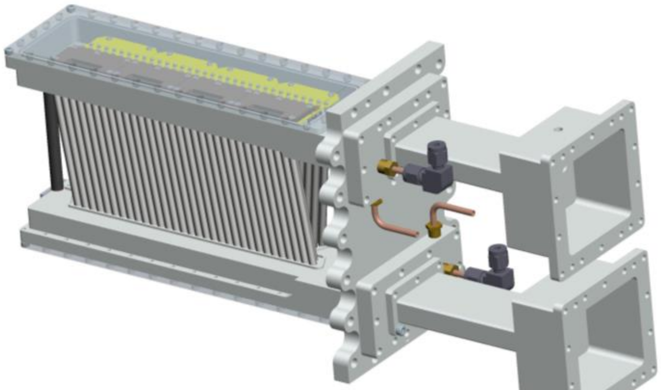
Trackers are used to determine beam position vs time



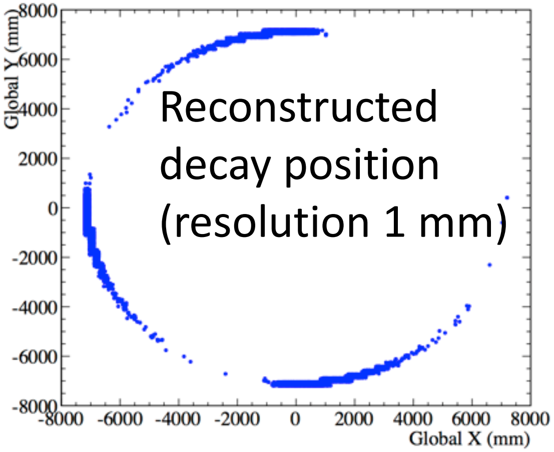
3 Trackers



8 UV stations per Tracker



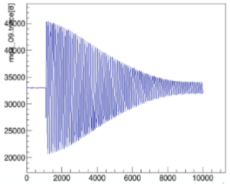
128 straws per station



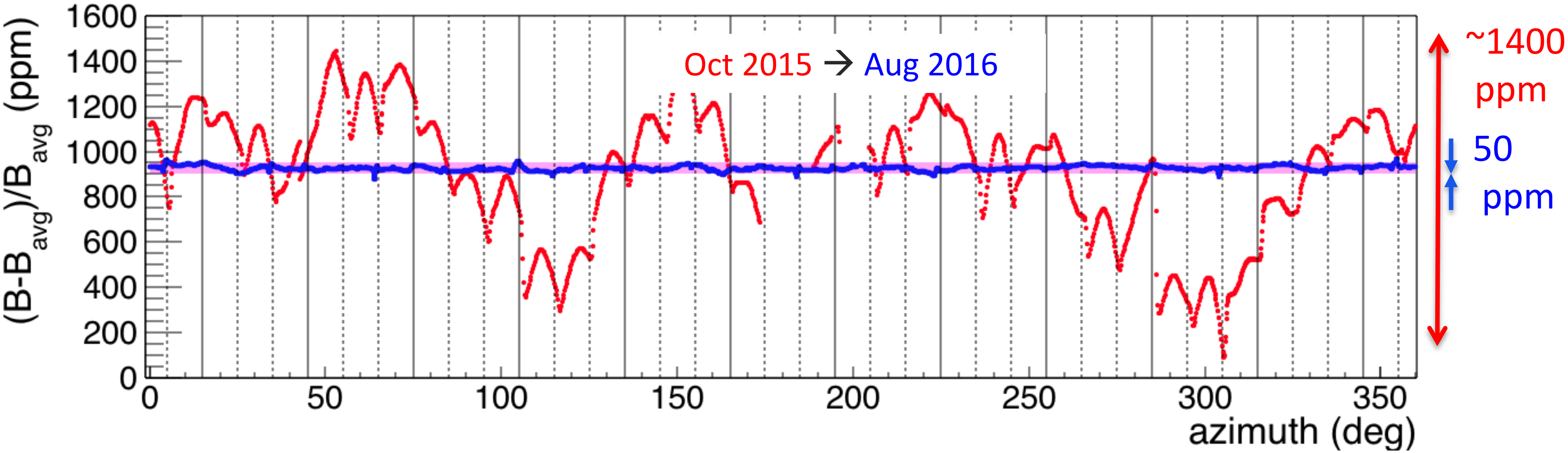
Reconstructed decay position (resolution 1 mm)

How it works: B/ω_p

- B measured with NMR probes (precision ~10 ppb)→
  - ω_p = free proton precession frequency $\propto$ B

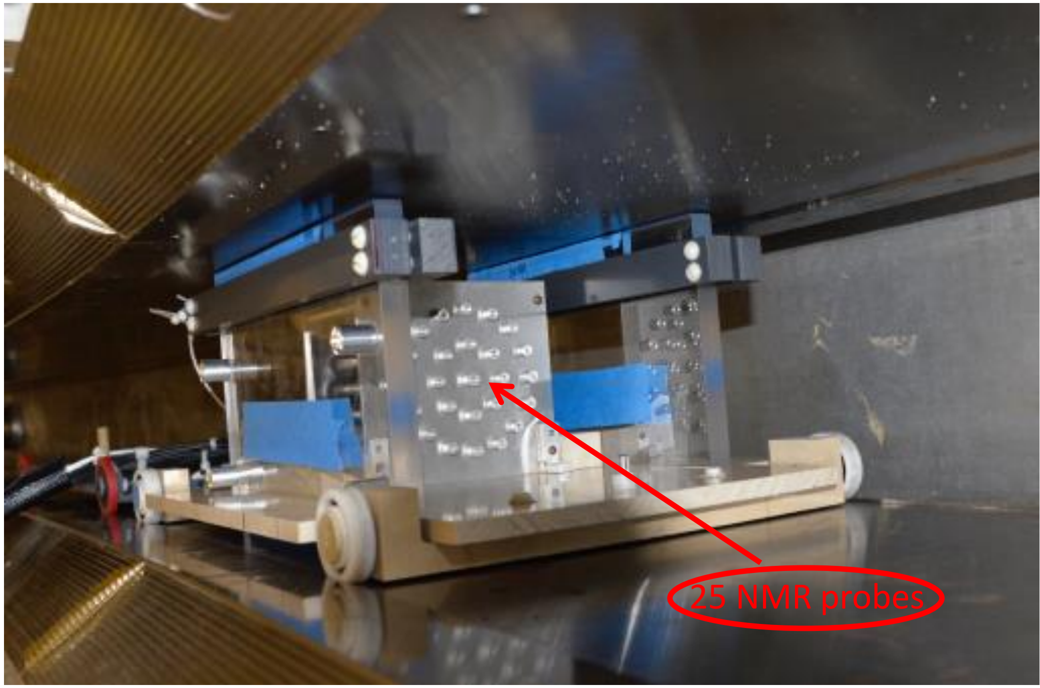


  - Probes in several fixed positions and on trolley that can move around the ring
    - What matters is average field around ring
    - Max deviation 15 ppm demonstrated in ring section with laminations



