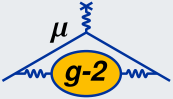
Status of the Fermilab Muon $g-2$ experiment

Alberto Lusiani
Scuola Normale Superiore and INFN, sezione di Pisa
on behalf of the Fermilab Muon $g-2$ Collaboration

SCUOLA NORMALE SUPERIORE

Introduction

- muon magnetic moment anomaly $a_\mu = \dfrac{g_\mu - 2}{2}$, $\quad \vec{\mu}_\mu = g_\mu \dfrac{q_\mu}{2m_\mu} \vec{S}_\mu$
- potentially sensitive to all known and **unknown** particles and forces
- because of the fundamental interconnectedness of all things [1],
  can search for Axions, WIMPs and WISPs by doing precision measurements on muons

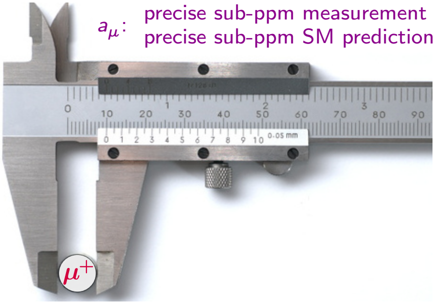


[1] D.Adams, Dirk Gently's Holistic Detective Agency

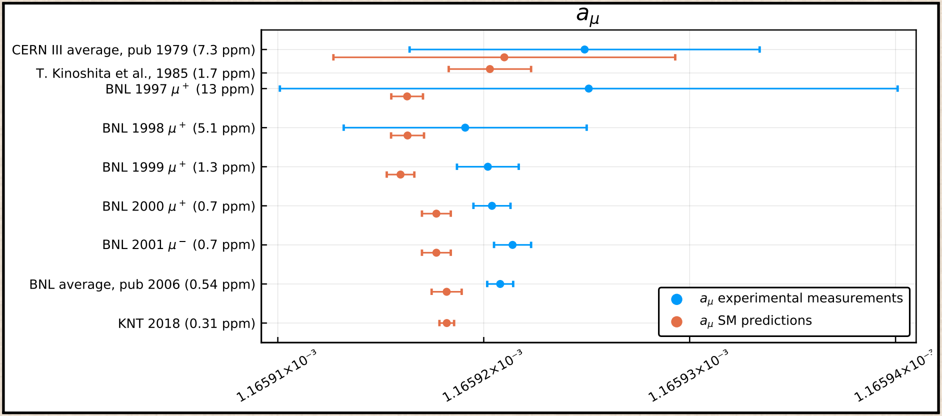
Searching for the unknown

Precisely measuring the well-known

a_μ: precise sub-ppm measurement
precise sub-ppm SM prediction

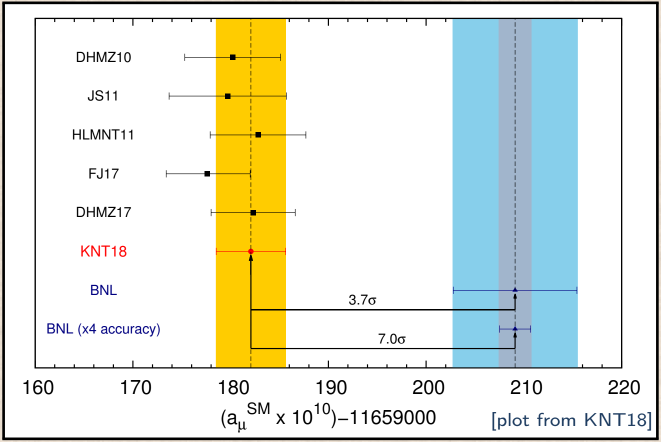


a_μ: measurements vs. SM predictions since 1979



- KNT18, Keshavarzi, Nomura, Teubner, arXiv:1802.02995, PRD 97, 114025 (2018)
- other SM predictions exist in addition to KNT18, e.g.
  - F. Jegerlehner, arXiv:1711.06089
  - Davier, Hoecker, Malaescu, Zhang, arXiv:1706.09436

The anomaly on the muon magnetic anomaly



[plot from KNT18]

- FNAL Muon $g-2$ collaboration (E989) aims at measuring a_μ with precision $\Delta a_\mu = 140$ ppb, $\sim$4 times better than BNL E821 (540 ppb)
- $\Rightarrow$ either find evidence of New Physics or provide stronger constraints on BSM models

