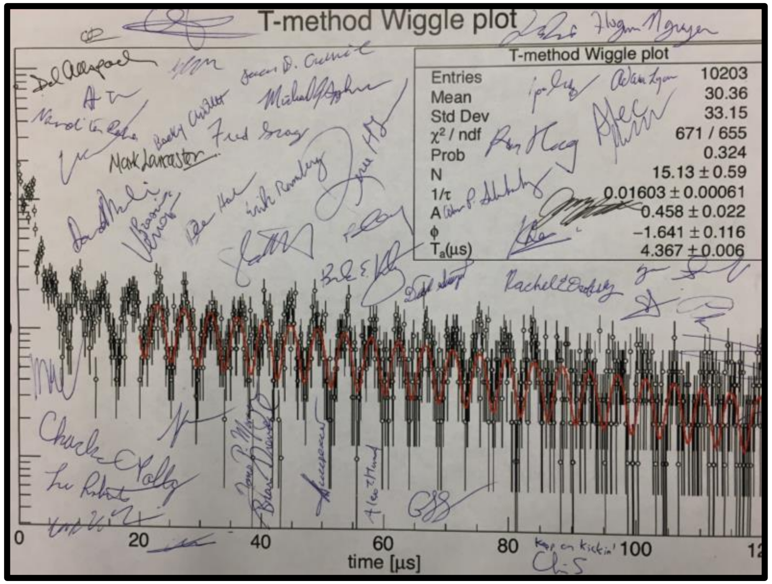
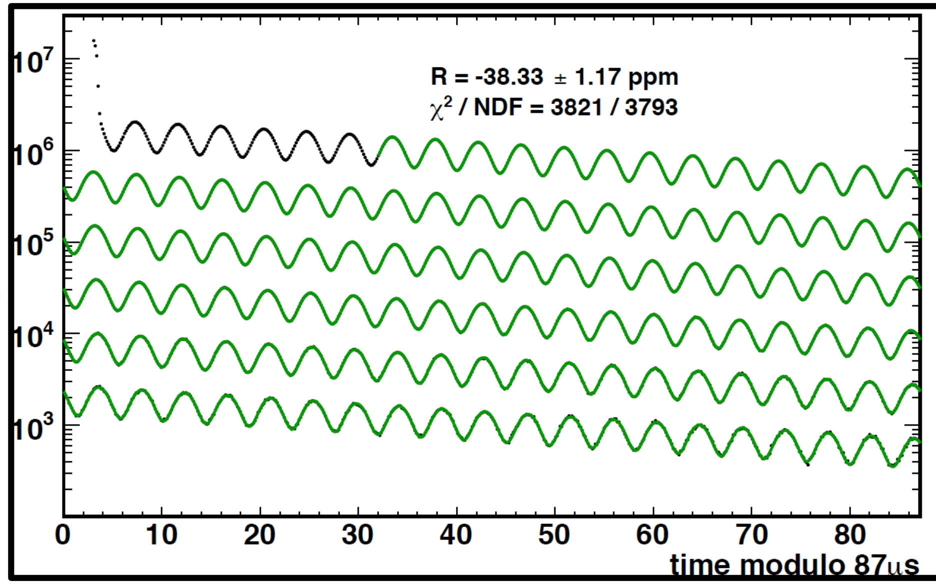




E989: Science and Experimental Performance

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

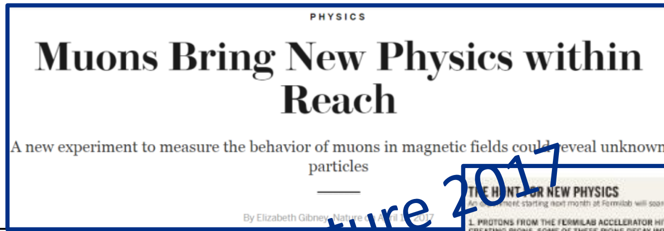
(and that’s almost everything)

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

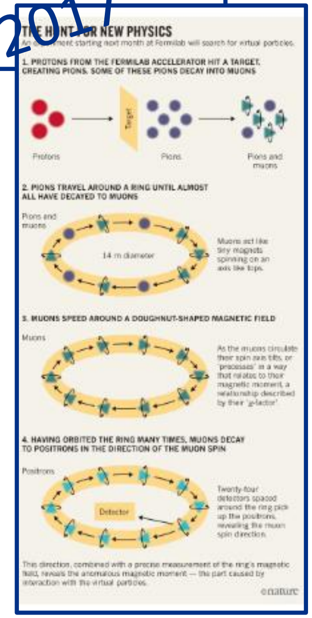

PHYSICS

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

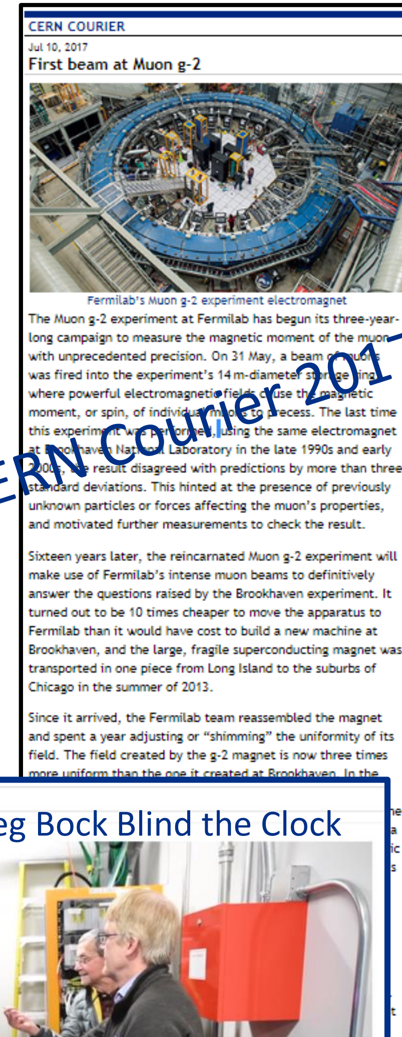
By Adrian Cho

Next week, physicists will pick up an old quest for new physics. A team of 190 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 particle is slightly more magnetic than predicted by the prevailing standard model of particle physics.

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

SCIENCE sciencemag.org

Science 2018


CERN COURIER

Jul 10, 2017

First beam at Muon g-2

Fermilab's Muon g-2 experiment electromagnet

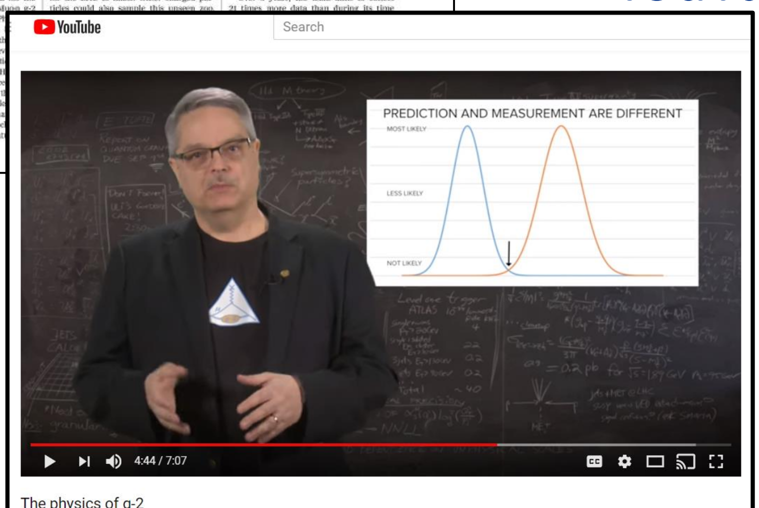
The Muon g-2 experiment at Fermilab has begun its three-year-long campaign to measure the magnetic moment of the muon with unprecedented precision. On 31 May, a beam of muons was fired into the experiment's 14 m-diameter storage ring, where powerful electromagnetic fields cause the magnetic moment, or 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

