Muon $g-2$
Current experimental status and future prospects

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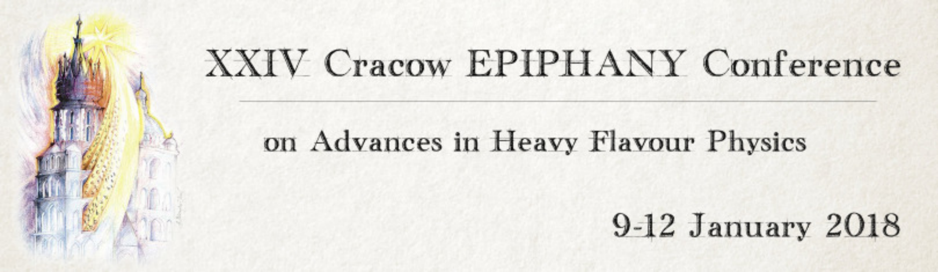


Magnetic moment, gyromagnetic factor, gyromagnetic anomaly

muon magnetic moment $\vec{\mu}_\mu = g_\mu \frac{q_\mu}{2m_\mu} \vec{S}_\mu$,

q_μ = muon charge
$\vec{S}_\mu$ = muon spin
g_μ = muon gyromagnetic factor

- $g_\mu = 2$ Dirac equation
- $g_\mu > 2$ QED, due to radiative corrections

muon gyromagnetic anomaly $a_\mu = \frac{g_\mu - 2}{2}$

- Standard Model prediction: $a_\mu = \frac{\alpha}{2\pi}$ + higher order corrections
- muon spin precession in magnetic field, at rest: $\omega_s = -g_\mu \frac{q_\mu B}{2m_\mu}$

g_μ measurement

- g_μ from measurements of ω_s, B, m_μ; $q_{\mu^-} = -e$
- g_μ accurately predicted by the theory ⇒ test theory and search for New Physics effects

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

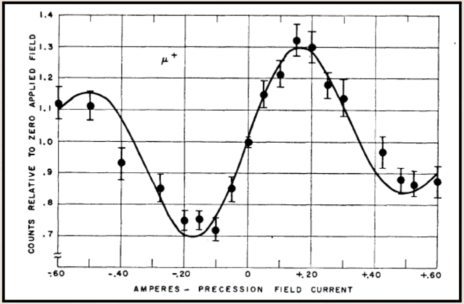
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

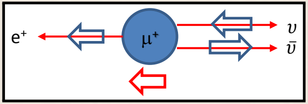
(Received January 15, 1957)

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

$$\pi^+ \to \mu^+ + \nu, \tag{1}$$

$$\mu^+ \to e^+ + 2\nu. \tag{2}$$



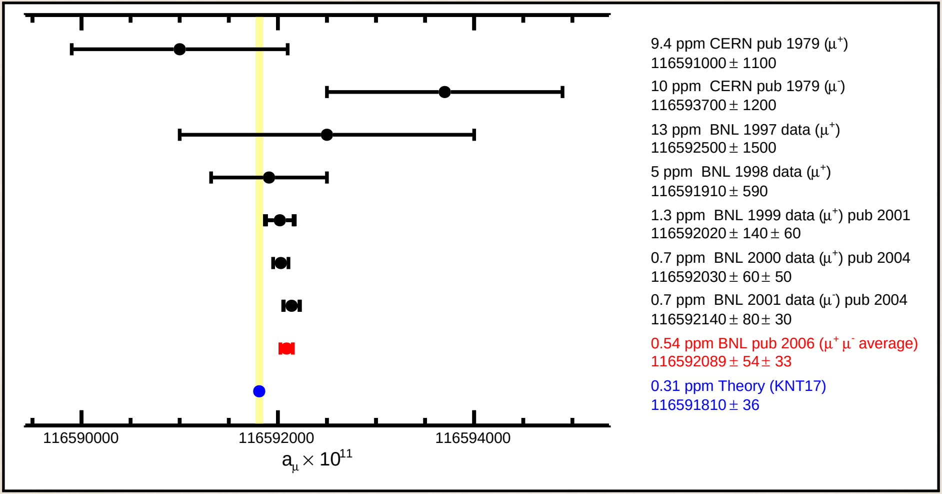


- study muon decays in magnetic field
- measurement of $g_\mu = 2.01 \pm 0.01$
- observation of parity violation in μ decay

