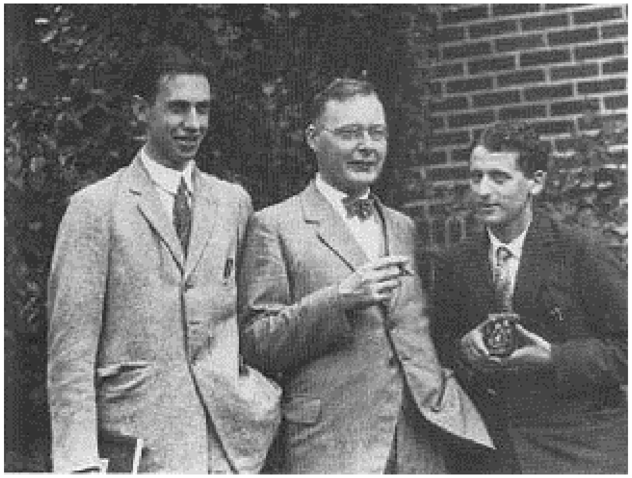
Searching for new physics at *the precision frontier*: muon g-2

Presentation to
REU Students
July 2014

Spin

1925 Goudsmit and Uhlenbeck:
Electron has spin $\hbar/2$.
Pauli objects this can't explain atoms but Thomas points out there is an important relativistic correction



Uhlenbeck, Kramers and Goudsmit

http://www.lorentz.leidenuniv.nl/history/spin/goudsmit.html

Heisenberg and Pauli

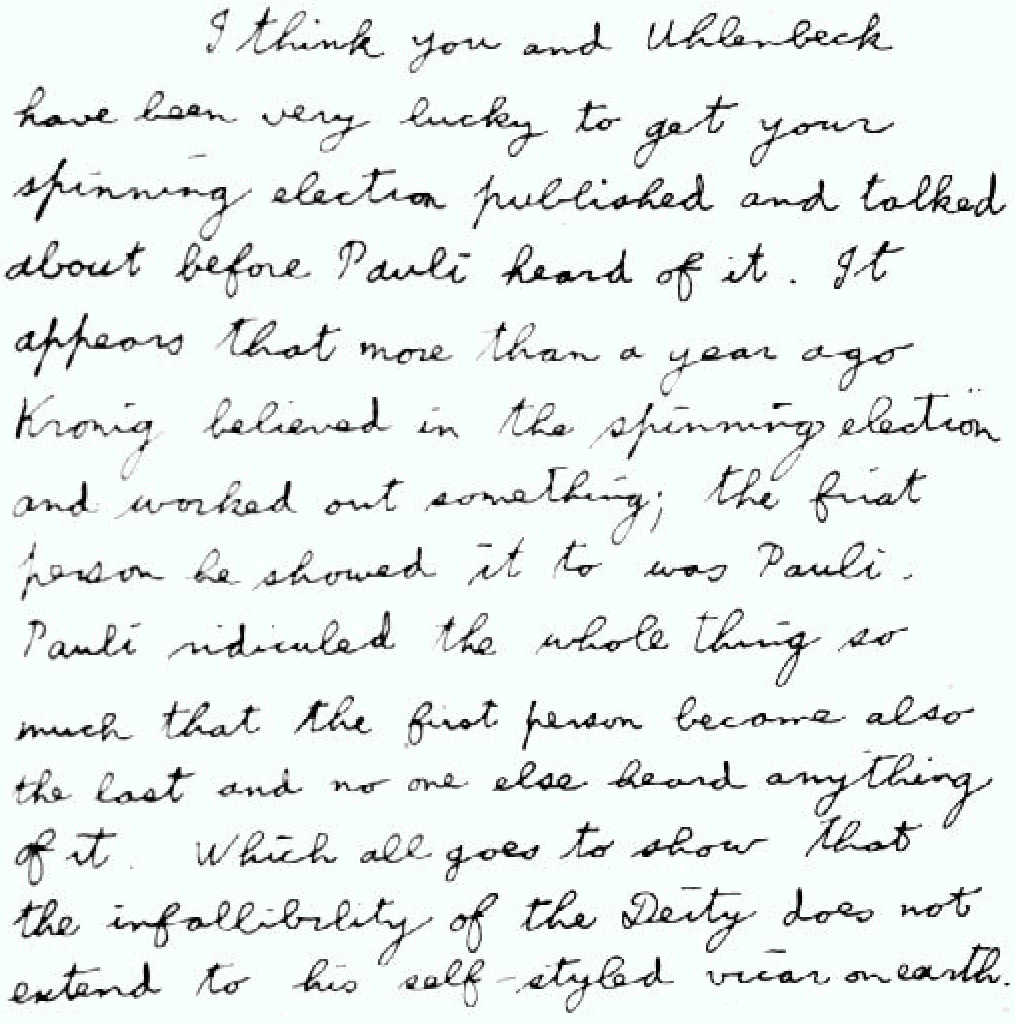
Quantum Mechanics:
To rotate to a new coordinate system:
$\psi_e' = \exp(-i\theta S/\hbar)\ \psi_e$
for $\theta = 2\pi$, $\psi_e' = -\ \psi_e$. This explained the Pauli Exclusion Principle.

Spin

1925 Gouds
Electron has
Pauli objects
atoms but Th
is an importa

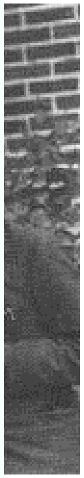
[http://www.lo
/goudsmit.ht](http://www.lo)

Quantum Me
To rotate to a
$\psi_e' = \exp(-i\theta$
for $\theta = 2\pi$, ψ
Exclusion Pr



I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth.

Part of a letter by L.H. Thomas to Goudsmit (25 March 1926). Reproduced from a transparency shown by Goudsmit during his 1971 lecture. The original is presumably in the Goudsmit archive kept by the AIP Center for History of Physics.



Uhlenbeck,
Kramers and
Goudsmit

enberg and Pauli

Gesellschaft

Classically, the magnetic moment of a particle with orbital angular momentum ***L*** is:

A. $\vec{\mu} = \frac{q\hbar}{2m}\vec{L};$

B. $\vec{\mu} = \frac{q}{2m}\vec{L};$

C. $\vec{\mu} = \vec{L};$

D. $\vec{\mu} = \frac{m}{2q}\vec{L};$

E. $\vec{\mu} = \frac{2m}{q\hbar}\vec{L}.$

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[✓ B. $\vec{\mu} = \frac{q}{2m}\vec{L};$]

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$$\mu = \frac{q}{T}\pi r^2 = \frac{q}{2\pi}\omega\pi r^2 = \frac{q}{2m}m r^2\omega$$

Magnetic moment $\boldsymbol{\mu} = g\, e\mathbf{S}/2m$ (g == "g-factor")
Dirac equation predicts $g = 2$ for a "point particle".

Early days measurements:

- Electron $g = 2.00 \pm 0.02$ (ok)
- Proton $g_p \sim 5$; Neutron $g_n \sim -4$! What?

Proton neutron explained in the 1960s by quark models: $\mu_p / \mu_n = -3/2 \sim -1.46$.

Anomalous g-factor: $a = (g-2)/2$

Electron magnetic moment anomaly, $a_e = (g_e\text{-}2)/2$:

1947:

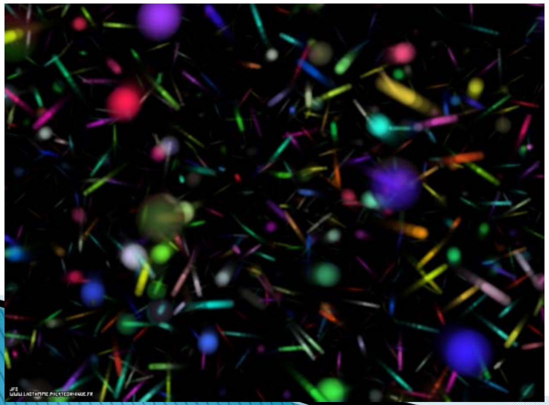
- Lamb shift measured;
- Kusch, Foley measured electron a = 0.00119(5).
- Schwinger, Feynman, Dyson et al. develop Quantum Electrodynamics (QED) and obtain the correct answer.

QED:

Electron zitterbewegung
trying to observe the motion of the electron in regions smaller than the Compton wavelength? Then you will observe pair production.

Compton wavelength: wavelength of a photon that has energy equal to mass of particle.

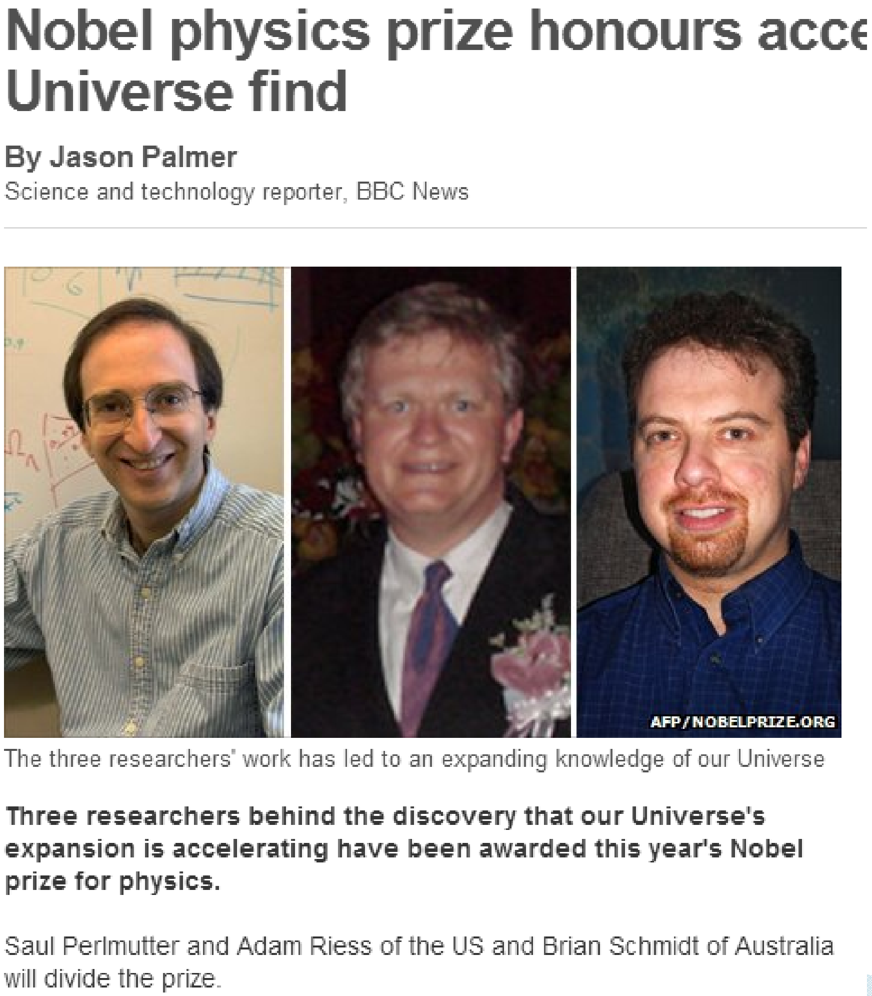
$$\lambda = \frac{hc}{mc^2}$$



Vacuum fluctuations: the "vacuum" is rich and active; the smaller the region we look, the larger the energy of the fluctuations.

