The g-2 experiment at Fermilab

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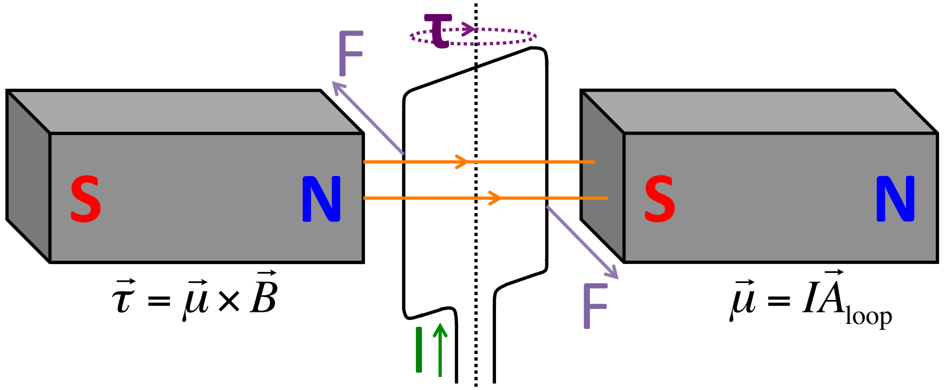
UK HEP Forum – The spice of flavour

28th November 2018

The Magnetic Moment

The magnetic moment determines how something interacts with a magnetic field

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



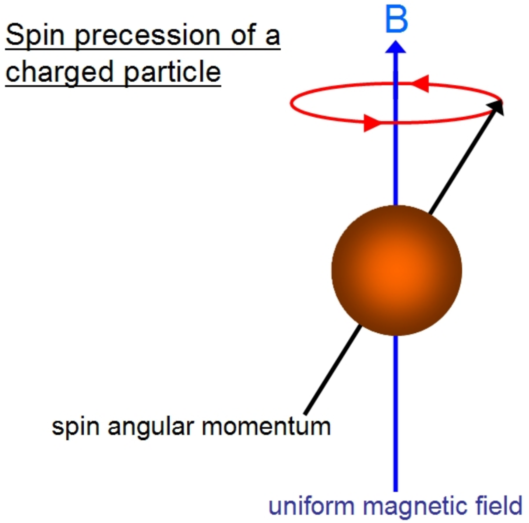
$\vec{\tau} = \vec{\mu} \times \vec{B}$

$\vec{\mu} = I\vec{A}_{\text{loop}}$

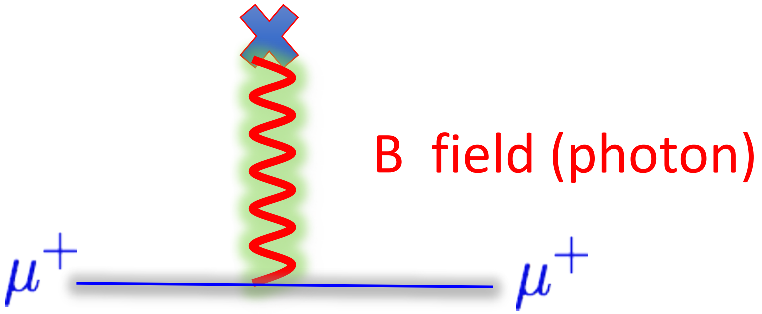
For particles the magnetic moment is related to the spin through the g factor

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

When placed in a magnetic field this causes the spin to precess

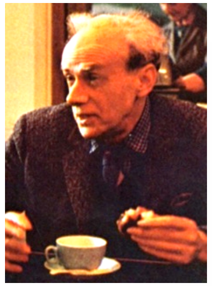


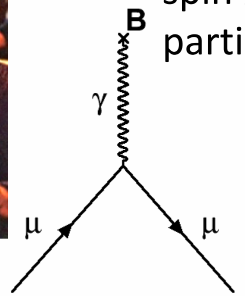
Dirac predicted that g = 2 :



The Magnetic Moment

Dirac

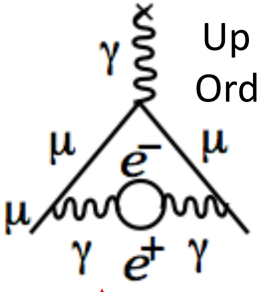




Charged,
spin ½
particle

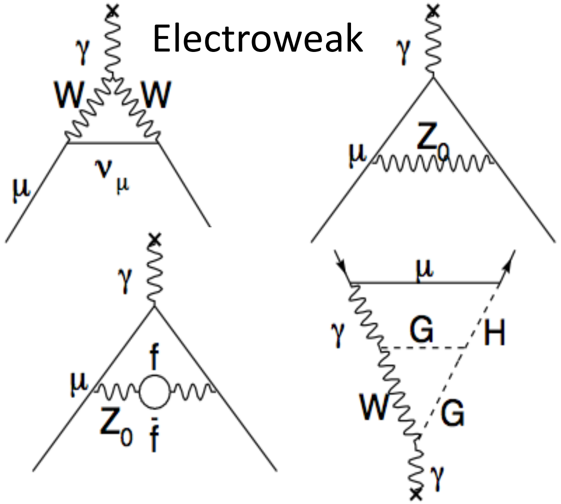
Kinoshita

12672
diagrams



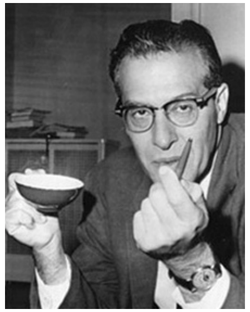
Up to 10th
Order QED

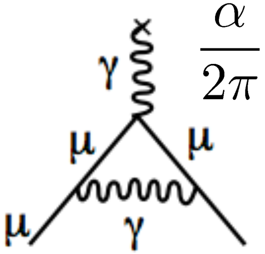
Electroweak



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

Schwinger

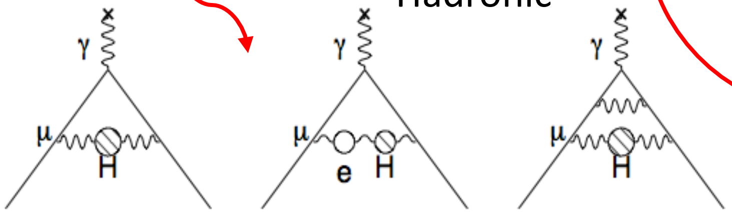


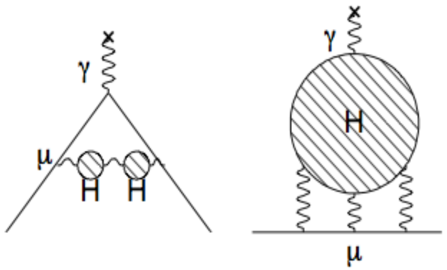


$$\frac{\alpha}{2\pi} = 0.00232$$

1st Order QED

Hadronic





Dominant
uncertainty in
calculation

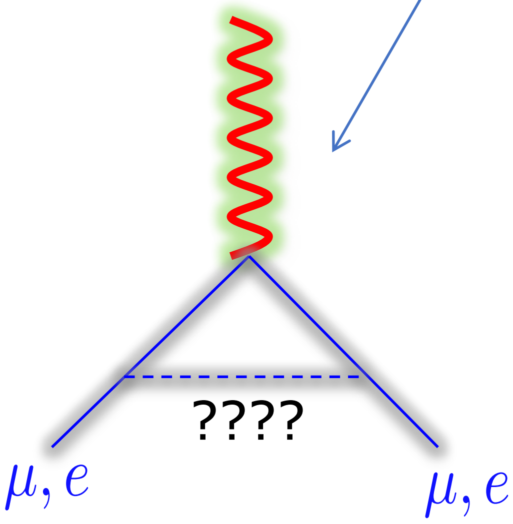
?

Motivation

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

Is this :

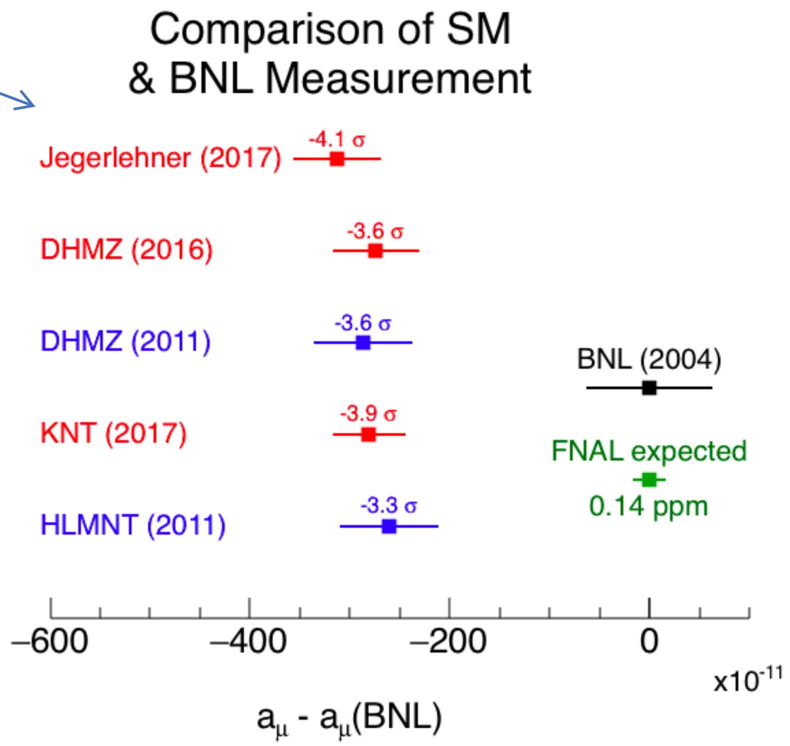
- A mistake in the theory
- A mistake / statistical fluctuation in the experiment
- A sign of new physics

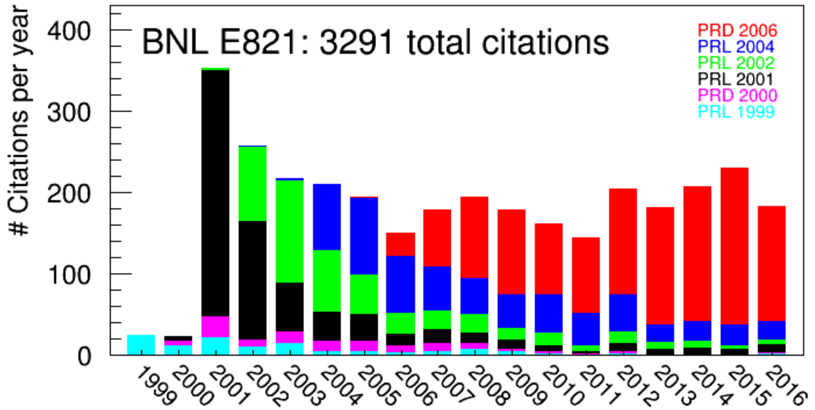


Contributes as $\left(\frac{m_\ell}{M_{\text{NEW}}}\right)^2$

The muon has a mass advantage

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





Muon g-2 is sensitive to new physics from MeV to TeV scales

Experimental Technique

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

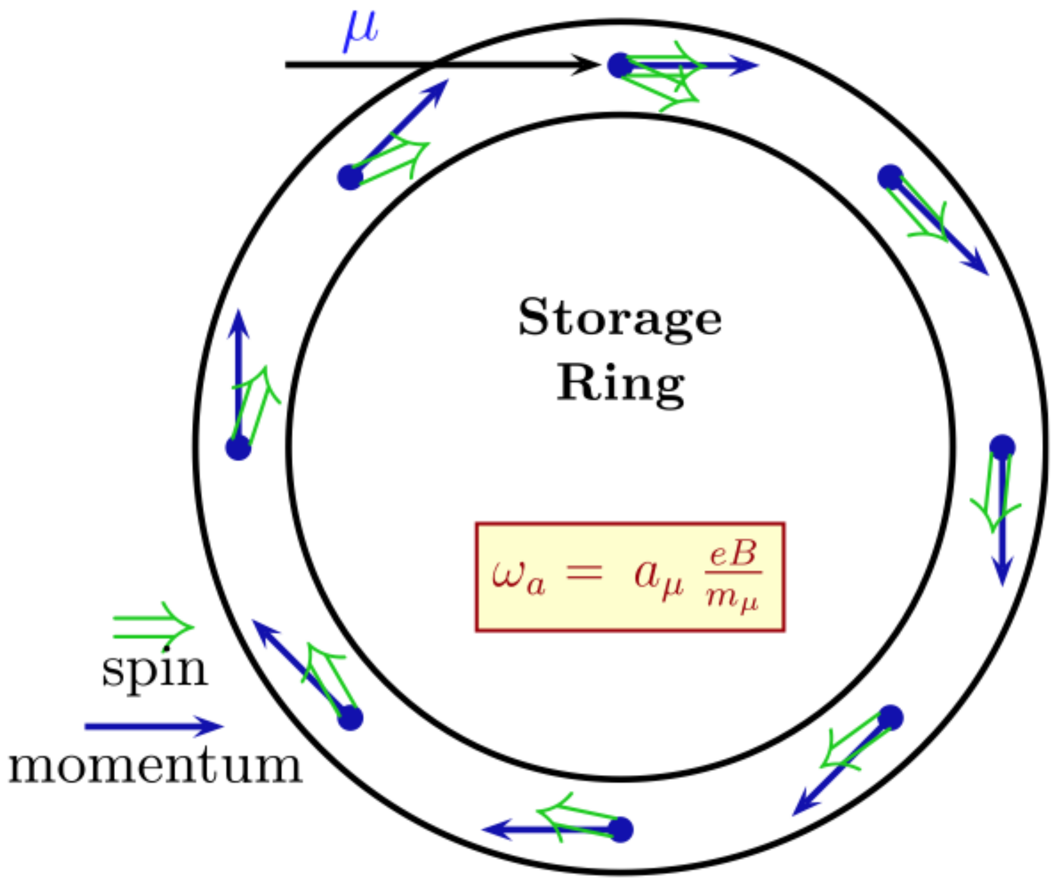
$$\omega_s = \frac{eB}{\gamma m} + \frac{eB}{m}\left(\frac{g-2}{2}\right) \qquad \omega_c = \frac{eB}{\gamma m}$$

$$\omega_a = \omega_s - \omega_c$$

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

Measure the magnetic field in the ring

Measure the spin precession from the positron decays



We actually measure 2 frequencies :

3ppb 22ppb 0.0003ppb

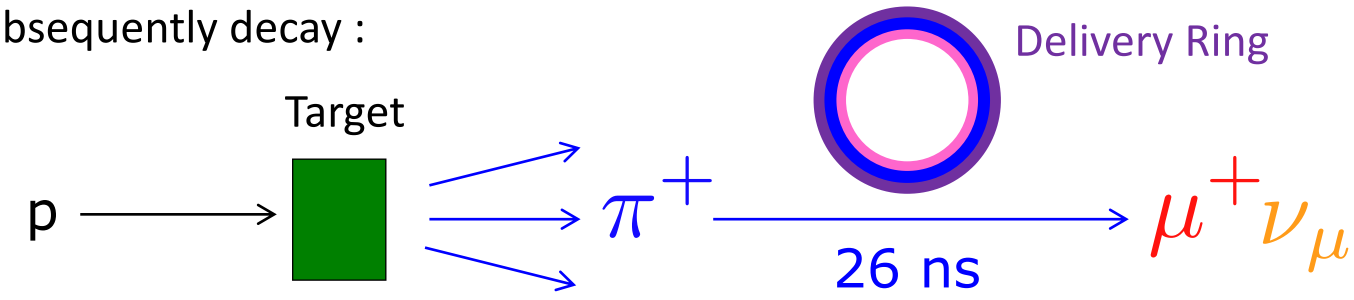
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

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

Muon Production

The Fermilab accelerator provides a purer muon beam giving more muons at a lower instantaneous rate

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



Target

p

π^+

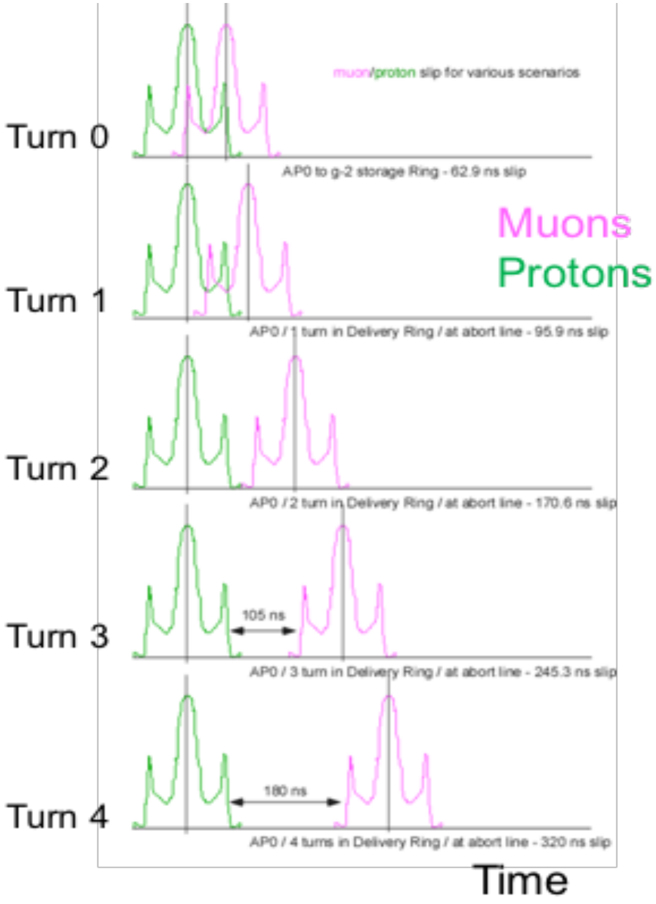
Delivery Ring

26 ns

$\mu^+\nu_\mu$

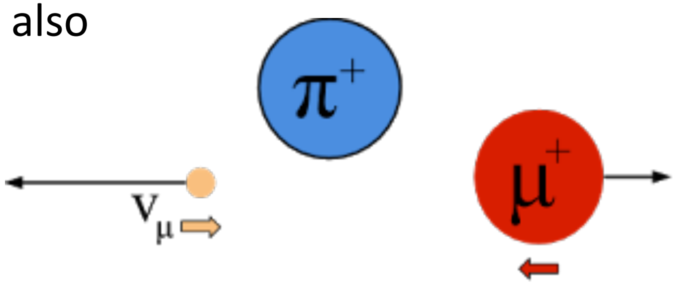
3.11 GeV pions selected using a lithium lens

