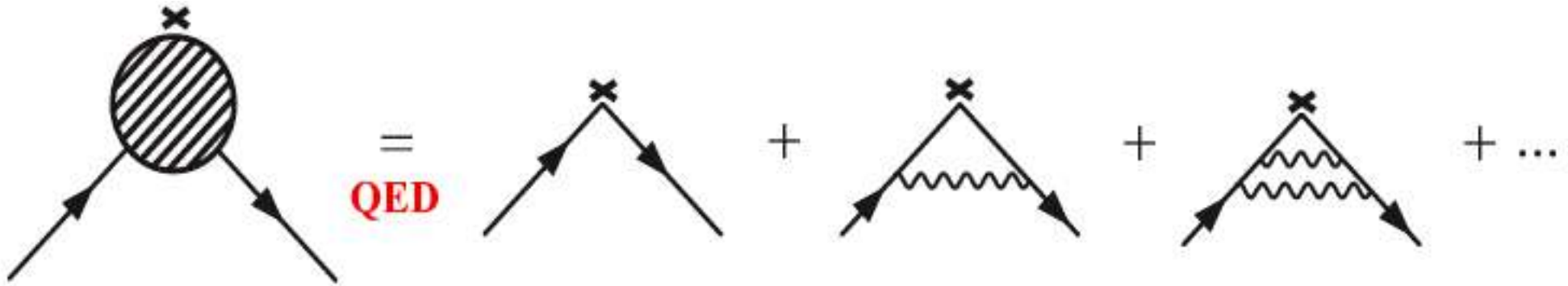
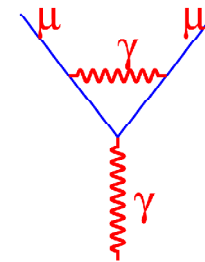


The anomalous magnetic moment



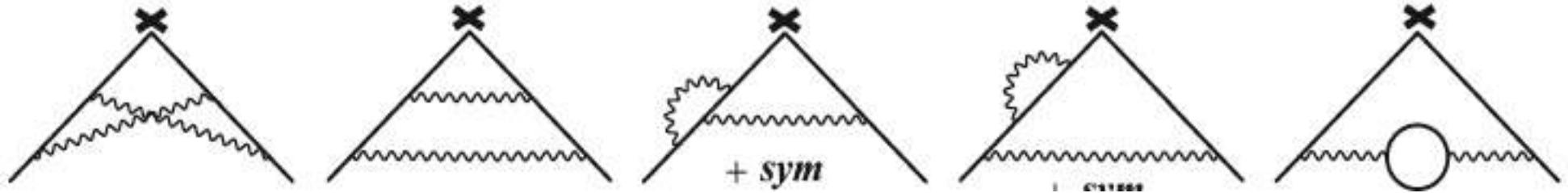
Second order :

$$a_{\mu} = \frac{\alpha}{2\pi} \frac{1}{800}$$



The anomalous magnetic moment

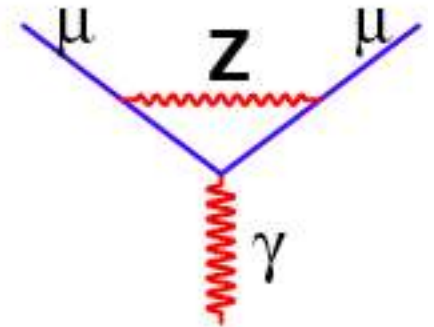
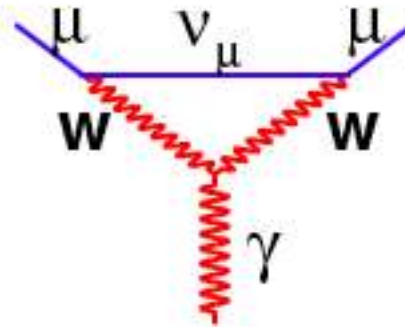
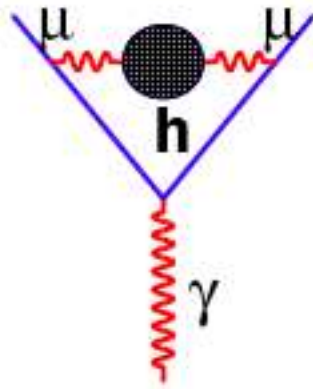
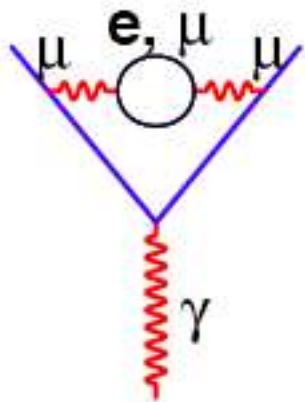
- Higher order contributions:



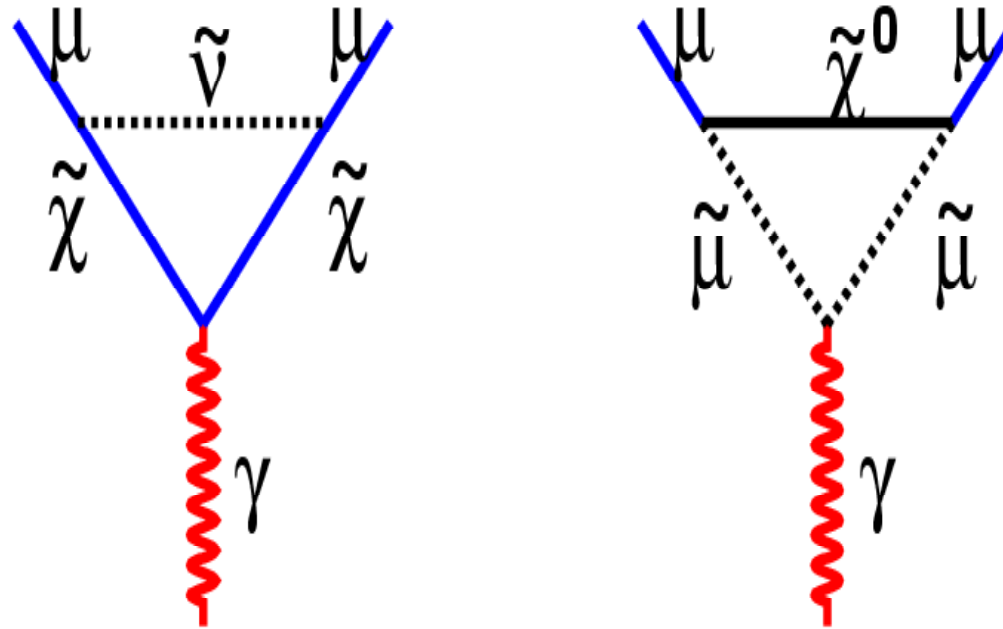
QED

Hadronic

Weak



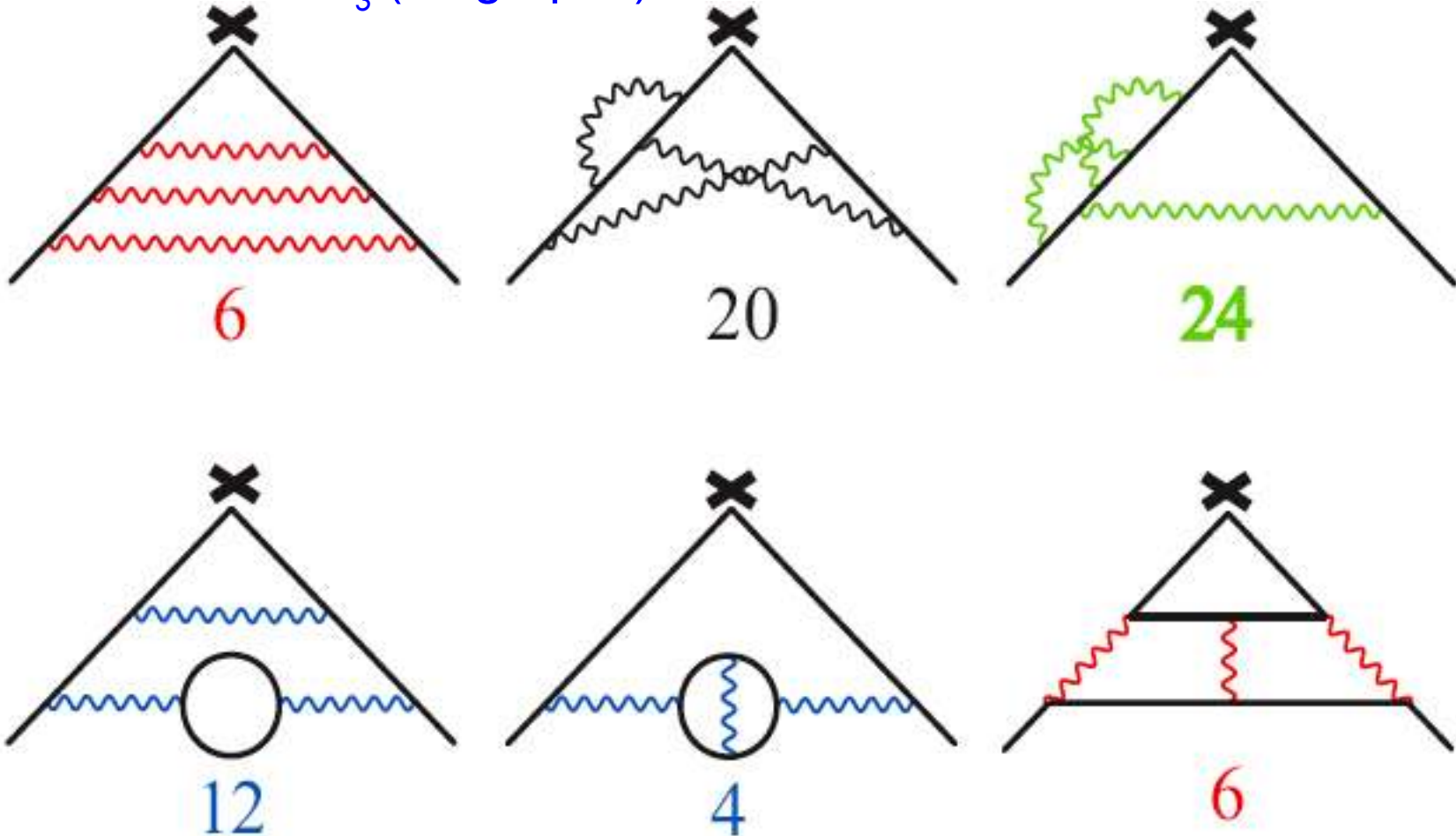
The anomalous magnetic moment



$$a_{\mu}^{\text{susy}} \equiv \text{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{m_{\text{susy}}} \right)^2 \tan \beta$$

The anomalous magnetic moment

- Contributions to A_3 (72 graphs):



- 891 diagrams contribute to A_4 ...

The anomalous magnetic moment

$$a_\mu(\text{theo}) = a_\mu(\text{QED}) + a_\mu(\text{had}) + a_\mu(\text{weak}) \quad (+ a_\mu(\text{new physics}) ?)$$

$$a_\mu(\text{QED}) = 11\,658\,470.6 \, (0.3) \times 10^{-10}$$

$$a_\mu(\text{had}) = 694.9 \, (8.) \times 10^{-10} \text{ (based on } e^+e^- \text{)}$$

$$a_\mu(\text{had}) = 709.6 \, (7.) \times 10^{-10} \text{ (based on } \tau \text{)}$$

$$a_\mu(\text{weak}) = 15.4 \, (0.3) \times 10^{-10}$$

$$a_\mu(\text{SM}) = 11\,659\,181(8) \times 10^{-10} \text{ (based on } e^+e^- \text{)}$$

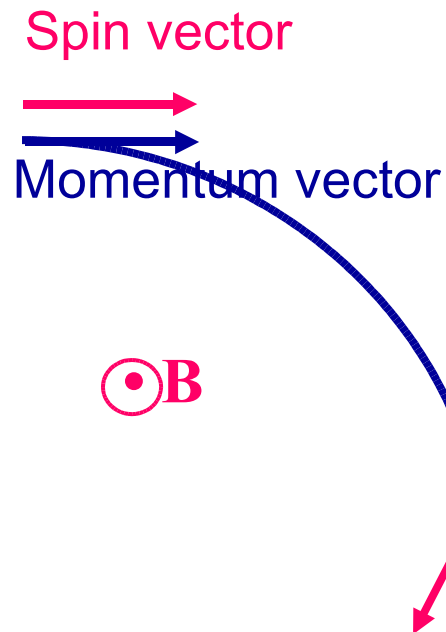
$$a_\mu(\text{SM}) = 11\,659\,196(7) \times 10^{-10} \text{ (based on } \tau \text{)}$$

$$\text{More recent value: } a_\mu = 11\,659\,179.5 \, (5.9) \times 10^{-10}$$

de Rafael, Miller, Roberts, Reports on Progress in Physics
S. Eidelman ICHEP conference, July 2006