By the way…

The vacuum has associated energy and this affects the expansion of the Universe.



Nobel physics prize honours acce Universe find

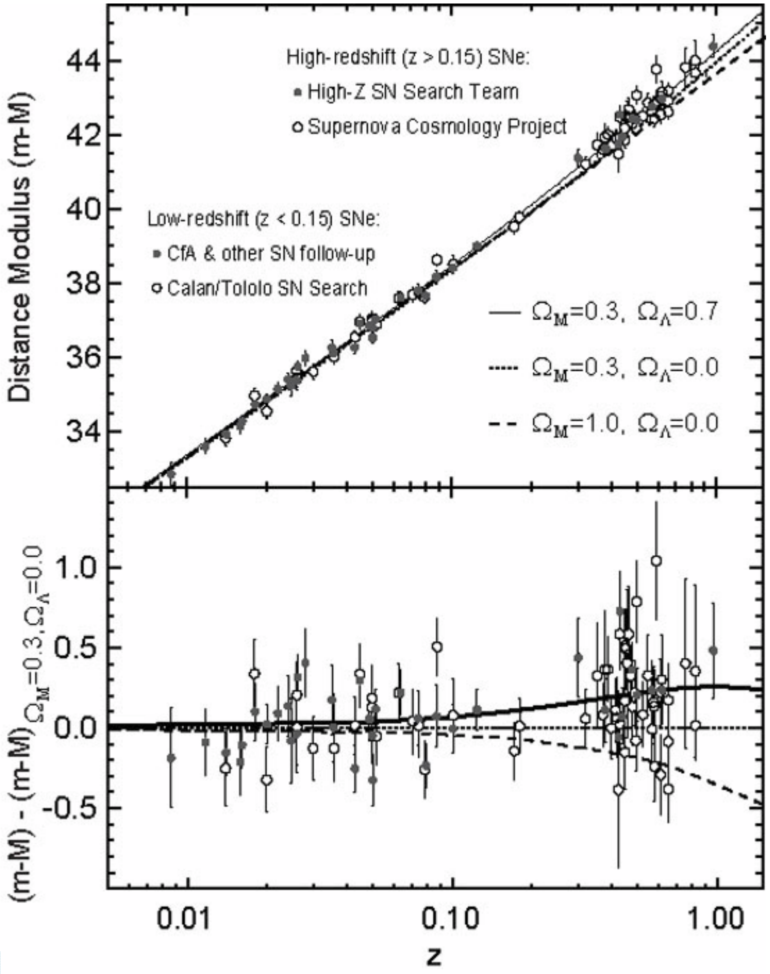
By Jason Palmer
Science and technology reporter, BBC News

AFP/NOBELPRIZE.ORG

The three researchers' work has led to an expanding knowledge of our Universe

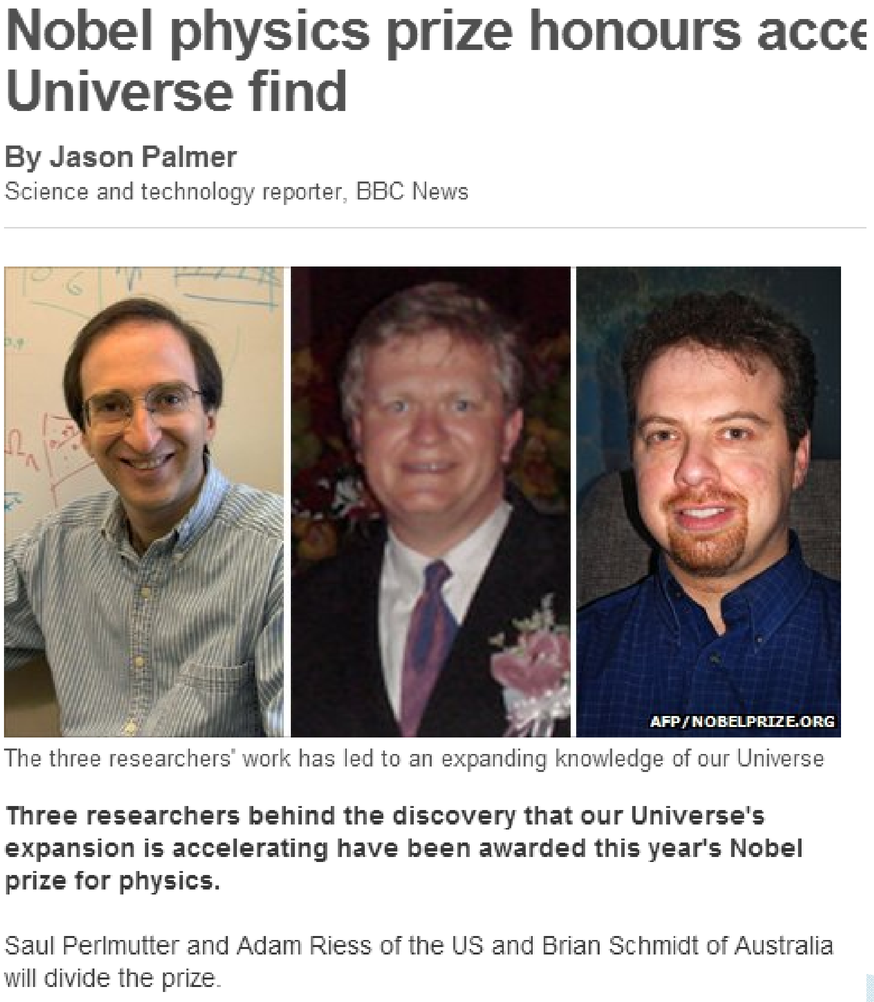
Three researchers behind the discovery that our Universe's expansion is accelerating have been awarded this year's Nobel prize for physics.

Saul Perlmutter and Adam Riess of the US and Brian Schmidt of Australia will divide the prize.



By the way…

The vacuum has associated energy and this affects the expansion of the Universe. **HOWEVER, the Standard Model prediction is about 54 orders of magnitude larger (!) than the measurement.**



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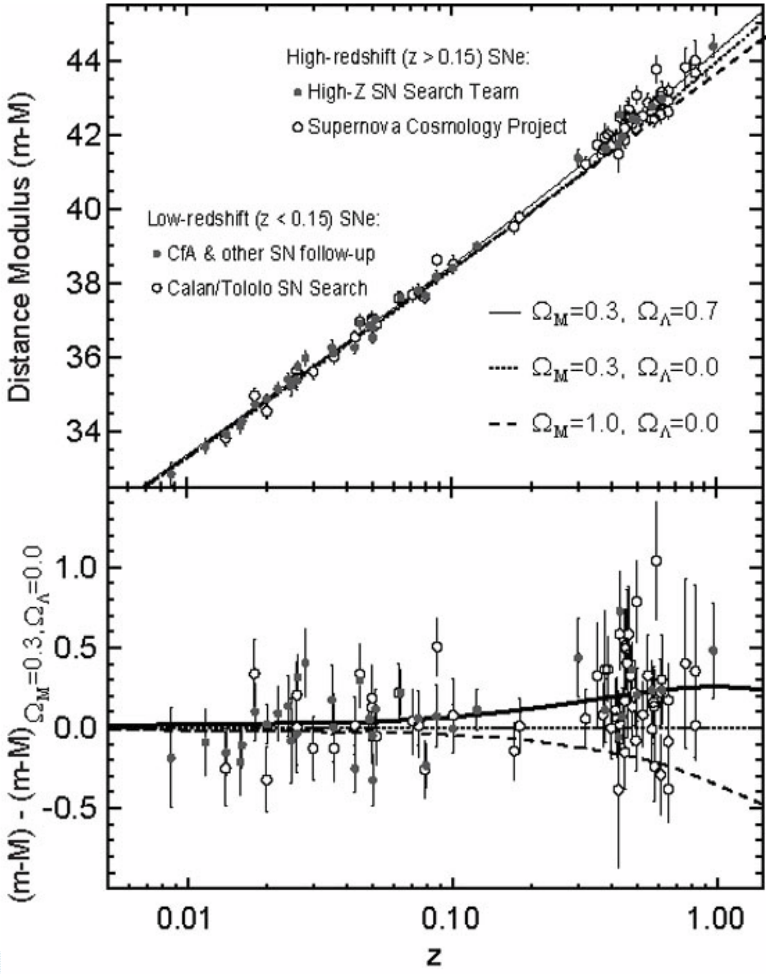

What is the order of magnitude of the Compton wavelength of the electron?

