Taking the Muon for a Spin

Thomas Gadfort
Fermilab
47th FNAL Users Meeting

- Spin and the Muon Anomalous Magnetic Moment
- Measuring a_μ with Polarized Muons
- The BNL Result and Goals for Fermilab Muon g-2
- Last Summer and This Summer's Big Move

Spin and Its Observable Effects

- In the Standard Model (SM), the **muon** is a point-like spin ½ particle.
  - With spin comes a magnetic dipole moment (MDM) of strength:

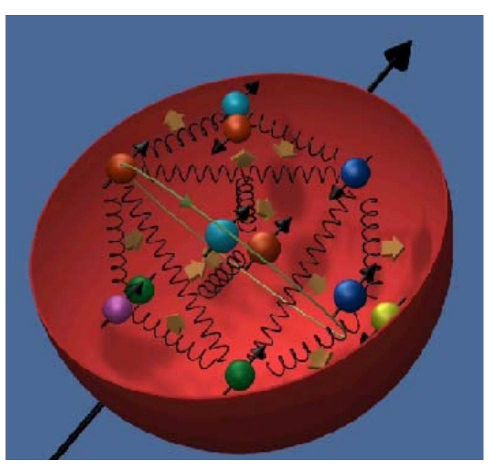
$$\vec{\mu} = g\frac{q}{2m}\vec{s} \longrightarrow$$

The Quantum Theory of the Electron.

By P. A. M. Dirac, St. John's College, Cambridge.

  - Dirac showed that **g = 2** for the electron as observed.

- The 1930's and 40's saw several breakthrough measurements of the g-factor that lead to a new understanding of particles and substructure.



$g_p \approx 5.6, g_n \approx -3.8$

→ nucleon substructure

Phys. Rev. **72** (1947)

Precision Measurement of the Ratio of the Atomic 'g Values' in the $^2P_{3/2}$ and $^2P_{1/2}$ States of Gallium*

P. Kusch and H. M. Foley

Columbia University, New York, New York

November 3, 1947

$g_e = 2.00229(8) \approx 2(1 + \alpha/2\pi)$

→ QM corrections

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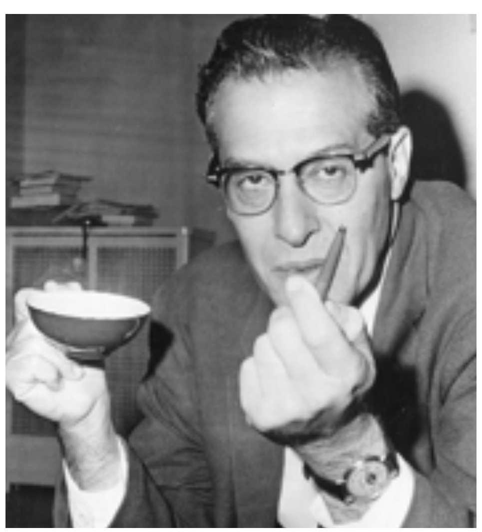
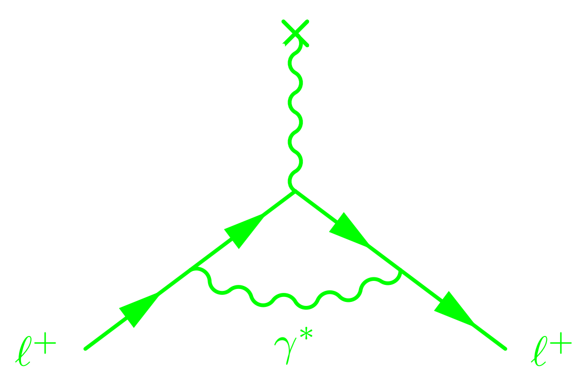


$$g_e = 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$



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D. Hanneke, S. Fogwell, and G. Gabrielse
PRL 100, 120801 (2008)

$$g_e/2 = 1.001\ 159\ 652\ 180\ 73(28)$$

→ QM corrections

Understanding The Muon

- There is a rich history of muon g-factor measurements starting in the 1950's at Nevis.

$$g_\mu = 2(10\%)$$

  - Evidence that the muon is a fundamental particle.

- The past 50 years have seen dramatic improvements in precision and experimental techniques.

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

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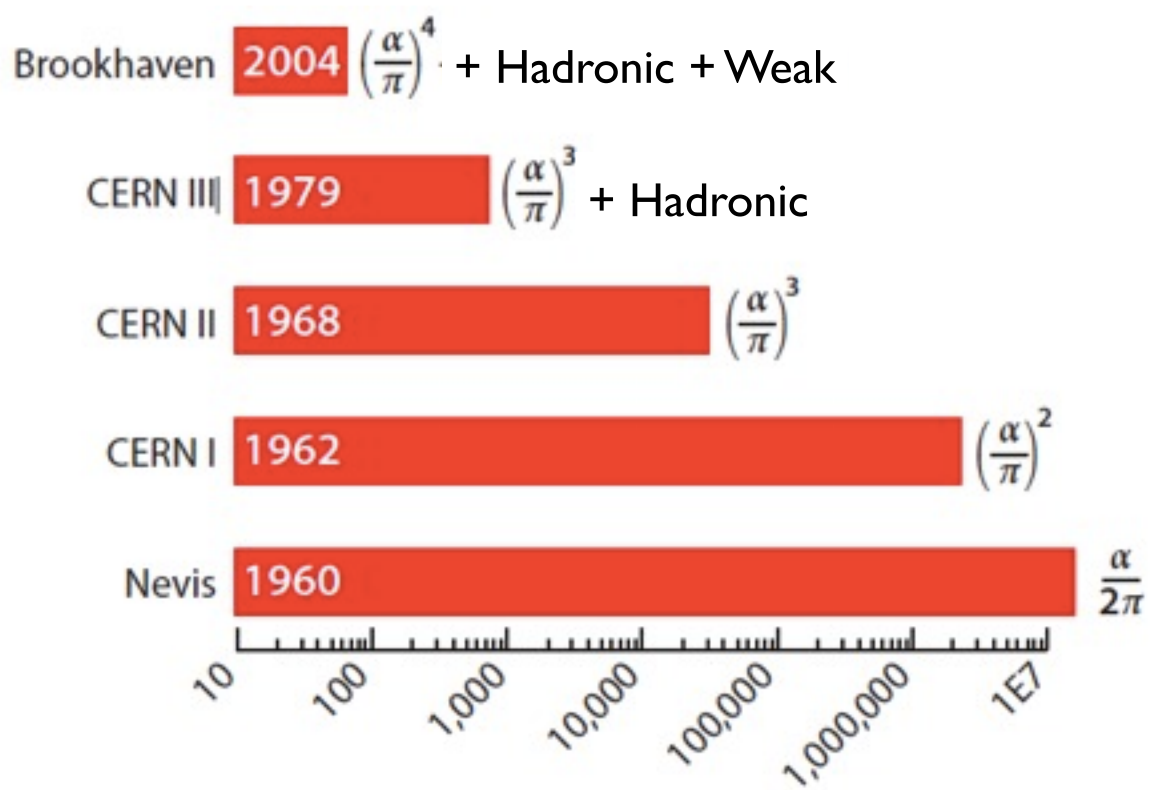
(Received January 15, 1957)

Phys. Rev. 105, 1415–1417 (1957)



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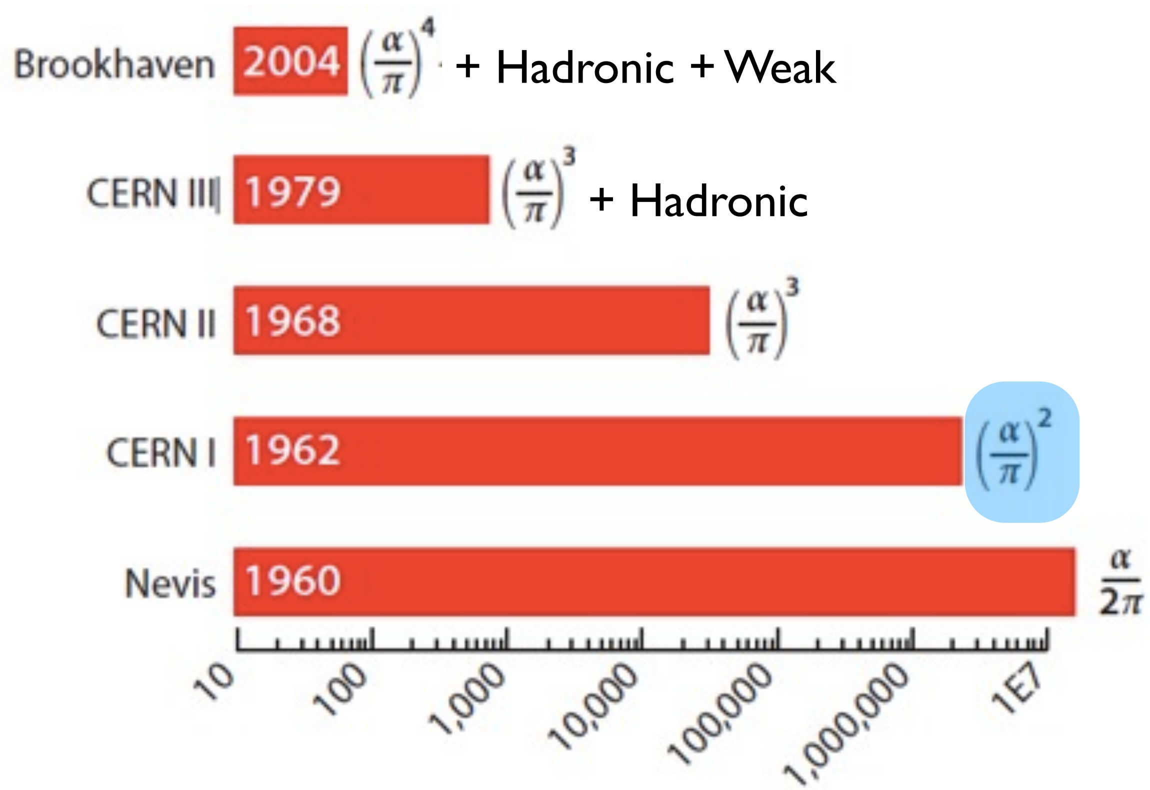

CERN I

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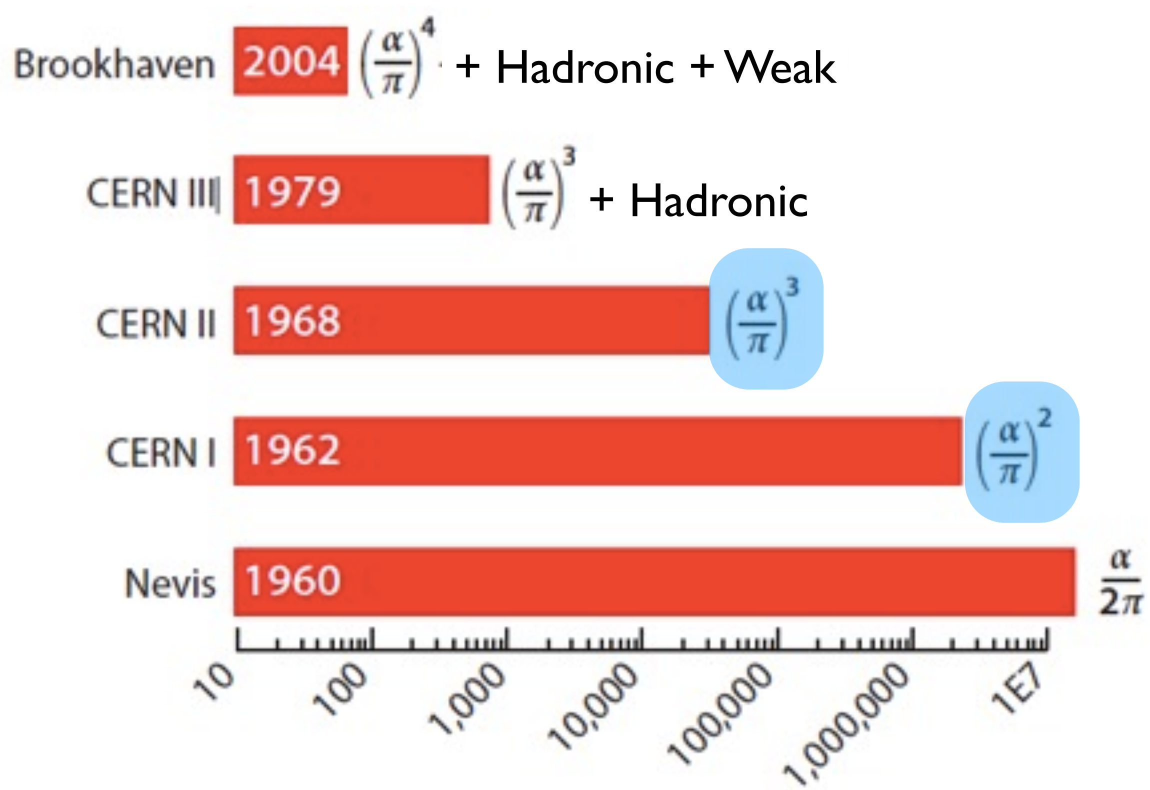

CERN I

CERN II

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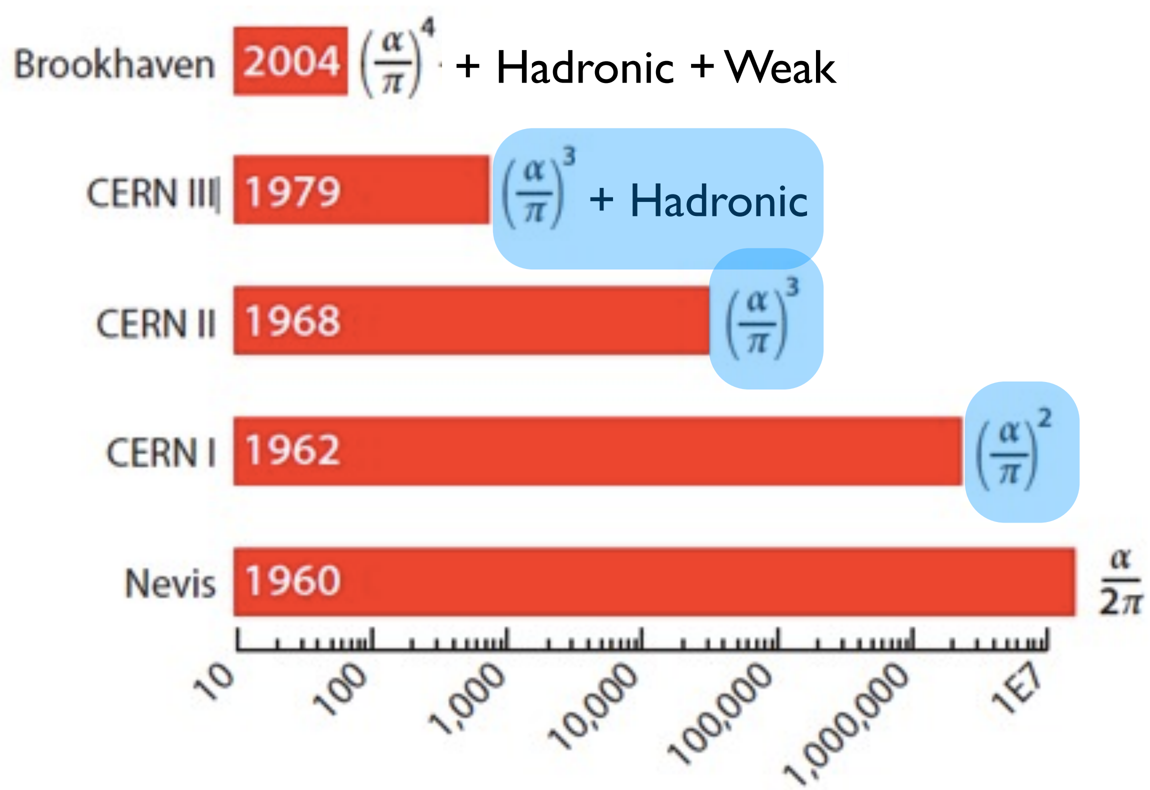
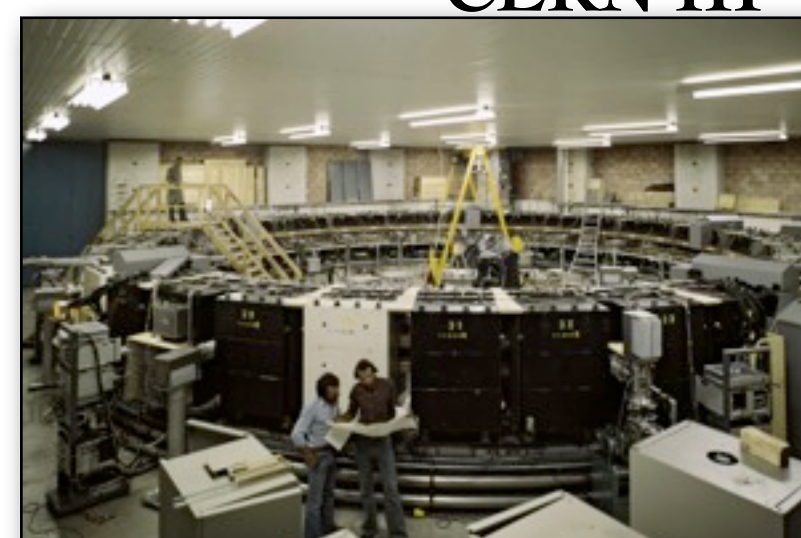


