Measurement of Muon Dipole Moments

a critical look at the future

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CERN, November 2005

Outline

Introduction

(Anomalous) Magnetic Dipole Moment

Electric Dipole Moment

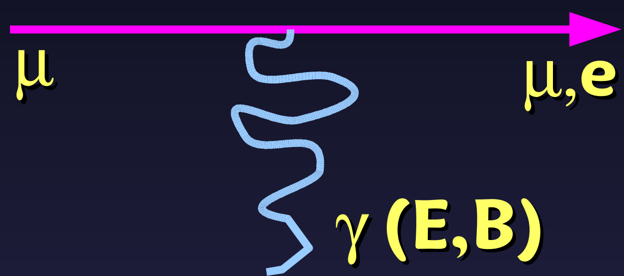
Conclusions

Dipole Moment in a Nut Shell

$d = \eta \times 4.7\times10^{-14}$ e·cm

MDM: $\vec{\mu} = g\dfrac{e}{2mc}\vec{S}$

EDM: $\vec{d} = \dfrac{\eta}{2}\dfrac{e}{2mc}\vec{S}$



MDM and EDM closely related to each other and *e.g.* $\mu \rightarrow e\gamma$ **(SUSY)**

Experimentally accessible through interaction with electric and magnetic field:

$$H = -\left(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}\right) \qquad \tau = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

MDM & EDM Probe Radiative Corrections

	MDM (g):	EDM (η):	
tree	2 (Dirac)	0	
QED	0.002···	0	
hadronic	0.00000012···	0	
weak	0.000000003···	0	
HO weak + hadr.	···	$\sim 10^{-22}$	CKM CPV
theory	2.0023318366(14)	$\sim 10^{-22}$	
experiment	2.0023318416(12)	$6 \cdot 10^{-6}$	
New Physics	<5 ppb	$\sim 10^{-9}$	

$\Rightarrow$ interesting physics in $a = (g-2)/2$

Measurement Principle

1. Prepare highly polarized ensemble of muons
   - Produce pions with high energy protons
   - parity violation in $\pi \to \mu\nu$
2. Let the muons interact with B and E field
   - Electromagnetic storage ring
   - BMT: $\vec{\omega} = \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \vec{E}\right)\right]$
3. Measure the evolution of the spin orientation
   - parity violation in $\mu \to e\nu_e\nu_\mu$
   - boost: $\theta^{cm} \to E_e^{lab}$

MDM

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MDM Measurement

Measure $a = (g-2)/2$ (we know "2" quite well)

Use a homogeneous magnetic field B (easy to measure)

