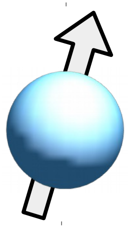
The Muon g-2 Experiment at Fermilab

James Stapleton
Muon g-2 Postdoctoral Research

Fermilab

Muon Magnetic Dipole Moment Anomaly as SM Test



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

Dirac point-like particle: $g = 2$

Real muon: $g = 2.0023318416 \pm 0.0000000013$

Brookhaven experiment measured unexpected ~3σ excess ~15 years ago!

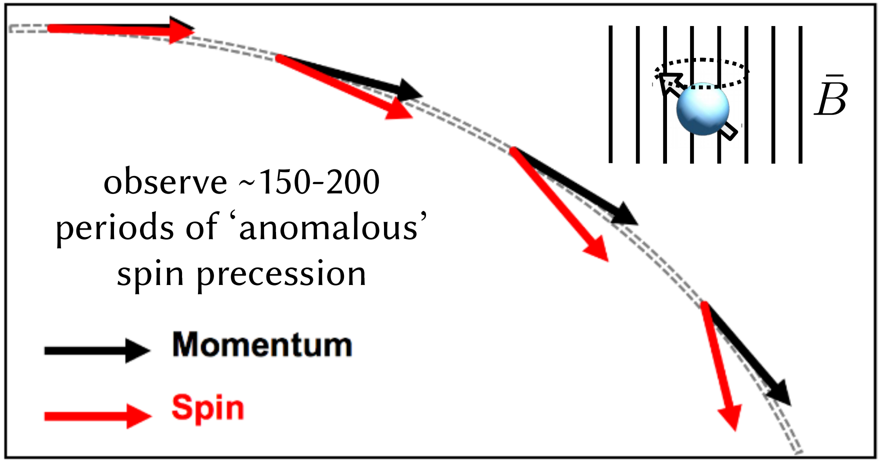
Pushing the Limits of Precision

- *g*-factors: some of the *most precisely* measured particle properties
- Reaching for precise SM predictions spurs development of theory

The Muon

- Produced in large quantities, with high polarization
- More sensitive to new physics than electron $(m_\mu/m_e)^2$
- Nice for *direct measurements* of spin precession (lifetime, E/m)

Brookhaven E821 Measurement

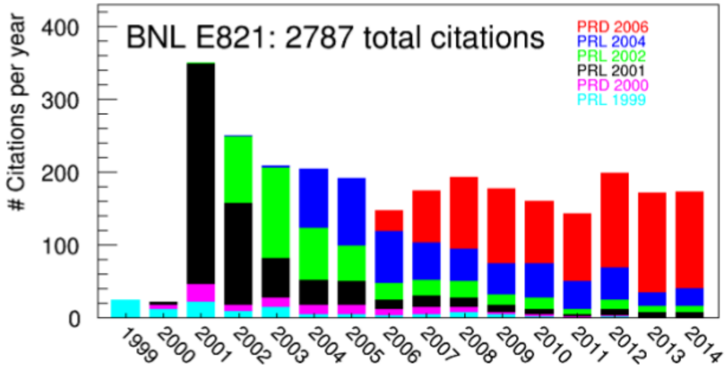


$$\mu \to \nu\nu e$$

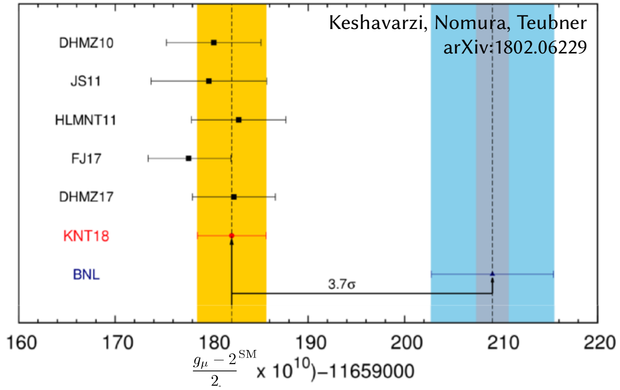
Parity-violating decay **correlates $e^{\pm}$ momentum with $\mu^{\pm}$ spin**

Muon Storage Ring @ Brookhaven National Lab

Brookhaven E821 Measurement



- result generated plenty of interest
- confirmation needed only statistics, but AGS was needed for other programs



- SM predictions continued refinement (hadronic vacuum polarization & light-by-light processes, plus lattice work)
- tension NOT alleviated
- updated SM prediction (using latest HVP refinements) is **3.7σ** below original measurement

Muon g-2 at Fermilab (E989)

- Pre-existing facilities & wealth of experience from Tevatron operation
- Adapt anti-proton source to impinge protons on heavy target
- Re-purpose buncher & accumulator to control $\pi \Rightarrow \mu$ evolution into a highly-polarized muon beam
- New muon line delivers 16 bunches/1.4 seconds, ring stores 10k-16k muons per bunch

- **Target: increase overall precision ~4x**
  - Accumulate **~20x BNL statistics** in 400-500 days of continuous running
  - Reduce systematics through ring & detector upgrades

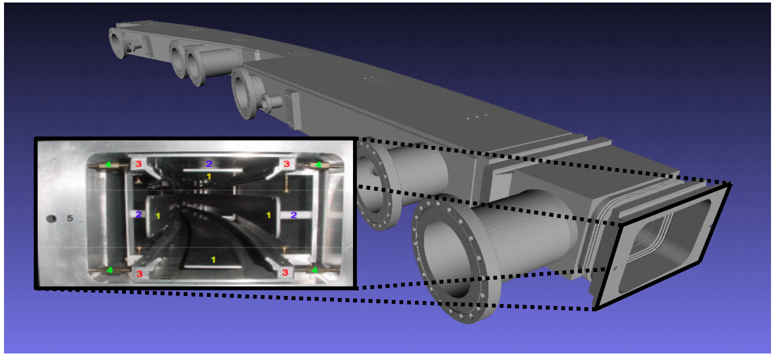
OVERSIZE LOAD
Pennsylvania
Philadelphia
Columbus
Maryland
New Jersey
West Virginia
Kentucky
Virginia
North Carolina
Charlotte
Atlanta
South Carolina
Alabama
Georgia
Louisiana
Tampa
TRIDENT


Educational Institutions
North Central College
College of DuPage
Wheaton College
University of Illinois
Northern Illinois University
DePaul University
THIS EXIT

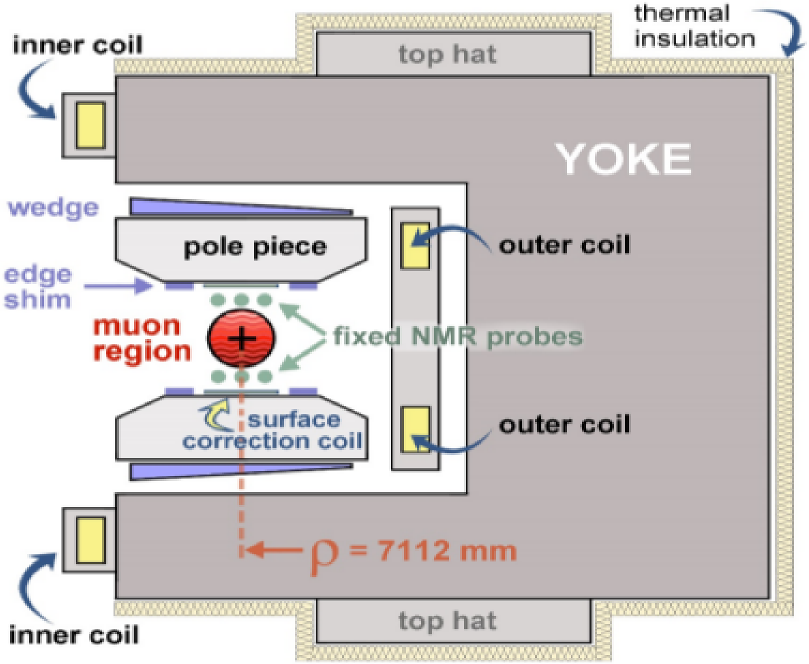
Installing the Ring

Muon Storage and Spin Precession

- ~14m diameter NbTi superconducting coils: ~4kA $\Longrightarrow$ 1.45 Tesla
- fine-tuning via wedges, shims, and correction coils (~3x more uniform for Fermilab g-2)
- vacuum chambers & electrostatic quadrupoles: beam integrity & focus
- **muon storage region**: 9cm diameter channel defined by circular beam collimators



vacuum chamber model (and photo showing electrostatic quadrupole plates)



ring/magnet cross section

Muon Storage and Spin Precession

- spin precession frequency (relative) in B dipole field (1.45T) and E quadrupole field (~20kV)

$$\bar{\omega}_a \equiv \bar{\omega}_s - \bar{\omega}_c \propto -\frac{q}{m}\left[\left(\frac{g-2}{2}\right)\bar{B} - \left(\frac{g-2}{2} - \frac{1}{\gamma^2-1}\right)\frac{\bar{\beta}\times\bar{E}}{c}\right]$$

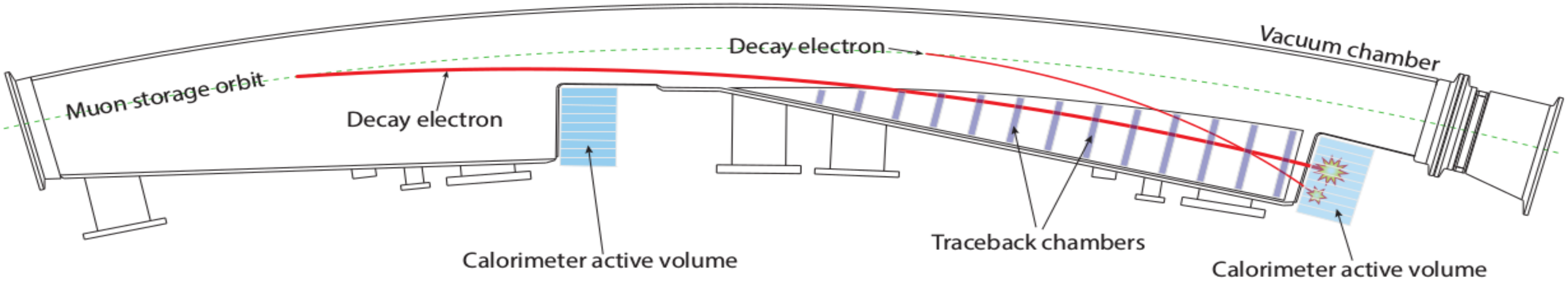
(*using $\bar{\beta} \perp \bar{B}$)

- quads introduce extra precession term $\propto \bar{\beta} \times \bar{E}$
  - ~cancel by running at the 'magic momentum' 3.09 GeV/c ⟶ $\frac{g-2}{2} - \frac{1}{\gamma^2-1} = 0$
  - this and B field sets the orbital radius to 7112cm
- precession period ~4.4μs (boosted muon lifetime ~64μs)

Beam storage systematics

- Muon bunch not perfectly centered in storage region
- Resulting betatron oscillations introduce other terms
- Vertical/horizontal oscillations affect e^+ calorimeter acceptance
- Introduction of tracker was a critical upgrade over Brookhaven

Detector Systems



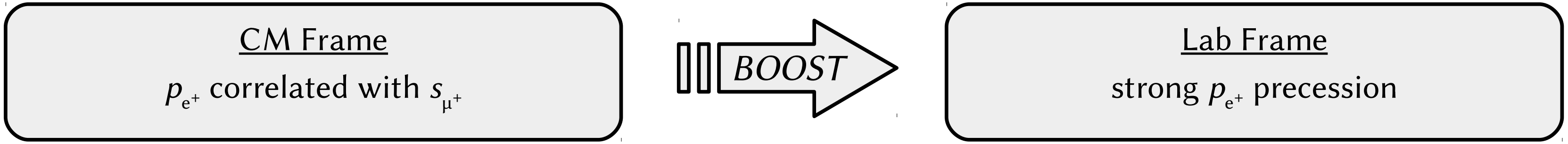
Calorimeters (24)

- capture ~1/3 of inward-spiraling positrons
- energy resolution ~ few percent
- segmented design for spatial separation
- *improved pileup discrimination is a significant upgrade over E821*

Straw Trackers (2)

