Measurement of the Muon Magnetic Anomaly to 0.20 ppm by the Muon $g-2$ experiment at Fermilab

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ON BEHALF OF THE MUON $g-2$ COLLABORATION

UNIVERSITY OF PISA, INFN PISA

17TH INTERNATIONAL WORKSHOP ON TAU LEPTON PHYSICS

LOUISVILLE, KY – 12/05/2023

FERMILAB-SLIDES-23-397-V

IN SUPREMÆ DIGNITATIS 1343

UNIVERSITÀ DI PISA

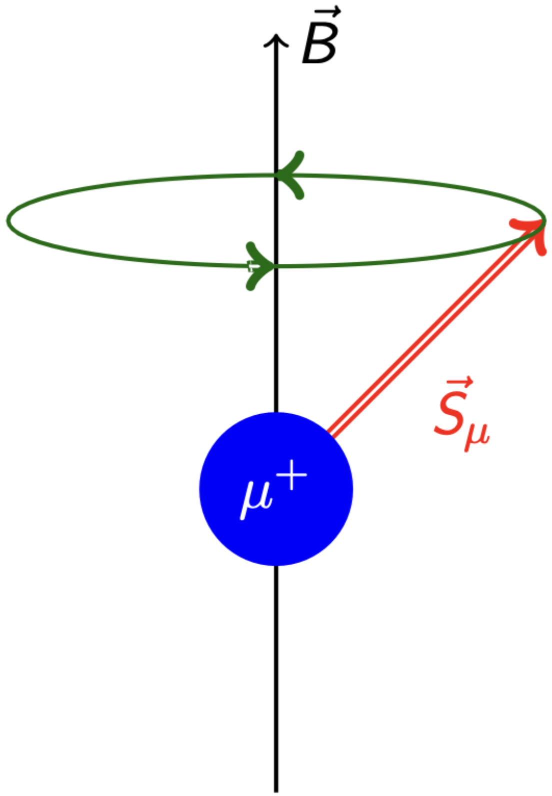
INFN Istituto Nazionale di Fisica Nucleare

Fermilab

τ2023

The anomalous magnetic moment

- Particle with spin in a magnetic B-field: $\vec{\mu} \equiv g \frac{e}{2m} \vec{S}$
- Torque in B-field: $\tau = \vec{\mu} \times \vec{B}$ Energy in B-field: U$= -\vec{\mu} \cdot \vec{B}$
- Classical mechanics prediction: $g = 1$
- Dirac's prediction for spin-1/2 elementary particles: $g = 2$
- Radiative corrections in Quantum Field Theories: $g \neq 2$
- Kusch and Foley's measurement, Schwinger's prediction (1948, electron $g_e - 2$):

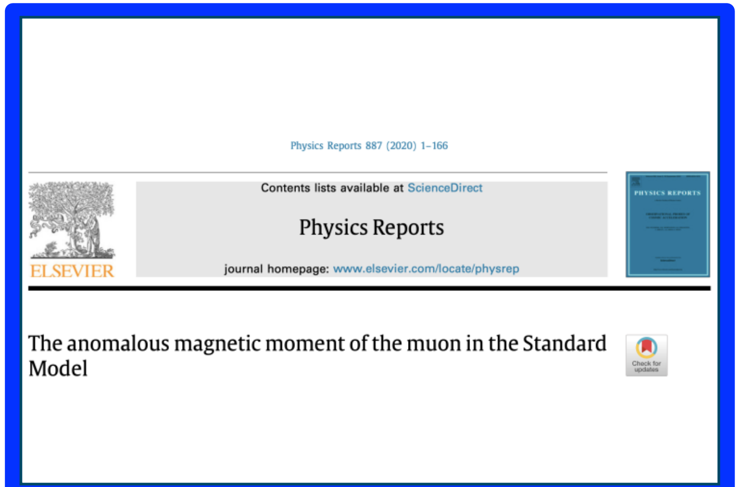


$$\frac{g_e - 2}{2} \equiv a_e \approx 0.00116$$

1^{st} order universal QED term: $\frac{\alpha}{2\pi}$

Outline

Theory Initiative White Paper 2020


Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

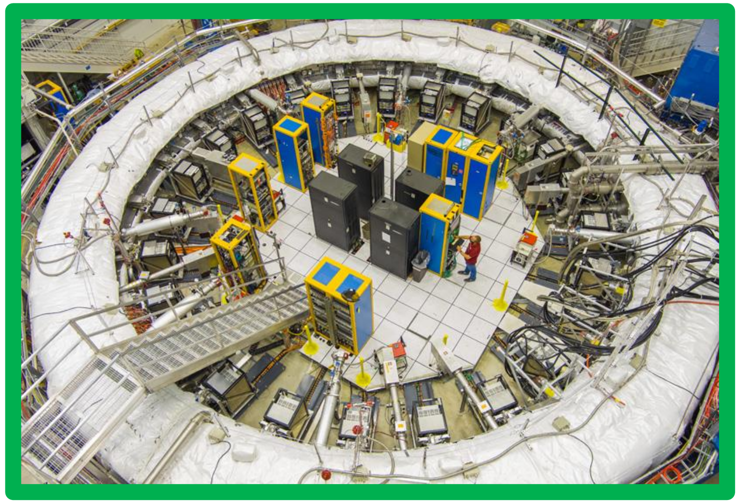
Physics Reports

journal homepage: www.elsevier.com/locate/physrep

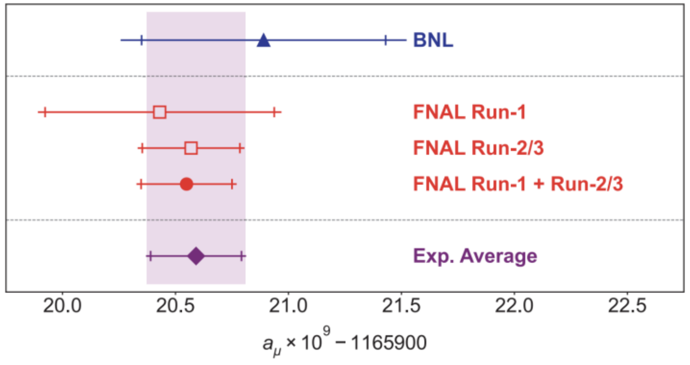
ELSEVIER

The anomalous magnetic moment of the muon in the Standard Model

2021 Run-1 results at Fermilab



Run-2/3 upgrades and 2023 results



Puzzles, prospects and outlook

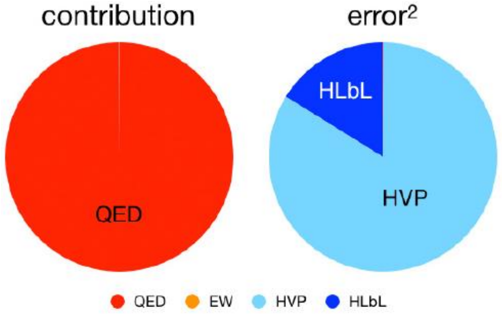
Muon $g-2$ before 2021

- Previous experiment at BNL (early 2000s): discrepancy between 0.54 ppm experimental uncertainty and 0.55 ppm theoretical uncertainty (1 ppm = part per million)

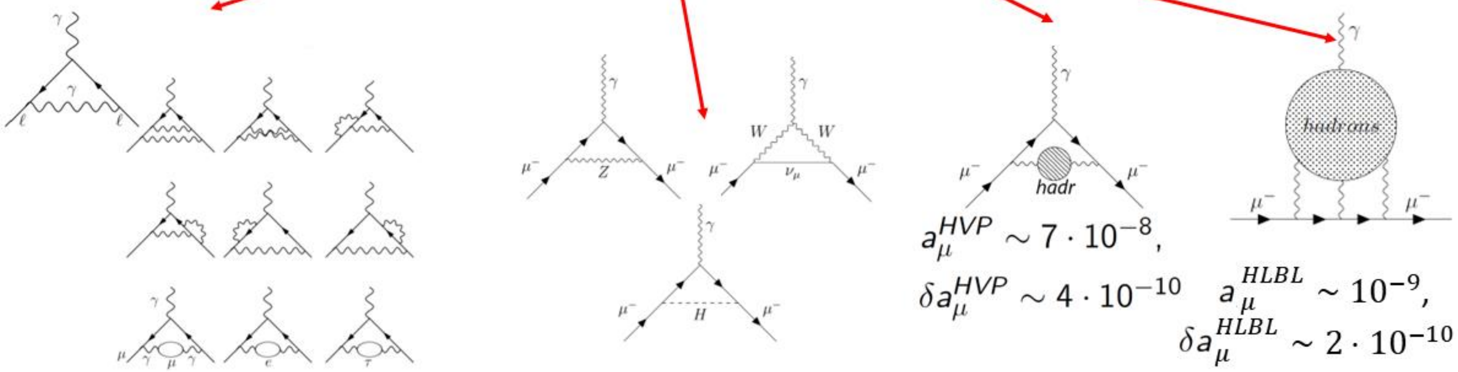
- Muon $g-2$ Theory Initiative: recommended theoretical value in 2020, White Paper (**WP2020**)
  T. Aoyama et al, Phys. Rept. 887 (2020)

- HVP in WP2020 based on e^+e^- hadronic cross section data

- 3.7σ discrepancy between BNL and WP2020 prediction:
  $a_\mu^{BNL} - a_\mu^{WP2020} = 279(76) \times 10^{-11}$



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{hadr}$$



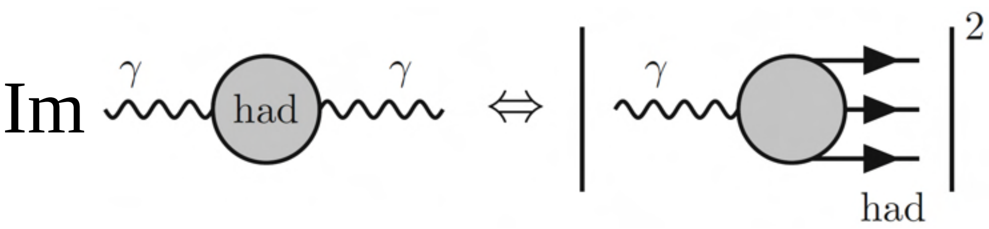
$a_\mu^{HVP} \sim 7 \cdot 10^{-8}$, $\delta a_\mu^{HVP} \sim 4 \cdot 10^{-10}$

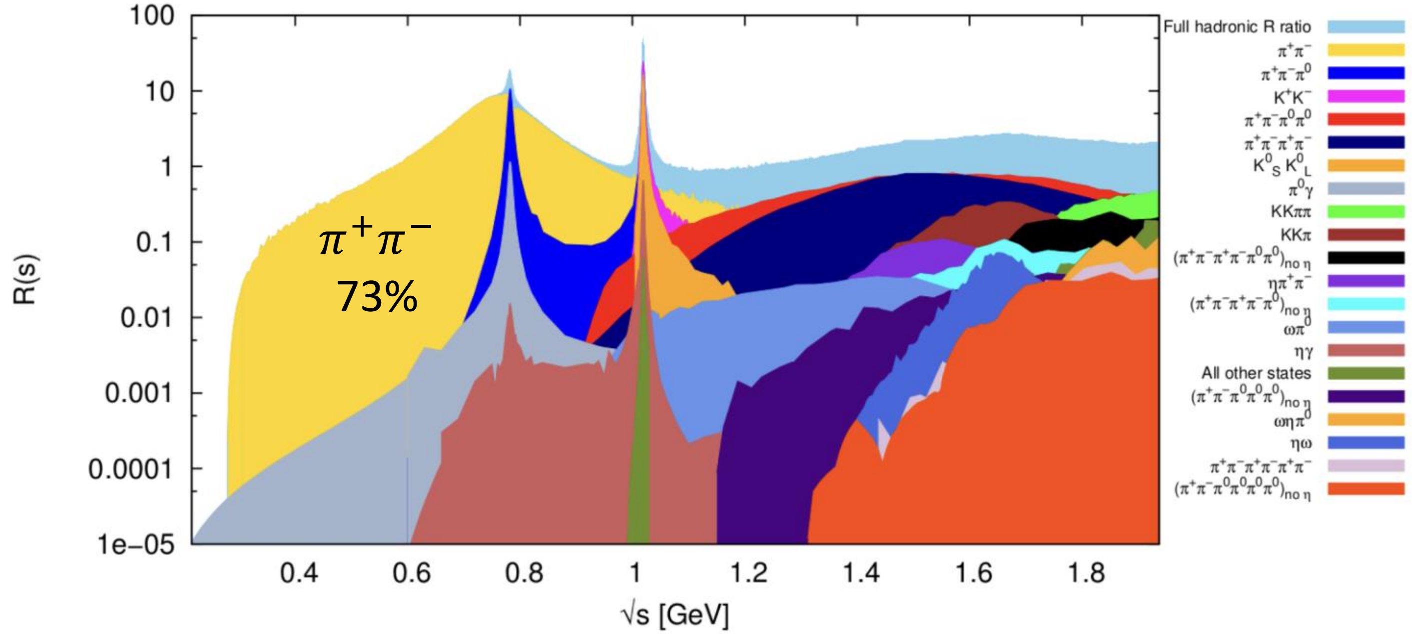
$a_\mu^{HLBL} \sim 10^{-9}$, $\delta a_\mu^{HLBL} \sim 2 \cdot 10^{-10}$

$a_\mu^{QED} \sim 10^{-3}$, $\delta a_\mu^{QED} \sim 10^{-12}$

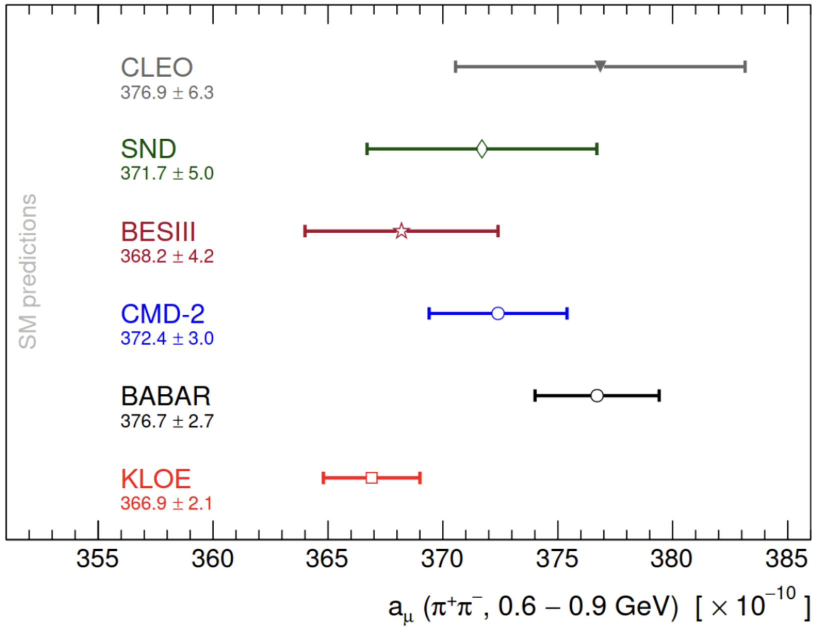
$a_\mu^{EW} \sim 10^{-9}$, $\delta a_\mu^{EW} \sim 10^{-11}$

Dispersive method (e^+e^-) for HVP

- Optical theorem:  $a_\mu^{HVP-LO} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$
- $R(s)$ is data-driven hadronic R-Ratio
- See talk today by K. Maltman
- 20+ years of e^+e^- experiments: CMD-2, SND, KLOE, BaBar, BESIII, CLEO-C included in WP2020



