

# E989: Science and Experimental Performance

David Hertzog

Muon g-2 Shutdown Mini-Review

June 13, 2018

**This is mostly the “feel good” talk**

**Science (re) Motivation**

**Stuff that’s working very well**

**(and that’s almost everything)**

**A Snapshot of where we are and where we are going**

# The Charge and our Outline

- **Claim:** we have 1 BNL (ish) but rate of data below TDR (**True**)
- Committee to comment on **performance goals** and readiness of experiment to execute shutdown work plan
  - This talk: **science and performance goals** related to the “measuring” systems (dwh)
    - Charge question 1
  - Next talk: performance overview for “muon storage” systems and conceptual improvement path using data and simulation (cp)
    - Charge questions 2, 4, 5
  - Detailed Shutdown Tasks: **Charge question 3**
    - Kicker voltage upgrade: shutdown detailed plan (cs)
    - Quad reliability: shutdown detailed plan (hn)
    - New Inflector: shutdown plans and options (kb)
  - Priorities from E989 and overall plan (cp)

# In the Press

PHYSICS

## Muons Bring New Physics within Reach

A new experiment to measure the behavior of muons in magnetic fields could reveal unknown particles

By Elizabeth Gibney, Nature

Nature 2017

PARTICLE PHYSICS

### Muon's magnetism could point to new physics

After a hiatus of nearly 20 years, experimental scrutiny of fleeting particle resumes

By Adrian Cho

Next week, physicists will pick up an old quest for new physics. A team of 150 researchers at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, will begin measuring to exquisite precision the magnetism of a fleeting particle called the muon. They hope to firm up tantalizing hints from an earlier incarnation of the experiment, which suggested that the muon is slightly more magnetic than the standard model predicts. It's a possibility that physicists are hunting for decades: proof of physics beyond the standard model. "Physicists could use a little shot of love from nature right now," says David Hertzog, a physicist at the University of Washington in Seattle and co-speakerson for the experiment, which is known as Muon g-2.

Place a muon in a magnetic field perpendicular to the orientation of its magnetization, and its magnetic polarity will turn, or precess, just like a twirling compass needle. At first glance, there seems to be a simple process at work: the muon's magnetic field is being tugged in all directions by the field of the magnet, so that the muon's spin precesses around its own axis. It would remain locked in that orientation if the muon were stationary. But it isn't. The muon is constantly emitting and reabsorbing other particles. That haze of particles popping in and out of existence increases the muon's magnetism and make it precess slightly faster than it circulates. Because the muon can emit and reabsorb any particle, its magnetism tallies all possible particles—even new ones too massive to be produced at the LHC to make. Other charged particles precess at a rate that depends on their mass, so the muon's precession rate is a sensitive probe for new physics.

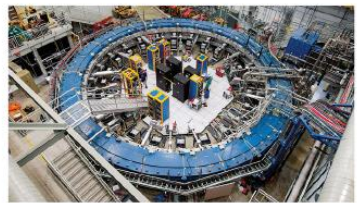
Over hundreds of microseconds, the positively charged muon decays into positrons, which tend to be spit out in the direction of the muon's polarization. Physicists can track the muon's precession by watching for positrons with detectors lining the edge of the ring.

The g-2 team first reported a slight excess in the muon's magnetism in 2001. That result quickly faded as theorists found a simple math mistake in the standard model prediction (Science, 21 December 2001, p. 2449). Still, by the time the team reported on the last of its Brookhaven data in 2004, the discrepancy had re-emerged. Since then, the result has grown, as theorists improved their standard model calculations. They had struggled to account for the process in which the muon emits and reabsorbs particles called hadrons, says Michel Davier, a theorist at the University of Paris-South in Orsay, France. By using data from electron-positron colliders, he says, the theorists managed to reduce this largest uncertainty.

Physicists measure the strength of signals in multiples of the experimental uncertainty,  $\sigma$ , and the discrepancy now stands at 3.5  $\sigma$ —short of the 5  $\sigma$  needed to claim a discovery, but interesting enough to warrant trying again.

In 2003, the g-2 team lugged the experiment on a 5000-kilometer odyssey from Brookhaven to Fermilab, taking the ring by barge around the U.S. eastern seaboard and up the Mississippi River (Science, 18 June 2003, p. 1277). Since then, they have made the magnetic field three times more uniform, and at Fermilab, they can generate far purer muon beams. "It's really a whole new experiment," says Lee Roberts, a g-2 physicist at Boston University. "Everything is better."

Over 3 years, the team aims to collect 10 times more data than during its time



The magnetism of muons is measured as the short-lived particles circulate in a 700-ton ring.

CERN COURIER

Jul 10, 2017

### First beam at Muon g-2

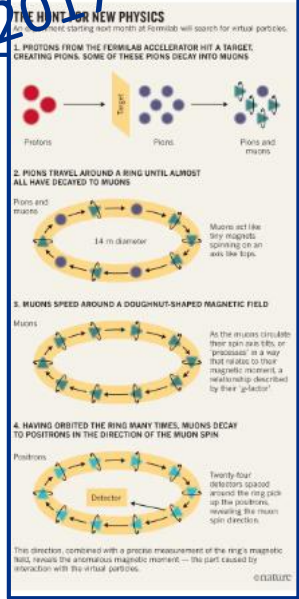
Fermilab's Muon g-2 experiment electromagnet

The Muon g-2 experiment at Fermilab has begun its three-year-long campaign to measure the magnetic moment of the muon with unprecedented precision. On 31 May, a beam of muons was fired into the experiment's 14-m-diameter storage ring, where powerful electromagnetic fields cause the magnetic moment, or spin, of individual muons to precess. The last time this experiment was performed, using the same electromagnet at Brookhaven National Laboratory in the late 1990s and early 2000s, the result disagreed with predictions by more than three standard deviations. This hinted at the presence of previously unknown particles or forces affecting the muon's properties, and motivated further measurements to check the result.

Sixteen years later, the reincarnated Muon g-2 experiment will make use of Fermilab's intense muon beams to definitively answer the questions raised by the Brookhaven experiment. It turned out to be 10 times cheaper to move the apparatus to Fermilab than it would have cost to build a new machine at Brookhaven, and the large, fragile superconducting magnet was transported in one piece from Long Island to the suburbs of Chicago in the summer of 2013.

Since it arrived, the Fermilab team reassembled the magnet and spent a year adjusting or "shimming" the uniformity of its field. The field created by the g-2 magnet is now three times more uniform than the one it created at Brookhaven. In the

CERN Courier 2017



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The physics of g-2

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### Joe Lykken and Greg Bock Blind the Clock

Why is the Muon g-2 Experiment Shifting Time?

Muon g-2

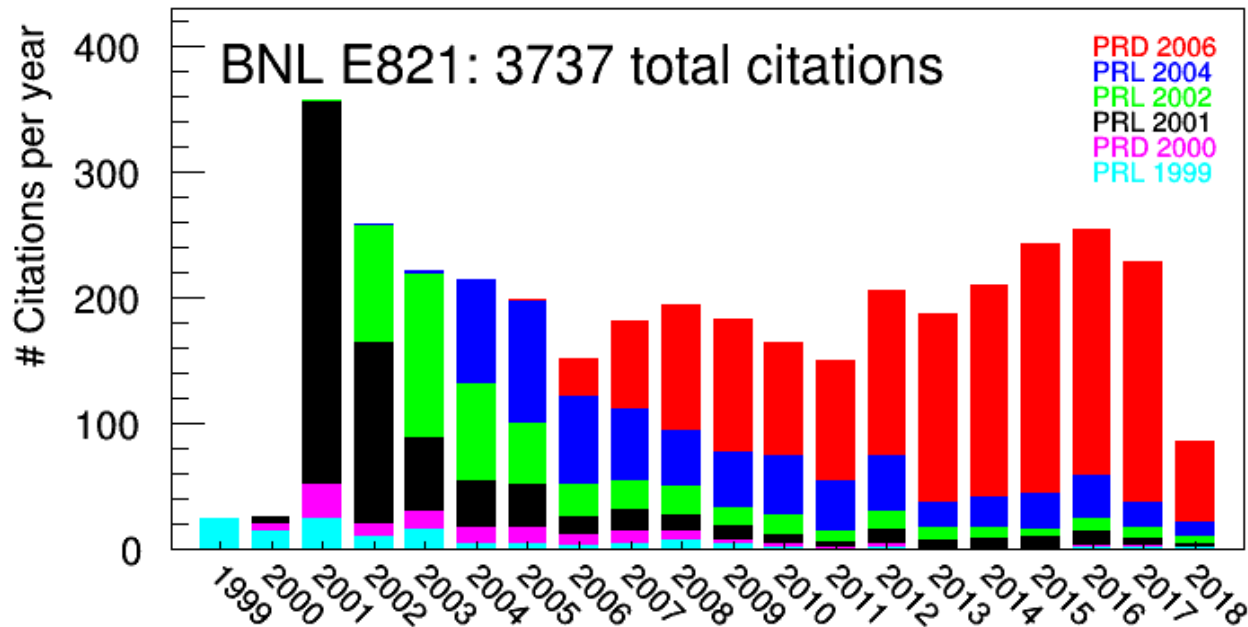
June 13, 2018

Muon g-2 Shutdown Mini-Review

Fermilab

# The Physics Community is Excited and Anticipating a very precise number from Fermilab

- Worldwide Muon  $g-2$  Theory Initiative progressing toward new result
  - They are presently at  $\sim$  half the experimental uncertainty and aggressively pursuing major reductions



