The Fermilab Muon g-2 Experiment

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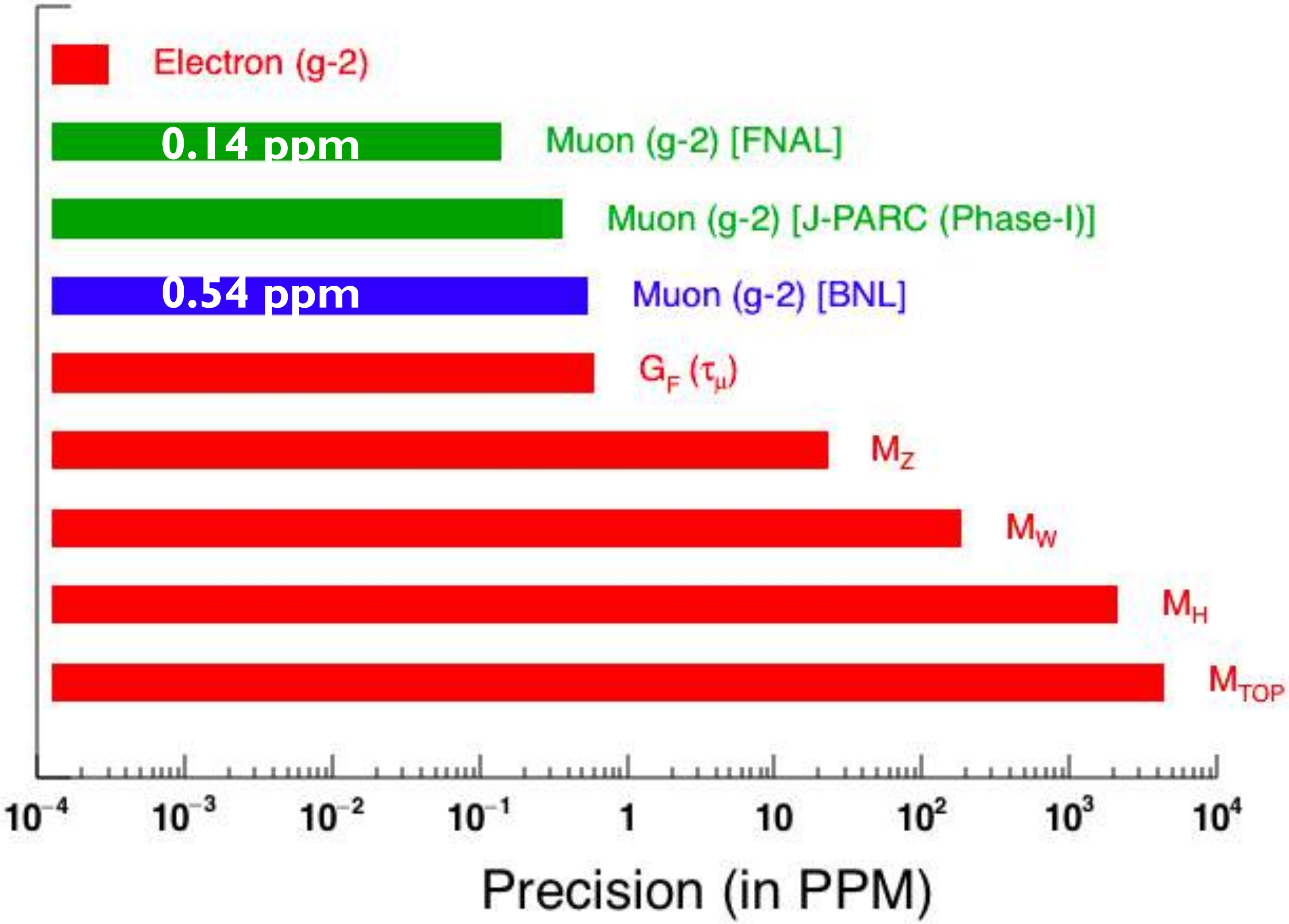
University College London

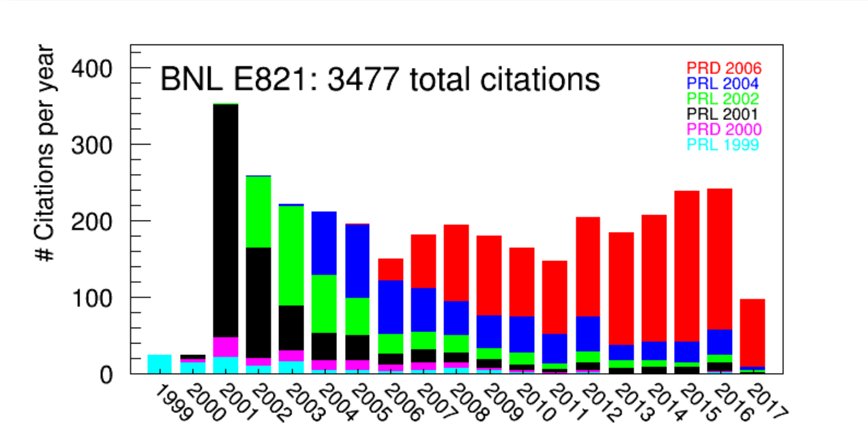
On behalf of the Fermilab Muon g-2 Collaboration

Aim



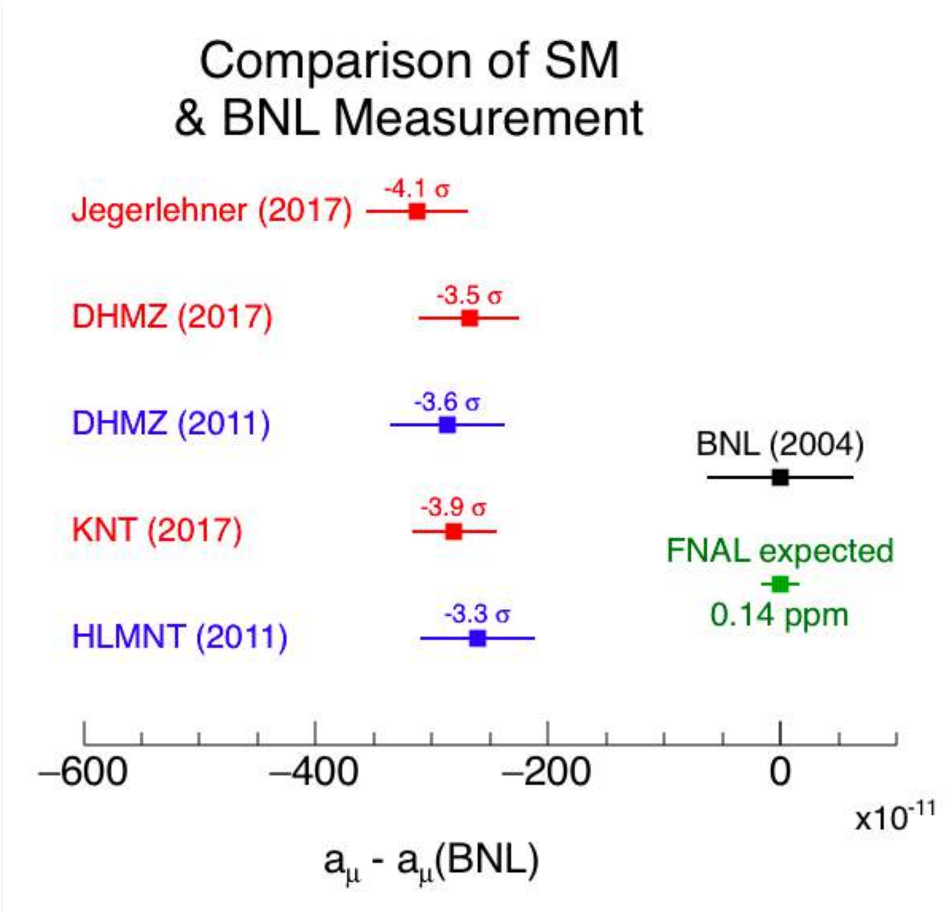
Electron (g-2)
0.14 ppm
Muon (g-2) [FNAL]
Muon (g-2) [J-PARC (Phase-I)]
0.54 ppm
Muon (g-2) [BNL]
G_F (τ_μ)
M_Z
M_W
M_H
M_{TOP}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4
Precision (in PPM)

Motivation



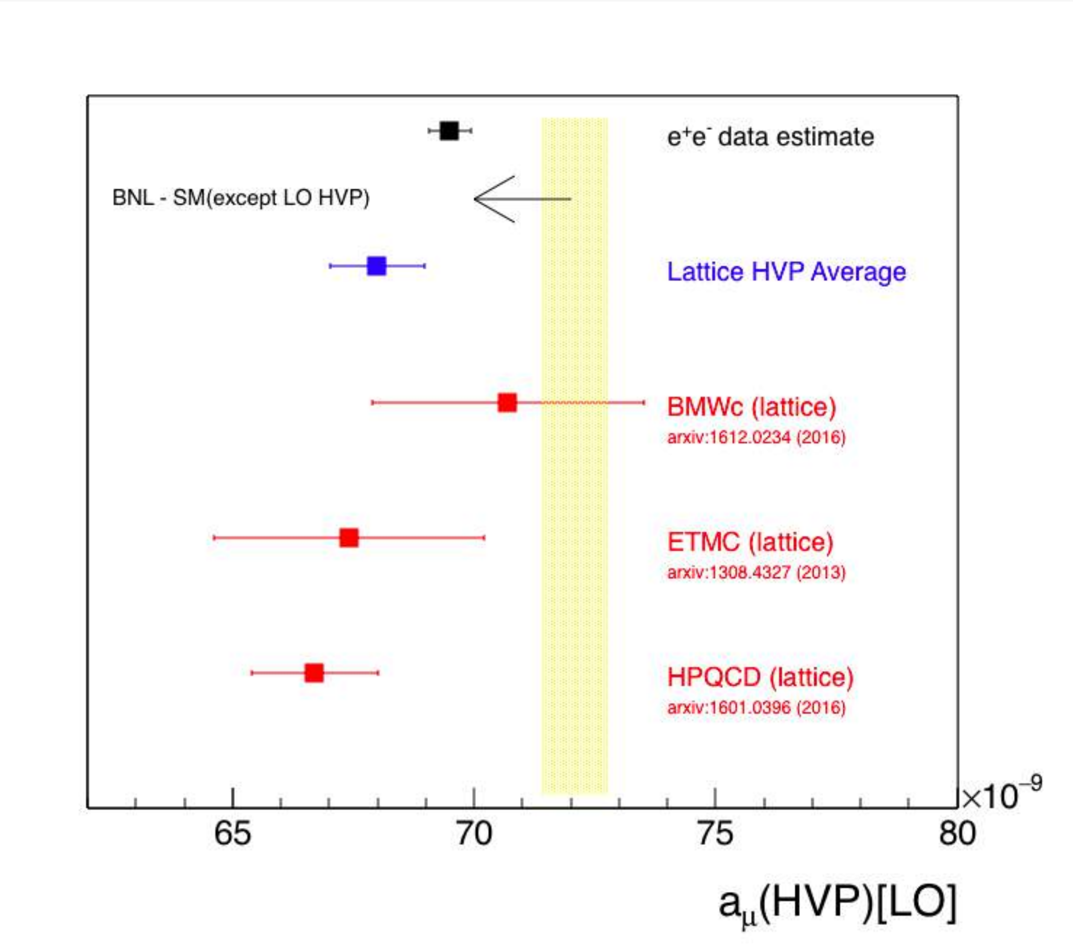
Data-based HVP estimates have improved 20-40%.

0.14ppm measurement and 2017 SM would give 6-7σ if central value stays the same and >10σ with expected theory improvements.

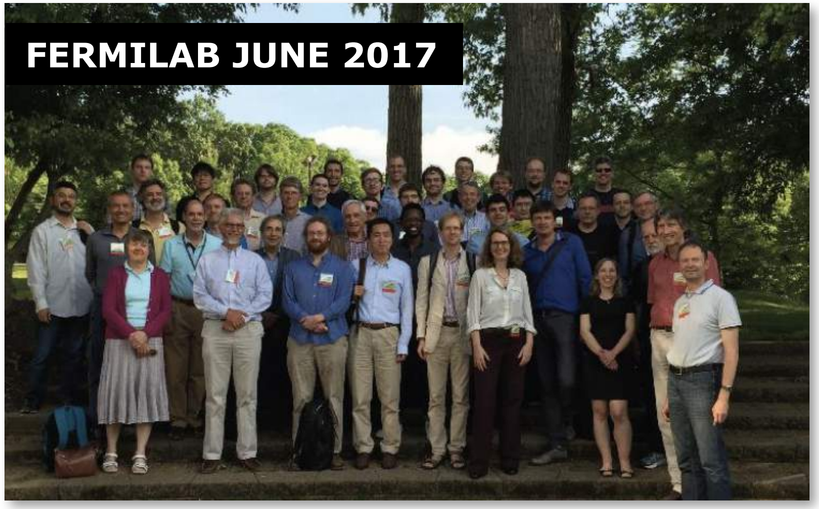


Theory Progress

Considerable progress in lattice calculations that confirm data-based SM prediction for HVP.



Also much work on the lattice for the Hadronic LBL contribution



More experimental input

Comparable precision on g-2 HVP from dedicated experiment

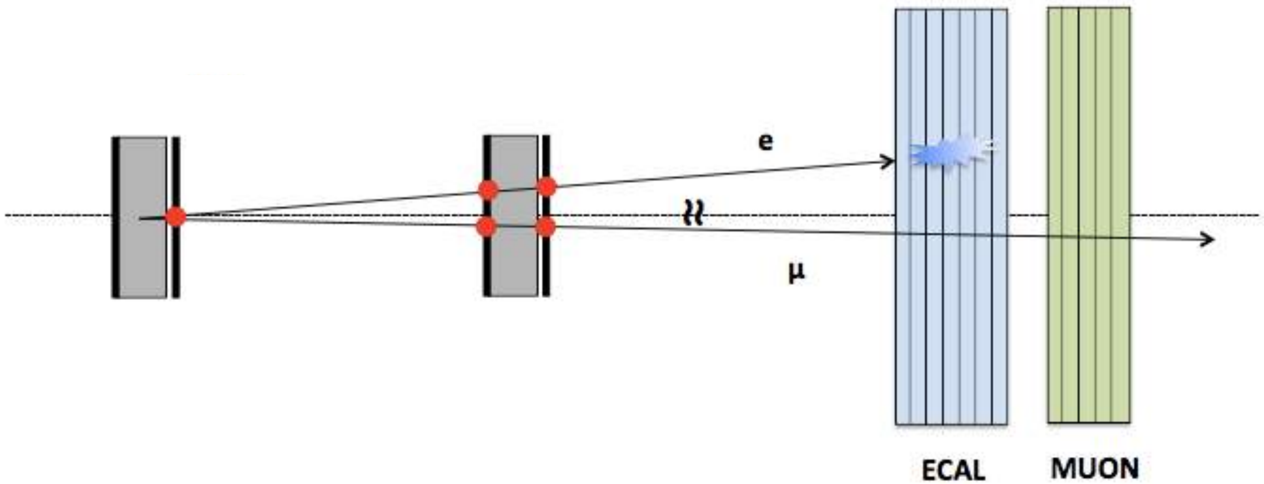
The European Physical Journal C

March 2017, 77:139

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

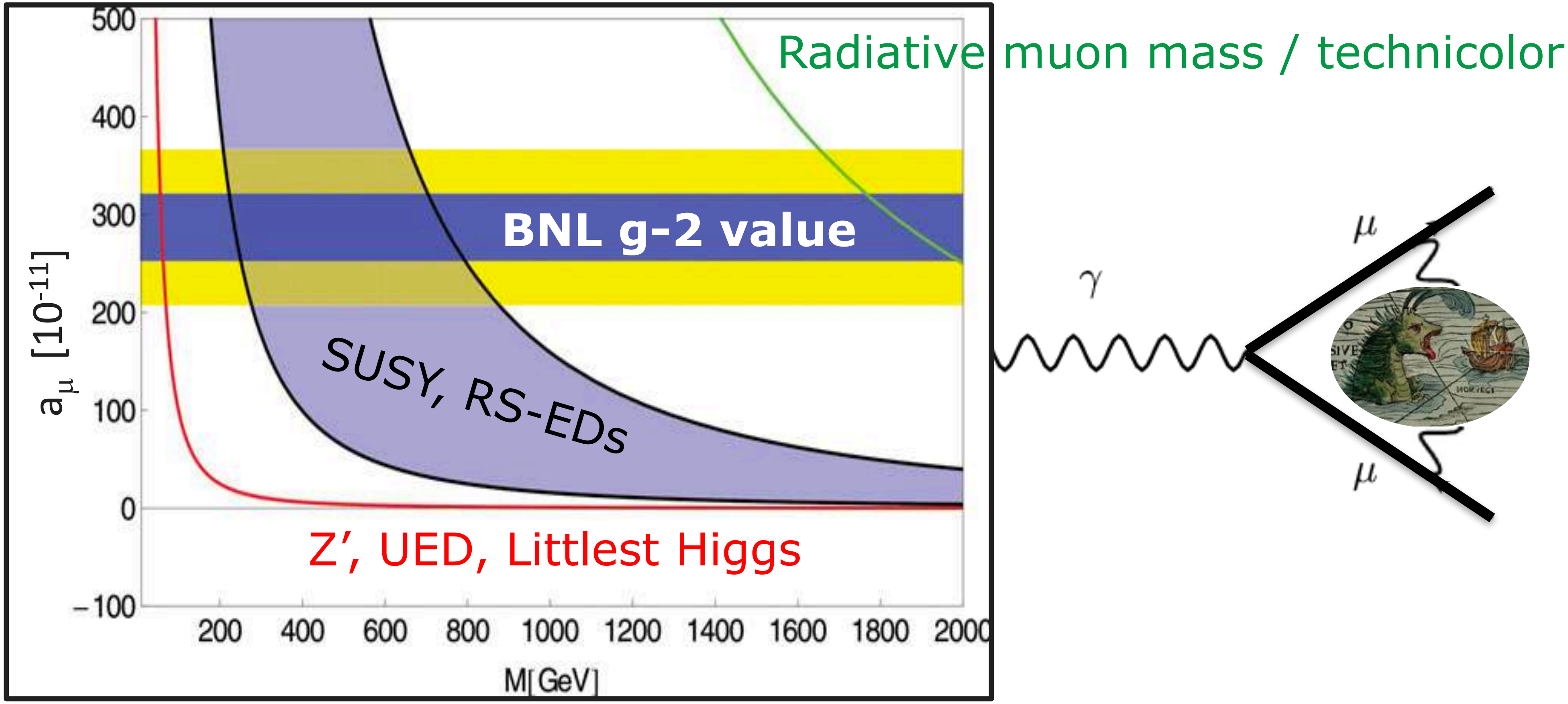
Authors | Authors and affiliations

G. Abbiendi, C. M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L. Trentadue, G. Venanzoni



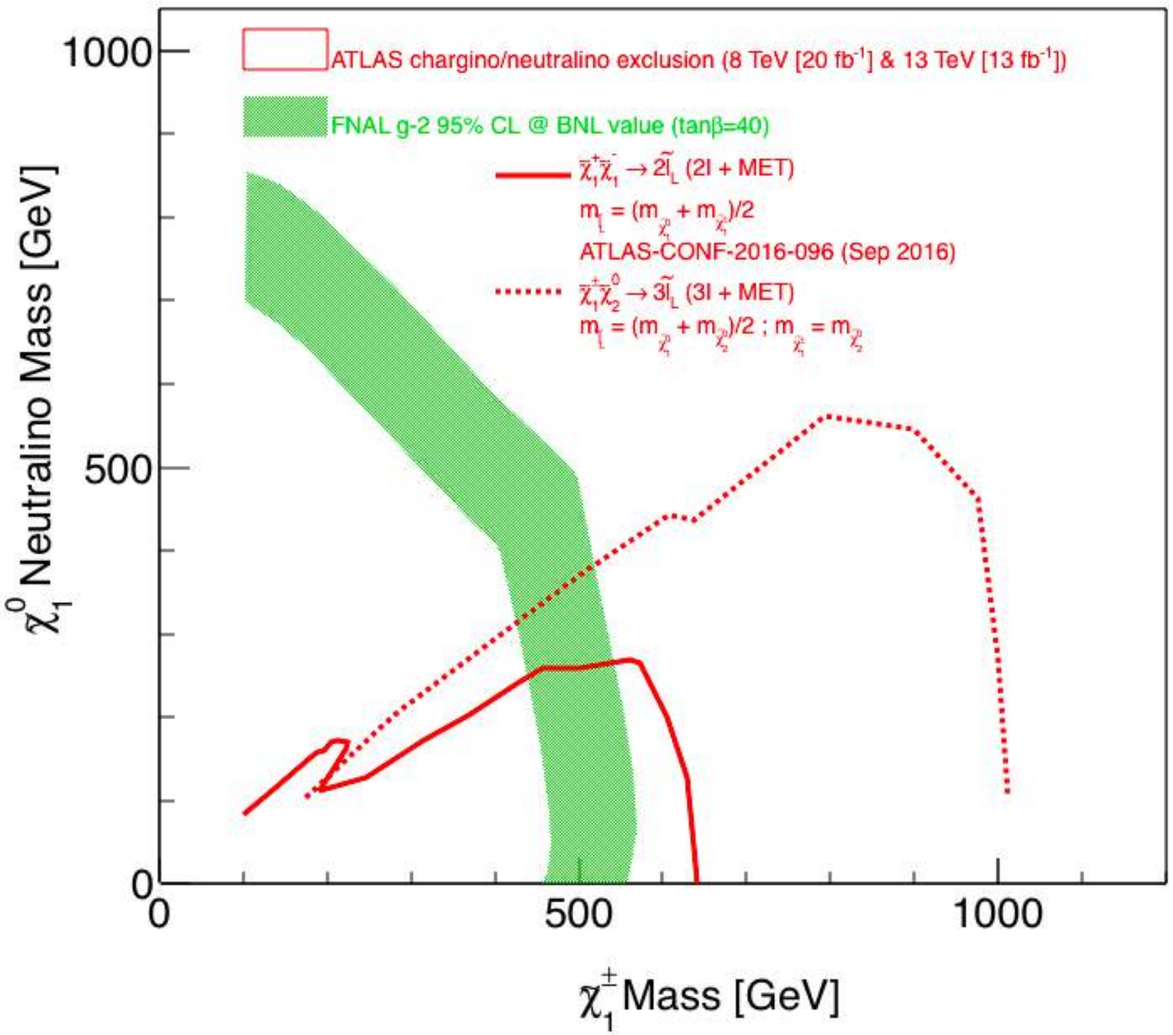
Would use CERN 150 GeV M2 beam for 2 years

Motivation



Radiative muon mass / technicolor
BNL g-2 value
SUSY, RS-EDs
Z′, UED, Littlest Higgs
a_μ [10^{-11}]
M[GeV]
500
400
300
200
100
0
−100
200
400
600
800
1000
1200
1400
1600
1800
2000
γ
μ
μ

Motivation



Probing new physics
in similar region as LHC

How to achieve 0.1 ppm

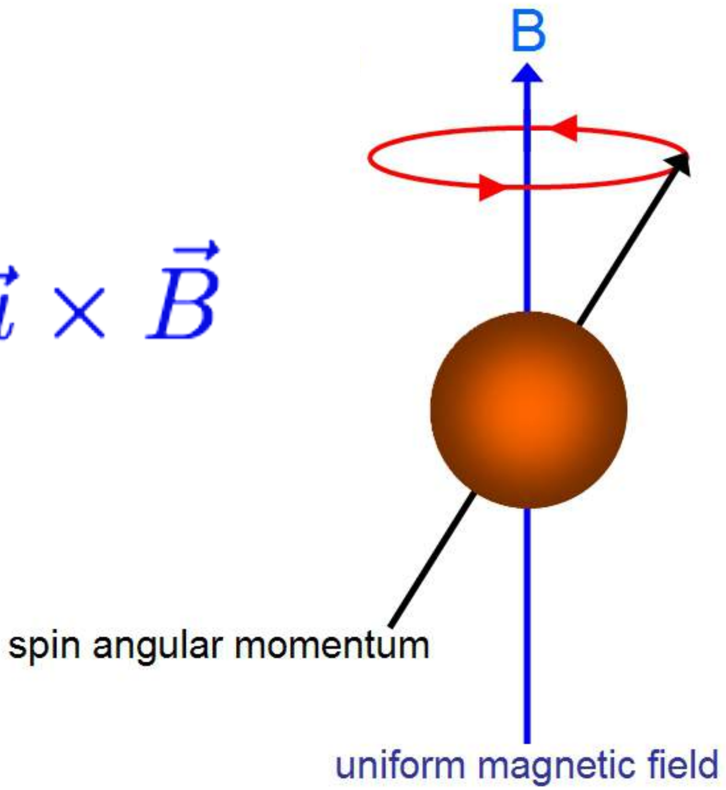
"Never measure anything but frequency"

I. Rabi

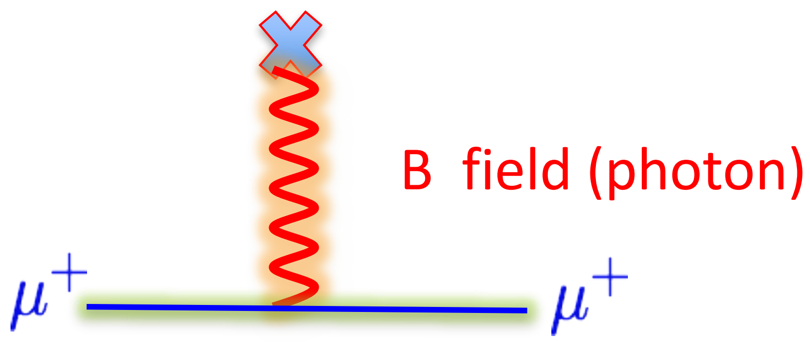
$$\vec{\mu} = g\frac{Qe}{2m}\vec{s}$$

Interaction between
magnetic moment (spin) with B-field.