The Principle of the muon g-2 measurement

Non-relativistic case



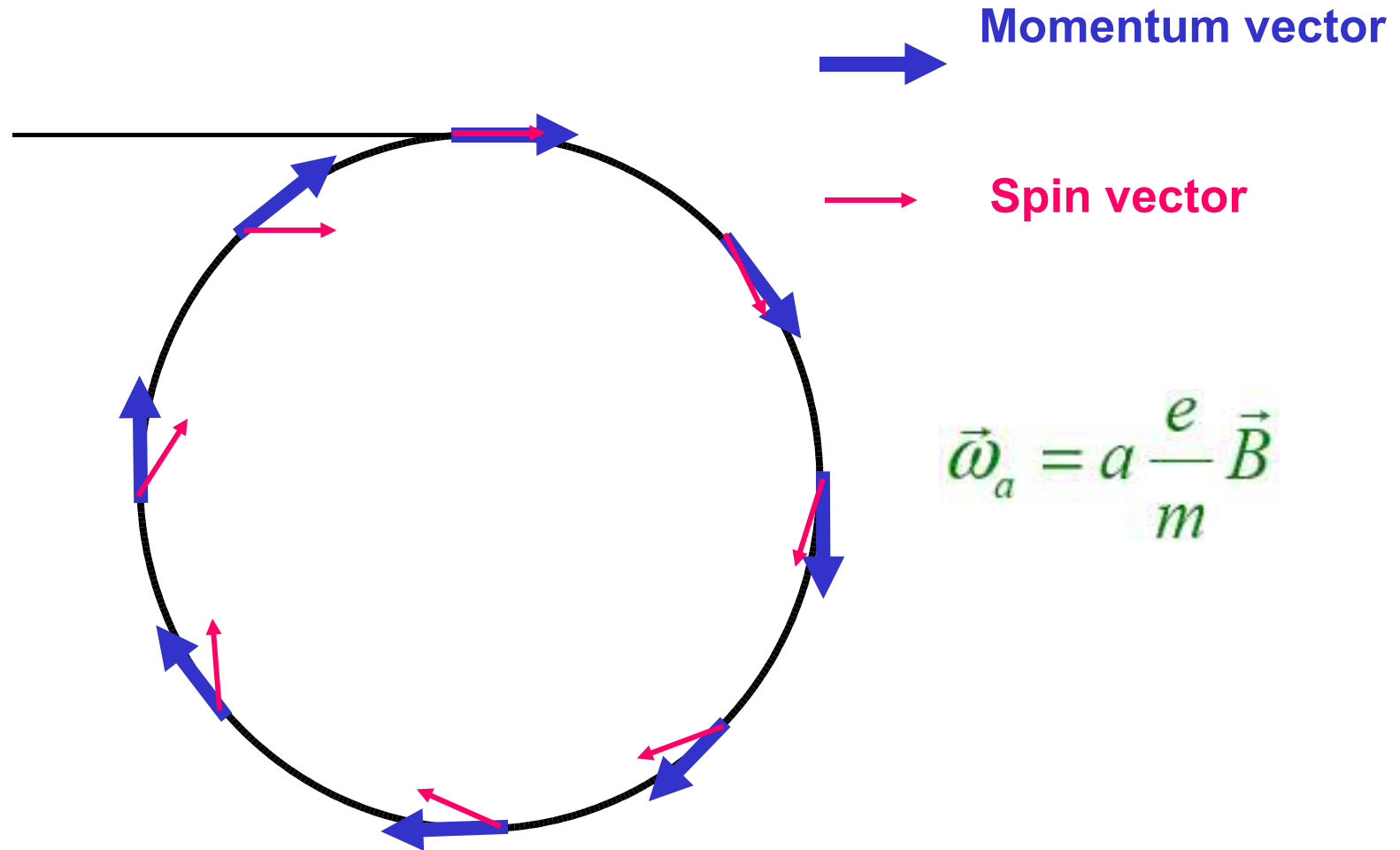
$$\omega_c = \frac{eB}{m}$$

$$\omega_s = \frac{g}{2} \frac{eB}{m}$$

$$\omega_a = \omega_s - \omega_c = \frac{g}{2} \frac{eB}{m} - \frac{eB}{m} = \left(\frac{g-2}{2} \right) \frac{eB}{m} \Rightarrow \boxed{\omega_a = a \frac{eB}{m}}$$

The Principle of the muon g-2 measurement

Spin Precession in Ring (Top View)



BNL Muon Storage Ring

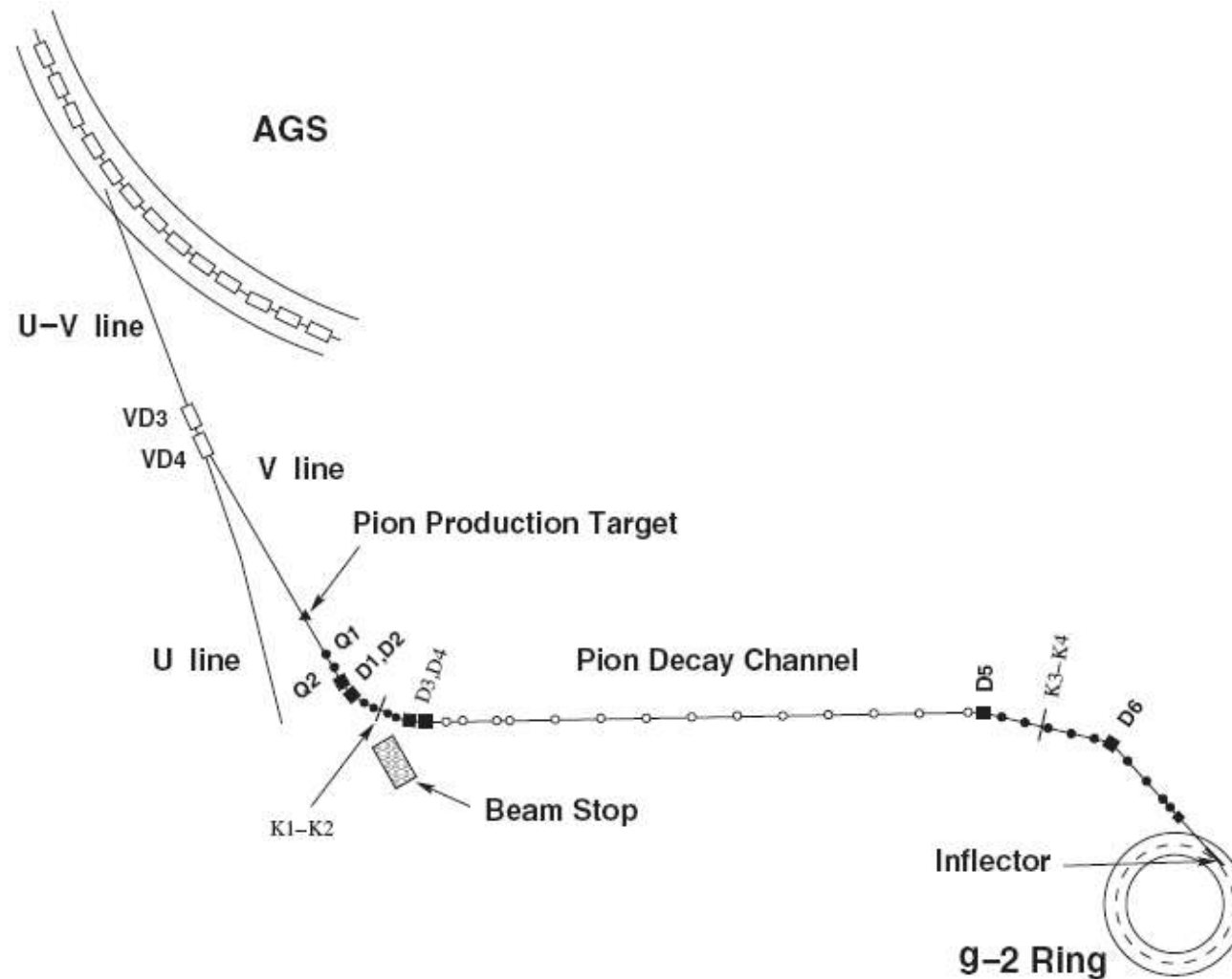
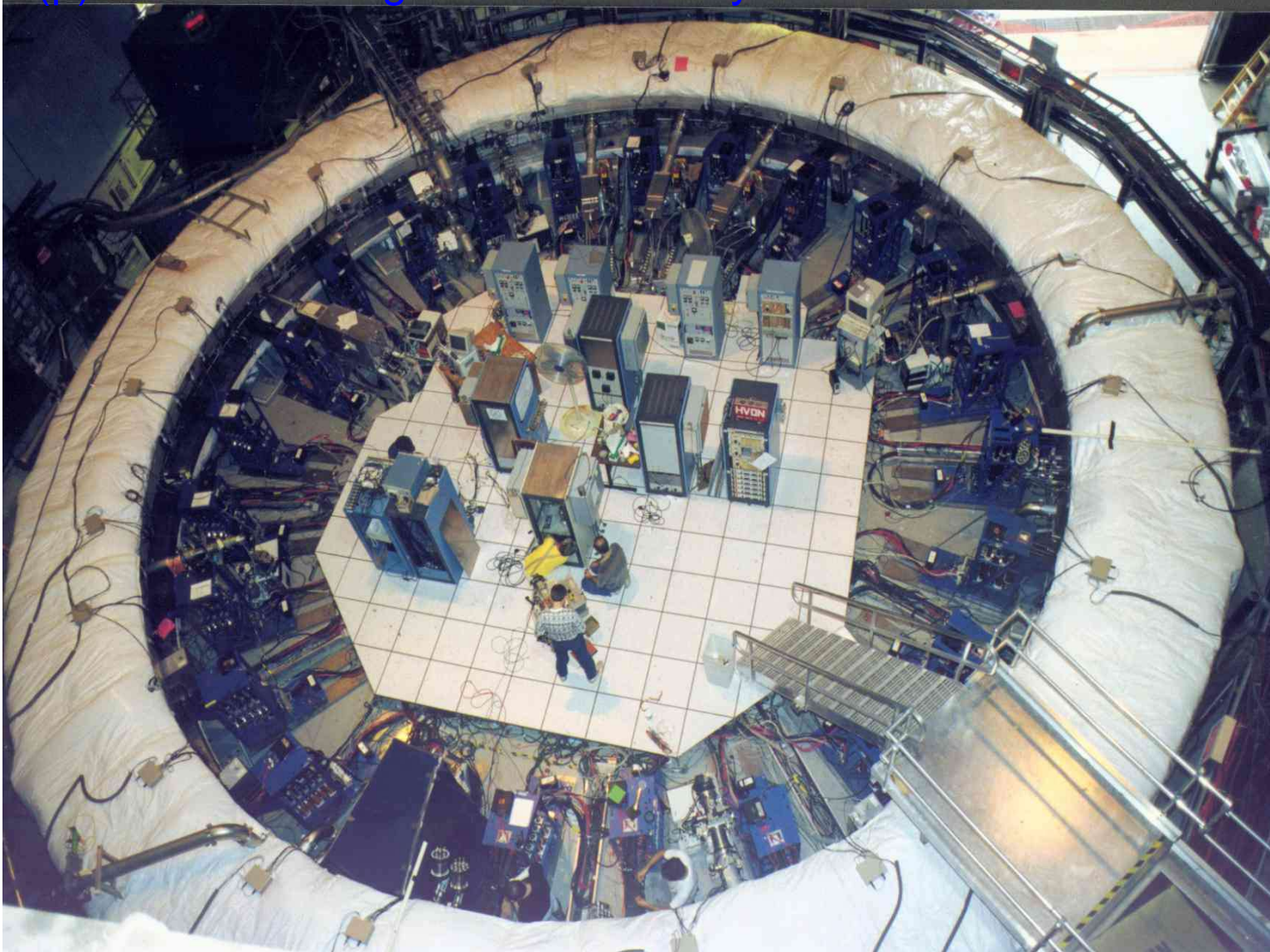


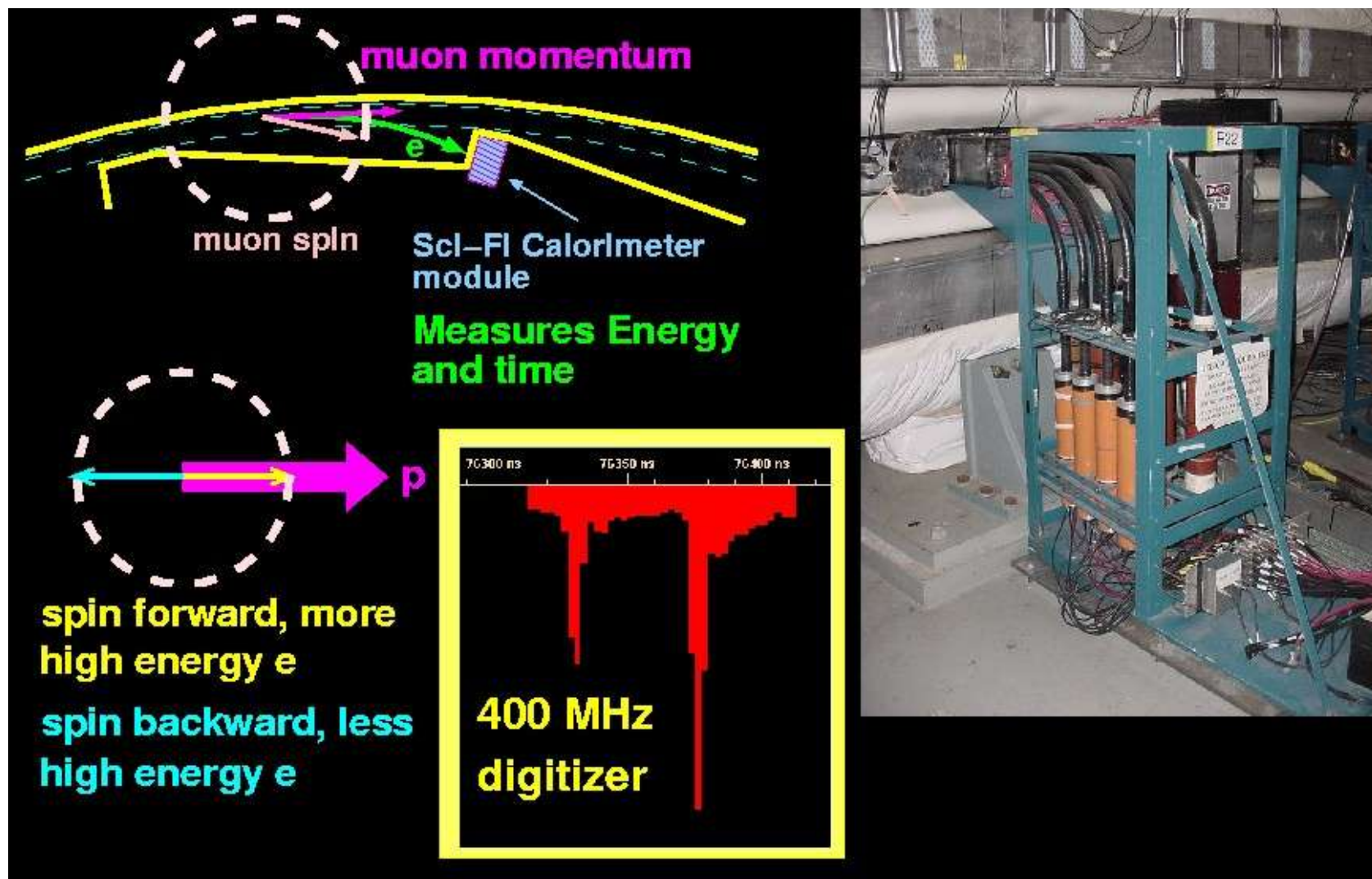
FIG. 3. Plan view of the pion/muon beamline. The pion decay channel is 80 m and the ring diameter is 14.1 m.