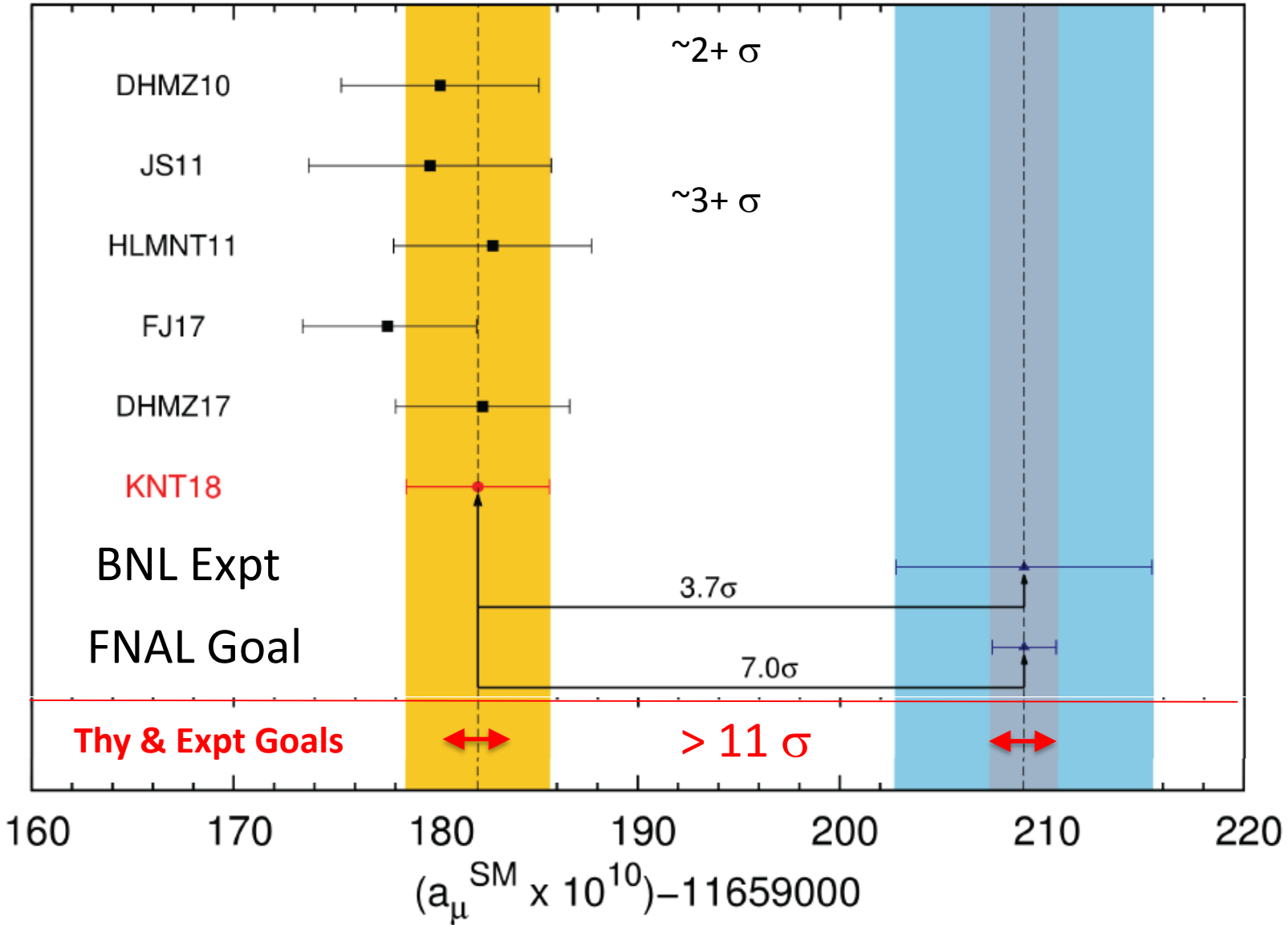
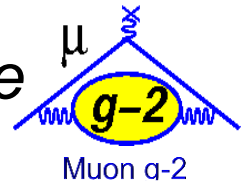
# “Muon $g-2$ <sup>SM</sup> theory initiative” formed in June 2017



“map out strategies for obtaining the **best theoretical predictions for these hadronic corrections** in advance of the experimental results”



# Extraordinary claims require extraordinary evidence

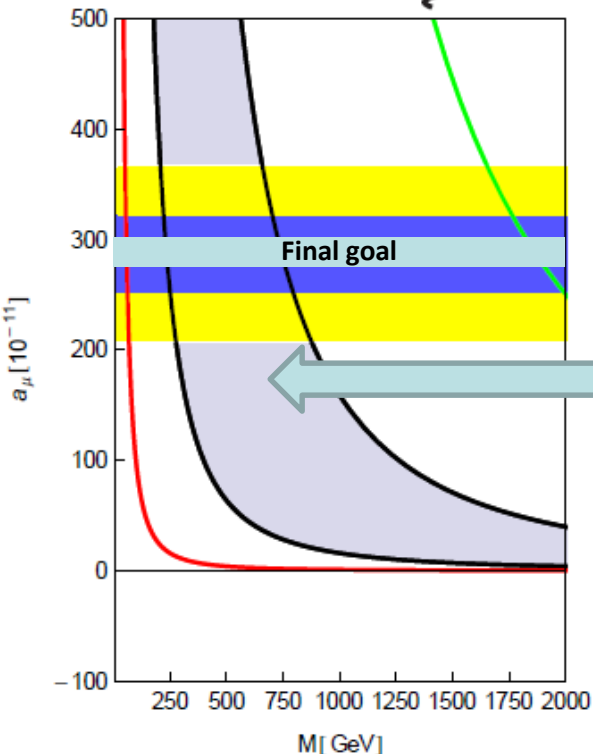
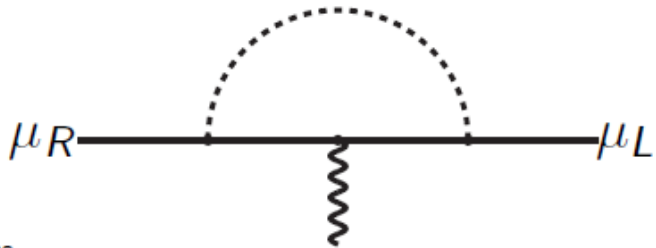


# What could it mean if Expt $\neq$ Theory?

Generically, “loop effects” couple to the muon **mass** and **moment** in similar fashion, characterized by a coupling,  $\propto \mathbf{C}$

$$\mathcal{O}(C) \left(\frac{m_\mu}{M}\right)^2$$

$$C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$



$\mathcal{O}(1)$

radiative muon mass generation ...

[Czarnecki, Marciano '01]

[Crivellin, Gorbach, Nierste '11][Dobrescu, Fox '10]

$\mathcal{O}\left(\frac{\alpha}{4\pi} \times \text{Factor}\right)$

supersymmetry ( $\tan \beta$ )

vectorlike fermions ...