CERN I

CERN III



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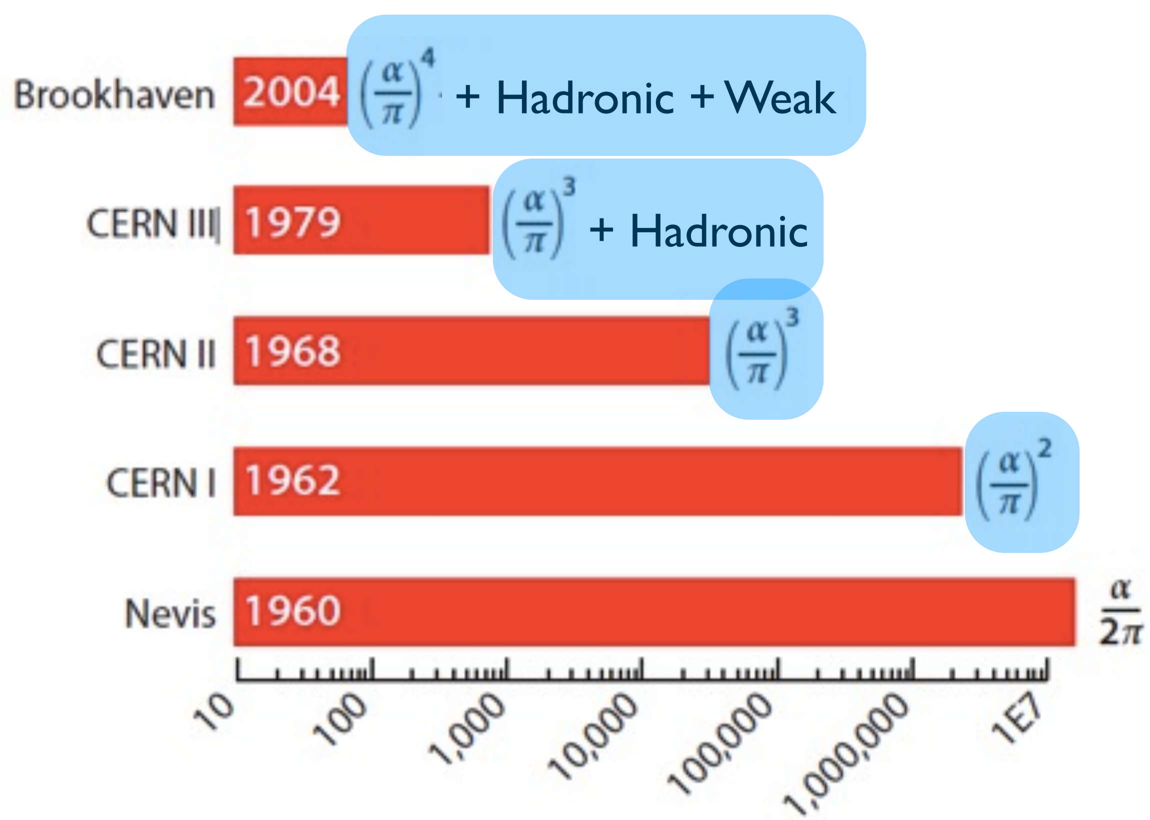
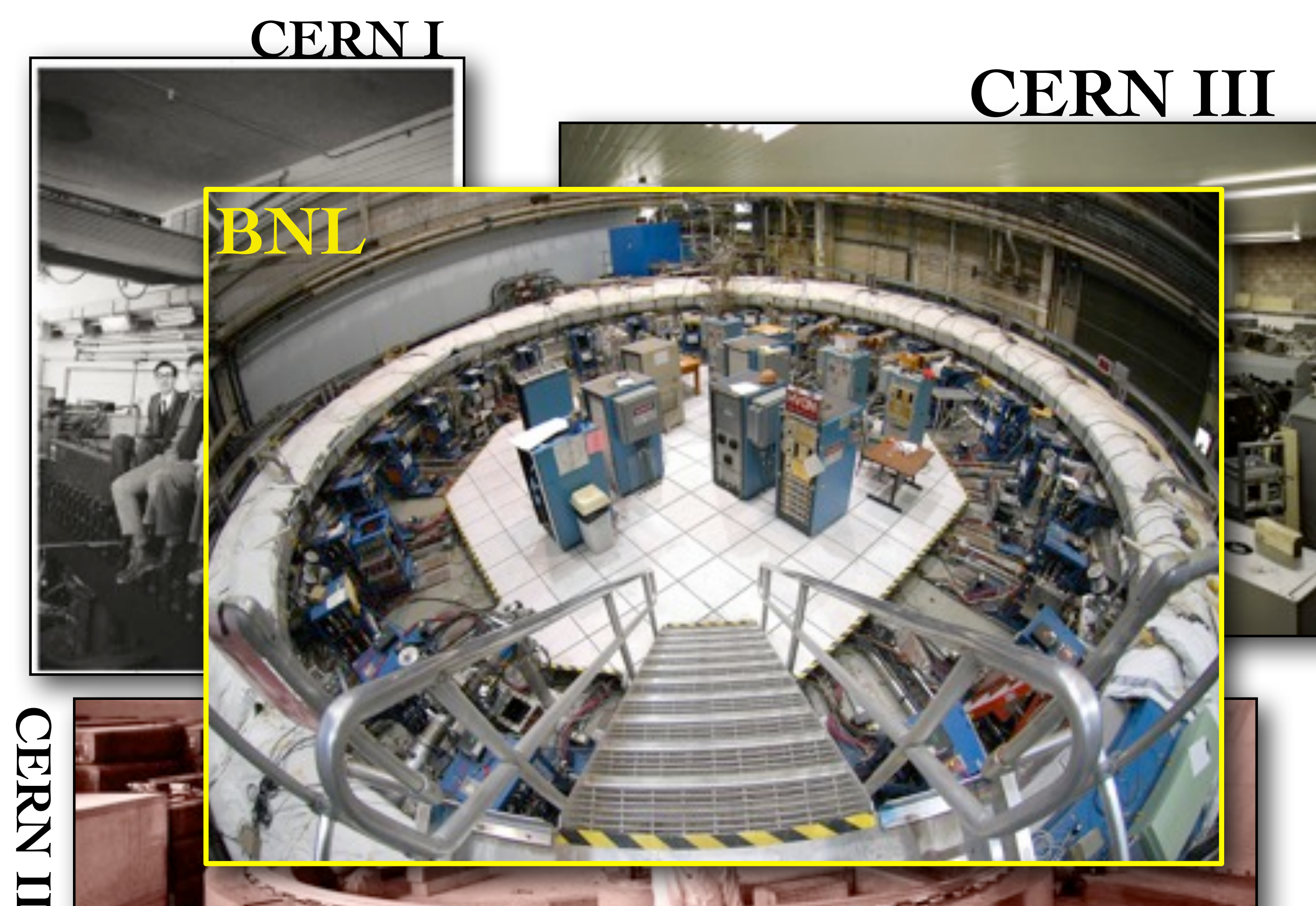
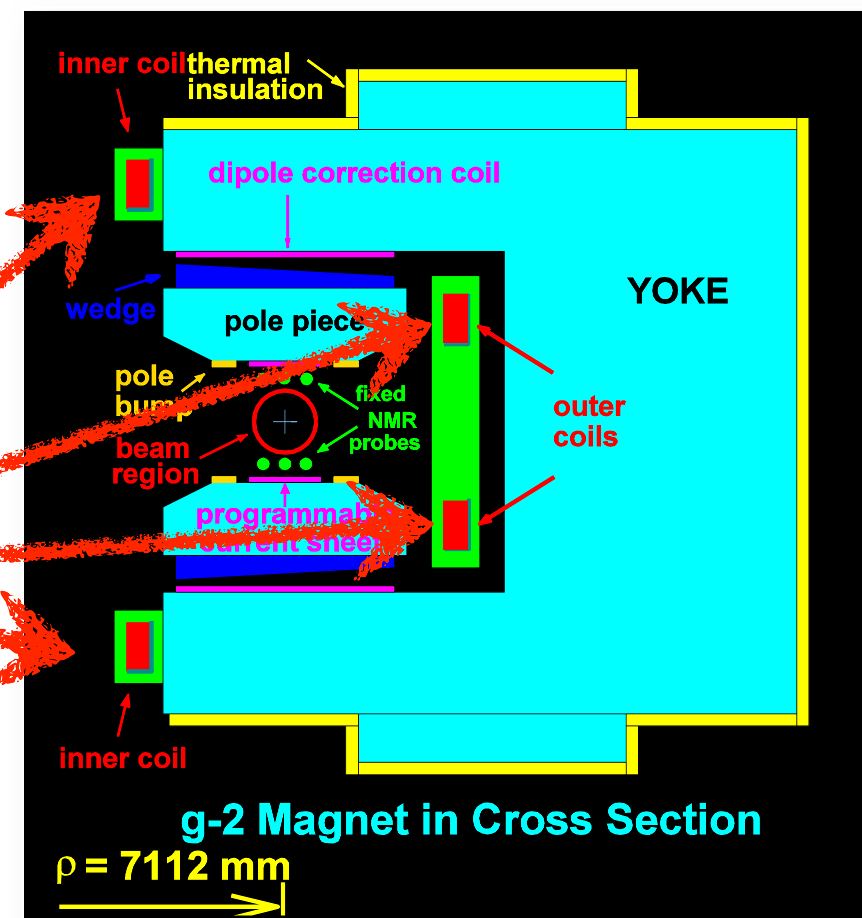




E821 Brookhaven Muon g-2

- Muon injection greatly improved statistics.
- Continuously wound superconducting (SC) main magnet coils + tunable shimming kit
  → Reduced multipole field terms.

Superconducting coil winding



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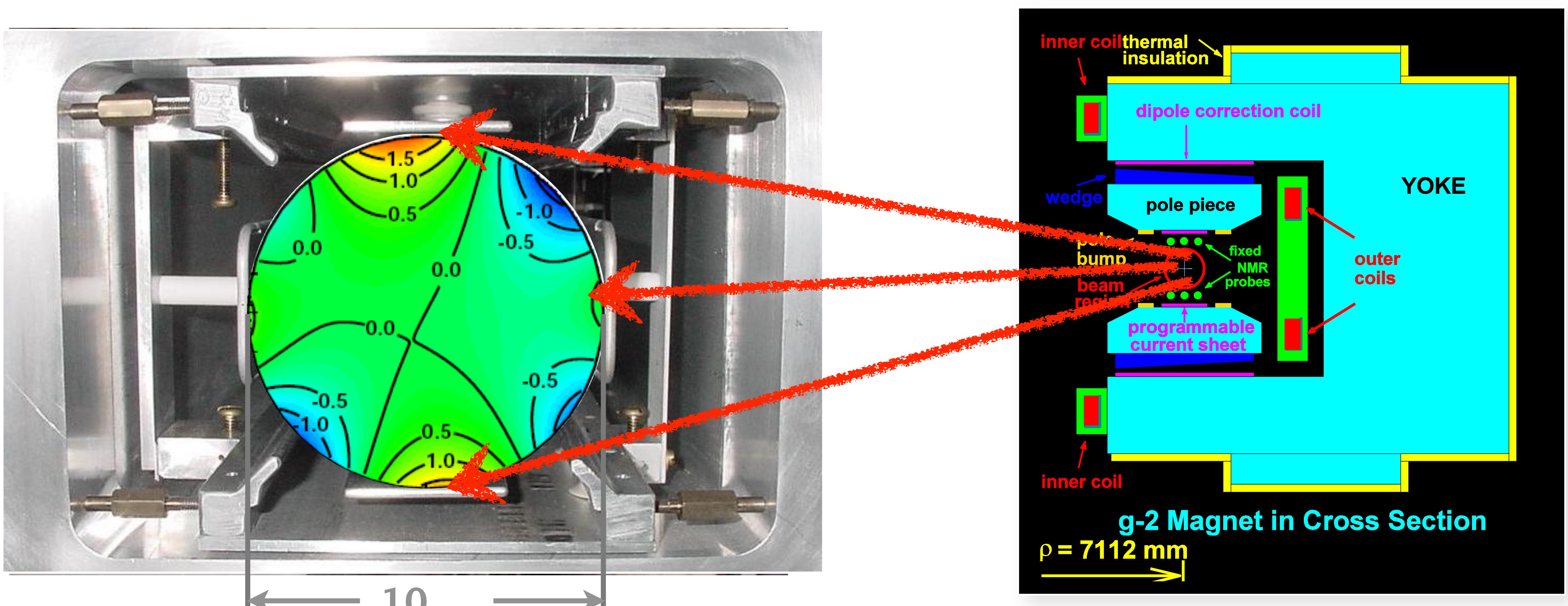
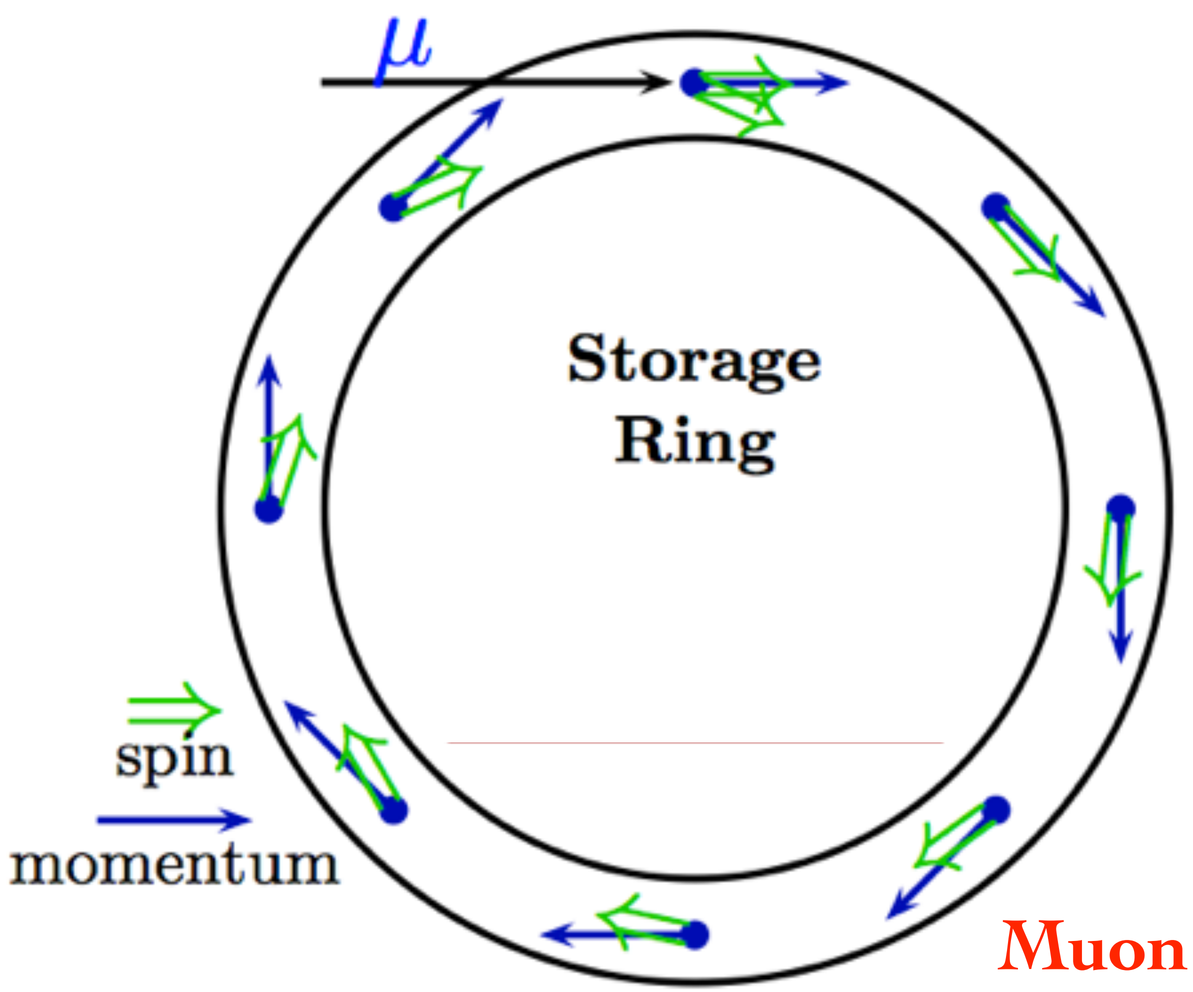
  - Dramatic improvement in field uniformity
    Contours in [ppm]!



