Status and prospects of the Muon $g-2$ experiment at FNAL

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SCUOLA NORMALE SUPERIORE

INFN PISA

ALPS 2023, Obergurgl University Centre, Austria, 28 March 2023

Muon magnetic anomaly

particle x such as a muon, electron, proton, neutron

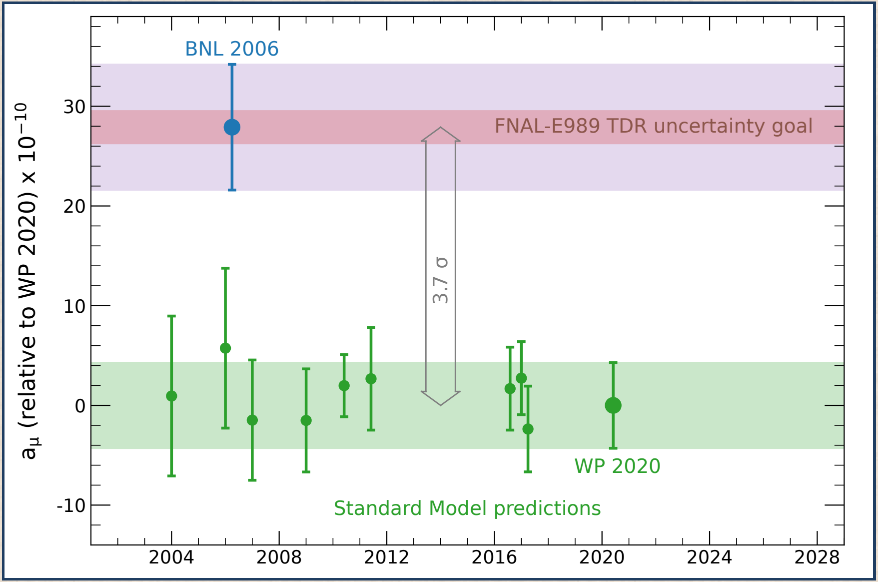
- magnetic moment $\vec{\mu}_x = g_x \frac{e}{2m_x} \vec{S}_x$,
  - e = absolute value of electron charge (used also for neutron)
  - $\vec{S}_x$ = spin (particle intrinsic angular momentum)
  - g_x = gyromagnetic ratio (defined also for neutral particles)
- classical charge distribution: $\rho_q/\rho_m = \text{constant} \Rightarrow g = 1$

leptons (electron, muon, tau): spin 1/2 fundamental point-like particles

- Standard Model
  - leading order: $g_e,\ g_\mu,\ g_\tau = 2$ (like Dirac eq.)
  - next to leading order: $g_e,\ g_\mu,\ g_\tau > 2$
- $a_x = \frac{g_x - 2}{2}$ anomalous gyromagnetic ratio or magnetic anomaly

- lepton g_x, a_x may be considered first most fundamental prediction of Standard Model

Muon $g-2$ anomaly motivated FNAL Muon $g-2$ experiment



- WP 2020: Muon $g-2$ theory initiative White Paper, Phys. Rept. 887 (2020) 1

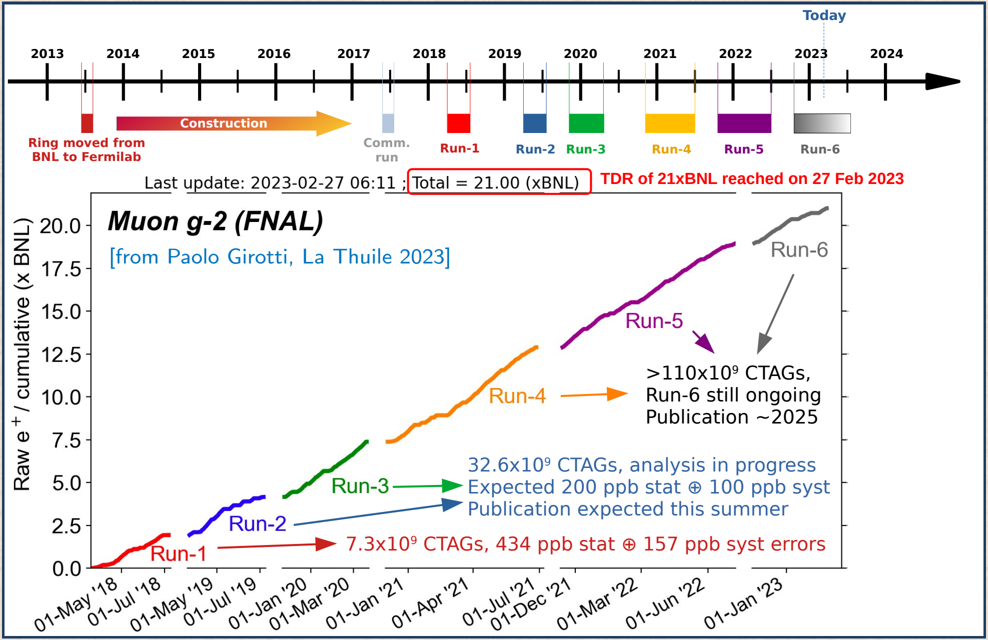
FNAL-E989 vs. BNL-E821

FNAL-E989 design precision, compared to BNL-E821 final report (2006)

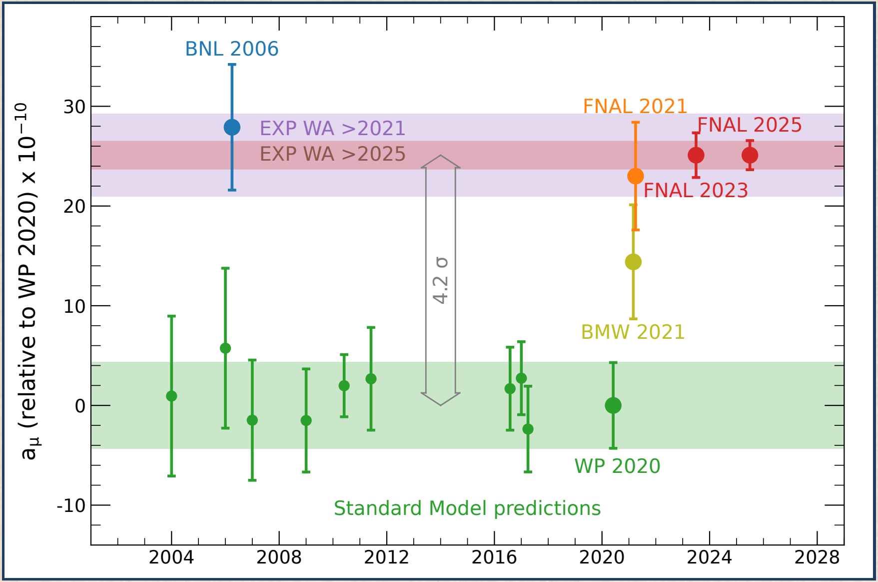
	BNL E821 (2006)	FNAL E989 final goal	
ω_a statistical	460 ppb	100 ppb	$\times$21 detected muon decays ($1.6{\cdot}10^{11}$)
ω_a systematic	210 ppb	70 ppb	faster calorimeter with laser calibration, tracker
ω_p systematic	170 ppb	70 ppb	more uniform B, improve NMR measurement
external measurements	negligible	negligible	
total	540 ppb	140 ppb	

ω_a: measured muon spin precession frequency in magnetic field
ω_p: measured proton spin precession frequency to measure magnetic field