The E989 collaboration

Domestic Universities

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

National Labs

- Argonne
- Brookhaven
- Fermilab

China

- Shanghai

Germany

- Dresden

Italy

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

Korea

- CAPP/ISB
- KAIST

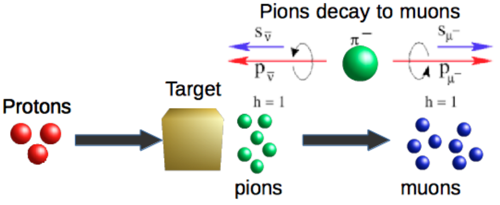
Russia

- Budker/Novosibirsk
- JINR Dubna

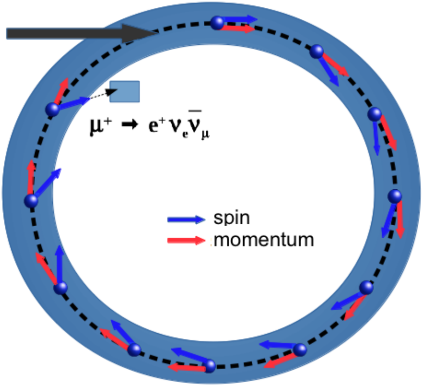
United Kingdom

- Lancaster/Cockcroft
- Liverpool
- University College London

a_μ measurement method



Polarized muons are injected into a magnetic storage ring and will precess in the magnetic field.



measure rotation of spin w.r.t. momentum for a muon rotating in a magnetic field

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

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

Larmor + Thomas precessions — cyclotron frequency — no γ!

a_μ measurement method, uncertainties, E989 goals

using proton spin precession (NMR) to measure B, $\omega_p = \mu_p \frac{q_p B}{m_p}$

using $\mu_{e,\mu,p} = g_{e,\mu,p} \frac{q_{e,\mu,p}}{2m_{e,\mu,p}} S_{e,\mu,p}$, $|q_{e,\mu,p}| = e$, $S_{e,\mu,p} = \hbar/2$

$$a_\mu^{\text{exp}} = \frac{g_e}{2} \frac{\omega_a}{\omega_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$$

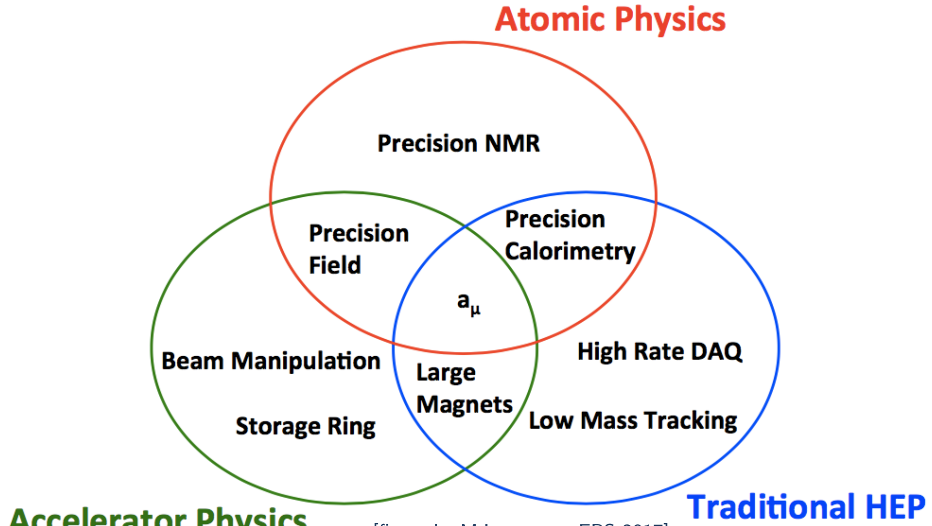
a_μ uncertainties budget

ω_a/ω_p	540 ppb	BNL E821 final report
ω_a statistical	460 ppb	
ω_a systematic	210 ppb	
ω_p systematic	170 ppb	
g_e	0.00026 ppb	CODATA 2014
m_μ/m_e	22 ppb	CODATA 2014
μ_p/μ_e	3 ppb	CODATA 2014

note: BNL measurement not systematically limited

	BNL E821	FNAL E989	
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
total	540 ppb	140 ppb	

Combine techniques of three areas of experimental Physics



[figure by M.Lancaster, EPS 2017]

a_μ measurement method, effect of electric field

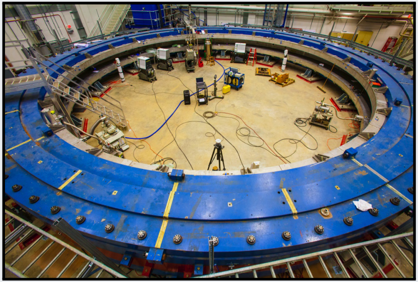
in a storage ring, if electric fields are used for focusing and containment of particles

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

CERN 1975-, BNL, FNAL

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

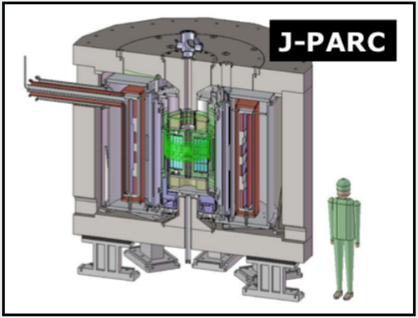
$$\Rightarrow \quad \left(a_\mu - \frac{1}{\gamma^2 - 1}\right) \simeq 0$$