Storage Ring Measurement Technique (I)

In a dipole magnetic field:



Muon momentum revolution frequency, ω_C

$$\omega_C = \frac{eB}{mc\gamma}$$

Muon spin revolution frequency, ω_S

$$\omega_S = \frac{geB}{2mc\gamma} + (1-\gamma)\frac{eB}{mc\gamma}$$

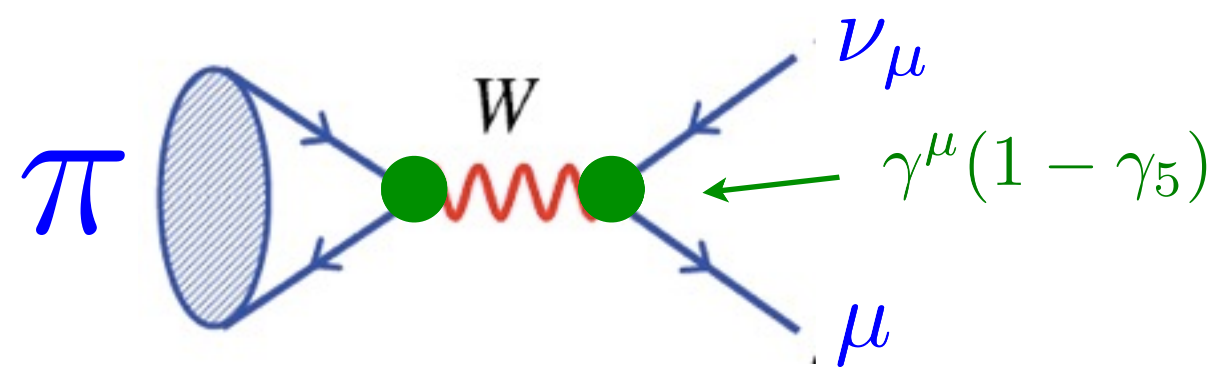
Muon anomaly revolution frequency, ω_a

$$\omega_a \equiv \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a_\mu \frac{eB}{mc}$$

Storage Ring Measurement Technique (II)

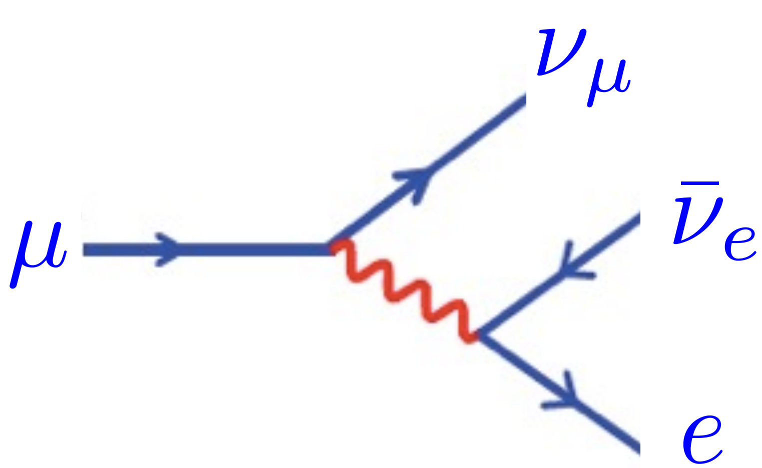
Source of Polarized Muons

Lucky break from parity violation

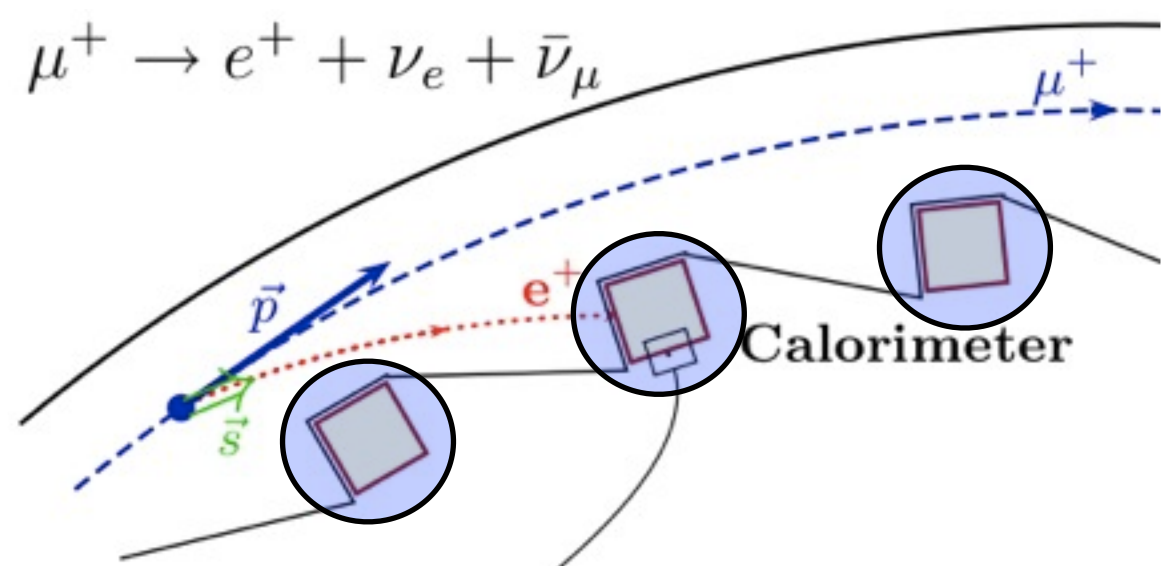


Measure Muon Spin → Measure Positron Energy

Weak decay correlates muon spin and electron momentum



Highest energy positrons when spin and momentum are aligned.



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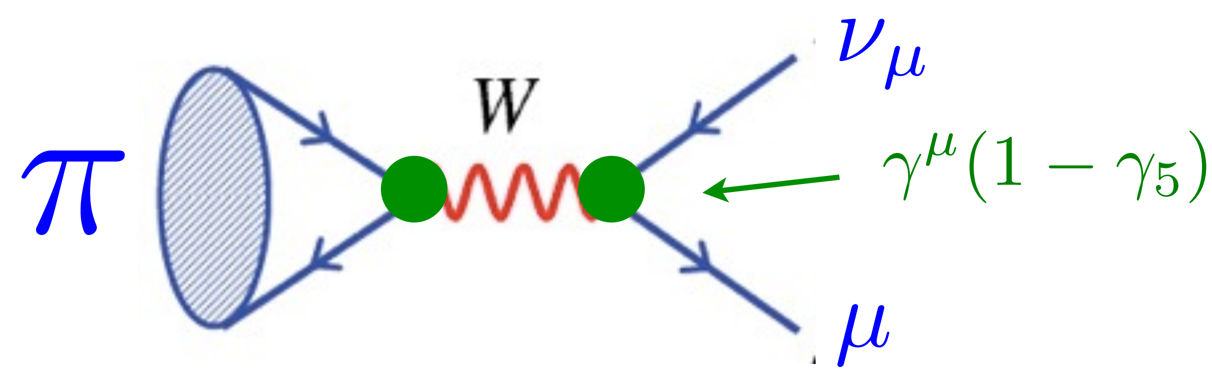

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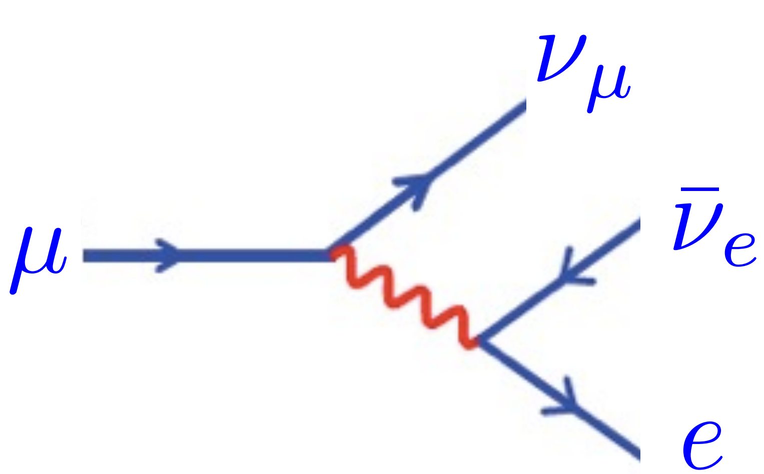

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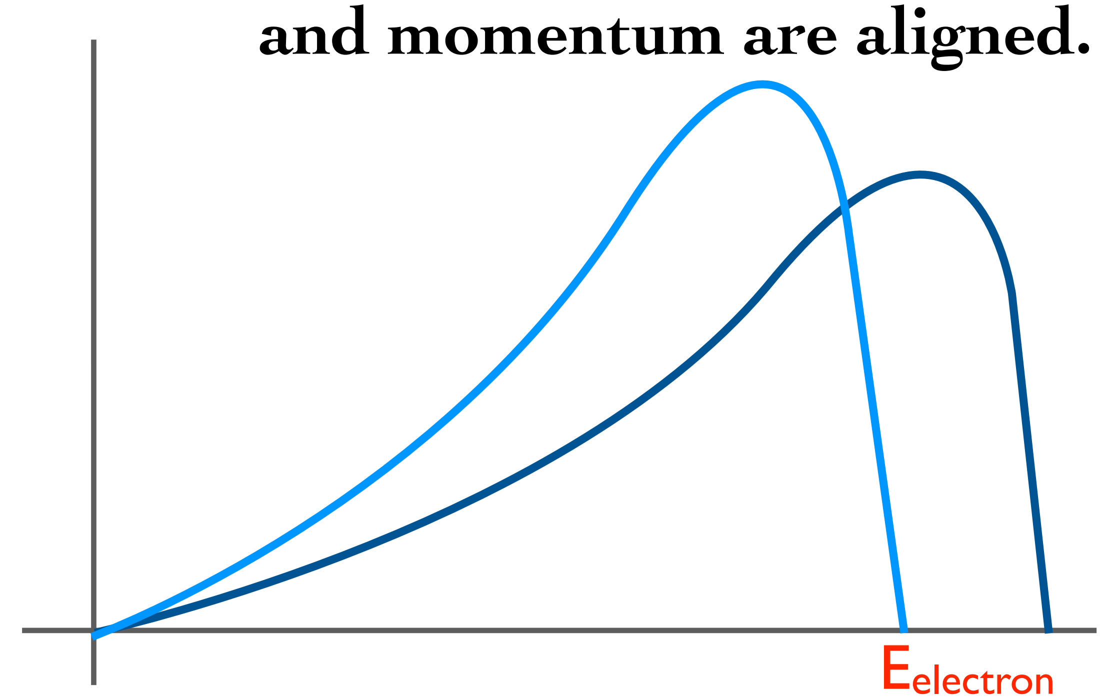

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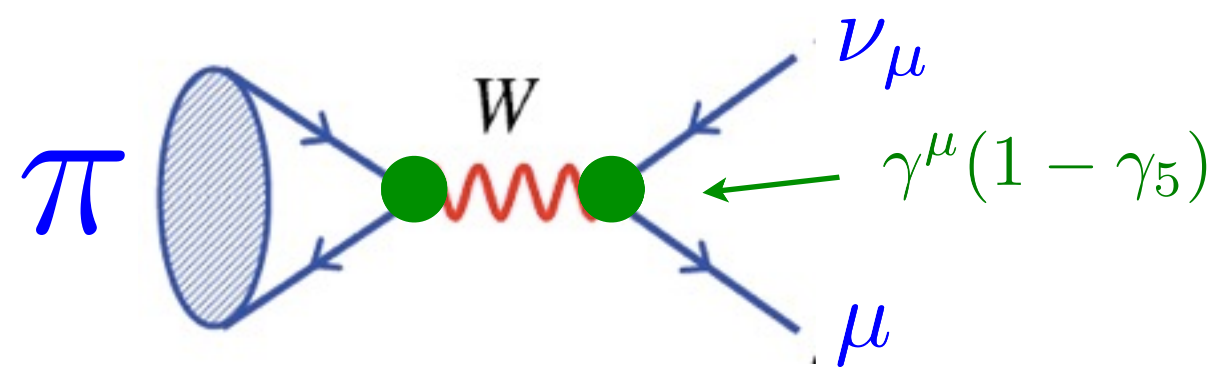

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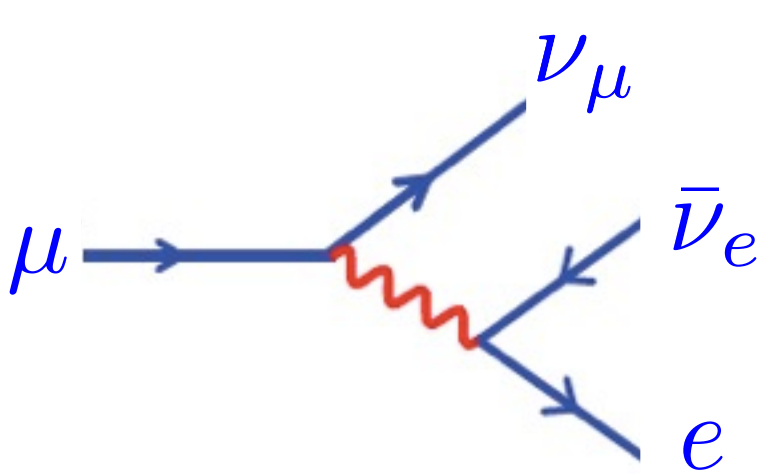

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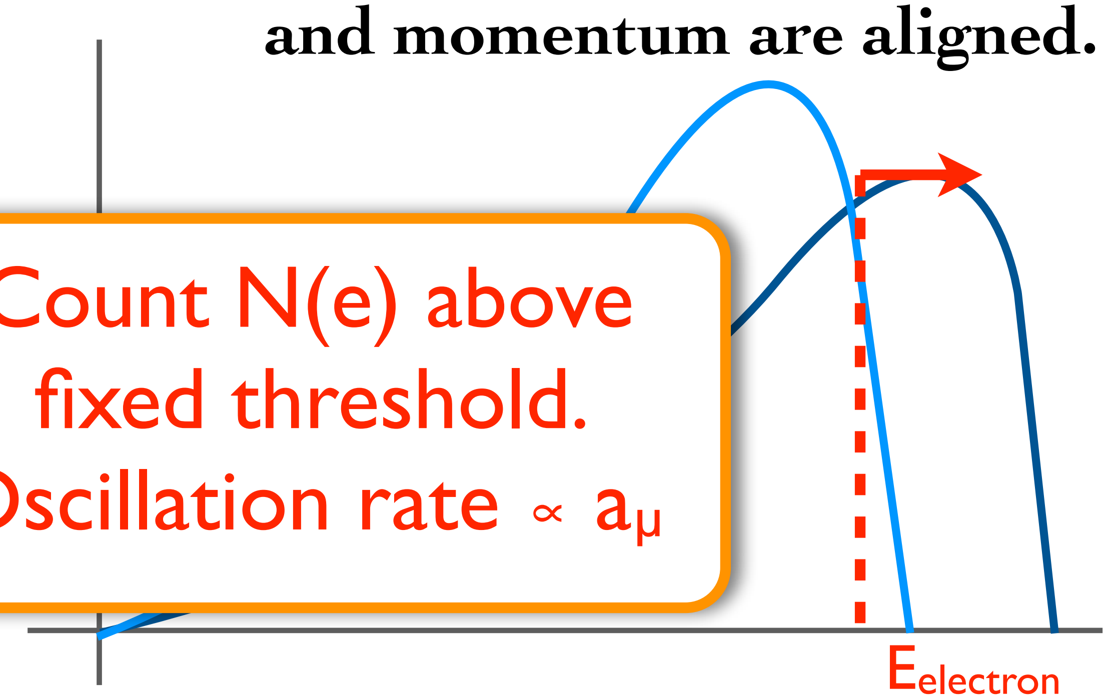
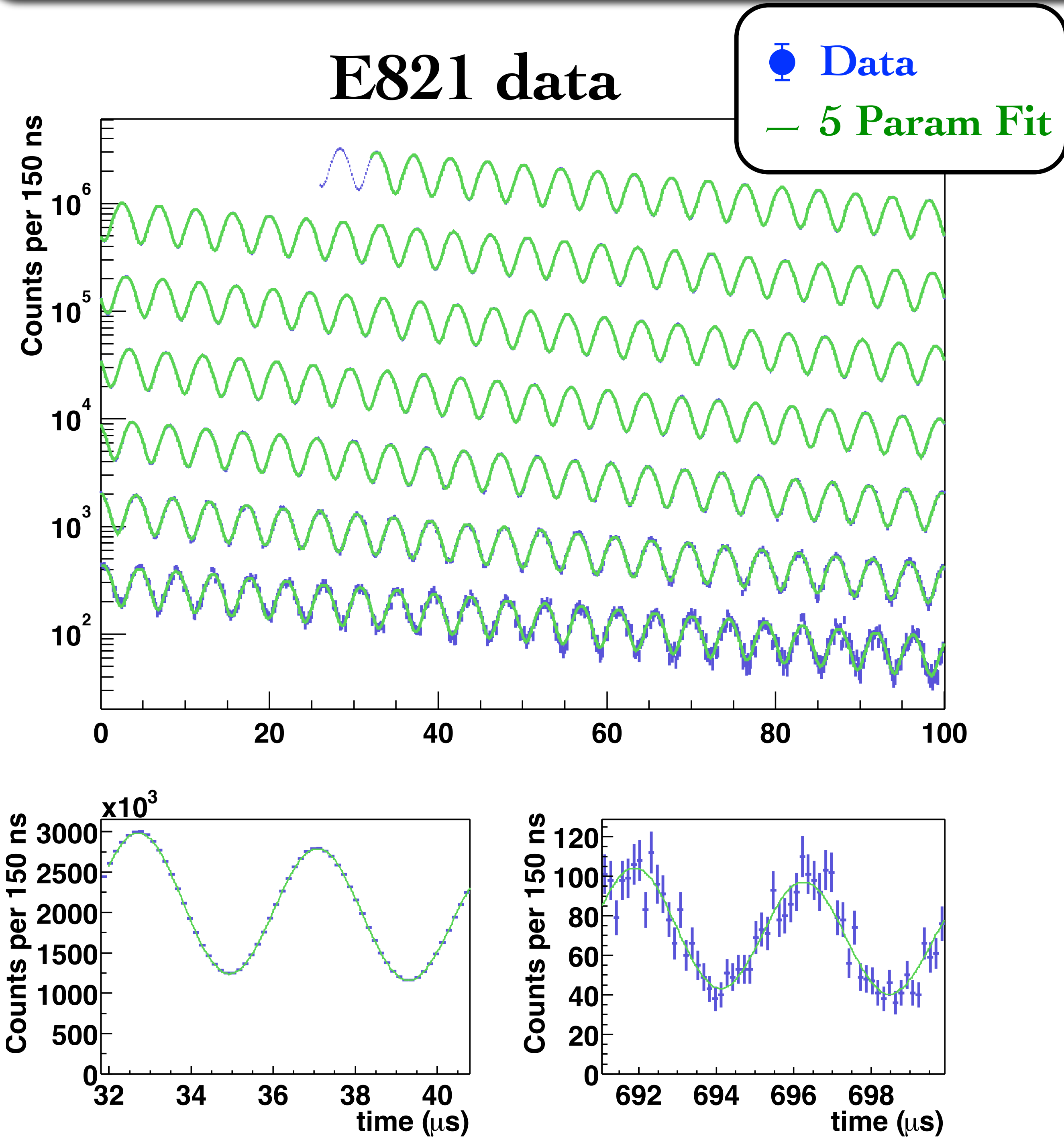