a_μ experimental measurements since 1960

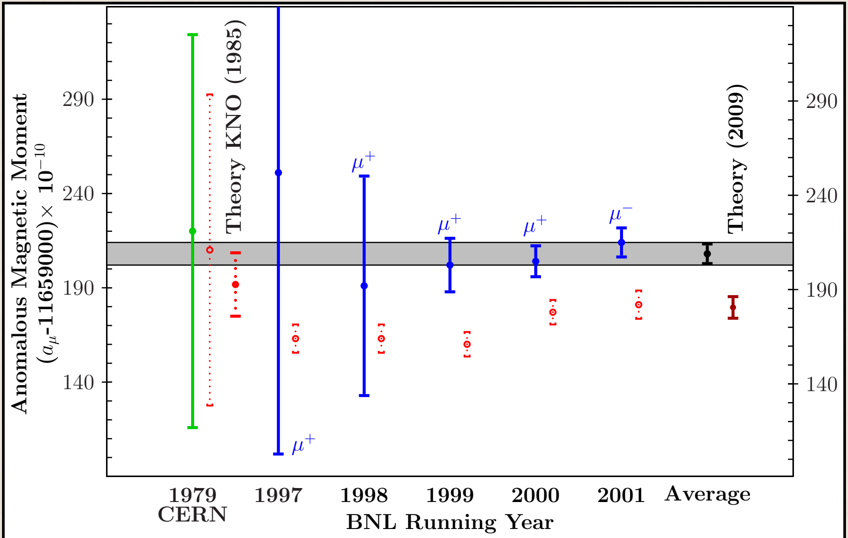
	data	pub		$a_\mu \cdot 10^3$	δa_μ
CERN cyclotron		1960		1.13 (14)	12.4%
CERN cyclotron		1961		1.145 (22)	1.9%
CERN cyclotron		1962		1.162 (5)	0.43%
CERN synchroton		1966		1.165 (3)	0.27%
CERN synchroton		1968		1.166 16 (31)	270 ppm
CERN synchroton	1975-1977	1979	μ^+	1.165 910 0 (110)	9.4 ppm
CERN synchroton	1975-1977	1979	μ^-	1.165 937 0 (120)	10 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	2000-2001	2006	$\mu^\pm$	1.165 920 89 (54) (33)	0.54 ppm

a_μ experimental measurements since 1979 vs. theory



exp. vs. theory discrepancy 2.9−3.9σ (M.Passera, Trento, Sep 2017)

a_μ experimental measurements, experiment vs. theory



[plot from F. Jegerlehner & A. Nyffeler, The muon $g-2$, Phys.Rep. 477 (2009) 1]

planned a_μ experimental measurements

experiment	δa_μ goal	status
FNAL E989	140 ppb total	commissioning run in 2017, starts in 2018
J-PARC E34 - phase 1	370 ppb stat	approved, expected to begin in ∼2020
- phase 2	100 ppb stat	proposed
BNL E821	540 ppb	completed in 2001
KNT17 (theory)	310 ppb	2017

improvement on exp. vs. theory comparison

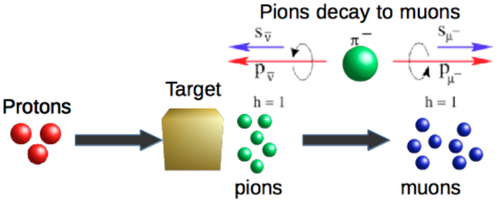
if

- FNAL E989 reaches 140 ppb goal
- exp. and theory values as today
- theory uncertainty remains as today

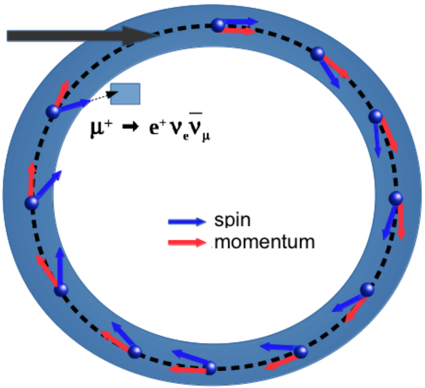
then

exp. − theory discrepancy ⇒ ∼7σ

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, effect of electric field

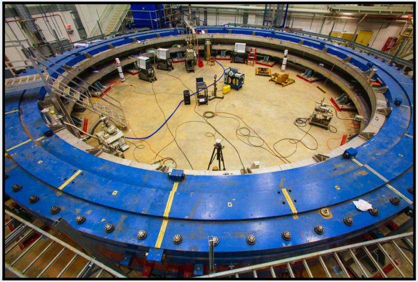
in a storage ring, electric fields are usually present for focusing and containment of particles

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

CERN 1975-, BNL, FNAL

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

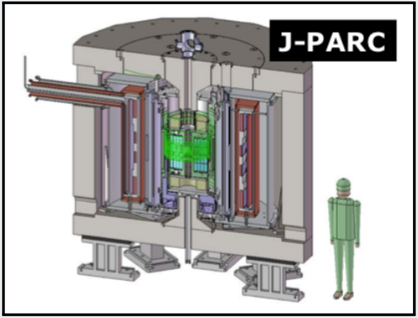
$$\Rightarrow \quad \left(a_\mu - \frac{1}{\gamma^2 - 1}\right) \simeq 0$$



J-PARC E34

ultra-cold muons

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



a_μ measurement method

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

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

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

a_μ uncertainties budget today		
ω_a/ω_p	540 ppb	BNL E821 final report
g_e	0.00026 ppb	CODATA 2014
m_μ/m_e	22 ppb	CODATA 2014
μ_p/μ_e	3 ppb	CODATA 2014