Reached 21× BNL goal on 27 Feb 2023

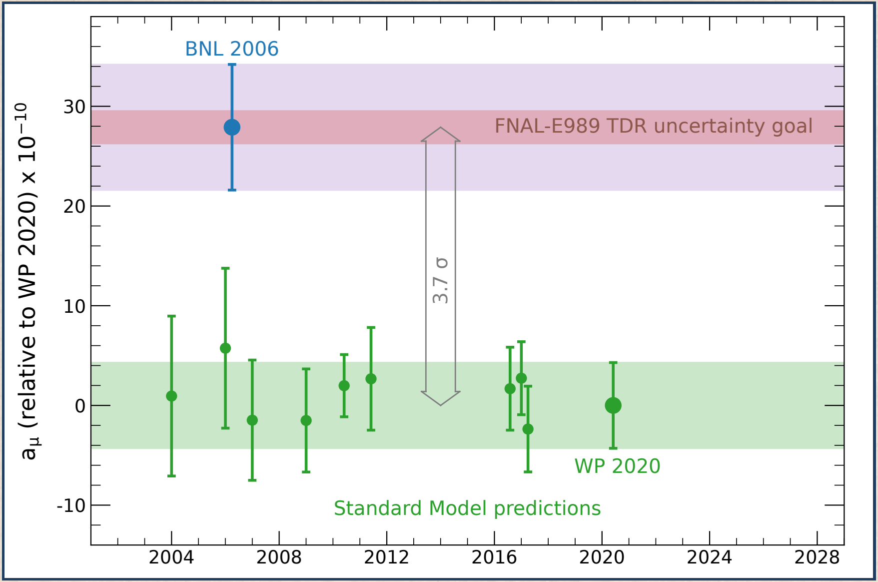


Status and prospects of muon anomaly measurement at FNAL



- band "EXP WA > 2025" obtained using conservative 100% correlation of systematics for all FNAL measurements

Status and prospects of muon anomaly measurement at FNAL



- estimate of final FNAL-E989 uncertainty match design goals

Motion and spin precession of muon in uniform magnetic field

muon spin precession relative to momentum

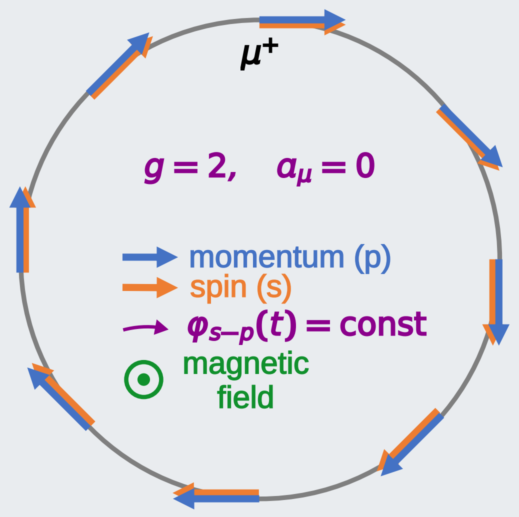
$$\omega_s \quad - \quad \omega_c \quad = \quad \omega_a$$

$$\boxed{-g_\mu \frac{eB}{2m_\mu} - (1-\gamma)\frac{eB}{m_\mu\gamma}} - \boxed{-\frac{eB}{m_\mu\gamma}} = \boxed{-a_\mu \frac{eB}{m_\mu}}$$

Larmor + Thomas precessions — cyclotron frequency — no γ!

- frequency measurements best for precision
- magnetic field NMR measurement also frequency
- angle between momentum and spin: $\varphi(t) = \omega_a t$

polarized muons in magnetic storage ring



Motion and spin precession of muon in uniform magnetic field

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$$\boxed{-g_\mu \frac{eB}{2m_\mu} - (1-\gamma)\frac{eB}{m_\mu\gamma}} - \boxed{-\frac{eB}{m_\mu\gamma}} = \boxed{-a_\mu \frac{eB}{m_\mu}}$$

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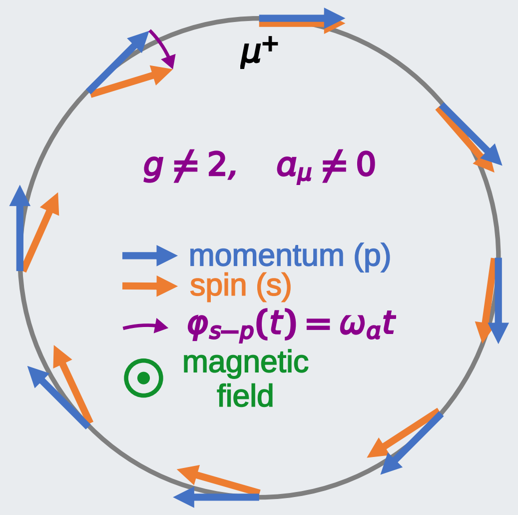
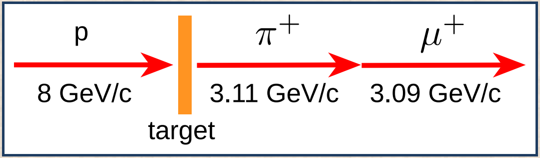
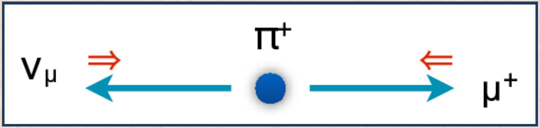


Production of polarized muons

- dump 8 GeV protons on target to produce pions
- select pions with momemtum $p \simeq 3.11$ GeV
- let them decay into muons
- in pion rest frame, parity violation in pion decay causes μ^+ spin aligned opposite to momentum vector
- in laboratory frame, highest energy muons are >90% polarized

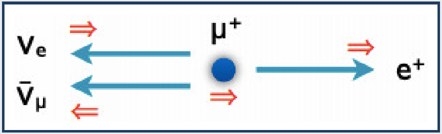




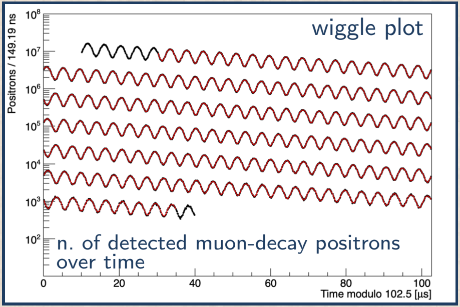
- with 8 GeV protons on target, μ^+ are produced ~4× more frequently than μ^-

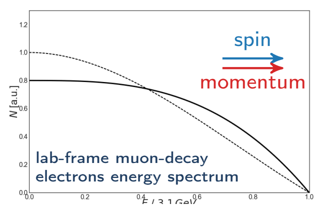
Rate of high-energy muon-decay electrons modulated with $\cos \omega_a t$

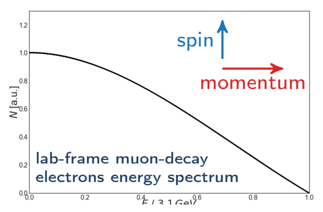
- because of parity violation in muon decay, decay electrons peak along muon spin

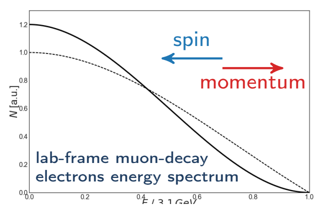


- electrons decaying along muon momentum have highest energy in laboratory frame
- $N_e(E_e > E_t) = N_{e0} e^{-t/\tau_\mu} (1 + A \cos \omega_a t)$









a_μ measurement: how sub-ppm precision can be obtained

measurement of magnetic field: ω_p

- proton spin precession frequency measures magnetic field (NMR): $\hbar\omega_p = 2\mu_p B$

measurements

- $\omega_a = a_\mu \frac{eB}{m_\mu}, \quad \hbar\omega_p = 2\mu_p B$

spin 1/2 particle x = proton, muon

- $S_x = \frac{\hbar}{2}, \quad \mu_x = g_x \frac{e}{m_x} S, \quad a_x = \frac{g_x - 2}{2}$