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



Spin **precesses** around B at
a frequency determined by "g"



Motion in B-field storage ring

Particle in a circular storage ring (B-field): two frequencies:

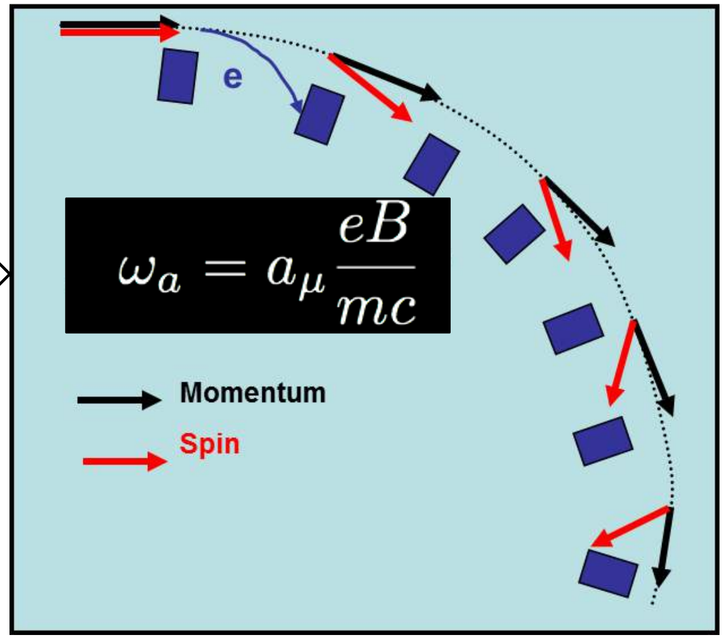
$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

Spin vector of muon rotates slightly quicker than Momentum vector.

For a 1.5T field spin rotates in 144ns and momentum in 149ns.

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

$$f_a = 228 \text{ kHz}$$

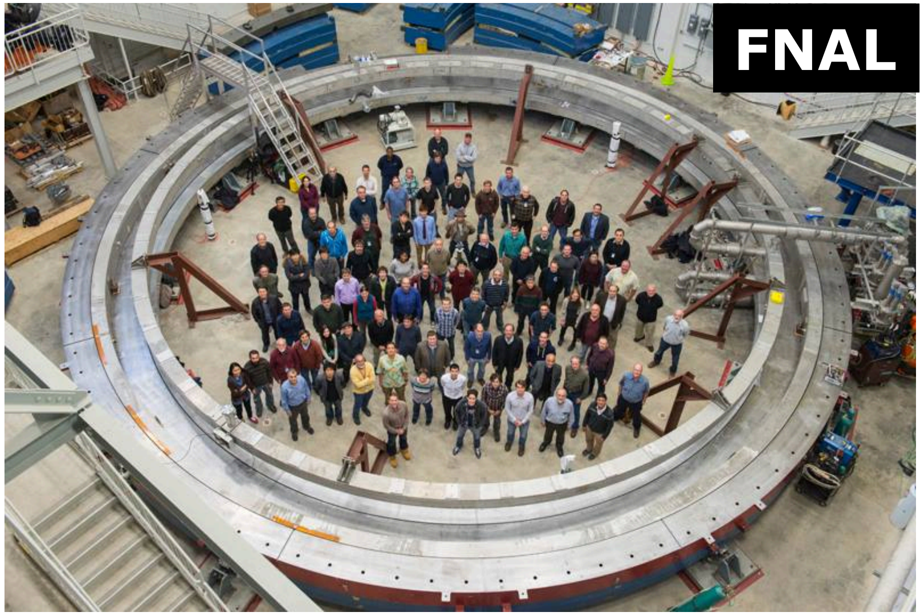


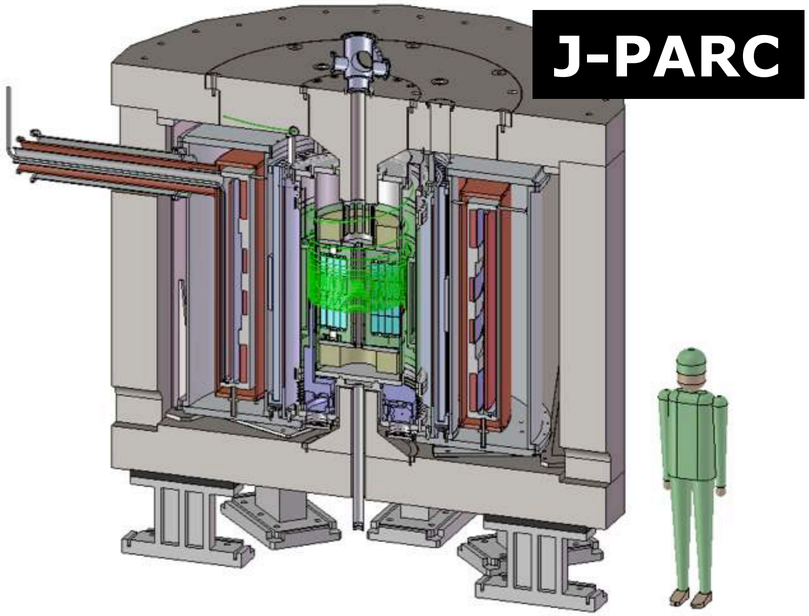
The real world

But real beams are not all on the same perfect circular orbit and can have a (small) transverse velocity component.
These imperfections causes beam to diverge vertically.

Two approaches:

- cancel the divergence with an electric quadrupole field (CERN,BNL, FNAL)
- minimise the divergence by reducing the beam p_T (J-PARC)





Addition of E-field

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

FNAL: MAKE ZERO BY CHOOSING "MAGIC" γ

J-PARC: MAKE ZERO BY HAVING E=0

$$a_\mu = \omega_a \frac{mB}{e}$$

Need to measure two quantities
- B field
- ω_a

To better than 0.1 ppm

Measure two quantities

B is measured using NMR in terms of the proton Larmor frequency : ω_p

Expression used in final analysis

$$a_\mu = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

ω_a: measured directly.

ω_p: *free proton precession frequency.*

$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\mathrm{ppt}$$

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\mathrm{ppb}$$

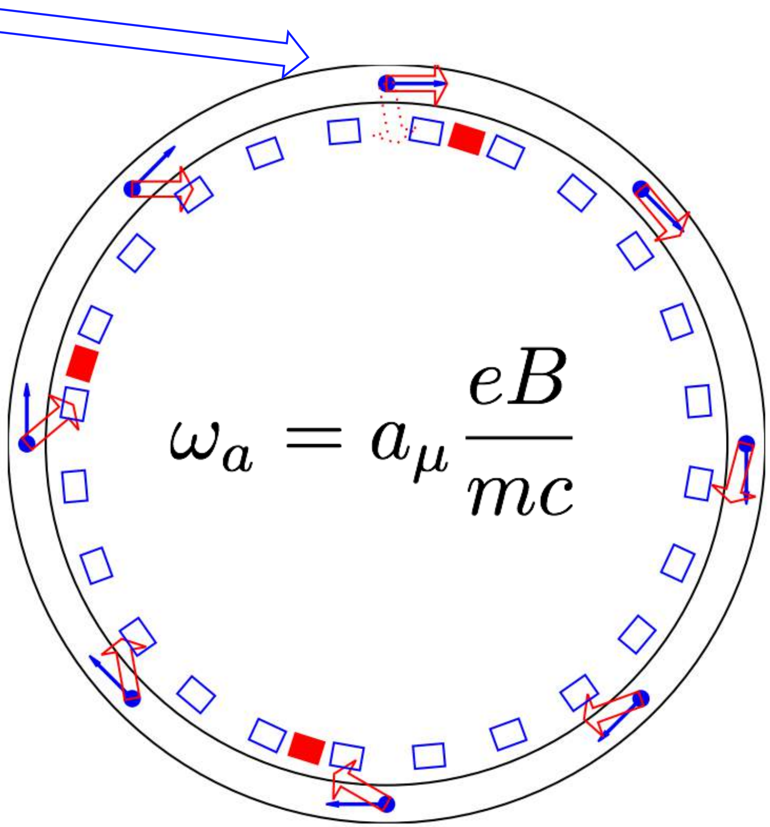
$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\mathrm{ppb}$$

Uncertainty in a_μ determined by precision of ω_p and ω_a measurements - 140 ppb vs 26ppb from rest.

FNAL g-2

Inject 3.09 GeV muons into a storage ring (B = 1.45 T)

Exploit property that direction of e^+ from μ^+ decay is strongly correlated with μ^+ spin for highest energy e^+

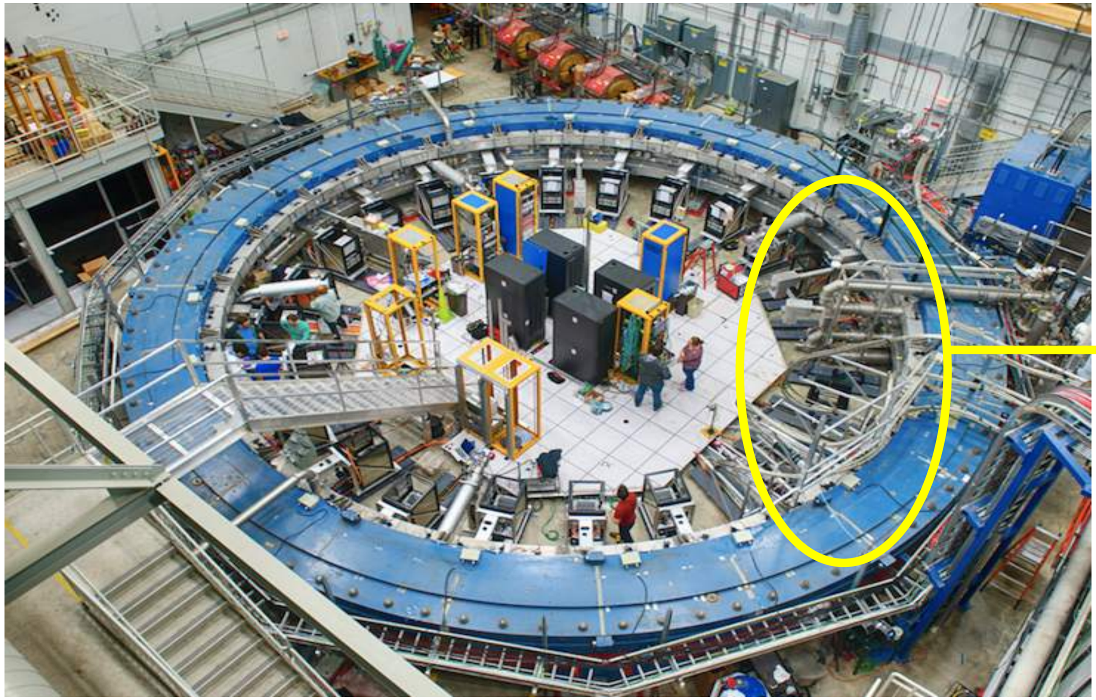


$$\omega_a = a_\mu \frac{eB}{mc}$$

24 calorimeters and 3 straw trackers measure e^+ for O(1 ms) for spills separated by 10ms.

16,000 stored 3.09 GeV muons from 10^{12} protons per spill.

The realisation of this ….

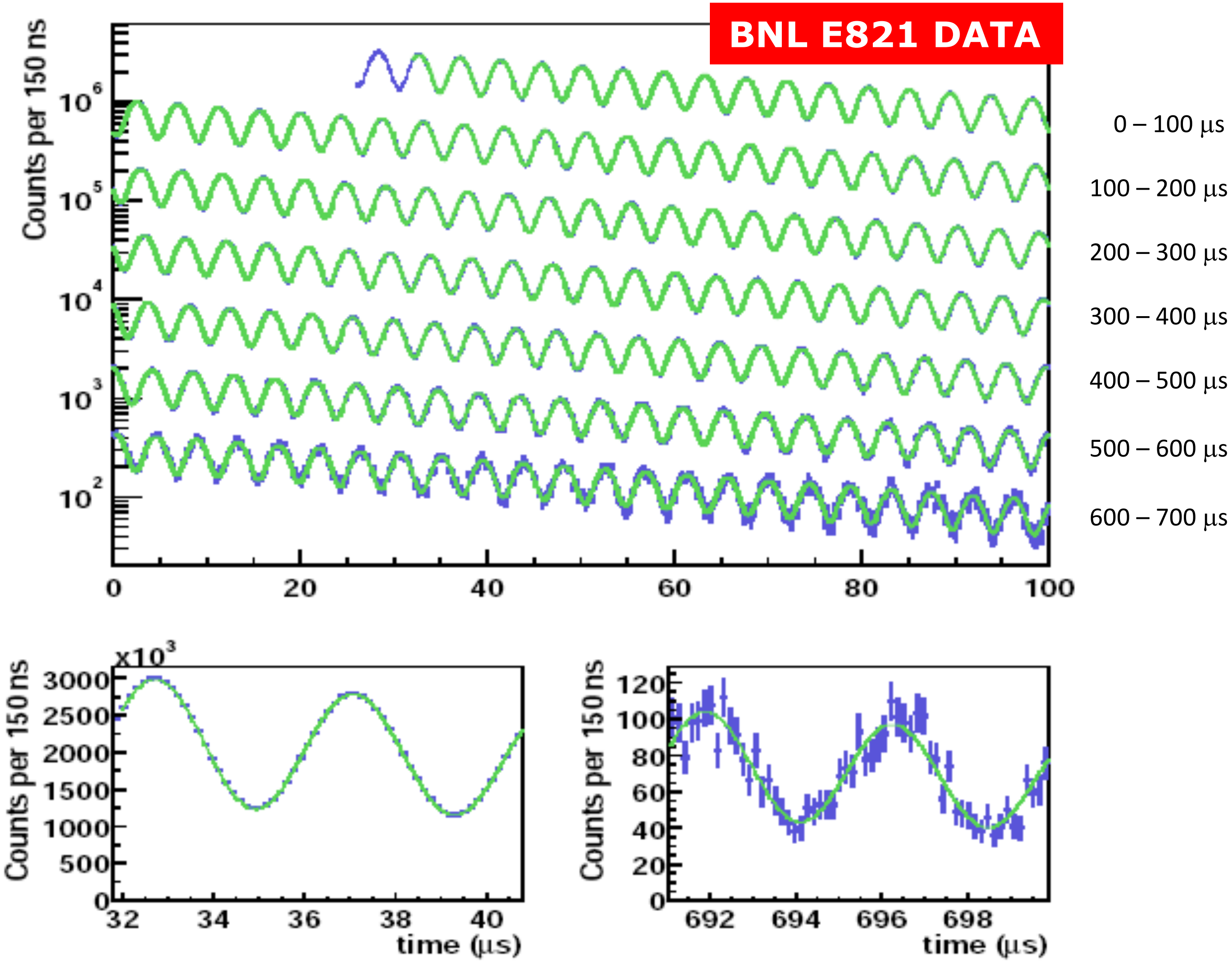


The Wiggle Plot

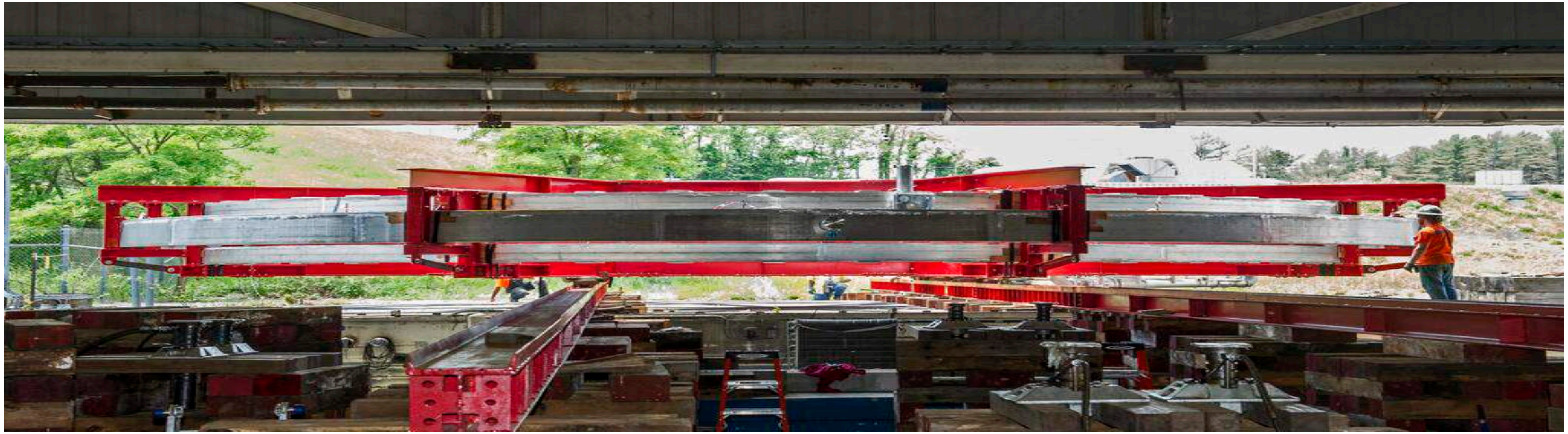
$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

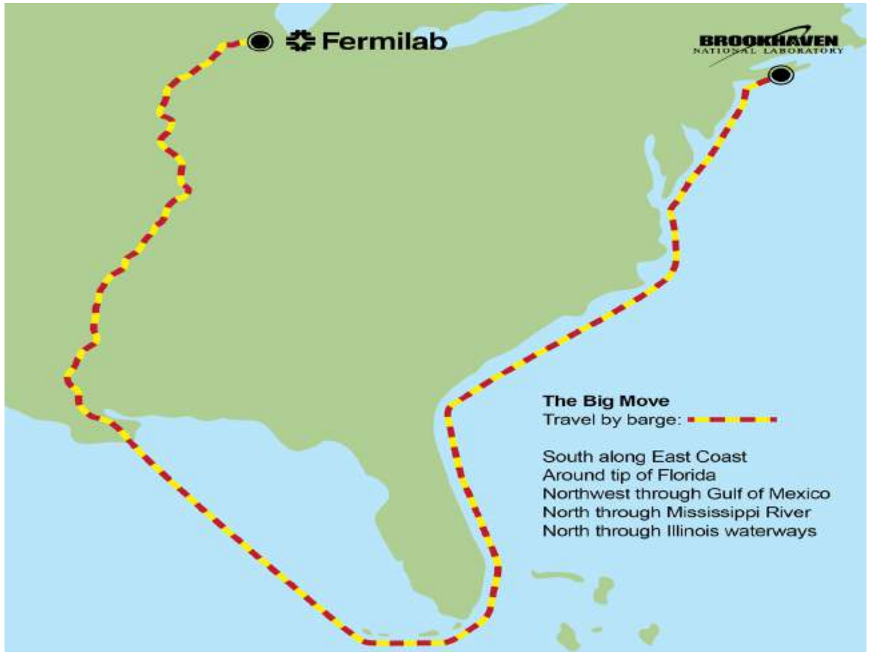
$E_{e^+} > 1.8\ \mathrm{GeV}$

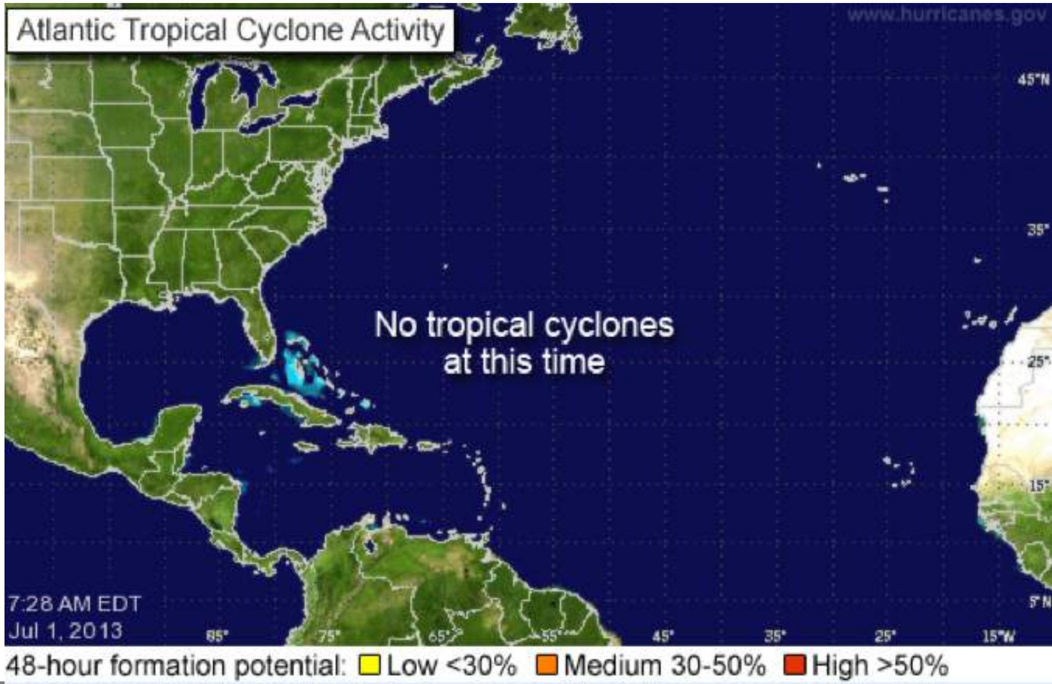
To get < 0.1 ppm statistical accuracy requires approx 100B muons !