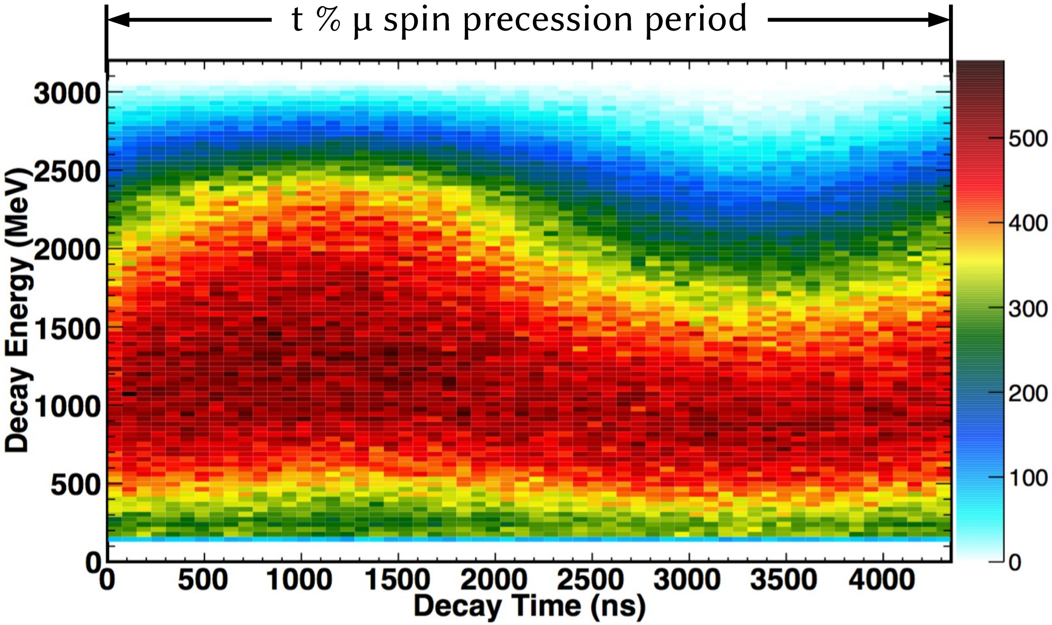
- positioned in front of two calorimeters
- 8 modules, each with 4 planes of straws
- angular resolution: extrapolate e^+ back to storage region & characterize beam dynamics
- *another significant upgrade over E821*

Anomalous Precession Frequency Measurement



angular asymmetry maximal for highest-energy positrons

simulated lab-frame energy of decay positrons, modulo 4362ns anomalous precession frequency (E989 TDR)



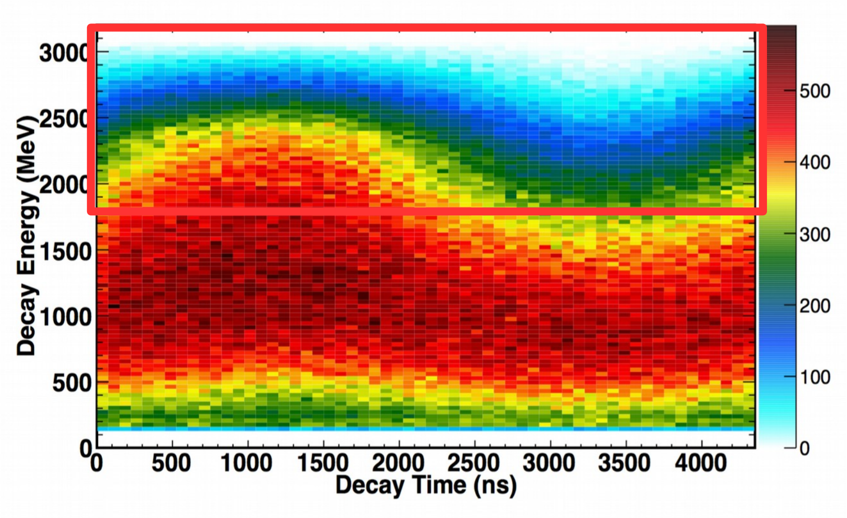
Anomalous Precession Frequency Measurement

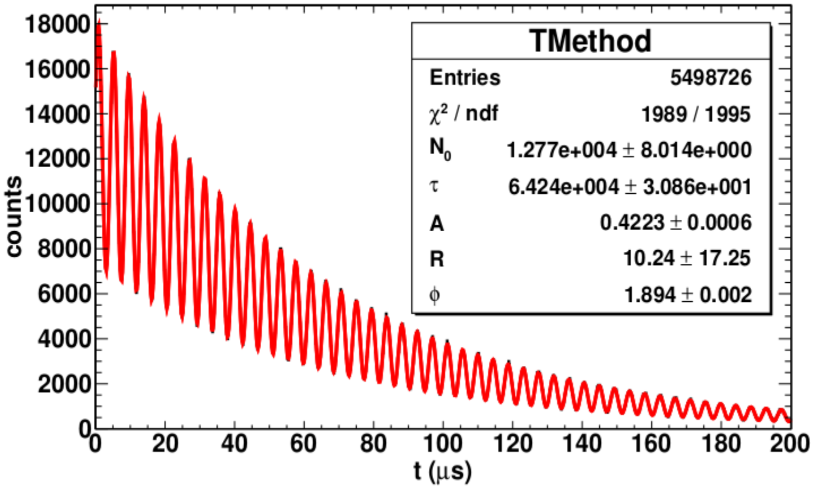
CM Frame
p_{e^+} correlated with s_{μ^+}

BOOST ⇛

Lab Frame
strong p_{e^+} precession

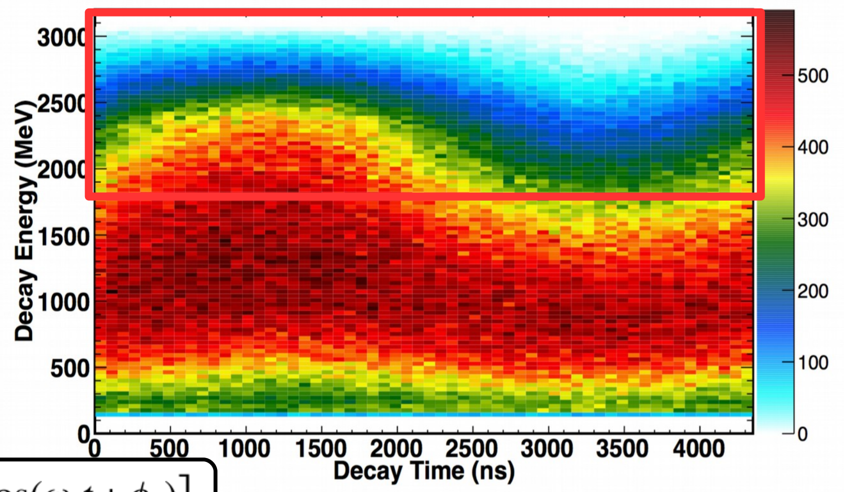
angular asymmetry maximal for highest-energy positrons



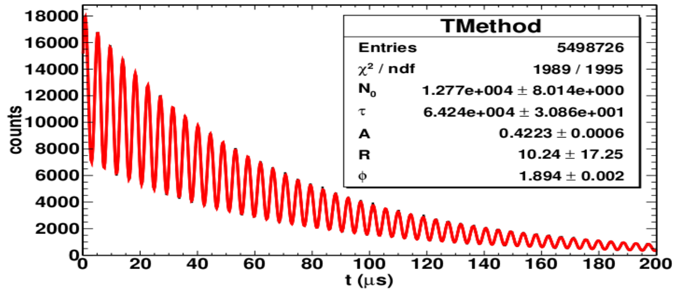


Quantifying the Precession

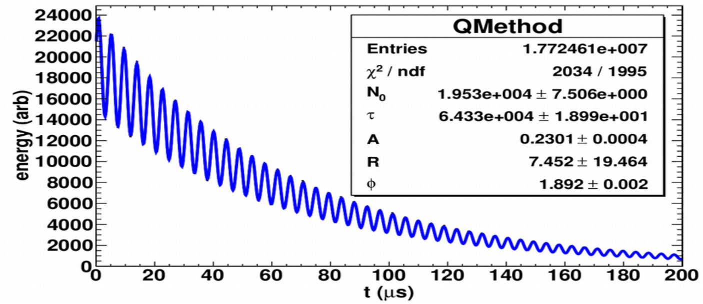
- Measure the wiggles!
- 1[st] order: time-binned positron hits above E threshold (~1.8GeV)
- redundant calibrations & reconstruction algorithms protect against bugs & other mistakes
- alternatives:
  - total energy deposit
  - asymmetry-weighting or E-binning (both rely on energy estimate)



Fit: $N_e(t) = N_0 e^{-t/\gamma\tau}\left[1 - A\cos(\omega_a t + \phi_a)\right]$



reconstructed e[+] above threshold energy (enhanced wiggle)



total accumulated energy deposit (more statistics)

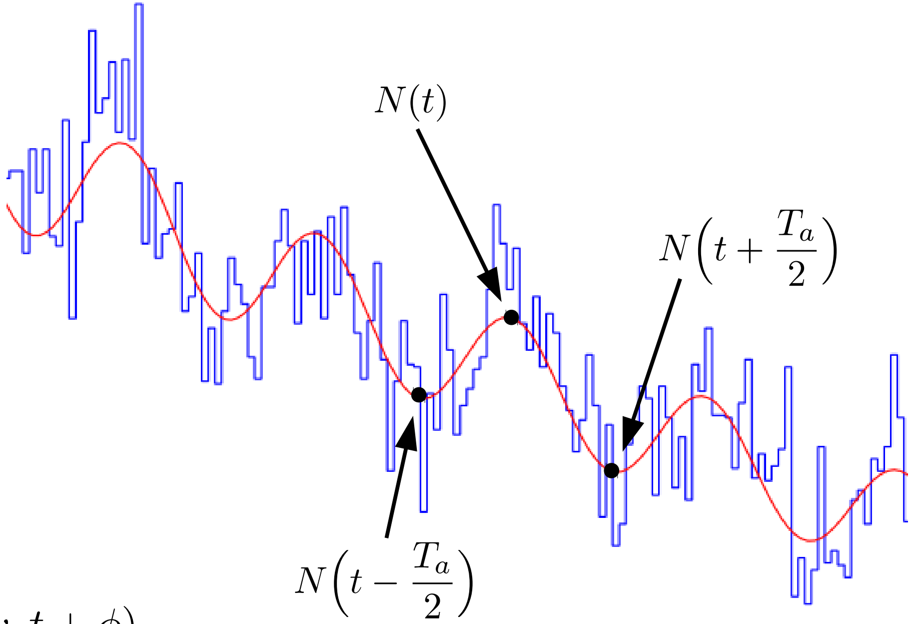
Analysis Systematics

$$N_e(t) = N_0 e^{-t/\gamma\tau}\left[1 - A\cos(\omega_a t + \phi_a)\right]$$

- Some effects directly introduce **systematic offsets** to the measured anomalous precession frequency
  - Example: time-dependence in phase $\phi_a(t) \simeq \phi_0 + \phi_1 t$
  - 1st order shift: $\cos(\omega t + \phi) \Rightarrow \cos(\omega t + \phi_1 t + \phi_0)$
- Other effects affect the overall shape & degrade fit quality
  - betatron oscillation + calorimeter acceptance introduce other modulation frequencies
  - many effects controlled directly by modeling terms in fit function
- Multiple factors contribute to 'apparent μ decay rate' (exponential)
  - pileup & SiPM gain variation skew exponential decay shape
  - 'lost muons' leak out of the storage region and hit calorimeters
  - one approach is very well-suited to control these…

Ratio Method

- Relationship between these three points describes both decay **and** wiggle
  - compare y-values differences from left & right interval
  - separates exponential from oscillation
- We use 'Recon East' positrons
- Perform three 'independent' fits for all datasets



