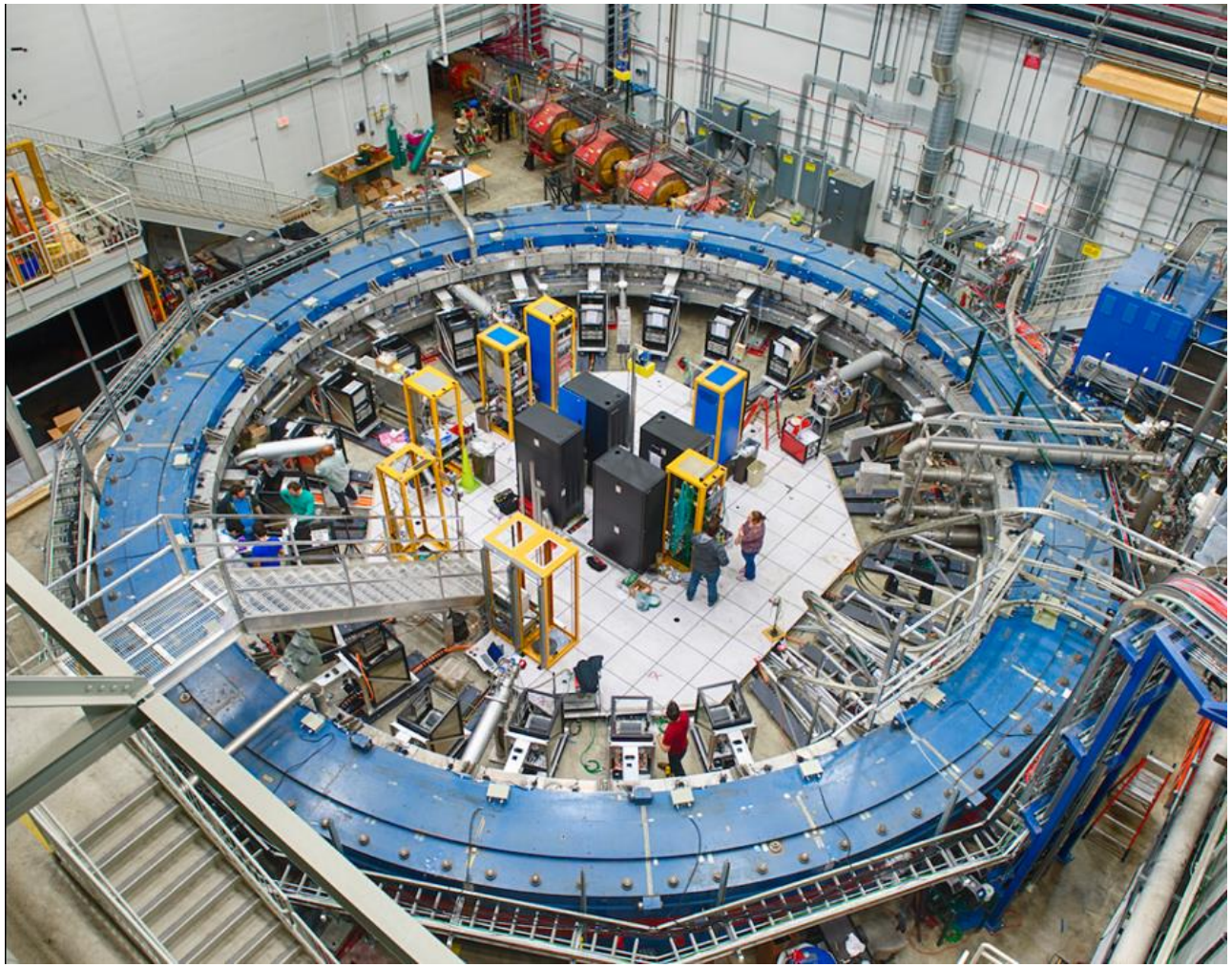


Muon g-2 Masterclasses

IMC SG Meeting, CERN, Nov 25th, 2024

Sean Foster & René Reimann

Fermilab

University of Kentucky

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Muon g-2 in a Nutshell

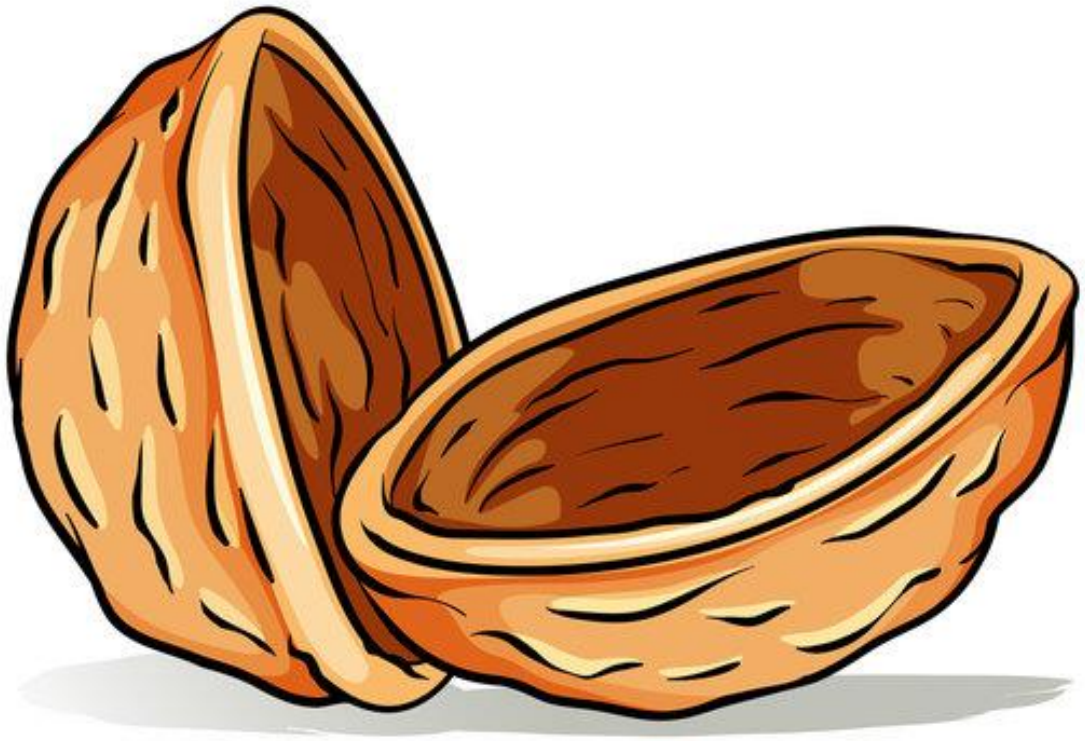
one of the most precise measurement in particle physics

