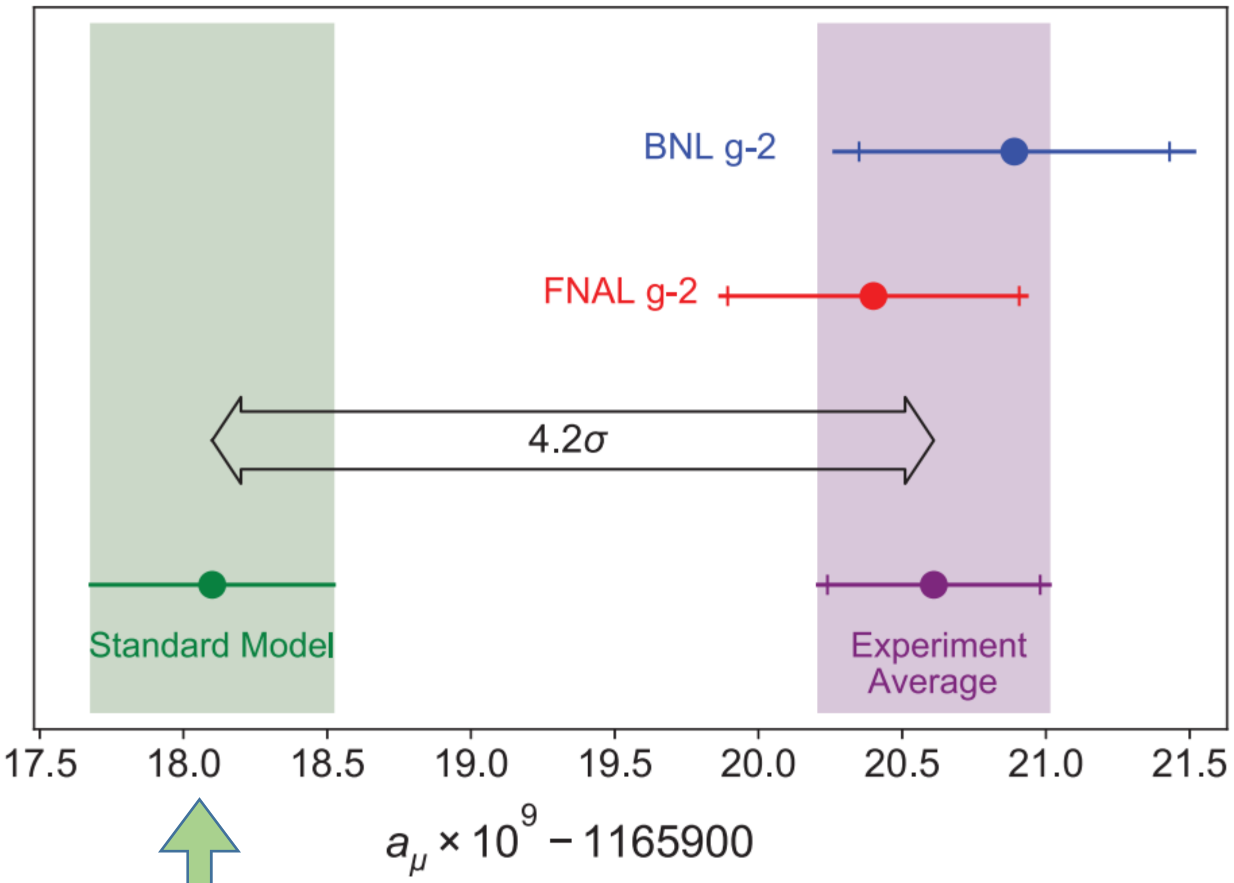
Updates and Perspectives on the Muon g-2 Experiment and SM Comparisons

A theory storm seems to be brewing

CENPA
Center for Experimental Nuclear Physics and Astrophysics

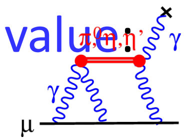
David Hertzog, University of Washington
USQCD Meeting
April 21, 2023

What everybody generally knows…



- The 2021 Run1 g-2 result:
  - Confirmed the BNL result
  - Led to net increase in discrepancy with theory above 4 σ
  - Statistical uncertainty: 434 ppb; Systematics: 159 ppb)
  - World average uncertainty: 350 ppb
  - Represents only 5% of our data set

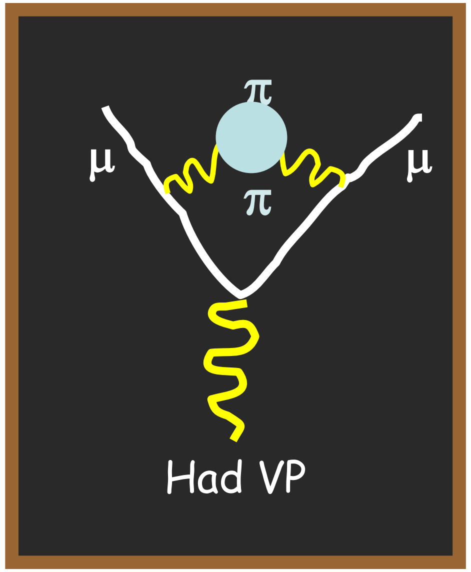
- The g-2 Theory Initiative recommended SM value:



  - 2020 Compilation from published work only
  - HLbL includes data-driven theory *and* lattice!
  - HVP entirely based on data-driven evaluation
  - Net uncertainty -- driven by HVP – is 368 ppb

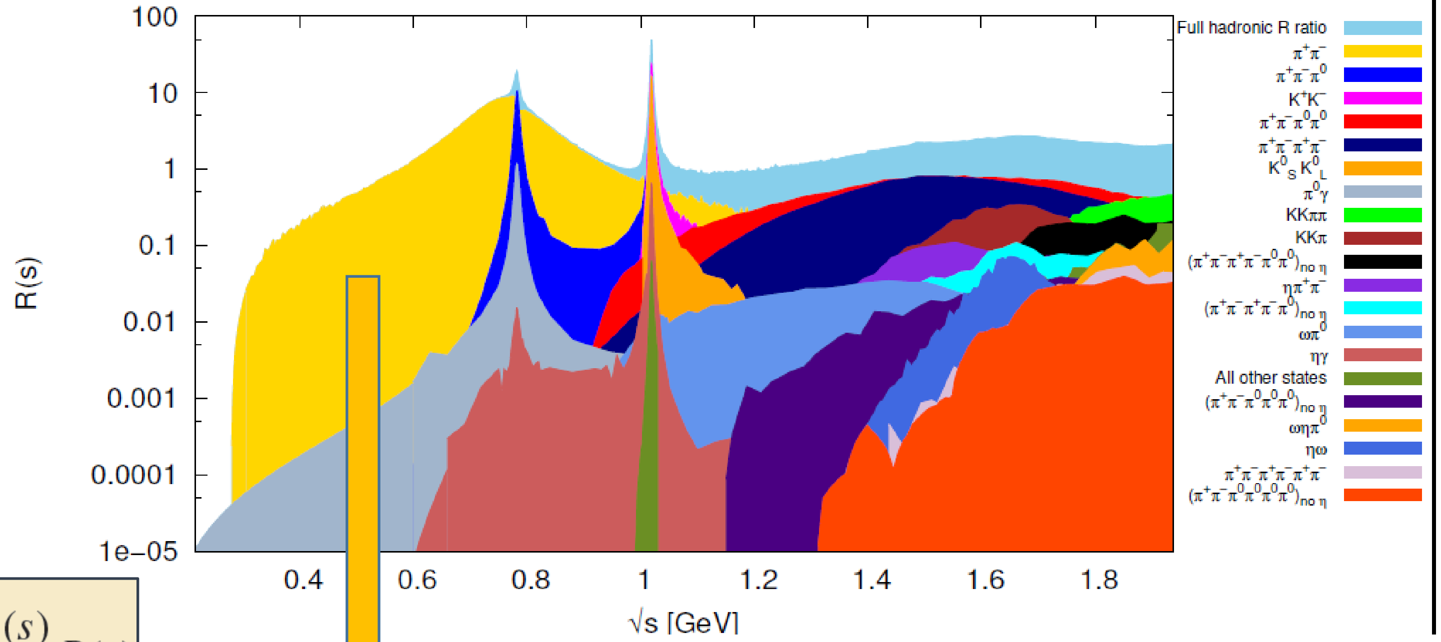
The uncertainty in the SM prediction is dominated by hadronic terms, essentially leading-order hadronic vacuum polarization (HVP)

To date: The recommended HVP value from e⁺e⁻ data

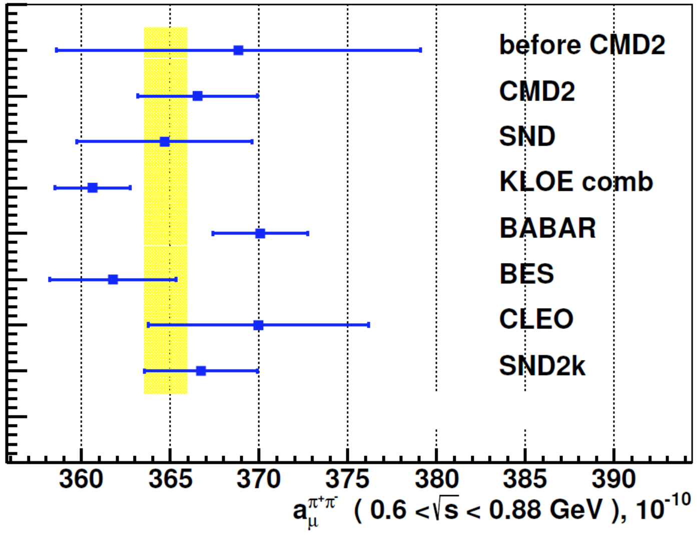


$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds\,\frac{K(s)}{s}R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mathrm{muons})}$$