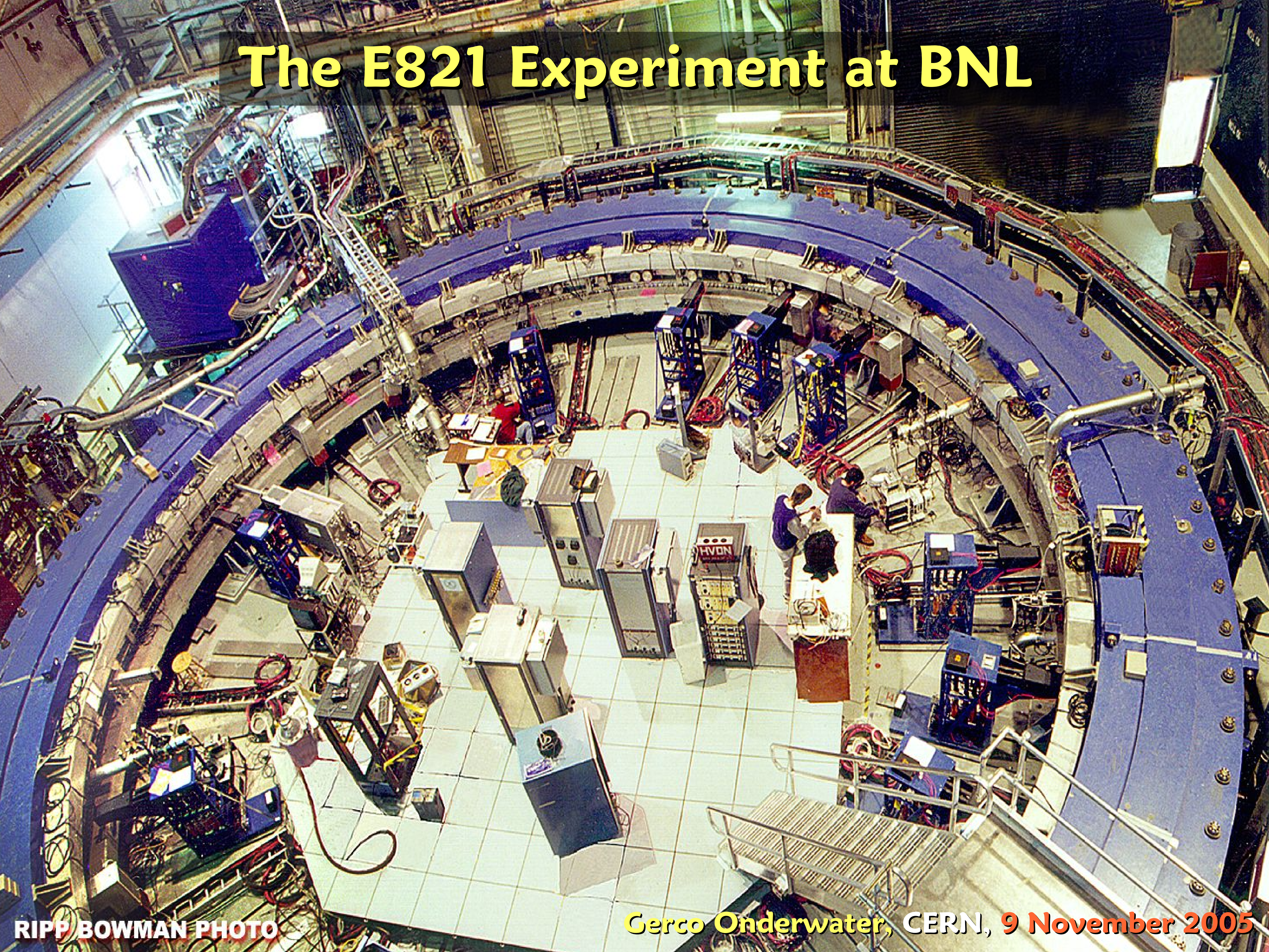
Pick $\gamma \approx 29$, so that $a_\mu - 1/(\gamma^2-1) = 0$

Focus beam with a quadrupole E (no need to measure)