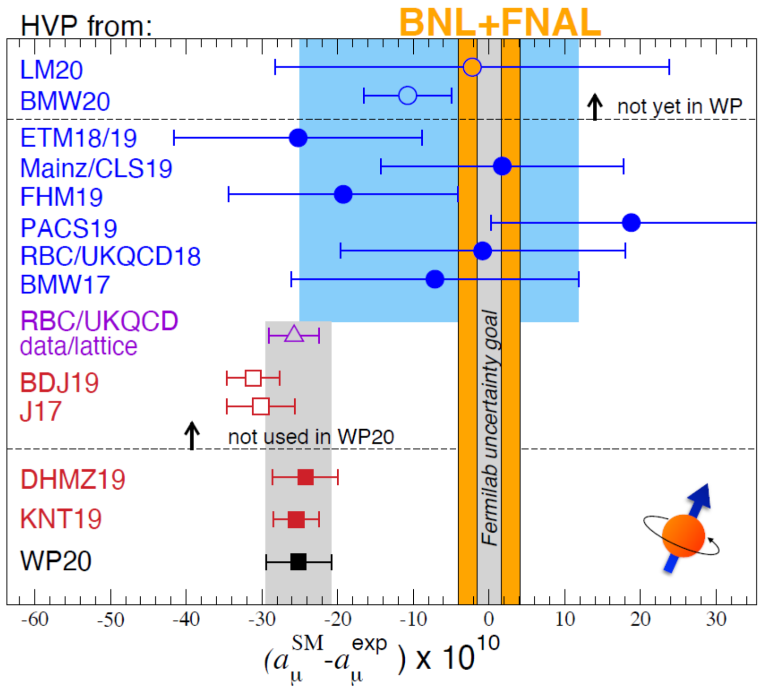
A. Keshavarzi et al, Phys Rev. D 97.11 (2018)



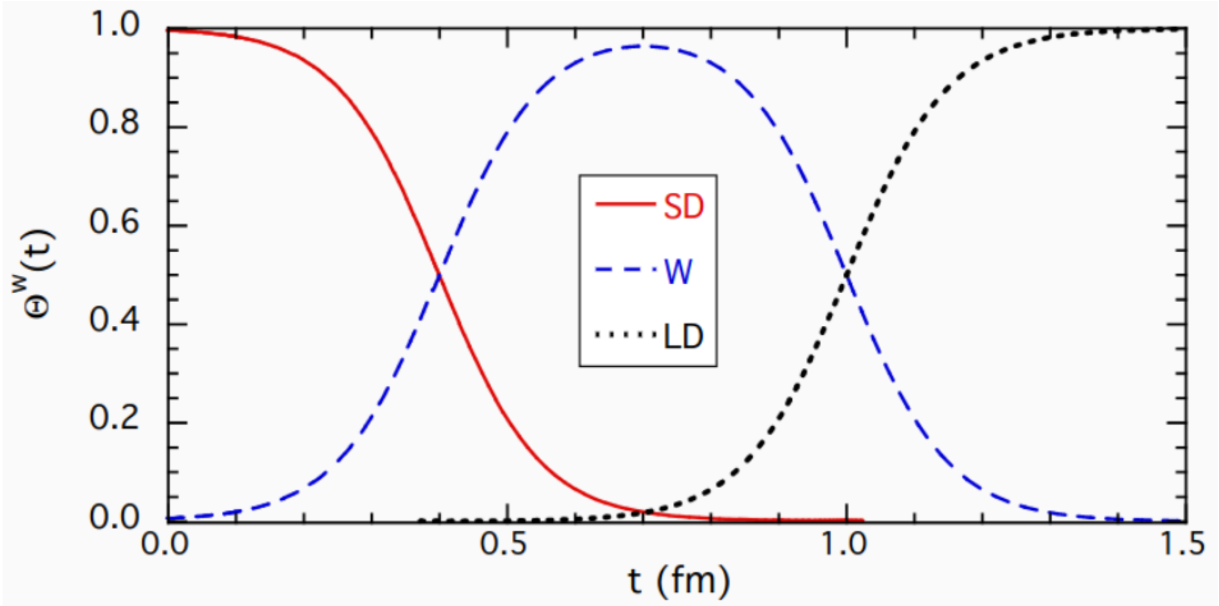
M. Davier et al, Eur. Phys. J. C 80 (2020)

Lattice QCD method for HVP

- Ab-initio calculation of HVP from first principles, approximation of discrete space-time
- After WP2020: BMW collaboration published first sub-percent uncertainty
- See talk on Friday by S. Kuberski

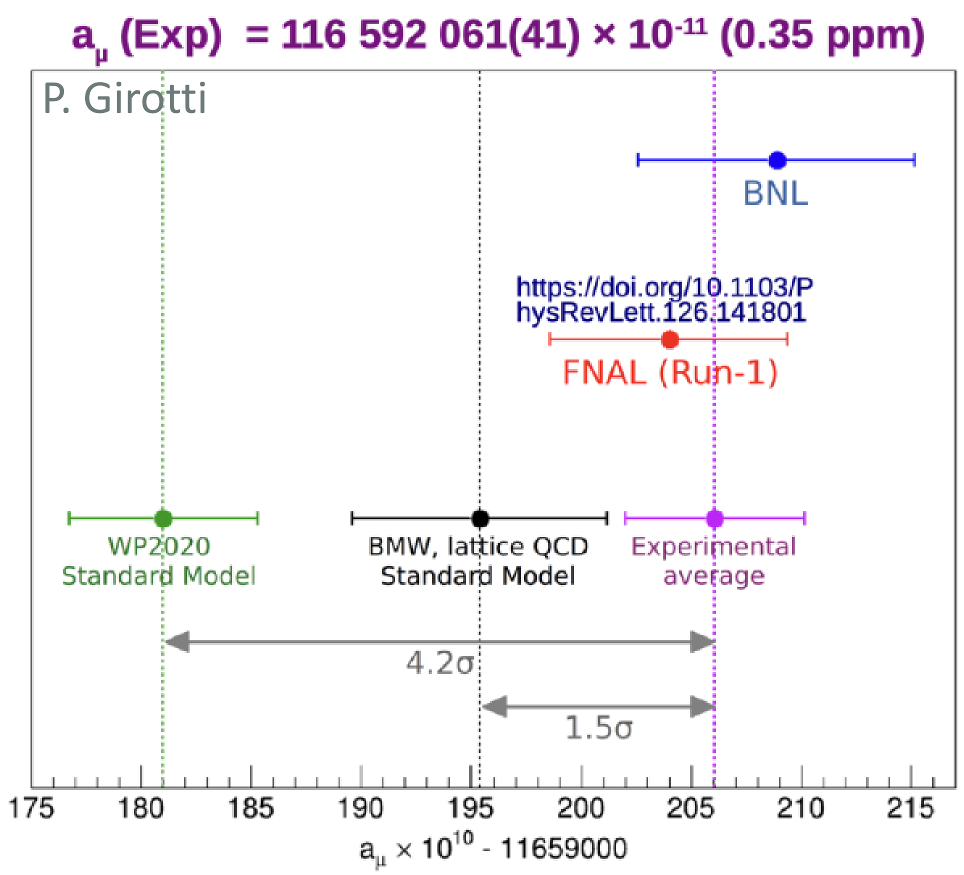


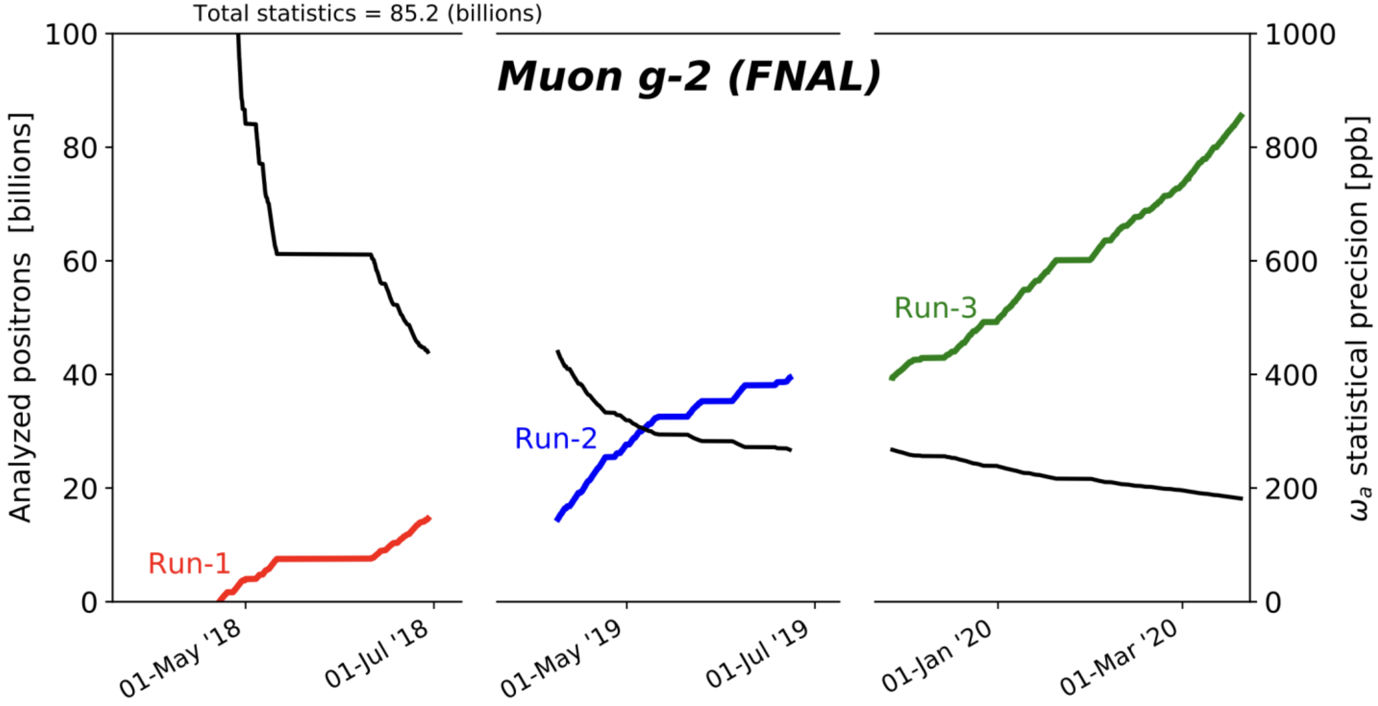
G. Colangelo et al, arxiv:2203.15810 (2022)



Window observables: excellent agreement in the intermediate window

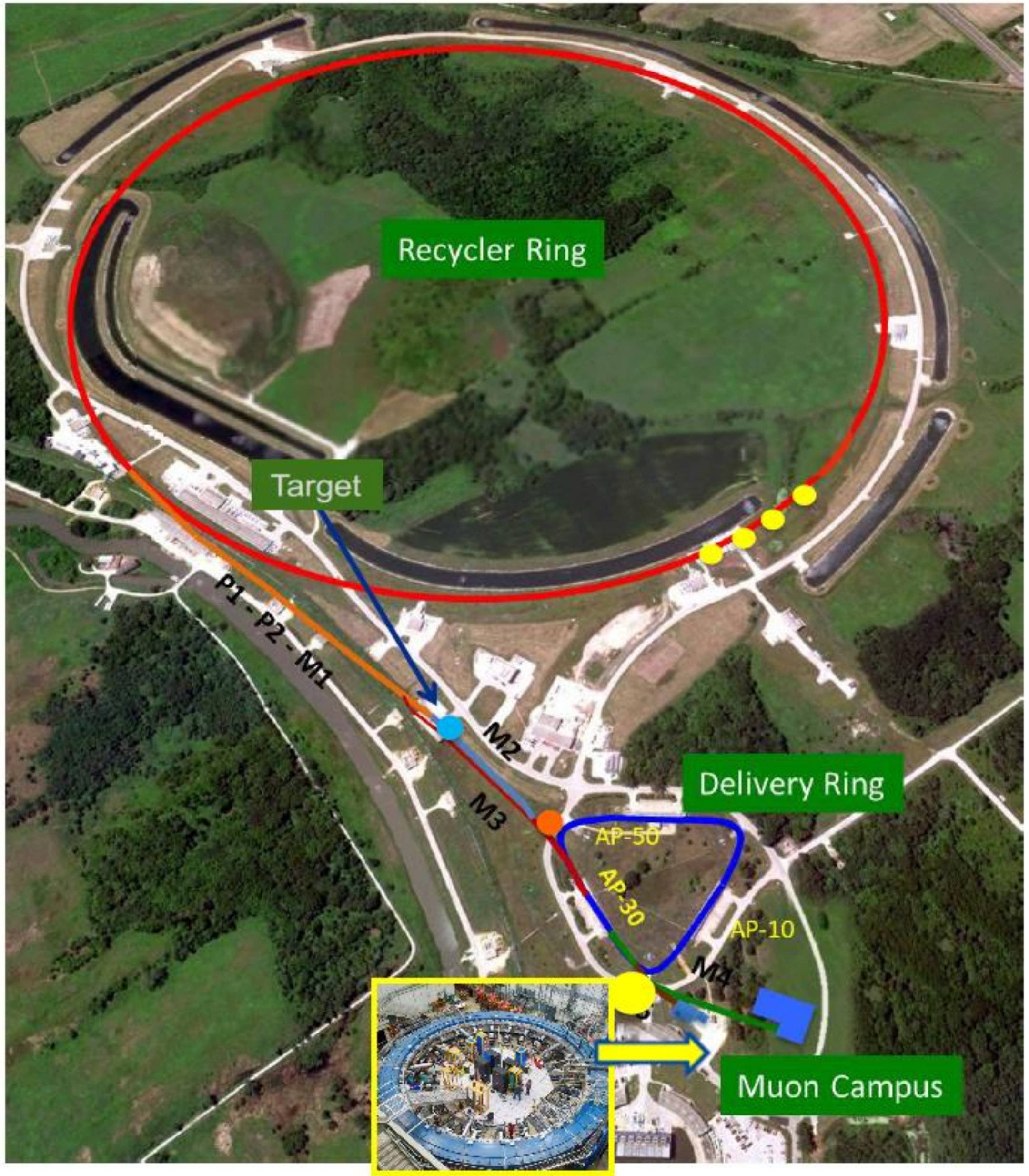
Muon $g-2$ result in 2021 (Run-1, 2018 data)