$\mathcal{O}\left(\frac{\alpha}{4\pi}\right)$

SM:  $Z, W$ . New physics:  $Z', W' \dots$

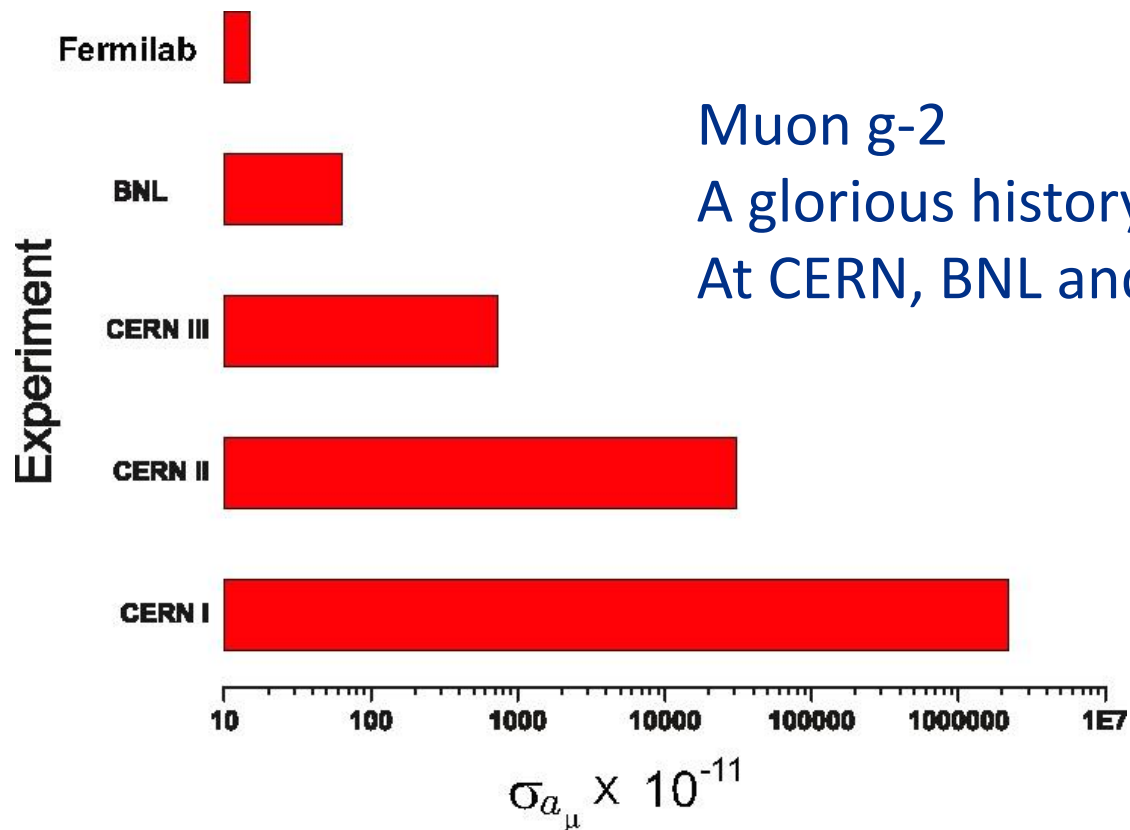
$< \frac{\alpha}{4\pi}$

2-Higgs doublet model, dark photon .



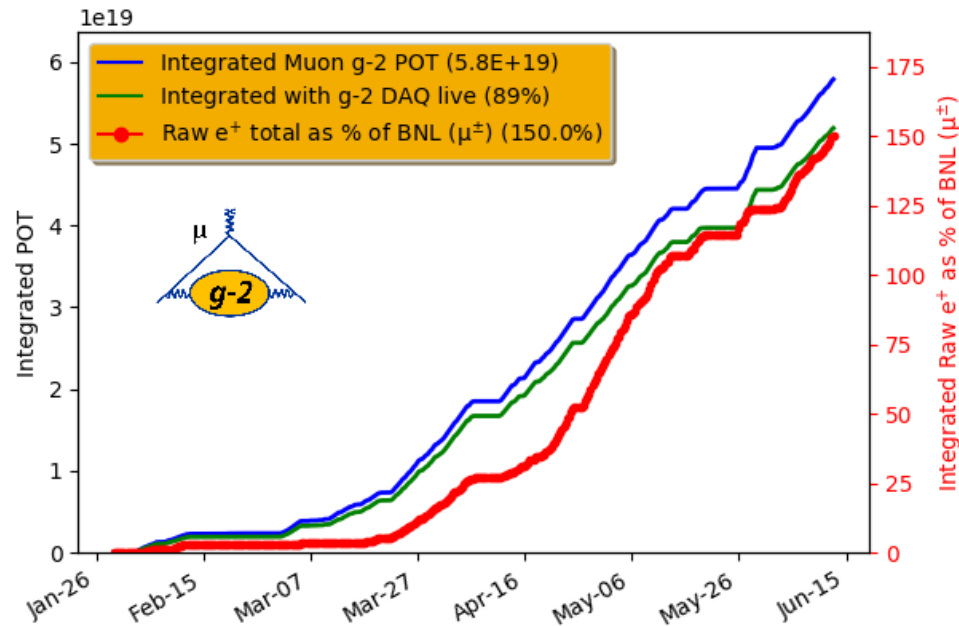
# Toward our Physics Goal

In April, 2009 the PAC and Fermilab Director endorsed the P989 Proposal to meet the stated goal of a measurement of  $a_\mu$  to 140 ppb, requiring 21 x the BNL accumulated statistics



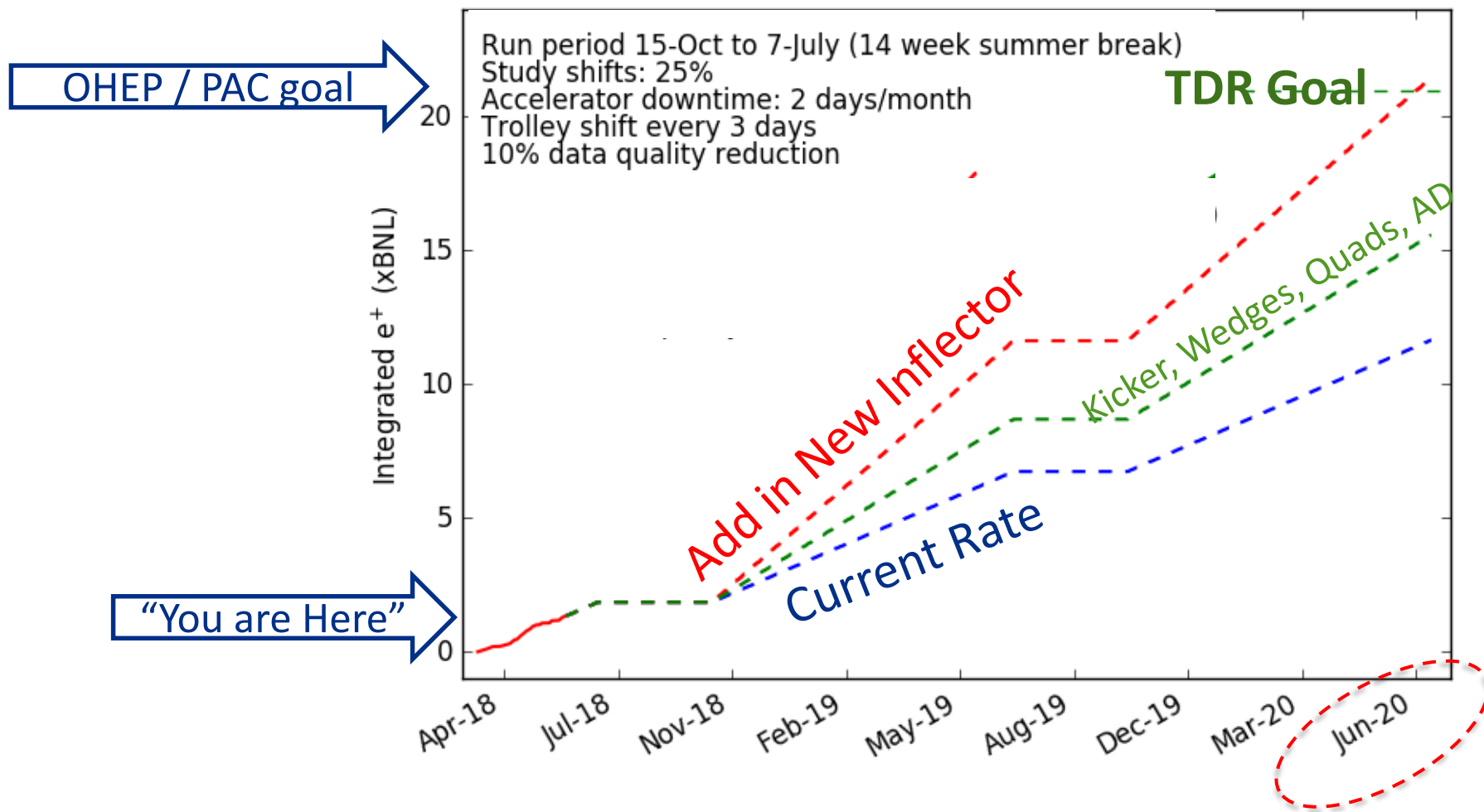
# During 1<sup>st</sup> Commissioning / Data Taking we will

- Achieve ~ 1.5 of BNL statistics; (BNL = 7.5% of our goal)
- Have tested the full system and analysis
- Have identified weaknesses we can address to increase Flux and improve many systematic challenges