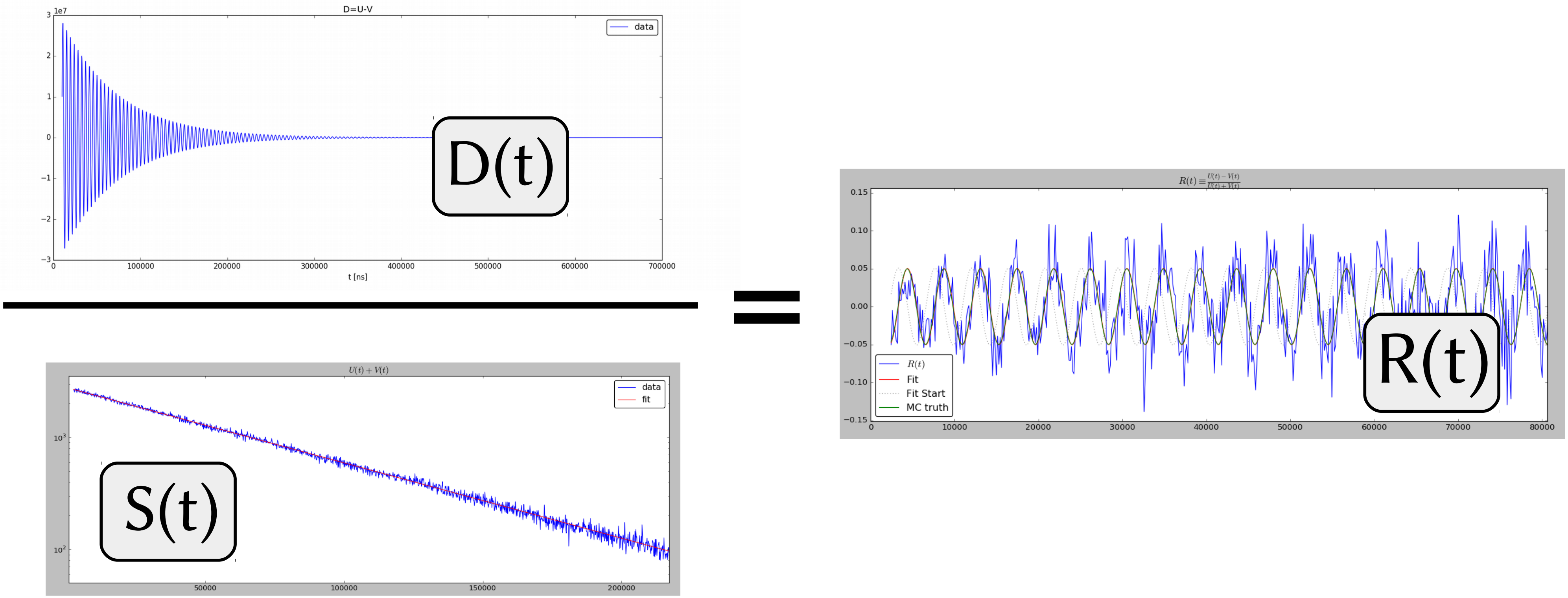
$$D \equiv N\left(t+\frac{T_a}{2}\right)+N\left(t-\frac{T_a}{2}\right)-2\,N(t) \sim e^{-t/\tau}\cos\left(\omega_a t+\phi\right)$$

$$S \equiv N\left(t+\frac{T_a}{2}\right)+N\left(t-\frac{T_a}{2}\right)+2\,N(t) \sim e^{-t/\tau}$$

$$R \equiv D/S \sim \cos\left(\omega_a t+\phi\right)$$

*You may sometimes see U = N_+ + N_- and V = 2N

Ratio Method



Illinois Ratio Method Analysis (IRMA)

- Muon spin precession analysis group
- Fermilab + University of Illinois, Urbana-Champaign
- Named for the ‘Ratio Method’ (but we are not restricted to that)
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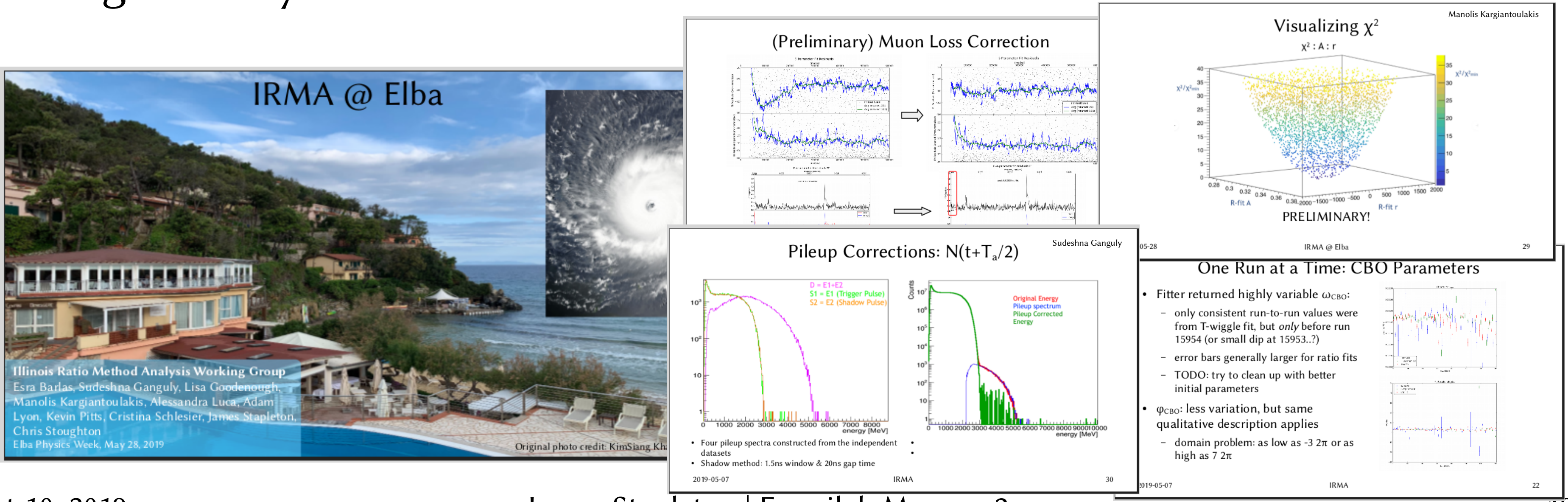


IRMA's Unique Contributions

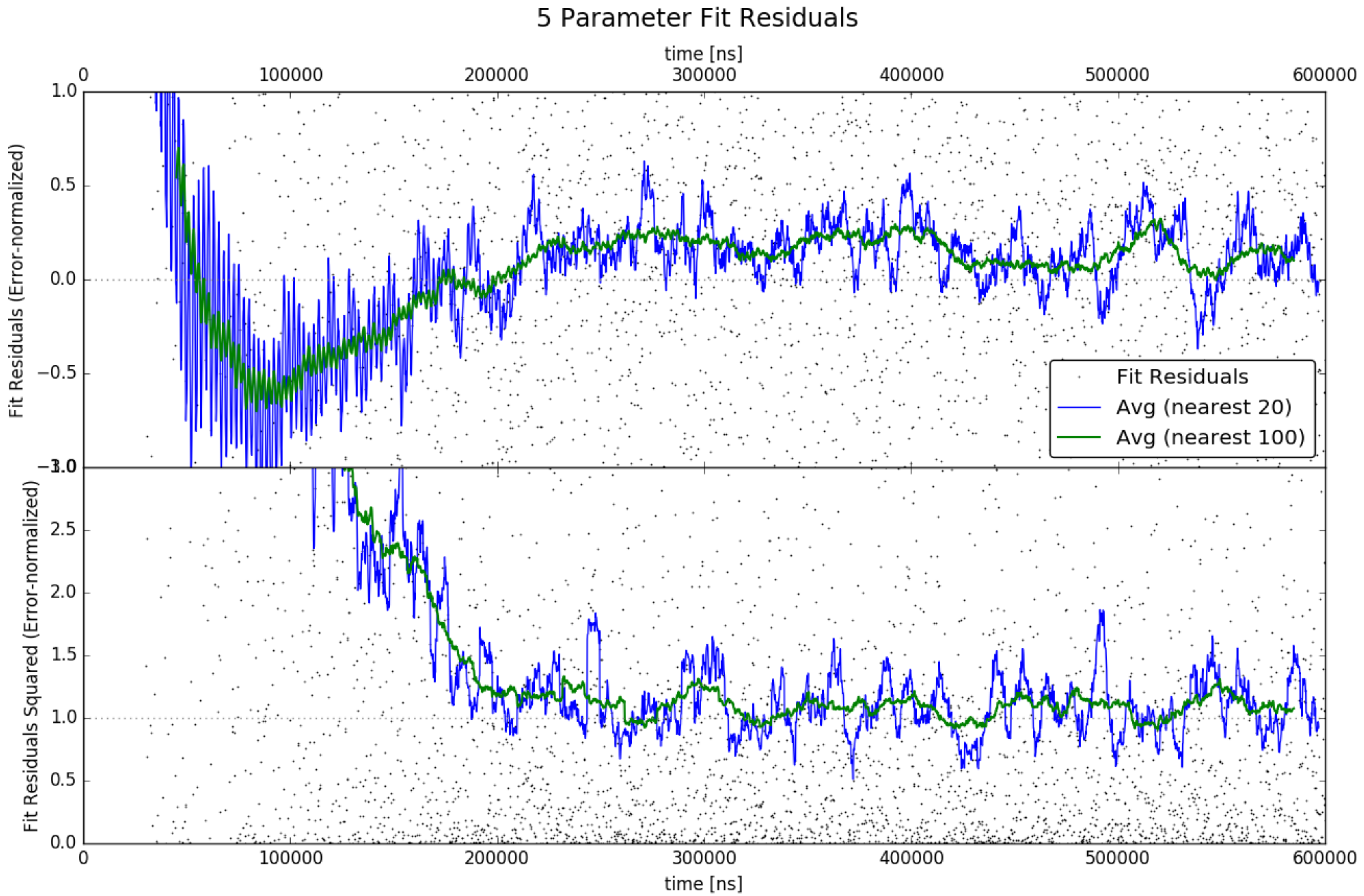
- Independently fit *three* representations of data
- art-to-Python analysis environment
- Unique combination of analysis variety + reconstruction
- Run-by-run fits
- Time-series residuals/pulls analysis
  - fit pulls usually seen as an *unordered distribution* (neglecting left-to-right ranking in fit)

Consistent & Independent Fits

- Functional form includes nearly all parameters in all three fits
  - time spectrum: $N(t) = N_5(t) \cdot \left(1 + A_{\rm cbo} e^{-t/\tau_{\rm cbo}} \cos(\omega_{\rm cbo} t + \phi_{\rm cbo})\right)$
  - note: not yet using $A(\omega_{cbo})$ and other forms as in Nick's parameterizations
- Ratio and exponential fitting functions call N(t) function at three separate times:
  - exponential fit function: $N(t + T_a/2) + N(t - T_a/2) + 2N(t)$
  - ratio fit function: $\frac{N(t + T_a/2) + N(t - T_a/2) - 2N(t)}{N(t + T_a/2) + N(t - T_a/2) + 2N(t)}$
- Statistical precision shows expected sensitivities
  - huge error bars for e.g. $\delta\omega_a$ in exponential fit, $\delta\tau_\mu$ in ratio fit
  - time-spectrum & ratio fit see roughly equal $\delta\omega_a$

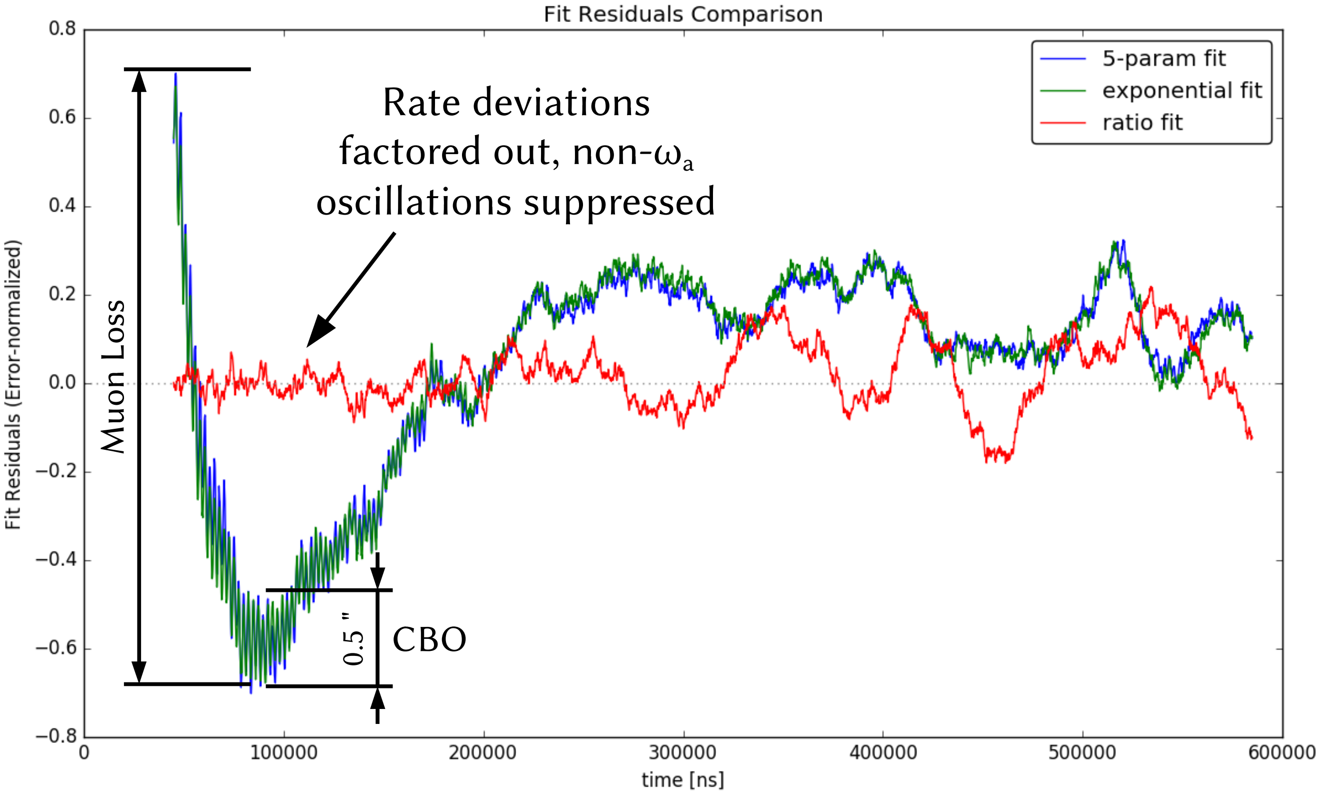
function of *ALL* fit parameters

function of *ALL* fit parameters (except normalization)