The BNL to FNAL Transition



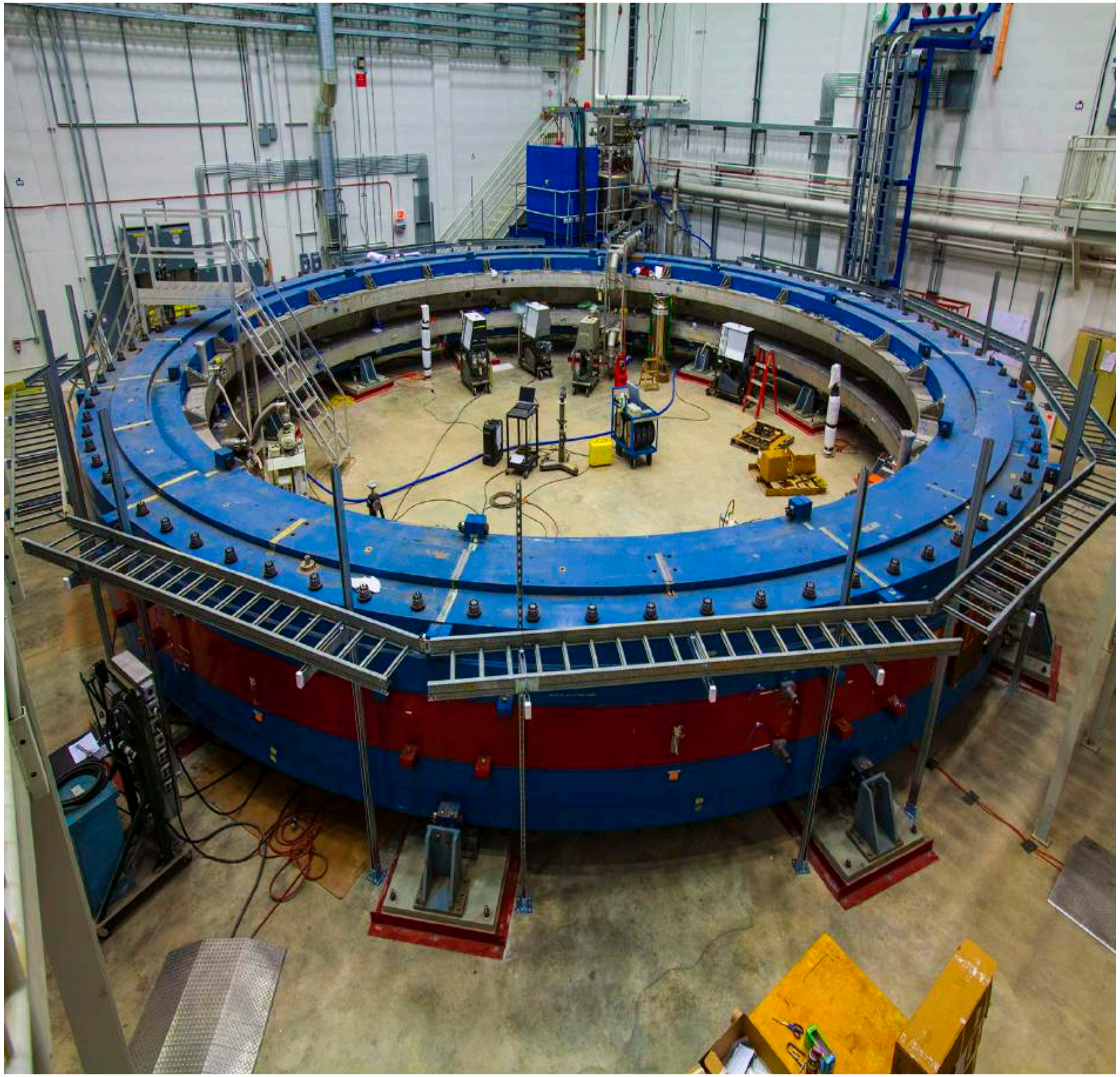




The Move : 2012

Long Live The Risk-Register

Installation : 2014/15



FNAL Improvements over 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

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

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

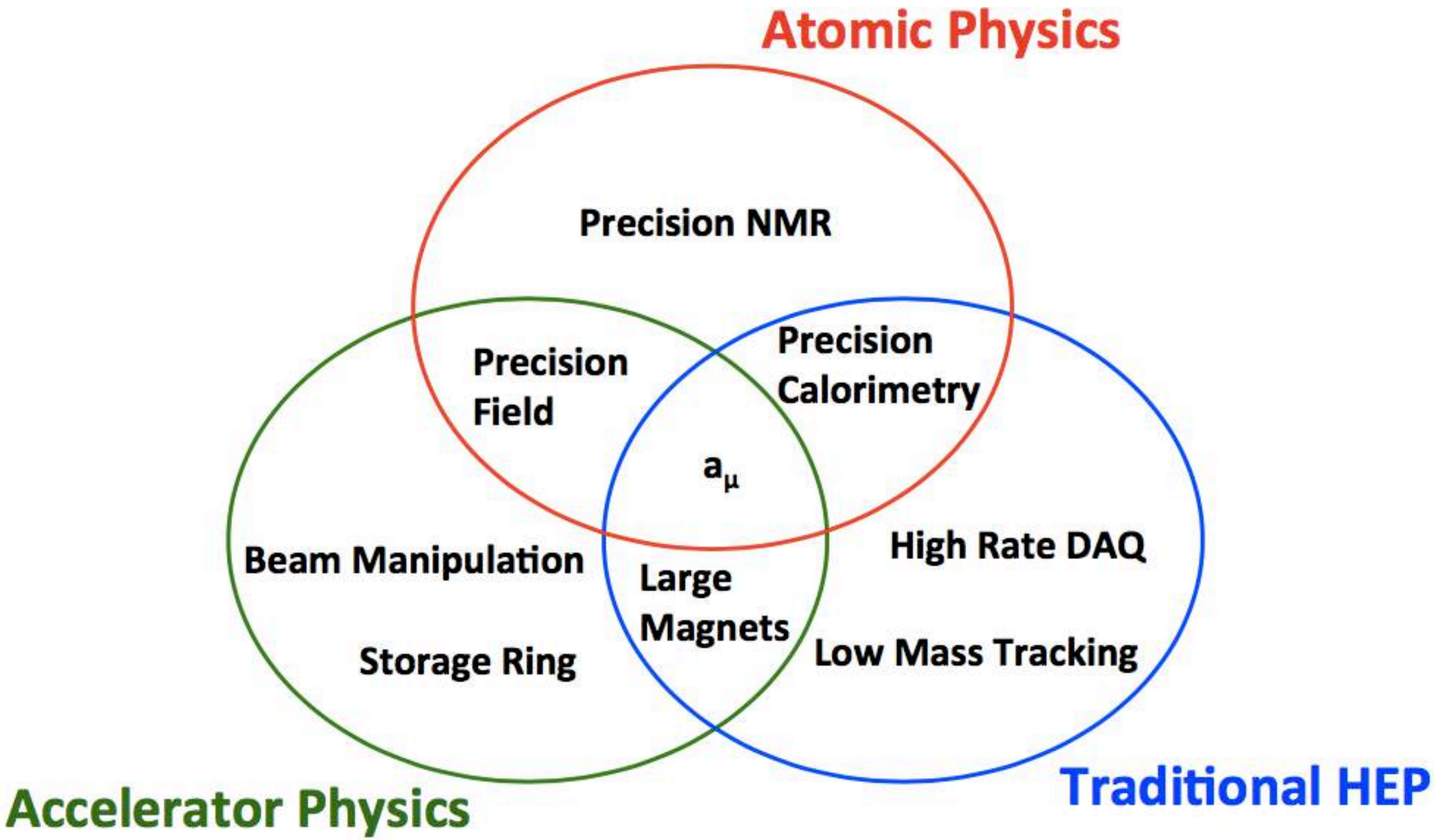
$$0.54\ \text{ppm} \rightarrow 0.14\ \text{ppm}$$

New / improved technologies

Additional collaborators

Building on wealth of experience from BNL E821 & other expts

Three experiments in one

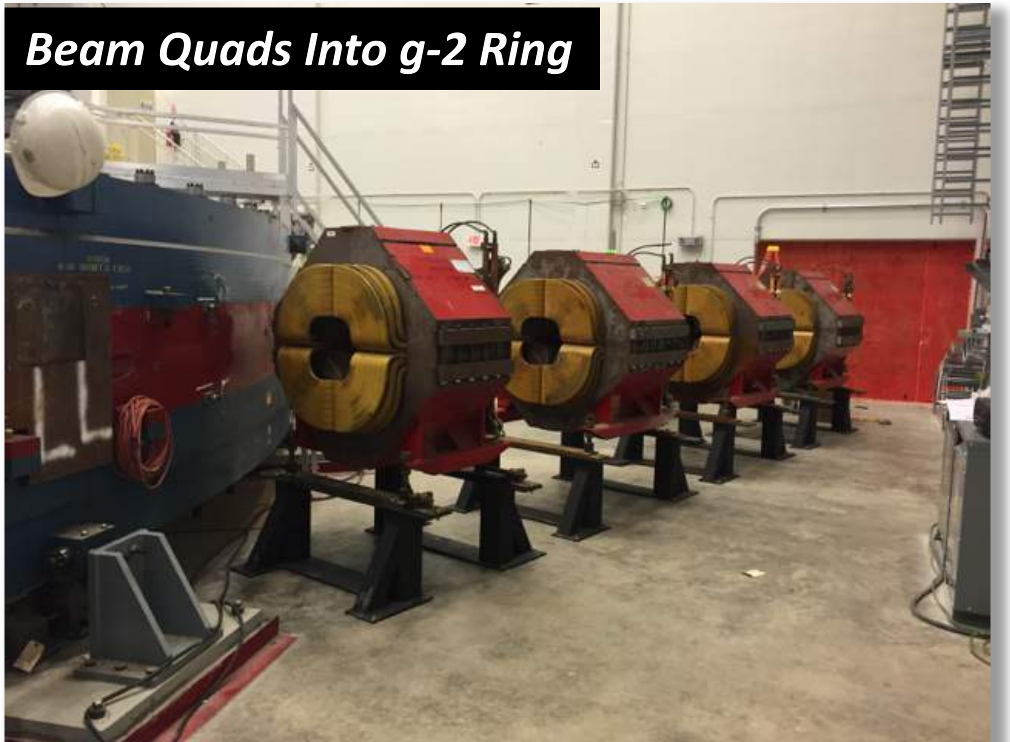


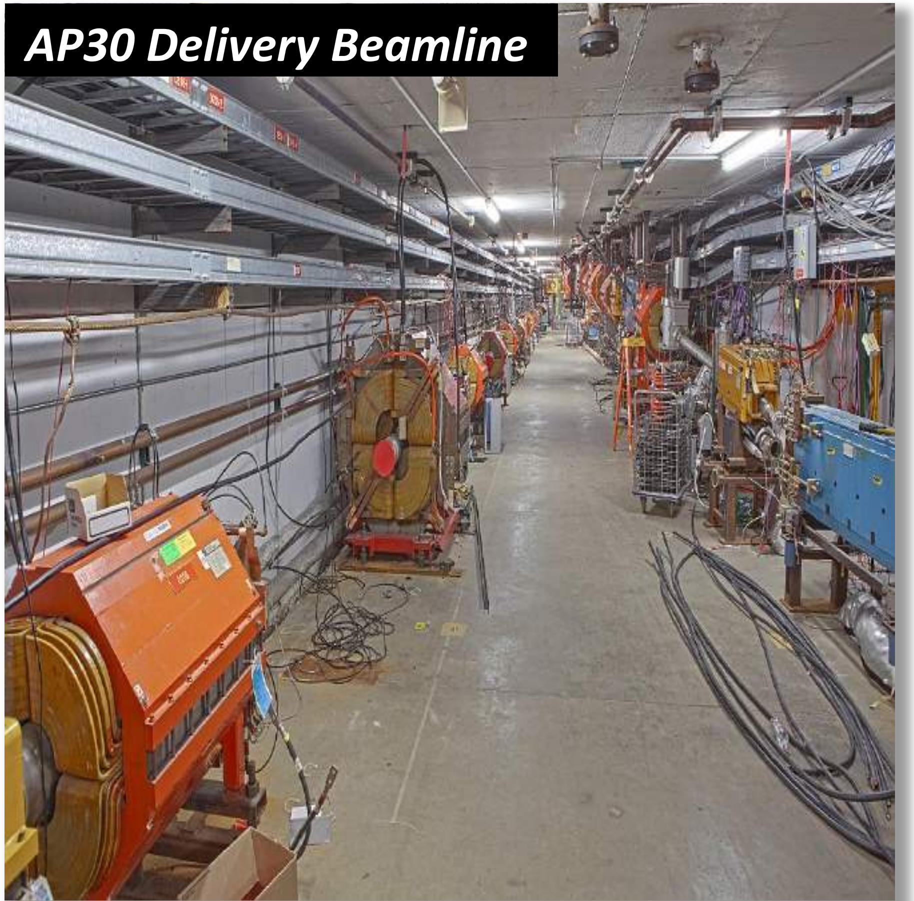
MAIN INJECTOR/RECYCLER RINGS
TEVATRON (RIP)
DR
BOOSTER
LINAC


BOOSTER
Mu2e
g-2
MUON TARGET & DELIVERY RING

Beamlines

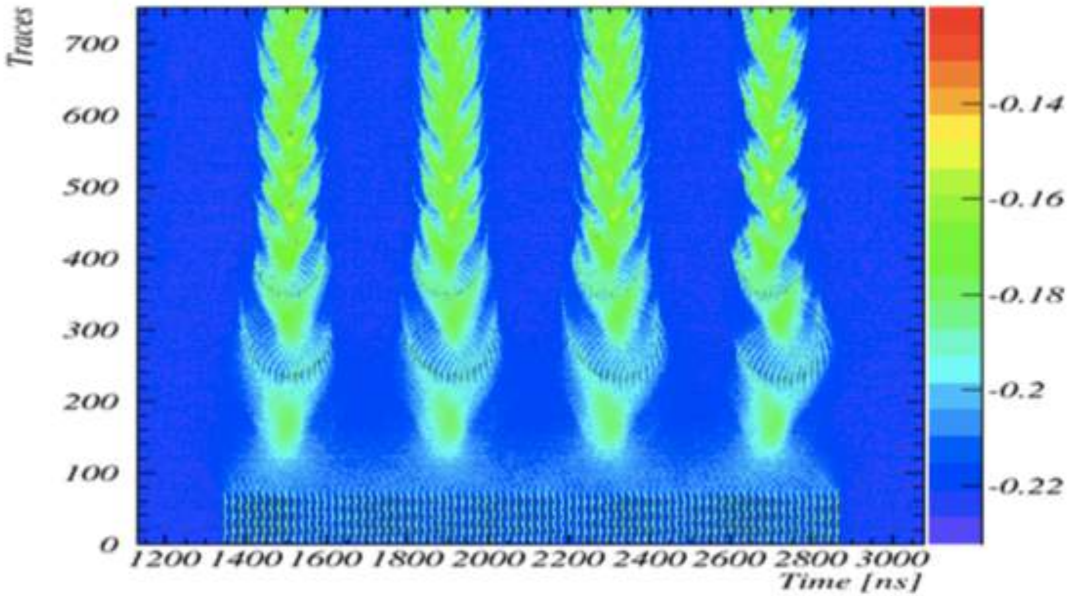
Beamlines all completed on schedule and first 8 GeV proton beam in delivery ring on April-24 2017 & first beam into g-2 ring on May-31

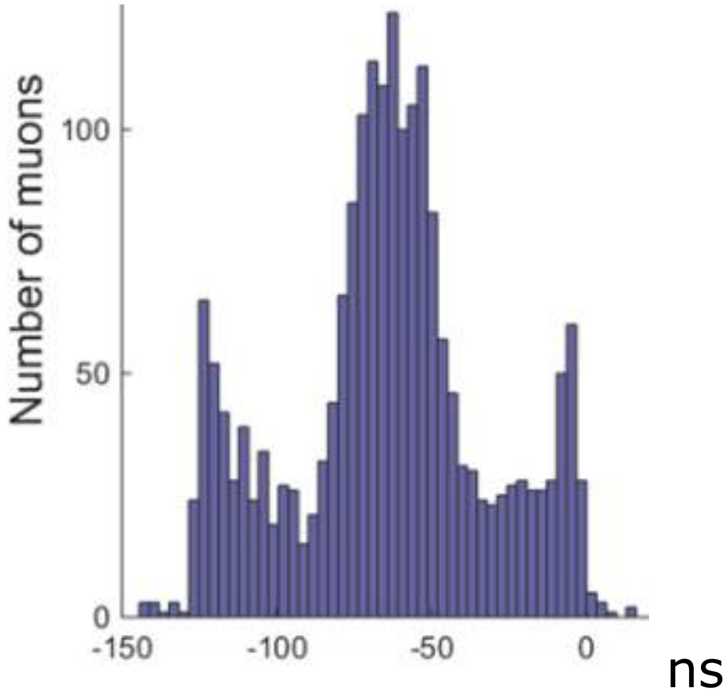




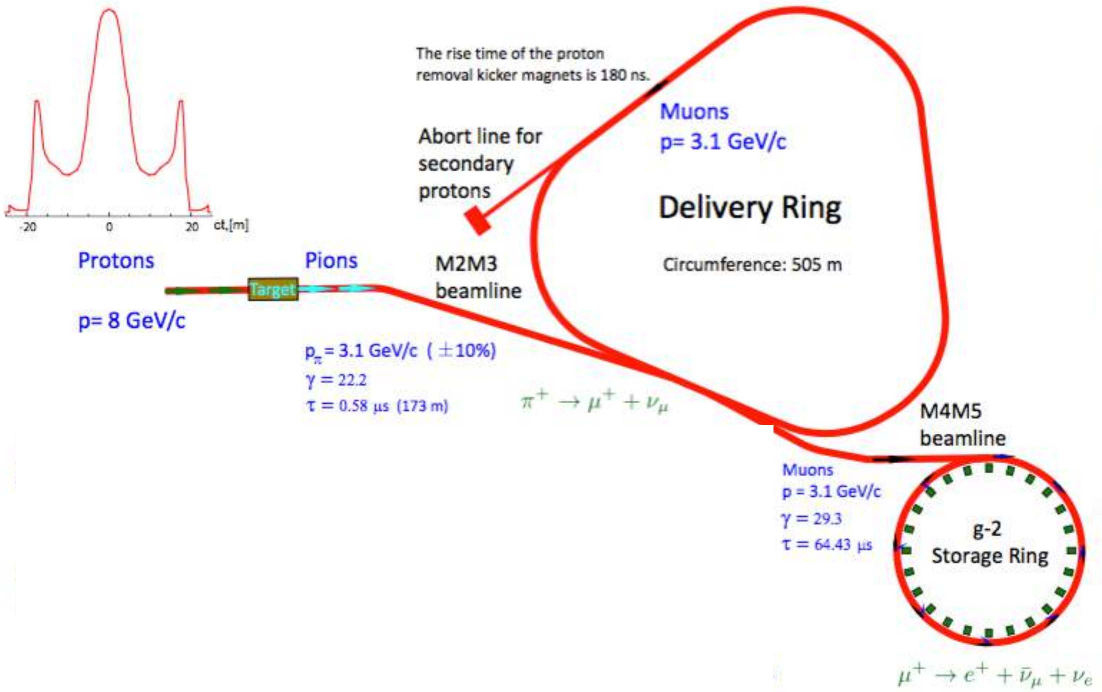
Additional RF in recycler

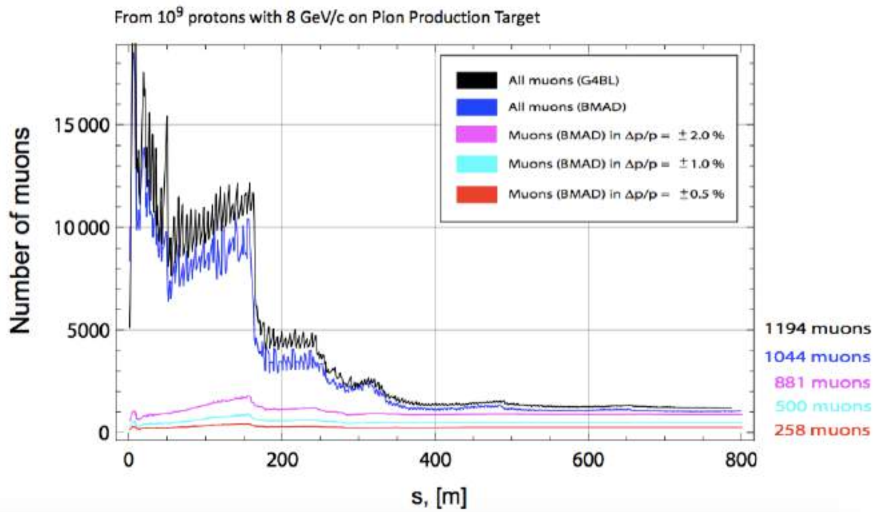
Six 2.5 MHz RF cavities provide 4x120ns wide spills over 1μs every 10ms.

