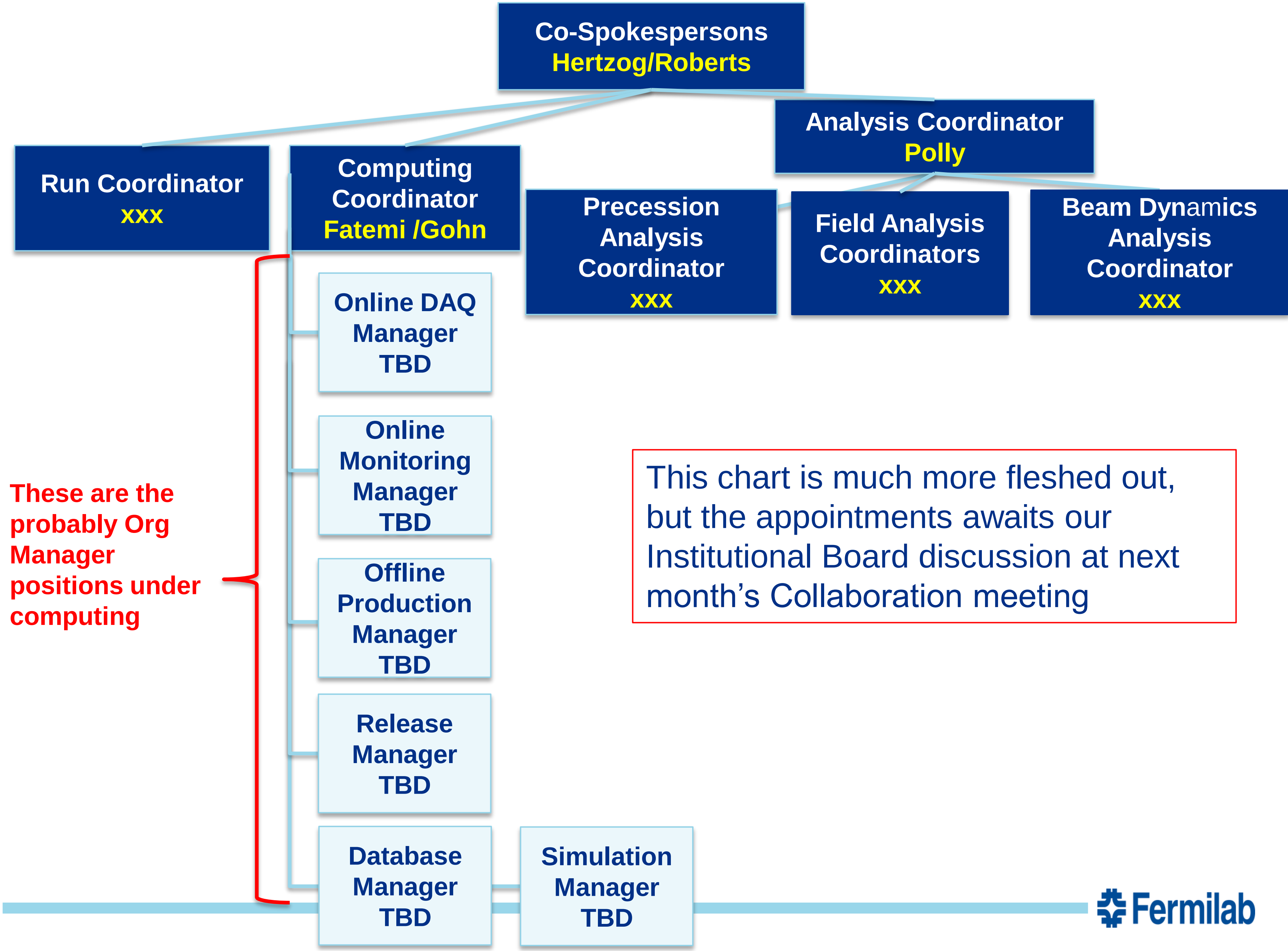
A g-2 “Compute-Centric” Overview

David Hertzog
Computing Readiness Review
Nov 7-8, 2016

This PDF version does not show animations or field movie



Co-Spokespersons
Hertzog/Roberts

Run Coordinator
xxx

Computing Coordinator
Fatemi /Gohn

Analysis Coordinator
Polly

Precession Analysis Coordinator
xxx

Field Analysis Coordinators
xxx

Beam Dynamics Analysis Coordinator
xxx

Online DAQ Manager
TBD

Online Monitoring Manager
TBD

Offline Production Manager
TBD

Release Manager
TBD

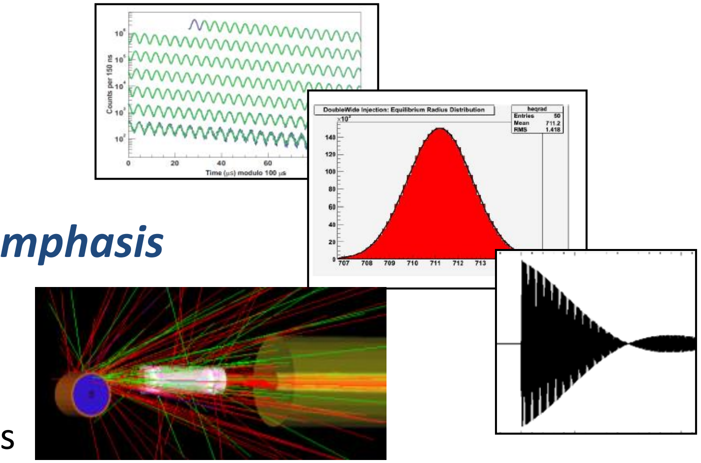
Database Manager
TBD

Simulation Manager
TBD

These are the probably Org Manager positions under computing

This chart is much more fleshed out, but the appointments awaits our Institutional Board discussion at next month’s Collaboration meeting

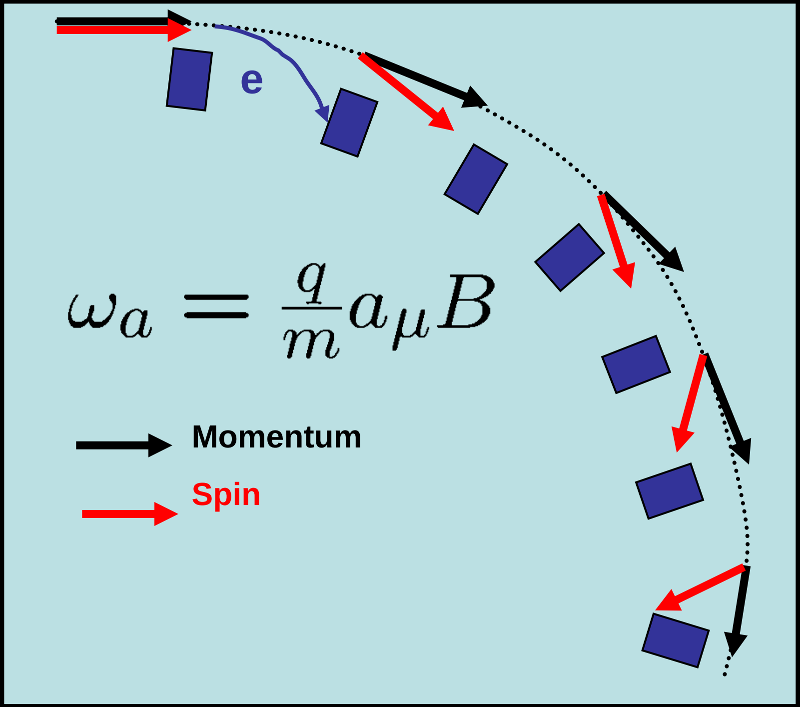
A g-2 Primer* / Outline



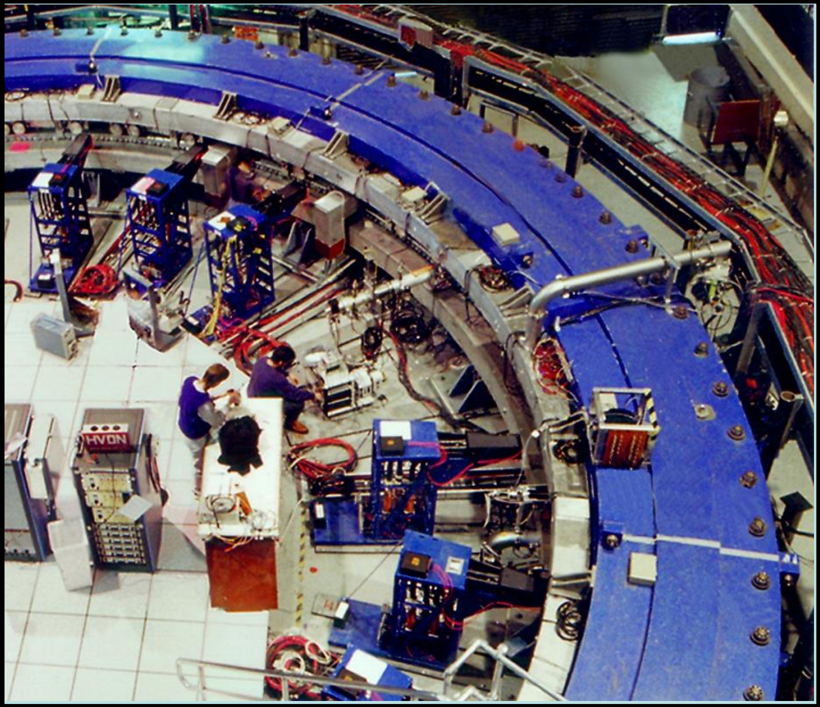
- ***What is the measurement?***
  - (1) precession frequency (detectors)
  - (2) muon distribution in ring (det & sim)
  - (3) magnetic field (NMR probes)
- ***How is the basic measurement done, with some emphasis on Simulation Tools***
  - Polarized muon beam and End-to-End simulations
  - Muon Storage hardware and Simulation optimization
  - Decay positron detection with Trackers and Calorimeters
  - Key reconstruction issues related to statistics and systematics
- ***How is the magnetic field determined***
  - What is measured
  - How it will be analyzed
- ***Important topics I will not discuss here***
  - Fast and Slow DAQ systems
  - Slow controls and Monitoring
  - Data base development
  - Online: Data Quality Monitoring (DQM)
  - Fast Turn-around: Nearline analysis
  - Offline: *art*-based production