BNL Muon Storage Ring

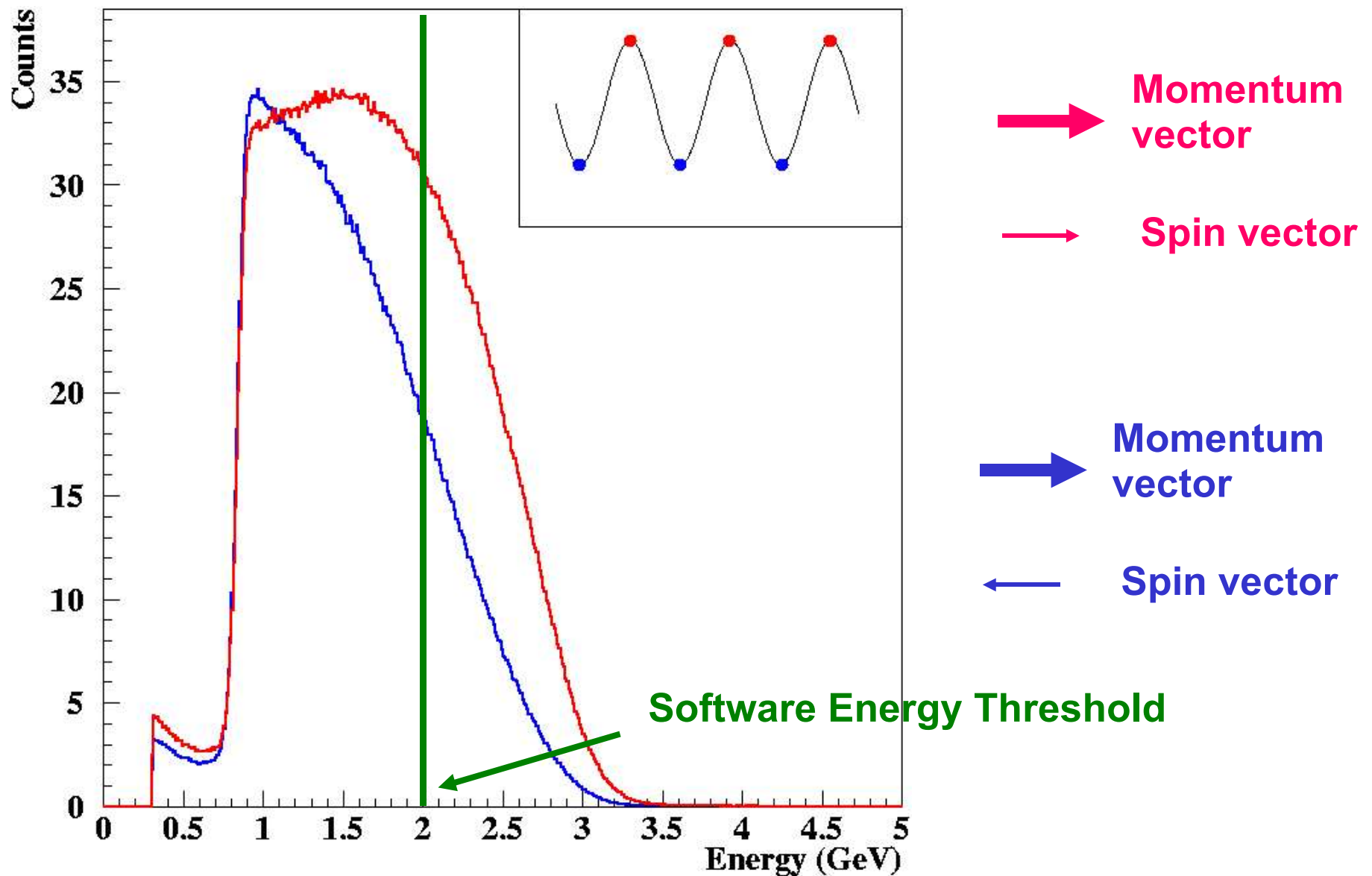
$B = 1.45\text{T}$, $P(\mu) = 3 \text{ GeV/c}$ - High Proton Intensity from AGS