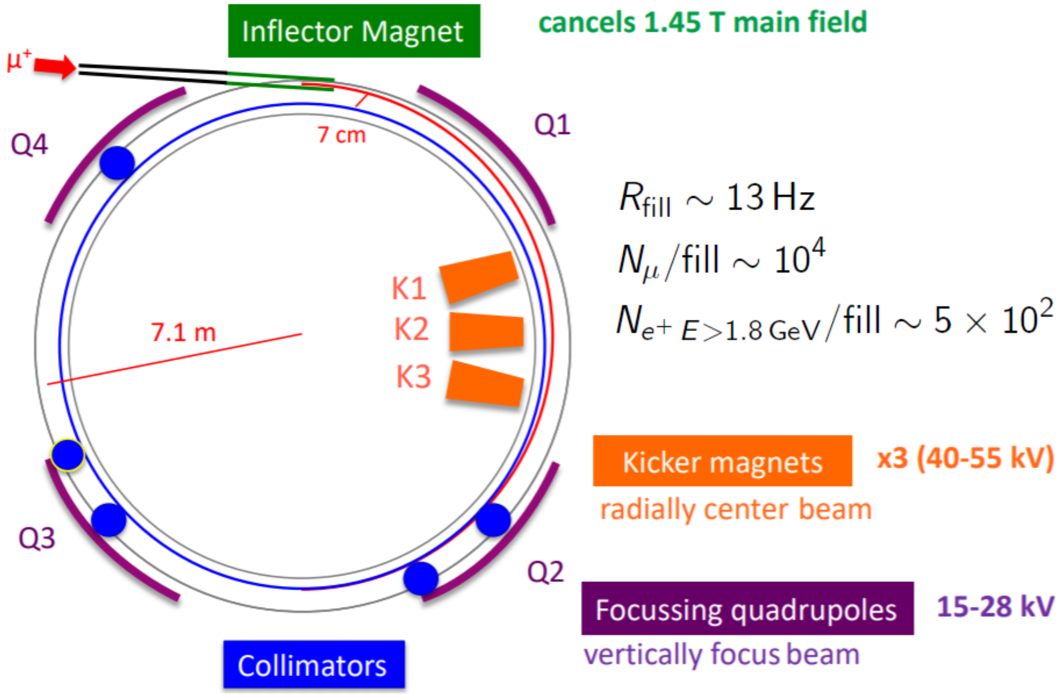


Run-1 uncertainties	Parts per billion [ppb]
Statistical	434
Systematic	157
Total	462

Fermilab accelerator complex: muon beam



- 8 GeV protons collide on target and produce pions
- Pions decay into muons along ~ 2 km in Delivery Ring
- Muons are injected in 7 m radius ring



$R_{\text{fill}} \sim 13\,\text{Hz}$

$N_\mu/\text{fill} \sim 10^4$

$N_{e^+\,E>1.8\,\text{GeV}}/\text{fill} \sim 5 \times 10^2$

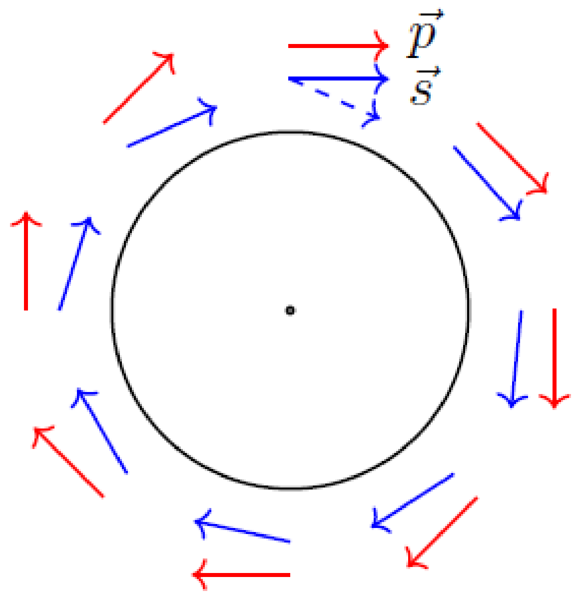
Anomalous precession in B-field

$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c \neq 0$: spin precesses with respect to momentum

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

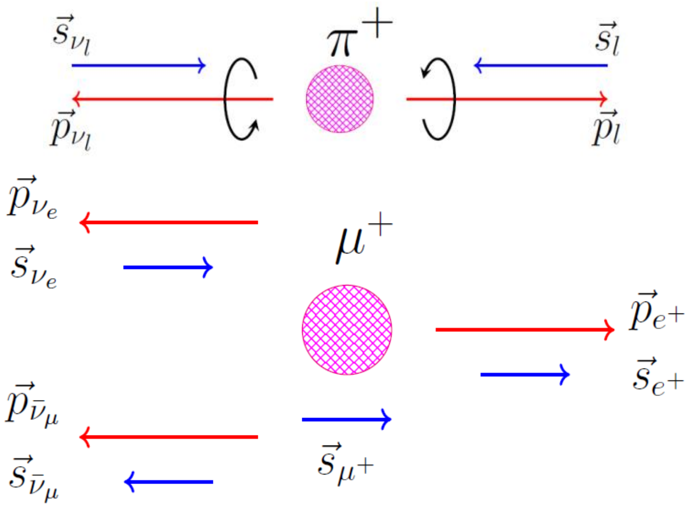
$$\vec{\beta} \cdot \vec{B} = 0$$

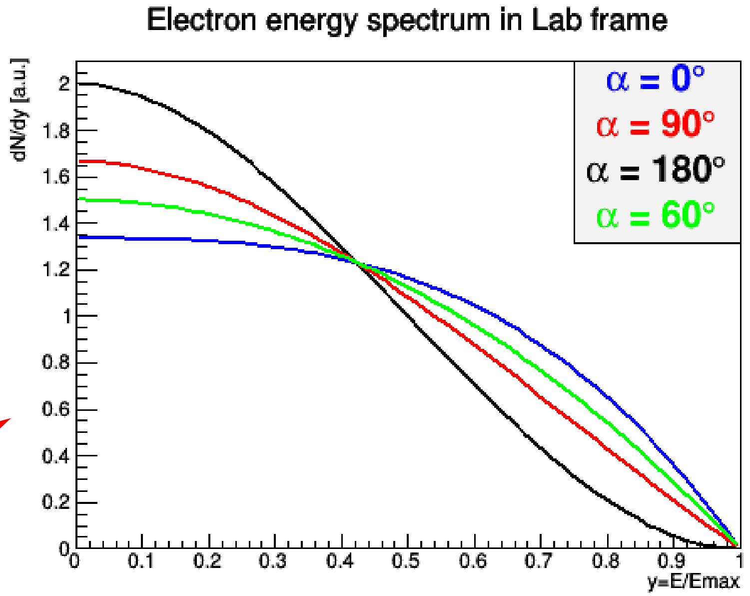
- $\vec{E}$ from electrostatic quadrupoles
- Relativistic boost of $\gamma = 29.3$
- 3.1 GeV/c «magic momentum»
- Red term is cancelled

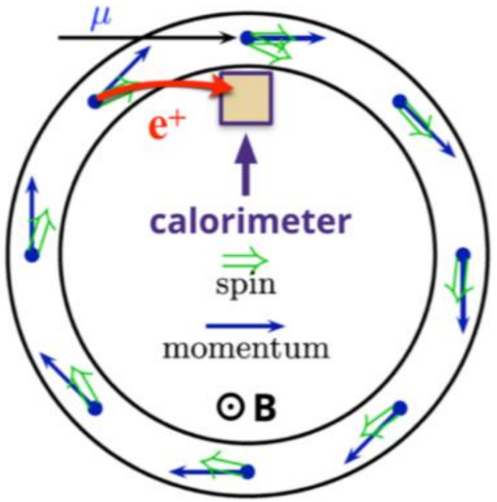


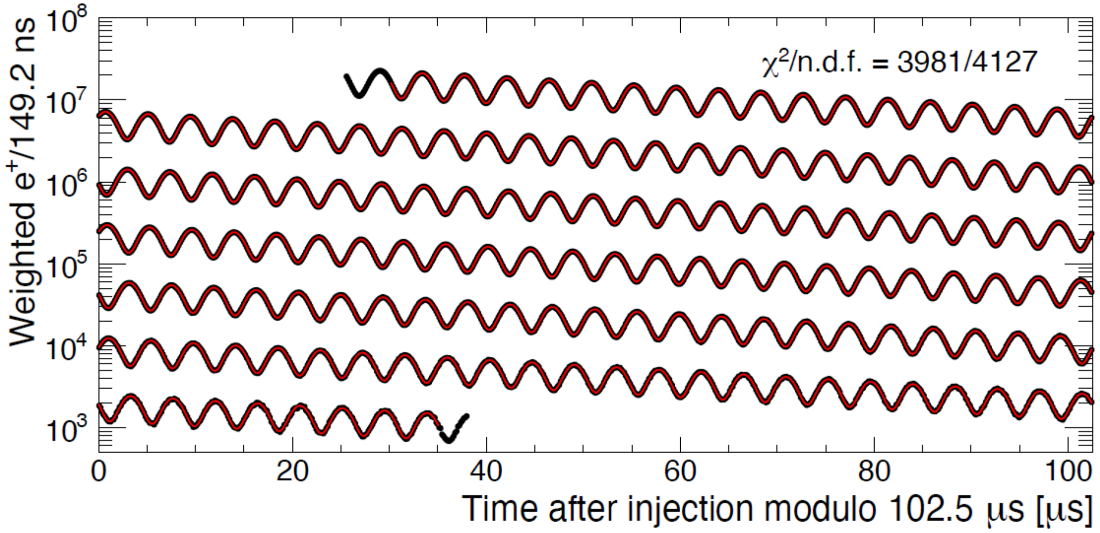
$$\vec{\omega}_a = -\frac{e}{mc} a_\mu \vec{B}$$

Principle of ω_a measurement



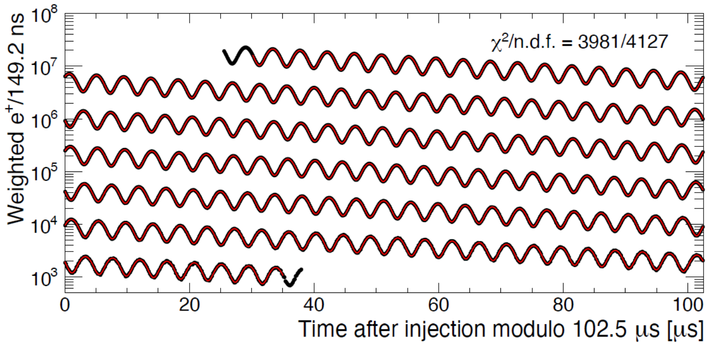


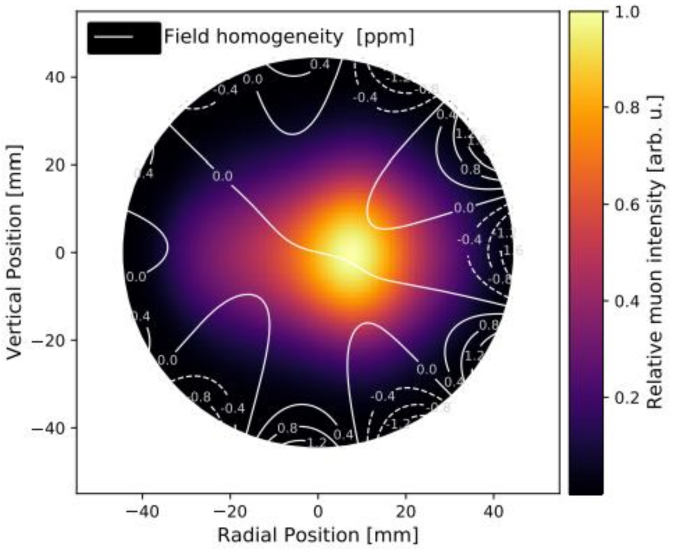




1. Weak decay violates parity
2. e⁺ spectrum depends on ω_a phase
3. Count high-energy e⁺ over time (muons have lifetime of ~ 64μs, we measure for 700μs)

Master formula for a_μ





$$a_\mu = \frac{\omega_a}{\omega_p} \times \frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

External factors, known to 25 ppb

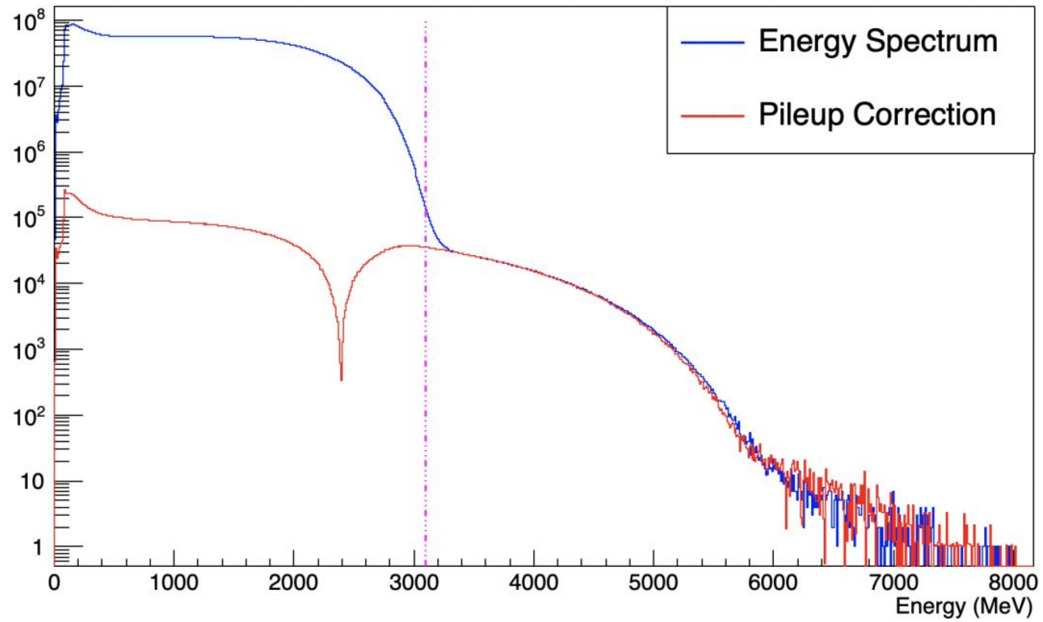
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \times$$ corrections for effects that

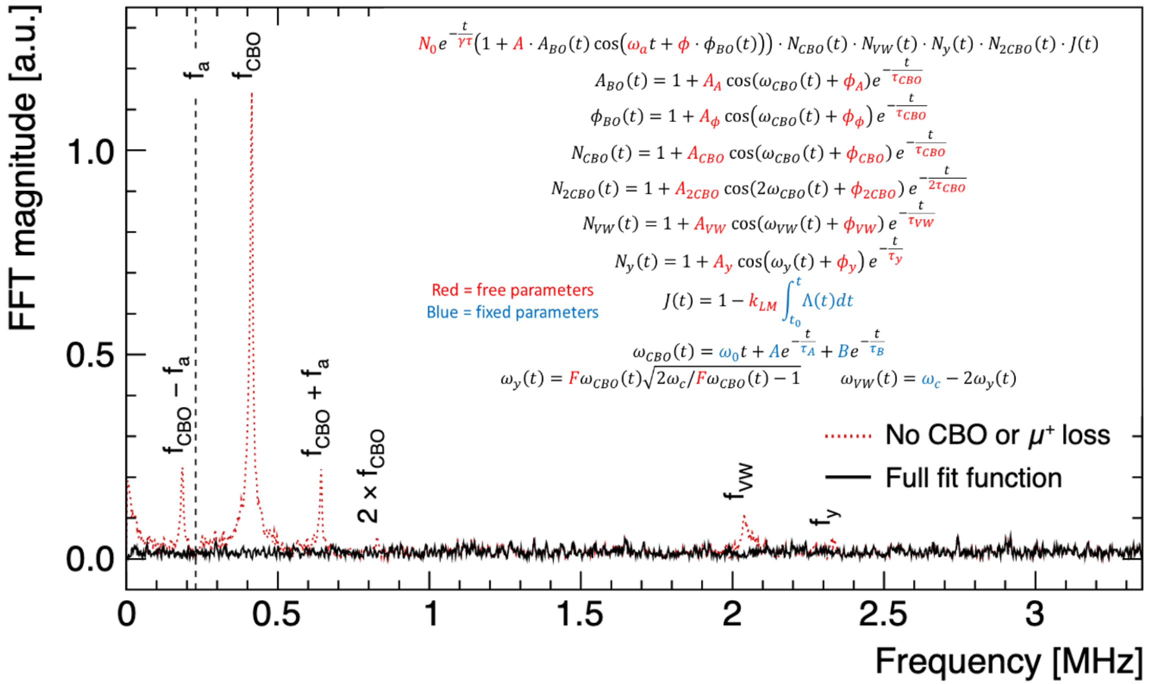
- Make spin precess slower (E-field, vertical motion)
- Make phase change within 700μs
- Induce transient magnetic fields