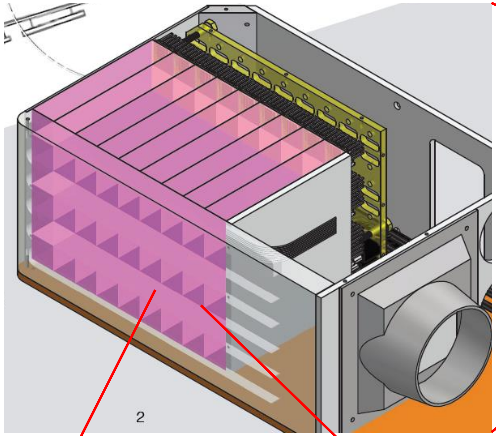
The magnetic field

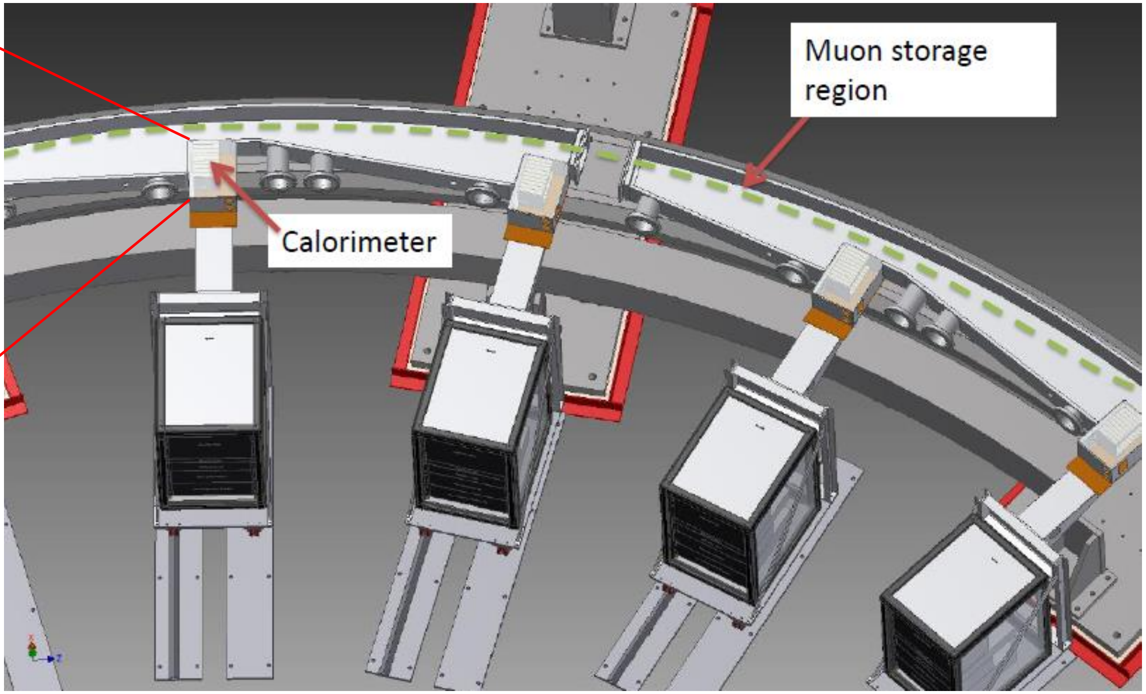
- Regularly map field inside vacuum chamber with NMR probe trolley
- Monitor field during data-taking with fixed probes and interpolate
- Shimming trolley contains array of probes that map whole storage volume
- Field in storage volume is measured using pulsed proton NMR (<10ppB single shot precision)

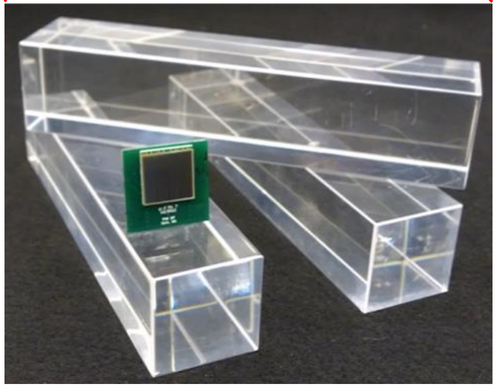


- BNL E821:
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989:
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

The detectors for ω_a : calorimeters

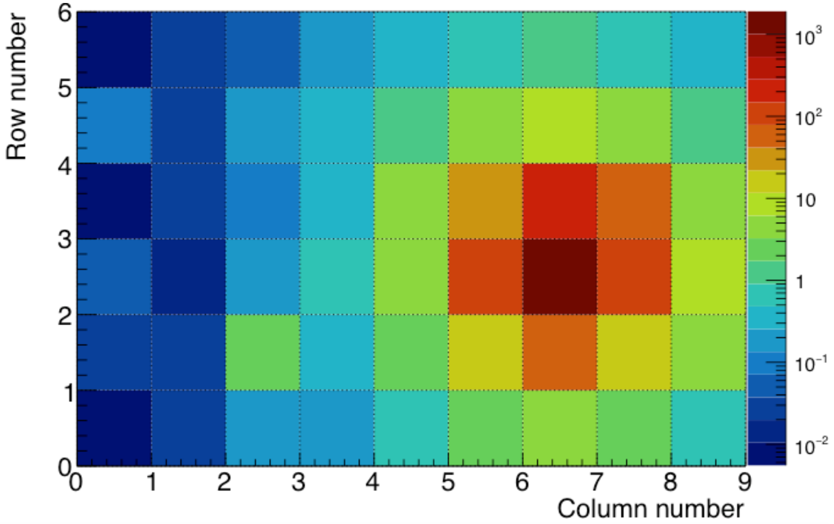


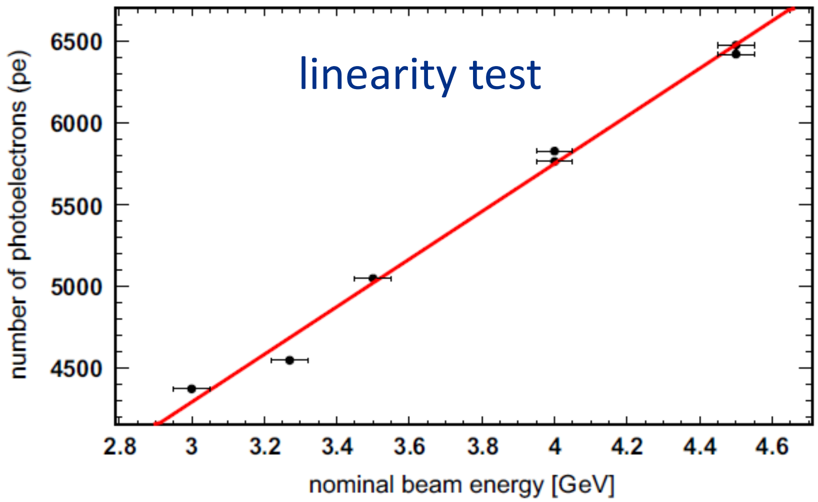




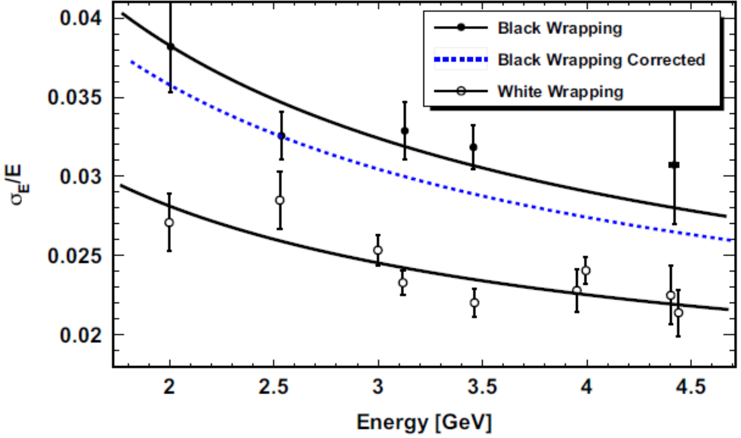
Energy and time of positrons is measured with 24 calorimeters, each one segmented in 54 channels. Each PbF_2 crystal is read out by a Silicon Photomultiplier (SiPM)