Detectors and vacuum chamber

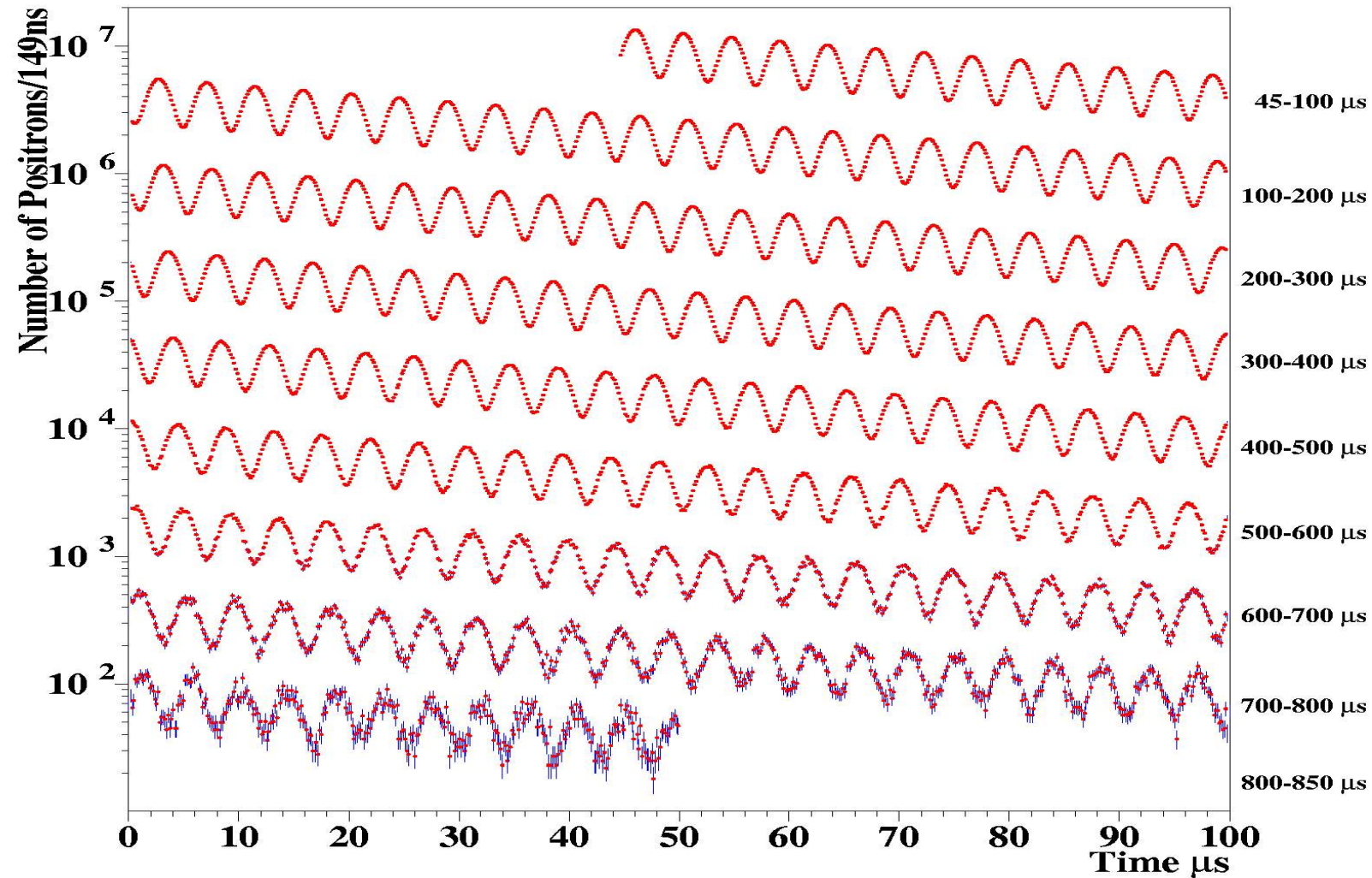


Energy Spectrum of Detected Positrons



Muon g-2 measurement

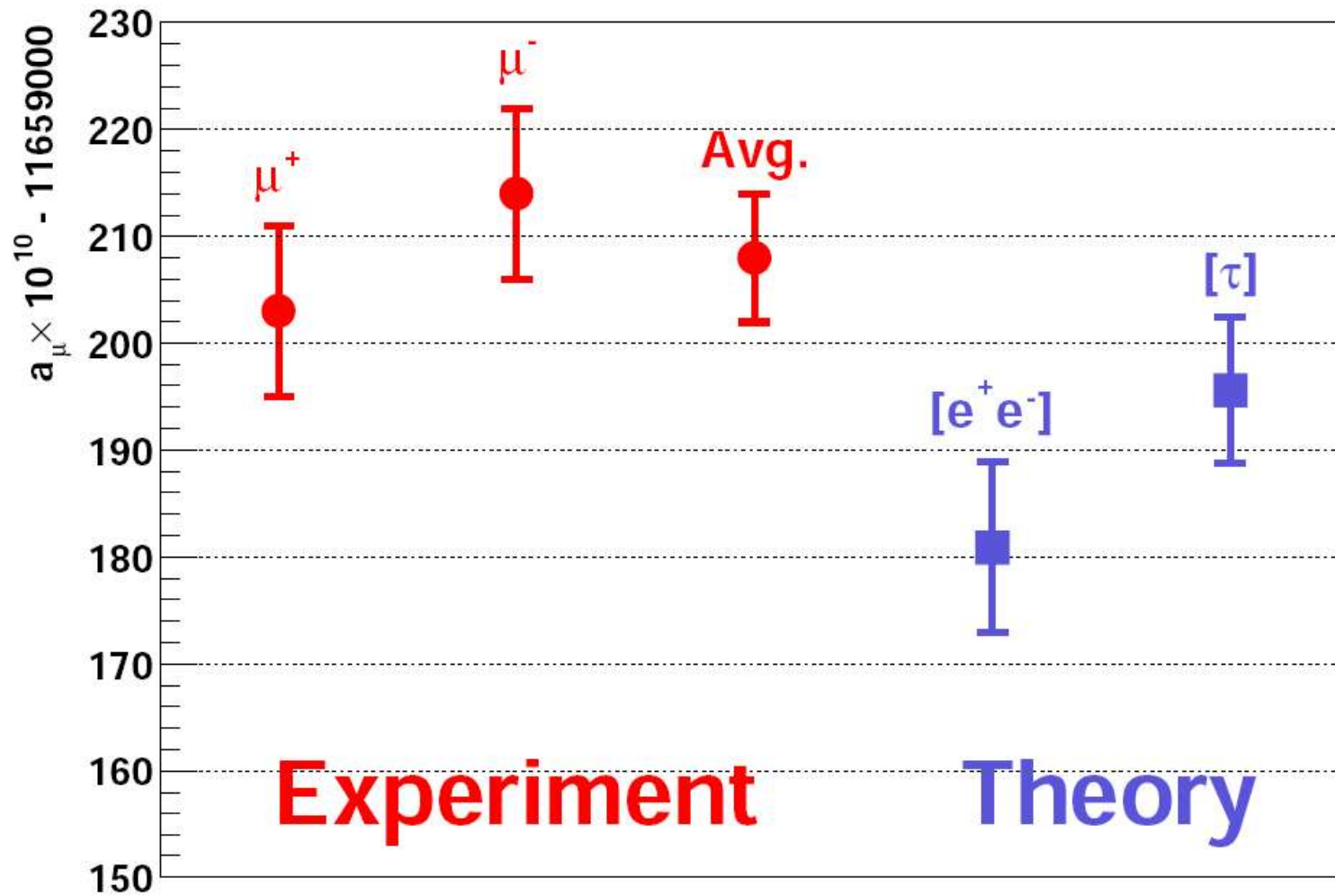
4 Billion e^+ with $E > 2\text{GeV}$



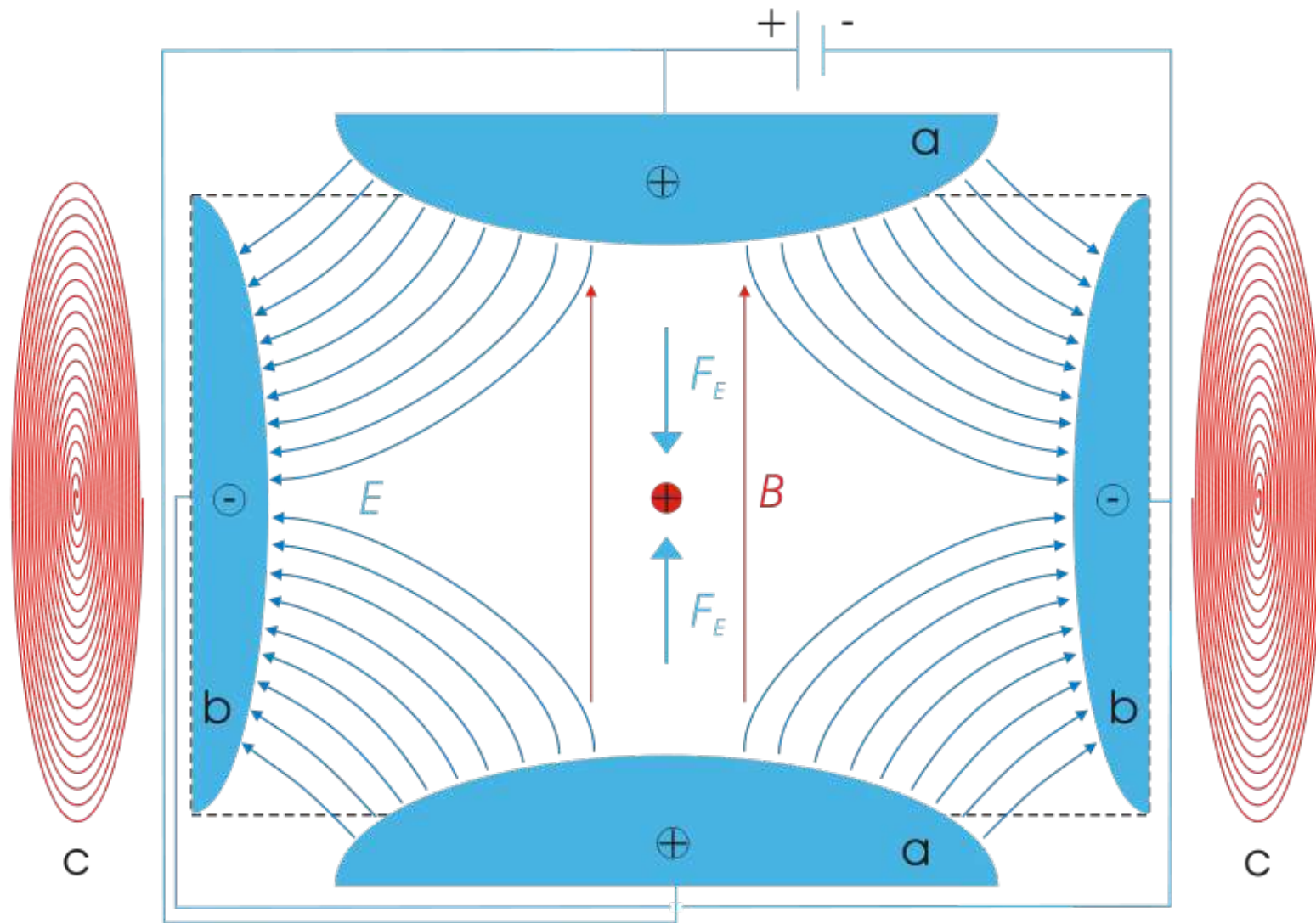
Muon g-2 measurement

- BNL measurement: $a_\mu = 0.001\,165\,920\,80\,(\,63) - 0.54\text{ ppm}$
Phys. Rev. D 73, 072003-1 (2006)
 - Theory: $a_\mu = 0.001\,165\,917\,95\,(\,59) - 0.51\text{ ppm}$
de Raphael, Miller, Roberts Reports on Progress in Physics
S. Eidelman ICHEP conference, July 2006
 - exp - theory = $0.000\,000\,002\,85\,(\,86)$
 $2.44 \pm 0.74\text{ ppm} - 3.3\text{ sigma} !$
 - Test of CPT: compare a_{μ^-} and a_{μ^+} :
 - $R_{\mu^+} = 0.0037072047\,(26)$
 - $R_{\mu^-} = 0.0037072083\,(26)$
 - $dR = R_{\mu^-} - R_{\mu^+} = (3.6 \pm 3.7) \cdot 10^{-10}$
$$a_\mu = \frac{R}{\lambda - R} \quad (\lambda = 3.18334539(10) - \text{muon-to-proton magnetic moment ratio})$$
-

Muon g-2 measurement



A Penning trap



A Penning trap

Drawing of a schematic Penning Trap for the storage of charged particles by the use of a constant electric field (blue), generated by a quadrupole (a: end caps) and (b: ring electrode) and a superposed constant and homogeneous magnetic field (red), generated by a toroidal magnet (c). A particle, indicated in red (here positive) is stored in between caps of the same polarity. The particle is trapped inside a vacuum chamber

One electron in a Penning trap

Geonium: bound electron, to external device

- Magnetron motion: ~ 12 kHz
- Axial oscillation: ~ 200 MHz
- Cyclotron motion: ~ 153 GHz

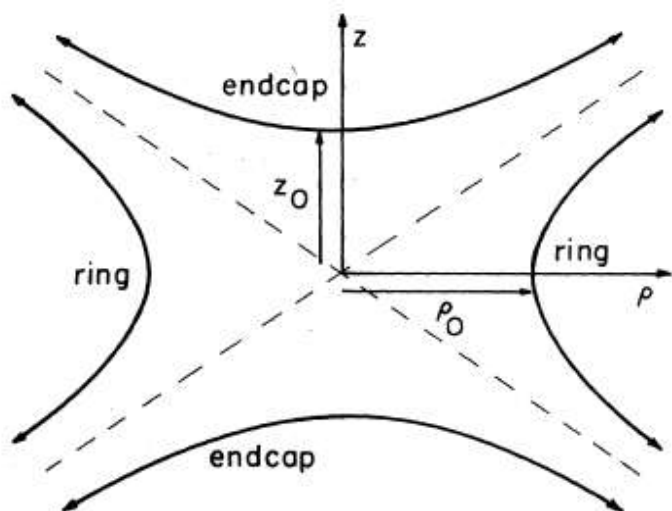
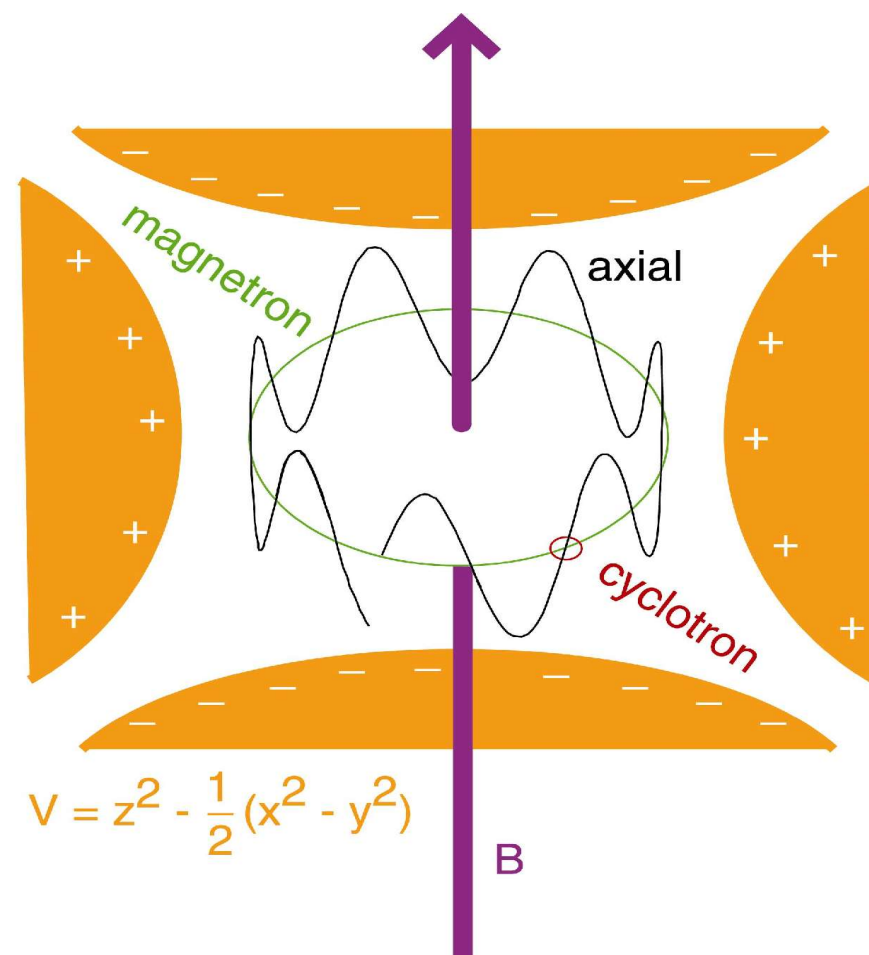
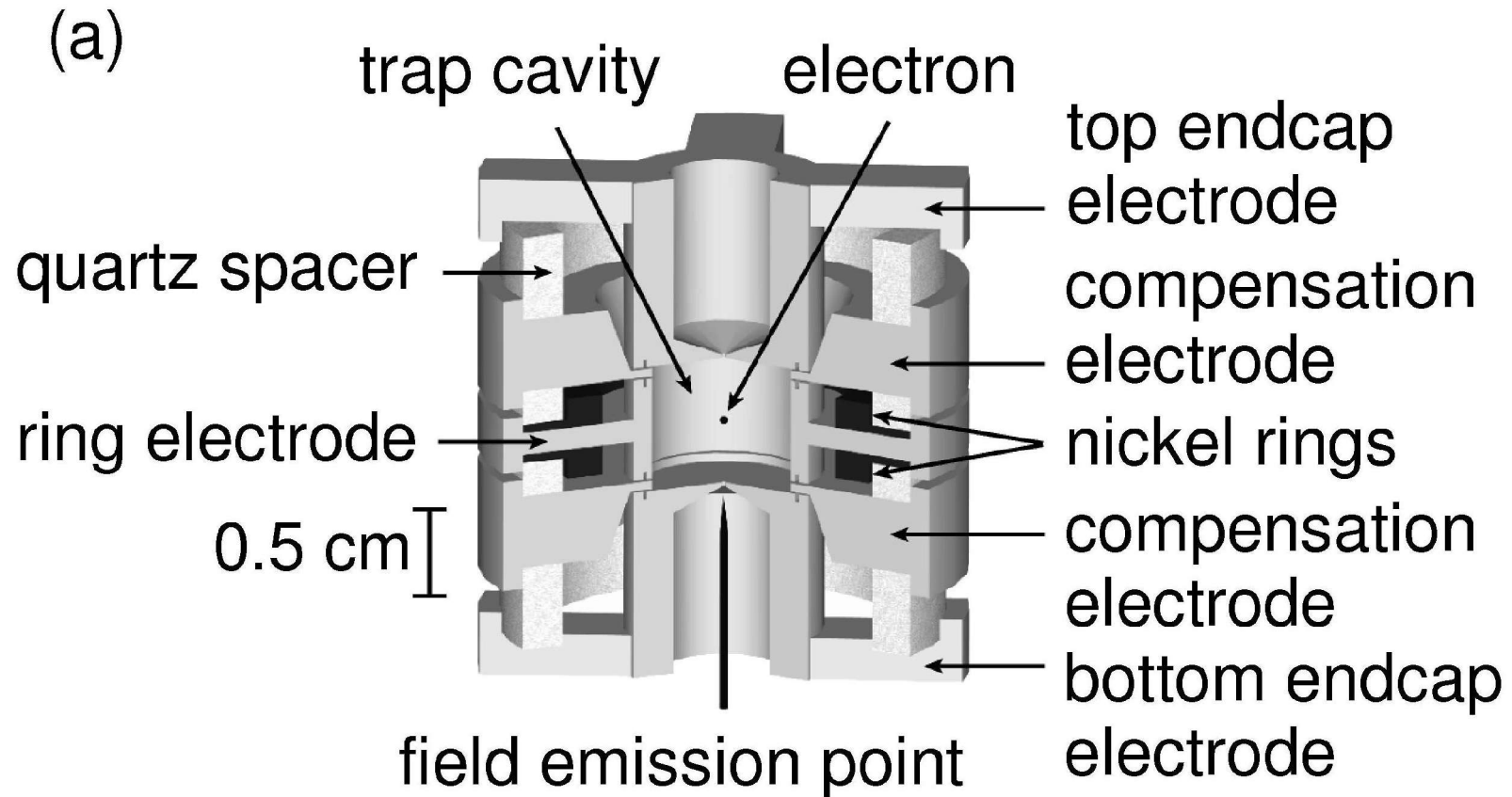


FIG. 6. Axially symmetric electrodes are used to produce a quadrupole potential of the form given by Eq. (2.2). The dashed lines represent the cones that are the asymptotes of the hyperbolas of revolution.