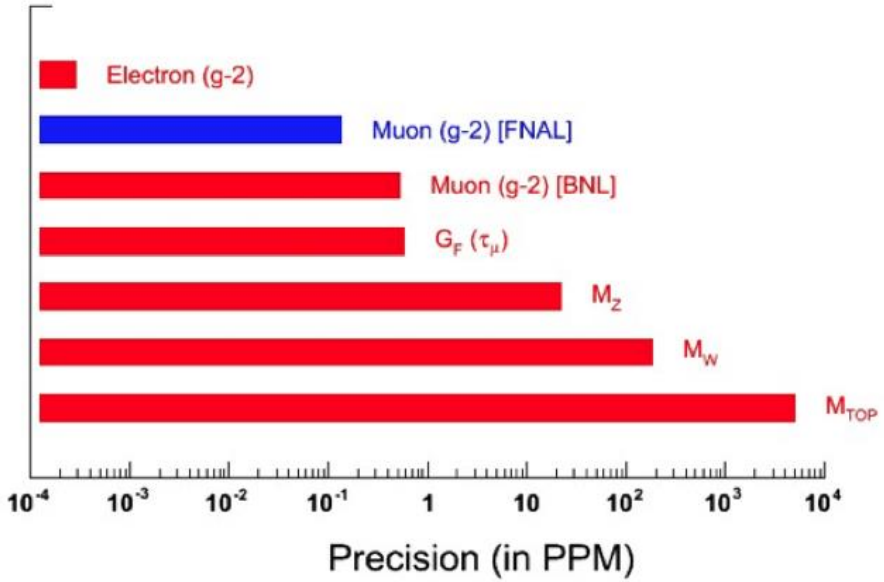
+

high precision theory calculation

=

one of the most stringent tests of SM of PP





proportionality factor between spin and magnetic moment

$$\vec{\mu}_\mu = -g_\mu \frac{e}{2m_\mu} \vec{S}$$

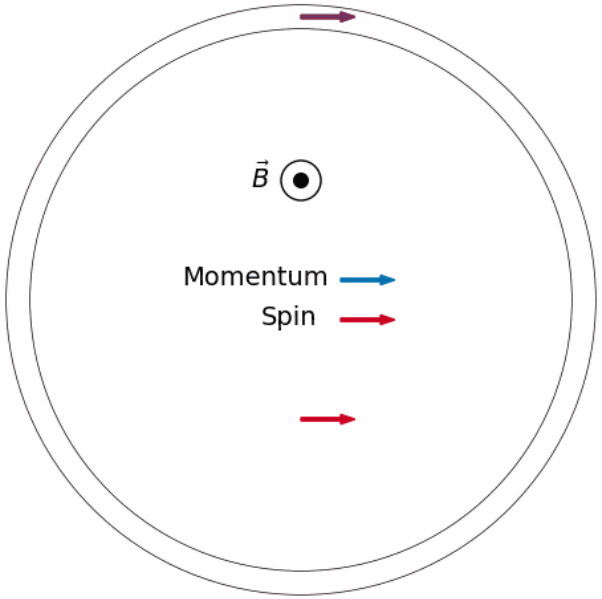
Measurement Principle

Muon in homogeneous magnetic field

Spin Precession

$$\vec{M} = \vec{\mu} \times \vec{B}$$

torque → precession



Cyclotron Motion

$$\vec{F} = q\vec{v} \times \vec{B}$$

perpendicular force → circular orbit

$$\underbrace{\omega_s - \omega_c}_{\omega_a} = \underbrace{\frac{g_\mu - 2}{2}}_{a_\mu} \frac{e}{m_\mu} B$$