J-PARC E34

ultra-cold muons

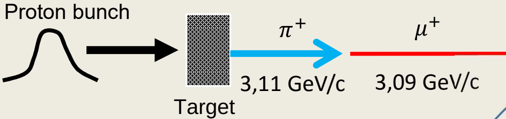
$$E = 0 \quad \Rightarrow \quad \vec{\beta}\times\vec{E} = 0$$



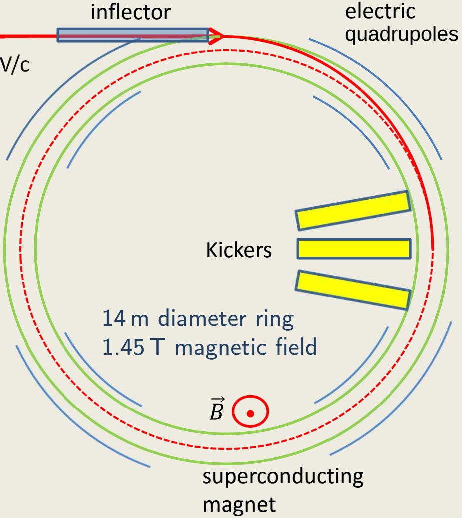
Transport the storage ring from BNL to FNAL

[figure by A.Driutti, Tau 2018]

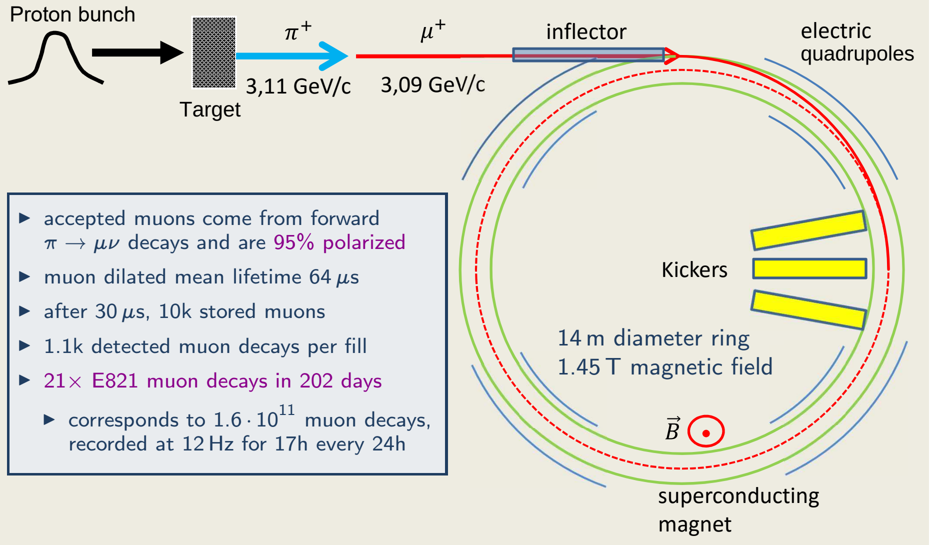
Muon production, storage and decay at FNAL (design numbers)



- FNAL booster+recycler: 12 Hz rate of 120 ns-long 10^{12} 8 GeV proton bunches
- protons hit target and produce pions
- pions focused with lithium lens
- pions with $p = 3.11$ GeV $\pm$ 10% selected
- pions decay into muons
- 3.09 GeV muons accepted in delivery ring, separation from p's and π's
- muons fills injected in storage ring using inflector canceling magnetic field
- kickers produce short magnetic pulse to put muons in correct orbit (shorter than revolution period)

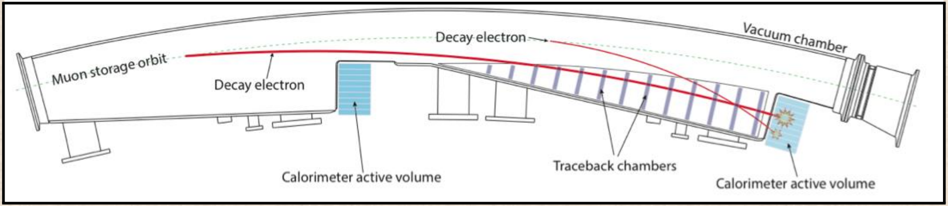


Muon production, storage and decay at FNAL (design numbers)



- accepted muons come from forward $\pi \to \mu\nu$ decays and are 95% polarized
- muon dilated mean lifetime 64 μs
- after 30 μs, 10k stored muons
- 1.1k detected muon decays per fill
- 21$\times$ E821 muon decays in 202 days
  - corresponds to $1.6 \cdot 10^{11}$ muon decays, recorded at 12 Hz for 17h every 24h