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

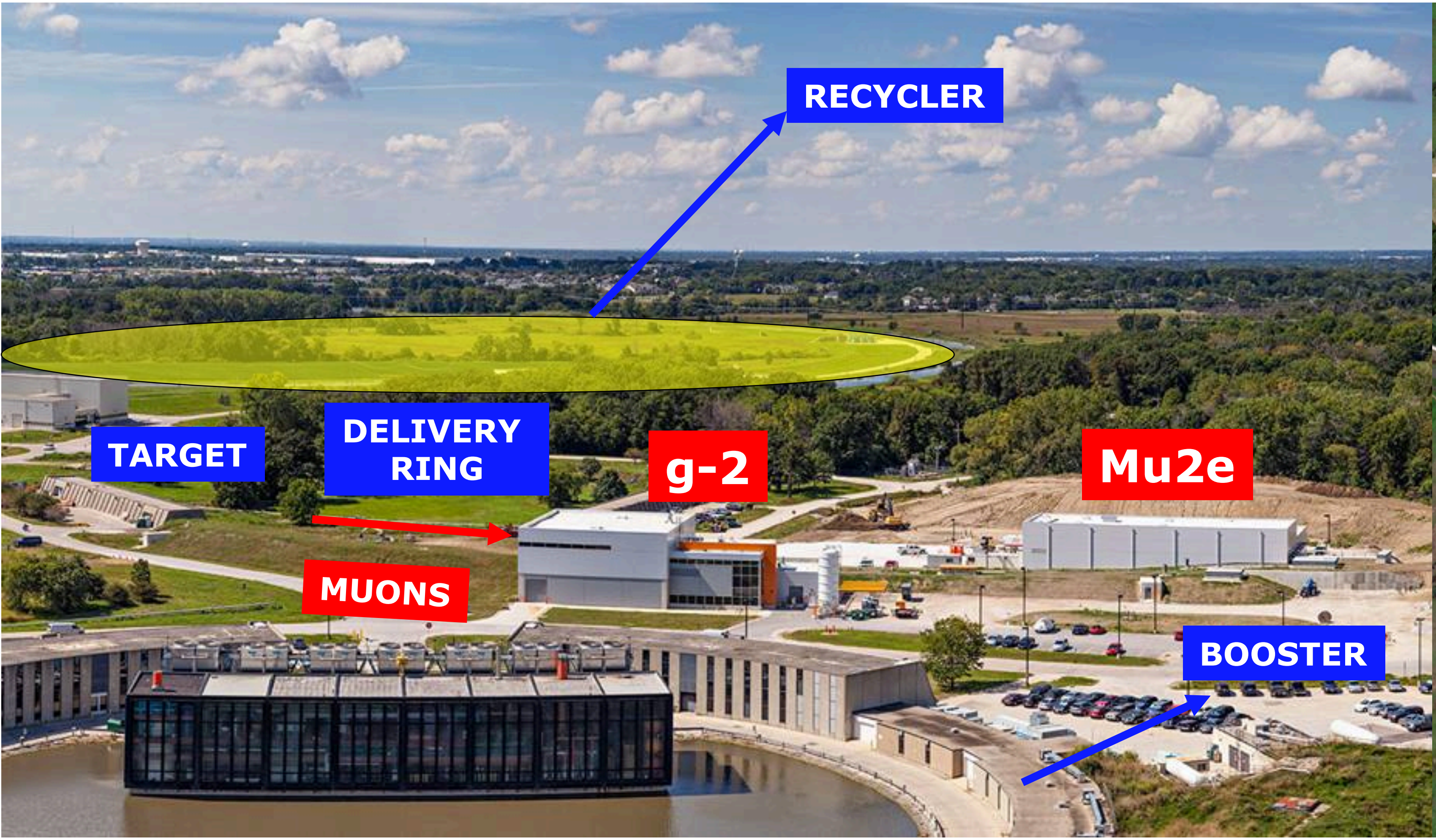


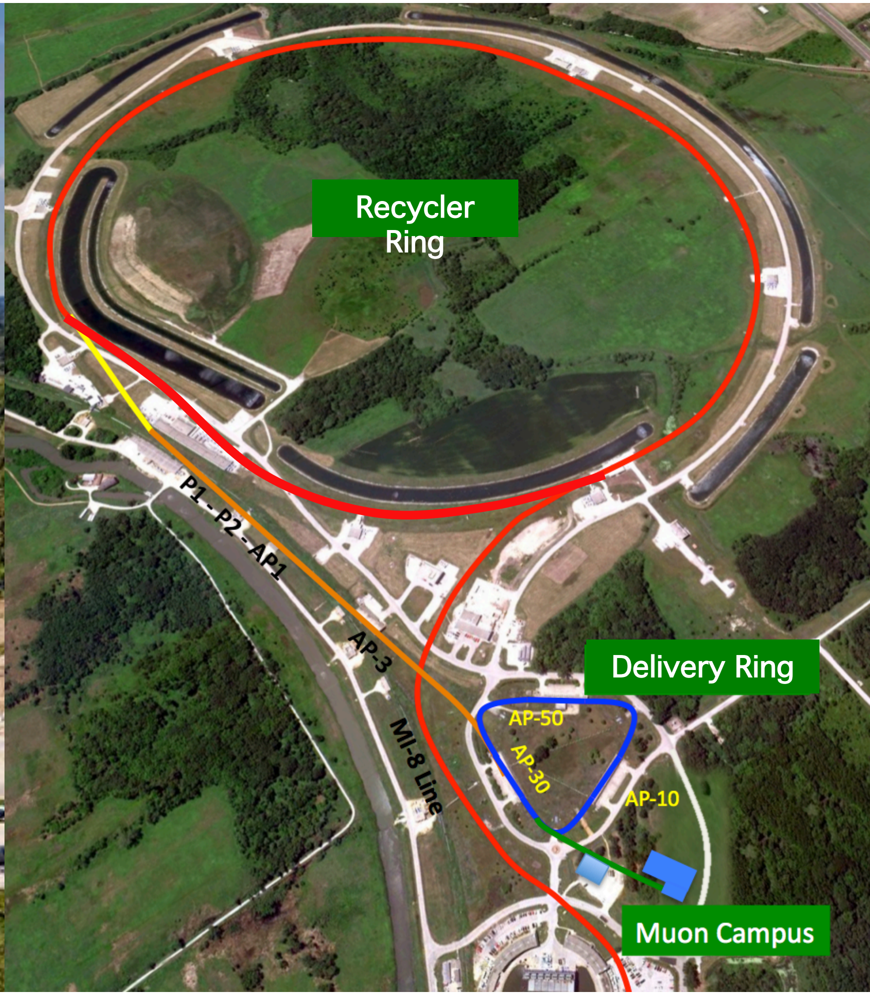
In the pion decay the neutrino must have spin opposite to the momentum

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



Accelerator Complex





Injection into the ring

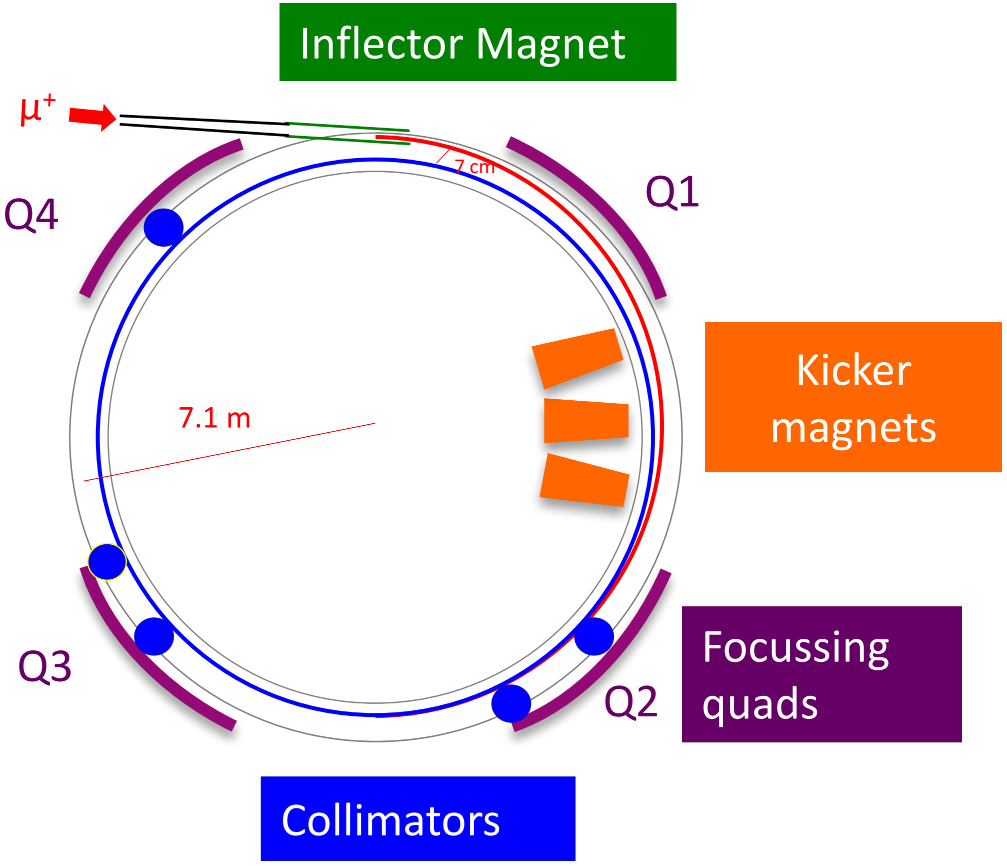
The Fermilab accelerator provides a purer muon beam giving more muons at a lower instantaneous rate

- Inflector provides a field free region for the muons to enter the ring
- The Kickers kick the beam onto the right orbit (~11mrad)
- The electrostatic quadrupole magnets provide vertical focusing

  But this field looks like a magnetic field to a moving particle :

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

This term is cancelled by running at the magic momentum, p = 3.094 GeV



Even so there are small effects :

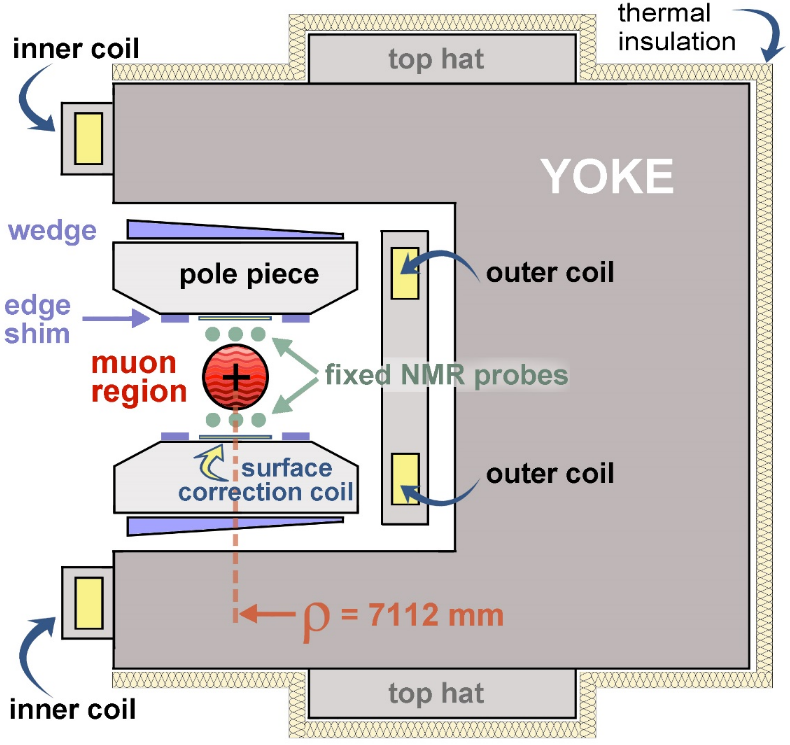
- **The muons aren't exactly at the magic momentum**
- **There is a small degree of vertical motion of the muons**

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

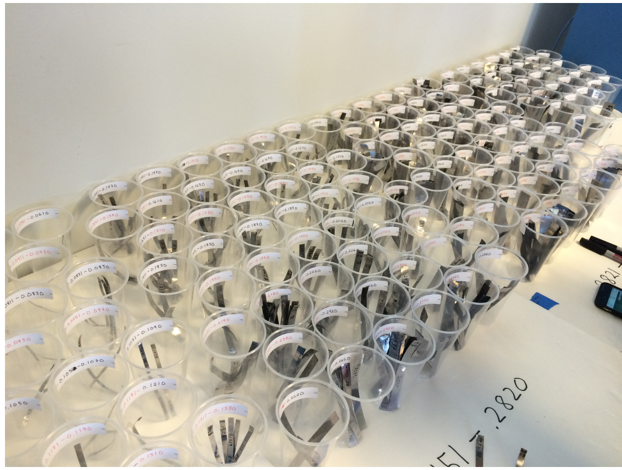
The magnetic field

There are many knobs on the magnet that can be tuned to achieve excellent field uniformity

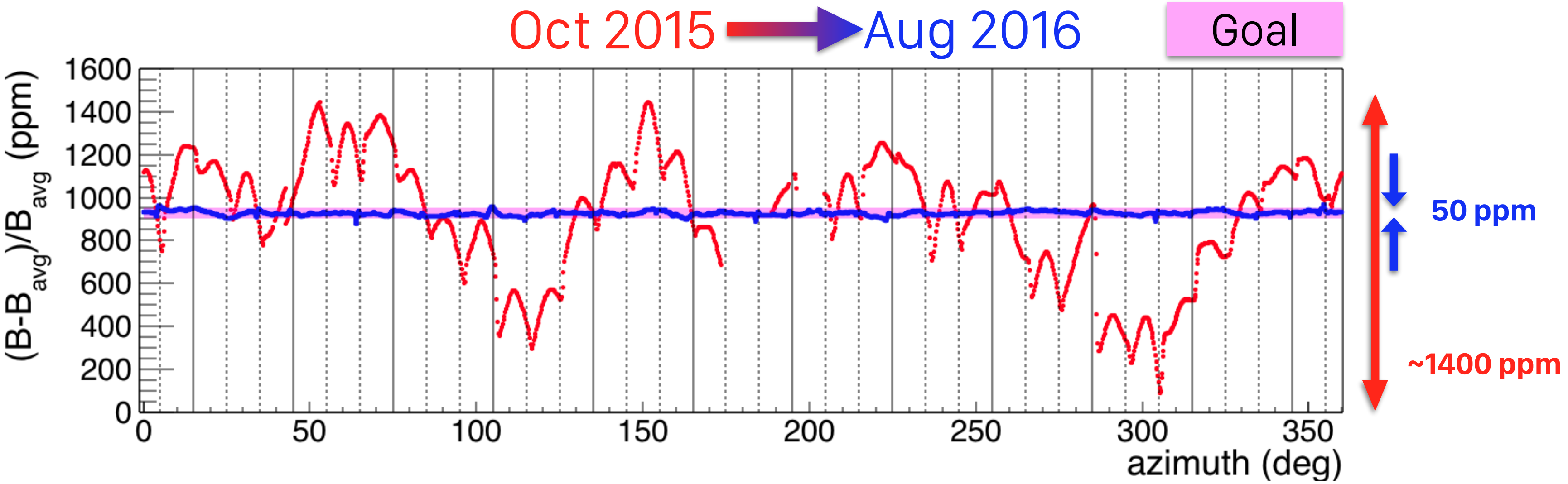
- 864 wedge shims, 48 top hats, 144 edge shims, 8424 laser cut iron foils
- 200 surface coils where the current can be adjusted



g-2 Magnet in Cross Section

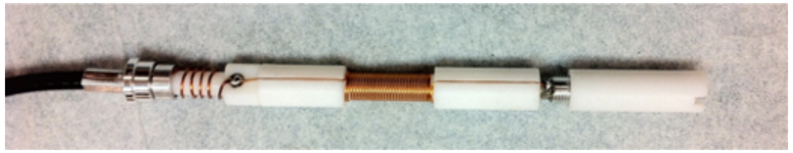


Rough Shimming Results

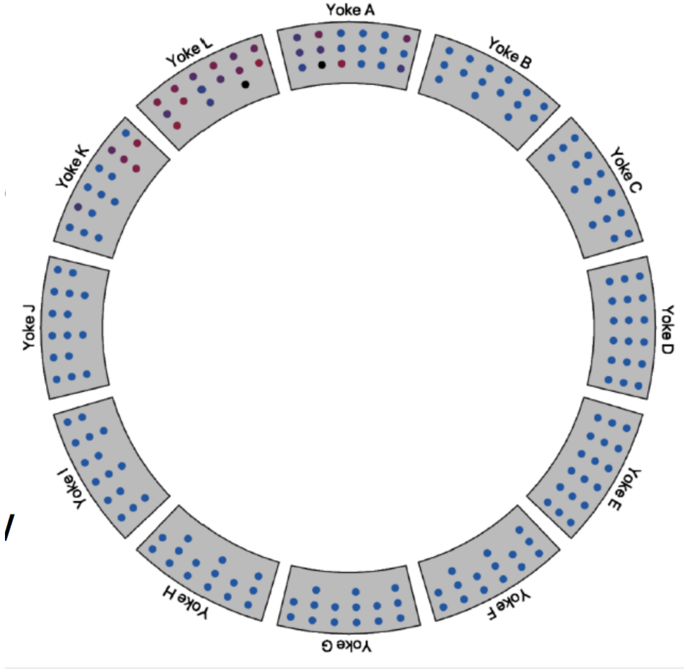


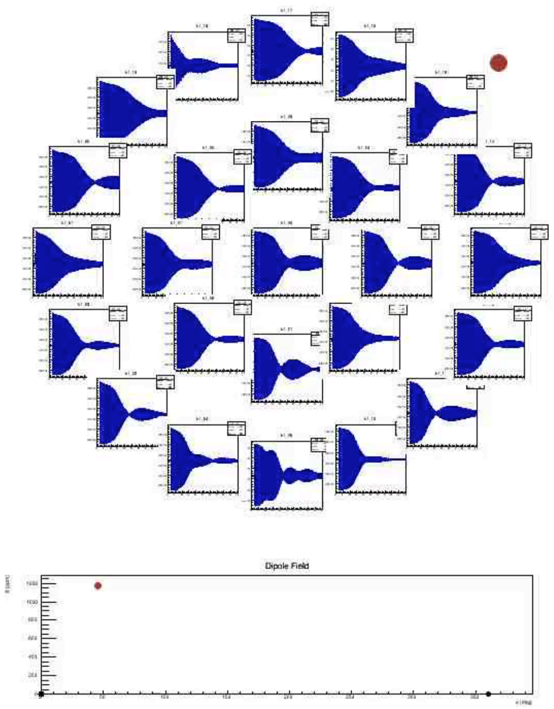
Measuring the Magnetic Field

The magnetic field is measured using pulsed NMR probes (375 fixed probes, 17 probes on a trolley, plunging probe)