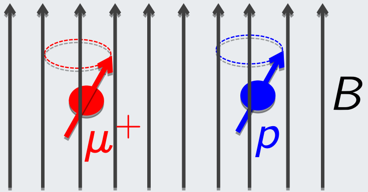
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

muonium & hydrogen hyperfine transitions

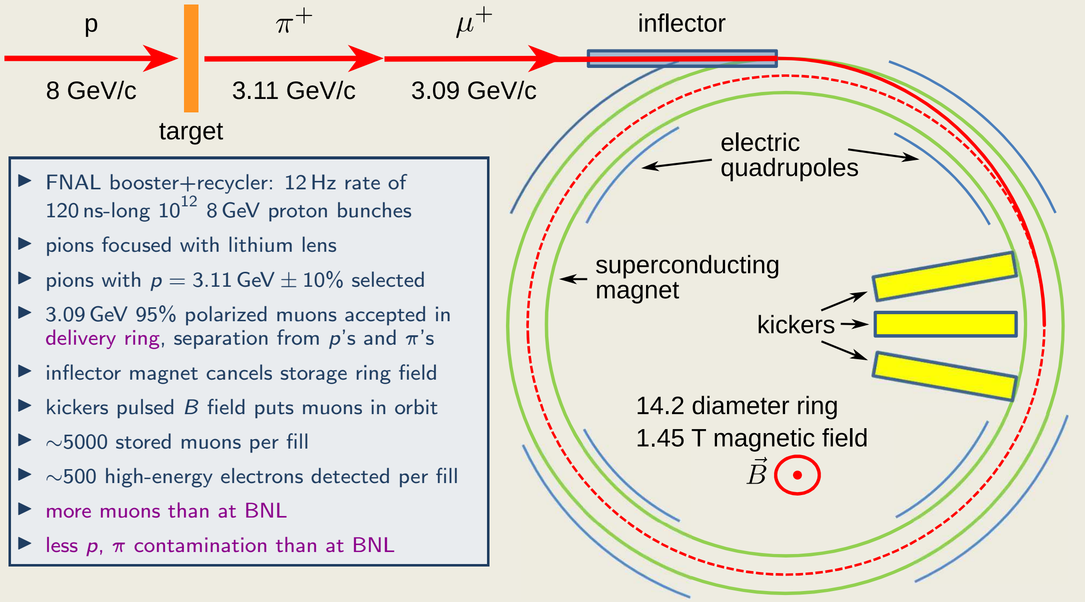
mainly LAMPF 1999 experiment
precision on CODATA 2018 fit: 22 ppb

actually, best a_μ obtained by adding ω_a/ω_p measurement to Fundamental Physical Constants CODATA fit

ω_a & ω_p in same magnetic field



Muon production, storage and decay at FNAL



- FNAL booster+recycler: 12 Hz rate of 120 ns-long 10^{12} 8 GeV proton bunches
- pions focused with lithium lens
- pions with $p = 3.11$ GeV $\pm$ 10% selected
- 3.09 GeV 95% polarized muons accepted in delivery ring, separation from p's and π's
- inflector magnet cancels storage ring field
- kickers pulsed B field puts muons in orbit
- ~5000 stored muons per fill
- ~500 high-energy electrons detected per fill
- more muons than at BNL
- less p, π contamination than at BNL

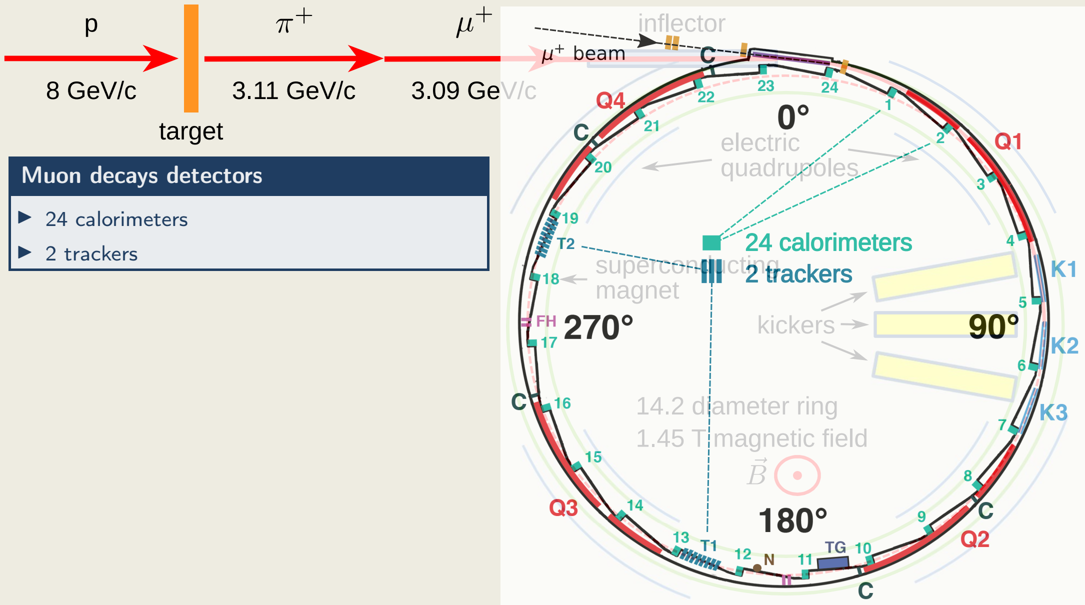
Beam storage and focusing

- weak horizontal focusing provided by uniform magnetic field
- vertical focusing with electric quadrupoles

magic energy

- $\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} \quad - \quad \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E}) \quad - \quad a_\mu \frac{\gamma}{\gamma + 1}\left(\vec{\beta} \cdot \vec{B}\right)\vec{\beta}\right]$
- $\left(a_\mu - \frac{1}{\gamma^2 - 1}\right) \simeq 0$ for $p_\mu^{\text{magic}} = 3.094\,\text{GeV}, \quad \gamma = 29.3$

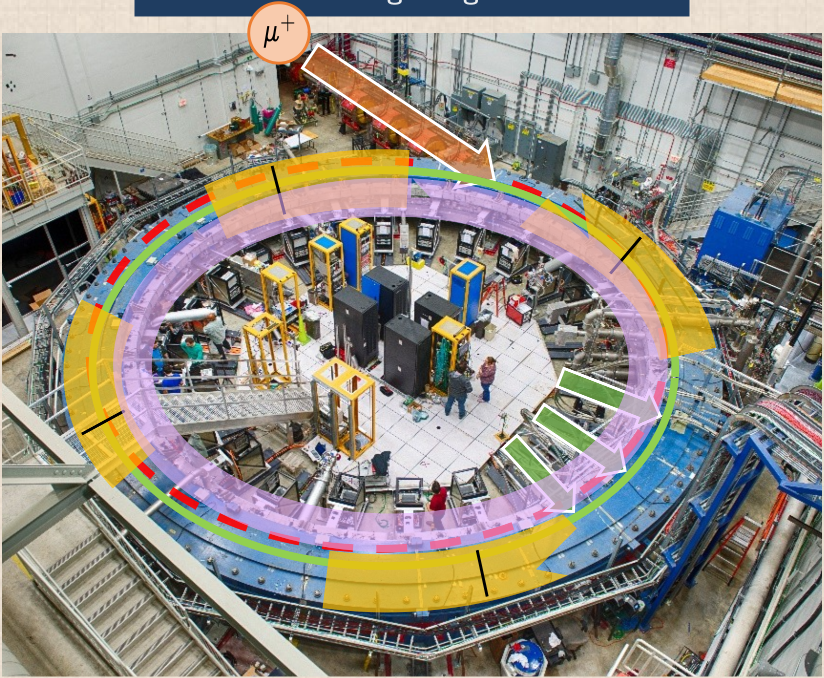
Muon production, storage, decay and detection at FNAL