$A.\quad \approx 10^{-2}\ \mathrm{m};$

$B.\quad \approx 10^{-3}\ \mathrm{m};$

$C.\quad \approx 10^{-6}\ \mathrm{m};$

$D.\quad \approx 10^{-9}\ \mathrm{m};$

$E.\quad \approx 10^{-12}\ \mathrm{m}.$

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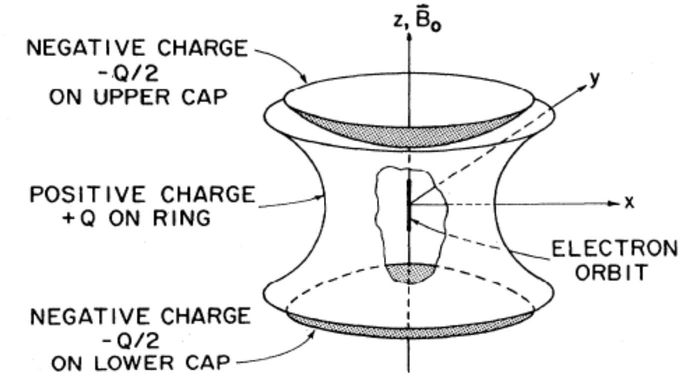
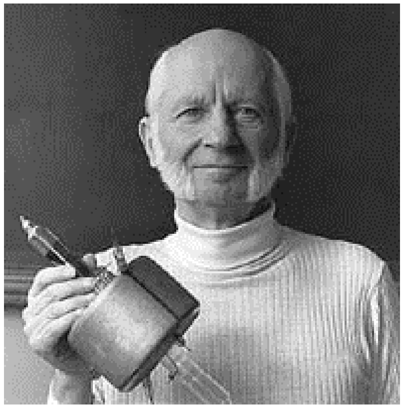
$C.\quad \approx 10^{-6}$ m; $\qquad D.\quad \approx 10^{-9}$ m;

[✓ $E.\quad \approx 10^{-12}$ m.]

$$\lambda = \frac{hc}{mc^2} = \frac{2\pi \quad 197.3}{0.511}\,\mathrm{fm} \approx 10^{-12}\,\mathrm{m}$$

Hans Dehmelt (from our department) got the Nobel prize for measuring a_e to 9 digits!





Professor Dehmelt

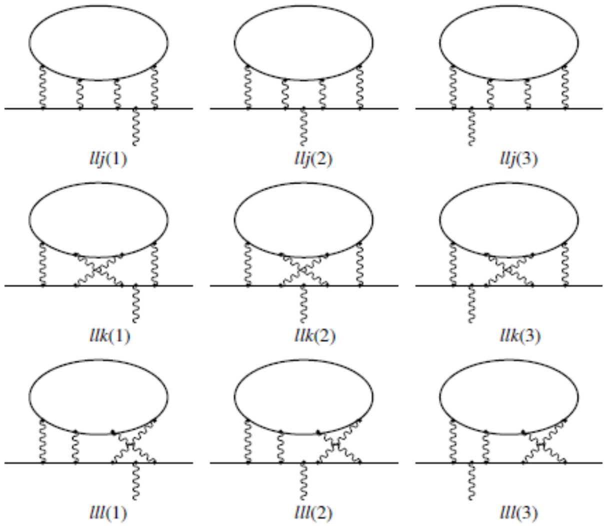
$$a_{e-}^{\exp} = 1.1596521884(43)\times 10^{-3}$$

$$(3\,ppb)$$

$$\boxed{\alpha = \frac{e^2}{4\pi\varepsilon_0}\frac{1}{\hbar c}}$$

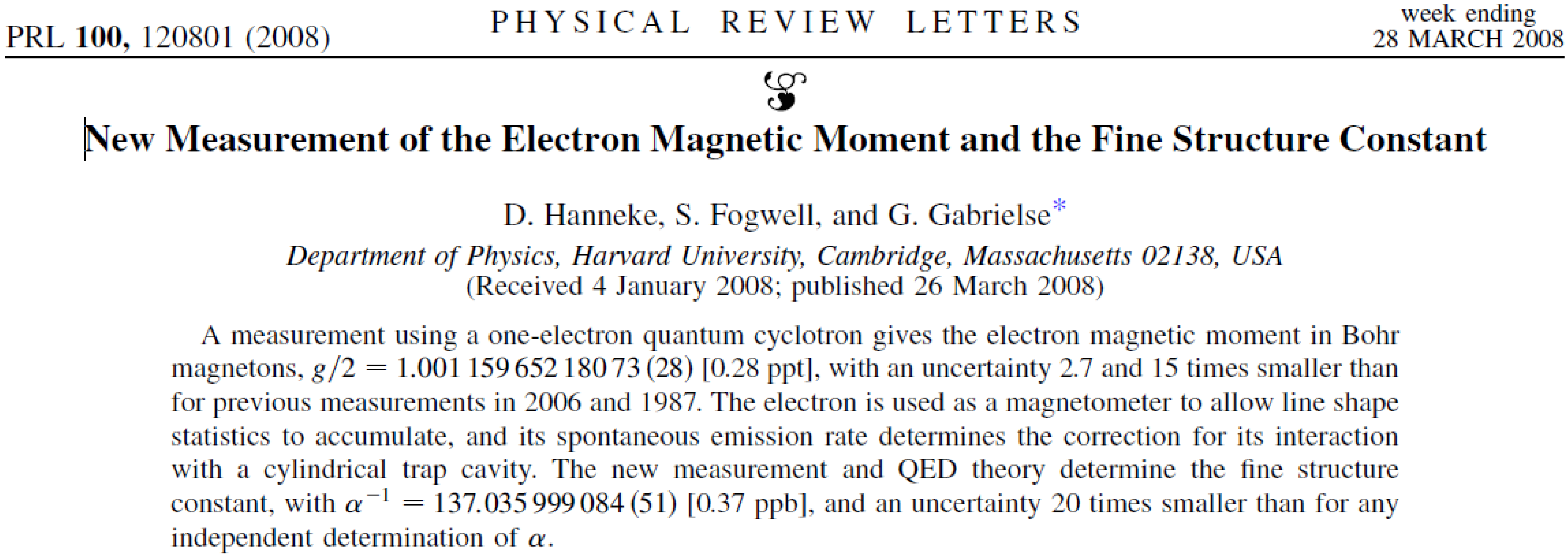
Comparison to theory allows extraction of α to 3 ppb

Some of the close-to-1000 Feynman diagrams that Kinoshita et al calculated…



Professor Kinoshita

More recently Gabrielse et al. determined a_e to 0.24 ppb (α to 0.37 ppb)



PRL **100,** 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

Is there a point to measuring with such precision?

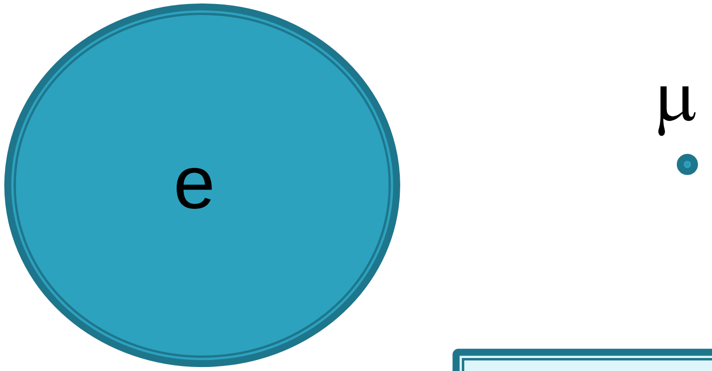
YES: **searching for new physics** at *the precision frontier .*
i.e. doing precision measurements of processes we can calculate well with the Standard Model.

Sensitivity to physics at higher energies grows as one probes the vacuum at smaller regions of space.

$$\lambda = \frac{hc}{mc^2}$$

Compton wavelength:
wavelength of a photon that has energy equal to mass of particle.

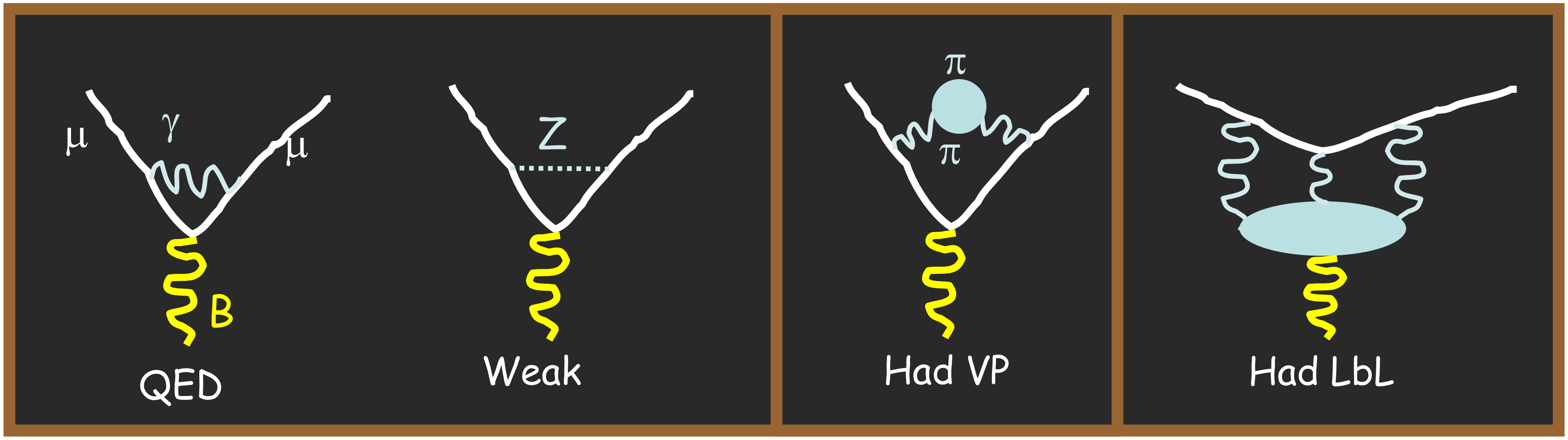
$$m_\mu \approx 200\, m_e \quad \Rightarrow \lambda_e \approx 200\, \lambda_\mu$$



Muon probes a smaller region of space.

Conclusion: muon probes vacuum fluctuations with 200 times the energy of those probed by electron.