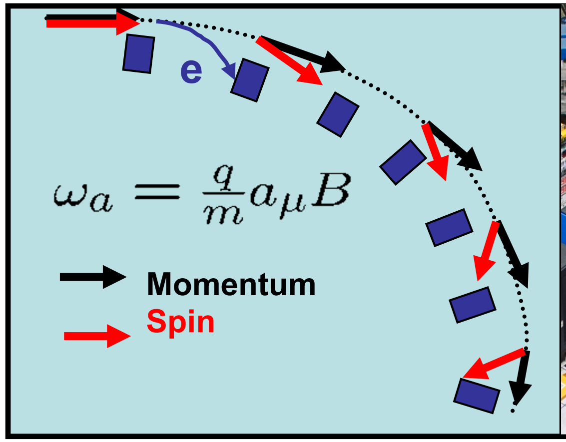
ππ region

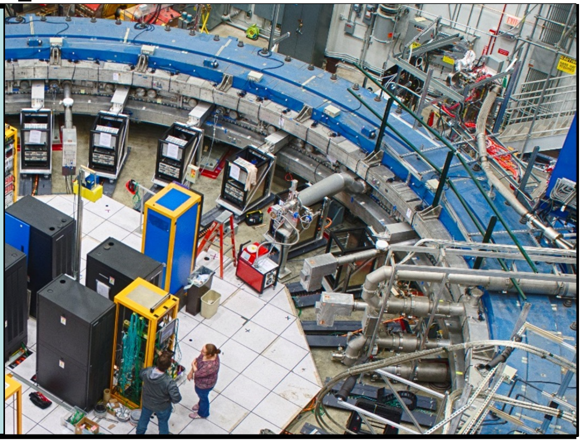


Here, **8** experiments contribute

We will return to this topic at the end

The Fundamental Experimental Principle





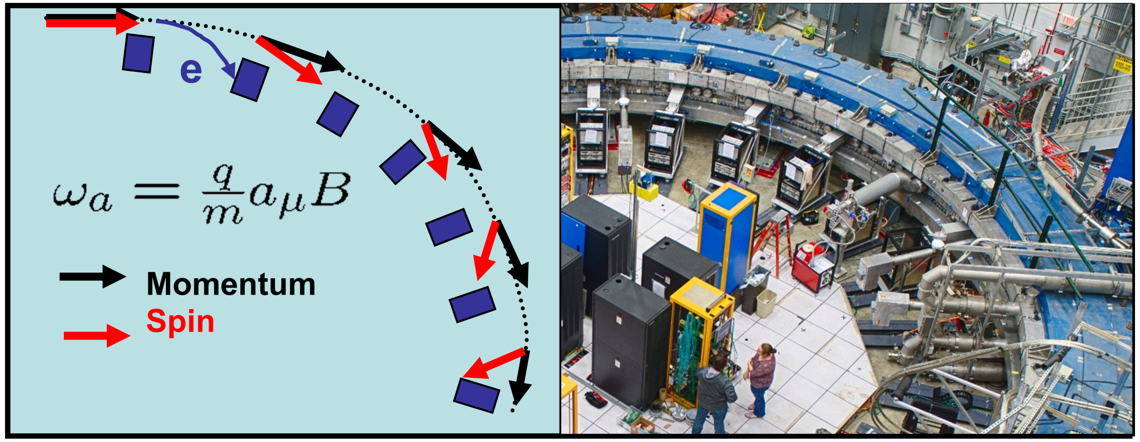
Determine difference between spin precession frequency and cyclotron frequencies for a muon moving in a magnetic field

Get a_μ

$$\vec{\omega}_s - \vec{\omega}_c \equiv \vec{\omega}_a = -\frac{q}{m} a_\mu \vec{B}$$

Measure these

The expression is more complicated when you add in *E*-field focusing and out of plane oscillations



The motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections

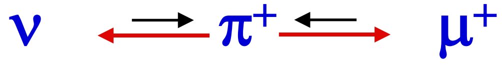
$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{\mathcal{E}}}{c}\right]$$

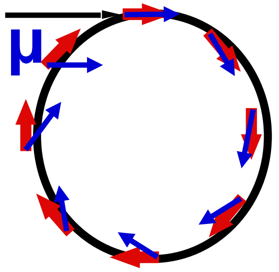
0 if “in plane” **Term cancels at 3.094 GeV/c, the “Magic γ”**

5 miracles permit g-2 to be measured to sub-ppm precision

1) **Polarized muons produced naturally in pion decay**

   ~97% polarized for forward decays

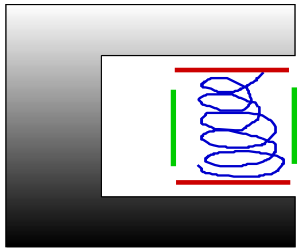




2) **The anomalous spin precession frequency is proportional to (g-2) … not to “g”**

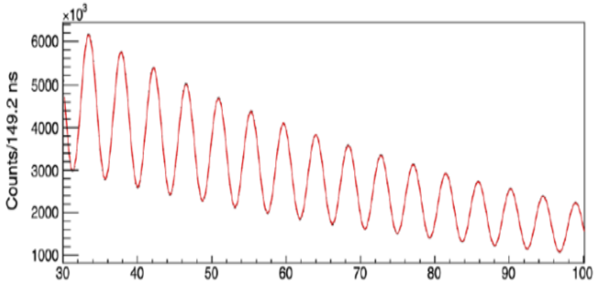
   ~850 easier vs measuring muon precession at rest

3) **The electric holding field does not perturb the spin frequency at the magic momentum**

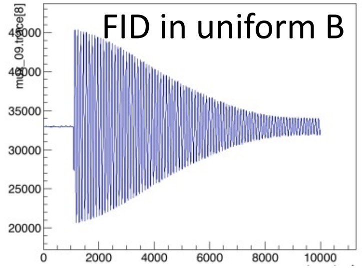


4) **Parity violation encodes the anomalous precession frequency in the e⁺ vs time spectrum**

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

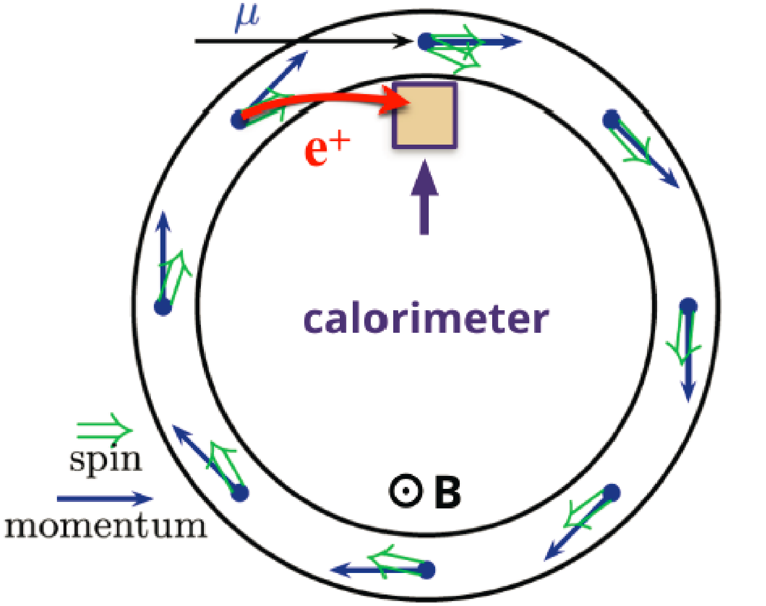


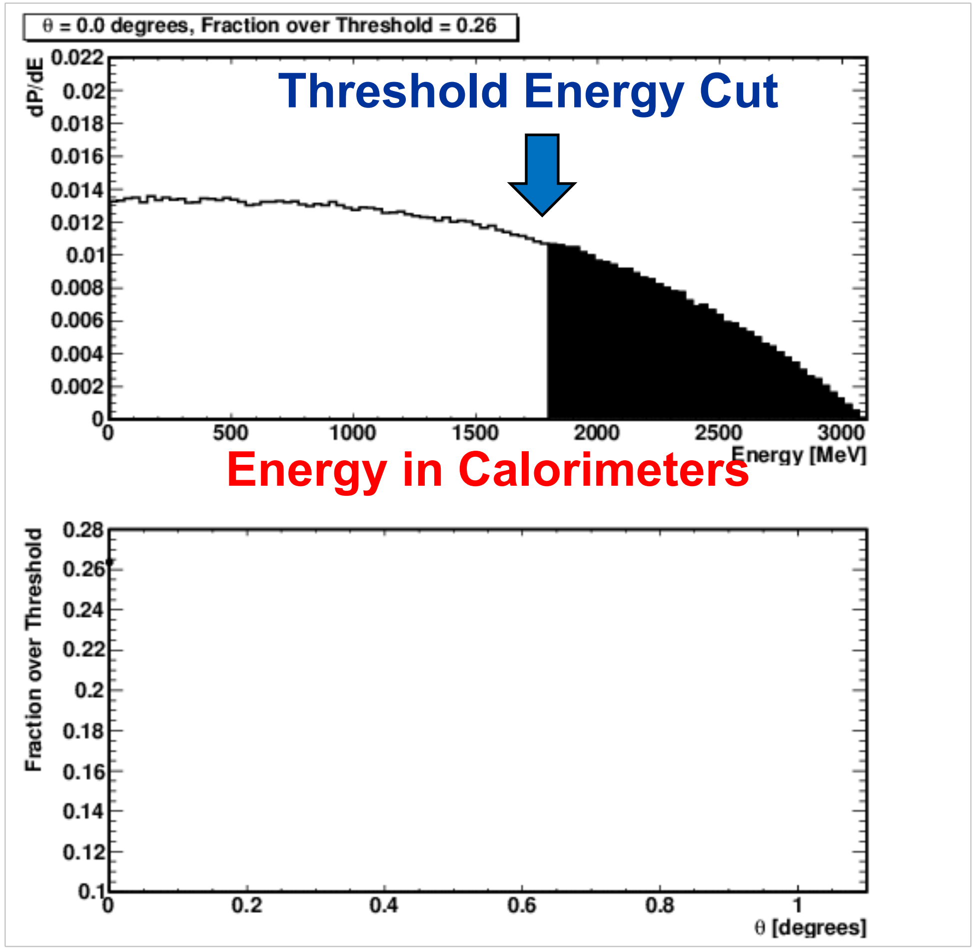
5) **Pulsed proton NMR allows the Field to be measured accurately to sub-100 ppb level**



Reminder: the precession frequency is the difference between the spin and cyclotron frequencies

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$





Phase of Muon Spin

a_μ is obtained from **2 frequency measurements** we make … and well-known fundamental factors from others

We measure these 2 frequencies

$$a_\mu = \left[\frac{\omega_a}{\tilde{\omega}'_p(T_r)}\right] \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$\frac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb at T = 34.7℃
Metrologia **13**, 179 (1977)

$\frac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting
Phys. Rev. Lett. **82**, 711 (1999)

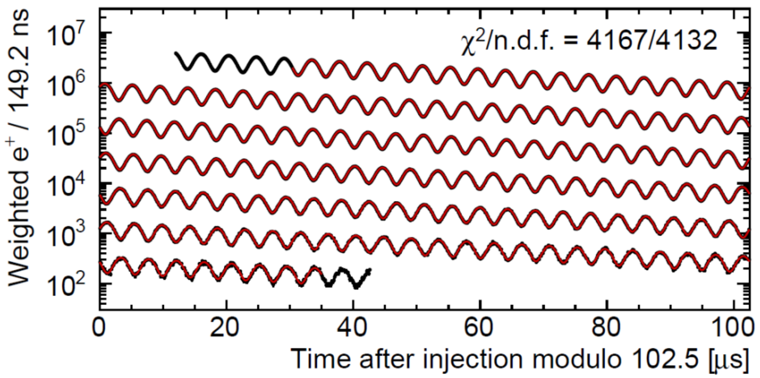
$\frac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)
Rev. Mod. Phys. **88** 035009 (2016)

