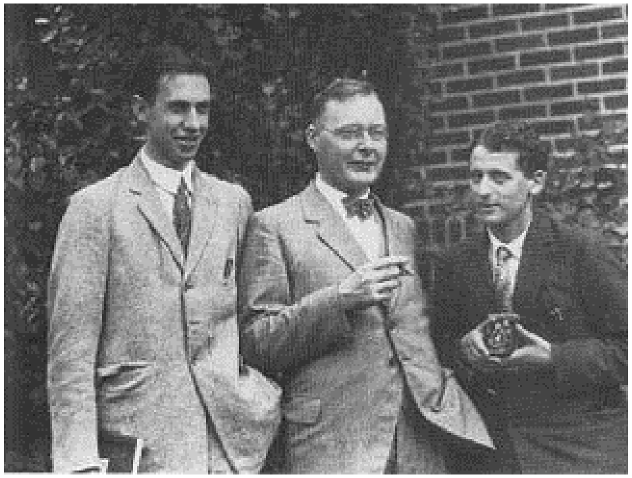
Searching for new physics at *the precision frontier*: muon g-2

Presentation to
REU Students
July 2013

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

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 leads to the Pauli Exclusion Principle, Chemistry, and life.

Heisenberg and Pauli

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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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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: $\mu_\mathrm{p} / \mu_\mathrm{n} = - 3/2 \sim -1.46$.

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

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

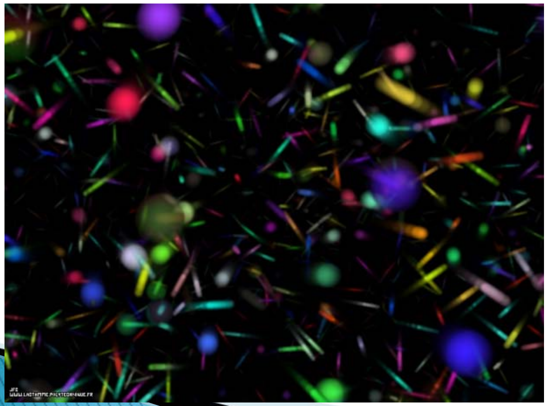
1930s: Oppenheimer et al. tried to calculate first order correction = infinity!

- 1947: Kusch, Foley, Rabi measured electron $g = 2.002$
- Schwinger et al. develop Quantum Electrodynamics (QED) and calculate the right 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.

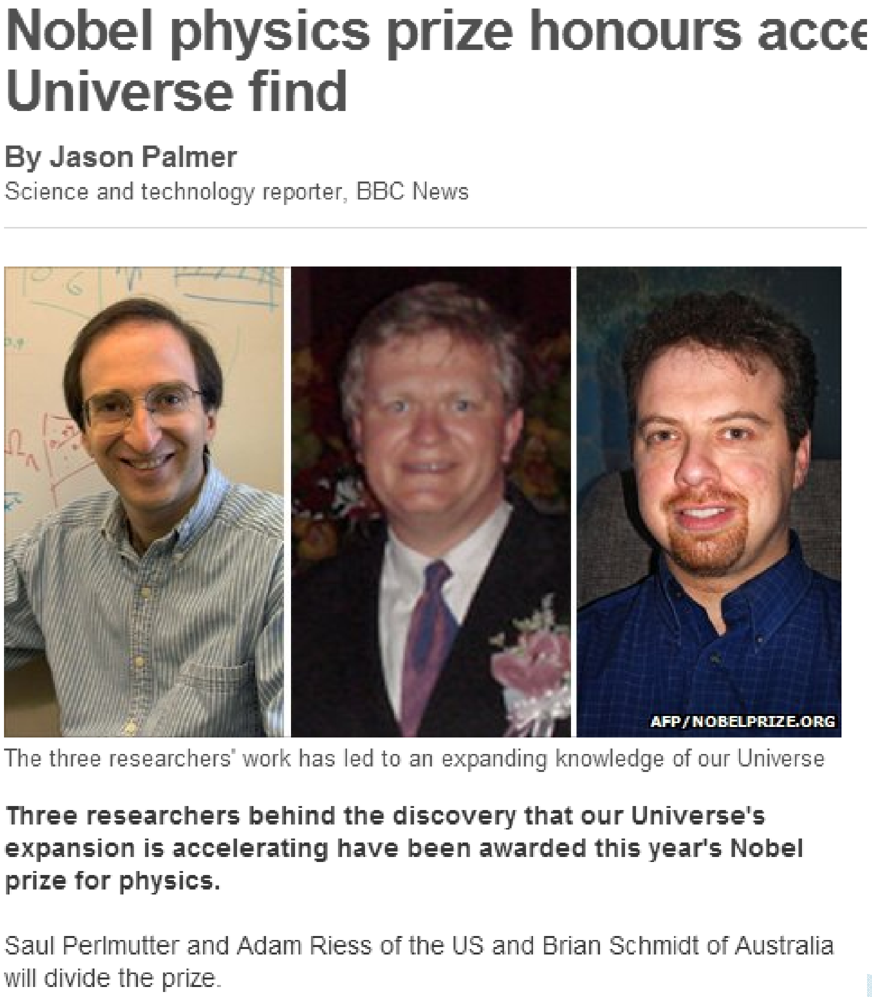
Compton wavelength: $\lambda = \dfrac{hc}{mc^2}$ wavelength of a photon that has energy equal to mass of particle.



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

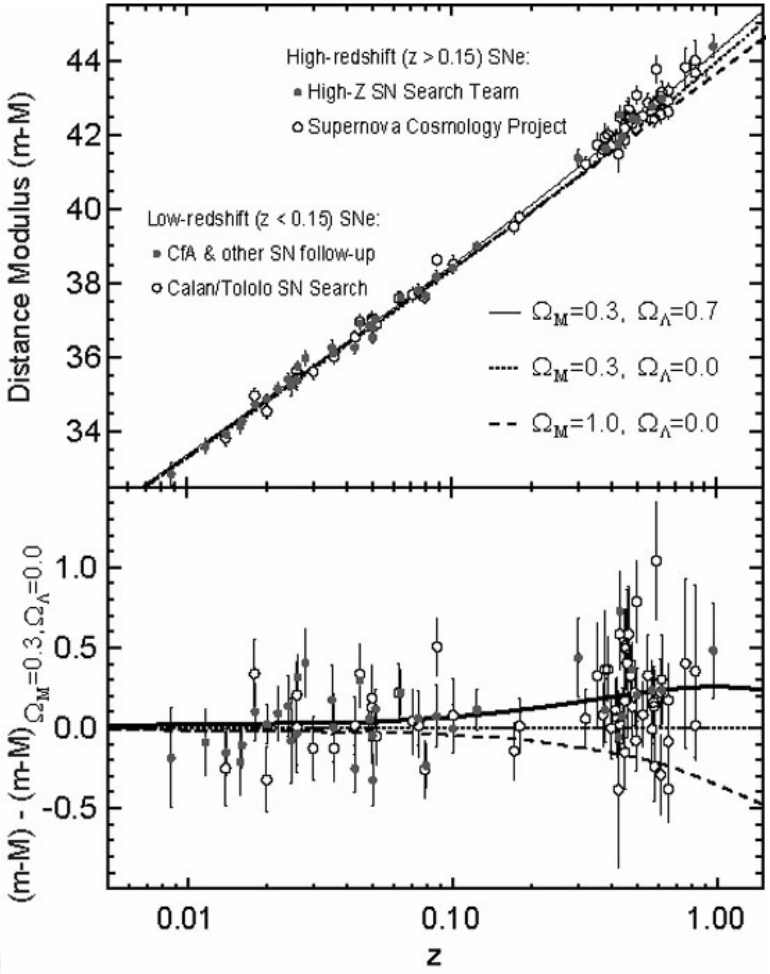
By Jason Palmer
Science and technology reporter, BBC News