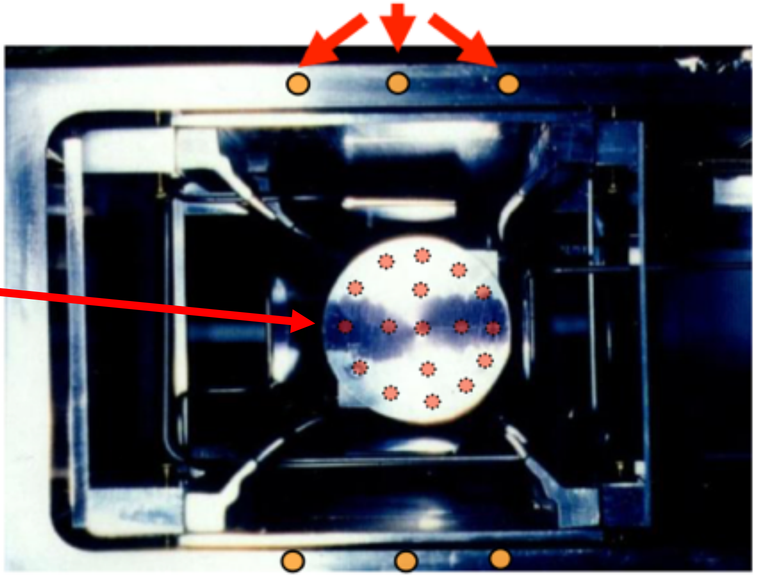


Fixed probes measure the magnetic field all the time outside the storage region

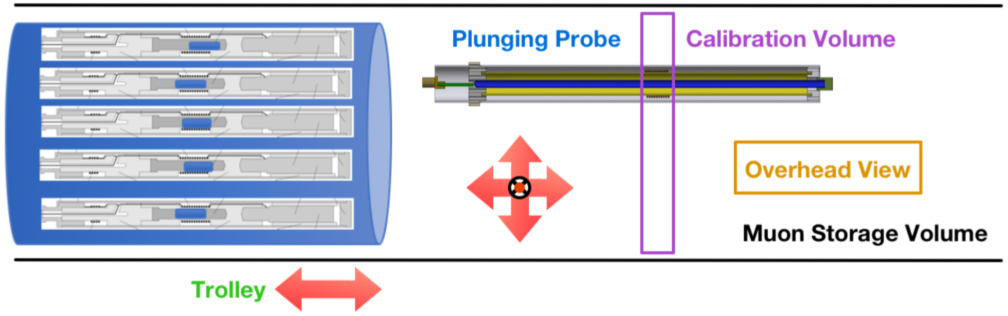




Trolley probes measure the magnetic field in the storage region during special trolley runs

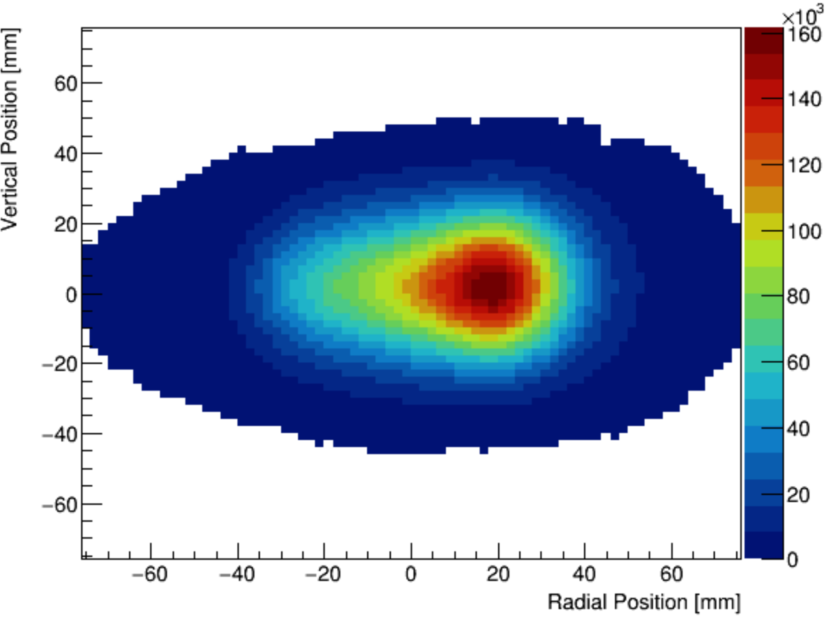


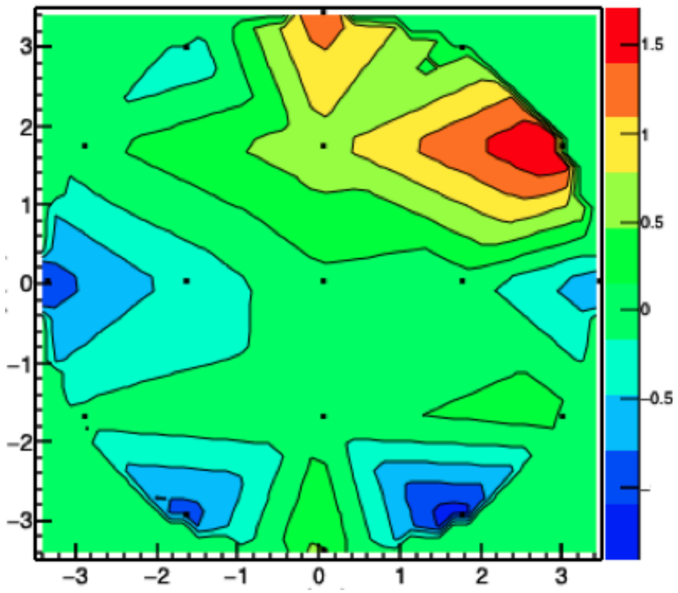
A plunging probe is used for calibration



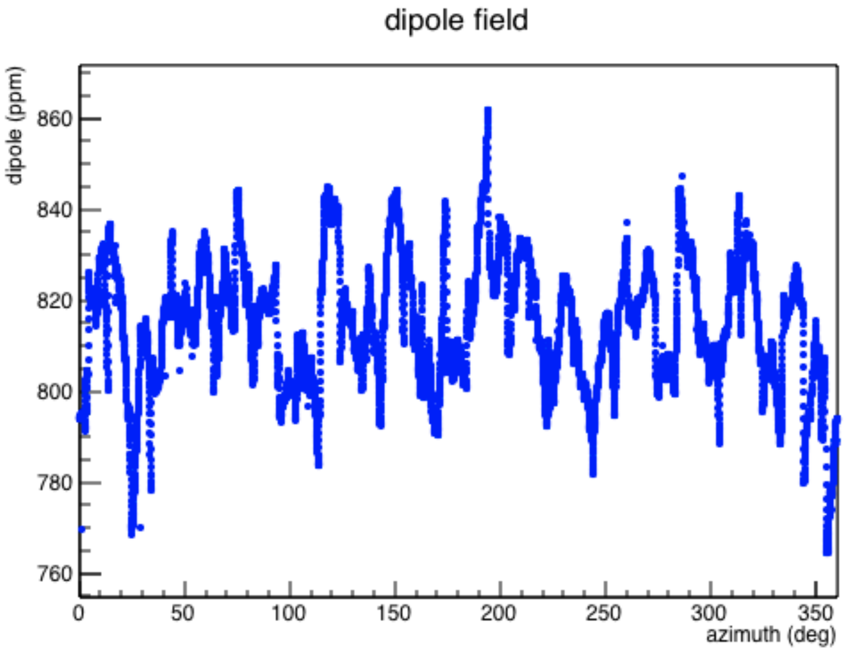
Magnetic field measurement

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





Need to know the field that the muon has experienced at the point of decay

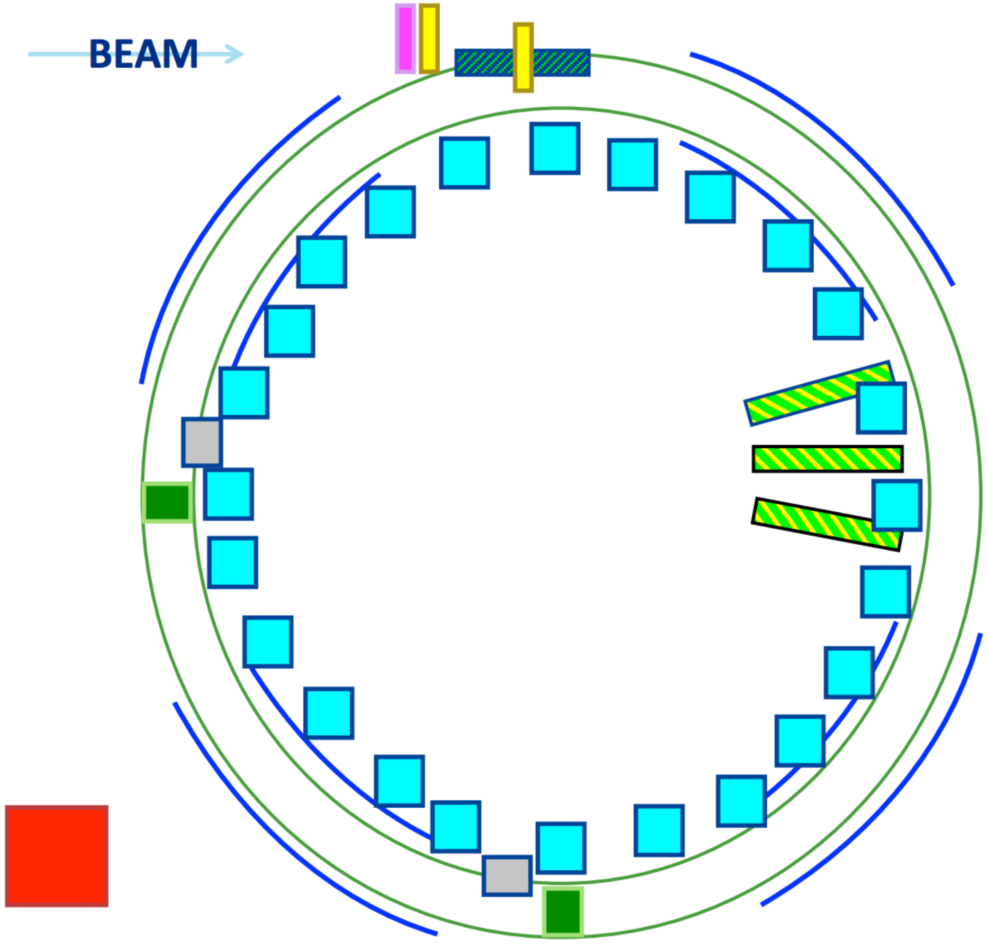


Over the past year of running trolley runs were conducted ~every 3 days at varying times of the day

The surface coils have been adjusted to minimise the multipole moments

G-2 detector systems

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



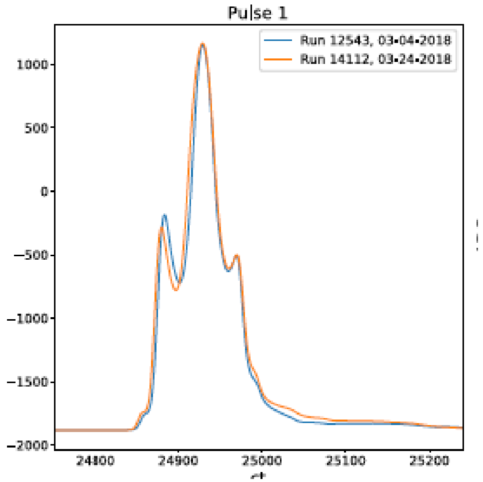
Detectors

- 🟪 T0
- 🟨 IBMS × 2
- 🟦 Calorimeter × 24
- 🟥 Laser Hut
- ⬜ Tracker × 2
- 🟩 Fiber Harp × 2

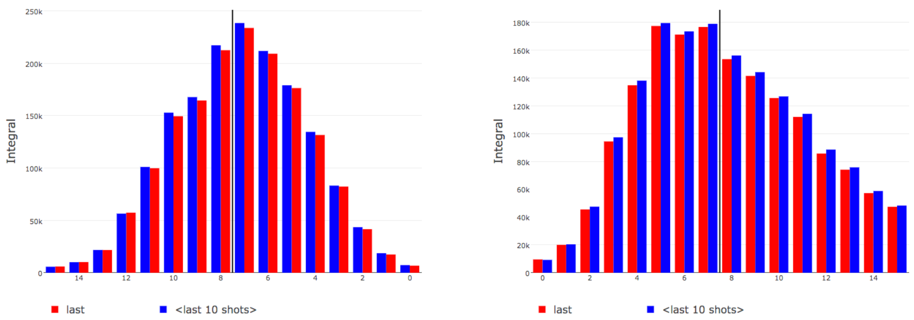
Ring instruments

- ▨ Kicker
- ▨ Inflector
- — Quadrupole

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

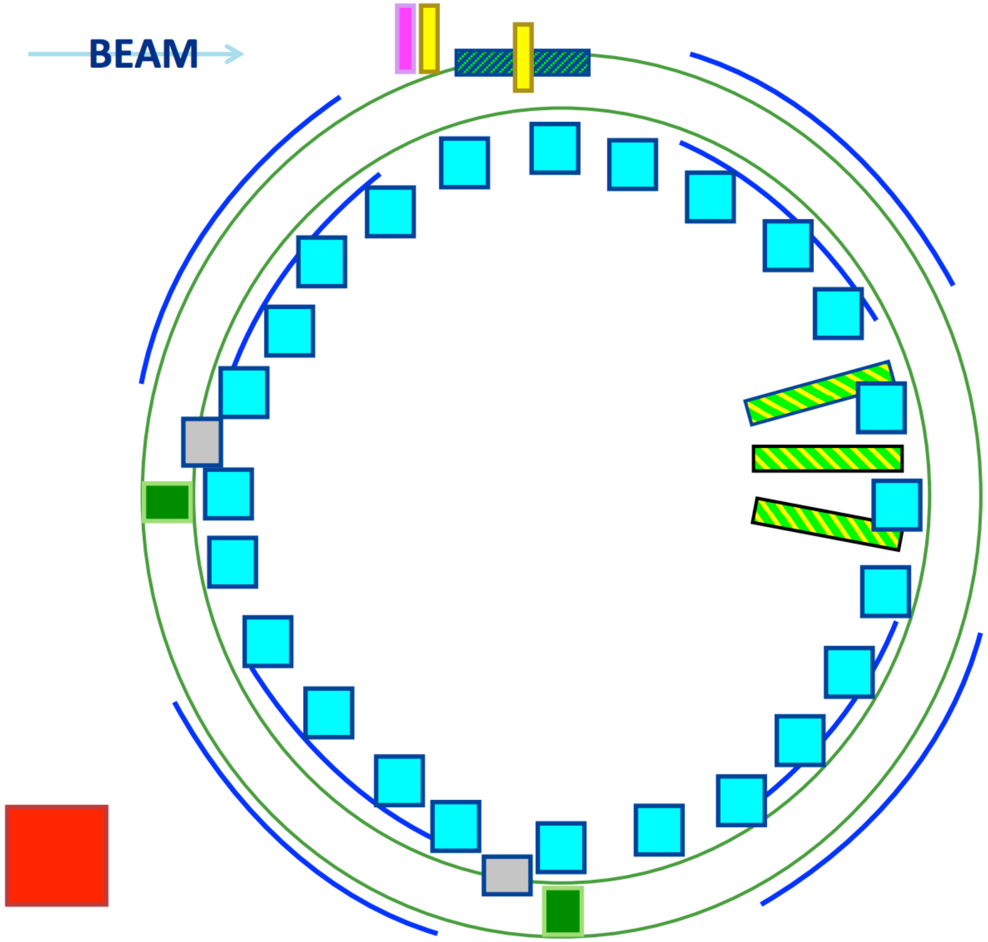


The IBMS measures the horizontal and vertical distributions on entry :