anomalous spin-precession frequency

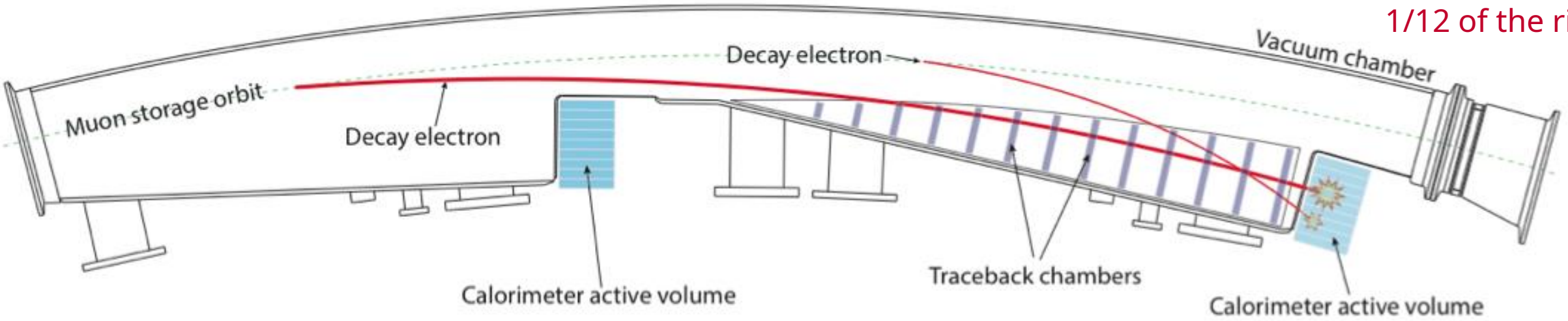
anomalous magnetic moment

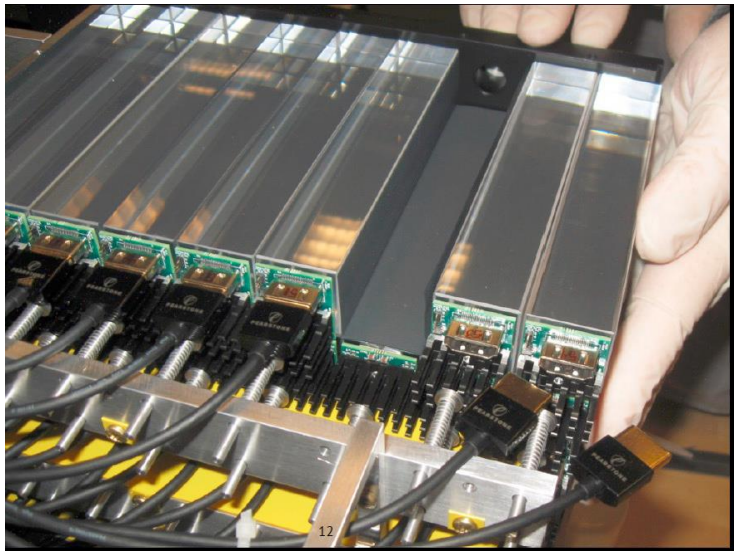
Event Reconstruction

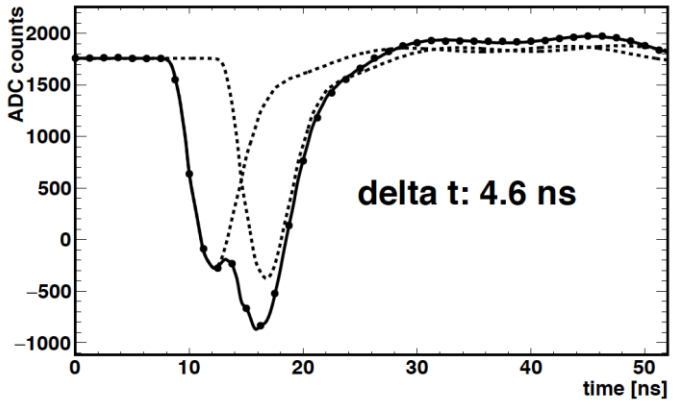
Task 1

Event Detection

1/12 of the ring



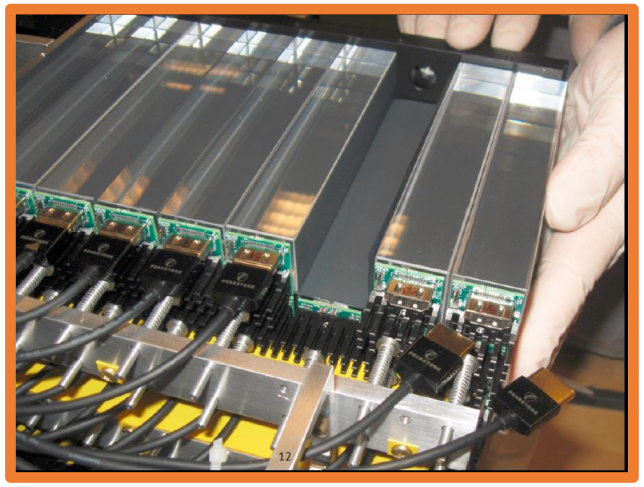




- Muon decay → positron
- Positrons spiral inwards
- Cherenkov light PbF2 crystals
- 24 calorimeters with 6x9 crystals

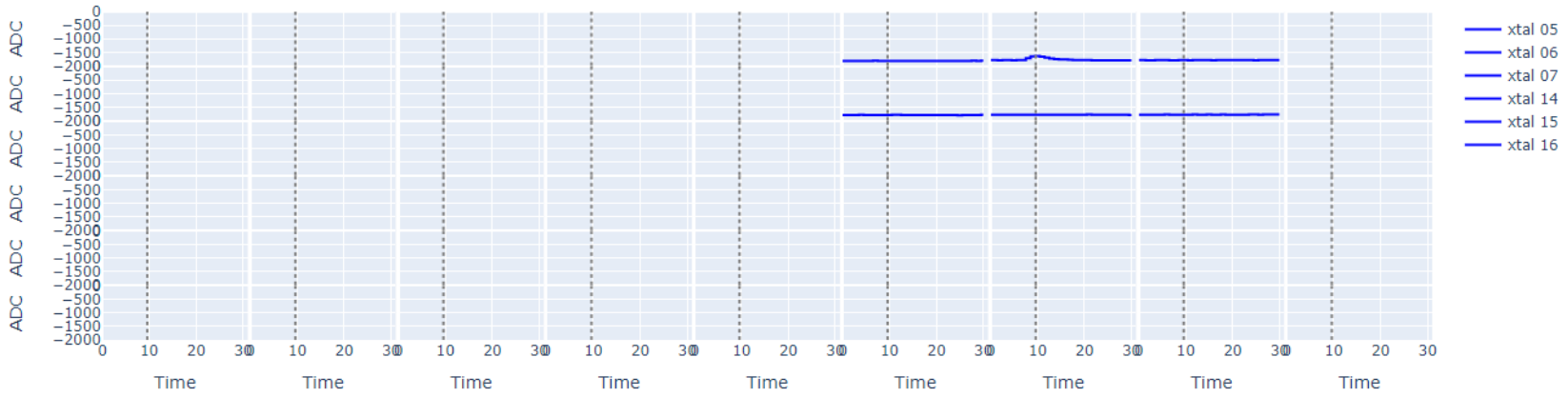
- Reconstruct Time and Energy

Event Reconstruction



- Event Display
- Event Navigation
- Slider fit
  - Event time
  - Event amplitude / energy
- Pile-up flag
- Save event information

Event Display



Fit Options

Is pile-up

Event Time [us]:

Event Energy [us]:

Event Info

Run	30252
Subrun	263
Event	2
Island	7
Calorimeter	1
First Sample Time	133751.25

<- Save ->

Saved Events

Event ID	Is Pile-Up?	Time	Energy
1	no	9.60000	224.000

Tasks

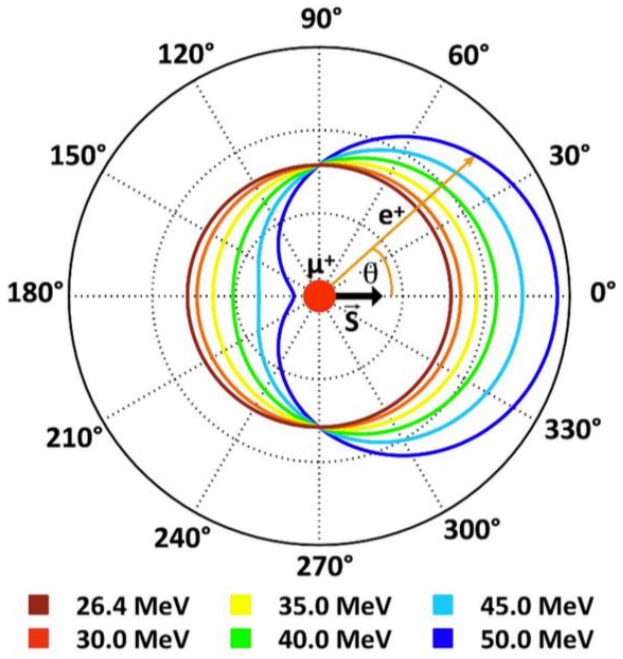
- Extract positron time and energy from "slider fits" to individual pulses
- Identify pile-up events
- Determine boosted muon lifetime from exponential decay of time spectrum $\dot{N}(t) \propto e^{-t/\gamma\tau}$
- Determine muon momentum from energy spectrum end point $p = \gamma m_\mu v$
- Determine muon rest lifetime from boosted lifetime and momentum τ_μ