AFP/NOBELPRIZE.ORG

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

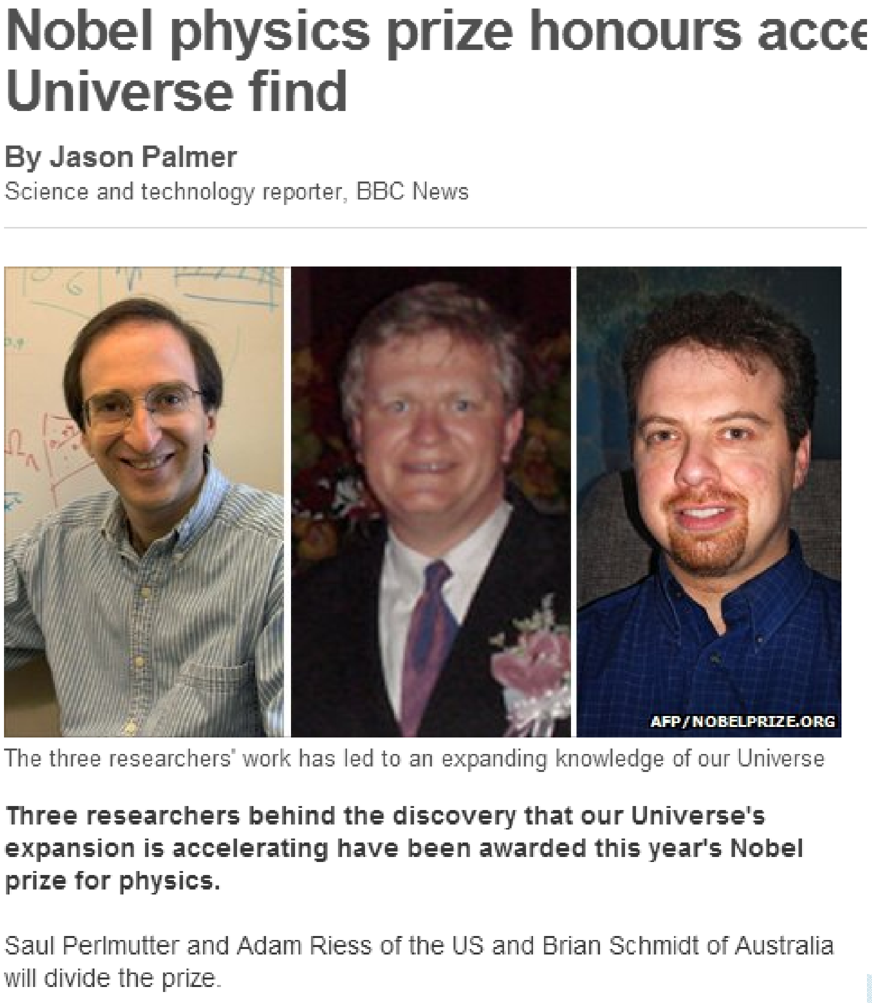
Three researchers behind the discovery that our Universe's expansion is accelerating have been awarded this year's Nobel prize for physics.

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 100 orders of magnitude off (YES!) from the measurement.**



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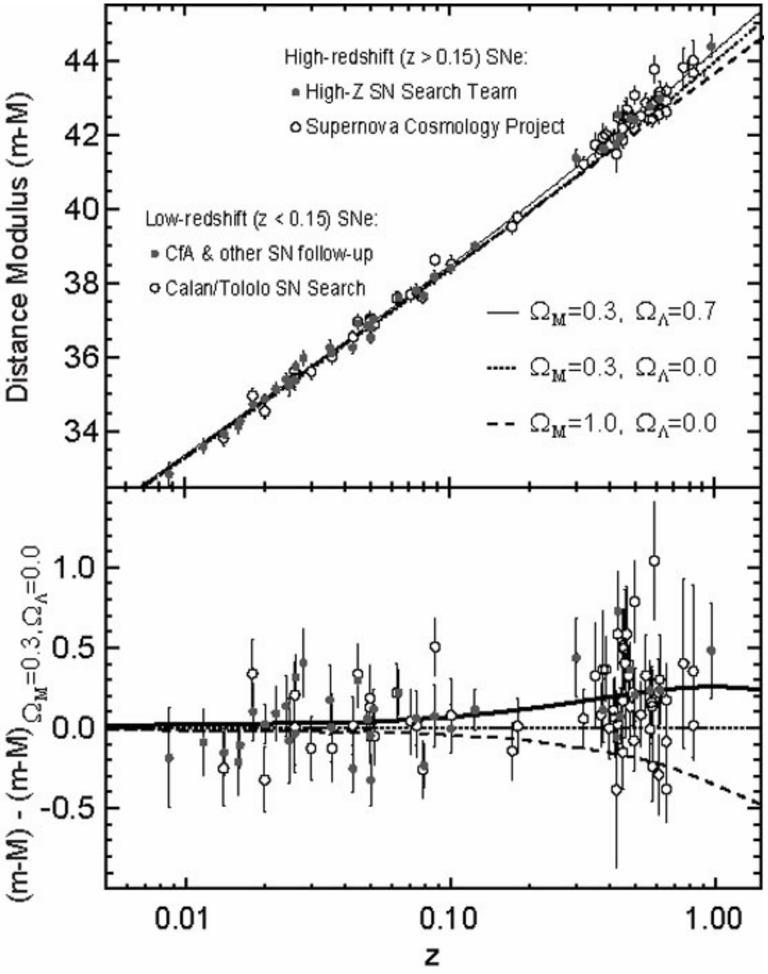

What is the order of magnitude of the Compton wavelength of the electron?

A. $\approx 1\,cm$;

B. $\approx 1\,mm$;

C. $\approx 1\,\mu m$;

D. $\approx 1\,nm$;

E. $\approx 1\,pm$.

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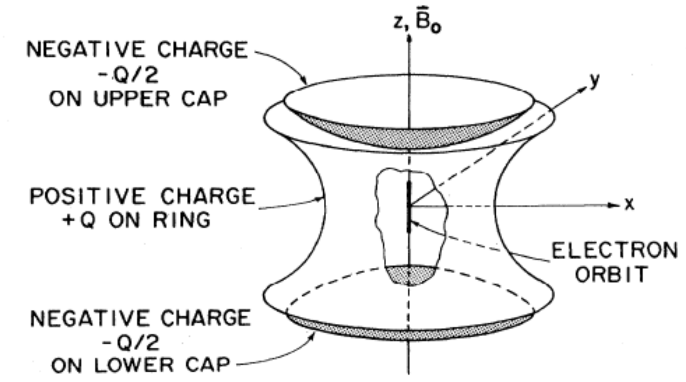
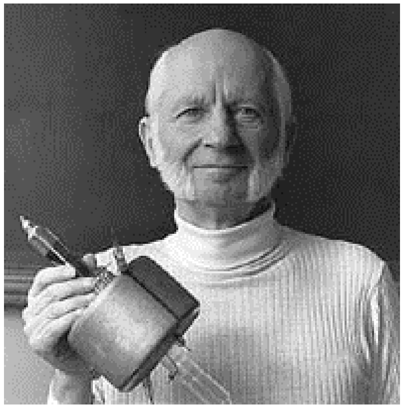
$C.\quad \approx 1\,\mu m;$

$D.\quad \approx 1\,nm;$

[✓ $E.\quad \approx 1\,pm.$]

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



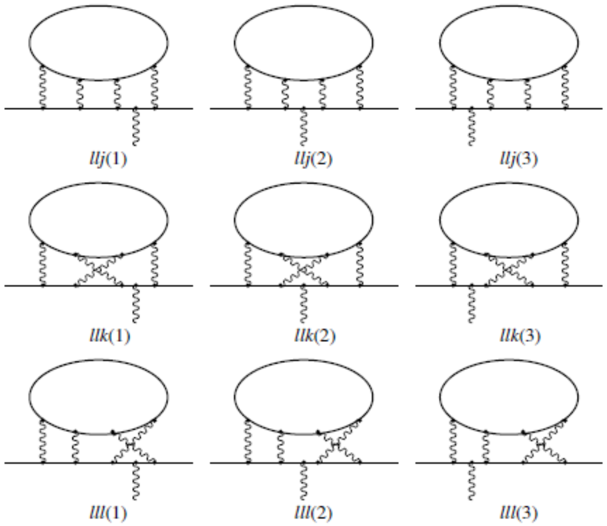


$$a_{e-}^{\text{exp}} = 0.0011596521884(43)$$

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

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

Is there a point to measuring with such precision? YES

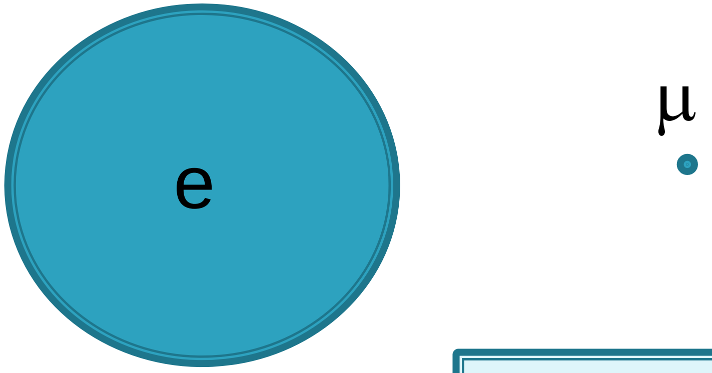
searching for new physics at *the precision frontier* by doing precision measurements of things we can calculate well with the Standard Model.

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.