ω_a/ω_p uncertainties budget (BNL E821)	
ω_a statistical	460 ppb
ω_a systematic	210 ppb
ω_p systematic	170 ppb

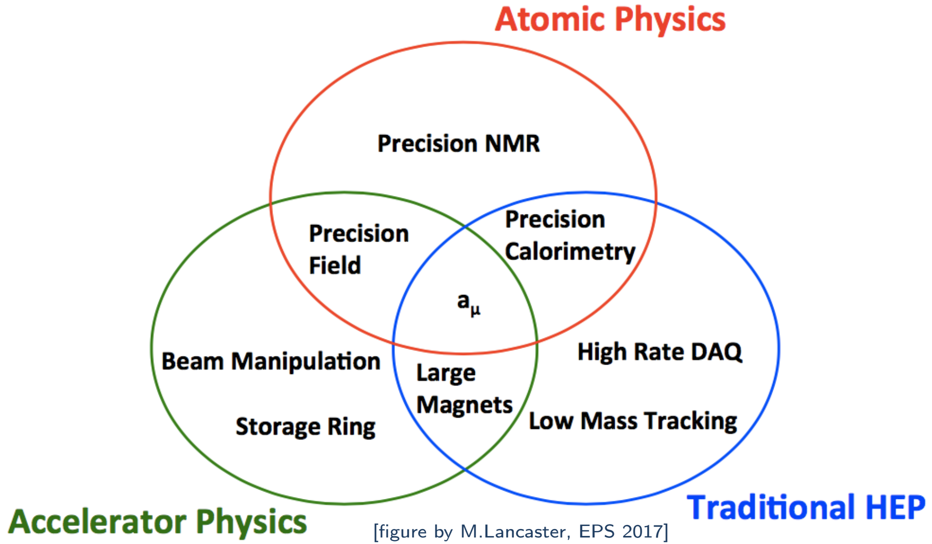
present experimental value is not systematically limited

FNAL E989 experiment

$\delta a_\mu = 140$ ppb goal

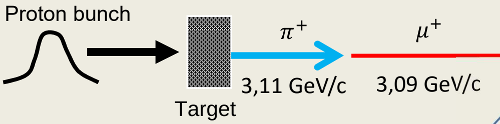
	BNL E821	FNAL E989	
ω_a statistical	460 ppb	100 ppb	$\times 21$ detected muon decays $(1.6 \cdot 10^{11})$
ω_a systematic	210 ppb	70 ppb	improve all significant contributions
ω_p systematic	170 ppb	70 ppb	improve all significant contributions
total	540 ppb	140 ppb	

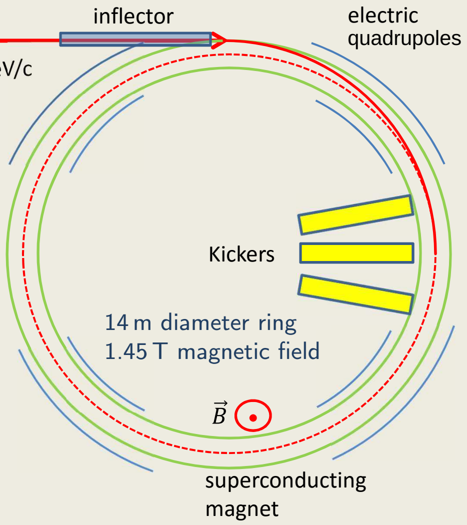
combine techniques of three areas of experimental Physics



[figure by M.Lancaster, EPS 2017]

Accelerator Physics: muon production, storage and decay at FNAL



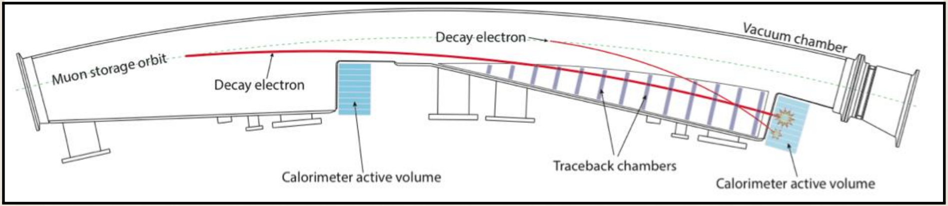


- FNAL booster+recycler: 12 Hz rate of 120 ns-long 10^{12} 8 GeV proton bunches
- protons hit target and produce pions
- pions with $p = 3.11$ GeV $\pm$ 10% selected
- pions decay into muons
- 3.09 GeV muons accepted in delivery ring, separation from p's and π's
- muons injected in storage ring
  muons 95% polarized
- after 30 μs, 10k stored muons
- 1.1k detected muon decays per fill
- 21$\times$ E821 muon decays in 202 days

Accelerator Physics: improvements at FNAL w.r.t. BNL

- more muons per proton
- more effective separation of muons from protons and pions
- lower instantaneous muon decay rate

High Energy Physics: detector



- 24 calorimeter modules of 6×9 PbF_2 crystals with SiPM readout
  - 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