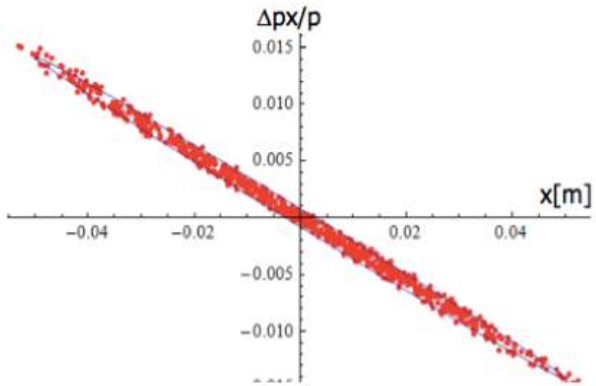




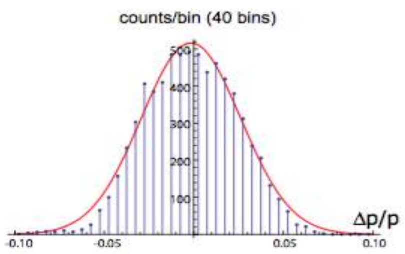
Beamline simulation





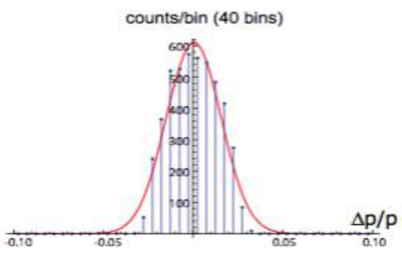


End of M2M3 beamline



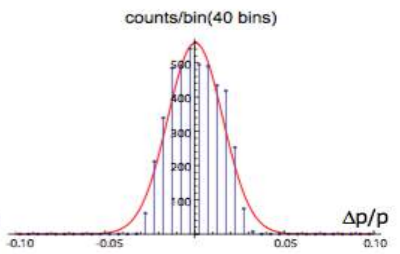
RMS momentum Δp/p: 0.0278

After 1st turn in DR



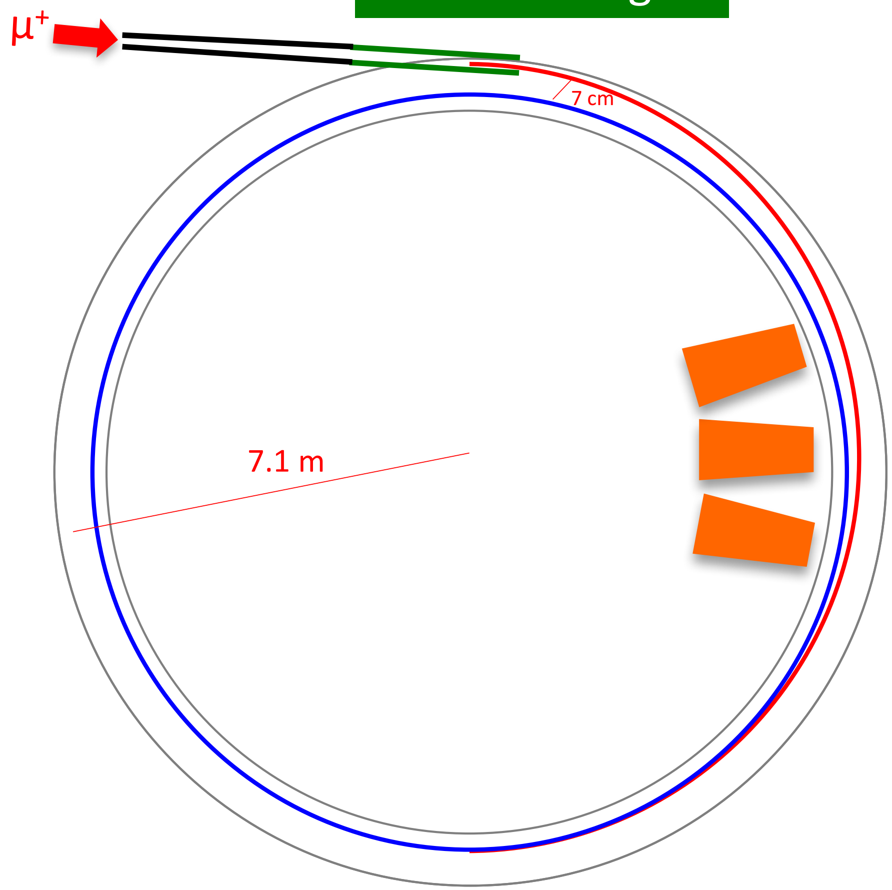
RMS momentum Δp/p: 0.0152

After 4th turn in DR



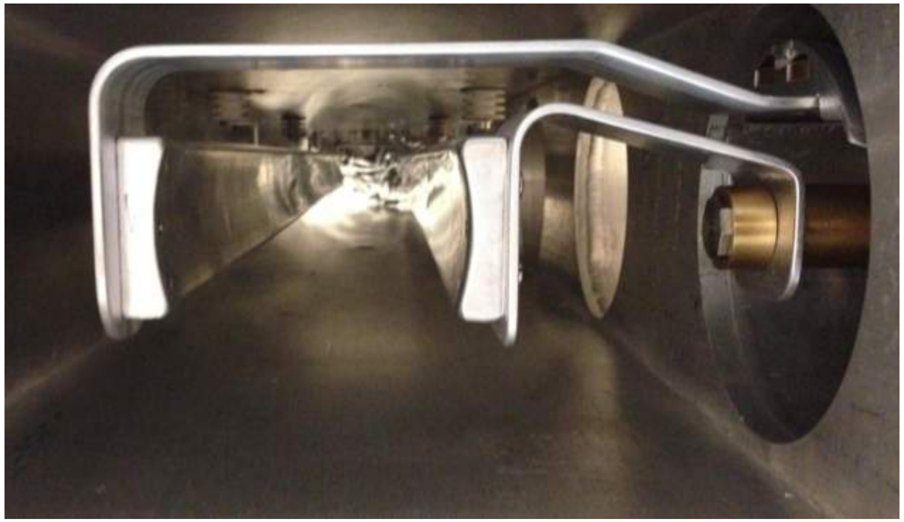
RMS momentum Δp/p: 0.0153

Beam Injection

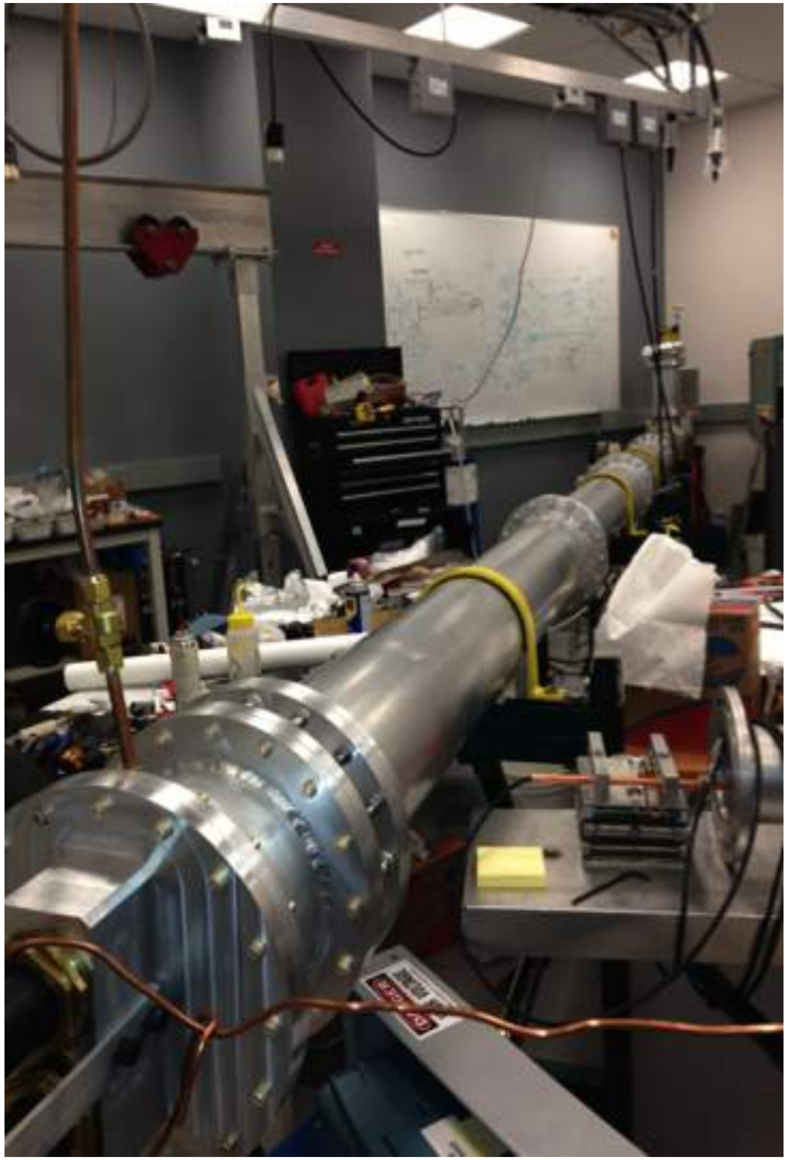


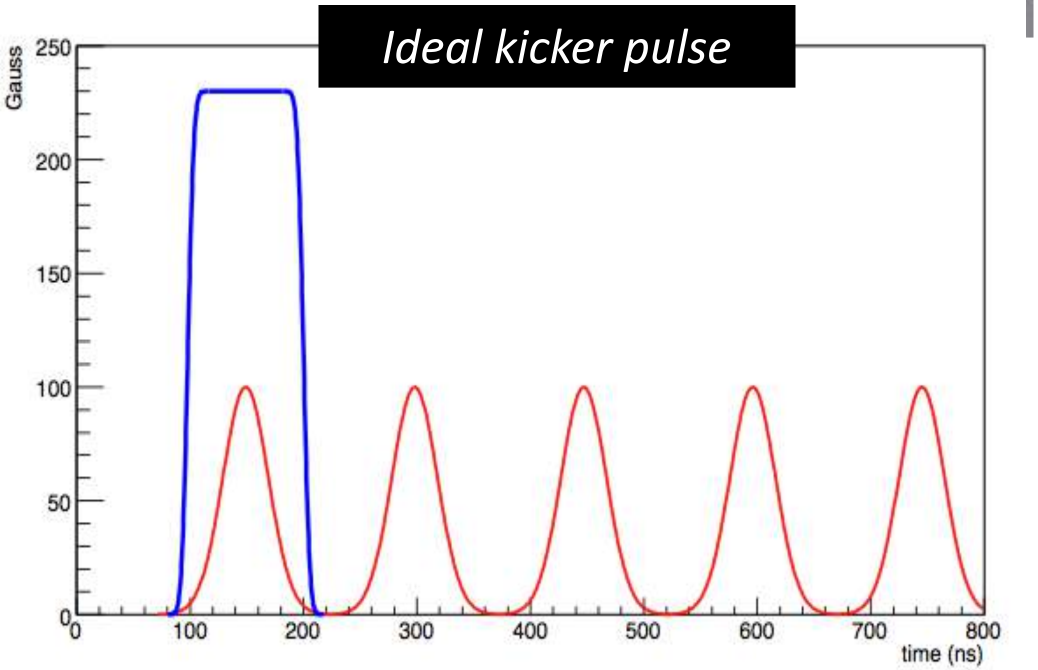
Beam doesn't enter on the correct orbit and needs a kick to get there !

Kicker magnets



Kicker

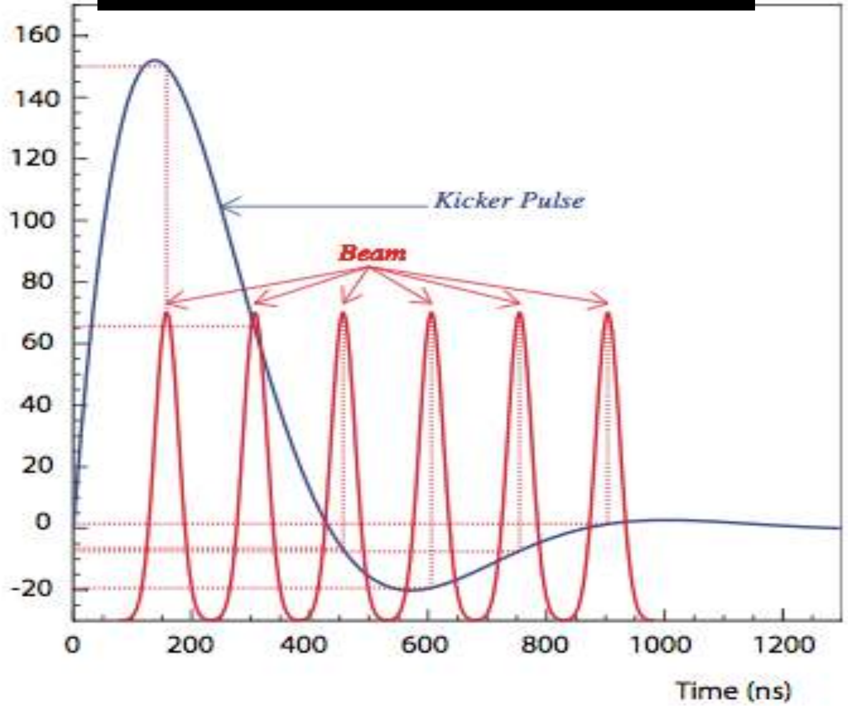




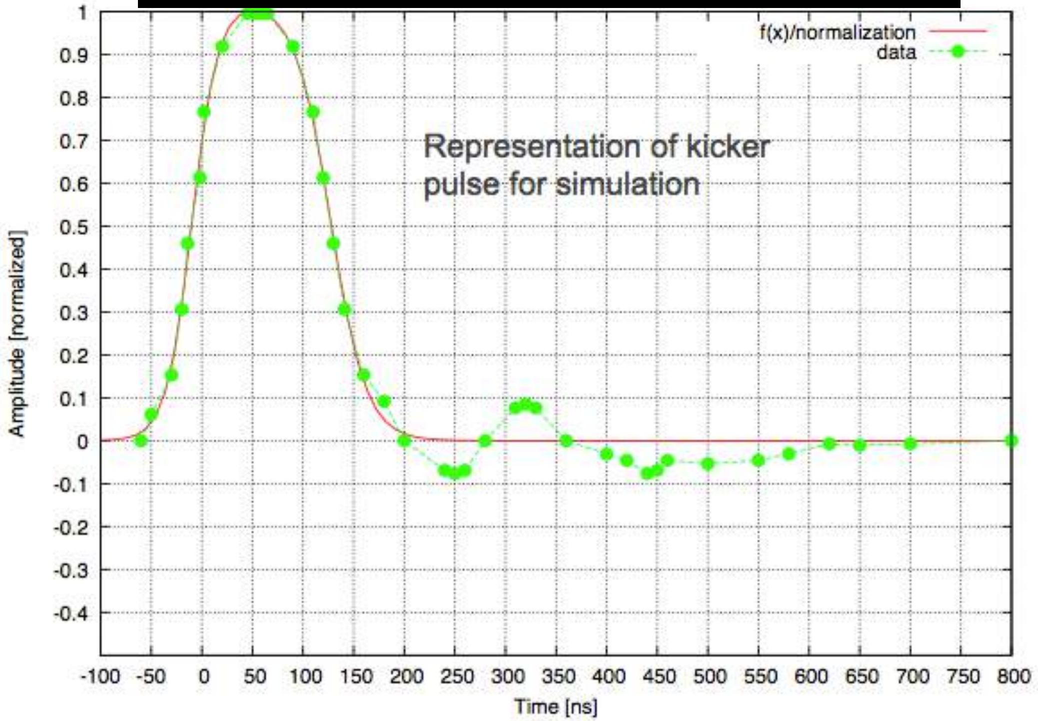
Ideal kicker pulse
Gauss
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
time (ns)

Kicker Pulse

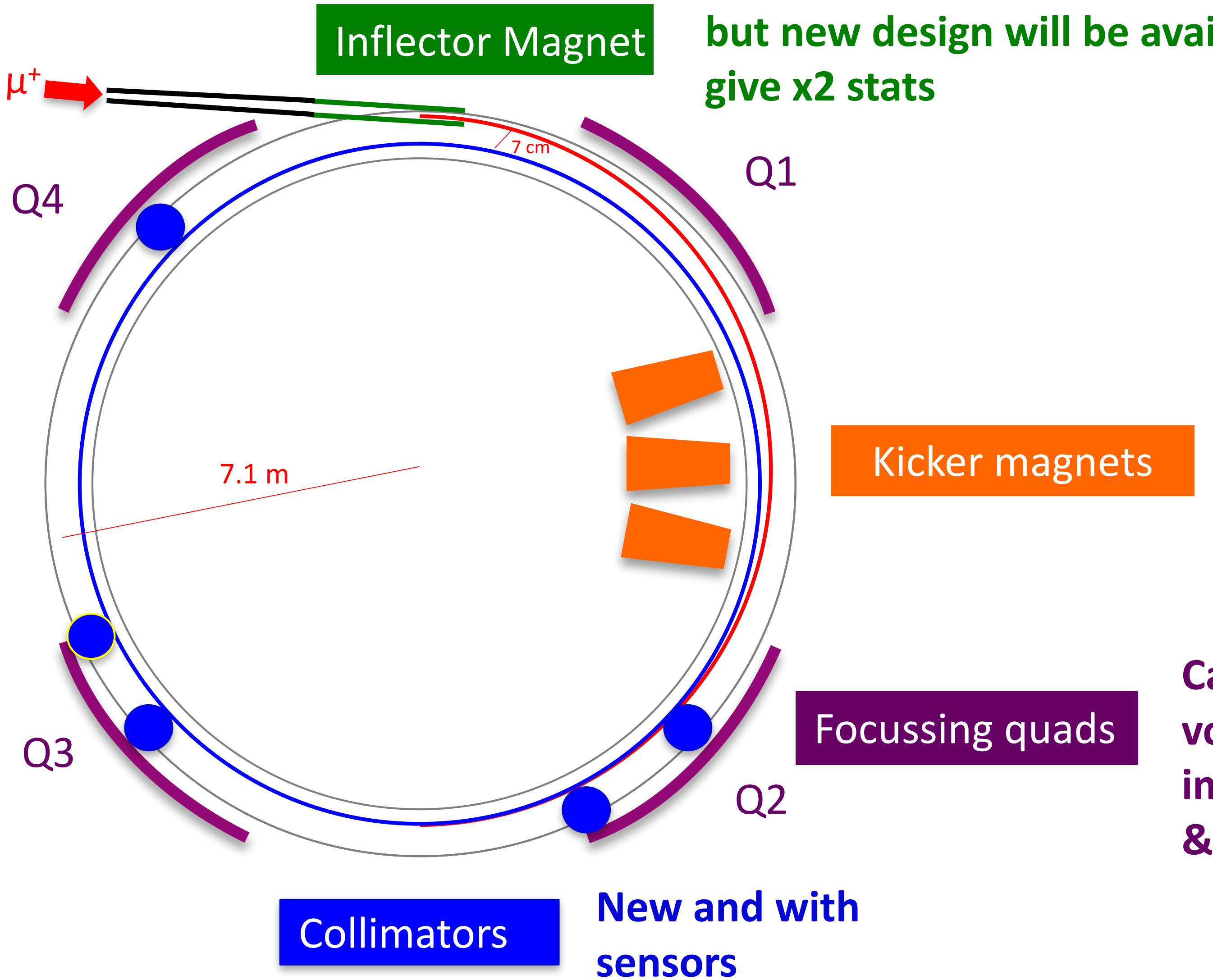
BNL kicker pulse



New FNAL (Cornell) kicker pulse



Improvements to injection system



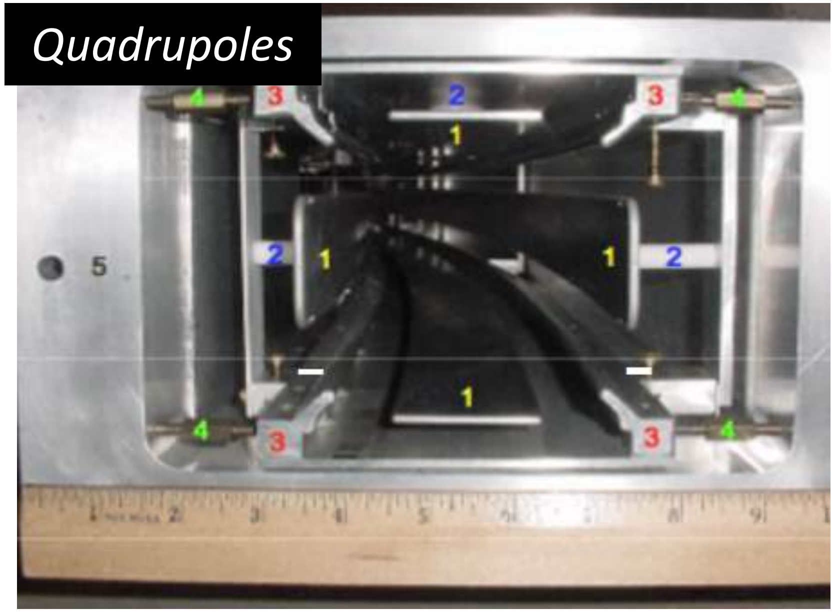
Presently using existing BNL inflector but new design will be available to give x2 stats

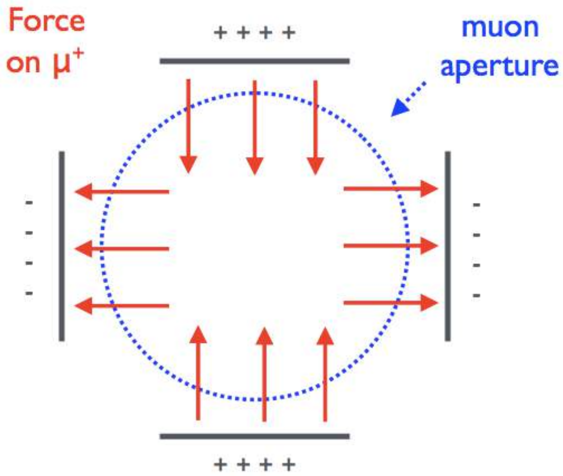
New with improved kick

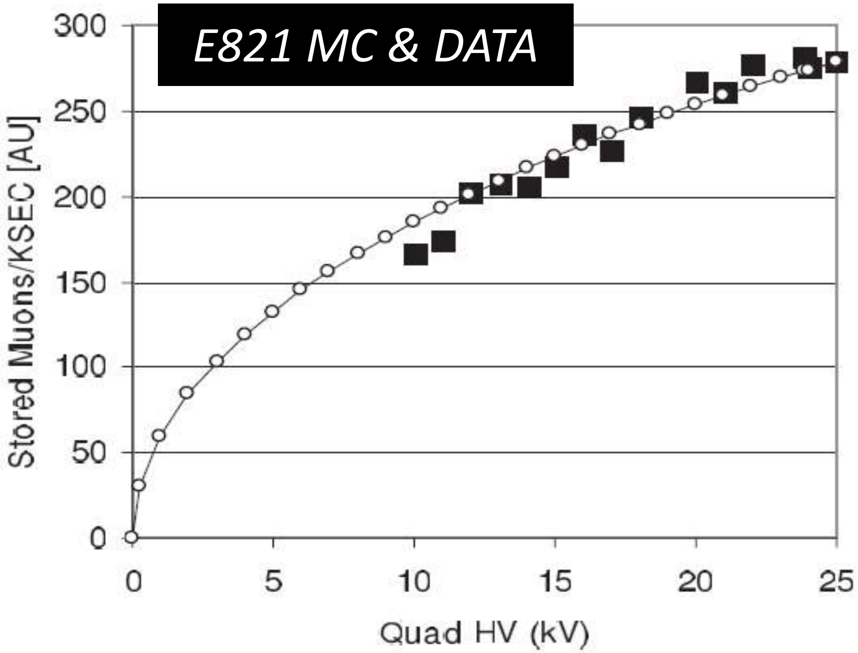
Can go to higher voltage for improved tune & higher stats