Measured, **blinded** ratio

ω_a analysis in a nutshell

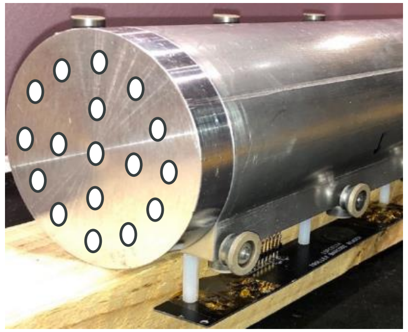
1. Count positrons and subtract pileup



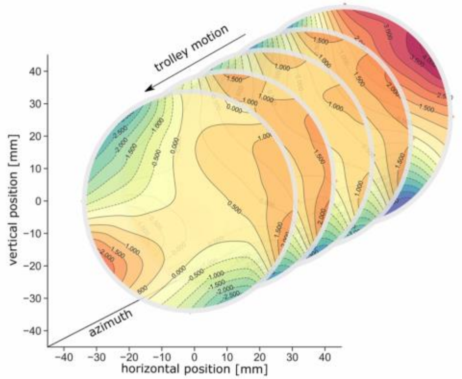


2. Fit wiggle plots with many parameters to account for beam dynamics effects

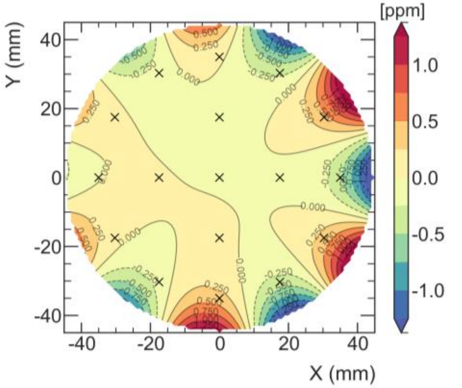
ω_p (field) analysis in a nutshell



17 petroleum jelly NMR probes

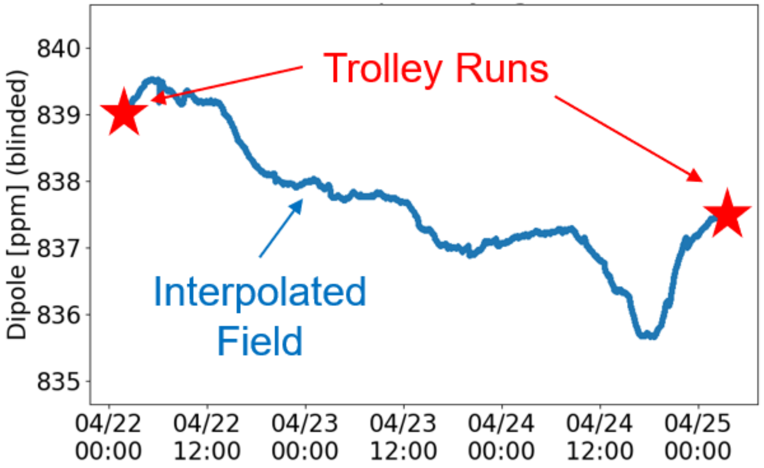


2D field maps (~8000 points)



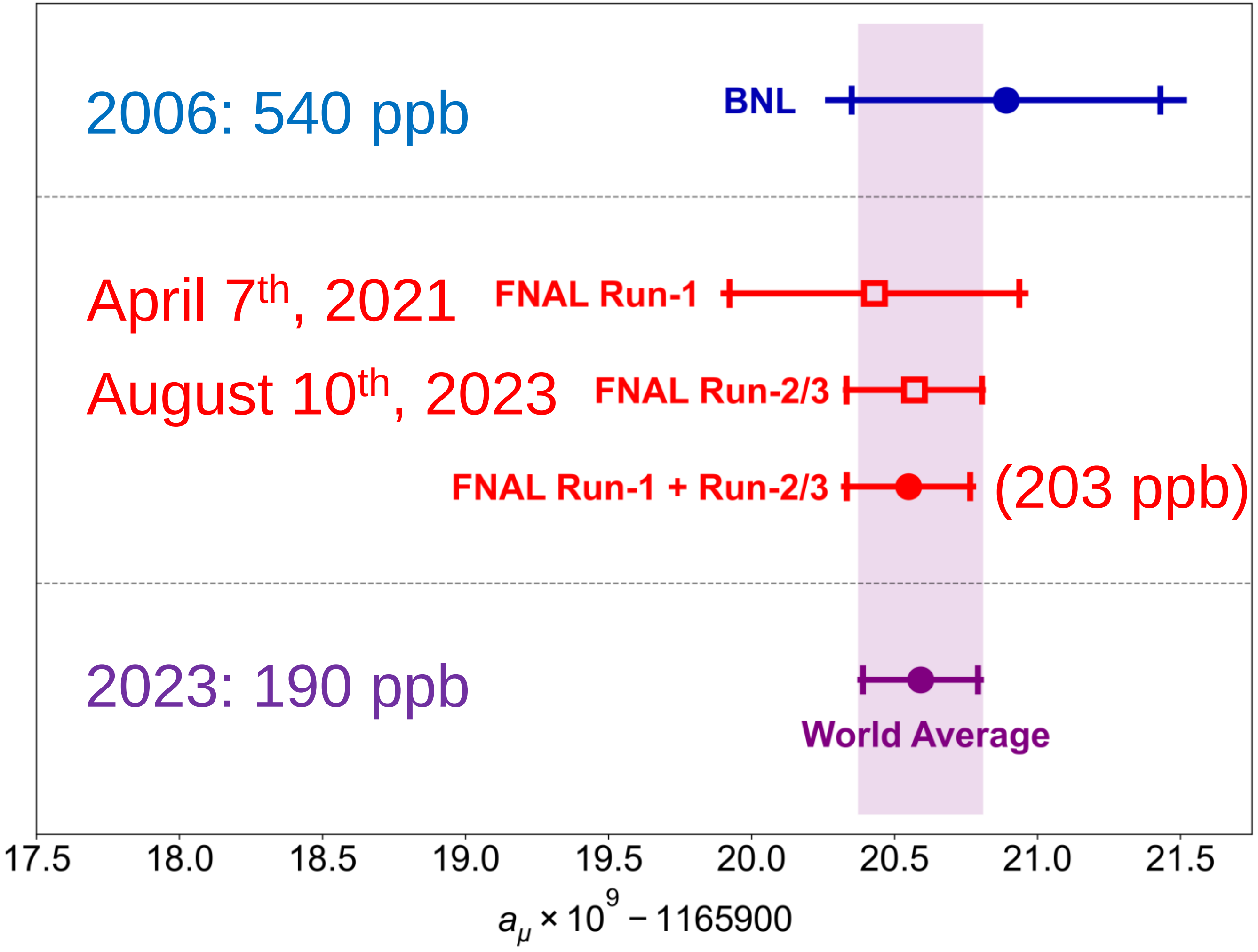
Azimuthally-Averaged **Variation < 1 ppm**

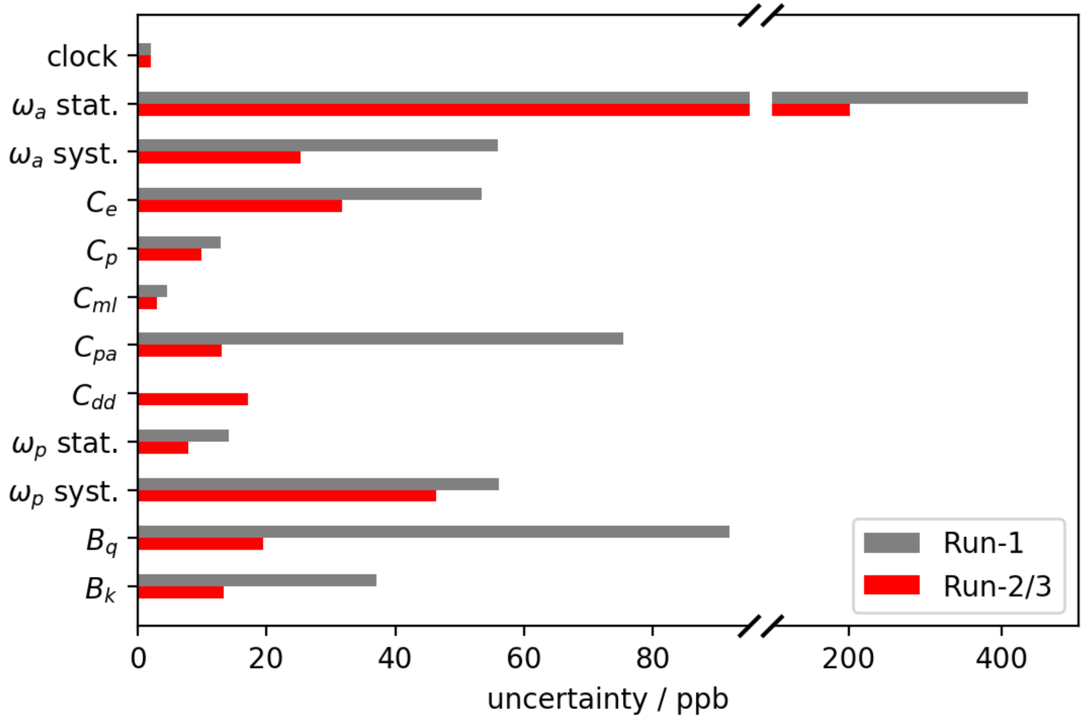
Nuclear Magnetic Resonance (NMR) probes: placed on trolley for special runs, every 2 or 3 days between muon fills



378 fixed NMR probes monitor field during muon storage at 72 azimuthal locations

Run-2/3 Result: FNAL + BNL Combination





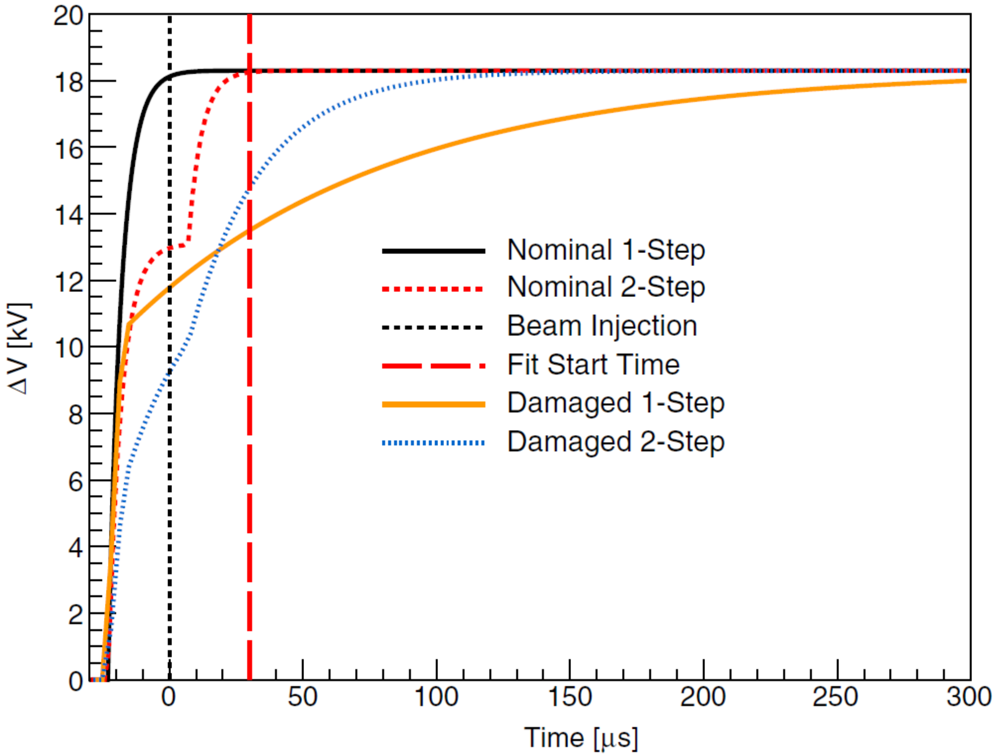
- Hardware improvements
- More studies (CBO systematics, pileup reconstruction, …)