G-2 detector systems

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



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- 🟪 T0
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Ring instruments

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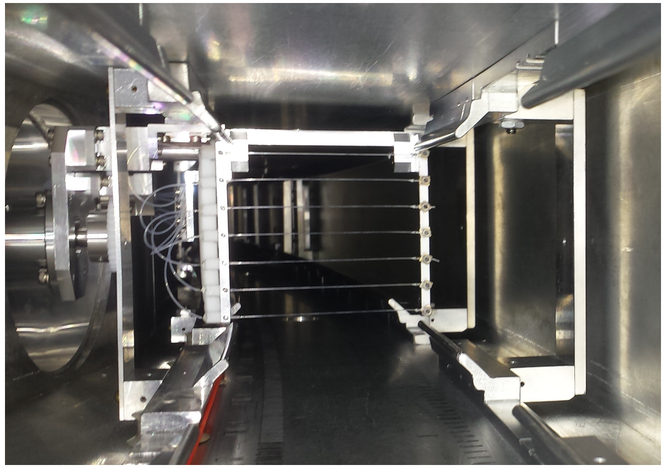
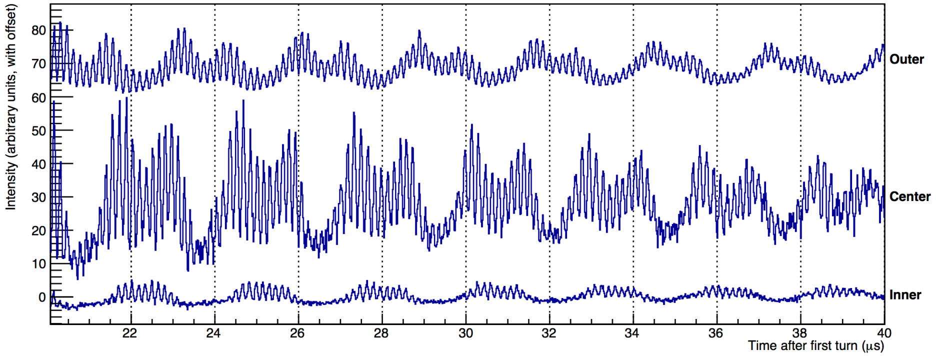
- — Quadrupole

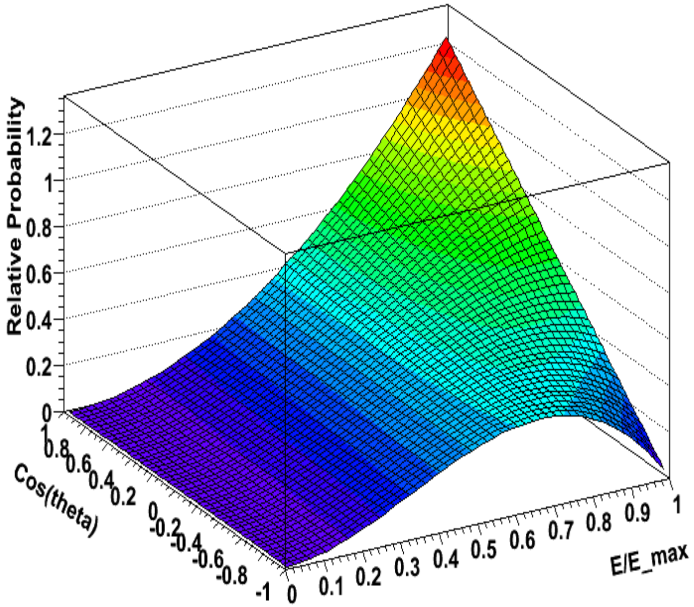
The fibre harps slide in to the beam to make a destructive measurement of the beam profile



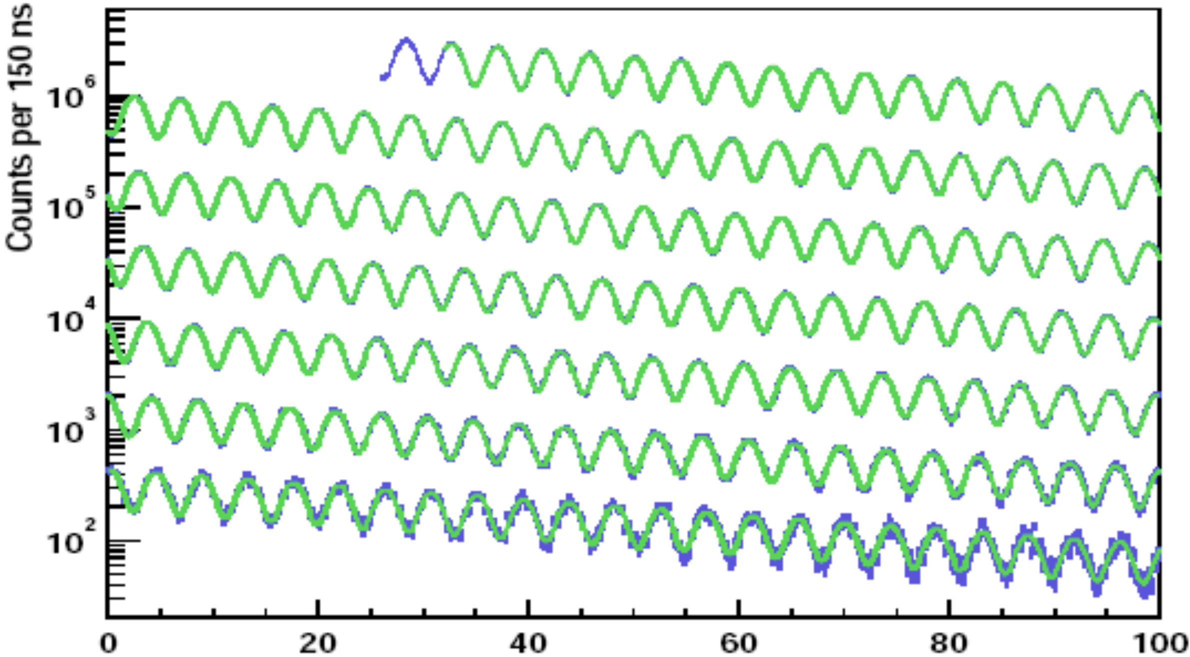


Measuring the precession frequency

The highest energy positrons from the muon decay are preferentially released along the direction of the muon spin



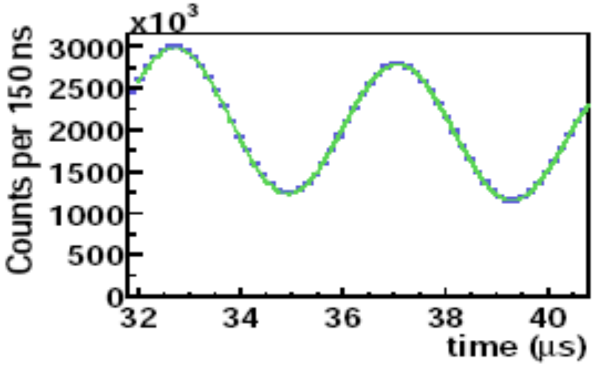
Count the number of positrons hitting the calorimeter above 1.8 GeV as a function of time

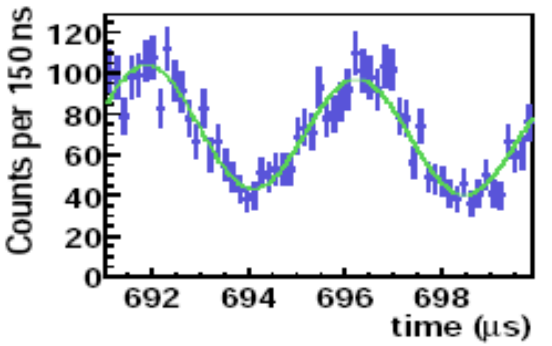


- Number oscillation due to spin precession
- Exponential decay as the number of stored muons decreases

The precession frequency is extracted from a fit to the data:

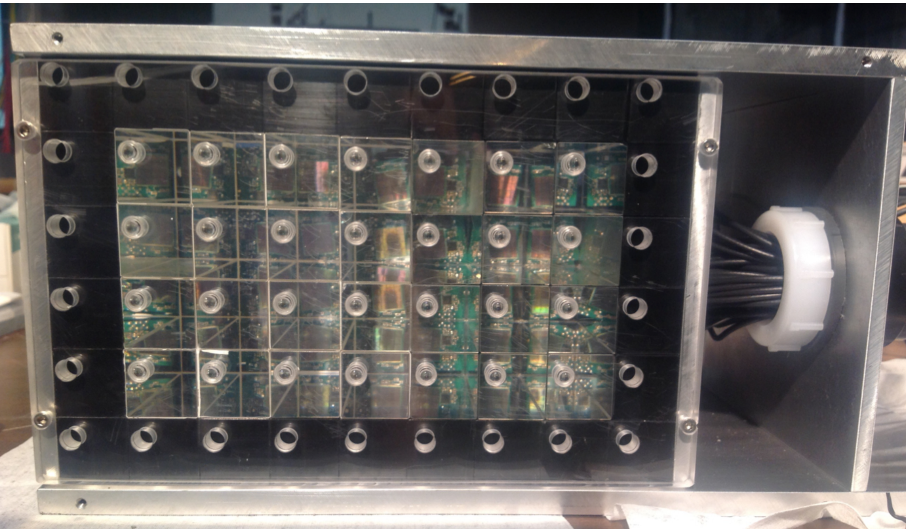
$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}} [1 - A\cos(\omega_a t + \phi_a)]$$





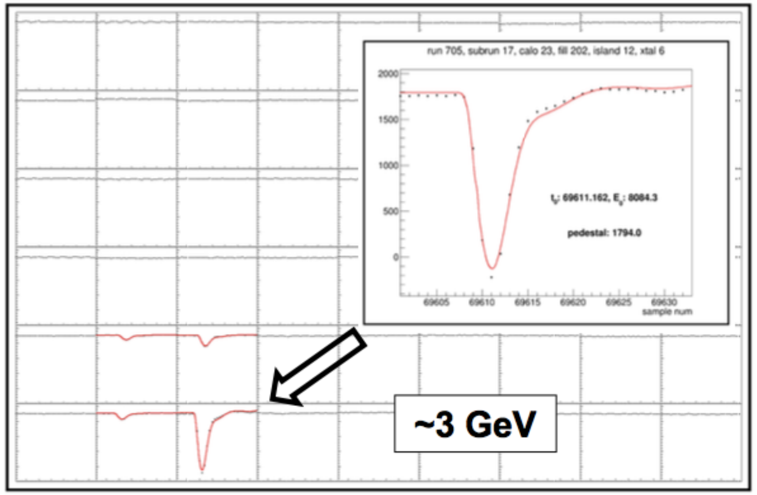
Calorimeters

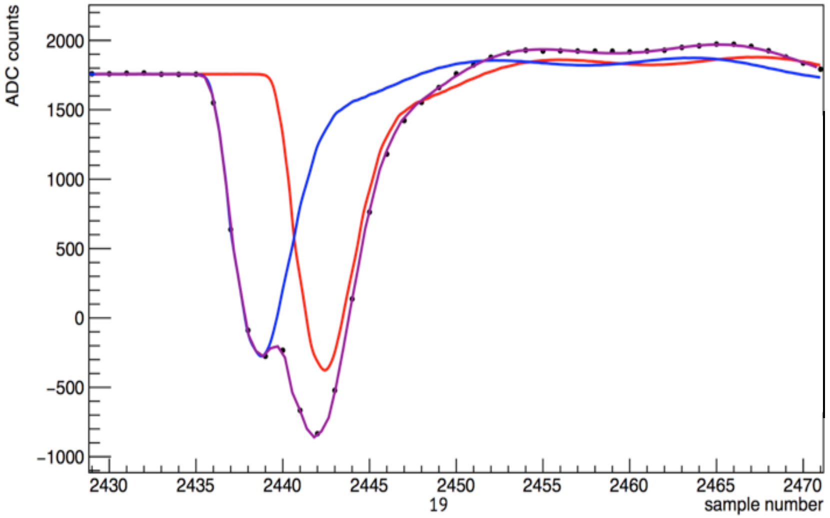
There are 24 calorimeters around the centre of the ring to measure the positrons from the muon decays

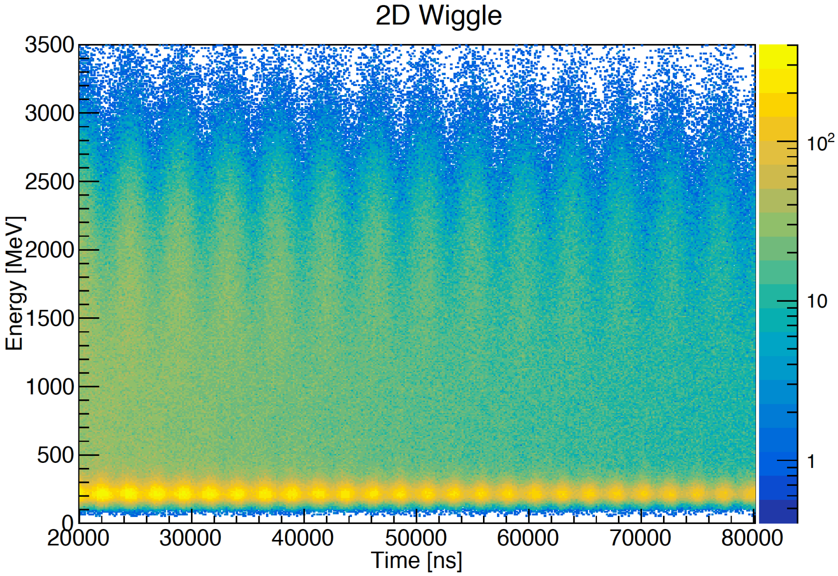


- 6 x 9 lead fluoride crystals

- Requirements :
    - Resolve pulses separated by more than 5ns
    - Better than 5% energy resolution
    - Time accurate to 100ps
    - Stable gain during a fill



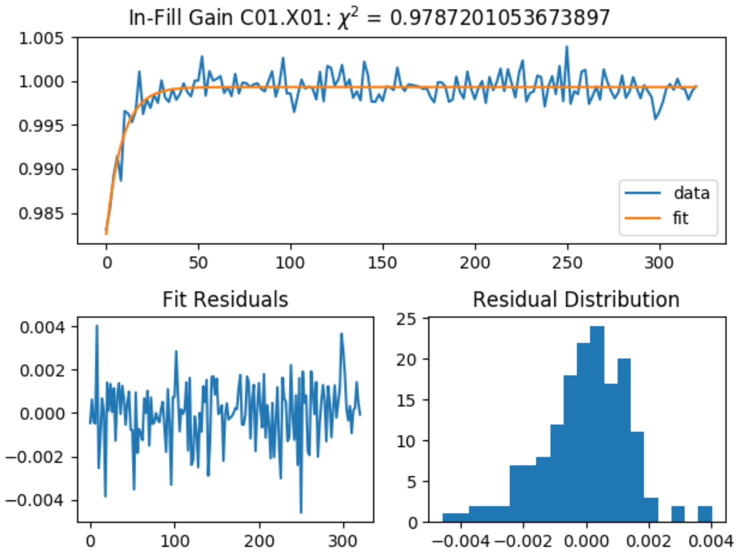




The calorimeters performed well during the run meeting all requirements

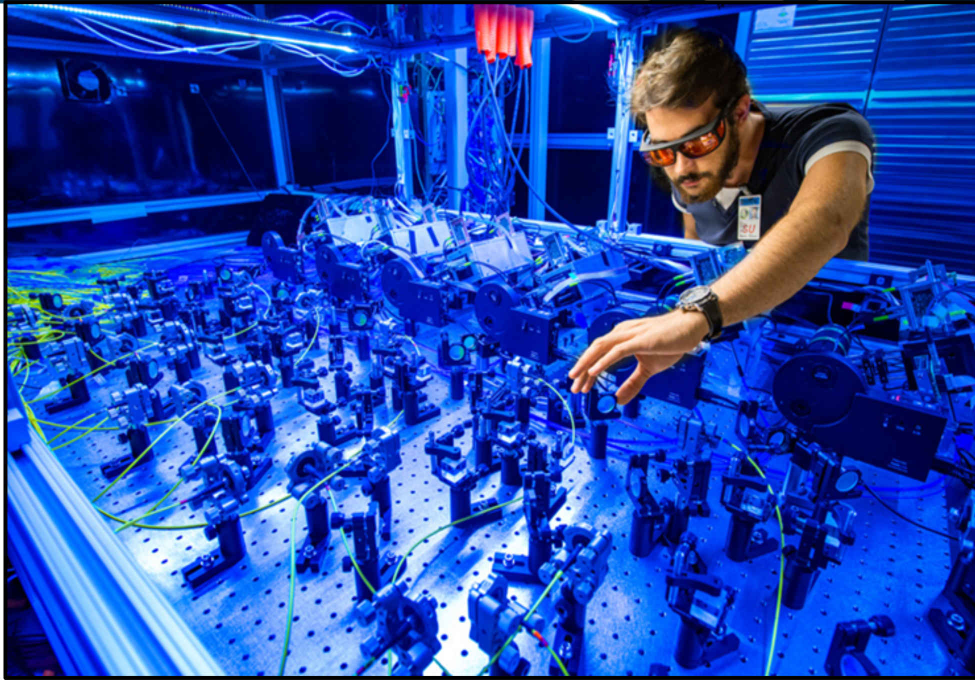
Laser calibration system

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



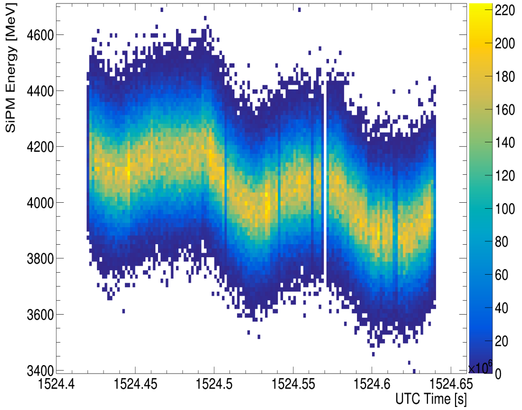
Sends laser pulses to every calorimeter both in and out of fill