Wiggle Plot Fit Extracting ω_a

Task 2

Spin Precession → Positron Energy

Muon Rest Frame

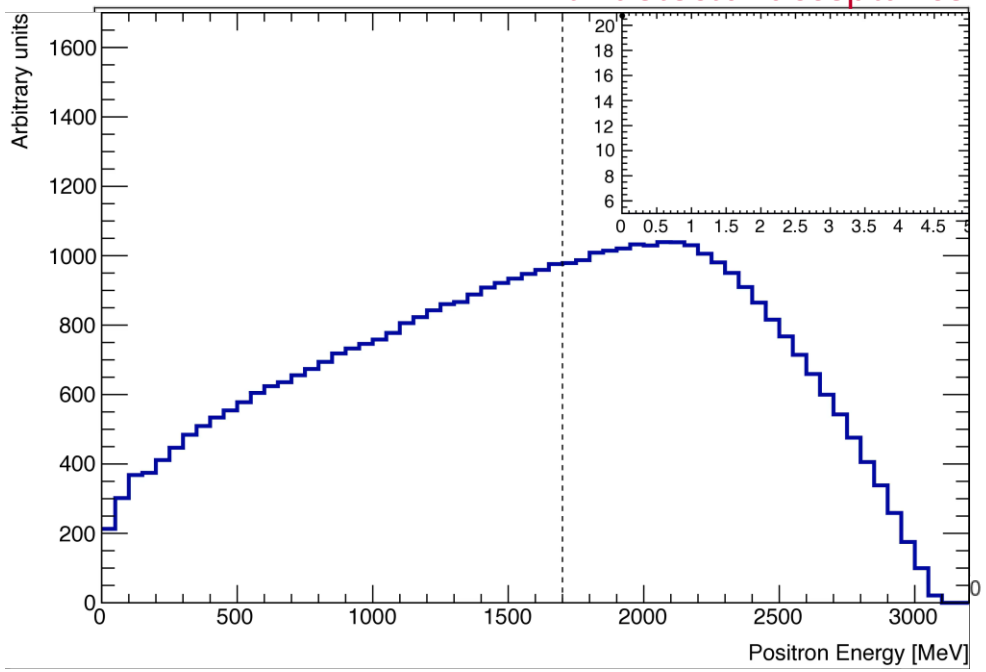


Weak decay → parity violation
Positron emission in direction of spin

Boost

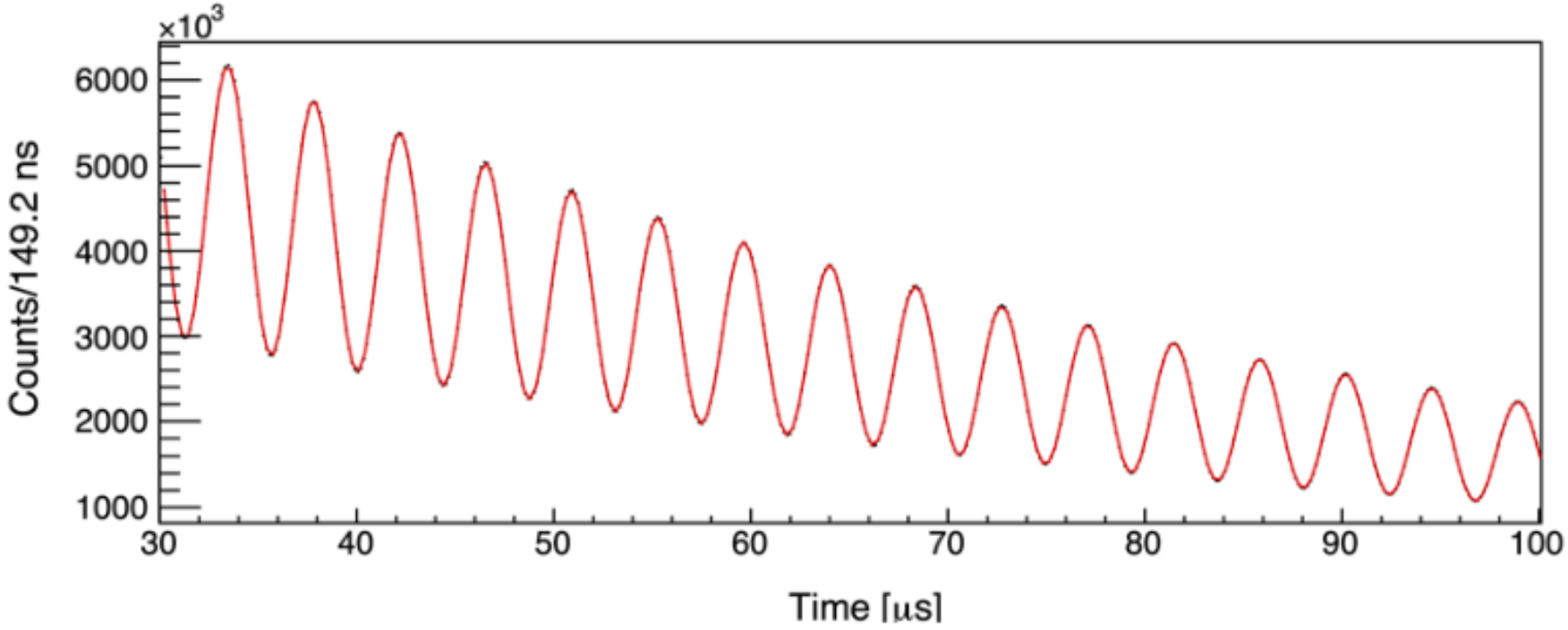
Lab Rest Frame

With detector acceptance



count rate above energy-threshold

Wiggle Plot



$$\dot{N}(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left(1 + \langle A \rangle_{\text{thres}} \cos\left(\omega_a t - \langle \phi \rangle_{\text{thres}}\right)\right)$$

normalization

muon decay

wiggle amplitude

wiggle frequency
measurement of g-2

wiggle phase

Wiggle Fit

- Fraction of data from run 3
- Linear & logarithmic representation
- 5-parameter fit
  - sliders
  - ~~automatic~~
- Fit result table
- Residuals & FFT of residuals
- Determine frequency:
  - counting wiggles by hand
  - slider fits

Histogram Options

Set y-axis to log scale

Fit Options

Fit start time [us]: 30 130 230

Fit end time [us]: 300 400 500

N0: 4M 6M 8M

tau [us]: 0 20 40 60 80 100

A: 0 0.25 0.50 0.75 1.0

R [ppm]: -200 -100 0 100 200

phi [rad]: 0 1 2 3 4 5 6

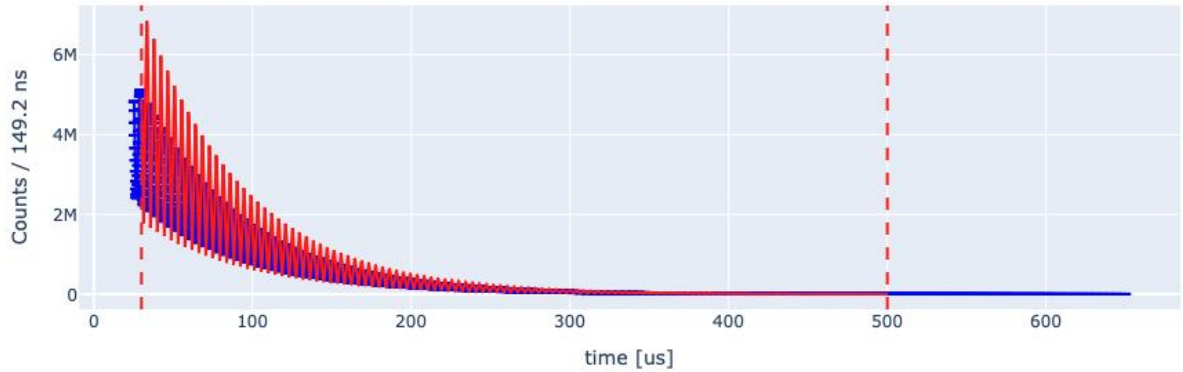
Do the Fit!

Fit Results

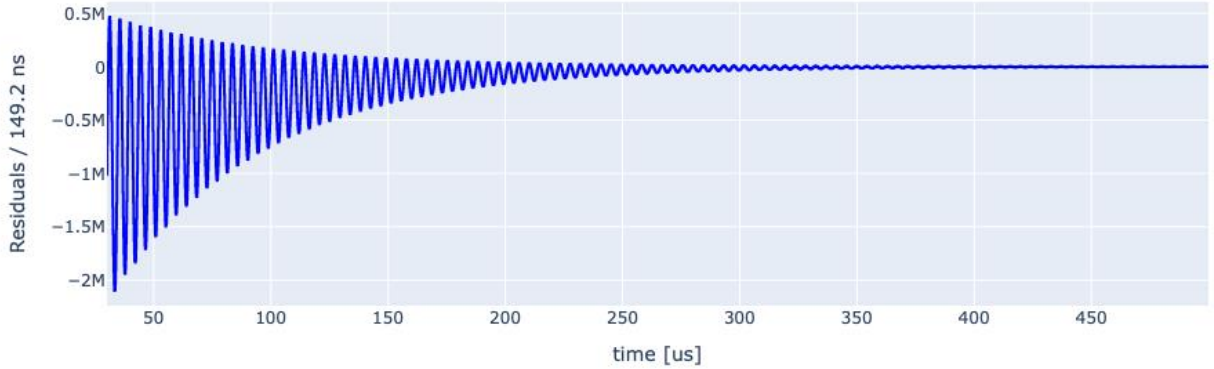
Parameter Name	Value	Unc
chi2	1.54091e+8	
ndf	3145.00	
p-value	0.00000	
N	7.20000e+6	
tau	64.4230	
A	0.600000	
R	-62.8308	
phi	2.16682	