Detector



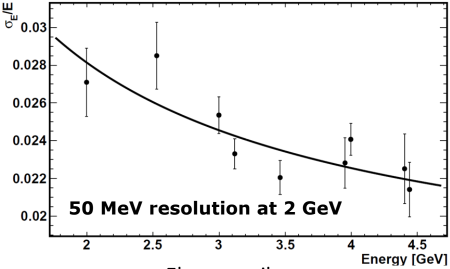
- 24 calorimeter modules of 6×9 PbF_2 crystals with SiPM readout along inside the ring
  - detect muon decay electrons, measure energy from Cherenkov light (fast)
- 3 straw chamber trackers with total of 1500 channels
  - reconstruct beam distribution inside storage ring from tracked muon decay electrons
- auxiliary detectors for beam position monitoring (fiber harps, entrance counters)
- laser calibration system to monitor and calibrate calorimeter energy measurements

comparison with E821

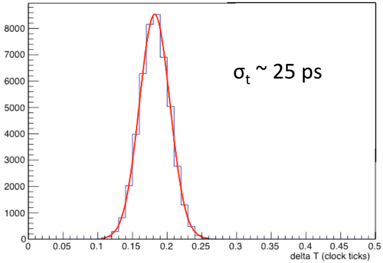
- more granular calorimeter, better tracker, faster data acquisition stores low-energy hits
- improved laser calibration system

calorimeter performance

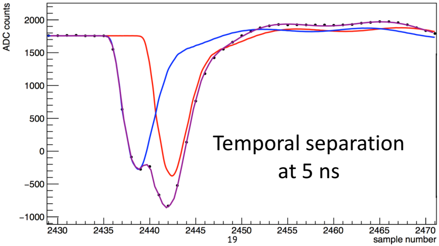
Energy Resolution



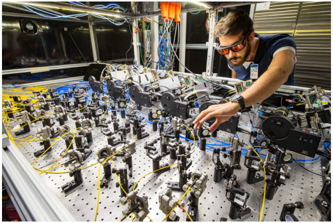
Timing Resolution



Electron pile-up



laser calibration system monitors calorimeter gain to 10^{-4}

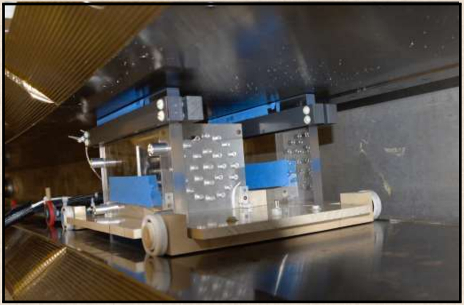


magnetic field

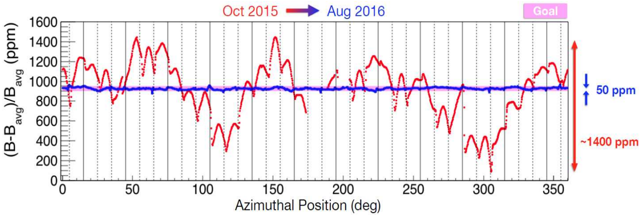
- make magnetic field as uniform as possible (shimming)
- keep magnets mechanically and thermally stable
- monitor field with fixed probes
- periodically map field inside storage ring with NMR probe trolley
  - pulsed proton NMR, < 10 ppb single shot precision

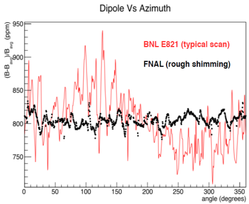
- BNL E821 precision
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989 goal
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

trolley with NMR probes for measurement of magnetic field inside the storage ring



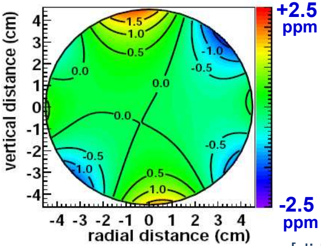
magnetic field shimming





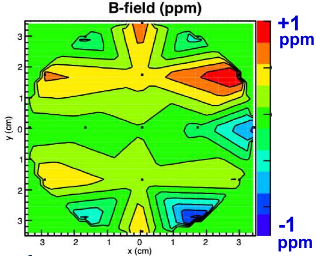
Shim 1.45 T field to high uniformity and measure it vs time

BNL Field Map



Averaged over azimuth: Shimmed to ± 1 ppm level

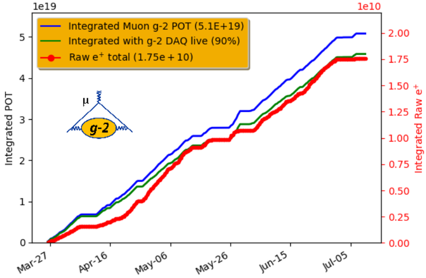
Field Map on 03/17/2018



[slide from Liang Li, ICHEP 2018]

