The g-2 experiment at Fermilab

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Birmingham University Seminar

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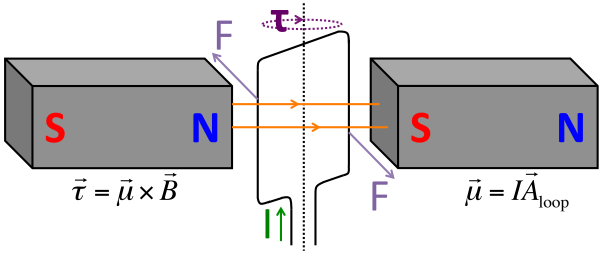
Magnetic moments

The magnetic moment determines how something interacts with a magnetic field

A magnetic moment placed in a magnetic field will experience a force :

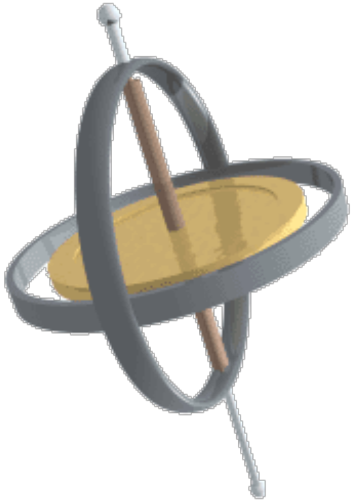
$$\vec{\tau} = \vec{\mu} \times \vec{B}$$



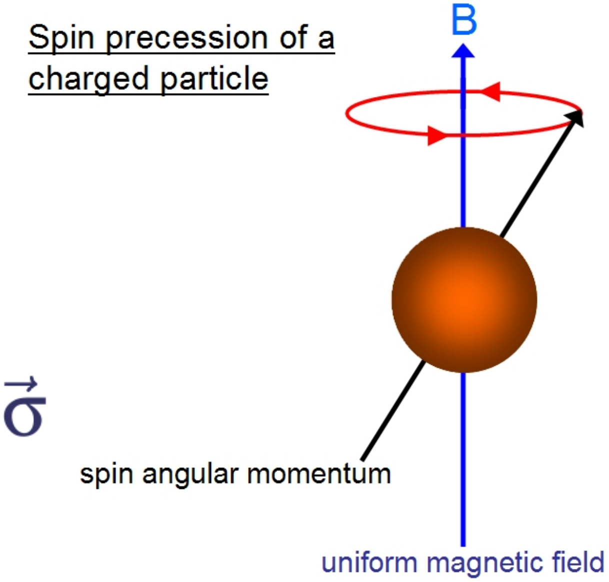
Classically the magnetic moment is :

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c}\vec{L}_i$$

The torque from the magnetic field causes the angular momentum and magnetic moment to **precess**



→ Analagous to a gyroscope



For particles with quantum mechanical spin (e.g. electrons) :

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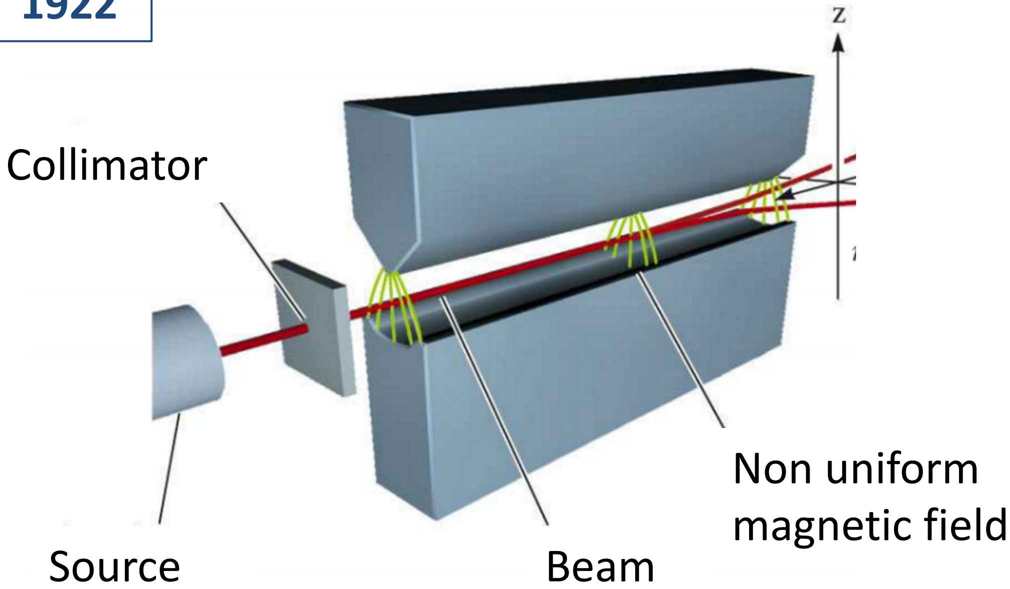
$$\vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

A brief history – Stern-Gerlach

1922



Stern fired silver atoms through a non-uniform magnetic field

Observed a quantised result (up or down) due to the magnetic moment of the silver atom

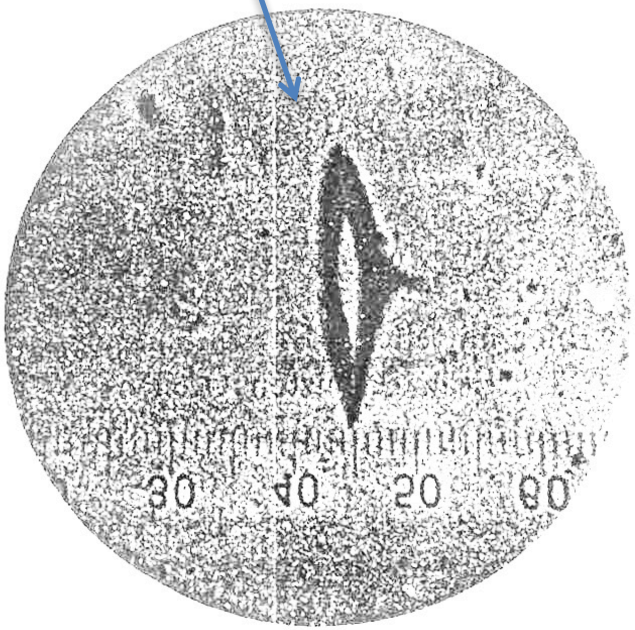


Fig. 3.

The magnetic moment of a silver atom comes from the lone electron in the outer shell

→ Demonstrated quantisation of spin

→ Showed electrons have spin ½

→ Showed that for electrons g = 2

A brief history – The Dirac equation

1928

The Dirac equation is a marriage of quantum mechanics and special relativity with two remarkable children – intrinsic spin and anti matter

$$\left(i\gamma^{\mu}\partial_{\mu}-m\right)\psi^{c}=0$$

The Dirac equation describes all spin ½ massive particles

If a magnetic field is introduced the equation predicts an intrinsic magnetic moment for the Dirac particle with g = 2

A brief history – proton magnetic moment

1933

It was assumed that the magnetic moment of the proton would be 2 like the electron

Pauli : "If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known"

Gerlach : "No experiment is so dumb, that it should not be tried"

Stern measured the magnetic moment of the proton using hydrogen to be between 4 and 6

Confirmed by Rabi using atomic hydrogen.

Also measured deuteron to find a non zero magnetic moment of the neutron

First evidence for substructure of the proton - quarks

A brief history – Shelter Island

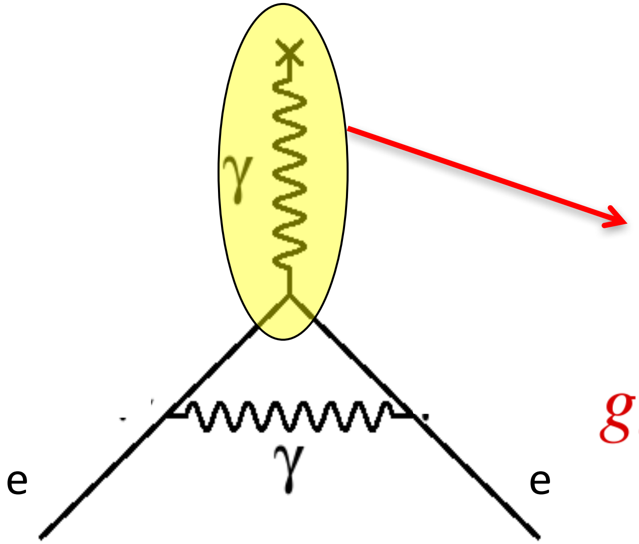
1947

Three measurements caused problems :

- Hyperfine structure of hydrogen
- The Lamb shift
- The magnetic moment of the electron

These results can be explained by a value of g slightly greater than the 2 predicted by Dirac

→ Schwinger's theory of renormalisable QED



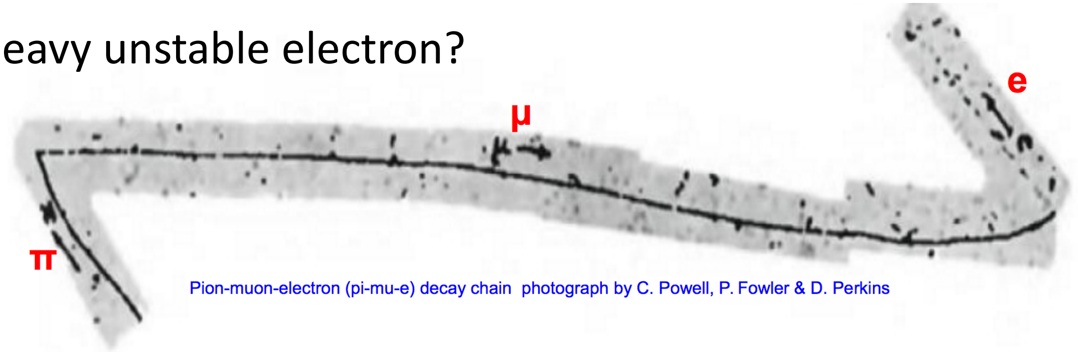
B-field is simply a photon

$$g_e \approx 2(1+\frac{\alpha}{2\pi}) \approx 2.00232$$

A brief history – Muons

The muon was first observed in a cloud chamber in 1933

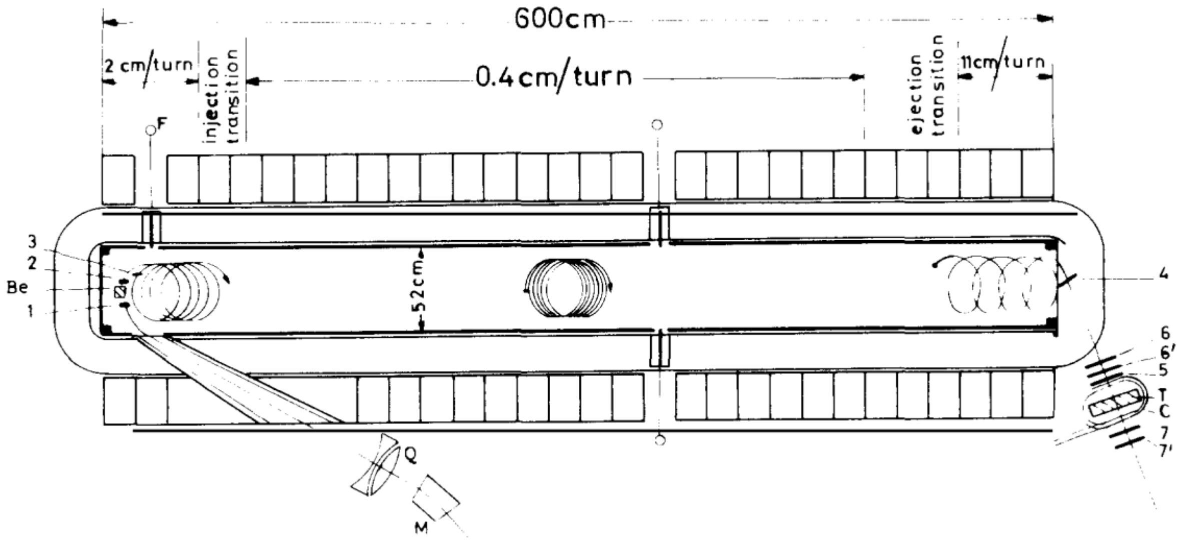
It was uncertain what the muon was – a heavy unstable electron?



Pion-muon-electron (pi-mu-e) decay chain photograph by C. Powell, P. Fowler & D. Perkins

1956 : Observed

- Parity violation in muon decays
- Muon magnetic moment about 2



1963 : CERN

Measured g-2 of the muon to 4300 ppm - showed that QED was correct

$$g = 2 + \frac{\alpha}{\pi}$$

There is no muon substructure

(above 0.2 fm)

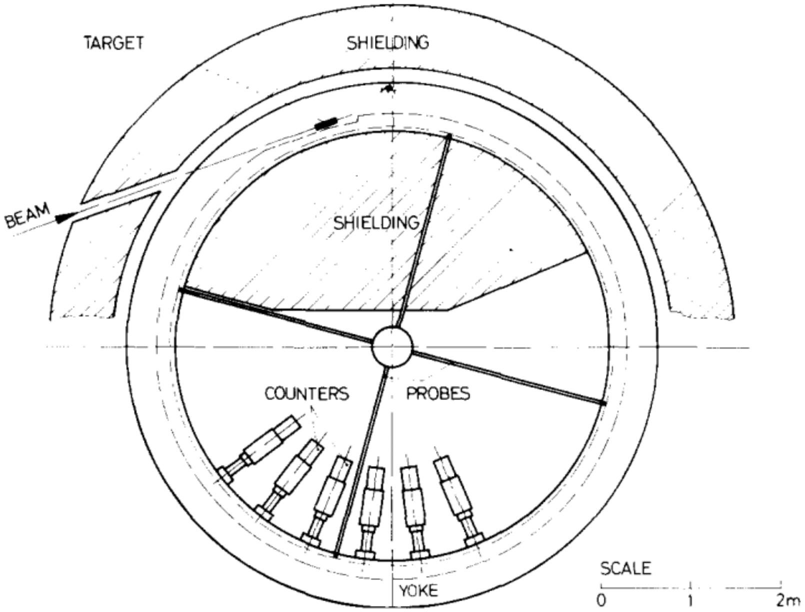
A brief history – CERN II

1968

The CERN II g-2 experiment was the first storage ring experiment

Head of CERN Theory : “The Muon obeys QED. g-2 is correct to 0.5%. In my opinion, it will be right to any accuracy. So it’s not worth doing the experiment”

F. Farley : “Would you like to predict the result?”



Measured g-2 of the muon to 265ppm

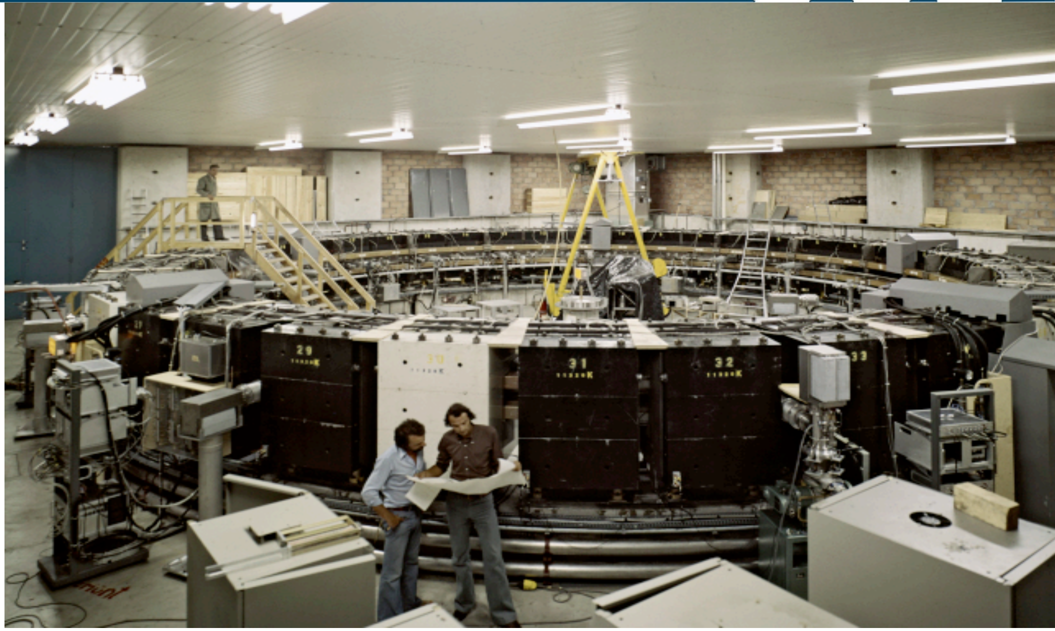
→ **Showed that QED alone wasn’t enough to predict the value theoretically**

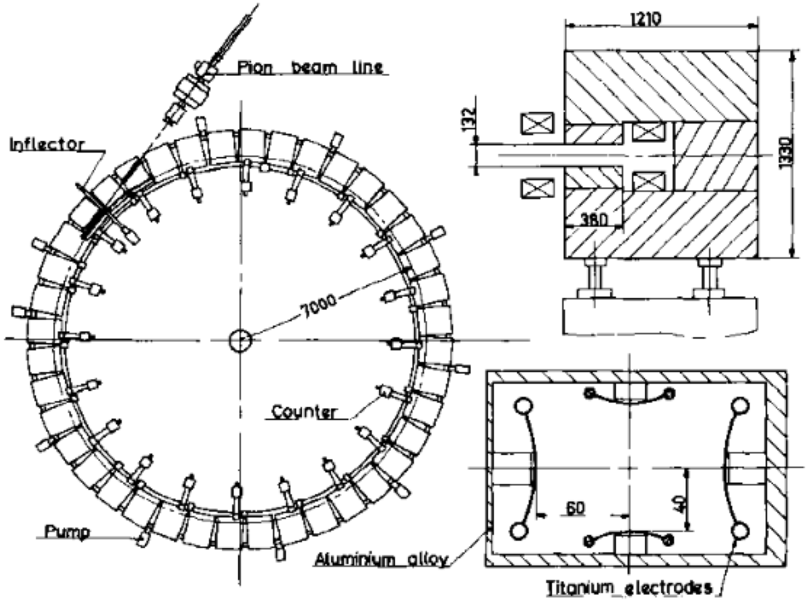
A brief history – CERN III

1976

The third experiment learnt from the lessons of the previous two

- Inject pions into the ring with fixed momentum and polarisation
- Use a constant magnetic field
- Use electric focussing
- Run at the magic momentum (3.094 GeV)





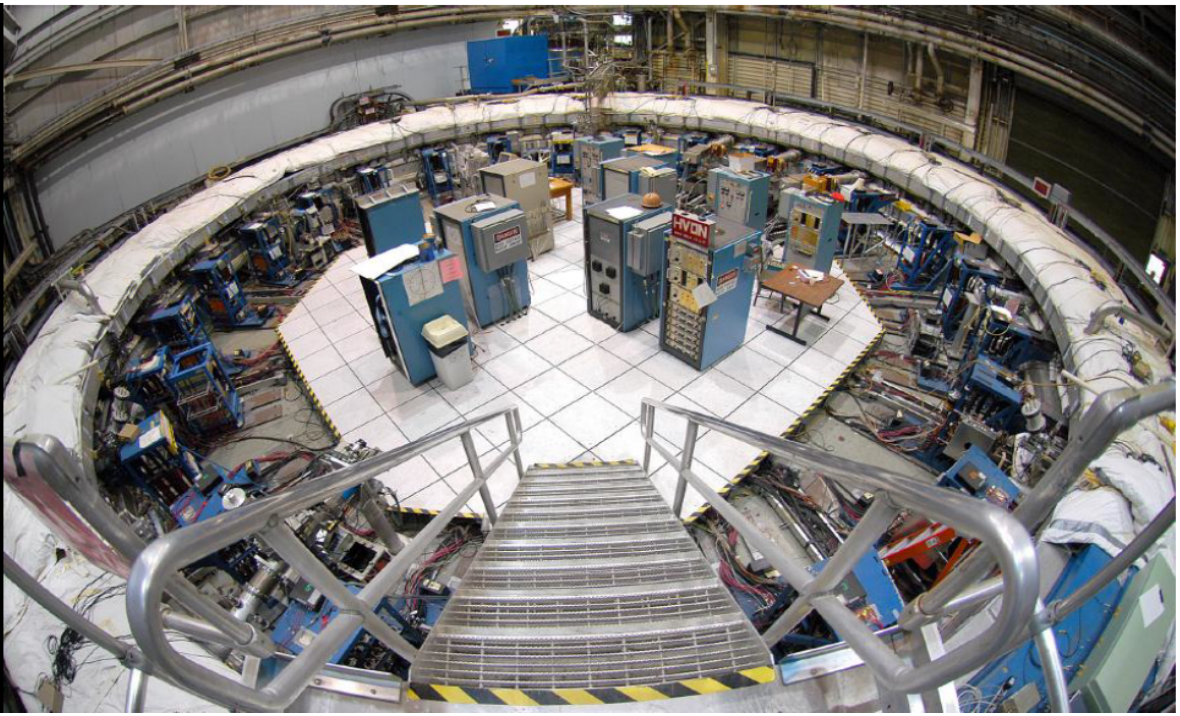
The muon g-2 was measured to 7ppm

→ Rules out muon substructure down to 0.005 fm

→ Confirms QED to third order

A brief history - BNL

The most recent g-2 experiment was done at Brookhaven using the same experimental technique as is being used at the new experiment at Fermilab

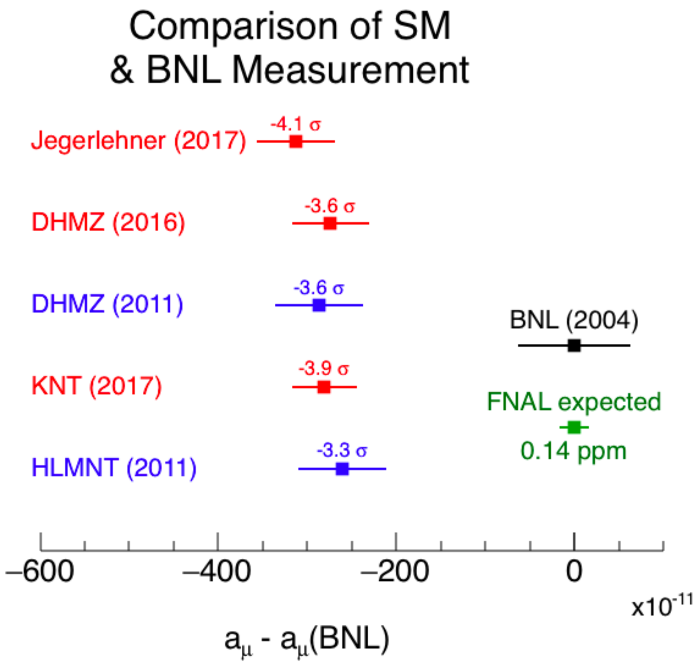


The measurement differs from the theoretical prediction by ~3.5σ.

Is this :

- A mistake in the theory
- A sign of new physics
- A mistake / statistical fluctuation in the experiment

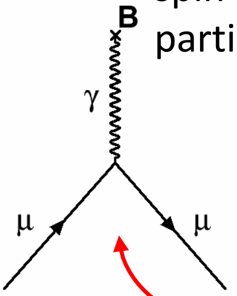
The BNL experiment measured g-2 to 0.54 ppm :



The Standard Model contributions

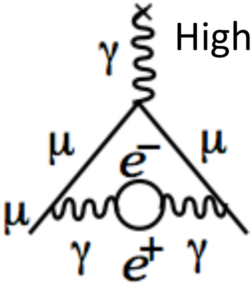
Dirac

Charged,
spin ½
particle



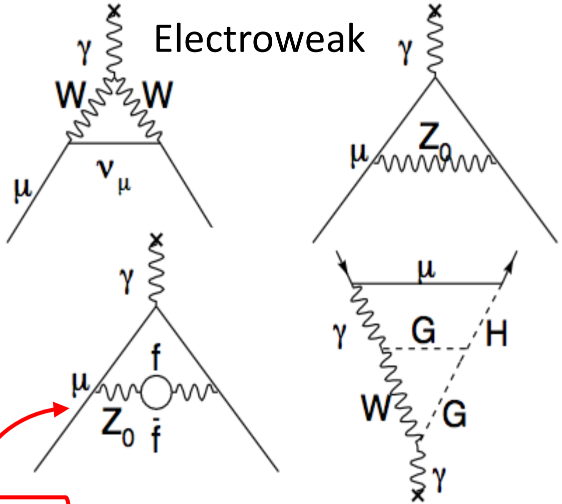
Kinoshita

12672
diagrams



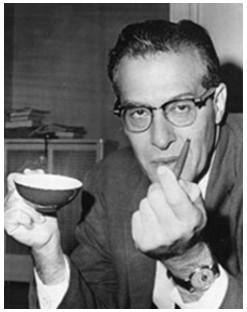
Higher Order
QED

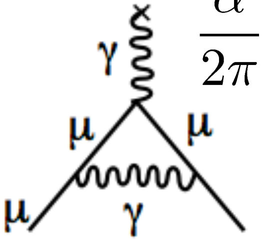
Electroweak



$$g_\mu = 2.002\,331\,841\,78(126)$$

Schwinger

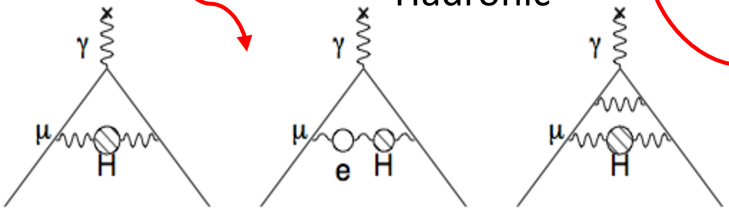




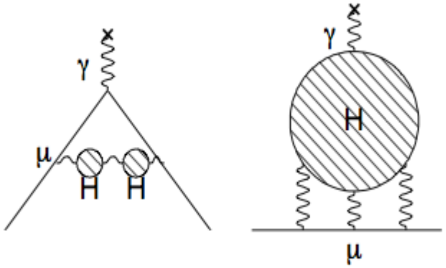
1st Order QED

$$\frac{\alpha}{2\pi} = 0.00232$$

Hadronic



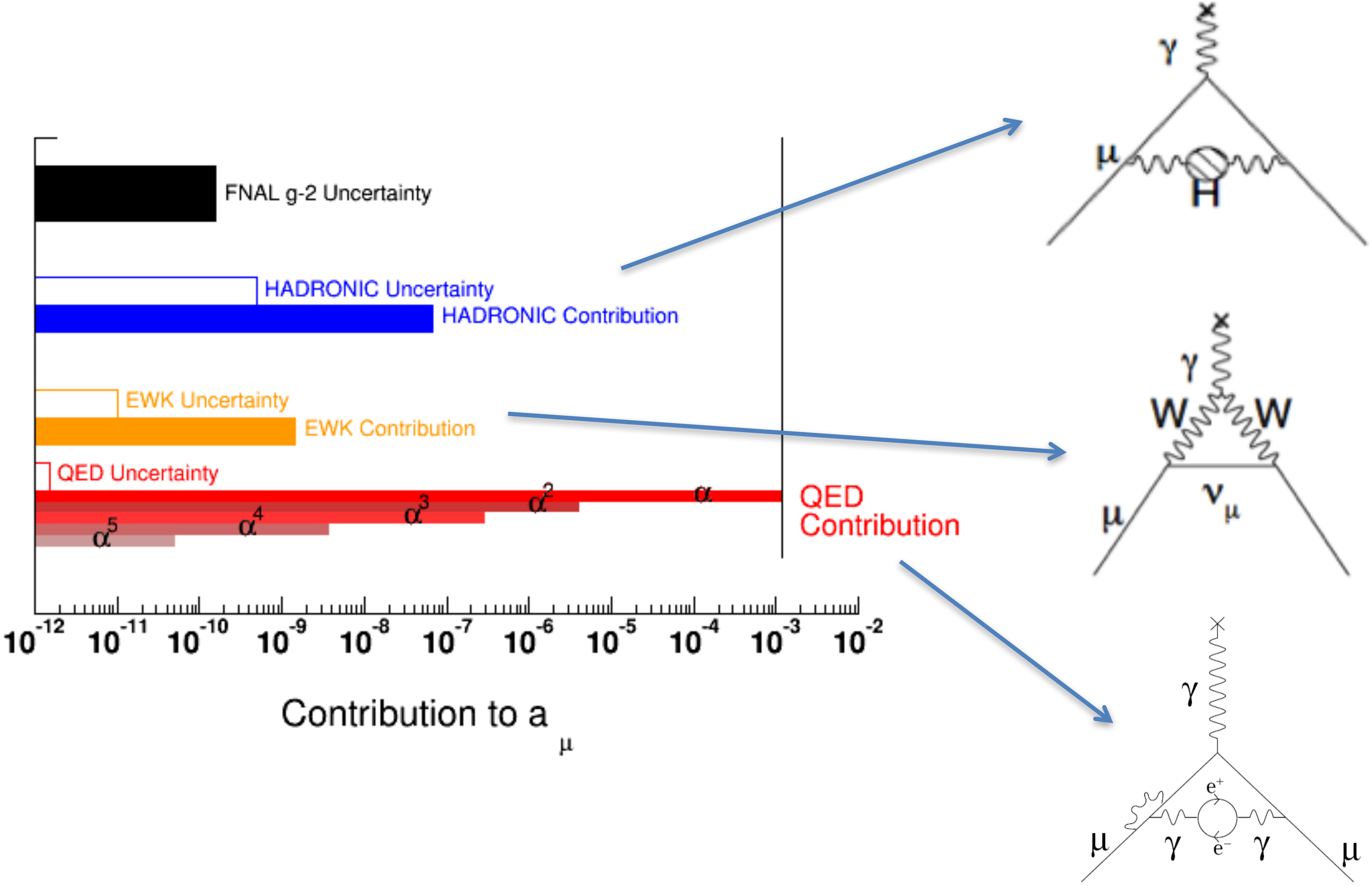
Dominant
uncertainty in
calculation



?