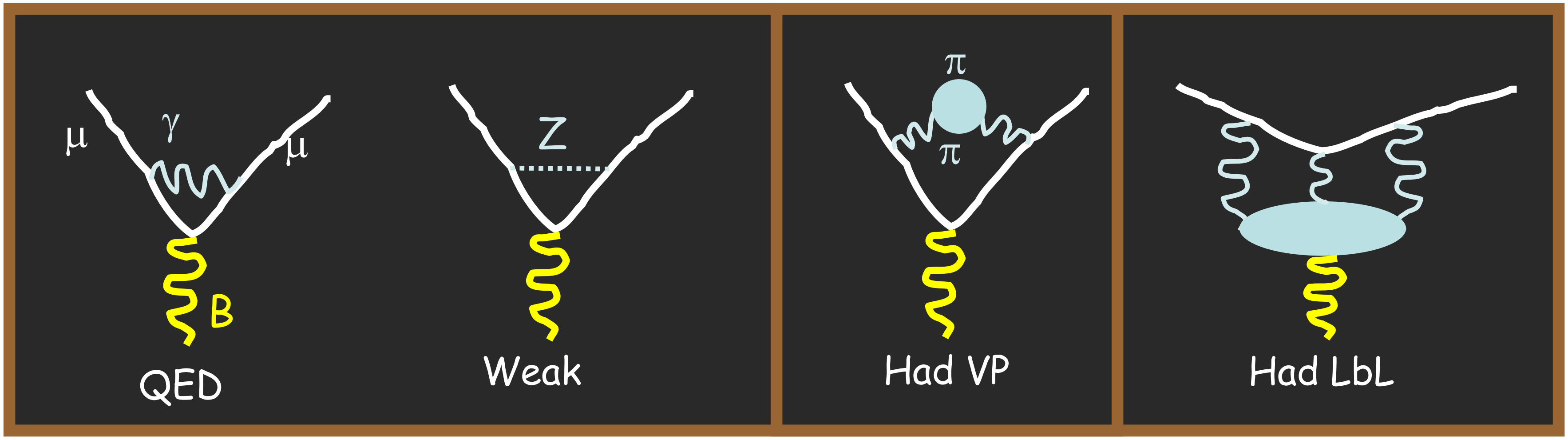
$$m_\mu \approx 200\, m_e \quad \Rightarrow \lambda_e \approx 200\, \lambda_\mu$$



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 very precisely



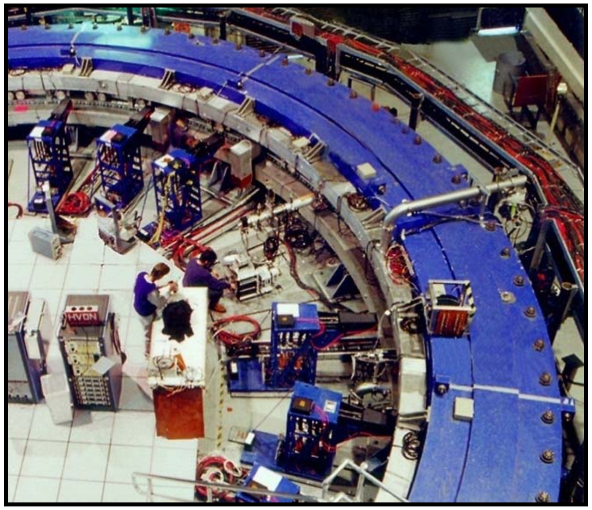
Known well

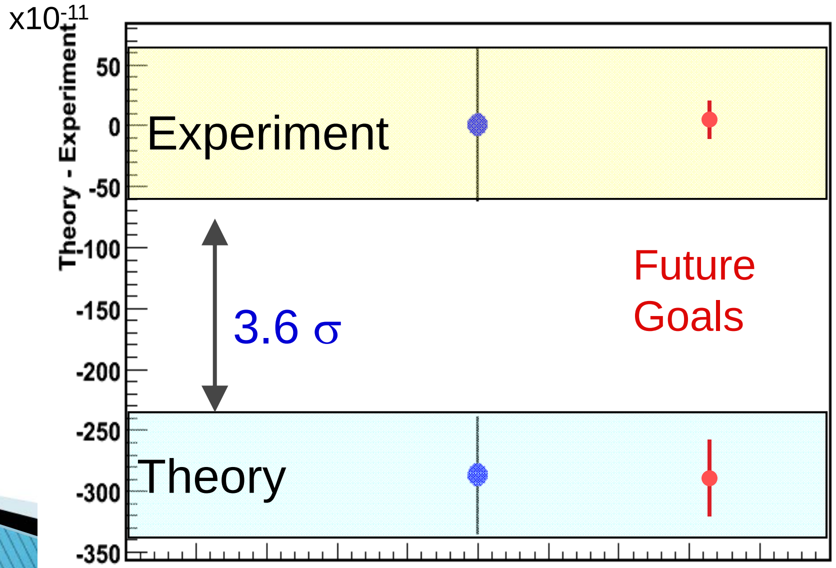
Theoretical work ongoing

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

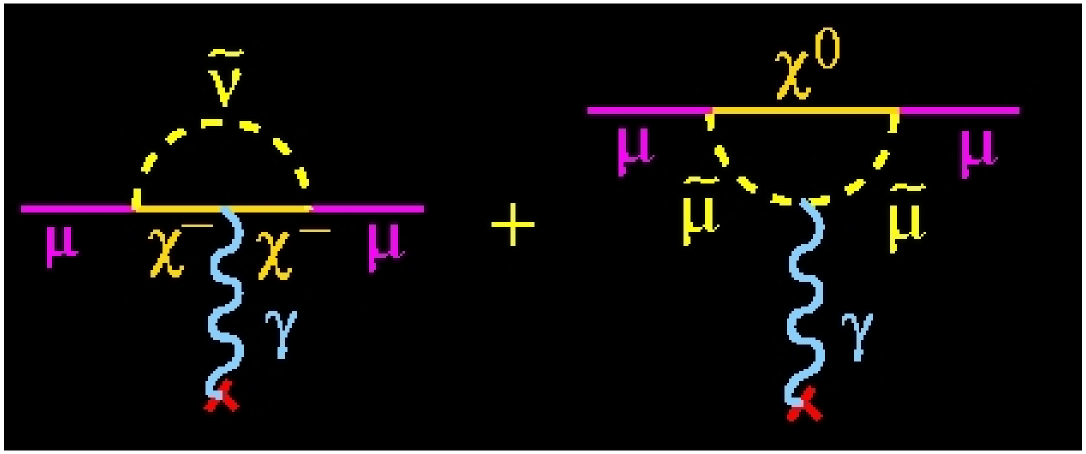




Goal: 0.14 ppm

Expected Improvement

SUSY contribution to a_μ:



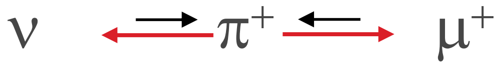
$$a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

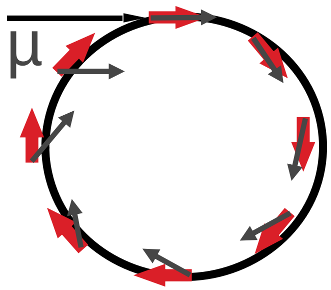
How can one measure g-2?

(1) Polarized muons

~97% polarized for forward decays

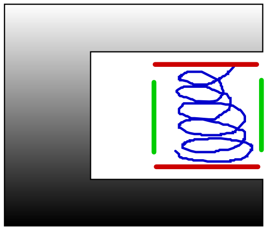


(2) Precession proportional to (*g*-2)

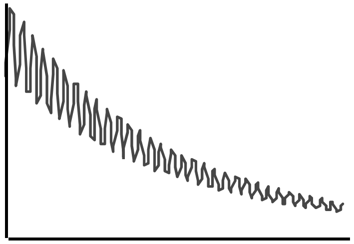


(3) P_m magic momentum = 3.094 GeV/c

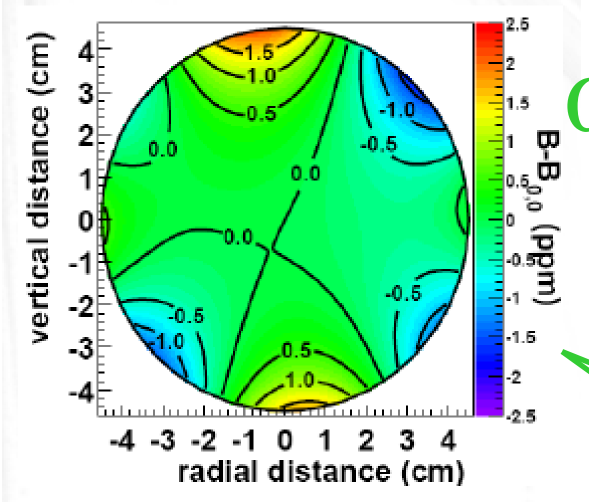
E field doesn't affect muon spin when $\gamma = 29.3$



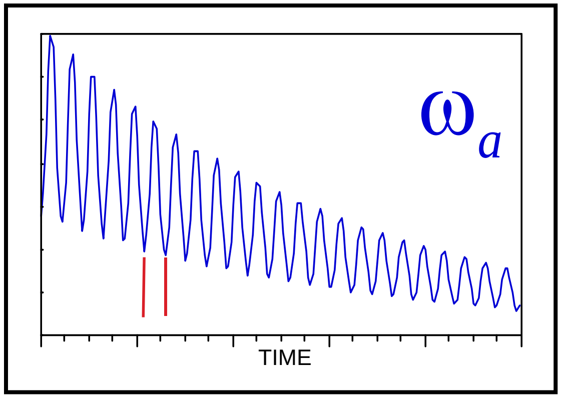
(4) Parity violation in the decay gives average spin direction