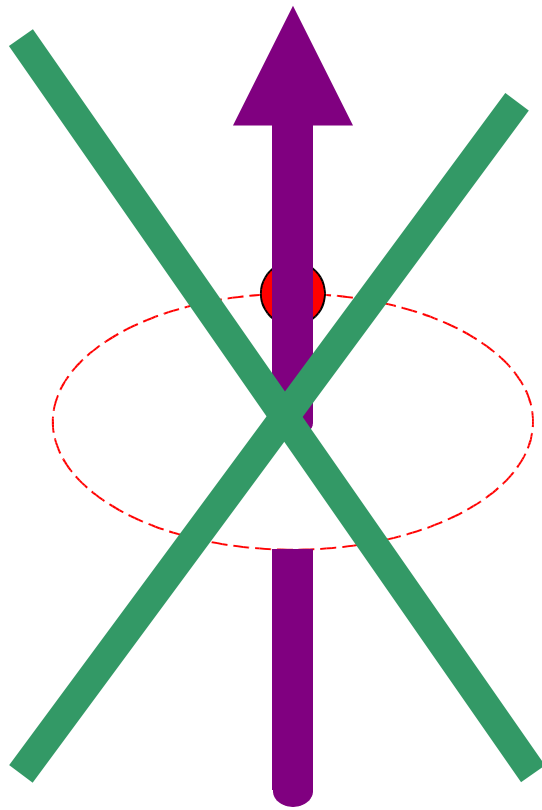


Cylindrical Penning Trap

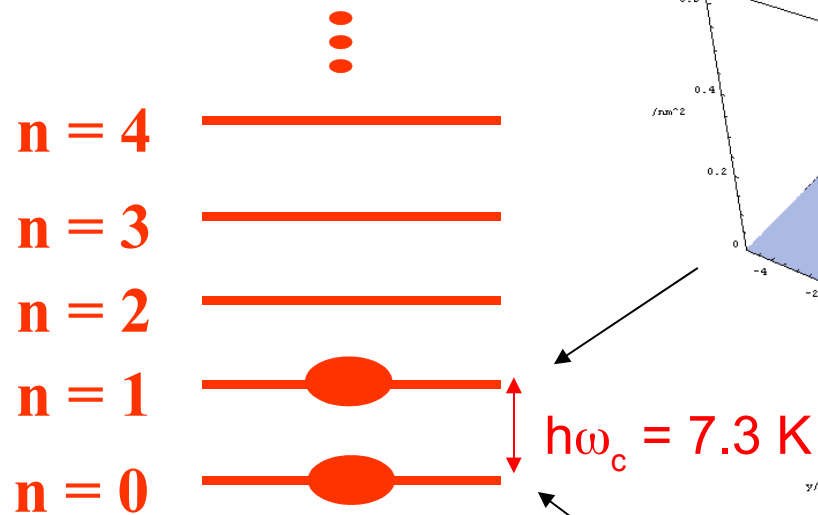


G.Gabrielse and F. C. MacKintosh; Int. J. Mass Spec. Ion Proc. 57, 1 (1984)

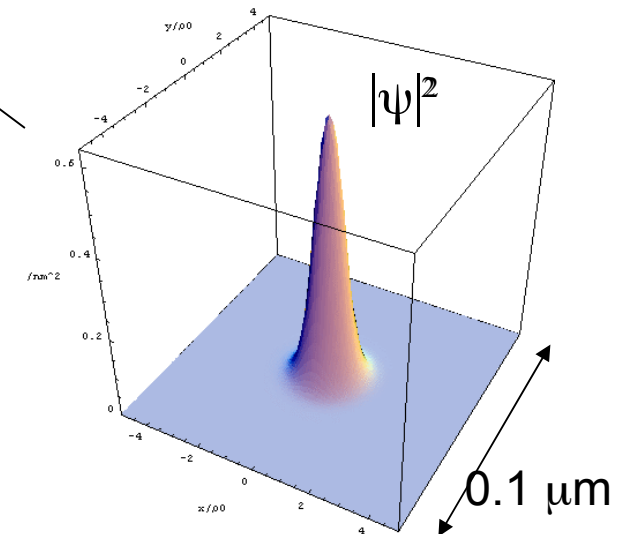
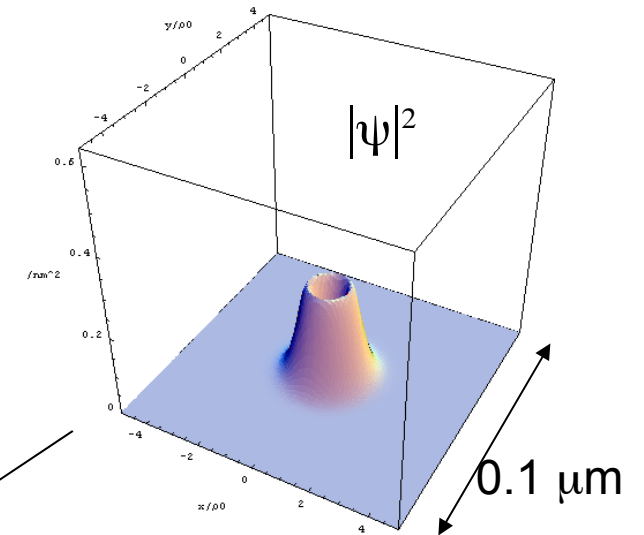
One Electron in a Magnetic Field



$B \sim 6 \text{ T}$



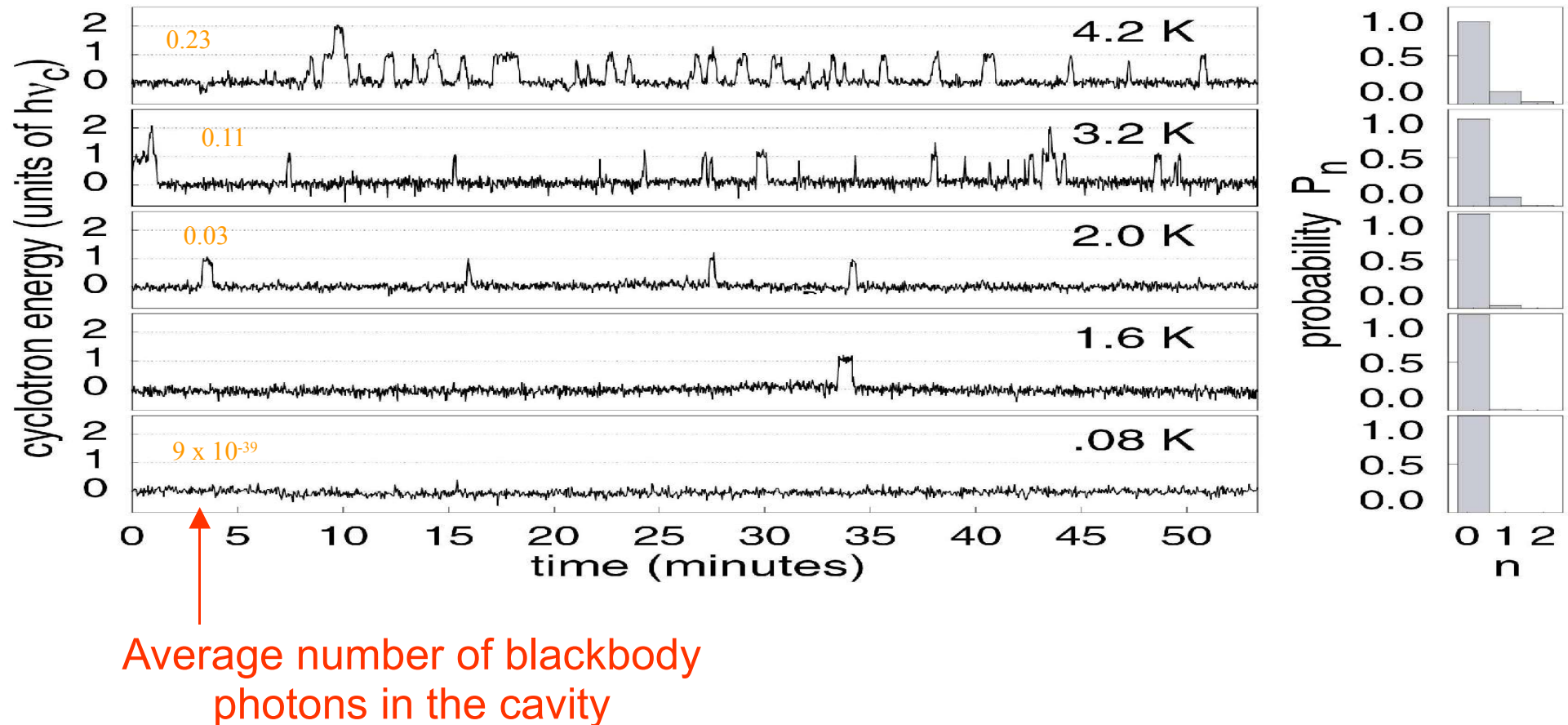
Need low
temperature
 $T \ll 7.2 \text{ K}$



Electron in Cyclotron Ground State

Measurement done at low temperature: ~ 0.07 K

S. Peil and G. Gabrielse, Phys. Rev. Lett. 83, 1287 (1999).



Geonium energy levels

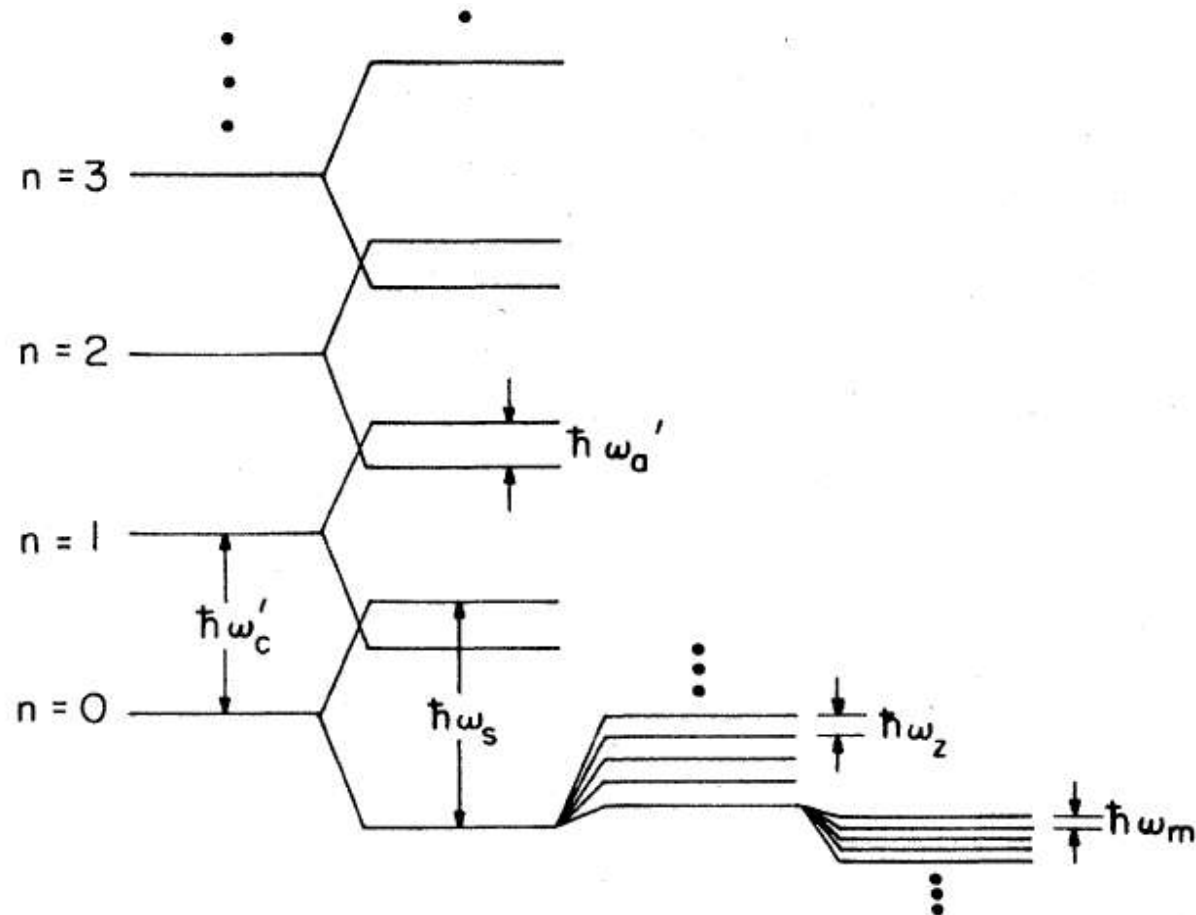
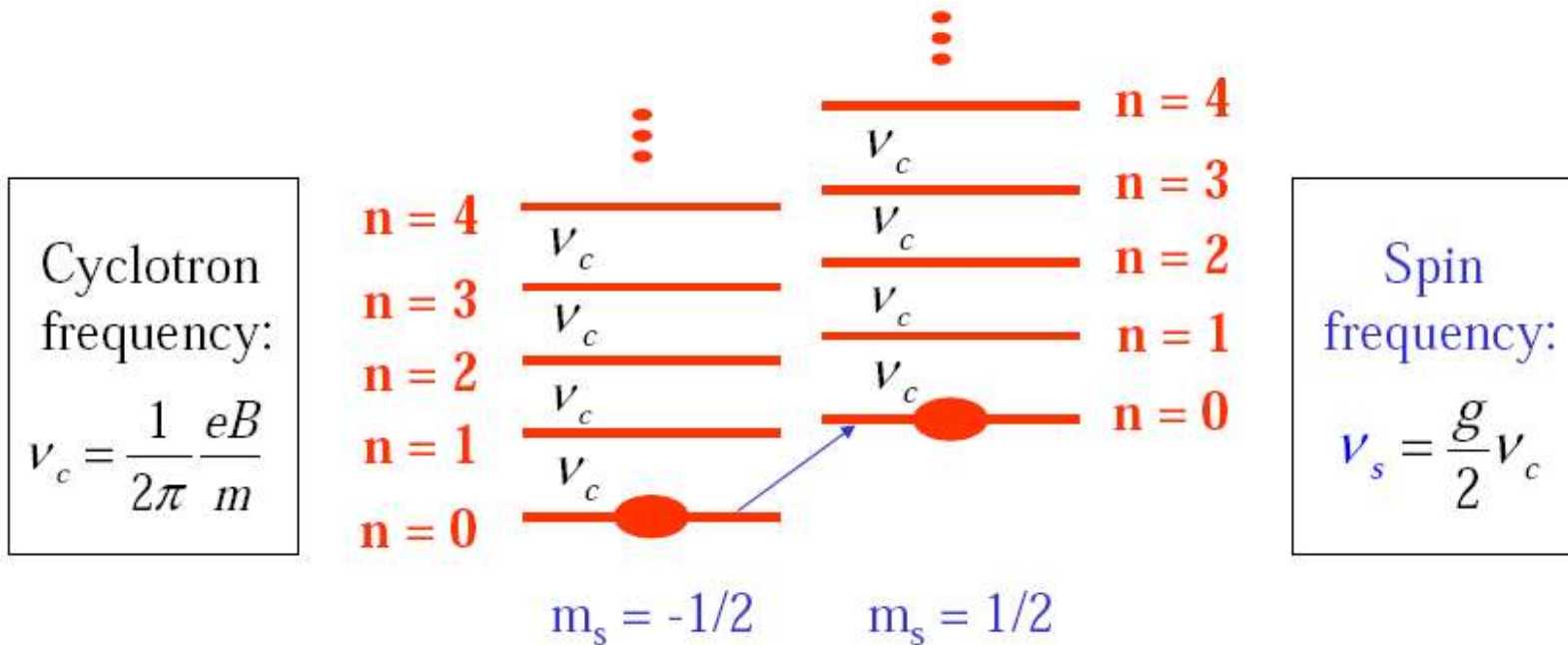
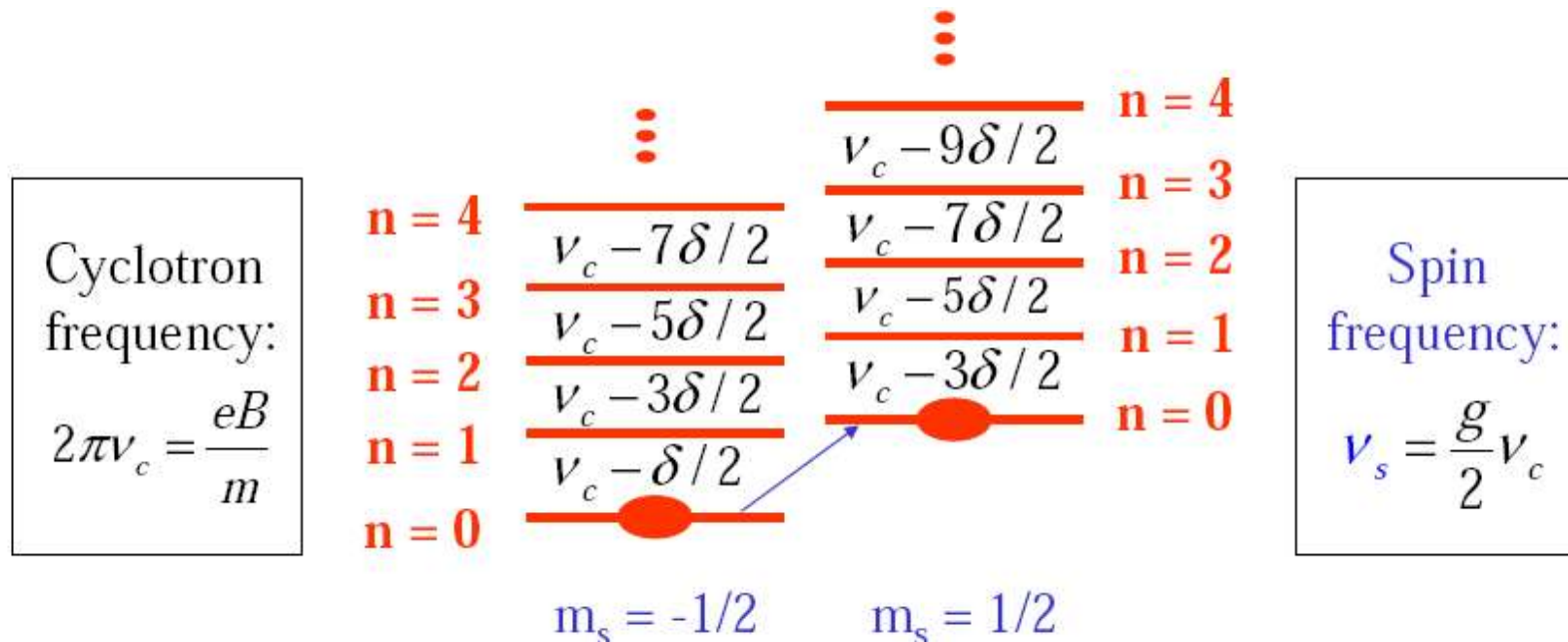