YouTube



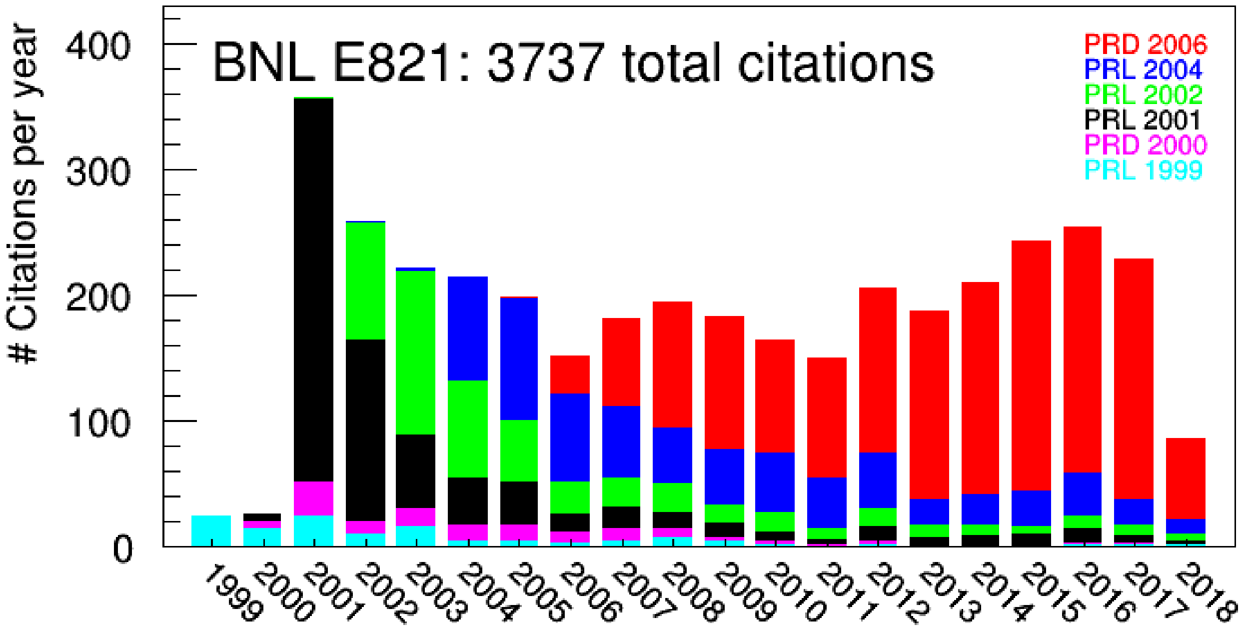
The physics of g-2

Joe Lykken and Greg Bock Blind the Clock

Why is the Muon g-2 Experiment Shifting Time?

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 ~ half the experimental uncertainty and aggressively pursuing major reductions

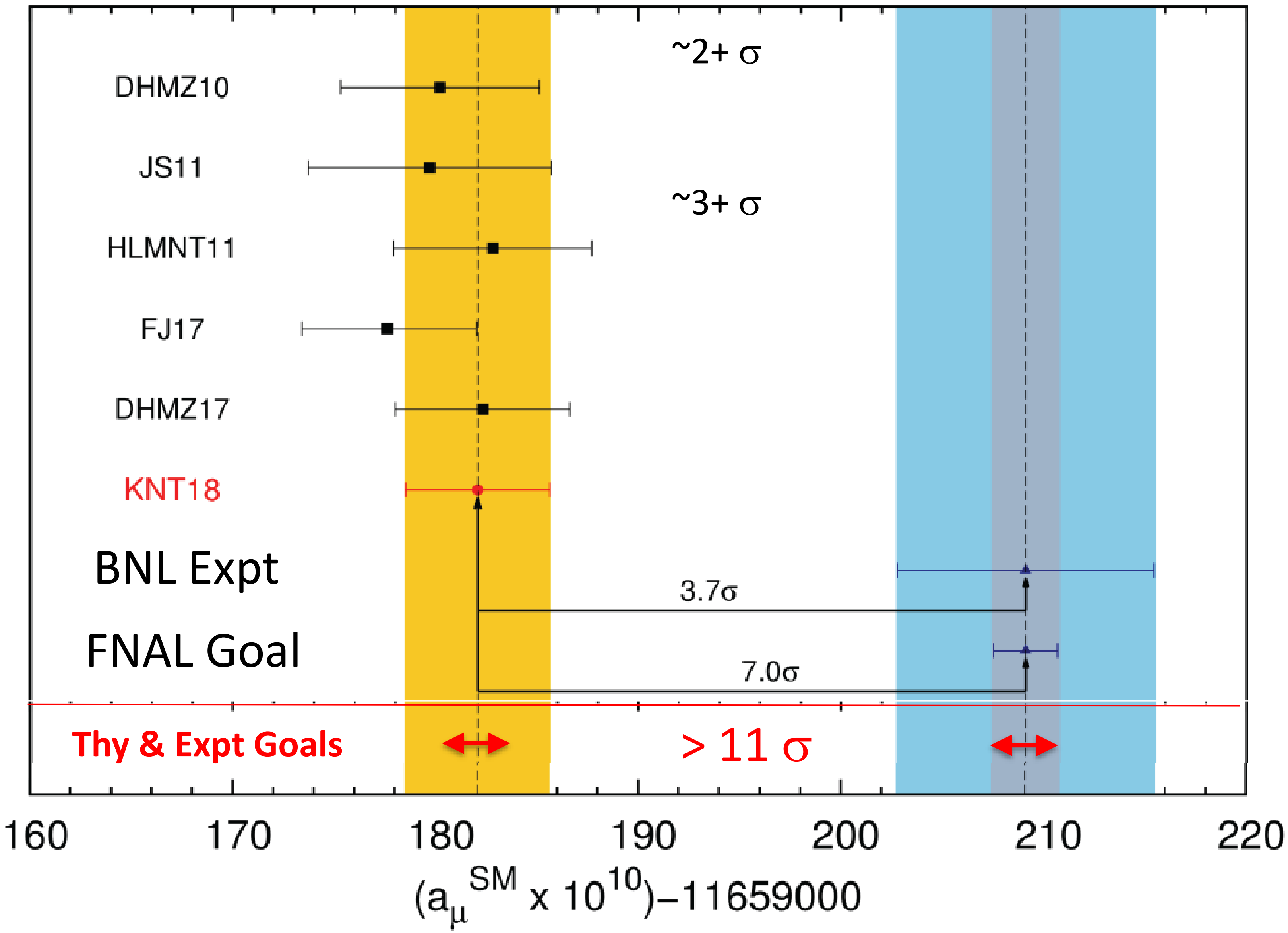


“Muon g-2^{SM} theory initiative” formed in June 2017

AIM: Error commensurate with expected FNAL and J-PARC goals

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

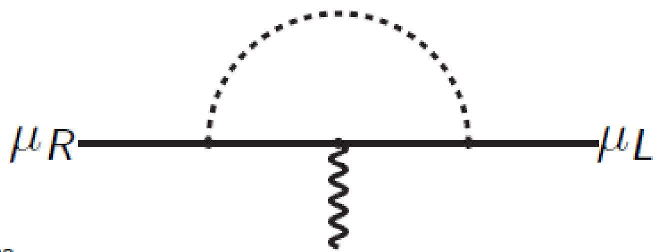
Extraordinary claims require extraordinary evidence

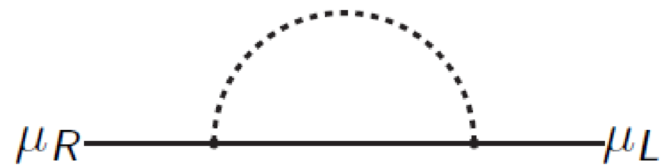


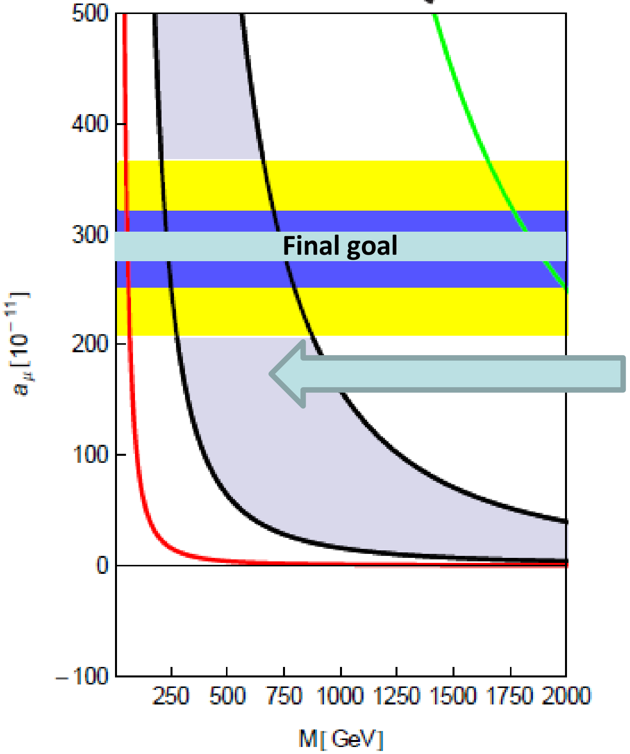
What could it mean if Expt ≠ Theory?