The anomaly is obtained from three well-measured quantities

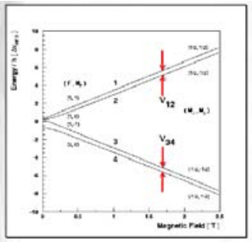


ω_p



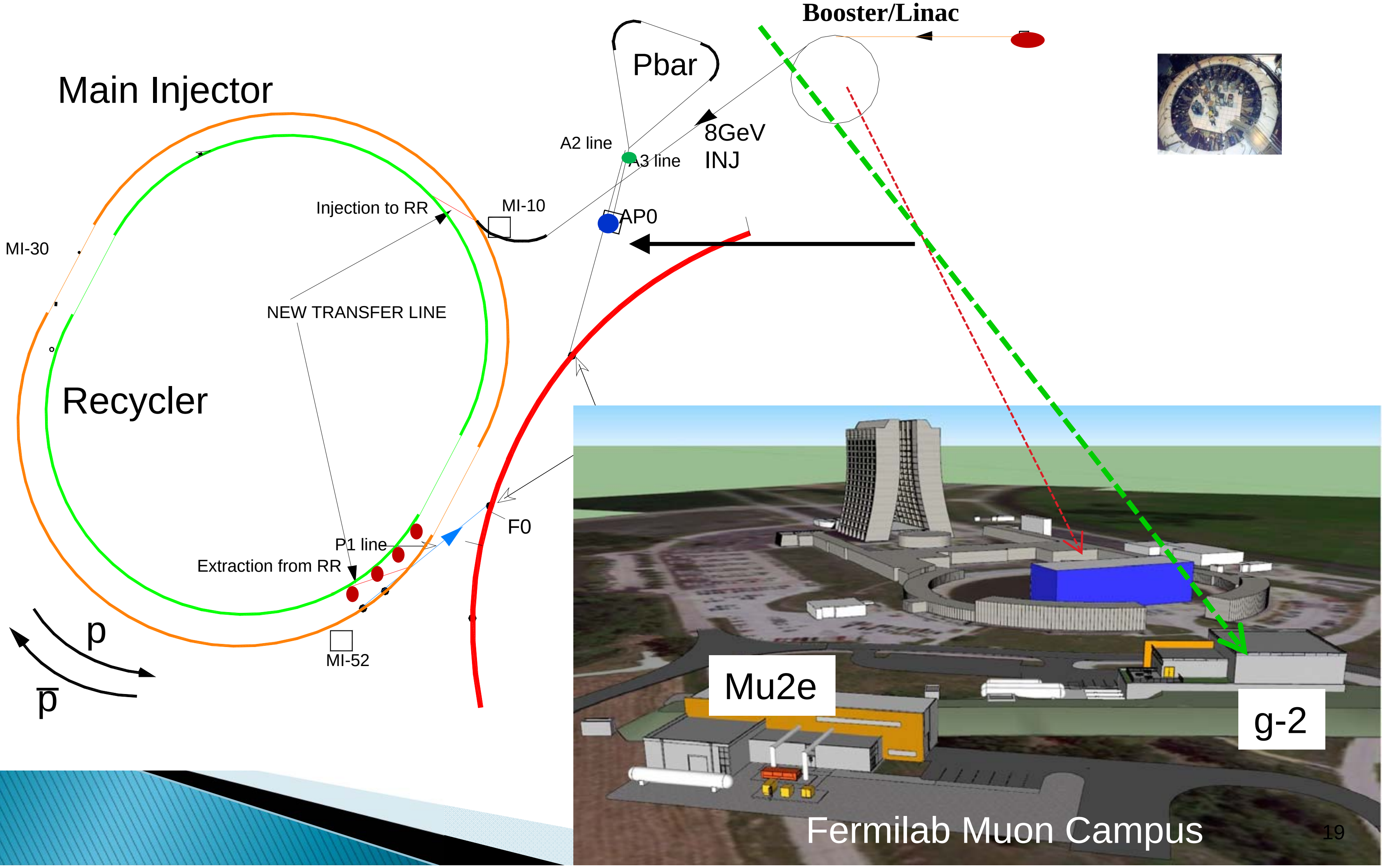
ω_a

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

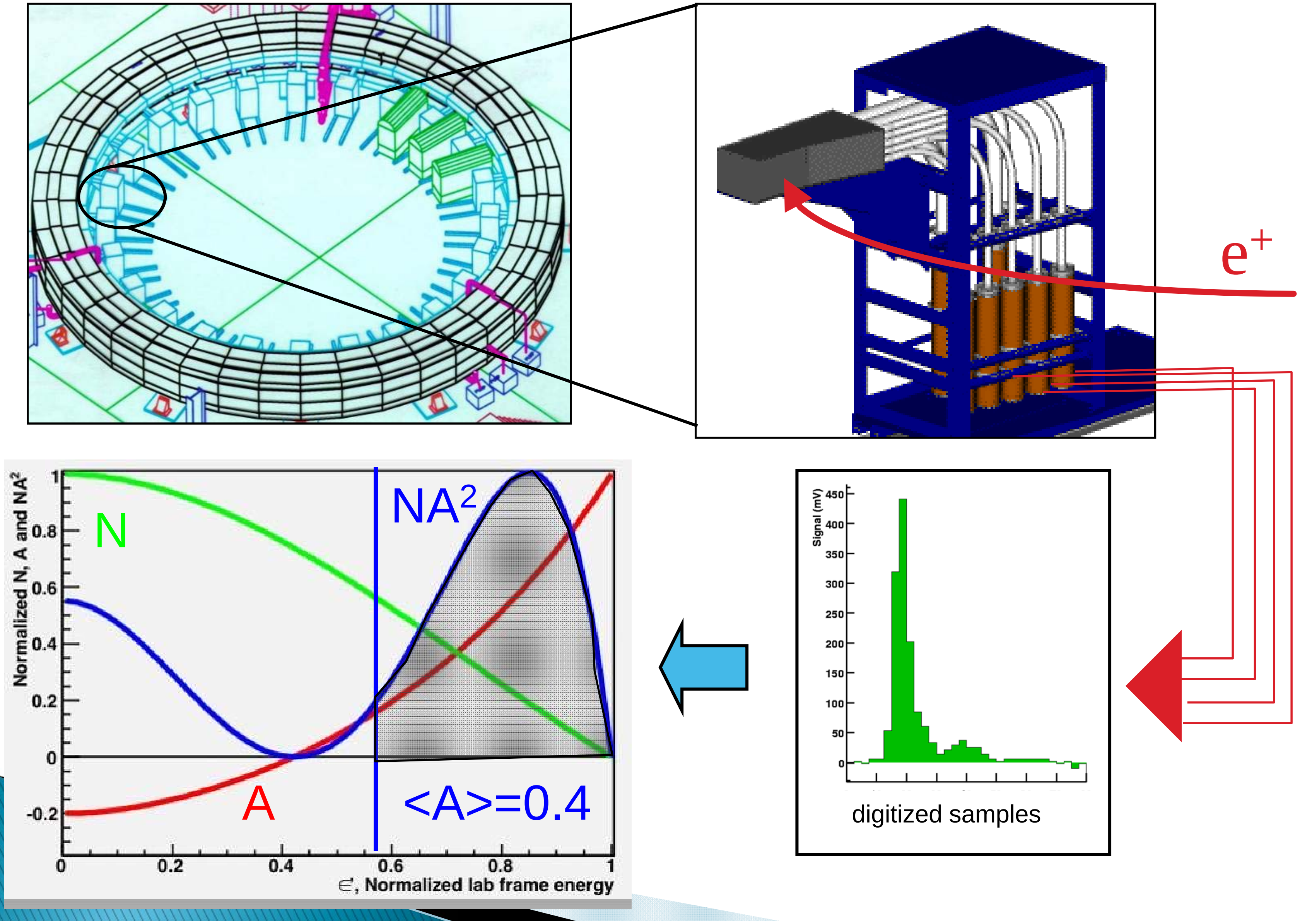


μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

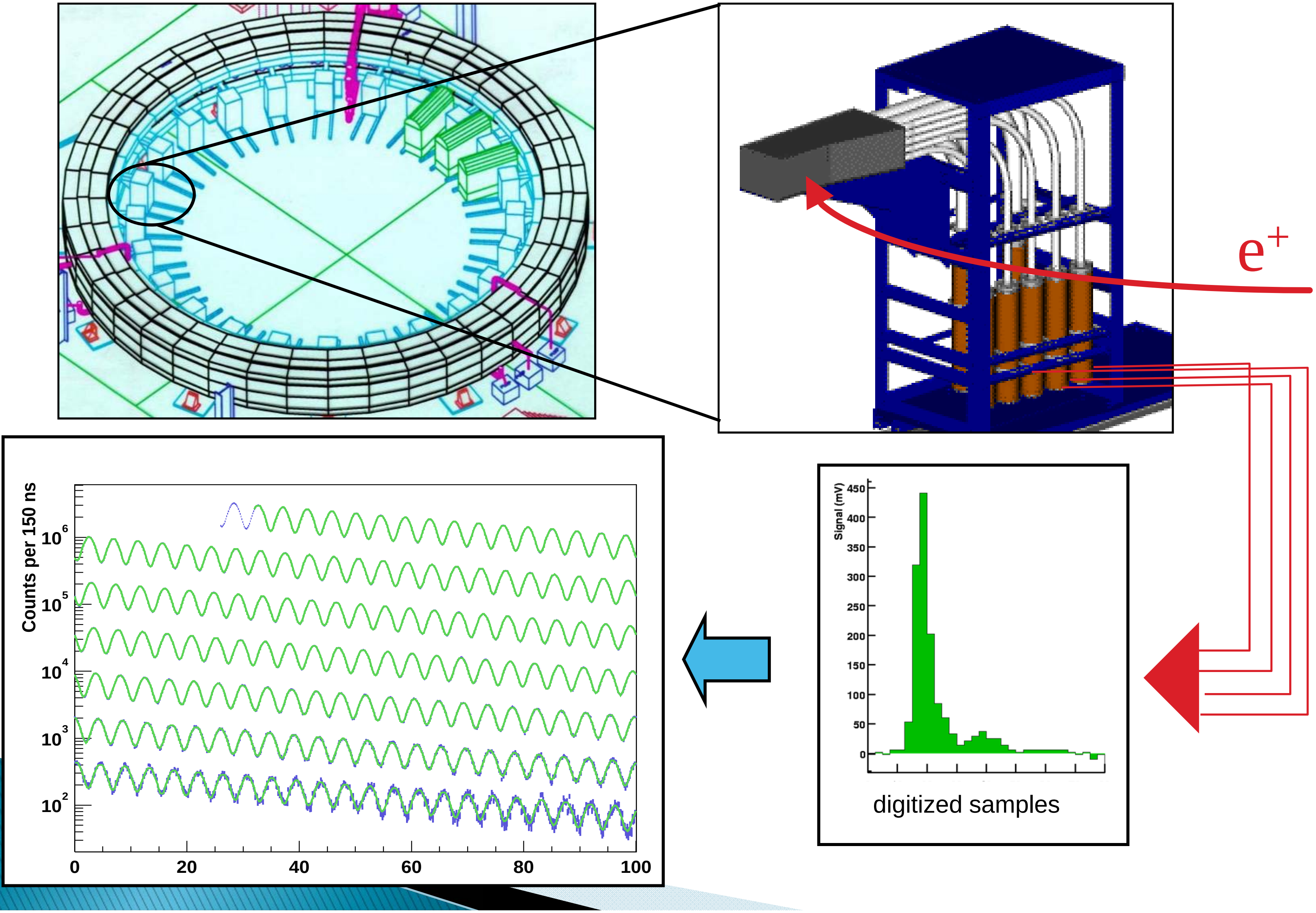