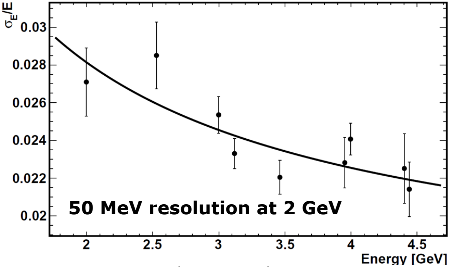
comparison with E821

- more granular calorimeter, faster data acquisition
- much improved laser calibration system

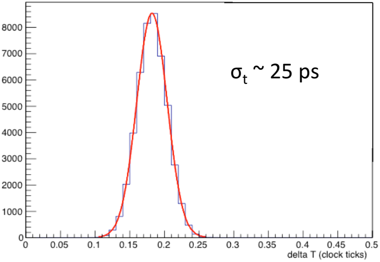
calorimeter performance

NIM A 783 (2015),

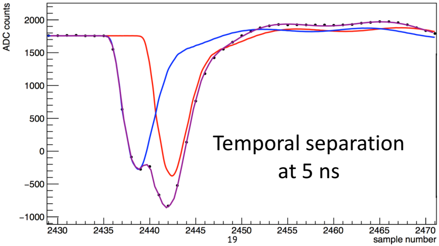
Energy Resolution



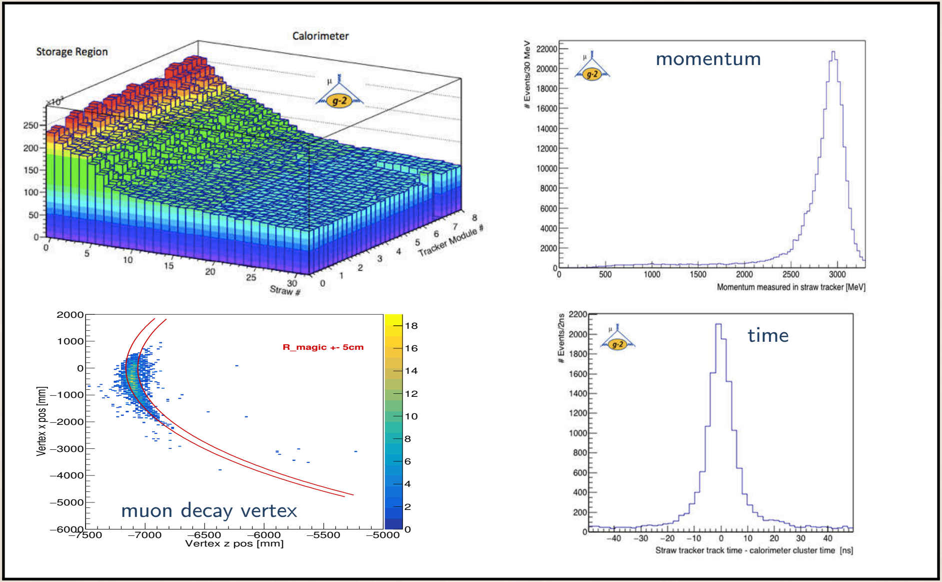
Timing Resolution



Electron pile-up

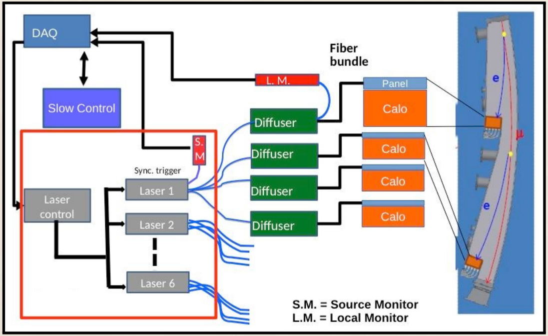


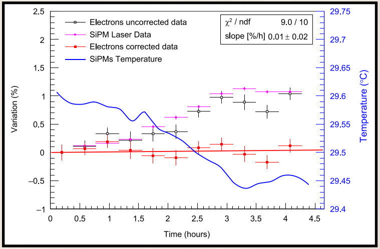
tracker performance



laser calibration system

- send laser pulses to all calorimeter crystals, read back SiPMs signals
- measure SiPMs gain variation induced by instantaneous hit rate
  - BNL E821 laser calibration system could not be used to this aim
- measure SiPMs gain variation induced by temperatures, detector power supplies voltage
- measure SiPMs response as function of number of photoelectrons

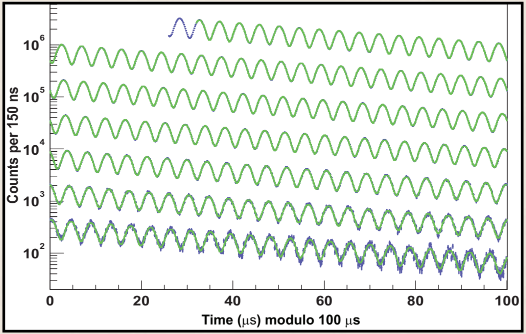




ω_a measurement

- 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
- fit on above-threshold electrons gives ω_a with close to maximal statistical sensitivity