Generically, "loop effects" couple to the muon mass and moment in similar fashion, characterized by a coupling, $\propto$ *C*

$$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2 \qquad\qquad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$





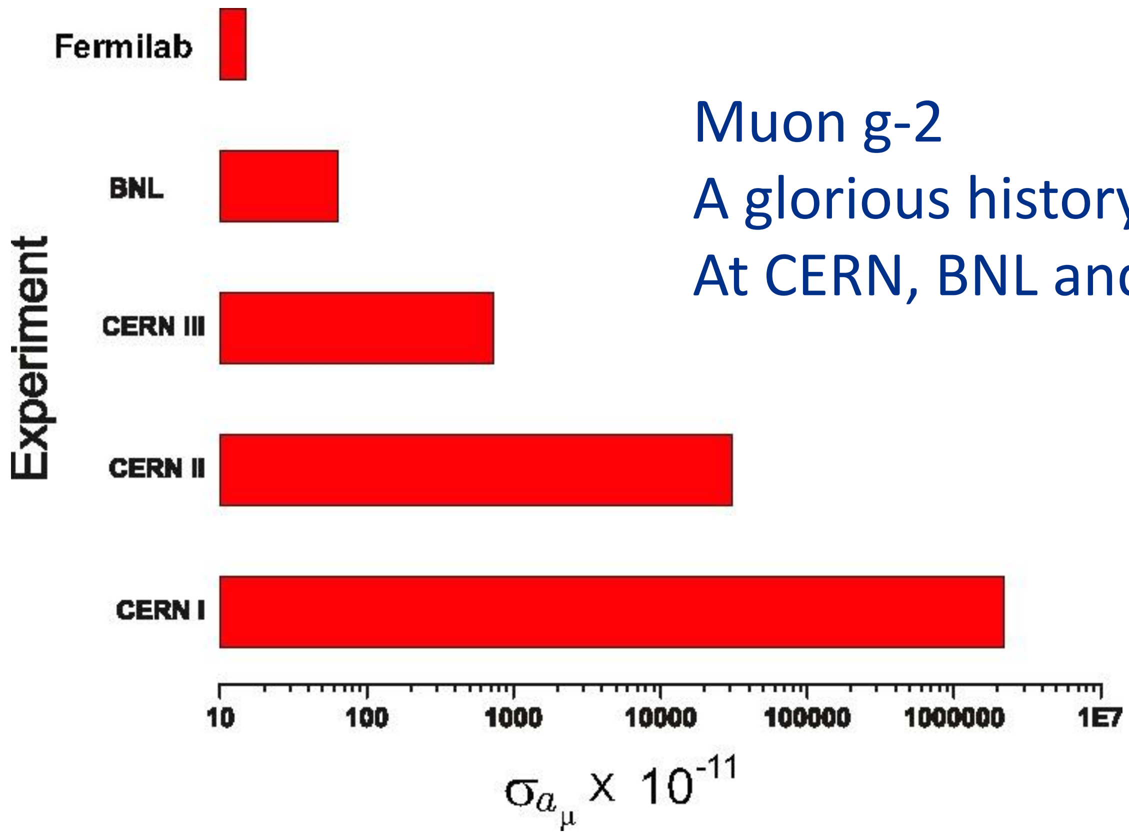


$\mathcal{O}(1)$	radiative muon mass generation ... [Czarnecki, Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$ xFactor	supersymmetry $(\tan\beta)$ vectorlike fermions ...
$\mathcal{O}(\frac{\alpha}{4\pi})$	SM: Z, W. New physics: $Z', W'\ldots$
$< \frac{\alpha}{4\pi}$	2-Higgs doublet model, dark photon .

Following Czarnecki, Marciano, and Stockinger

Toward our Physics Goal

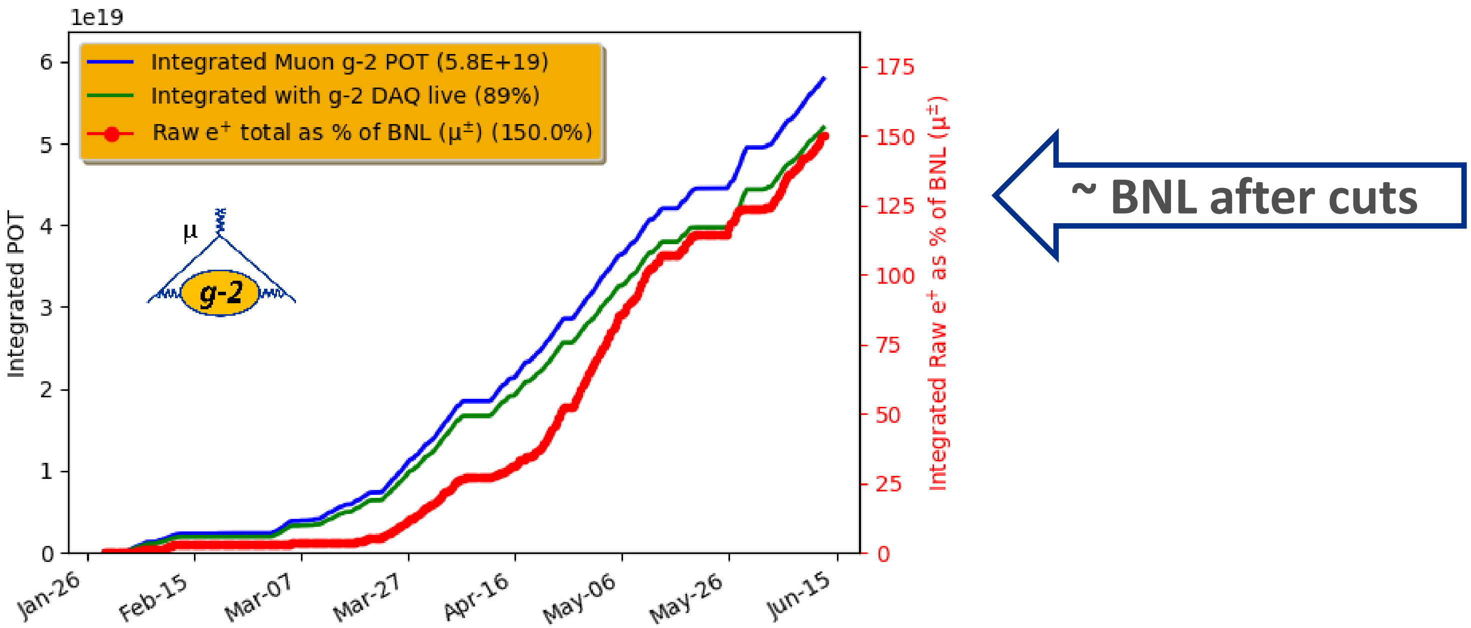
In April, 2009 the PAC and Fermilab Director endorsed the P989 Proposal to meet the stated goal of a measurement of a_μ to **140 ppb, requiring 21 x the BNL accumulated statistics**