Muon decays detectors

- 24 calorimeters
- 2 trackers

FNAL-E989 storage ring and detectors

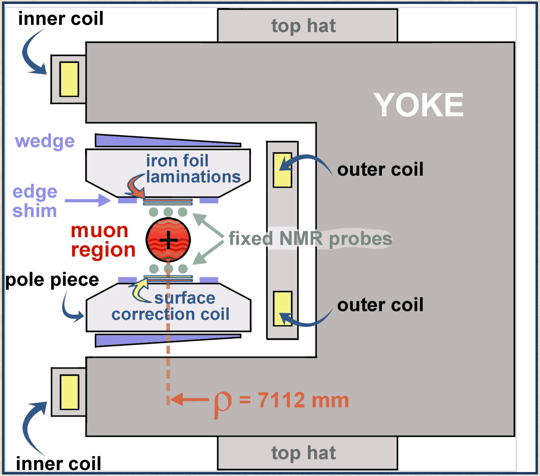


Storage ring magnet

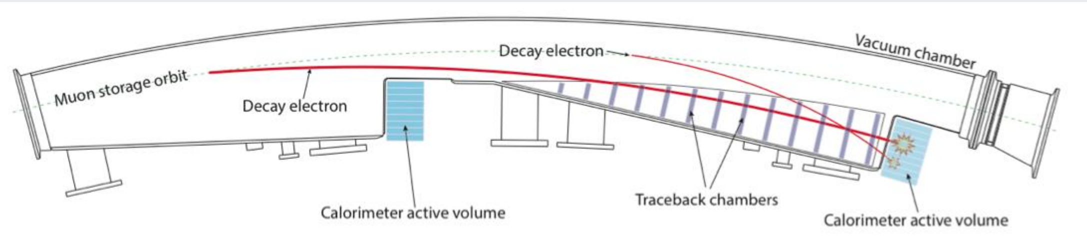
- superconductive magnet cooled at ∼5 K
- 1.45 T vertical uniform magnetic field
- shimmed passively with iron foils
- actively stabilized with correction coils
- <50 ppm RMS B field homogeneity
- <14 ppm RMS B field azimuth-averaged

magnetic field measurement

- 378 fixed probes to track field continuously
- trolley with 17 NMR probes maps magnetic field periodically during off-beam intervals
- trolley probes calibrated with reference NMR probe



Muon-decay positrons and lost muons detectors



count muon-decay positrons over time

- 24 calorimeter modules of 6×9 PbF_2 crystals with 800 MHz-sampling SiPM readout
  - measure positron energy detecting Cherenkov light (fast)
  - accurate gain monitoring with laser calibration system

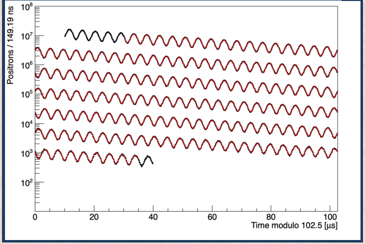
measure beam distribution inside storage ring

- 2 straw chamber trackers with total of about 1000 channels
  - track muon-decay positron, reconstruct muon-decay vertices in storage region
  - partial ring coverage, muon distribution extrapolated with beam dynamics simulation

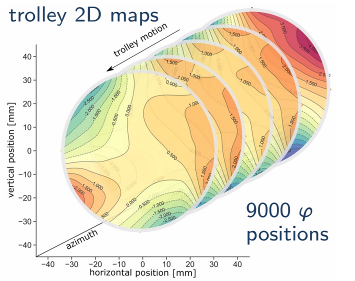
Conceptual formula for $R'_\mu(T) = \omega_a/\tilde{\omega}'_p(T)$

$$R'_\mu(T) = \frac{\omega_a}{\tilde{\omega}'_p(T)} \overset{\text{conceptually}}{=} \frac{f_{\text{blind}}\ \omega_a^{\text{m}}\ (1 + C_e + C_p + C_{\text{ml}} + C_{\text{pa}})}{f_{\text{calib}}\ \langle \omega'_p(T)(x,y,\varphi) \times M(x,y,\varphi)\rangle\ (1 + B_k + B_q)}$$

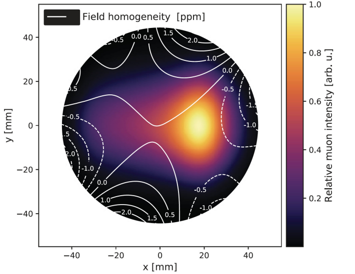
ω_a^{m}



$\omega'_p(T)(x,y,\varphi)$



$M(x,y,\varphi)$

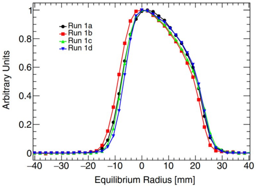


- f_{blind} correction for blinding clock offset
- f_{calib} magnetic field probes calibration
- $\omega'_p(T)$ precession frequency of shielded proton spin in spherical water sample at $T = 34.7\,°\text{C}$

ω_a beam dynamics corrections (from P. Girotti, La Thuile, 2023)

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

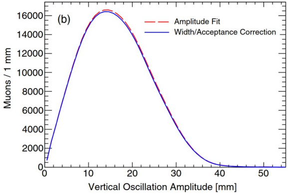
$$C_e \approx 2n(1-n)\beta_0 \frac{\langle x_e^2 \rangle}{R_0^2}$$

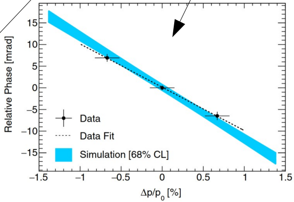


Electric field correction

Pitch correction

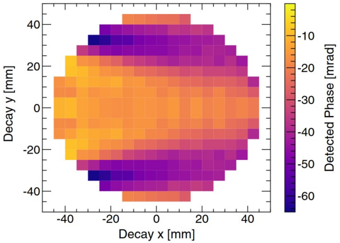
$$C_p \approx \frac{n}{4}\frac{\langle A_y^2 \rangle}{R_0^2}$$





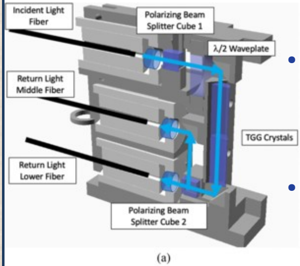
Lost muons momentum correlation

Phase-acceptance correction

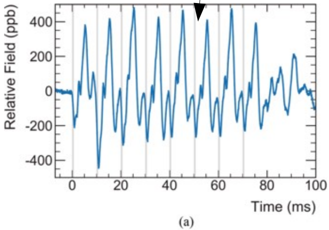


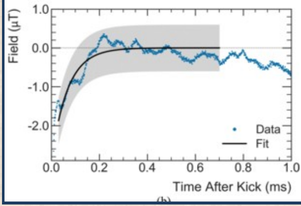
$\tilde{\omega}'_p(T)$ transient fields corrections (from P. Girotti, La Thuile, 2023)

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

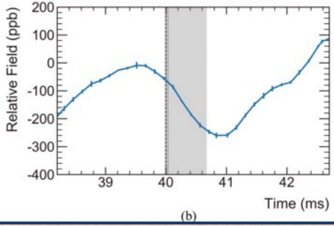


- Millisecond-long eddy currents induced by the kicker pulse
- Measured with dedicated Faraday magnetometers





- Low-frequency oscillations of the electrostatic quadrupole plates
- Measured with dedicated probes



Muon precession frequency ω_a fit

fit model for number of detected positrons with $E > 1.7$ GeV in time bins from 30 to 650 μm

$$N_{e^+}(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a t + \phi_0 \cdot \phi_x(t))]$$

$$N_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{N,x,1,1} \cos\left(\omega_{\text{CBO}} t + \phi_{N,x,1,1}\right) + e^{-2t/\tau_{\text{CBO}}} A_{N,x,2,2} \cos\left(2\omega_{\text{CBO}} t + \phi_{N,x,2,2}\right)$$

$$N_y(t) = 1 + e^{-t/\tau_y} A_{N,y,1,1} \cos\left(\omega_y t + \phi_{N,y,1,1}\right) + e^{-2t/\tau_y} A_{N,y,2,2} \cos\left(\omega_{\text{VW}} t + \phi_{N,y,2,2}\right)$$

$$A_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{A,x,1,1} \cos\left(\omega_{\text{CBO}} t + \phi_{A,x,1,1}\right)$$

$$\phi_x(t) = 1 + e^{-t/\tau_{\text{CBO}}} A_{\phi,x,1,1} \cos\left(\omega_{\text{CBO}} t + \phi_{\phi,x,1,1}\right)$$

$$\Lambda(t) = 1 - K_{\text{loss}} \int_0^t e^{t'/\gamma\tau} L(t') dt'$$

$$\omega_{\text{CBO}} \cdot t \to \omega_{\text{CBO}} \cdot t + A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$$