Count N(e) above fixed threshold.
Oscillation rate ∝ a_μ

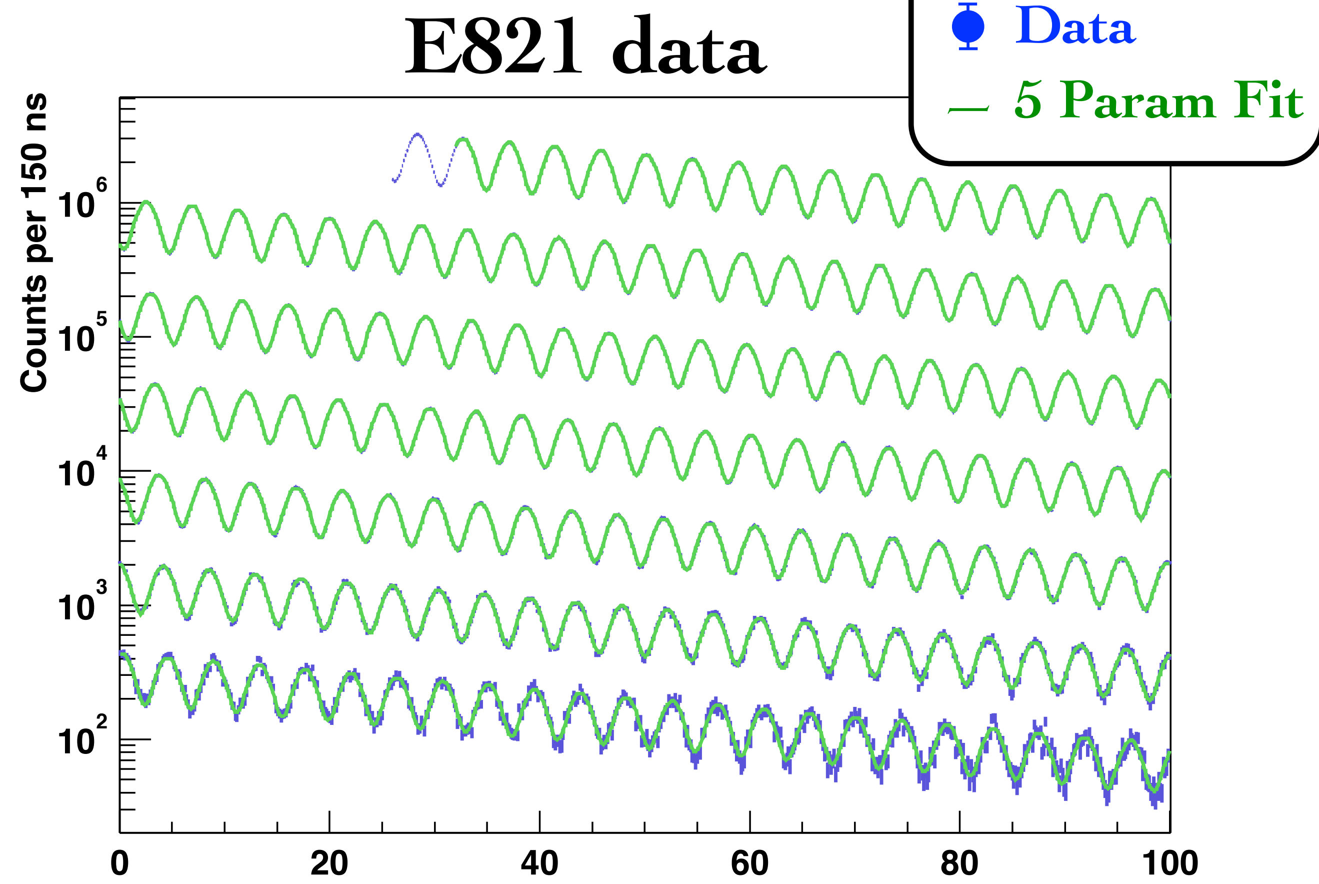
The Wiggle Plot, ω_a, ω_p, and a_μ



$$N(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left[1 + A\cos(\omega_a t + \phi)\right]$$

4 billion muon decays
(≈15% yield >1.8 GeV positrons)

The Wiggle Plot, ω_a, ω_p, and a_μ



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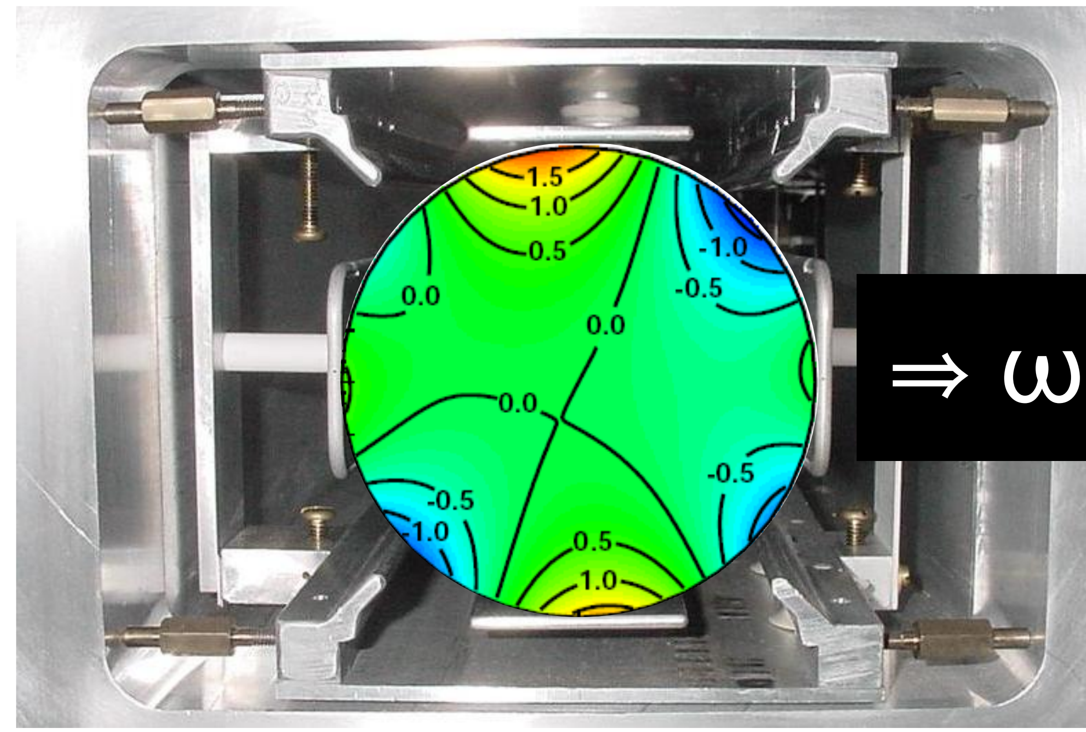
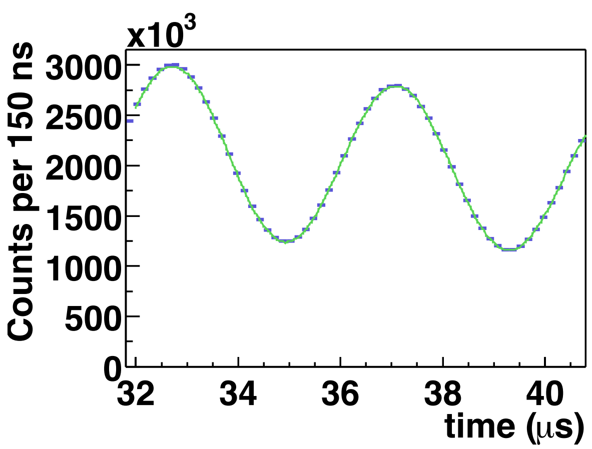
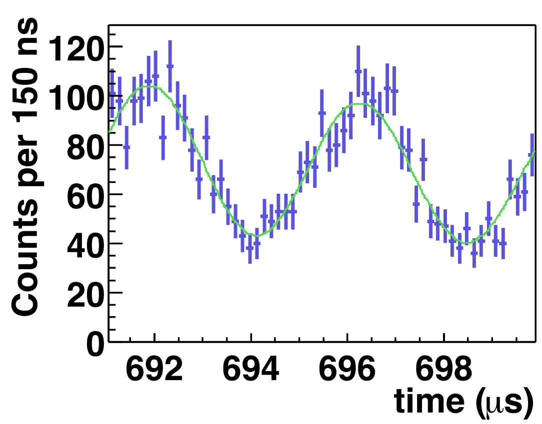


$\Rightarrow \omega_p\ (\langle B \rangle)$





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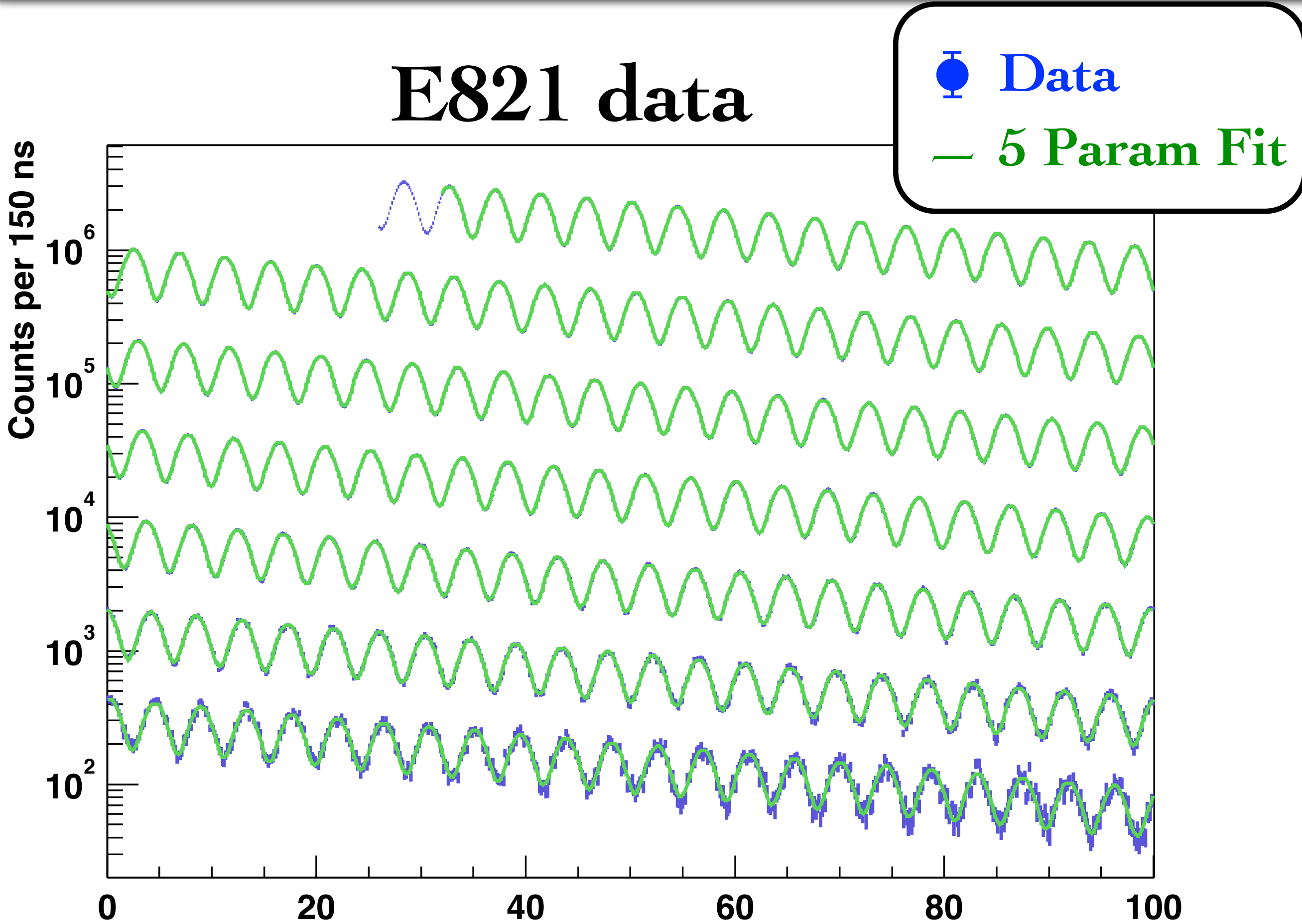

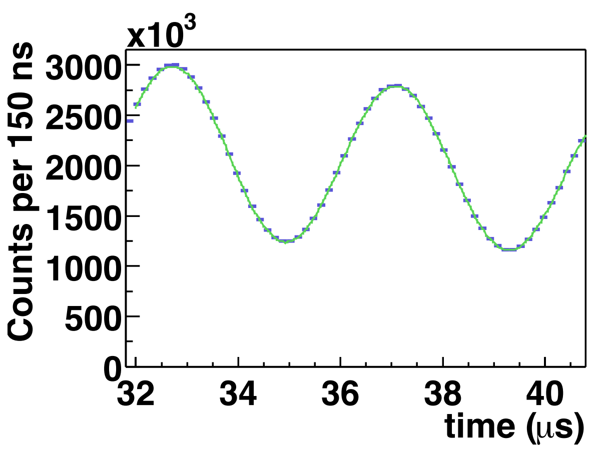

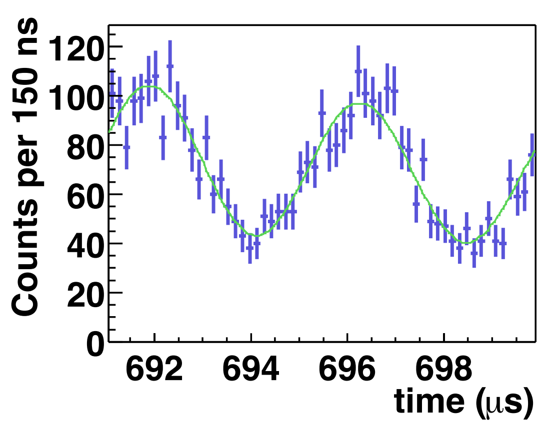

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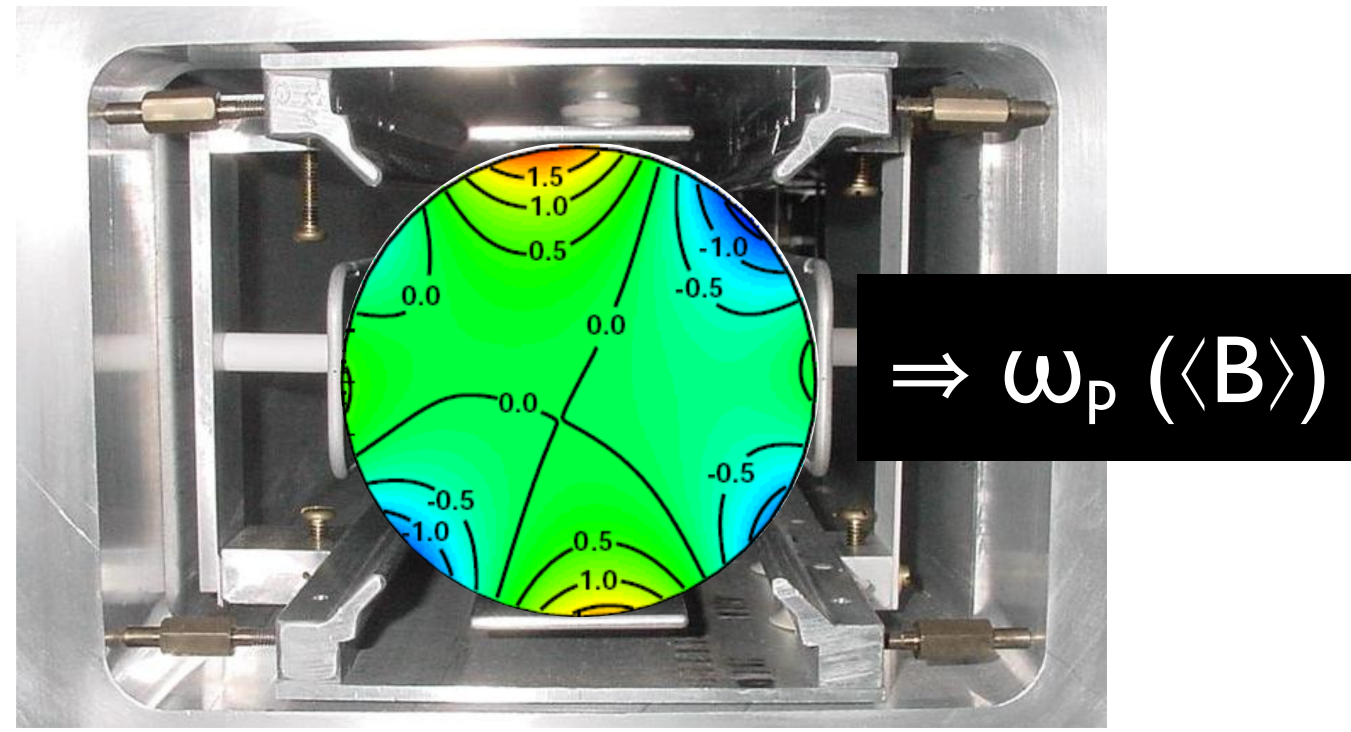
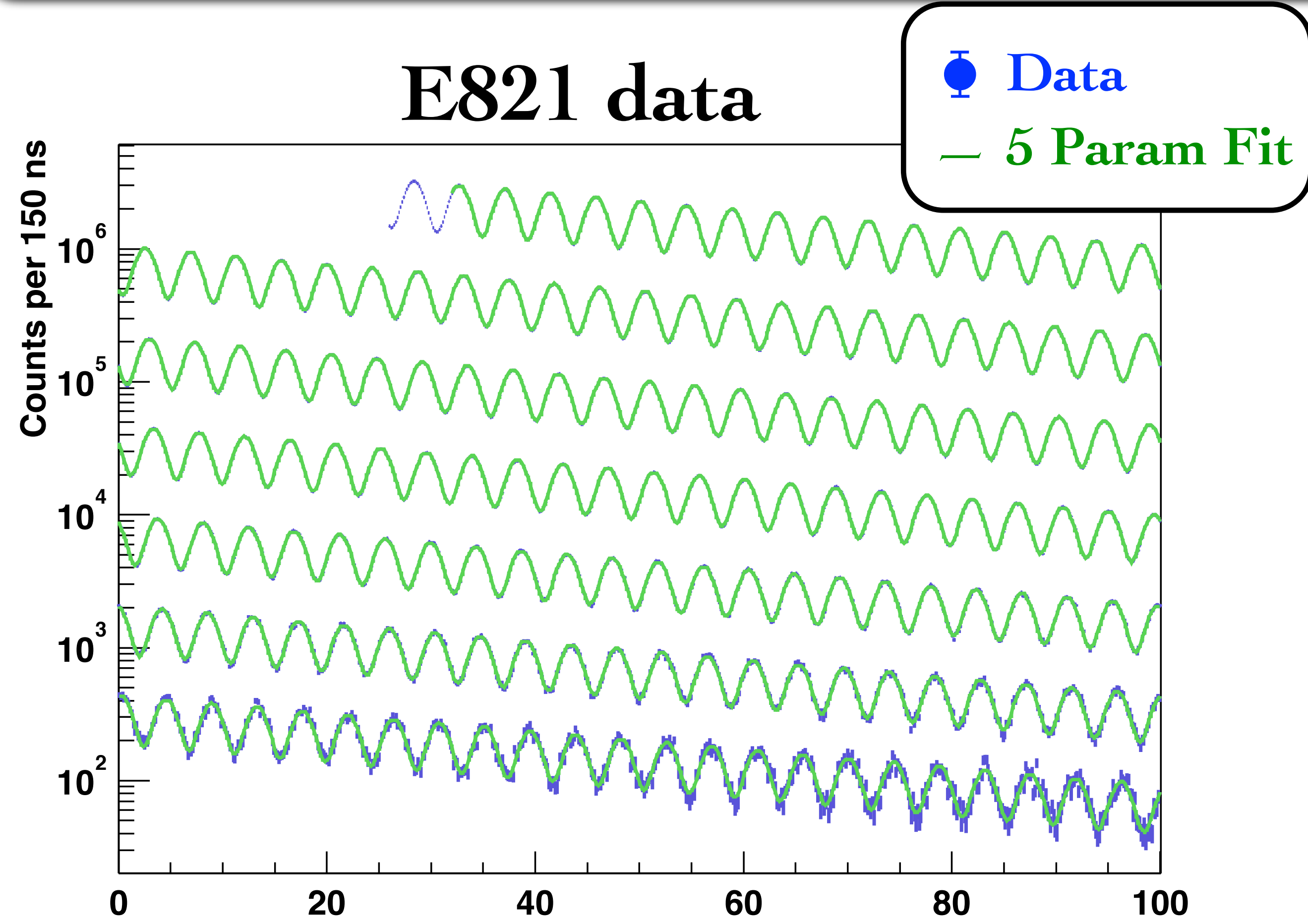
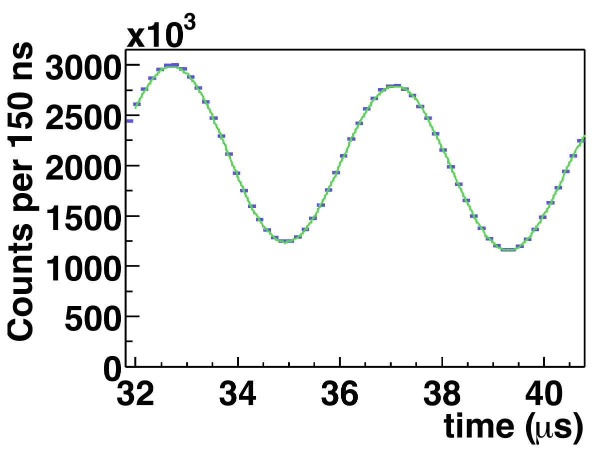