Polarized muons delivered and stored in the ring at the magic momentum, 3.094 GeV/c



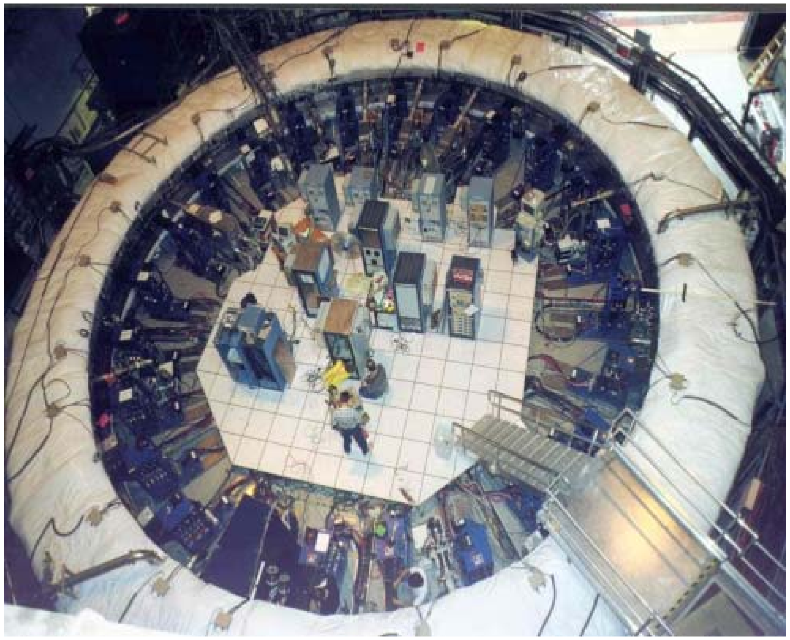
Detectors

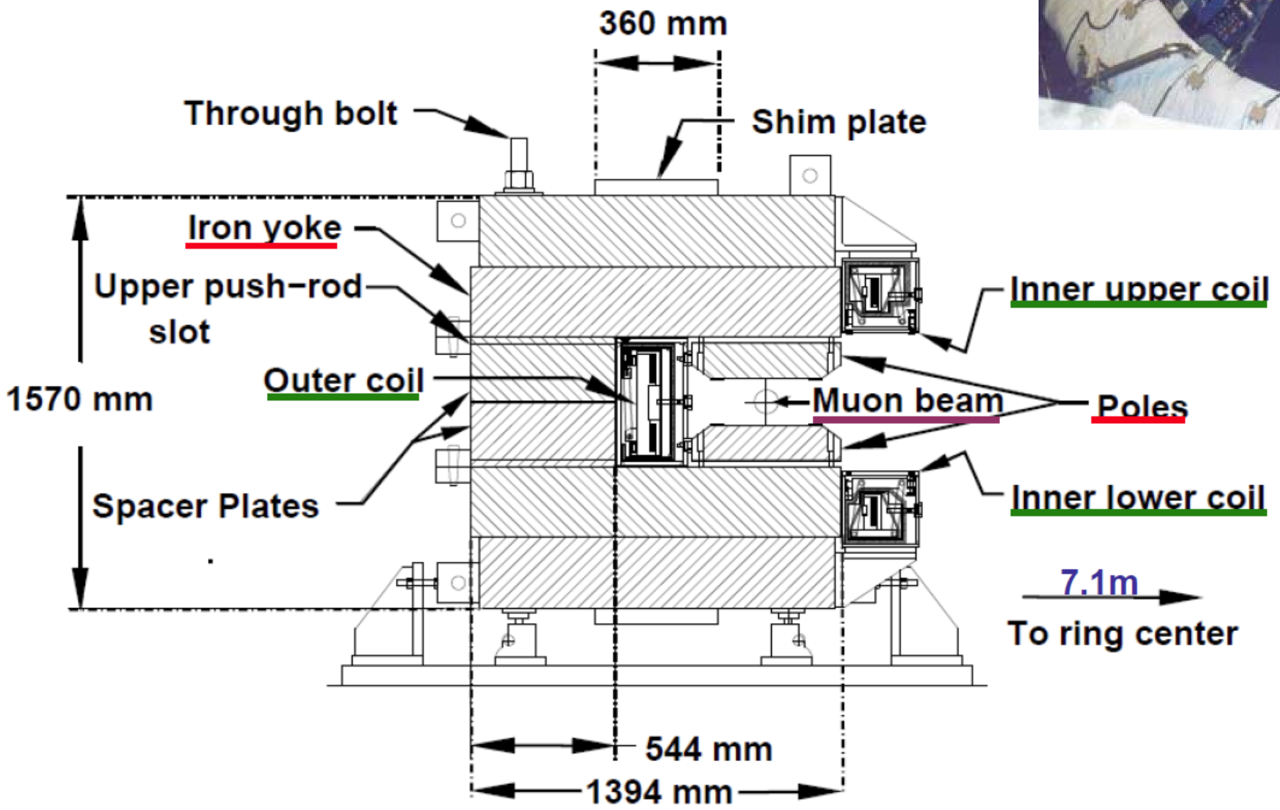

e+
Signal (mV)
450
400
350
300
250
200
150
100
50
0
digitized samples
NA²
N
A
<A>=0.4
Normalized N, A and NA²
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.2
0.4
0.6
0.8
1
∈, Normalized lab frame energy