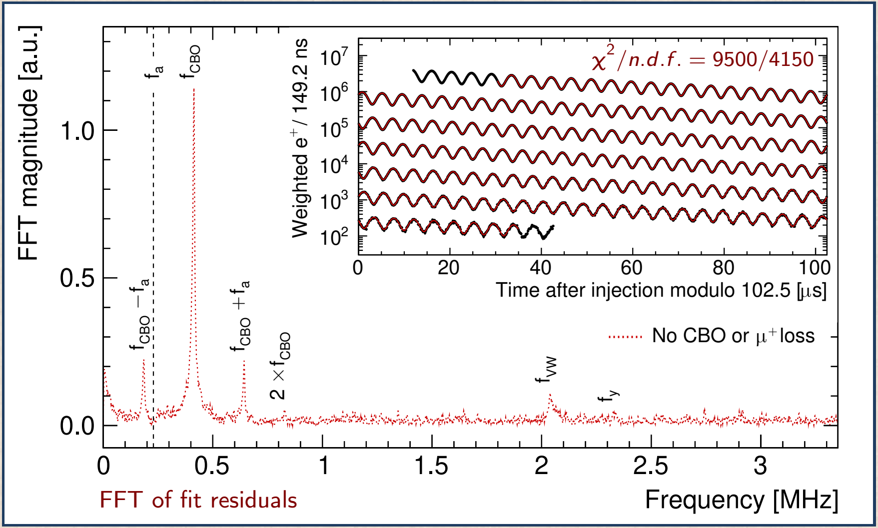
$$\omega_y(t) = \kappa_y \cdot \omega_{CBO}(t) \left(\frac{2\omega_c}{\kappa_y \cdot \omega_{CBO}(t)} - 1 \right)^{1/2}$$

$$\omega_{\text{VW}}(t) = \omega_c - 2\omega_y(t)$$

- from 16 to 27 (22 typical) fit parameters, depending on analysis group and measurement method

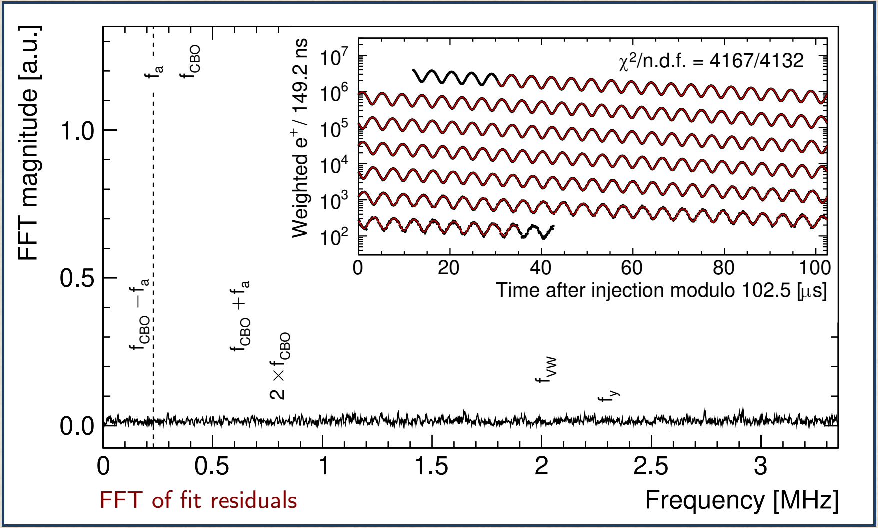
Fourier transform of fit residuals of ω_a fit

- 5-parameter fit $N(t) = N_0 e^{-t/\tau_\mu} [1 + A \cos(\omega_a t + \varphi)]$



Fourier transform of fit residuals of ω_a fit

- 22-parameter (typical) fit



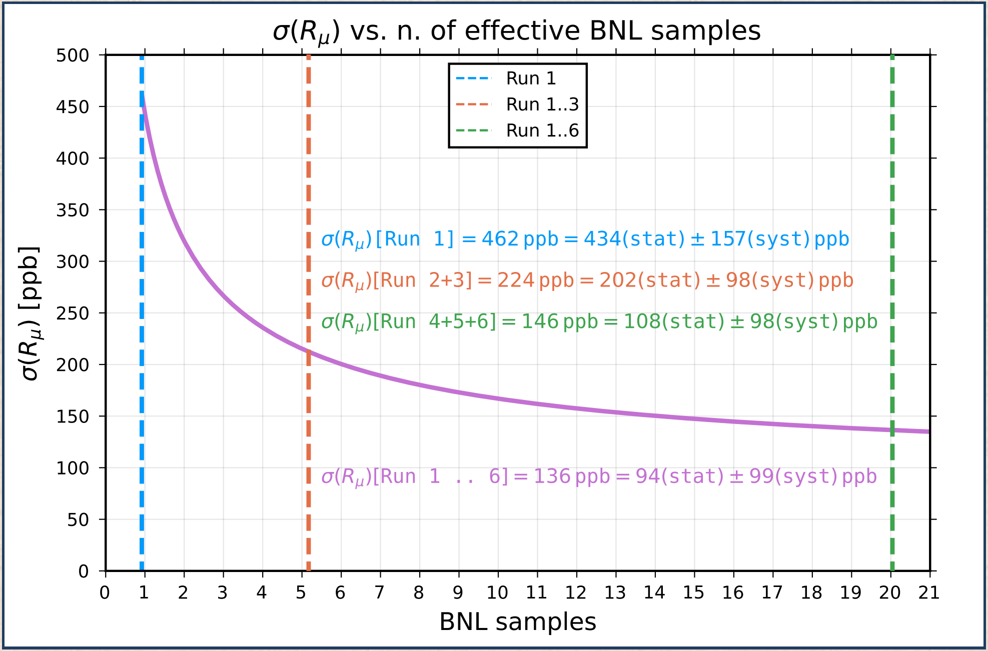
Personal 1-year-old estimate of Run 2+3 ω_a systematic uncertainties

	Run 1	Run 2+3	design	notes
ω_a^m (statistical)	434	202	100	
base clock	2	same		
ω_a^m (systematic)	56	33		
- Time randomization	9	same		
- Time correction	1	same		
- Gain	8	same		
- Pileup	35	18		expect 50% reduction
- Muon Loss	3	same		
- CBO	38	25		expect 33% reduction
- Residual slow term	17	0		expect will be understood
C_{BD}	93	51		
- C_e	53	43		expect 20% reduction
- C_p	13	same		
- C_{ml}	5	same		
- C_{pa}	75	24		estimate
ω_a total systematic	109	61	70	

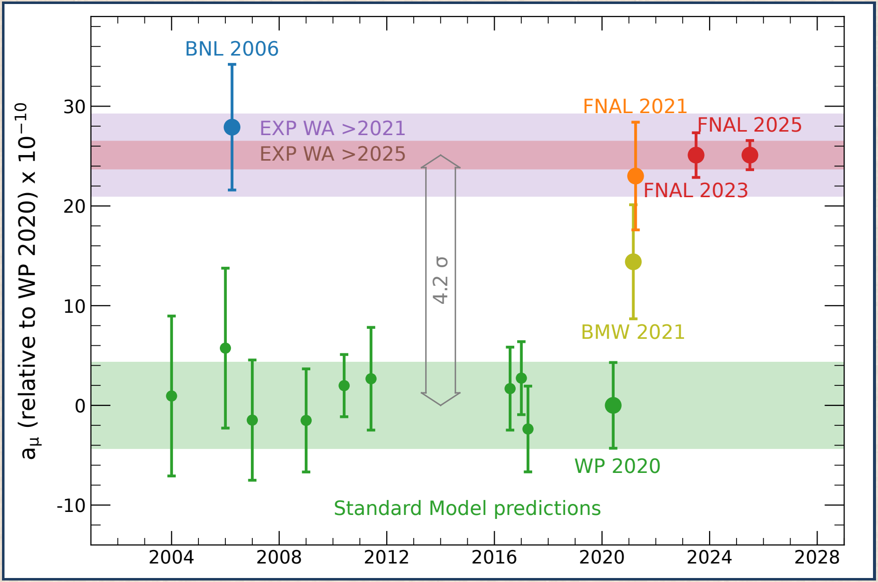
Personal 1-year-old estimate of Run 2+3 ω_a / $\tilde{\omega}'_p(T)$ uncertainties

	Run 1	Run 2+3	design	notes
ω_a (statistical)	434	202	100	
ω_a (total systematic)	109	61	70	
$\omega'_p(T)$	56	same	70	
$\tilde{\omega}'_p(T)$ (transient fields)	99	53		
- B_q	92	46		expect 50% reduction
- B_k	37	26		expect 30% reduction
$\tilde{\omega}'_p(T)$ (total)	114	77	70	
R_μ (total systematic)	157	98	100	
total	462	224	140	

Expected precision on a_μ



Conclusion: expect quite more precise a_μ measurement soon



Thanks for your attention!