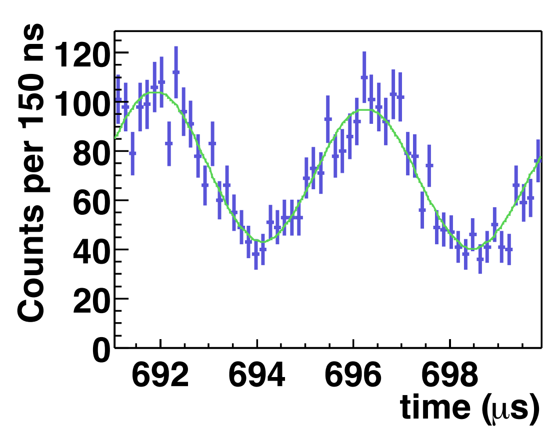
Add prior knowledge...

$$a_\mu = \frac{\omega_a/\omega'_p}{\mu_\mu/\mu_p - \omega_a/\omega'_p}$$

The Wiggle Plot, ω_a, ω_p, and a_μ







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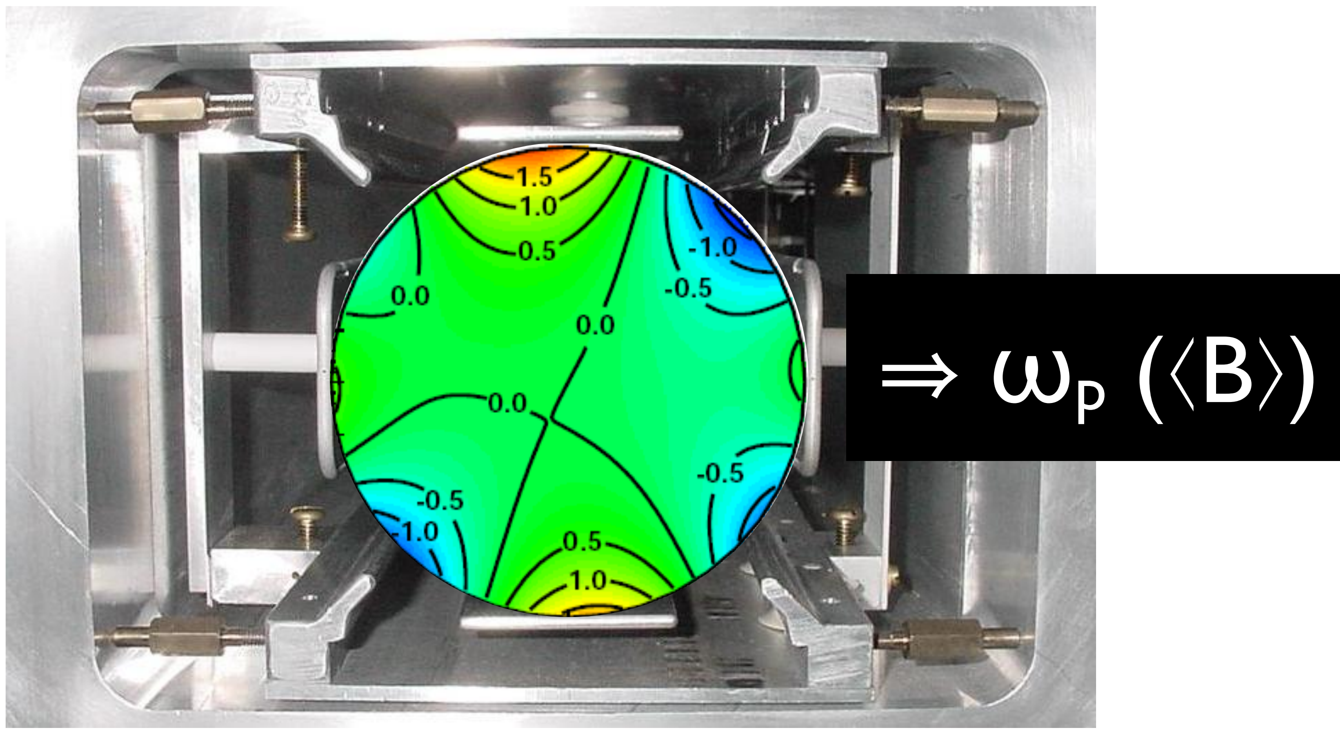
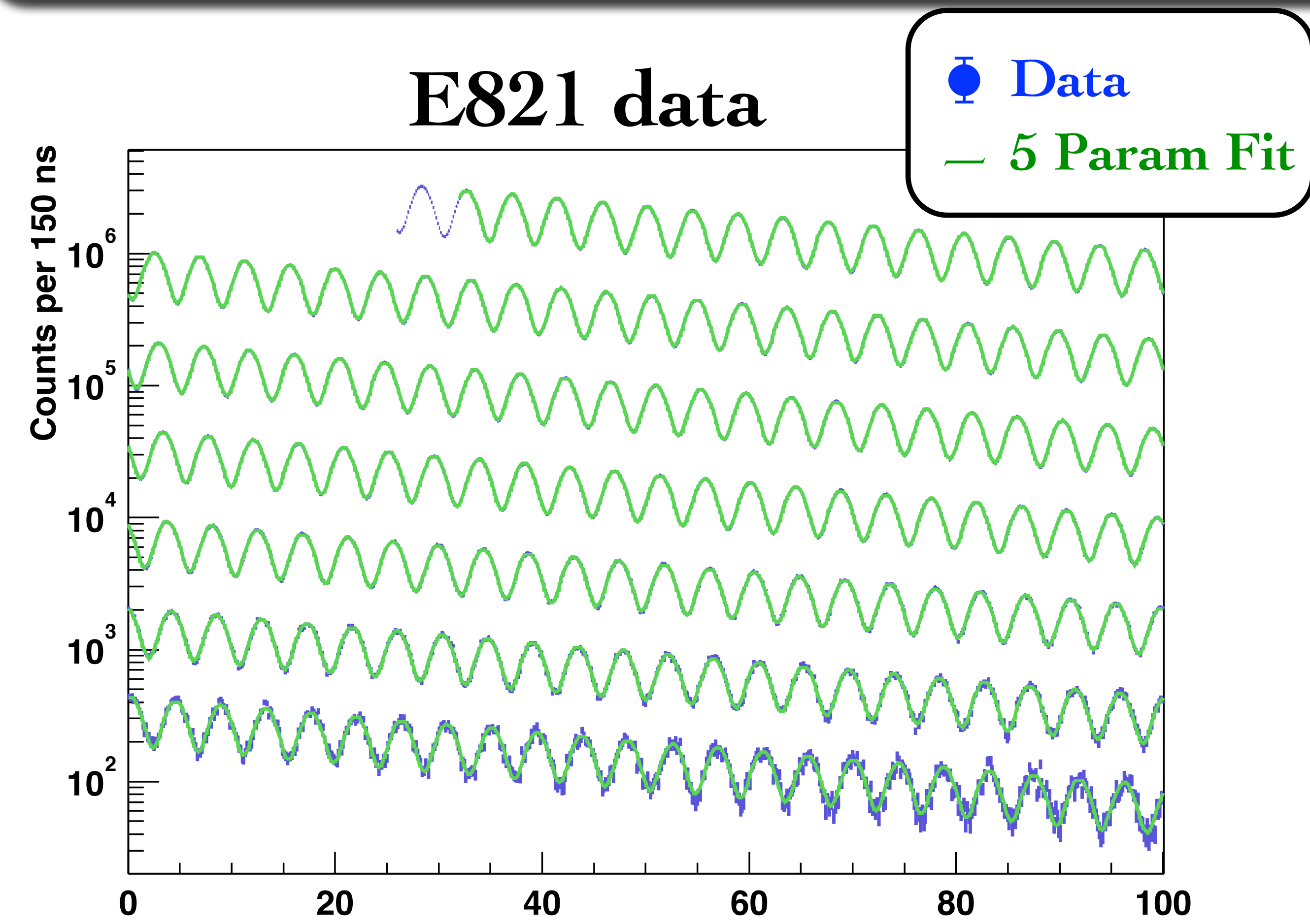
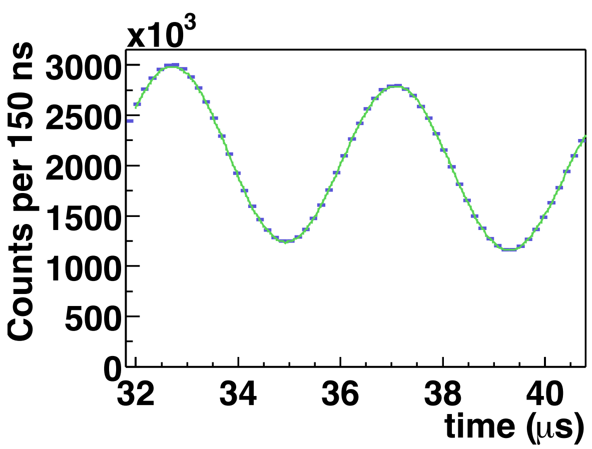


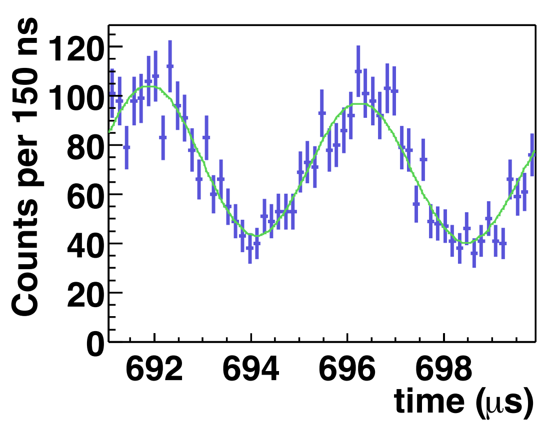
$$a_\mu^{\mathrm{E821}} = 0.00\ 116\ 592\ 089(63)$$
$$a_\mu^{\mathrm{SM}} = 0.00\ 116\ 591\ 802(49)$$

The Wiggle Plot, ω_a, ω_p, and a_μ

E821 data







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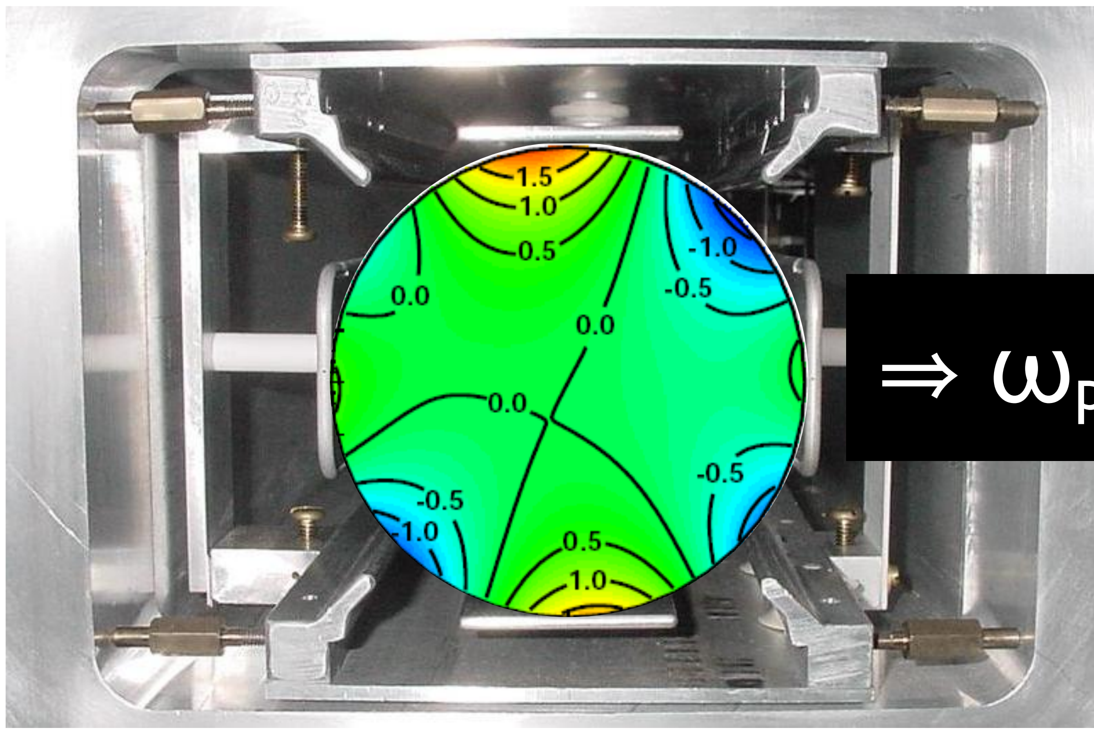


$\Rightarrow \omega_p$ (⟨B⟩)

$$a_\mu^{\mathrm{E821}} - a_\mu^{\mathrm{SM}} = 287 \pm 80$$

>3σ From SM Prediction!

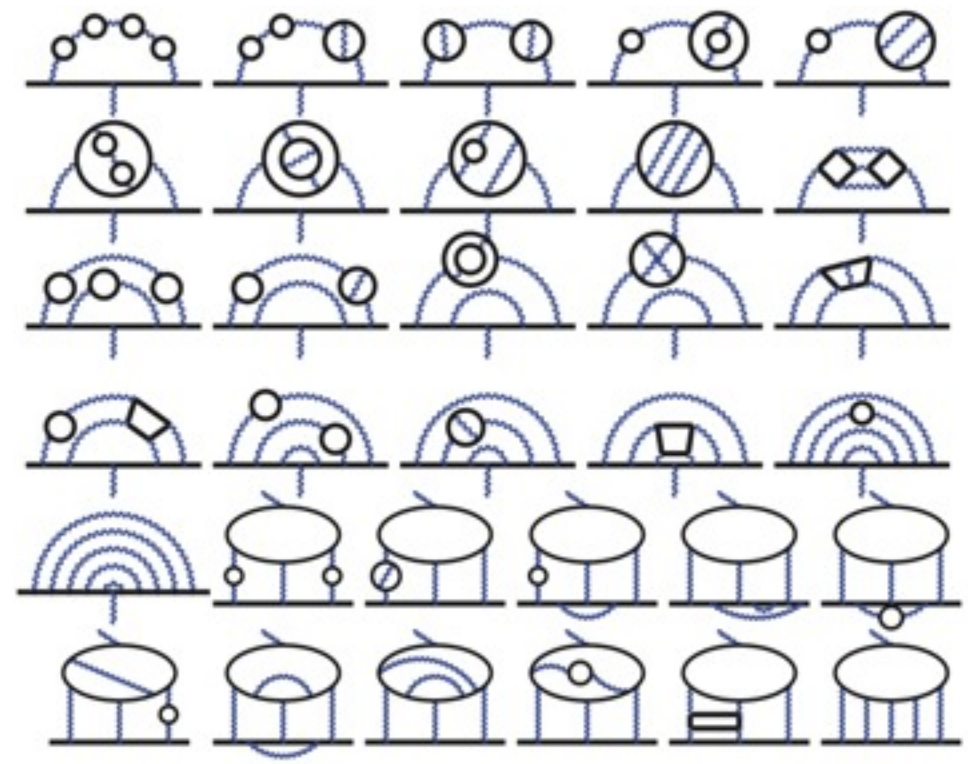
Explanations

- Standard Model calculation is incomplete/wrong?