FIG. 8. Splitting of geonium energy levels for an electron (not to scale). The ladder on the far left represents the basic cyclotron energy levels. Progressing to the right, these levels are split first by the spin ($=\frac{1}{2}$), then by the axial binding, and finally by the magnetron motion. The magnetron levels are inverted, since the motion is unbound.

Basic Idea of the Fully-Quantum Measurement



Special Relativity Shift the Energy Levels



$$\frac{\delta}{\nu_c} = \frac{h\nu_c}{mc^2} \approx 10^{-9}$$

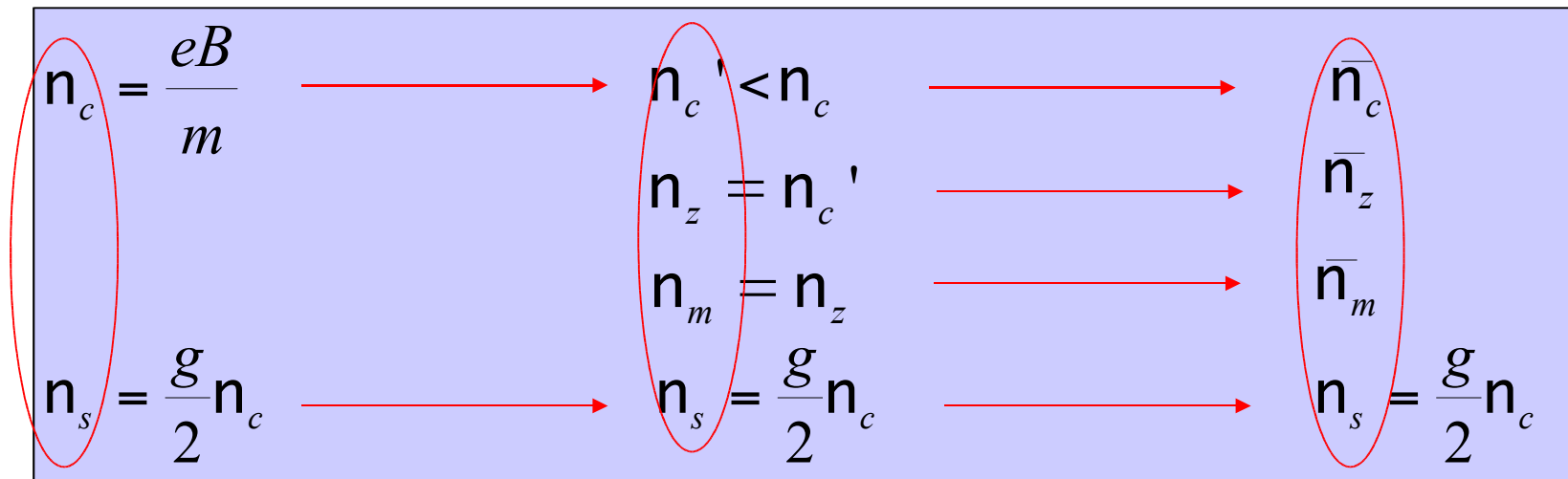
In reality...

B in Free Space

**Perfect Electrostatic
Quadrupole Trap**

Imperfect Trap

- tilted B
- harmonic distortions to V



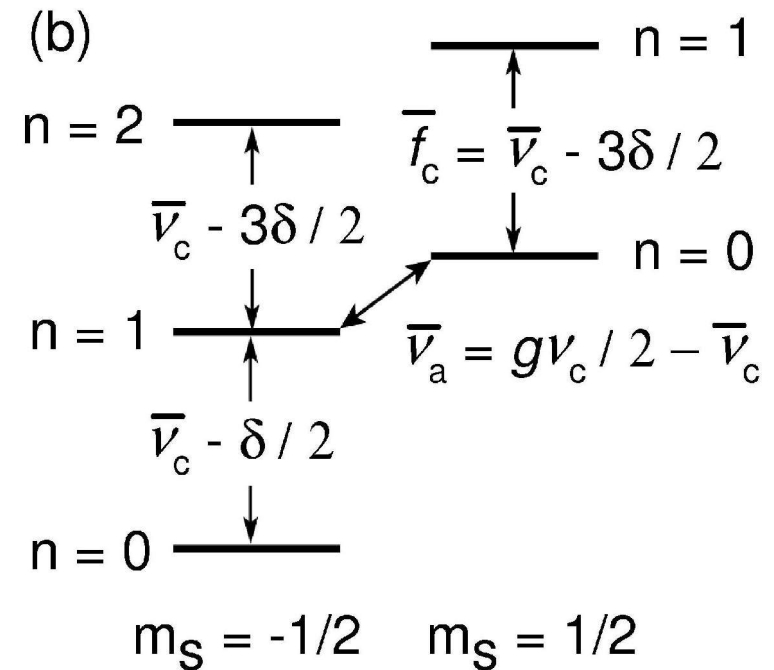
Brown-Gabrielse invariance theorem:

$$v_c = \sqrt{(\bar{v}_c)^2 + (\bar{v}_z)^2 + (\bar{v}_m)^2}$$

The measurement

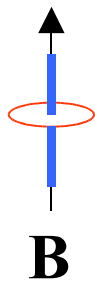
- Measure lowest cyclotron and spin states/transitions:

$$\frac{g}{2} \approx 1 + \frac{\bar{\nu}_a - \frac{(\bar{\nu}_z)^2}{2\bar{\nu}_c}}{\bar{f}_c + \frac{3\delta}{2} + \frac{(\bar{\nu}_z)^2}{2\bar{\nu}_c}}$$



The magnetic bottle

- Magnetic bottle field:



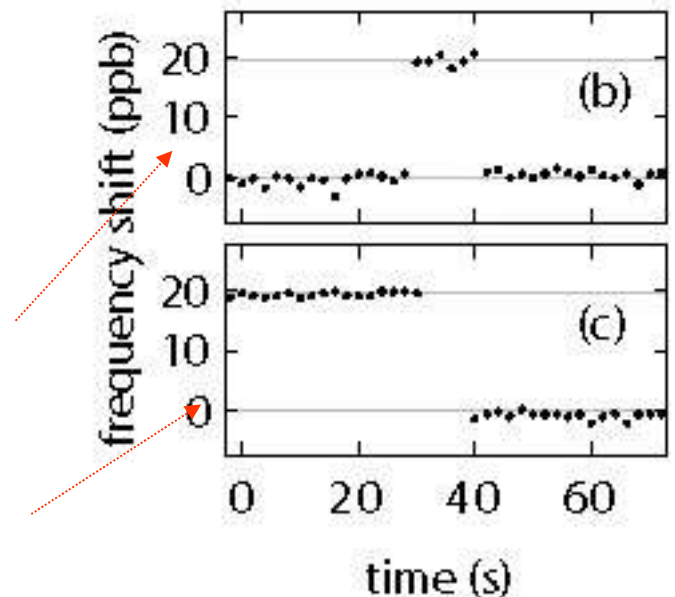
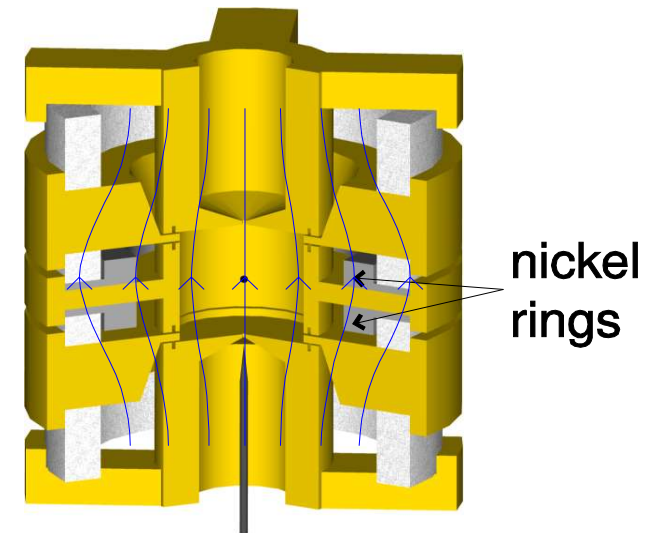
- Couples the axial frequency ω_z to the cyclotron and spin oscillations.
- Small measurable shift in ω_z indicates a change in cyclotron or spin energy levels

$$\Delta \vec{B} = B_2 [(z^2 - \rho^2) \hat{z} - z \vec{\rho}]$$

$$H = \frac{1}{2} m \omega_z^2 z^2 - \mu B_2 z^2$$

One quantum
cyclotron excitation

Spin-flip



Axial resonance

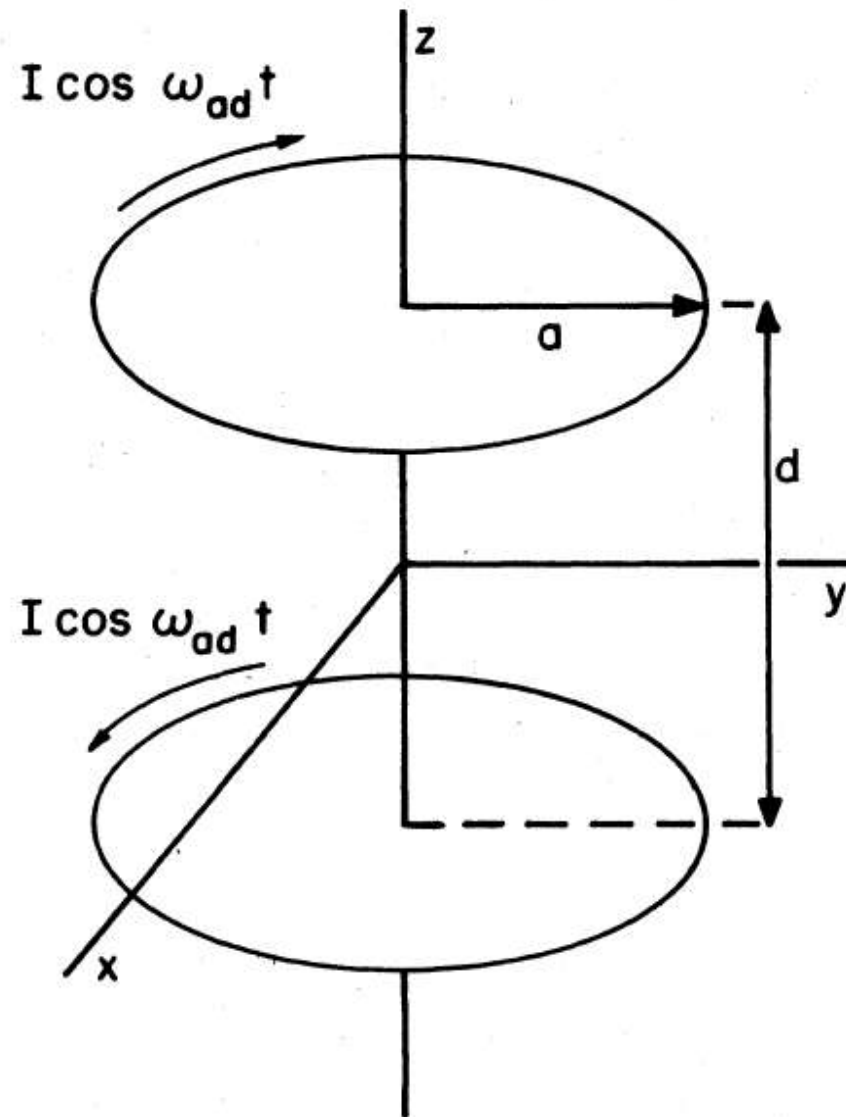


FIG. 23. Effective current loops, which produce the alternating magnetic field near the center of the trap given by