*We also measure EDM parasitically

Muons in the Storage Ring

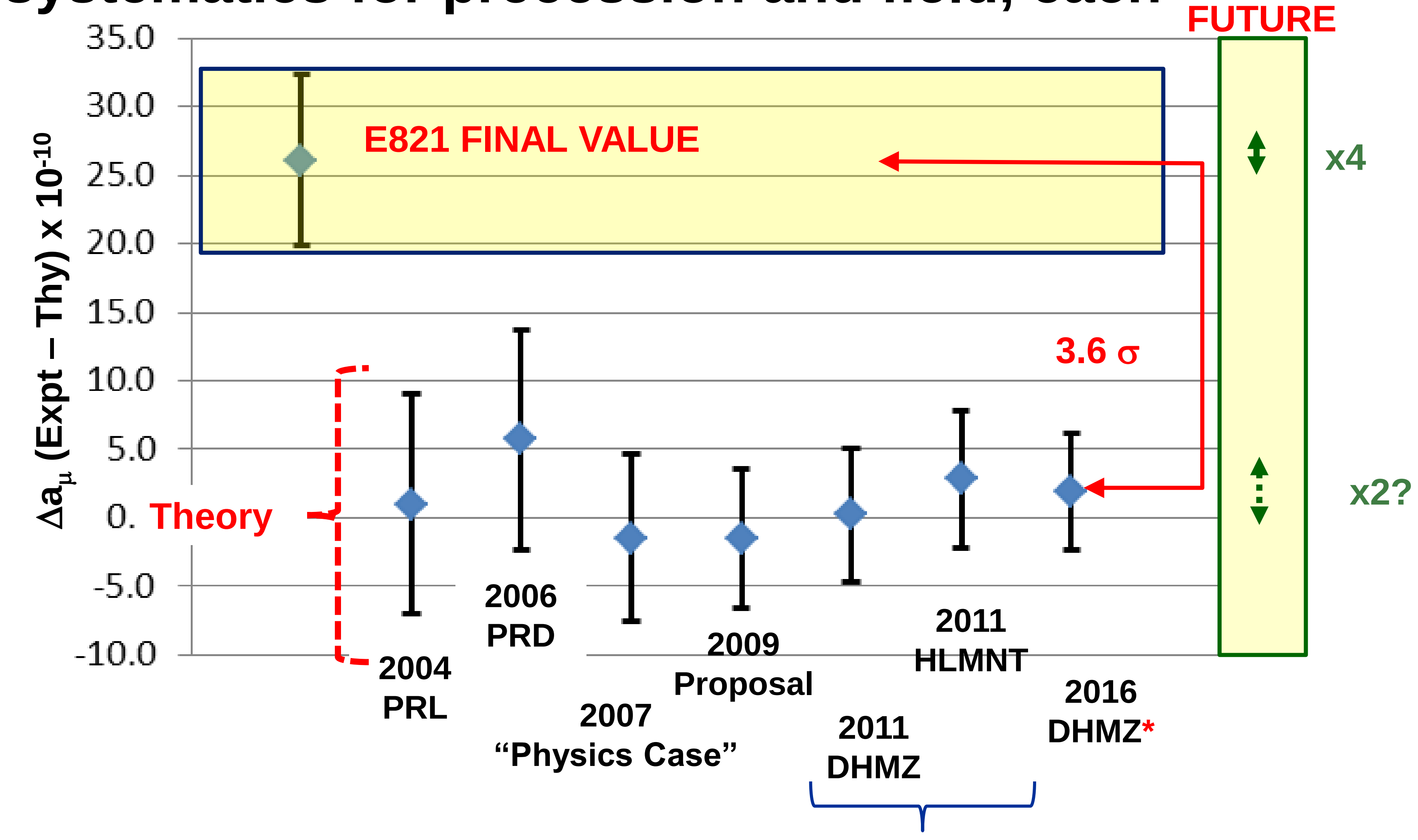


$$\omega_a = \frac{q}{m} a_\mu B$$



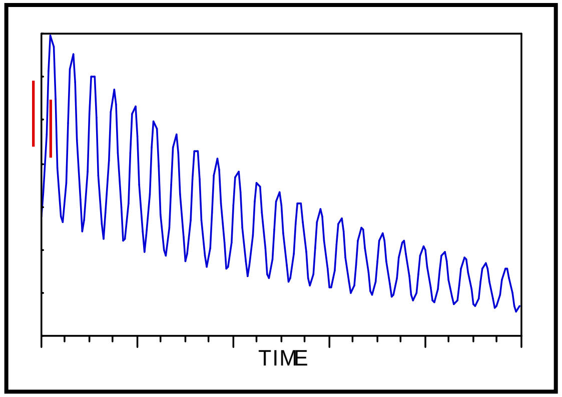
The experiment compares how fast a muon spin rotates in a magnet compared to the predictions from theory

The goal of E989 is a x4 improvement over BNL That’s 140 ppb. 100 ppb statistics; 70 ppb systematics for precession and field, each



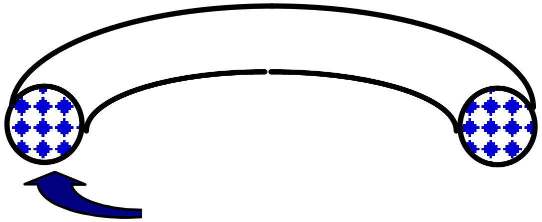
*Preliminary; Tau2016

Two “blinded” frequency measurements are made. The ratio gives $a_\mu \equiv (g-2)/2$



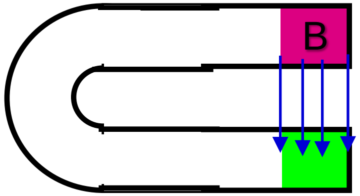
(1) Precession frequency

- (1) Calorimeters



(2) Muon distribution

- (2) Trackers



(3) Magnetic field

- (3) proton NMR

$$\boxed{(g-2) \propto \frac{(1)}{\left\langle \int (2)(3) \right\rangle}}$$

How do we get each of these?

How computing enters this picture:

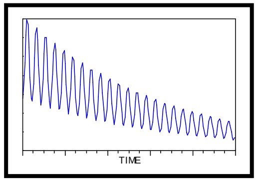
$$(g-2) \propto \frac{(1)}{\langle \int (2)(3) \rangle}$$

0. It starts with stored beam

- Beamline simulations (rate)
- Optimization guidance on setting muon storage hardware
- Beam dynamics (systematics)

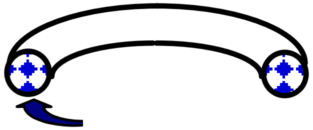
1. Precession frequency

- High data rate for DAQ
- Large number of fits and clusters
- Extraordinary calibration gain stability requirements
- Interplay between trackers and calorimeters

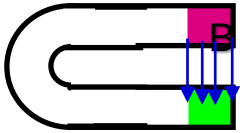


2. Muon distribution

- Fast rotation simulation
- Non-trivial tracking in non-uniform magnetic field
- Development of beam profile vs. time from traceback
- Simulation of muon storage and comparison



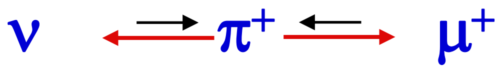
3. Magnetic field

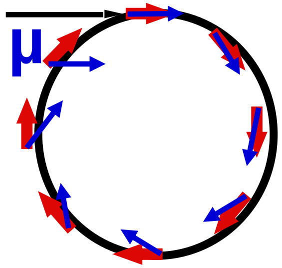


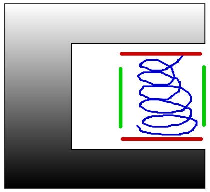
- 2D and 3D OPERA modeling to guide shimming and establish field map
- Continuous DAQ for field monitoring and custom DAQs for special measurements
- Analysis of FIDs with fitting and multipole analysis

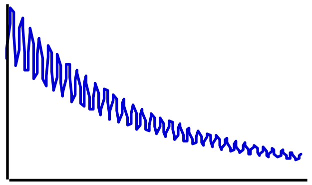
4 Key elements of a storage-ring g-2 experiment

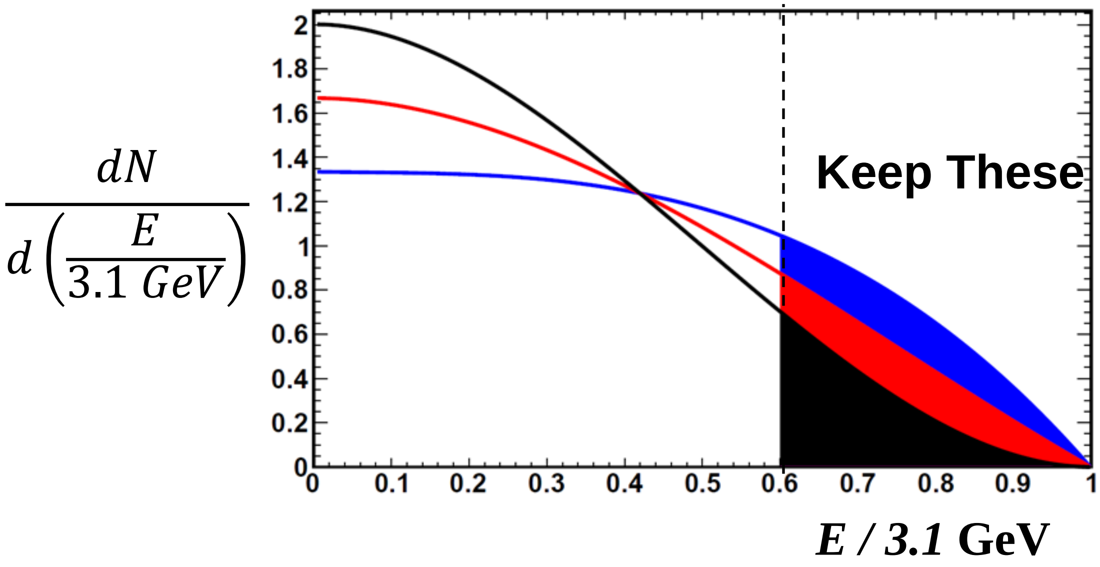
1. **Polarized muons** ~97%
2. **Precession proportional to (*g*-2)**
3. **P$_\mu$ magic momentum = 3.094 GeV/c**
4. **Parity violation in the decay gives average spin direction. It appears as energy oscillation**