$a_\mu = (g - 2)/2$ is non-zero because of virtual loops, which can be calculated precisely



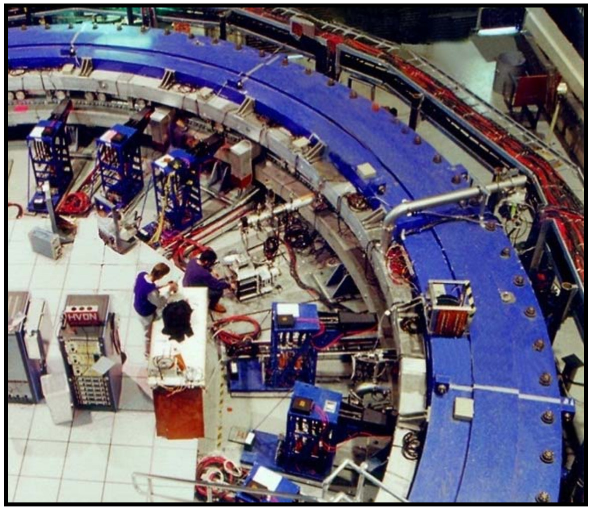
Known well

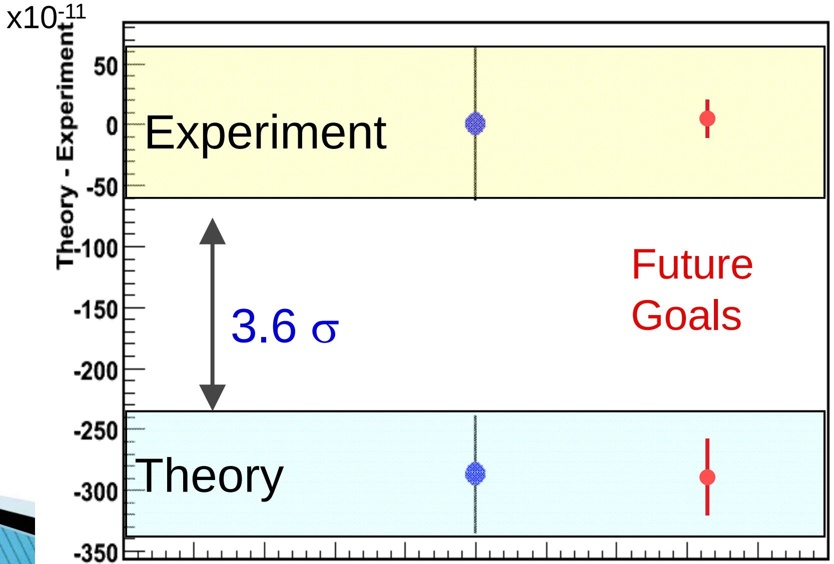
Theoretical work ongoing

The “g-2 test”: Compare experiment to theory. Is SM complete?

$$\delta a_\mu^{NewPhysics} = a_\mu^{Expt.} - a_\mu^{Theory}$$

The New Muon g-2 Experiment at Fermilab
g-2 collaboration (D. Hertzog and L. Roberts, spokepersons)

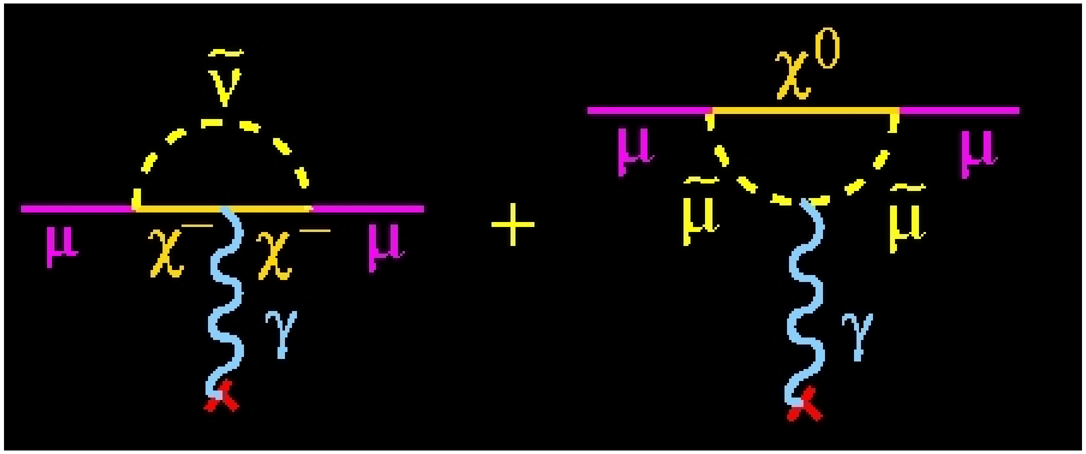




Goal: 0.14 ppm

Expected Improvement

SUSY contribution to a_μ :



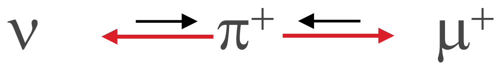
$$a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

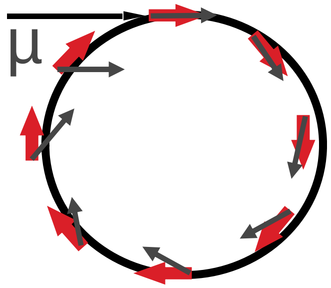
How can one measure g-2?

(1) Polarized muons

~97% polarized for forward decays

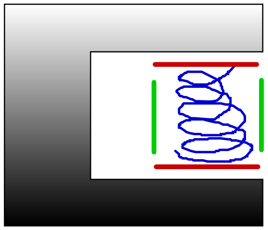


(2) Precession proportional to (*g*-2)

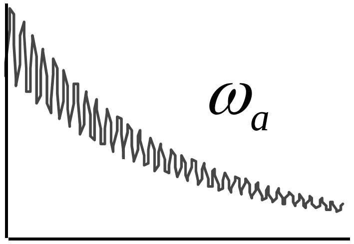


(3) P_m magic momentum = 3.094 GeV/c

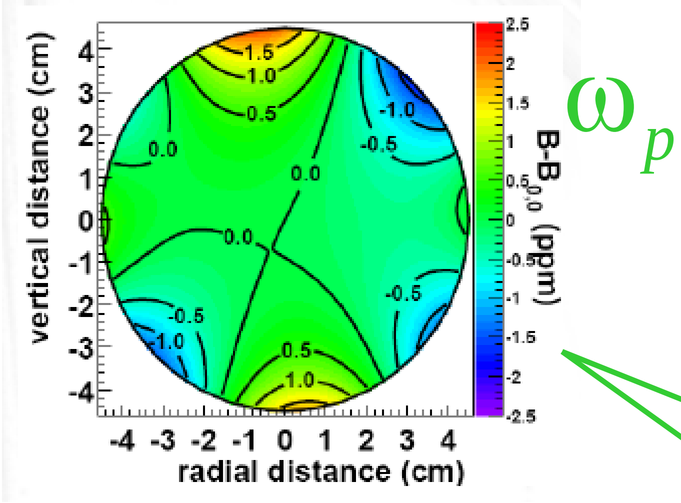
E field doesn't affect muon spin when γ = 29.3

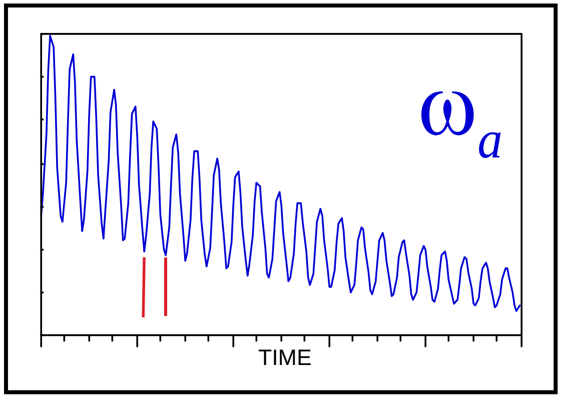


(4) Parity violation in the decay gives average spin direction

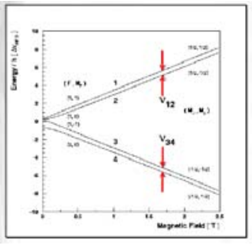


The anomaly is obtained from three well-measured quantities





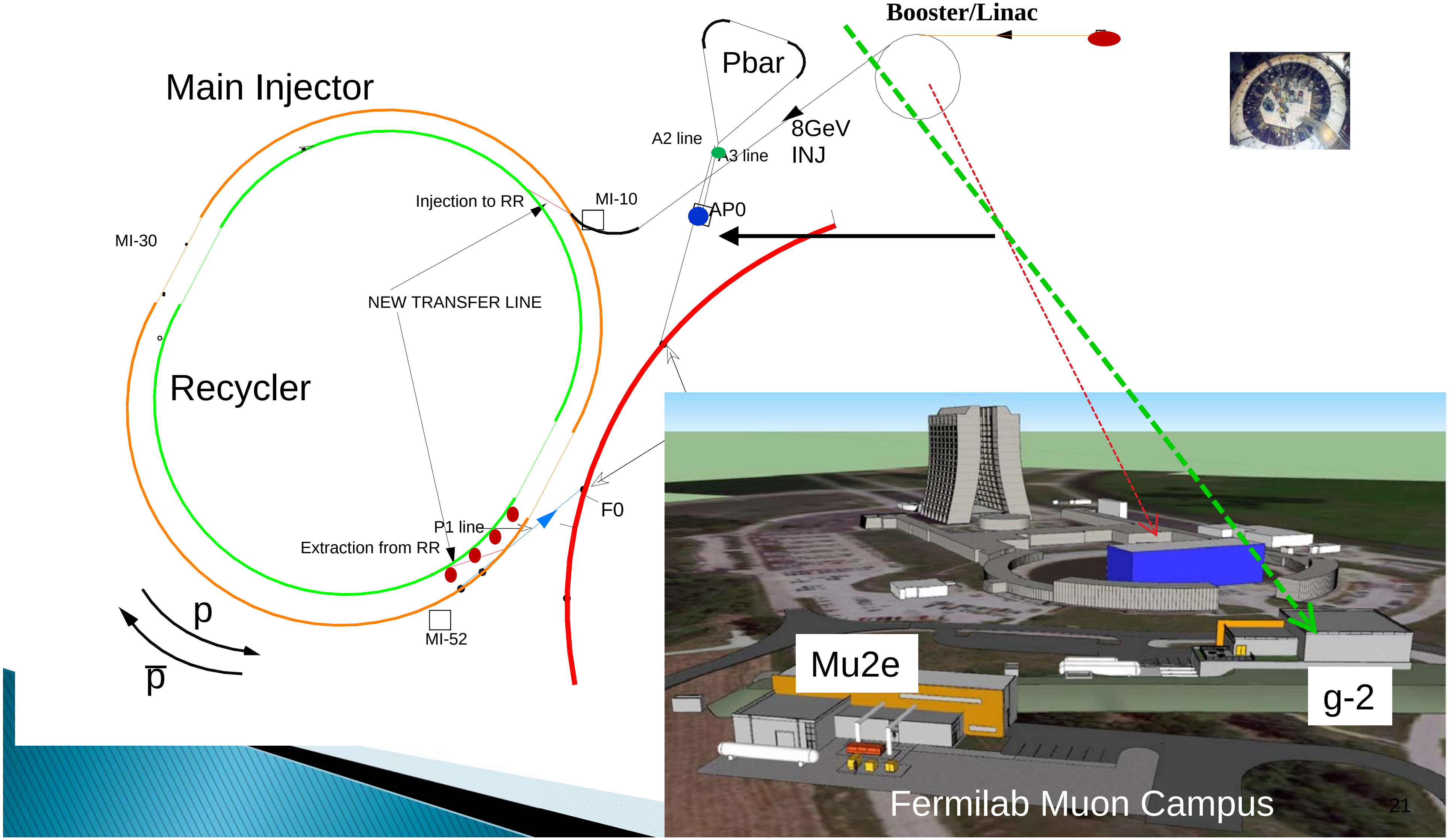
$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$