Assume $\eta = 0$

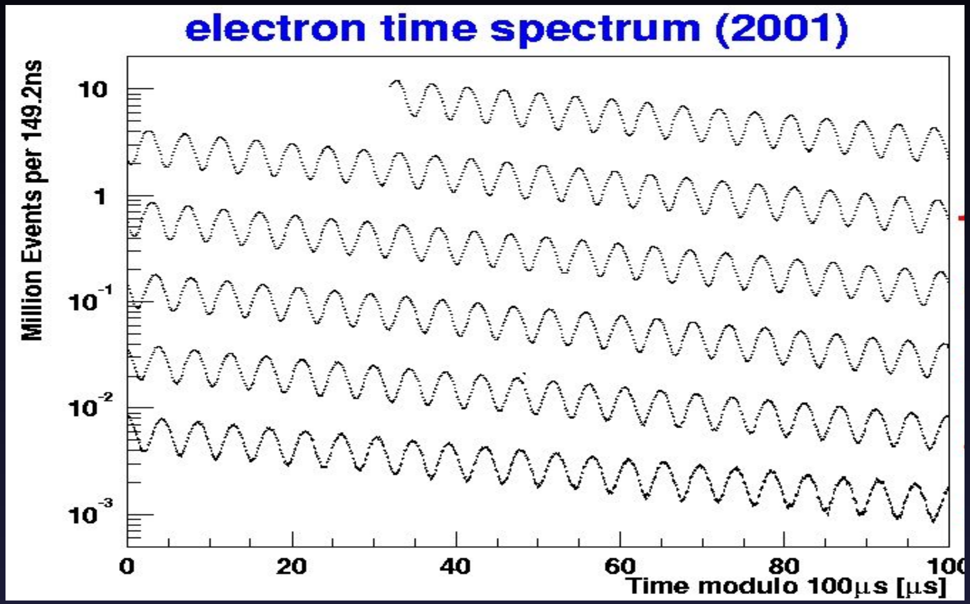
$$\omega_a = a \frac{e}{m} B$$

The E821 Experiment at BNL

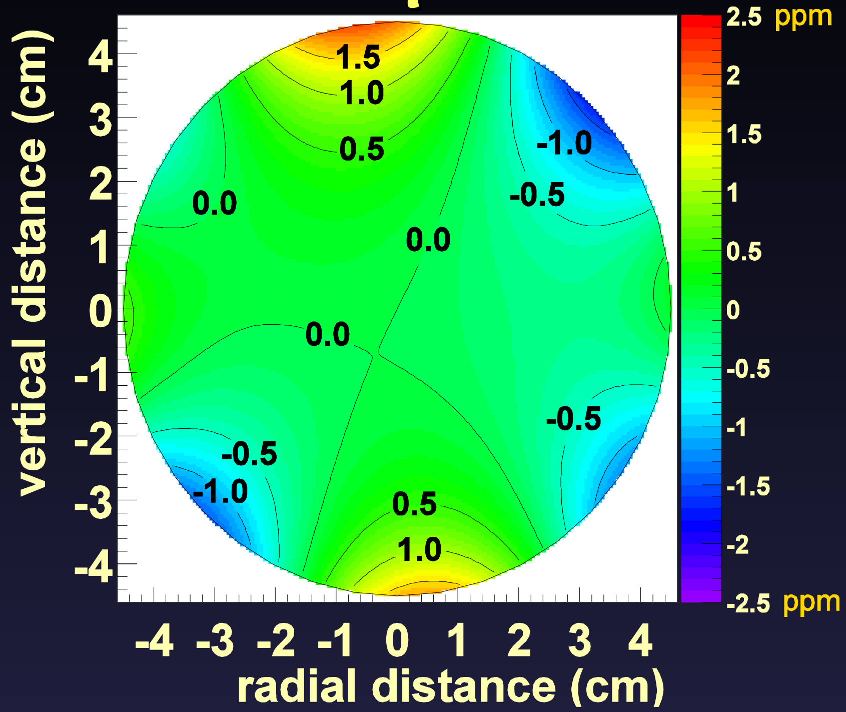


Data Sample

ω_a (6x10^9 counts)



ω_p



$$a_\mu = \frac{m}{e}\frac{\omega_a}{B} = \frac{\omega_a/\omega_p}{\lambda - \omega_a/\omega_p}$$

$$\lambda = \frac{\mu_\mu}{\mu_p} \qquad \frac{\delta\lambda}{\lambda} = 3\times10^{-8}$$