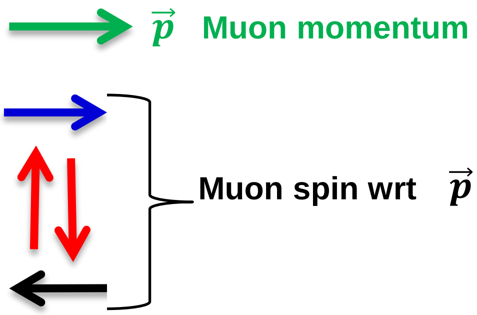








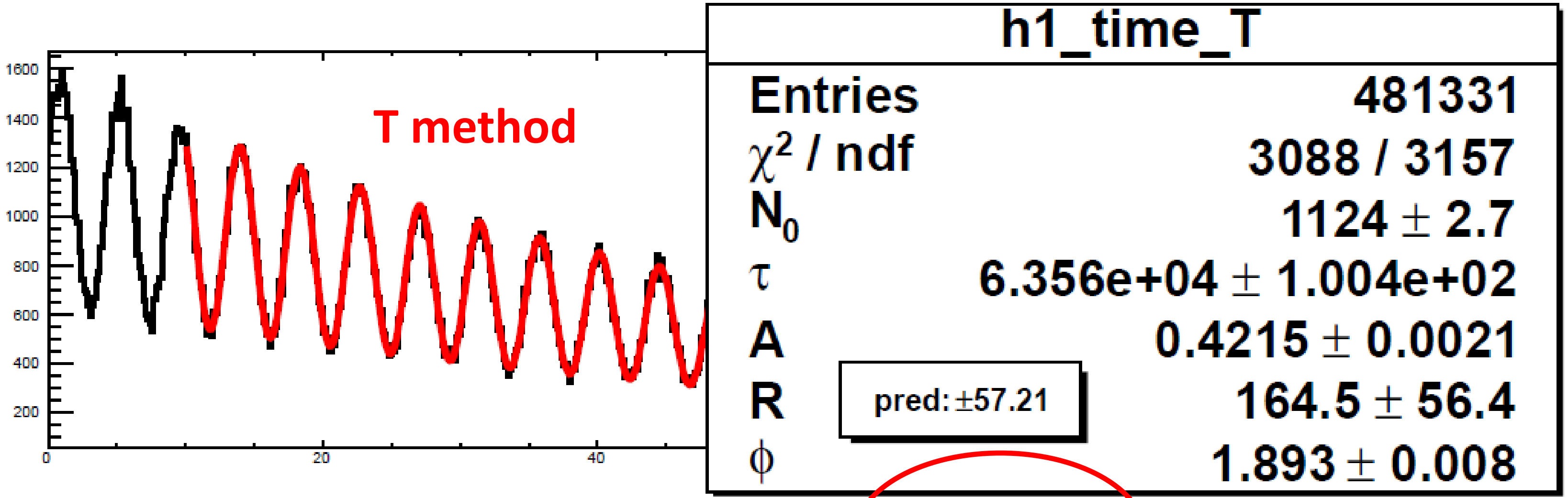




“T” and “Q” method analyses. You will be hearing these frequently.

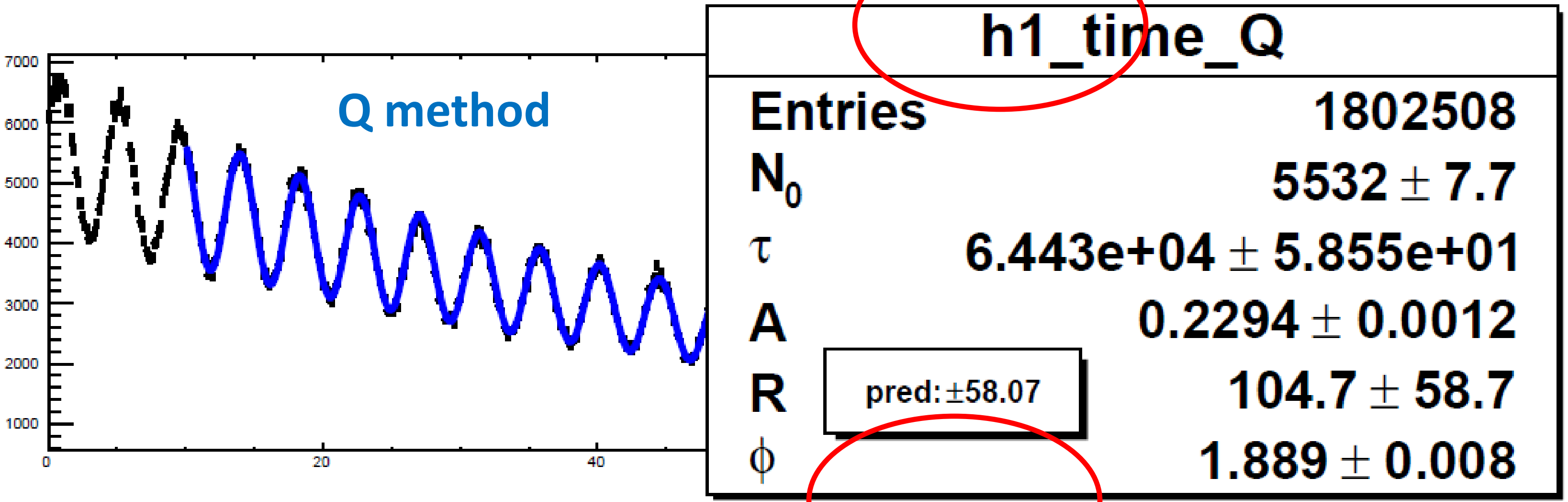
- **T (time) Method**
  - For positrons above 1.8 /3.1 GeV threshold, histogram number of events vs. time in fill
    - **Requires accurate reconstruction of positron showers in calorimeters, including pileup identification and correction**
  - Maximizes Figure of Merit (NA^2) in simplest way
- **Q (charge) Method**
  - The total energy striking a calorimeter vs. time oscillates at g-2 frequency. Plot “Energy in Calorimeter” vs. time by adding the undisturbed raw waveforms
    - **Does NOT require reconstruction of events or pulse fitting**
  - Has x2 lower asymmetry and overall slightly lower precision
  - Introduces new systematics related to noise
  - No pileup correction needed

Q vs T methods from simulations.



h1_time_T	
Entries	481331
χ^2 / ndf	3088 / 3157
N_0	1124 ± 2.7
τ	6.356e+04 ± 1.004e+02
A	0.4215 ± 0.0021
R	164.5 ± 56.4
ϕ	1.893 ± 0.008