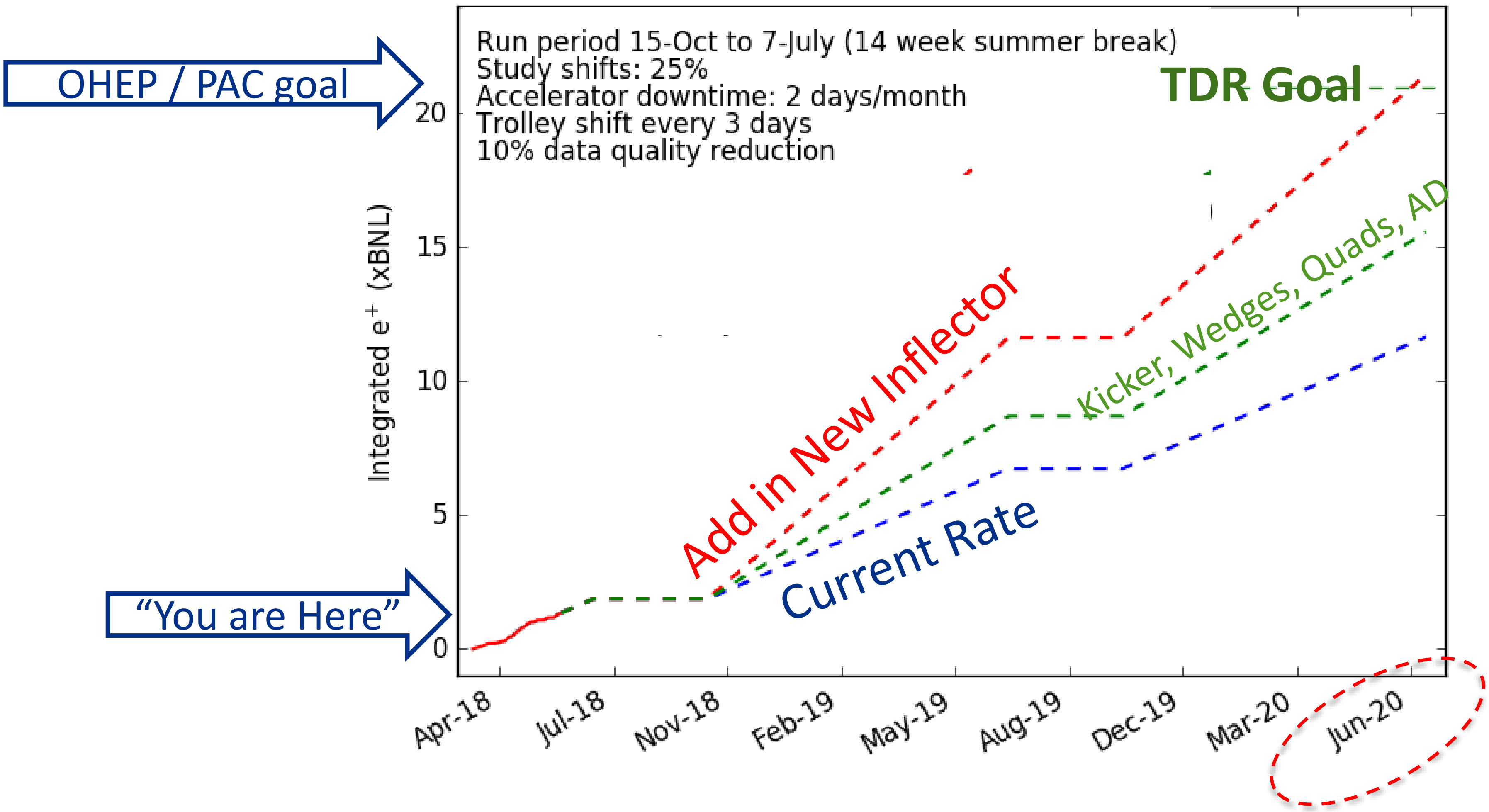
Muon g-2
A glorious history
At CERN, BNL and Fermilab

During 1st Commissioning / Data Taking we will

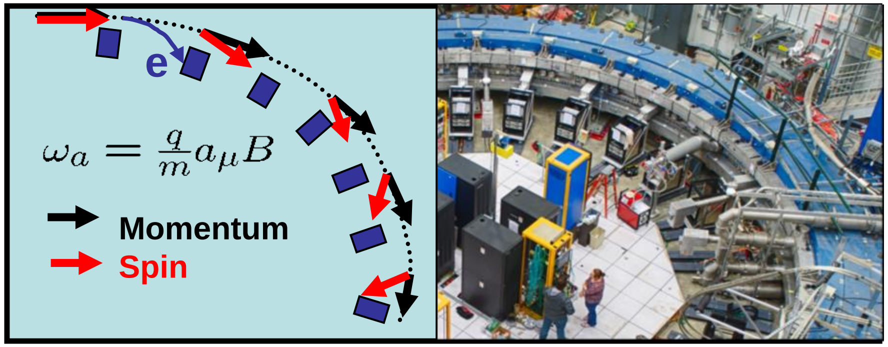
- Achieve ~ 1.5 of BNL statistics; (BNL = 7.5% of our goal)
- Have tested the full system and analysis
- Have identified weaknesses we can address to increase Flux and improve many systematic challenges



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 μEDM

Get a_μ

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

Measure these

Magic γ = 0

±δP μ'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_μ to 140 ppb

1. Store More Muons
   - 21 x BNL in statistics … (100 ppb)

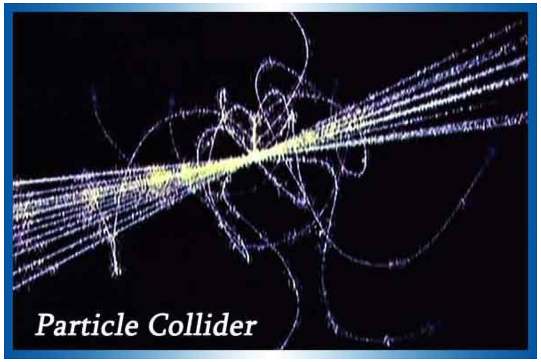
Today we focus on this

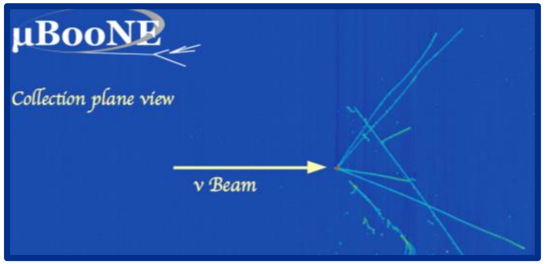
2. Prepare A More Uniform Magnetic Field ✓
   - Goal → 3 x better and more carefully measured (70 ppb)

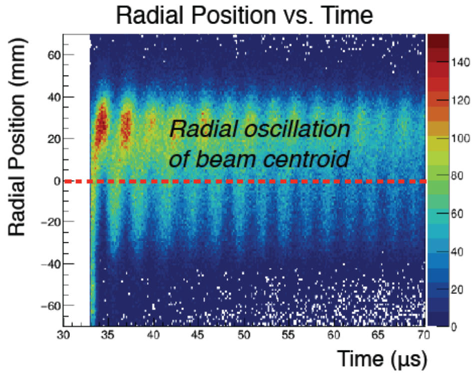
3. Improve the Precession Frequency Measurement ✓
   - All new instrumentation with high-fidelity recording of muon decays by many systems (70 ppb)

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**



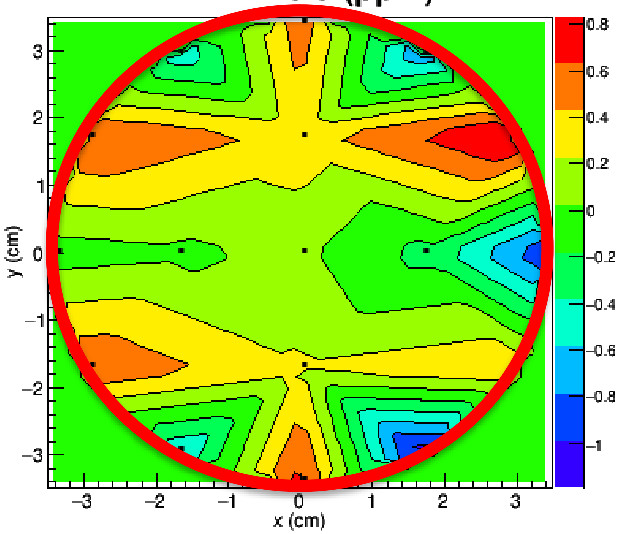




The Magnetic Field is Very Good

- 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)

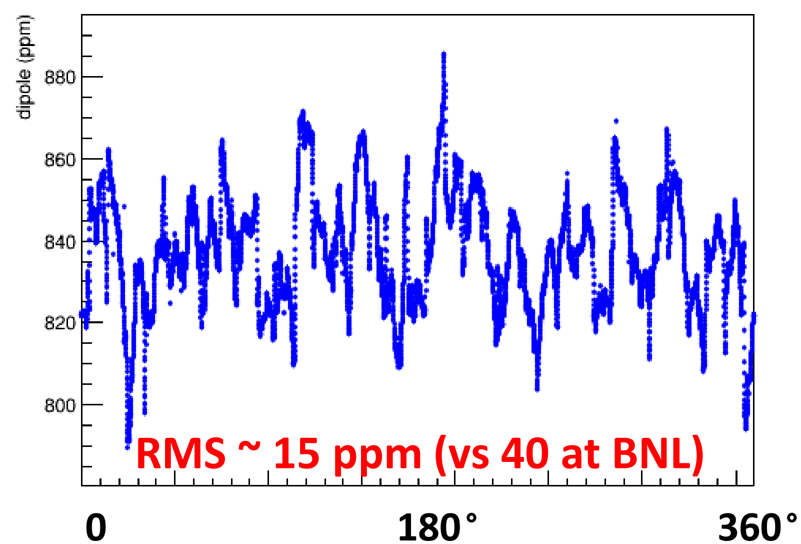
B-field (ppm)