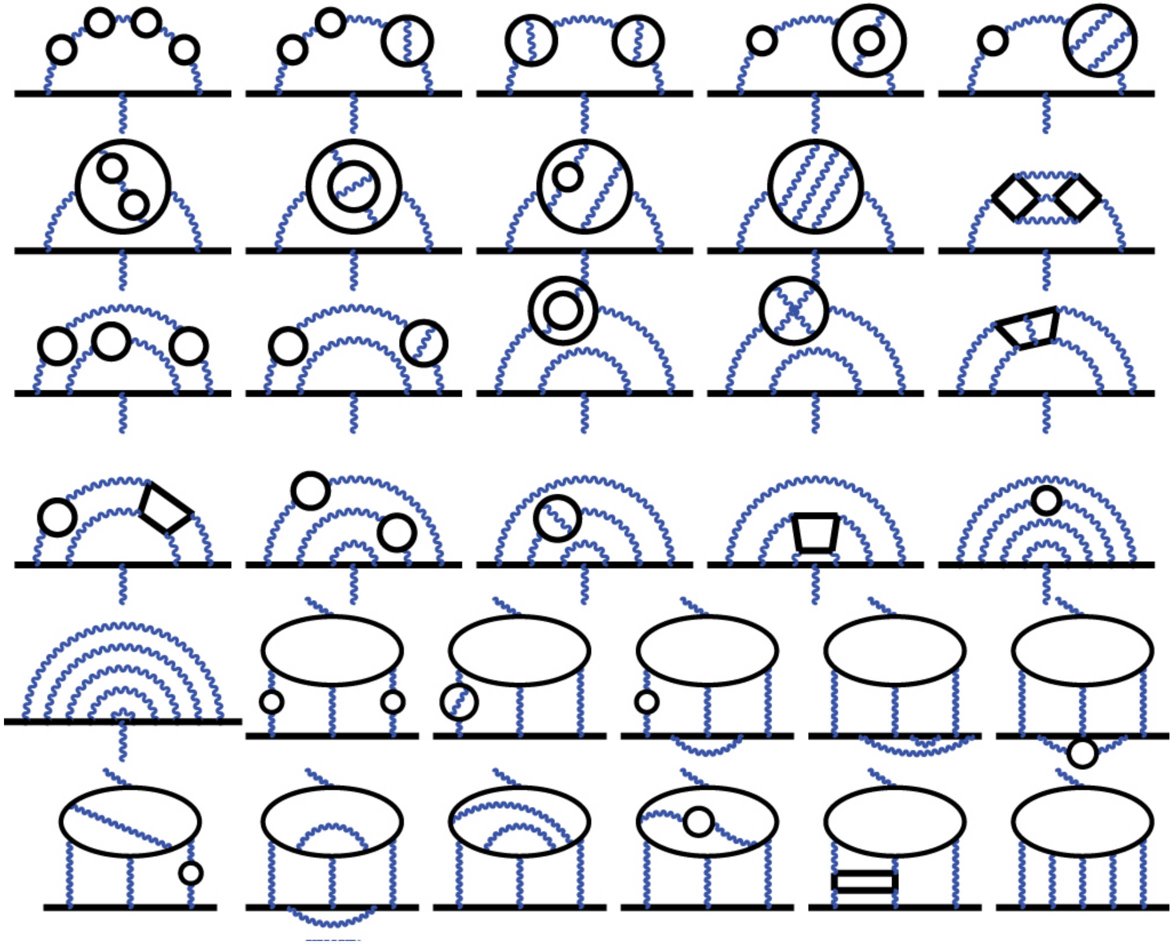
The theoretical prediction

The theoretical calculation has to include QED, electroweak and hadronic contributions



QED

The QED contribution has been calculated exactly up to 5 orders



The calculation includes 12,672 Feynman Diagrams

Theory :
2.00231930436356 ± 0.00000000000154

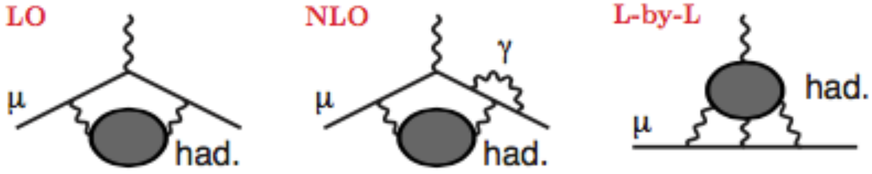
Experiment :
2.00231930436146 +- 0.00000000000056

Hadronic Contribution

The hadronic contribution to g-2 cannot be calculated exactly and instead uses experimental e^+e^- cross section data

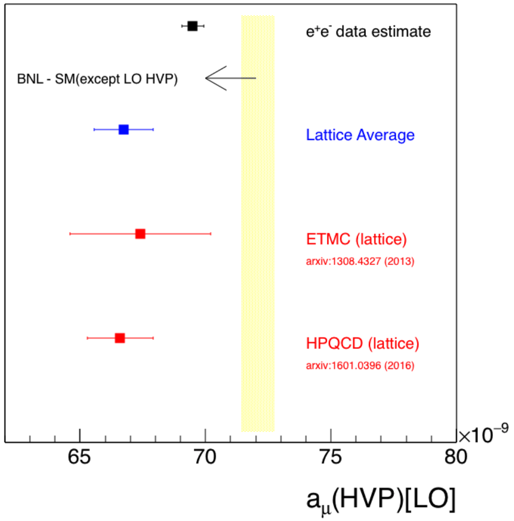
The largest contribution to the theoretical uncertainty comes from the uncertainties in the low energy cross section data

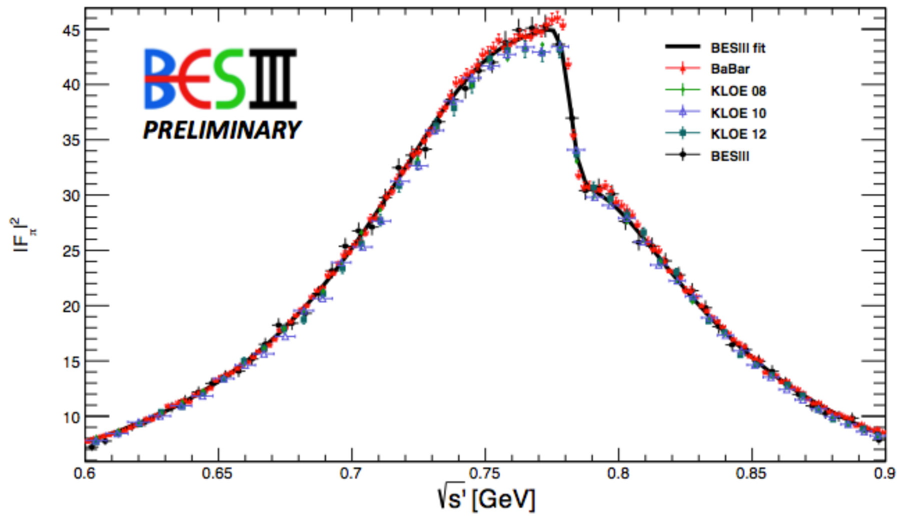
$$a_\mu^{\text{had}} = a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$



Contribution to hadronic uncertainty	75%	~ 0%	25%

The result is also backed up by lattice calculations

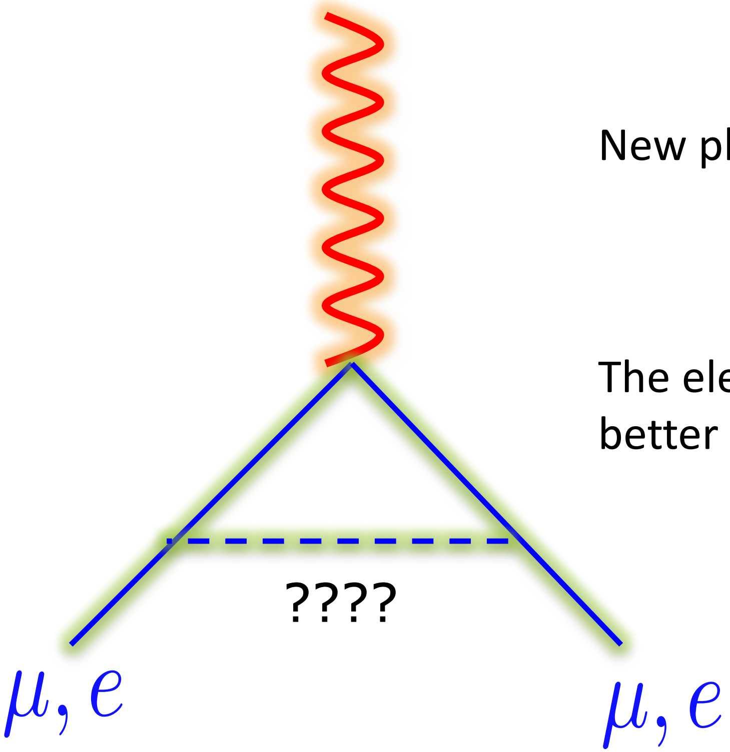




Expect a factor 2 improvement in the theoretical value due to more precise data

New Physics?

New physics can contribute in the loops and adjust the value of g-2



New physics would contribute as $\left(\frac{m_\ell}{M_{\mathrm{NEW}}}\right)^2$

The electron g-2 is measured 2000 times better than the muon g-2, but

$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 44{,}000$$

→ **Muon g-2 is sensitive to new physics from MeV to Tev scales**

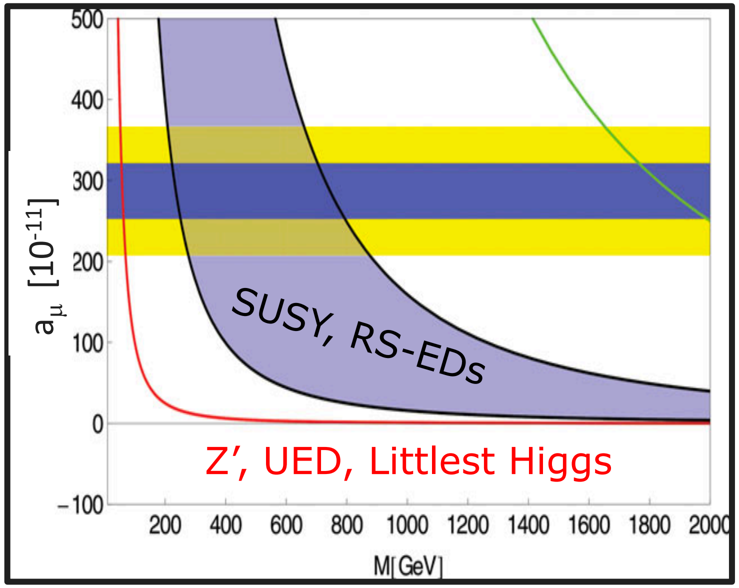
→ Electron g-2 is limited to new physics below 100 MeV

New Physics?

The muon g-2 can probe new physics at TeV scales – complementary to the LHC

The value of the muon g-2 can help set limits on models of new physics

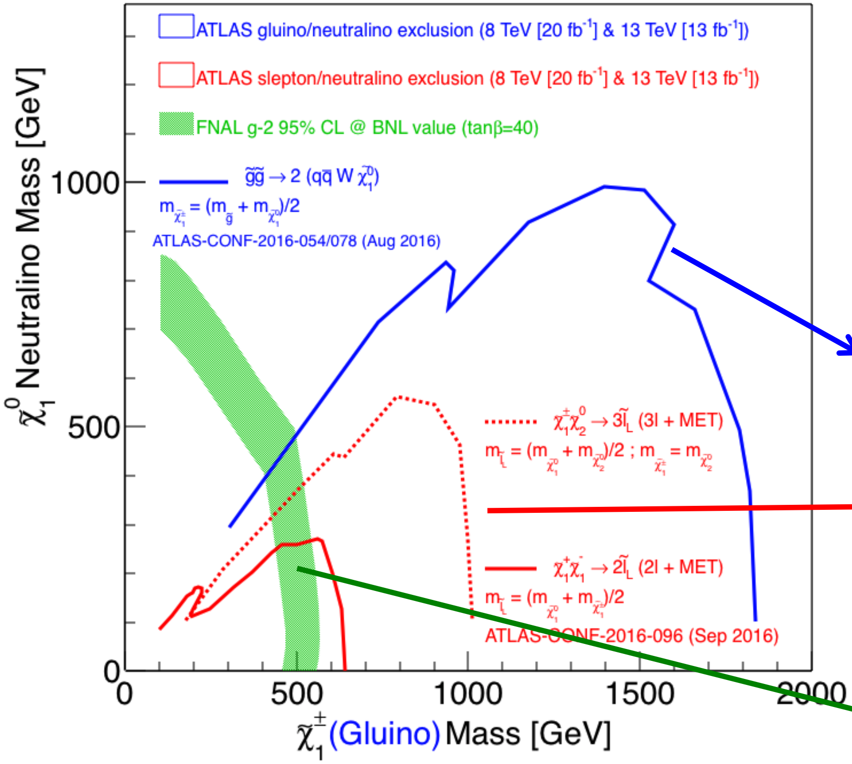
The g-2 interactions flip the chirality of the muon but conserve flavour and CP



Radiative muon mass / technicolor

SUSY, RS-EDs

Z′, UED, Littlest Higgs



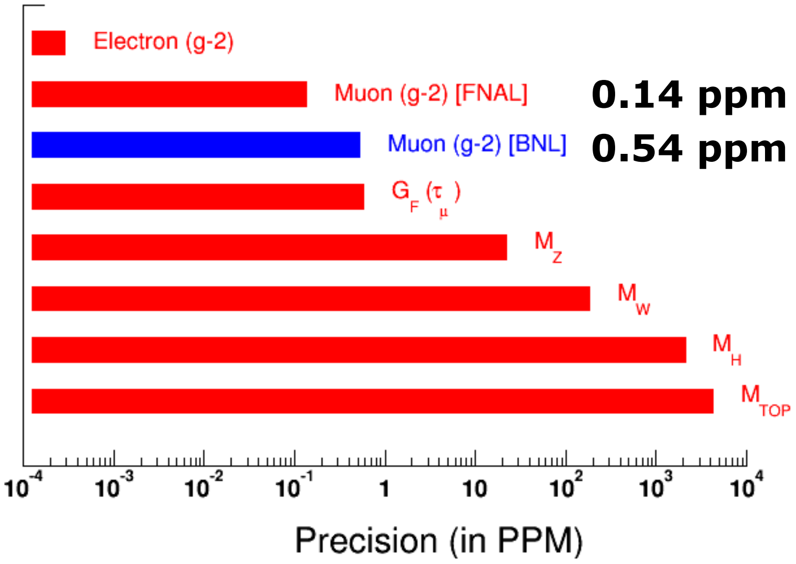
The LHC has good sensitivity to strongly interacting new physics (SUSY)

But is less sensitive to weakly interacting new physics

Muon g-2 is probing similar phase space as the LHC with more sensitivity in some areas

Redo the measurement…

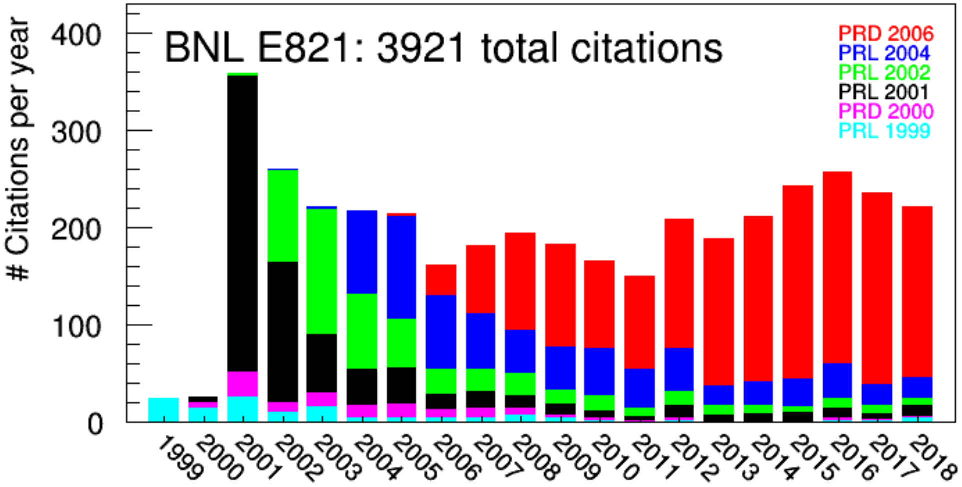
In order to find out if there really is a discrepancy between the theory and experiment we need a higher precision measurement

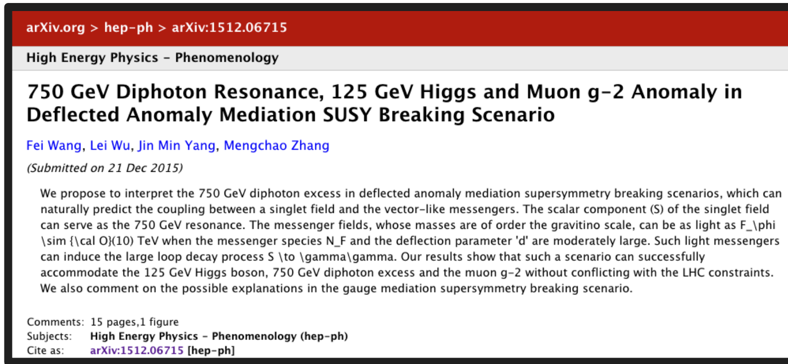


0.14 ppm

0.54 ppm

Enough to establish 5-10 σ





arXiv.org > hep-ph > arXiv:1512.06715

High Energy Physics – Phenomenology

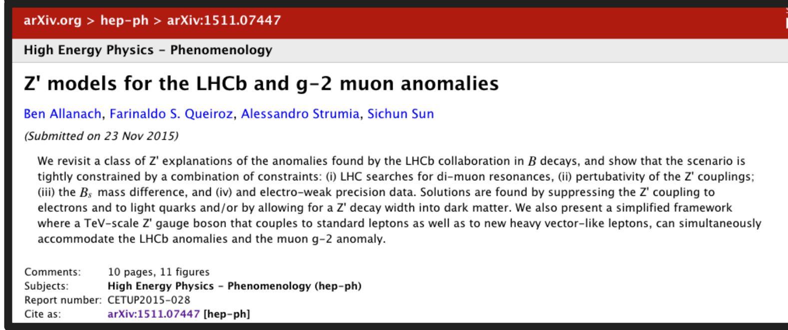
750 GeV Diphoton Resonance, 125 GeV Higgs and Muon g-2 Anomaly in Deflected Anomaly Mediation SUSY Breaking Scenario

Fei Wang, Lei Wu, Jin Min Yang, Mengchao Zhang

(Submitted on 21 Dec 2015)

We propose to interpret the 750 GeV diphoton excess in deflected anomaly mediation supersymmetry breaking scenarios, which can naturally predict the coupling between a singlet field and the vector-like messengers. The scalar component (S) of the singlet field can serve as the 750 GeV resonance. The messenger fields, whose masses are of order the gravitino scale, can be as light as F_\phi \sim {\cal O}(10) TeV when the messenger species N_F and the deflection parameter 'd' are moderately large. Such light messengers can induce the large loop decay process S \to \gamma\gamma. Our results show that such a scenario can successfully accommodate the 125 GeV Higgs boson, 750 GeV diphoton excess and the muon g-2 without conflicting with the LHC constraints. We also comment on the possible explanations in the gauge mediation supersymmetry breaking scenario.

Comments: 15 pages,1 figure
Subjects: **High Energy Physics - Phenomenology (hep-ph)**
Cite as: arXiv:1512.06715 **[hep-ph]**



arXiv.org > hep-ph > arXiv:1511.07447

High Energy Physics – Phenomenology

Z' models for the LHCb and g-2 muon anomalies

Ben Allanach, Farinaldo S. Queiroz, Alessandro Strumia, Sichun Sun

(Submitted on 23 Nov 2015)

We revisit a class of Z' explanations of the anomalies found by the LHCb collaboration in B decays, and show that the scenario is tightly constrained by a combination of constraints: (i) LHC searches for di-muon resonances, (ii) pertubativity of the Z' couplings; (iii) the B_s mass difference, and (iv) and electro-weak precision data. Solutions are found by suppressing the Z' coupling to electrons and to light quarks and/or by allowing for a Z' decay width into dark matter. We also present a simplified framework where a TeV-scale Z' gauge boson that couples to standard leptons as well as to new heavy vector-like leptons, can simultaneously accommodate the LHCb anomalies and the muon g-2 anomaly.

Comments: 10 pages, 11 figures
Subjects: **High Energy Physics - Phenomenology (hep-ph)**
Report number: CETUP2015-028
Cite as: arXiv:1511.07447 **[hep-ph]**

Experimental setup

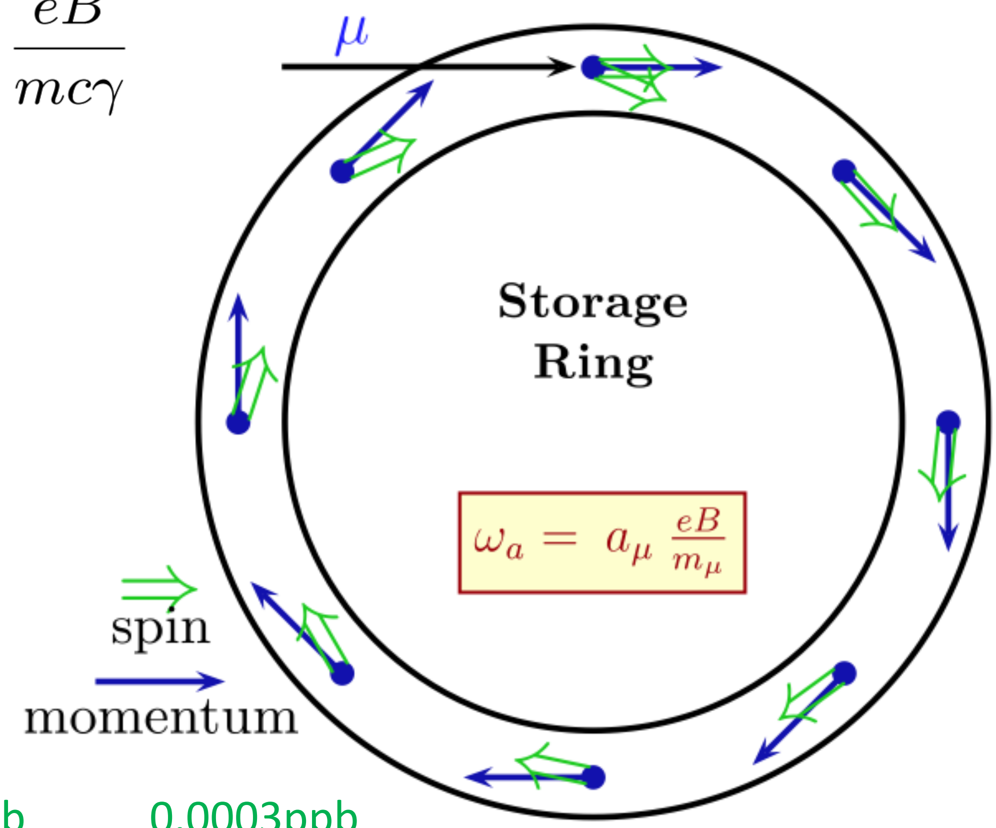
The anomalous magnetic moment causes the spin to precess faster than the momentum vector as the muon moves around the ring

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

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

Measure the spin precession from the positron decays

Measure the magnetic field in the ring



3ppb 22ppb 0.0003ppb

We actually measure 2 frequencies :

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

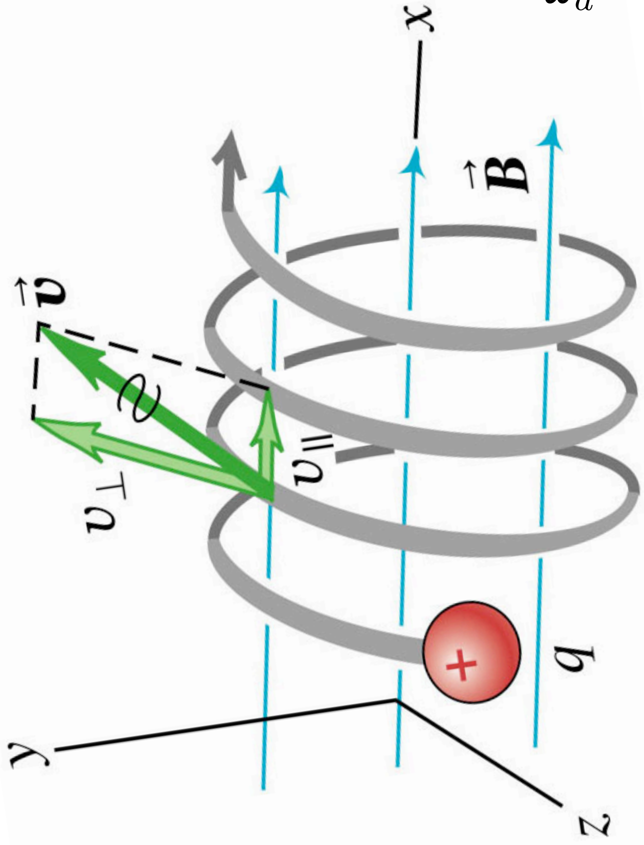
In a 1.5 T magnetic field the spin rotates in 144ns and the momentum in 149ns

Vertical Focussing

The magnetic field that keeps the muon in orbit causes the beam to diverge vertically so we need a vertical constraining force – an electric quadropole

The electric field looks like an addition magnetic field to a moving particle and so adds a term to the precession frequency :

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



By choosing γ = 29.3 we can cancel out this term

Run at the magic momentum, p = 3.094 GeV – the CERN-III miracle!