pred: ±57.21

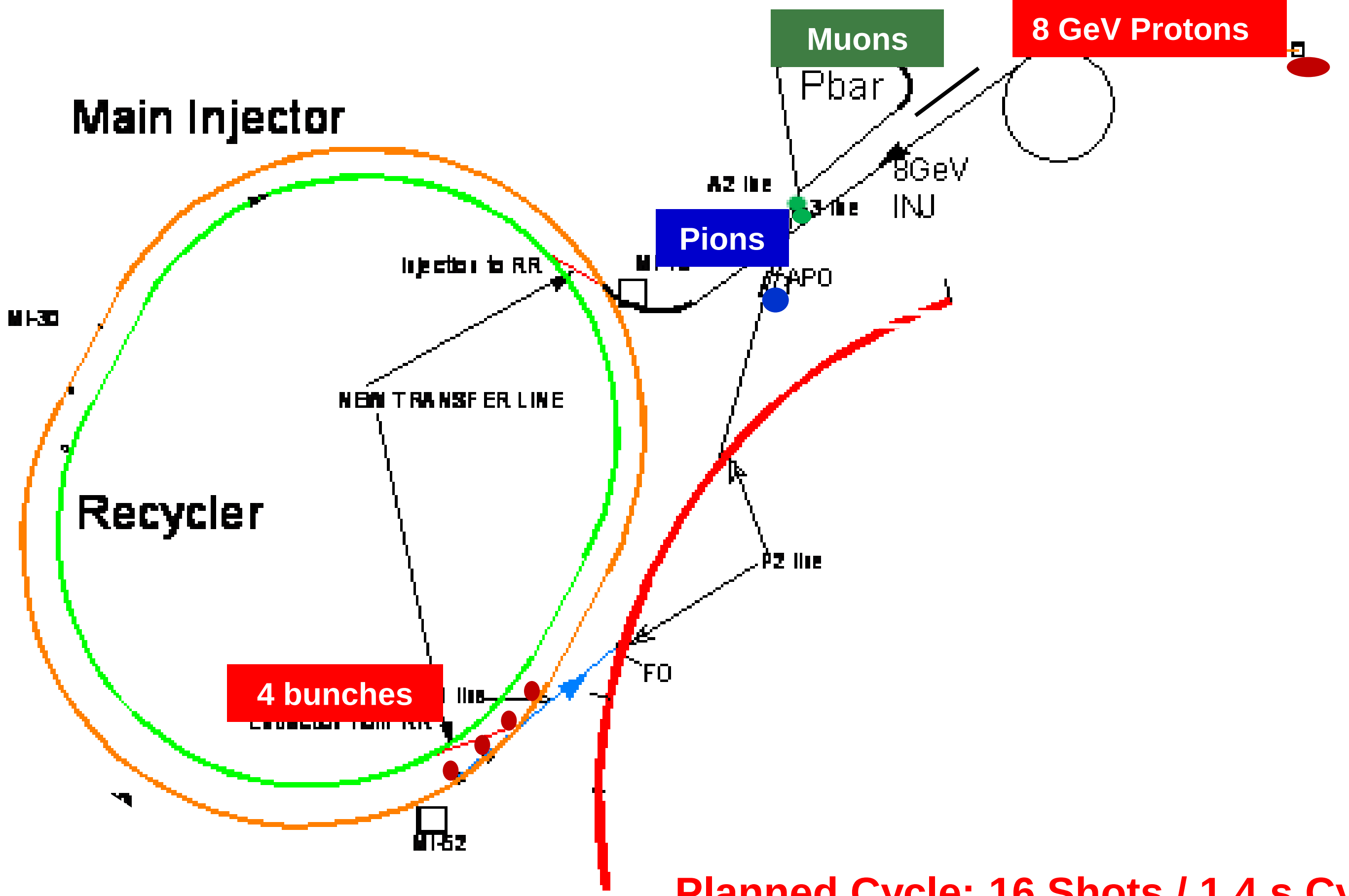


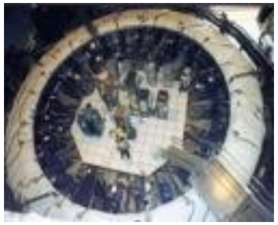
h1_time_Q	
Entries	1802508
N_0	5532 ± 7.7
τ	6.443e+04 ± 5.855e+01
A	0.2294 ± 0.0012
R	104.7 ± 58.7
ϕ	1.889 ± 0.008

pred: ±58.07

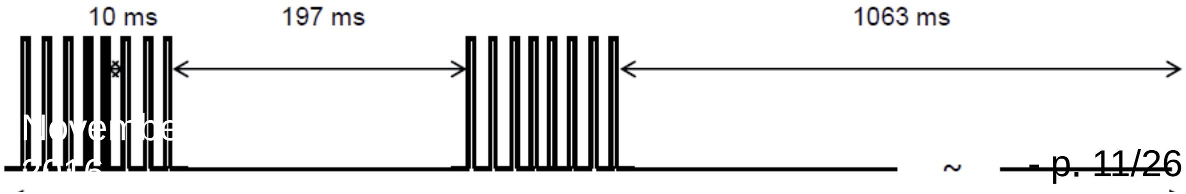
3.1 GeV/c pions are created at the old pbar target. Muons are collected from pion decay and are guided along a very long magnetic channel to the storage ring. By then, the pions are gone.

This occurs 12 times/s with 100 Hz bursts define the data flow.



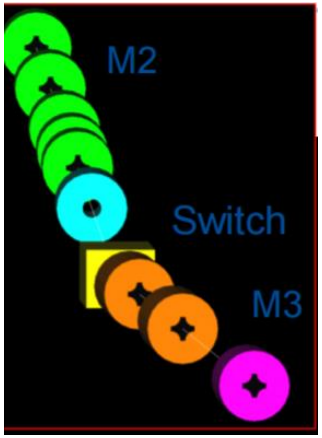


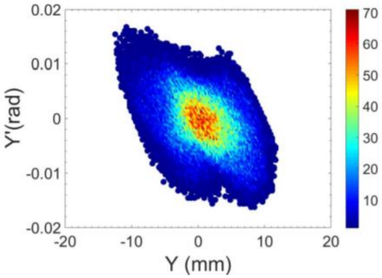
Planned Cycle: 16 Shots / 1.4 s Cycle



Critical issue where high-performance computing enters

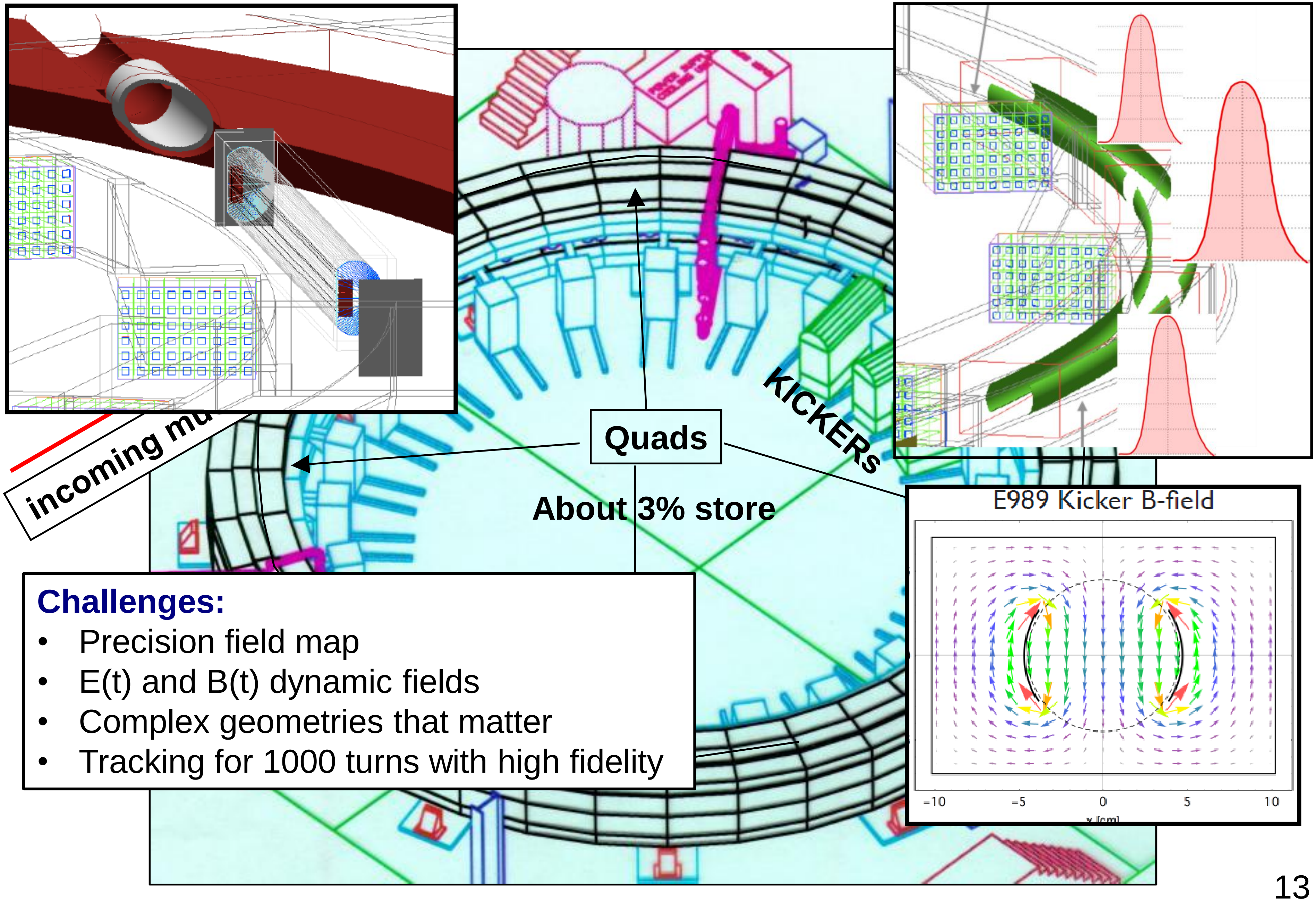
- **End-to-End beamline simulation must predict**
  - Pion production phase space at target modeled with expected proton time distribution
  - Pion to muon decay & forward muon capture in FODO line
  - Removal of protons in Delivery Ring
  - Muon polarization and spin tracking
- **Product:**
  - Files with 100's of thousand of muons at Storage Ring entrance to hand off to next simulation state
  - Rate and momentum distribution
  - Phase space properties (P_{xyz}, β_x, β_y, η_x, η_y, "Twiss parameters", time)
  - 3 models used and compared to generate results





Talk: Stratakis

Next: Simulate injection, kicker, scraping, and beam motions in Storage Ring: g2ringsim using "Injection Gun" tools