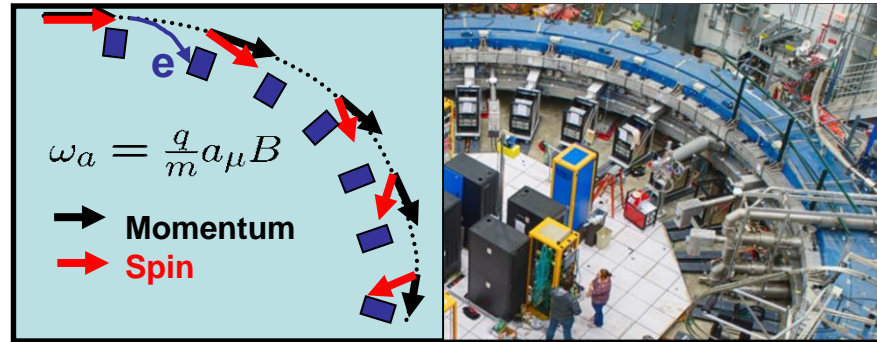


← ~ BNL after cuts

# Today, we will tell you how to get there ... and when



# The Fundamental Experimental Principle



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

The expression including *E*-field focusing and possible  $\mu$ EDM

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

Get  $a_\mu$  ↓  
↑ Measure these ↑  
Magic  $\gamma = 0$   
± $\delta$ P  $\mu$ 's → E-field correction ~0.5 ppm  
EDM  
We can determine well enough

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

# Requirements to measure $a_\mu$ to 140 ppb

## 1. Store More Muons

- 21 x BNL in statistics ... (100 ppb)

} Today we  
focus on this

## 2. Prepare A More Uniform Magnetic Field

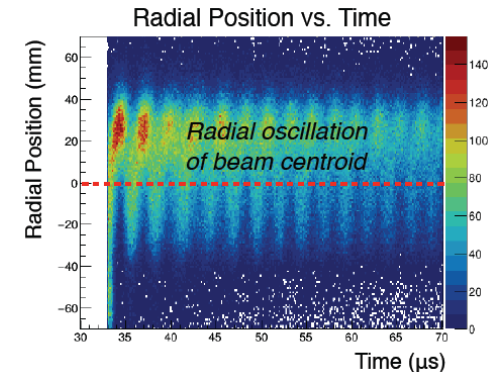
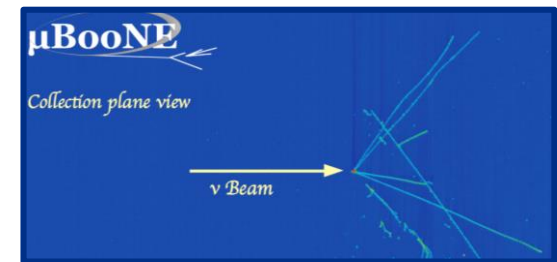
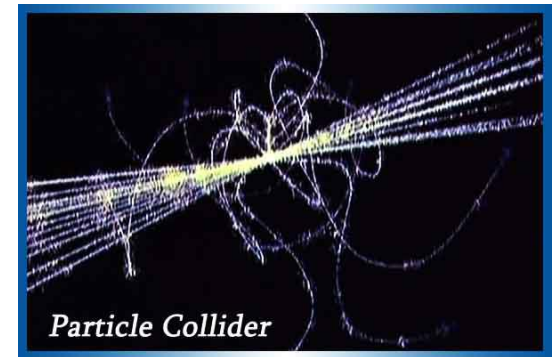
- ✓ • Goal → 3 x better and more carefully measured (70 ppb)

## 3. Improve the Precession Frequency Measurement

- ✓ • All new instrumentation with high-fidelity recording of muon decays by many systems (70 ppb)

# What is unique about this particle physics experiment?

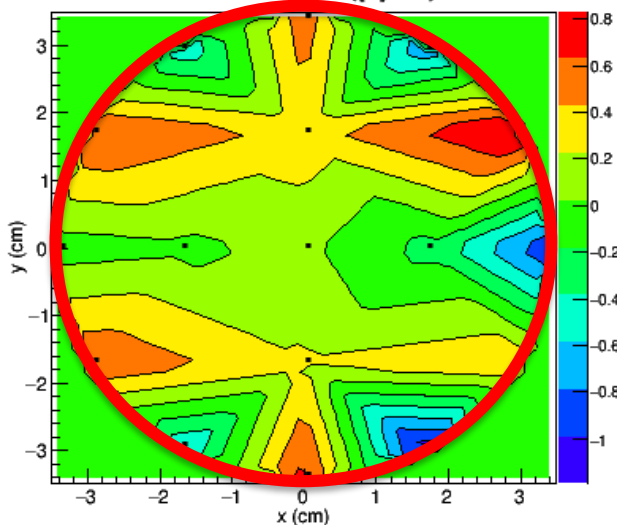
- The muons **do not collide** with another beam
- And they **do not strike a target**
- **We must observe them “from a distance”** to infer their spin orientation and their path around the magnet
  - Decays reveal spin from self-analyzing PV
  - Betatron motions are manifest in acceptance variations of the detectors
  - Trackers can image muon spatial distribution
- More than most, this is an experiment that relies considerably on AD beam delivery and **Storage Ring properties**



# The Magnetic Field is Very Good

- Much better than at BNL
- > 25 Flawless Trolley mappings in last few months
- Plunging Probe to Trolley probe inter calibration working
- Fixed-probe monitoring at nearly 100% of probes (vs < 50% at BNL)

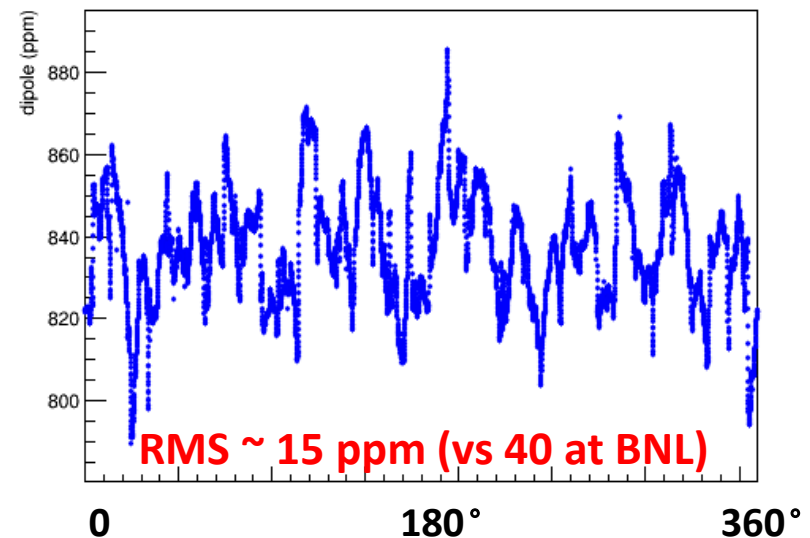
B-field (ppm)



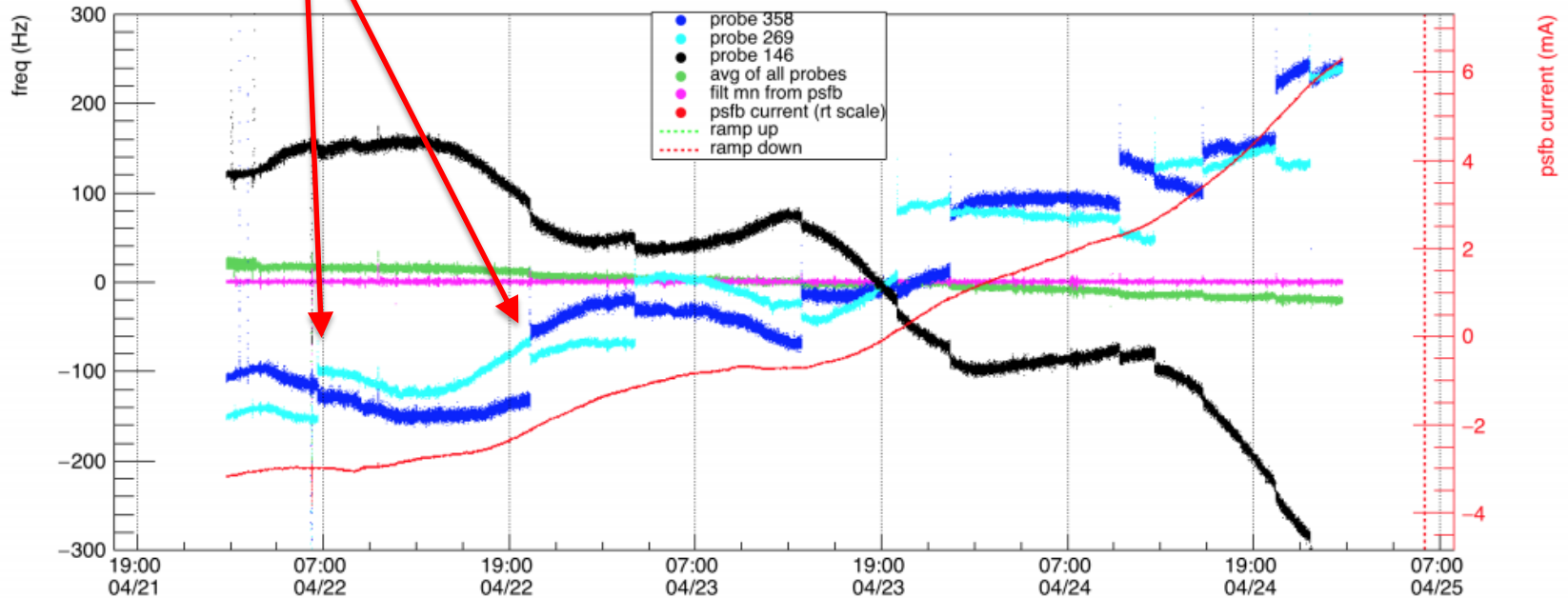
Averaged around azimuth

	Norm	Skew
Quad	-0.29	0.10
Sext	0.06	0.19
Octu	-0.06	0.25
Decu	0.25	0.05
Dipole	-0.0	