The One-Particle Self-Excited Oscillator

Measure axial oscillation through One-Particle Self-Excited Oscillator

- Digital Signal Processor:
 - Real time fourier transforms to measure oscillation
 - Feedback to endcaps to drive SEO (adjust gain so oscillation unchanged)

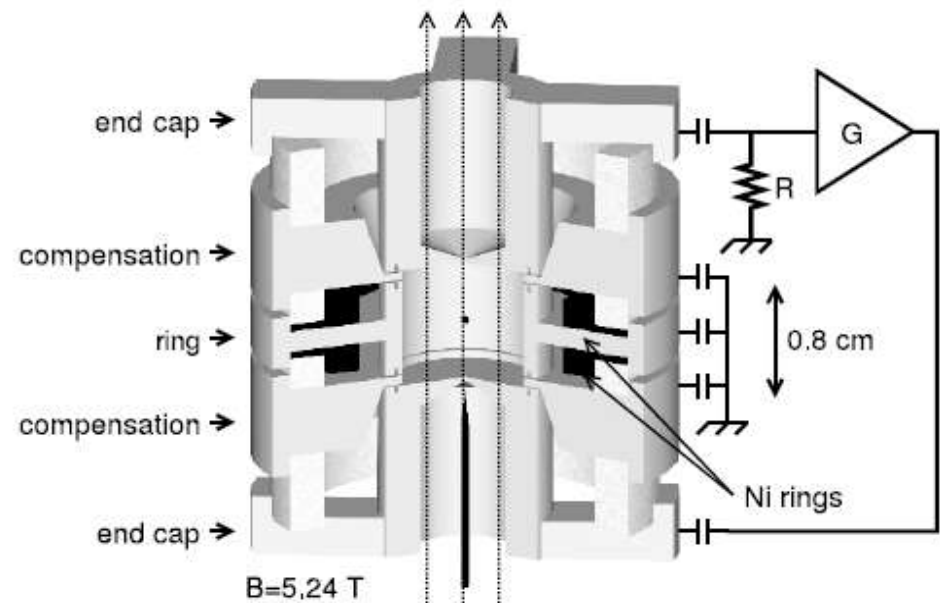


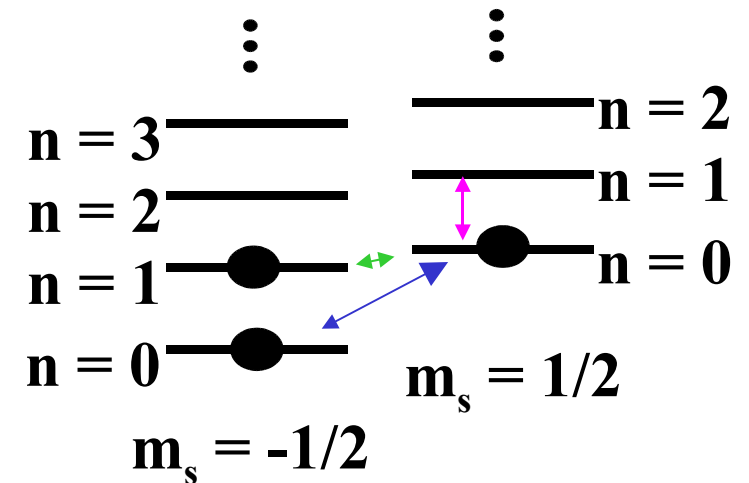
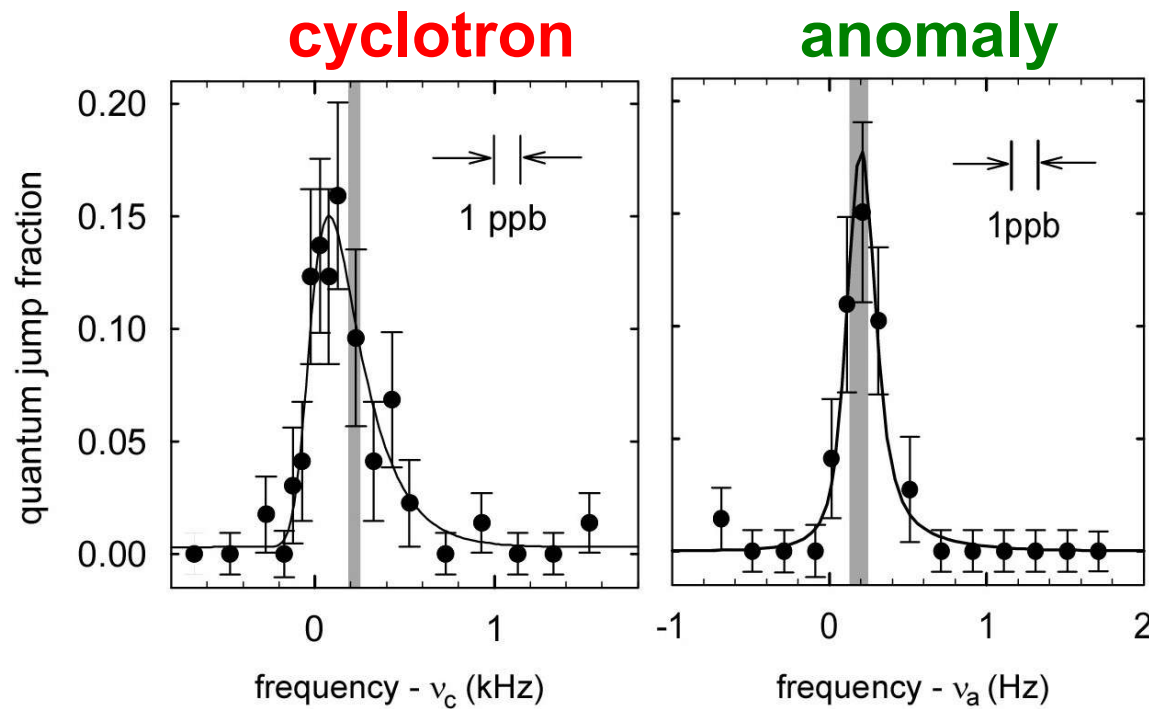
FIG. 1. The vertical oscillation of a trapped electron, shown within a cutaway of a cylindrical Penning trap, induces a voltage across resistor R that is amplified and fed back to drive the oscillation. Unavoidable trap capacitance in parallel to R is tuned out at ω_z with a parallel inductor.

"Single-Particle Self-excited Oscillator"

B. D'Urso, R. Van Handel, B. Odom, G. Gabrielse, Phys. Rev. Lett. 94, 113002 (2005).

electron (g-2) measurement

- Prepare $n=0, m=1/2$ -> measure anomaly transition
- Prepare $n=0, m=1/2$ -> measure cyclotron transition

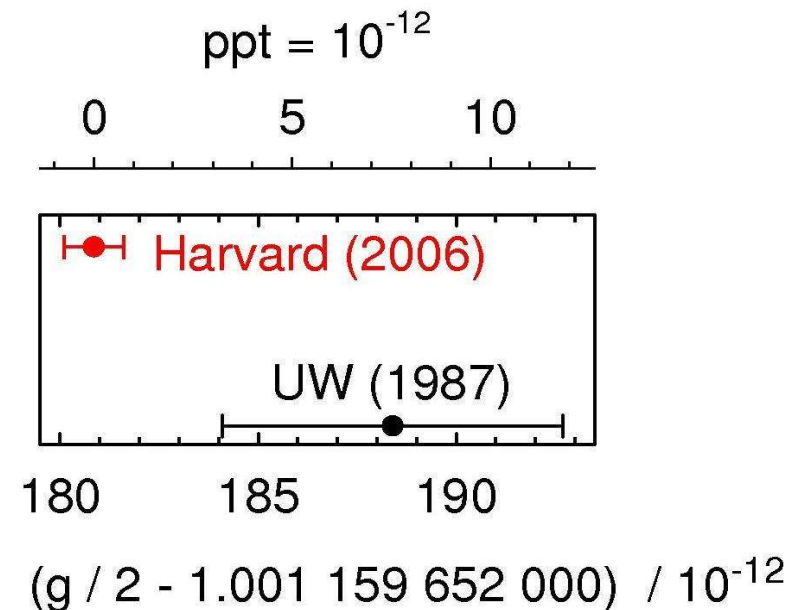


Measurement of the magnetic moment

$$g/2 = 1.001\,159\,652\,180\,85\,(76)$$

B. Odom, D. Hanneke, B. D'Urso, G. Gabrielse, Phys. Rev. Lett. 97, 030801 (2006).

- First improved measurement since 1987
- Nearly six times smaller uncertainty
- 1.7 standard deviation shift
- Likely more accuracy coming
- 1000 times smaller uncertainty than muon g



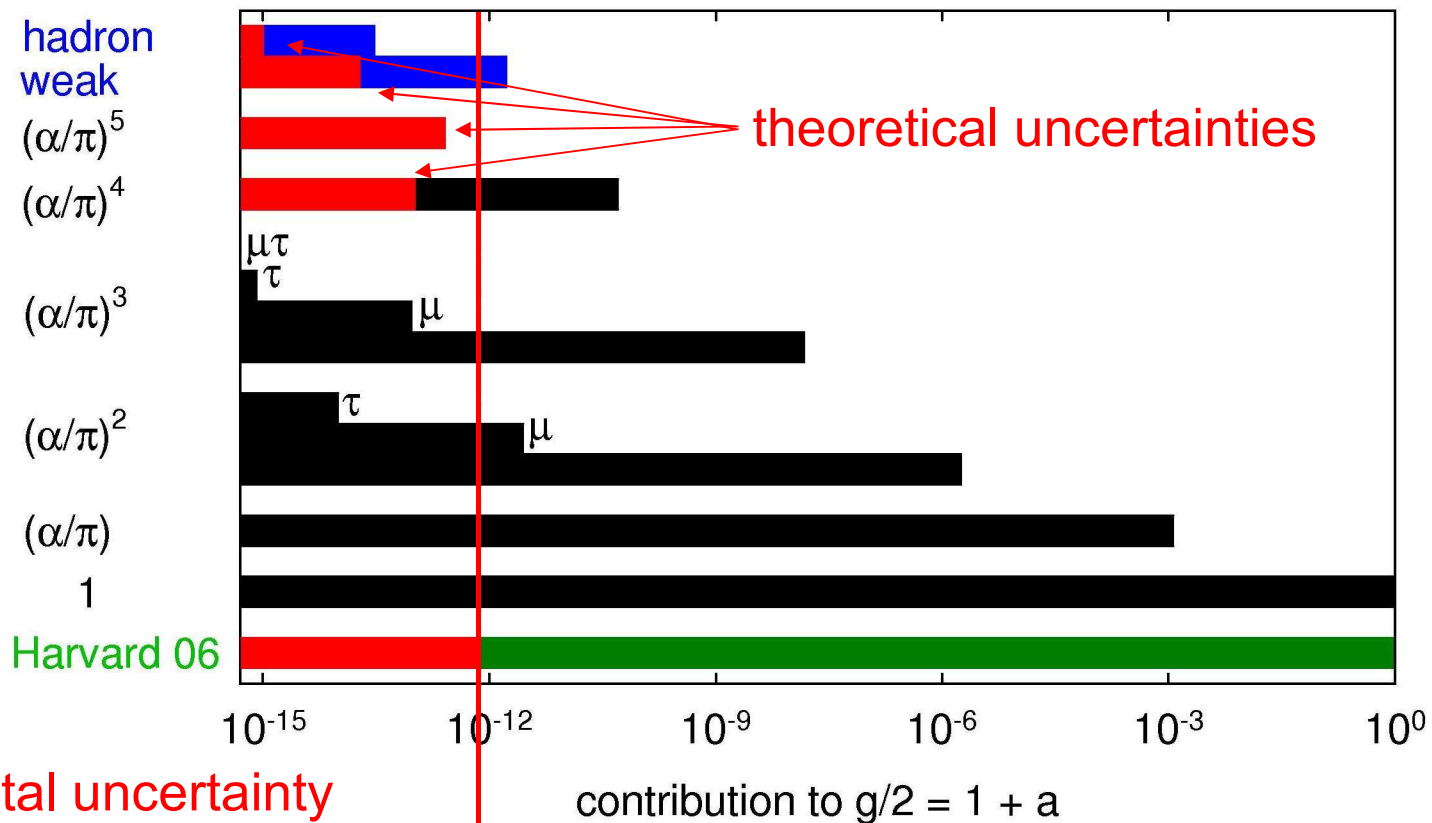
Determination of the Fine Structure Constant