incoming mu

Quads

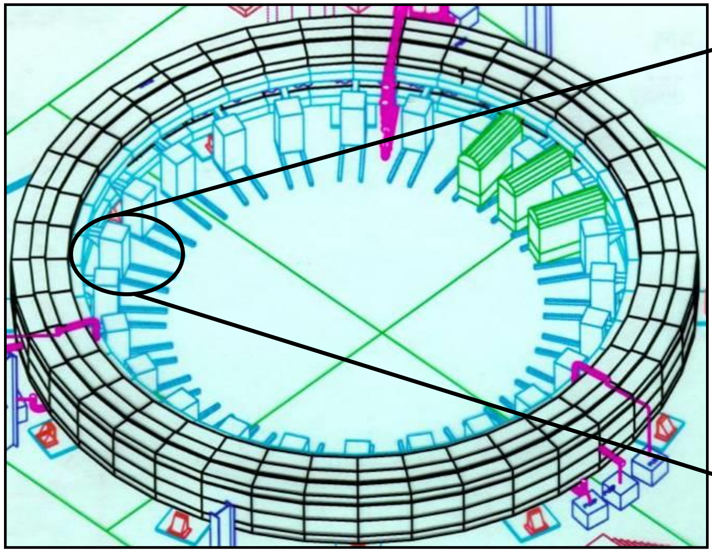
KICKERs

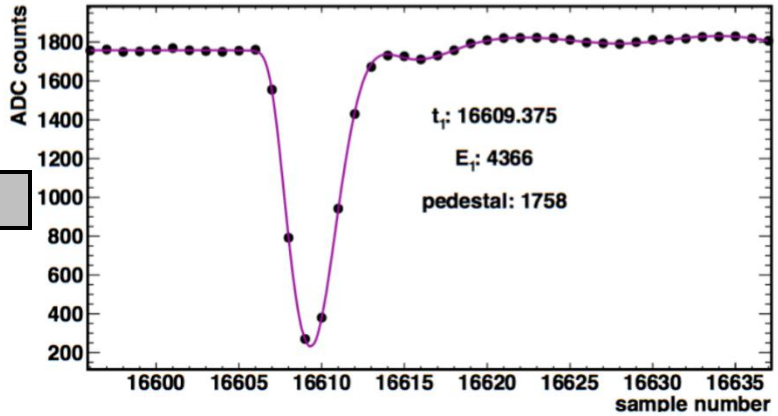
About 3% store

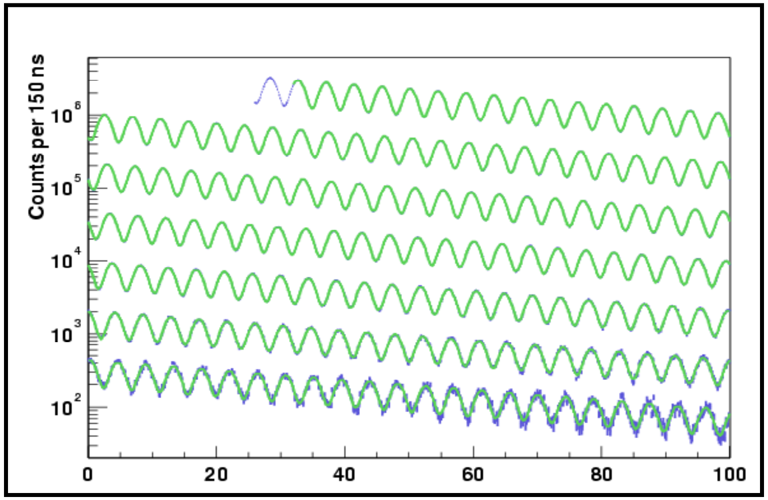
Challenges:

- Precision field map
- E(t) and B(t) dynamic fields
- Complex geometries that matter
- Tracking for 1000 turns with high fidelity

The positron decays curl inward and hit the Calorimeters
We must know their Energy and Time of hitting detector

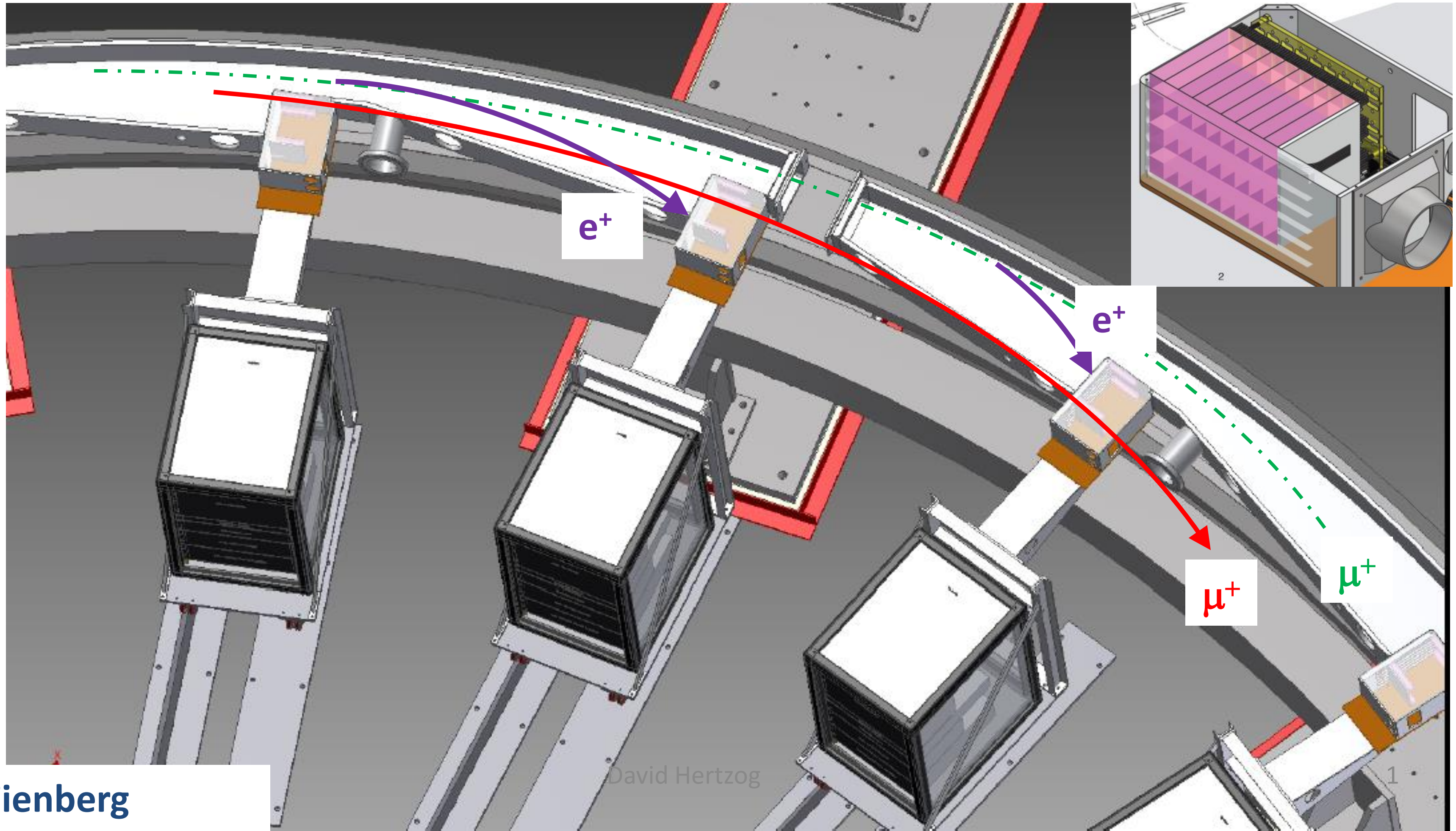






24 Calorimeters produce 18 Gb/s raw data

- Continuous 800 MSPS, 12-bit sampling of 1300 SiPMs viewing PbF2 crystals for 700 μs duration
- Online GPU processing to identify and capture pulse histories in all crystals for “any” software trigger within 54 crystal calorimeter
- Online GPU fitting of every pulse (independent of above step)
- Software is relatively mature to handle data flow & reconstruct data (**Fienberg talk**)