Even so there are small effects :

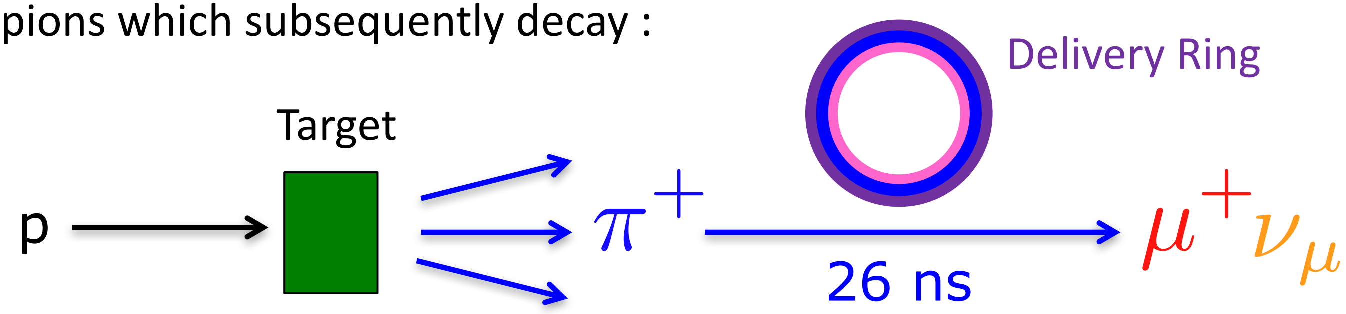
- **The muons aren't exactly at the magic momentum**
- **There is a small degree of vertical motion of the muons**

These small corrections can be calculated using the tracker and beam dynamics models

Muon production

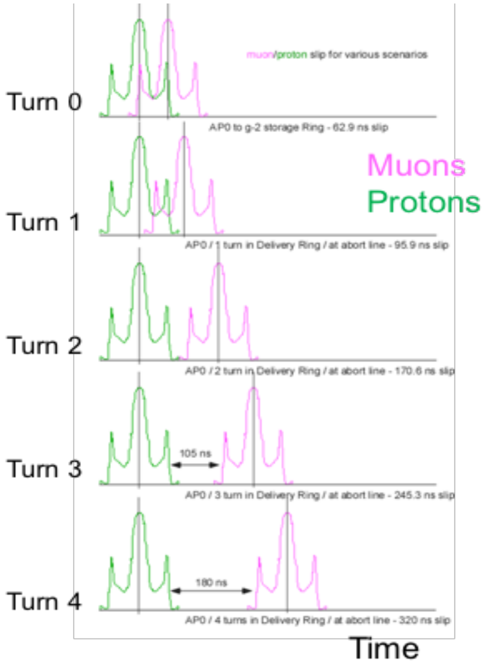
A proton beam is hit into a pion production target and the muons from the pion decays are collected

Protons hit a pion target to produce pions which subsequently decay :



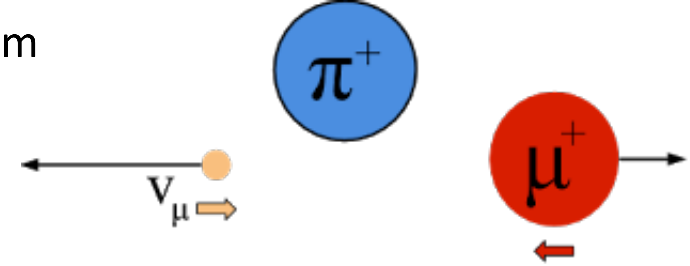
3.11 GeV pions selected using a lithium lens

The muons and protons separate as they go around the delivery ring



In the pion decay the neutrino must have spin opposite to the momentum

→ To conserve spin the muon spin must also be opposite to the momentum



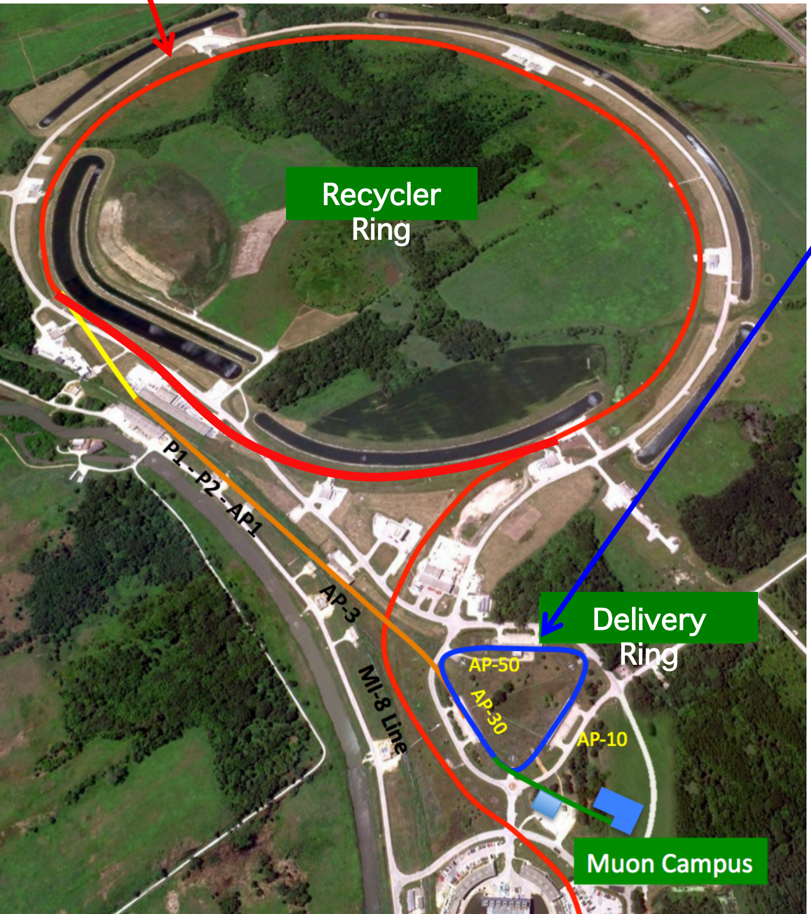
We get a naturally polarised muon beam from the physics of the pion decays

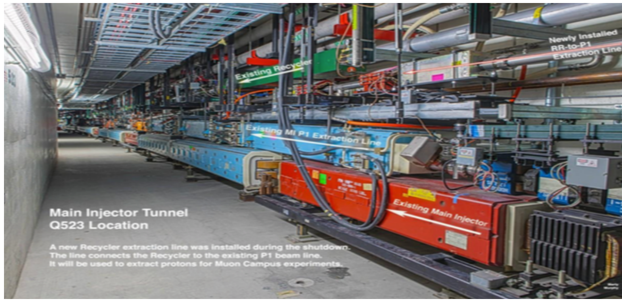
Accelerator Modifications

The Fermilab accelerator complex has been adjusted to provide 20 times more muons at lower instantaneous rate with reduced pion contamination compared to BNL

Modifications to the proton accelerator to allow for the pulsed beam

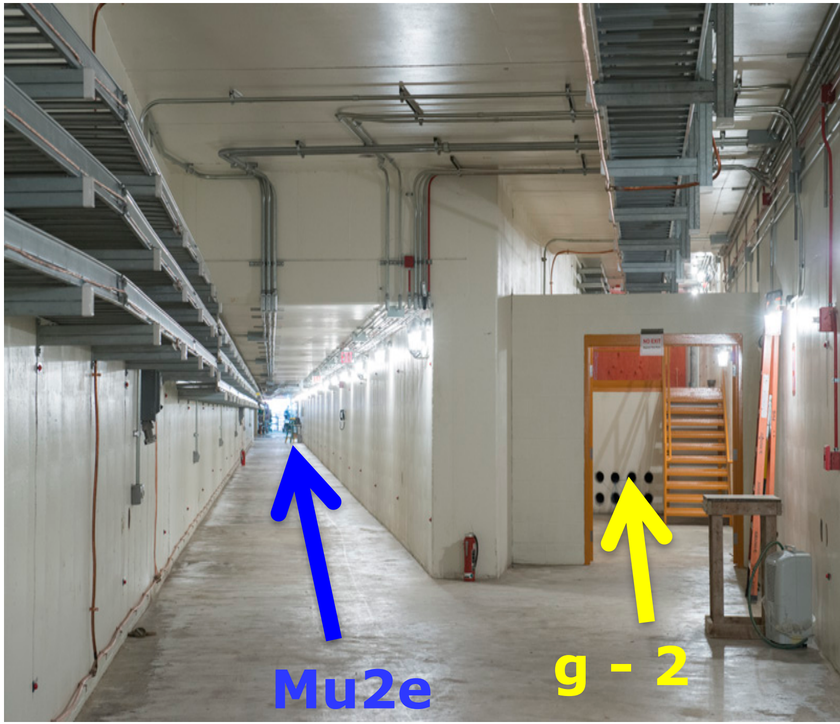
The old antiproton complex is reconfigured to provide muons





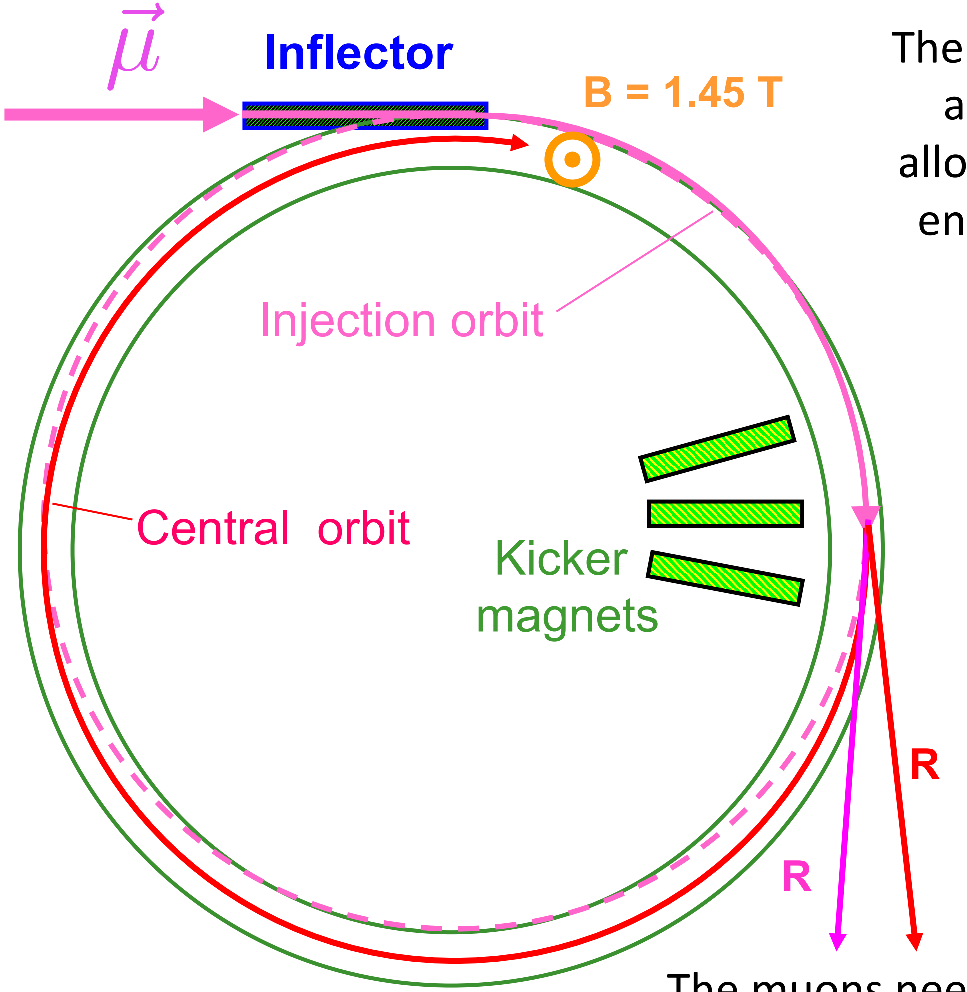
Main Injector Tunnel
Q523 Location

A new Recycler extraction line was installed during the shutdown.
The line connects the Recycler to the existing P1 beam line.
It will be used to extract protons for Muon Campus experiments.



Injection into the ring

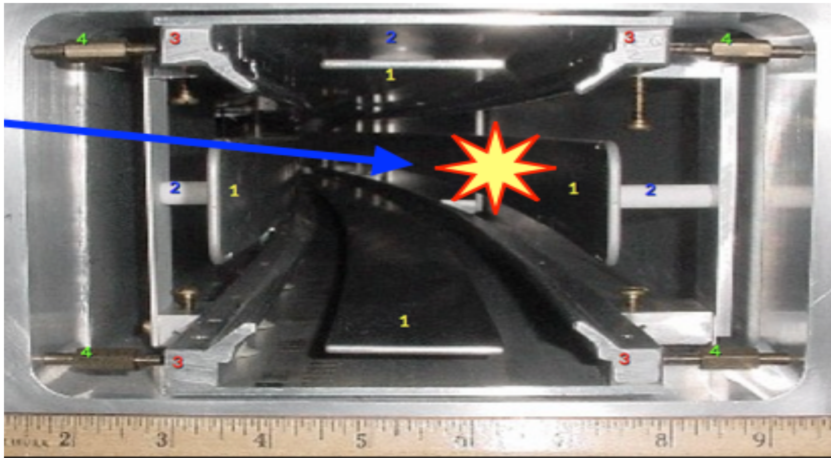
The muon beam enters through the inflector magnet on the wrong orbit and needs a kick to get onto the correct orbit



The muons need a ~11mrad kick

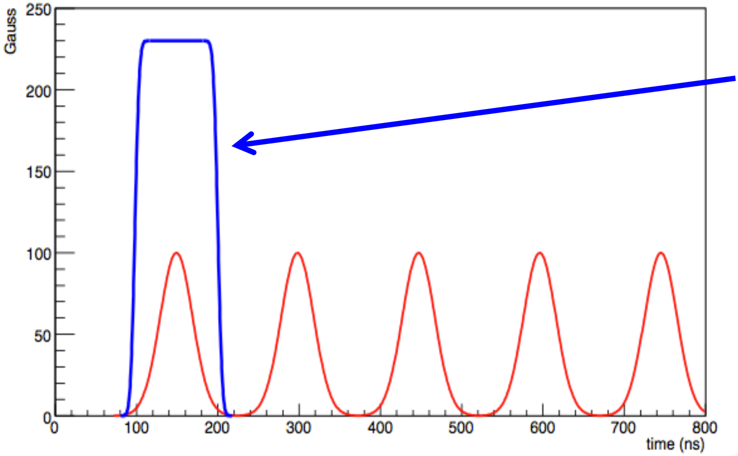
The inflector magnet is a field free region allowing the muons to enter tangentially to the orbit

The kicker magnets provide a vertical magnetic field to put the muons on the correct orbit

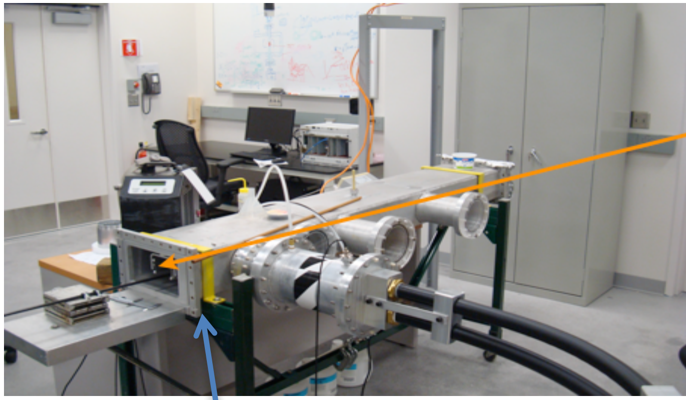


New Kicker Magnet

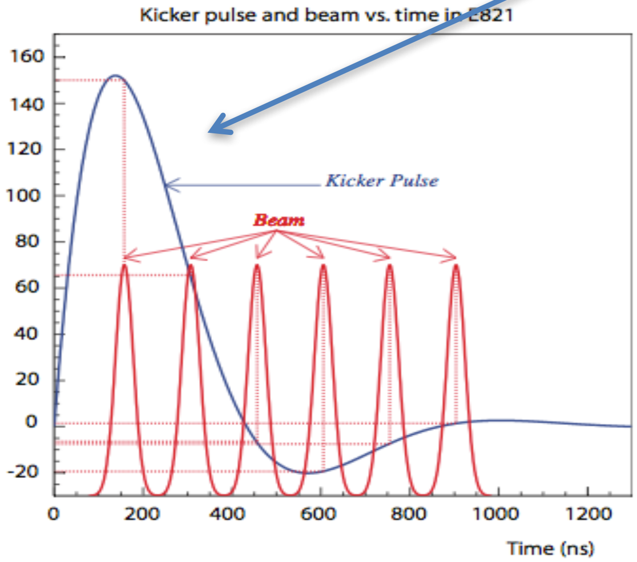
A new kicker magnet has been designed for the Fermilab experiment which should provide a shorter pulse

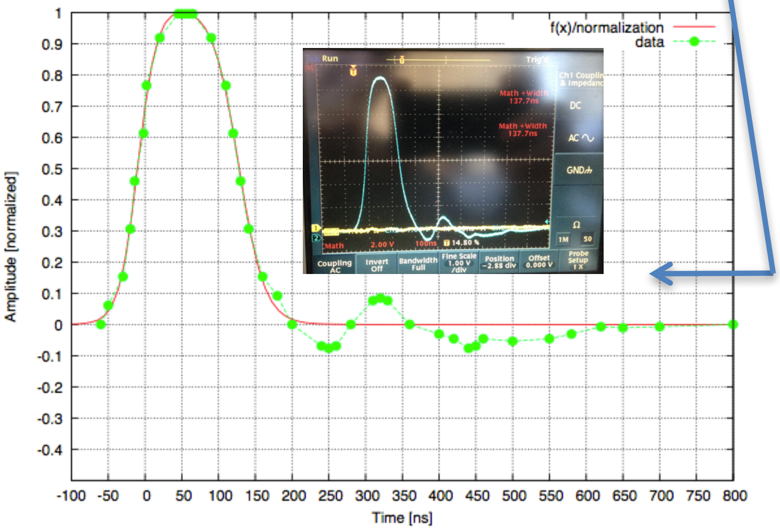


The ideal kicker pulse is a constant field across one orbit of the beam



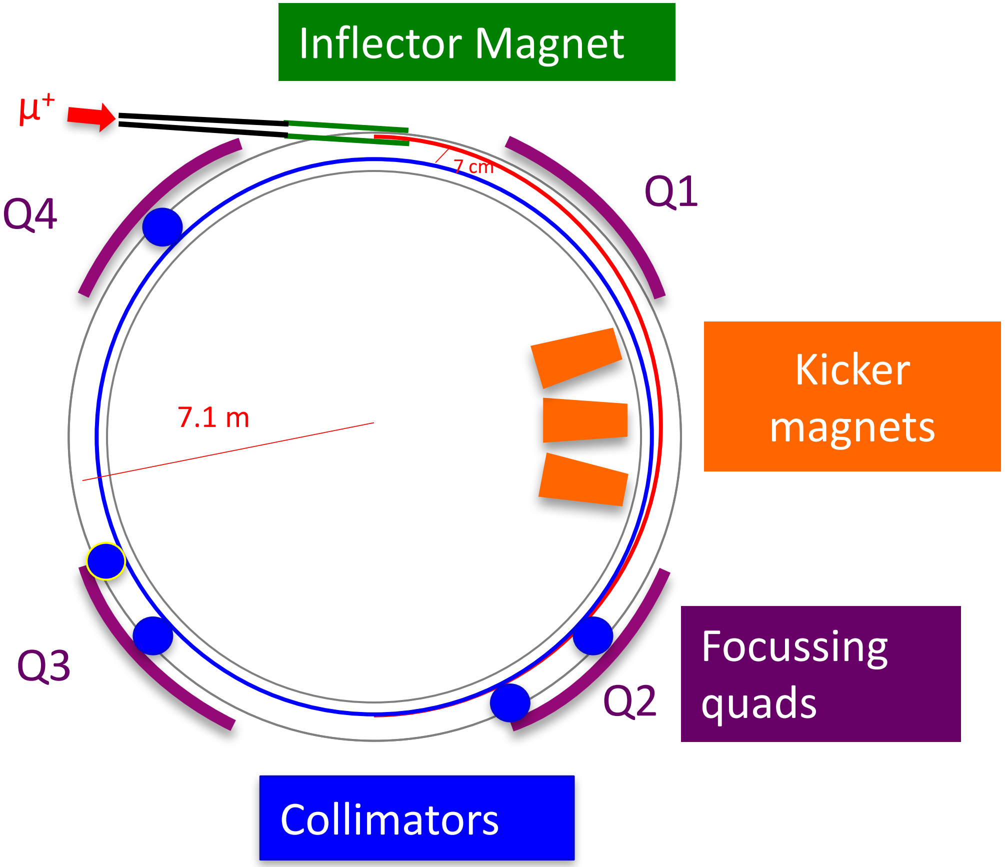
The BNL kicker pulse went across 3 beam cycles


Kicker pulse and beam vs. time in E821

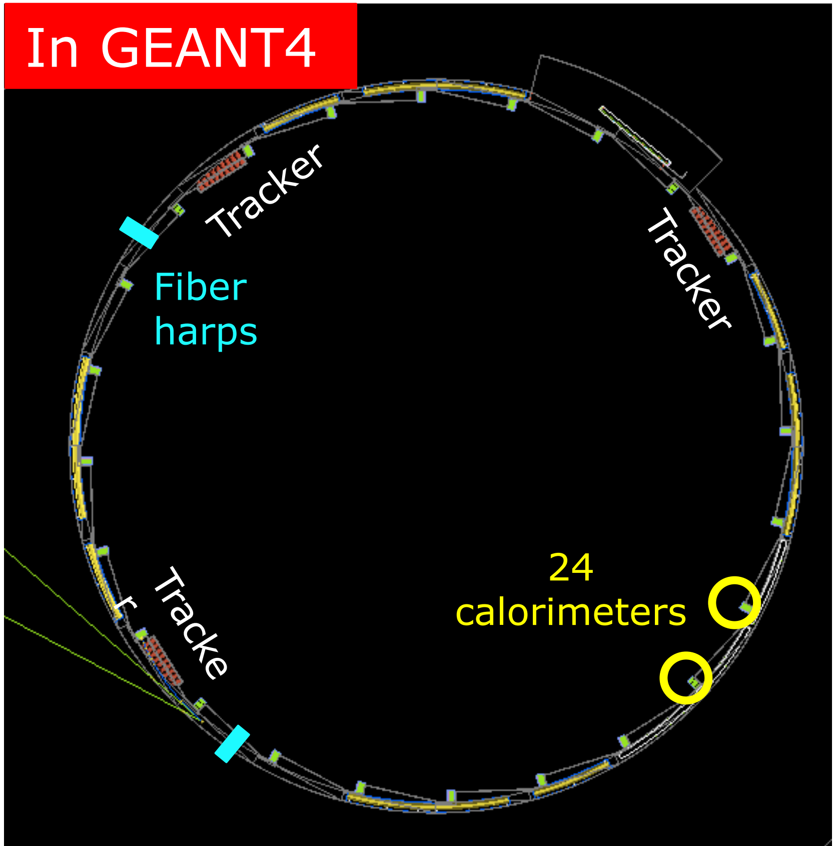


A new kicker has been designed at Cornell with 200ns width

Final Ring Design

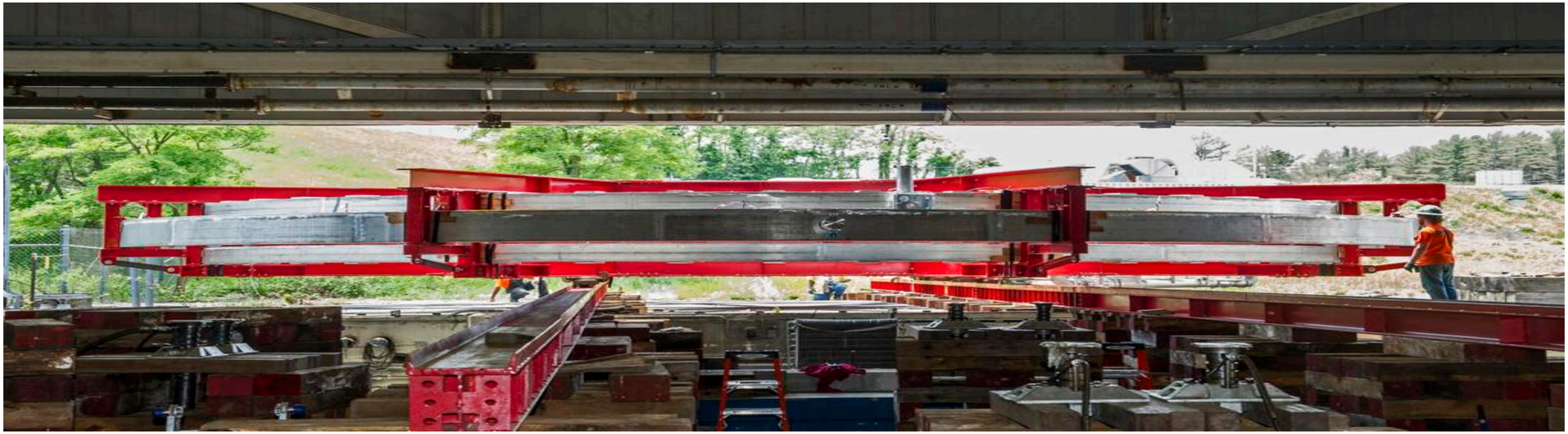


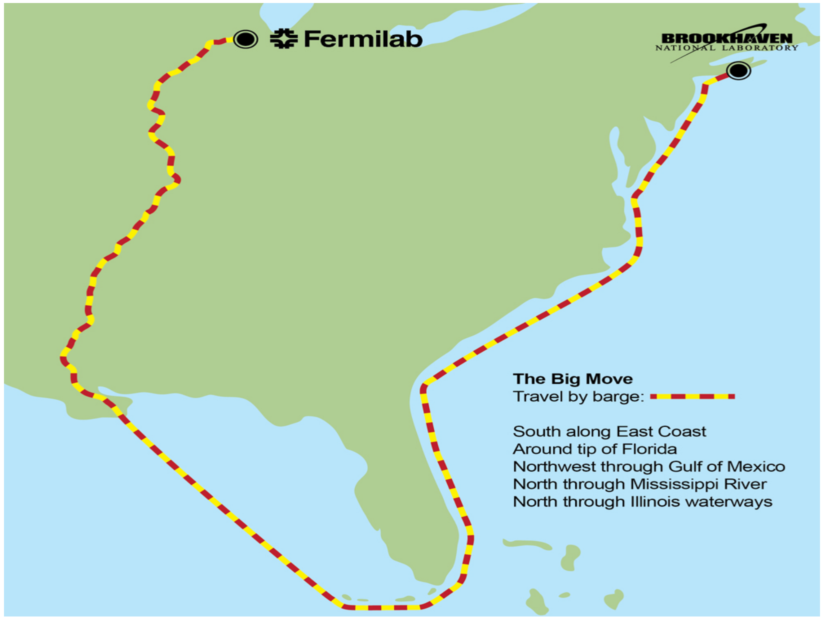
The storage ring for the Fermilab experiment is the same as the one used at BNL