The detectors for ω_a : calorimeters

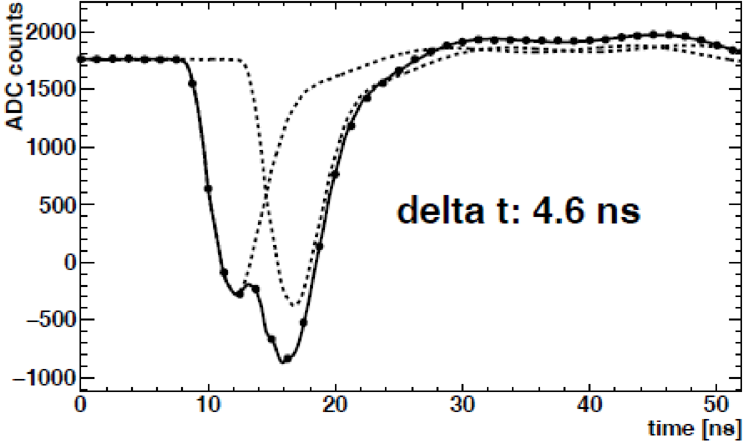



linearity test

energy resolution

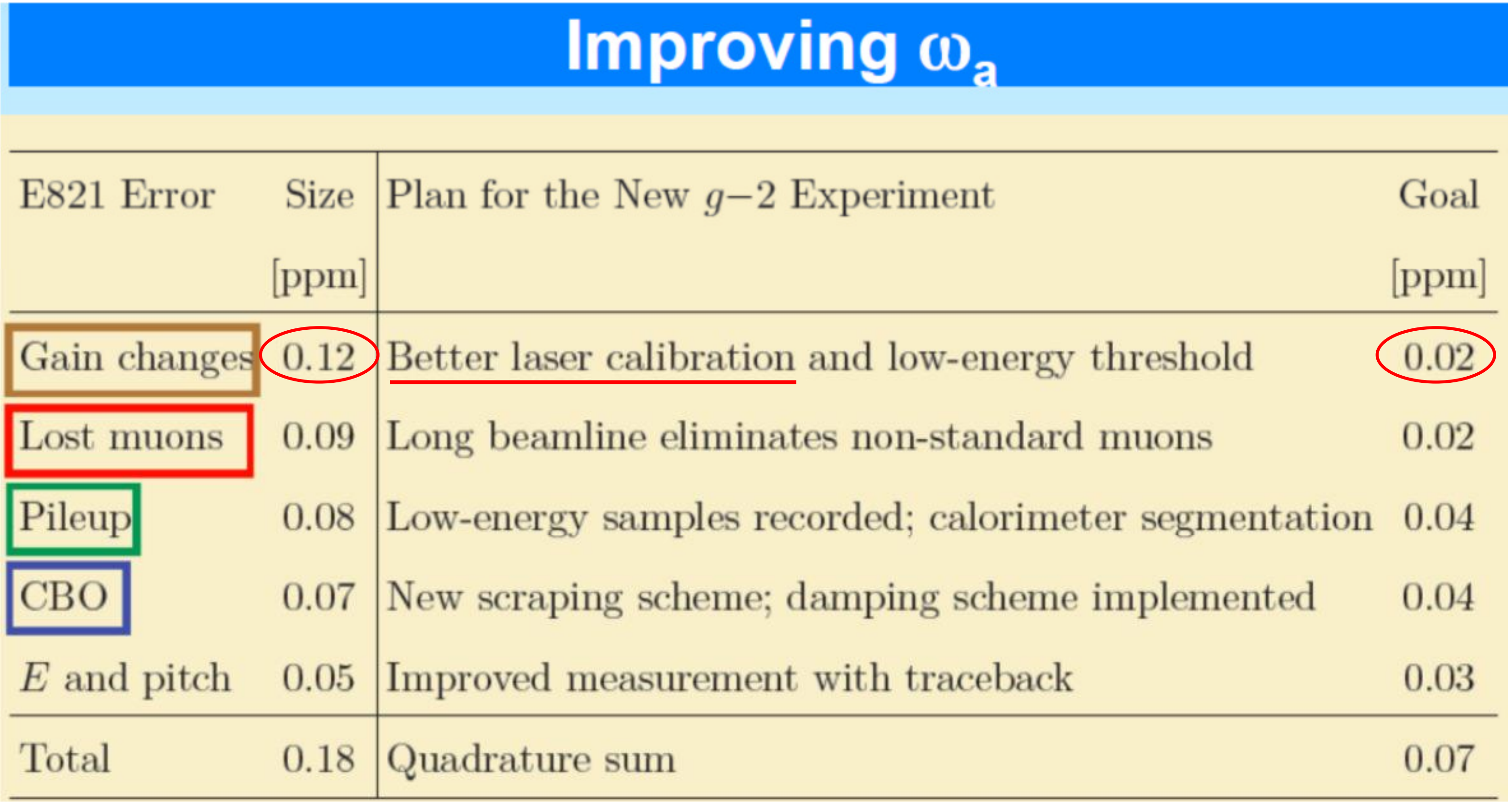


time resolution



A. Fienberg, NIM A 783, 12 (2015); J. Kaspar, Jinst (2017)

Systematic Errors on ω_a



Improving ω_a

E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

Muon (g-2) Technical Design Report [arXiv:1501.06858]

The laser calibration system

Idea:

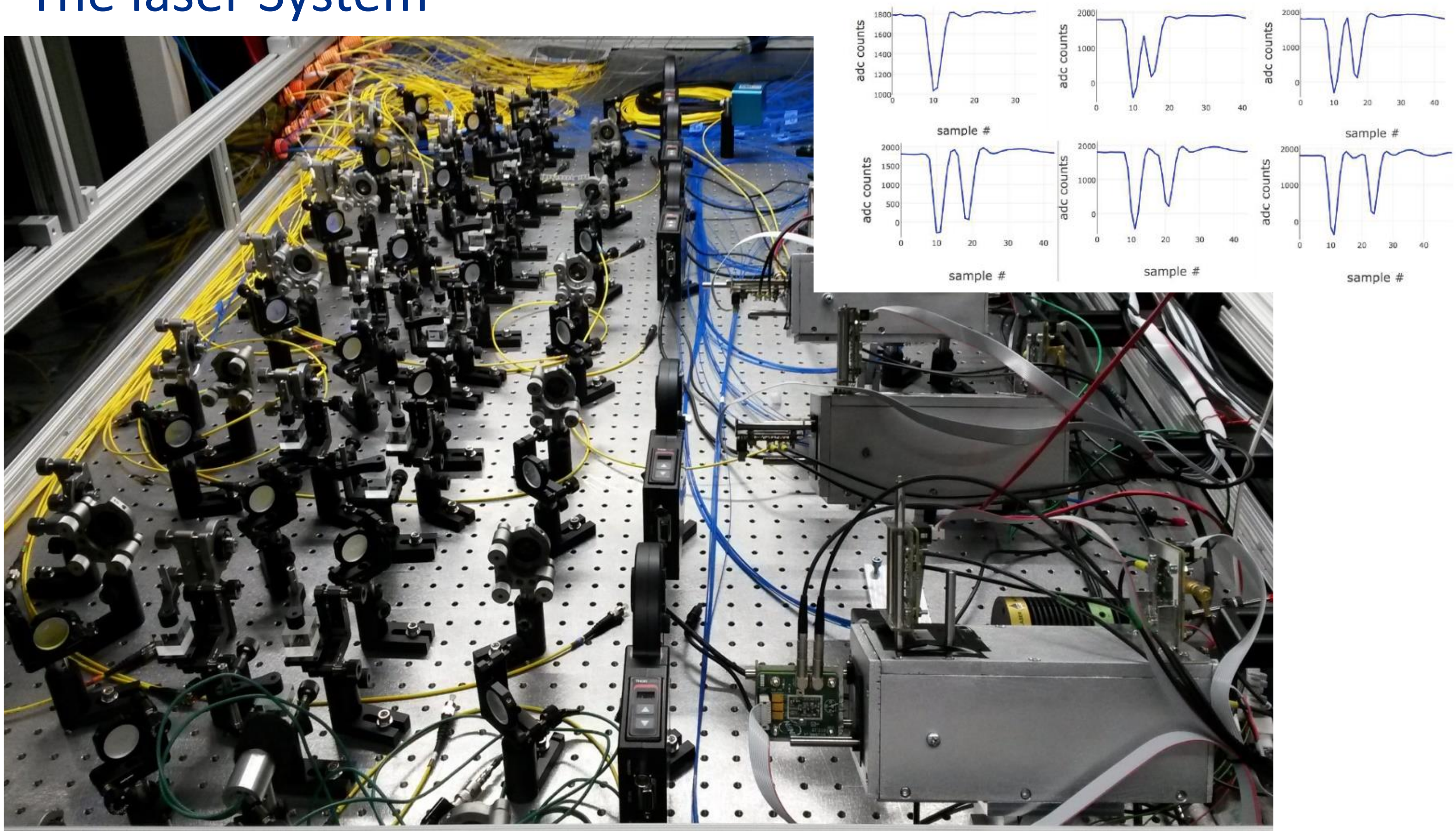
- Send trains of laser pulses on known intensity synchronously on all calorimeters' channels (1296)