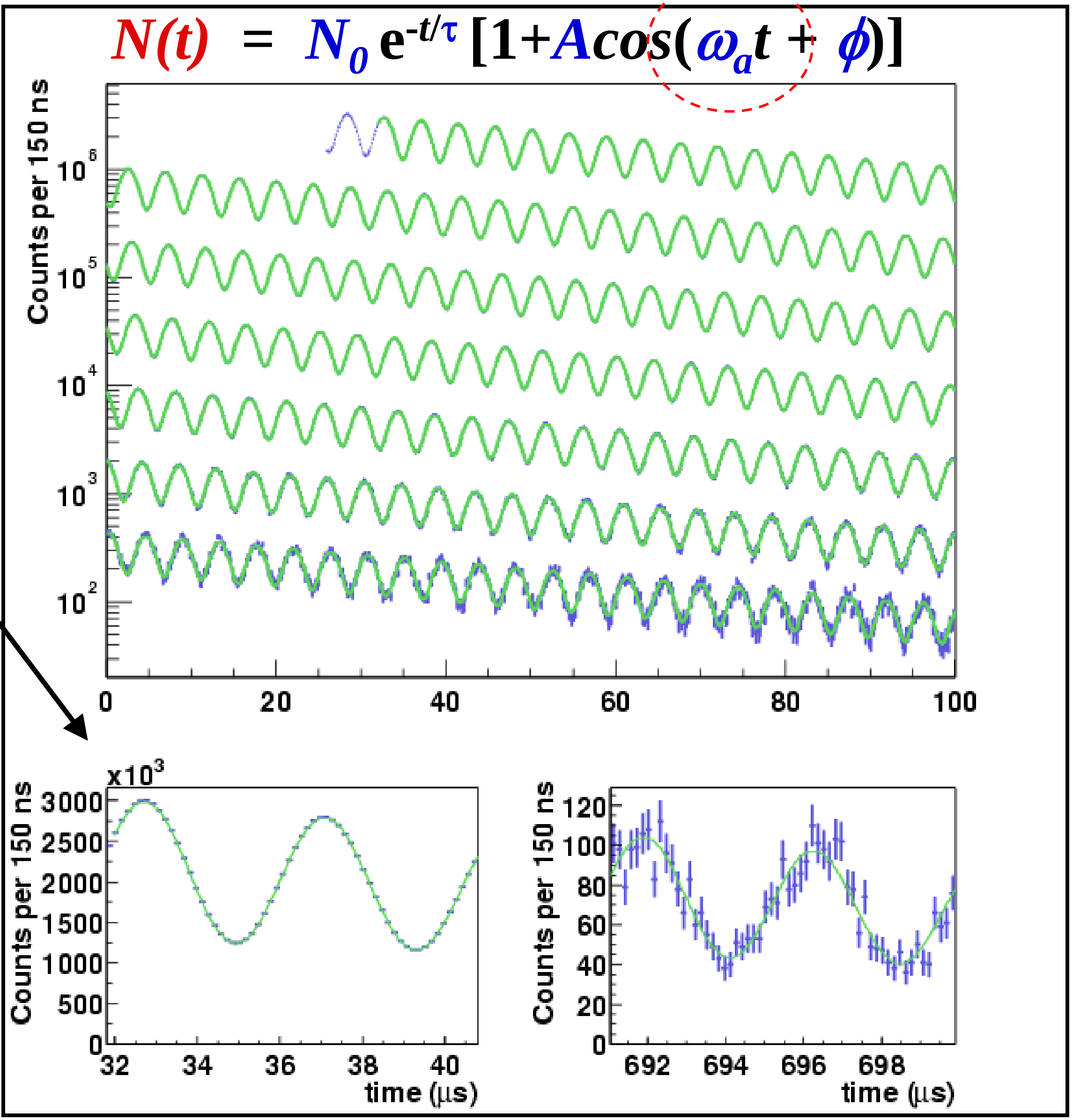


Talk: Fienberg

In the end, we fit to a modified version of this simple function

With … 2 x 10^{11} events

Getting a good χ^2 is a challenge



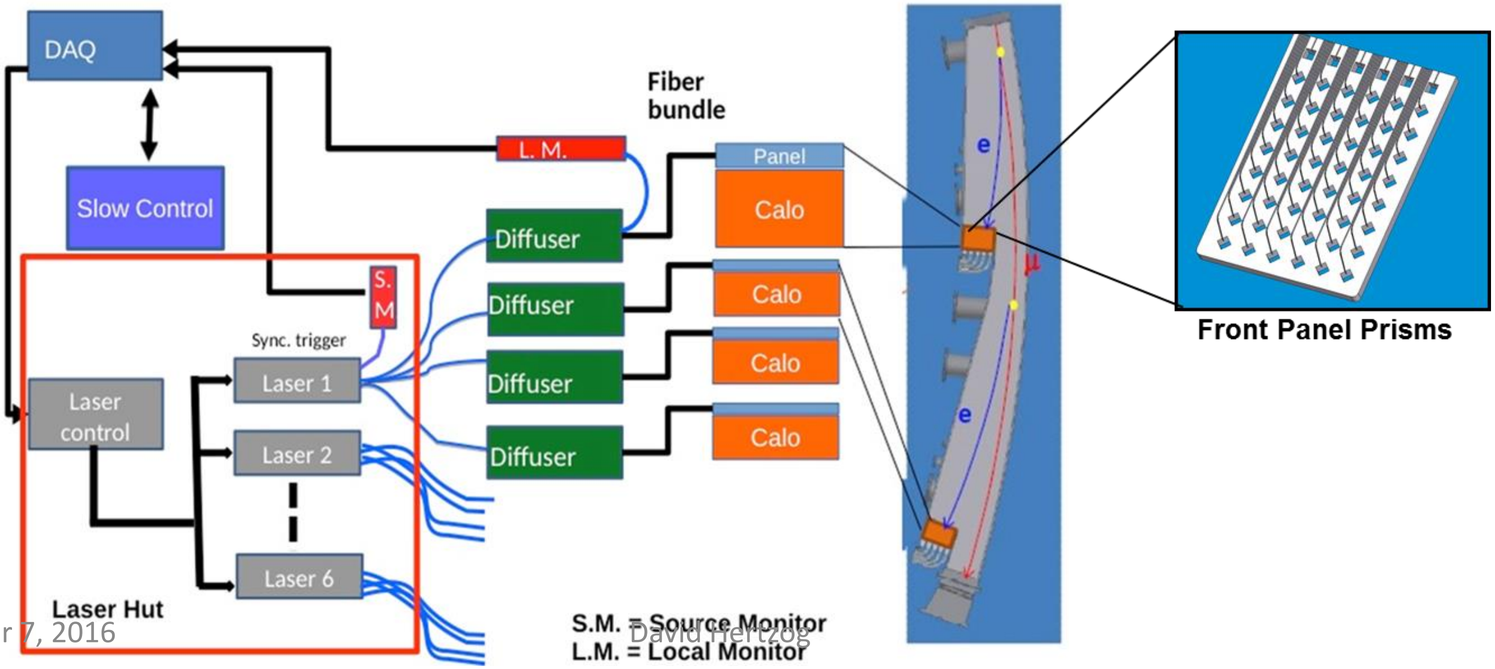
$$N(t) = N_0 e^{-t/\tau}[1+A\cos(\omega_a t + \phi)]$$

Challenging because of:

- **Pileup**
- **Gain changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**

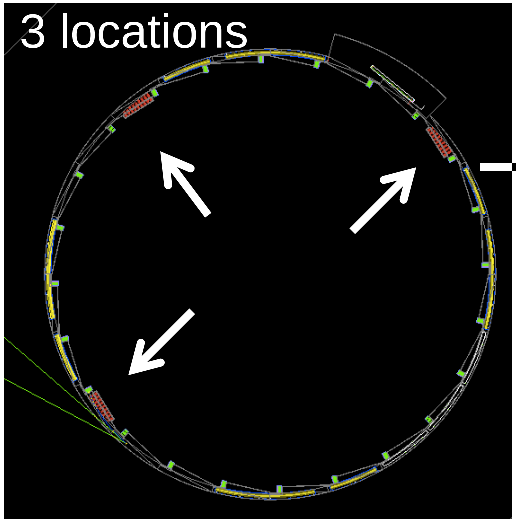
A laser-based calibration system weaves data around and on top of the real data

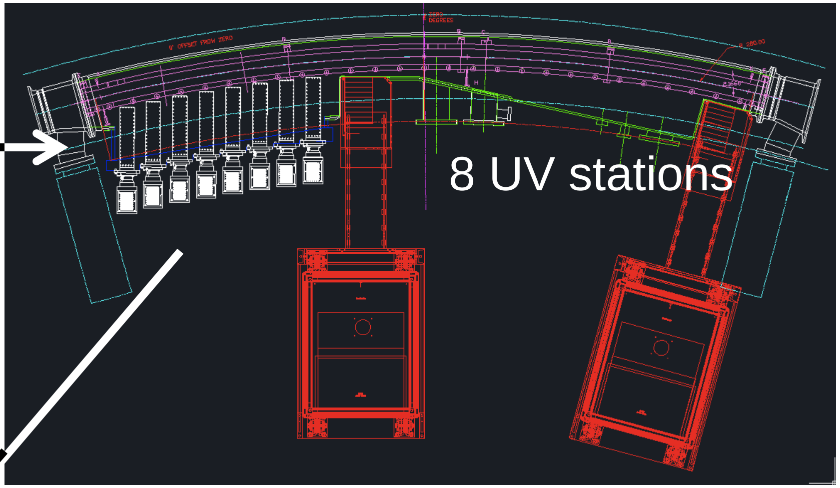
- **Compute implications**
  - Lots of calibration events that strike all 1300 detectors at once
  - Monitors of laser stability cause special DAQ sequences to be developed
  - Offline requires corrections on the fly and after the fly

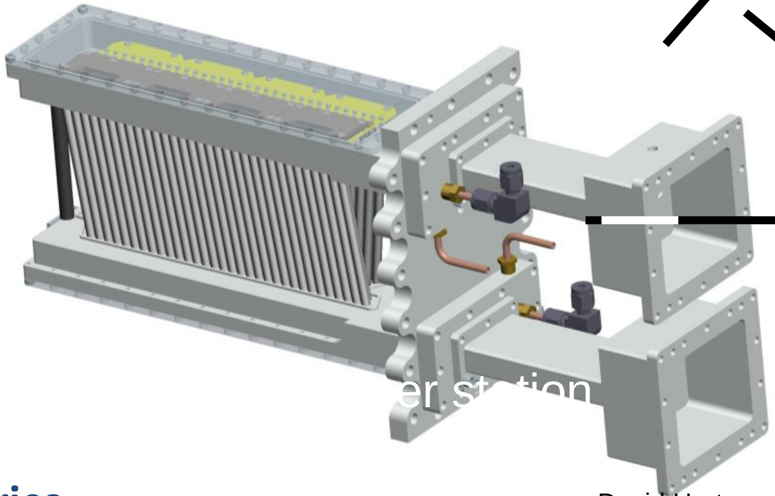


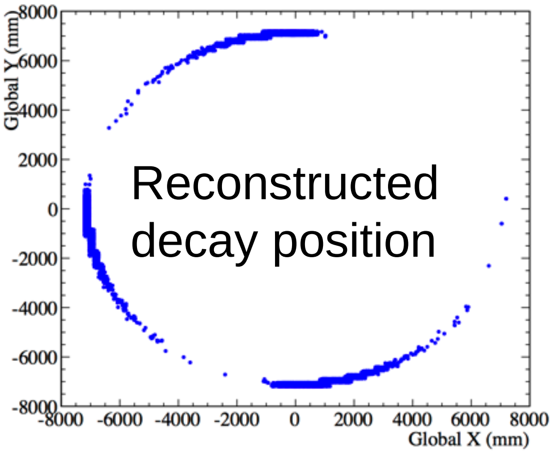
An in-vacuum Tracker can reconstruct the stored muon distribution from the decay trajectories