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}}$$

Calculated out to 5 loops!

Contribution	a_μ Result $\times 10^{-11}$
QED	116 584 718.09 ± 0.15
EW	153 ± 1
HVP(LO)	6 949 ± 43
HVP(NLO)	−98 ± 1
LbL	105 ± 26
SM	116 591 802 ± 49
Exp-SM	287 ± 80(3.3σ)



T. Aoyama, M. Hayakawa, T. Kinoshita, M. Nio Phys. Rev. Lett. **109** 111807

Explanations

- Standard Model calculation is incomplete/wrong?

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}$$

2 loop calculation + known Higgs mass correction

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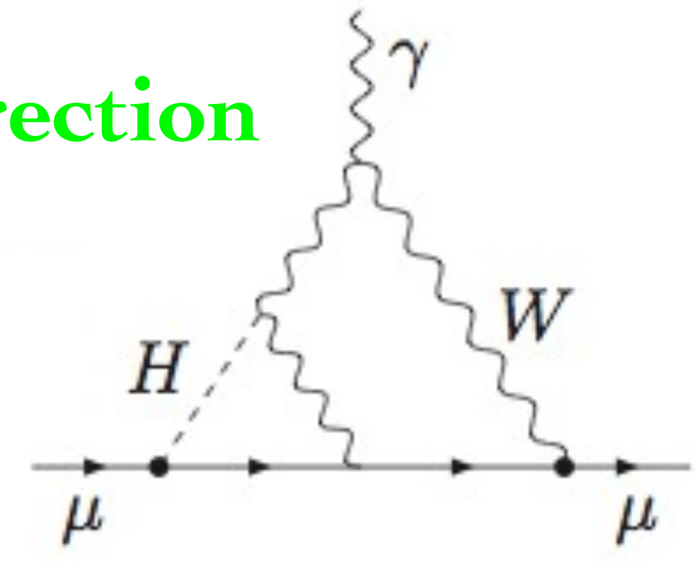

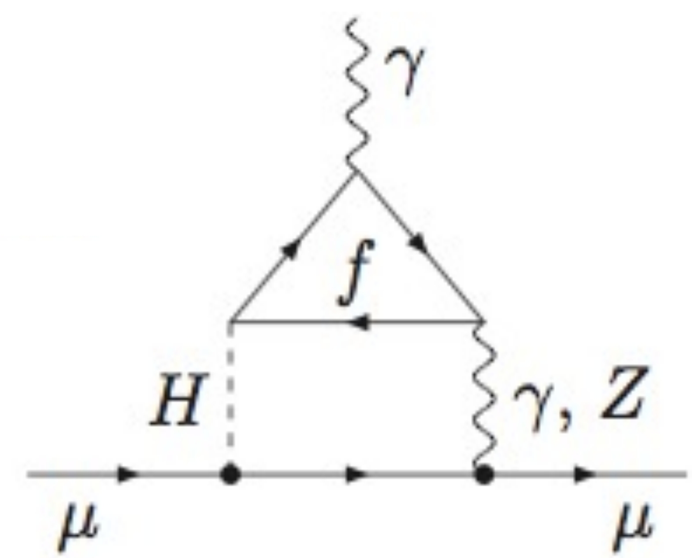

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Dominant source of uncertainty

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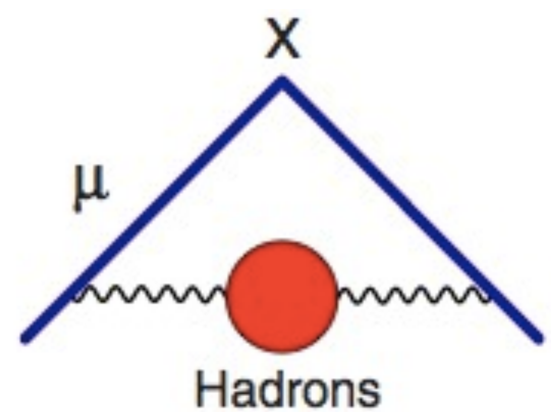
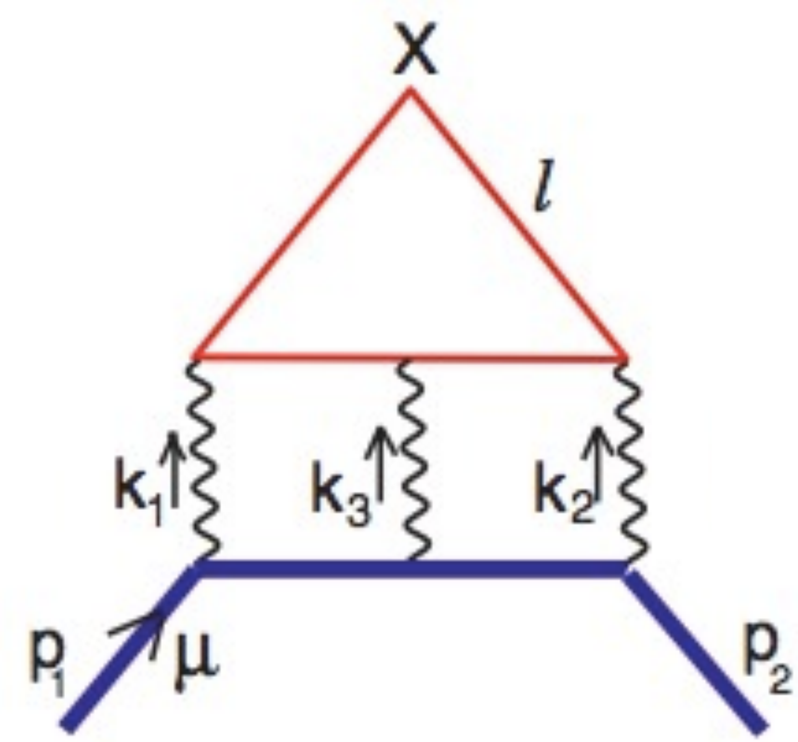




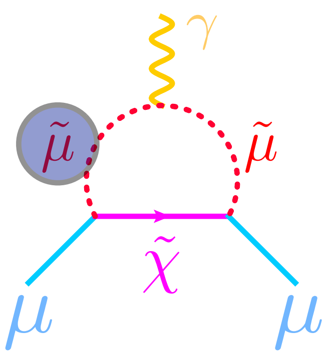
Coming Soon: Constrain HVP with low energy $e^+e^- \rightarrow \pi^+\pi^-$ data, LbL needs first principles LatticeQCD.

New Physics?

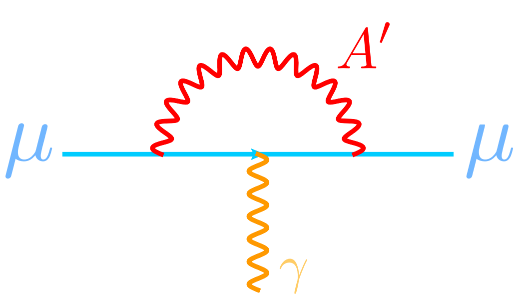
- Standard Model calculation is fine. We are just seeing new physics.

$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{Had}} + \boxed{a_\mu^{\text{NP}}}$$

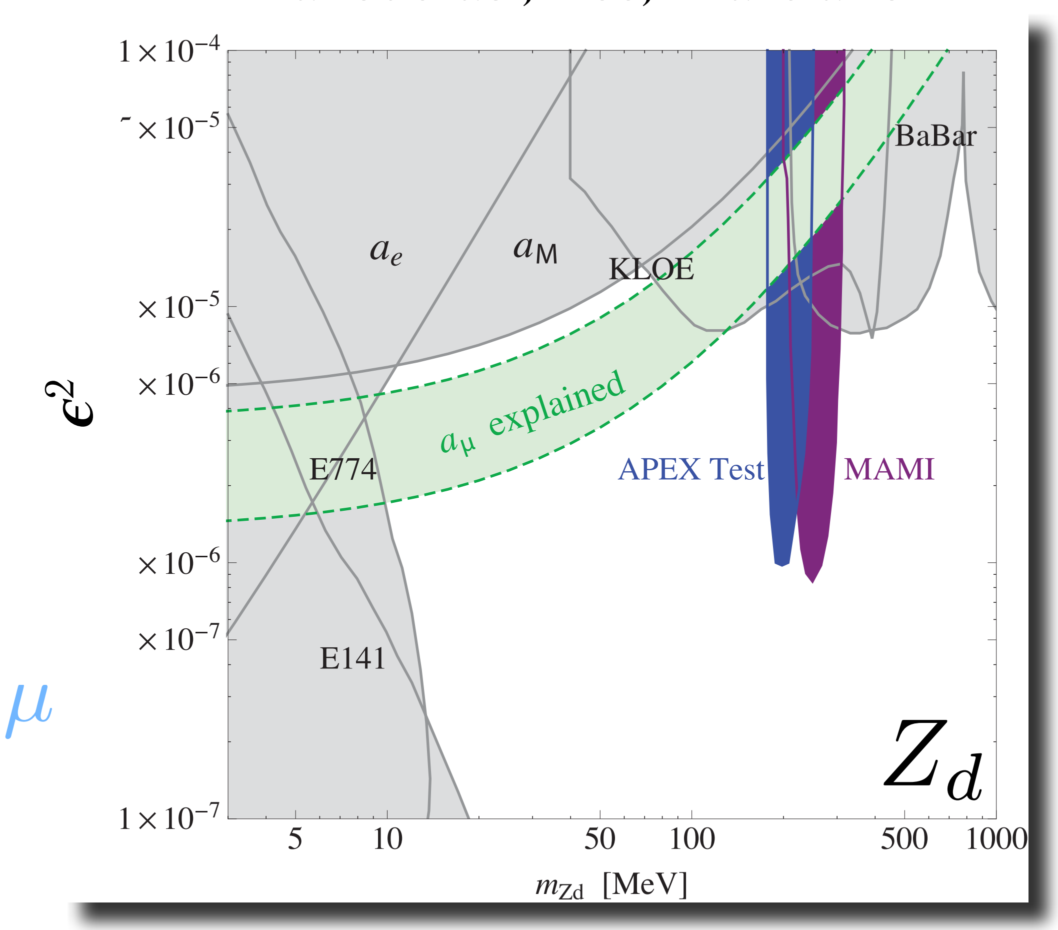
SUSY



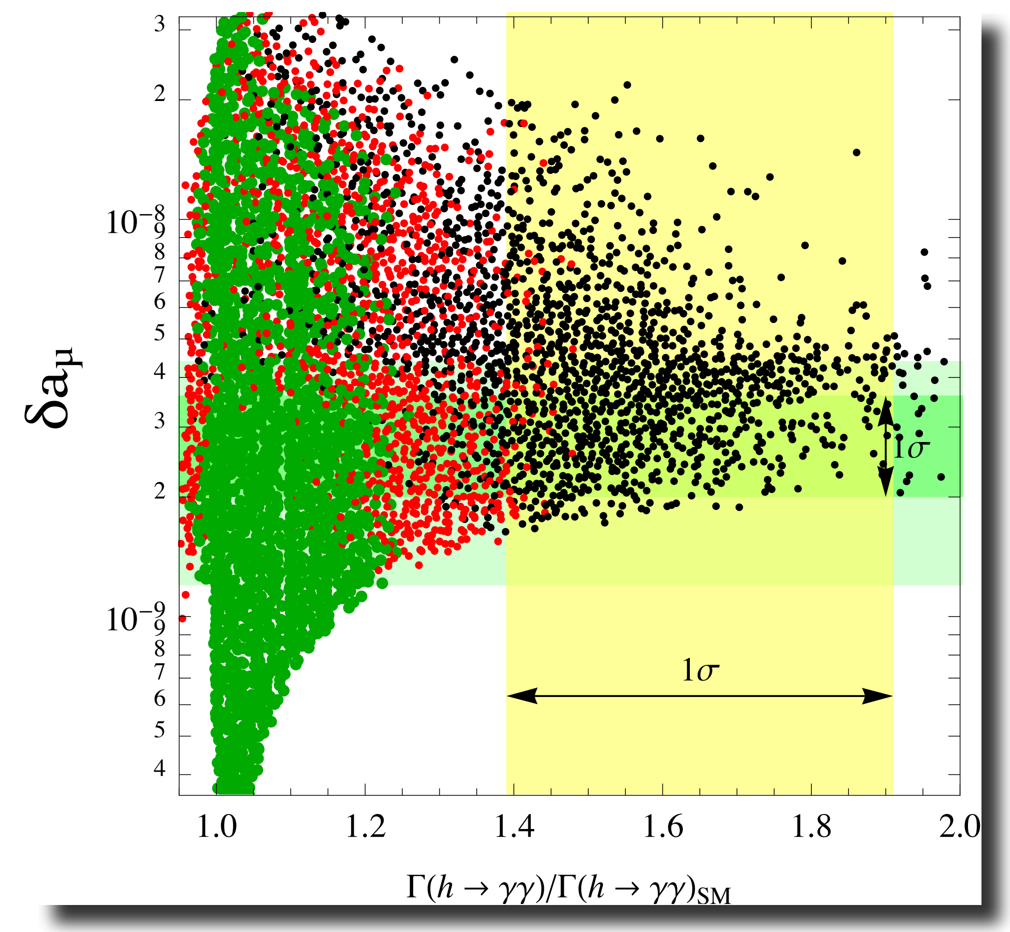
Dark Sector



Davoudiasl, Lee, Marciano '12



Giudice, Paradisi, Strumia '12

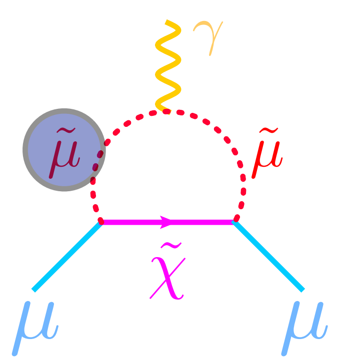


New Physics?

- Standard Model calculation is fine. We are just seeing new physics.

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}} + \boxed{a_\mu^{\mathrm{NP}}}$$

SUSY



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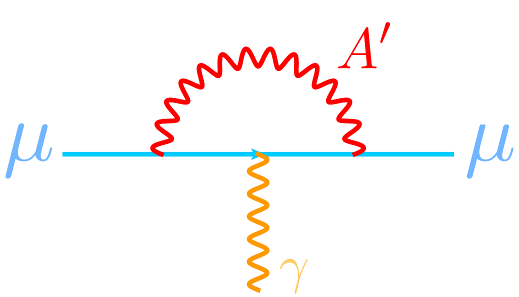

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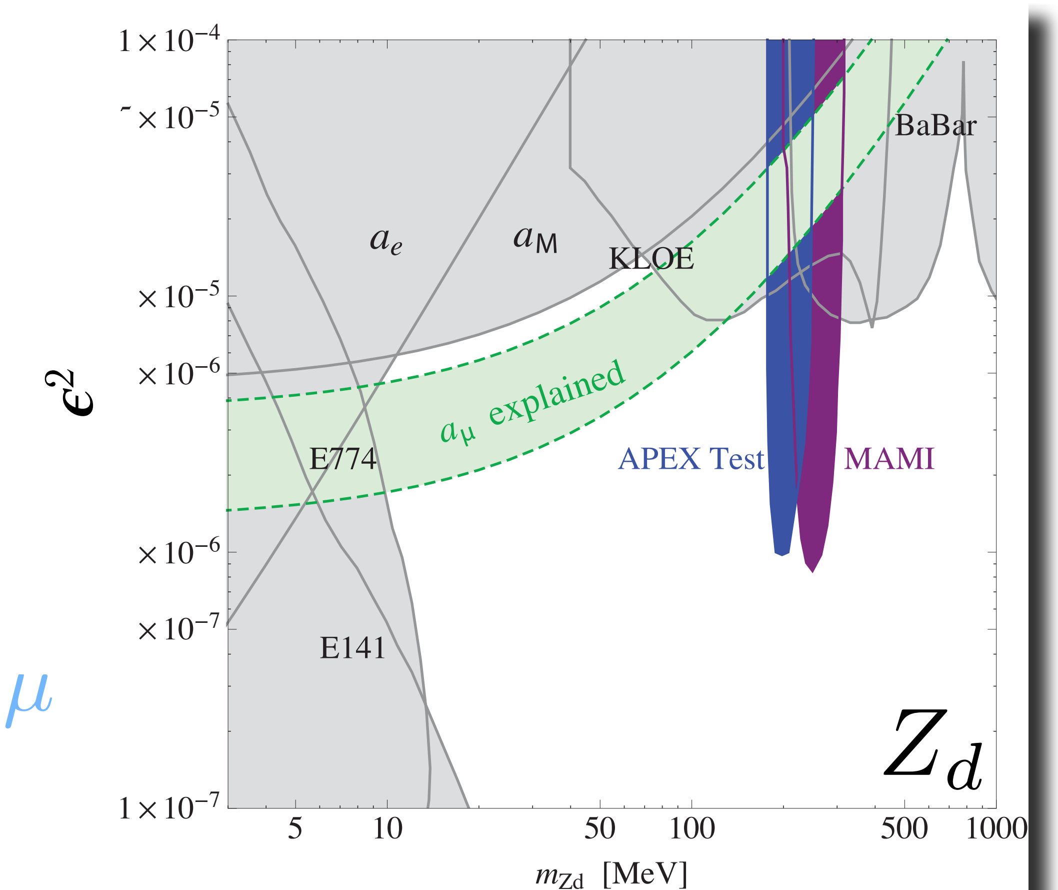