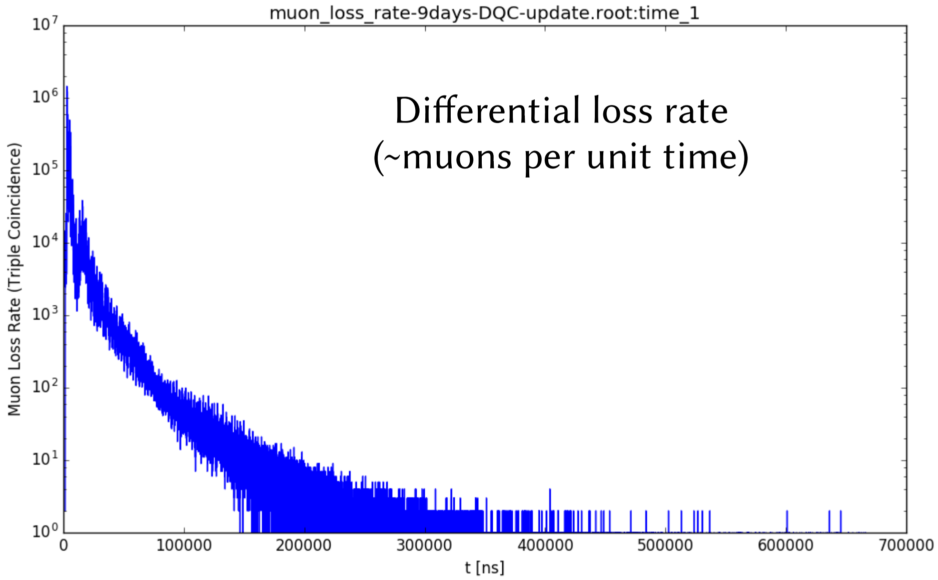


5 Parameter Fit Residuals
time [ns]
0
100000
200000
300000
400000
500000
600000
1.0
0.5
0.0
−0.5
−1.0
Fit Residuals (Error-normalized)
Fit Residuals
Avg (nearest 20)
Avg (nearest 100)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Fit Residuals Squared (Error-normalized)
0
100000
200000
300000
400000
500000
600000
time [ns]

Separation of Rate-based Systematics



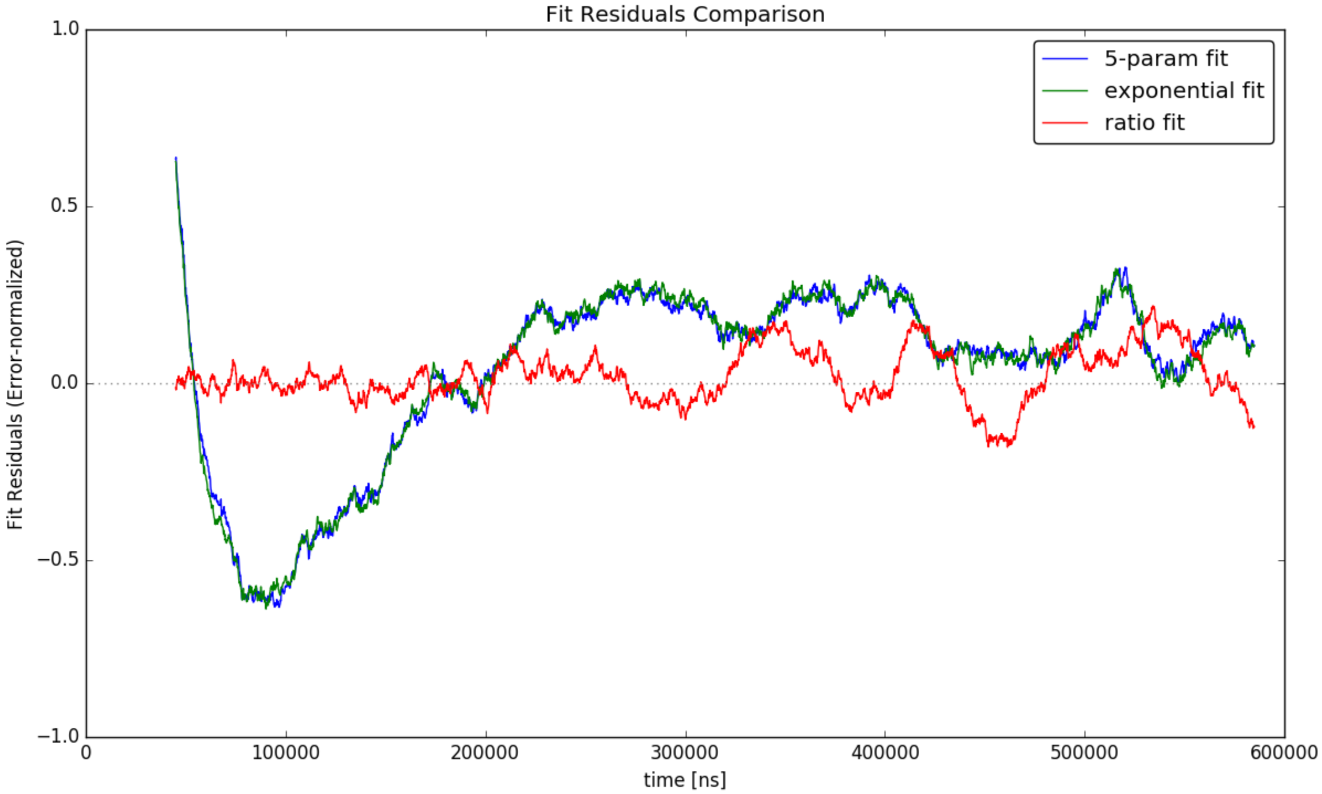
Muon Loss



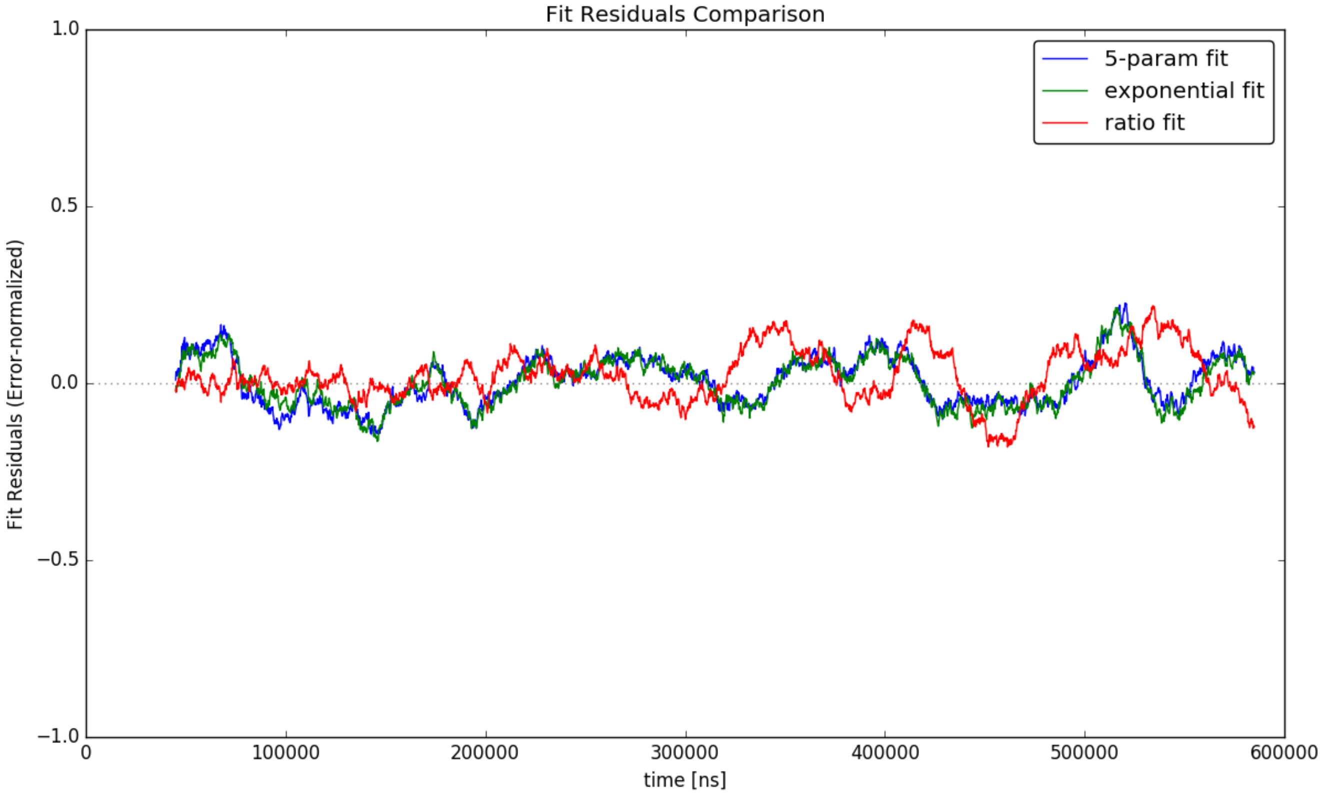
- Significant deviation from bulk ~exponential shape
- Latest mu loss rate from Sudeshna
  - triple coincidences
- Multiply model by integrated loss count (with scaling factor)

$$N(t) \longrightarrow N(t) \cdot \left(1 - Ce^{-\frac{t_0}{\tau_a}} \int_{t_0}^{t} L(t')\, e^{\frac{t'}{\tau_a}}\, \mathrm{d}t'\right)$$

Muon Loss Mitigation: Before



Muon Loss Mitigation: After



Error Budget

Final g-factor anomaly computed like: $a_\mu = \frac{g_e}{2}\left(\frac{\omega_a}{\omega_p}\right)\left(\frac{m_\mu}{m_e}\right)\left(\frac{\mu_p}{\mu_e}\right)$

Standard definition of anomaly: $g_\mu \equiv 2(1+a_\mu)$

Our contribution: ratio of anomalous precession frequency to proton NMR measurements of B field

Other factors listed with high precision in CODATA & other sources:

g_e	0.28 ppt
m_μ/m_e	25 ppb
μ_p/μ_e	8 ppb

Final E989 Target Precision [as ppb a_μ]	
precession ω_a (syst.)	70ppb
precession ω_a (stat.)	100ppb
B field ω_p (syst.)	70ppb
Total	**140ppb**

Compare to E821's **540ppb** precision on a_μ

Example breakdown: $\boldsymbol{\omega_a}$ targets for systematic error

ω_a systematics [ppb a_μ]	BNL	Target
gain variation	120	20
e^+ pileup	80	40
‘lost’ muons	90	20
betatron motion	70	<30
E field/vertical motion	50	30
Total (quadrature)	**180**	**70**

Muon g-2 Software & Computing

- Nature of g-2 shapes computing resources
  - quasi-HEP experiment + NMR experiment
  - *one* precession analysis
- Medium-sized experiment
  - adopted many Fermilab-native tools
  - developers: wide variety of computing & physics backgrounds
  - most code written by a few distinct small groups
- I won't cover everything here!
- Just my personal experience with:
  - CVMFS
  - code development & release for offline processing & analysis
  - interactive access to data in framework files

CVMFS for Muon g-2

- We have CVMFS mounted on our group VMs, on grid nodes, and in the occasional personal VM or container (all SLF6, for now)
  - distributes in-house software as well as externals to cover dependencies
- Externals: requirements like build tools, Python interpreter, ROOT, Geant4, etc
- Muon g-2 CVMFS share:
  - two people authorized to publish to Stratum-0
  - build tool can [de]select packages from CVMFS installation & set up an area for local build to replace them
  - periodic releases cut from several (17) git repositories
- Online & Offline: supplies code for offline running, but also hosts installations of online code (DAQ, quality monitoring) for offline compile-time & run-time dependencies
- Our user experience with CVMFS has been excellent
- Use with a VM: great for times when WiFi is far away…

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…or when in a concrete pit!