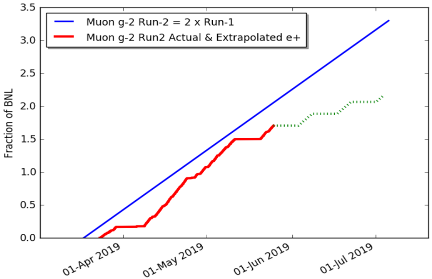
Recorded muon decays

Run 1, Apr-Jun 2018



- collected 1.4×BNL good data

Run 2, Apr-Jun 2019



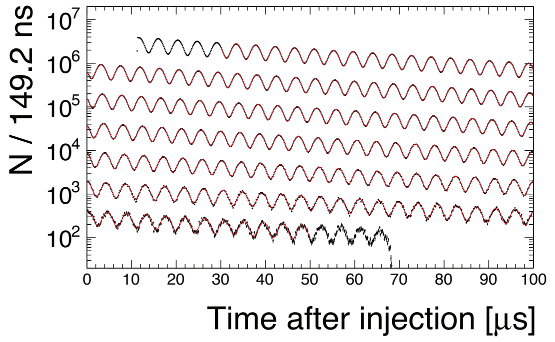
- expect 2.2×BNL data

- now running with fills of about 500 muons, 50% of design
- about 30% more muons from Run 1 to Run 2
- several items have performances 5-20% less than design:
  - lithium lens, kickers, quadrupoles, beamline aperture
  - DAQ up-time, accelerator up-time
- shutdown work will provide some improvement for Run 3, starting Oct 2019

ω_a measurement, canonical wiggle plot

- let polarized muons in magnetic field decay for 700 μs (lab muon lifetime $\gamma\tau_\mu = 64\,\mu$s)
- higher energy electrons from muon decay correlated with muon spin
- rate of electrons above threshold of $0.6E_{\rm MAX}$ over 700 μs fill is decaying exponential modulated by the precession frequency

E989 T-method wiggle plot fit (illustrative)

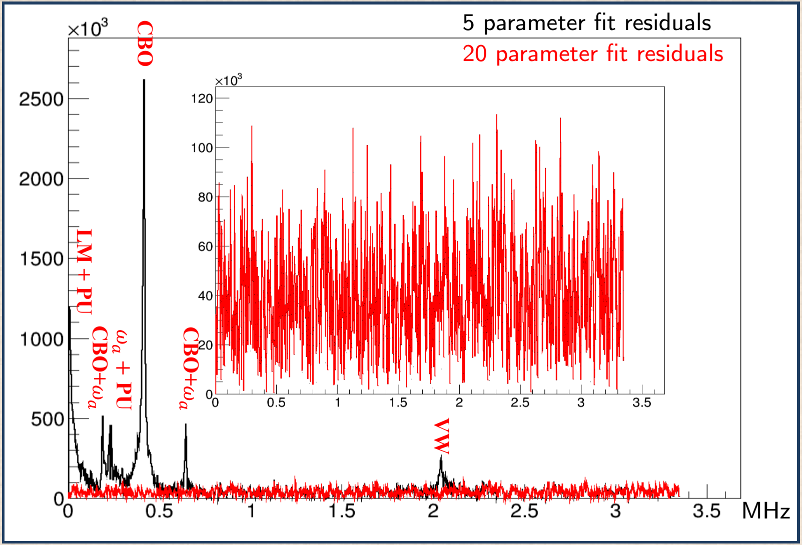


$$N(t) =$$

$$N_0 e^{-t/\tau} \cdot (1 + A\cos(\omega_a t + \phi_a))$$

5 parameters: N_0, τ, A, ω_a, ϕ_a

Fourier analysis of ω_a fit residuals (illustrative)



ω_a 20-parameter fit function
(example, different analyses have different details)

$$N(t) = N_0 \cdot \Lambda(t) \cdot N_{1\mathrm{CBO}}(t) \cdot N_{2\mathrm{CBO}}(t) \cdot N_{VW}(t) \cdot e^{-t/\tau} \left[1 + A_0 \cdot A_{1\mathrm{CBO}}(t) \cdot \cos(\omega_a(R) \cdot t + \phi_0 + \phi_{1\mathrm{CBO}}(t))\right]$$

$$\Lambda(t) = 1 - \kappa_{\mathrm{loss}} \int_0^t L(t') \cdot e^{t'/\tau}\, dt',$$

$$N_{1\mathrm{CBO}}(t) = 1 + A_{N,1\mathrm{CBO}} \cdot \cos(\omega_{\mathrm{CBO}}(t) \cdot t + \phi_{N,1\mathrm{CBO}}) \cdot e^{-t/\tau_{\mathrm{CBO}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{N,2\mathrm{CBO}} \cdot \cos(2\,\omega_{\mathrm{CBO}}(t) \cdot t + \phi_{N,2\mathrm{CBO}}) \cdot e^{-t/\tau_{\mathrm{CBO}}}$$

$$N_{\mathrm{VW}}(t) = 1 + A_{N,\mathrm{VW}} \cdot \cos(\omega_{\mathrm{VW}} \cdot t + \phi_{N,\mathrm{VW}}) \cdot e^{-t/\tau_{\mathrm{VW}}}$$

$$A_{1\mathrm{CBO}}(t) = 1 + A_{A,1\mathrm{CBO}} \cdot \cos(\omega_{\mathrm{CBO}}(t) \cdot t + \phi_{A,1\mathrm{CBO}}) \cdot e^{-t/\tau_{\mathrm{CBO}}}$$

$$\phi_{1\mathrm{CBO}}(t) = A_{\phi,1\mathrm{CBO}} \cdot \cos(\omega_{\mathrm{CBO}}(t) \cdot t + \phi_{\phi,1\mathrm{CBO}}) \cdot e^{-t/\tau_{\mathrm{CBO}}}$$