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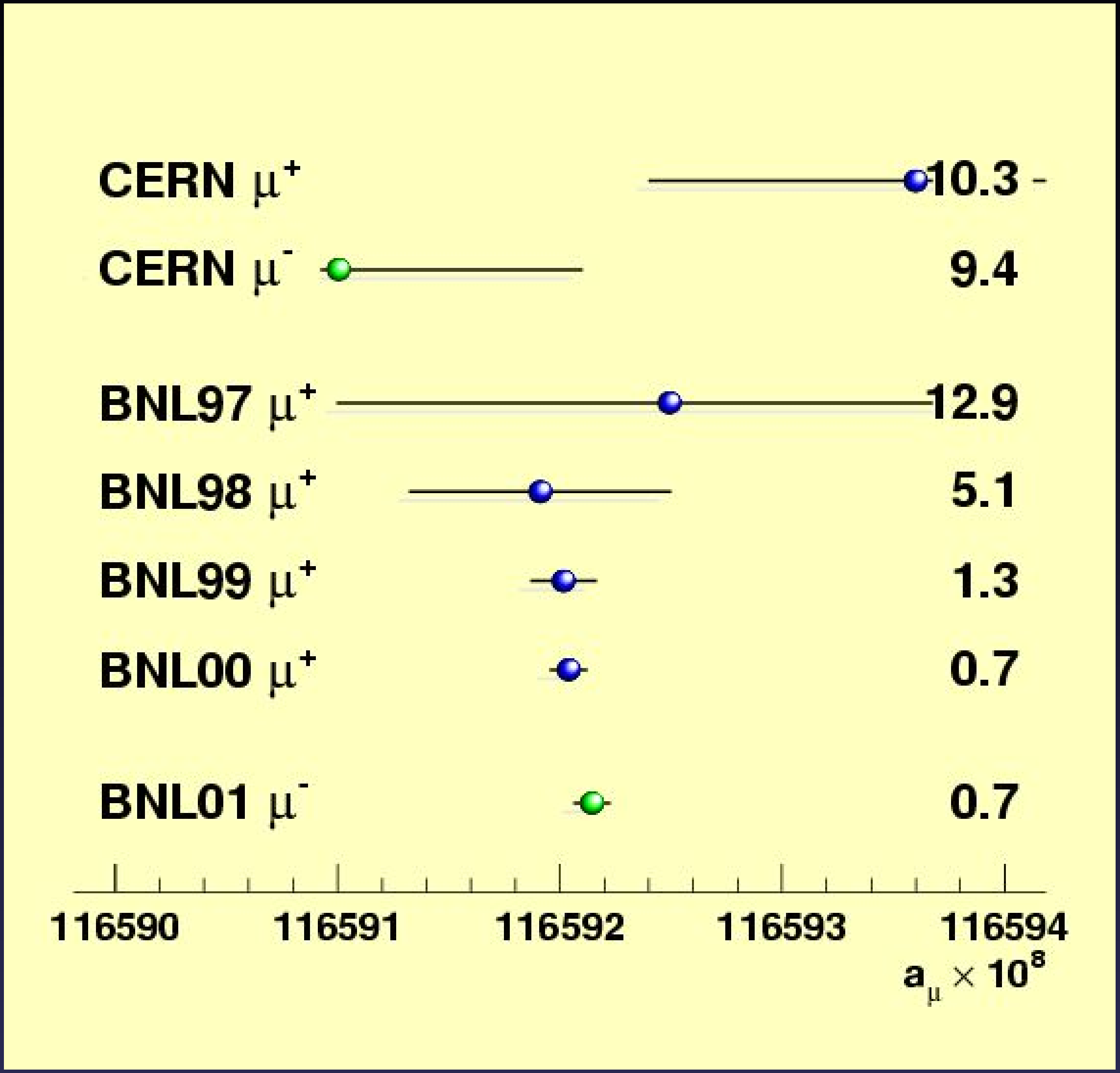
History of g-2$_\mu$



$\Delta a/a$ = 0.5 ppm(stat.) $\pm$ 0.2 ppm(ω_p) $\pm$ 0.2 ppm(ω_a)

Is there room to wiggle?

Possible improvements to the experiment

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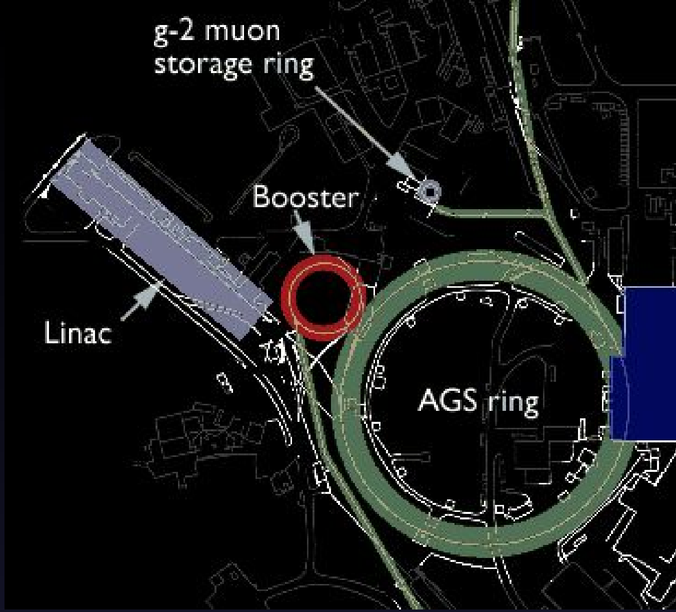
Proton Source



AGS near ideal:
few TP/pulse @ 30GeV, σ = 25ns

Less than ideal pulse structure: 12 bunches, Δt=33ms, T_{rep}=2.5s

Would like: $\Delta t = T_{rep} \approx$ 1ms (J-PARC?)