$\frac{g_e}{2}$ Measured to 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

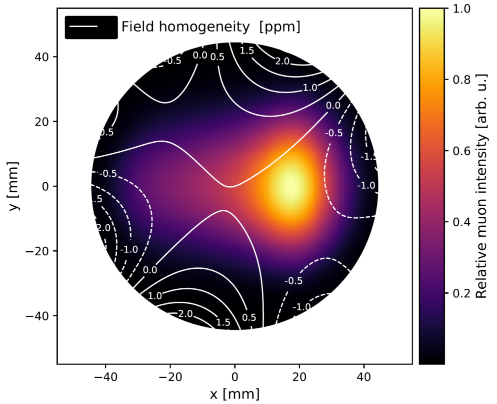
The "ω_a/ω_p" ratio is expanded to include important correction factors that are evaluated by teams

$$a_\mu \propto \frac{f_{\text{clock}} \ \ \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle \ (1 + B_k + B_q)}$$

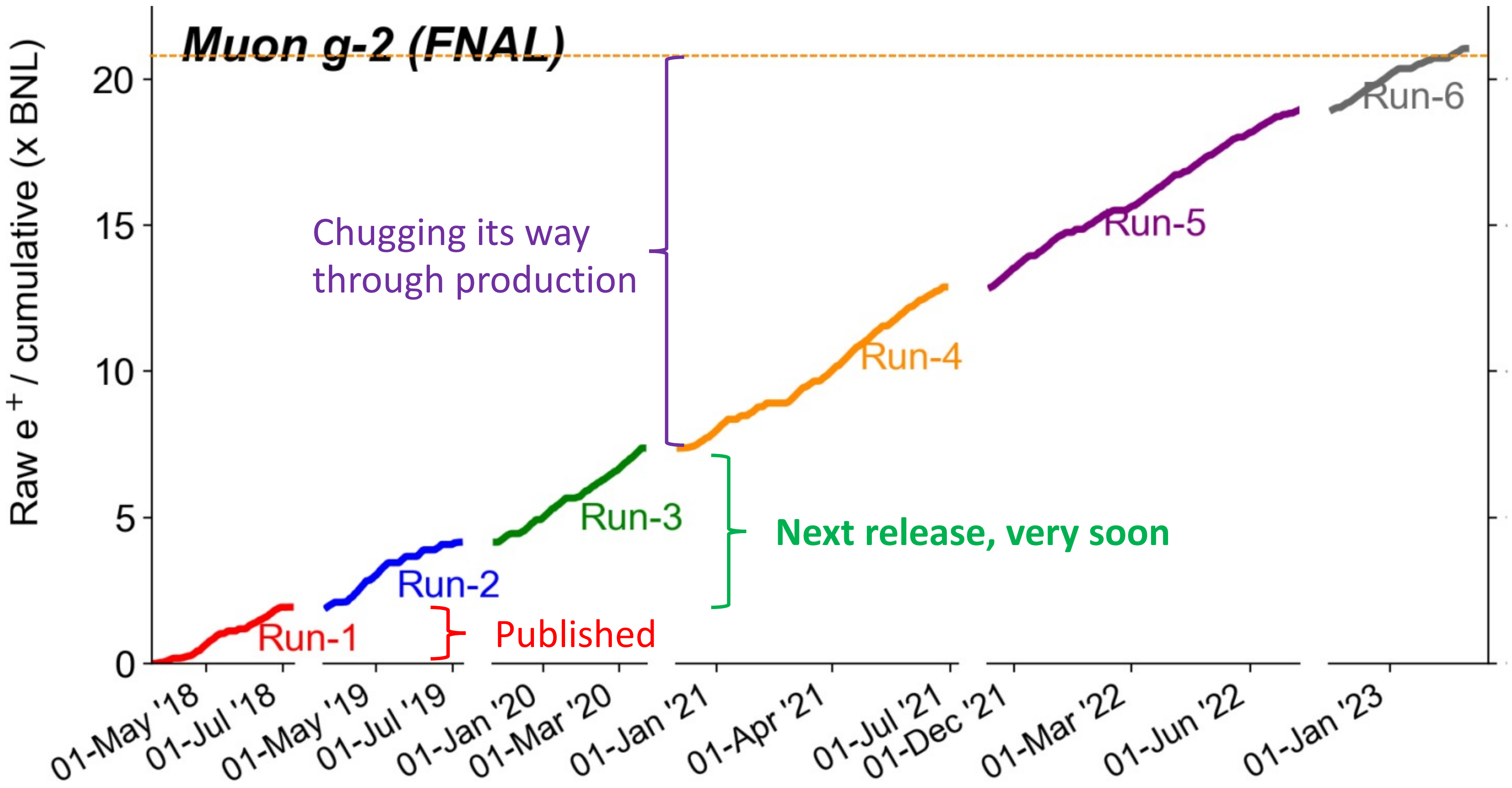
- f_{clock} • Blinded clock
- ω_a^m • Measured precession frequency
- C_e • Electric field correction
- C_p • Pitch correction
- C_{ml} • Muon loss correction
- C_{pa} • Phase-acceptance correction



- f_{calib} • Absolute magnetic field calibration
- $\omega_p'(x,y,\phi)$ • Field tracking multipole distribution
- $M(x,y,\phi)$ • Muon weighted multipole distributed
- B_k • Transient field from the eddy current in kicker
- Bq • Transient field from the quad charging

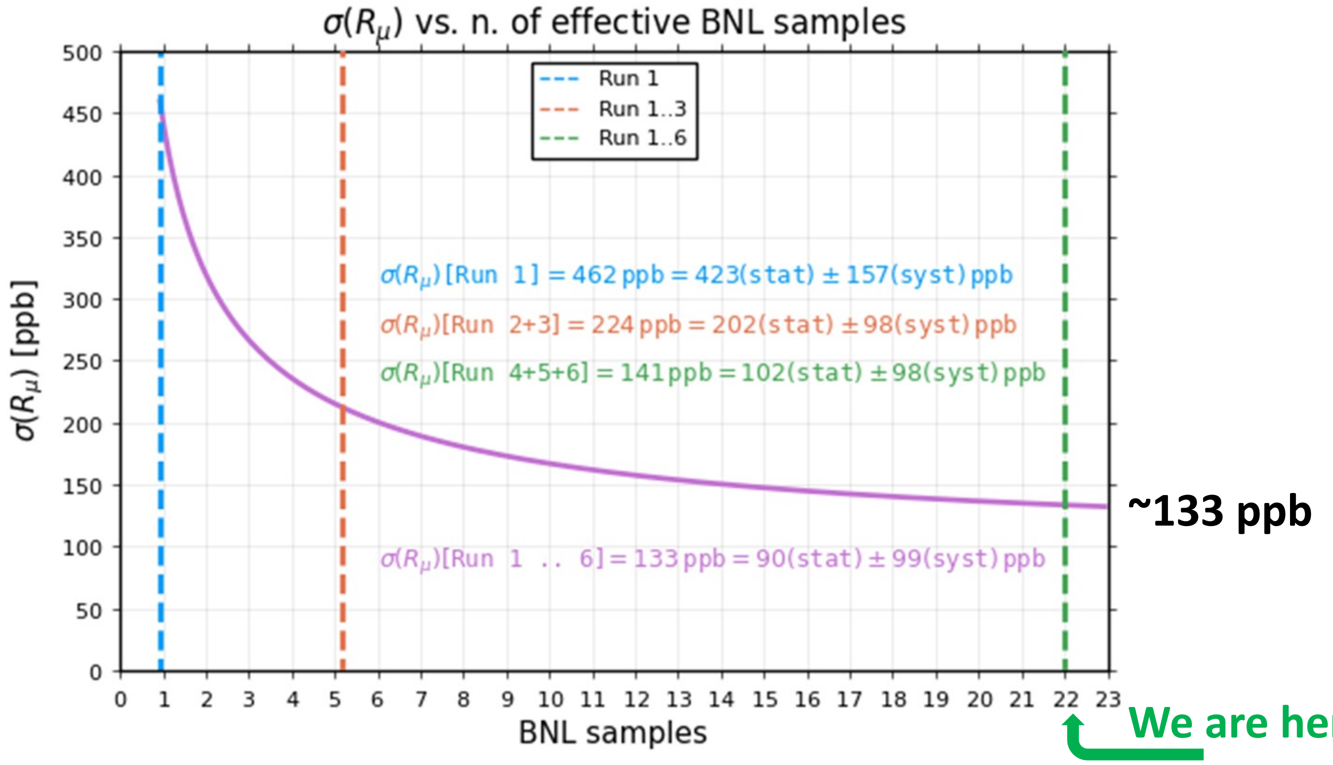


Data collected met proposal goals … “21 BNLs”



Original Goals and Where we are trending *

- Final precision: δa_μ = 140 ppb
  - Statistics 100 ppb
  - Precession systematics 70 ppb
  - Field systematics 70 ppb
  - Not thought of then 0 ppb ☺
- Trending toward: δa_μ = <140 ppb (slightly)
  - Statistics <100 ppb
  - Precession systematics <<70 ppb
  - Field systematics <<70 ppb
  - Not thought of then ~50? ppb (my guess)

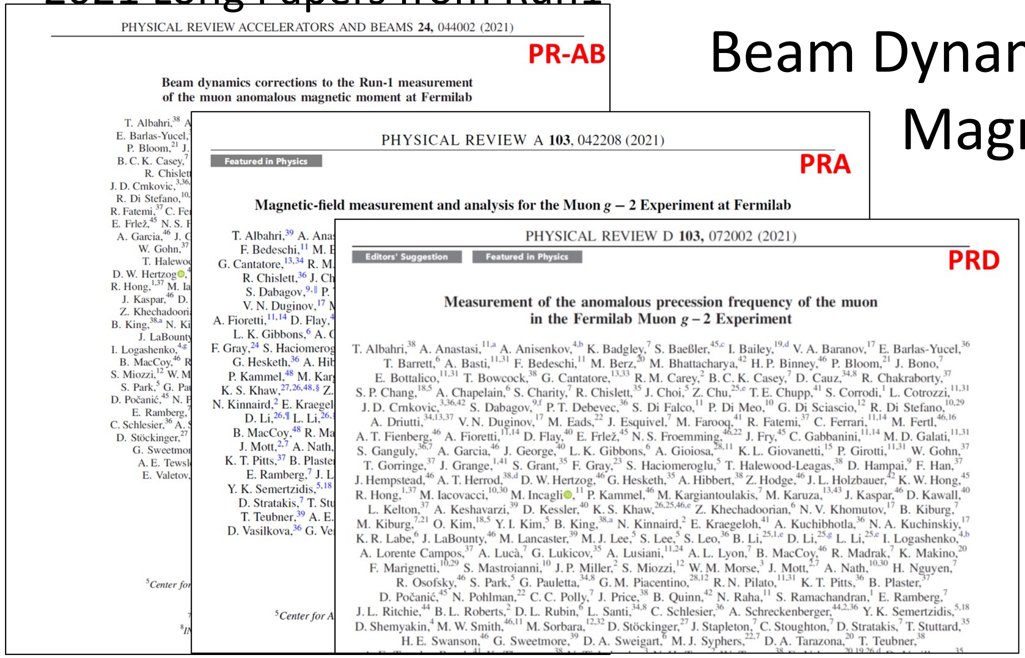


*Warning: until we look at the data, we can't be sure about final systematics, so this is just a good guess