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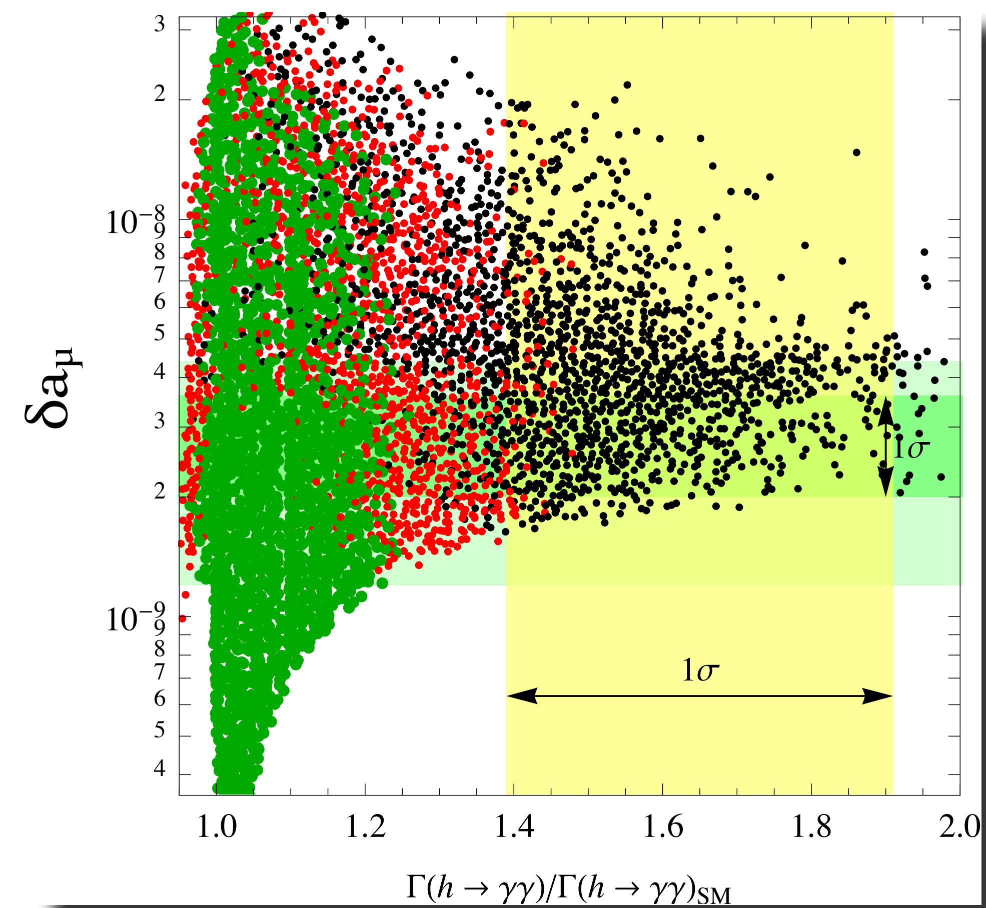
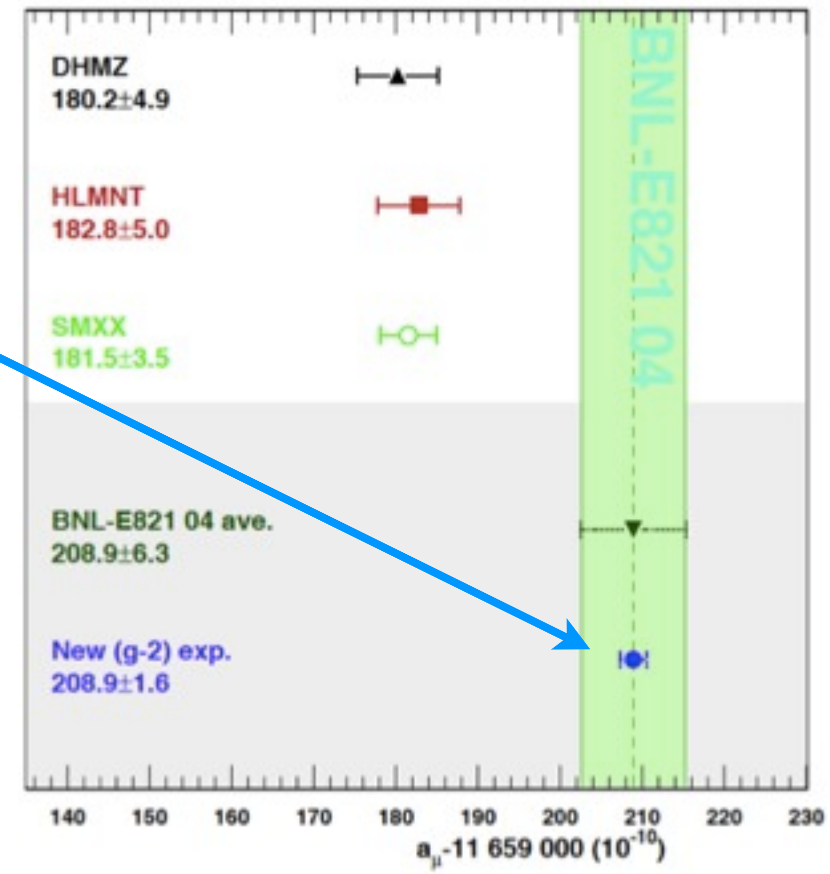


- A precise g-2 measurement is complimentary to Higgs measurements and a future LHC discovery.

The Fermilab Muon g-2 Experiment

Goal: Resolve E821 3σ measurement with >5σ sensitivity

$$\sigma_{a_\mu} = 0.54 \rightarrow 0.14 \text{ ppm}$$



- Increased Statistics: Fermilab will provide us with **>20x** more muons.

$$\sigma_{\text{stat}} = 0.4 \rightarrow 0.1 \text{ ppm}$$

- New segmented calorimeters, straw wire tracker, Fast muon kicker (and more).

$$\sigma_{\omega_a} = 0.18 \rightarrow 0.07 \text{ ppm}$$

- Long shimming period, magnet temperature stability, more in-situ calibrations (and more).

$$\sigma_{\langle B \rangle} = 0.17 \rightarrow 0.07 \text{ ppm}$$

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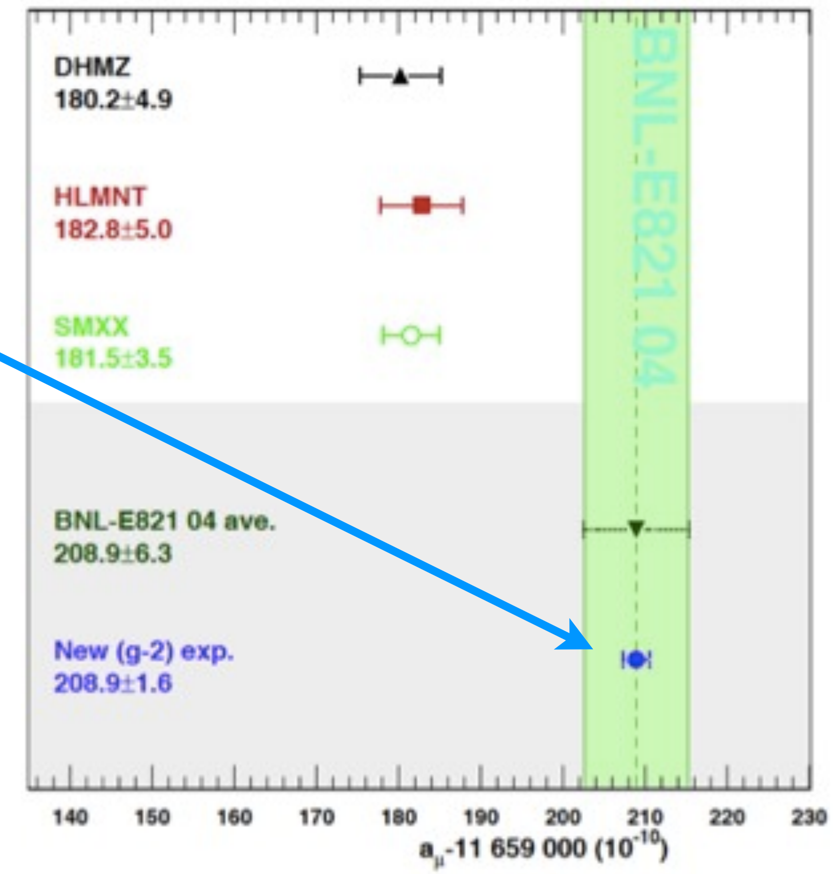

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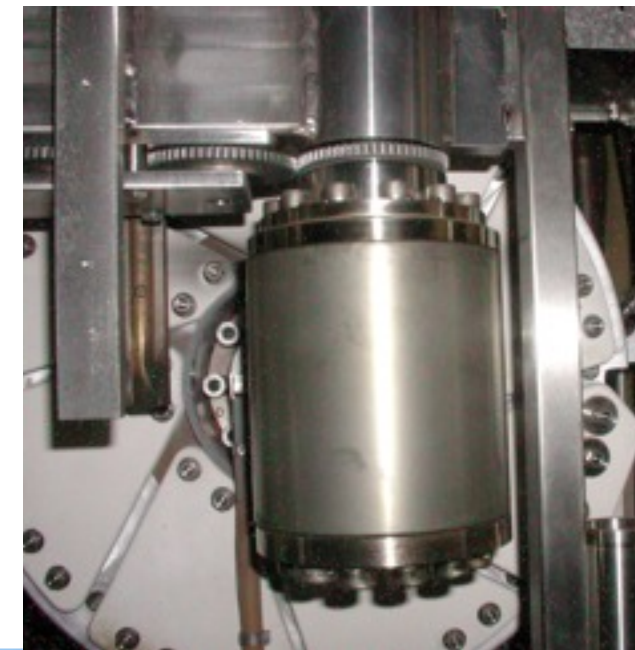
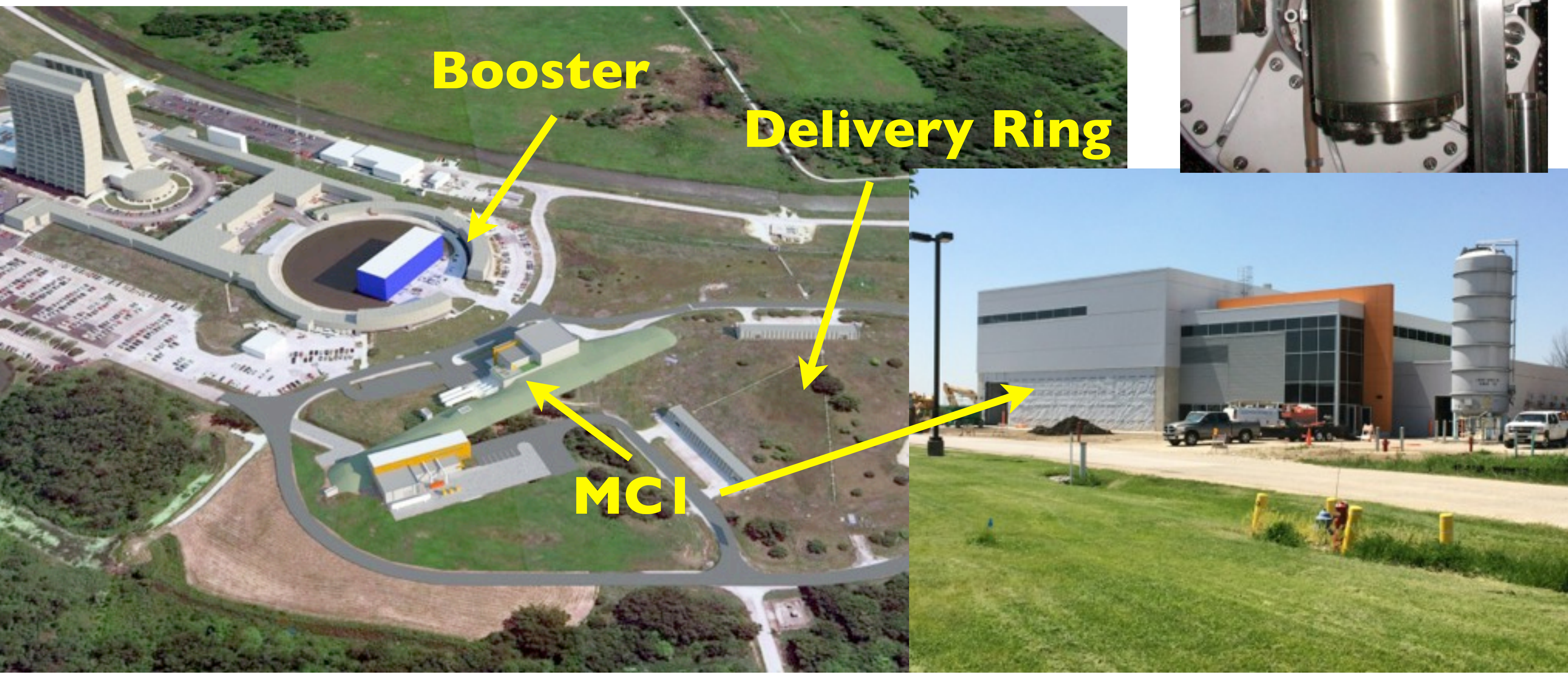
Fermilab Muon Campus

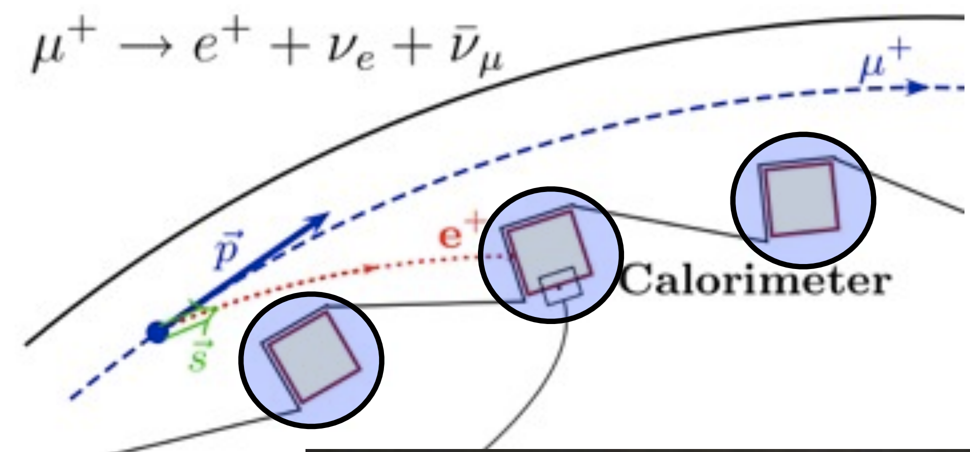
- Fermilab will produce pions using 8.9 GeV protons impacting the former antiproton production target
  - Pions decay along long path ⇒ Pure muon beam. (E821 had large pion contamination).

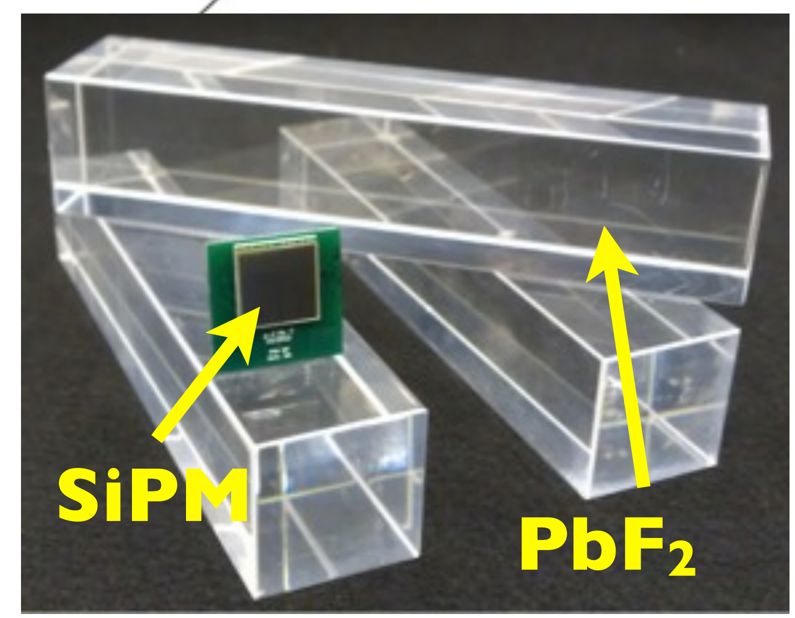




New Calorimetry

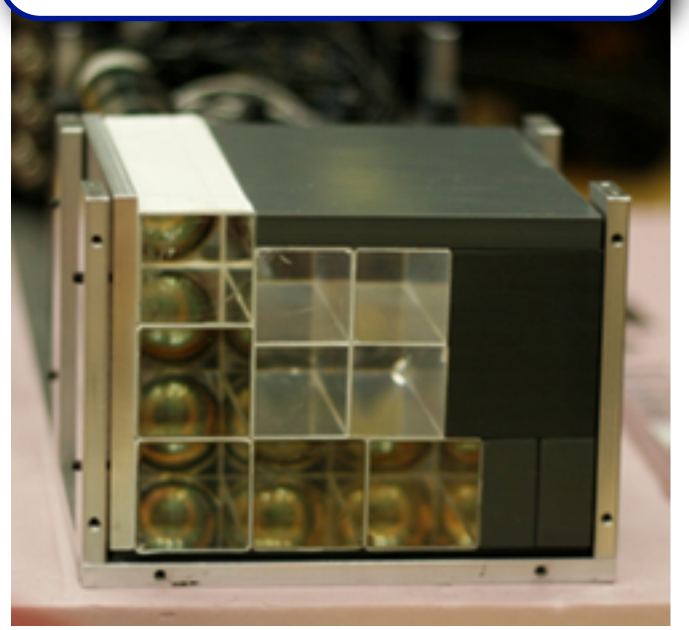
- Segmented Calorimeters and SiPMs
  - We will use a 9x6 array of PbF_2 crystals with SiPM for light readout.
- Segmentation reduces pileup (two positrons in same time window). Laser calibration system and lower energy thresholds