New high intensity facility would be helpful

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Pion Decay Line

Must have p_μ = 3.094 GeV/*c*

Two options to get polarized muons:

- **p_π = 3.1 GeV/*c* (forward decay in CM)** **done**

  L = 100m → about 50% of πs decay

  Many πs make it into storage ring: flash

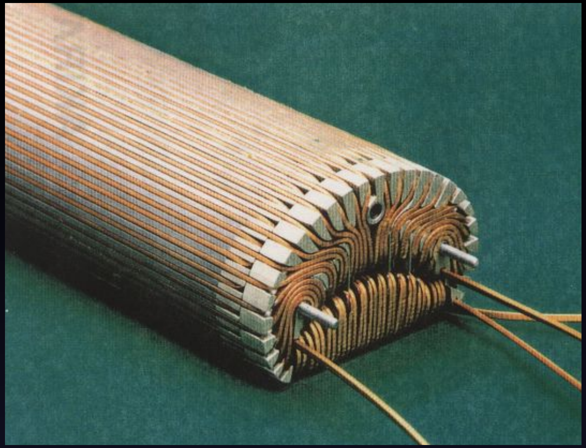
- **p_π = 5.3 GeV/*c* (backward decay in CM)** **planned**

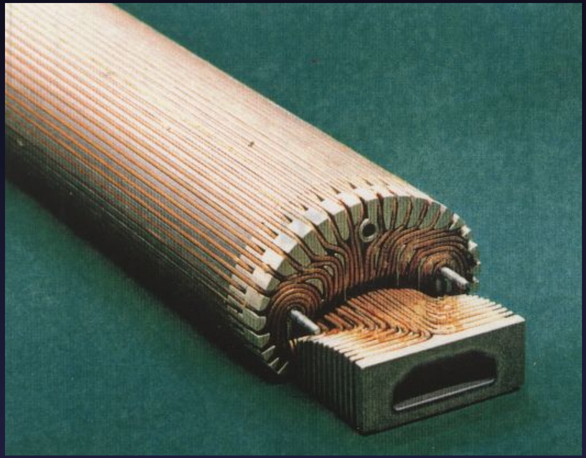
  L = 100m → about 30% of πs decay

  Excellent π rejection; "stiffer" beamline, $p_\mu \neq p_\pi$

Both cases: could use larger acceptance **planned**

Muon Injection





Large improvement over CERN exp't.

Superconducting Inflector:

engineering masterpiece!
BUT: limited acceptance
Could gain factor 2 in flux from open end
Larger acceptance difficult