- Determines beam position vs. time



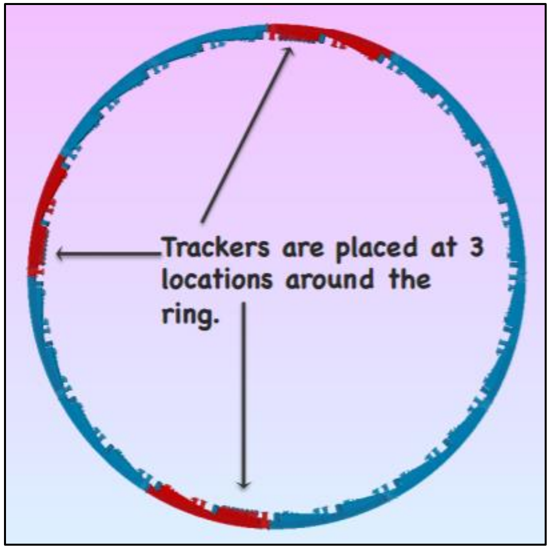




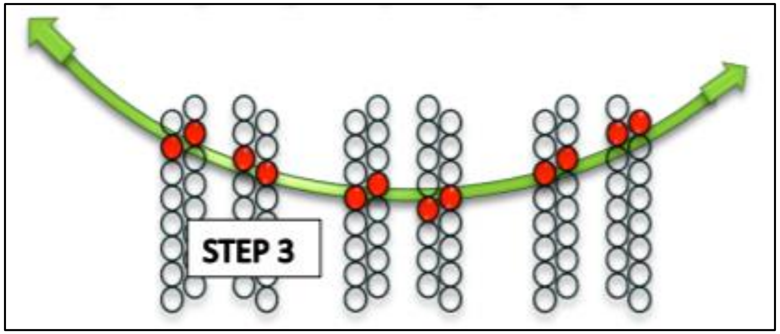


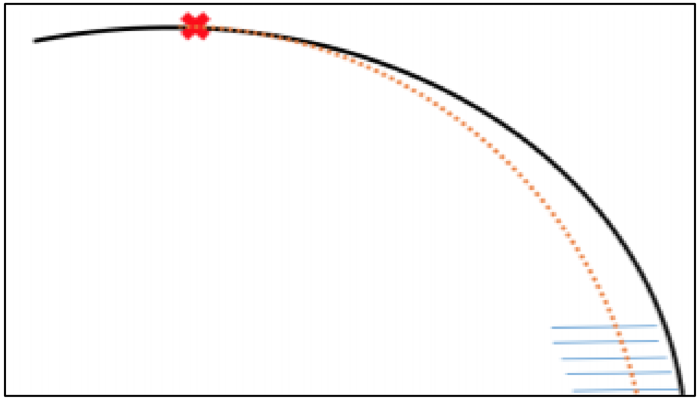
Talk: Price

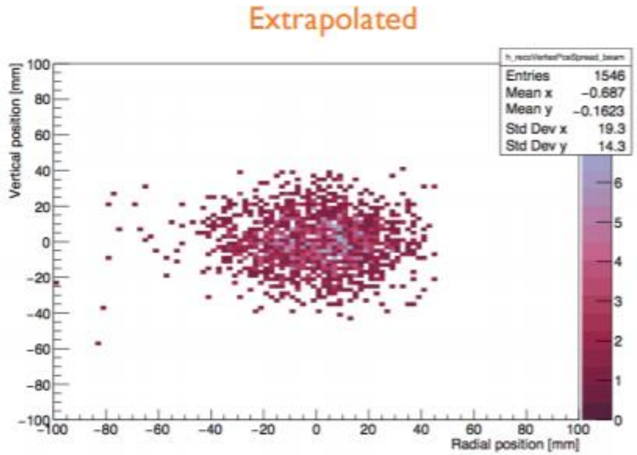
3 tracker stations with >3000 straws



Trackers are placed at 3 locations around the ring.





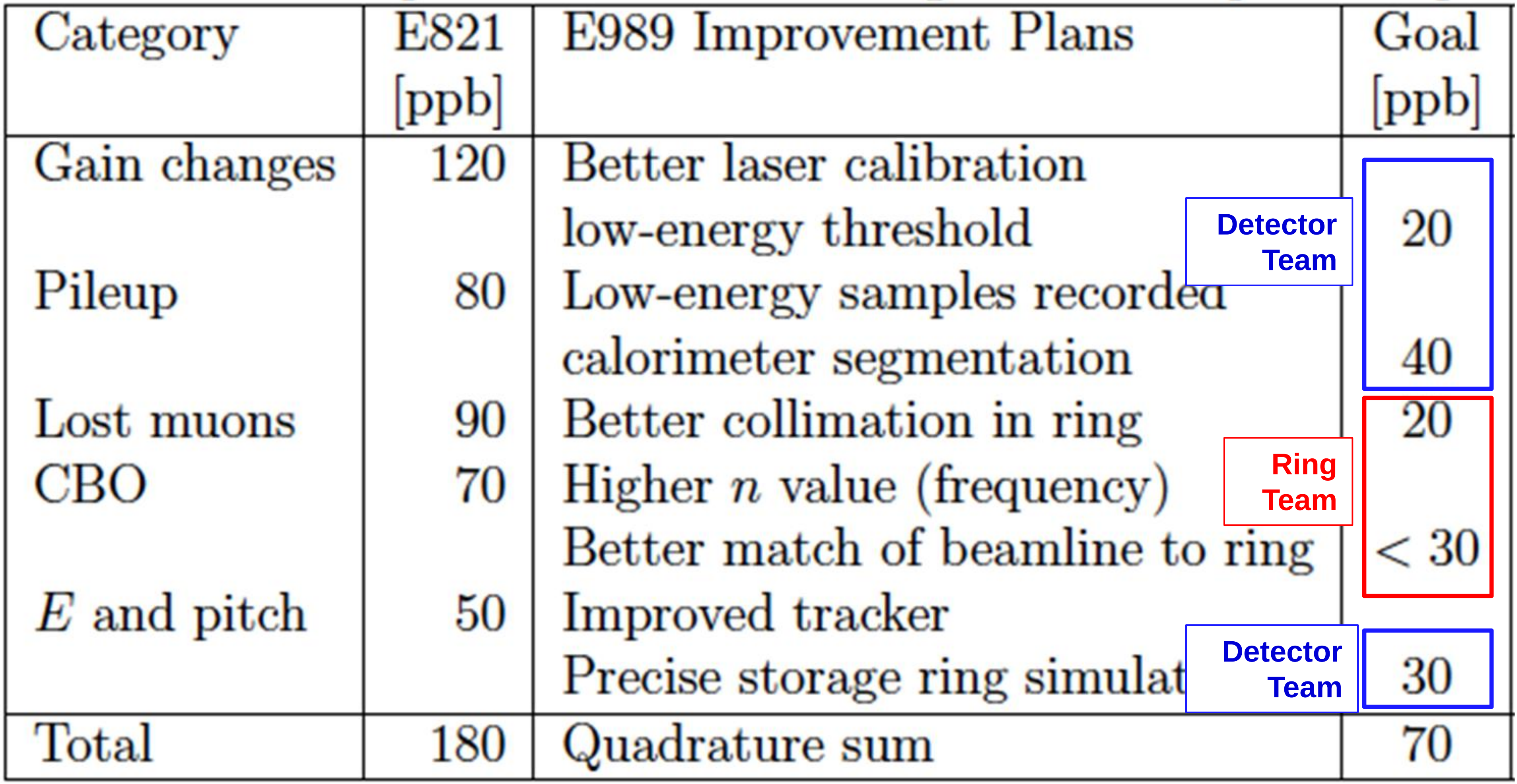


Muon Distribution
Essential to measure

Bonus: Improved muon EDM measurement by up to x100 by comparing ratio of up to down sloping tracks vs. g-2 frequency

Talk: Walton

Systematic Errors on ω_a (ppb)



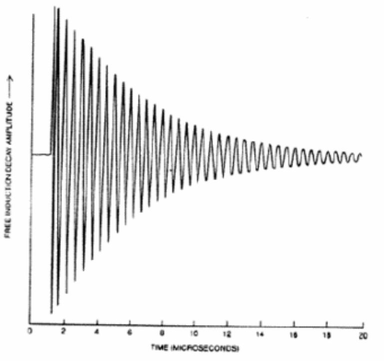
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulat	30
Total	180	Quadrature sum	70

Detector Team

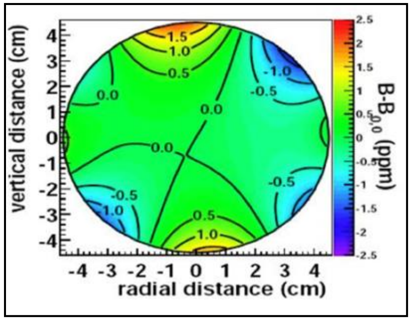
Ring Team

Detector Team

Precision measurement and mapping of the magnetic field



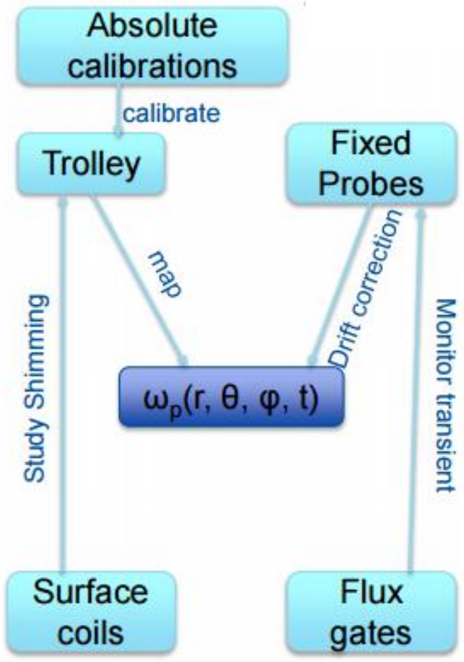
- **The Data**
  - Free induction decay waveforms
- **Challenges**
  - Continuous running "slow" DAQ reading 378 NMR probes:
    - → field stability vs time
  - Custom ~2-hour long "trolley runs" inside storage vacuum
    - → the field map seen by the muons
  - Custom readout of specialized NMR probes
    - → establish the absolute magnetic field value
- **Analysis issues**
  - Convolute field maps with positron-weighted muon distributions
  - This is the term $\langle \int (2)(3) \rangle$ in our main expression
- **Comments**
  - Running magnet for a year; basic tasks are working already
  - Relatively small team on DAQ and analysis side compared to precession teams and EDM teams