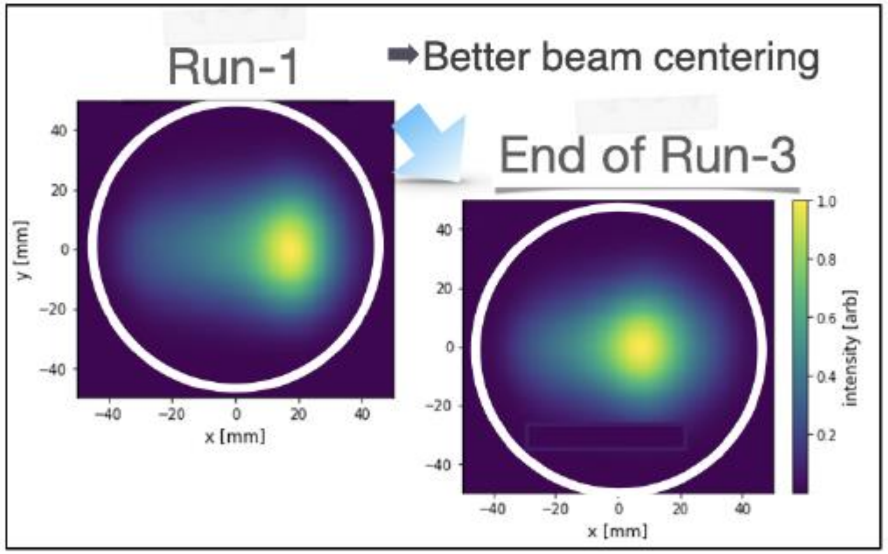
Run-2/3 hardware improvements

- Fixed 2 out of 32 quadrupole resistors that strongly affected beam dynamics

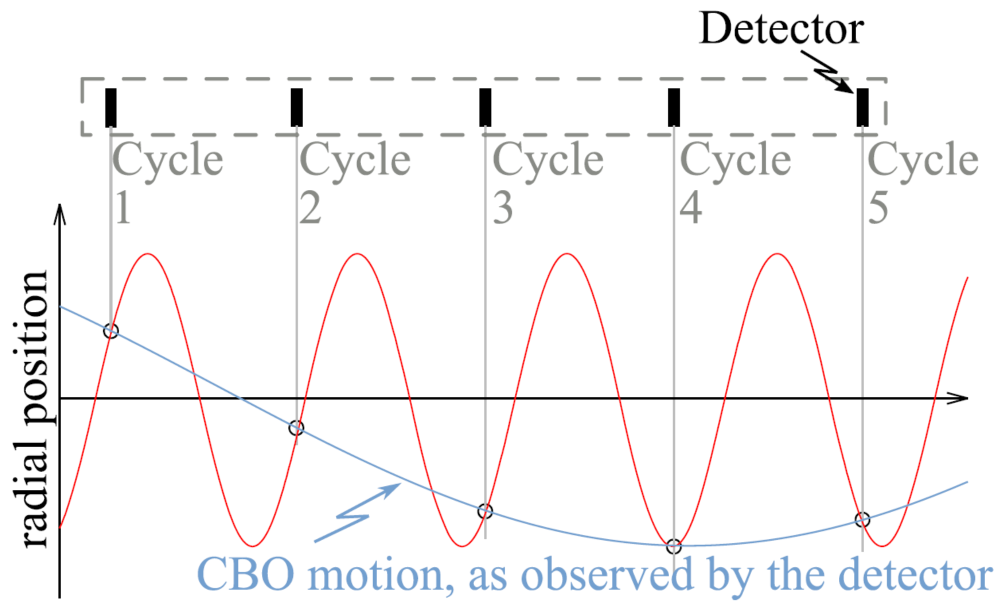
- Added thermal blanket to ring

- Replaced kicker cables for optimal kick

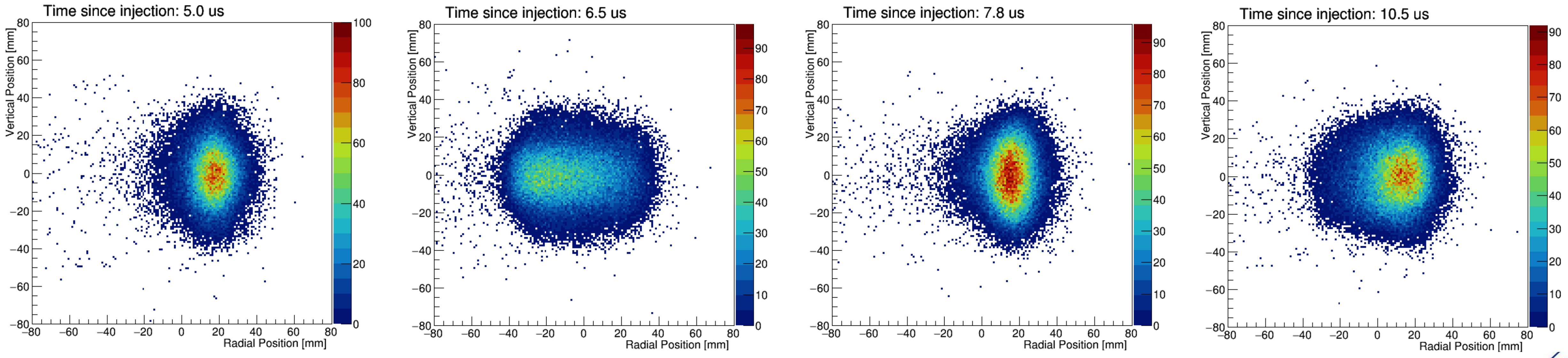




Coherent Betatron Oscillations (CBO)

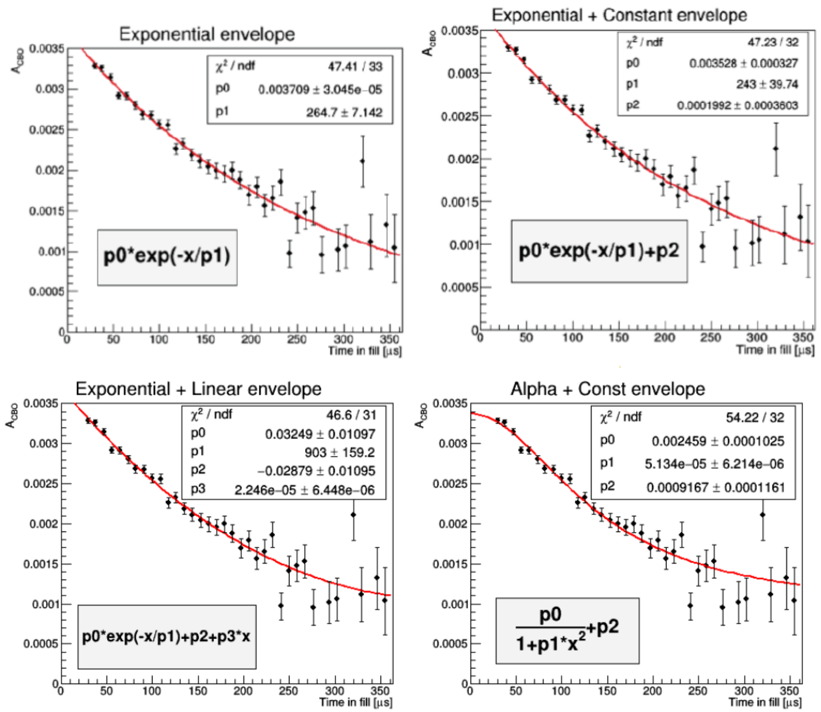


O. Kim et al, New J. Phys. 22, 063002 (2020)



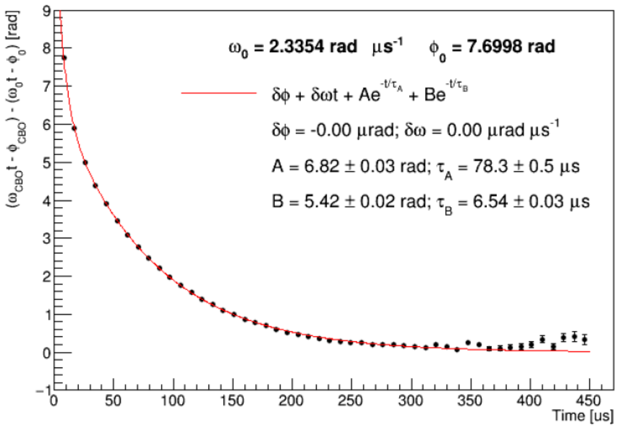
CBO systematics: more studies

More statistics
→more models tested
→reduced systematic

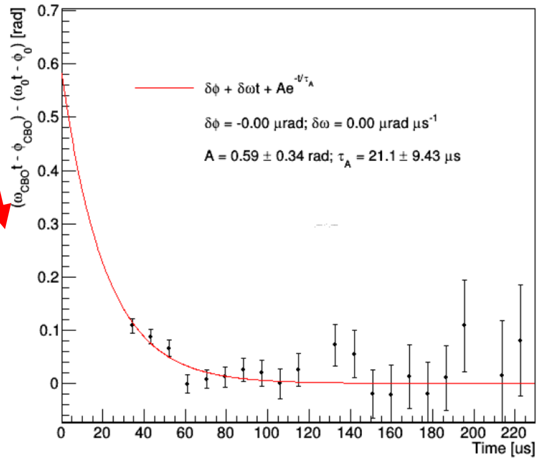


From Run-1 to Run-2/3: fixed bad resistors + Stronger kick
→more stable beam dynamics

Run-1



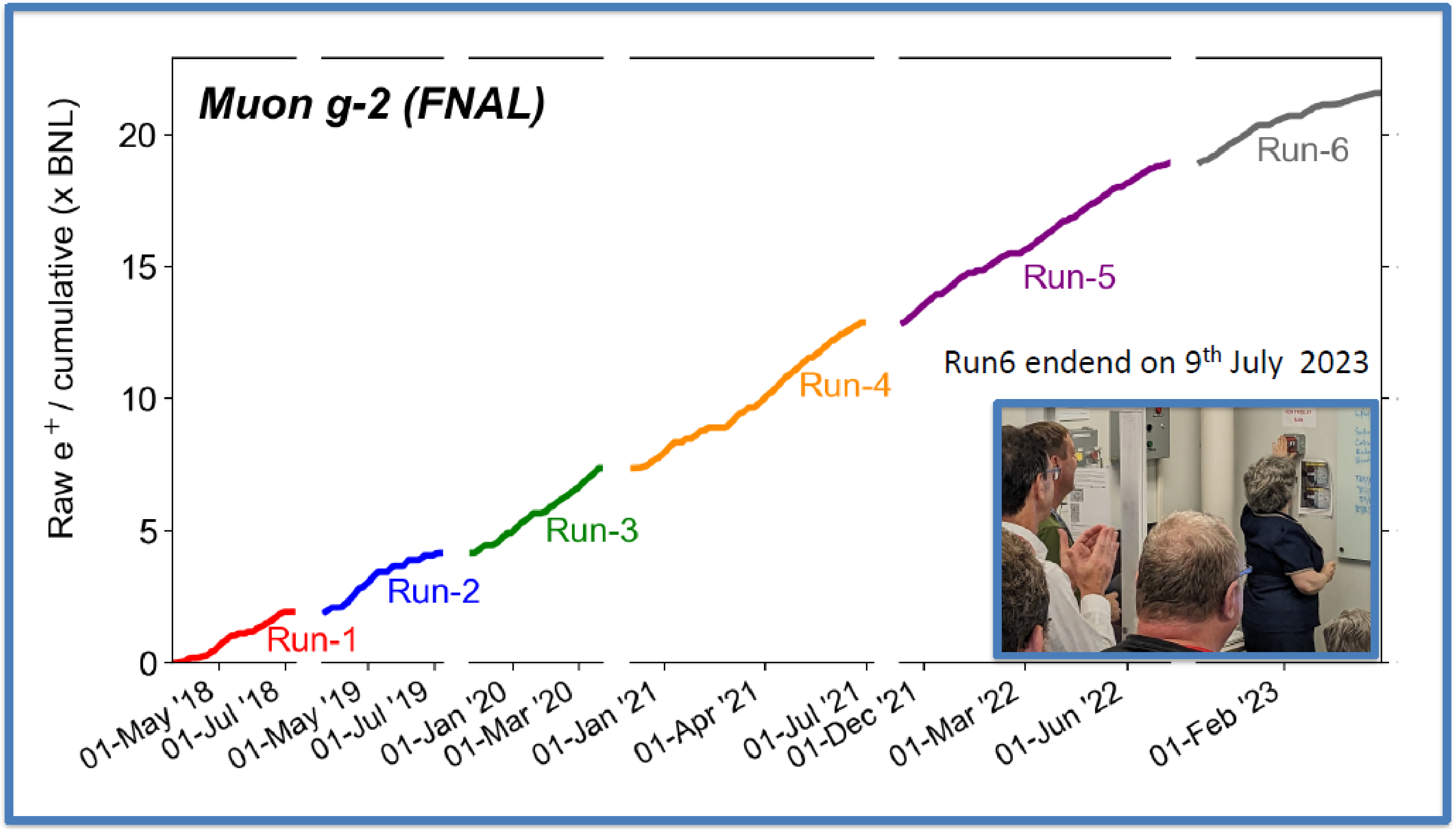
Run-2/3



CBO dominated Run-1 systematics (38 ppb).
Now reduced to 21 ppb!

Improvement of statistical uncertainty

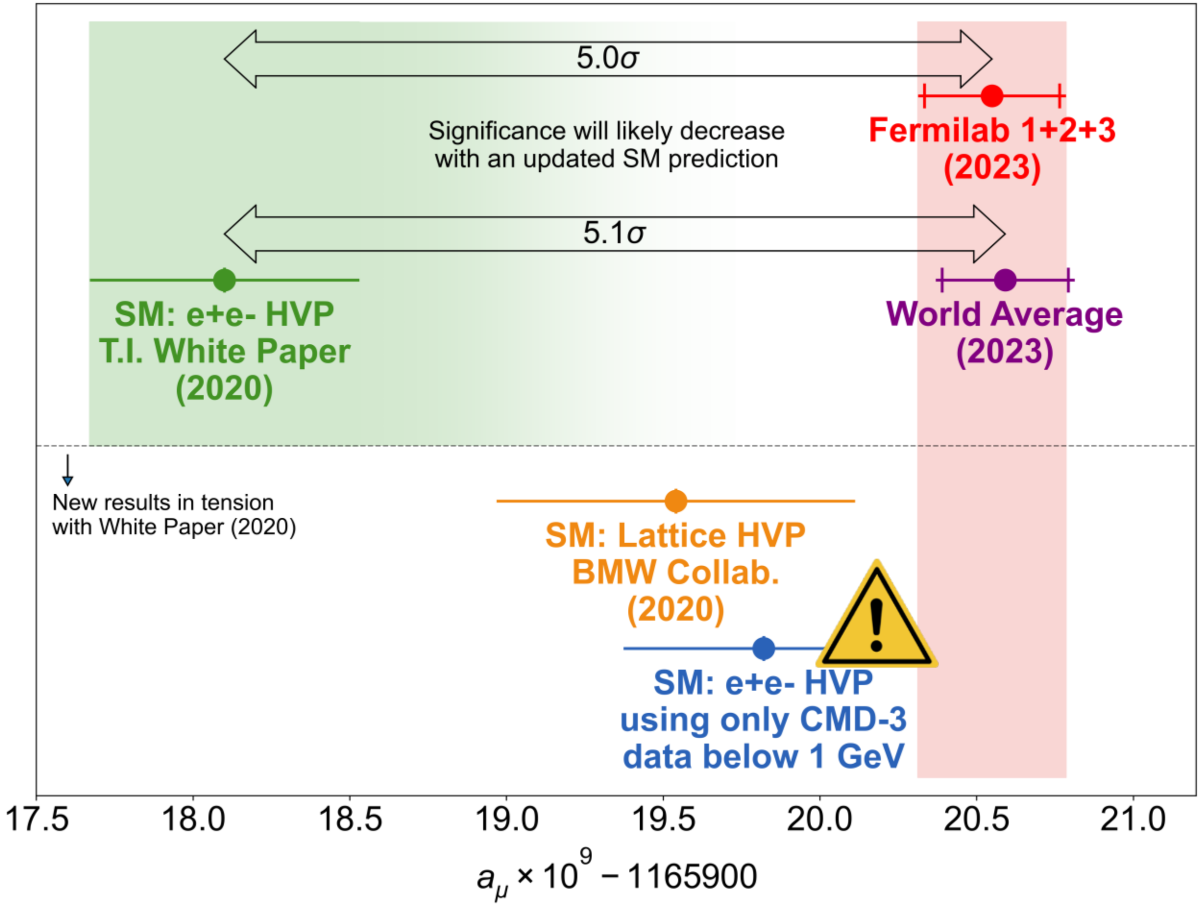
On 27 February 2023: proposal Goal of x21 BNL datasets!