ω_a measurement

- several analyses performed in parallel
- blinding techniques used to prevent experimenter biases
- two reconstruction methods from ADC counts to caloritemer clusters
- variations of T-method wiggle plot fit
  - Q method: fit variation of total energy in calorimeters
  - asymmetry-weighted method: weight decays with amplitude of wiggle $= f(E)$
  - energy-binned method: fit number of events in several energy bins
  - ratio method: use data to divide out the exponential decay

Conclusions

- E989 recorded data since April 2018
- reached about 50% of design luminosity since June 2018
- Run 2 ends in early July 2019
- Run 3 expected to begin on October 2019
  - planned improvements during the shutdown (inflector)
- by July 2019 E989 will have about 3.6 $\times$ the BNL statistics
- aim at a preliminary result by the end of 2019
  - ω_a statistical precision $\sim 2\times$ better than BNL
  - finalization of systematic uncertainties' estimates will require time
- by 2021 expect to collect 21 $\times$ the BNL statistics

Backup Slides

First g_μ measurement (1957)

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

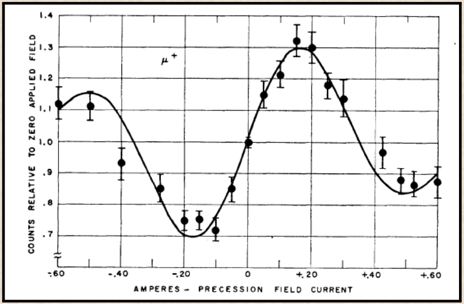
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

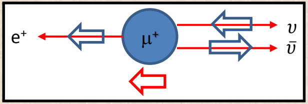
(Received January 15, 1957)

LEE and Yang[1–3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \to \mu^+ + \nu, \quad (1)$$

$$\mu^+ \to e^+ + 2\nu. \quad (2)$$





- study muon decays in magnetic field
- measurement of $g_\mu = 2.01 \pm 0.01$
- observation of parity violation in μ decay

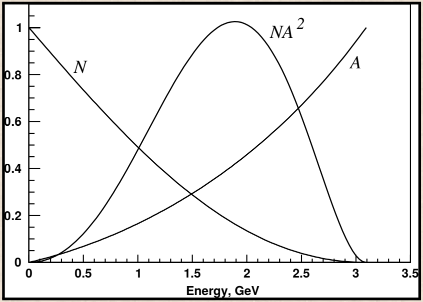
a_μ experimental measurements since 1960

	data	pub		$a_\mu \cdot 10^3$	δa_μ
CERN cyclotron		1960		1.13 (14)	12.4%
CERN cyclotron		1961		1.145 (22)	1.9%
CERN cyclotron		1962		1.162 (5)	0.43%
CERN synchroton		1966		1.165 (3)	0.27%
CERN synchroton		1968		1.166 16 (31)	270 ppm
CERN synchroton	1975-1977	1979	μ^+	1.165 910 0 (110)	9.4 ppm
CERN synchroton	1976-1977	1979	μ^-	1.165 937 0 (120)	10 ppm
CERN synchroton	average	1979	$\mu^\pm$	1.165 924 9 (85)	7.3 ppm
BNL	1998		μ^+	1.165 919 1 (59)	5 ppm
BNL	1999		μ^+	1.165 920 2 (14) (6)	1.3 ppm
BNL	2000	2004	μ^+	1.165 920 3 (6) (5)	0.7 ppm
BNL	2001	2004	μ^-	1.165 921 4 (8) (3)	0.7 ppm
BNL	average	2006	$\mu^\pm$	1.165 920 89 (54) (33)	0.54 ppm

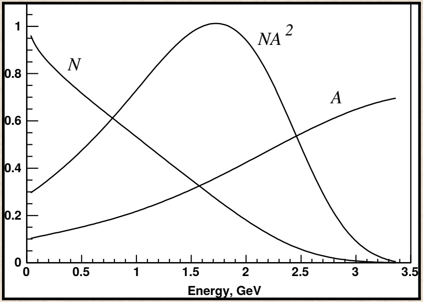
ω_a measurement statistical uncertainty

- fit $N_e(E_e > E_{thr}) = N_0(E_{thr}) e^{-t/\gamma\tau} [1 + A(E_{thr}) \cos(\omega_a t + \phi(E_{thr}))]$
- $\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a \gamma \tau_\mu} \sqrt{\frac{2}{N A^2 P^2}}$ N = number of muons, P = muon polarization, A = asymmetry
  - improves with B field since $\omega_a \propto B$
  - improves with number of muons, asymmetry, polarization
  - improves with muon momentum (γ)