Backup slides

FNAL Muon $g-2$ collaboration

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

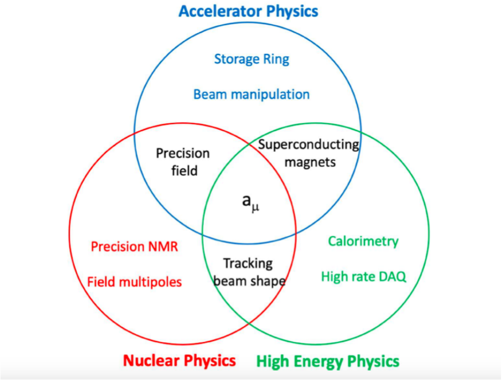
Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London



~200 collaborators
~40 institutions
7 countries

Main ω_a measurement systematics mentioned in E989 TDR

	E821 [ppb]	E989 improvement plans	goal [ppb]	Run 1 [ppb]
gain changes	120	better laser calibration low-energy threshold	20	20
pileup	80	low-energy samples recorded calorimeter segmentation	40	35
lost muons	90	better collimation in ring	20	5
CBO	70	higher n value (frequency) better match of beamline to ring	<30	38
E and pitch	50	improved tracker precise storage ring simulation	30	55
total	180		70	109

Focusing electric field and magic energy

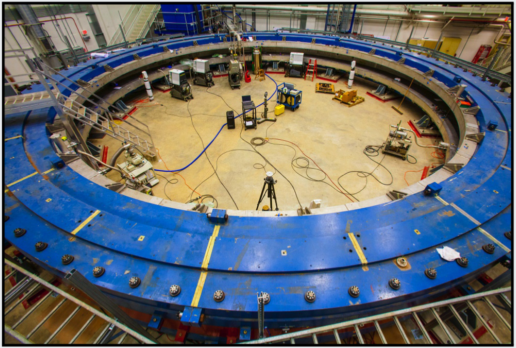
in presence of (focusing) electric field and motion not perfectly transverse to magnetic field

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

CERN 1975-, BNL, FNAL

$$p_\mu^{\text{magic}} = 3.094\,\text{GeV} \quad \Rightarrow \quad \gamma = 29.3$$

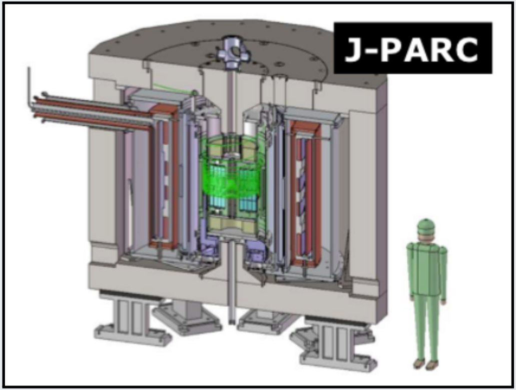
$$\Rightarrow \quad \left(a_\mu - \frac{1}{\gamma^2-1}\right) \simeq 0$$



J-PARC E34

ultra-cold muons

$$E = 0 \quad \Rightarrow \quad \vec{\beta}\times\vec{E} = 0$$



Beam dynamics frequencies

			f [MHz]	T [μs]
Anomalous precession	f_a		0.2291	4.3649
Cyclotron	f_c		6.7024	0.1492
Horizontal betatron	f_x	$= f_c\sqrt{1-n}$	6.2874	0.1590
Vertical betatron	f_y	$= f_c \cdot \sqrt{n}$	2.3218	0.4307
Coherent betatron oscillation	f_{CBO}	$= f_c - 1 \cdot fx$	0.4150	2.4097
Vertical oscillation	f_{VO}	$= f_c - 1 \cdot fy$	4.3806	0.2283
Vertical waist	f_{VW}	$= f_c - 2 \cdot fy$	2.0589	0.4857

field index $n = 0.12$

Measurement formula in more detail

$$a_\mu = \left[\frac{\omega_a}{\tilde{\omega}'_p(T)}\right] \cdot \left[\frac{\mu'_p(T)}{\mu_e(\mathrm{H})}\right] \left[\frac{\mu_e(H)}{\mu_e}\right] \left[\frac{m_\mu}{m_e}\right] \left[\frac{g_e}{2}\right]$$

(equivalent to

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

using CODATA constants)

measurements by the Muon $g-2$ collaboration

- ω_a — precession of muon spin relative to momentum rotation in magnetic field
- $\tilde{\omega}'_p(T)$ — precession frequency of shielded proton spin in spherical water sample at $T = 34.7\,^\circ\mathrm{C}$ in muon-beam-weighted magnetic field, $\tilde{\omega}'_p(T) = \langle \omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi)\rangle$

notation

- $\mu'_p(T)$ — magnetic momentum of proton in spherical water sample at 34.7 °C
- $\mu_e(\mathrm{H})$ — magnetic momentum of electron in hydrogen atom

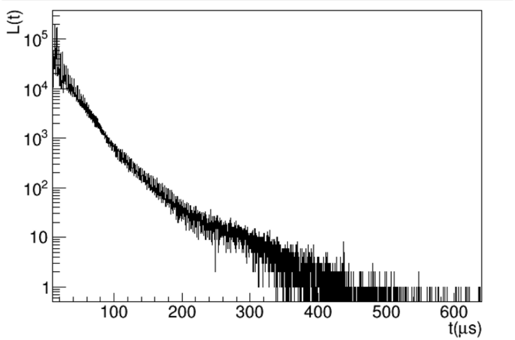
external measurements

- $\mu'_p(T)/\mu_e(H)$ — 10.5 ppb precision, Metrologia 13, 179 (1977)
- $\mu_e(H)/\mu_e$ — 5 ppq (negligible) theory QED calculation, Rev. Mod. Phys. 88 035009 (2016)
- m_μ/m_e — 22 ppb precision — CODATA 2018 fit, primarily driven by LAMPF 1999 measurements of muonium hyperfine splitting, Phys. Rev. Lett. 82, 711 (1999)
- $g_e/2$ — 0.28 ppt (negligible), Phys. Rev. Lett. 100, 120801 (2008)

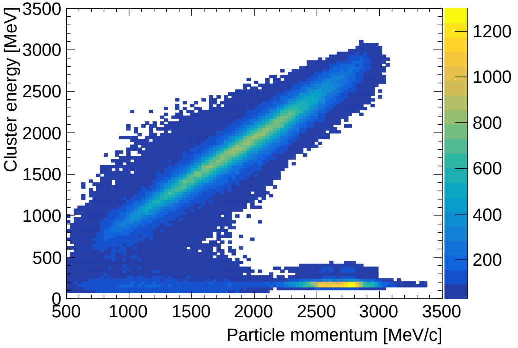
Extend ω_a fit model to account for lost muons on collimators