$$a_e = C_1 \left(\frac{\alpha}{\pi} \right) + C_2 \left(\frac{\alpha}{\pi} \right)^2 + C_3 \left(\frac{\alpha}{\pi} \right)^3 + C_4 \left(\frac{\alpha}{\pi} \right)^4 + \dots + \delta a$$

$$\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c}$$

QED calculation

Weak/strong contribution



Determination of the Fine Structure Constant

$$\alpha = 137.035\,999\,710\,(96)$$

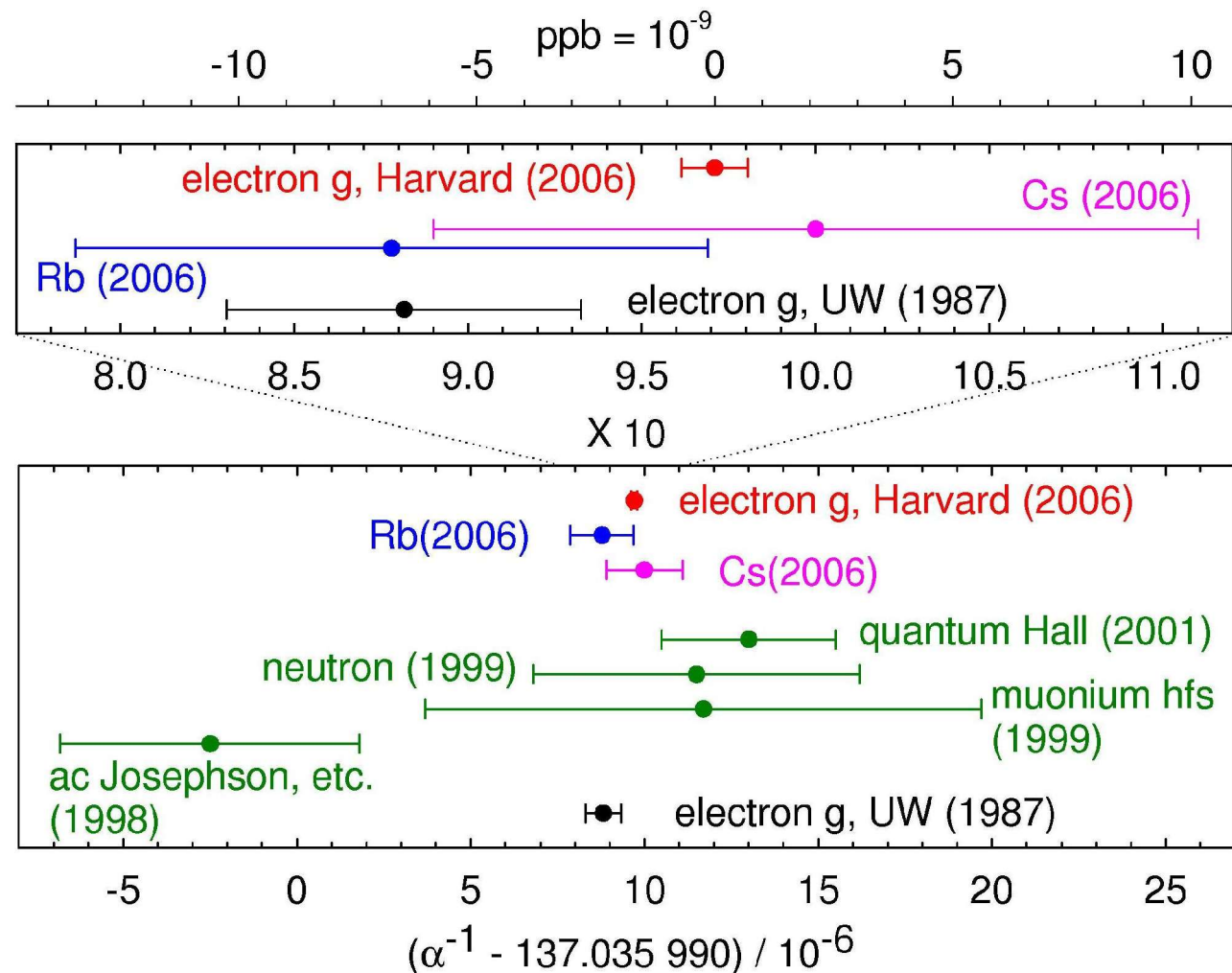
» G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, B. Odom, Phys. Rev. Lett. 97, 030802 (2006).

$$\alpha = 137.035\,999\,710\,(96)$$

$$\alpha = 137.036\,000\,0\,(11)$$

$$\alpha = 137.035\,998\,84\,(91)$$

$$\alpha = 137.035\,998\,80\,(52)$$



CPT conservation

- From a previous measurement:
 - Van Dyck, Schwinberg, Dehemelt, Phys. Rev. Lett. 59, 26 (1987)
- Test of CPT conservation:

$$\frac{g_{e-} - g_{e+}}{g_{\text{average}}} = (0.5 \pm 2.1) \cdot 10^{-12}$$

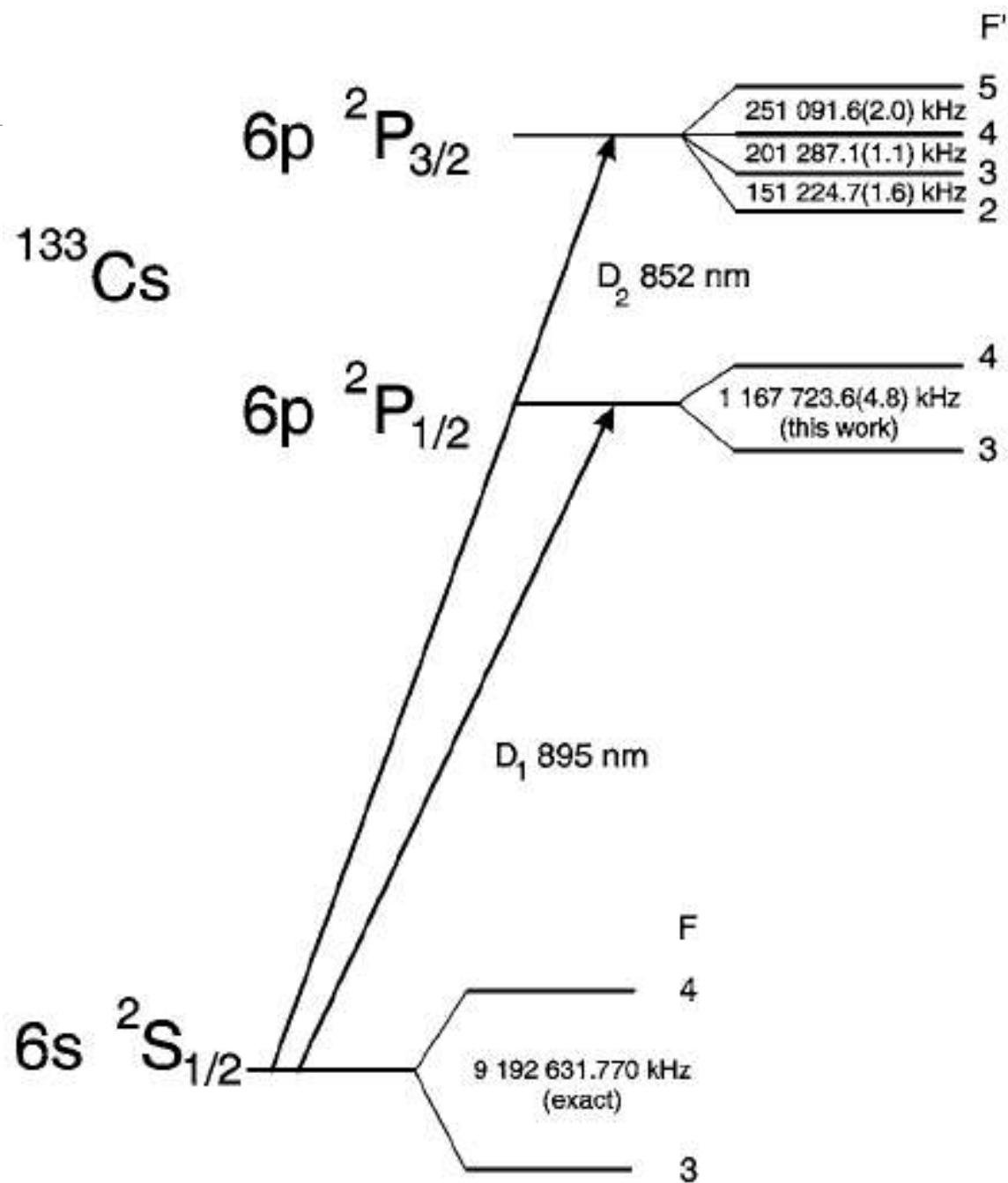
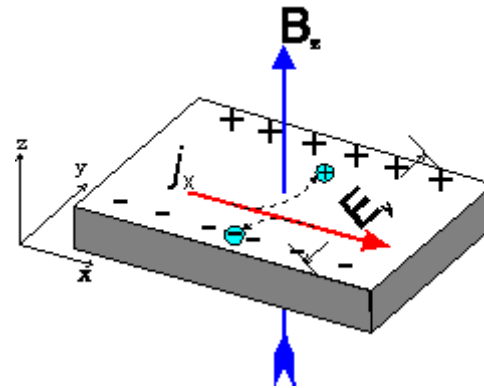


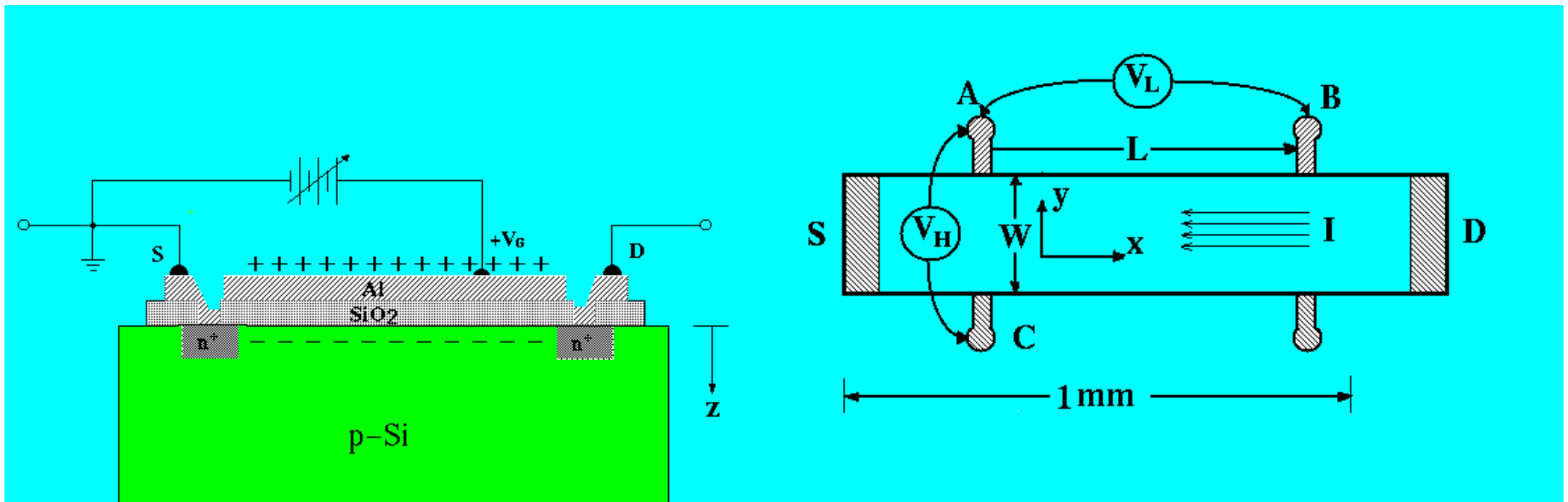
FIG. 2. Neutral ^{133}Cs energy level diagram (not to scale).

The Quantum Hall Effect

- The classical Hall Effect

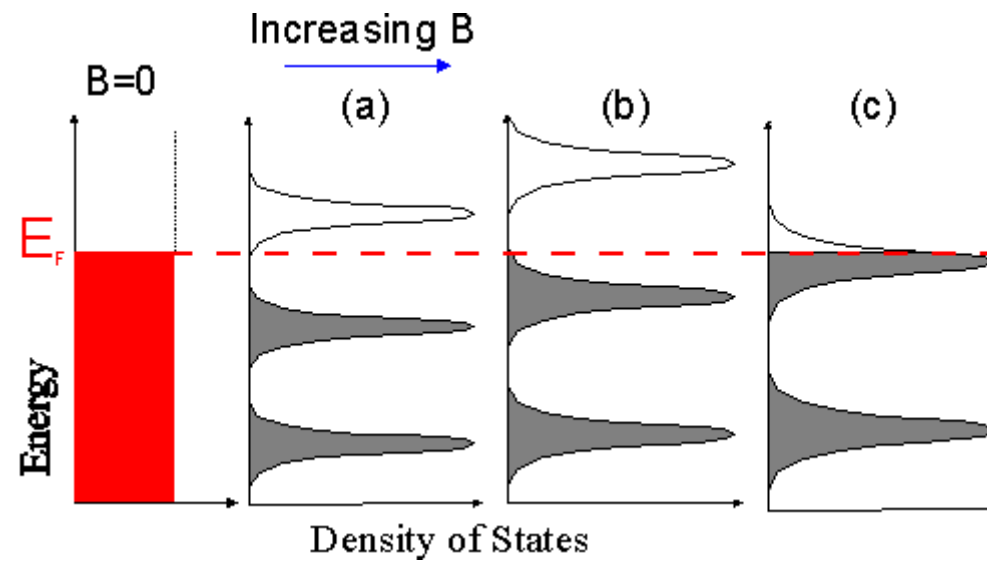


- The Quantum Hall Effect in a 2D-Electron Gas in a MOSFET :



The Quantum Hall Effect

- Landau levels



Click to add title