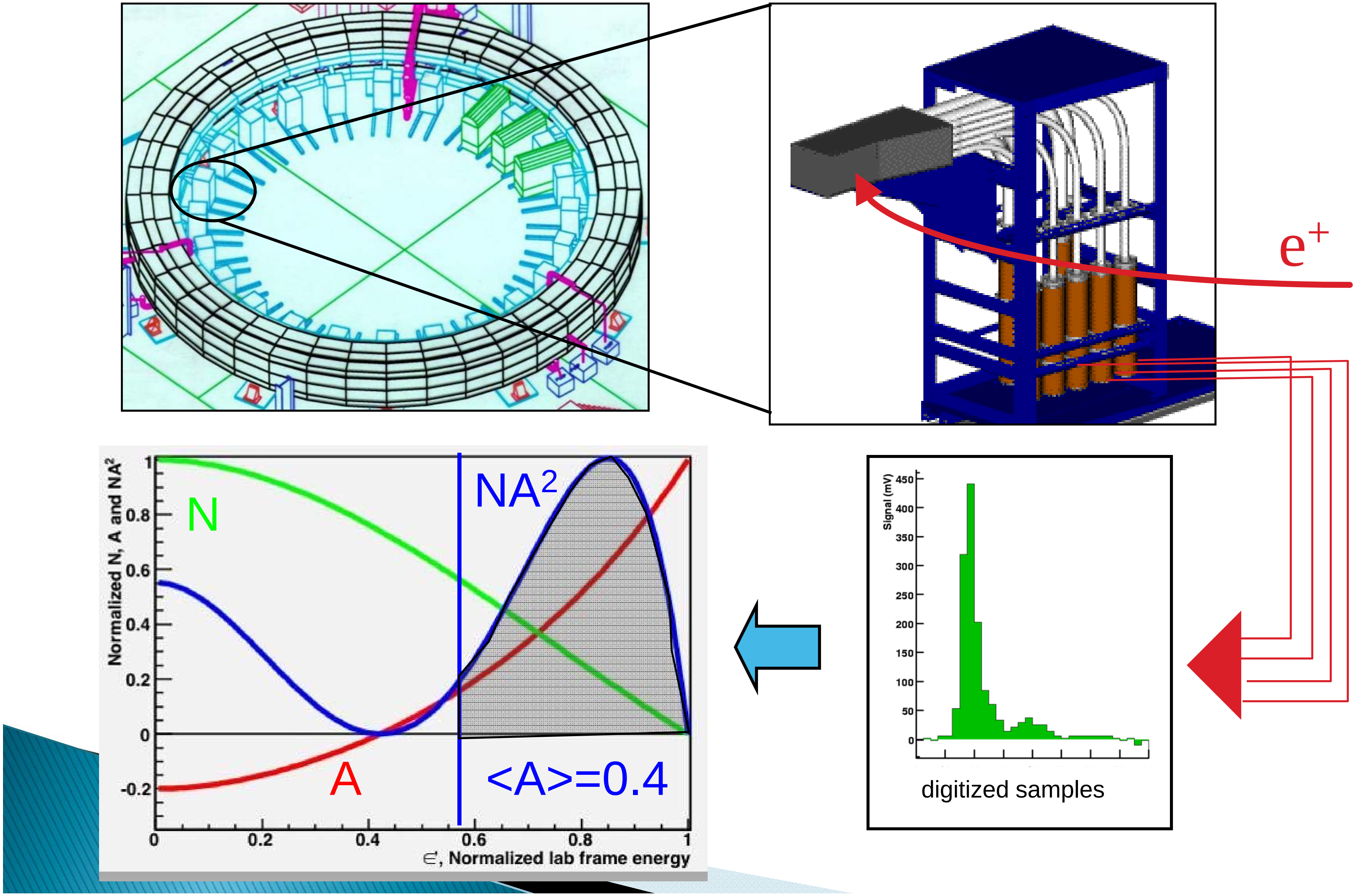
μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

= *3.183 345 39(10) (31 ppb)*

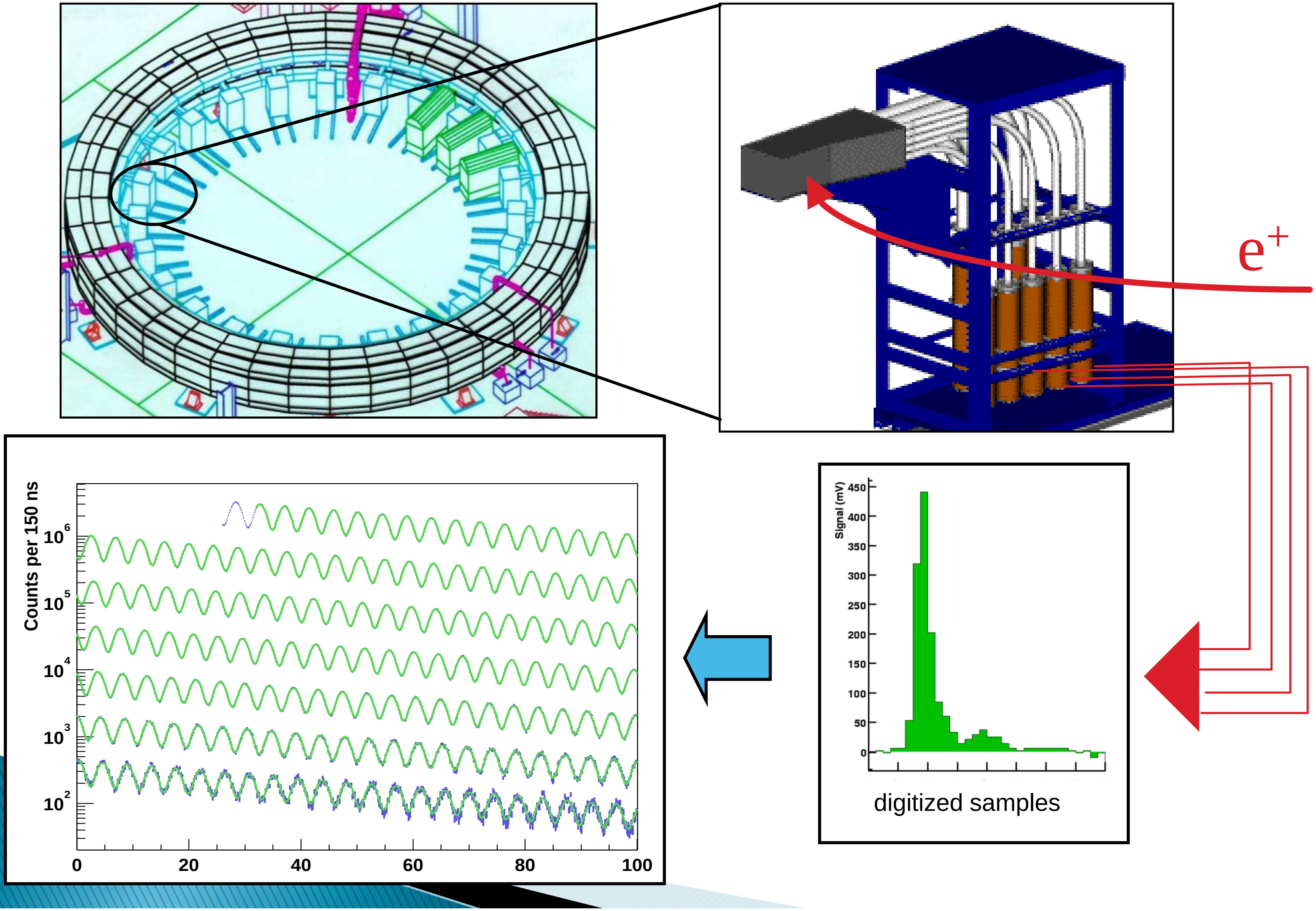
Polarized muons delivered and stored in the ring at the magic momentum, 3.094 GeV/c