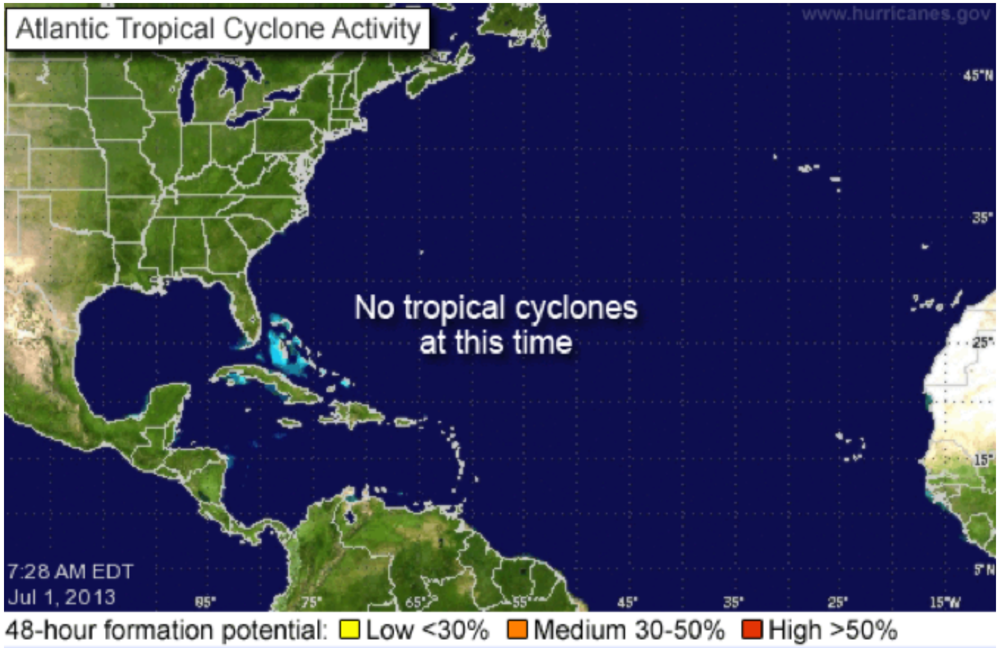


The detectors lie on the inside of the ring for beam monitoring and measuring the precession frequency from positron decays

The Big Move




Fermilab
BROOKHAVEN NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways


Atlantic Tropical Cyclone Activity
www.hurricanes.gov
No tropical cyclones at this time
7:28 AM EDT
Jul 1, 2013
45°N
35°
25°
15°
5°N
85°
75°
65°
55°
45°
35°
25°
15°W
48-hour formation potential: Low <30% Medium 30-50% High >50%

The Big Move


BAY CRANE
CUSTOMWELD INDUSTRIES INC
214 W. MAIN ST
PATCHOGUE NY 11772


Muon g-2

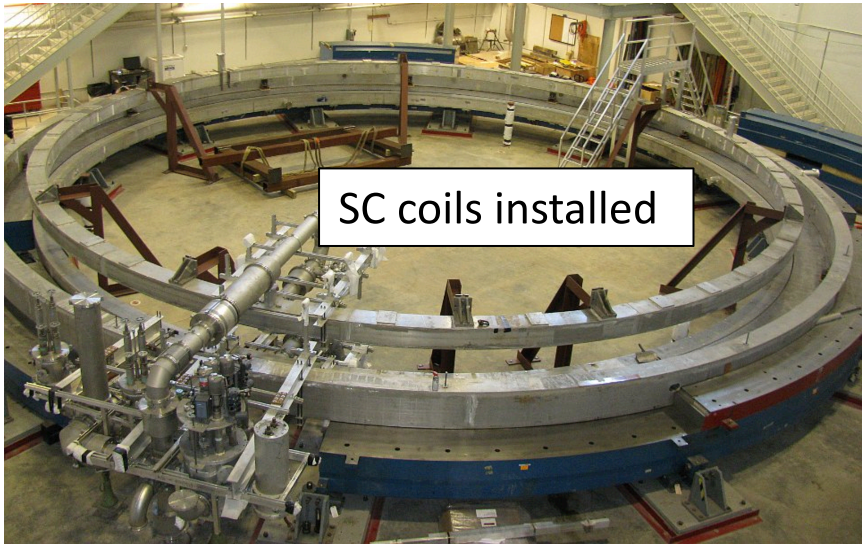

OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

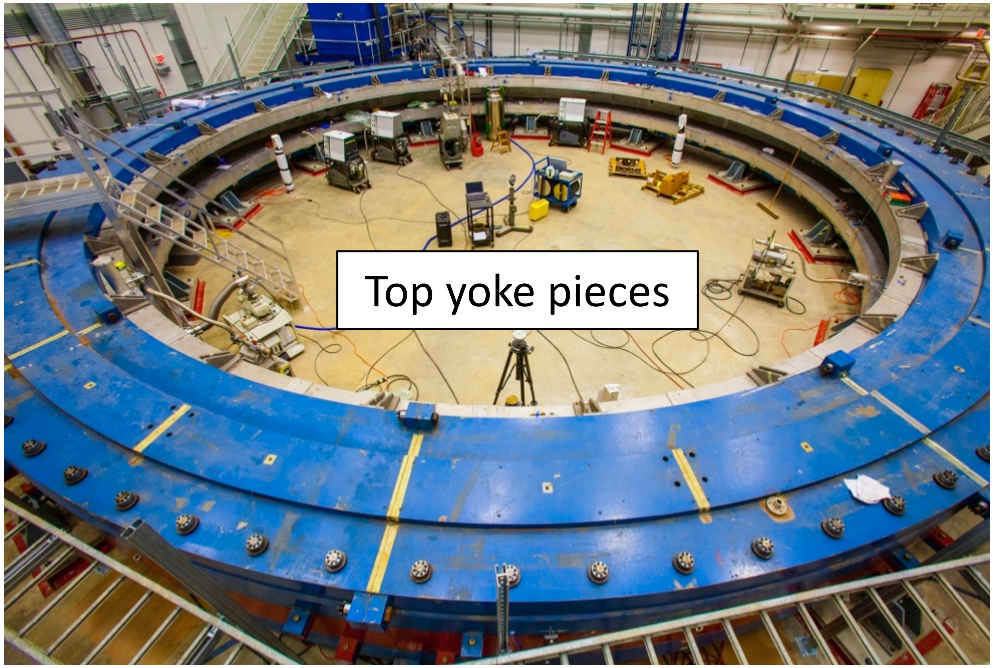
Arrival at Fermilab

Arrival at Fermilab…

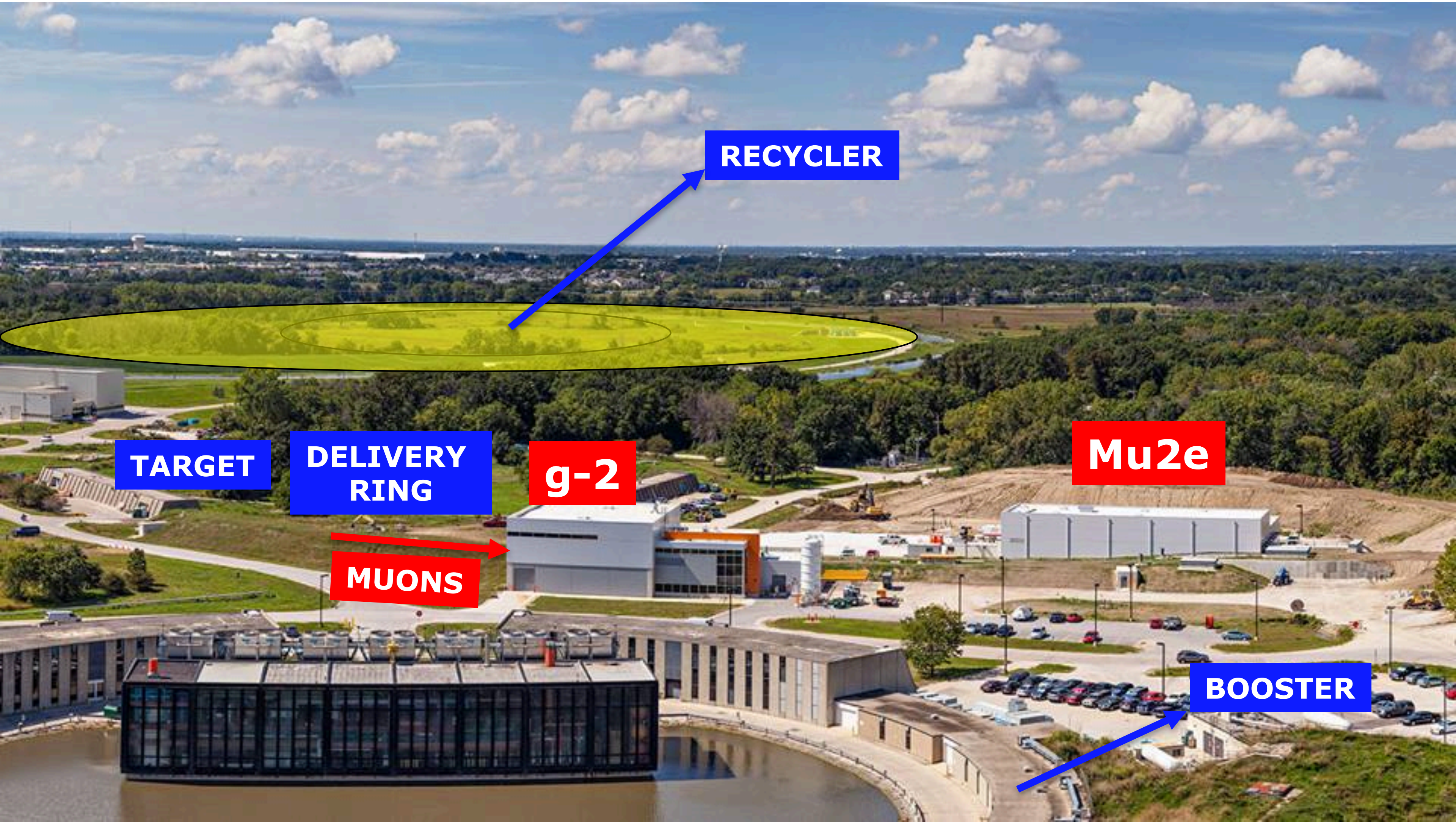
Installation


Bottom yoke pieces


SC coils installed


Top yoke pieces

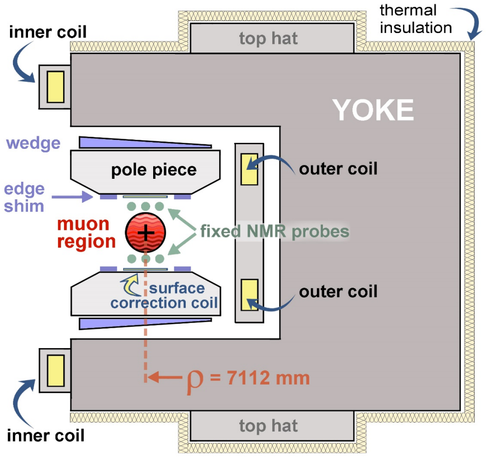
Installation



The magnetic field

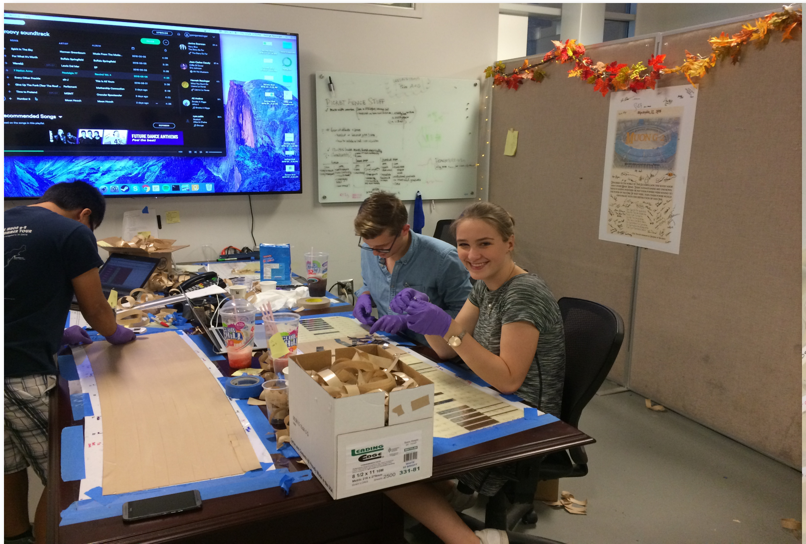
The measurement of g-2 requires a very uniform and precisely measured magnetic field in the storage region

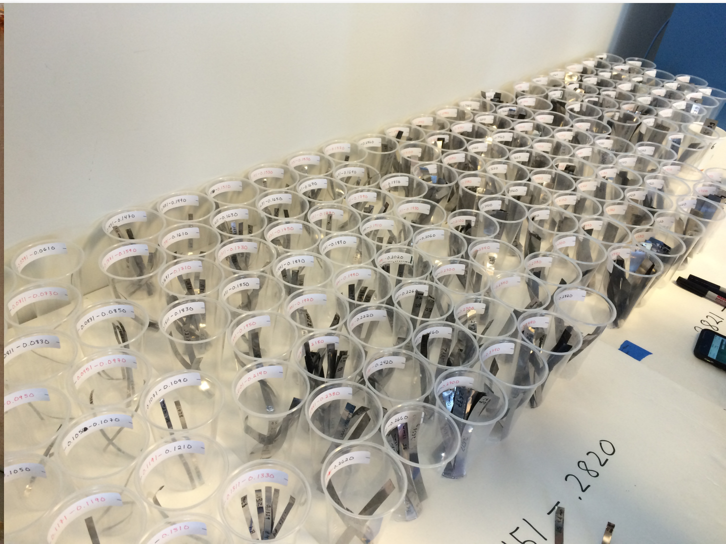
The magnetic field has been shimmed to achieve ±25ppm uniformity



g-2 Magnet in Cross Section

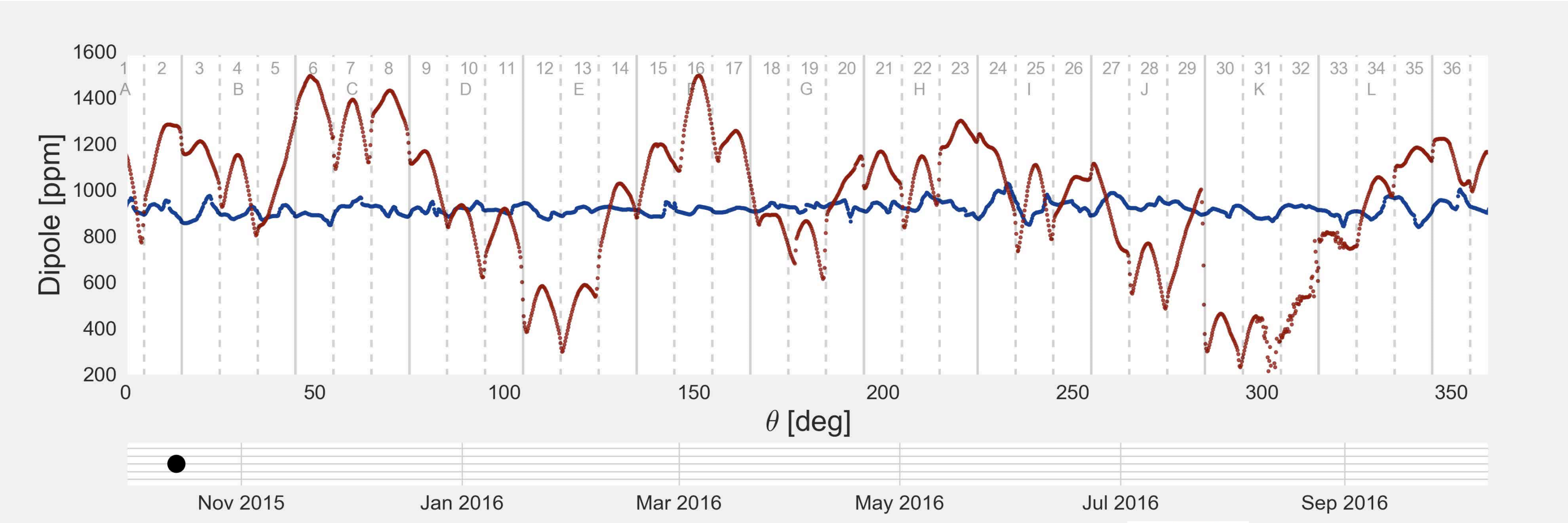
Shimming involved using shims that are thinner than a human hair!

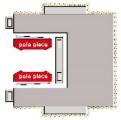




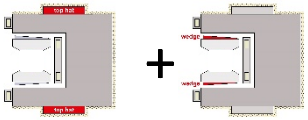
Shimming progress

The magnet uniformity is now 4 times better than it was at BNL

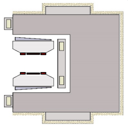




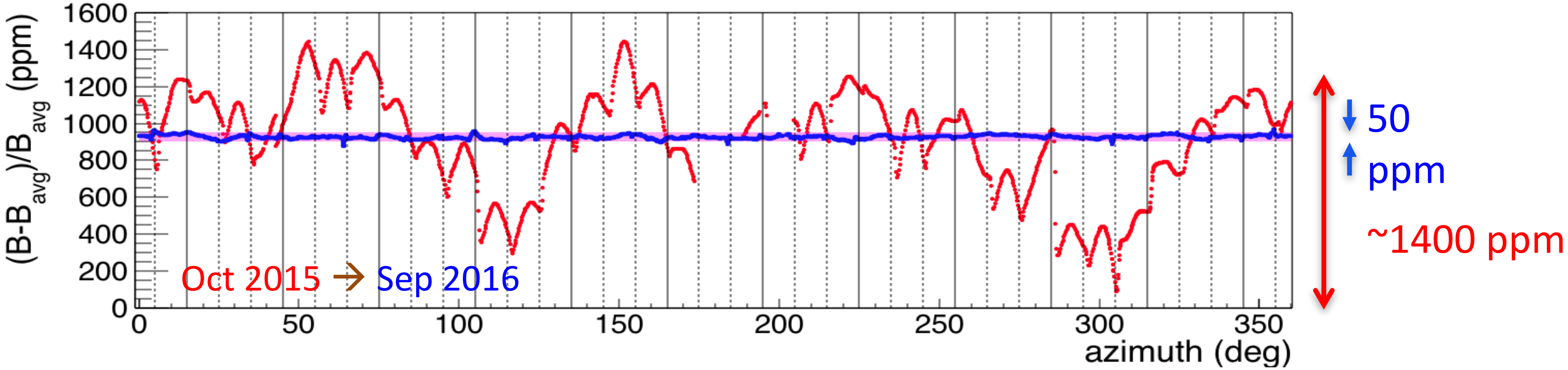
Poles



Top hats & wedges



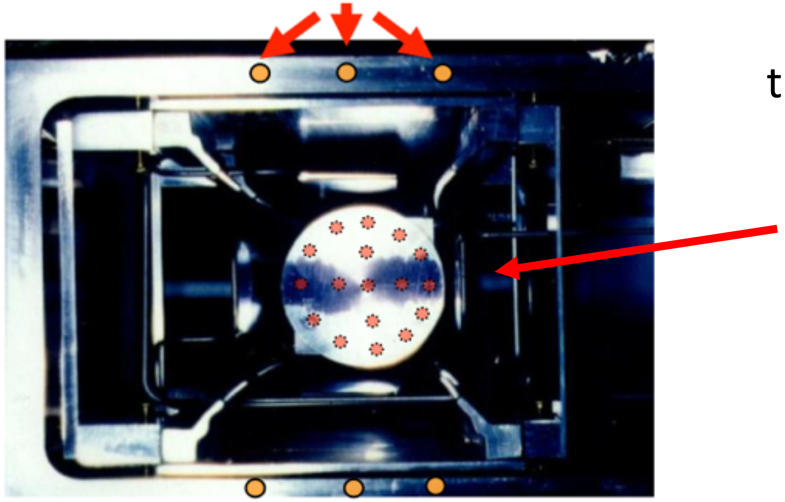
Surface foils



Measuring the Magnetic Field

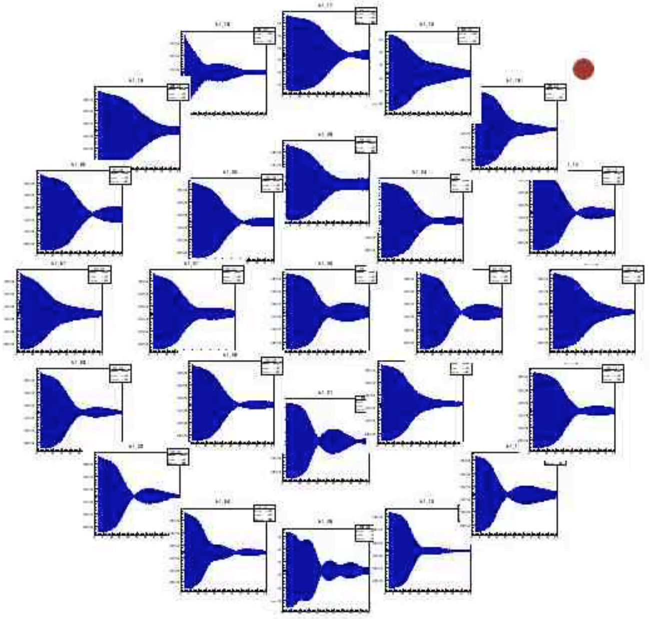
The magnetic field is measured using 375 fixed probes and 17 probes on a trolley that is driven around the ring every 2 hours

Fixed probes measure the magnetic field all the time outside the storage region

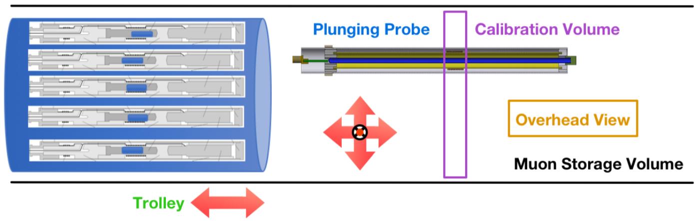


Trolley probes measure the magnetic field in the storage region during special trolley runs

Field measurement as the trolley moves around the ring during the early stages of shimming

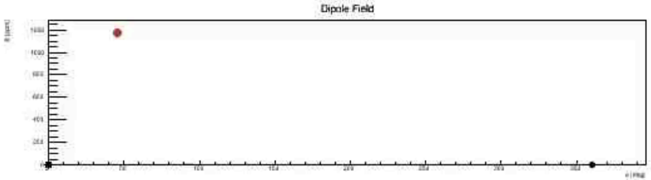


A plunging probe is used for calibration



Improvements since BNL :

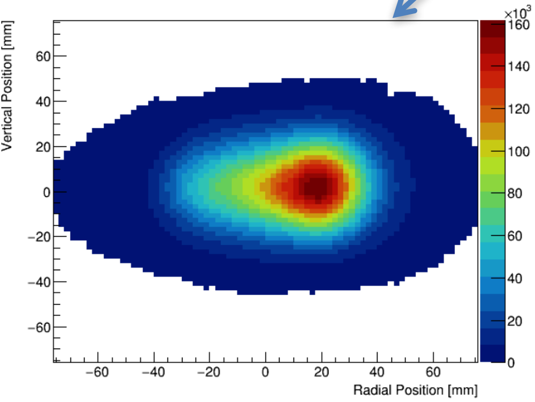
- Better probes
- Improved temperature control
- More frequent measurements



Measuring the magnetic field

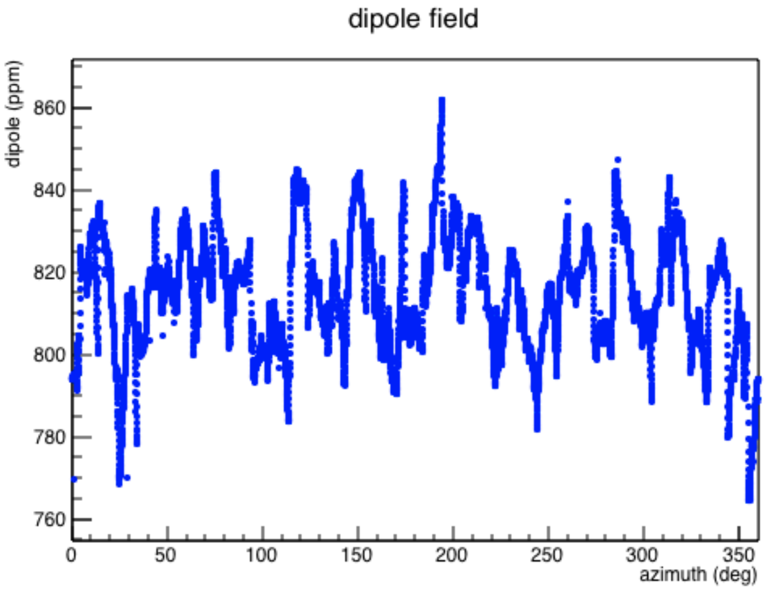
The muon distribution must be convoluted with the magnetic field in order to calculate the final result

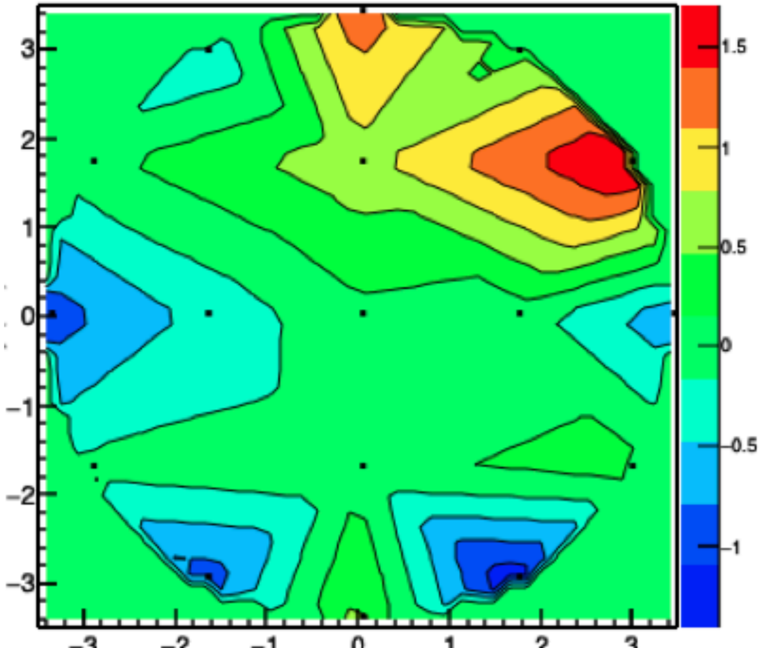
The muon distribution in the storage region



We need to know the magnetic field that a muon has experienced at the point of decay.