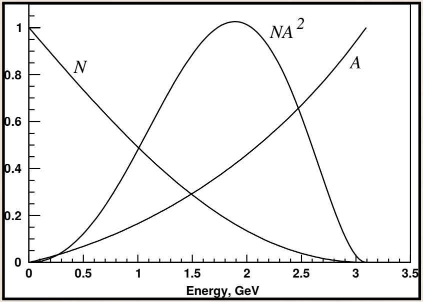
E821 wiggle plot ($\gamma\tau_\mu = 64\,\mu$s, $\tau_a = 2\pi/\omega_a = 4.36$ ns)



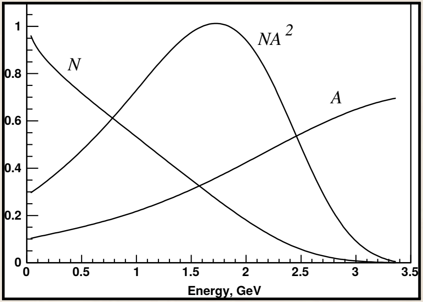
ω_a measurement statistical uncertainty

- fit $N_e(E_e > E_{\mathrm{thr}}) = N_0(E_{\mathrm{thr}}) e^{-t/\gamma\tau} [1 + A(E_{\mathrm{thr}}) \cos(\omega_a t + \phi(E_{\mathrm{thr}}))]$
- $\dfrac{\delta\omega_a}{\omega_a} = \dfrac{1}{\omega_a \gamma \tau_\mu} \sqrt{\dfrac{2}{NA^2P^2}}$ 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

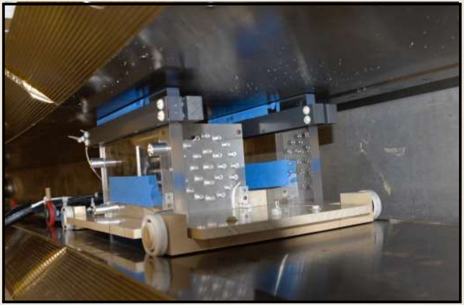
	E821 [ppb]	E989 improvement plans	goal [ppb]
gain changes	120	better laser calibration low-energy threshold	20
pileup	80	low-energy samples recorded calorimeter segmentation	40
lost muons	90	better collimation in ring	20
CBO	70	higher n value (frequency) better match of beamline to ring	<30
E and pitch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

Atomic and Accelerator Physics: magnetic field

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

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



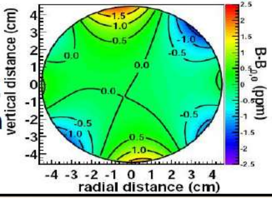
magnetic field shimming

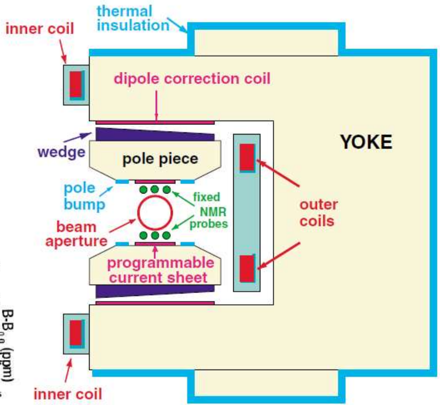
- Many passive and active shimming tools to achieve unprecedented field homogeneity for such a large volume.
- Each "knob" adjusts nearly orthogonal components of the field shape

Passive shims
- Iron wedges
- Pole tilt
- Iron pole bumps

Active shims
- Dipole correction coils
- Surface correction coils

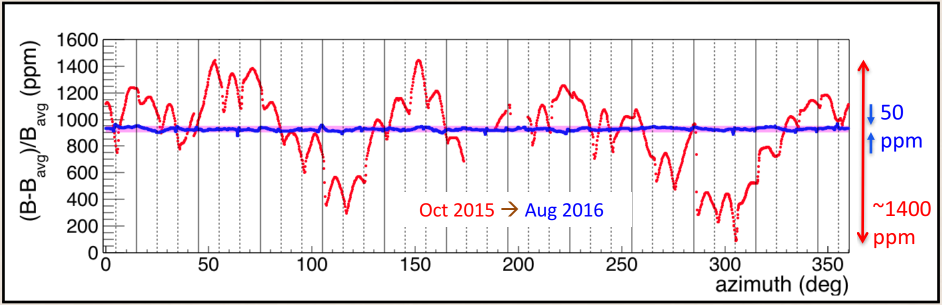
FNAL goal is x2 improvement in homogeneity





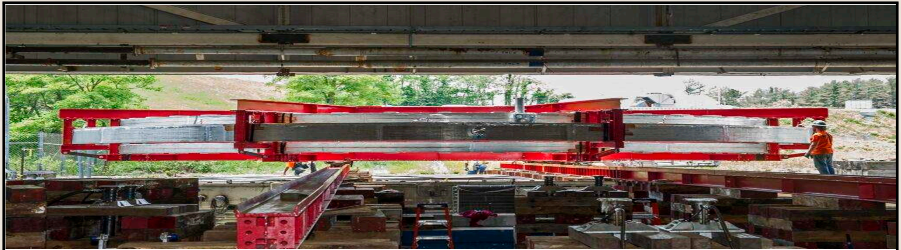
[slide by Joe Grange, Argonne]