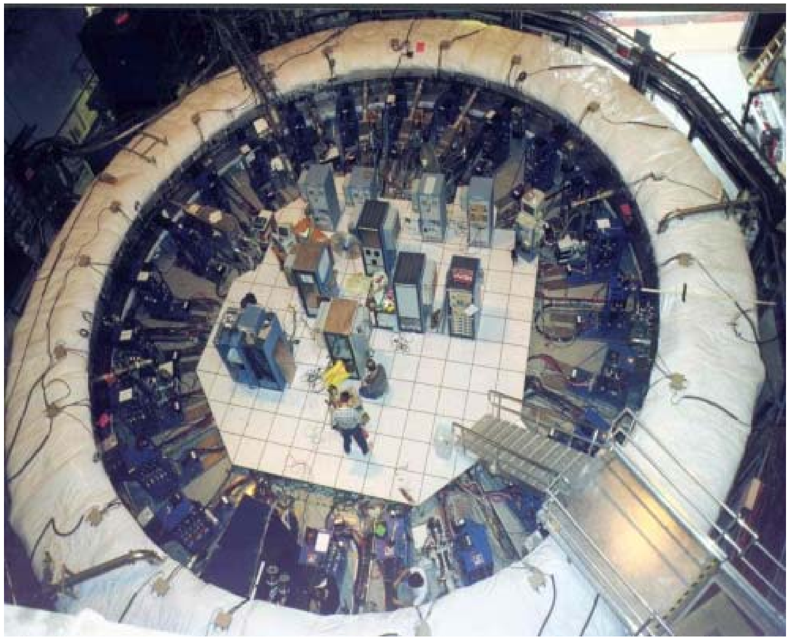
Detectors

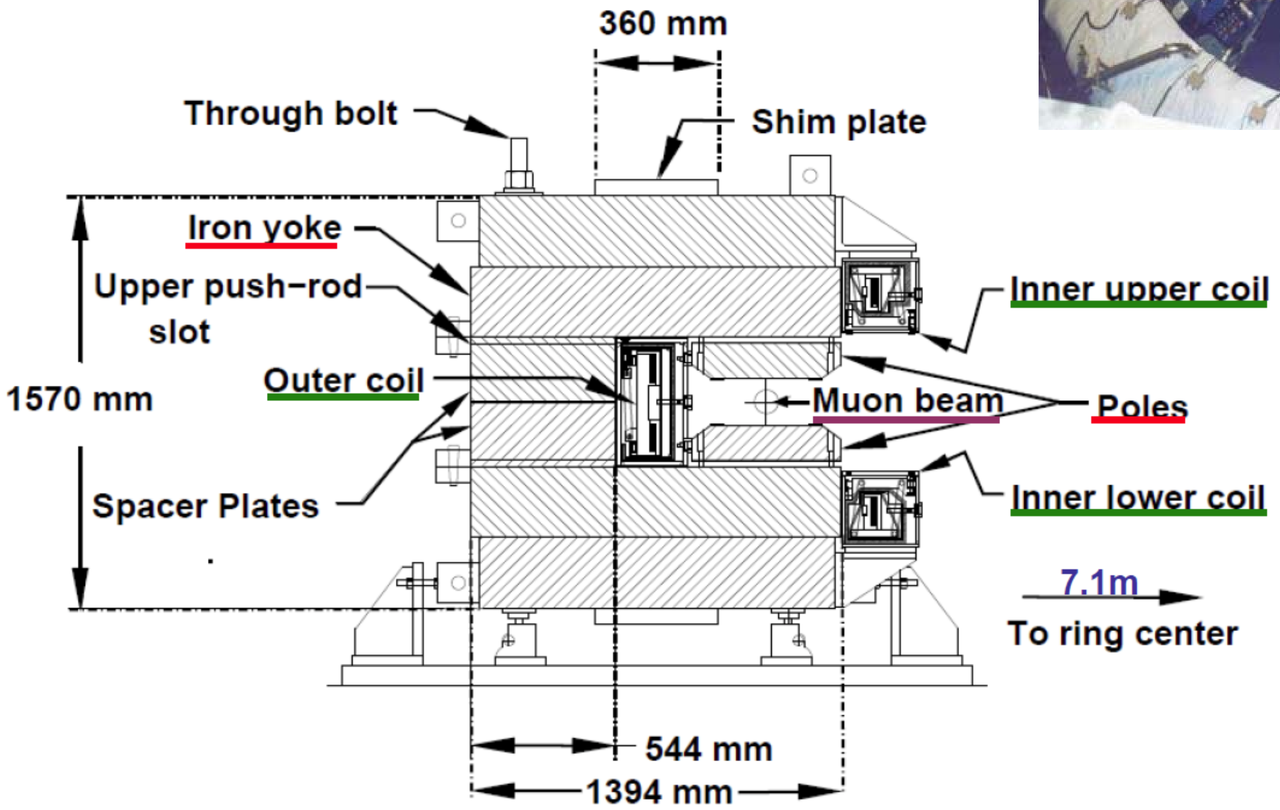

e+
Signal (mV)
450
400
350
300
250
200
150
100
50
0
digitized samples
Normalized N, A and NA²
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
∈', Normalized lab frame energy
N
NA²
A
<A>=0.4

An “event” is an isolated positron above a threshold.

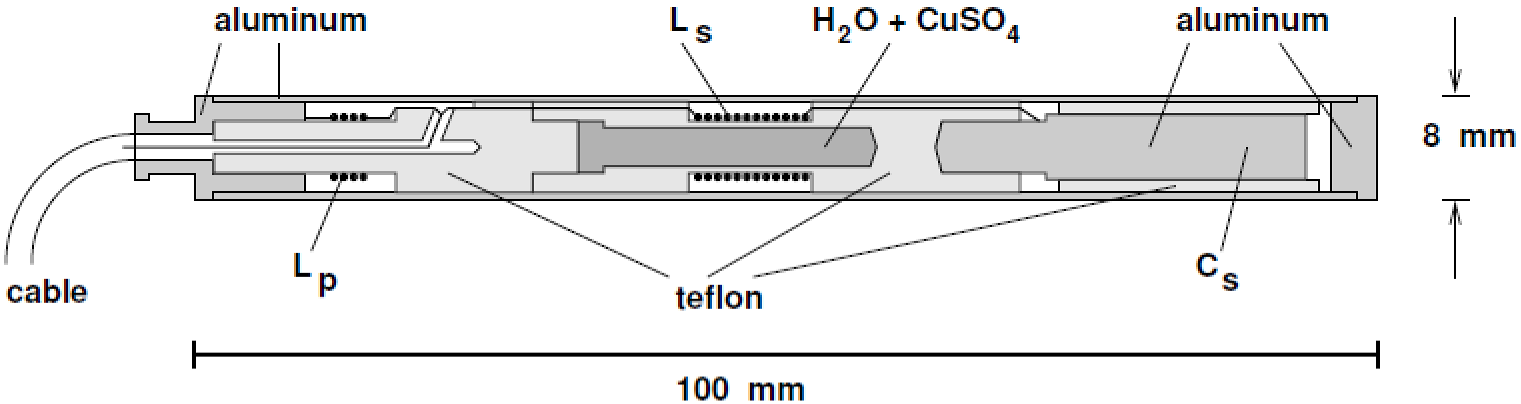


The Magnet




360 mm
Through bolt
Shim plate
Iron yoke
Upper push-rod slot
Inner upper coil
1570 mm
Outer coil
Muon beam
Poles
Spacer Plates
Inner lower coil
7.1m
To ring center
544 mm
1394 mm

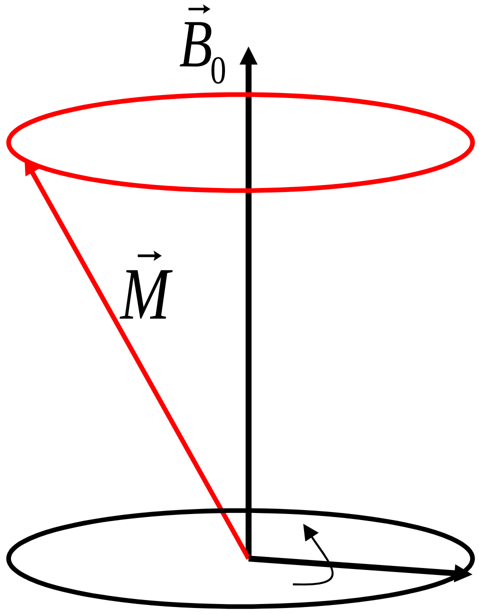
Basic unit to measure B field is NMR probe



(b) Trolley and fixed probe

Magnetic moment in magnetic field

$$\frac{d\vec{M}}{dt} = \gamma\, \vec{M} \times \vec{B} \qquad\qquad \vec{M} = \gamma\, \vec{J}$$



In a frame rotating with freq. ω:

$$\frac{d\vec{M}}{dt} = \frac{\partial \vec{M}}{\partial t} + \vec{\omega} \times \vec{M}$$

$$\frac{\partial \vec{M}}{\partial t} = \gamma\, \vec{M} \times (\vec{B} + \frac{\vec{\omega}}{\gamma})$$

$$\vec{B}_e = \vec{B} + \frac{\vec{\omega}}{\gamma}$$

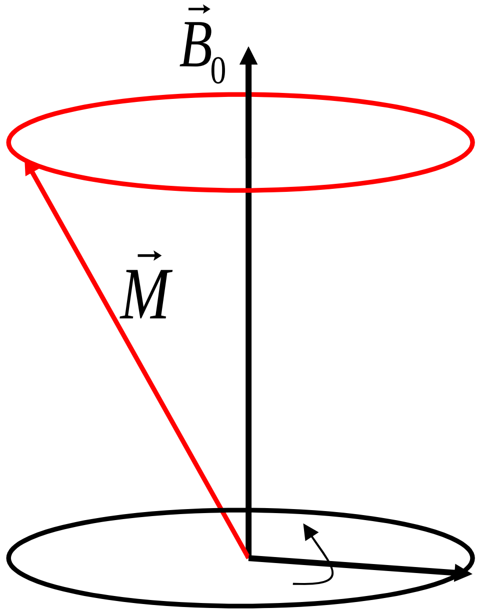
Magnetic moment in magnetic field

$$\frac{d\vec{M}}{dt} = \gamma\, \vec{M} \times \vec{B} \qquad\qquad \vec{M} = \gamma\, \vec{J}$$

In a frame rotating with freq. ω:

$$\frac{d\vec{M}}{dt} = \frac{\partial \vec{M}}{\partial t} + \vec{\omega} \times \vec{M}$$

$$\frac{\partial \vec{M}}{\partial t} = \gamma\, \vec{M} \times (\vec{B} + \frac{\vec{\omega}}{\gamma})$$



Field ***B***

Field $\boldsymbol{B_1}$ rotating with freq. ω around $\boldsymbol{B_0}$.

$$\vec{B} = \hat{k}\, B_0 + \vec{B}_1$$

$$\vec{B}_e = \hat{k}(B_0 + \frac{\omega}{\gamma}) + \hat{i}\, B_1 \longrightarrow \boxed{\vec{B}_e = \hat{k}(-\frac{\omega_0}{\gamma} + \frac{\omega}{\gamma}) - \hat{i}\,\frac{\omega_1}{\gamma}}$$

strength of B_0

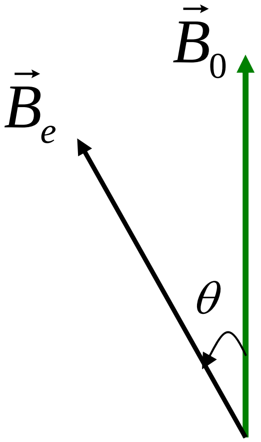
freq. of B_1

strength of B_1

Magnetic moment in magnetic field

$$\boxed{\vec{B}_e = \hat{k}\left(-\frac{\omega_0}{\gamma}+\frac{\omega}{\gamma}\right)-\hat{i}\left(\frac{\omega_1}{\gamma}\right)}$$

$$\left|\vec{B}_e\right| = \sqrt{\left(\frac{\omega-\omega_0}{\gamma}\right)^2+\left(\frac{\omega_1}{\gamma}\right)^2} = -\frac{a}{\gamma}$$