E_{thr} dependence for E821



E_{thr} dependence including E821 acceptance



ω_a measurement systematics

largest systematic contributions to ω_a

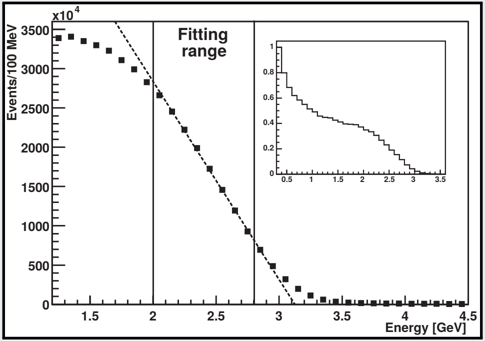
	E821 [ppb]	E989 improvement plans	goal [ppb]
gain changes	120	better laser calibration low-energy threshold	20
pileup	80	low-energy samples recorded calorimeter segmentation	40
lost muons	90	better collimation in ring	20
CBO	70	higher n value (frequency) better match of beamline to ring	<30
E and pitch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

CBO = coherent betatron oscillation due to quadrupole focusing

pitch = oscillating vertical inclination of muon momentum

ω_a systematics from detector gain variation (E821)

- detector gain variation causes effective E_{thr} variation $\Rightarrow$ ω_a shift
- large event rate variation over one fill causes deterministic gain variation within fills
- laser gain calibration system could not be used (unknown systematics)
- fit gain variation in fill from E spectrum end-point: $\dfrac{G(t)-G(\infty)}{G(\infty)} = f \cdot \dfrac{\bar{E}(t)-\bar{E}(\infty)}{\bar{E}(\infty)}$
- estimated systematic is 100% of the correction

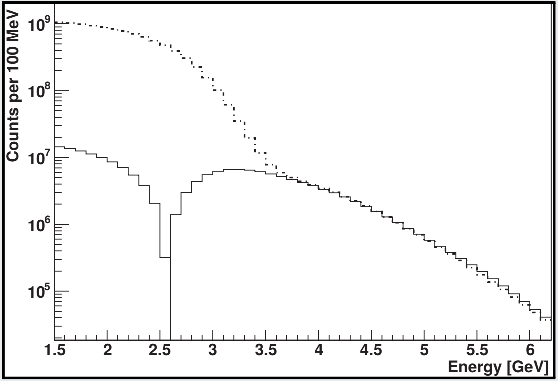


ω_a systematics from event pileup (E821)

- double event pileup probability $\propto$ event rate square ($e^{2t/\gamma\tau}$), affects ω_a fit
- at each time, contribution from pileup to energy distribution subtracted on average
- $D(E,t)$ energy distribution of actually pileup of "trigger" pulse and "shadow" pulse
- $S_T(E,t)$ energy distribution of "trigger" pulse
- $S_S(E,t)$ energy distribution of additional "shadow" pulse on top of "trigger" pulse
- pileup contribution $P(E,t) = D(E,t) - S_T(E,t) - S_S(E,t)$
- subtracting $P(E,t)$ from measured energy distribution restores true energy distribution
  - consistency check: resulting energy distribution invariant w.r.t. event rate
  - use to correct above-energy-threshold counts
  - systematic uncertainty from approximations of procedure

ω_a systematics from event pileup (E821)

pileup contribution to N(E,t), $P(E,t) = D(E,t) - S_T(E,t) - S_S(E,t)$



- dotted line corresponds to observed distribution
- pileup contribution is negative for $E < 2.5\,\text{GeV}$, but plotted as positive
- above 3.1 GeV total observed distribution corresponds to pileup as expected

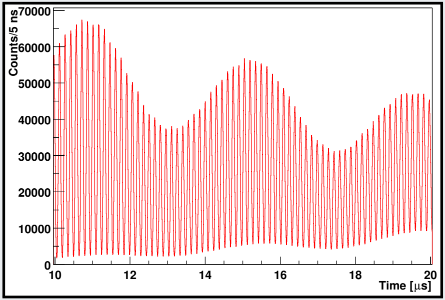
ω_a systematics from lost muons (E821)

- storage ring defects may originate periodic forces that lead to muon losses
- beam scraping short after injection reduces further losses of marginal injected muons
- dedicated scintillators on triple coincidence detect lost muons
- muon loss is included in the fit
- uncertainties on lost muons phase contribute to ω_a systematic uncertainty

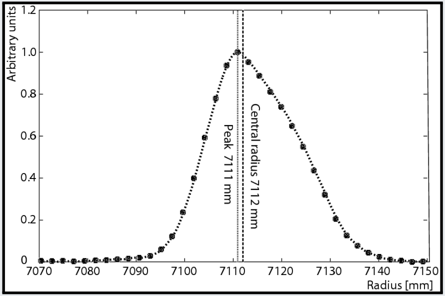
ω_a systematics, fast rotation interlude (E821)