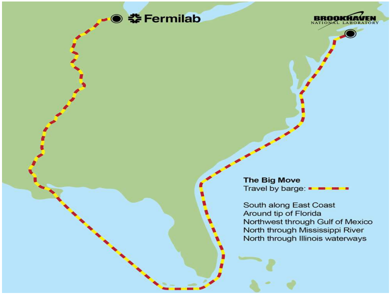
magnetic field shimming results

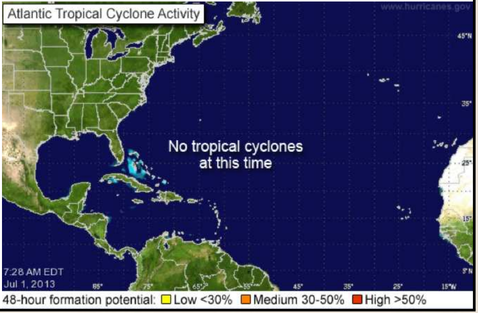


- shimming process improved field uniformity $\times 30$ over a year
- uniformity $\times 4$ better than achieved at BNL after 1st shimming round

BNL storage ring magnet moved from BNL to FNAL (2012)







BNL storage ring magnet moved from BNL to FNAL (2012)

ω_p measurement systematics, part 1

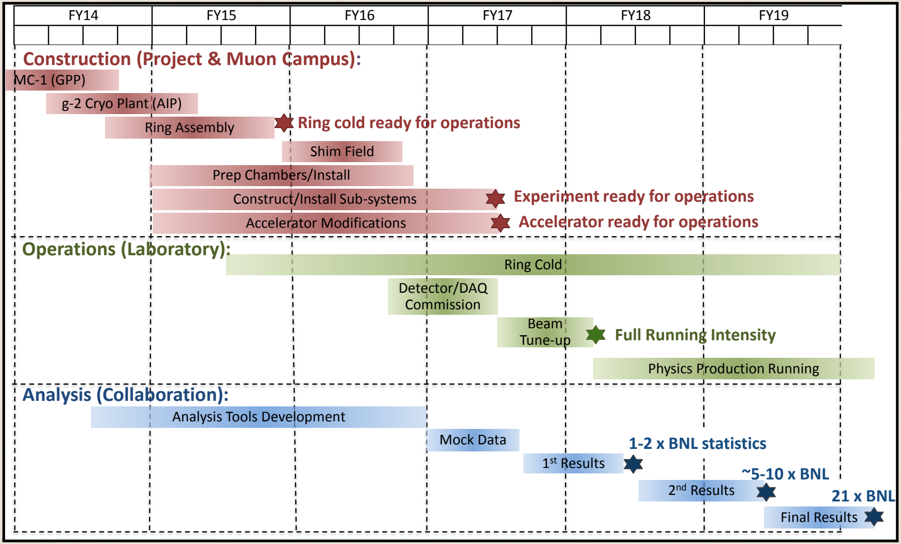
	E821 [ppb]	E989 improvement plans	goal [ppb]
absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
trolley probe calibration	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical 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

...

ω_p measurement systematics, part 2

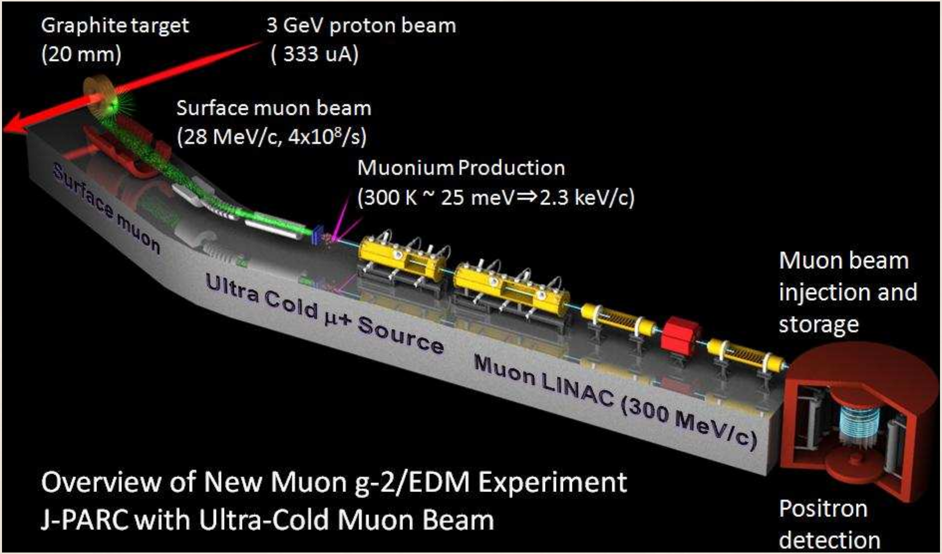
	E821 [ppb]	E989 improvement plans	goal [ppb]
		. . .	
higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure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