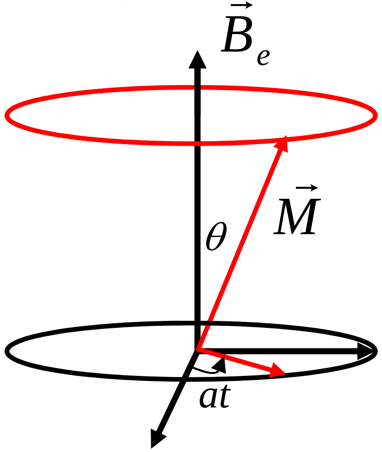
$$\cos\theta = \frac{\omega_0-\omega}{a}$$

$$\sin\theta = \frac{\omega_1}{a}$$

In S’ motion is precession around ***B$_e$*** with angular velocity ***a = -γB$_e$***

$$\vec{M} = (M\sin\theta\cos(at), M\sin\theta\sin(at), M\cos\theta)$$

$$\vec{B}_0 = (B_0\sin\theta, 0, B_0\cos\theta)$$



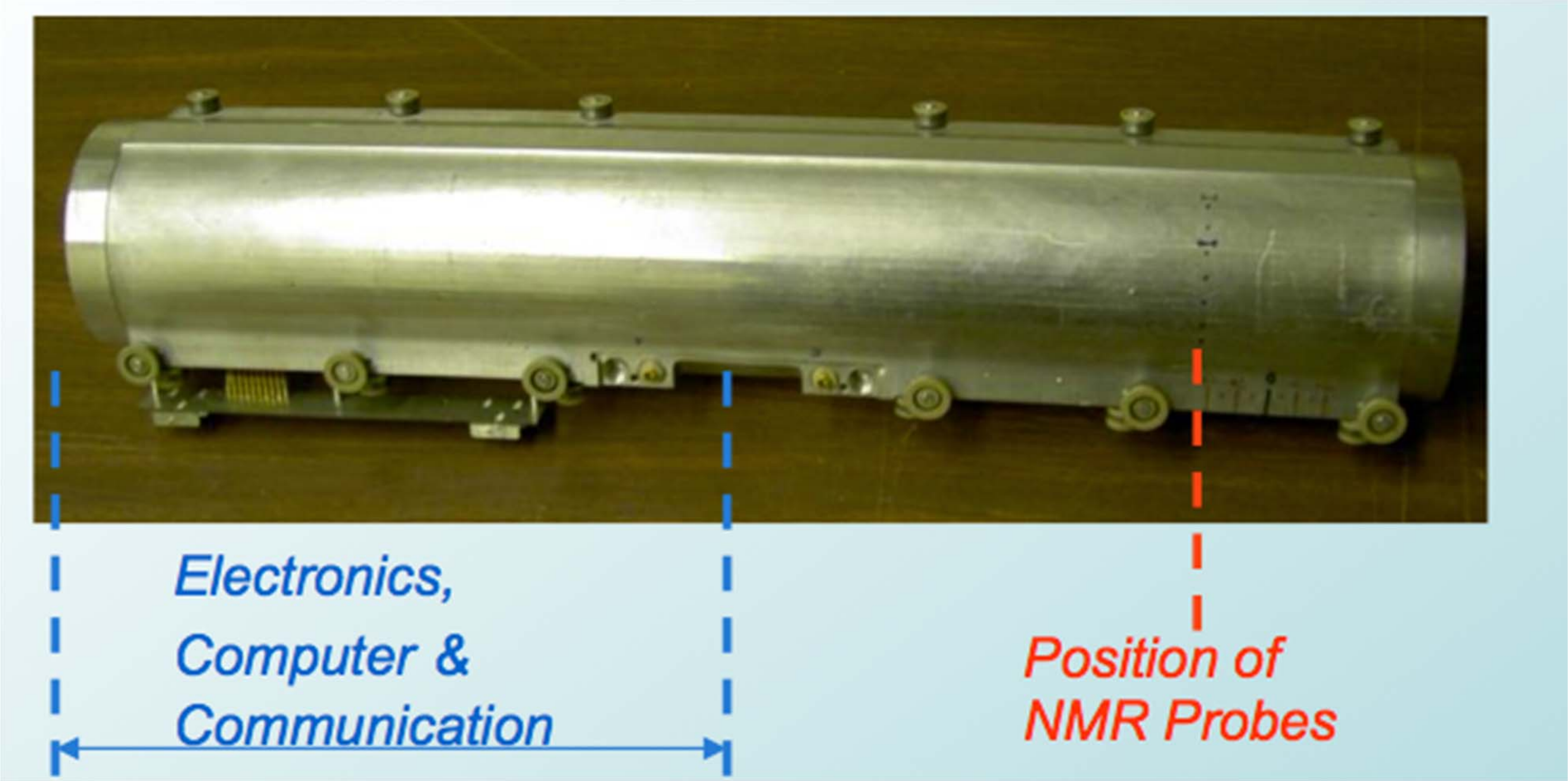
Angle between ***M*** and ***B$_0$***

$$\cos\alpha = \frac{\vec{M}\cdot\vec{B}_0}{\left|\vec{M}\right|\cdot\left|\vec{B}_0\right|}$$

$$\boxed{\cos(\alpha) = \cos^2\theta + \sin^2\theta\cos(at)}$$

Show Mathematica animations

Field is measured with “Trolley”



- Distortion of trolley on field is very small !
- Low power consumption (on average P < 1 W) !

17 NMR probes on the trolley

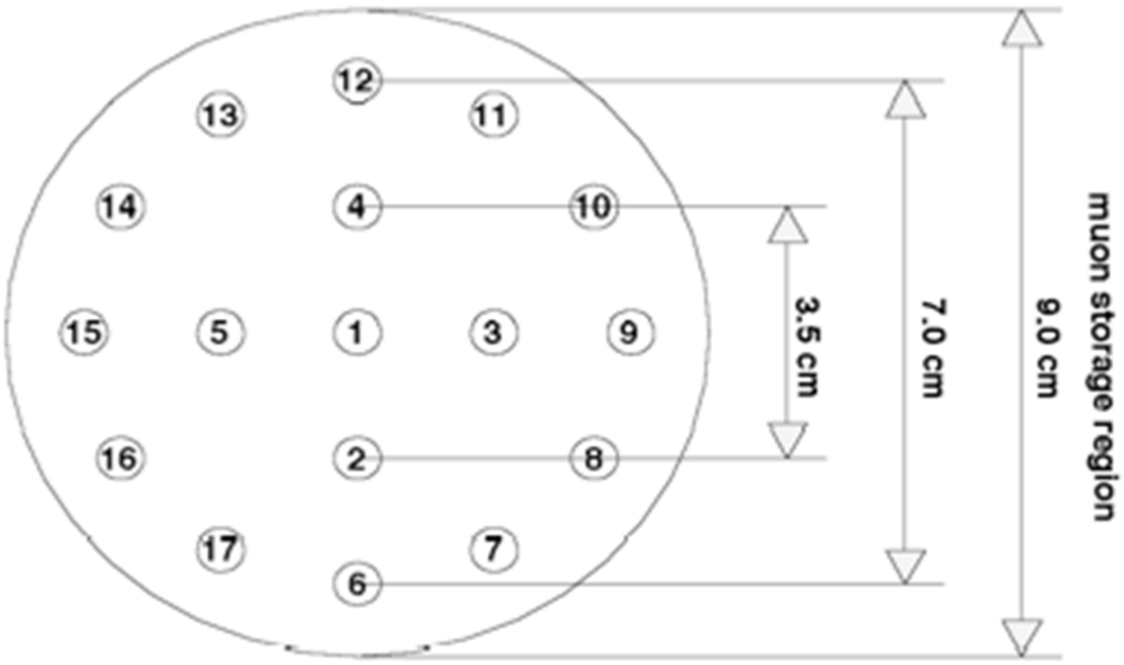
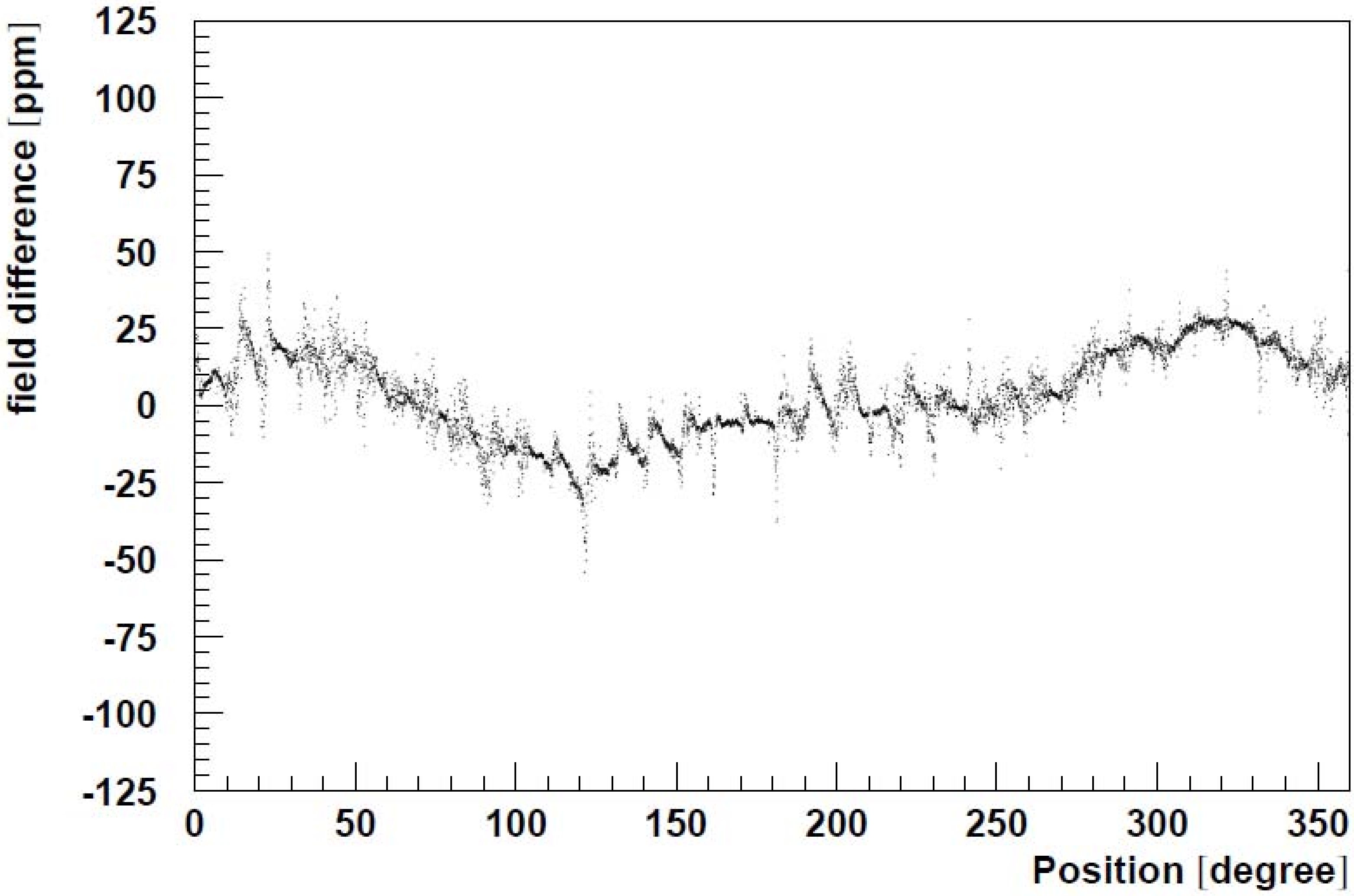