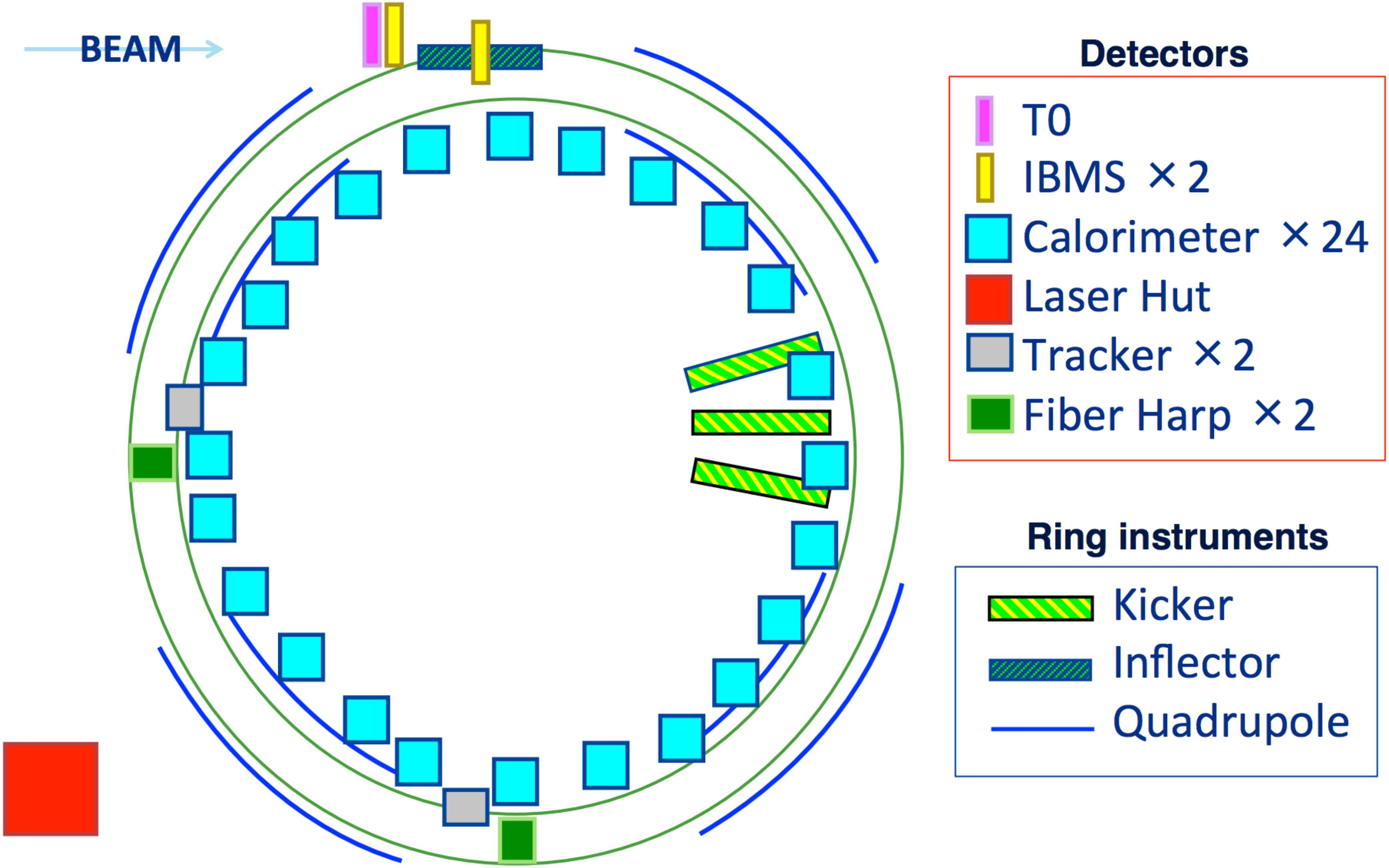
As the magnetic field is not perfectly uniform over the storage region we convolve the two





The g-2 detector systems

The different detector systems measure the precession frequency and monitor the beam distribution



Detectors

- ▮ T0
- ▮ IBMS × 2
- ■ Calorimeter × 24
- 🟥 Laser Hut
- ■ Tracker × 2
- 🟩 Fiber Harp × 2

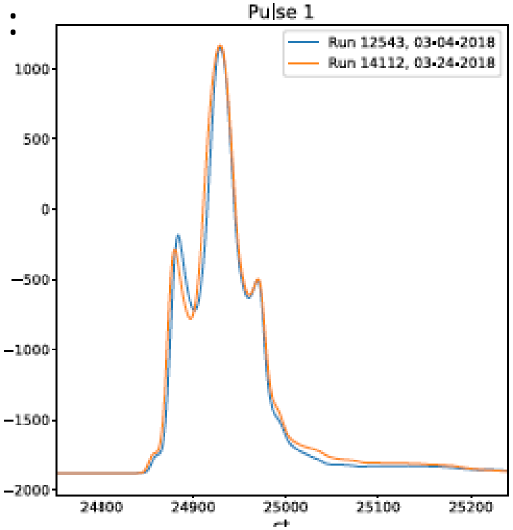
Ring instruments

- ▨ Kicker
- ▨ Inflector
- — Quadrupole

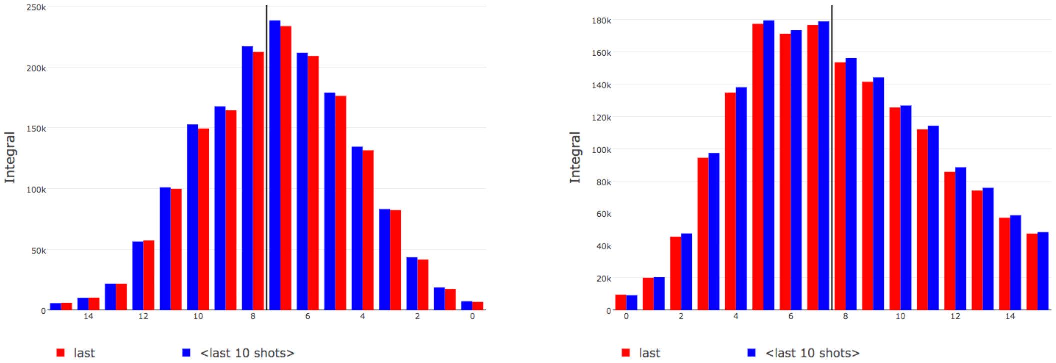
The g-2 detector systems

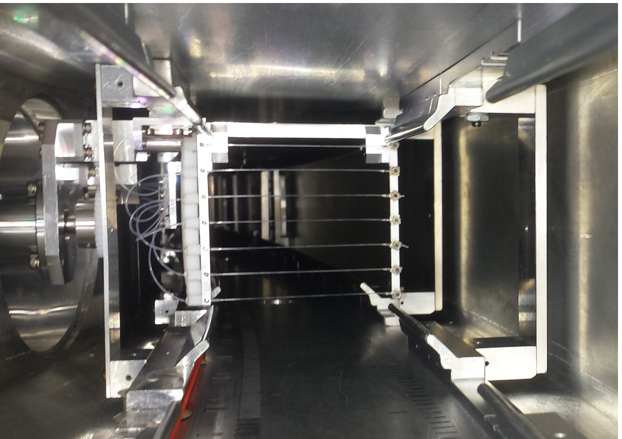
The different detector systems measure the precession frequency and monitor the beam distribution

T0 detector measures the beam arrival time and the temporal distribution :

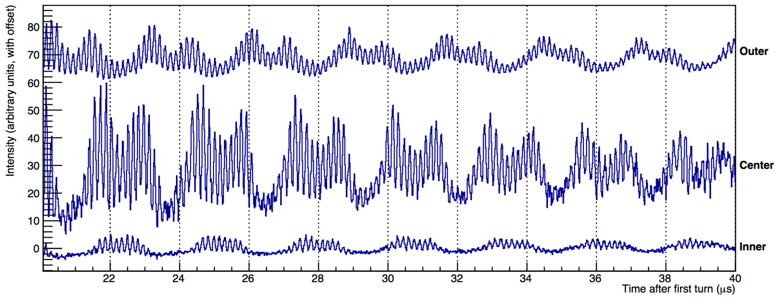


The IBMS measures the horizontal and vertical distributions on entry :



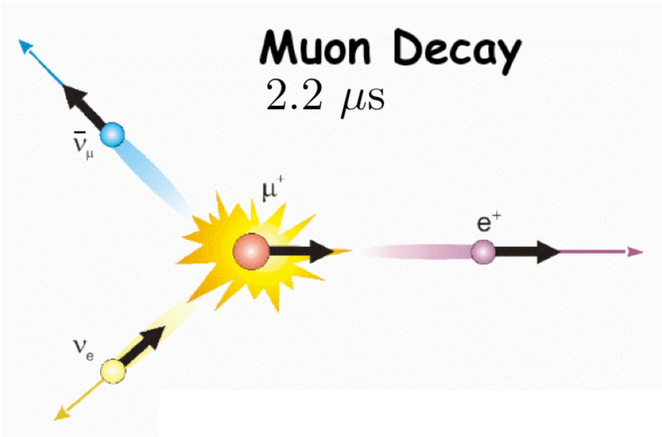


The fibre harps slide in to the beam to make a destructive measurement of the beam profile

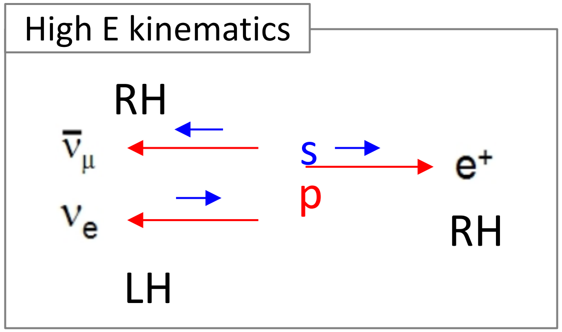


Measuring the spin precession

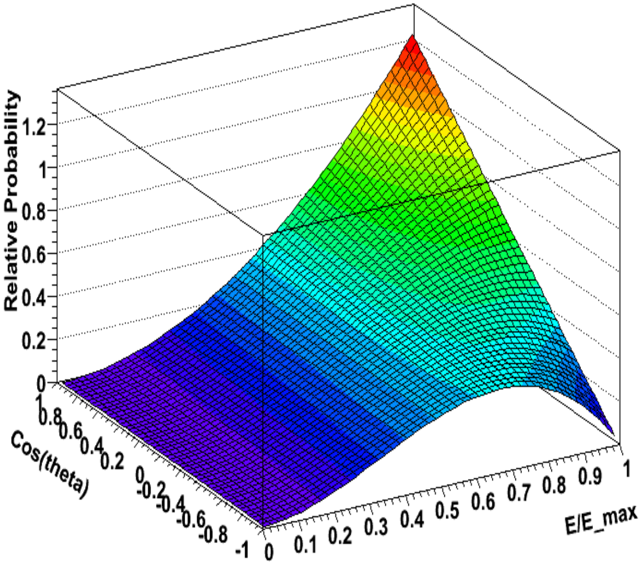
The spin precession is measured by detecting the positrons from the muon decays using detectors in the centre of the ring



A consequence of the weak decay is that the highest energy positrons are emitted along the direction of the muon spin



Complicated by the fact that the muon is not decaying at rest, but this is precisely predicted



Measure the number of the highest energy positrons decaying at a fixed location as a function of time

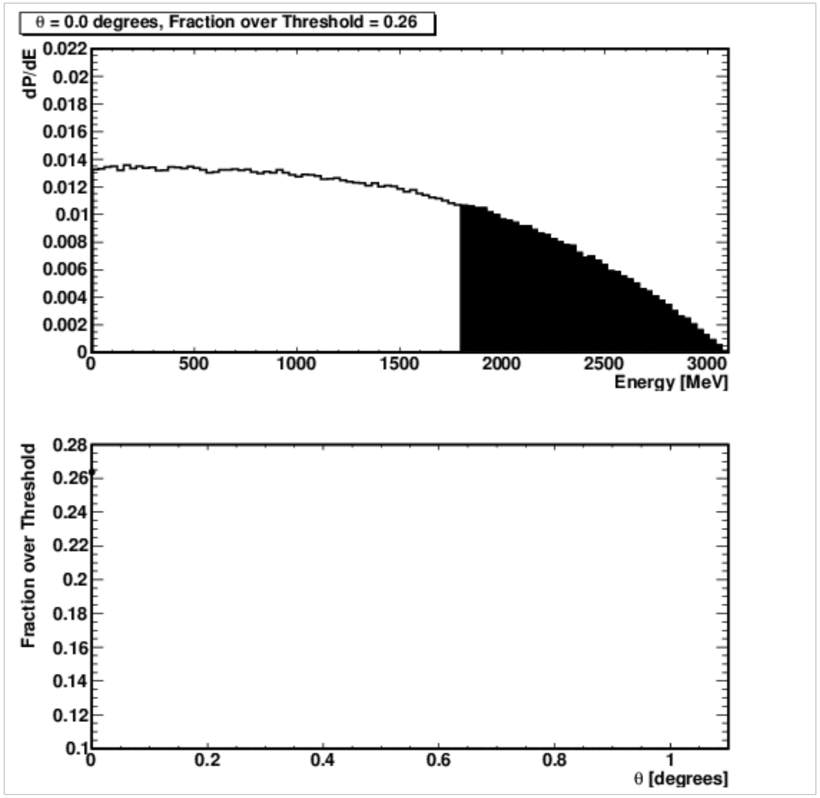
The number varies at the frequency determined by the spin precession (g-2)

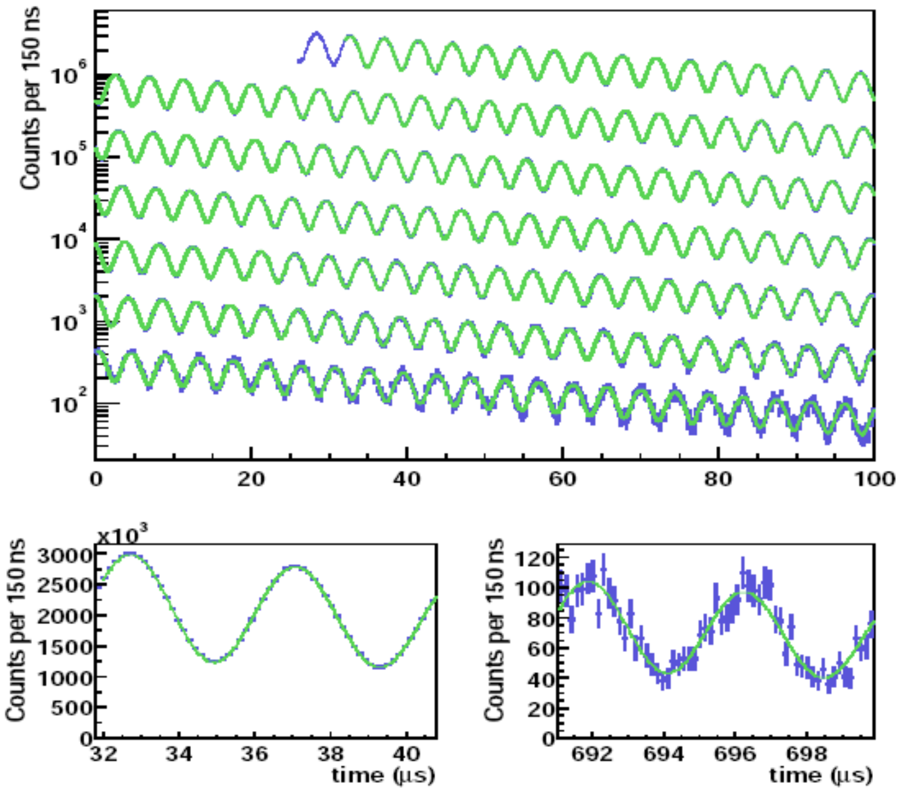
Wiggle plot

Plot the number of positrons arriving in the calorimeters with an energy larger than 1.8 GeV as a function of time

The data is from the BNL g-2 experiment :

- The number oscillates due to the spin oscillation
- The total number decreases exponentially as the number of stored muons decreases



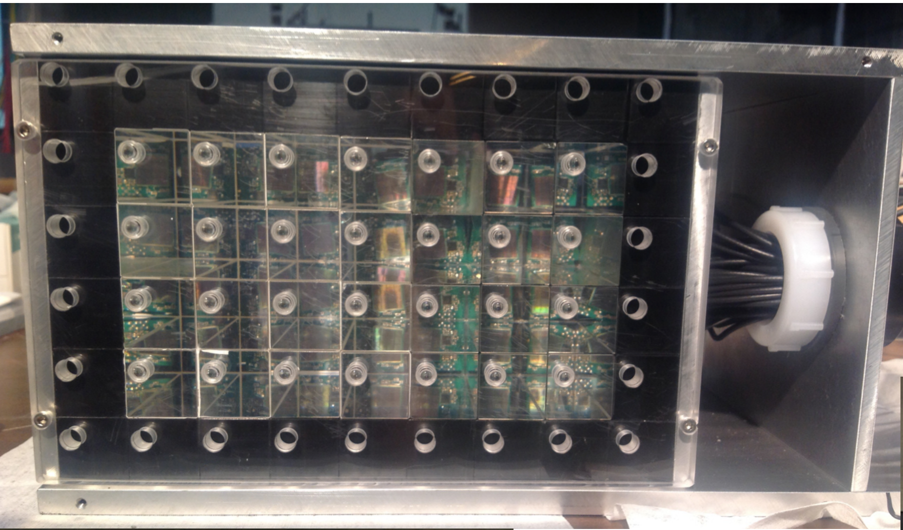


In order to extract the precession frequency the data is fitted :

$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

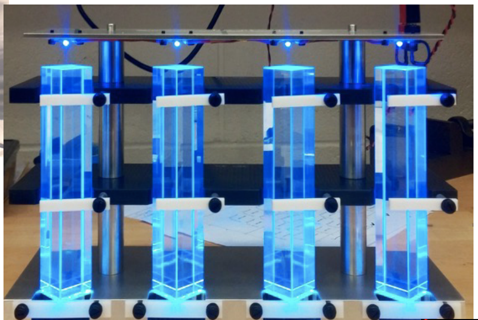
Calorimeters

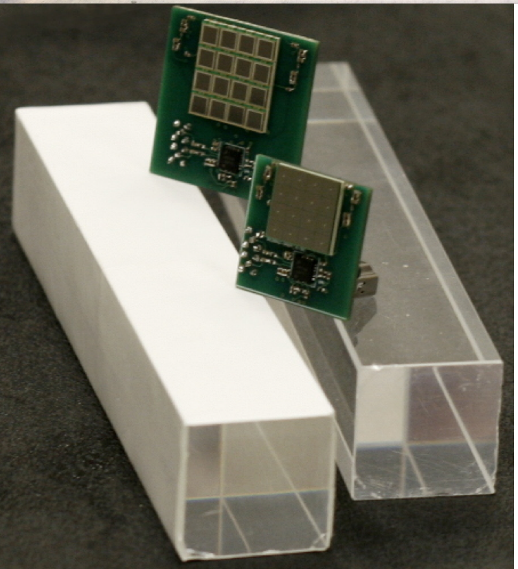
The calorimeters need to accurately measure the energy and time of the positrons from the muon decays



Requirements :

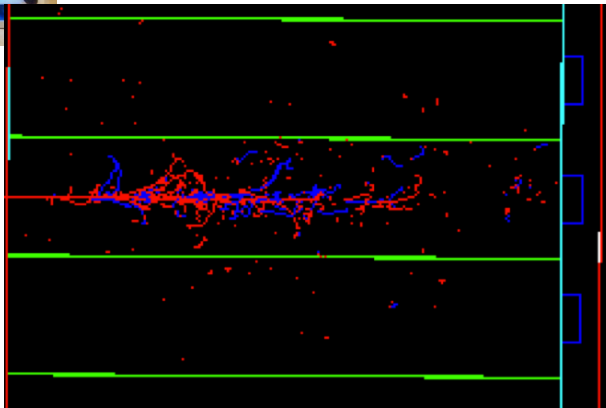
- Better than 5% energy resolution
- Time accurate to 100ps
- Resolve all showers separated by more than 5ns, and most below that
- Stable gain during a fill





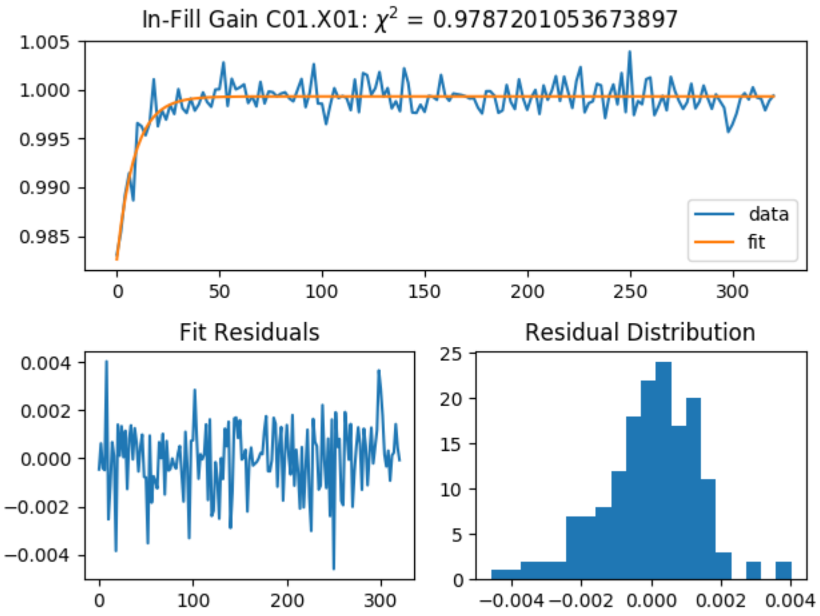
Improvements :

- Segmented calorimeter
- Faster sampling rate
- Quicker response
- Improved energy resolution and gain
- Laser calibration system



Laser calibration system

The laser calibration system allows any gain variations over time to be calibrated out

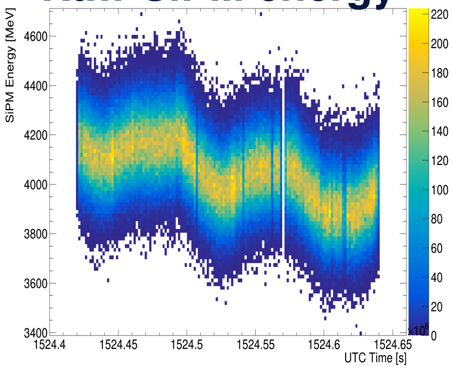


Sends laser pulses to every calorimeter both in and out of fill

Allows for both long and short term gain corrections

Performed well achieving gain stability of 0.04%

Raw SiPM energy



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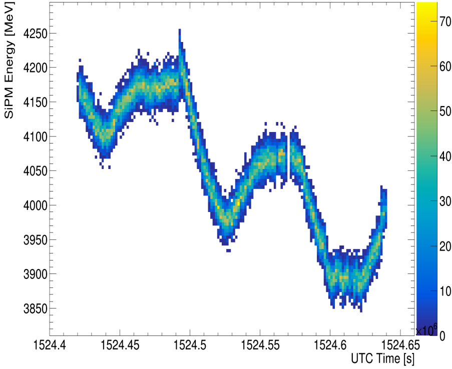
Out of fill correction