Goals:

- Absolute calibration of the SiPMs response (photoelectrons/photons response)
- Provide **short term** (in fill, gain saturation) and **long term** (bias and temperature variations) calibration of the of the SiPM gain function
- provide additional synchronization signals

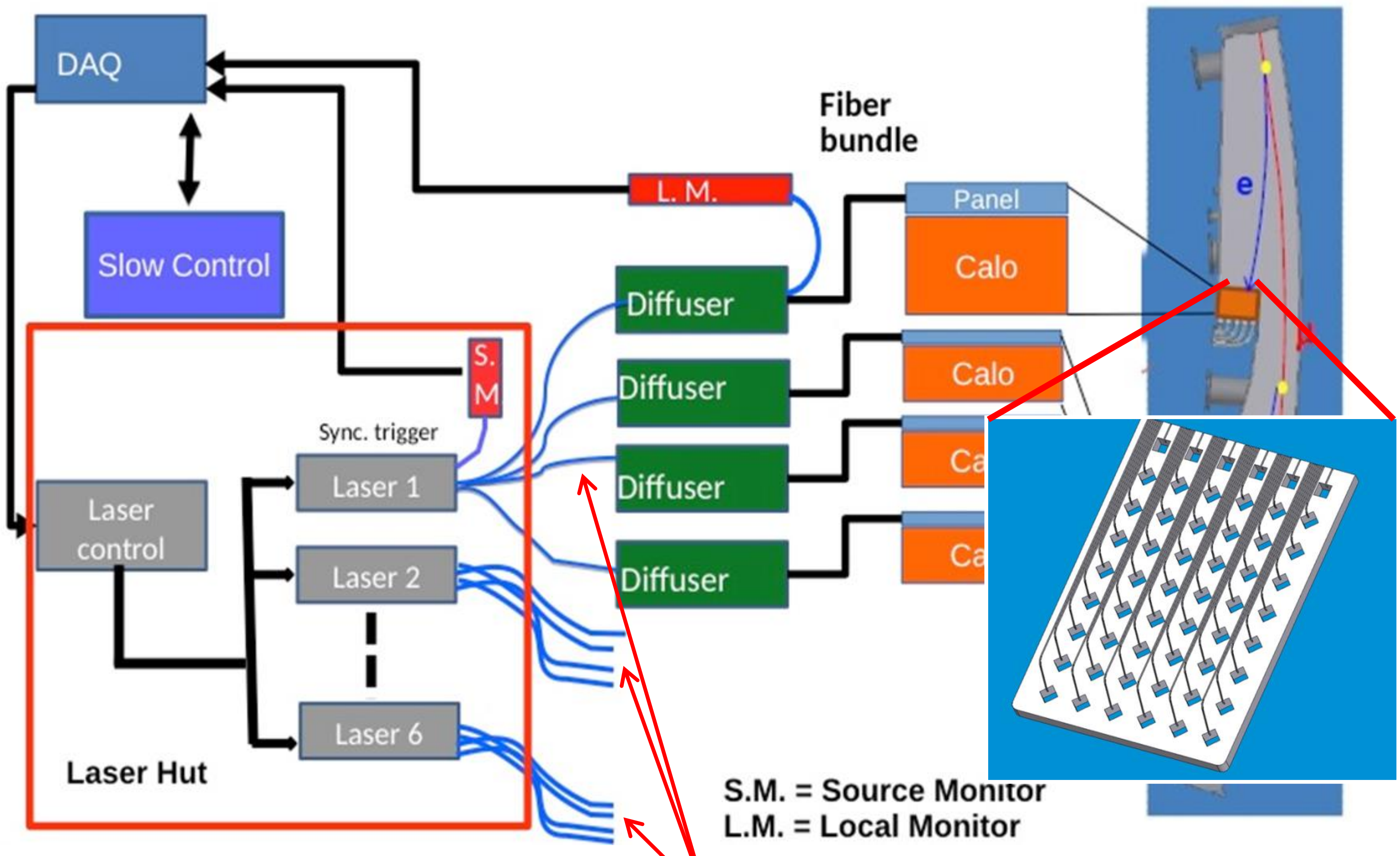
The laser calibration system

The laser System



Laser diodes @405nm, 600ps, 1nJ/pulse, 0-40 MHz rep. rate

The laser calibration system

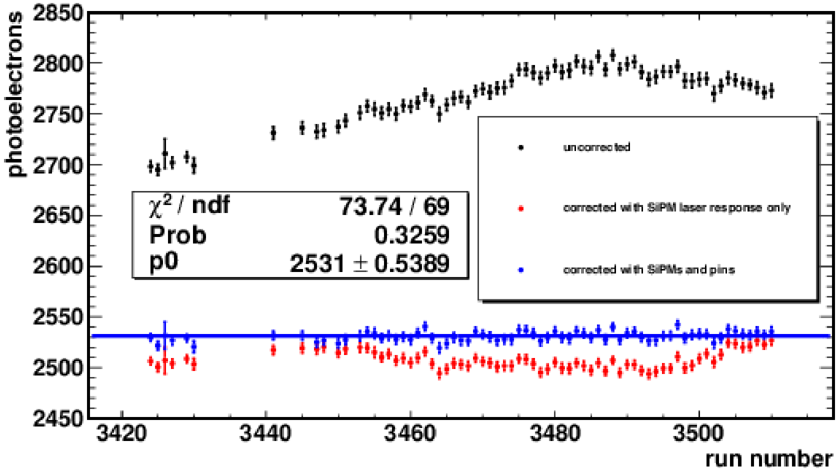


S.M. = Source Monitor
L.M. = Local Monitor

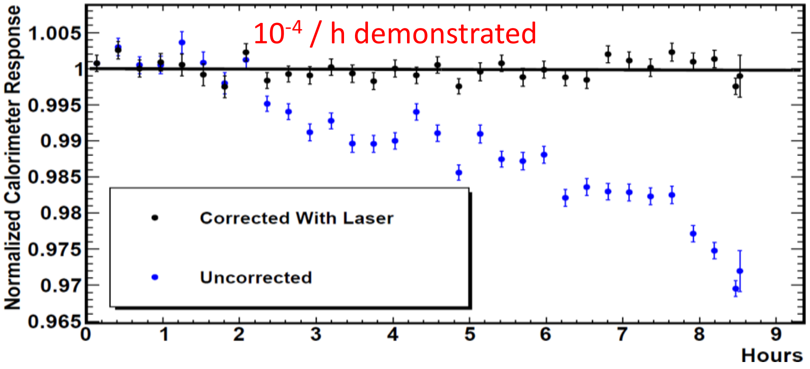
25m silica fibers

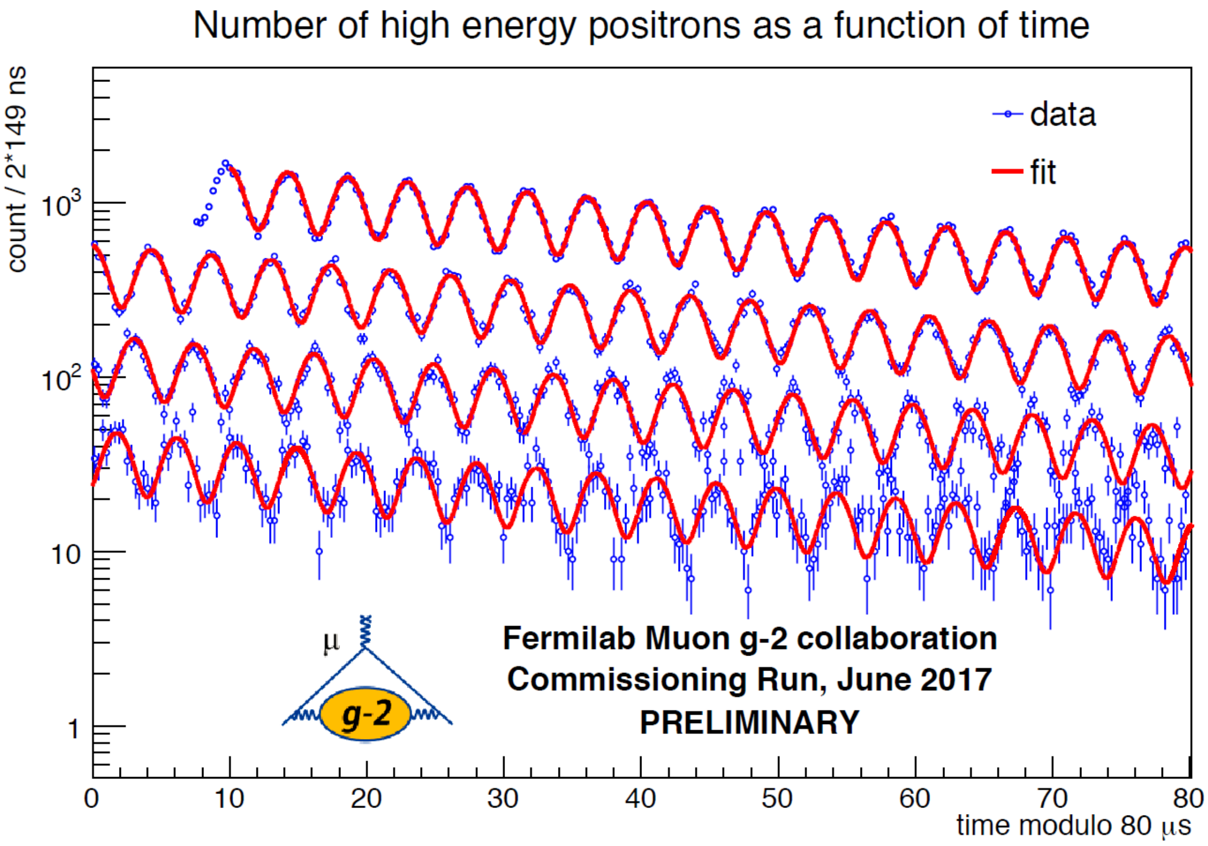
GAIN stability established to ~few x 10^{-4}

State-of-the-art Laser-based calibration system

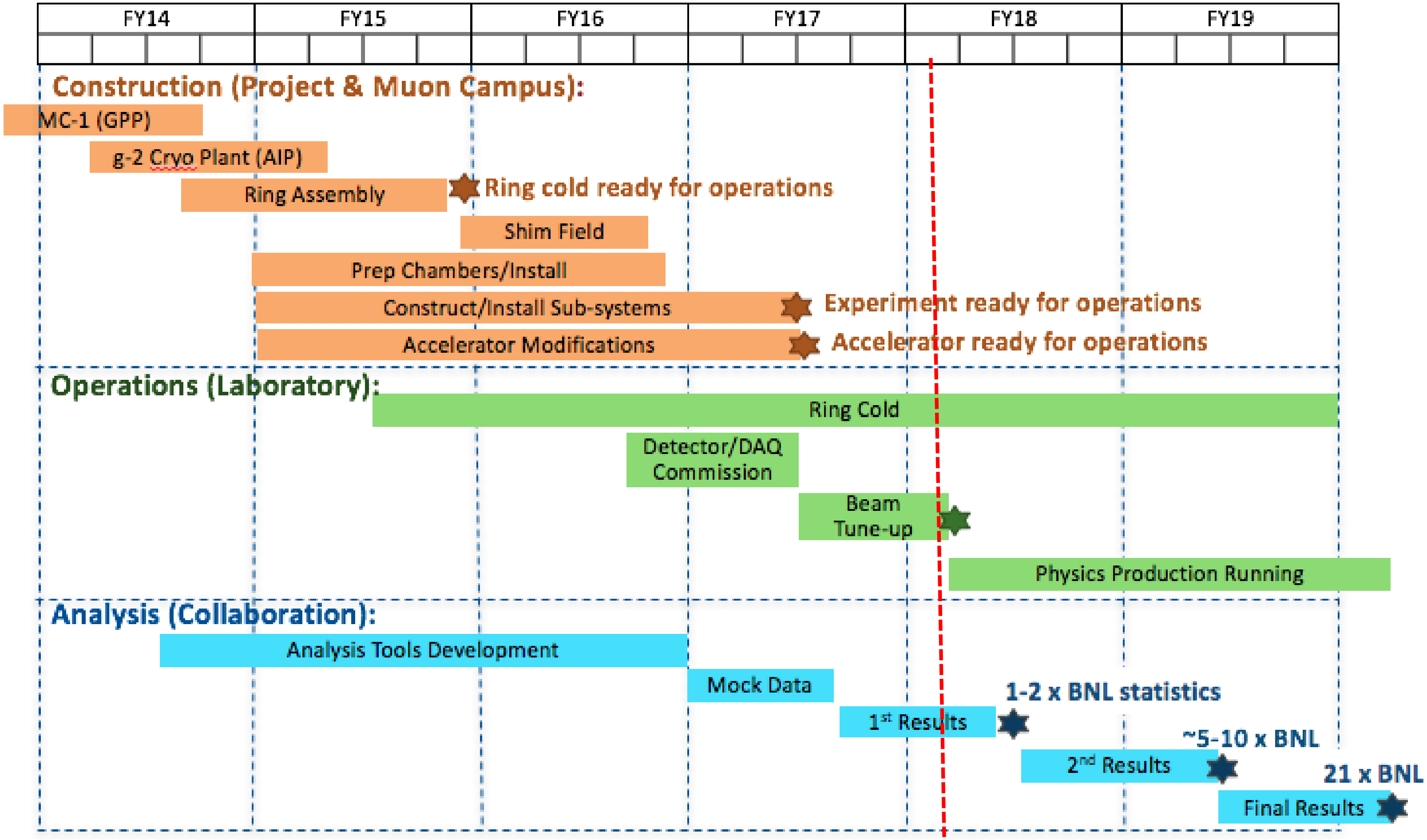


in Test Beam
BTF and SLAC


10^{-4} / h demonstrated


Number of high energy positrons as a function of time
count / 2*149 ns
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
time modulo 80 μs
data
fit
μ
g-2
Fermilab Muon g-2 collaboration
Commissioning Run, June 2017
PRELIMINARY

Status of the experiment



FY14 FY15 FY16 FY17 FY18 FY19

Construction (Project & Muon Campus):

- MC-1 (GPP)
- g-2 Cryo Plant (AIP)
- Ring Assembly
- Ring cold ready for operations
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems
- Experiment ready for operations
- Accelerator Modifications
- Accelerator ready for operations

Operations (Laboratory):

- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up
- Physics Production Running

Analysis (Collaboration):

- Analysis Tools Development
- Mock Data
- 1st Results
- 1-2 x BNL statistics
- 2nd Results
- ~5-10 x BNL
- Final Results
- 21 x BNL

Conclusioni

- L'esperimento g-2 è in fase di presa dati a Fermilab da un mese circa

- Le varie componenti dell'esperimento funzionano come da previsione, tranne flusso muoni (1/6 del TDR)

- Primo risultato (1xBNL o 2xBNL) atteso fine luglio

- Risultato finale (21xBNL) atteso per fine 2019 / 2020

E989 Scientific collaboration

Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Kentucky
  - Massachusetts
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois
  - Regis
  - UT Austin
  - Virginia
  - Washington
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab

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

China
  - Shanghai

Germany
  - Dresden

England
  - Lancaster
  - Liverpool
  - University College London

Korea
  - CAPP/IBS
  - KAIST

Russia
  - JINR/Dubna
  - Novosibirsk

Grazie per l’attenzione

SPARE

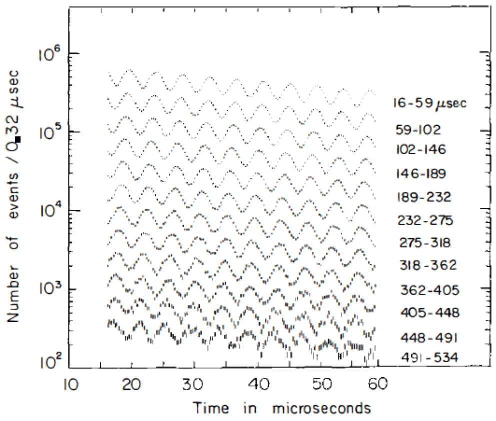
The magic momentum

An Electric field is necessary for vertical focusing of the beam so:

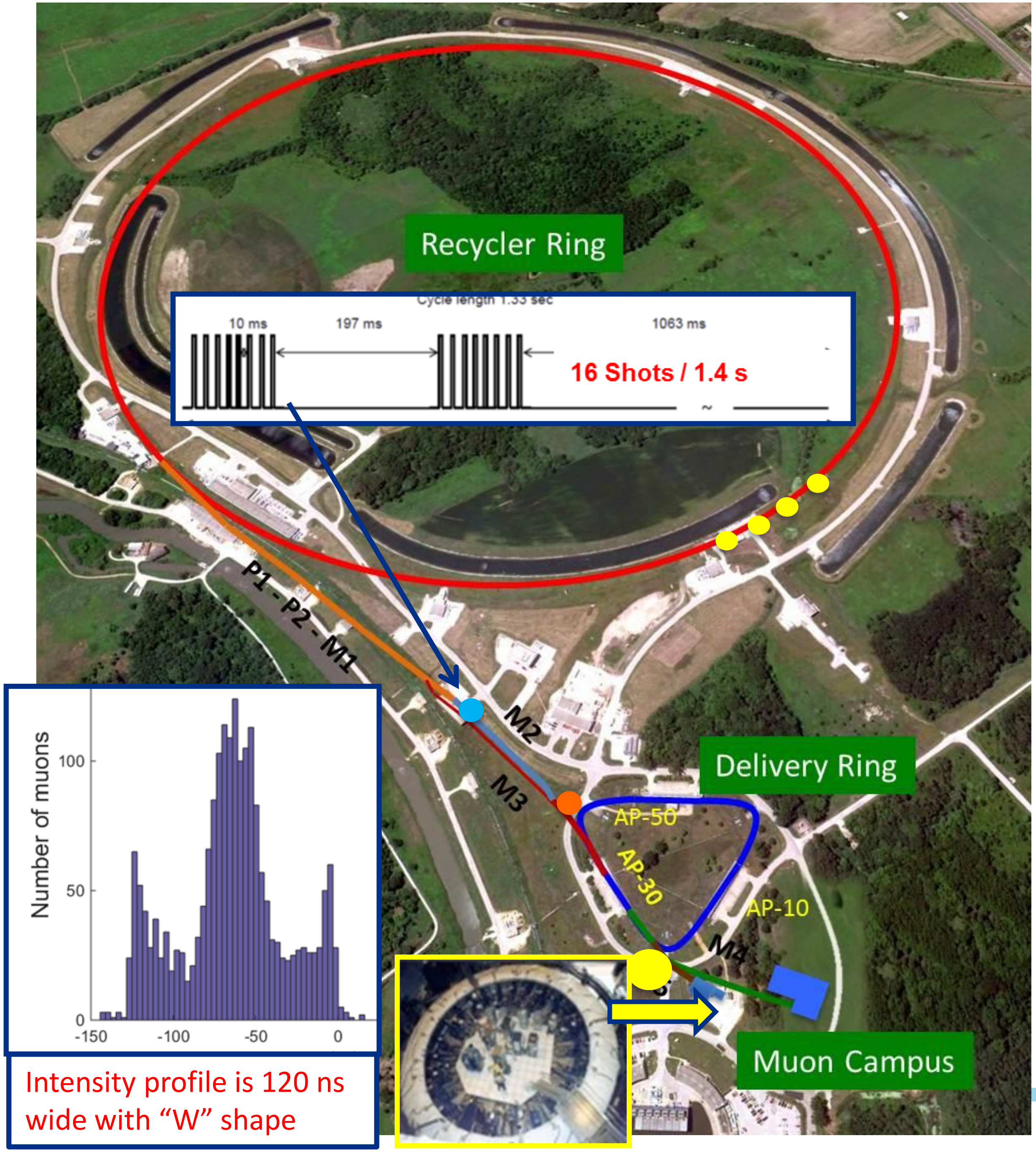
$$\overrightarrow{\omega_a} = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \vec{\beta} \times \vec{E}\right]$$

The extra term is zero for $\gamma = 29{,}3$ ($P_\mu = 3.09$ GeV/c)

CERN III
(1979)



Creating the Muon Beam for g-2

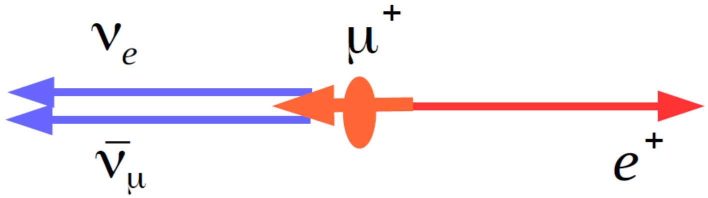


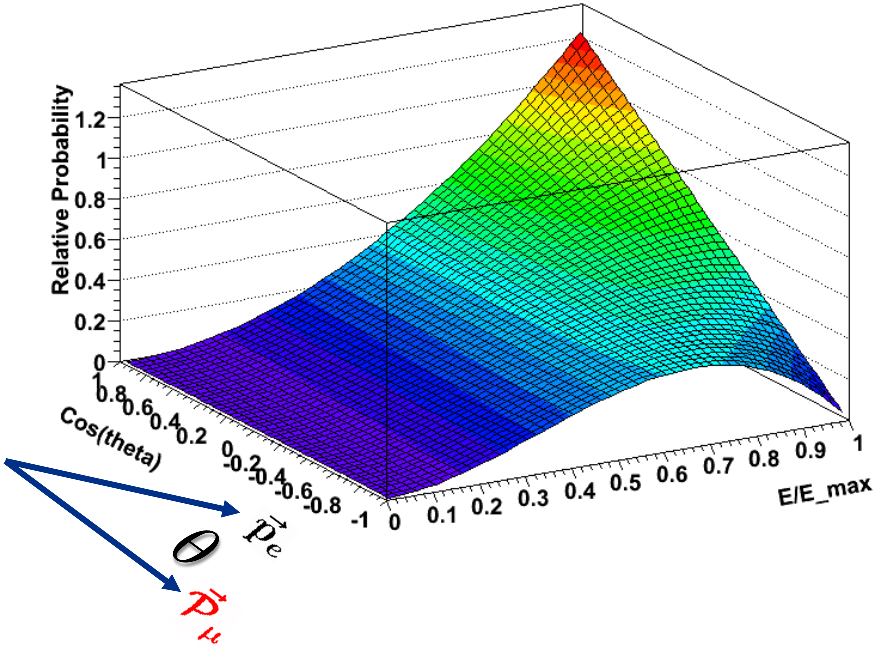
Intensity profile is 120 ns wide with "W" shape

- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- p/π/μ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