Dipole Field



... but, not perfect. Temp fluctuations in MC-1 are significant and “quantum” jumps for a few probes keep us busy



J. Grange

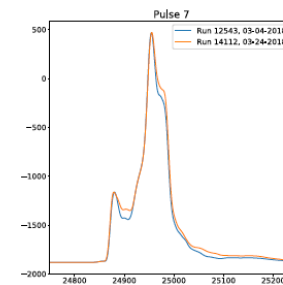
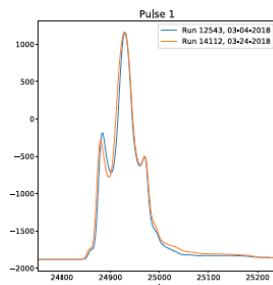
We are installing insulation

We are increasing our Fixed Probe – to-PowerSupply feedback

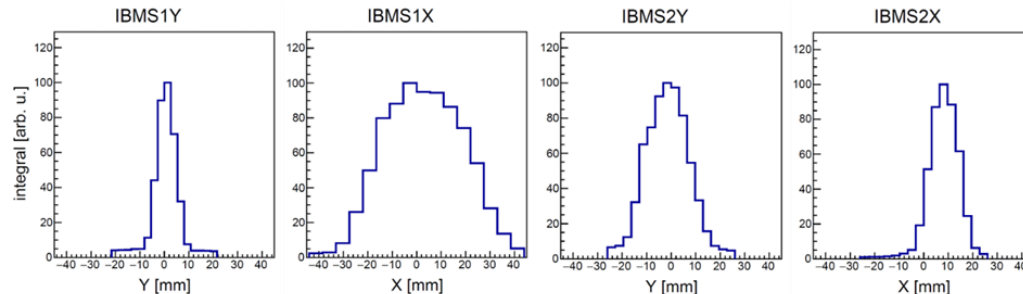
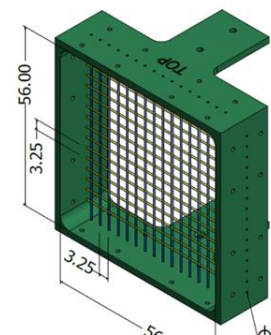
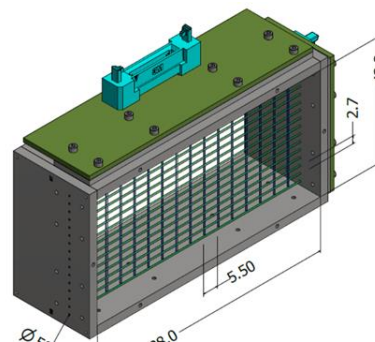


# Detectors to measure *incoming* beam properties, used to optimize beam tuning

- **T0** Scintillator:
  - 8 different shapes to monitor
  - (not what was advertised)

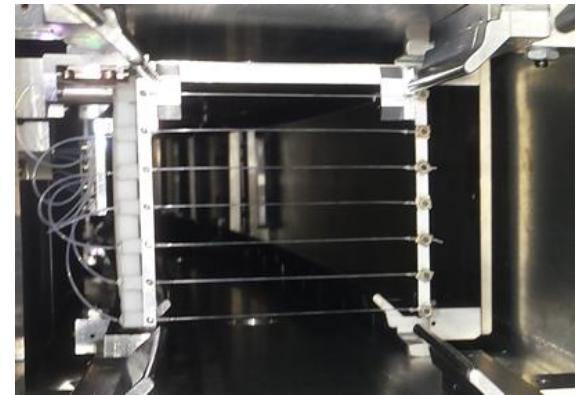
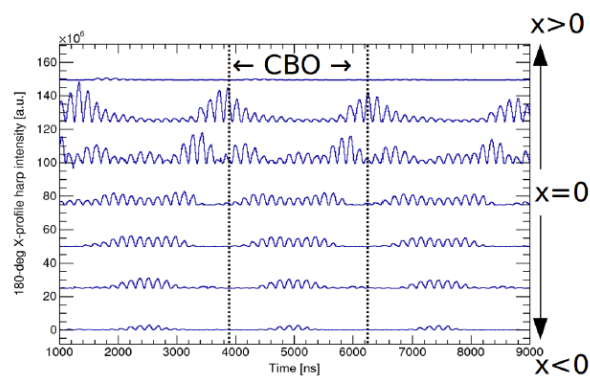
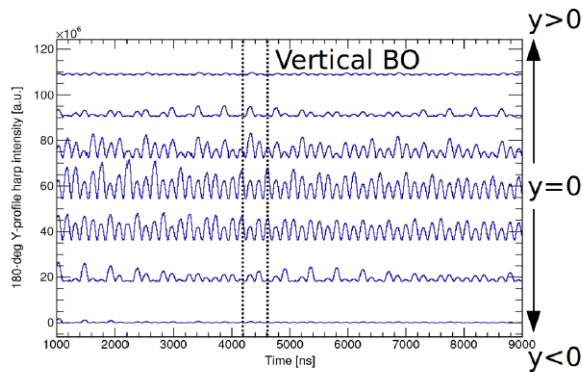


- **IBMS** scintillating fiber arrays
  - To guide tuning  $\mu$  into ring
  - At entrance to Ring
  - At entrance to Inflector

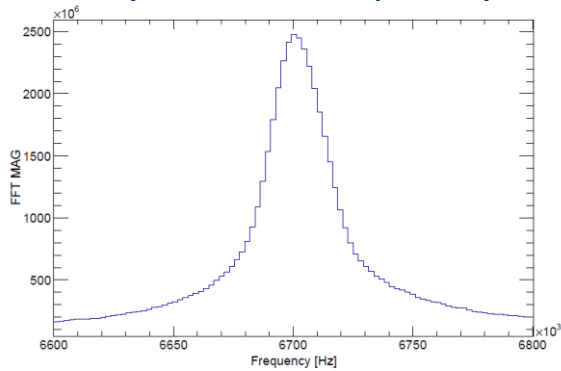


# Detectors to measure *dynamics* of stored muons

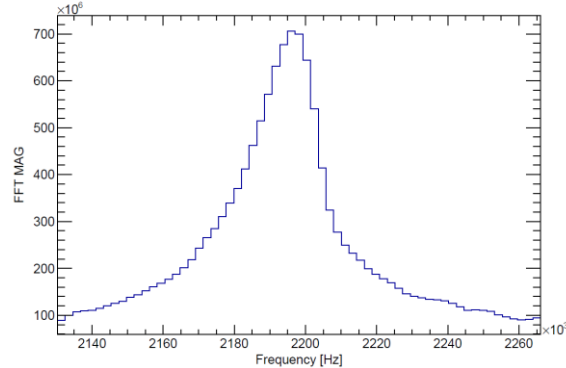
- Two, In-ring X & Y measuring Fiber Harps