Figure 1: The positions of the trolley probes

Problem: temperature fluctuations result in variations at the level of 10 ppm.
About 400 fixed NMR probes around the magnet will monitor these variations.

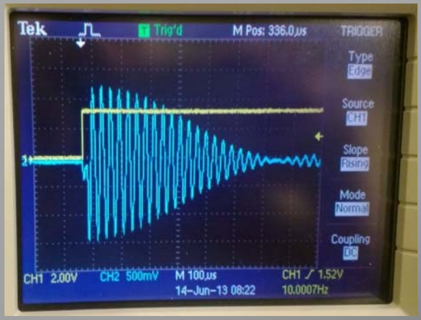


NMR Magnet Calibration Probes and Electronics

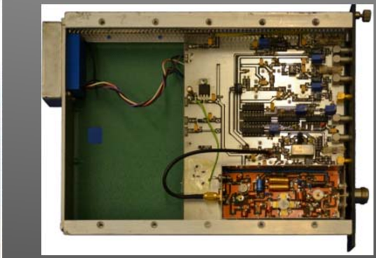
Will manufacture new fixed probes and refurbish the pulsed NMR electronics needed to determine ω_p

Triage and Repairs of Fixed Probes

1.45 T CENPA test magnet



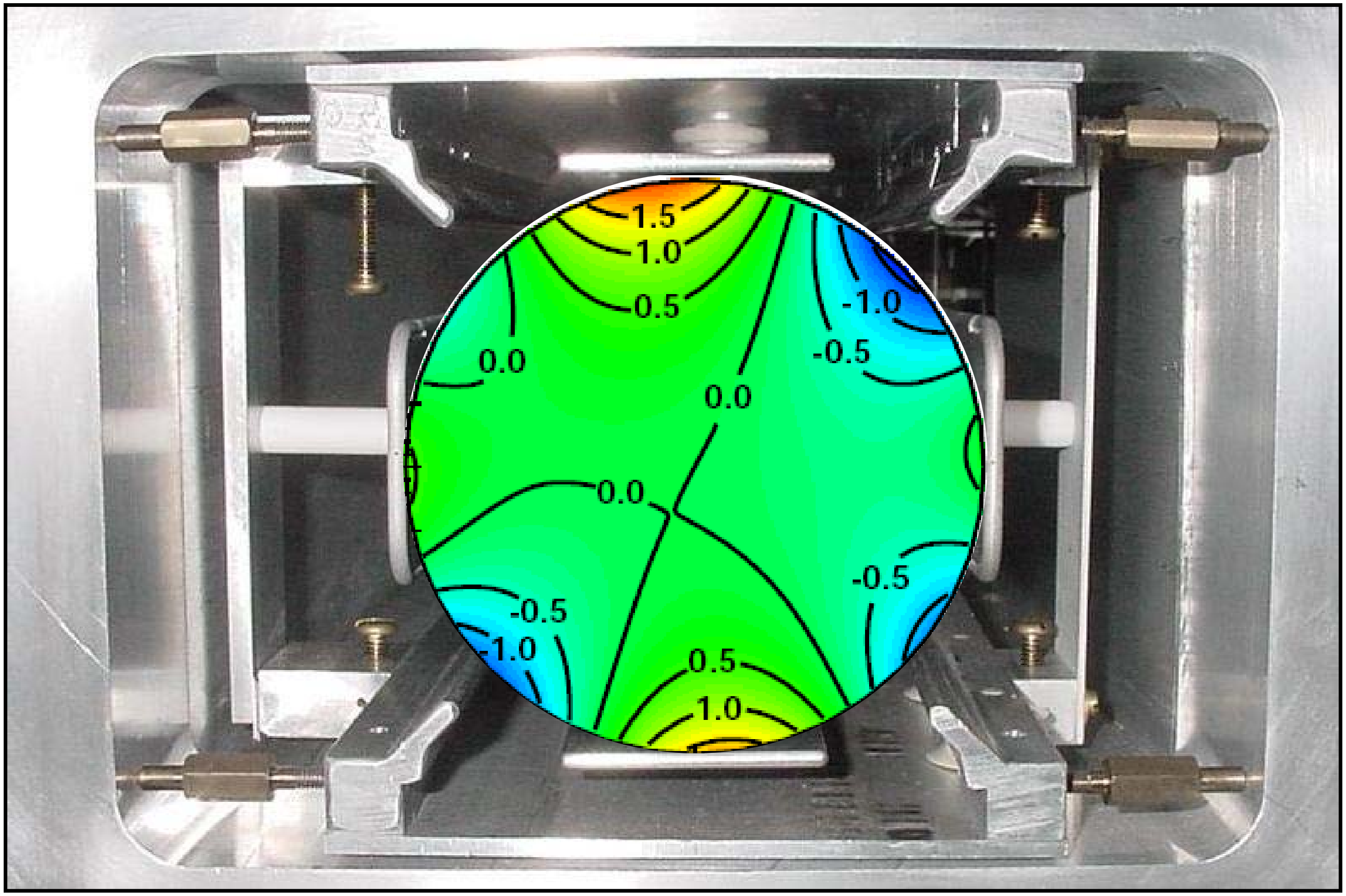
Proton Free Induction Decay



Electronics to be refurbished, rebuilt or replaced

Garcia, Swanson et al

Field will be measured to 70 parts per billion!



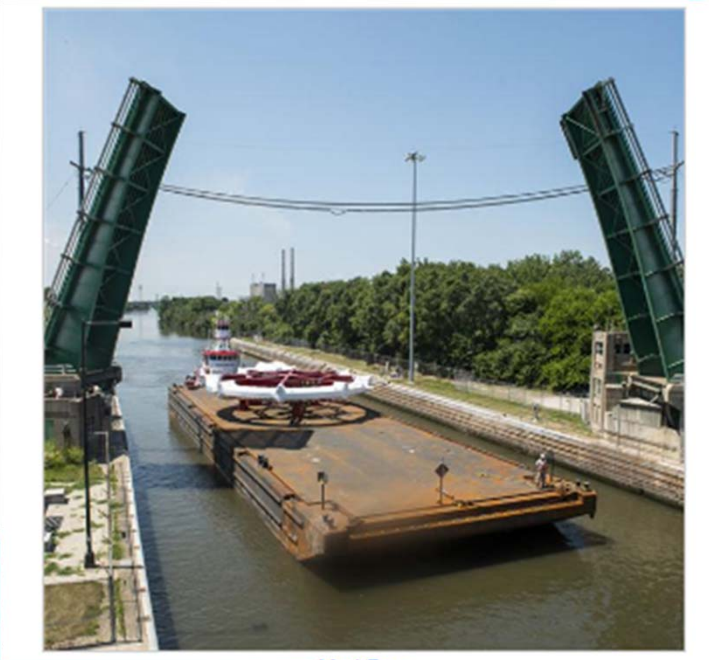
We need to measure magnetic field where the muons are

Moving the storage ring has begun

SCIENTIFIC AMERICAN™

Honk If You Love Muons: 3,200 Mile Road Trip Planned For Muon G-2 Storage Ring

If you're driving from New York to Illinois this summer and you find yourself getting really annoyed because you're crawling behind a slow truck with an oversize load, check out that load.



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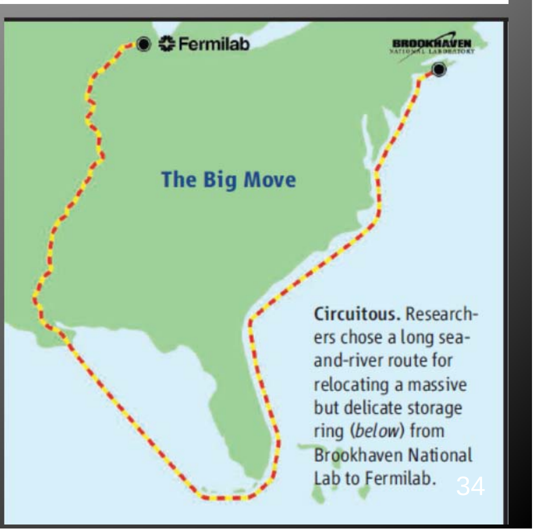

Circuitous. Researchers chose a long sea-and-river route for relocating a massive but delicate storage ring (*below*) from Brookhaven National Lab to Fermilab.

Design of new building for new g-2 experiment at FNAL.

FNAL, April 18 2014

Bottom of magnet yoke being assembled at FNAL, June 26 2014

The end