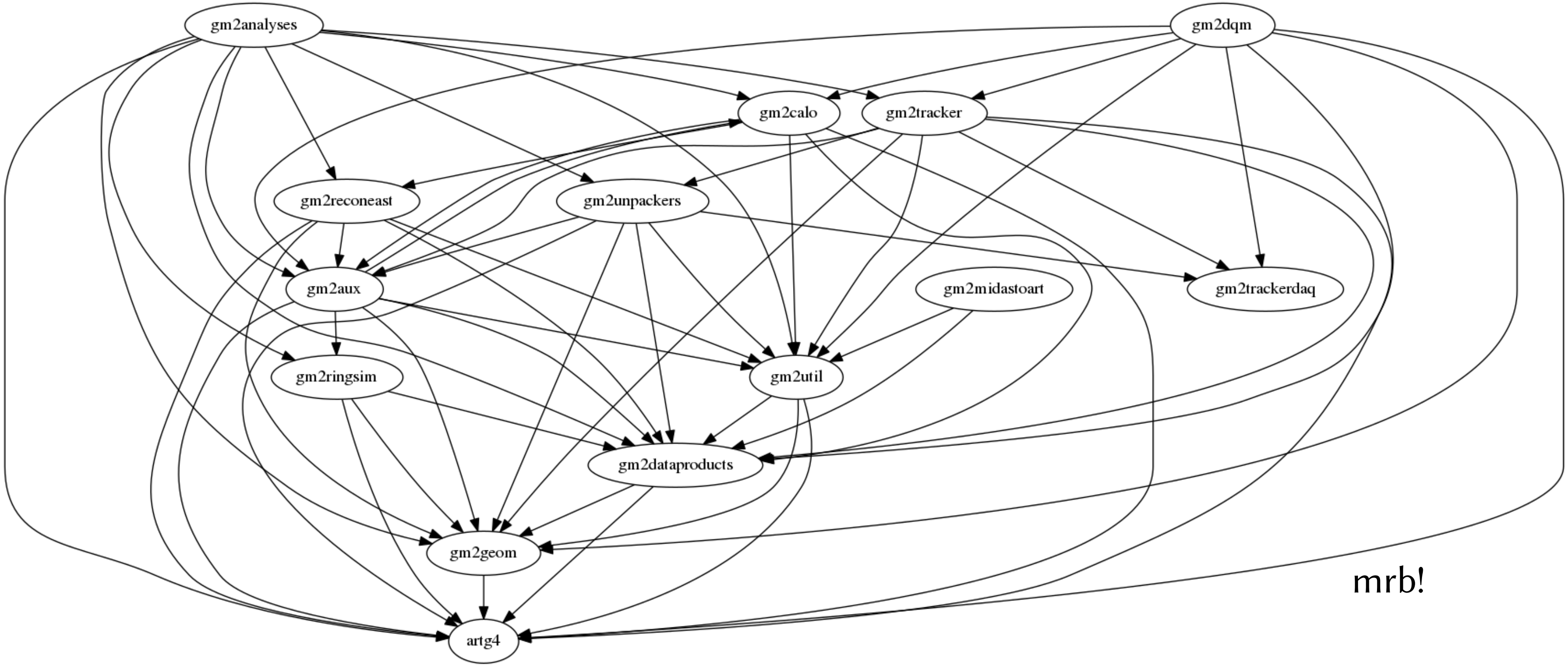
‘Off-Label’ Use

- Serve as a text file ‘database’ (calibration constants, etc)
  - NOT exactly recommended for calibration constants (but works great if you need it to!)
- Online/DAQ operations: very convenient for quick software deployment
  - not possible to track clients, which matters during breaking upgrades (lots of people forgot they were getting libXYZEtc from CVMFS)
- Lots of other convenient corner cases not targeting Offline purposes

Code Development & Release

- We have 20-25 git repositories with different purposes.
  - official 'Offline Releases' include 17 interdependent repos
  - 10-20 active developers (<10 *very* active)
- History has driven evolution of code
  - Summer 2016: SLAC testbeam run (calorimeter) ← Releases not critical
  - Summer 2017: Ring/Beam Commissioning } Release as-needed
  - Winter-Spring 2018: Physics Run 1 } Release as-needed
  - Spring-Summer 2019: Physics Run 2 } Run 2 release every two weeks
  - Summer 2018-present: Run 1 Analysis } Run 1 release as-needed
  - Near future (post Run 1 Analysis) ← Release every ~month

Code Repositories



mrb!

NOT shown: ~half a dozen 'non-release' packages

Flexible & Responsive Release Management

- Adapt! (primary customer changes over time, as well as core product)
- Need intuition for the growth & stability of the codebase
- Regular or irregular releases? Depends on experiment's growth phase!
- Flexible coding conventions, development cycle recommendations
- CRITICAL for good administration of g-2 software:
  - contact with developers (communication!)
  - solicit discussions of code evolution often, keep an eye on important tasks, respond to developers' timelines & priorities
  - gauge relative strengths/weaknesses of developers in order to help them efficiently
  - keep a Linux expert on hand ;-)

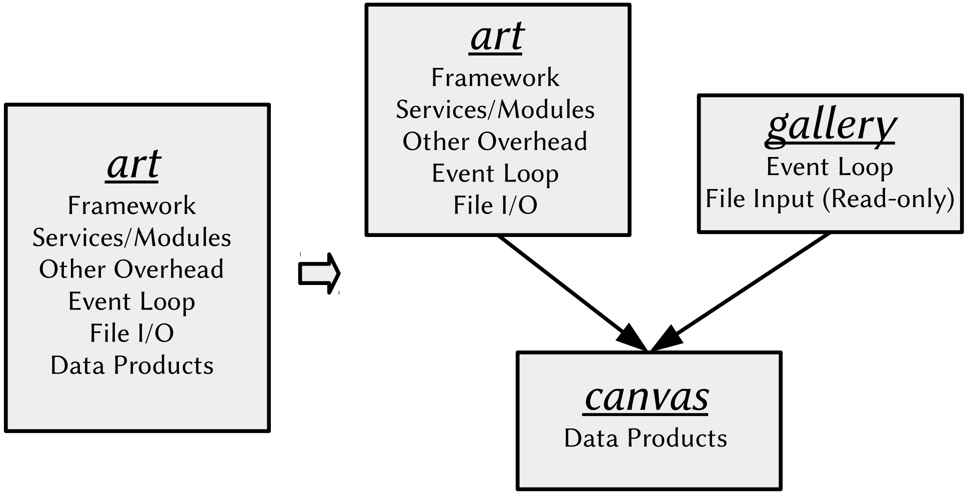
art

- *art*: Fermilab's event-processing framework, developed in-house
  - greatest asset: responsive developer team
- File format is custom specification on a ROOT file substrate: put Data Products (arbitrary objects with a system of labels) into a Run, SubRun, or Event
- Events processed through a Module Path, modules append Data Products to Event, SubRun, or Run
- Analyzer module base class requires implementation of `void analyze(art::Event & e)` (executes once for each event)
- Data Products accessed by Handle
  - requested from Event, SubRun, or Run via templated member `GetValidHandle<>()`
  - specify Module Label, Instance Name, and Process ID
  - specify C++ type of Data Product in templated call to `GetValidHandle<>()`

Data Inspection

- Accessing file content is nontrivial
- The Only Native (Event-based) Interface to Content: create a new framework module and run it!
  - implement a new module, build & link to framework stuff, create new config file, load/run framework executable, etc
  - …and the event-processing software exists in an environment with lots of requirements (only specific OSs, exact compiler version enforced, etc)
- *Non-framework* access is possible through TTree/TBrowser, but this has limitations (i.e. unintended use)
- Problem: no *spontaneous & interactive* route to inspecting contents of data files

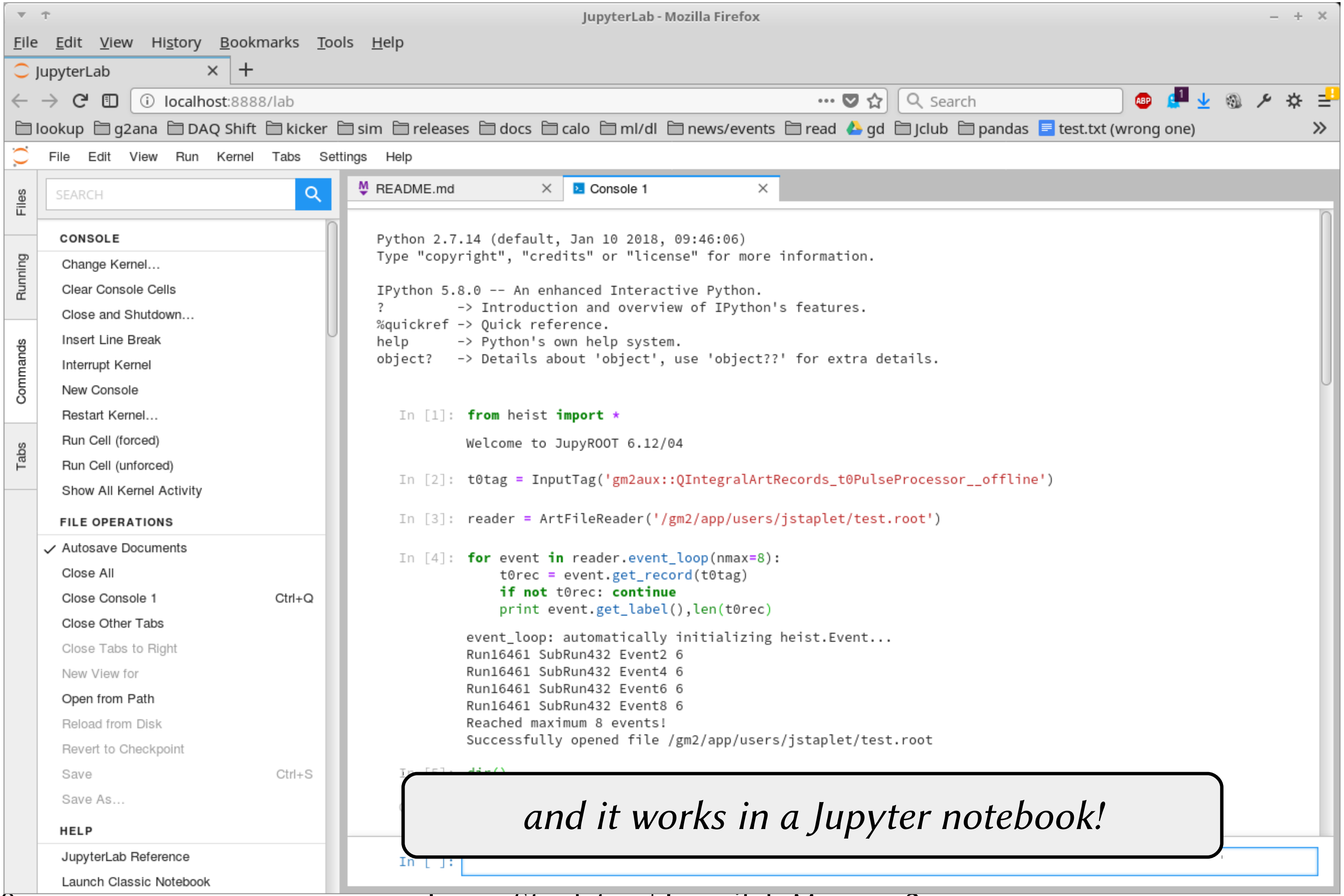
Refactor: *art*, *canvas*, *gallery*



- *art* developers moved 'Data Provenance' code to the new dependency *canvas*
- new package *gallery* provides similar interface:
  - native 'event loop'
  - fetch Data Products by handle
  - good for prototyping art framework code
  - (read-only)
- available via gcc, ROOT macro, or Python
- *gallery* via Python suggests *interactive inspection of data*

heist!