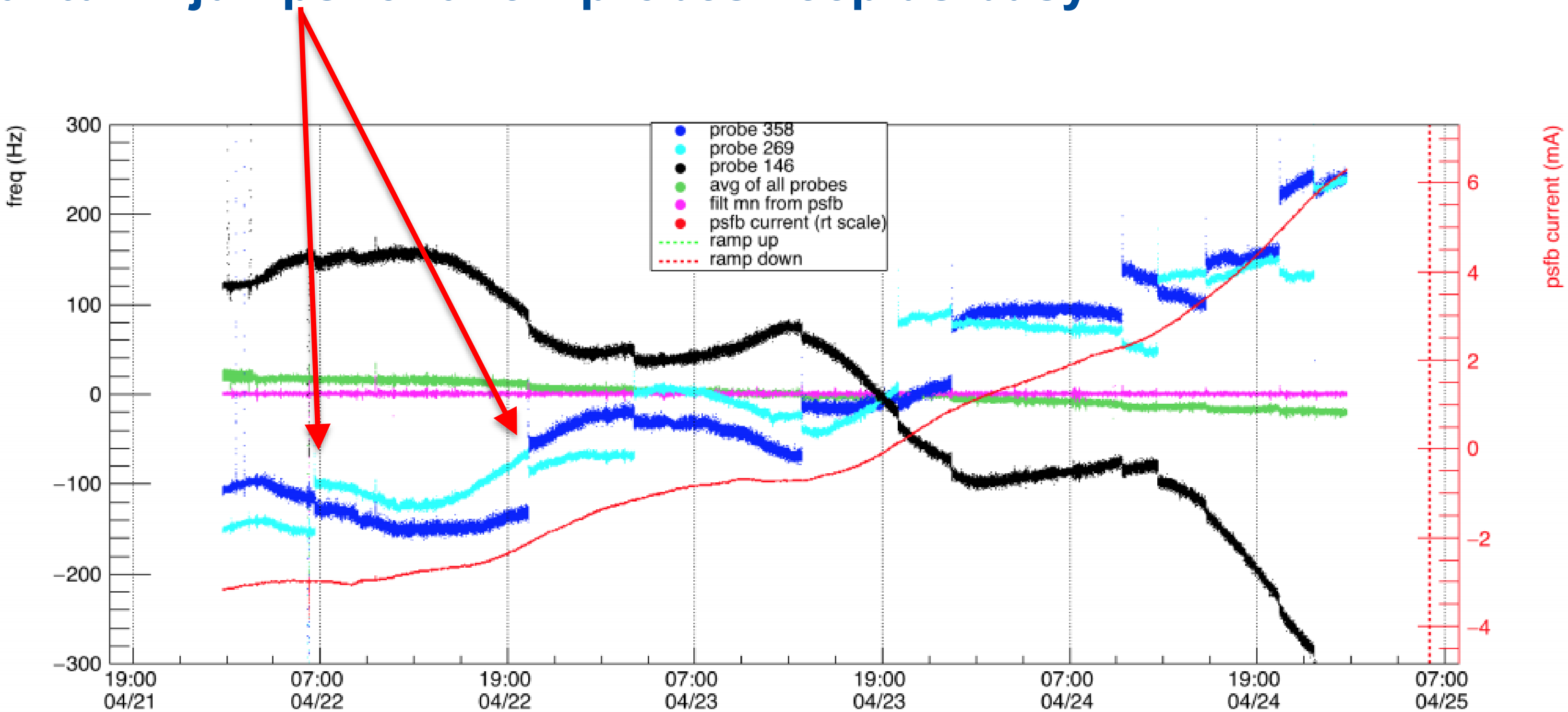
Averaged around azimuth

	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



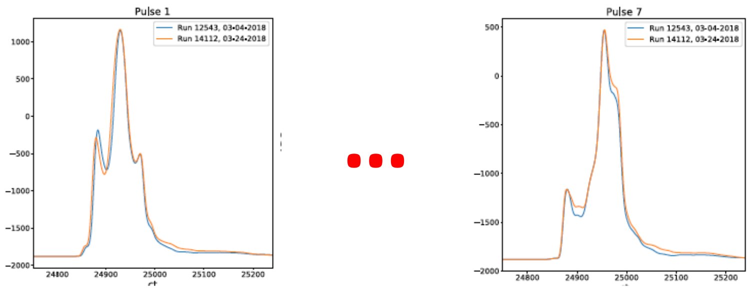
J. Grange

We are installing insulation

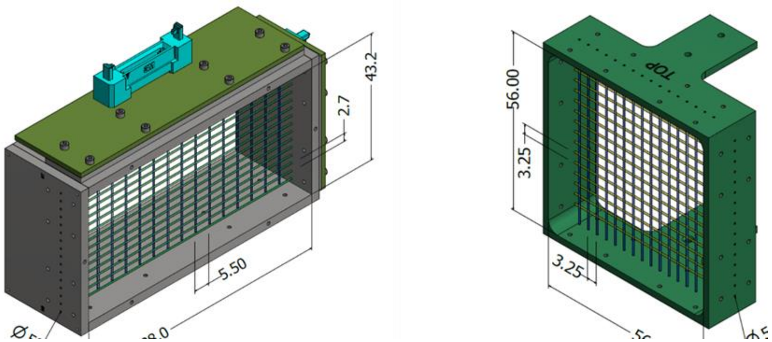
We are increasing our Fixed Probe – to-PowerSupply feedback

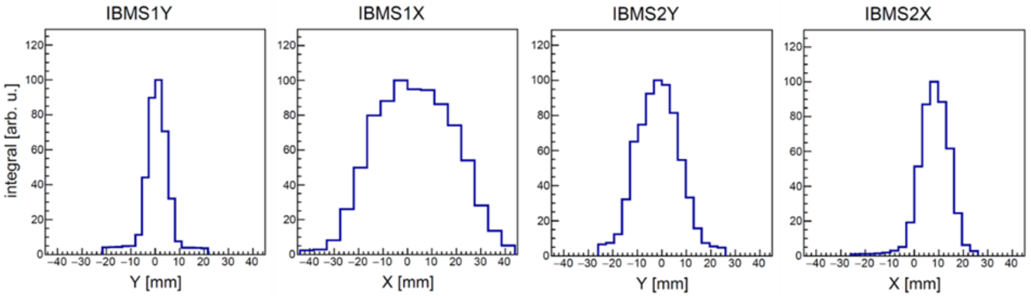
Detectors to measure *incoming* beam properties, used to optimize beam tuning

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



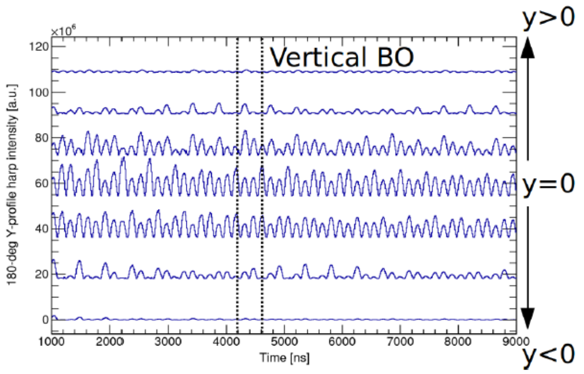
- **IBMS** scintillating fiber arrays
  - To guide tuning μ into ring
  - At entrance to Ring
  - At entrance to Inflector

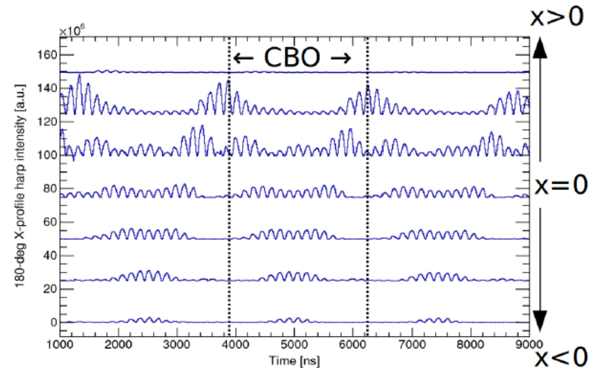


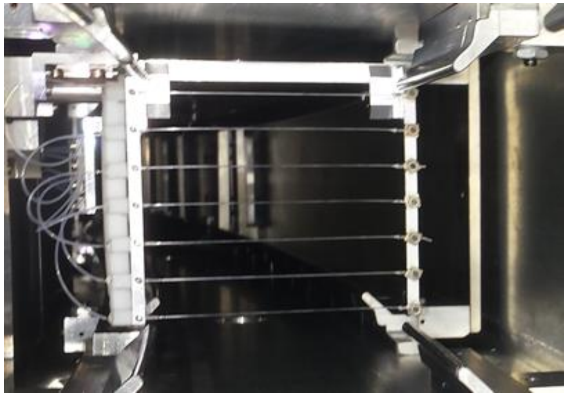


Detectors to measure *dynamics* of stored muons

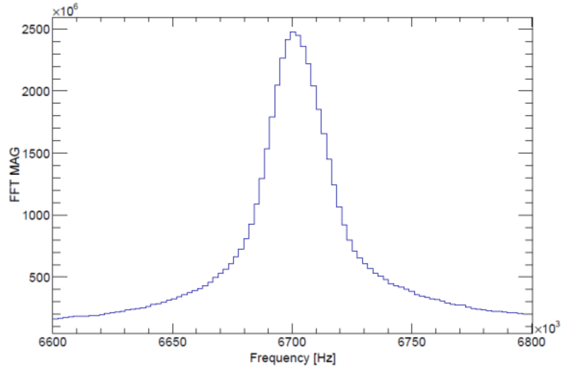
- Two, In-ring X & Y measuring **Fiber Harps**