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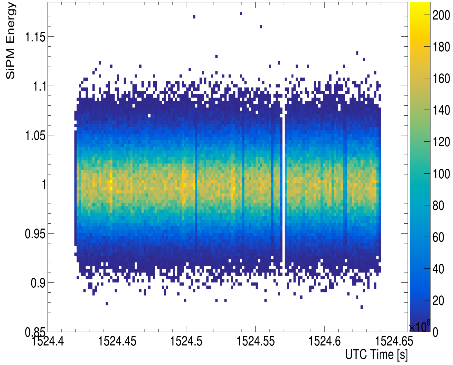
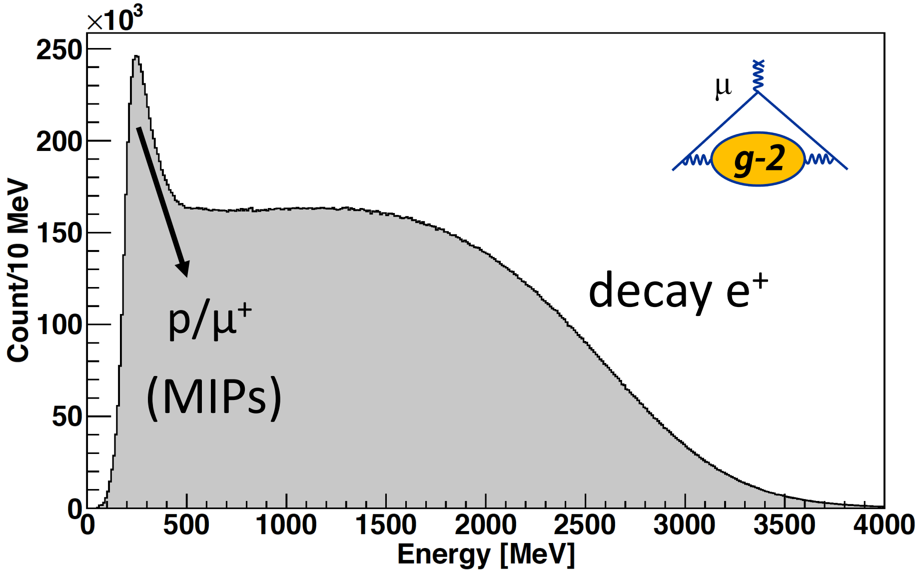
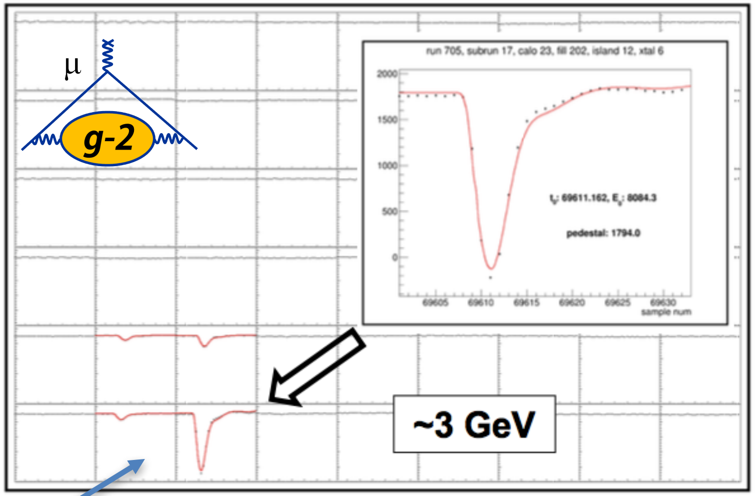
Corrected energy



Calorimeter Data

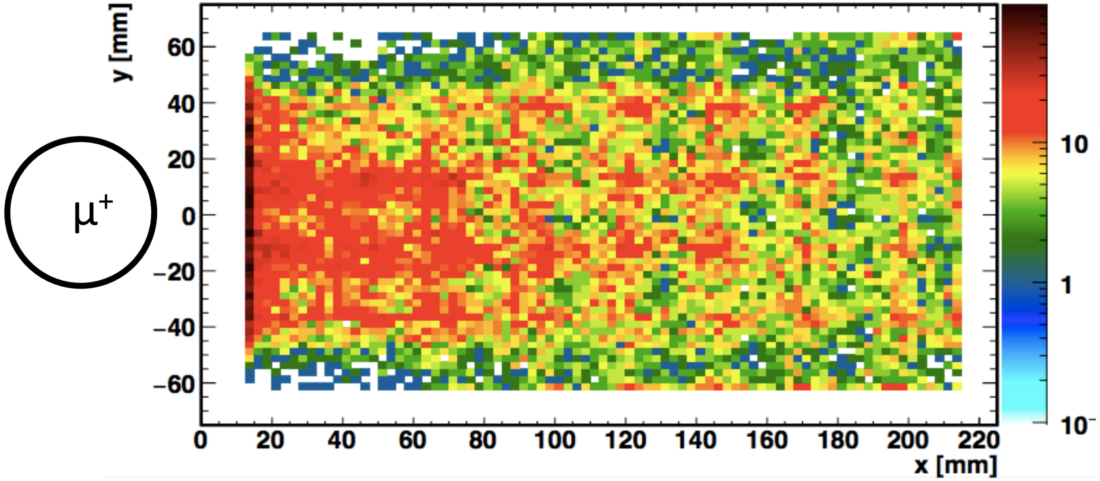
A first look at some of the data taken in the calorimeters from the start of the run



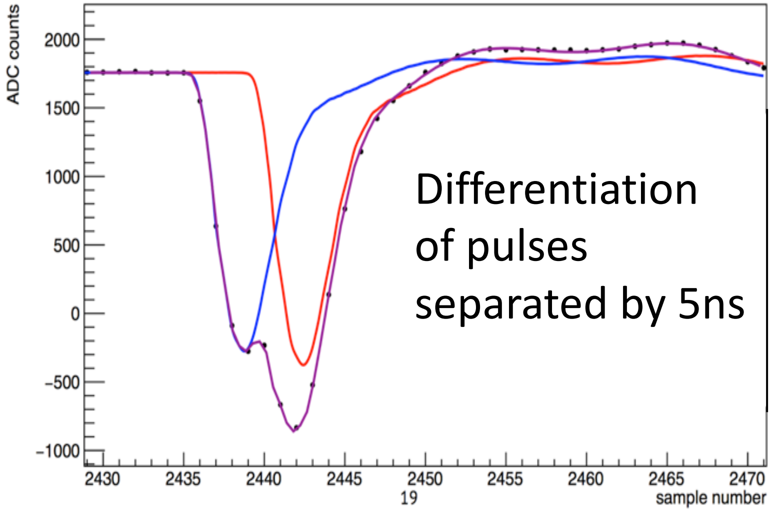


3 GeV e⁺ in few crystals

Spatial Reconstruction



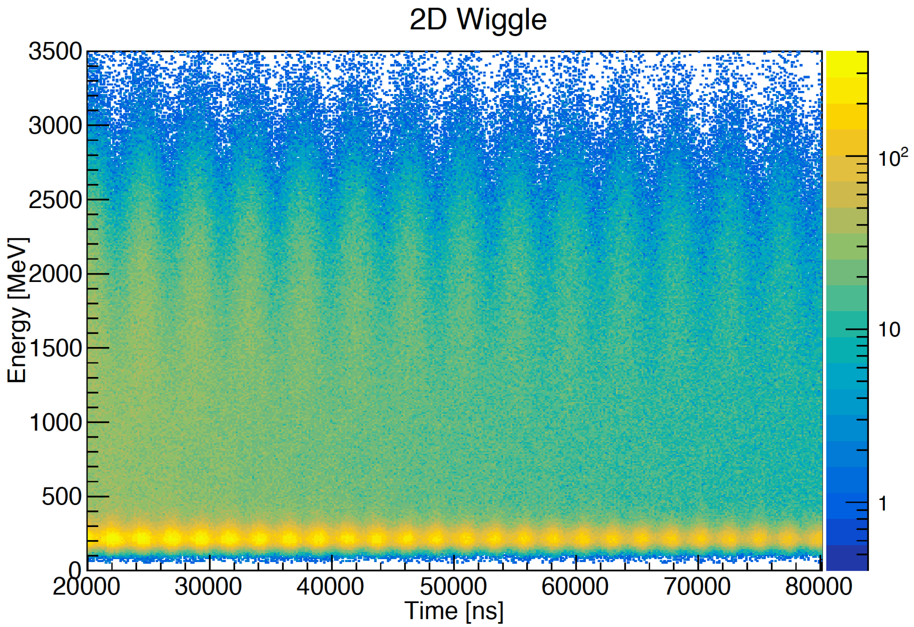
Majority of particles hit crystals closest to beam



Differentiation of pulses separated by 5ns

Last years data

These plots were made using data from 60 hours of this years running

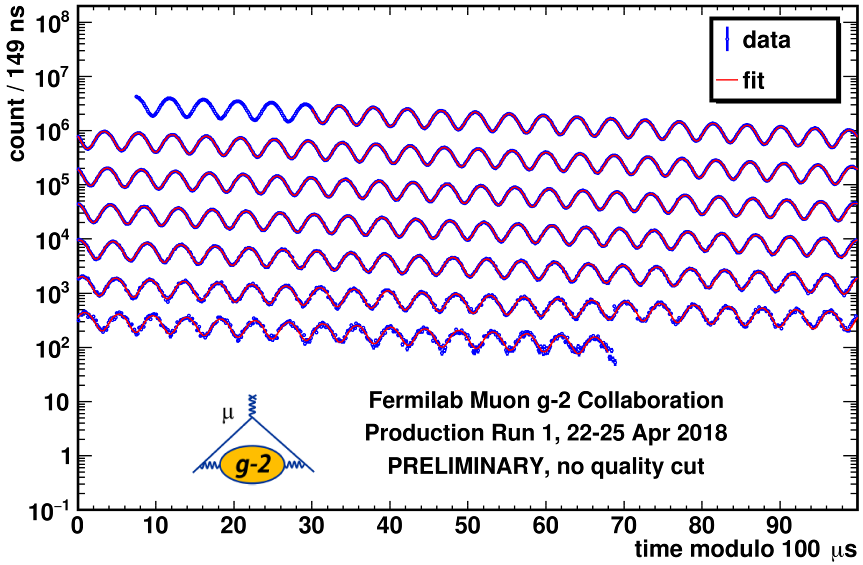


The energy of particles detected on the calorimeters shows :

- The g-2 oscillation as a function of time from the positrons
- The beam oscillations in the lost muons at low energies

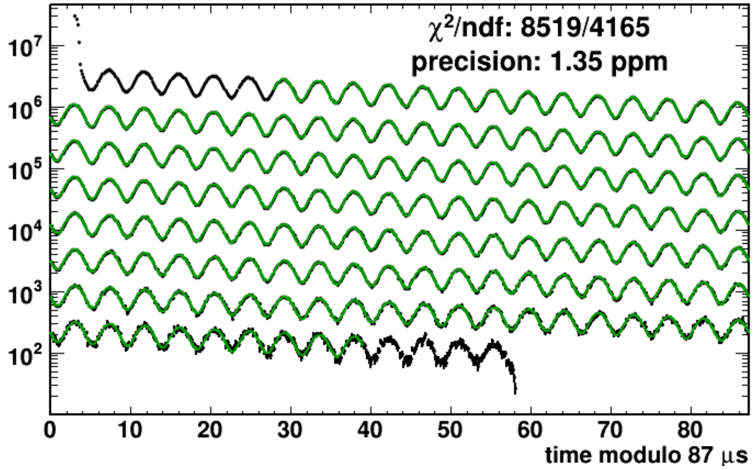
This wiggle plot was made using 60 hours of the data taken in April

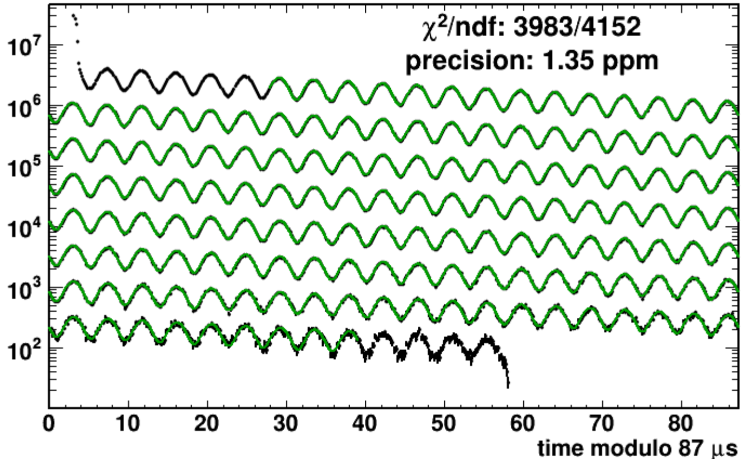
This has a similar amount of data to the 1999 BNL run



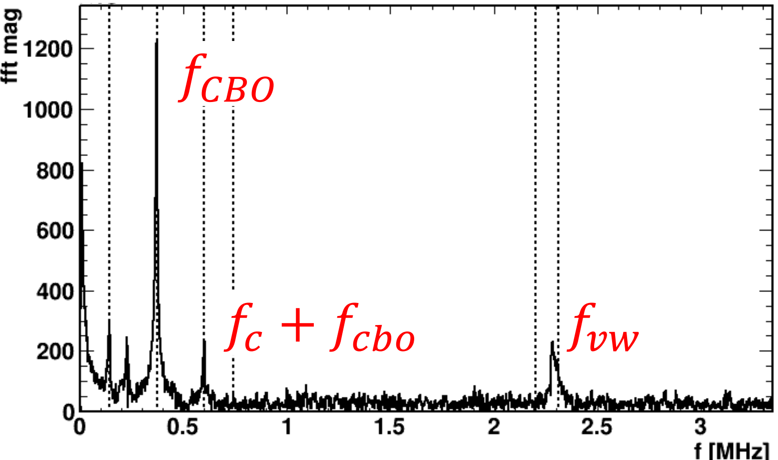
Measuring the precession frequency

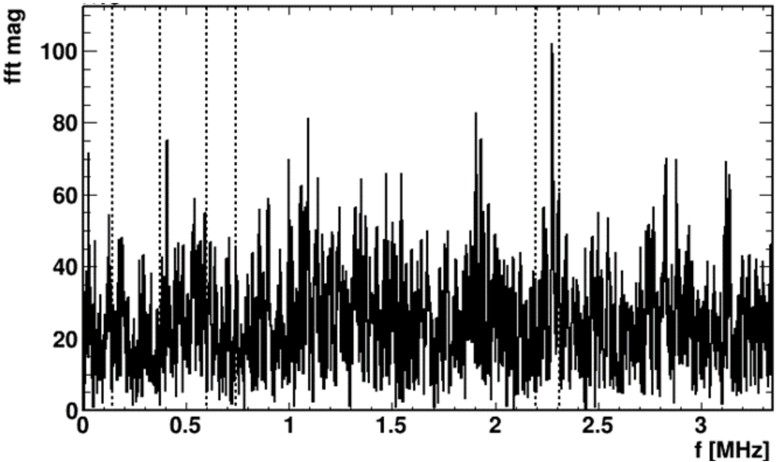
But it's actually more complicated than that as you have to account for the beam motions and other effects





Account for vertical and horizontal beam motion, pile up, muon losses and energy scale



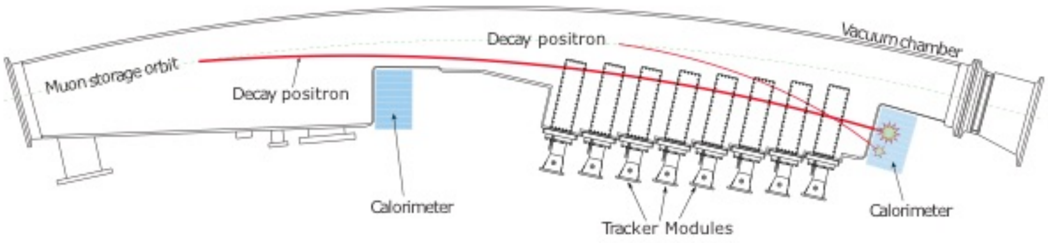


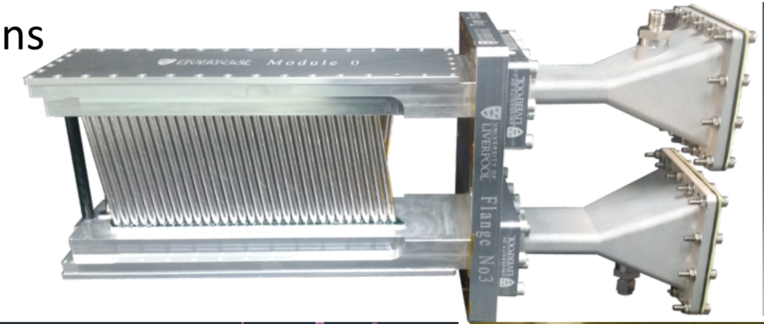
Straw Trackers (UK)

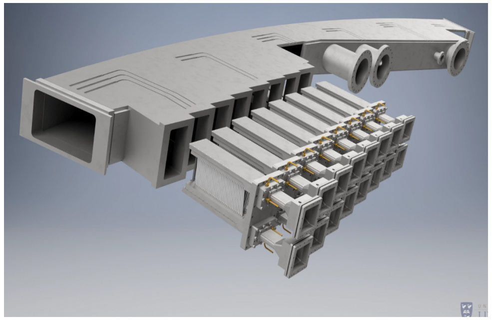
The straw trackers allow for the reconstruction of the positron tracks and traceback to the storage region

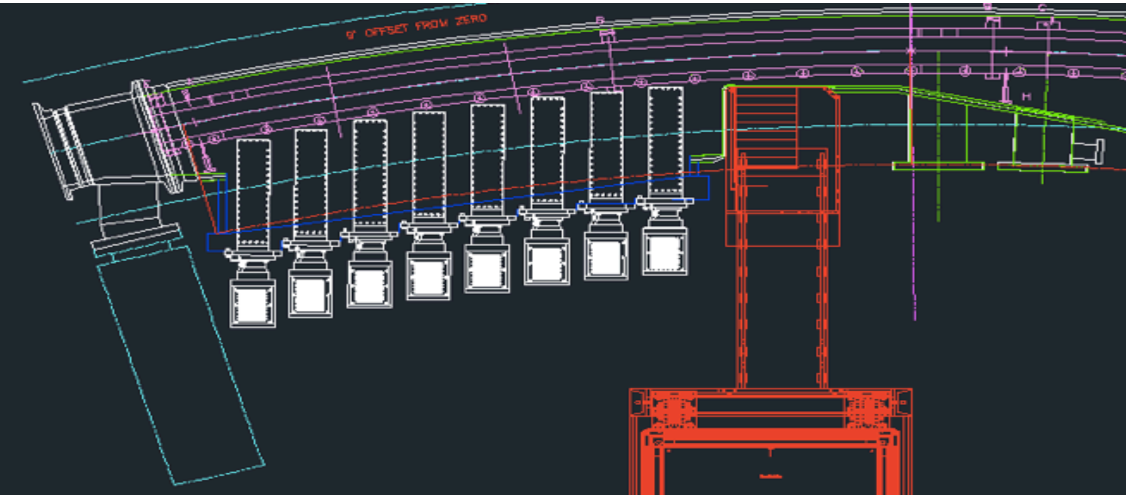
Aims :

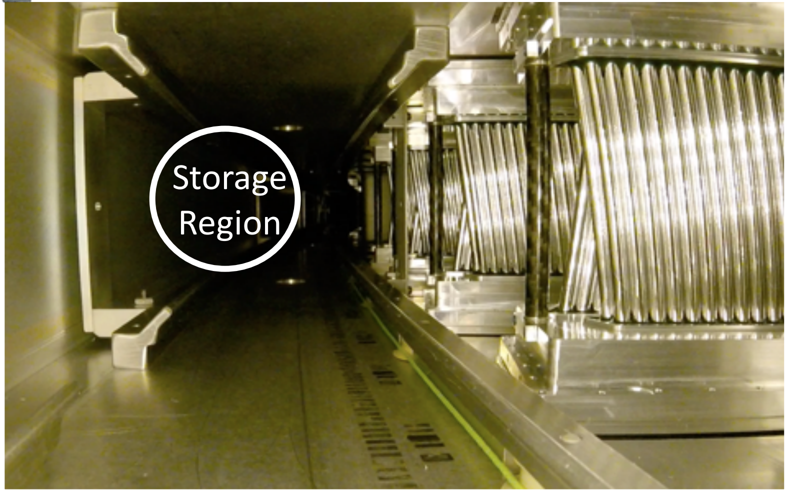
- Measure the beam profile in multiple locations around the ring as a function of time
- Calibration and acceptance of the calorimeters
  - Pile up, gain, lost muons
- Measure or set a limit on a muon EDM





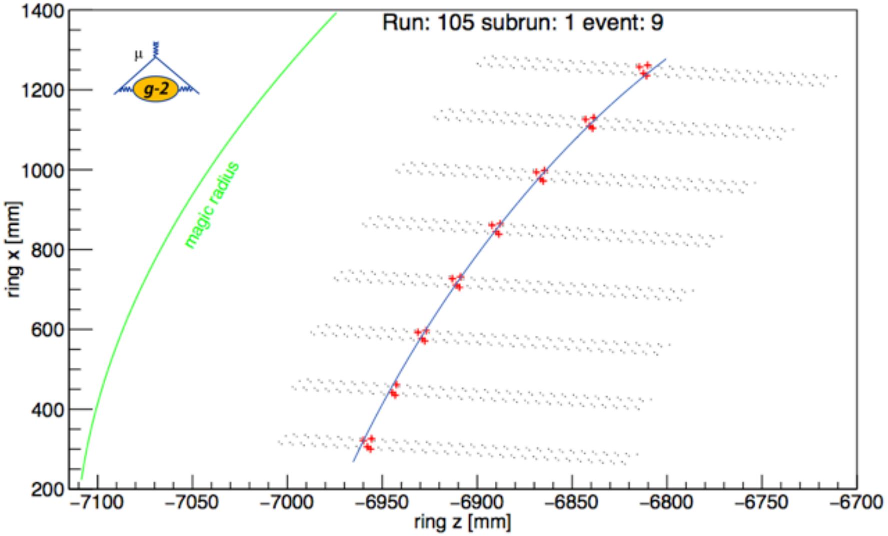


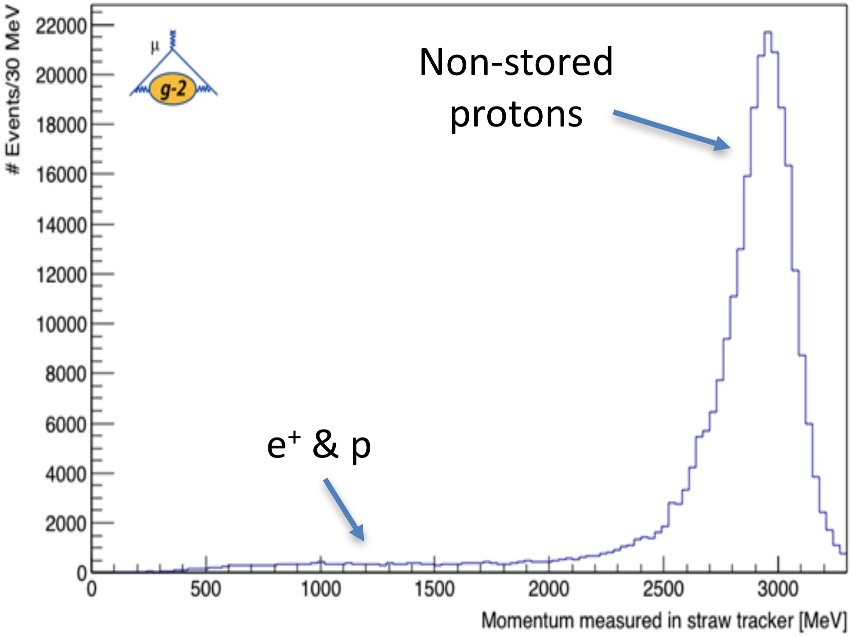




Commissioning run – first tracks!