schedule

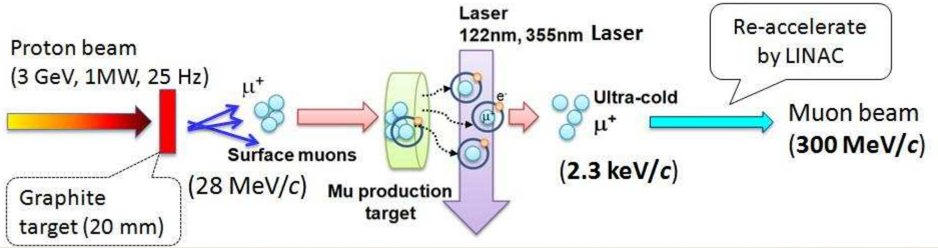

FY14
FY15
FY16
FY17
FY18
FY19
Construction (Project & Muon Campus):
MC-1 (GPP)
g-2 Cryo Plant (AIP)
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Operations (Laboratory):
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Full Running Intensity
Physics Production Running
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1st Results
1-2 x BNL statistics
2nd Results
~5-10 x BNL
21 x BNL
Final Results

J-PARC E34 experiment

overview

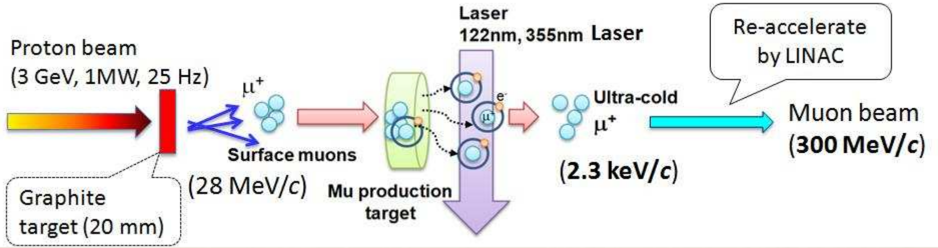

Graphite target
(20 mm)
3 GeV proton beam
(333 uA)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon beam
injection and
storage
Positron
detection
Overview of New Muon g-2/EDM Experiment
J-PARC with Ultra-Cold Muon Beam

muon production and storage



- pions stop in target and decay to polarized muons
- surface muons stop in muon production target and form muonium ($e^{-}\mu^{+}$)
- 300 K° muons have 2.3 keV average momentum (ultra-cold)
- resonant laser ionization splits muonium
- muons are accelerated to $p_L = 300\,\text{MeV}$ keeping $p_T \sim 2.3\,\text{keV}$ $\Rightarrow$ $p_T/p_L \simeq 10^{-5}$
- muons stored in 33 cm-radius MRI 3 T magnet
- very weak magnetic focusing, no electric field
- requires several non-trivial research developments

muon production and storage



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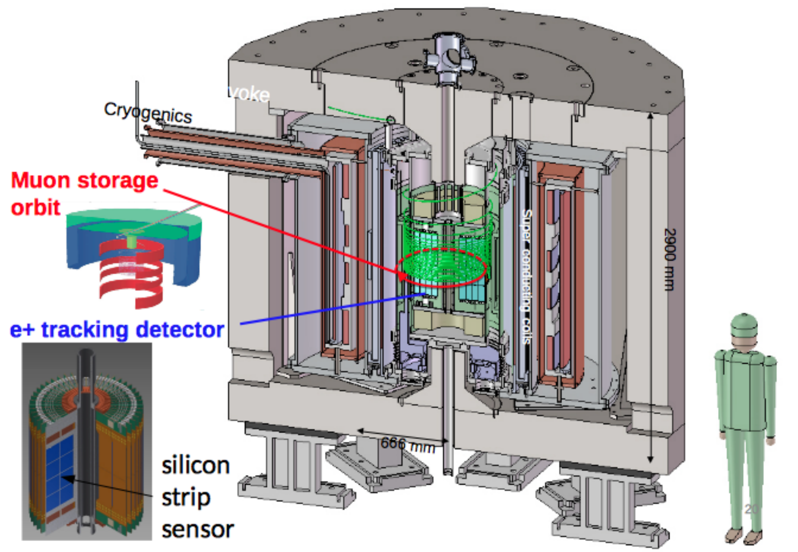
storage ring and detector



comparison with E821

	BNL E821	J-PARC E34
muon momentum	3.09 GeV/c	0.3 GeV/c
storage ring radius	7 m	0.33 m
storage field	1.5 T	3.0 T
focusing field (n-index)	0.14 (electric)	1.5 E-4 (magnetic)
average field uniformity	≈1 ppm	<< 1ppm
(local uniformity)	≈50 ppm	≈1ppm
Injection	inflector + kick	spiral + kick
Injection efficiency	3-5%	80%
muon spin reversal	--	pulse-to-pulse
positron measurement	calorimeters	tracking
positron acceptance*	65%	≈100%
muon polarization	≈100%	≈50%
events to 0.46 ppm	9×10^{9}	5×10^{11}