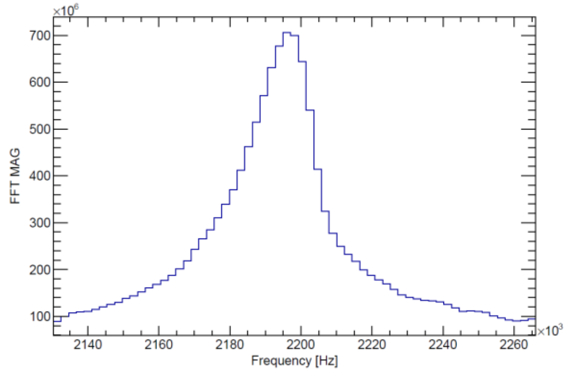




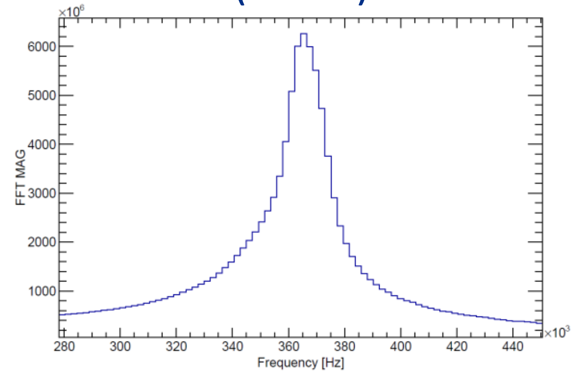
Cyclotron Frequency



Vertical Betatron



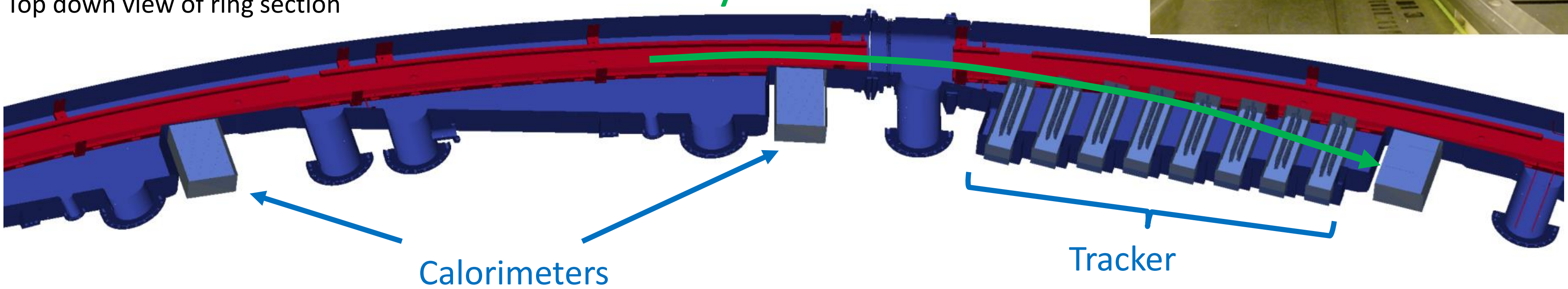
Coherent (radial) Betatron

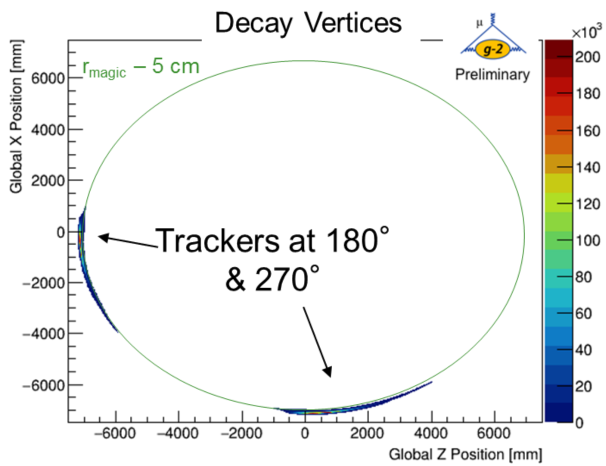


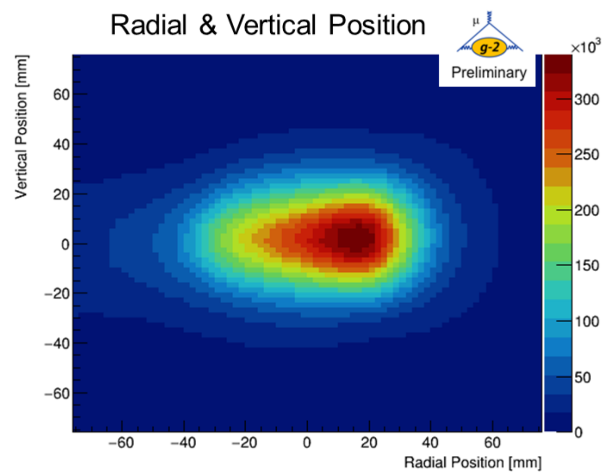
Trackers are working spectacularly to image our stored beam

Muon's-eye view inside vacuum chamber

Top down view of ring section

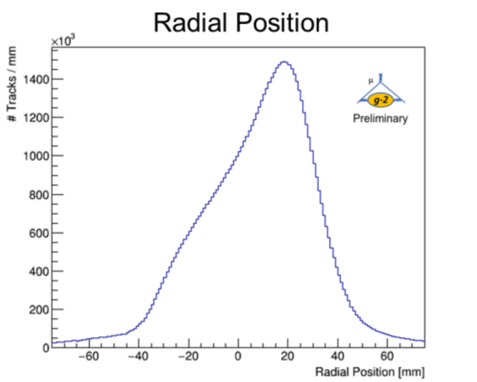


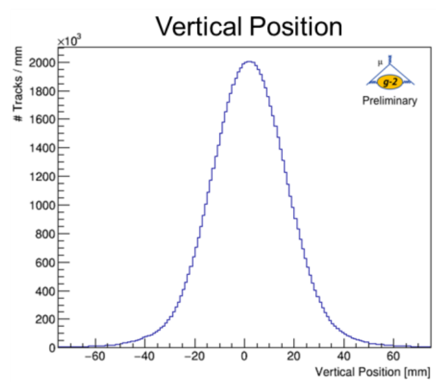


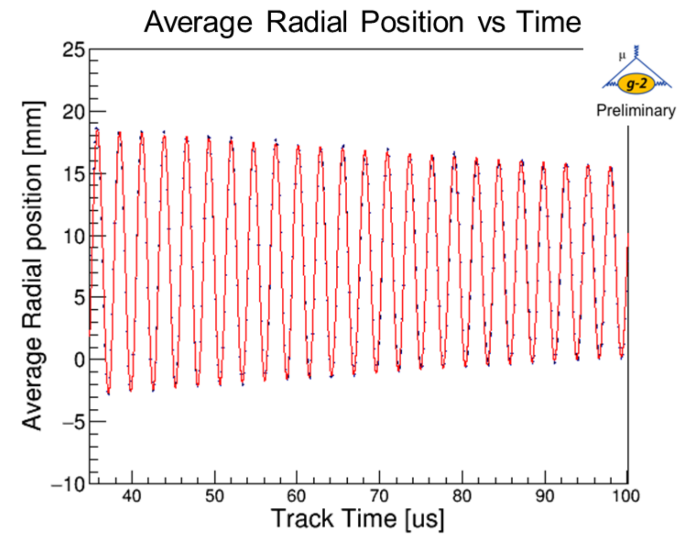


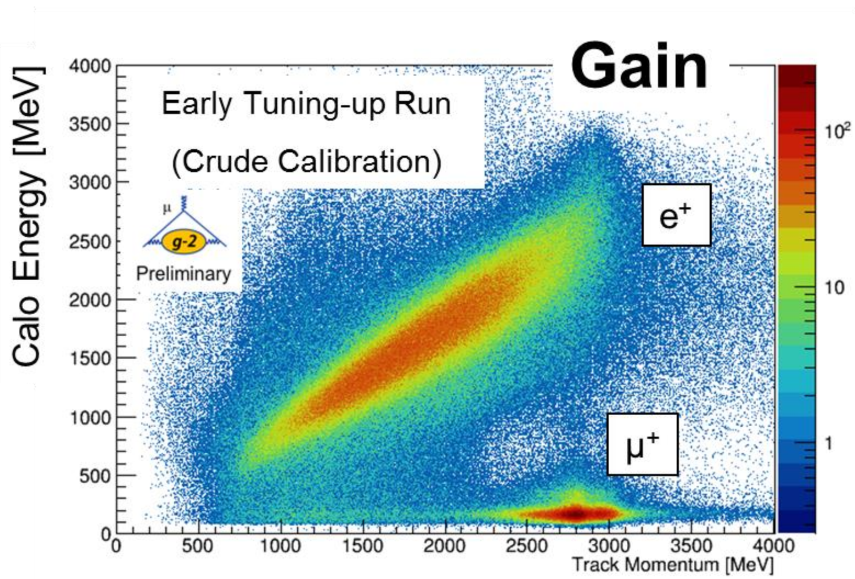
Extrapolate tracks back to point of tangency to get beam distribution:

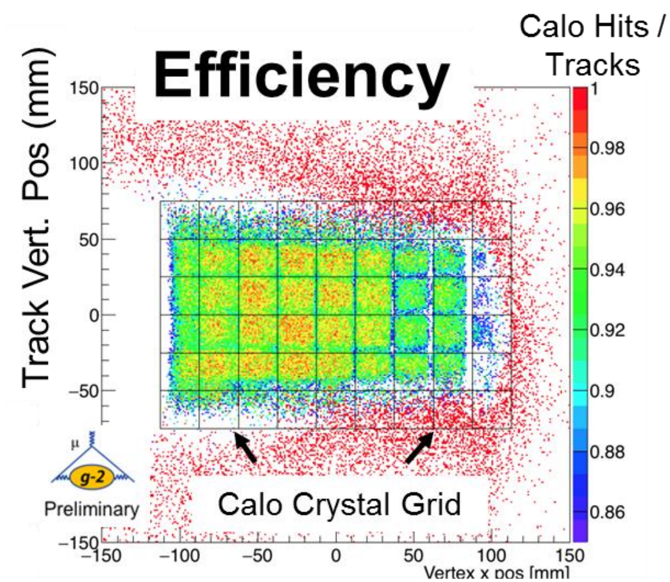
The information gives us …



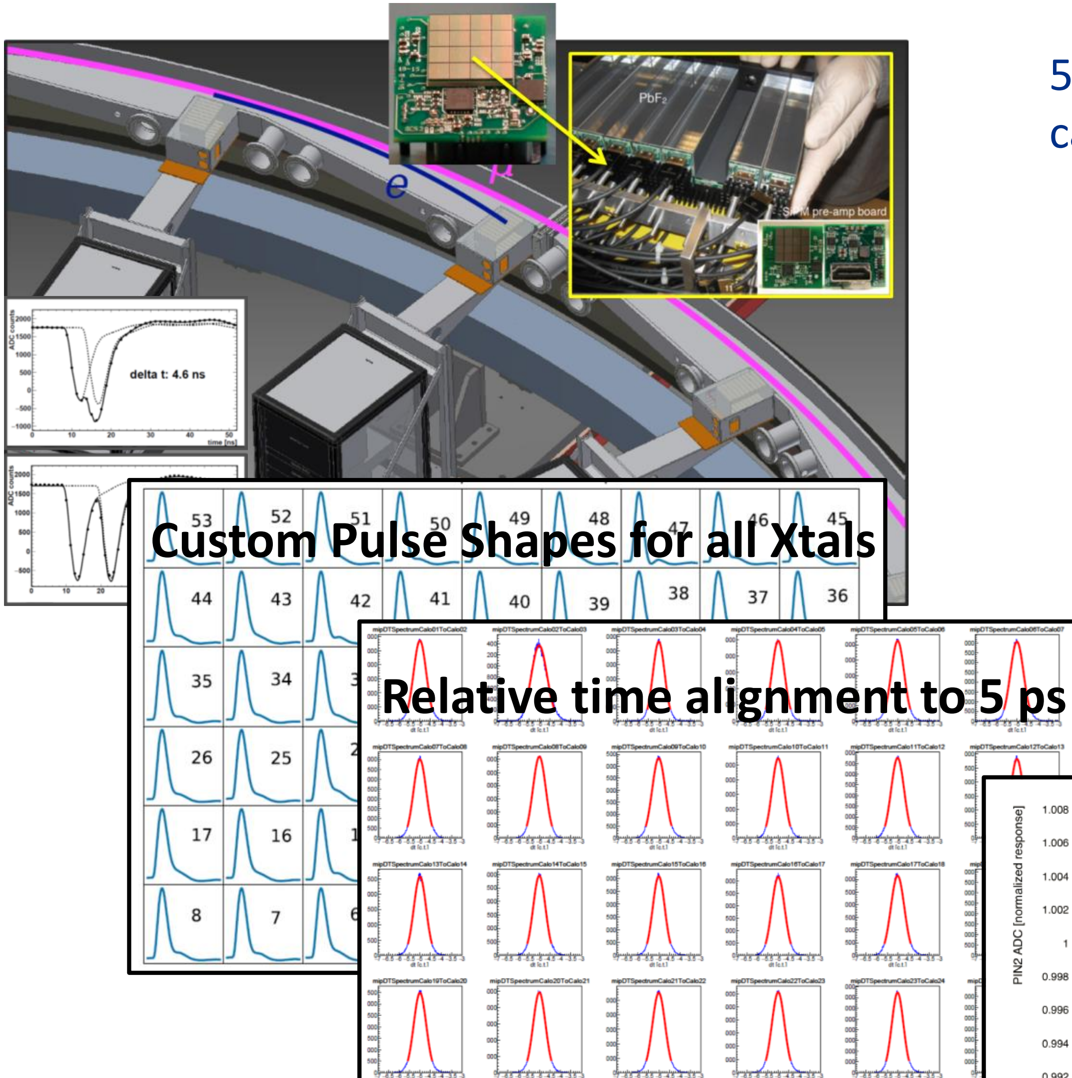




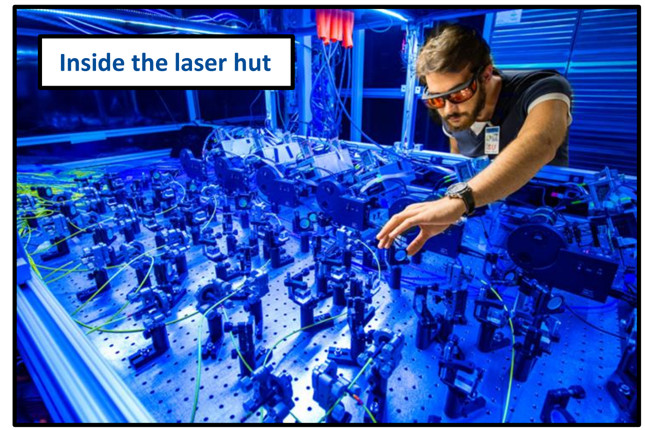




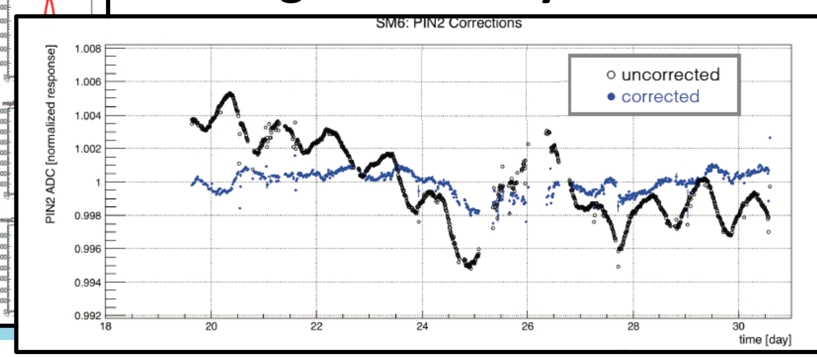
The 24 Calorimeters are working great …
… together with the Laser Calibration System