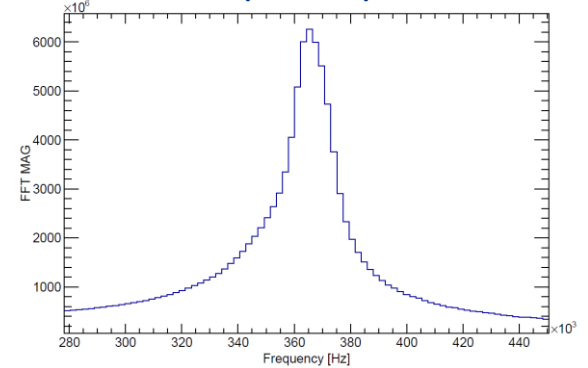
Cyclotron Frequency



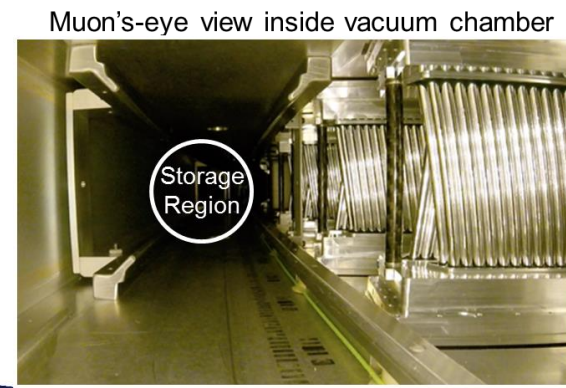
Vertical Betatron



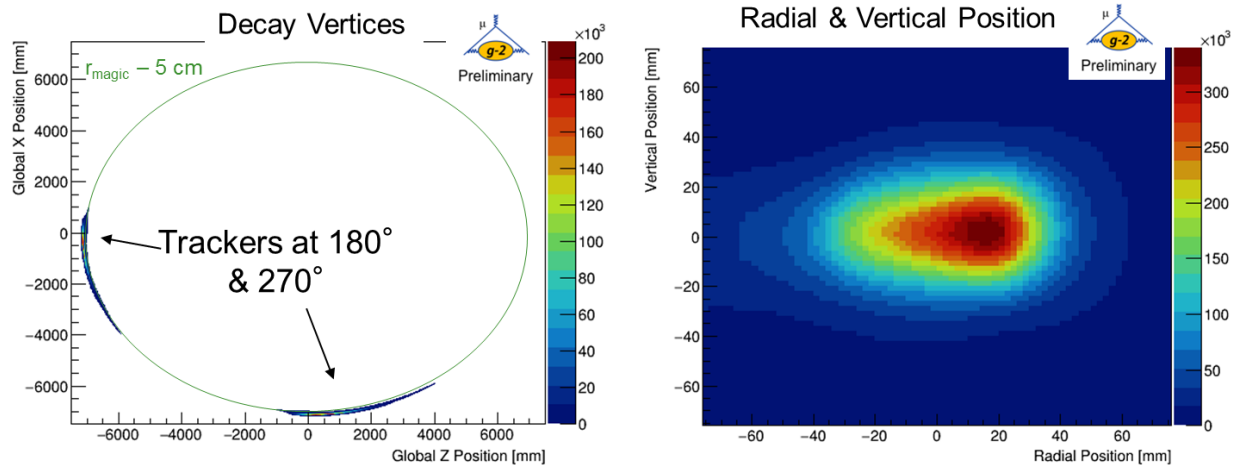
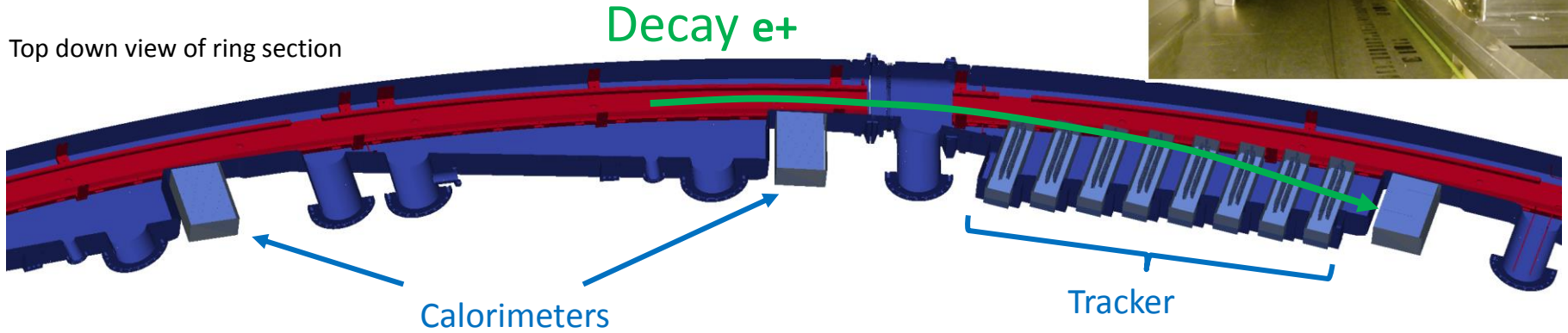
Coherent (radial) Betatron



# Trackers are working spectacularly to image our stored beam

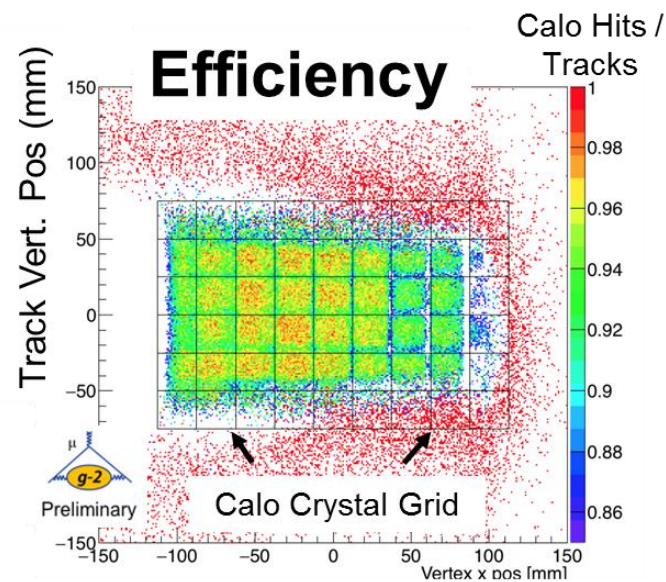
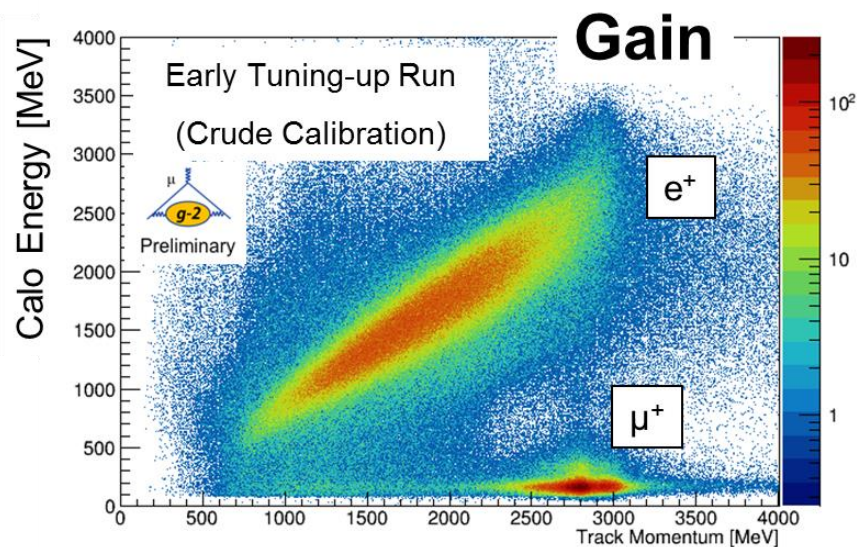
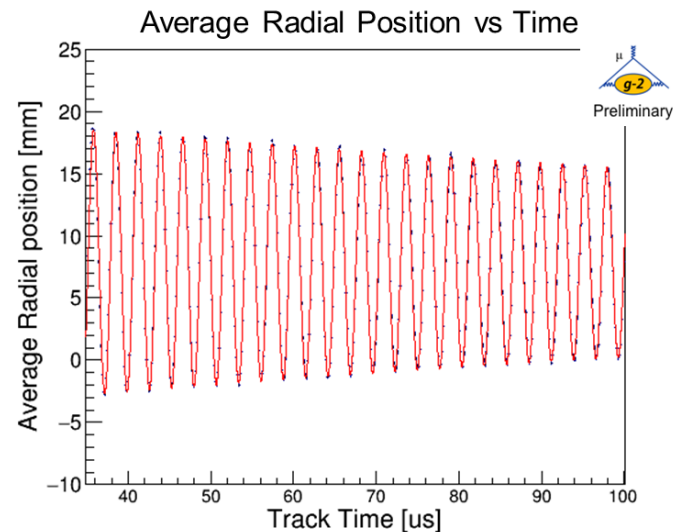
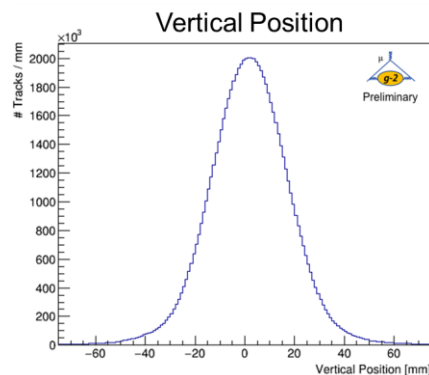
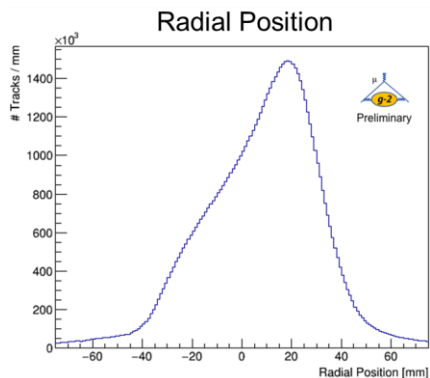