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

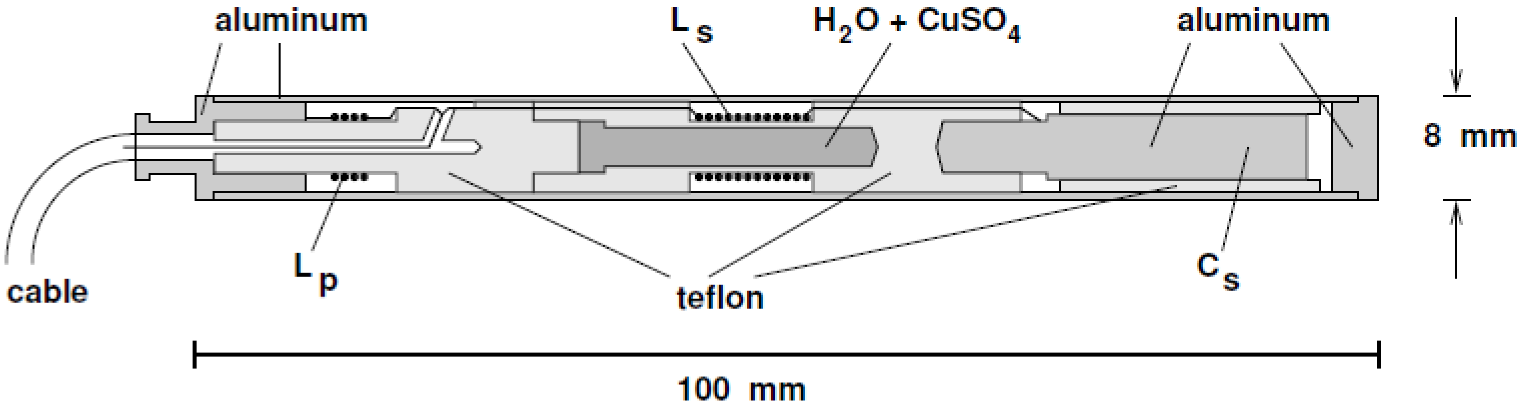


The Magnet




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

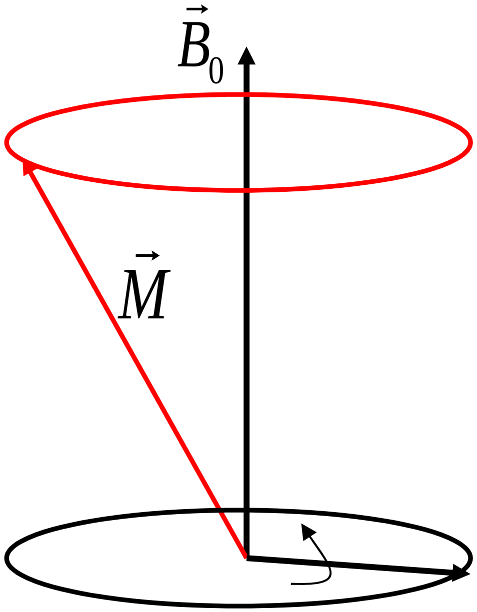
Basic unit to measure B field is NMR probe



(b) Trolley and fixed probe

Magnetic moment in magnetic field

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



In a frame rotating with freq. ω:

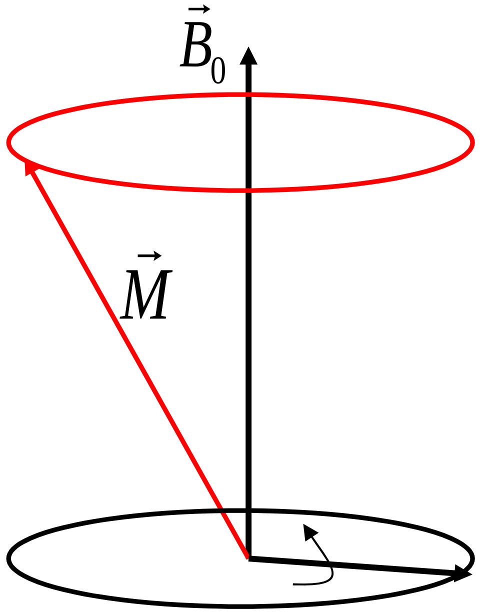
$$\frac{d\vec{M}}{dt} = \frac{\partial\vec{M}}{\partial t} + \vec{\omega} \times \vec{M}$$

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

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

Magnetic moment in magnetic field

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



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

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

In a frame rotating with freq. ω:

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

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

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

strength of B_0

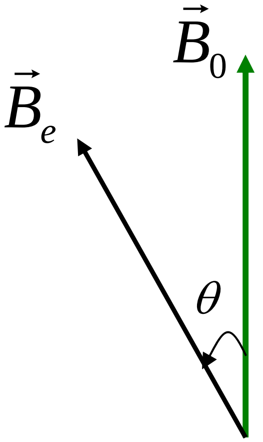
freq. of B_1

strength of B_1

Magnetic moment in magnetic field

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

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



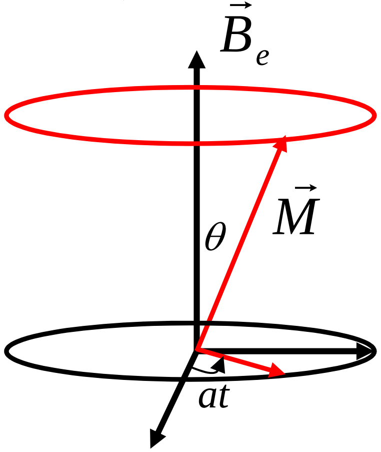
$$\cos\theta = \frac{\omega_0-\omega}{a}$$