Fast electrostatic kicker: 95kV, 150ns

works quite well
could improve storage efficiency with larger kick

Imperfections lead to hard-to-understand beam dynamics

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Magnetic Storage Ring

Magnificent (average) homogeneity in B-field of 0.1 ppm

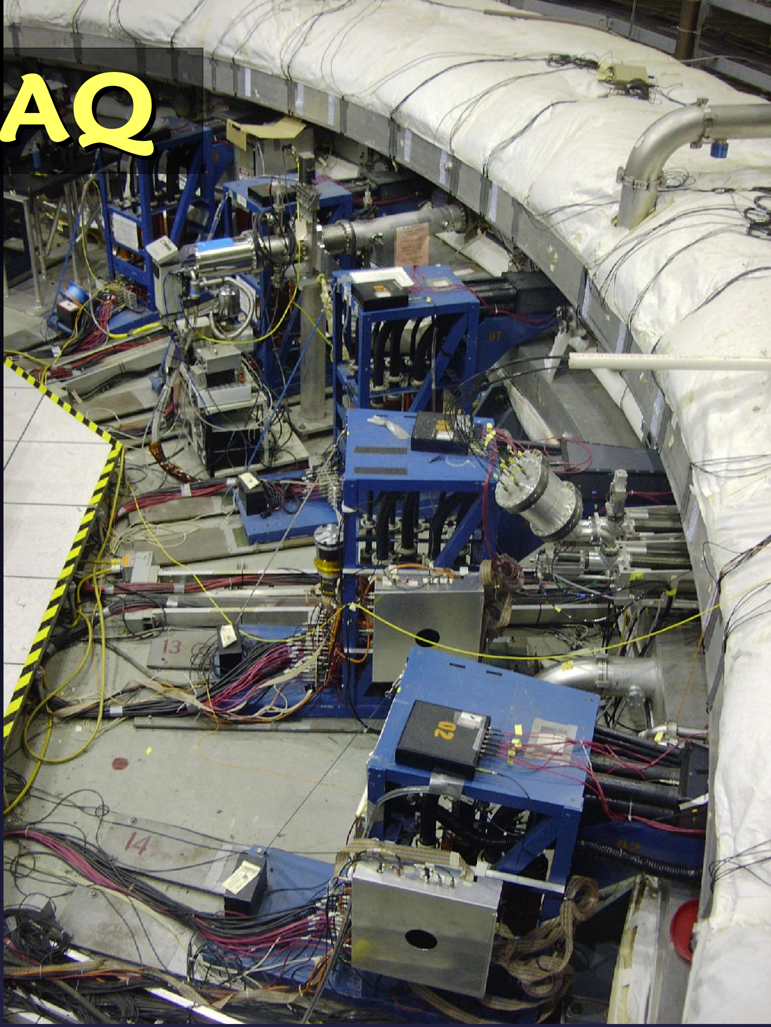
Would like $\delta B/B$ same order as $\delta a/a$

Would like better temperature stability (field gradients!)

Would like faster field measurement (now: 2hours)

Need DAQ/hardware upgrade

Polarimetry & DAQ



PbSciFi calorimeters, Scint. Hodoscope

- 400 Mhz interlaced WFD
- combined readout of 4 PMTs
- highest E showers not fully contained
- fairly robust, but outdated DAQ
- fast switching gate; fast recovery

Would like:

- 500 Mhz non-interlaced WFD
  - individual readout of >4 PMTs, with position sensitivity
    - full shower containment
      - new DAQ
        - no (need for) flash gate

Getting the Answer

E-field and Pitch Corrections: +0.81 ±0.08 ppm

may become critical

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

λ measured at 0.12ppm @ LANL in μ^+e^- h.f.s.
used same equipment as in g-2 (common syst. drop out!)
with theory 0.03ppm (how reliable?)
possibly problematic

Comparing to Theory

QED error very small, but "*monopoly*" by Kinoshita
He's had the guts to do it! Who else?

Hadronic error > exp't error
Sigh ... (see next talk)

Weak contribution
Seems to be under control

New Physics
plenty ... especially interesting sensitivity to SUSY

Prospects for the Future

BNL E821: done 0.5 ppm!

BNL E969: Scientific approval; no *pecunia* 0.2 ppm!

J-PARC LOI: 0.03 ppm?

Farley concept: NMR in-flight, $\gamma \neq \gamma_{magic}$ speculative

Theory: hinges on hadronic contribution 0.2 ppm?

New Physics Potential: competitive sensitivity

If LSP found: best measurement for tan(β)

EDM

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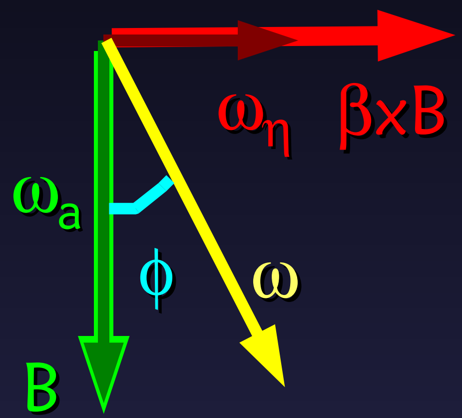
EDM Measurement

$$\vec{\omega} = \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \vec{E}\right)\right] \equiv \vec{\omega}_a + \vec{\omega}_\eta$$