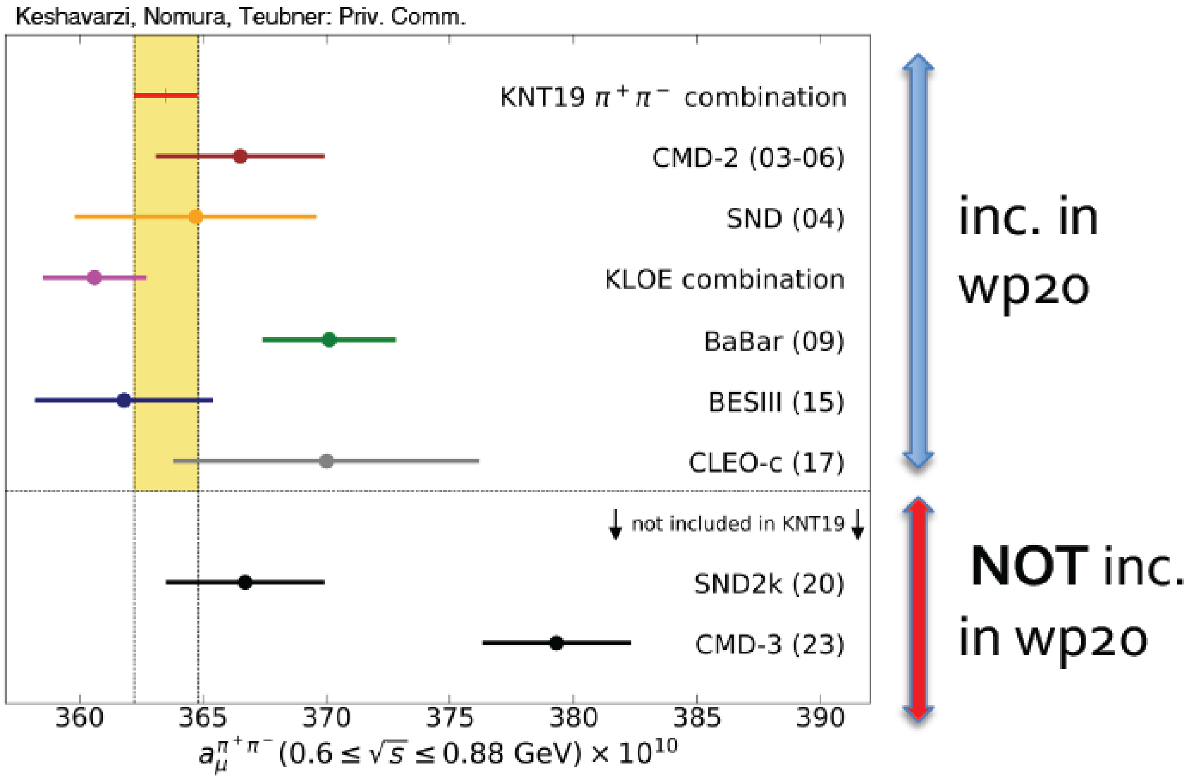


Dataset	Statistical Error [ppb]
Run-1	434
Run-2/3	201
Combined Run-1+Run-2/3	185
Expected total from Run-1 to Run-6	≤100

We expect to complete analysis by 2025

Updates since WP2020



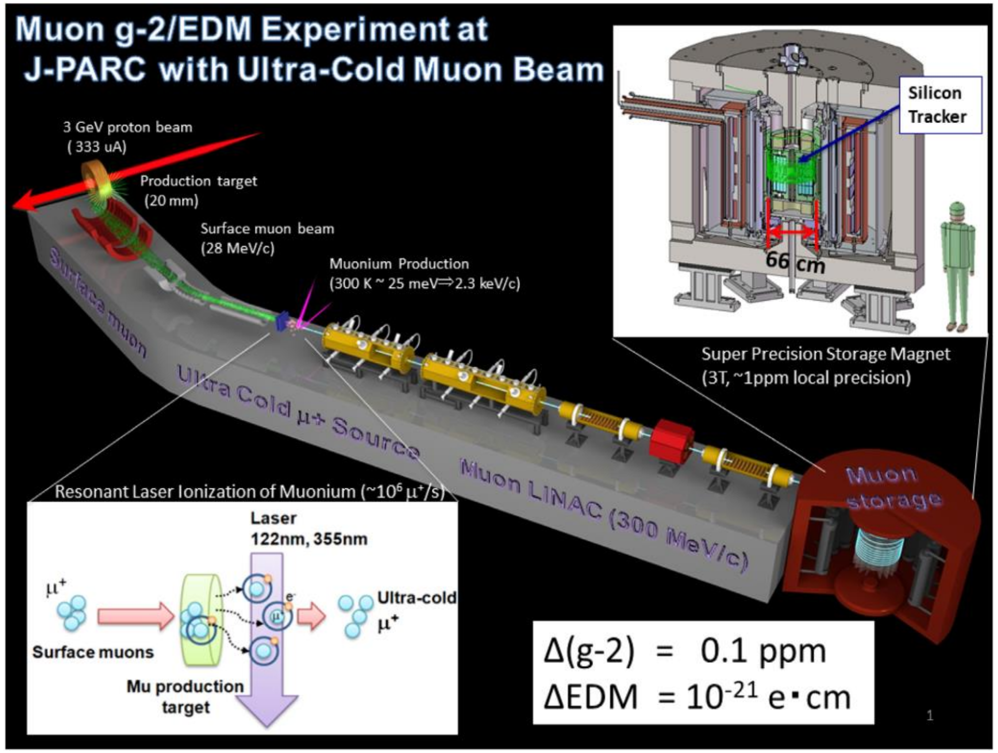


Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!

- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → <u>should not be taken as final!</u>

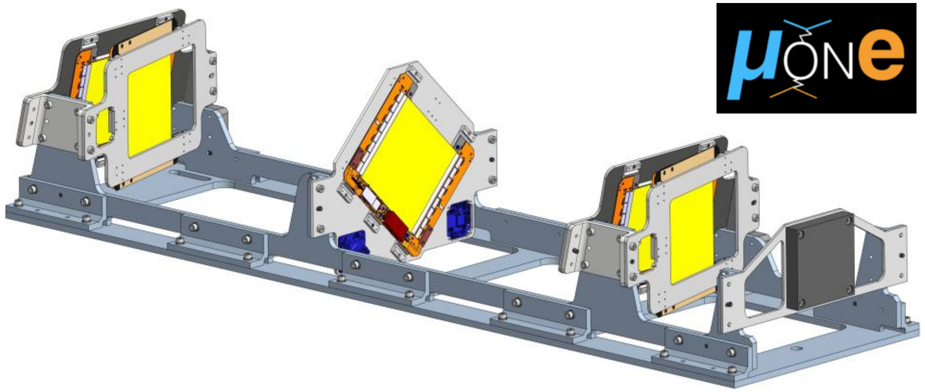
Future experiments: JPARC and MUonE



J-PARC Muon g-2/EDM (see next talk by T. Mibe and picture of the apparatus above)

MUonE (see next talk by R. Pilato):

- Extract leading-order HVP from hadronic running of α_{QED} in the space-like region
- Measure directly muon-electron elastic scattering differential cross section shape
- Goal of 0.3% uncertainty statistical, similar systematic; comparable with data-driven HVP



Summary and conclusions

- Improvements from Run-1 (2021 result) to Run-2/3 (2023 result):
  - **Statistic**: 4.7 times the Run-1 events → **2.2 smaller**
  - **Systematic**: many hardware and software improvements, like new reconstruction, more studies on beam dynamics→ **2.2 times smaller**
- New experimental average has **unprecedented precision of 190 ppb**
- **Puzzles** in the muon $g-2$ theory: a firm comparison between theory and experiment cannot be established (see https://muon-gm2-theory.illinois.edu/)
- Talk on Friday by B. Kiburg: «Wishlist of G-2 results for Tau2025»

THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS?

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UNIVERSITY OF PISA, INFN PISA

July 2023 collaboration meeting @ Liverpool, UK

BACKUP SLIDES

Extracting a_μ

2017 CODATA

FNAL Projected Errors:
140 ppb (total) =
100 (stat)⊕ 100 (syst)

-0.001 519 270 380(5) [3 ppb] Hydrogen Maser

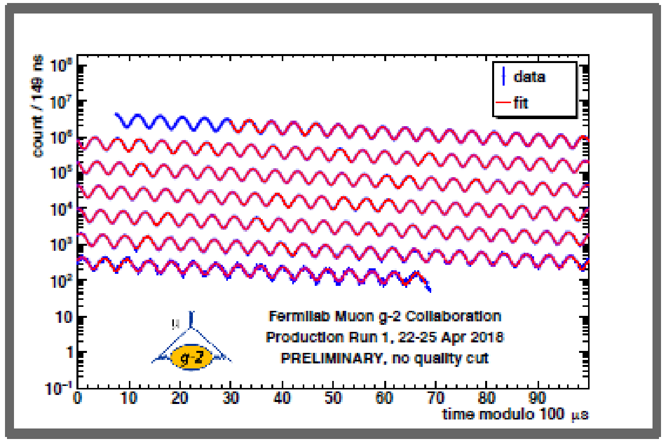
206.768 2826(46) [22 ppb] Muonium Hyperfine

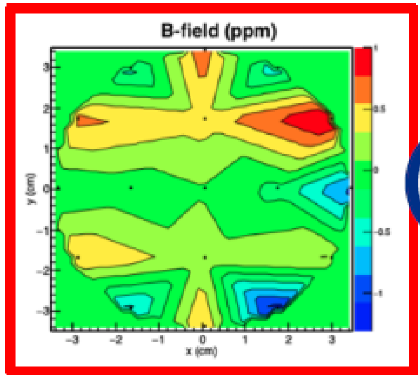
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$\Downarrow$$

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





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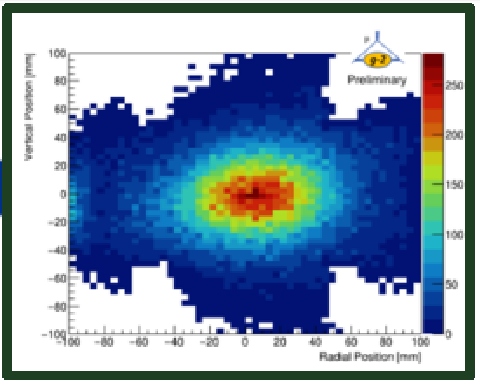
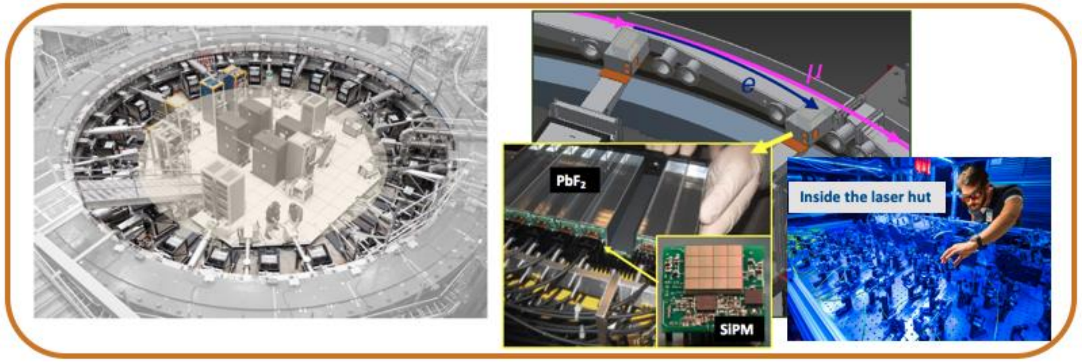
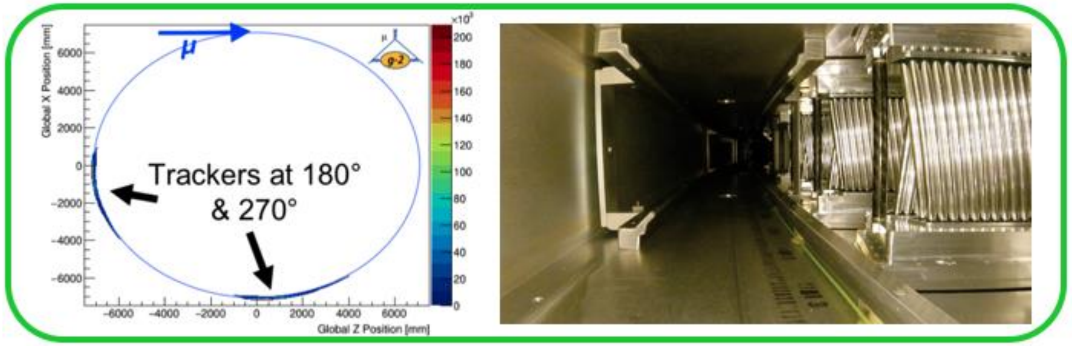


Muon g-2 detectors



24 calorimeters

- Each made of 6x9 PbF_2 crystals read out by large-area SiPMs
- 1296 channels individually calibrated by state-of-the-art laser system



2 straw trackers

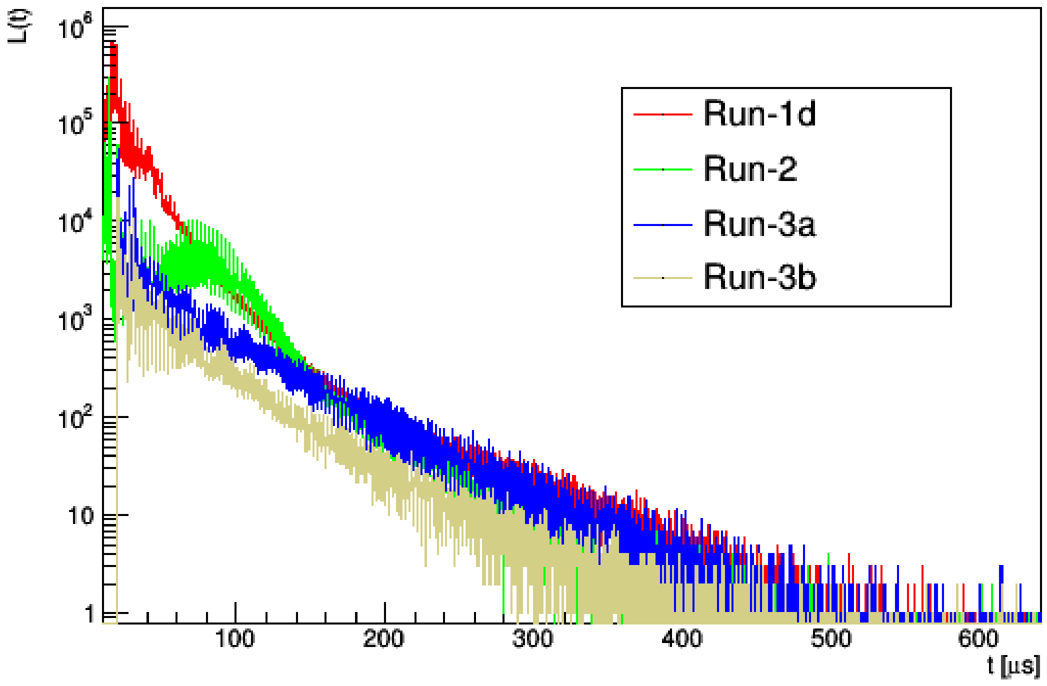
- Each consisting of 8 modules
- Gas filled straws