Toward the Run-2/3 Release …

1. It's a lot of data, taken in 2019 and 2020 …until the Covid shutdown
2. Many improvements leading to final "ideal" conditions only at end of Run3
    1. Fixed bad HV resistors that caused major systematic in Run1
    2. Ring and Hall temp stabilized; significant for magnet and detector stability
    3. Muon kicker gradually upgraded to center beam & minimize CBO amplitudes (see later)

2021 Long Papers from Run1



Beam Dynamics Corrections vs Run1

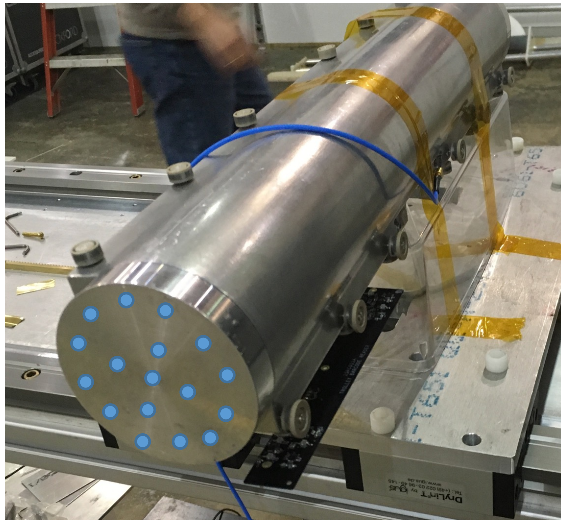
Magnetic Field Status vs Run1

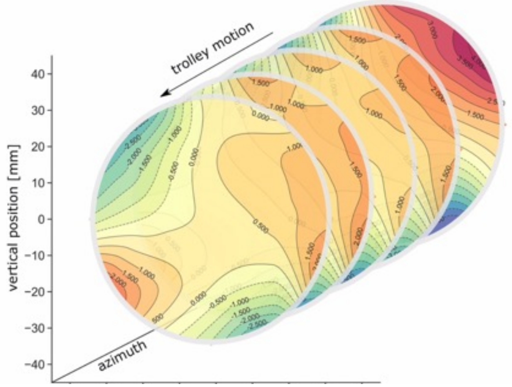
Muon Precession Frequency Status vs Run1

Measure the field moments vs time

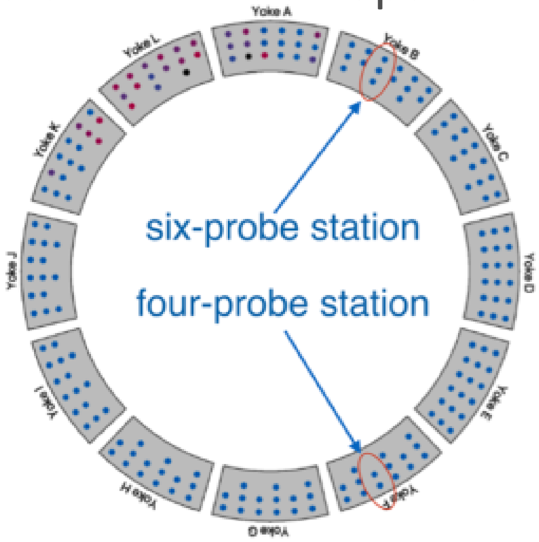
$$a_\mu \propto \frac{f_{\text{clock}} \quad \omega_a^m \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle \ (1 + B_k + B_q)}$$

- 17-element Trolley maps full azimuth every few days (muons not present)
- 378 Fixed probes monitor between trolley runs (during muon data collection)
- Field map is interpolated between trolley runs using fixed probe information
- Fold with Muon Spatial Distribution

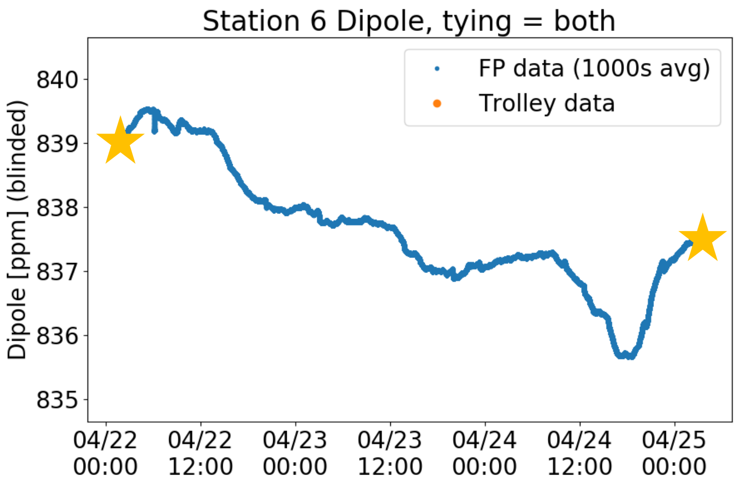


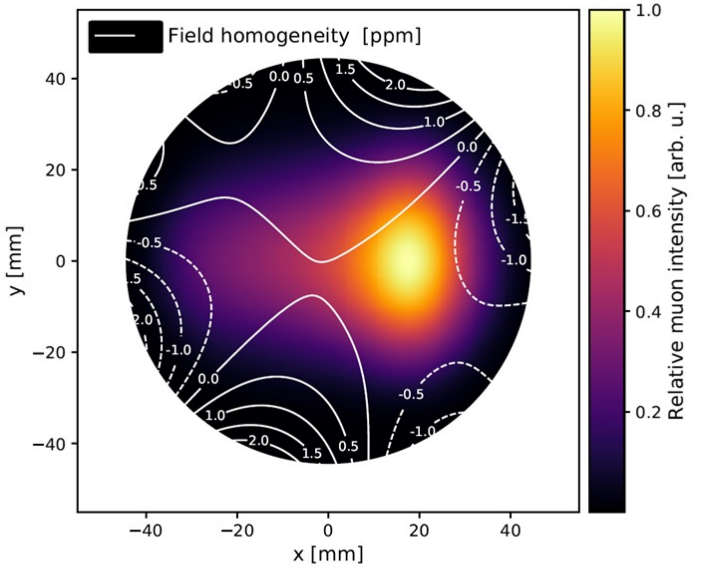


Sequence of field 2D field slices as trolley moves



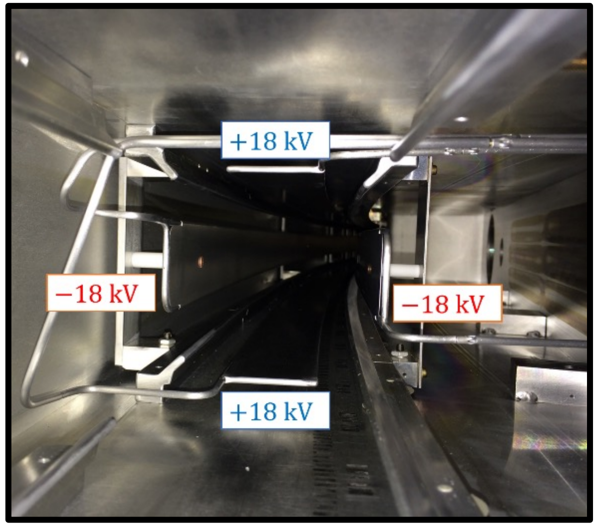
Fixed probes





Two **transient** effects perturbed *B* within the kicker and quadrupole plates at injection

$$a_\mu \propto \frac{f_{\text{clock}} \;\; \omega_a^m \,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \;\; \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle \;\; (1 + B_k + B_q)}$$



Quads pulsed on every fill

→ induces mechanical vibrations

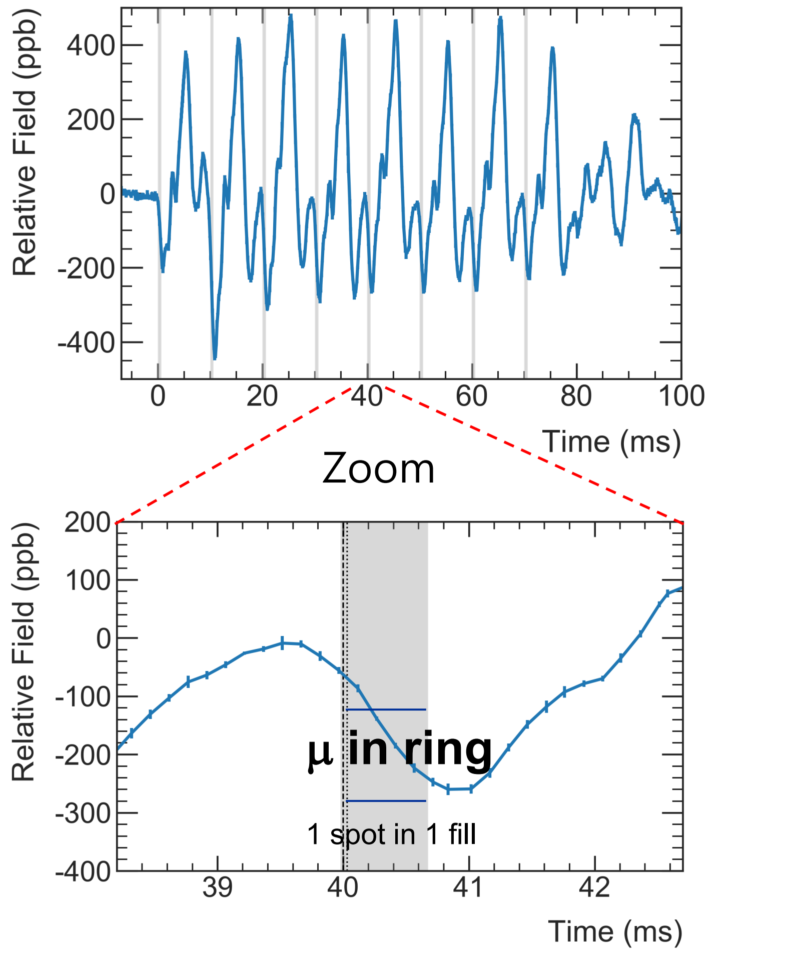
→ oscillating B field

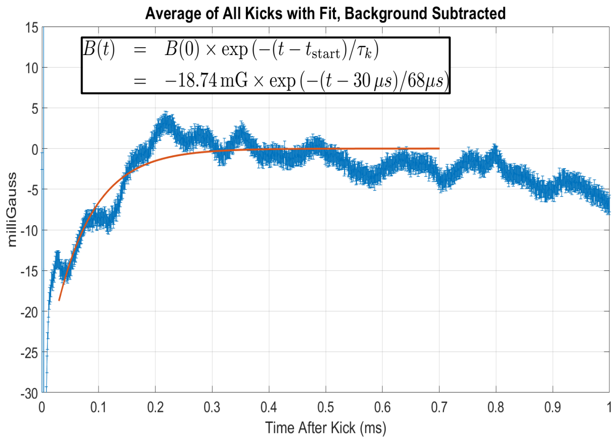
→ Net effect was small, but… complicated!