New and with sensors

Beam Injection





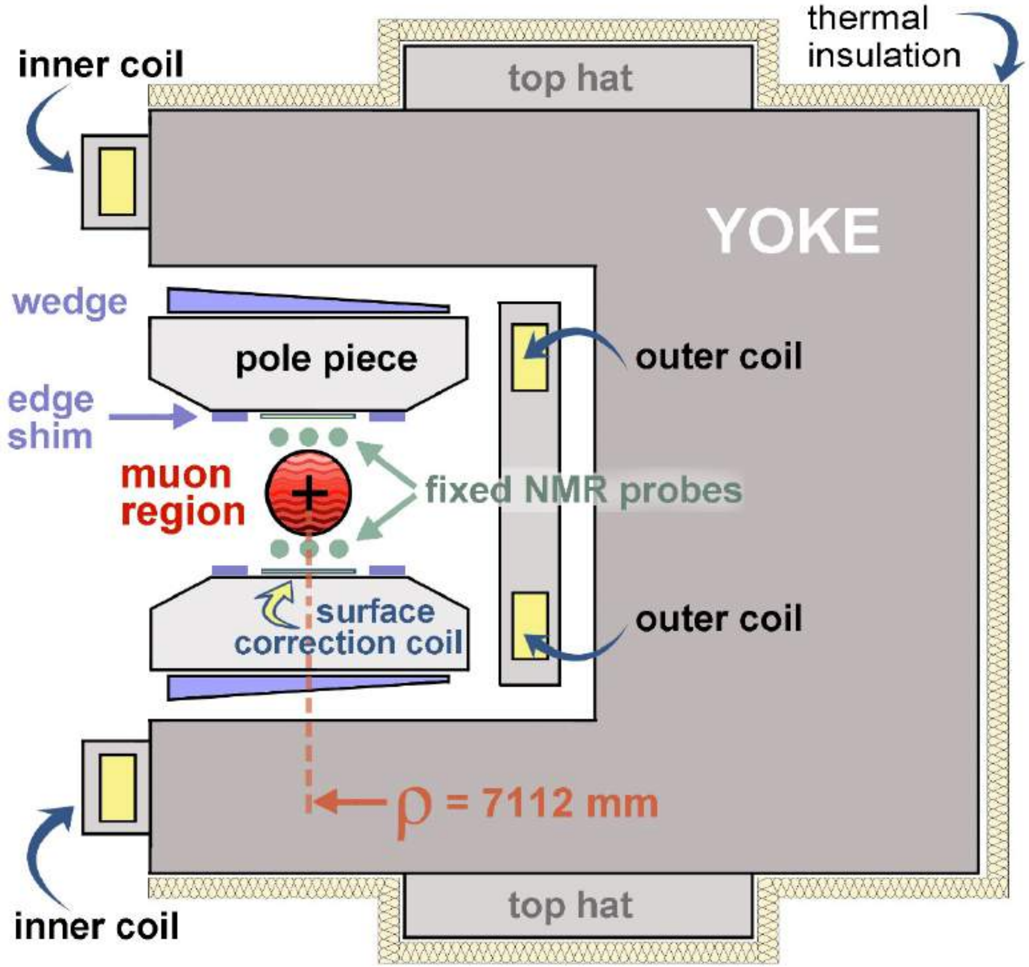


g-2 Magnet

Not simply a coil & 72 pole pieces but:

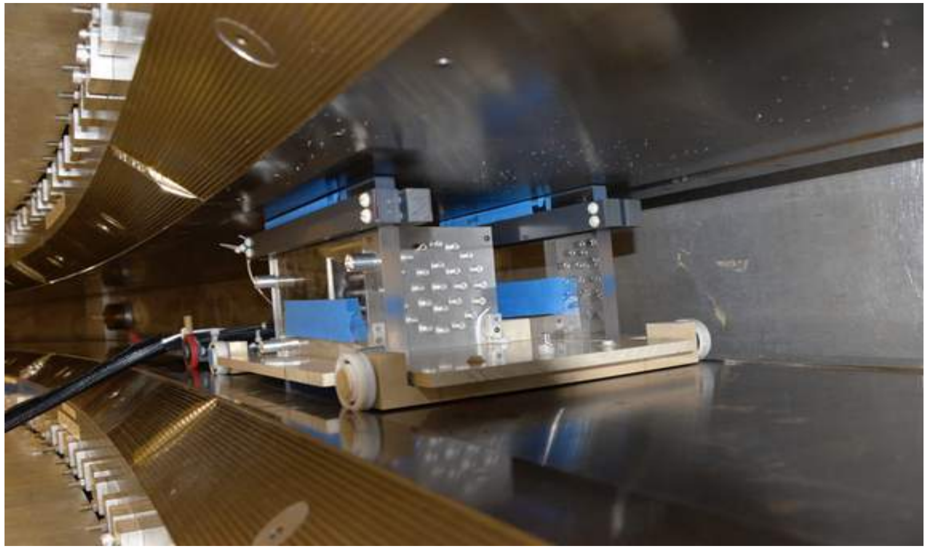
864 wedges
48 iron “top hats”
144 edge shims
8000 surface iron foils
100 active surface coils

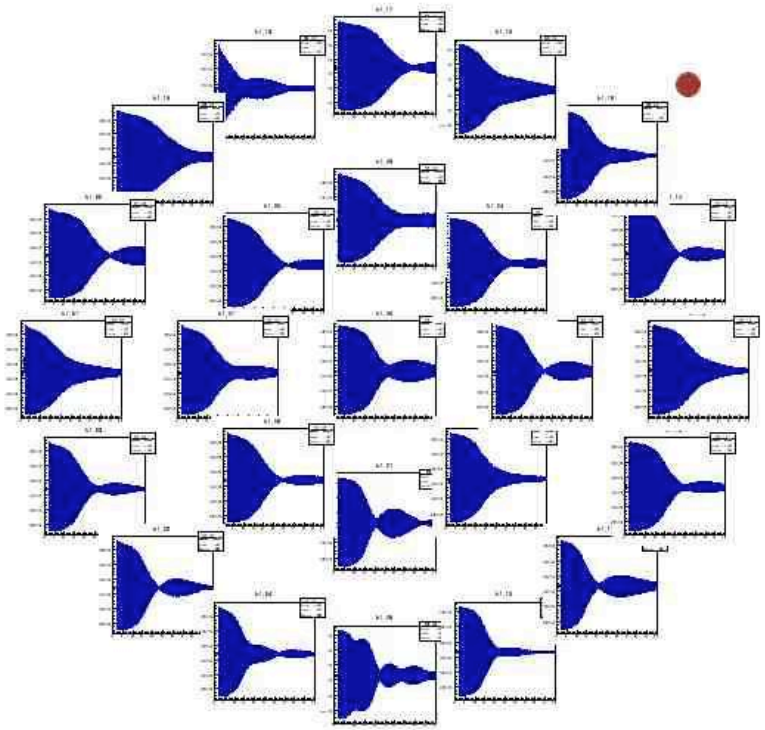
requiring precision alignment & “shimming”

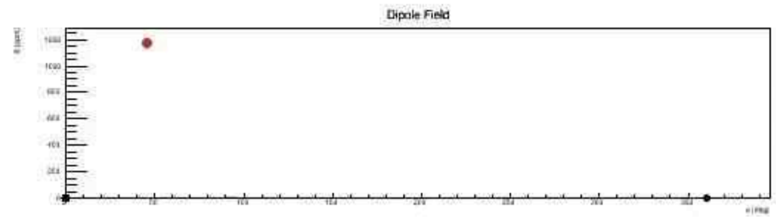


Yoke : 26 tons to 125 microns….

The laminators !

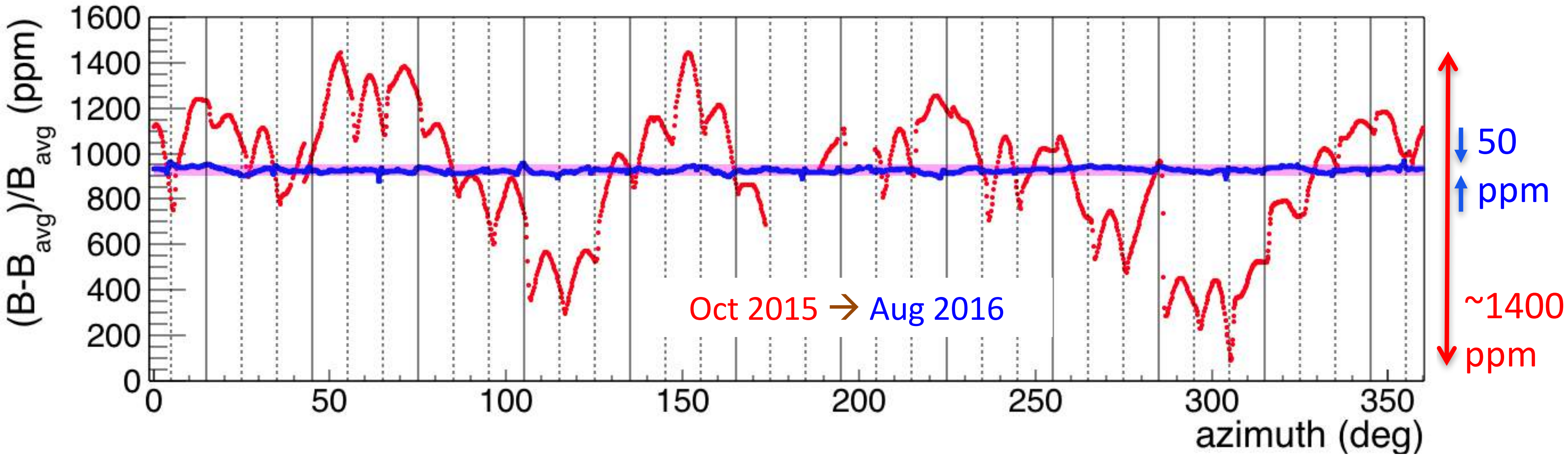






Field Uniformity

Shimming process improved field uniformity x30 over a year

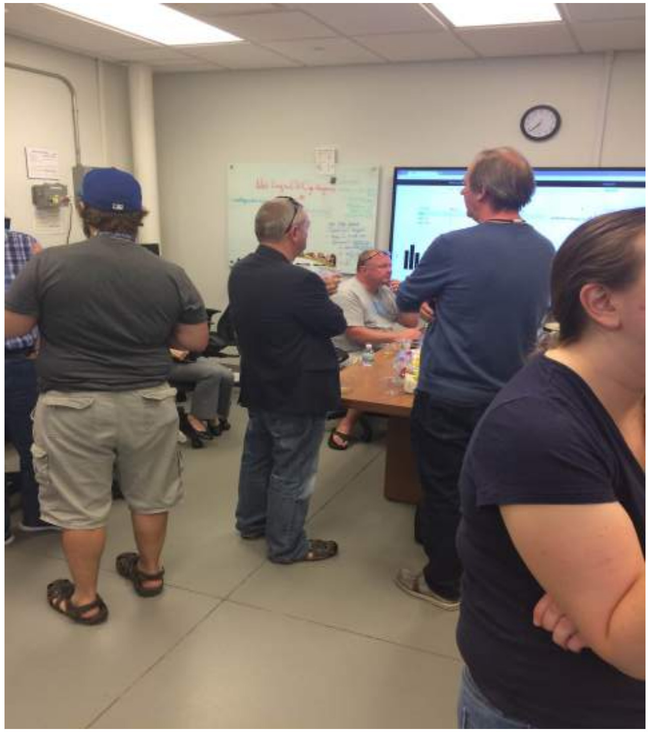


Uniformity x4 better than achieved at BNL after 1st shimming round

First Beam

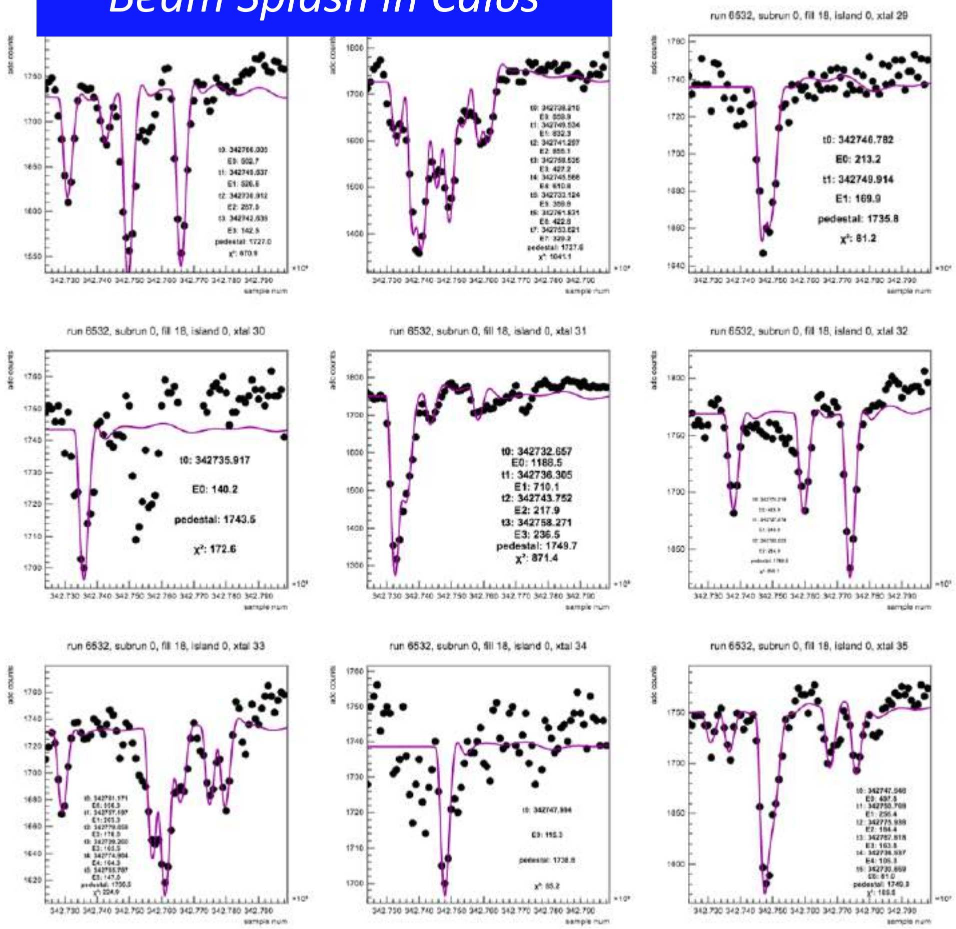
Ground breaking : May 2013
First Beam : May 2017

Project delivered on time and on budget.

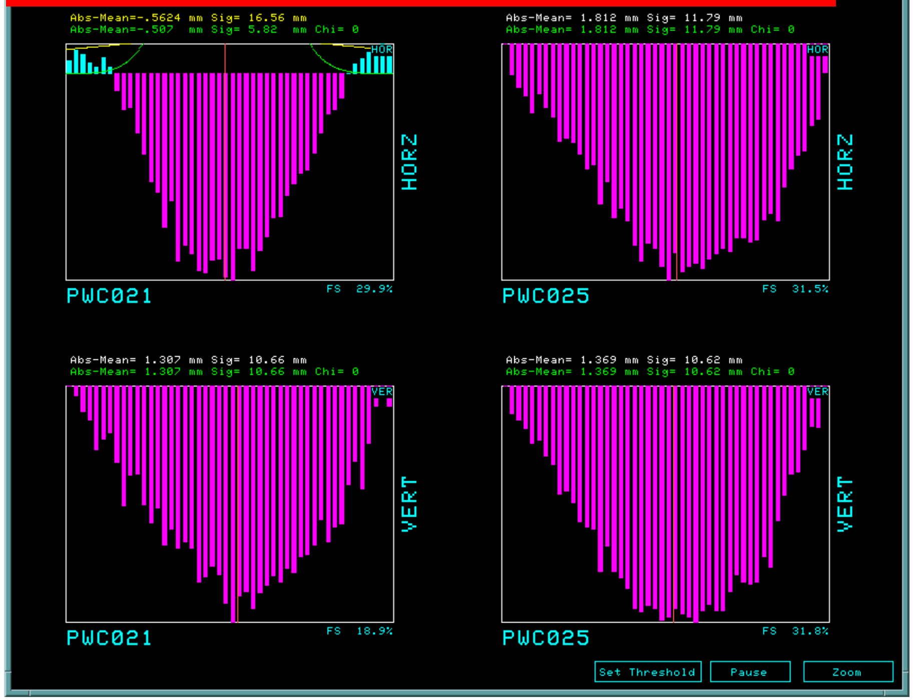


First Beam

Beam Splash in Calos

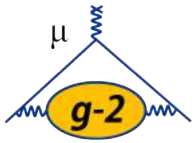


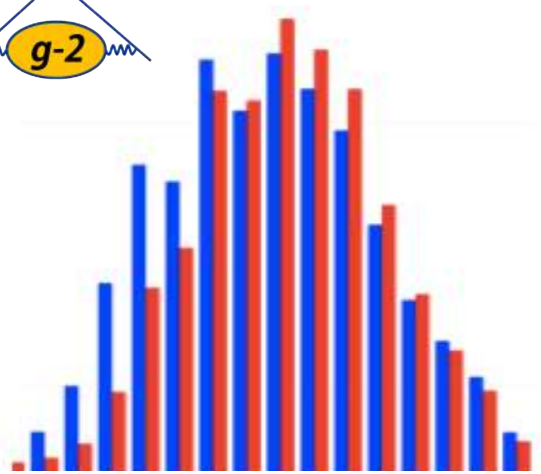
Beam Profile Just Before g-2 Ring



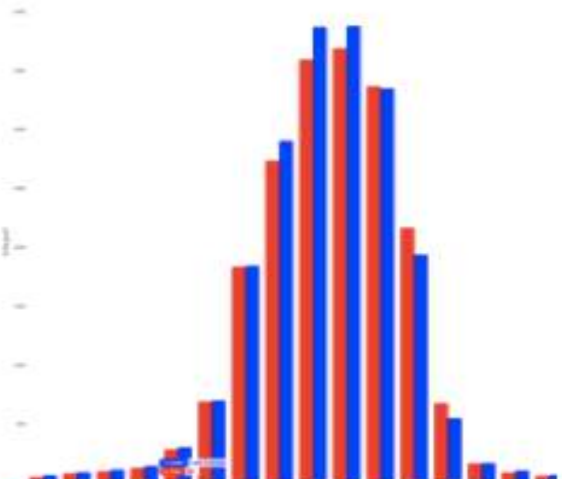
Predominantly protons
& O(1%) muons

g-2 Scintillators in Injection Channel

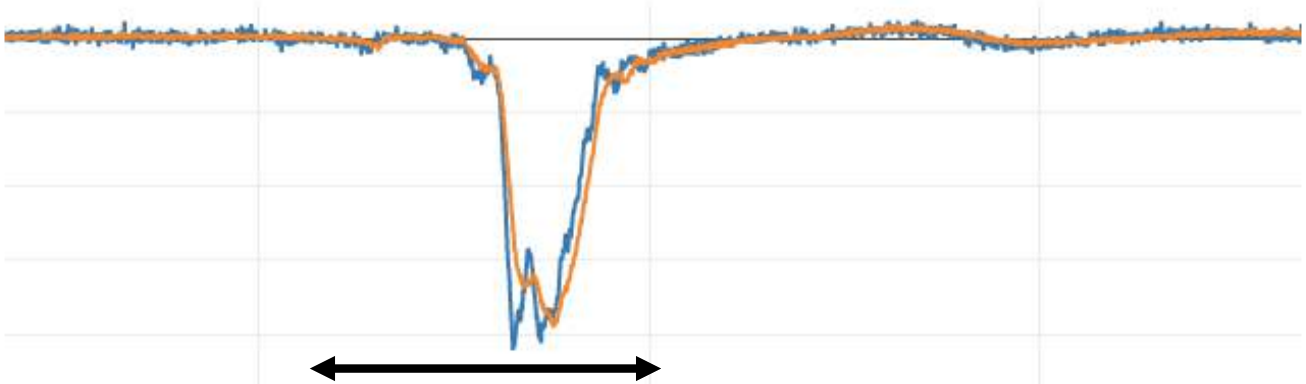




10cm (X)

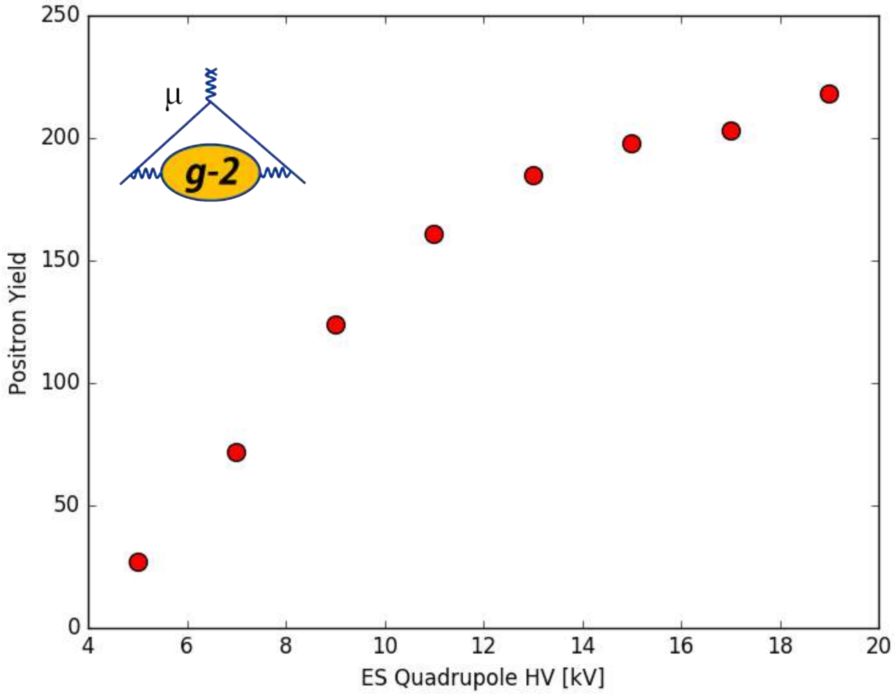


10cm (Y)