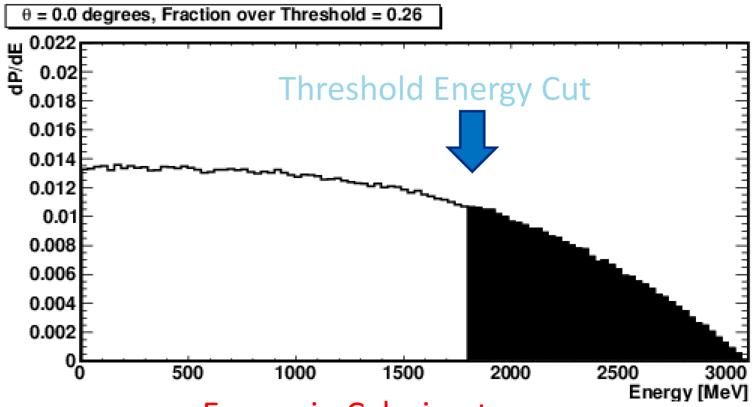
Analyzing the muon spin

- Parity violation in muon decay → highest energy decay positron emitted opposite of muon spin
- When spin is aligned/anti-al. with momentum, the boost subtracts/adds, and the decay positron energy is reduced/increased in the lab frame
- This results in a modulation of the energy spectrum at the ω_a frequency



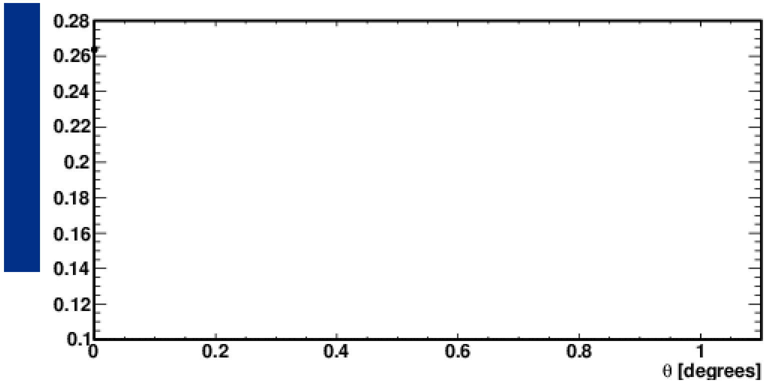


What makes the “wiggle” ?



Energy in Calorimeters

Fraction e^+ above Threshold

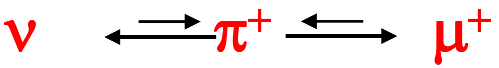


Phase of Muon Spin

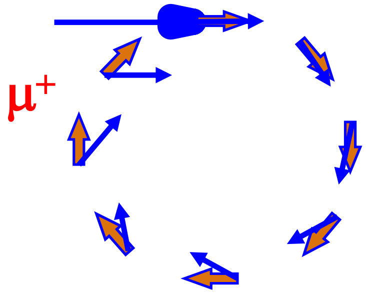
Recap the 4 key elements

(1) **Polarized muons**

~ 97% polarized for forward decays

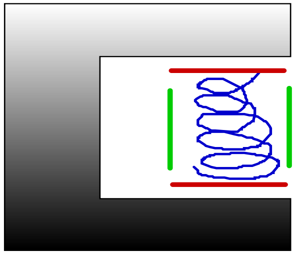


(2) **Precession proportional to (*g*-2)**

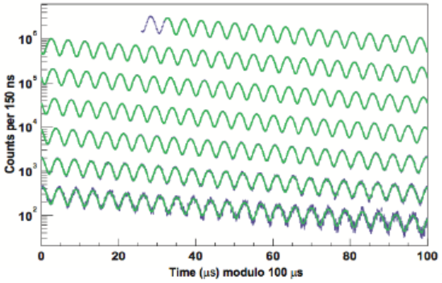


(3) **P$_\mu$ magic momentum = 3.094 GeV/c**

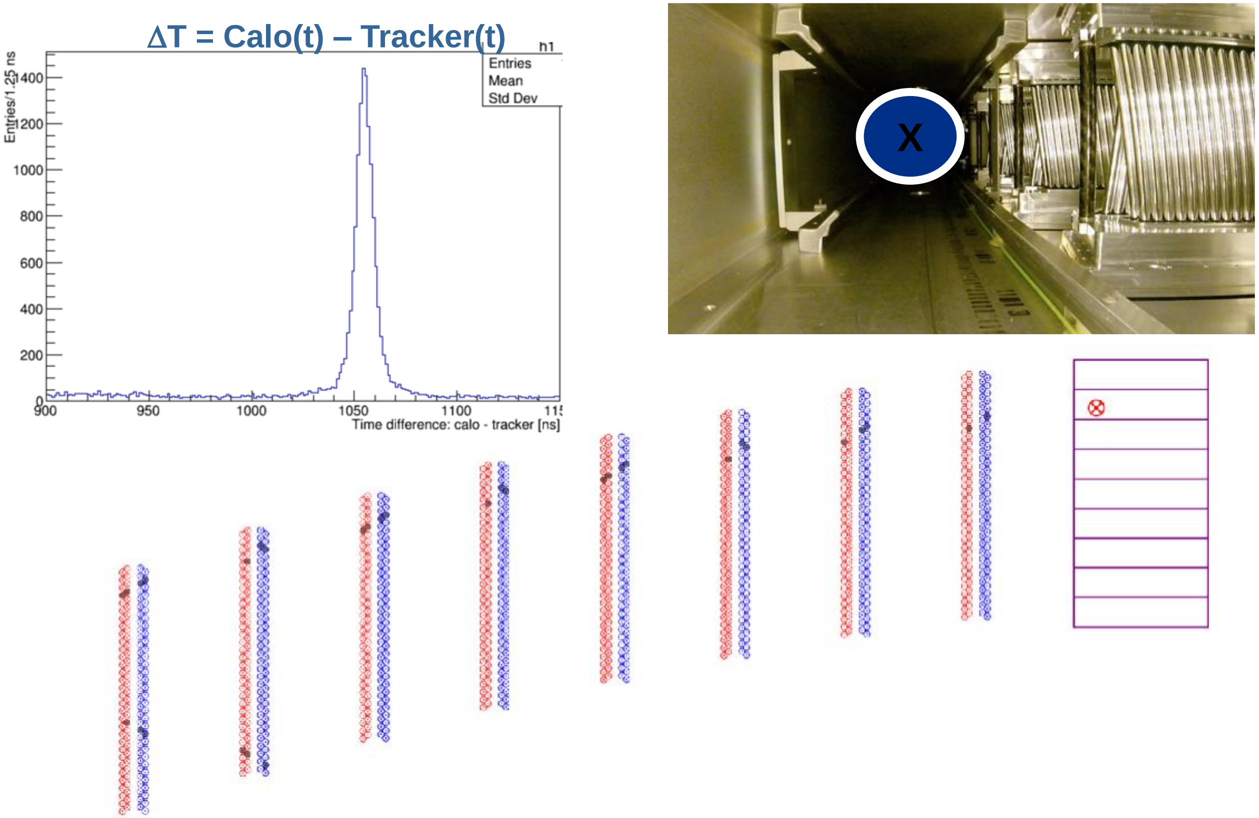
No *E* effect on precession when $\gamma = 29.3$



(4) **Parity violation in the decay gives average spin direction.** The number of higher energy positrons is modulated at ω_a



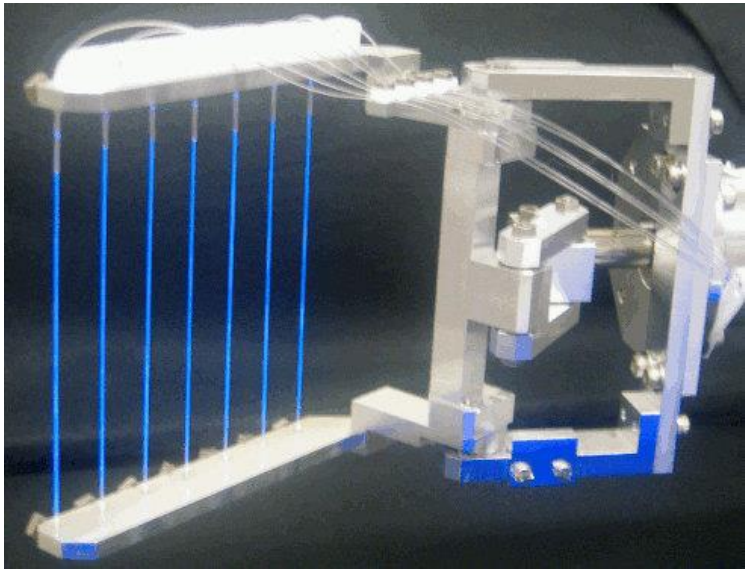
In-vacuum Straw Tracker determines Muon Distribution needed for the “~” in ω_p formula