~~$B_q = -17$ ppb, $\delta_{B_q} = $~~ 92 ~~ppb~~

$B_q = -\text{xx}$ ppb, $\delta_{B_q} = \sim$21 ppb

Run 2/3 -PRELIMNARY





Kickers fire on every fill

→ induces small Eddy currents

→ We measured with custom magnetometers based on the Faraday effect

~~$B_k = -27$ ppb, $\delta_{B_k} = 37$ ppb~~

$B_k = -22$ ppb, $\delta_{B_k} = $ 13 ppb

Run 2/3 -PRELIMNARY

Fresh update from Field Team

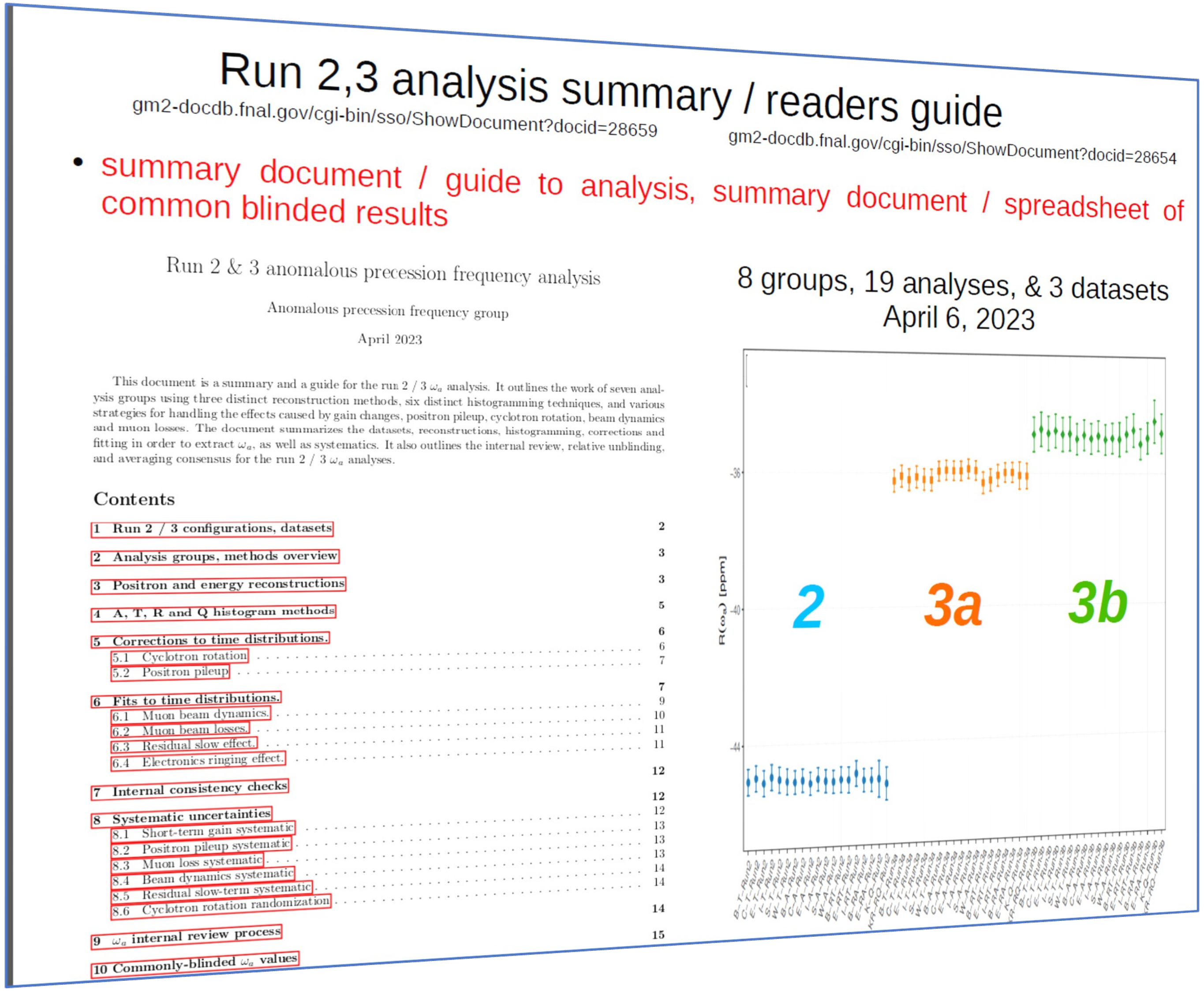
Error budget for Run-2/3

Area: Variance
Radius: $\tilde{\omega}_p'$ uncertainty

Largest uncertainties were transients, now understood much better

René Reimann for the field team

Precession frequency… 19 analyses x 3 runs periods = 57 ω_a !



Run 2,3 analysis summary / readers guide

gm2-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=28659 gm2-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=28654

- summary document / guide to analysis, summary document / spreadsheet of common blinded results

Run 2 & 3 anomalous precession frequency analysis

Anomalous precession frequency group

April 2023

This document is a summary and a guide for the run 2 / 3 ω_a analysis. It outlines the work of seven analysis groups using three distinct reconstruction methods, six distinct histogramming techniques, and various strategies for handling the effects caused by gain changes, positron pileup, cyclotron rotation, beam dynamics and muon losses. The document summarizes the datasets, reconstructions, histogramming, corrections and fitting in order to extract ω_a, as well as systematics. It also outlines the internal review, relative unblinding, and averaging consensus for the run 2 / 3 ω_a analyses.

Contents

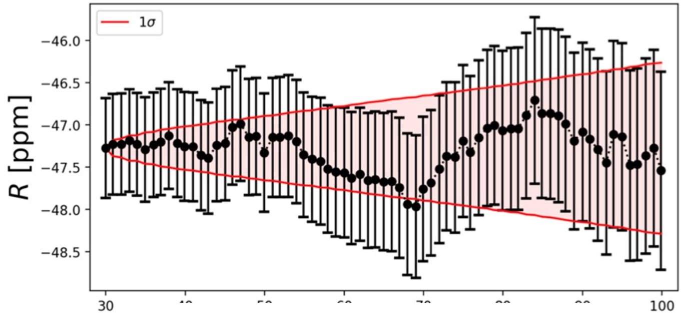
8 groups, 19 analyses, & 3 datasets
April 6, 2023

Enormous work in final Review stages…

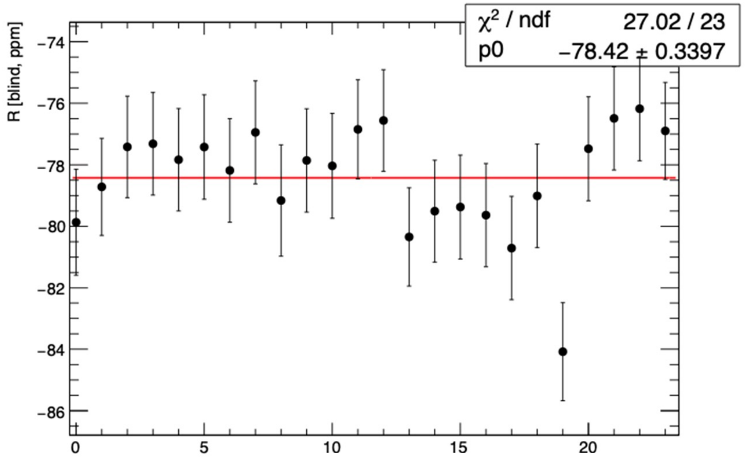
Note, various blinding factors and no magnetic field denominator here so don't compare different colors to one another

Tim Gorringe, ω_a Analysis Co-Lead

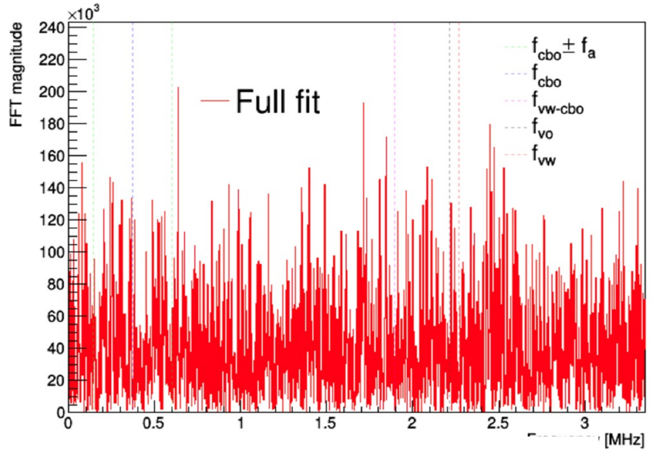
Overall message: Results are consistent and are supported by many quality control checks