- some muons hit collimators and are lost
- muon loss rate during a fill measured with 3-4-5 coincidences of m.i.p. on calorimeters
- overall normalization of muon loss included as fit parameter

muon loss vs. time



energy in calorimeter vs. momentum in tracker



Early to late effects

- unaccounted variations of conditions during muon fill time can induce biases on ω_a fit result

example of early-to-late effect: phase variation due to muon loss

- $N(t) = N_0 e^{-t/\tau_\mu} [1 + A\cos(\omega_a t + \varphi)]$ phase $\varphi =$ muon spin-momentum angle at injection
- muon loss depends on momentum $\Rightarrow$ muon sample momentum varies $\bar{p} = \bar{p}(t)$
- single muon phase depends on momentum (because of production chain) $\bar{\varphi} = \bar{\varphi}(\bar{p})$
- at first order $\bar{\varphi}(t) = \bar{\varphi}_0 + \frac{d\bar{\varphi}}{dt} t = \bar{\varphi}_0 + \frac{d\bar{\varphi}}{d\bar{p}}\frac{d\bar{p}}{dt} t \simeq \bar{\varphi}_0 + \bar{\varphi}' t$
- muon rate modulation $\cos(\omega_a t + \bar{\varphi}(t)) \simeq \cos\left(\omega_a t + \bar{\varphi}_0 + \bar{\varphi}' t\right) = \cos[(\omega_a + \bar{\varphi}')t + \bar{\varphi}_0]$
  $\Rightarrow$ fit result for ω_a is biased when muon sample phase varies in the fit time window
- note: muon loss phase effect is different and additional to muon loss effect on positron rate

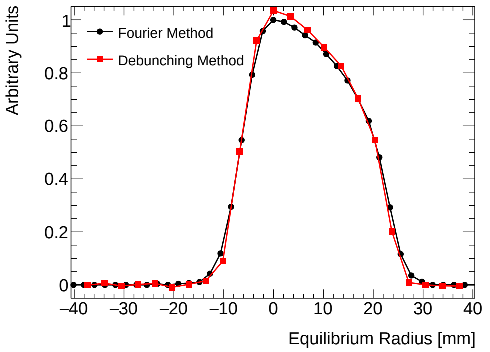
other early to late effects

- variation of calorimeter gain (corrected before the wiggle plot fit)
- variation of pileup (proportional to $[N(t)]^2$, corrected before the wiggle plot fit)
- variation of beam average position and size (phase acceptance)
- transient magnetic field due to electric quadrupoles plates vibration
- transient magnetic field due to kicker eddy currents

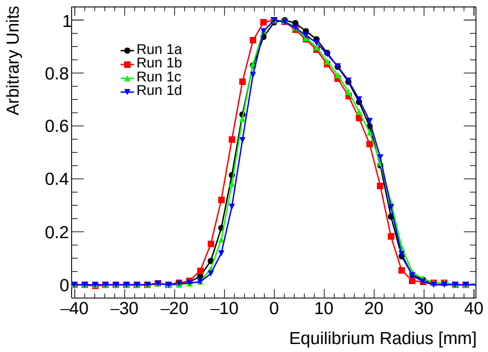
Electric field correction $C_e = +489 \pm 53$ ppb

- compute momentum distribution from electrons detected at early times after injection
  - using cosine Fourier transform of rate vs. time
  - measuring change of shape of rectangular bunches (debunching)
- compute radial muon distribution from momentum distribution
- compute electric field contribution to ω_a due to quadrupoles electric field

cosine Fourier vs. debunching method



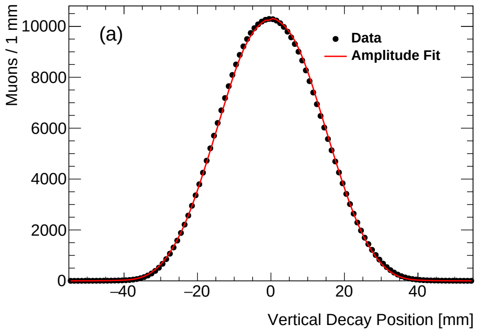
radial distributions in the four datasets



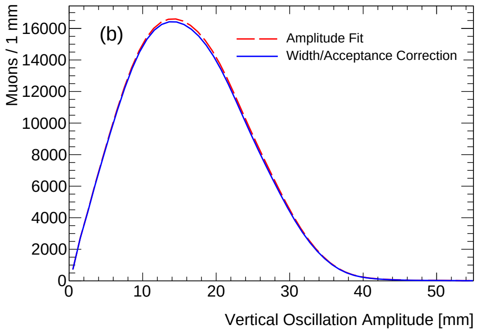
Pitch correction $C_p = +180 \pm 13\,\text{ppb}$

- reconstruct muon vertical position from decay electrons measurend on trackers
- compute corresponding pitch correction to ω_a

vertical decay vertices distribution

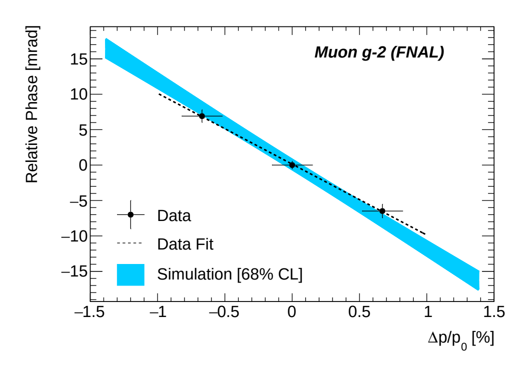


vertical oscittation amplitude distribution



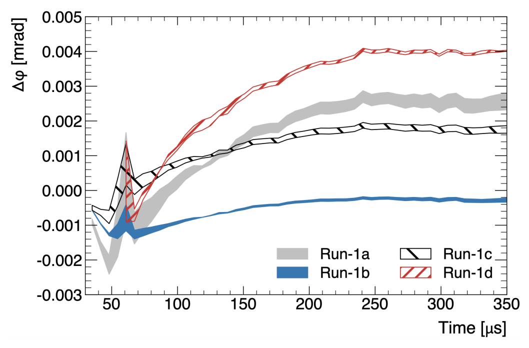
Lost muons phase-variation effect correction $C_{ml} = -11 \pm 5$ ppb

measured and simulated $\varphi - p$ correlation



- $\mathrm{d}\varphi/\mathrm{d}p$ measured on dedicated runs by varying magnetic field by -0.68%, +0.68%
- measurement consistent with simulation

estimated $\Delta\varphi(t)$ due to muon loss

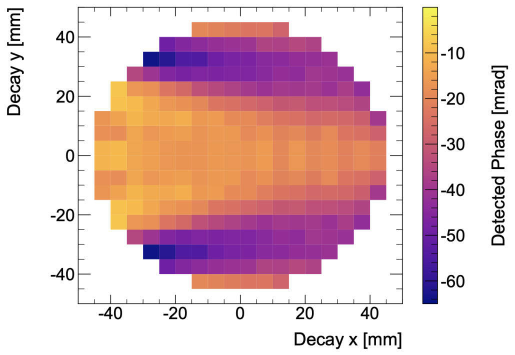


- use delivery ring collimators to change the muon momentum distribution
- muon loss function of time and momentum fitted using simulation-inspired analytic function to model observed beam loss for different muon momentum distributions

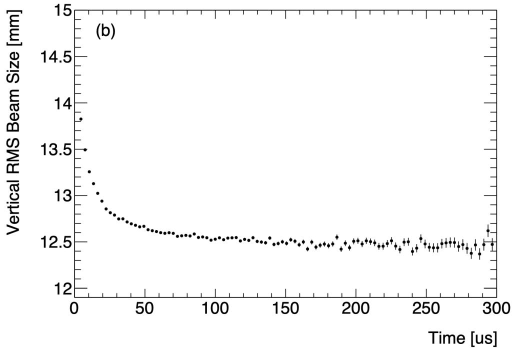
Phase-Acceptance correction $C_{pa} = -158 \pm 75$ ppb

- effective phase variation due to variation of beam horizontal and vertical position and spread
- example: $\Delta\omega_a = \frac{d\varphi}{dt} = \frac{d\varphi}{dY_{RMS}} \cdot \frac{dY_{RMS}}{dt}$
- obtained with simulation
- measured with trackers and extrapolated to whole ring with beam dynamics simulations