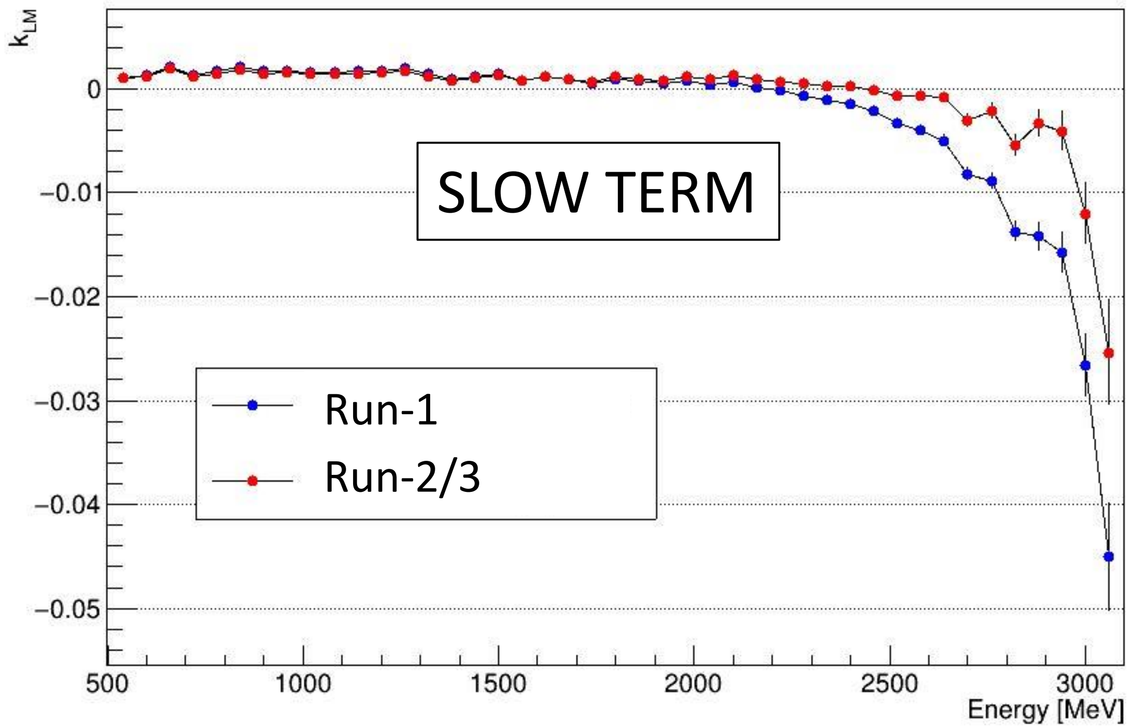
More auxiliary detectors for dedicated runs, muon beam profile, …

Lost muons and residual slow term

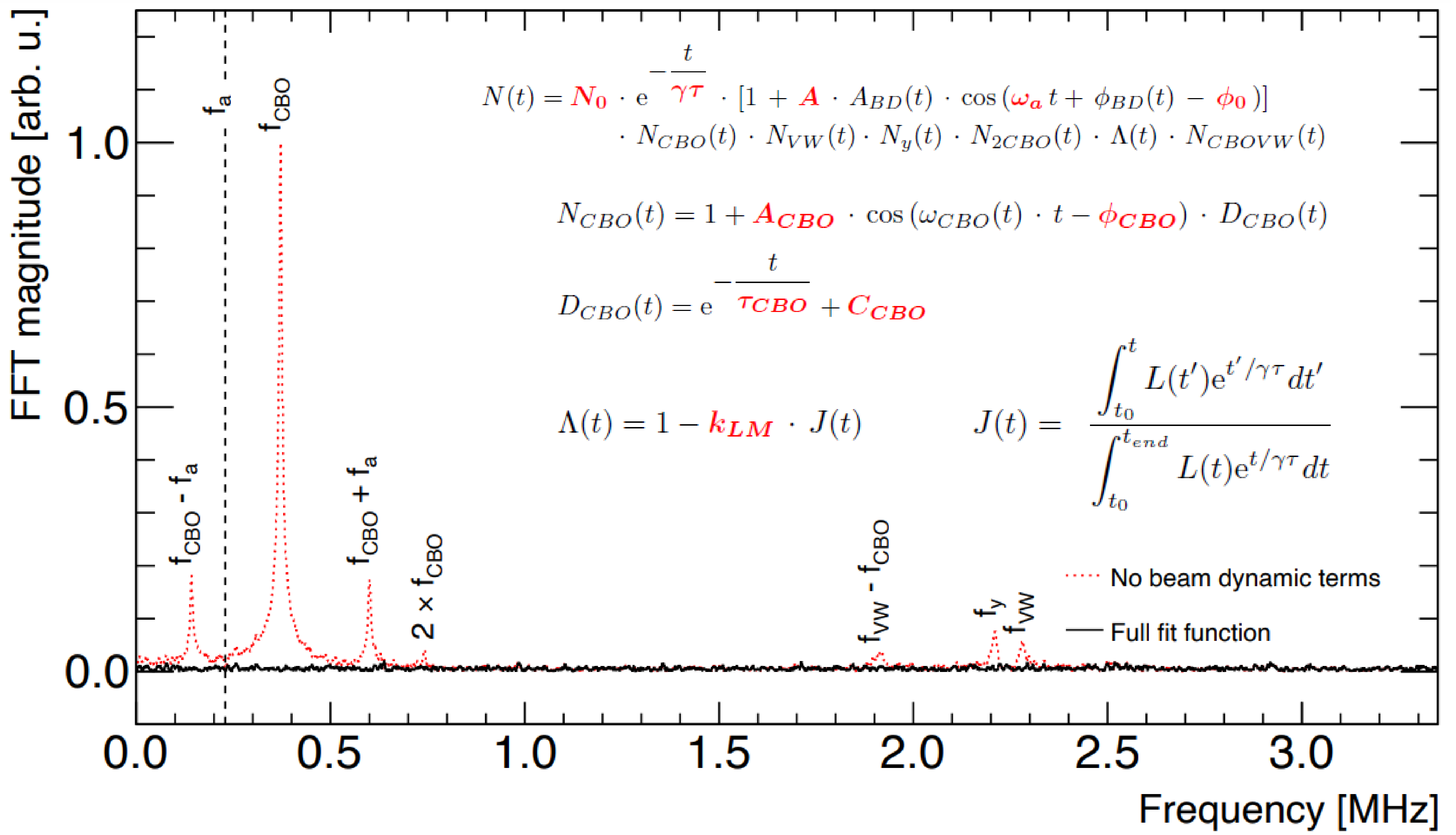
$$\Lambda(t) = 1 - k_{LM} \cdot J(t)$$

$$J(t) = \frac{\int_{t_0}^{t} L(t')e^{t'/\gamma\tau}dt'}{\int_{t_0}^{t_{end}} L(t)e^{t/\gamma\tau}dt}$$



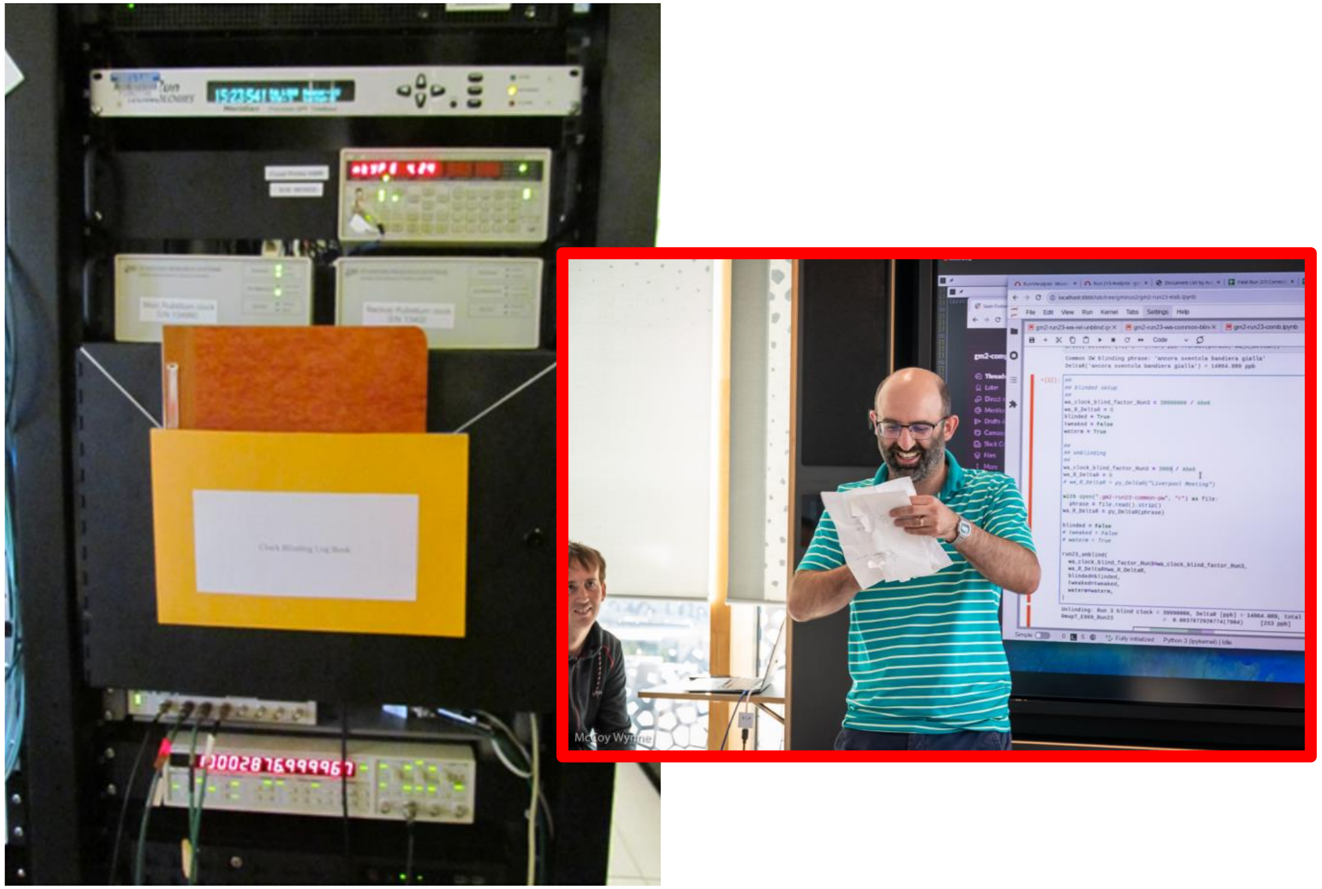


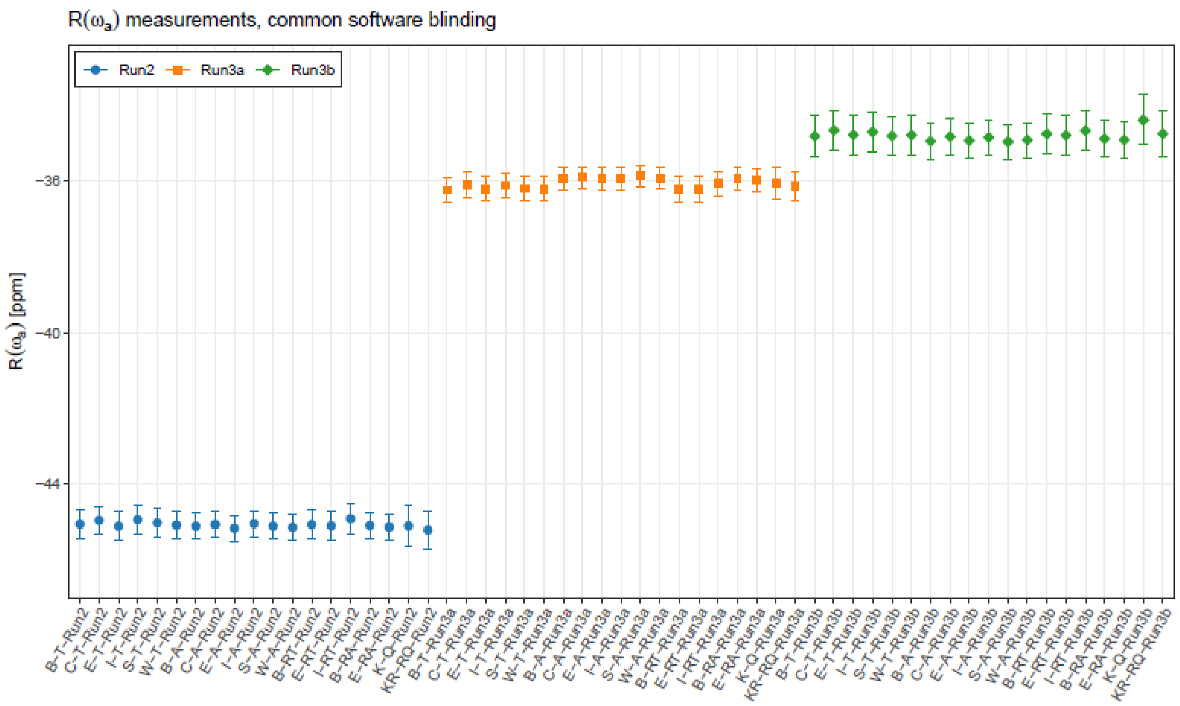
28-Parameter fit and FFT of residuals



Two-level blinding

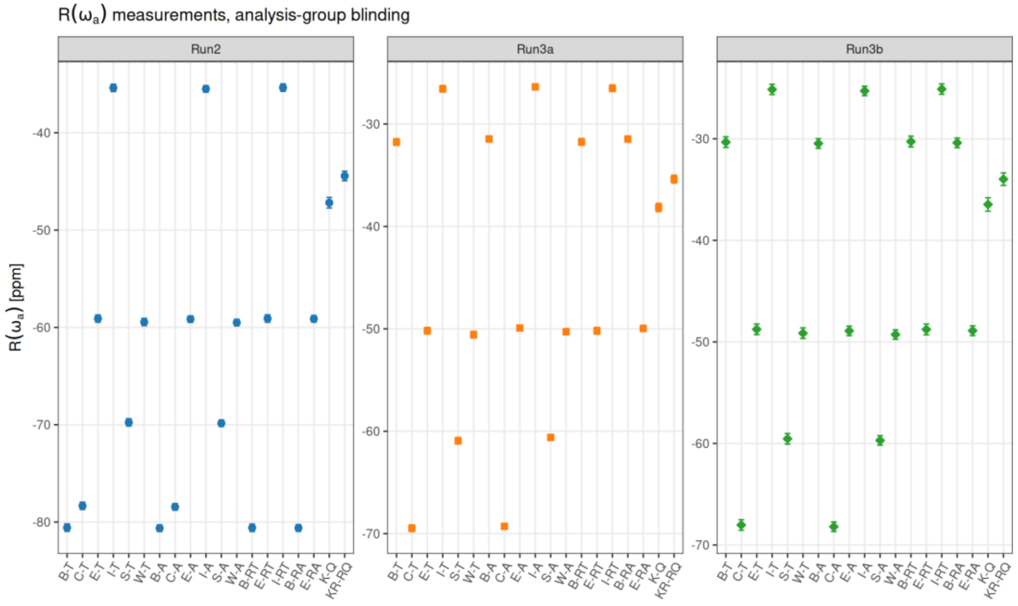
- Hardware: secret clock frequency, unknown to collaboration