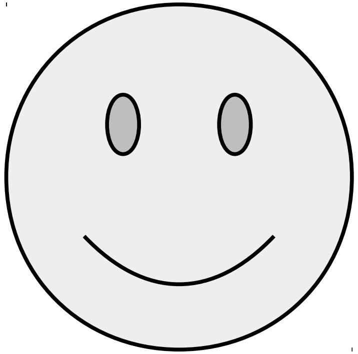
- Bare Python interface is clunky, so *heist* Python module wraps *gallery* interface generated by PyROOT
- A heist script is analogous to a single module directly fed art Events from file
  - event loop, data product handles, dereference `art::Ptr()` (smart pointer to another data product), easy to skip events with no matching entries
  - …plus the introspection/reflection awesomeness of Python!
- Includes some extra useful tools:
  - list Data Products in a file, search by simple match, and a magic `ls()` function to describe Data Products (and lists of them)
- I use heist nearly exclusively, and we use it in the analysis group I lead
- Others in Muon g-2 have started to pick it up
- Almost ready to advertise to other experiments



and it works in a Jupyter notebook!

Path Toward Results

- Run 1 analysis is wrapping up & targets first publication within a few months
- Run 2 production starts in earnest soon
- IRMA group uniquely targets Run 2



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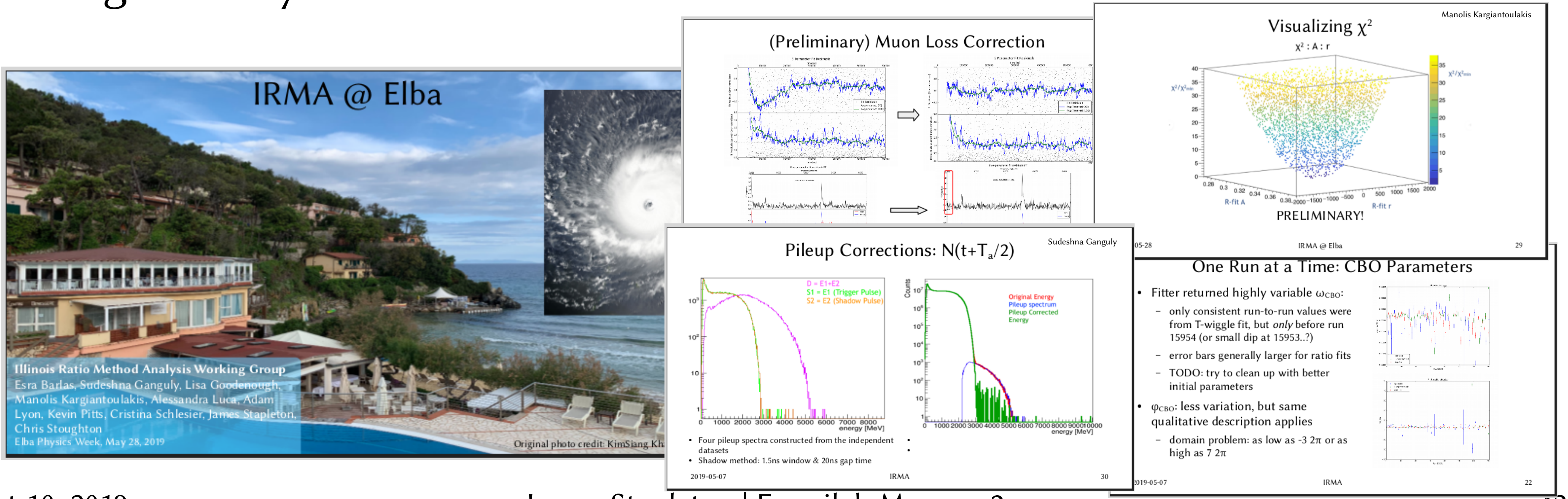


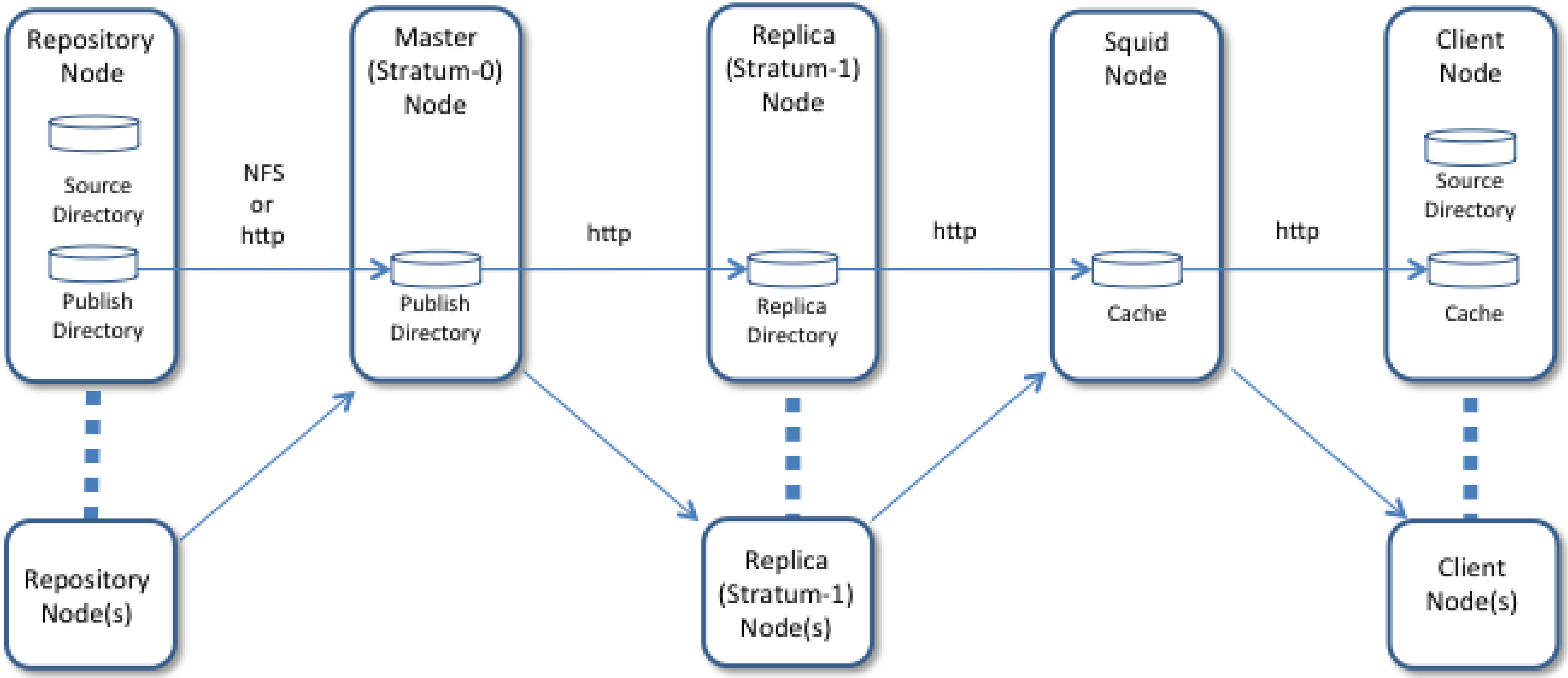
Final Notes

- Muon g-2 are happy CVMFS customers!
  - does exactly what is advertised, no headaches
- Zen of computing: *it's really about people* (not computers)
  - true for our software, and true for Fermilab's support (*art*, etc)
- Scientific computing designs make assumptions about data (content, format/type, sizes) but should also assume
  - unexpected variation in data
  - a human will need to inspect the data at various points

CernVM FileSystem (CVMFS)

- POSIX read-only user-space filesystem (FUSE)
- Optimized for distribution of program files!
  - low-latency, on-demand directory listing & single-file access
  - entirely HTTP
  - aggressive caching
  - easy parallelization for computing grid nodes
- Accessible at data centers worldwide ("already there" for FermiGrid and many other computing facilities)
- Lots of handy features
  - low-maintenance
  - easy to publish files, revisioned filesystem image with named tags
  - stability on client (no FUSE problems, always mounts & unmounts cleanly, handles network outages well)
  - distributed mirroring (provided setup of certain networks)
  - good configurable parameters for clients, but defaults are well-chosen!

CVMFS



Graphic from S. Fuess

CVMFS Strengths & Limitations

Strengths

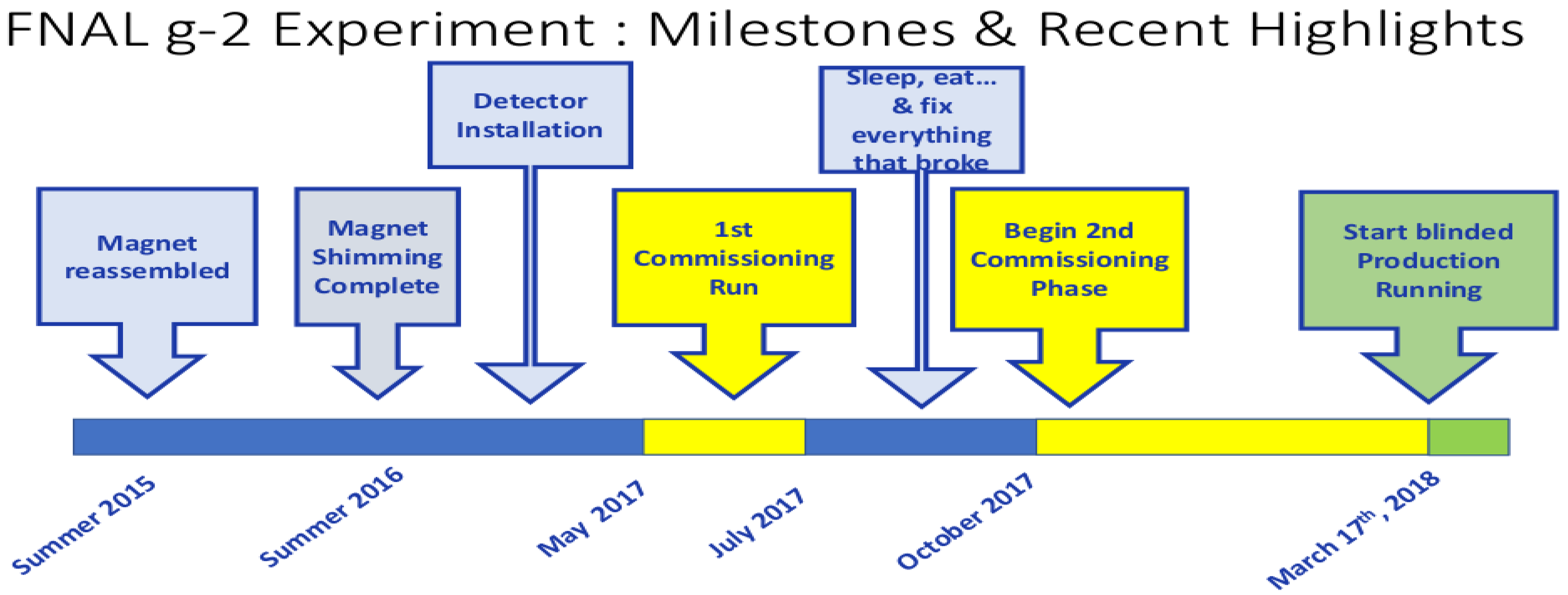
- Excellent for program files
- Absurdly stable
- Bandwidth efficiency
- Easy to scale on grid (HTTP caching)
- No concurrency issues
- Easy client installation & configuration (c.f. NFS, Samba)
- Unexpected shutdown precipitates no issues due to journaling, etc