- muons are injected as a short bunch
- muon momentum spread progressively distributes bunch over whole ring
- bunch spreading measured from event rate variation with cyclotron frequency

detected electron rate modulation with cyclotron frequency, decreasing in amplitude as the bunch spreads

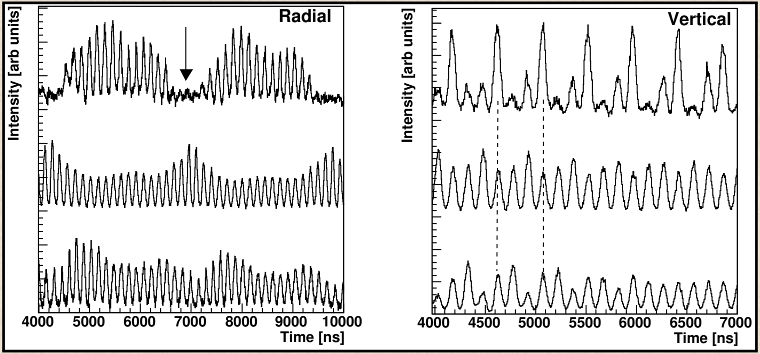


reconstructed muons radial distribution from fast rotation measurement



ω_a systematics from coherent betatron oscillations or CBO (E821)

- electric field quadrupole focusing causes betatron oscillations
- beam oscillations detected with scintillating fiber beam monitors
- beam oscillations start with amplitude determined by beam injection
- beam oscillations amplitude decays due to tune spread (focusing quads imperfections)



muons on inner, middle, outer fiber

muons on top, middle bottom fiber

ω_a systematics from coherent betatron oscillations or CBO (E821)

Physical frequency	Variable	Expression	Frequency	Period
Anomalous precession	f_a	$\frac{e}{2\pi m} a_\mu B$	0.23 MHz	4.37 μs
Cyclotron	f_c	$\frac{v}{2\pi R_0}$	6.71 MHz	149 ns
Horizontal betatron	f_x	$\sqrt{1-n} f_c$	6.23 MHz	160 ns
Vertical betatron	f_y	$\sqrt{n} f_c$	2.48 MHz	402 ns
Horizontal CBO	f_{CBO}	$f_c - f_x$	0.48 MHz	2.10 μs
Vertical waist	f_{VW}	$f_c - 2f_y$	1.74 MHz	0.57 μs

- horizontal CBO modulates detector acceptance hence N, A and ϕ
- amplitude and decay time of all modulations are fit on wiggle plot
- CBO effects suppressed by factor ~10 by approx. detector azymuthal symmetry
- CBO systematic contribution from varying remaining fixed parameters not fit on data

ω_a systematics from electric field corrections (E821)

electric-field correction

- momentum and beam radial spread induces non-zero electric field corrections
- $\left\langle \frac{\delta\omega_a}{\omega_a} \right\rangle = -2\beta^2 n(1-n) \left\langle \left(\frac{R}{R_0} \right)^2 \right\rangle$
- radial spread measured from fast rotation analysis
- additionally
  - σ on muon radius vs. E quadrupole center ± 0.5 mm (± 0.01 ppm in a_μ)
  - σ on muon vertical position vs. E quadrupole center ± 1 mm (± 0.02 ppm in a_μ)
- typical uncertainty on correction 50 ppb for single run

ω_a systematics from pitch corrections (E821)

- vertical inclination of muon momentum of angle ψ, $\dfrac{\delta\omega_a}{\omega_a} = -\dfrac{1}{2}\psi^2$
- $\psi_m =$ amplitude of angle oscillation
- $\langle\psi_m^2\rangle = n\langle y^2\rangle / R_0^2$, $\quad\langle y^2\rangle$ mean-squared vertical spread measured with FBM
- average effect of oscillation on muon ensemble $\dfrac{1}{4}\langle\psi_m^2\rangle$
- typical uncertainty on correction 40 ppb for single run

ω_p systematics from absolute calibration of standard probe (E821)

- ideal case: precession of free protons in vacuum, unperturbed B field
- reality:
  - protons in water with a $CuSO_4$ additive
  - B field perturbed by magnetization of the materials in probe and trolley

absolute calibration

- absolute calibration probe, protons in water sphere, low magnetic susceptibility
- correction of $\tilde{\omega}_p$ in water to vacuum using
  - ratio of g for proton in water to g of e in ground state of hydrogen atom (10 ppb)
  - ratio of g electron to proton in hydrogen (9 ppb)
  - proton g corrections from vacuum to bound state (theory calculatiom, 9 ppb)

ω_p measurement systematics, part 1

	E821 [ppb]	E989 improvement plans	goal [ppb]
absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
trolley probe calibration	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
trolley measurements of B_0	50	reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
time-dependent external magnetic fields	-	direct measurement of external fields; simulations of impact; active feedback	5

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ω_p measurement systematics, part 2

	E821 [ppb]	E989 improvement plans	goal [ppb]
		...	
higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
total	170		70