Talk: Smith

Field analysis efforts are beginning to emerge

Talk: Hong



Absolute calibrations

calibrate

Trolley

Fixed Probes

map

Drift correction

Study Shimming

$\omega_p(r, \theta, \varphi, t)$

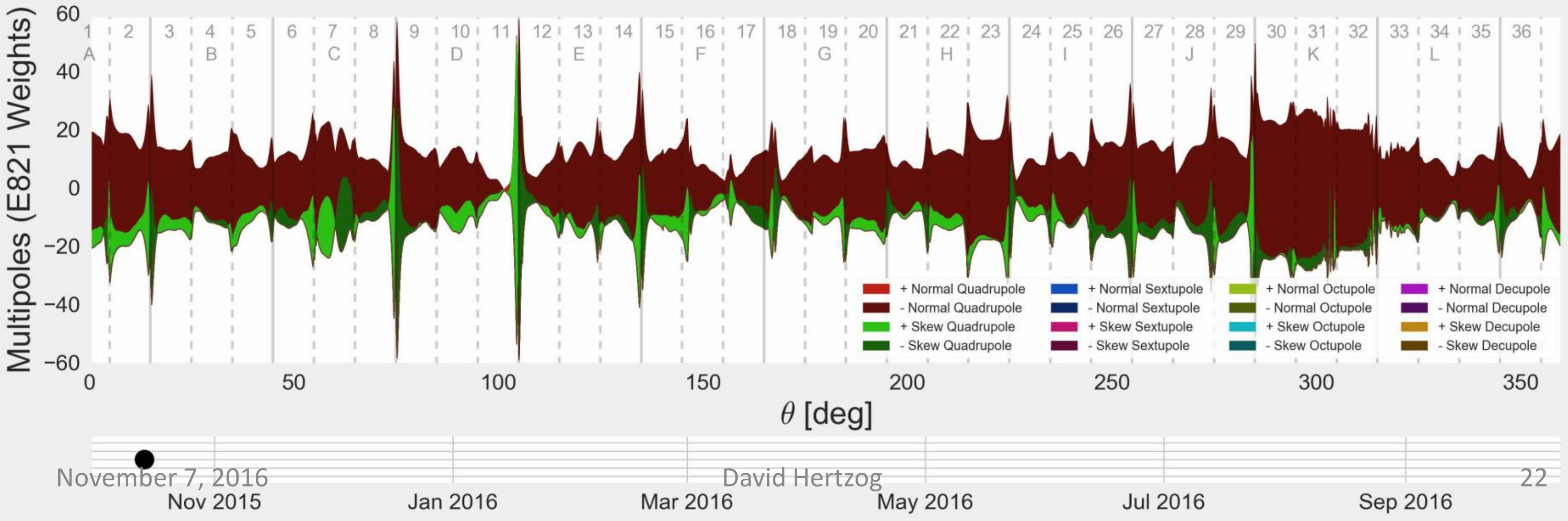
Monitor transient

Surface coils

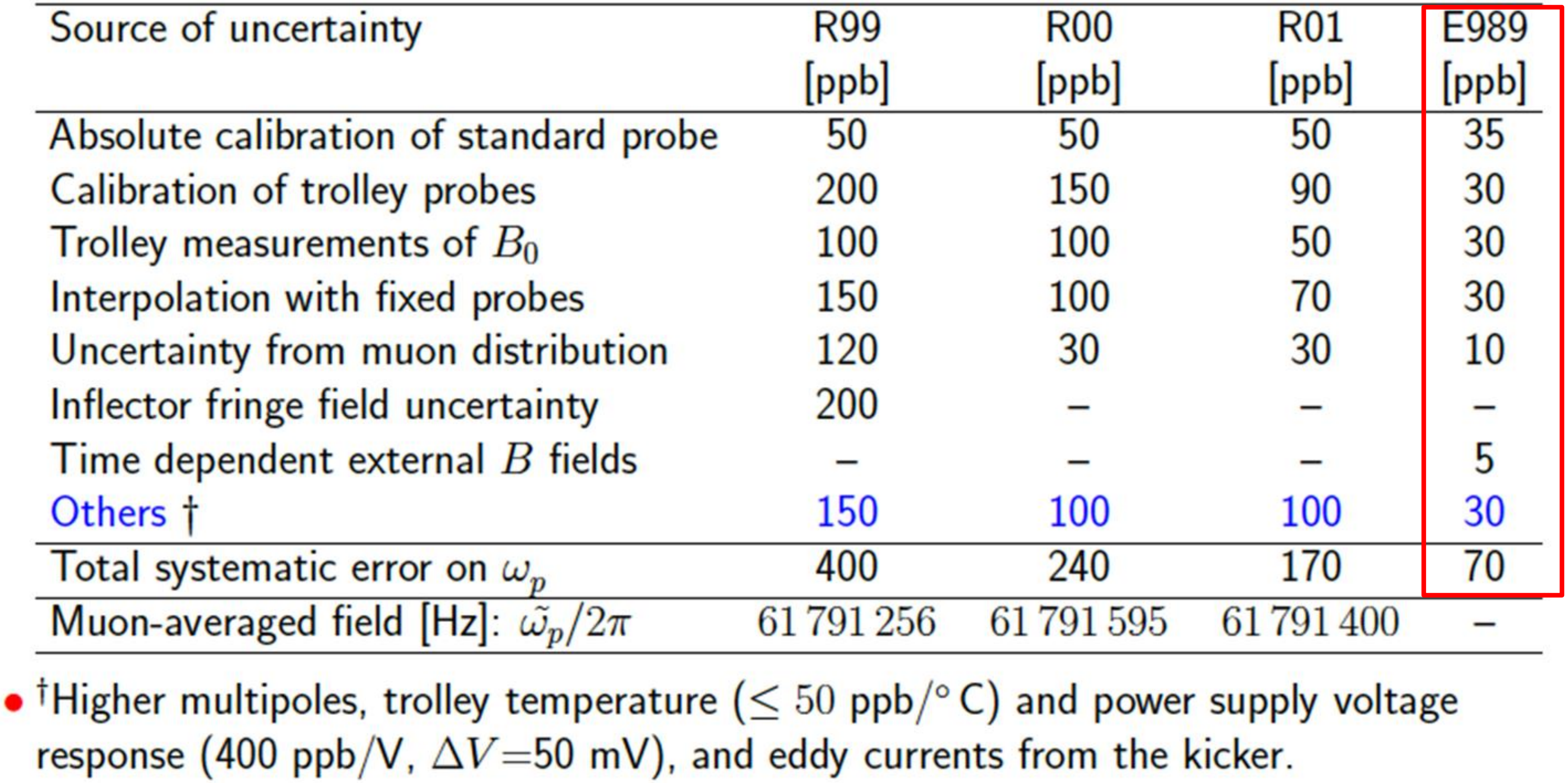
Flux gates

Example of Analysis of Field Multipoles around ring over 9 months of shimming

Analysis/Movie/Talk: Smith



Systematic Errors on ω_p (ppb)

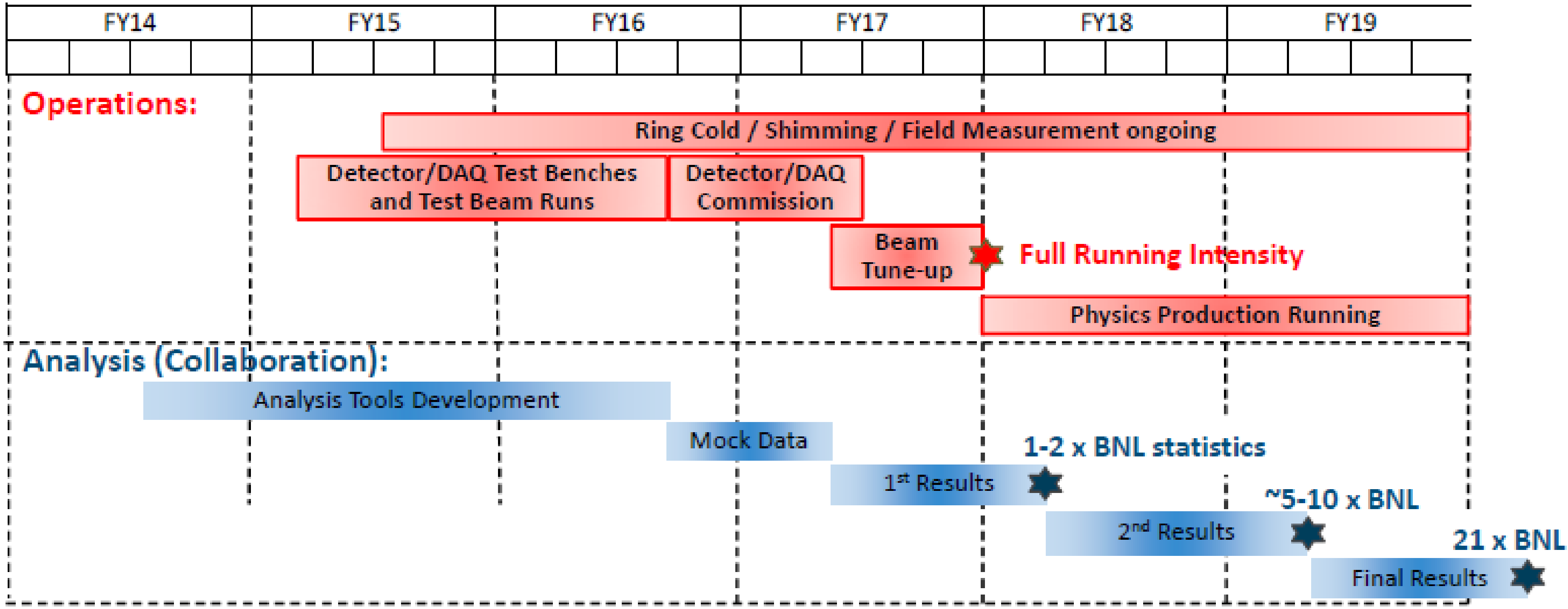


	Brookhaven E821			FNAL
Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 50 ppb/° C) and power supply voltage response (400 ppb/V, $\Delta V = 50$ mV), and eddy currents from the kicker.

Schedule overview

(assume construction and project phase complete)



Summary

- Many hands contributing
- But one goal: ***We are all measuring g-2***
- It takes Coherence
- And it takes accuracy

- Thanks for review this part of g-2