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

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

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

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



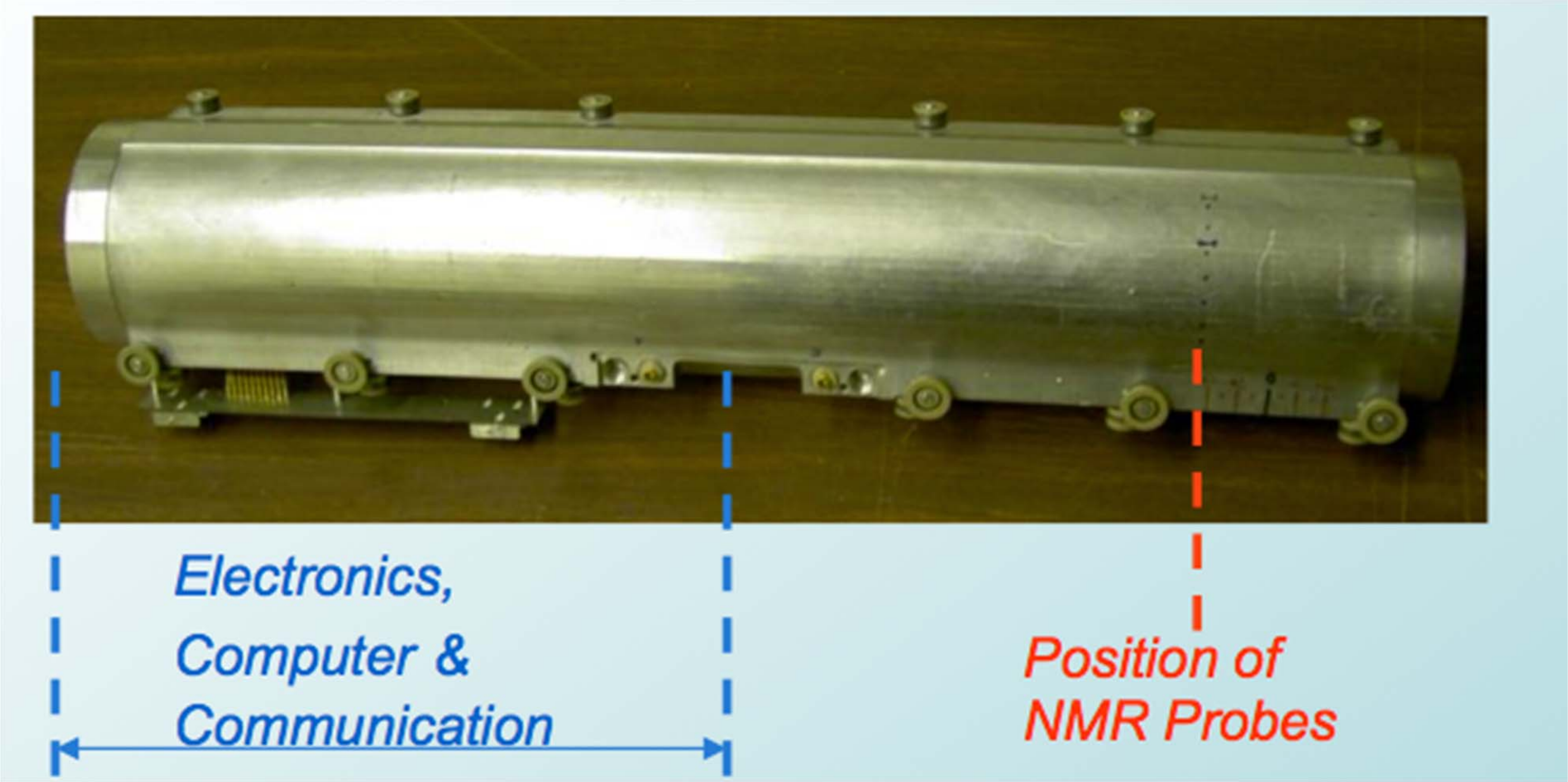
Angle between ***M*** and ***B***$_0$

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

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

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

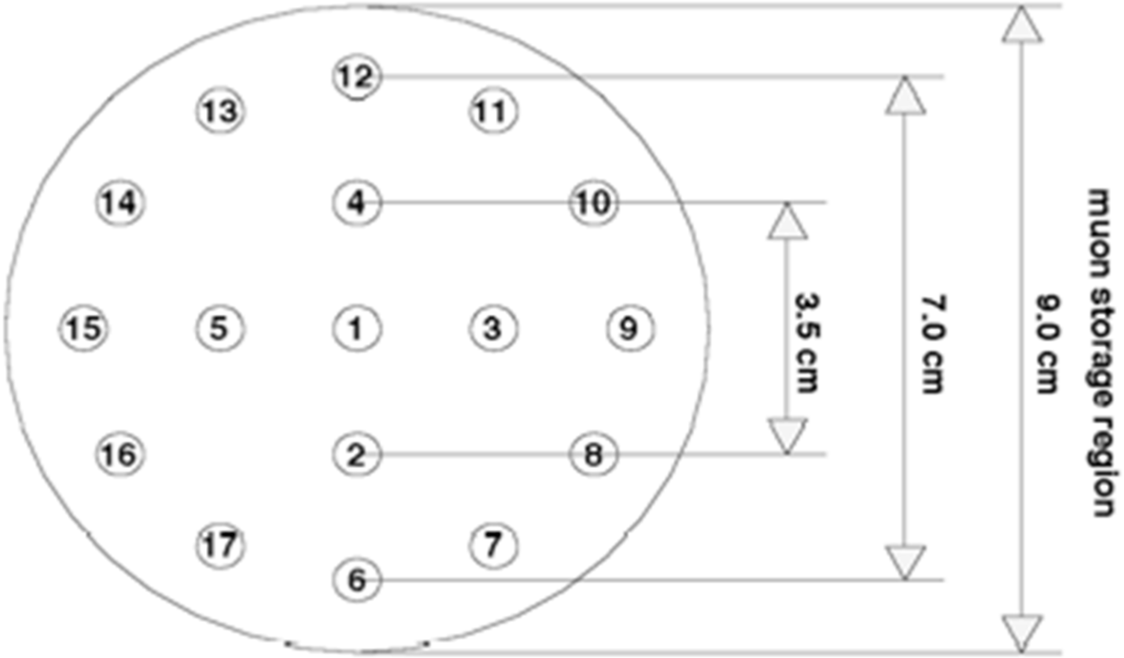
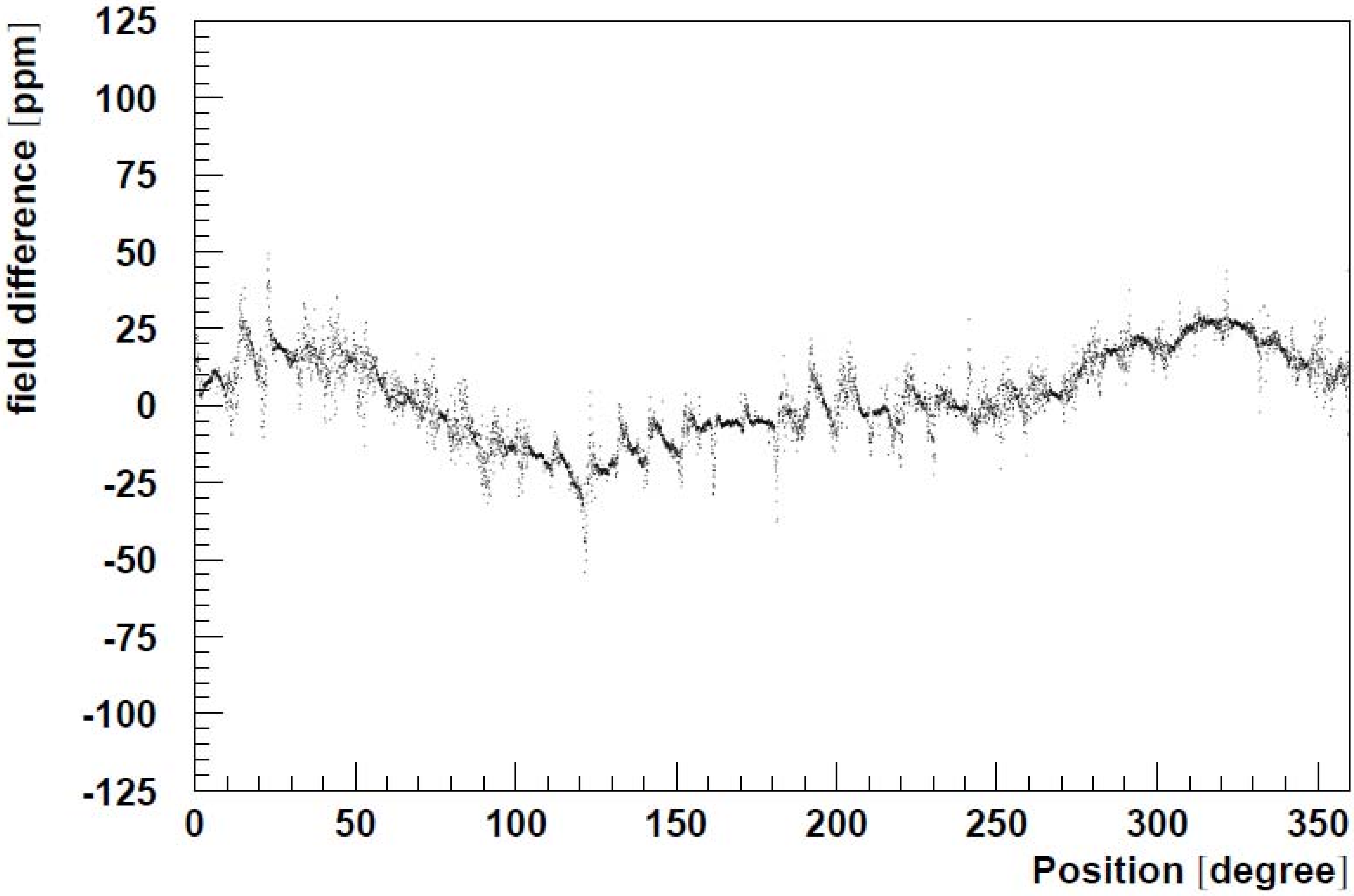


Figure 1: The positions of the trolley probes

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

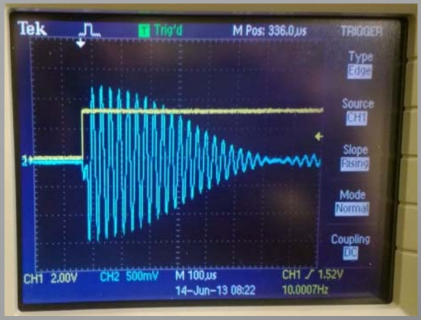


NMR Magnet Calibration Probes and Electronics

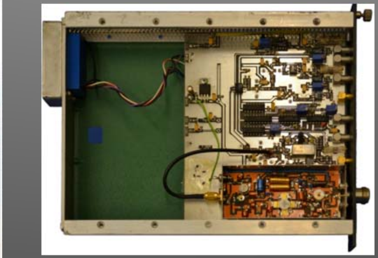
Will manufacture new fixed probes and refurbish the pulsed NMR electronics needed to determine ω_p