Top down view of ring section

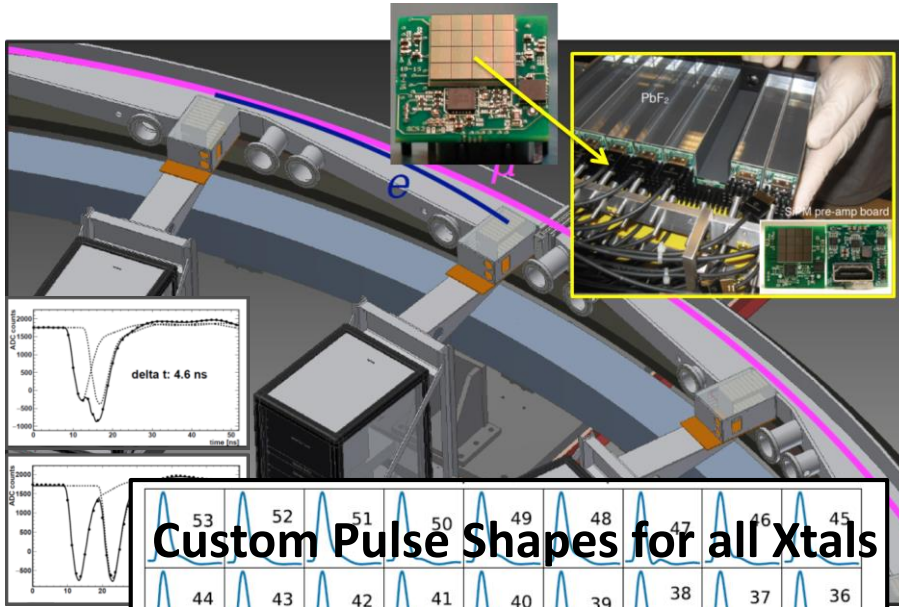


Extrapolate tracks back to point of tangency to get beam distribution:

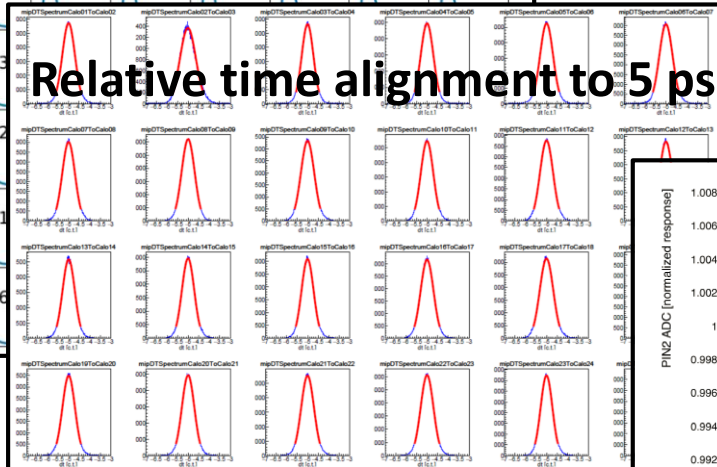
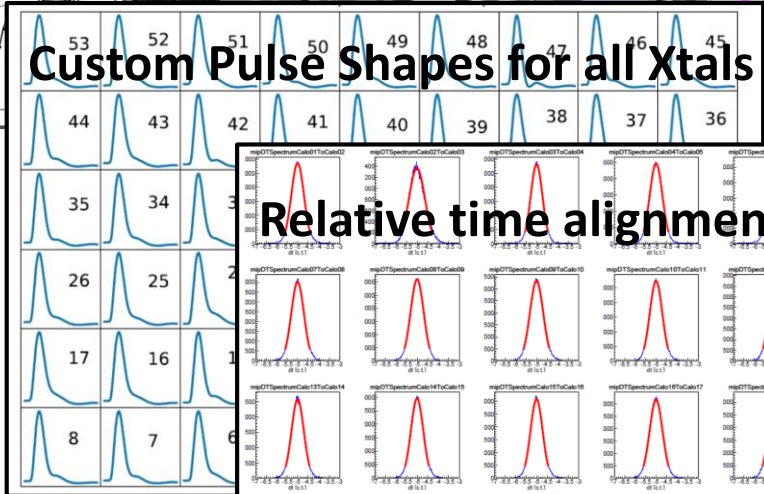
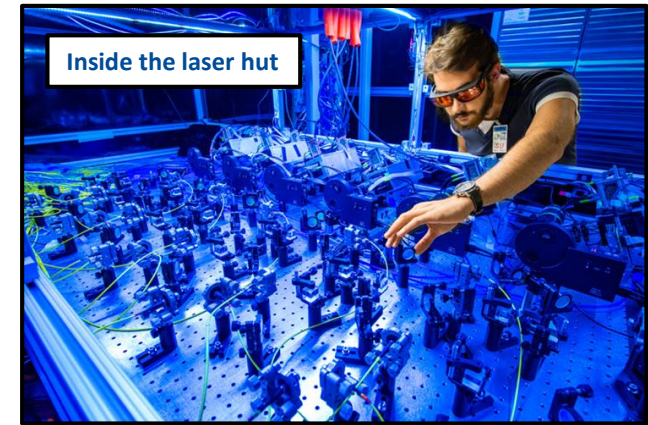
# The information gives us ...



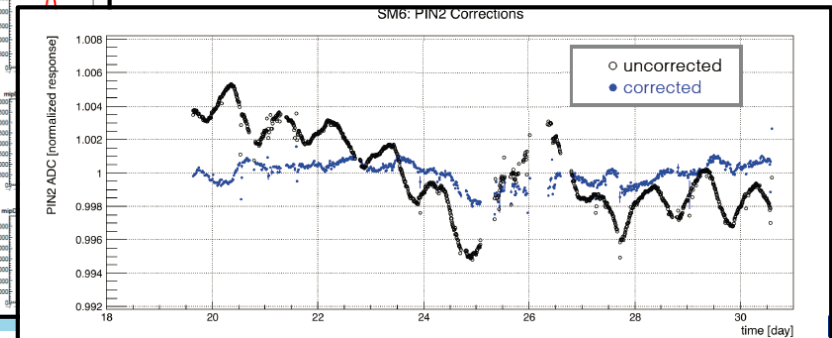
# The 24 Calorimeters are working great ... ... together with the Laser Calibration System



54  $\text{PbF}_2$  crystals with individual laser calibrations into each channel



Laser gain stability to  $10^{-4}$



# Offline analysis quite mature already ...

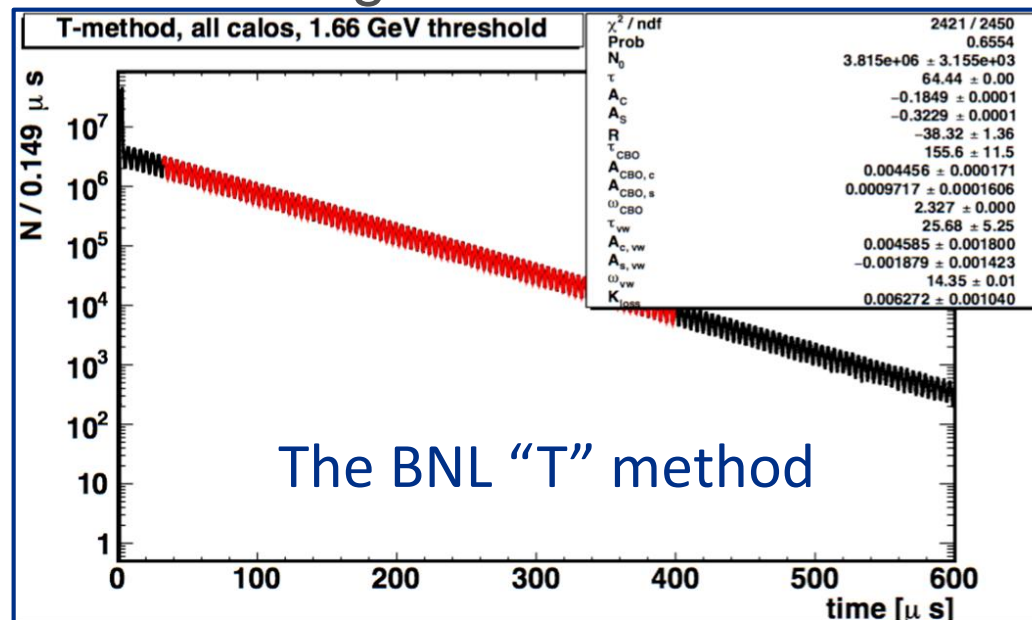
- Included effects for **60-hr** Data Challenge