$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2}$$

In E821:
$d = 2.8\times10^{-18}$ e·cm ⇒ 2.9 ppm
$\beta \times B$ = 435MV/m

Tilt in precession plane: $\phi \cong \omega_\eta / \omega_a = \eta\beta/2a$

$S_v \cong S_0\, \phi \sin(\omega_a t)$ $S_L \cong S_0 \cos(\omega_a t)$

Modulation of vertical distribution @ 90° w.r.t. g-2

EDM Sensitivities

$$d_\mu < 2.7 \times 10^{-19}\, e \cdot cm$$

ϕ ~ few nrad

Thesis Ron McNabb (E821)
systematic limited

Boost sensitivity ($\phi \rightarrow 90°$) by

$$\vec{\omega}_a = a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} \rightarrow 0$$

$$\mathbf{E} \cong \mathbf{aBc}\beta\gamma^2$$

Tilt in precession plane: $\phi = \mathrm{atan}(\omega_\eta / \omega_a) \cong 90°$

$$S_v \cong S_0\, \omega_\eta t \qquad S_L \cong S_0$$

Linear growth of vertical spin component

Planned Activities

J-PARC LOI (2003) to search for d_{μ} at the level of 10^{-24} e·cm

To reach this sensitivity, need $NP^2 = 5\times10^{16}$

with $P \sim 0.3$, need 5×10^{17} detected muons (wow!!!)

At $\gamma = 5$, cycle time is about 100 μs $\rightarrow$ need **10 kHz** rep. rate

For $T=10^7$ s, need $>5\times10^6$ muons per spill

ONLY @ NEXT GENERATION μ FACTORY

and then it's still statistics limited

Conclusion

Conclusion

Measurement of muon g-2 at the level of 0.2ppm is certainly possible (mainly requires statistics)

Several technological challenges, none problematic, and lots of room for improvement

Potential problems appear near 0.1 ppm: λ and E/pitch

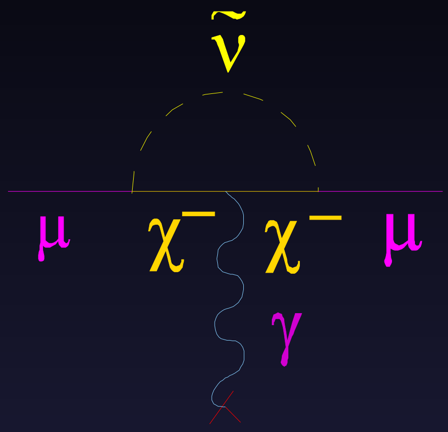
Theory: break QED monopoly, reduce δa_μ(hadr.) <0.6ppm

Search for muon EDM at the level of 10^{-24} e·cm seems technically doable, but .....

Requires new, very high intensity facility

Extra Slides

New Physics: SUSY with large tanβ



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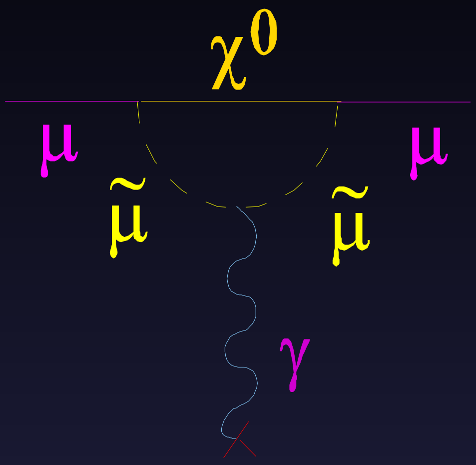

$$a_\mu(\mathrm{SUSY}) \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W}\frac{m_\mu^2}{\tilde{m}^2}\tan\beta\left(1-\frac{4\alpha}{\pi}\ln\frac{\tilde{m}}{m_\mu}\right)$$

$$\simeq (\mathrm{sgn}\mu)\ 13\times 10^{-10}\ \tan\beta\ \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

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Connection between d_μ and a_μ in SUSY

$$d_\mu = 2\times10^{-22}\, e\cdot cm\, \frac{a_\mu^{SUSY}}{25\times10^{-10}} \tan\phi_{CP}$$