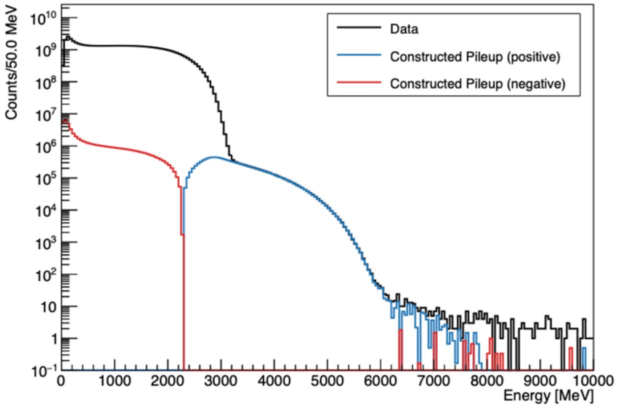
ω_a vs Start of Fit in Fill



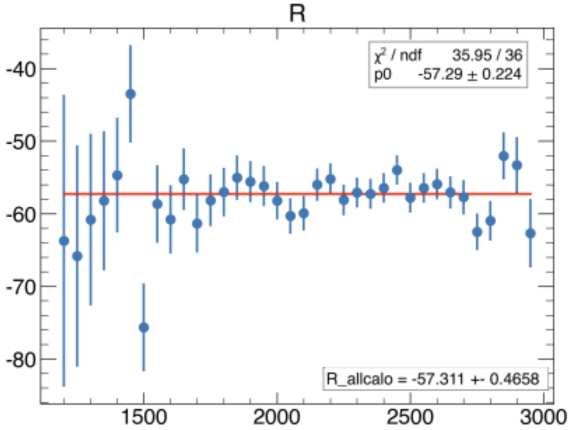
ω_a vs Calorimeter



Residuals of FFT



Match of raw Energy spectrum and Pileup Correction

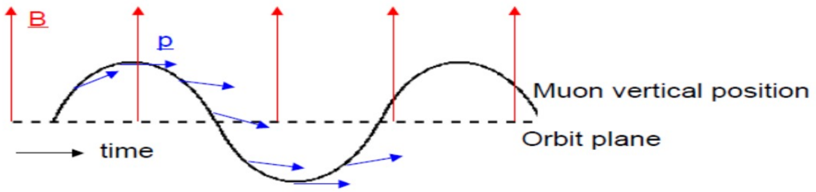


ω_a vs Energy Bin

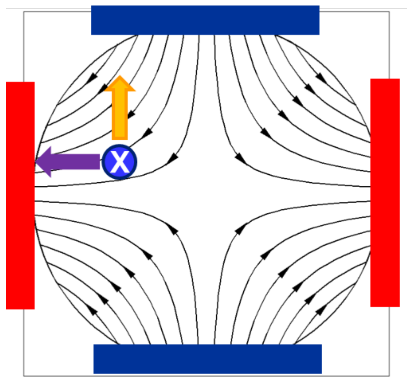
Etc, millions more…

Beam Dynamics Corrections to measured ω_a

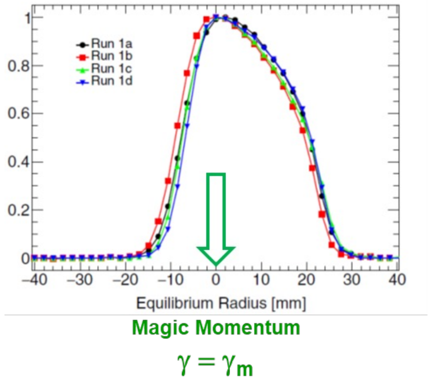
- Because the Run1 bad resistors were replaced,
  - C_{ml} "muon loss" are now <u>negligible</u>
  - C_{pa} "phase-acceptance" was largest, but now much smaller
- C_{dd} "differential decay" newly evaluated, but a small entry



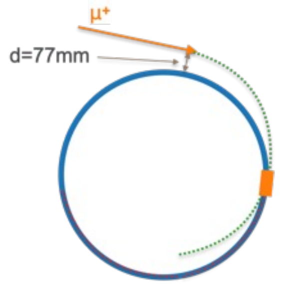
- C_p "pitch" -- no difficulties; evaluated by 2 teams

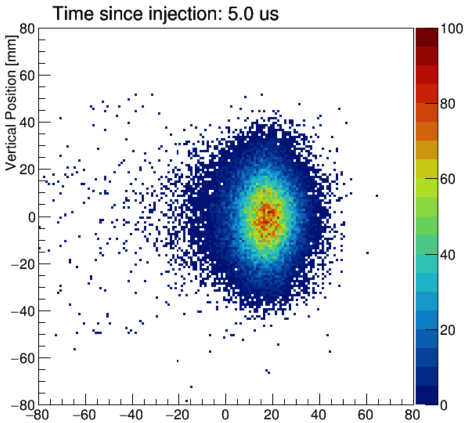


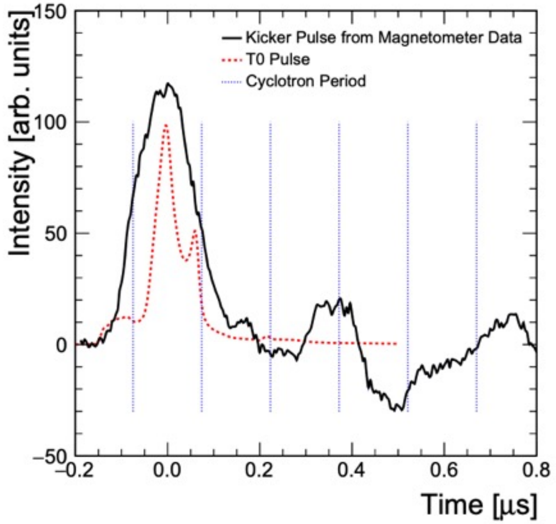
- C_E "Electric Field" --
  - largest correction so investigating if anything couples to it
  - uncertainty being carefully evaluated with new hardware and software special efforts



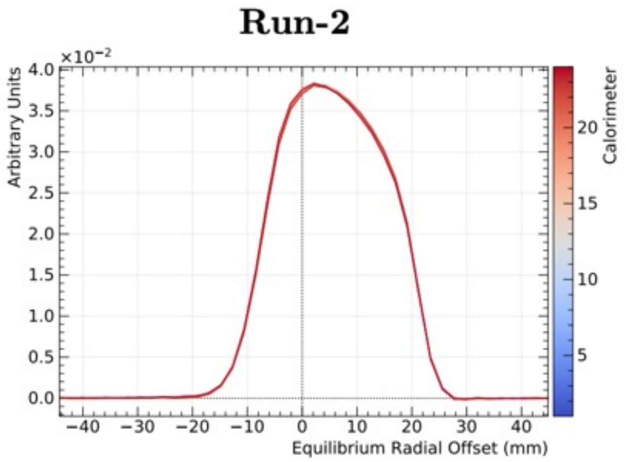
Major post Run 1 improvements – kicker strength

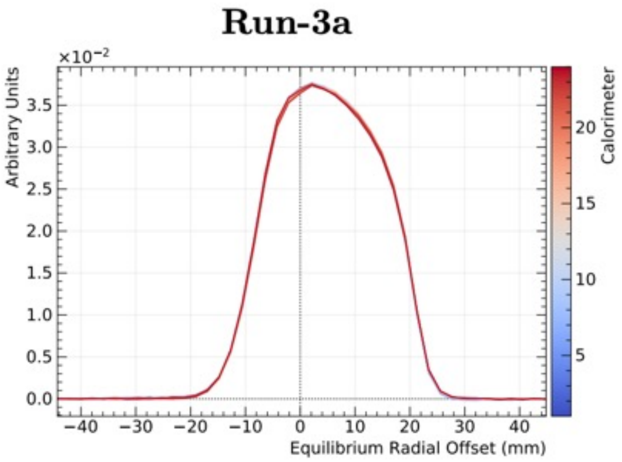


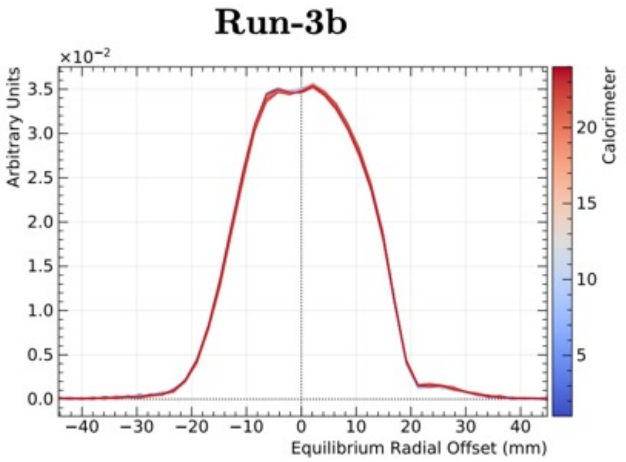




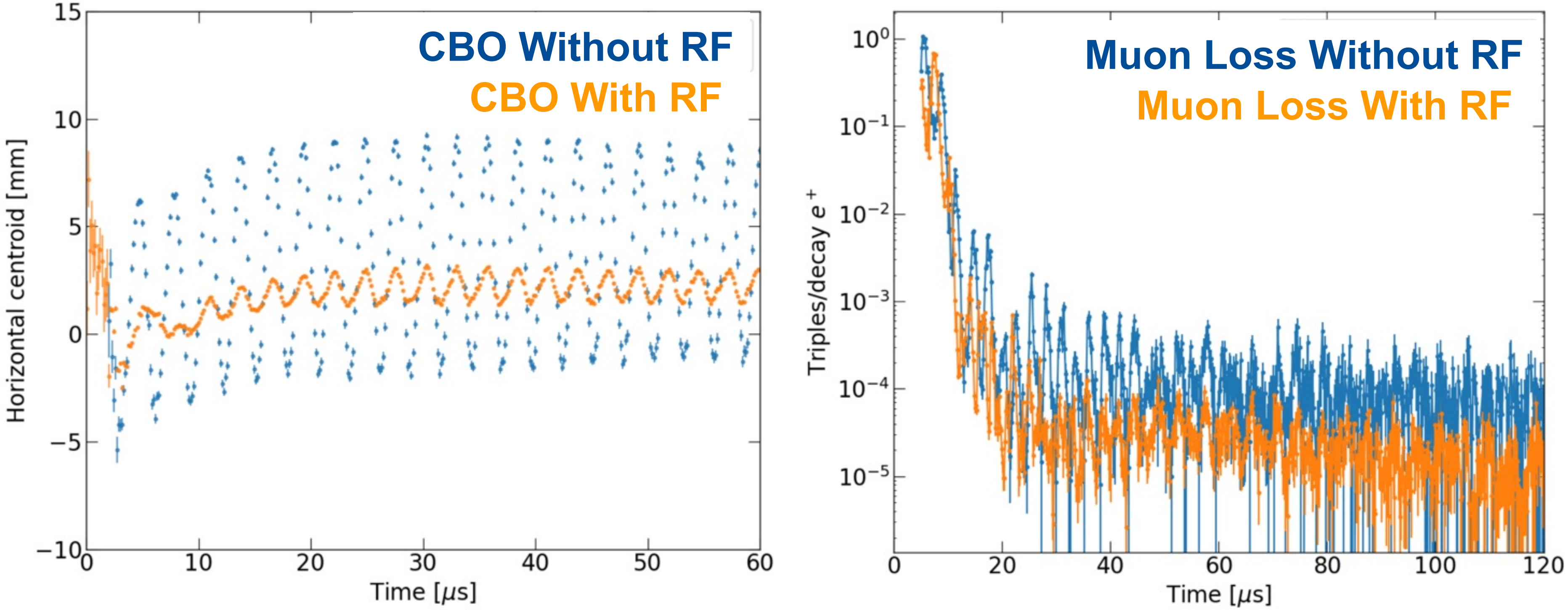
- R1: Kickers did not center beam
- Negative impacts
  - Larger CBO amplitude
  - Muons live in less uniform B field
  - Off-center → off-momentum → large C_e correction
- Major upgrade campaign completed by end of Run 3