Triage and Repairs of Fixed Probes

1.45 T CENPA test magnet



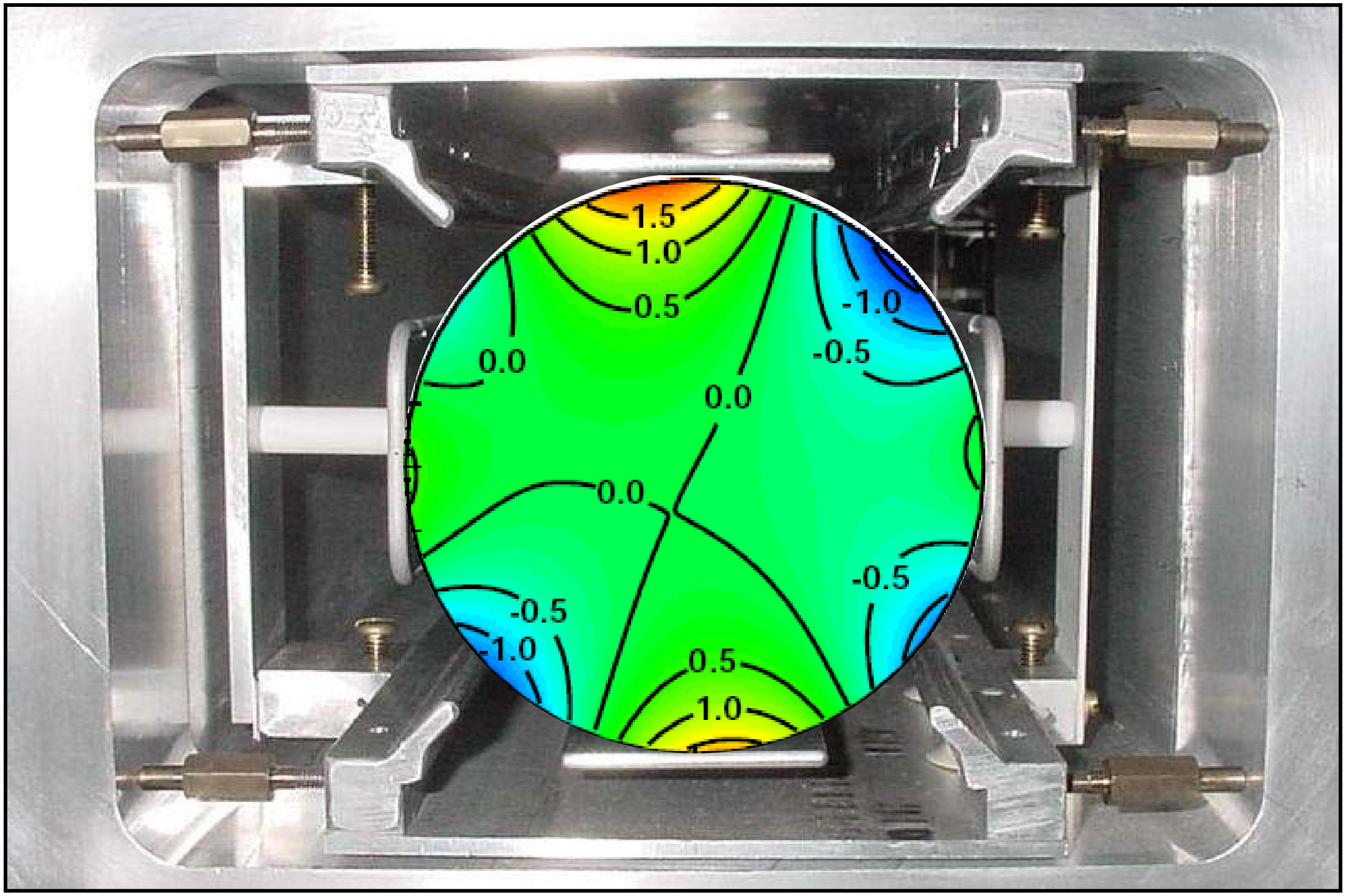
Proton Free Induction Decay



Electronics to be refurbished, rebuilt or replaced

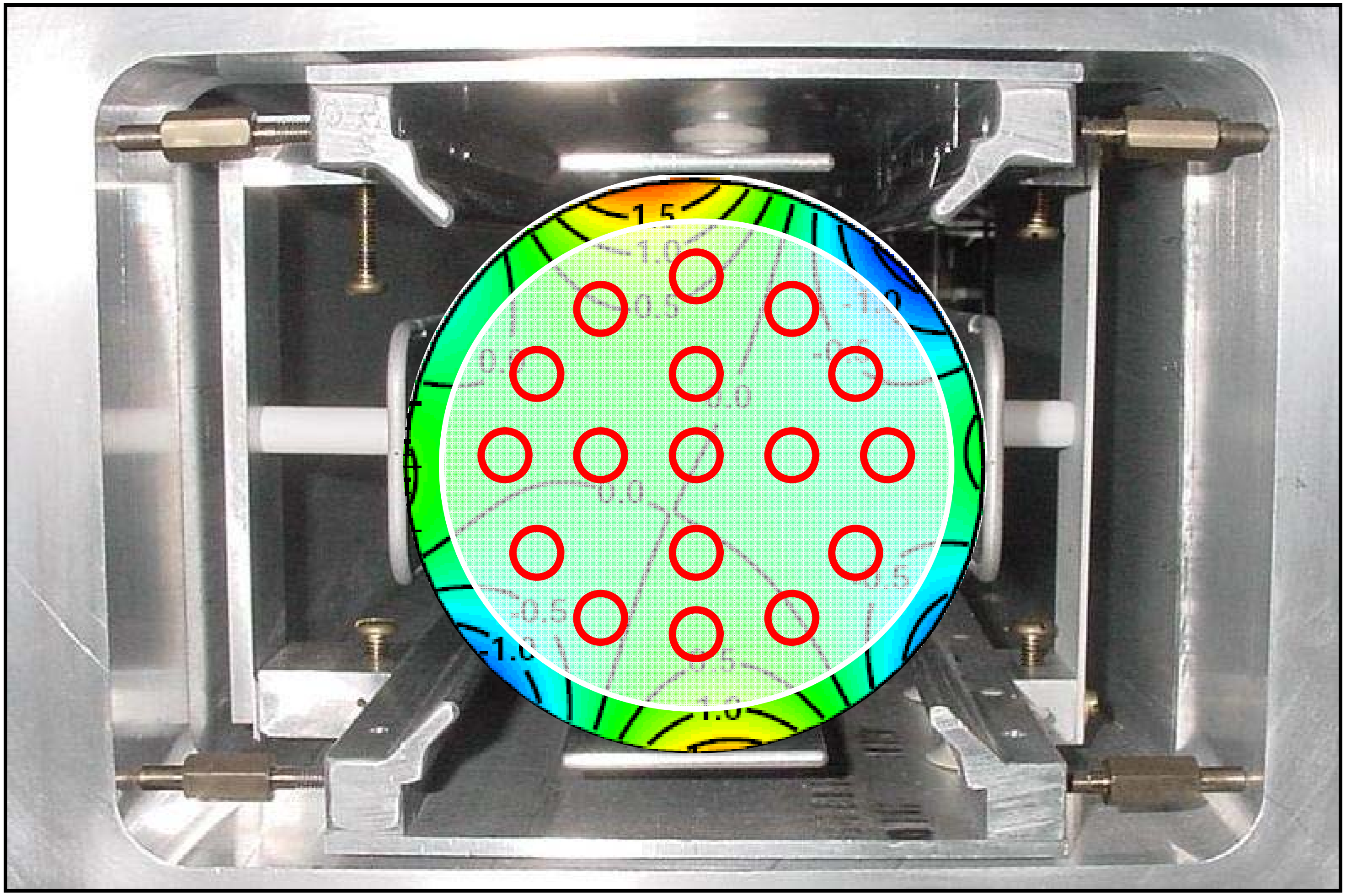
Garcia, Swanson et al

Field will be measured to 70 parts per billion!



We need to measure magnetic field where the muons are

Transverse position uncertainty



- Trolley probes are tied to the rails
- IDEALLY: Trolley center always on central muon orbit

Moving the storage ring has begun

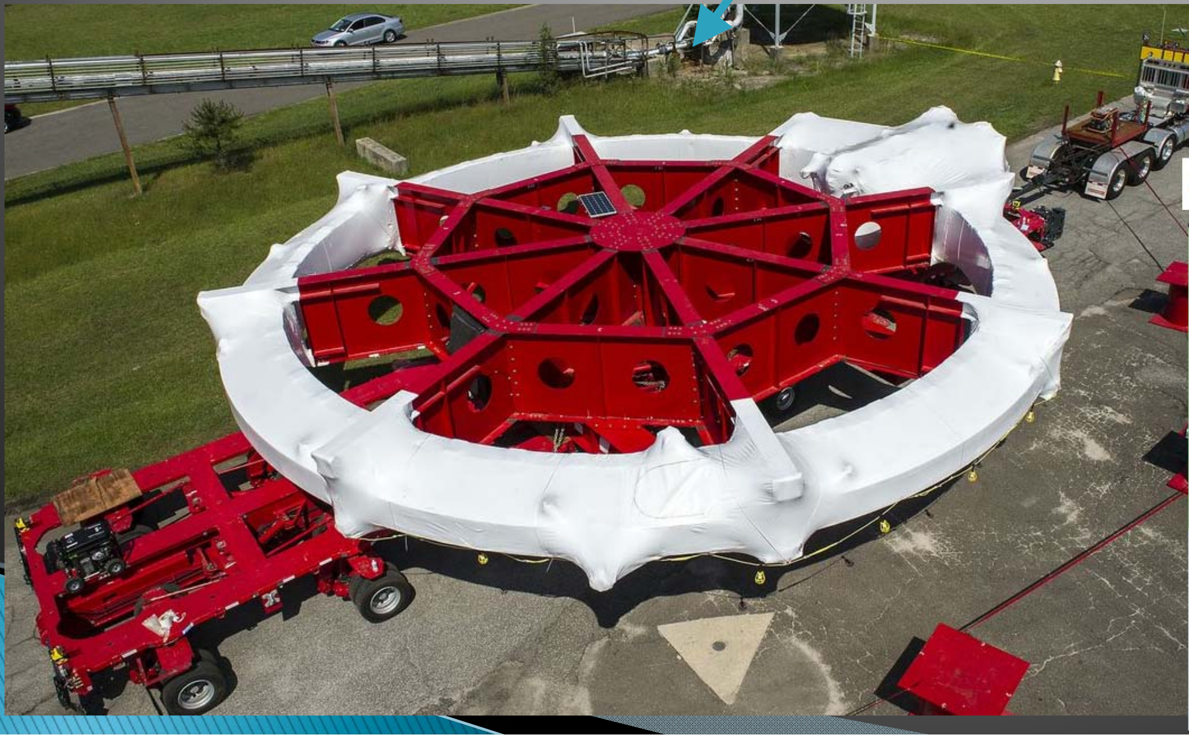
Dismantling at BNL

SCIENTIFIC AMERICAN™

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

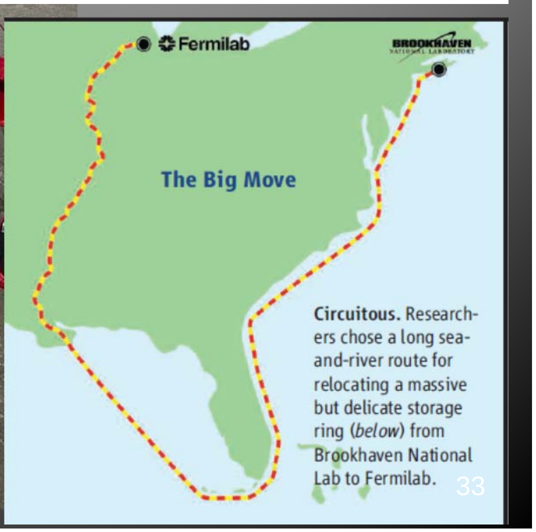
If you're driving from New York to Illinois this summer and you find yourself getting really annoyed because you're crawling behind a slow truck with an oversize load, check out that load.

Where is the ring.html



Steel now at FNAL

SCIENCE VOL 340 14 JUNE 2013



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


That's all Folks!