Allows for both long and short term gain corrections



Performed well achieving gain stability of 0.04%

Raw SiPM energy



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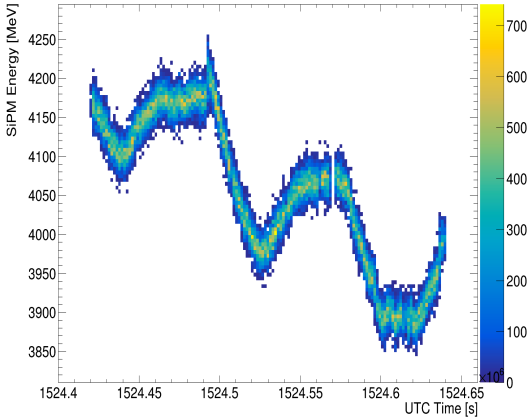
Out of fill correction



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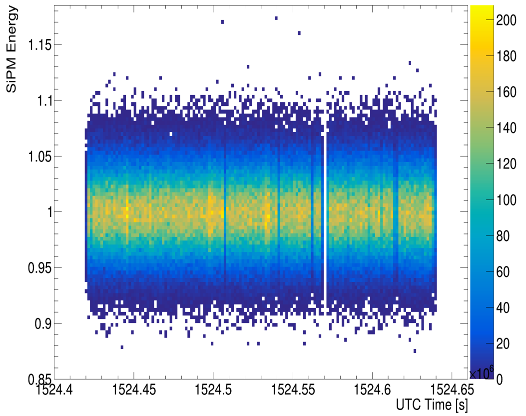
Corrected energy

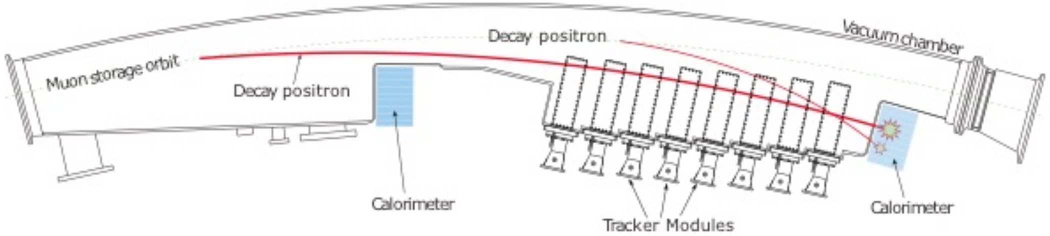


Tracking detectors

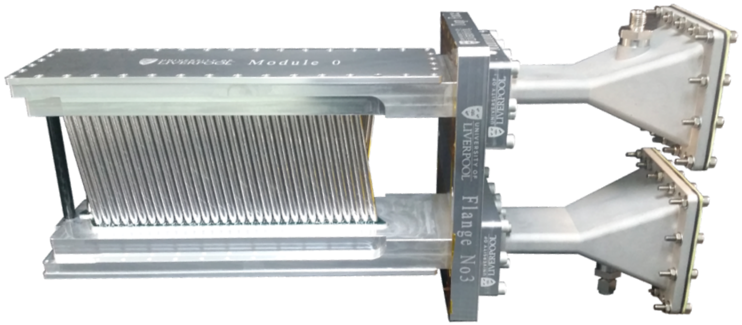
Tracking detectors are located at two locations around the ring allowing reconstruction and traceback of positron tracks

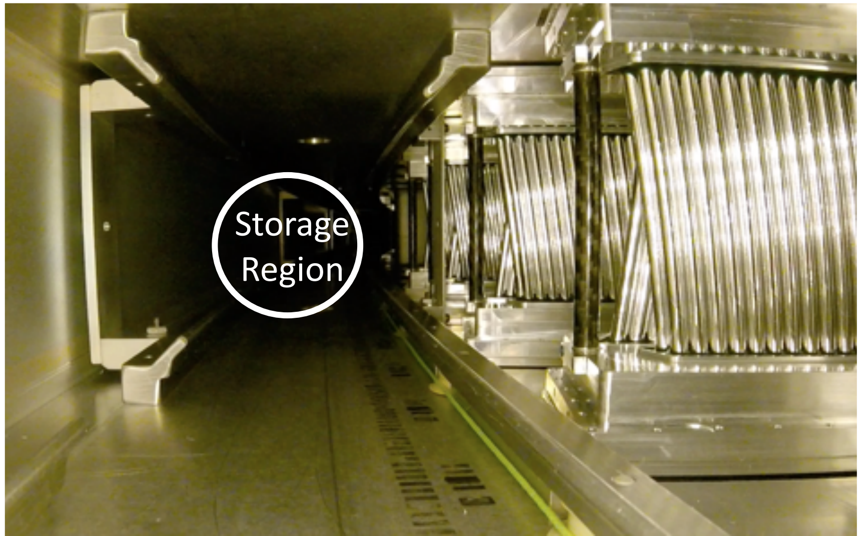
Aims :

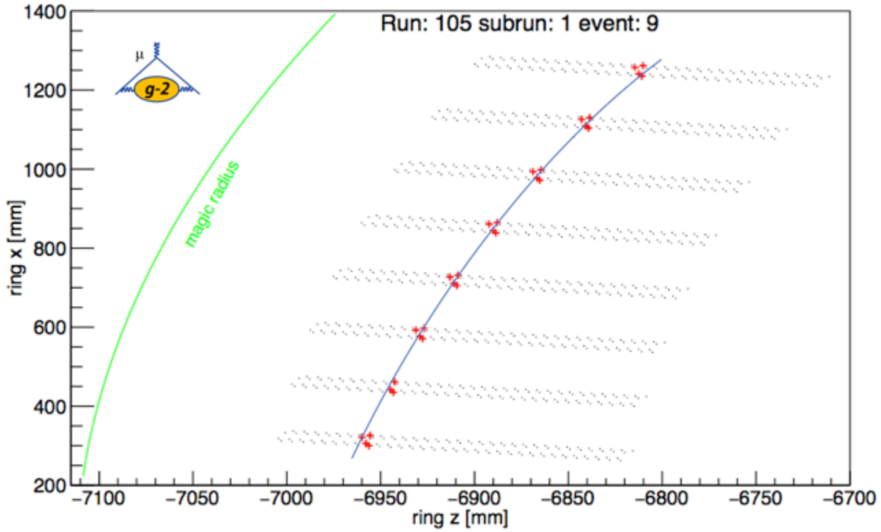
- Measure the beam profile in multiple locations around the ring as a function of time
- Calibration and acceptance of the calorimeters
    - Pile up, gain, lost muons
- Measure or set a limit on a muon EDM



One of the first reconstructed tracks :



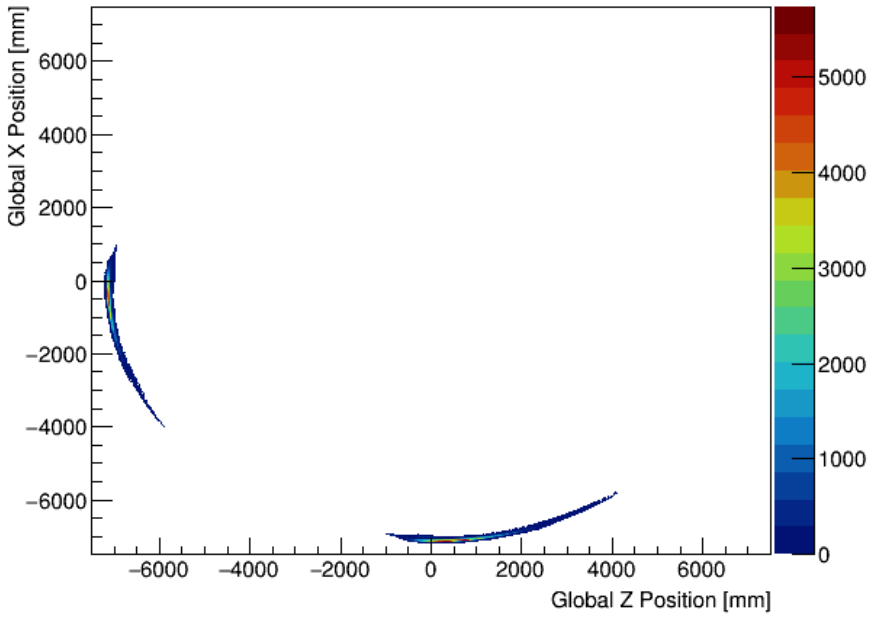




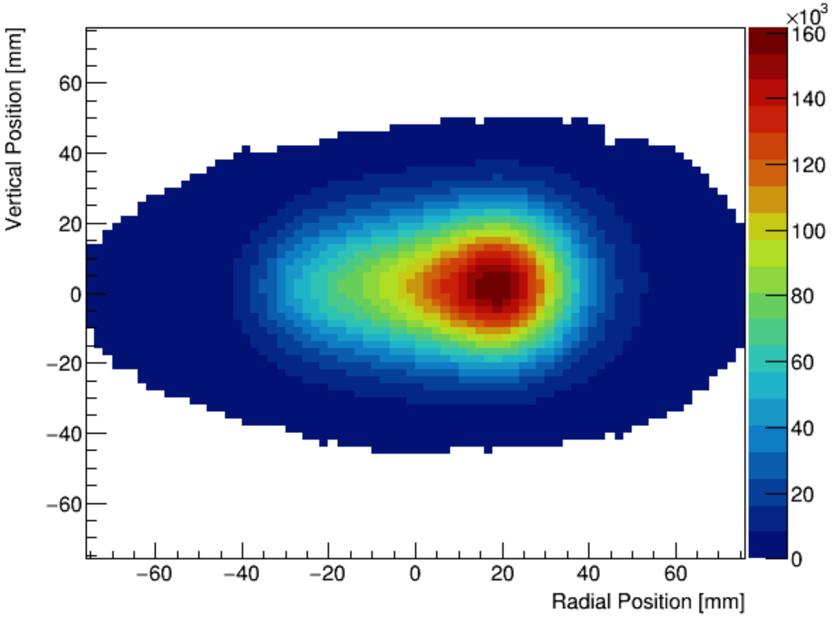
Tracker performance

The trackers performed very well providing a good insight into the beam movements

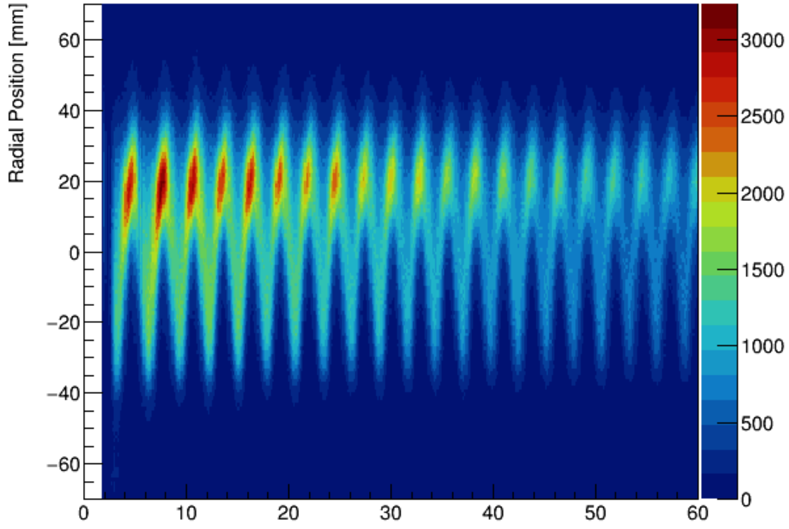
Decay Vertices

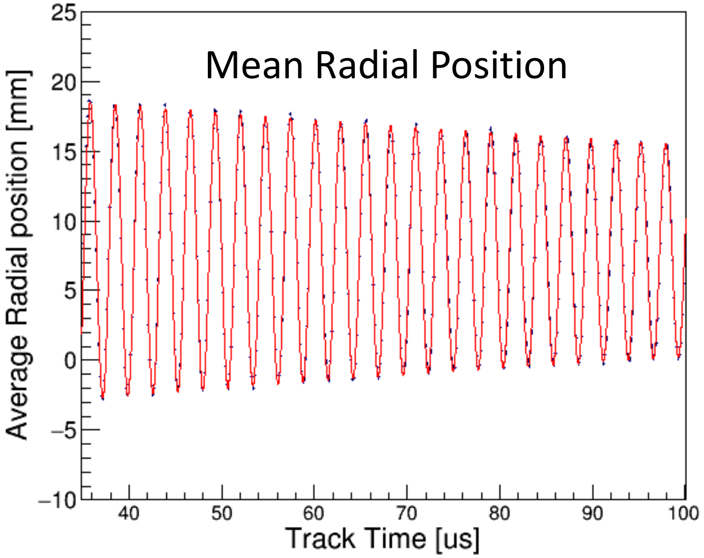


Reconstructed beam distribution



Radial position vs. time



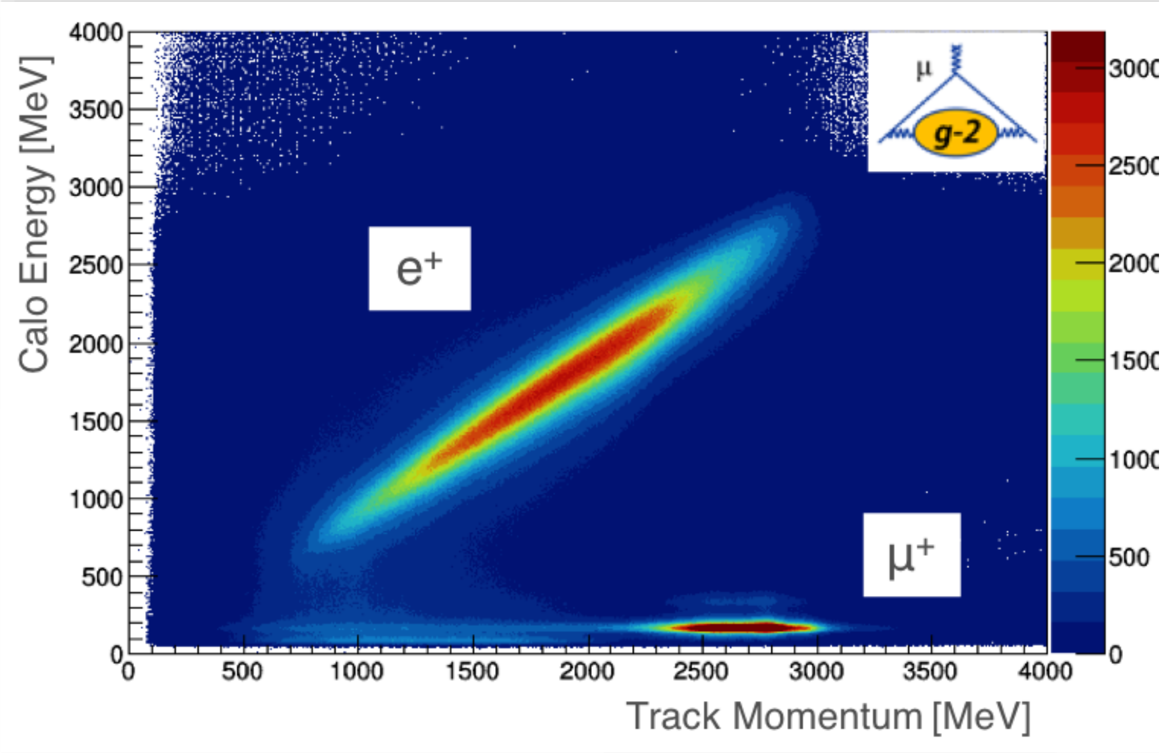


Mean Radial Position

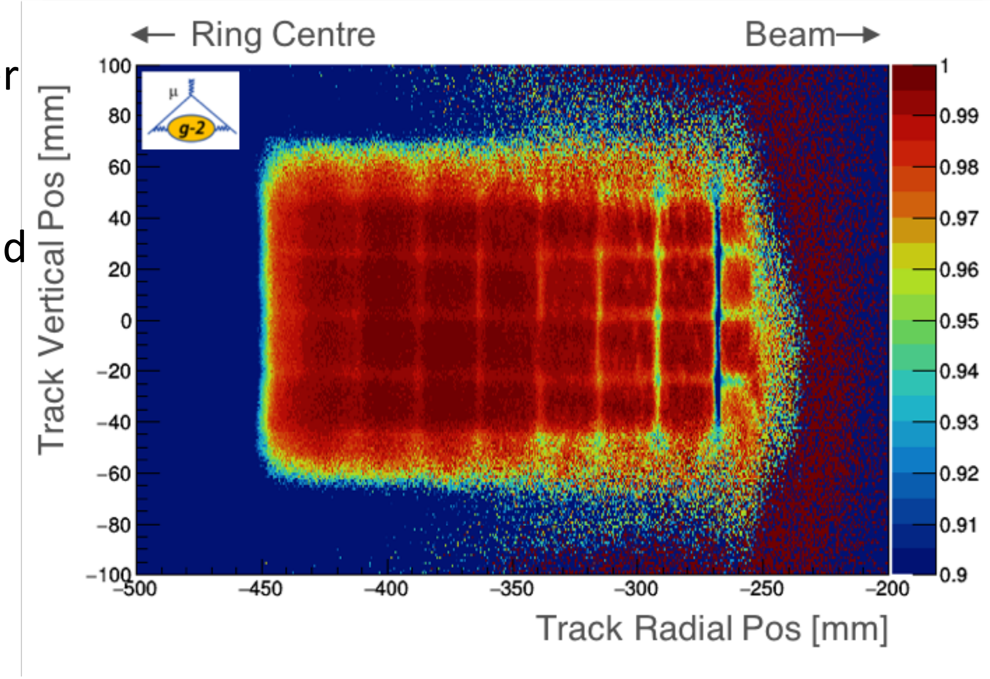
Tracker performance

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

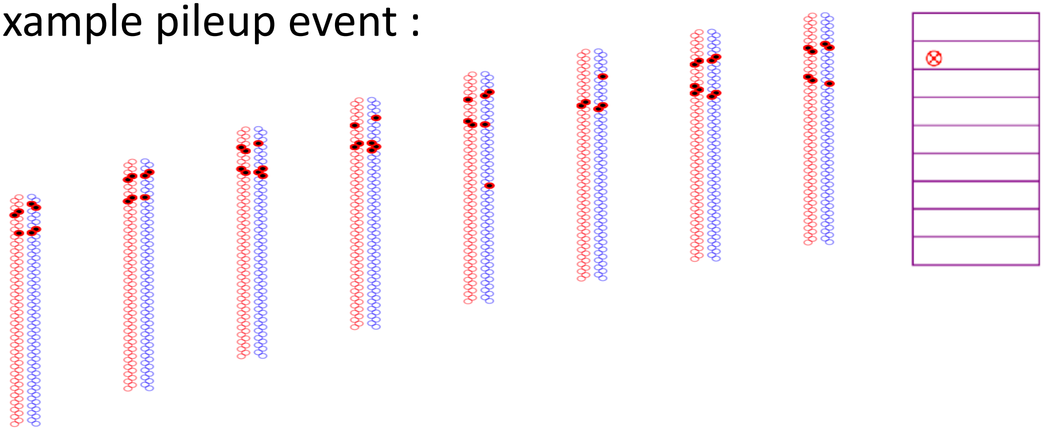
Calorimeter energy vs. track momentum



Calorimeter efficiency (based on extrapolated tracks)