Interactive Wiggle Fit

Wiggle plot



Residuals = Data - Fit



Combining Results & Interpretation

Task 3

Calculation of g-2

- Provide few different datasets for task 2

$$\underbrace{\omega_s - \omega_c}_{\omega_a} = \underbrace{\frac{g_\mu - 2}{2}}_{a_\mu} \frac{e}{m_\mu} B$$

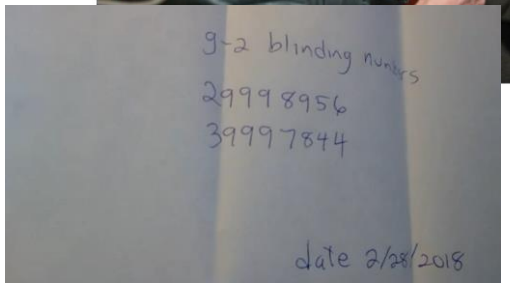
- Compare results for ω_a of different groups for same dataset
  - up to 19 different analysis in Muon g-2 to extract ω_a
  - estimate uncertainty

- Provide magnetic field values per dataset
  → calculate g-2 per dataset

- Combine values from different datasets

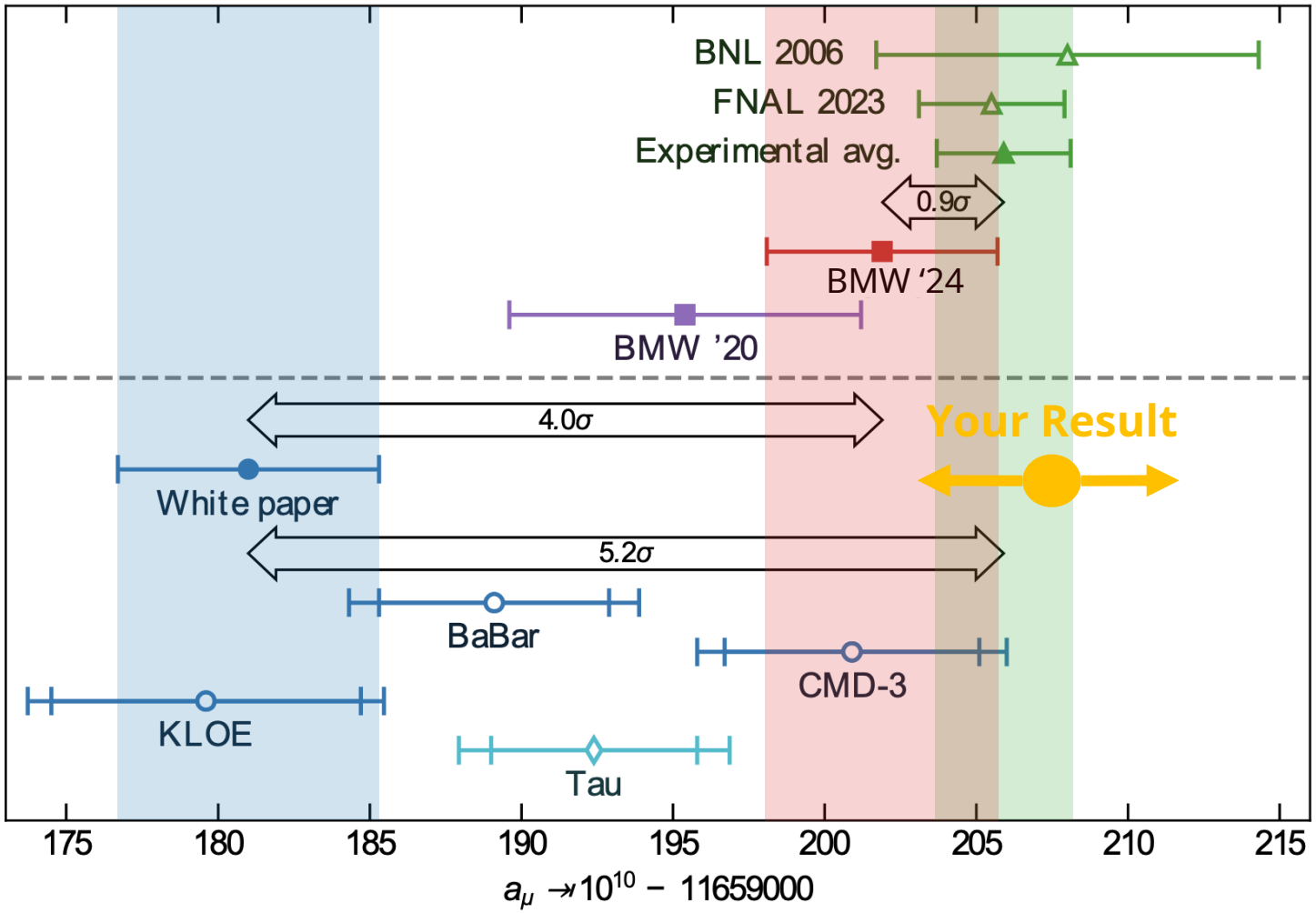
- Unblinding: time given in clock ticks

The 40 MHz clock was really set to:
39 997 844 MHz



Compare to Theory Prediction

M. Hoferichter, Workshop of TI, Sep 2024 @KEK



Muon g-2 Puzzle

tension between theory (white paper) and experiment

New muon g-2 Puzzle

Inconsistency between

- lattice and data-driven approach
- different e^+e^- experiments

Experiment

→ improve statistics & systematics of measurement

Timeline

- Idea presented to collaboration at last Collaboration meeting
  - very positive feedback
- Prototype interactive wiggle fit & event reconstruction
  - running in web-browser (python web-application)
- Two meetings with FNAL education section
  - very helpful feedback on tools and concept

- Outlook:
  - Prepare introduction material
  - Improve event reconstruction tool (calibration factors, speed)
  - Prepare additional datasets
  - Test muon lifetime extraction
  - Test with few first semester students and other Masterclasses tutors in Mainz in January