Limitations

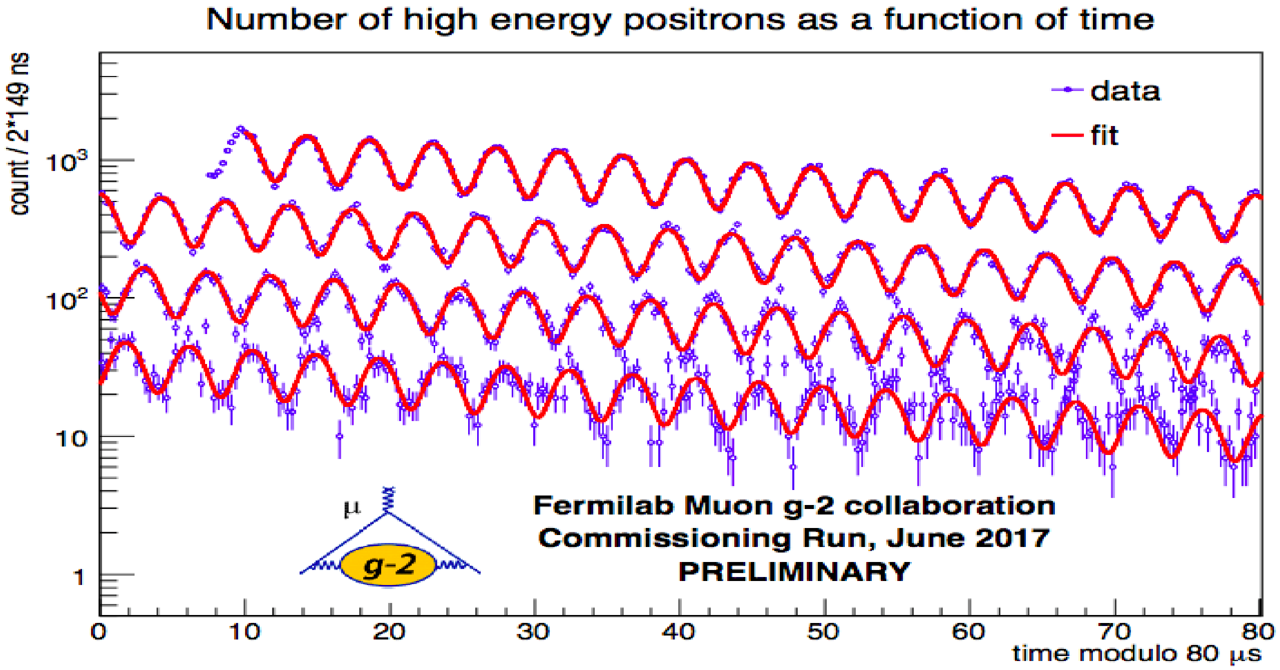
- Read-only, not easy to track clients*
- Scalability *like Muon g-2 has seen* requires setup of Stratum-1 network & HTTP grid caching, some coordination with remote processing sites
- Can be finicky about file permissions
- Does not like >200k entries in the same volume*

* More *design choice* than *limitation*

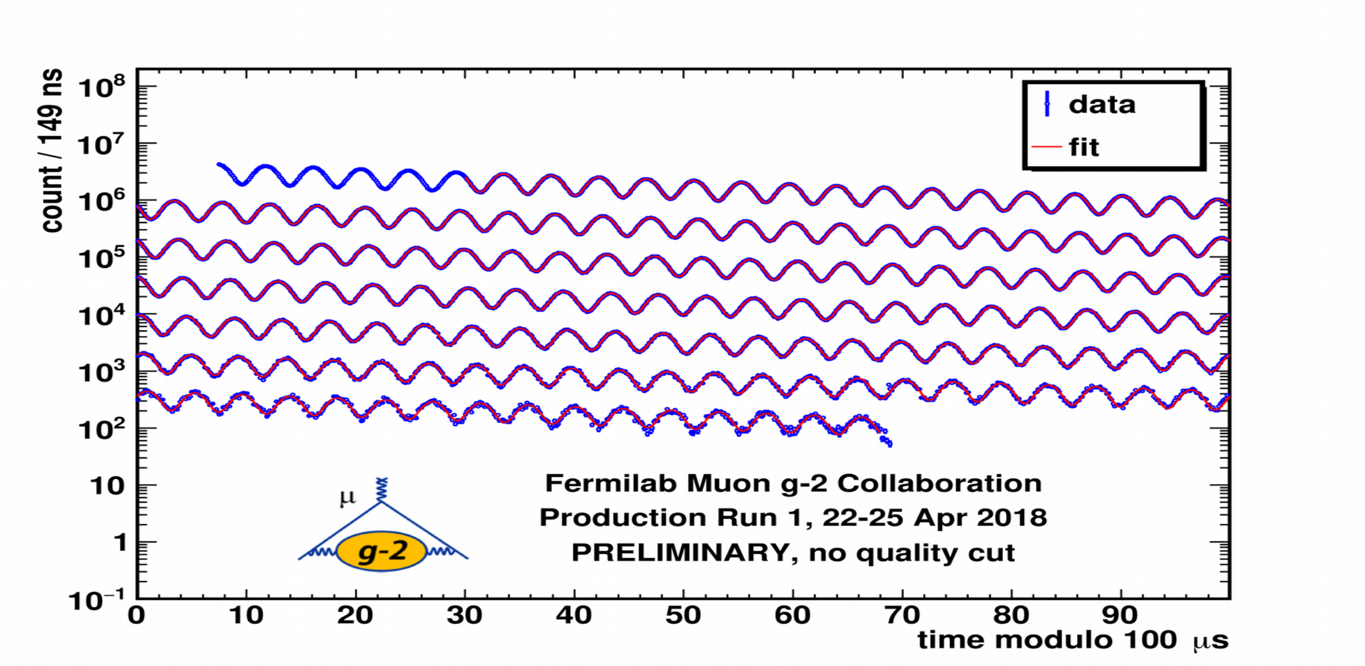
Timeline


FNAL g-2 Experiment : Milestones & Recent Highlights
Magnet reassembled
Magnet Shimming Complete
Detector Installation
1st Commissioning Run
Sleep, eat… & fix everything that broke
Begin 2nd Commissioning Phase
Start blinded Production Running
Summer 2015
Summer 2016
May 2017
July 2017
October 2017
March 17th, 2018