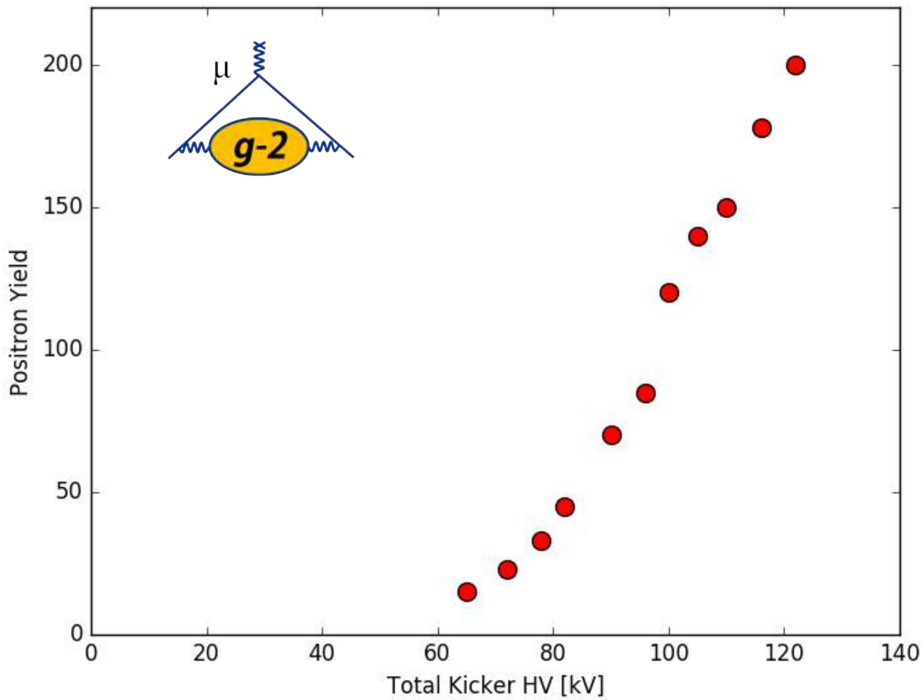
500ns

Beam Storage



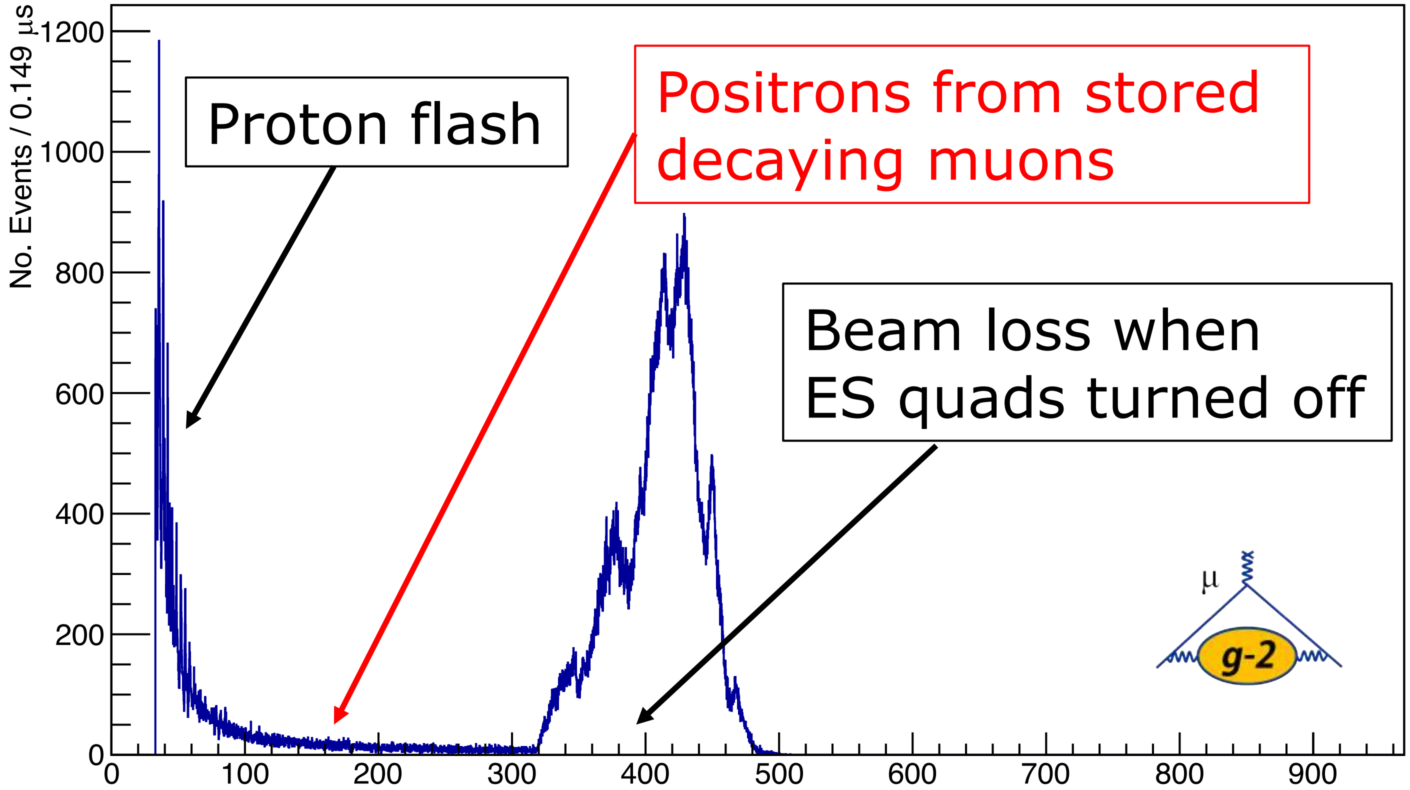
Efficiency (vs HV) of storing Muons in ring very similar to E821 with new quadrupoles and kicker magnet