* in the energy region of interest

status and prospects

some accomplisced research and development

- measurement of thermal muonium production yield and distributions
- built ionization laser with 10% of design power
- demonstration of electro-static acceleration of slow muons
- design of spiral injection scheme
- demontration of magnetic field shimming to 1 ppm
- development of full size silicon detector and custom frontend electronics

prospects

- completion of R&D in 2018
- data-taking expected about 2020
- first stage with 370 ppm statistical sensitivity approved
- final sensitivity goal 100 ppm statistical
- systematics radically different from FNAL experiment ones

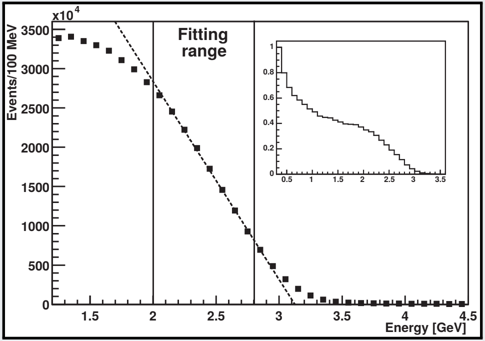
Conclusions

- interesting times ahead for muon $g-2$
- in late 2018 FNAL E989 may measure a_μ with precision comparable to BNL E821
- in 2-3 years from now a 140 ppb measurement is possible
- in 2020 J-PARC E34 will start data-taking
  - new method, different systematics
- meanwhile, a large composite effort is on-going to improve the theory prediction

Backup Slides

ω_a systematics from detector gain variation (E821)

- detector gain variation causes effective $E_{\rm thr}$ variation $\Rightarrow \omega_a$ 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

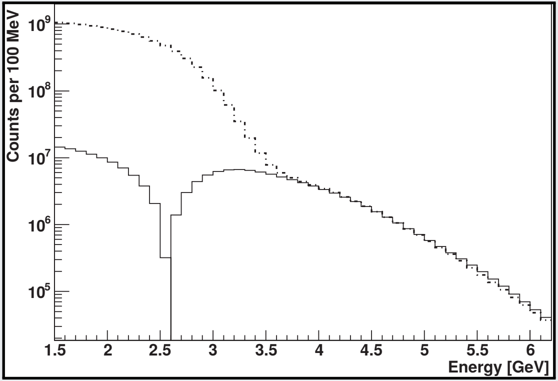


ω_a systematics from event pileup (E821)

- 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 $E < 2.5$ GeV, but plotted as positive
- above 3.1 GeV total observed distribution corresponds to pileup as expected

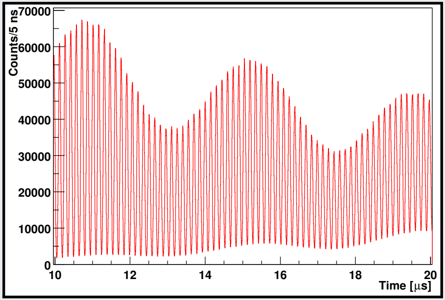
ω_a systematics from lost muons (E821)

- 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

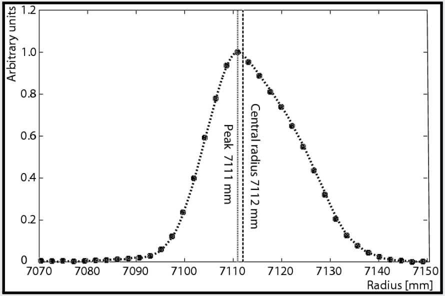
ω_a systematics, fast rotation interlude (E821)

- 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

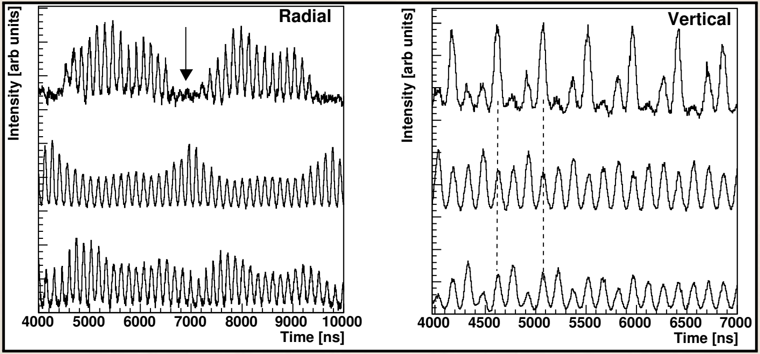


reconstructed muons radial distribution from fast rotation measurement



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 $\sim$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 $\pm 0.5\,\mathrm{mm}$ ($\pm 0.01\,\mathrm{ppm}$ in a_μ)
  - σ on muon vertical position vs. E quadrupole center $\pm 1\,\mathrm{mm}$ ($\pm 0.02\,\mathrm{ppm}$ 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)