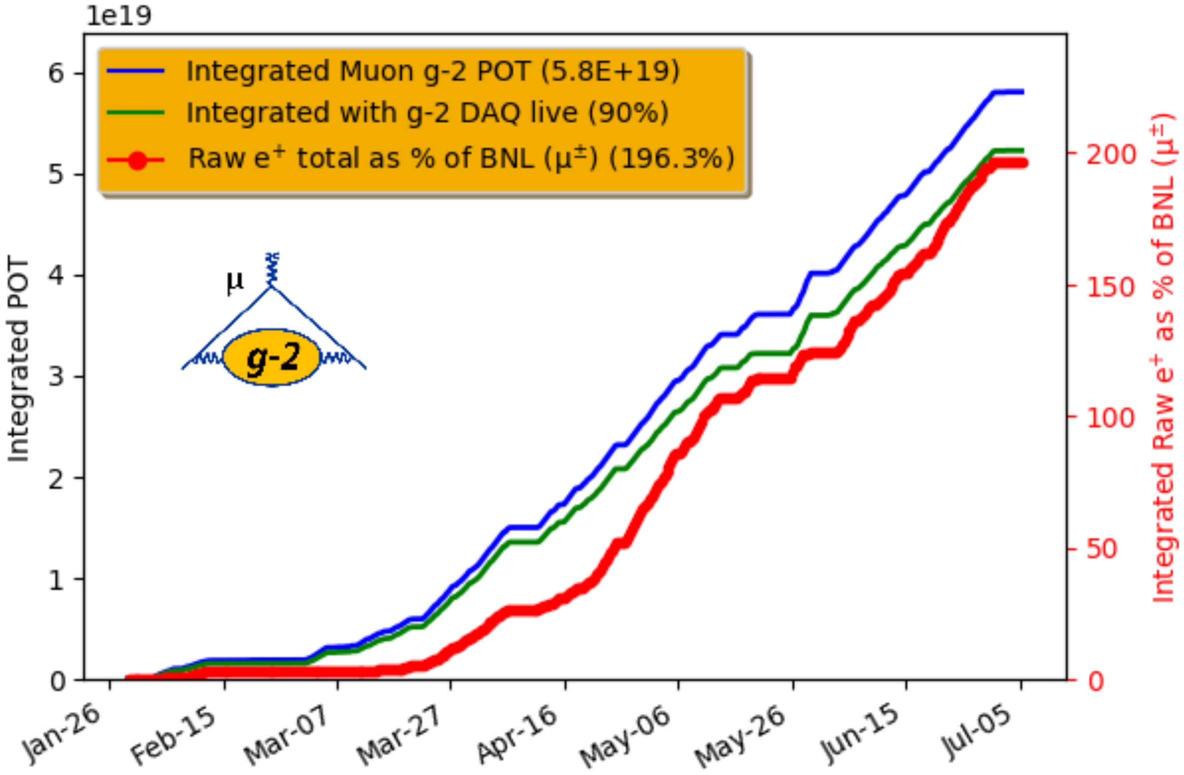
Example pileup event :

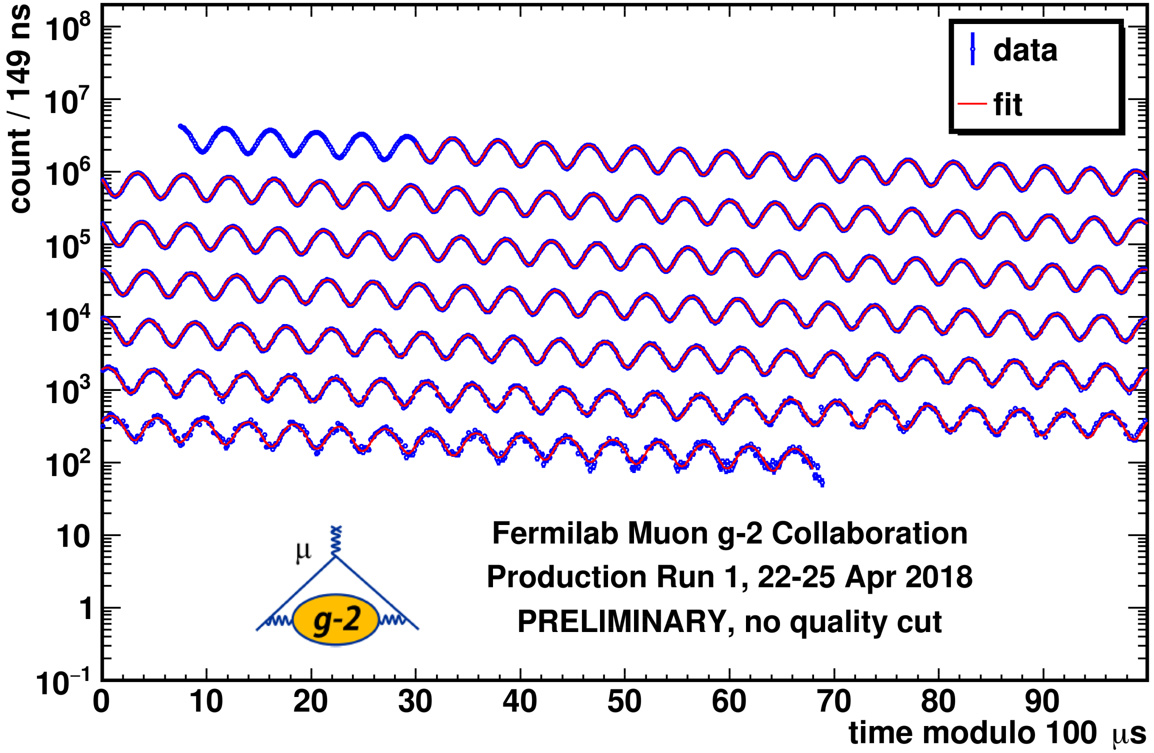


Where we are now

The first year of data taking finished in July collecting nearly 2 x BNL statistics

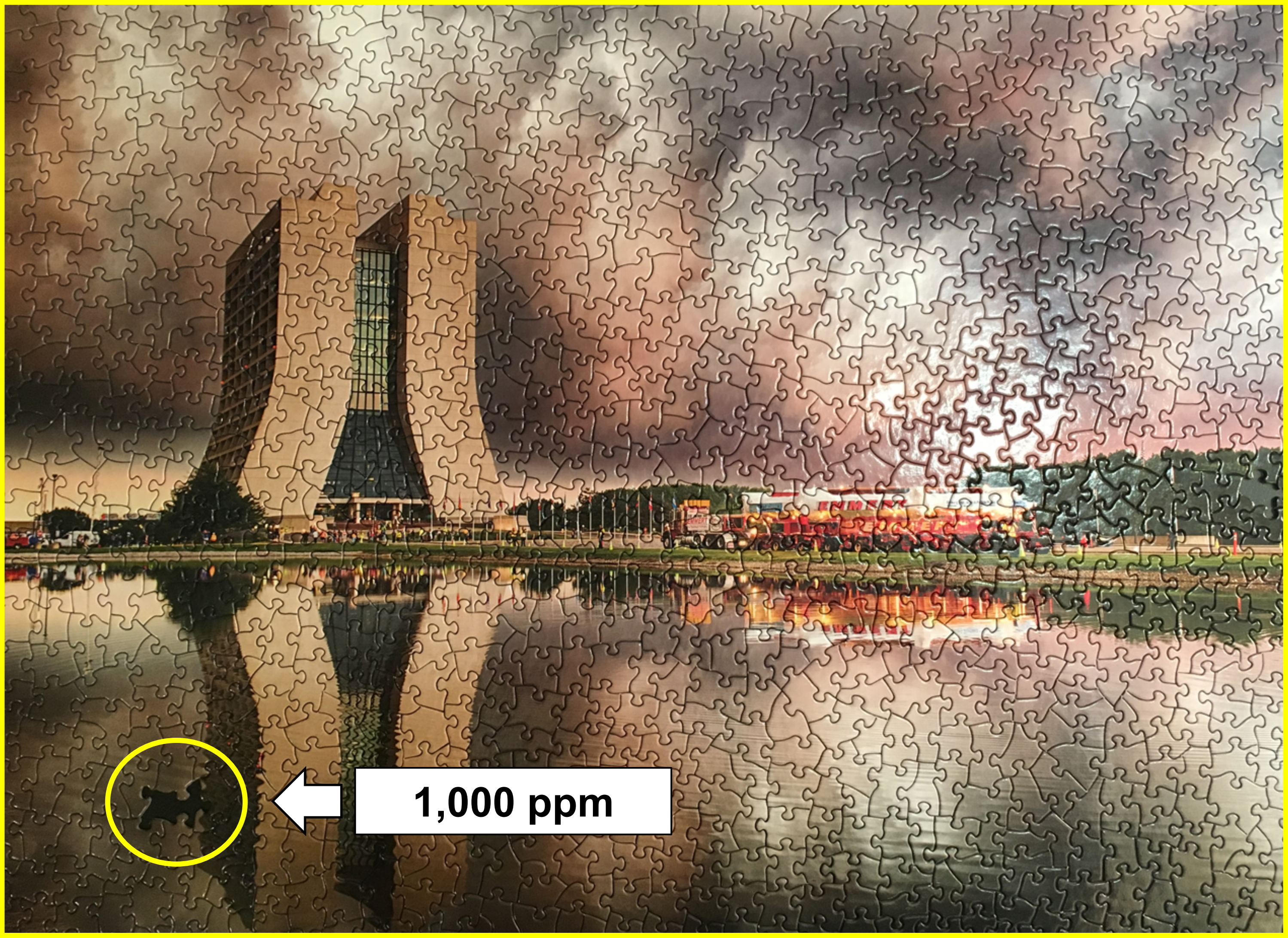
- First physics run complete, the analysis is underway expecting a physics result in spring next year
- Next run starts in October and will run through to July
- Currently systems are being upgraded to increase reliability, uptime and muon storage





What we are aiming for

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



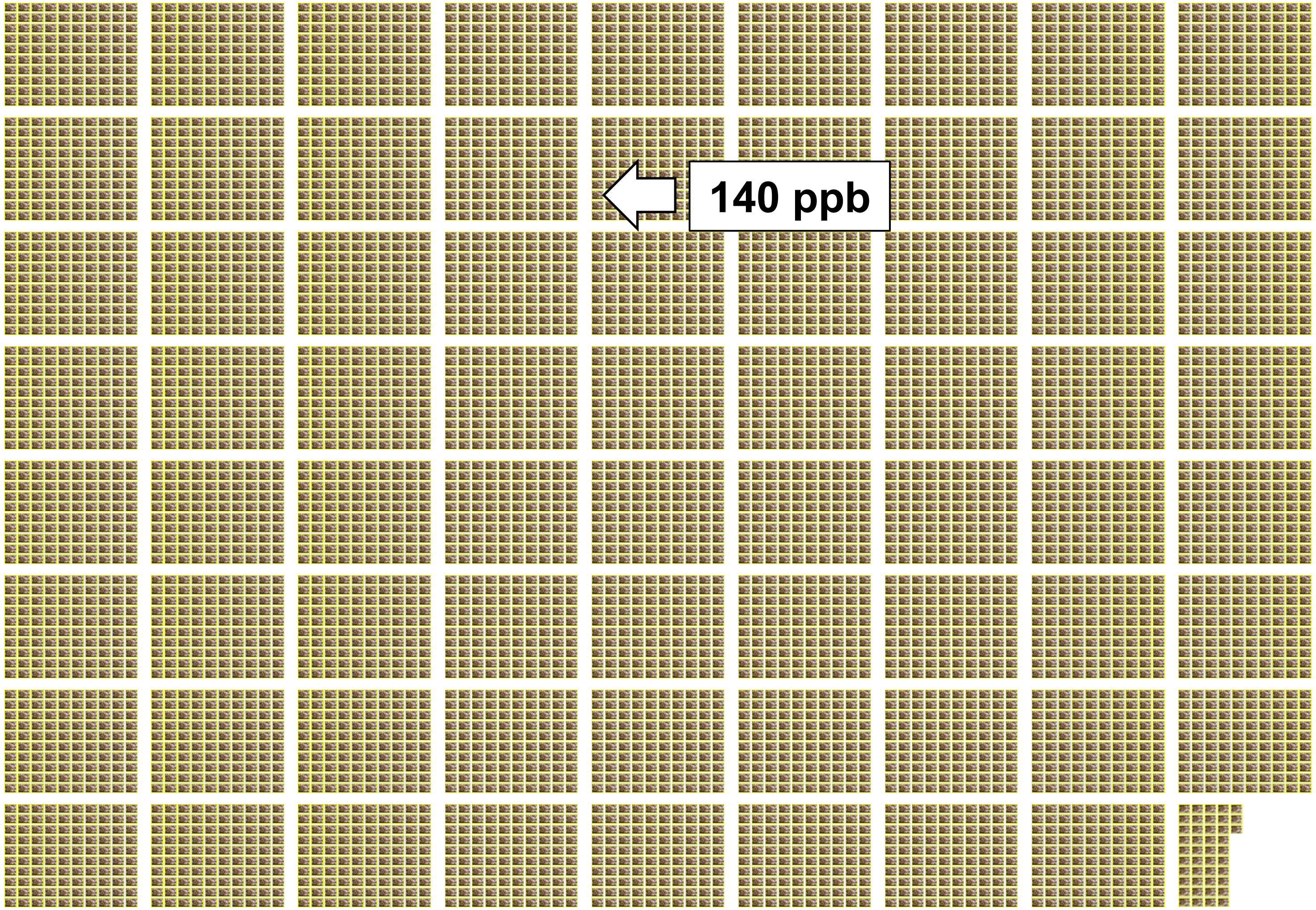
1,000 ppm

What we are aiming for

Consider 100 jigsaw puzzles with only one missing piece

Similar precision to the
CERN III experiment (1976)

What we are aiming for



7143 jigsaw puzzles with one missing piece

Lose one piece

→ 140ppb (Fermilab aim)

Every detail counts!