Thank you for your attention

Summer Collaboration meeting at University of Liverpool July 24-28, 2023

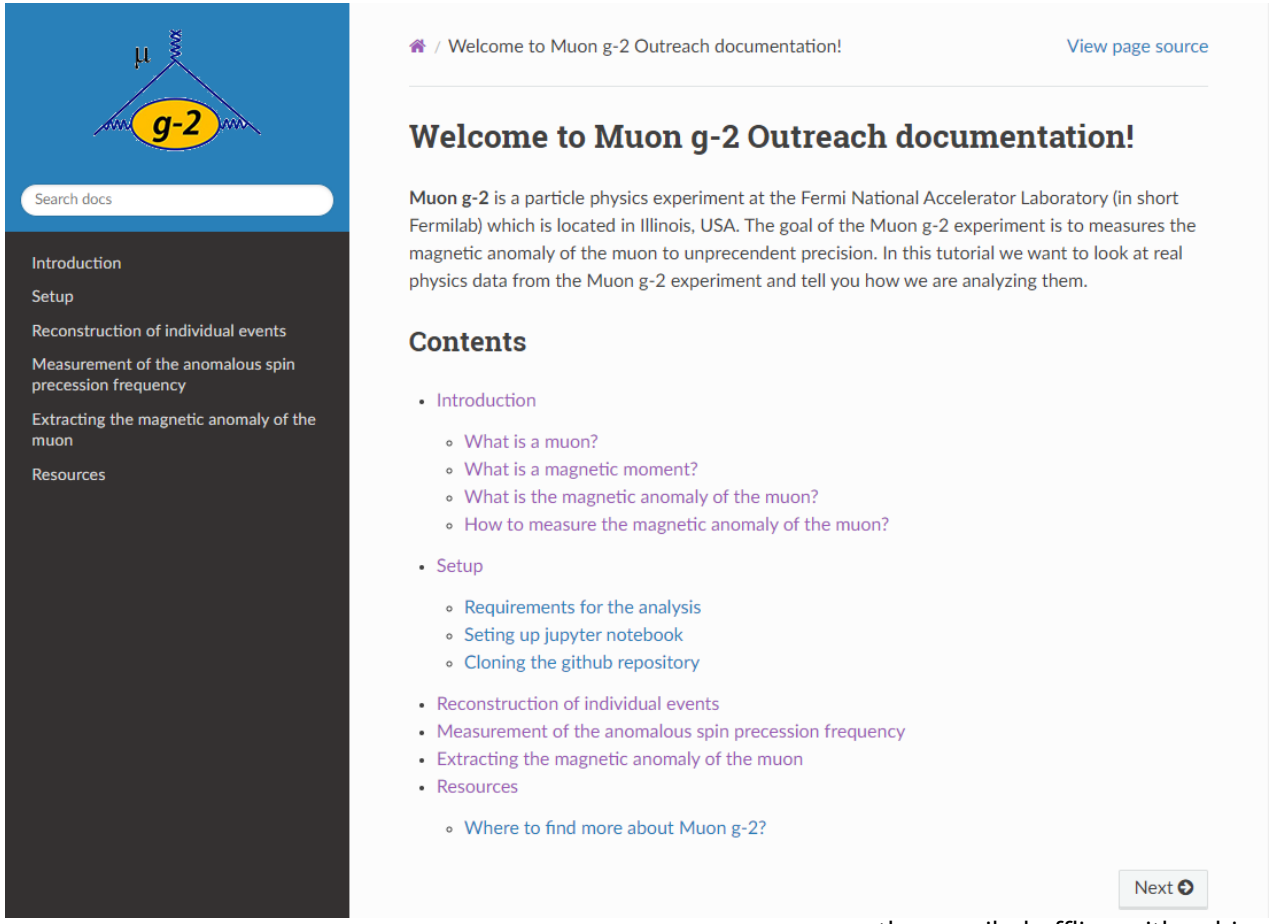
Backup

Analysis Tasks

1. **Extract time and energy from calo hits** — Event reconstruction
   - classification of pile-up / no pile-up event
   - fit amplitude and position of template
   - Dataset: ~100 events at most
   - Estimate muon lifetime — Main Task: ω_a extraction
2. **Fit wiggle plot with 5-parameter fit**
   - dataset: one run 3 letter datasets per group
   - optional: change start/stop time to estimate systematic impact
3. **Combine results from 5-parameter fit of different letter datasets**
   - magnetic field per data-set to combined result — Bonus: group experience
   - calculate weighted mean
   - unblinding factor

Online Format – Read the Docs

- Online tutorial page
- Write documentation so students can perform analysis themselves
- Setting tutorial up in gm2outreach using reStructuredText and sphinx
- ReadTheDocs can automatically generate and publish documentation from GitHub repositories online