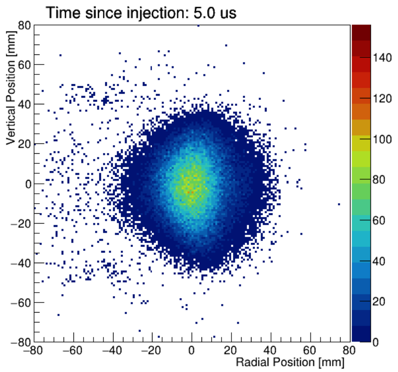


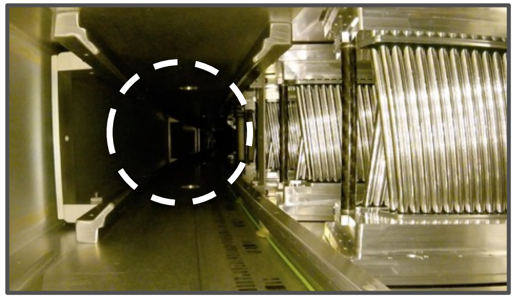
RF system deployed in Run 5 to damp CBO, reduce muon losses during storage

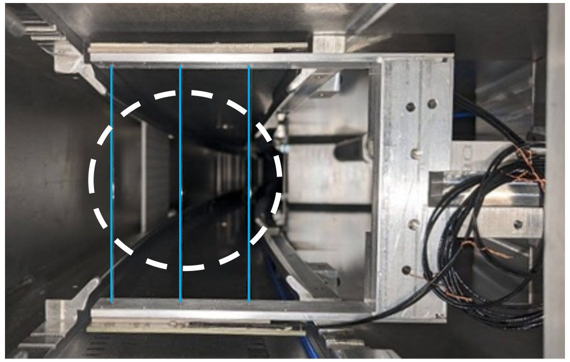


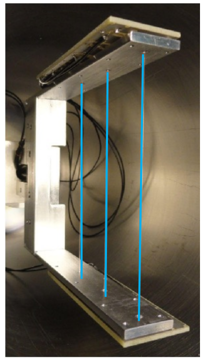
- Implemented active RF system in Run 5 (first time in any g-2 storage ring)
- Turns on for first few microseconds to damp CBO
- Will make fitting time-dependent precession distribution easier

We've recently added a new beam imaging tool that directly observes the stored muons with minimum perturbation for the first time





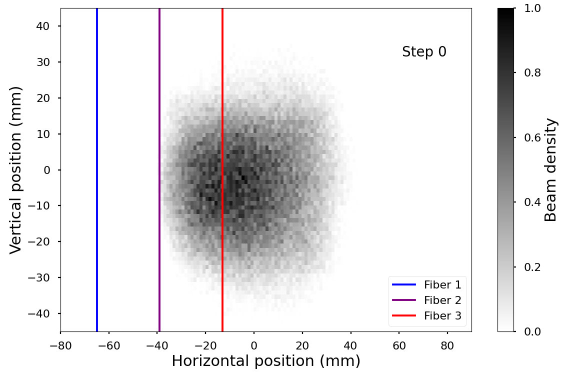


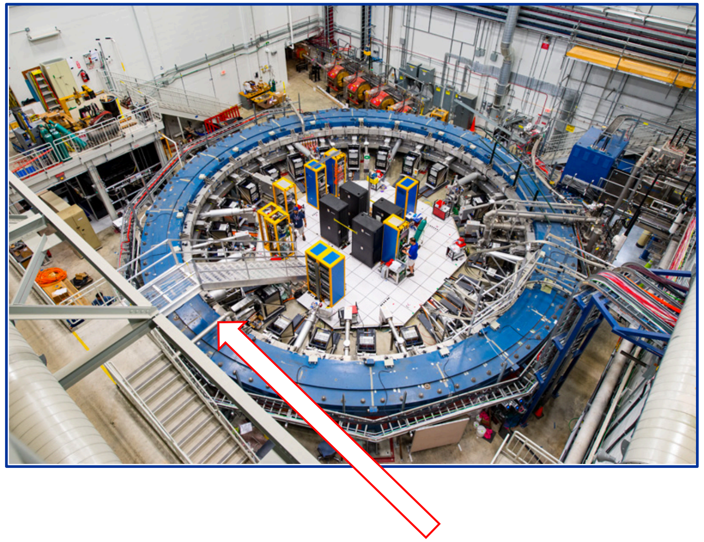


The "indirect" view from tracked decay positrons

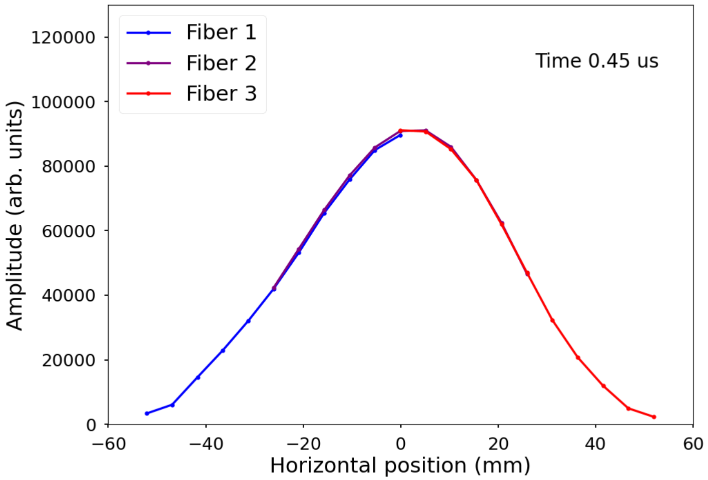
250 μm fibers, too thin to see, so I overlaid with blue lines

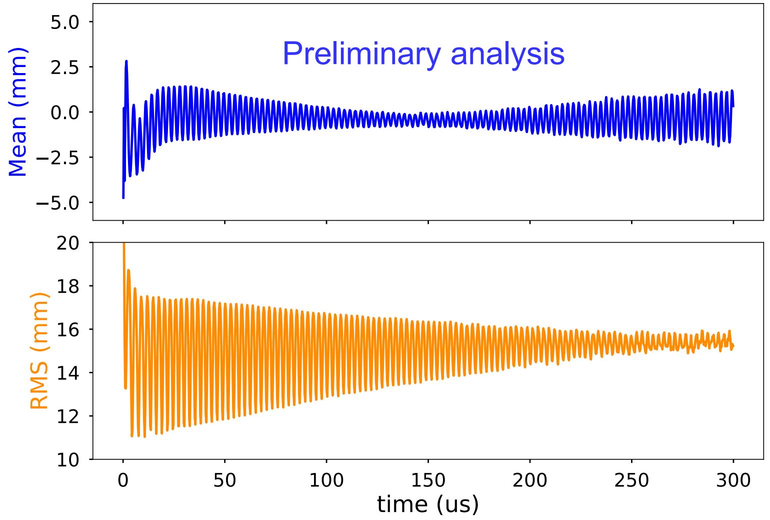
A precision scan is made





Profile at 180°



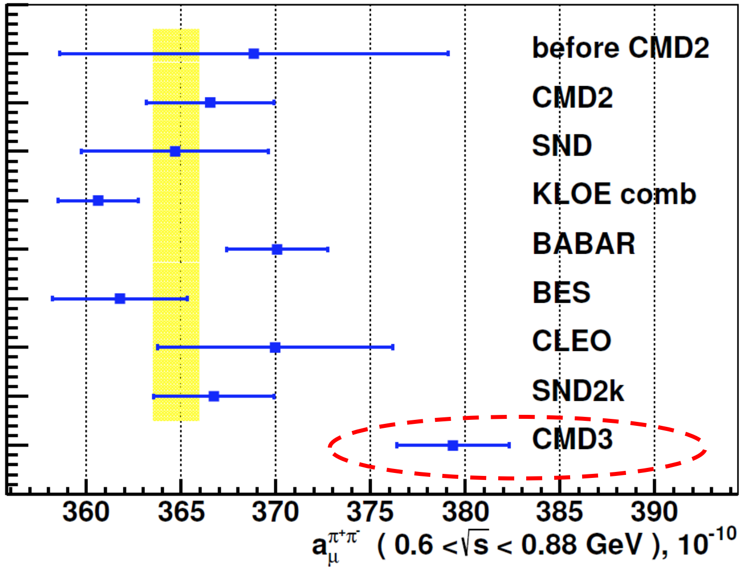


Plans for Release of Run 2/3

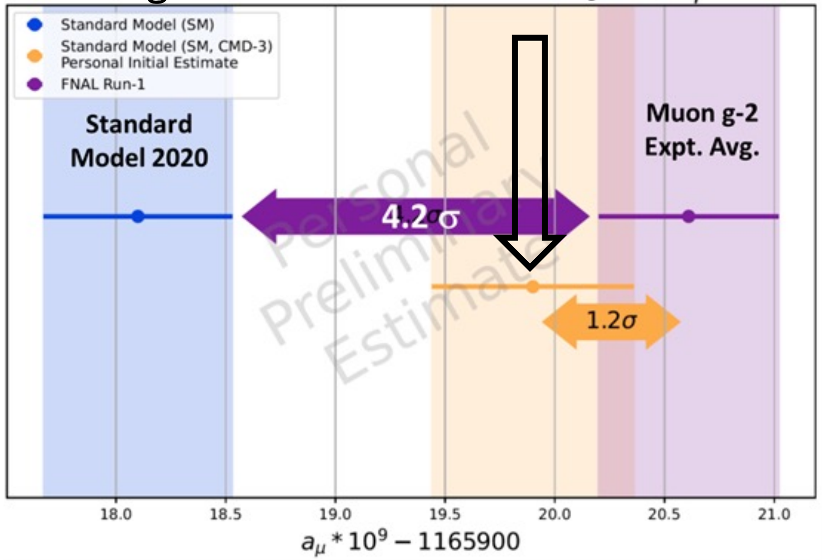
- All ω_a measurements are now *relatively* unblinded;
  - 6 pre-selected methods have the greatest sensitivity and independence; the will be averaged to provide the best and most robust result
    - 2 Recons; 2 Asymmetry Weighted Fits; 2 Ratio-Asymmetry Fits
- The magnetic field analysis is very mature and thoroughly reviewed
- The various "Beam Dynamics" corrections are nearly complete
- After documents are blessed, we will vote to unblind.
- Public release follows within a few weeks