Aside : 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:

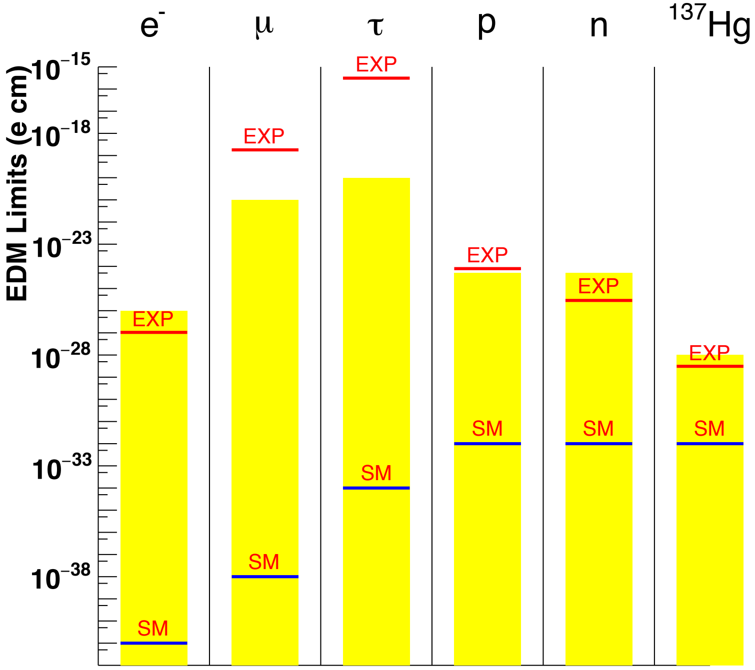
$$\vec{d} = \eta \frac{Qe}{2mc}\vec{s} \qquad \vec{\mu} = g\frac{e}{2mc}\vec{s}$$

Defined by the Hamiltonian:

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

	E	B	μ or d
P	-	+	+
C	-	-	-
T	+	-	-

Provides an additional source of CP violation



Standard scaling : $\frac{d_\mu}{d_e} \sim \frac{m_\mu}{m_e}$

d_e limits imply d_μ scale of 10^{-25} e•cm

But some BSM models predict non-standard scalings

(quadratic or even cubic)

The muon is a unique opportunity to search for an EDM in the 2nd generation

Aside : EDM

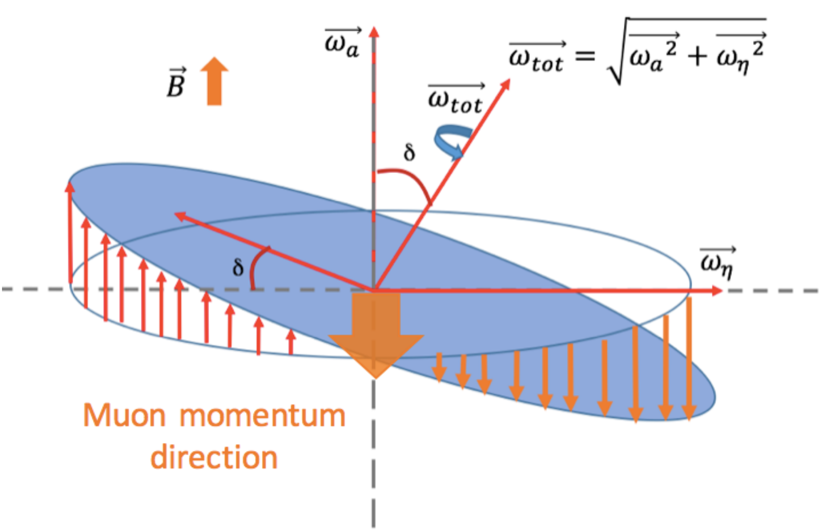
If an EDM is present the spin equation is modified to:

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

Dominant term

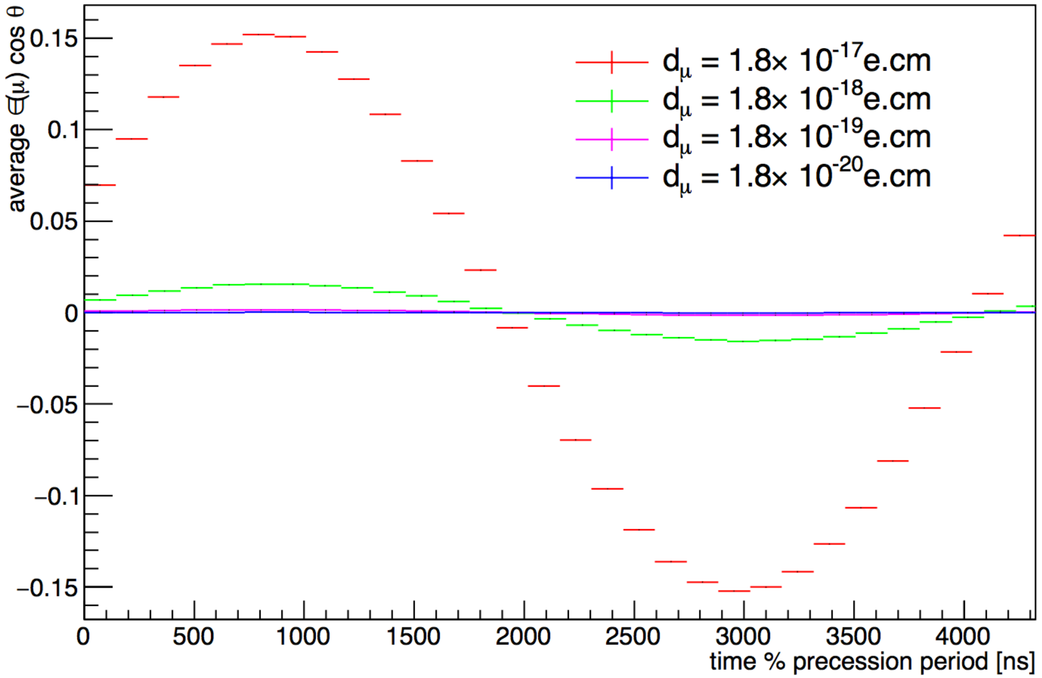
An EDM tilts the precession plane towards the centre of the ring

$\longrightarrow$ Vertical oscillation (π/2 out of phase)



Expect tilt of ~mrad for d_μ ~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)

Aside : JPARC g-2

There is also an experiment to measure the muon g-2 at JPARC which uses a different technique

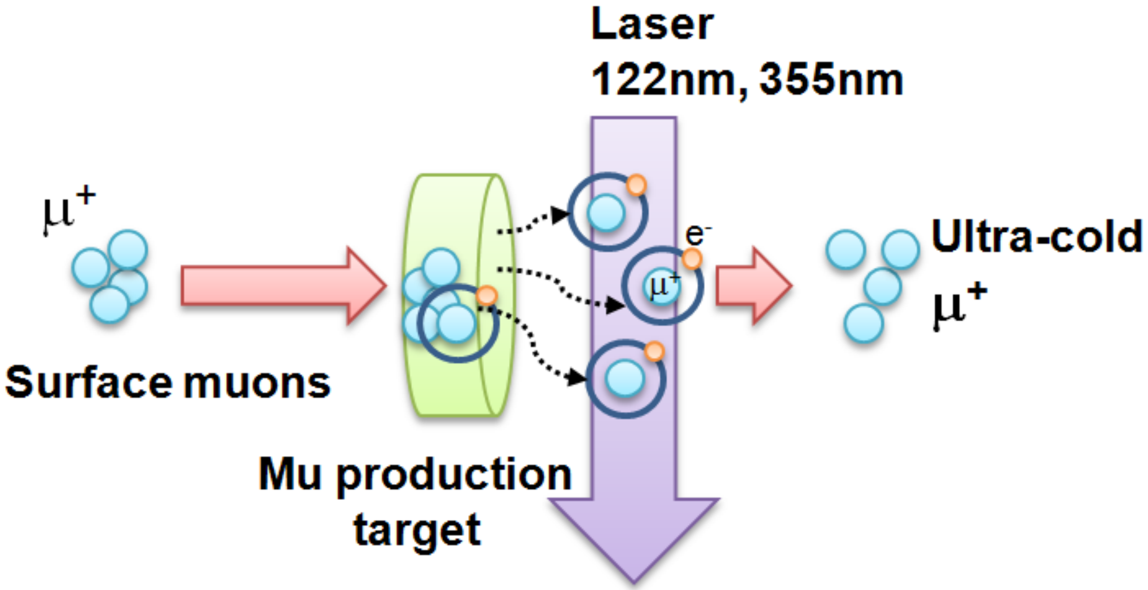
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \boxed{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\,\boxed{\vec{\beta}\times\vec{E}} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}\right]$$

The Fermilab experiment cancels this term by running at the magic momentum

The JPARC experiment instead runs with no electric field

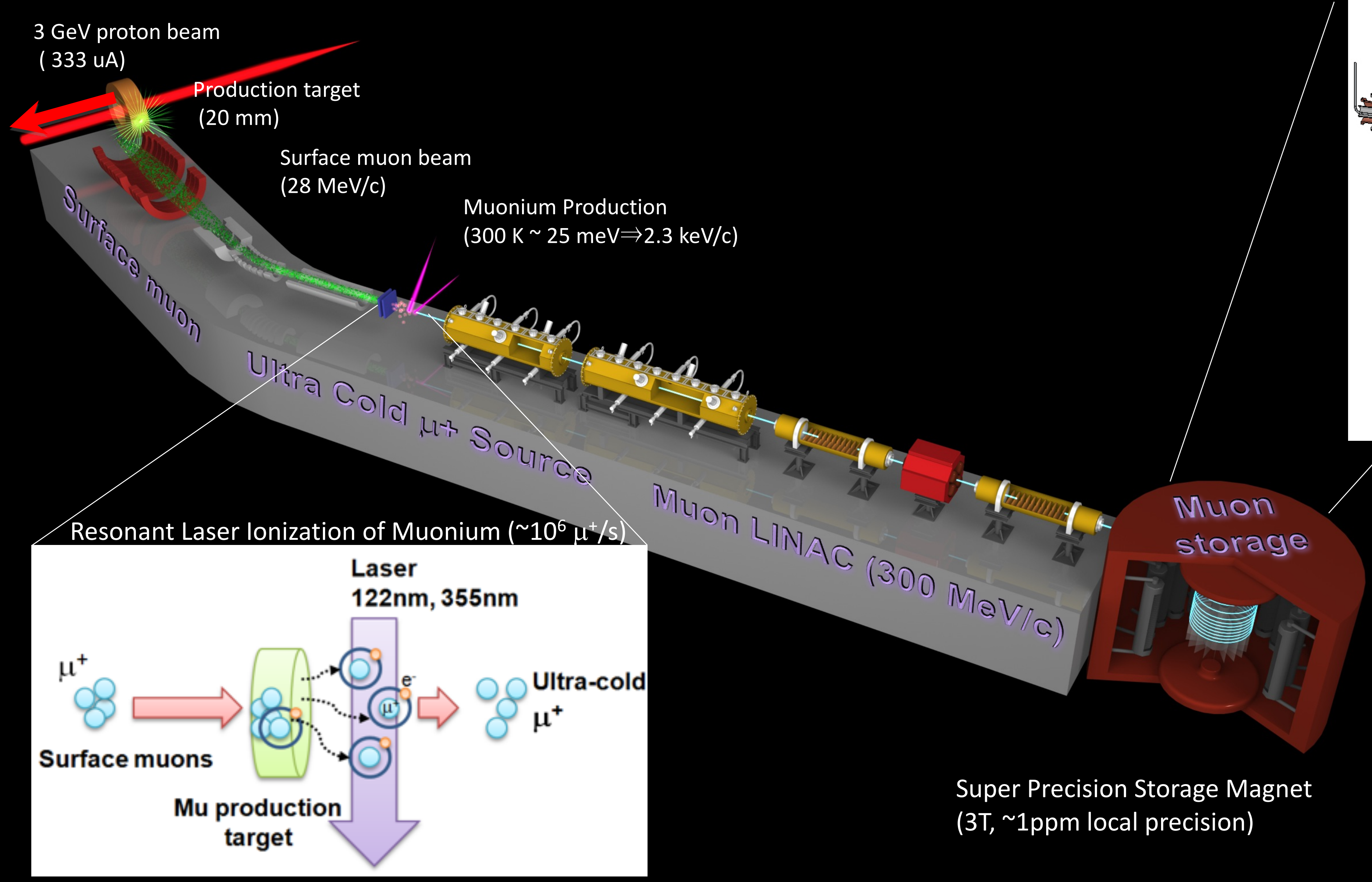
→ Use ultra cold muons to reduce the emittance

To produce the muons laser resonant ionization of muonium is used



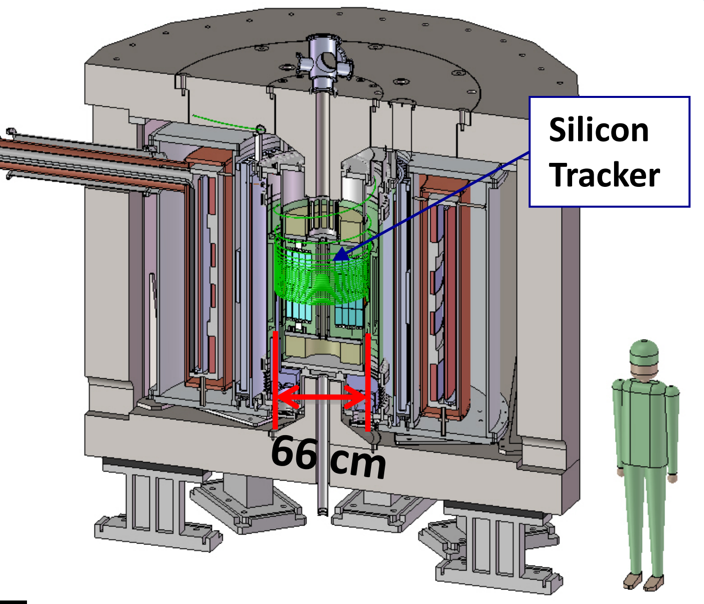
The muons produced have very low transverse dispersion which are then accelerated

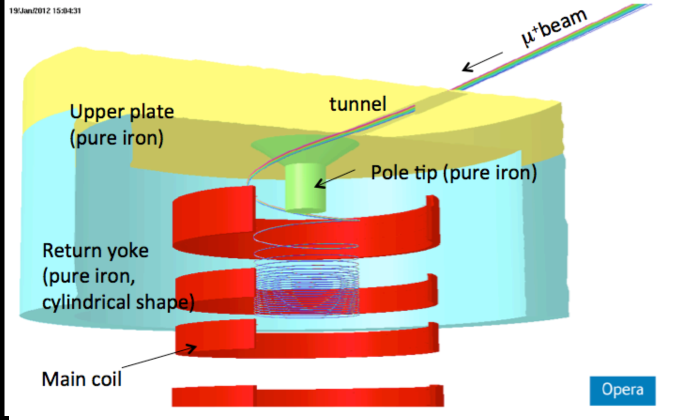
Aside : JPARC g-2



Resonant Laser Ionization of Muonium (~10^6 μ^+/s)

Super Precision Storage Magnet
(3T, ~1ppm local precision)





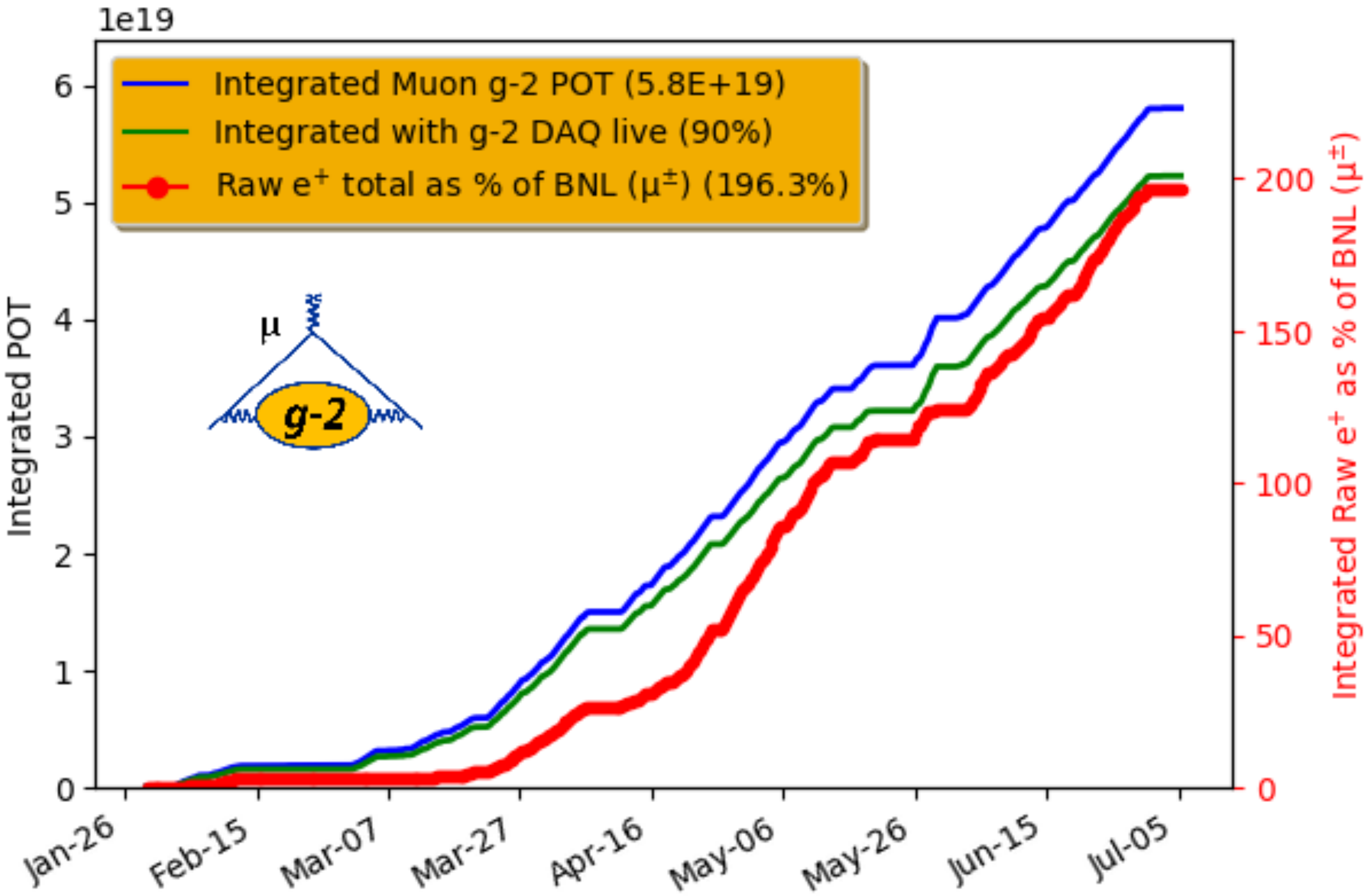
Summary

The new g-2 experiment at Fermilab has just finished the first year of physics data taking

- 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 by early 2019 (based on the data taken between now and the summer)