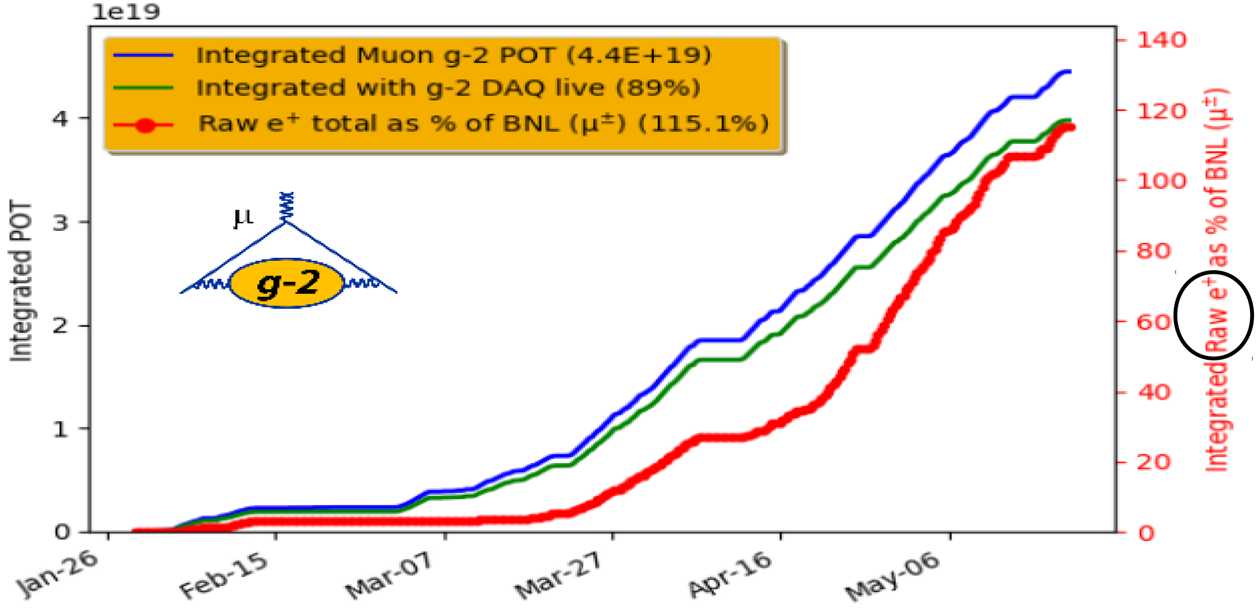
June 2017 Commissioning Run



Production Run 1

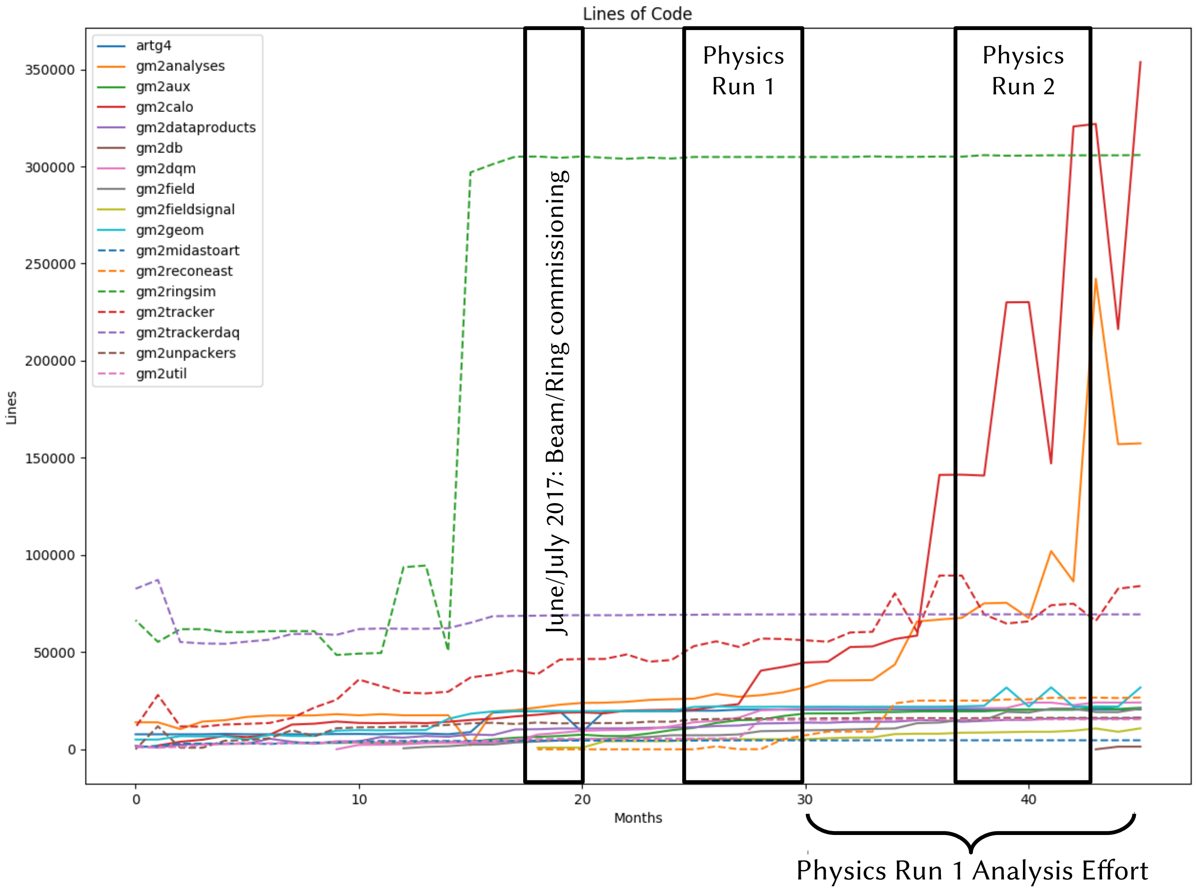


Data Accumulation This Year



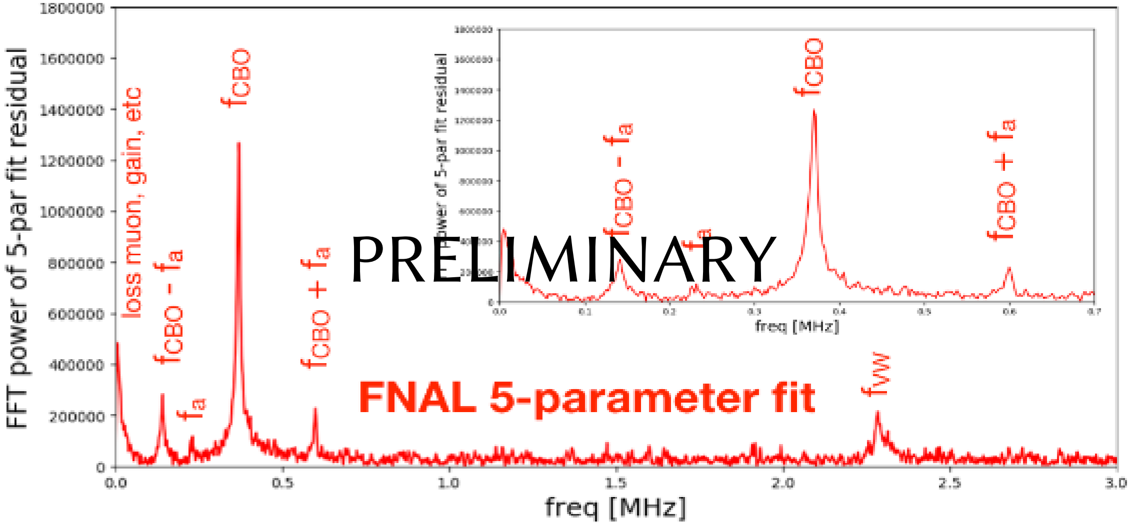
NOTE: no quality cuts here

Code Development



Correcting Precession Frequency Systematics

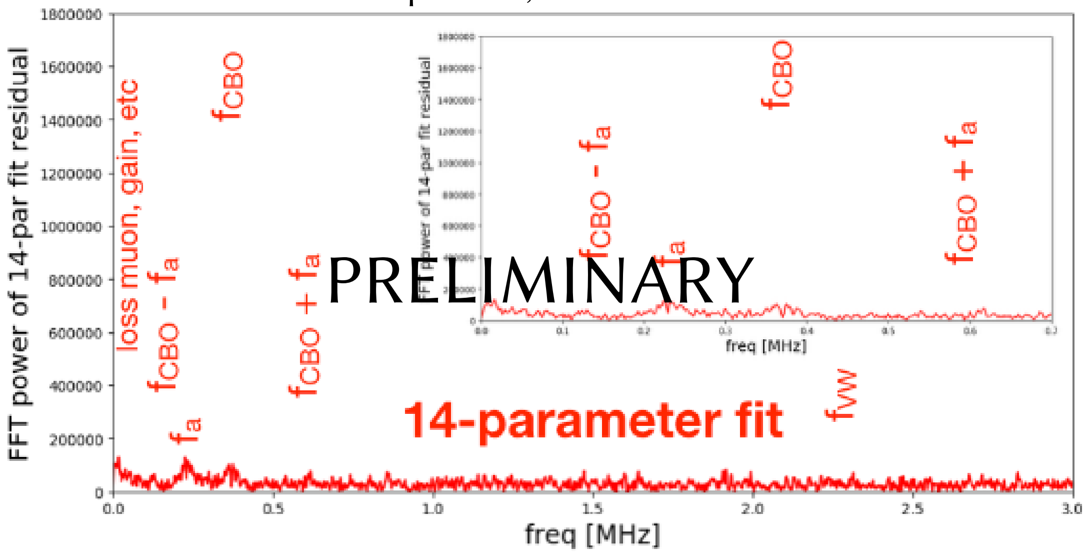
Systematics analysis of Production Run 1 (April 22-25) using ~a billion positrons (~10% final BNL dataset)



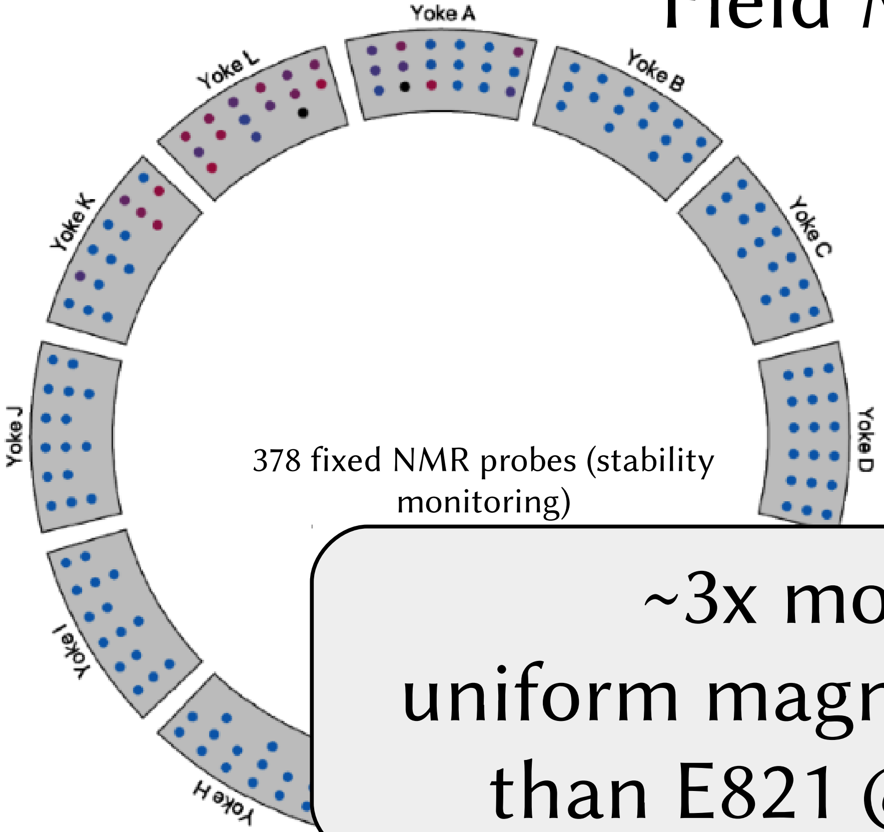
FT residuals from naive fit
show other frequencies

Correcting Precession Frequency Systematics

Extend fit form to model vertical/horizontal betatron oscillation, lost muon CBO frequencies, and other effects

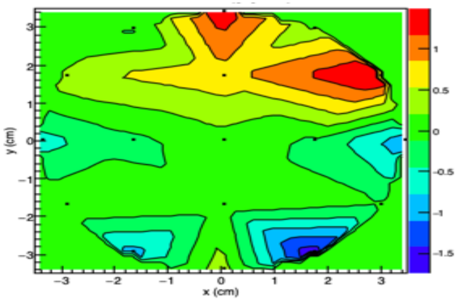


Field Monitoring

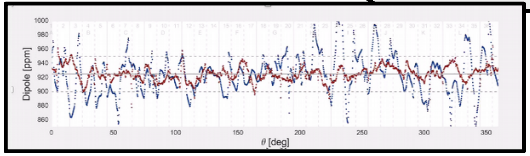


378 fixed NMR probes (stability monitoring)

NMR probe 'trolley' (measurements within storage region & cross-calibration of fixed probes)

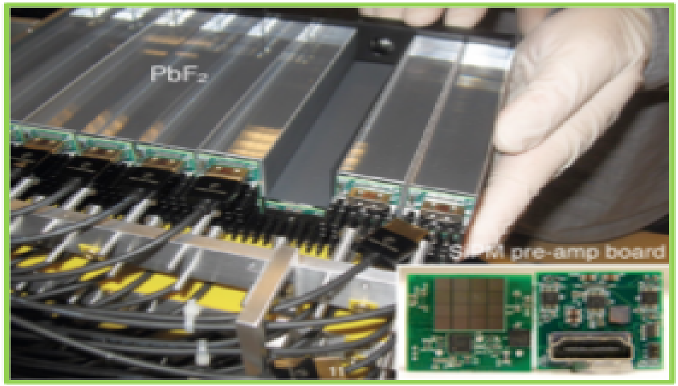


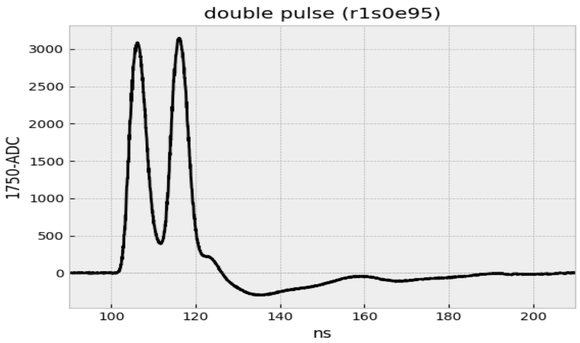
~3x more
uniform magnetic field
than E821 @ BNL

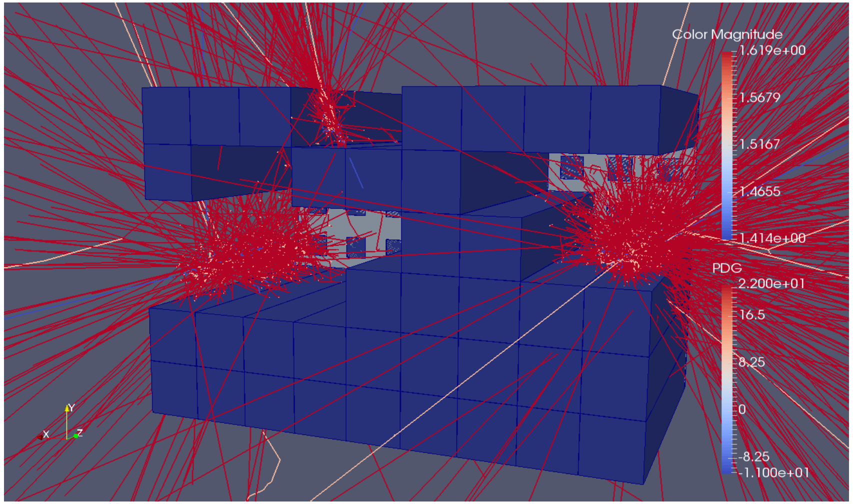


Calorimeters

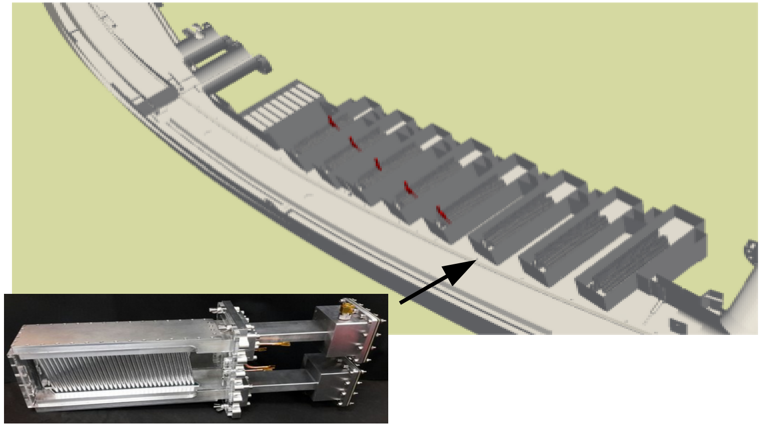
- 6x9 array of PbF_2 crystals (2.5cm x 2.5cm)
- Cerenkov shower from positron (and secondaries)
- readout via SiPMs
- fast recovery in readout electronics
- digitized @ 800MHz
  - <5ns time separation in a single crystal
- energy resolution scales as 1/sqrt(E)
  - 5% at 1GeV, 2% at 3GeV
- SiPM gain monitored via laser calibration



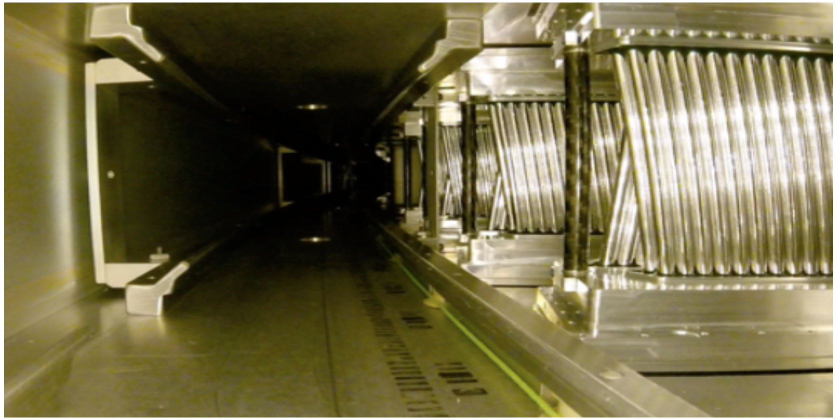


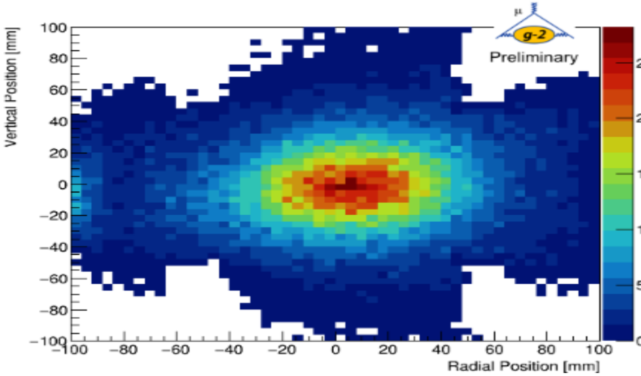


Straw Trackers



- 4 layers of aluminized mylar straws filled with Ar:ethane
- critical for reducing calorimeter reconstruction systematics
- reconstruct muon distribution during runtime ($\rho \otimes \bar{B}$)
- monitor horizontal & vertical beam oscillations in storage region





reconstructed muon beam distribution