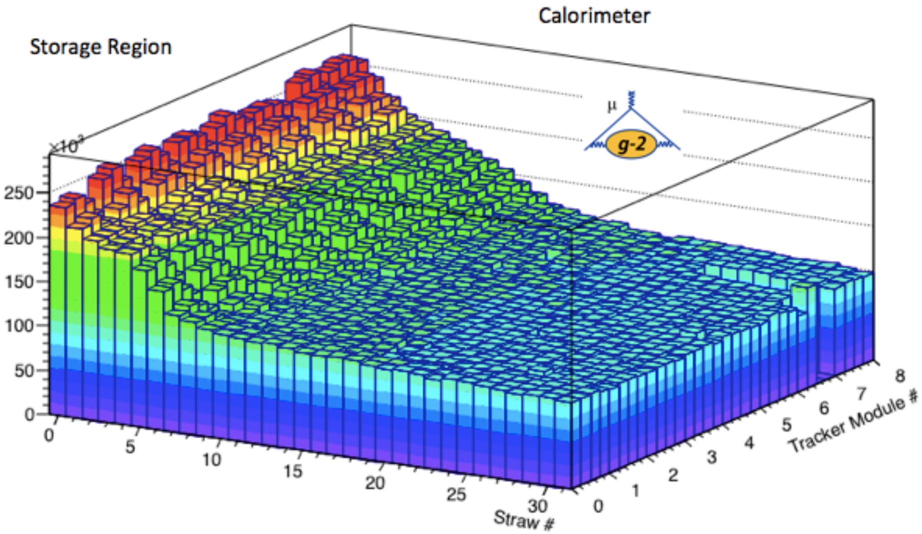
The commissioning run was the first test of the tracker and tracking algorithms with real data





Non-stored protons

e^+ & p



Nice long tracks (hitting many modules) from the protons

Uniform illumination of the tracker with more hits closest to the storage ring

Momentum distribution consistent with a proton dominated beam

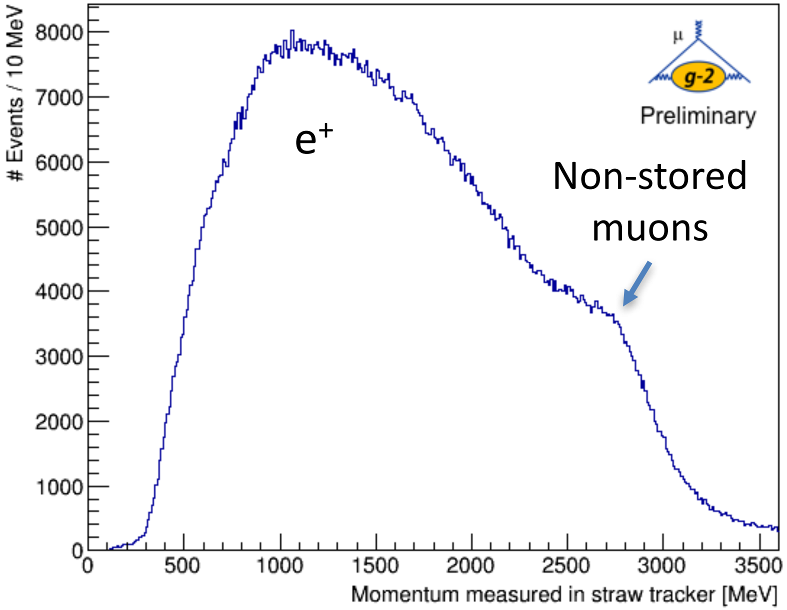
Beam tuning data

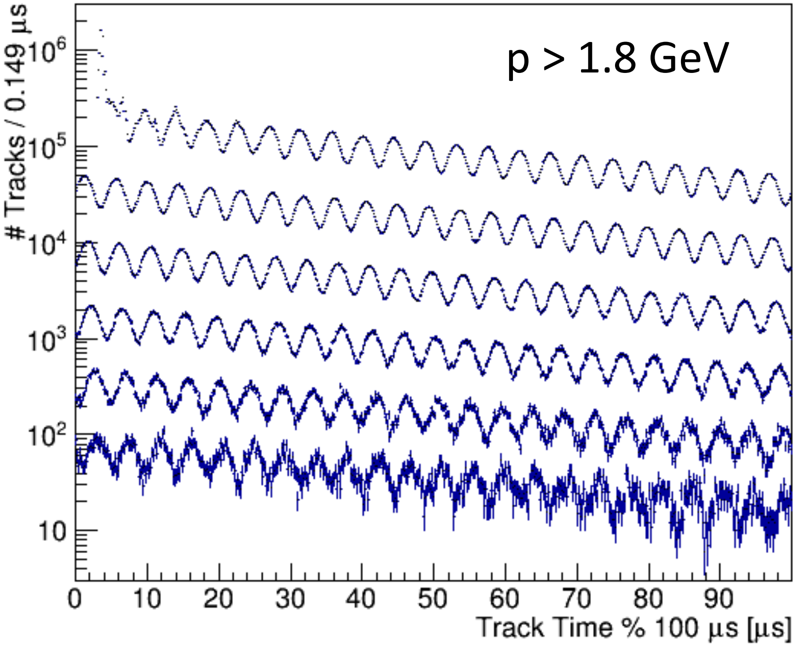
The more recent beam is not proton dominated

The momentum distribution is mostly from positron decays

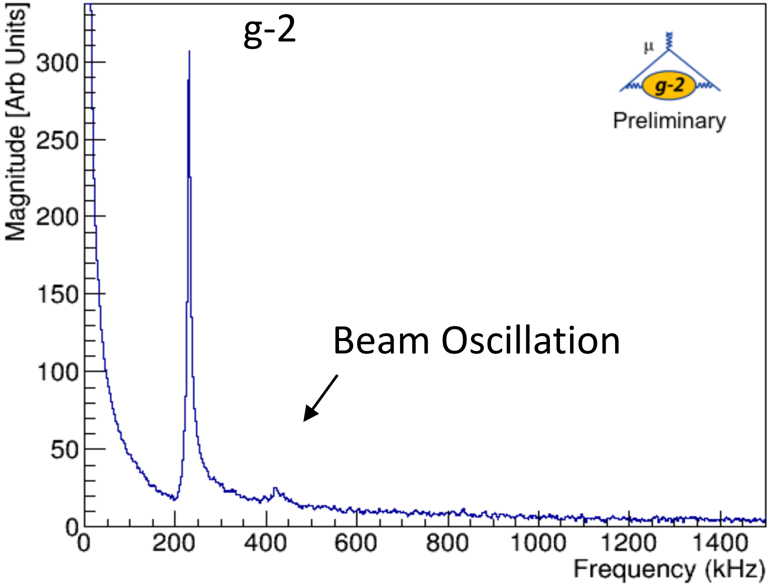
The g-2 wiggle also appears in the trackers after a momentum cut

The FFT shows up the g-2 frequency and the beam oscillation frequency





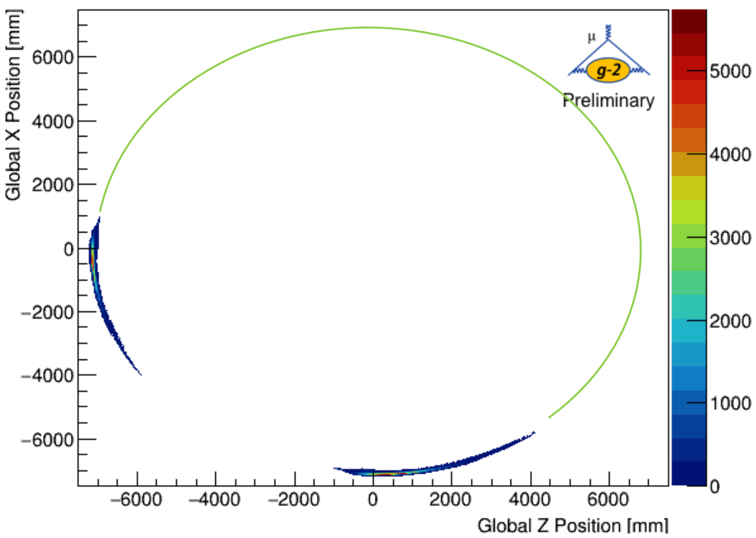
FFT



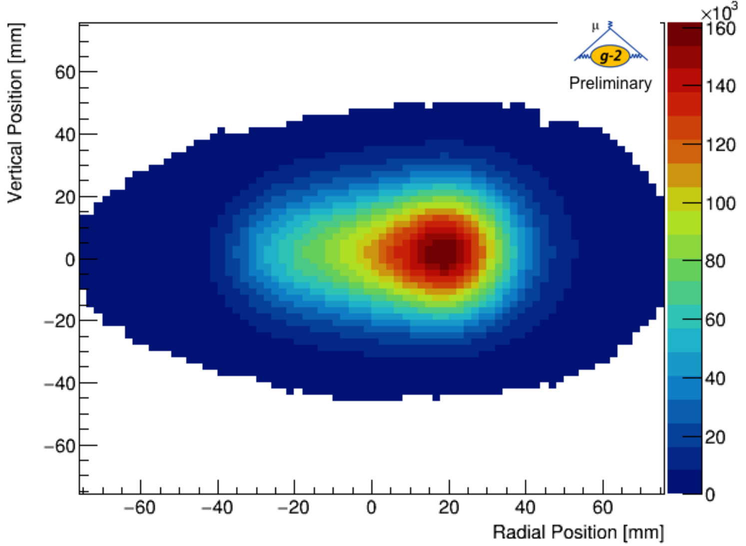
Beam distribution from the trackers

The tracks can be extrapolated back from the point of tangency to get the beam distribution

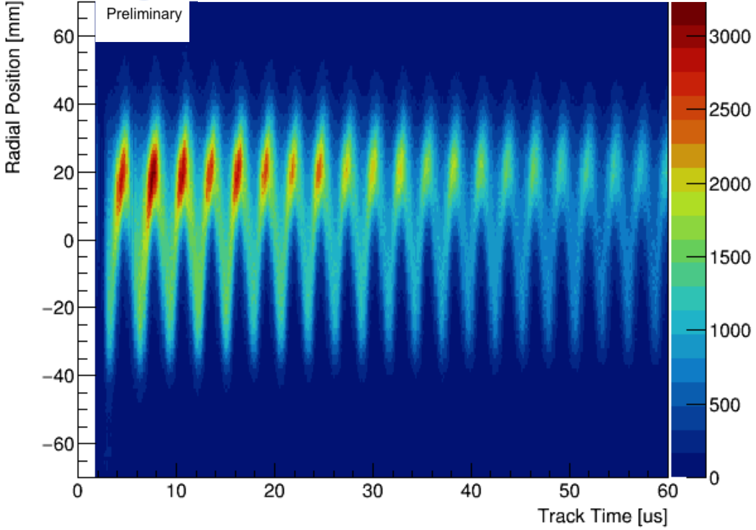
Decay Vertices



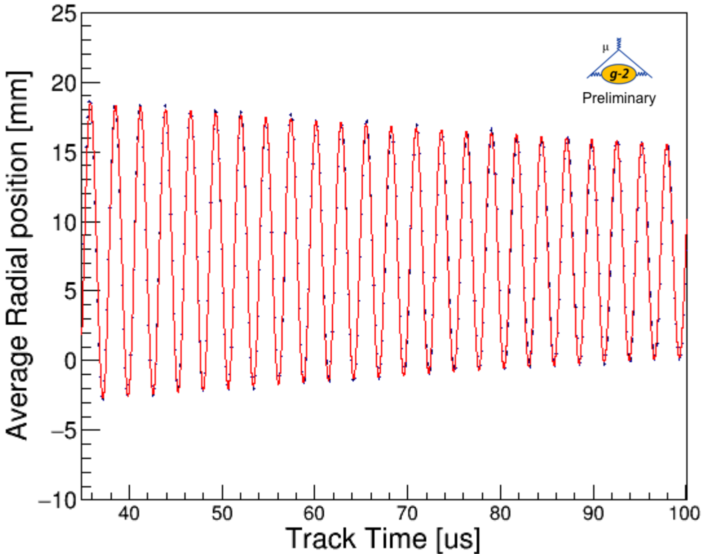
Radial & Vertical Position



Radial Position within Fill



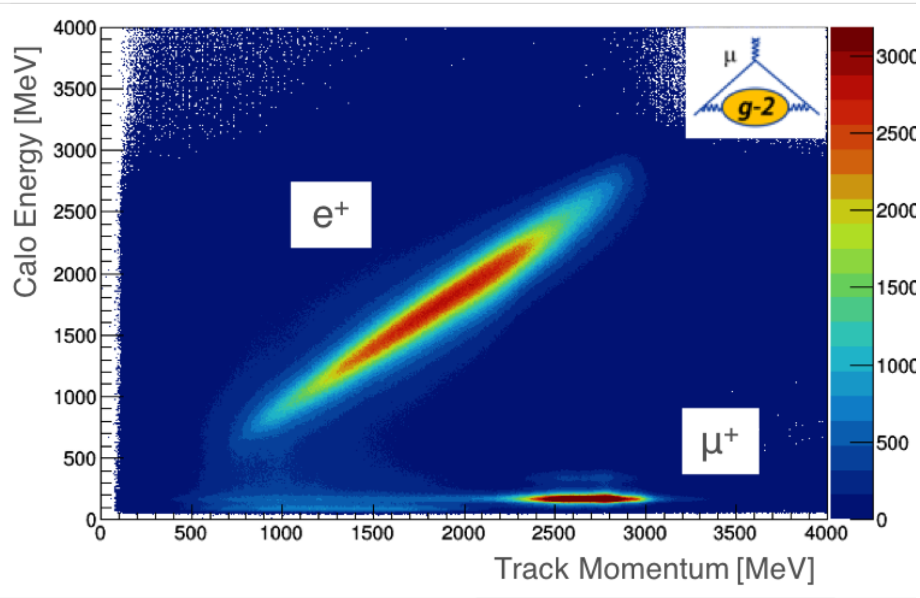
Mean Radial Position



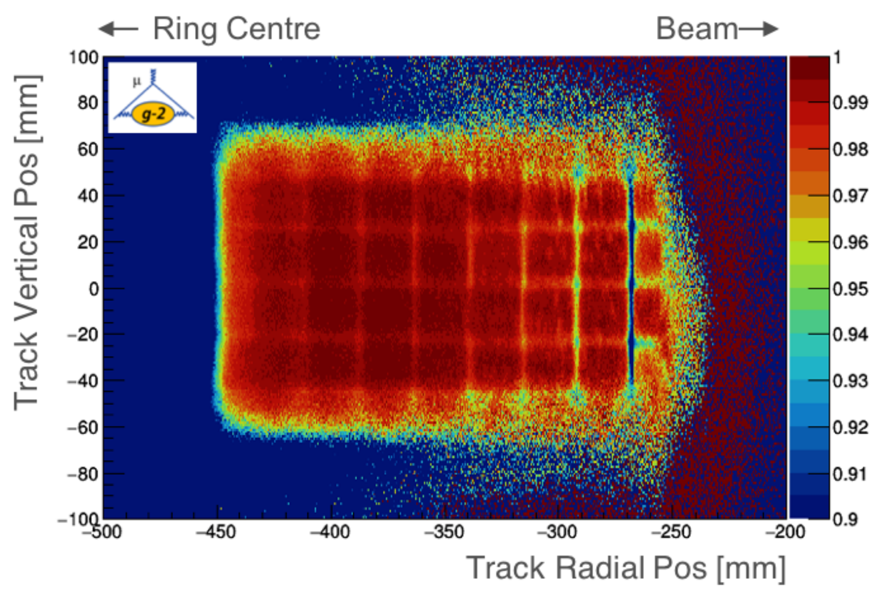
Tracker – Calo Cross Checks

The trackers are located in front of 2 of the calorimeters so can be used for systematic checks in terms of gain and pile up

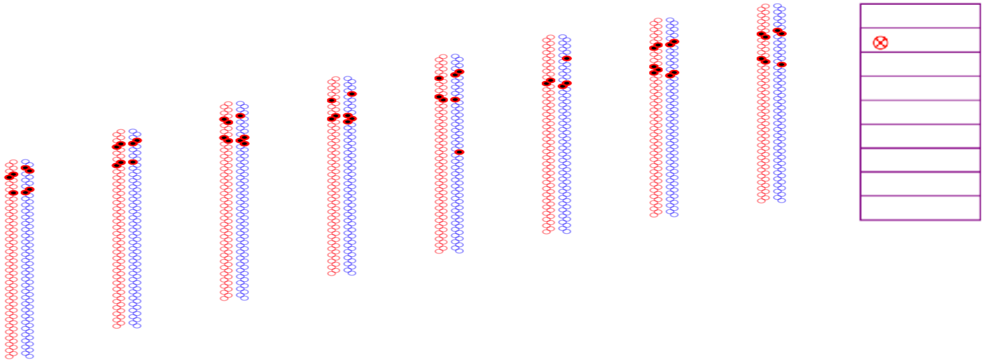
Comparison between calorimeter energy and tracker momentum



Calorimeter efficiency (based on extrapolated tracks)



Can check the pileup in the calorimeter – for example here there are 2 tracks but only one calorimeter cluster



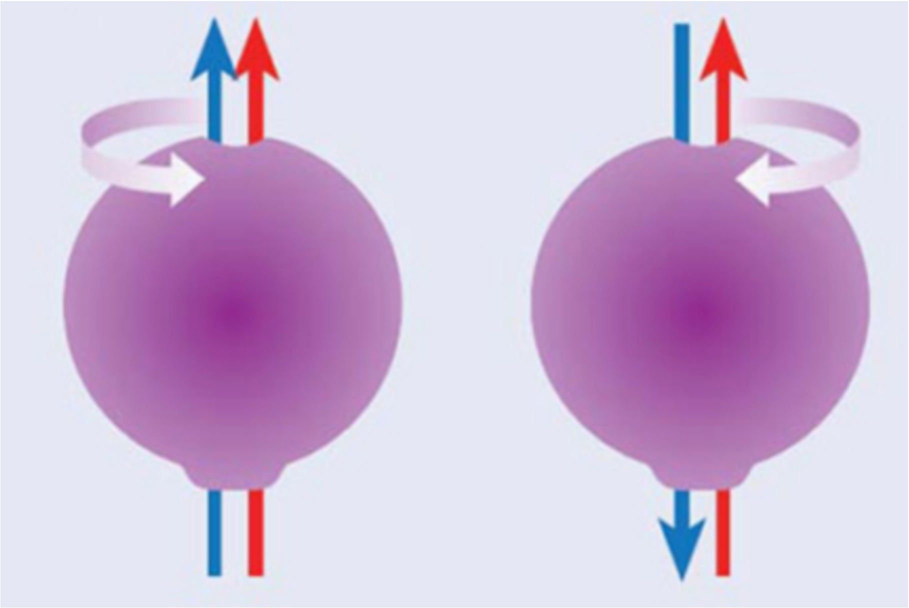
EDM

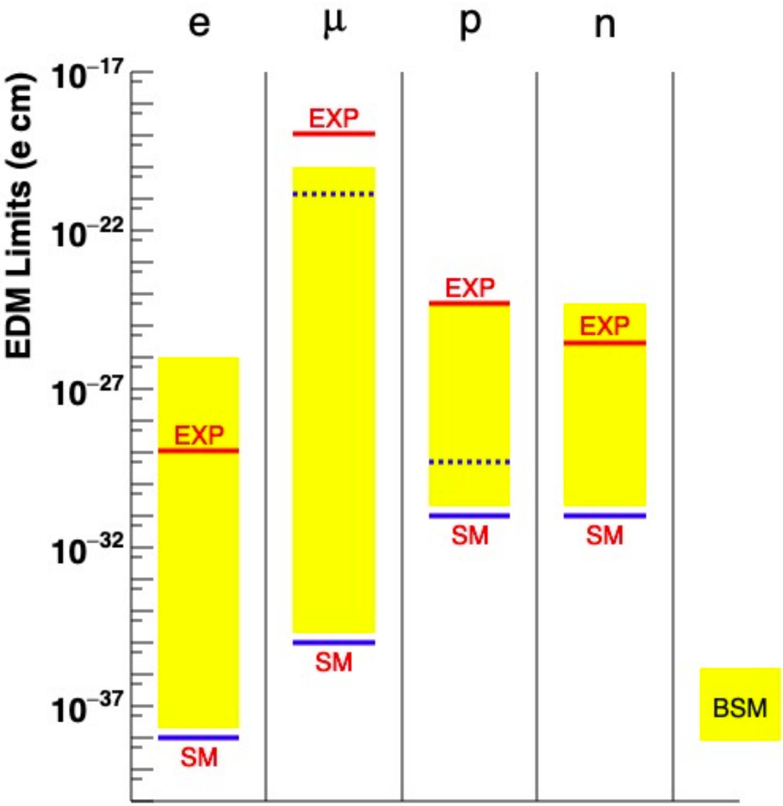
The g-2 experiment at Fermilab can also look for a potential muon EDM

Fundamental particles can also have an EDM defined by an equation similar to the MDM:

$$\vec{d} = \eta \frac{Qe}{2mc} \vec{s} \qquad \vec{\mu} = g \frac{e}{2mc} \vec{s}$$

Provides an additional source of CP violation

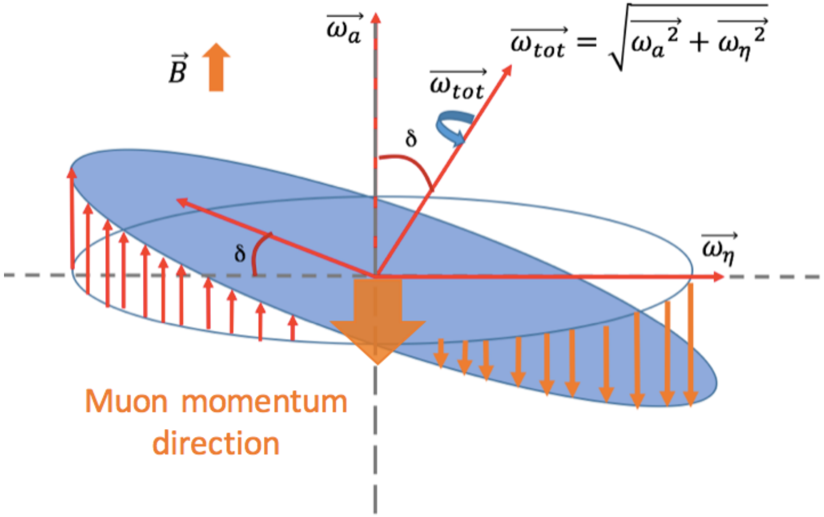




The power of EDM measurements has recently been demonstrated by the latest electron EDM measurement

EDM

If an EDM is present the spin equation is modified to:



$$\vec{\omega}_{a\eta} = \vec{\omega}_a + \vec{\omega}_\eta = \overbrace{-\frac{Qe}{m}a\vec{B}}^{\text{MDM}}\overbrace{-\eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \boxed{\vec{\beta}\times\vec{B}}\right]}^{\text{EDM}}$$

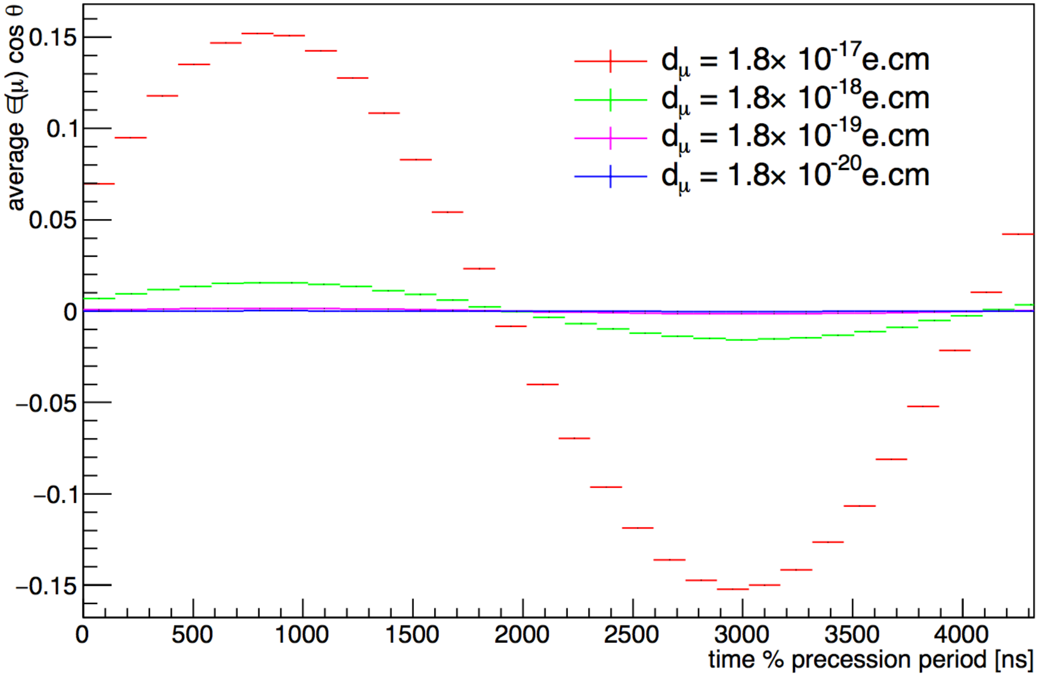
Dominant term

An EDM tilts the precession plane towards the centre of the ring

→ Vertical oscillation
(π/2 out of phase)

Expect tilt of ~mrad for $d_\mu \sim 10^{-19}$

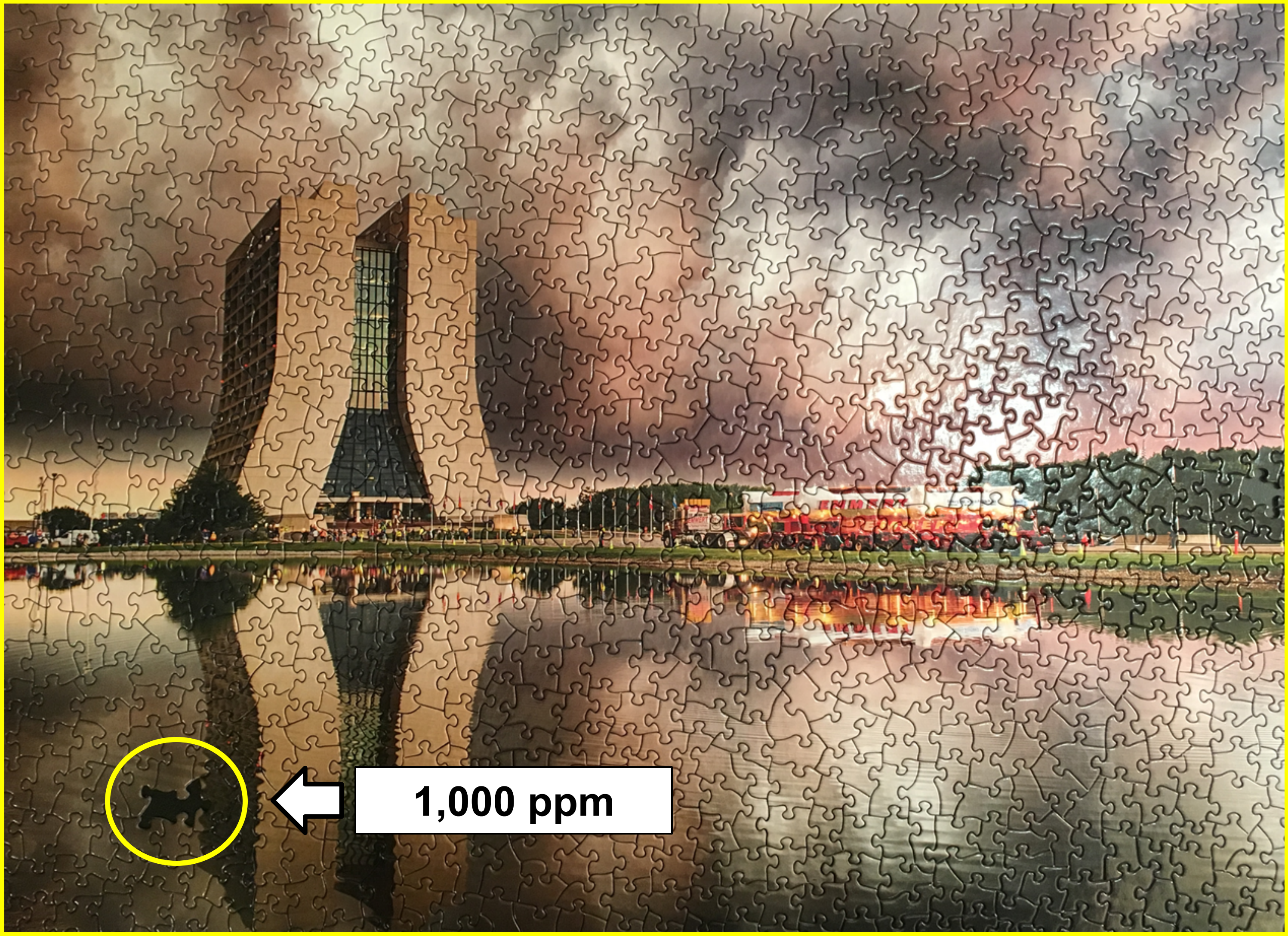
An EDM also increases the precession frequency



Should reach BNL sensitivity in a few weeks (~1 million tracks)
Expect to reach 10^{-21} by the end of the experiment (several billion tracks)

Systematics

To put the precision into context consider this 1000 piece jigsaw with 1 missing piece…



Systematics

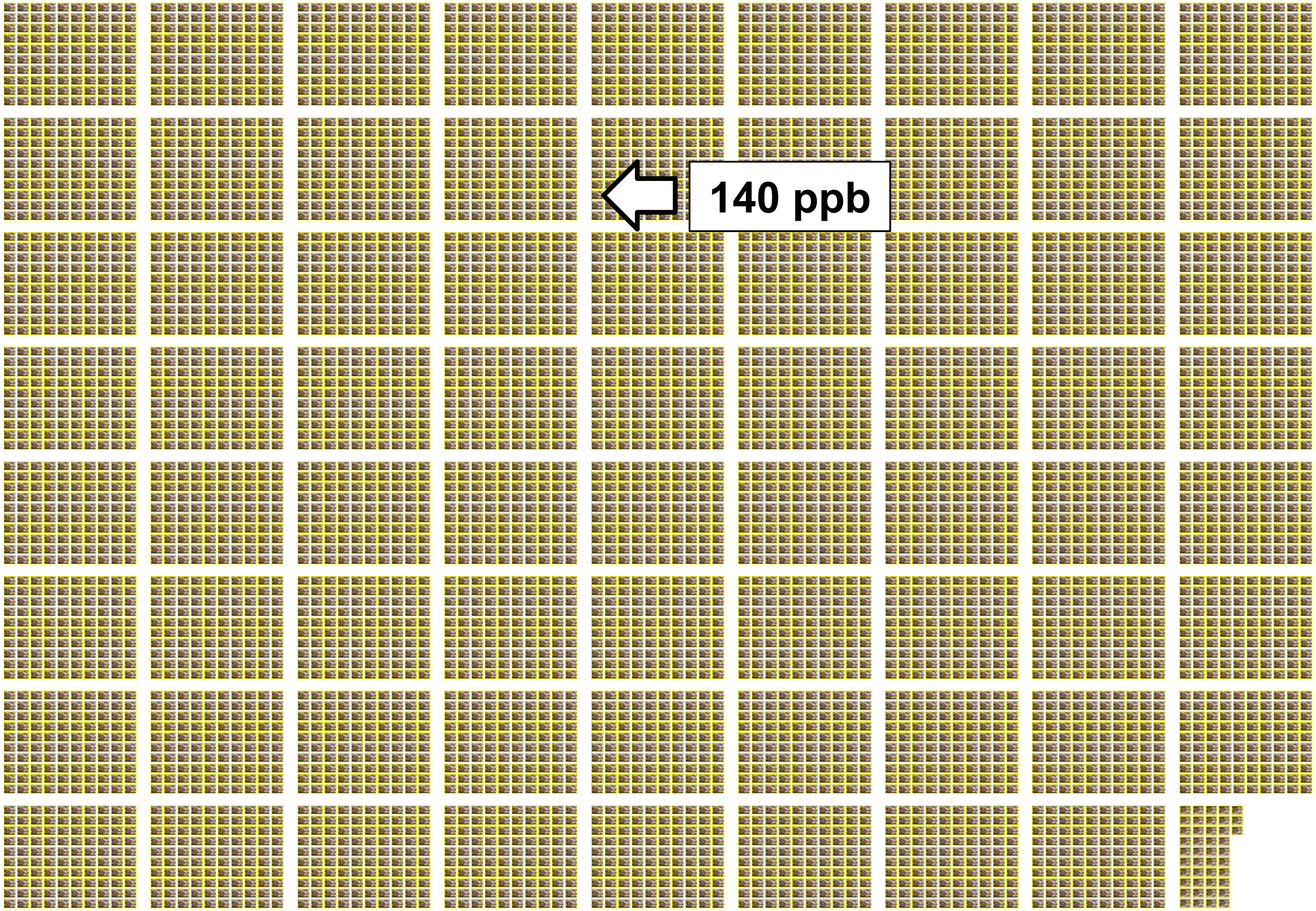
Consider 100 jigsaw puzzles with only one missing piece

10 ppm

CERN result was ~7ppm

Systematics

7143 jigsaw puzzles with one missing piece



140 ppb

Lose one piece → 140ppb (Fermilab aim)

Every detail counts!