ΔT = Calo(t) – Tracker(t)

Aux detectors: harps and counters

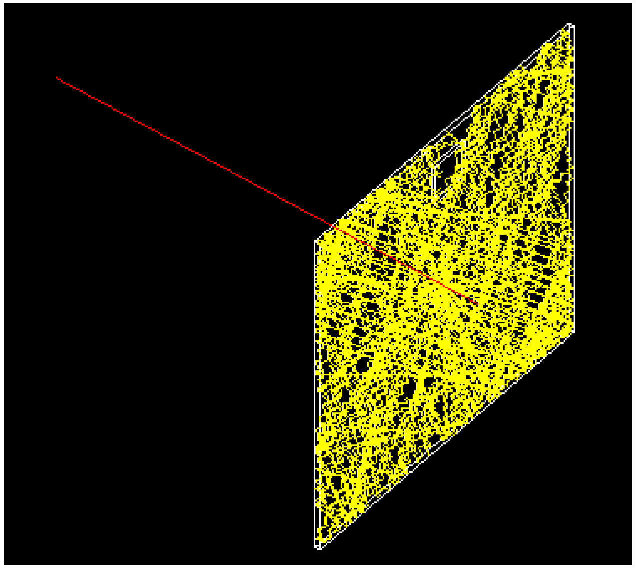
Fiber Harps



2 locations, 2 axis

- used to monitor the muon beam entrance position and angle during commissioning
- measures betatron oscillations during run

Entrance counters



outside the inflector

- gives relative intensity of fill
- timing of the fill (resolution << 150ns, cyclotron period)

Measuring the Field, ω_p

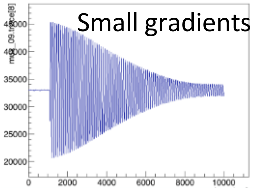
- **Systematic error total ω_p budget:**

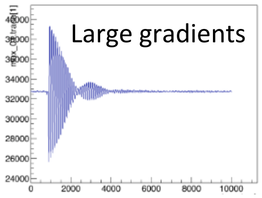
  [from 170 ppb → **70 ppb**]

- **The recipe:**

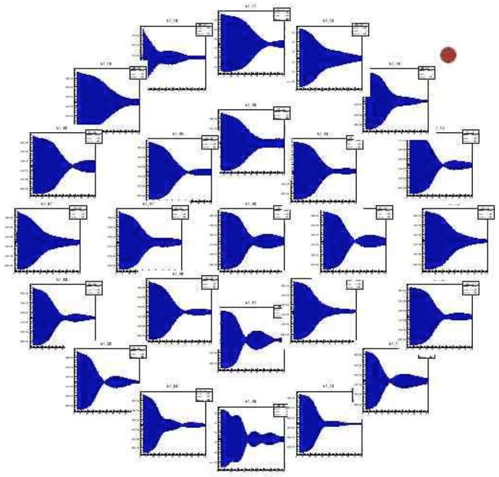
  1. **Make a highly uniform dipole field**
  2. **Install NMR probes "everywhere" to monitor its stability**
  3. **Build a NMR "trolley" map the field in the vacuum region where the muons will be stored**
  4. **Build a system of "absolute" magnetic field measuring special probes that can cross calibrate the many used in the fixed and trolley locations**
  5. **Don't make any mistakes**
  6. **Figure out where the muons were storing and calculate the average integrated field they experiences.**

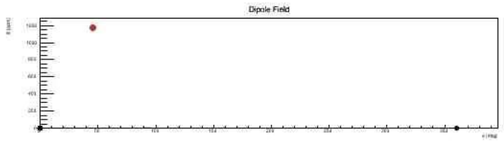
A 25-element pNMR *Trolley* maps the field during shimming





Probe Matrix





Free Induction Decay (FID) Waveforms

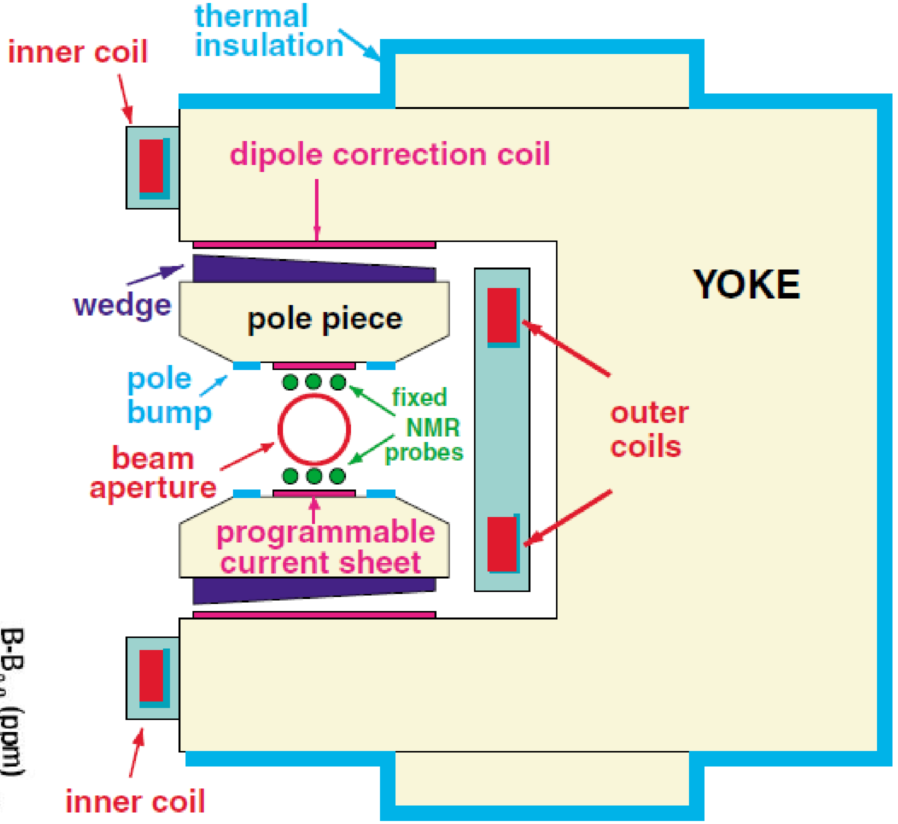
Extracted frequency precision is ~10 ppb per FID

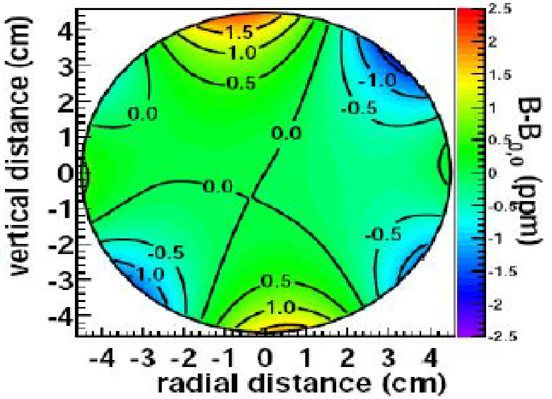
The magnetic field

- Many passive and active shimming tools to achieve unprecedented field homogeneity for such a large volume.
- Each “knob” adjusts nearly orthogonal components of the field shape

Passive shims
- **Iron wedges**
- **Pole tilt**
- **Iron pole bumps**

Active shims
- **Dipole correction coils**
- **Surface correction coils**





FNAL goal is x2 improvement in homogeneity

Slide credits: Joe Grange, Argonne Nat. Lab