- Pileup subtraction
- Muon loss terms
- CBO effects
- Long-term gain

- Not yet included\*

- In-fill gain corrections
- Fill-by-fill QC filter

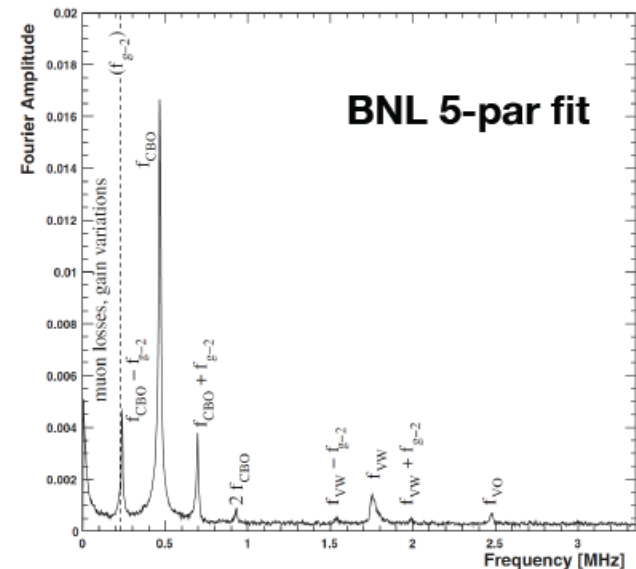
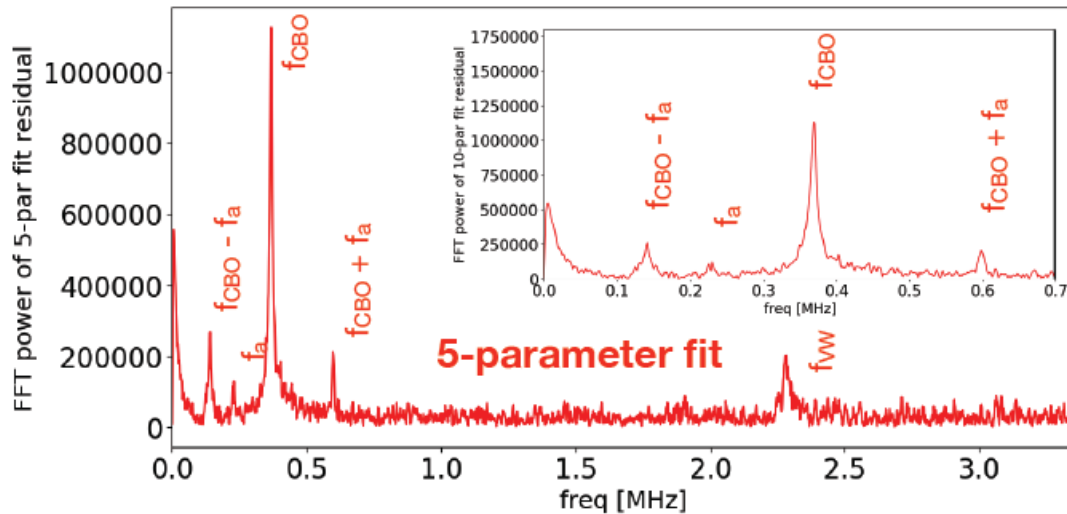
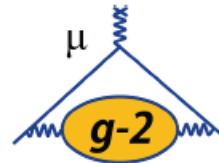
- And yet, already good  $\chi^2$



\*In next release, this week

# We see the expected rich beam motion structure; our tools and analysis are rather mature

## Fit residual analysis (FNAL vs BNL)



Physical frequency	Variable	Frequency (MHz)	Period ( $\mu$ s)
Anomalous precession	$f_a$	0.23 MHz	4.37
Cyclotron	$f_c$	6.70 MHz	0.149
Horizontal Betatron	$f_x$	6.34 MHz	0.158
Vertical Betatron	$f_y$	2.2 MHz	0.455
CBO	$f_{CBO}$	0.37 MHz	2.7
Vertical Waist	$f_{vw}$	2.3 MHz	0.435

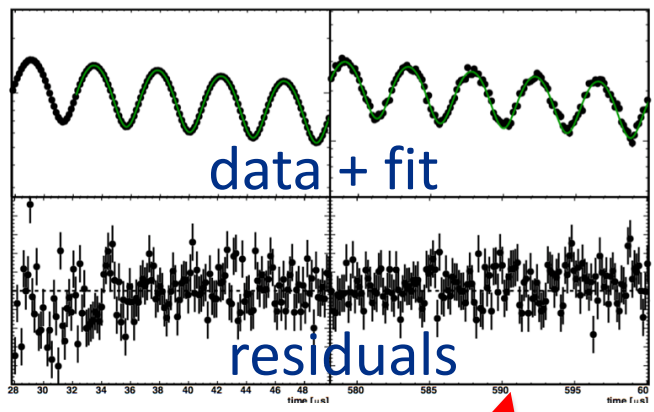
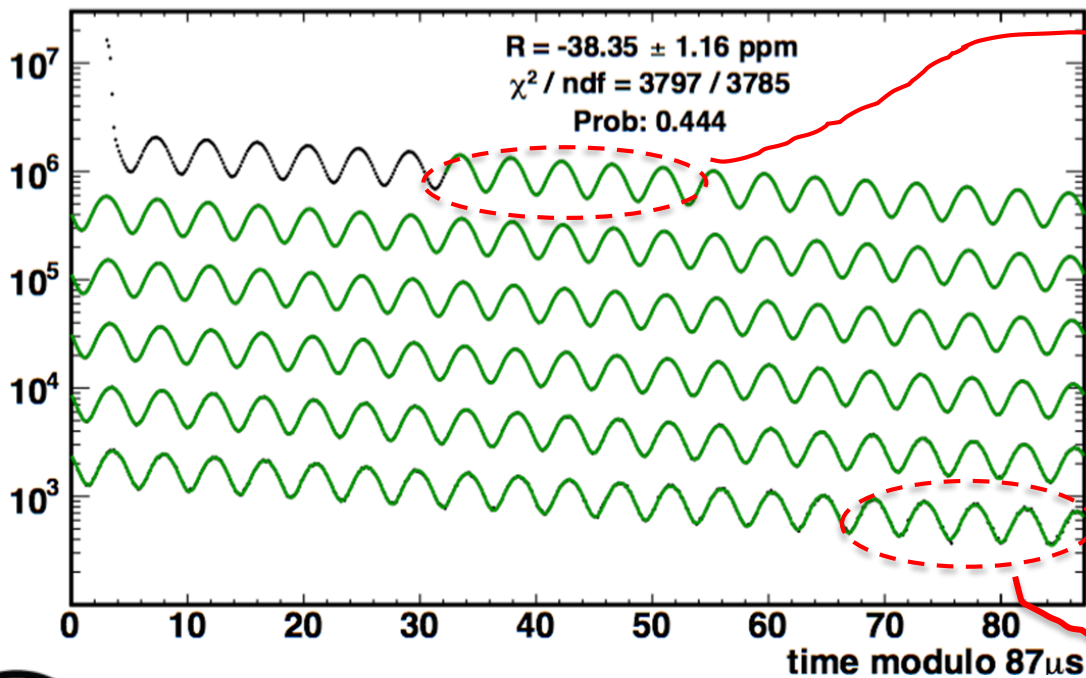
TABLE VIII. Important frequencies and periods in the  $(g - 2)$  storage ring for  $n = 0.137$ .

Physical frequency	Variable	Expression	Frequency	Period
Anomalous precession	$f_a$	$\frac{e}{2\pi m} a_\mu B$	0.23 MHz	4.37 $\mu$ s
Cyclotron	$f_c$	$\frac{v}{2\pi R_0}$	6.71 MHz	149 ns
Horizontal betatron	$f_x$	$\sqrt{1 - n} f_c$	6.23 MHz	160 ns
Vertical betatron	$f_y$	$\sqrt{n} f_c$	2.48 MHz	402 ns
Horizontal CBO	$f_{CBO}$	$f_c - f_x$	0.48 MHz	2.10 $\mu$ s
Vertical waist	$f_{vw}$	$f_c - 2f_y$	1.74 MHz	0.57 $\mu$ s

# Exploiting the excellent energy resolution and low threshold for data accumulation with our **800 MSPS 12-bit digitizers**

Example: Asymmetry weighted method (**1.16 ppm**, 17% improvement vs “T”)

A-weighted hit times, 60-hour dataset





# A too-brief tour of what is good ..

- Although there are **Challenges** which will be discussed
  - **Muon Storage Rate and Momentum Distribution**
  - & Some stability & reliability issues we are dealing with
- The experiment remains *highly motivated*
  - If anything, the interest has GROWN since we started
  - And, we are not alone. J-PARC is planning a competitive effort
  - Fermilab should set the benchmark that will be unsurpassed
- The *instrumentation* is working at or better than TDR specifications
  - It was prepared to meet the PAC-approved Goal of 140 ppb
- The 1<sup>st</sup>-year data is being analyzed in near real time and we are learning a lot from it.
- We have slightly exceeded BNL this year in statistics