Measured in last two weeks



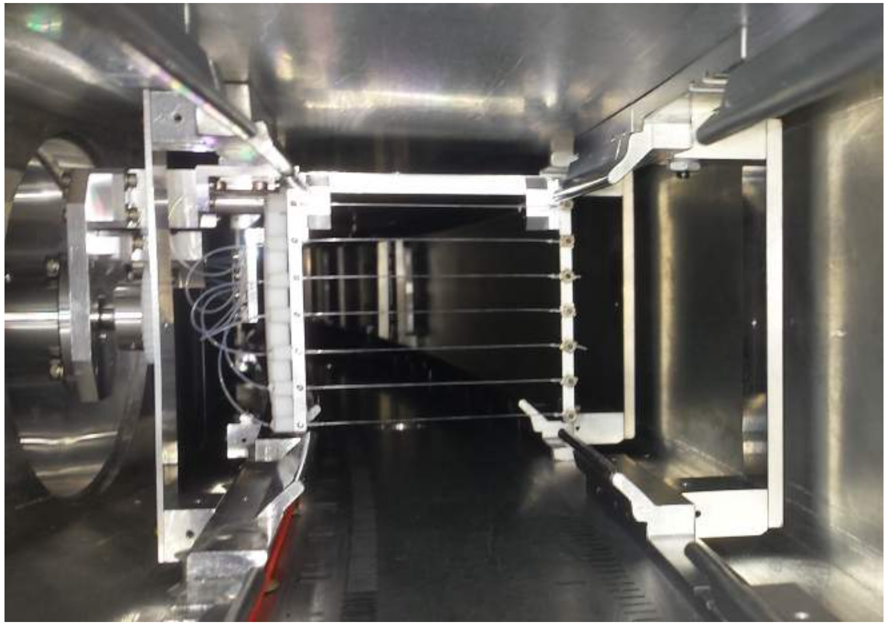
Beam being stored

Storing beam (protons and muons) for several hundred turns

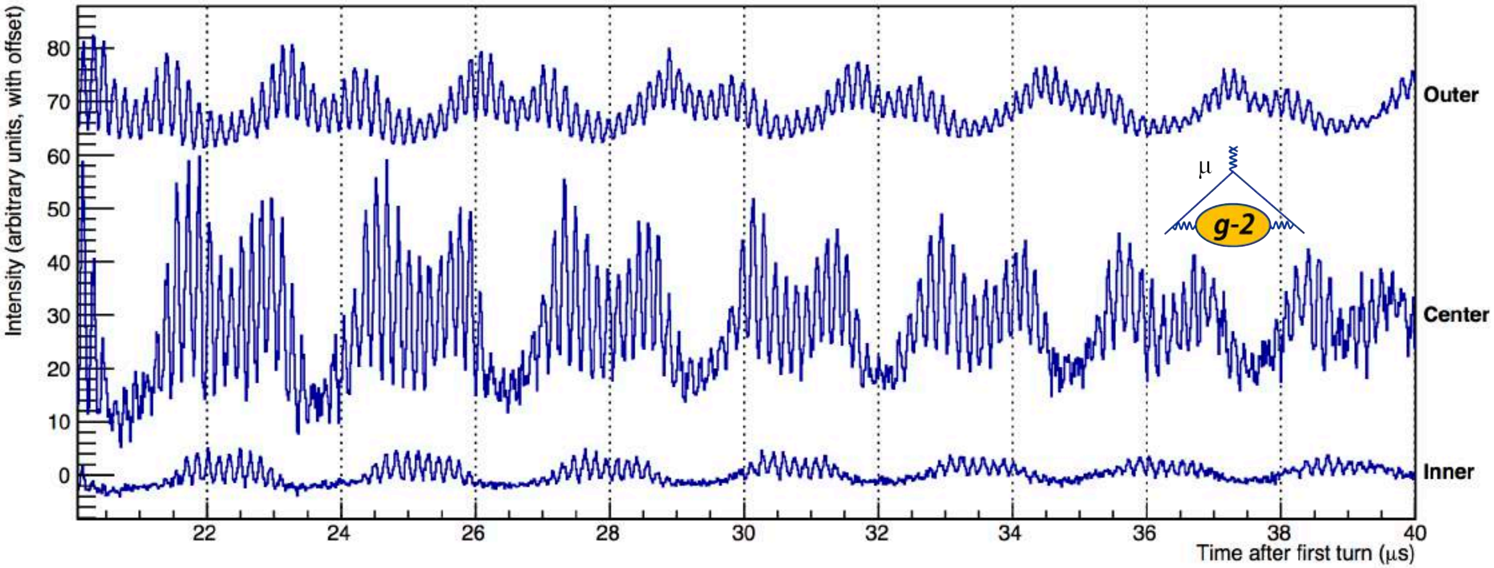


Time (μs) : one bin=one turn

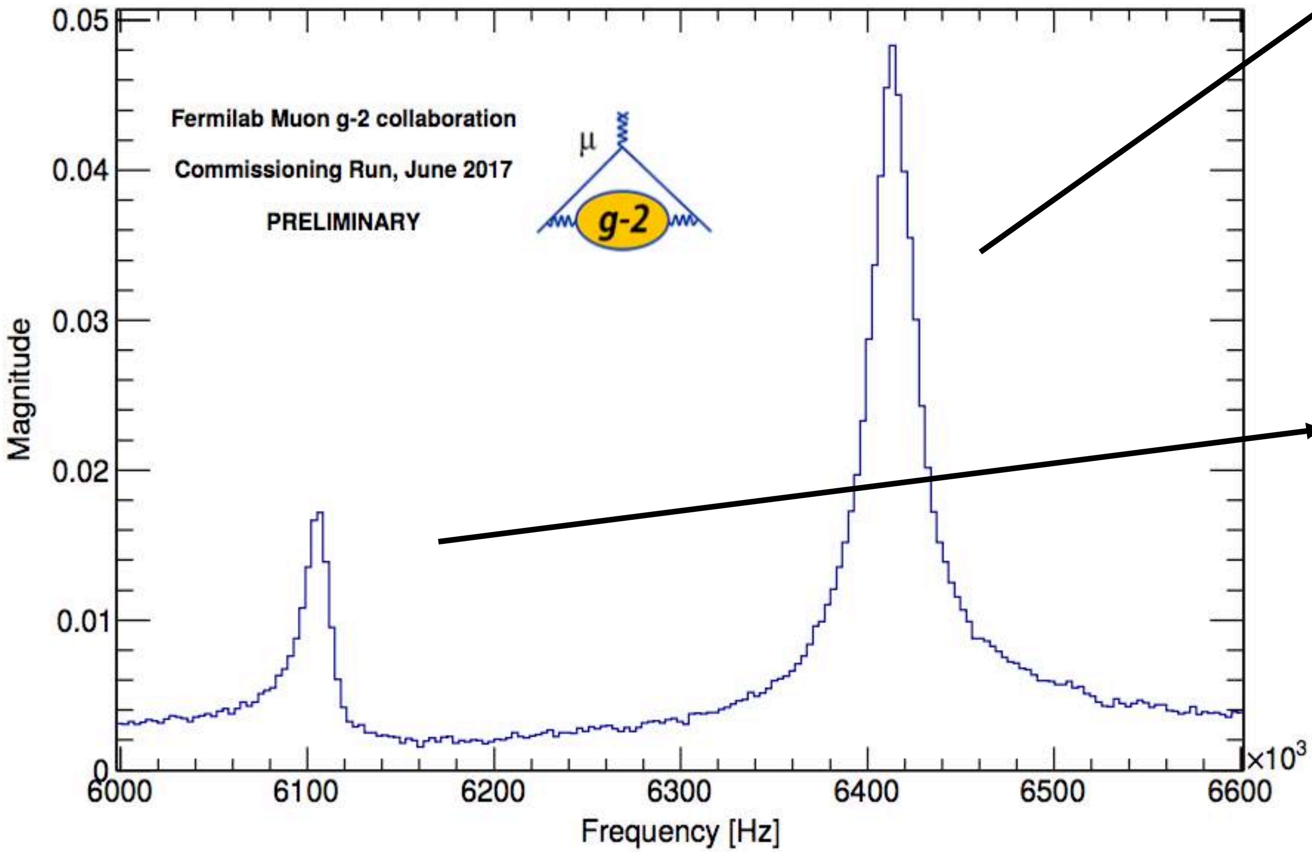
In situ beam measurements



Scintillating fibers periodically measure beam in X & Y



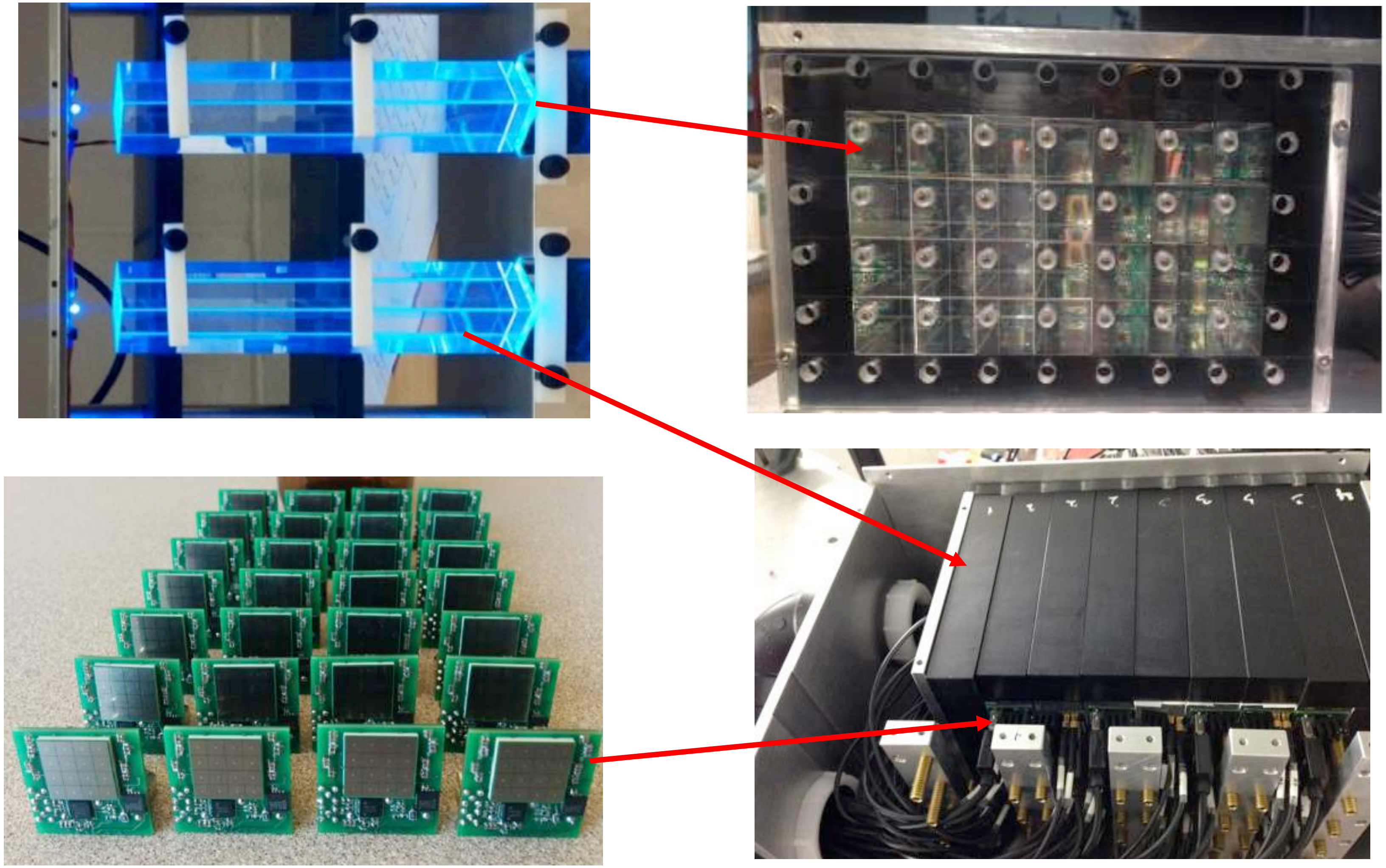
FFT of beam in radial direction



Proton cyclotron frequency

Proton **C**oherent **B**etatron **O**scillation (CBO) frequency

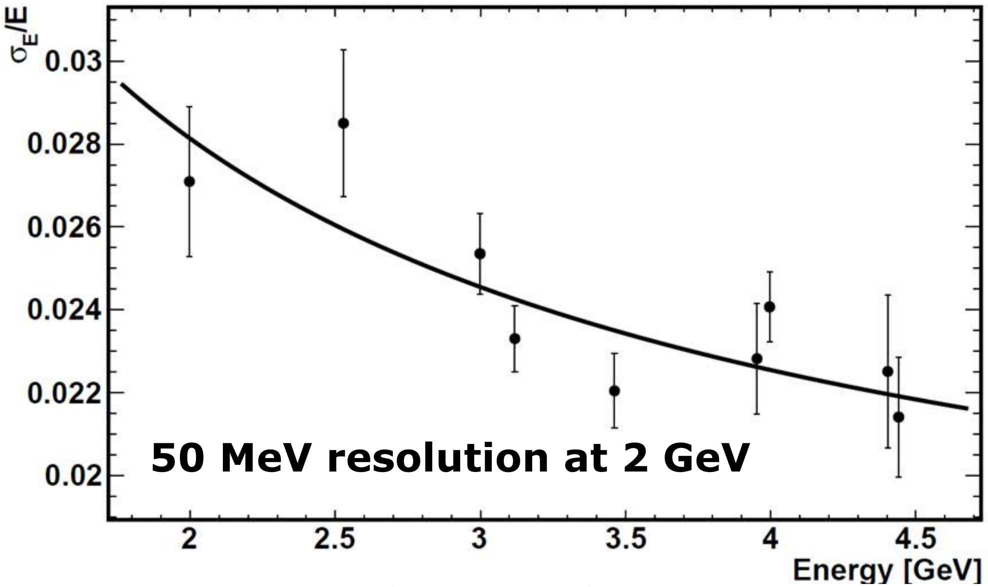
PbF_2 calorimeter



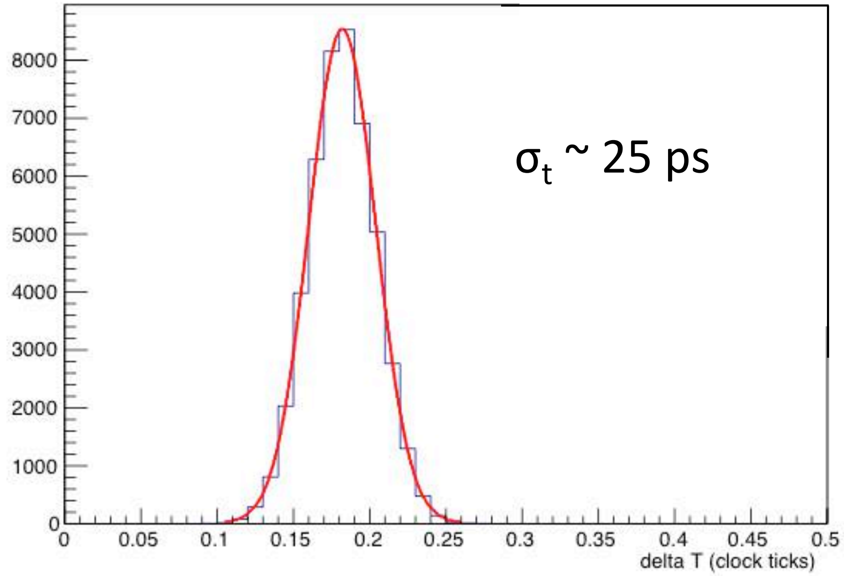
Calorimeter testbeam results

NIM A 783 (2015),

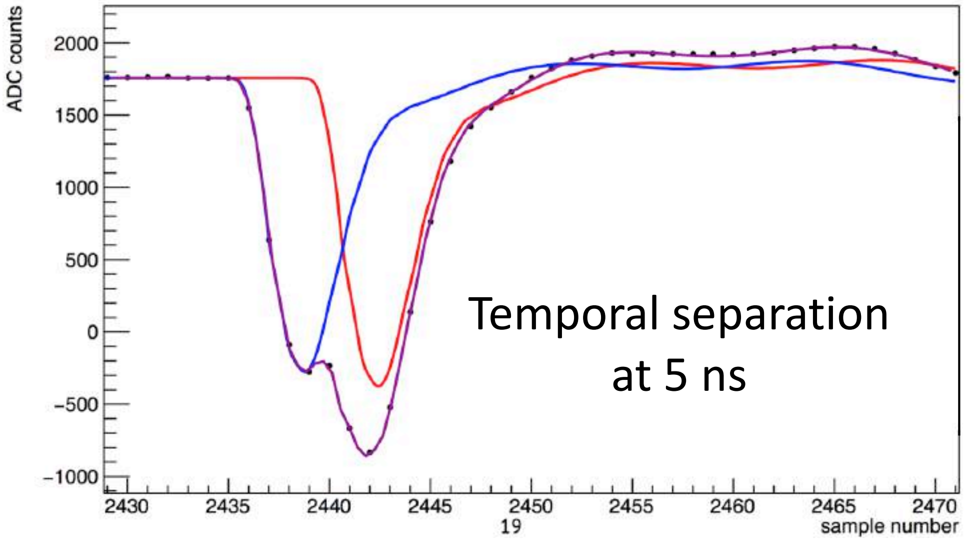
Energy Resolution



Timing Resolution

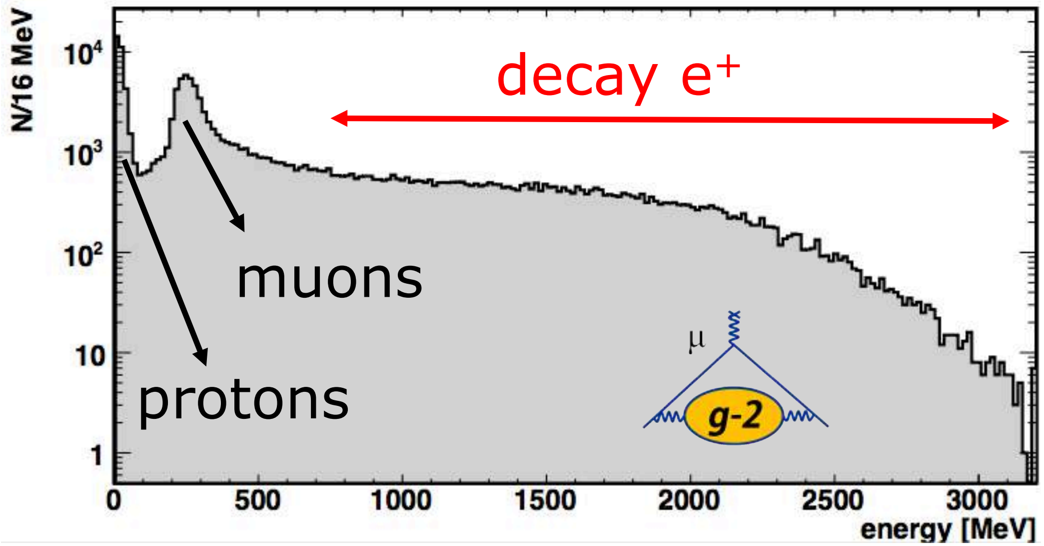


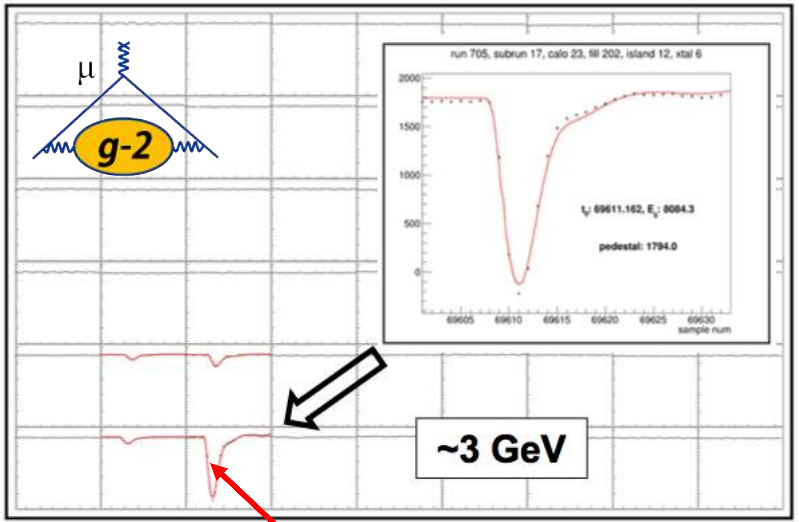
Electron pile-up



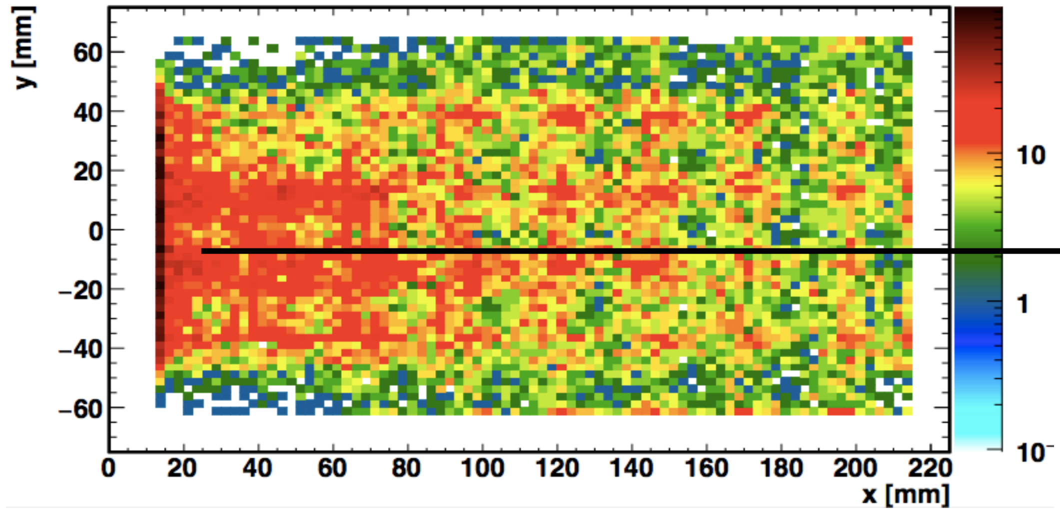
Laser Calibration System

Calorimeter g-2 beam data

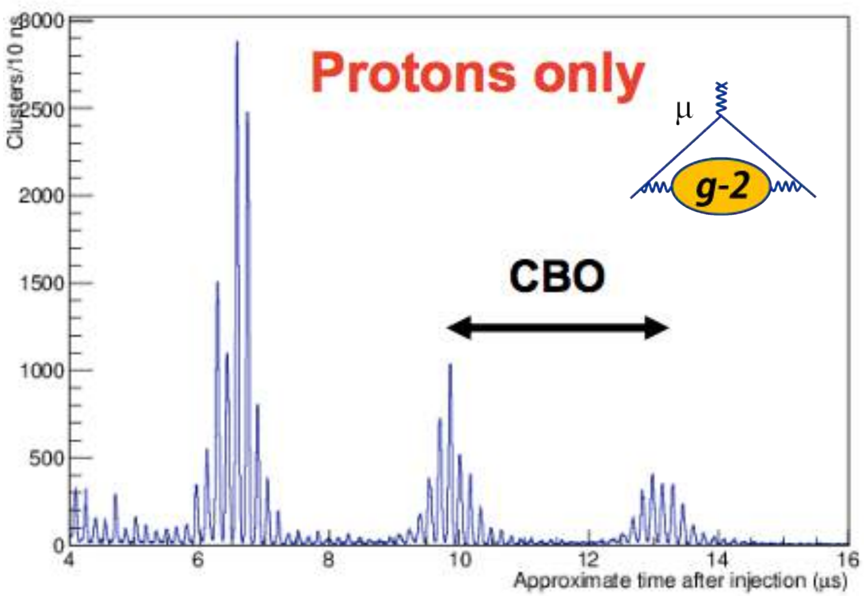




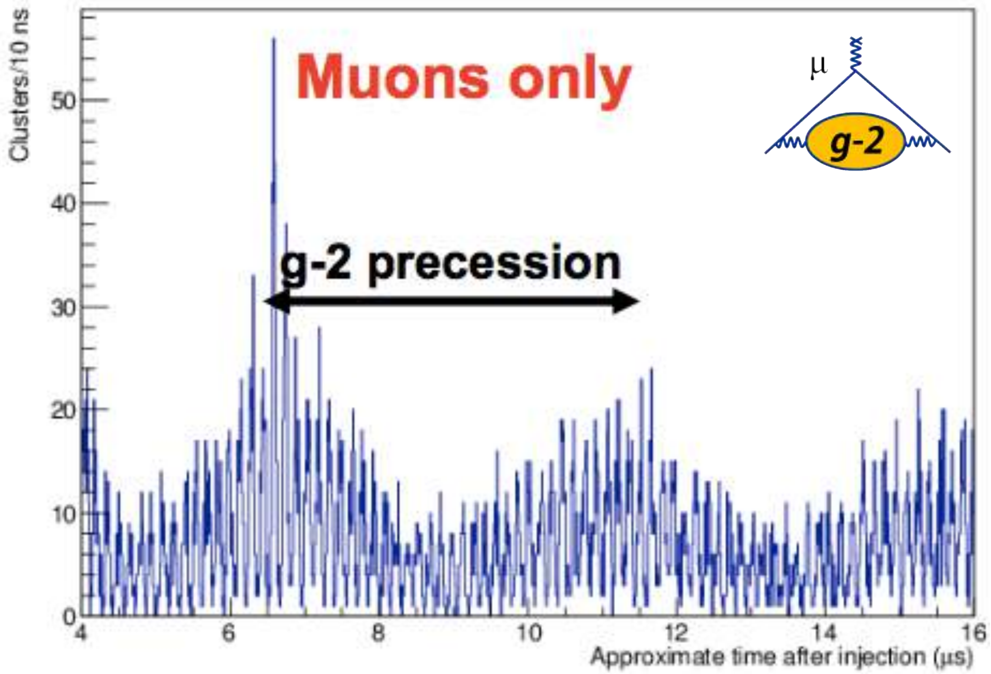
3 GeV e^+ in single crystal



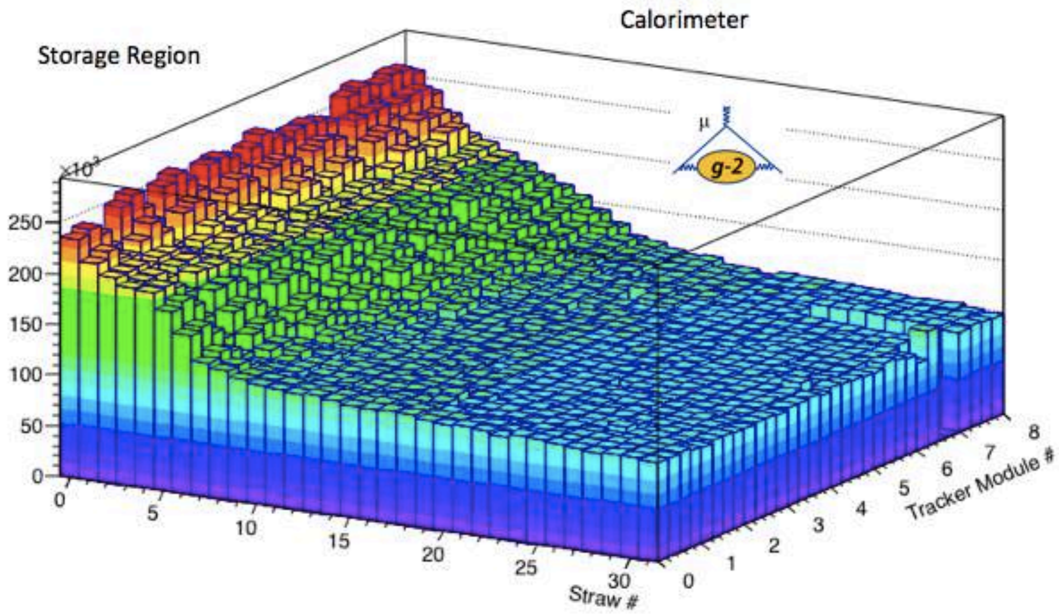
Majority of particles measured at small radii closest to beam

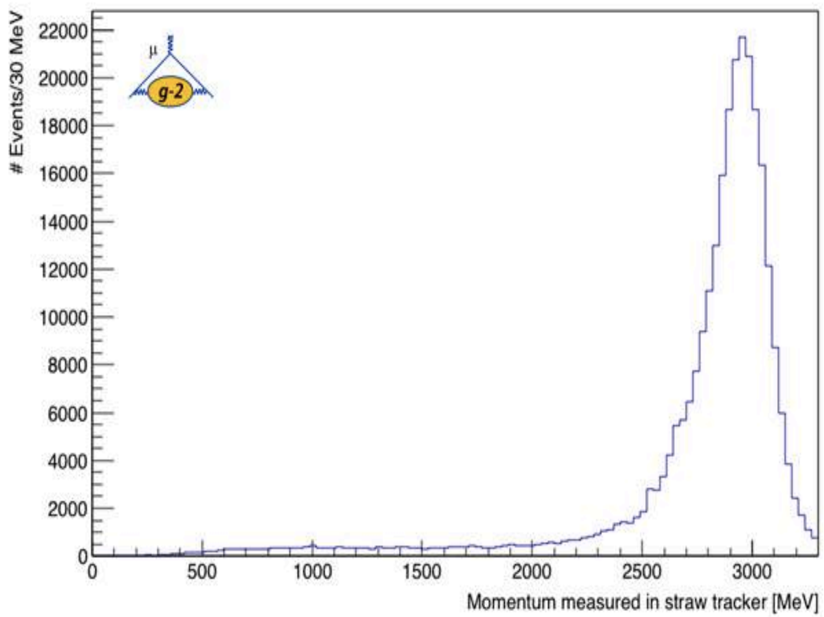


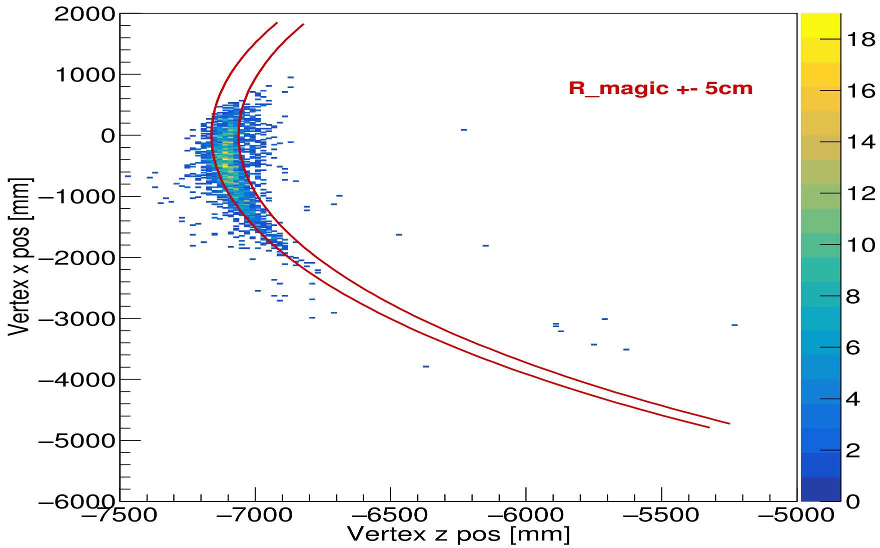
Observing radial motion of beam & characteristic "wiggle" of g-2

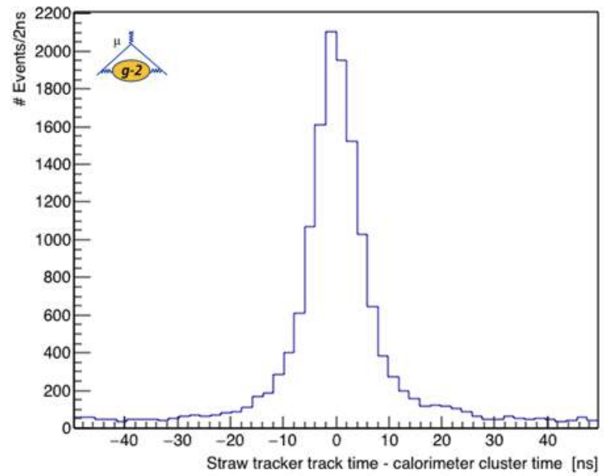


Straw Trackers



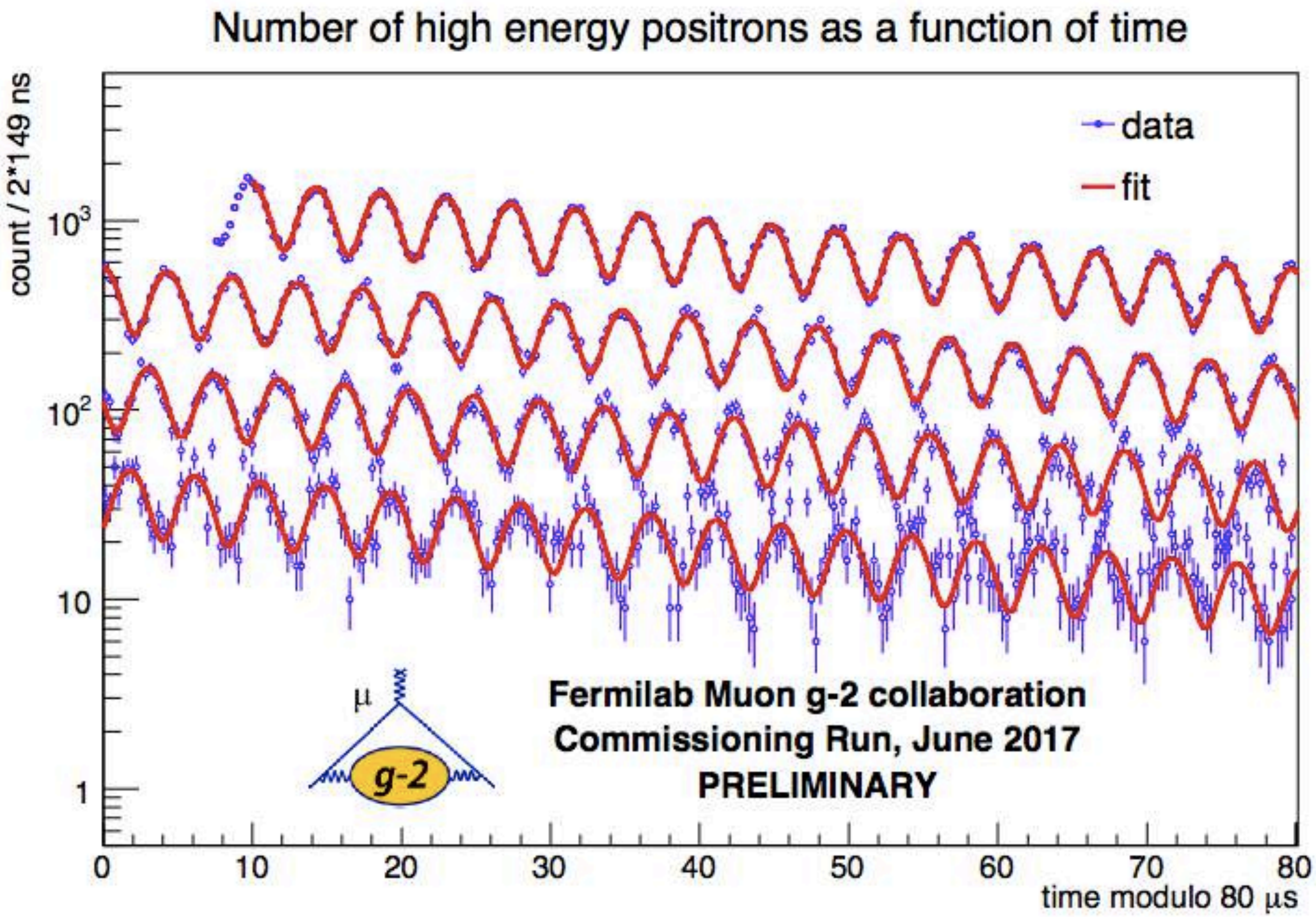






First "wiggle" plot….

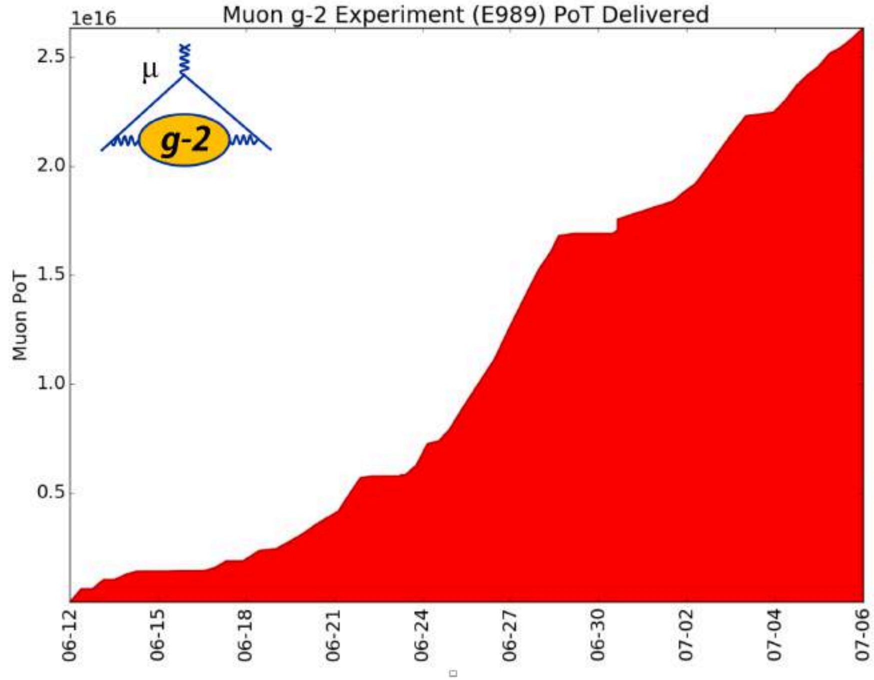
4 years after groundbreaking, g-2 is now taking data.
1st commissioning run completed & shows that everything is working

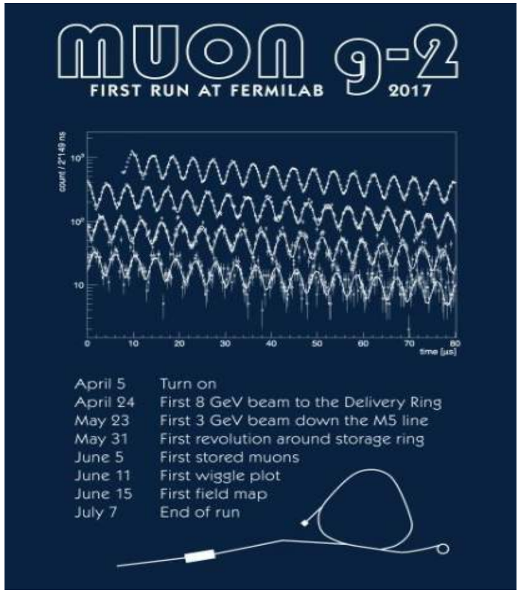


10^{-5} of final stats !!

Outlook

Physics running starts in November and BNL dataset within 6 months.
Dataset x20 of BNL will be accumulated through to June 2019.





We should be presenting a result at the next EPS !