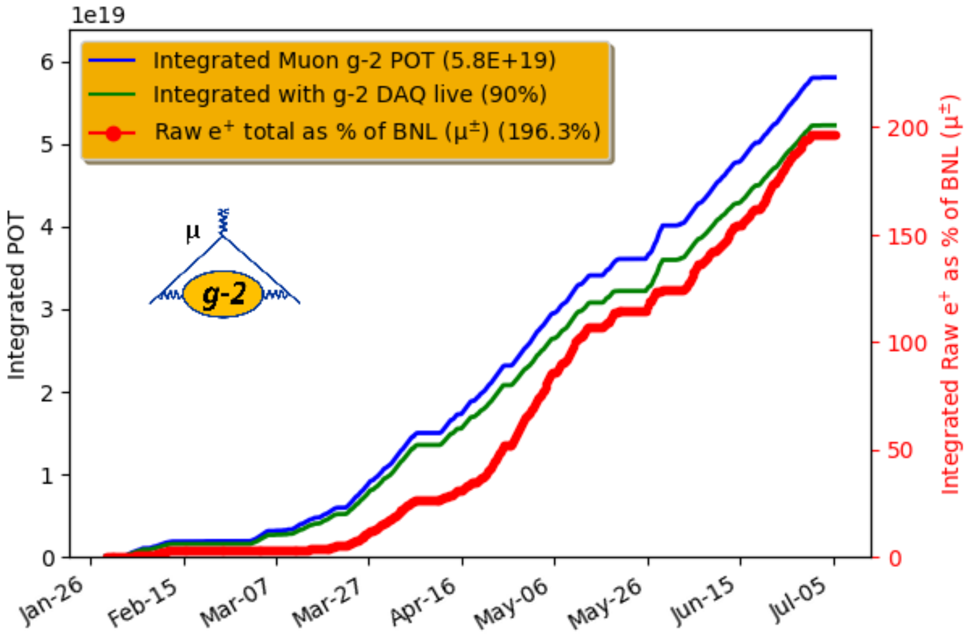
Summary

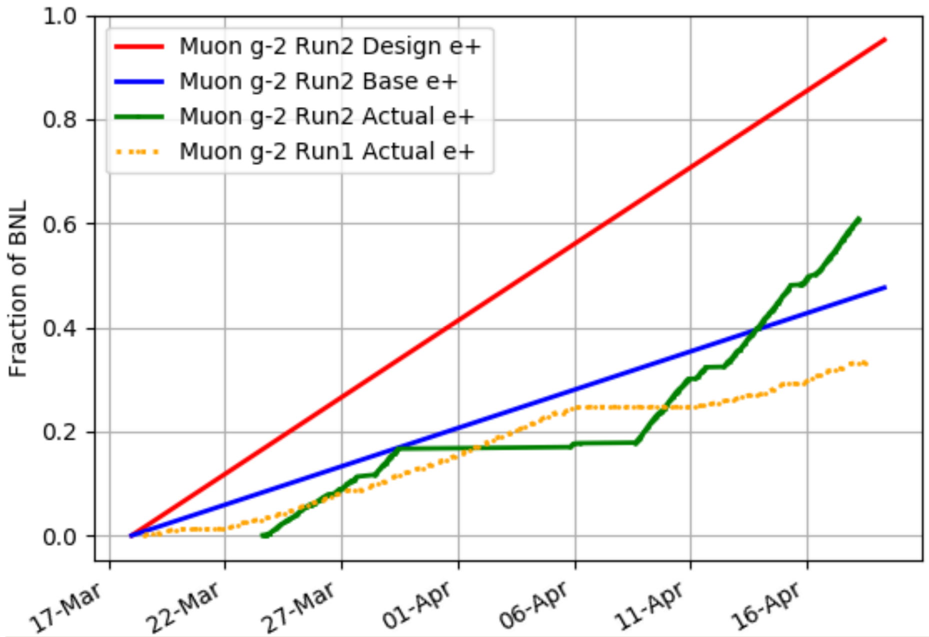
The new g-2 experiment at Fermilab has started collecting physics quality data

- The new experiment aims to reduce the experimental uncertainty by a factor of 4 to investigate the current discrepancy between experiment and theory of ~3.5

- Expect to publish an early result with comparable to BNL precision in the summer(based on the data taken last year)

- An intermediate result will be published in 2020 and then the final full precision result in 2021





Thank you

Back up

Improvements since BNL

- More μ per proton
- Lower inst. rate
- Fewer pions

Unique capabilities of FNAL accelerators

- Improved detectors
- Improved stored muon beam dynamics
- Improved field uniformity, field measurement & calibration
- Improved modeling of beam & detectors

$$\text{BNL} \rightarrow \text{FNAL}$$

$$[54\ (\text{stat.}) \oplus 33\ (\text{syst.}) \rightarrow 11\ (\text{stat.}) \oplus 11\ (\text{syst.})] \times 10^{-11}$$

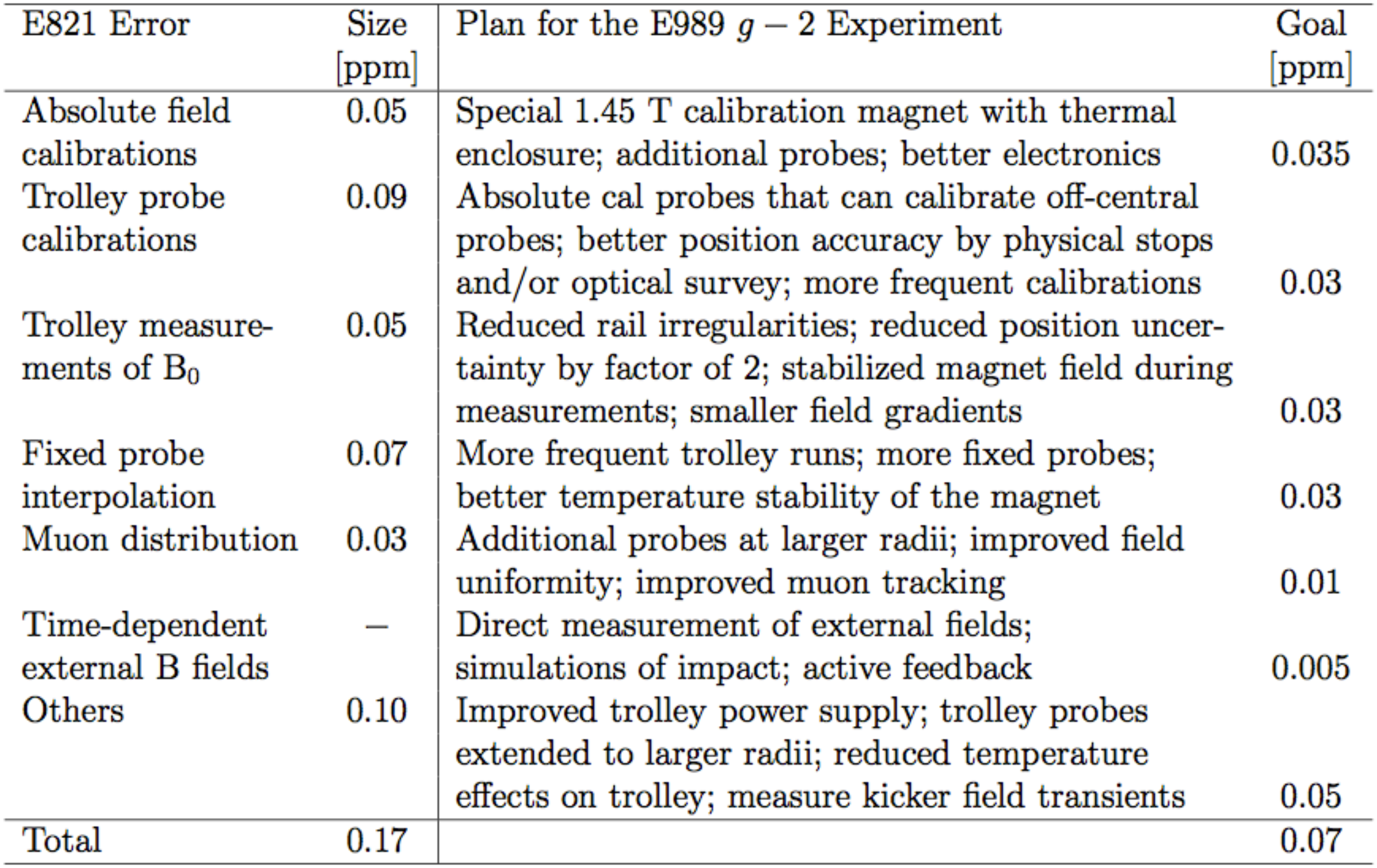
$$0.54\ \text{ppm} \rightarrow 0.14\ \text{ppm}$$

New / improved technologies

Additional collaborators

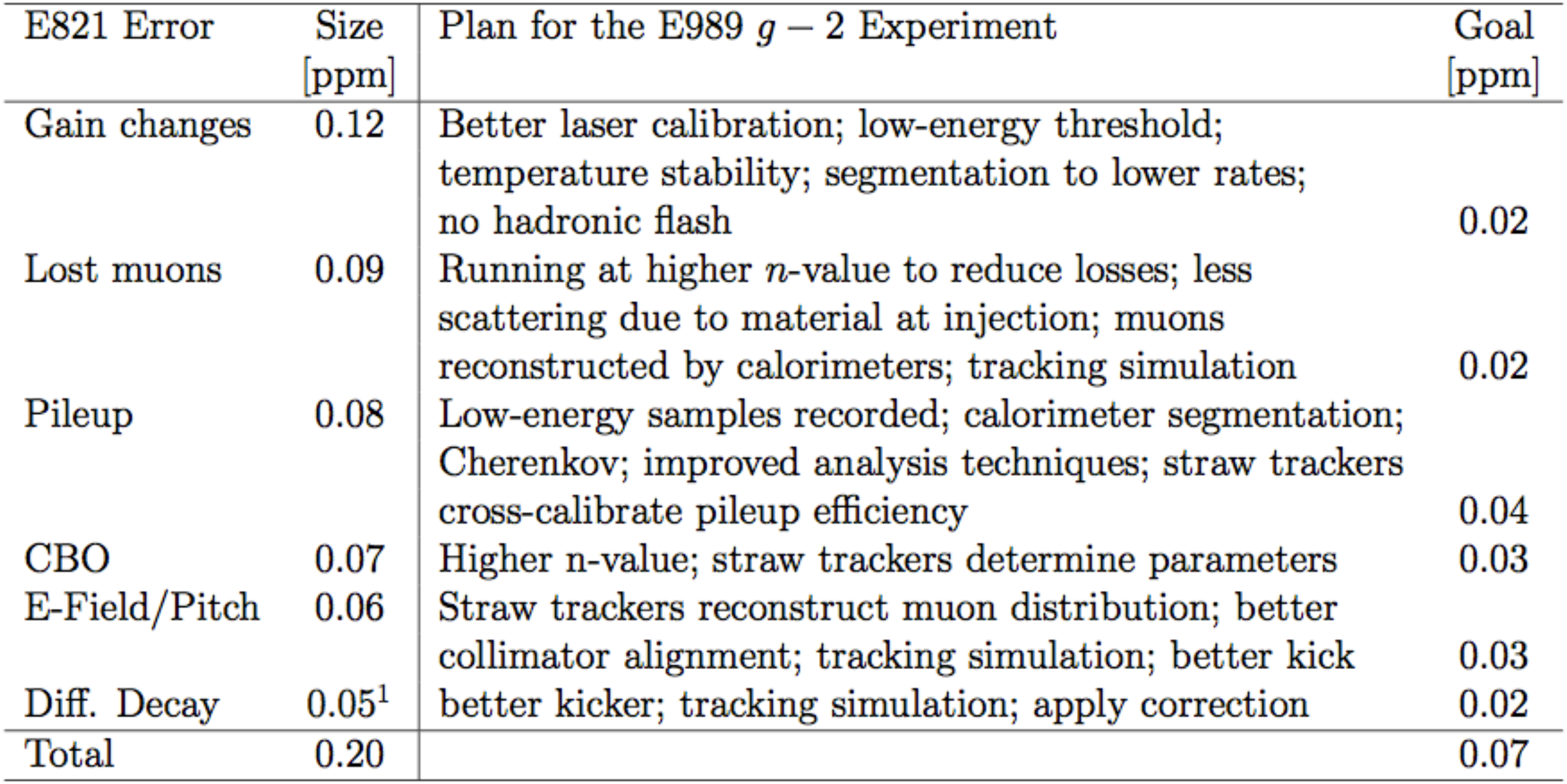
Building on wealth of experience from BNL E821 & other expts

Magnetic Field Systematics



E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

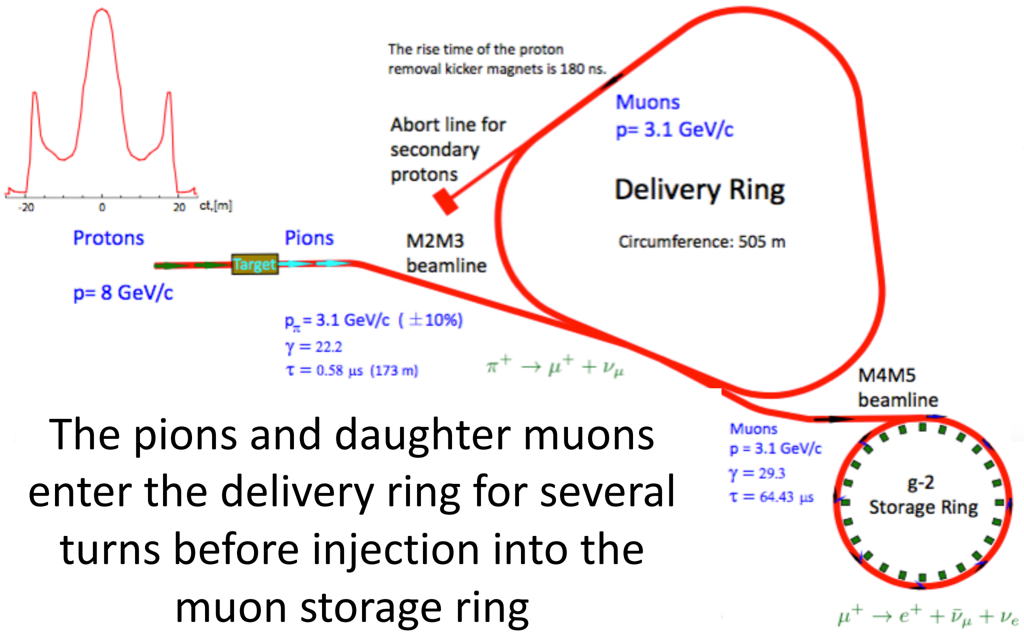
Spin Precession Systematics



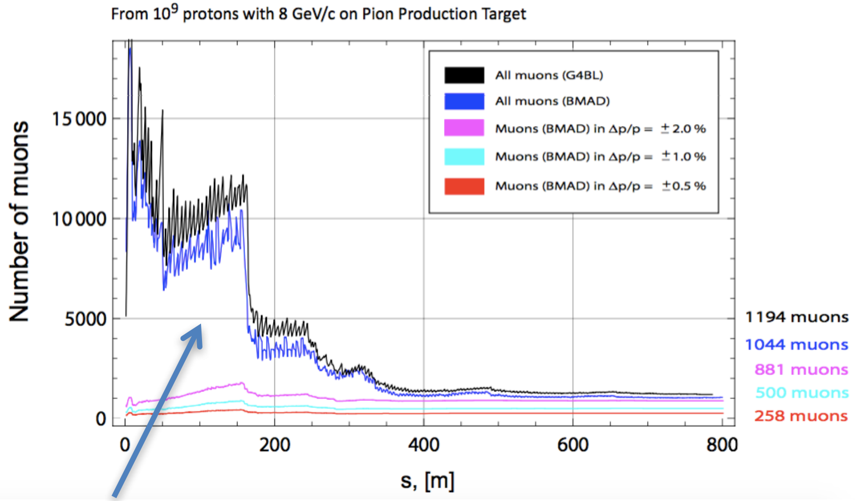
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

Beam distribution

In reality we need to accurately model the beam for vertical polarisation components and momentum distribution

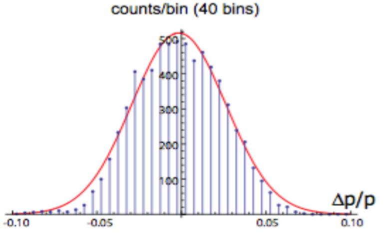


The pions and daughter muons enter the delivery ring for several turns before injection into the muon storage ring



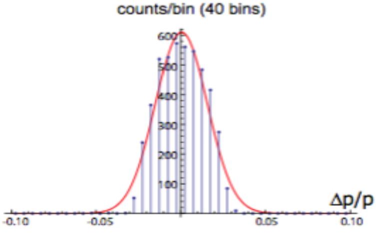
BMAD simulation of the beamline

End of M2M3 beamline



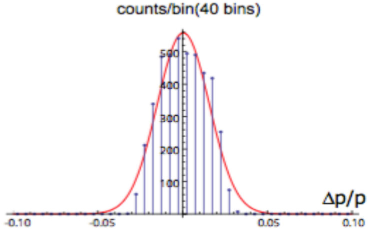
RMS momentum Δp/p: 0.0278

After 1st turn in DR

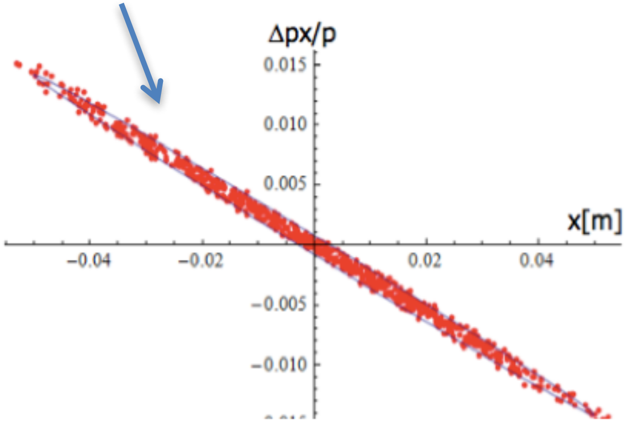


RMS momentum Δp/p: 0.0152

After 4th turn in DR

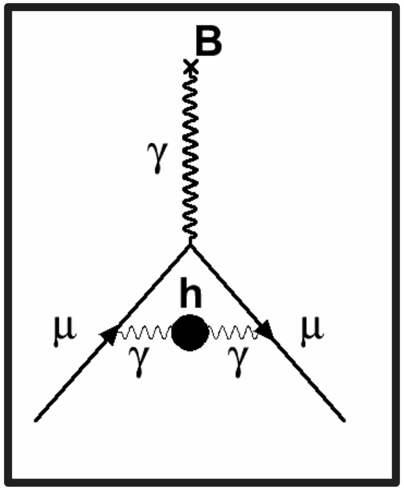


RMS momentum Δp/p: 0.0153

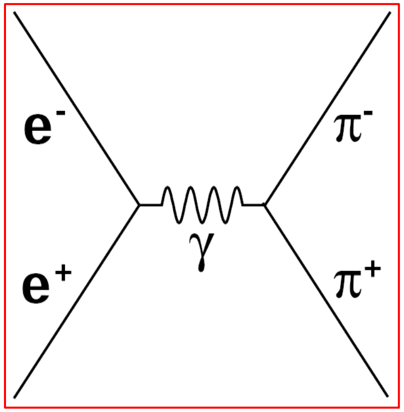


Back up

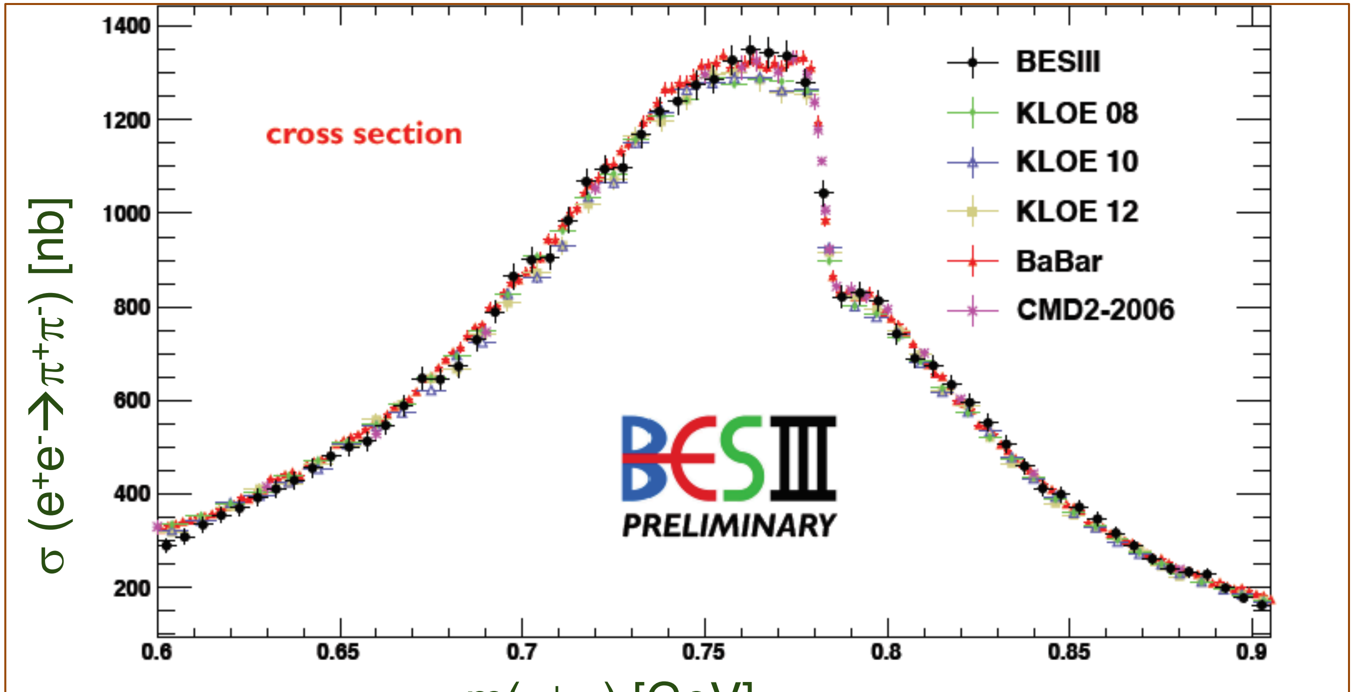
HVP



$e^+ e^- \rightarrow$ hadrons



σ (600-900 MeV)



$m(\pi^+\pi^-)$ [GeV]

B. Kloss, CIPANP 2015

Fermilab Muon g-2 Collaboration …

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas
- Virginia
- Washington

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- INFN
  - LNF Frascati,
  - Naples
  - Pisa
  - Roma 2
  - Trieste
  - Lecce
- Udine
- Naples
- Trieste
- Rjeka
- Molise
- SNS Pisa

China

- Shanghai

The Netherlands

- Groningen

Germany

- Dresden (thy)

England

Cockroft Institute
Lancaster
Liverpool
University College London

Korea

KAIST
CAPP

Russia

Dubna
Novosibirsk