currently compiled offline with sphinx

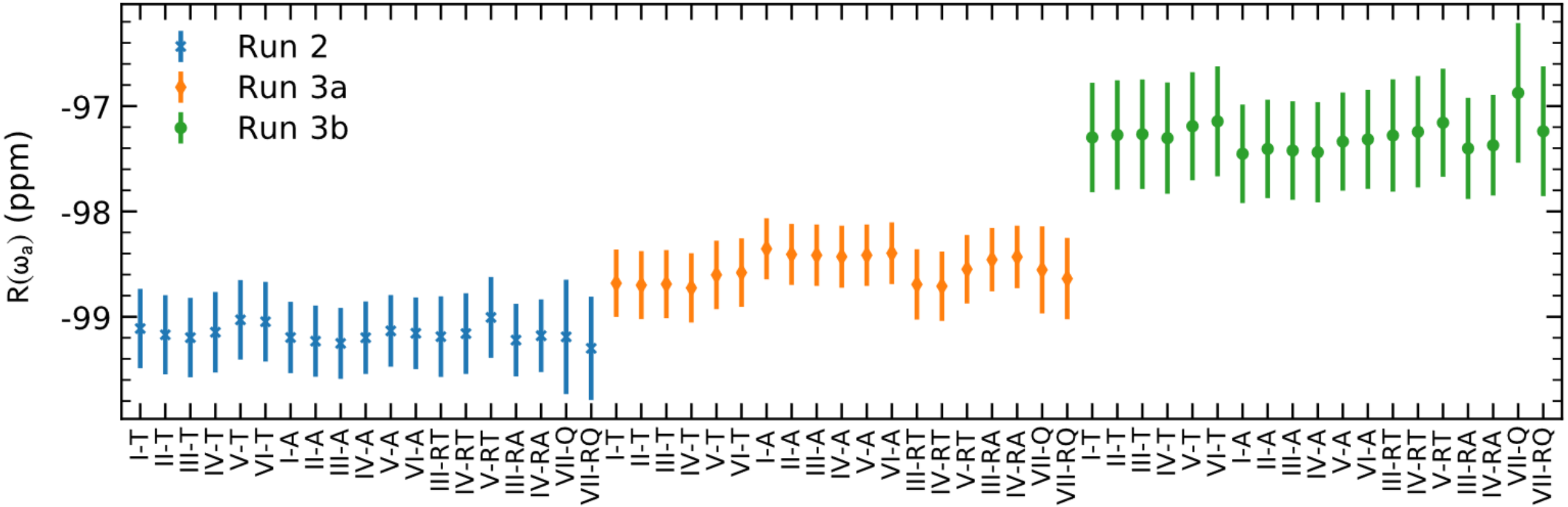
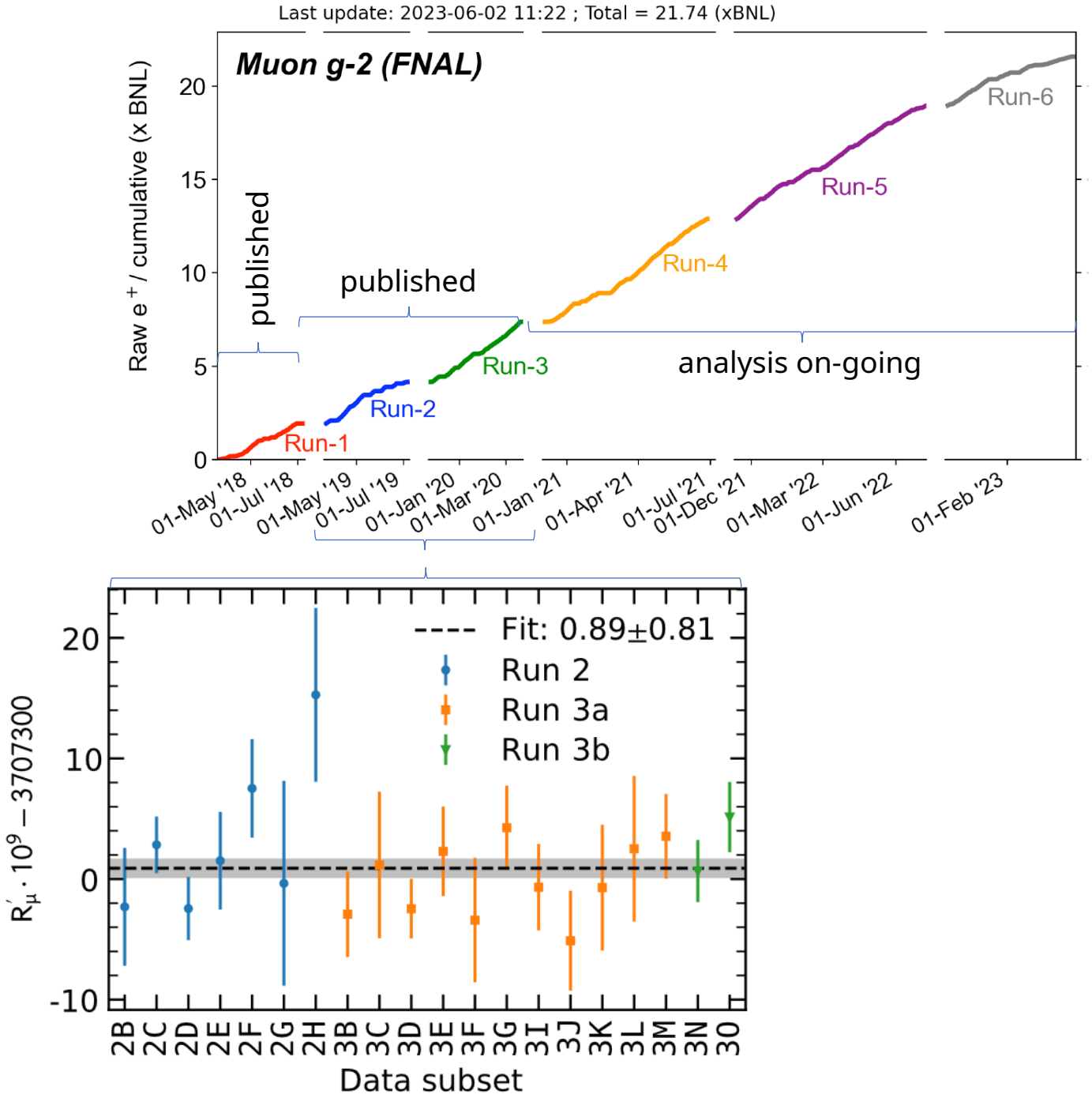


FIG. 8. Plot of the results for the 19 analyses of the three different datasets. Note the muon-weighted magnetic field (Sec. VI F) and beam dynamics corrections (Sec. V) are different for the three datasets. The plotted uncertainties are the statistical uncertainties from the multiparameter fits to the associated time distributions. The allowed statistical and systematic differences between the results for a given dataset are discussed in Sec. IV H.

Datasets


Last update: 2023-06-02 11:22 ; Total = 21.74 (xBNL)
Muon g-2 (FNAL)
Raw e+ / cumulative (x BNL)
published
published
analysis on-going
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23
Fit: 0.89±0.81
Run 2
Run 3a
Run 3b
$R'_\mu \cdot 10^9 - 3707300$
Data subset
2B
2C
2D
2E
2F
2G
2H
3B
3C
3D
3E
3F
3G
3I
3J
3K
3L
3M
3N
3O