Backup

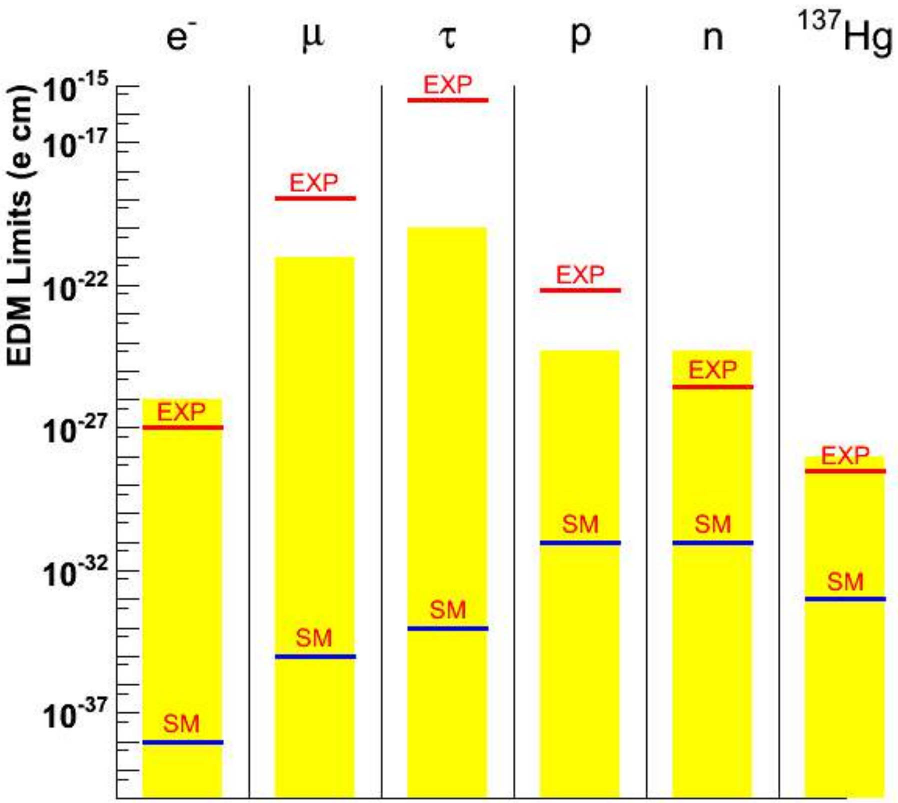
FNAL B-field / ω_p systematics

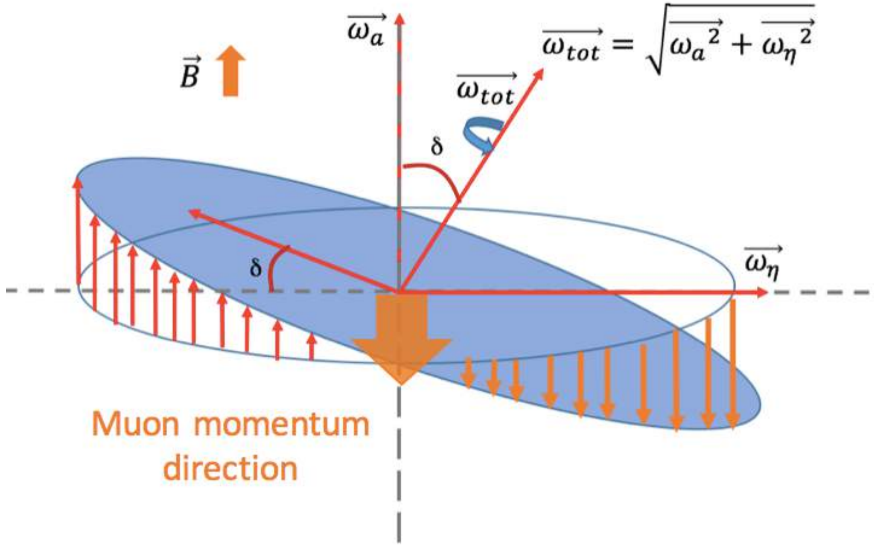
E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better 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

FNAL ω_a 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

Essentially zero in SM : any observation is new physics



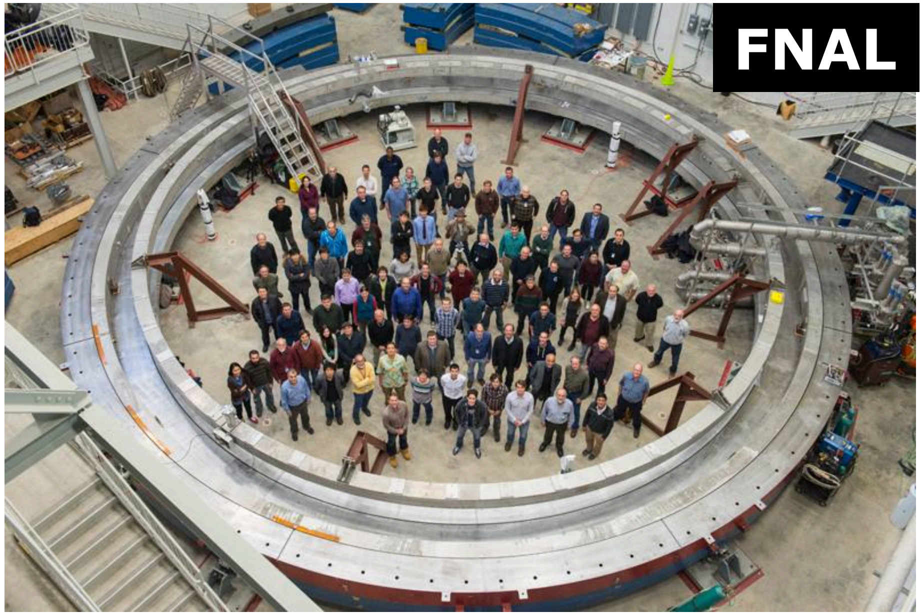


Expect several billion events in the trackers and so reach 10^{-21} vs 2×10^{-19} at BNL

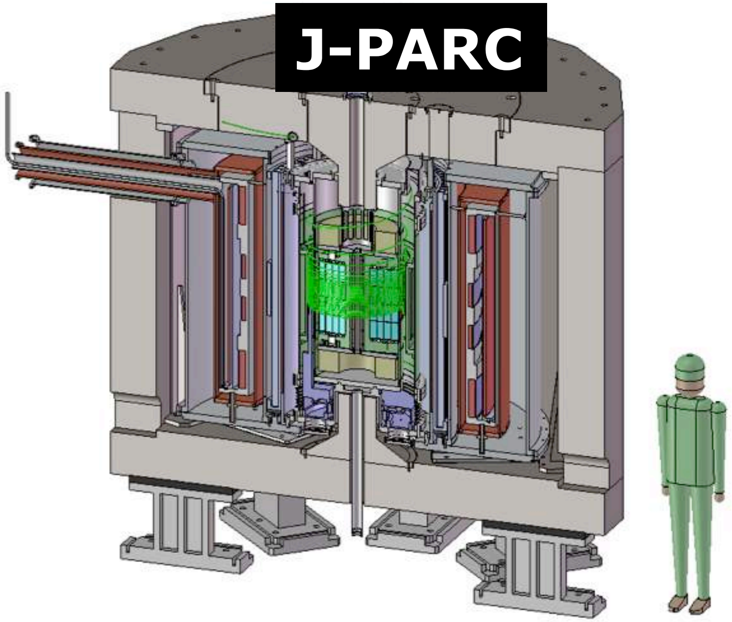
Needs non mass-scaling BSM effects to be in expt's reach given e^- EDM limit

J-PARC Status

Two very different experiments



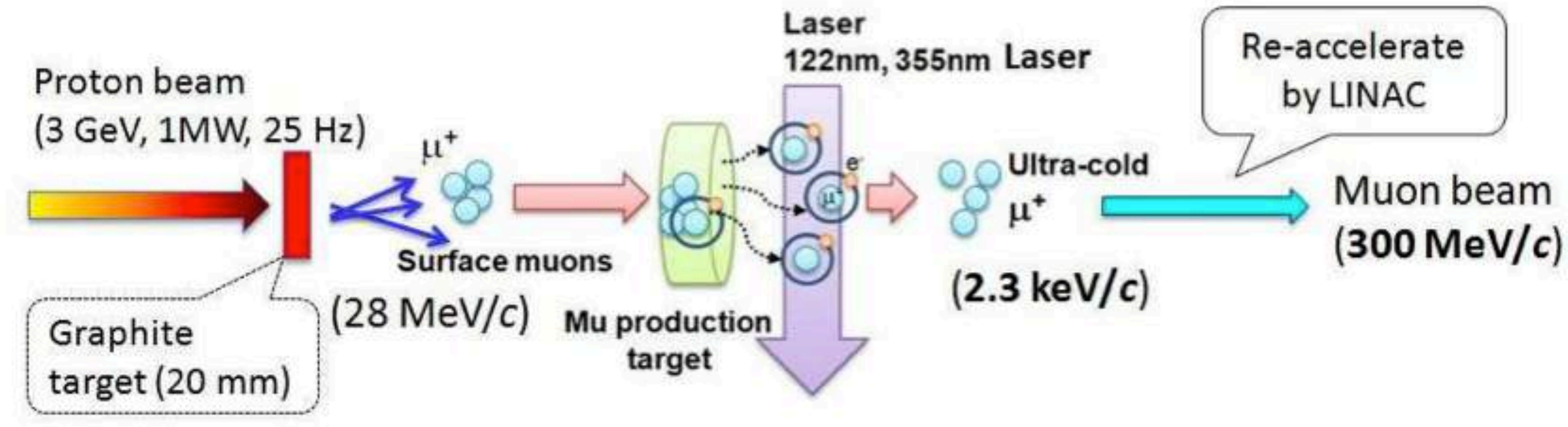
3.094 GeV muons
1.45 T, 14m bespoke magnet
Focussing quadrupoles
Kicker magnets
Emittance: 1000pimm



0.3 GeV muons
3T, 66cm MRI magnet
$\Delta p_T / p_T = 1e\text{-}5$

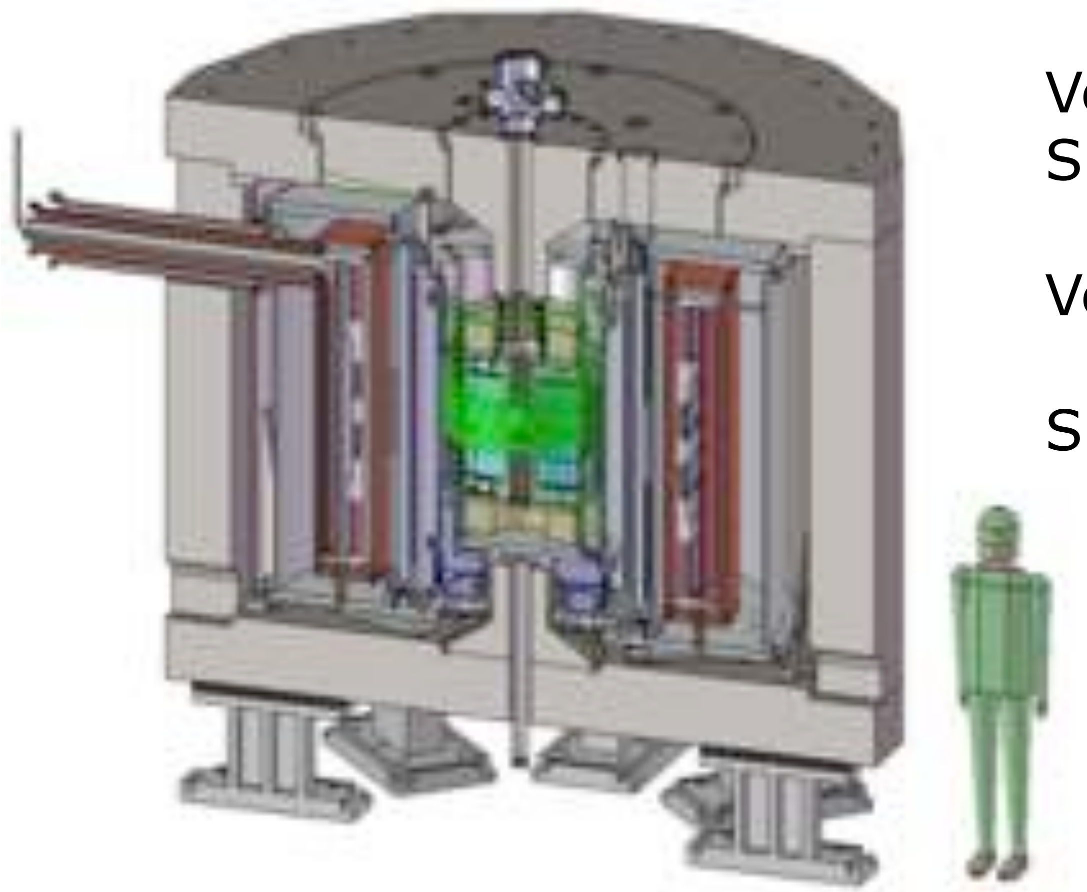
Apparatus and hence systematics are very different

J-PARC g-2 Experiment



Requires several innovations to achieve 10^6 muons/sec
- production of sufficient muonium using special materials
- pulsed 100 μJ VUV lasers to ionise muonium
- muon linac keeping $\Delta p_T/p_T < 1e\text{-}5$: world's 1st muon accelerator !

MRI magnet and Si detectors



Very precise tracking using
Si detectors

Very uniform field (MRI magnet)

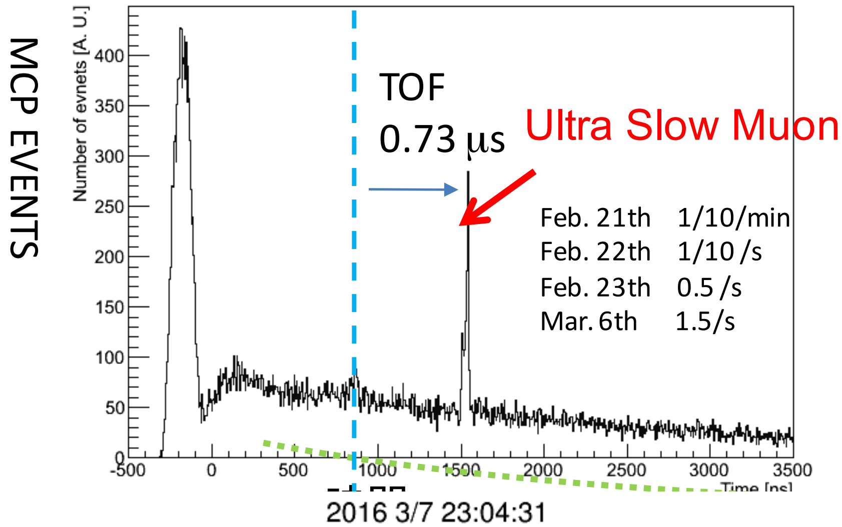
Spiral 3D beam injection !

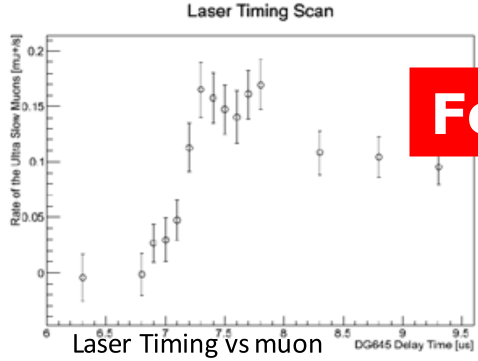
First slow muons in beamline

Observation of Ultra Slow Muons @U-Line

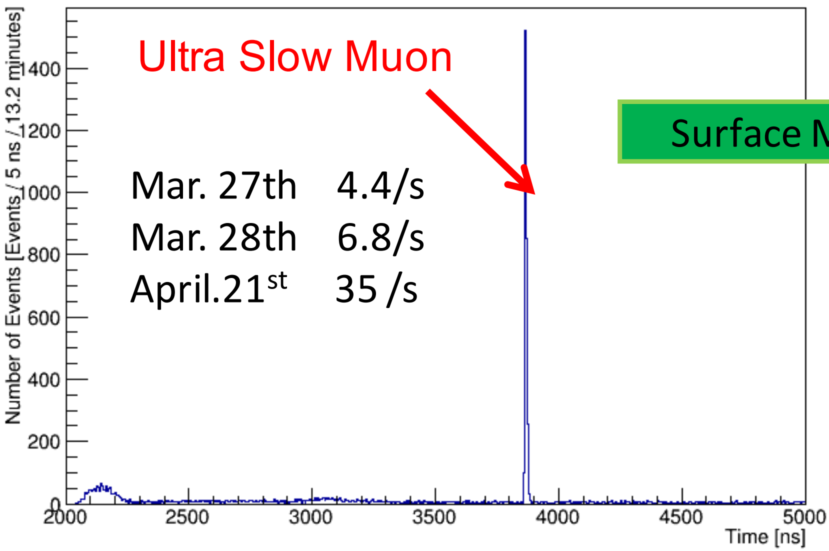
ULTRASLOW MUON MICROSCOPE

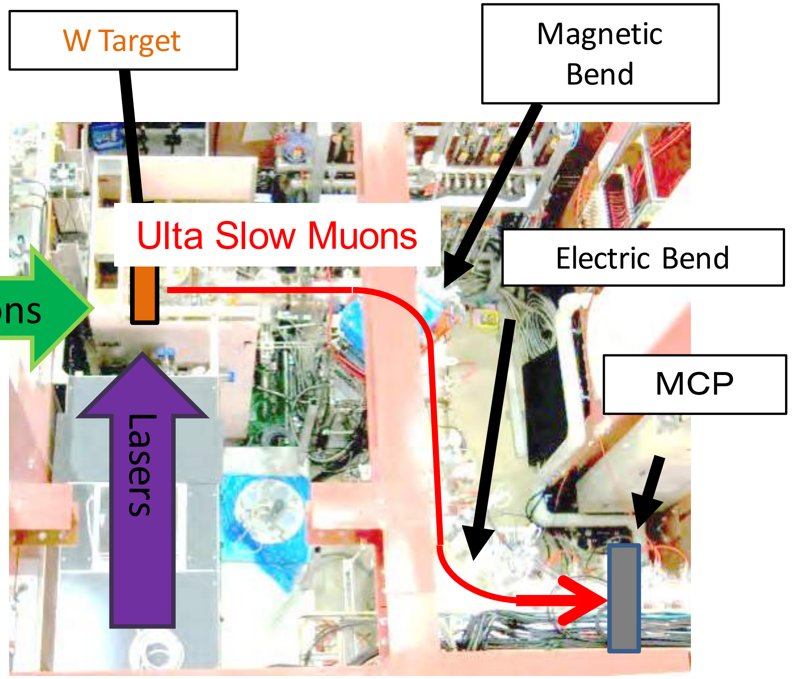
Events of the MCP



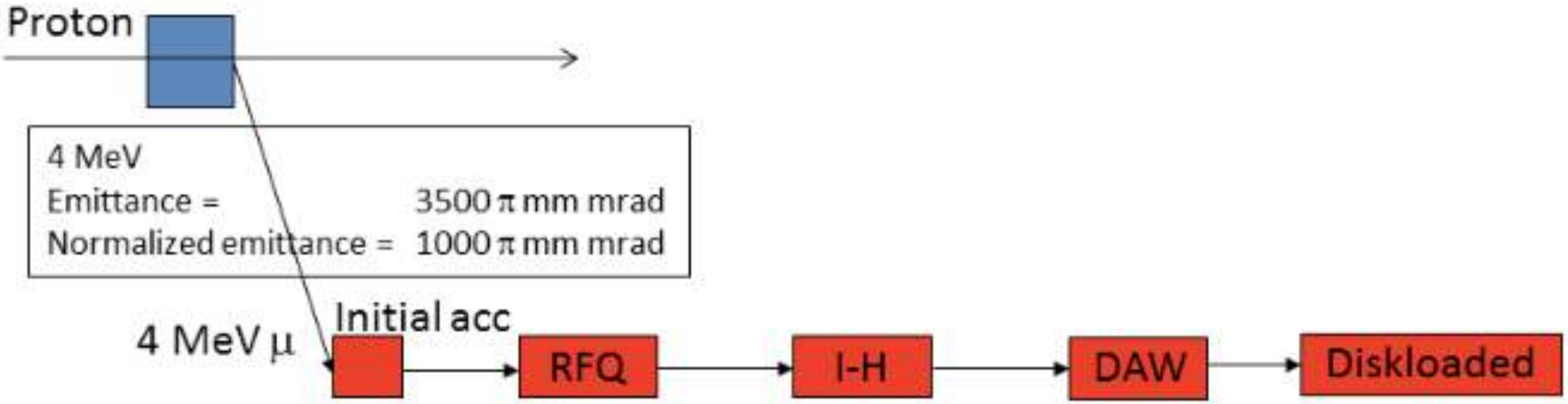


Feb 2016





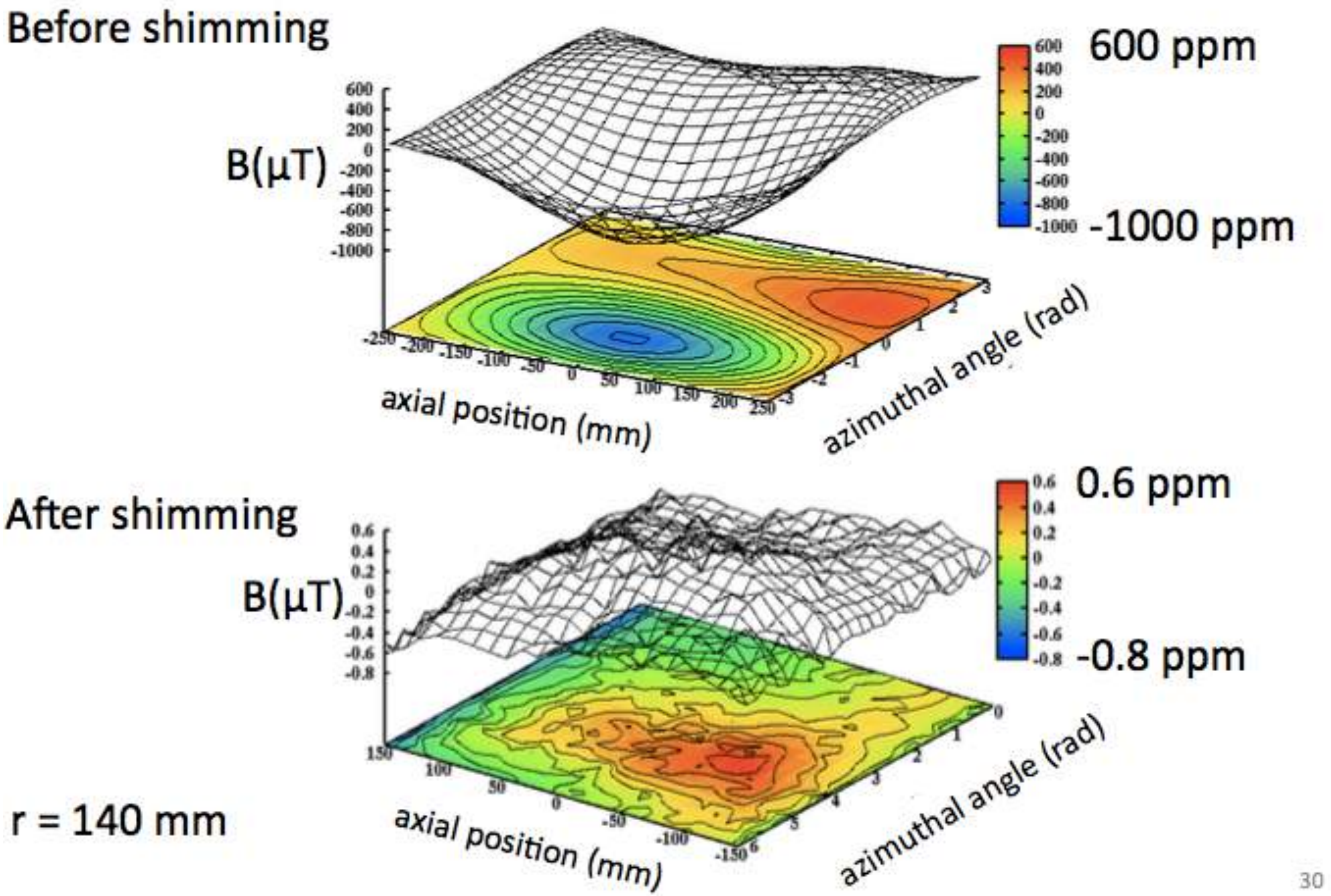
Topview of U-Line



	5.7keV	340 keV	4 MeV	50MeV	200 MeV
βγ	0.01	0.08	0.278	0.98	2.71
Emittance(mm mrad)	150	19	5.4	1.5	0.55
Normalized emittance	1.5	1.5	1.5	1.5	1.5

Tests of 1st two acceleration stages completed.

B-field uniformity / shimming



J-PARC STATUS

R&D phase being completed in next year

Funds for most of construction are secured.

Expect data taking to begin after FNAL g-2 i.e. 2020.

Initial sensitivity at 0.37 ppm (stat) reducing to 0.1 ppm (stat)
i.e. similar to FNAL 0.1 ppm (stat) [0.1 ppm (syst)]

This will provide a crucial measurement with completely different systematic effects compared to the FNAL measurement.