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



Back up

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

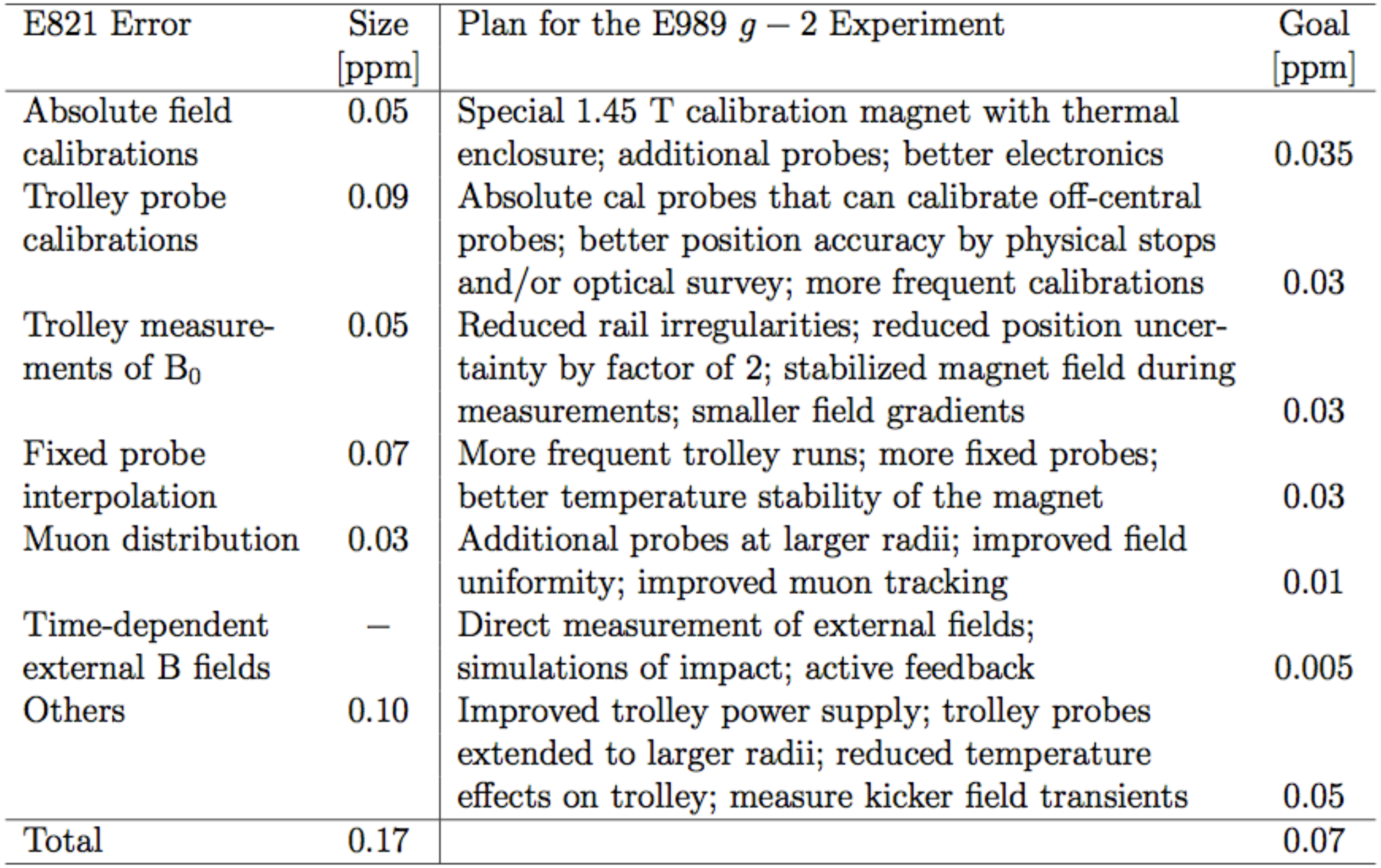
KAIST
CAPP

Russia

Dubna
Novosibirsk

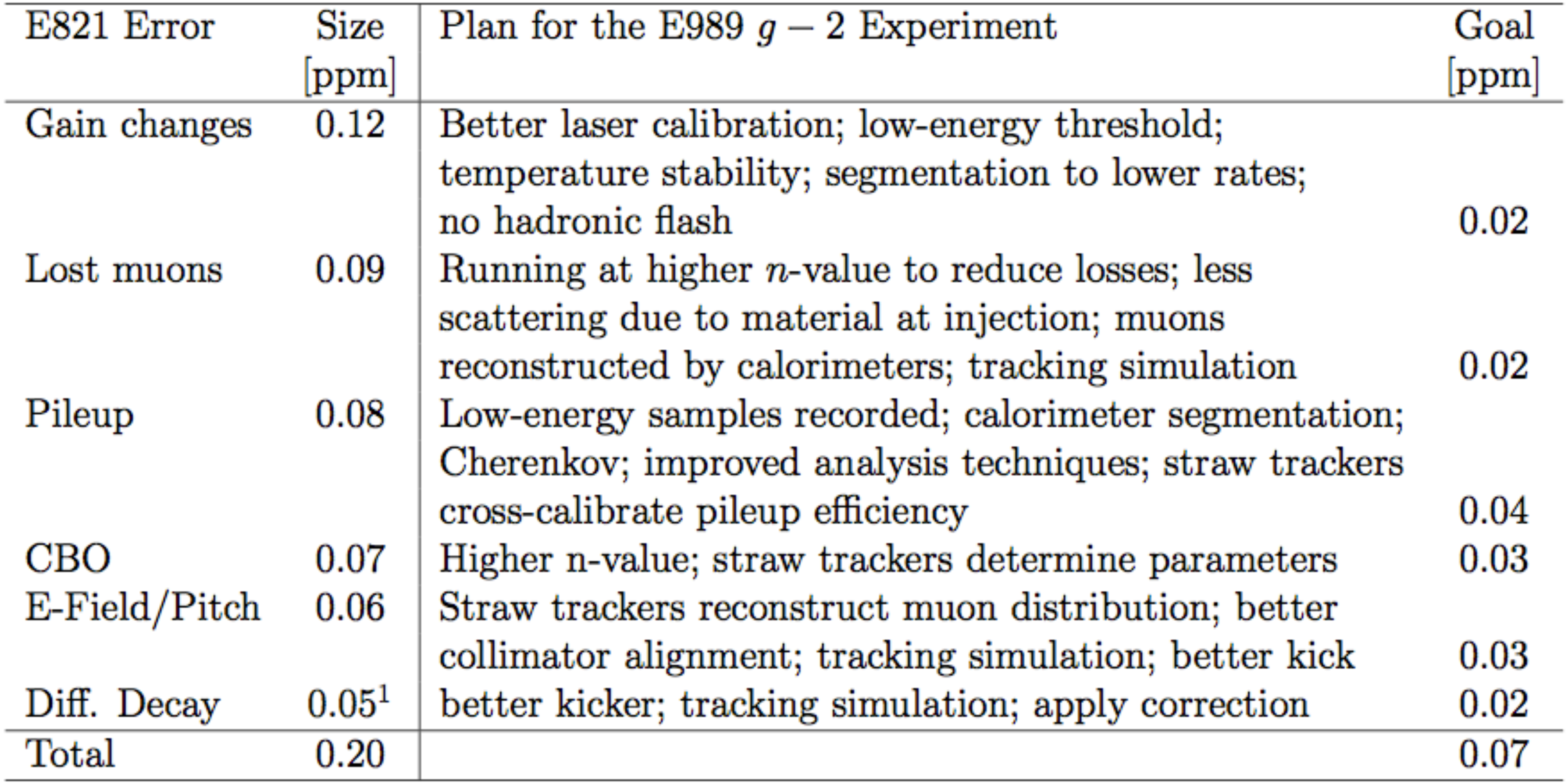
Fermilab

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

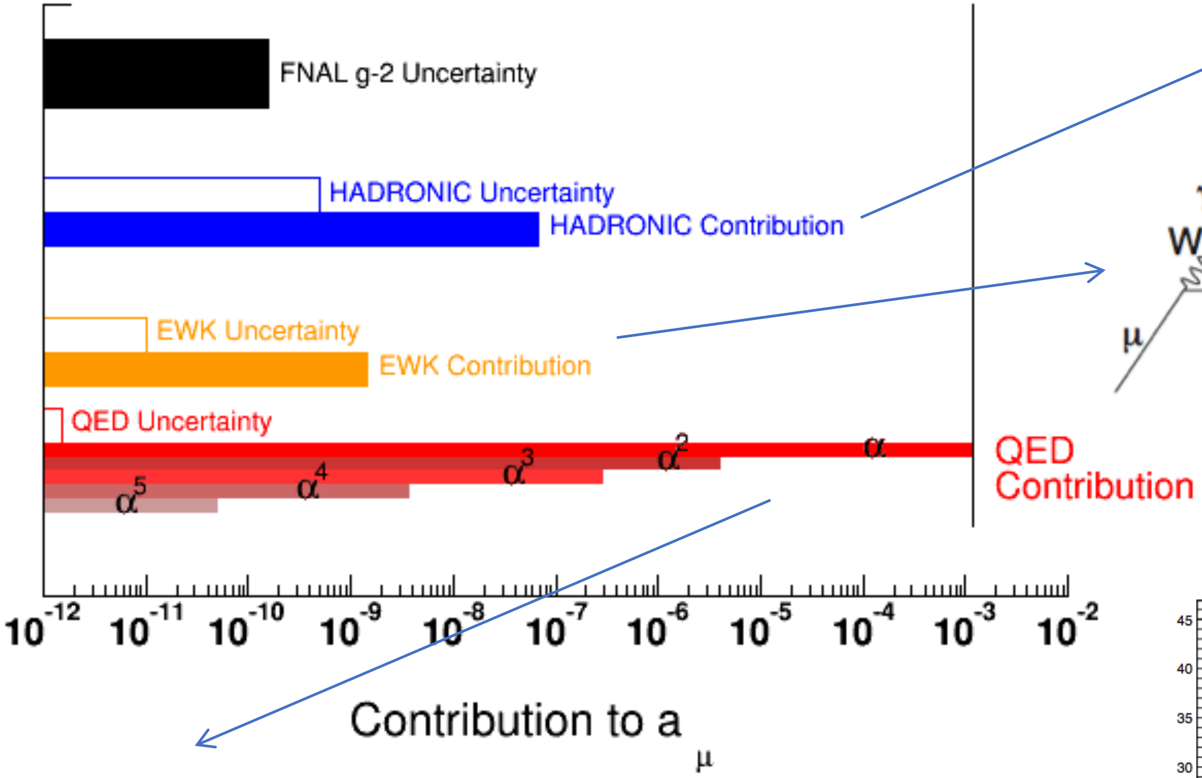
Spin precession systematics



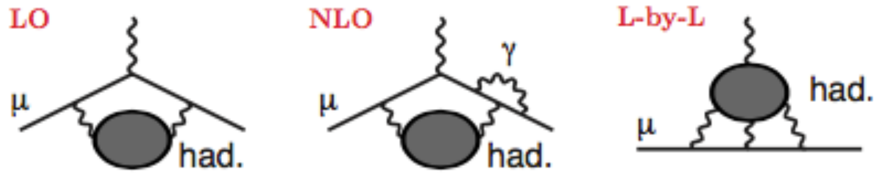
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material 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

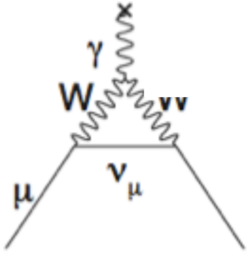
The Magnetic Moment

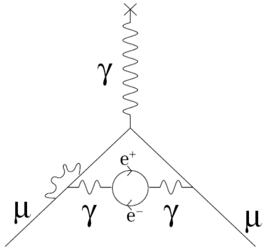
The hadronic uncertainty dominates in the theoretical calculation



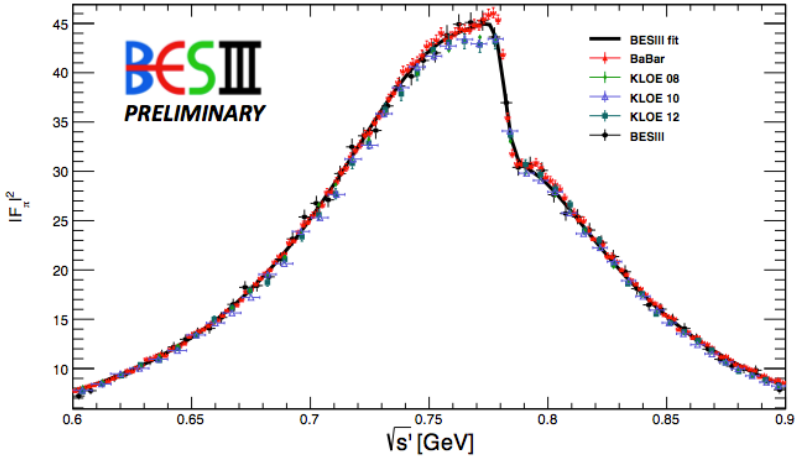
$$a_\mu^{\rm had} = a_\mu^{\rm had,VP\ \ LO} + a_\mu^{\rm had,VP\ \ NLO} + a_\mu^{\rm had,Light-by-Light}$$



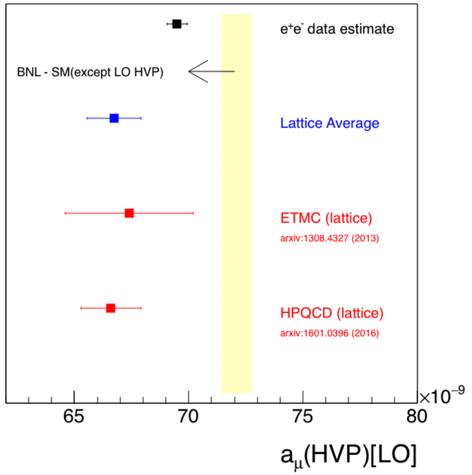




Improved data should bring down the uncertainty :



Lattice calculations are also catching up :

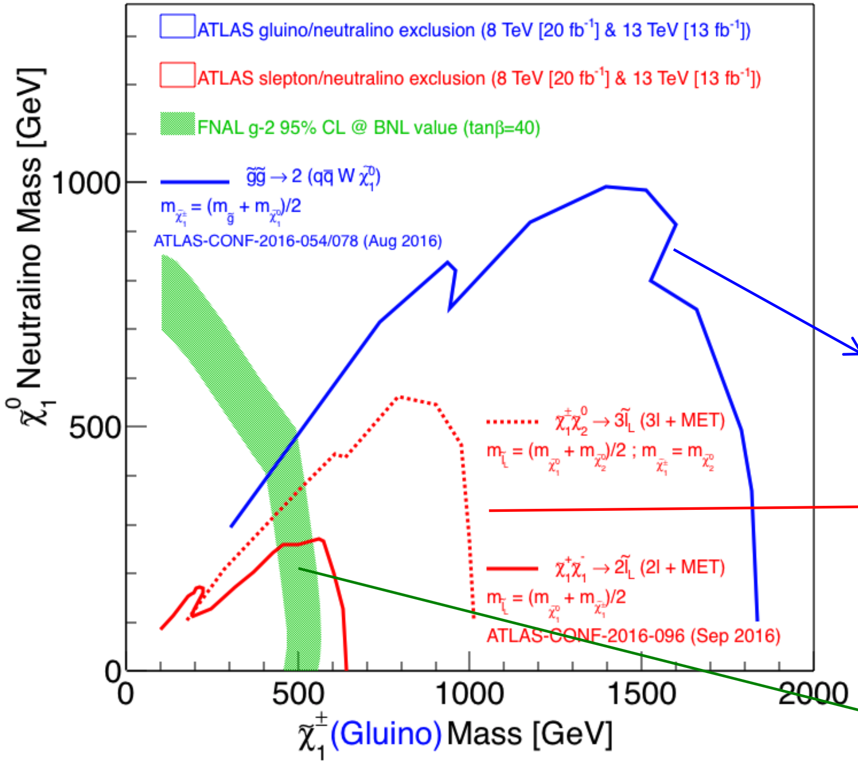


New Physics

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

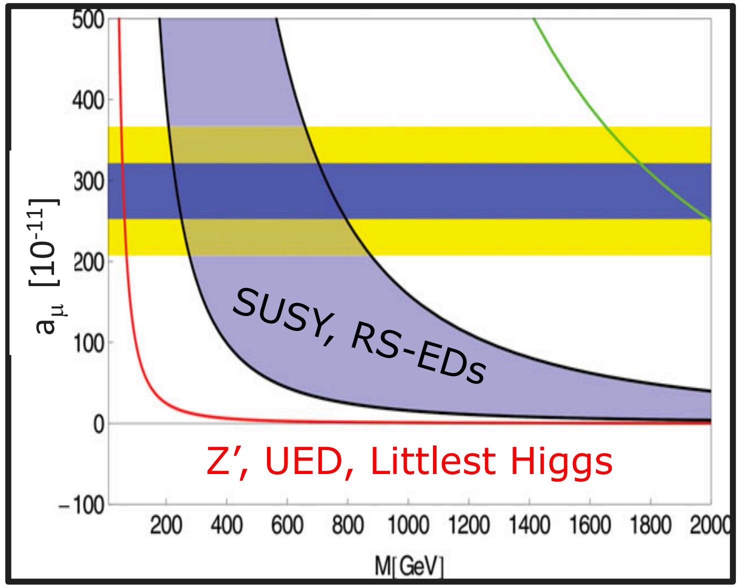


The LHC has good sensitivity to strongly interacting new physics (SUSY)

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

Radiative muon mass / technicolor



SUSY, RS-EDs

Z′, UED, Littlest Higgs

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

$$\mathrm{BNL} \rightarrow \mathrm{FNAL}$$

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

$$0.54\ \mathrm{ppm} \longrightarrow 0.14\ \mathrm{ppm}$$

New / improved technologies

Additional collaborators

Building on wealth of experience from BNL E821 & other expts