54 PbF_2 crystals with individual laser calibrations into each channel

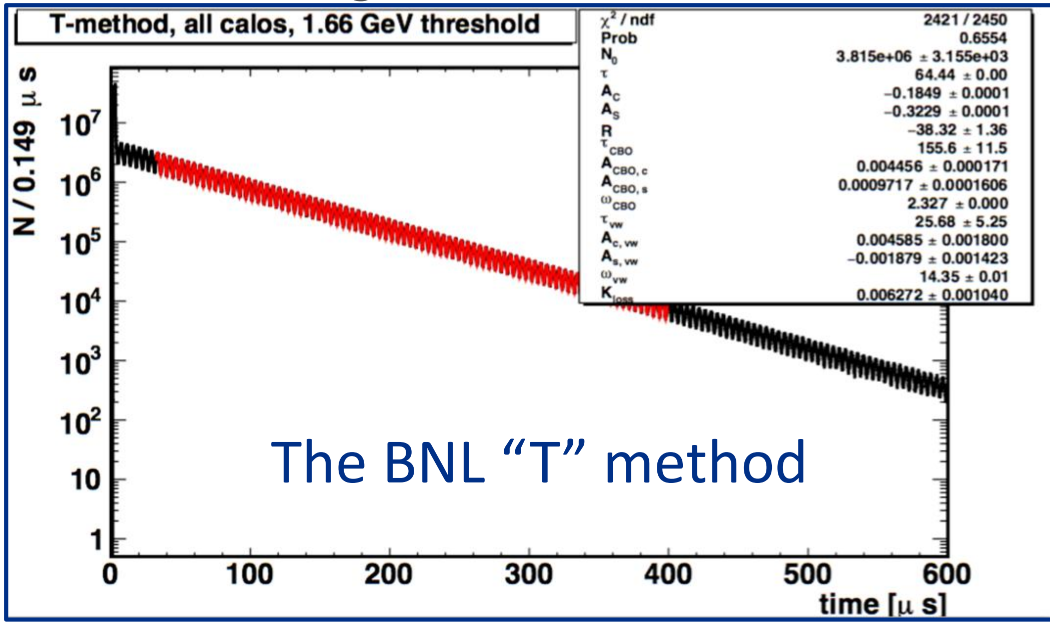


Laser gain stability to 10^{-4}



Offline analysis quite mature already …

- Included effects for 60-hr Data Challenge
  - Pileup subtraction
  - Muon loss terms
  - CBO effects
  - Long-term gain



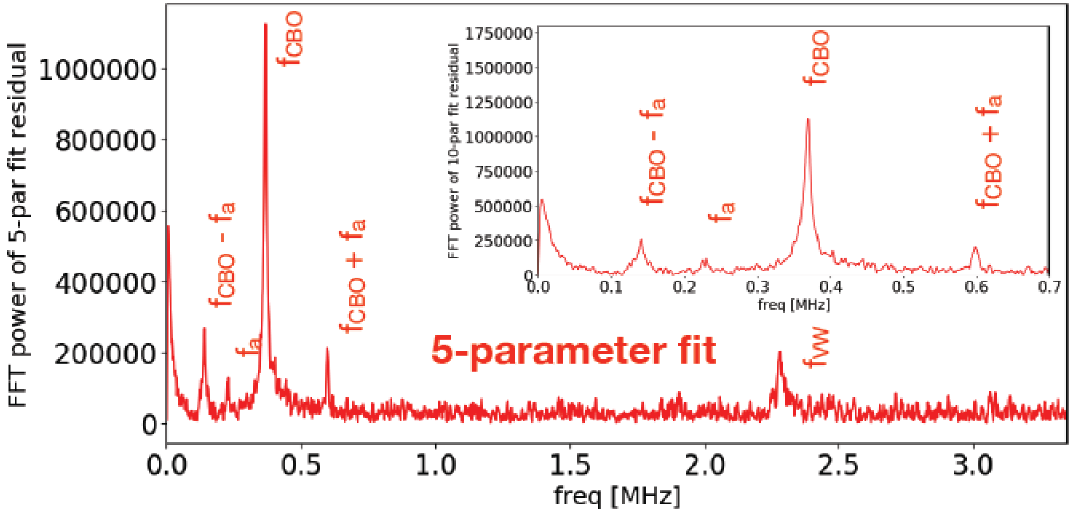
- Not yet included*
  - In-fill gain corrections
  - Fill-by-fill QC filter

- And yet, already good χ^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 (μs)
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

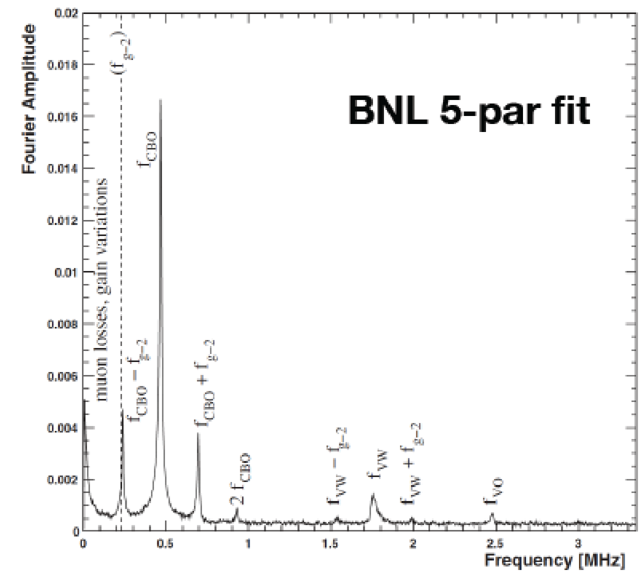
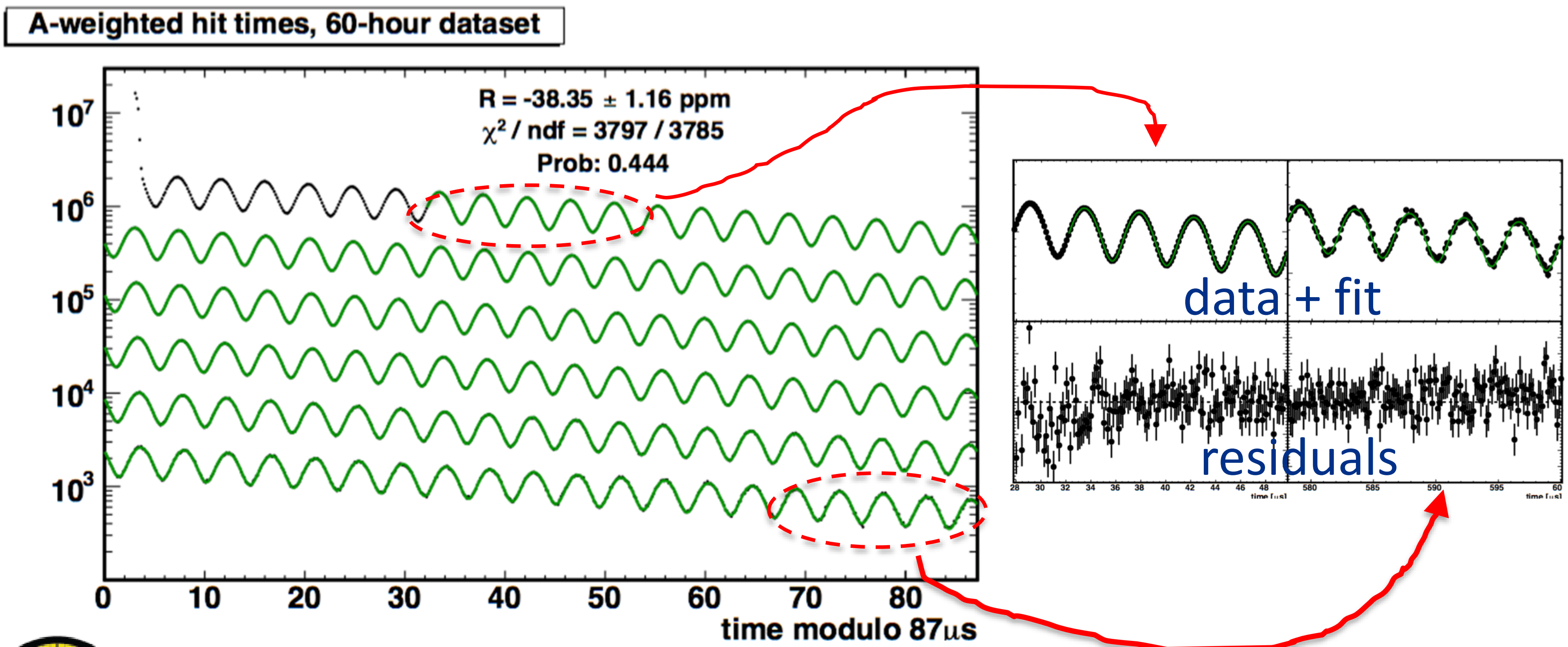


TABLE VIII. Important frequencies and periods in the $(g-2)$ storage ring for $n = 0.137$.

Physical frequency	Variable	Expression	Frequency	Period
Anomalous precession	f_a	$\frac{e}{2\pi m} a_\mu B$	0.23 MHz	4.37 μs
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 μs
Vertical waist	f_{VW}	$f_c - 2f_y$	1.74 MHz	0.57 μs

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 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 1st-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