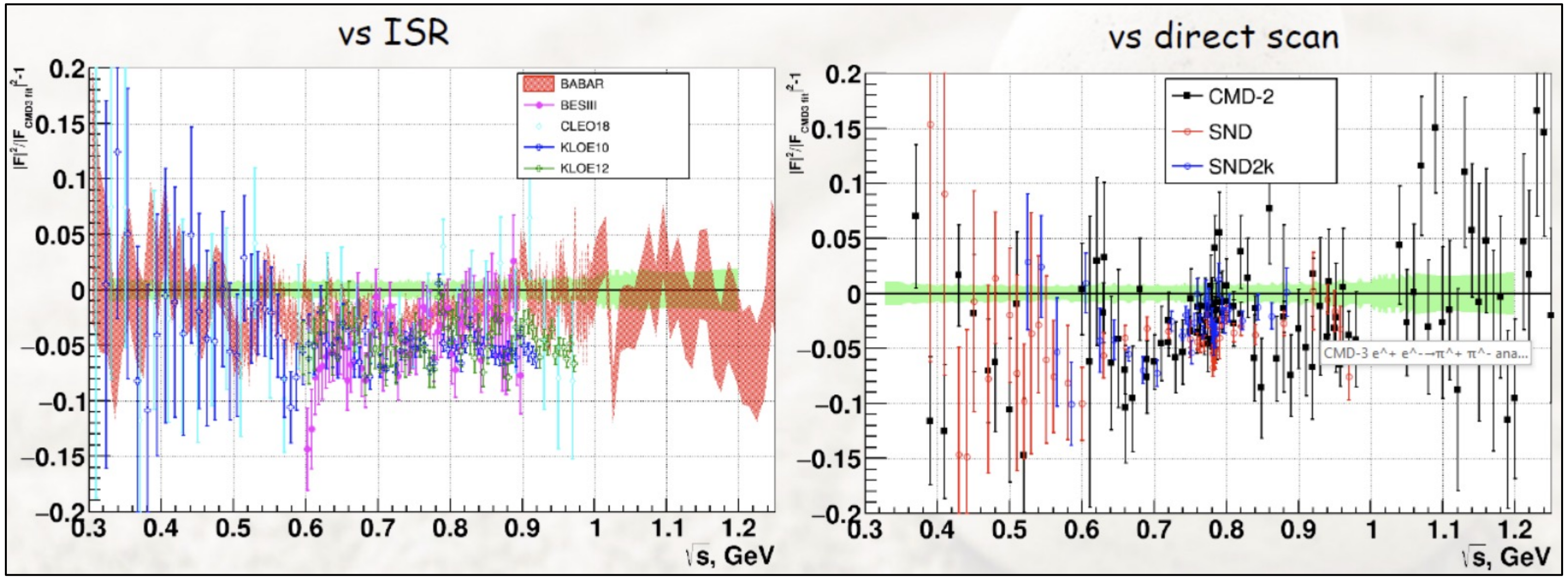
Now back to the SM and why you are important!!

- The CMD-3 "February Surprise" [F. Ignatov et al, arXiv:2302.08834]
  - $e^+e^- \rightarrow \pi^+\pi^-$ in important low-energy regime disagrees with all other results by many σ !
  - Questions arise:
    - What might they have wrong?
    - How rigorously were results vetted?
    - Did older exeriments miss something big and common?
  - After lengthy seminar/panel discussion, nothing is at all obviosly wrong on new or older result and methods.
  - This is a big PUZZLE that must get resolved, …



Might look like this if confirmed





The experimental landscape will improve …

Ongoing work in experimental inputs

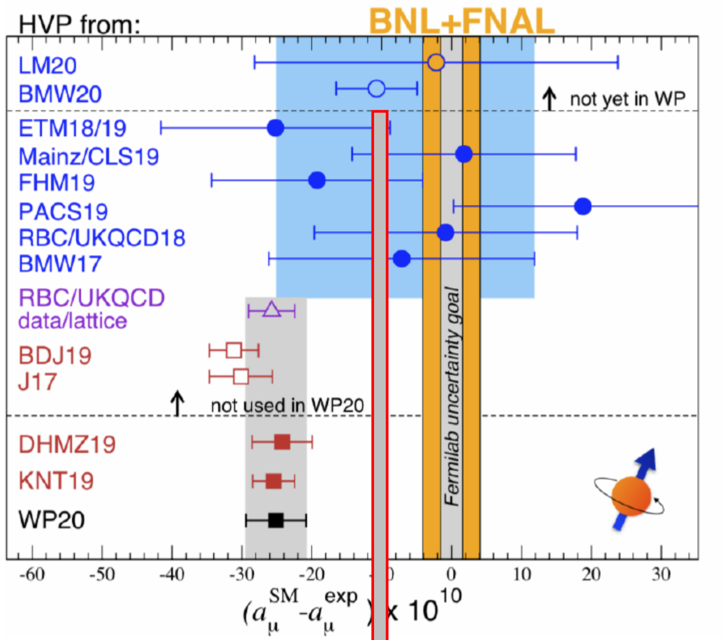
- BaBar: new analysis of large $\pi\pi$ data set with better detector
- KLOE: new analysis of 7x larger $\pi\pi$ set
- SND: new results for $\pi\pi$ channel
- BESIII: new results for $\pi\pi$ channel and $\pi\pi\pi$
- Belle II: promising greater statistics than BaBar or KLOE and similar or better systematics for low-energy cross sections

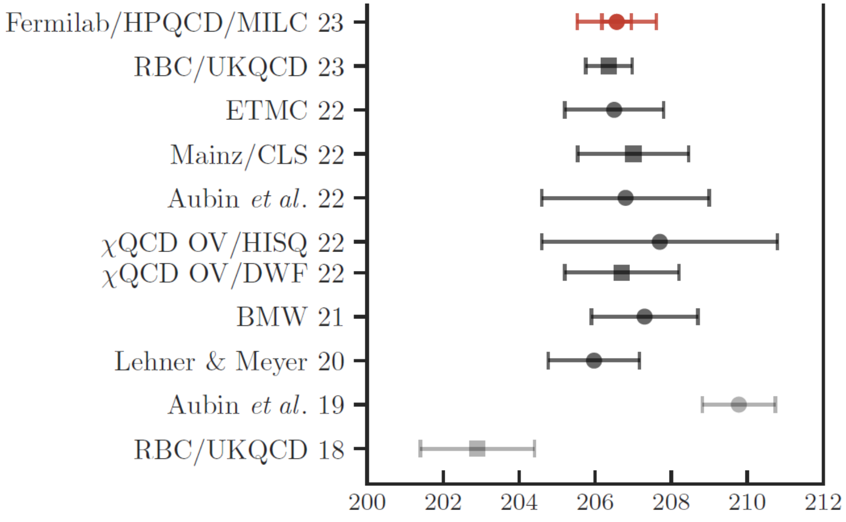
If the differences between experiments are resolved:
data-driven evaluations of HVP with $\sim 0.3\,\%$ feasible by ~2025

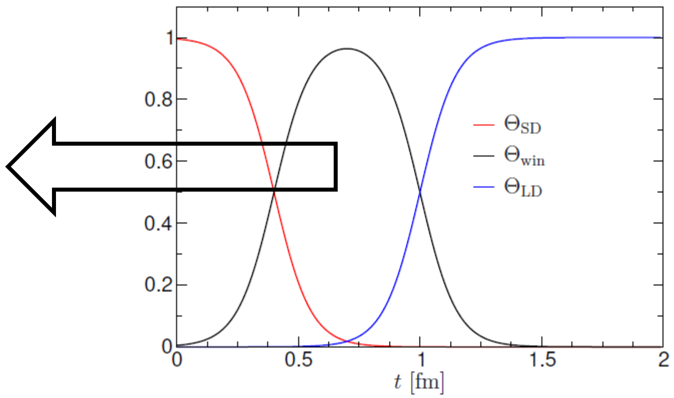
See Aida El-Khadra's P5 presentation, March 2024 for lots of details on the g-2 Theory Initiative and the recent lattice efforts related to HVP

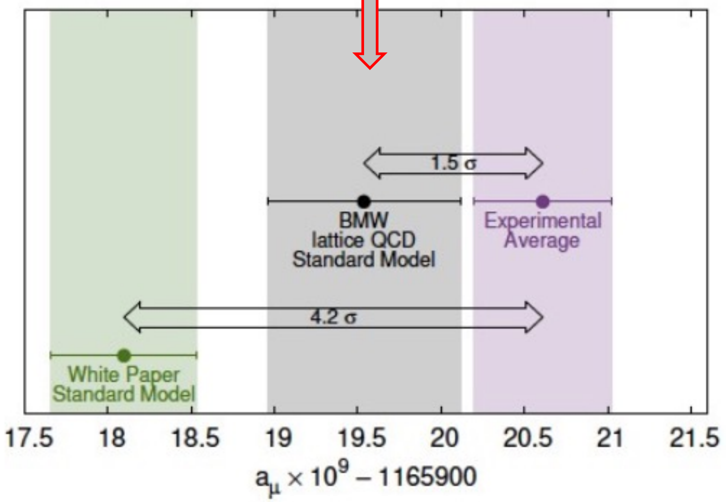
And finally, the lattice … eventually the most precise HVP method?

- Not yet included in the Theory Initiative recommendation.
- The 2021 BMW HVP publication is an impressive, sub-percent calculation. The result is closer to experiment
- Since then, quite a buzz among groups trying to reconcile and find common areas to compare
- Biggest problem is short- and long-distance extrapolations that are needed for such a diagram
  - Step 1: "Intermediate" Euclidian Window









Looks consistent

… and, then ?

- We are all excited to see the next g-2 result with ~½ the uncertainty

- But, to what SM value can we compare it to this time?

  A) The "recommended" 2020 Theory Initiative value remains a standard (for now)

  B) But, they and we know, the situation is dynamic and could greatly change

  - Need Confirmed Lattice Calculations. This is imperative.
  - The Lattice could take us to 0.1% !! and even push for next-generation measurements
  - The CMD-3 result is a true outlier right now, but that does not imply it is wrong. Fortunately a lot of new data is being analyzed so we have a "wait and see" situation

- "Discovery" takes time.
  - We do not know the final implications of our measurements of g-2.
  - We can only control the quality of the effort and analysis.