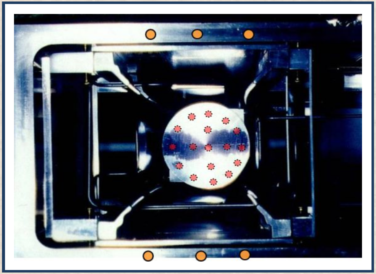
phase as a function of muon position



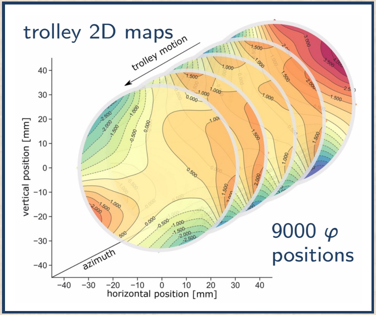
variation of Y_{RMS}

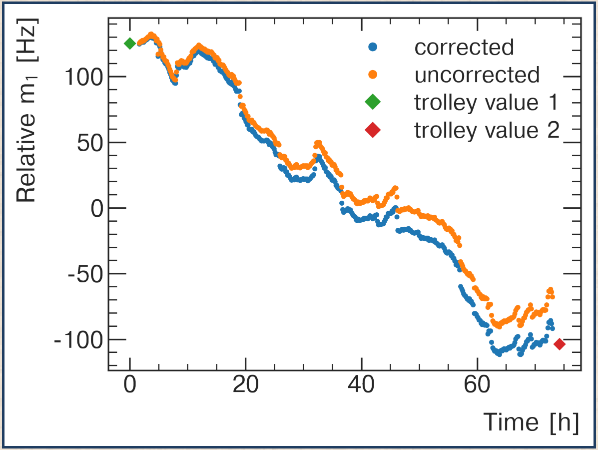


Measuring ω_p / magnetic field with fixed and trolley probes



- 378 fixed probes measure continuosly the magnetic field
- 17-probes trolley run along muons path every $\sim$3 days
- fixed probes measurements corrected using trolley measurements





Measuring ω_p magnetic field: calibration of probes

calibration

- each trolley probe calibrated with absolute cylindrical probe placed in the same position inside the storage ring
- absolute cylindrical probe calibrated to reference absolute spherical probe in MRI magnet at Argonne National Laboratory
- absolute spherical probe consistent with novel absolute ^{3}He probe
- 17 probes calibration uncertainty 20 – 48 ppb

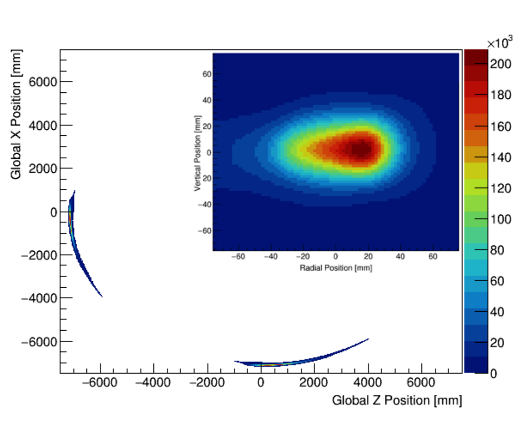
reference temperature

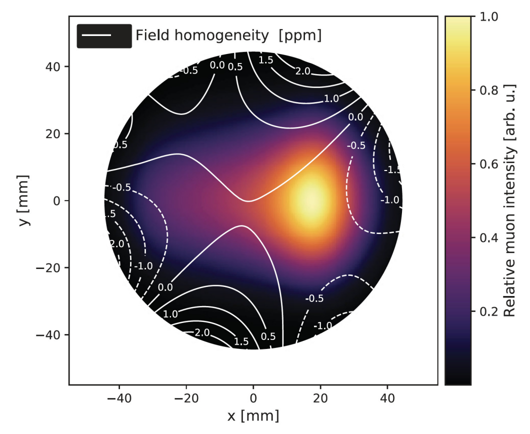
- magnetic field measurements corrected to be expressed as $\omega'_p(T)$, precession frequency of shielded proton spin in spherical water sample at reference temperature of 34.7 °C

absolute spherical probe

$\tilde{\omega}'_p(T)$ (magnetic field experienced by the muons) measured to 56 ppb

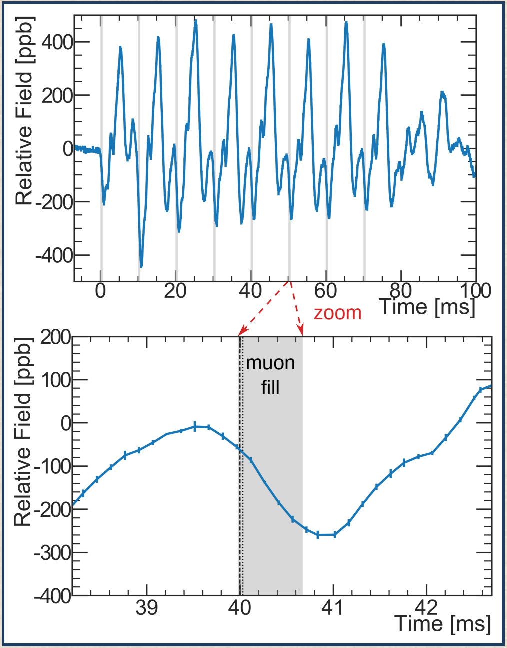
- tracker reconstructs muons decay vertices in parts of storage region
- beam dynamics simulation used to extrapolate to whole storage region
- magnetic field map averaged over muon distribution
- two independent groups did the measurement, one additional group the calibration





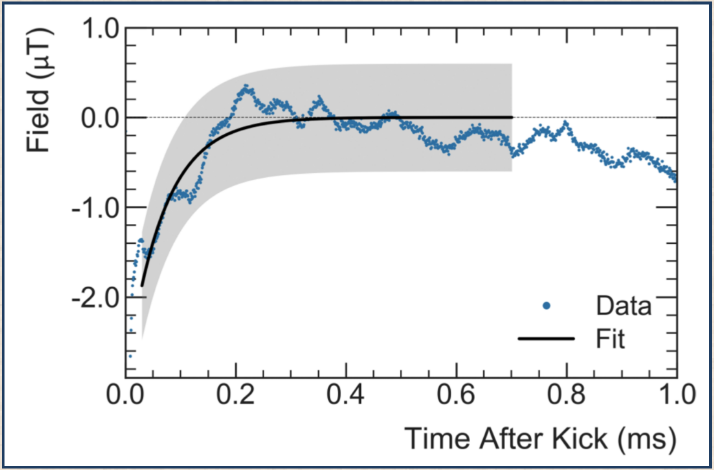
Electric quadrupoles transient field correction $B_q = -17 \pm 92$ ppb

- electric quadrupoles are pulsed (to prevent static charge accumulation)
- plates vibration perturbs magnetic field
- special NMR probes measure the transient field perturbation in muon region
- large uncertainty because mapping incomplete will improve in Run 2+



Kicker magnets transient field correction $B_k = -27 \pm 37\,\text{ppb}$

- kicker magnets pulsed before start of fit window
- induced eddy currents perturb magnetic field inside fit window
- magnetic field perturbation measured with a Faraday effect magnetometer



FNAL-E989 Run 1 $\omega_a/\tilde{\omega}'_p(T)$ measurement

	Correction	Uncertainty	Design goal
ω_a^m (statistical)	–	434	100
ω_a^m (systematic)	–	56	
base clock	–	2	
C_e	489	53	
C_p	180	13	
C_{ml}	-11	5	
C_{pa}	-158	75	
ω_a beam dynamics corrections ($C_e + C_p + C_{ml} + C_{pa}$)	499	93	
ω_a total systematic	499	109	70
$\omega'_p(T)(x, y, \varphi)$	–	54	
$M(x, y, \varphi)$	–	17	
$\langle \omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi) \rangle$	–	56	
B_q	-17	92	
B_k	-27	37	
$\tilde{\omega}'_p(T)$ transient fields corrections ($B_q + B_k$)	-44	99	
$\tilde{\omega}'_p(T)$ total [note: correction sign now for $\omega_a/\tilde{\omega}'_p(T)$]	44	114	70
$\omega_a/\tilde{\omega}'_p(T)$ total systematic	544	157	100
external measurements	–	25	
total [correction is for $\omega_a/\tilde{\omega}'_p(T)$]	544	462	140