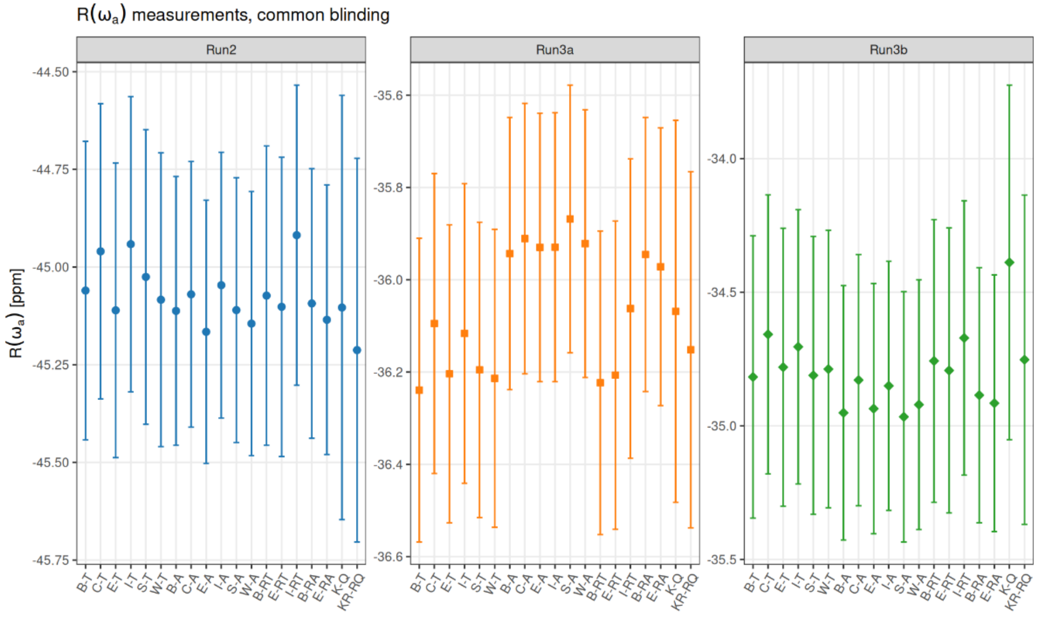




- Software: avoid biases among analyzers from 7 different groups

Software unblinding for Run-2/3





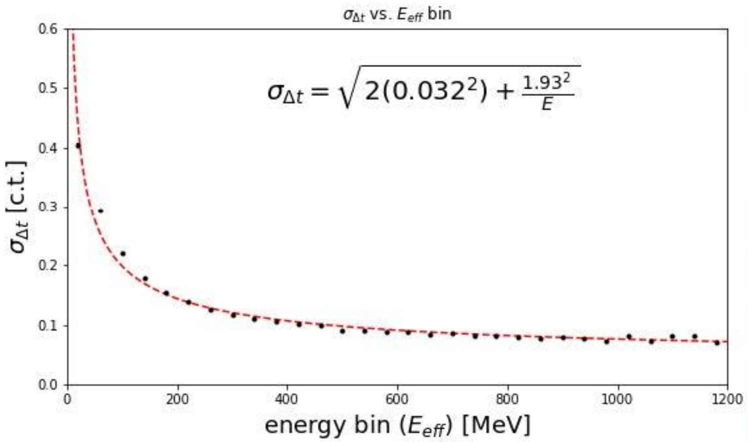
Common blinding among the 6 analyses

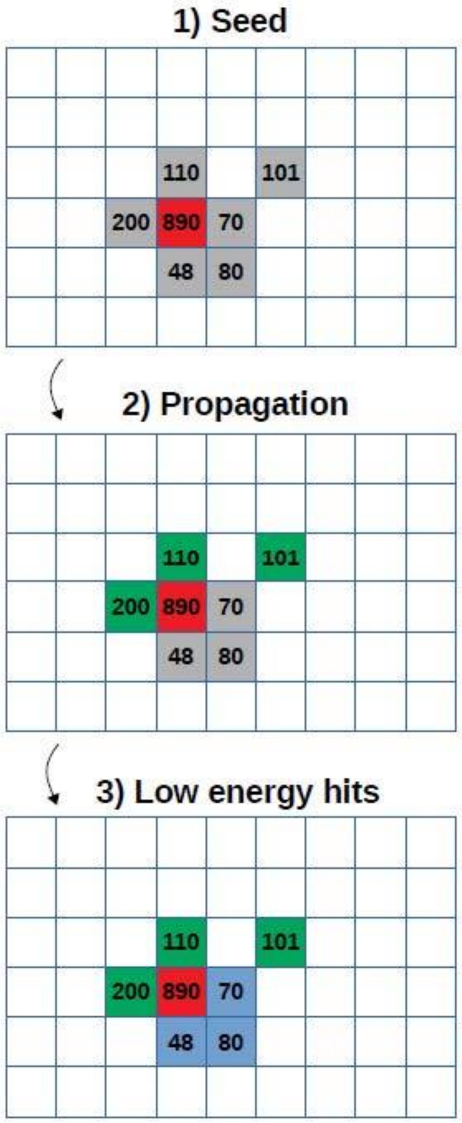
Detailed systematic effects on ω_a

Source	E989 goal [ppb]	Run-1 [ppb]	Run-2/3 [ppb]
Gain	20	8	5
Pileup	40	35	7
CBO	30	38	21
Total (including all contributions)	70	157	70

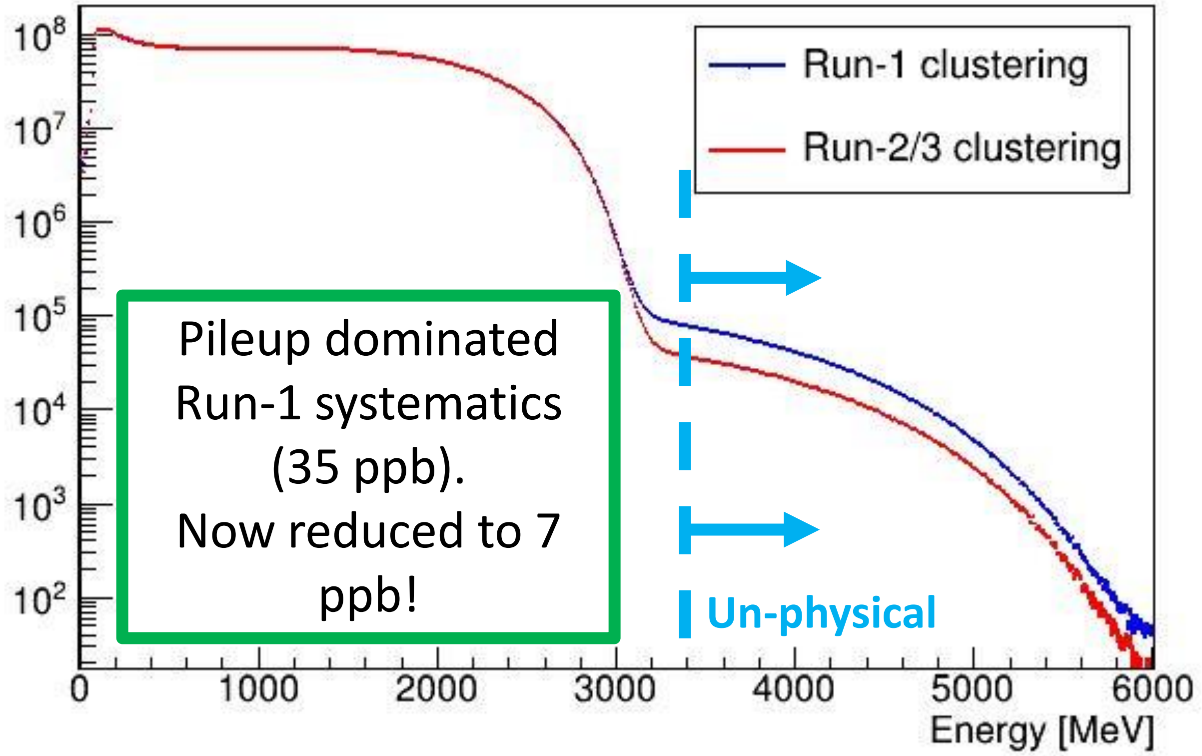
Reconstruction improvements

Seed-and-propagation algorithms that take into account time and energy resolution of detectors



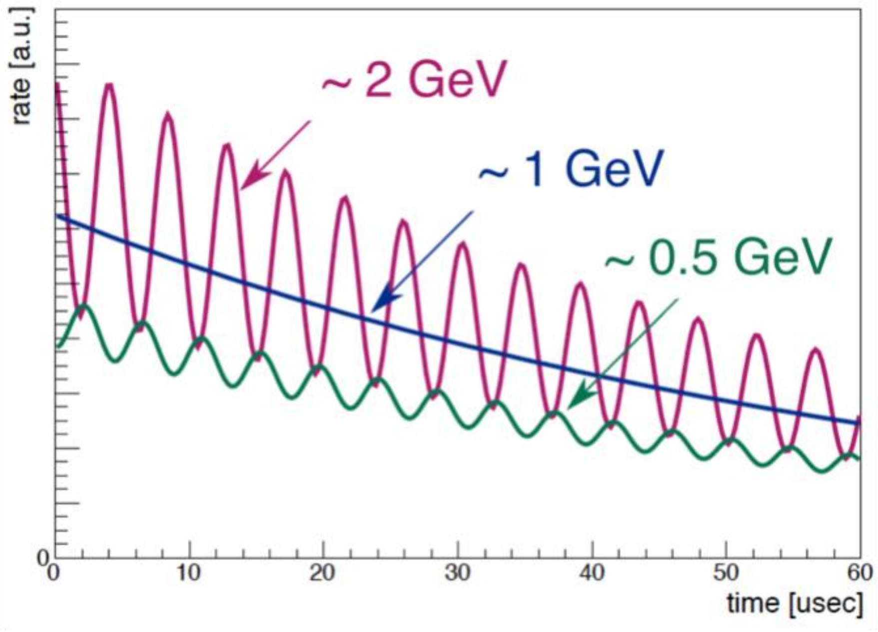


Reduced pileup in un-physical region (decay e^+ with more energy than muons) by ~ 2.

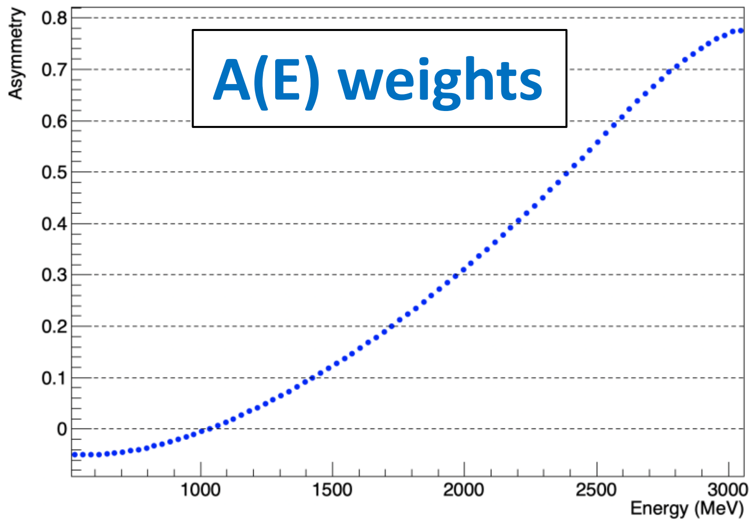


Energy methods to build wiggle plot

- T-Method: count high-energy (>1.7 GeV) positrons over time
- A-Method: positron rate weighted by A(E) i.e. the asymmetry for each energy bin
  - More positrons (>1.0 GeV)
  - Maximize statistical power



<u>A-Method was the standard in Run-1</u>



Beam dynamics uncertainties

Systematics	Description	Run-1 [ppb]	Run-2/3 [ppb]
C_e	Electric field effect on ω_a, minimized by «magic momentum» of 3.1 Gev/c. Improved analysis of momentum spread vs bunch time, and complimentary tracker information to reduce uncertainty	53	25
C_p	Caused by vertical betatron oscillations	13	10
C_{pa}	Correlation between muon decay position and ensemble-averaged initial phase. Mostly reduced because we fixed the damaged ESQ resistors that enhanced it in Run-1	75	15
C_{dd}	Higher-momentum muons have longer boosted lifetime	-	17
C_{ml}	Muons that are scattered away from the ring change the momentum distribution. Also reduced by fixing resistors	5	3

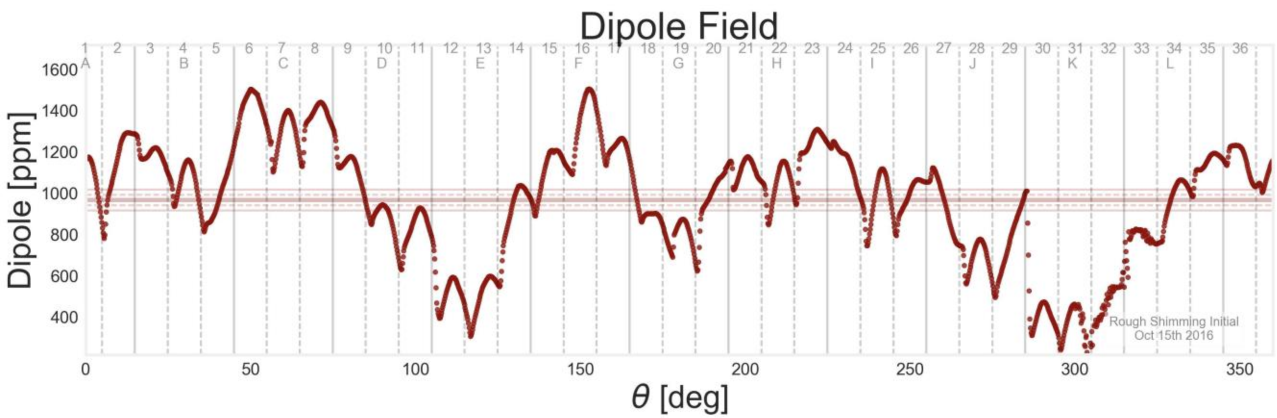
C_{dd} was not evaluated in Run-1 but it was known to be significantly smaller than other evaluated beam dynamics systematics

Field uncertainties

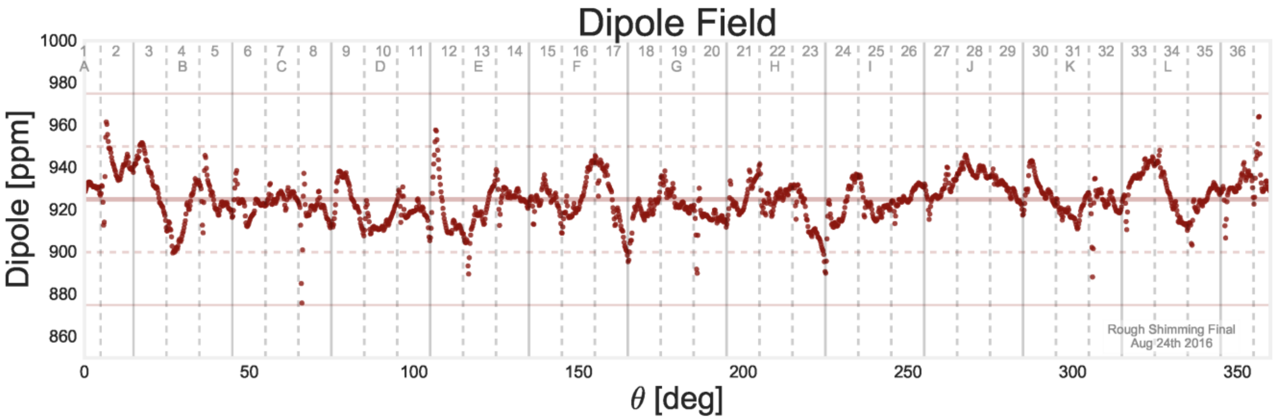
Systematics	Description	Run-1 [ppb]	Run-2/3 [ppb]
B_q	Vibrations caused by Quadrupole pulsing. Better mapping in azimuth in Run-2/3	92	20
B_k	Kicker-induced Eddy currents. Improved magnetometer measurements thanks to more stable setup that greatly reduced vibrations	37	13
Trolley calibration, tracking, muon weighting	Improvements in analysis and more trolley measurements. Stabilized temperature in the hall to reduce diurnal variations in the field	56	46

Field shimming: 2015-2016 campaign

Before



After



72 steel poles to increase homogeneity

864 wedges for dipole/quadrupole fields

144 edge shims for quadrupole/sextupole fields

48 iron top hats + 8000 surface iron foils to achieve desired uniformity