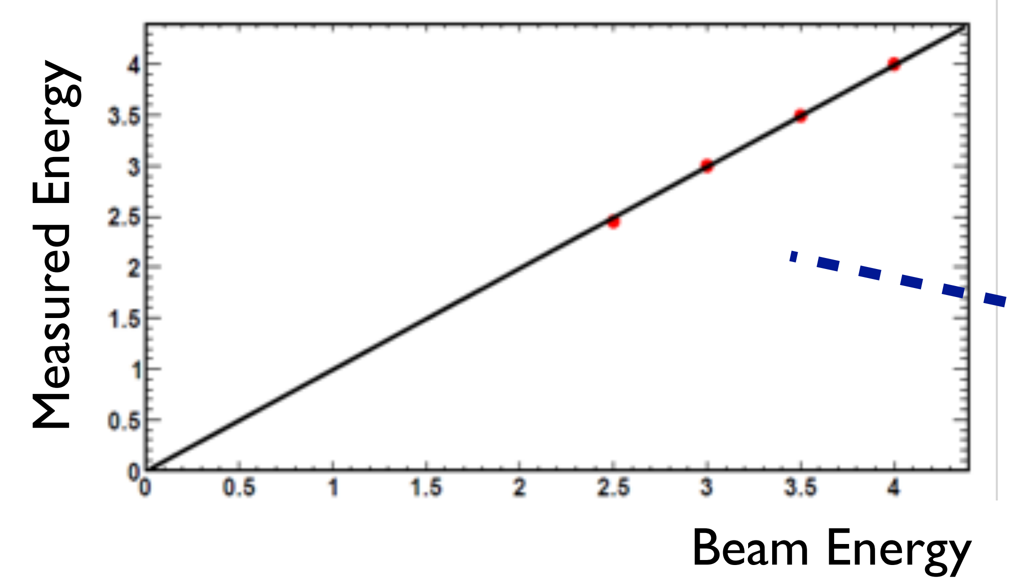




$$\sigma_{\text{pileup}} = 80_{(\text{E821})} \rightarrow 40 \text{ ppb}$$
$$\sigma_{\text{gain}} = 120_{(\text{E821})} \rightarrow 20 \text{ ppb}$$

SLAC Test Beam, Nov '13



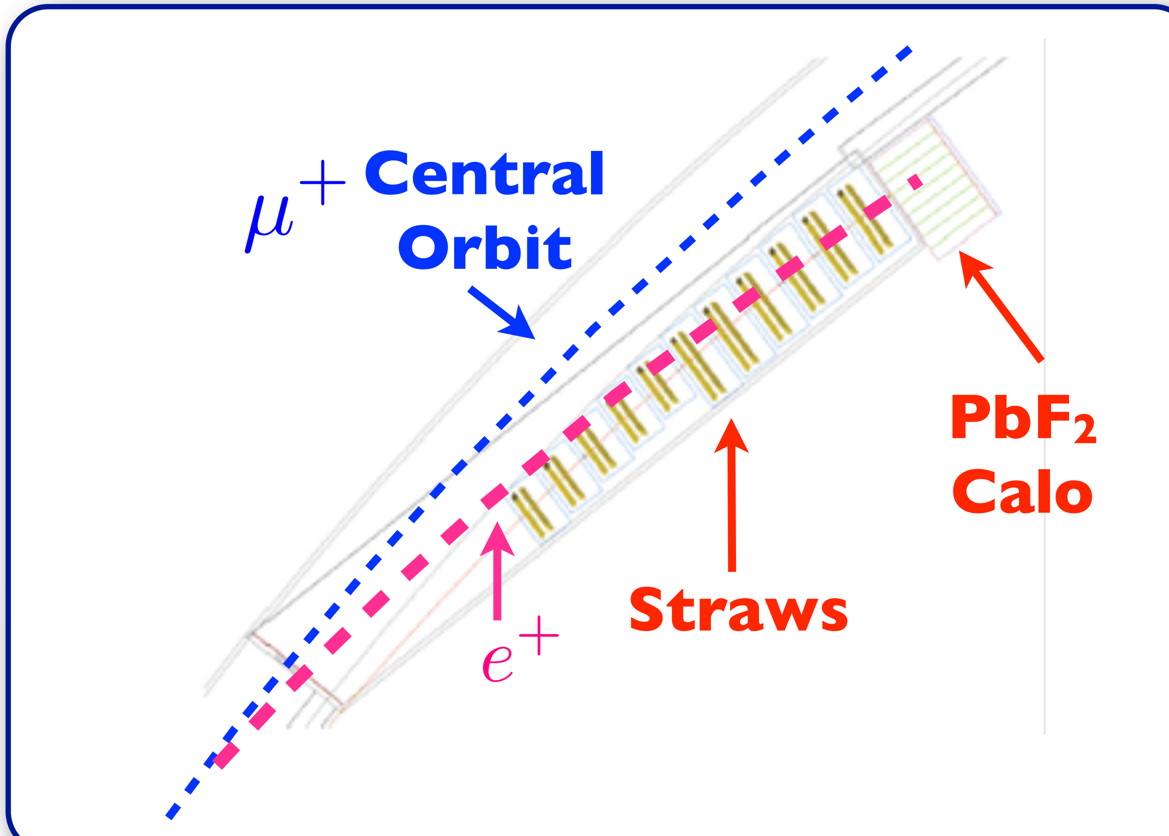


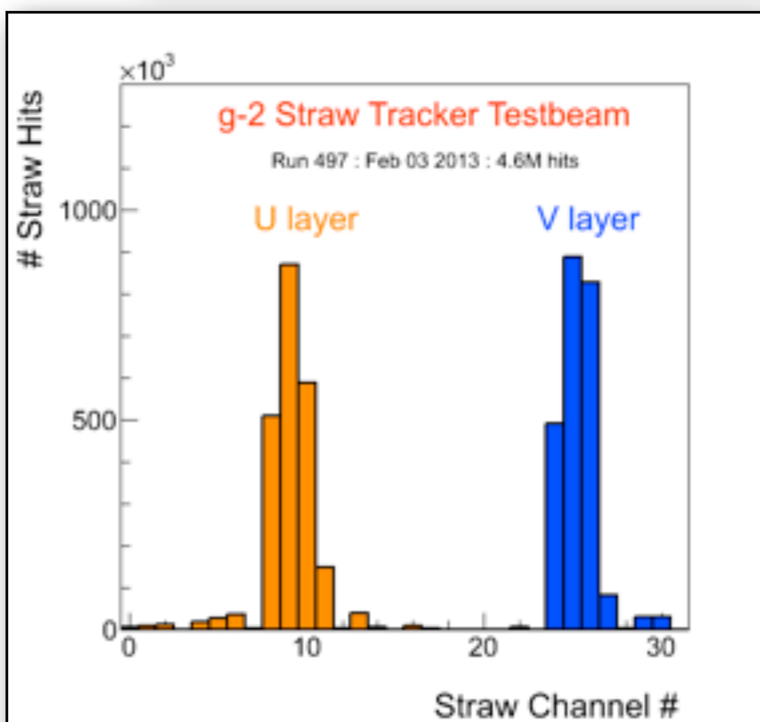
$$\frac{\sigma(E)}{E} = 2.8\%$$

New Tracking Detectors

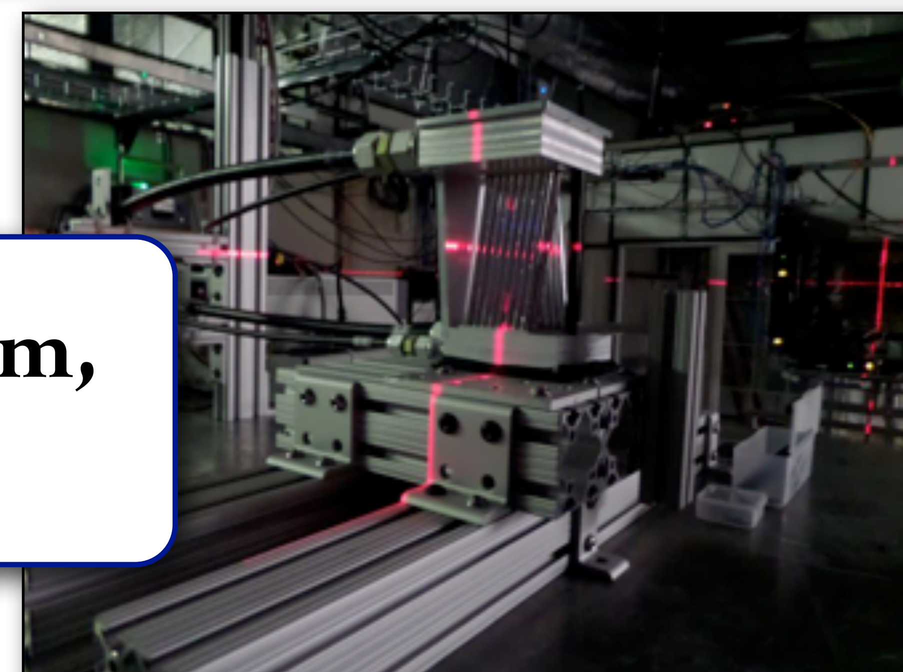
- Straw tracking detectors will measure muon decay vertex and momentum.
  - Monitor beam profile fill-by-fill (required for ⟨B⟩ and ω_a measurements)
  - Measure pile-up ↔ calorimeter hits

$$\sigma_{\langle B \rangle} = 30_{(\mathrm{E821})} \rightarrow 10 \text{ ppb}$$
$$\sigma_{\mathrm{beam}} = 50_{(\mathrm{E821})} \rightarrow 30 \text{ ppb}$$





FNAL Test Beam, Jan/Apr '14



The Big Move From Long Island ...

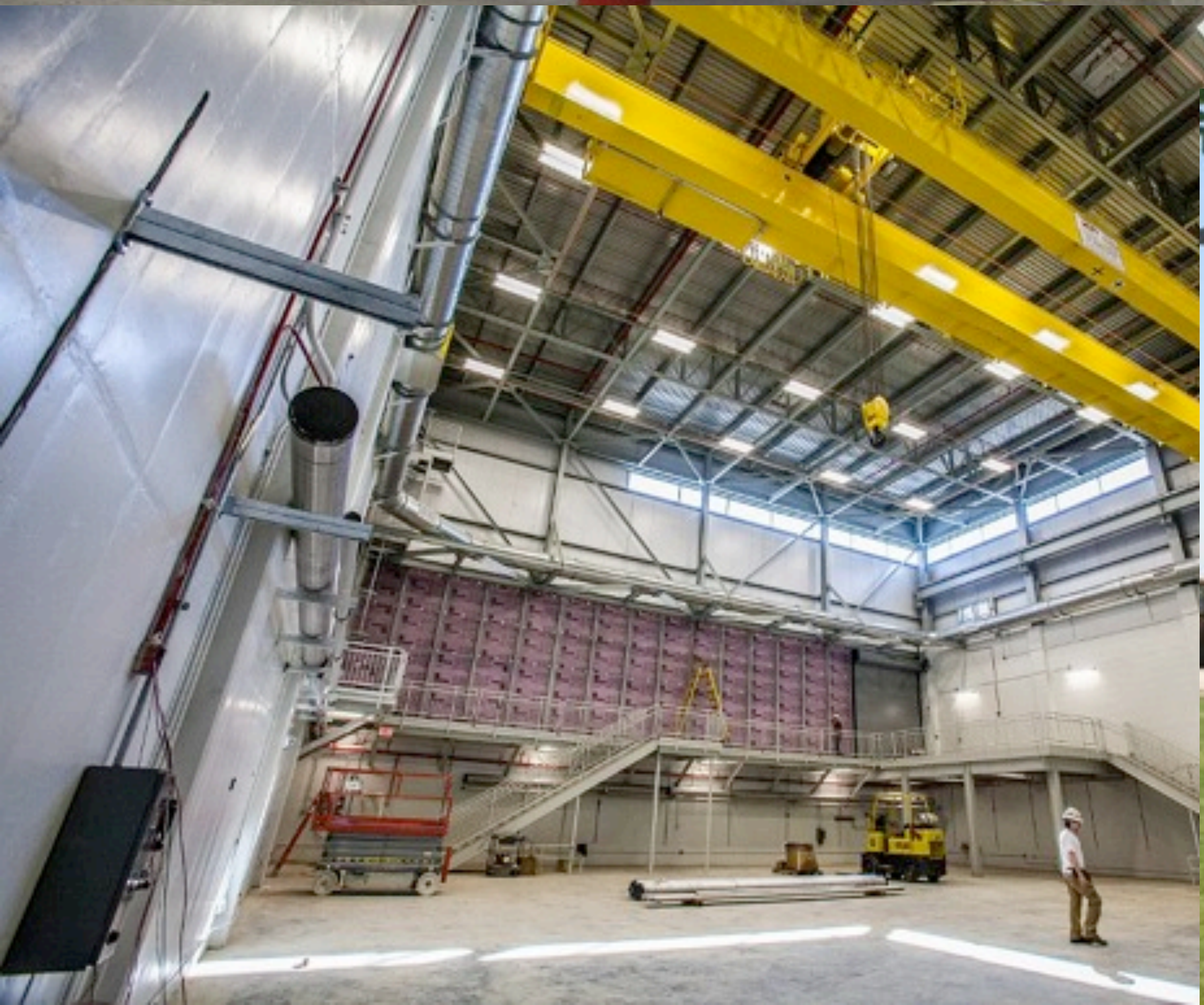
… To Fermilab


EMMERT
OVERSIZE LOAD


OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

... To Its Final Resting Place in MC1

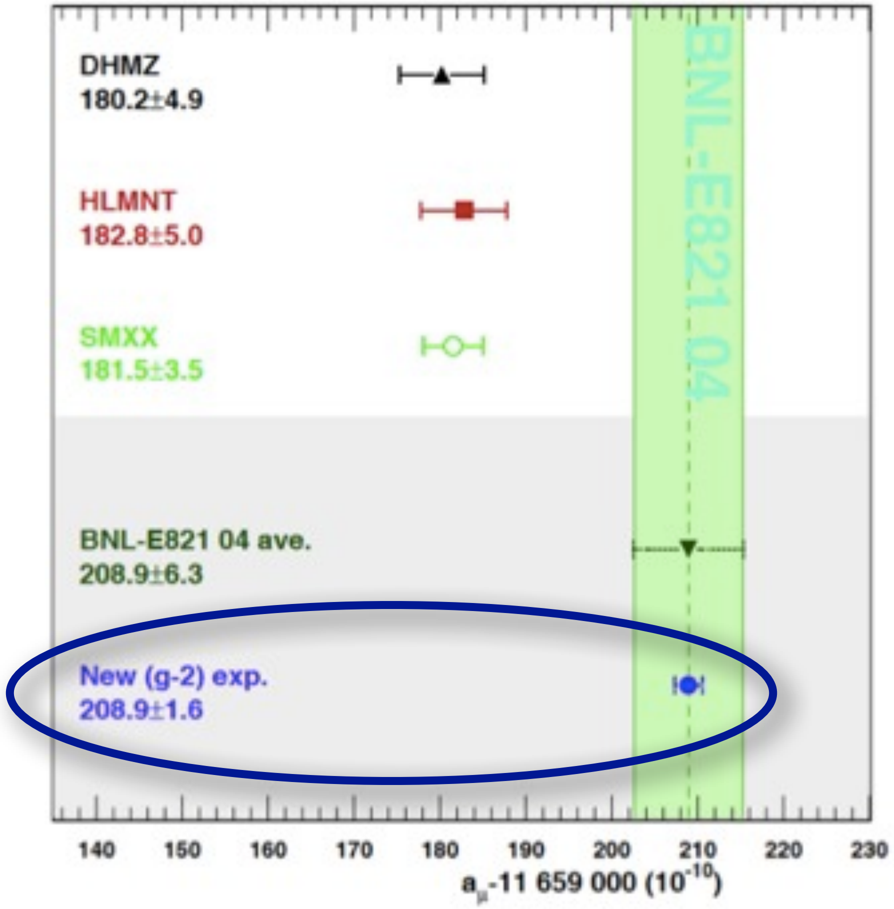
(from Brian Drendal)



(from Lee Roberts)

Summary

- Fermilab muon g-2 will measure the muon anomalous magnet moment to sub-ppm level.
  - >5σ sensitivity to new physics!
- CD-1 approval. CD-2/3 review this July.
- Magnet shimming and detector commissioning in 2015/2016.
  - Hopefully, stored muons in 2017.



"Magnetic Moment" from Two Brothers in Warrenville, IL

Luckily, we've got plenty to keep us busy

Back Ups

Fast Muon Kicker

- Fast muon injection kicker
  - Produce a fast (**<150 ns**) ≈11 mrad kick. to place muons on central orbit.
  - Must turn OFF before 2nd orbit begins

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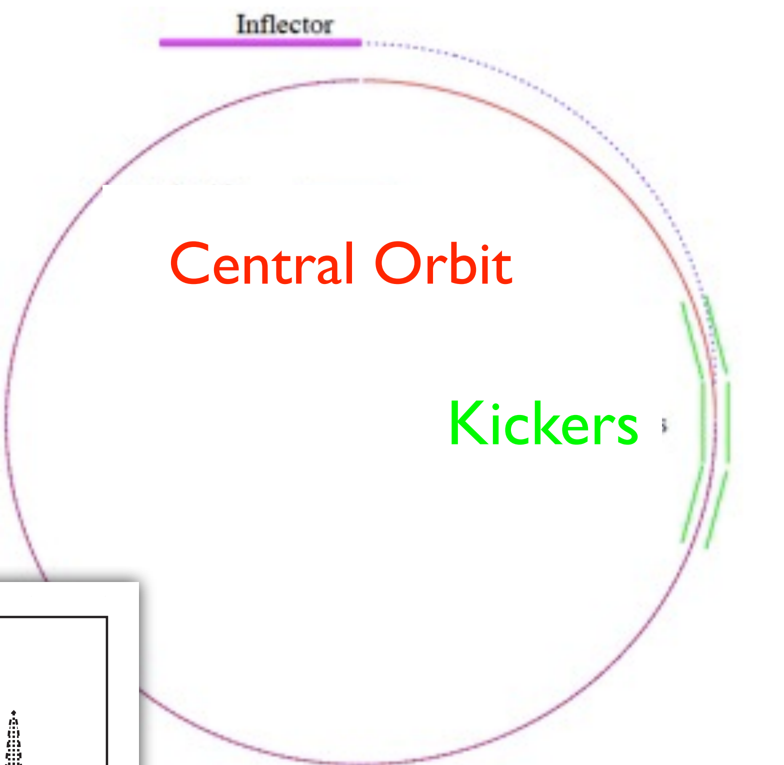

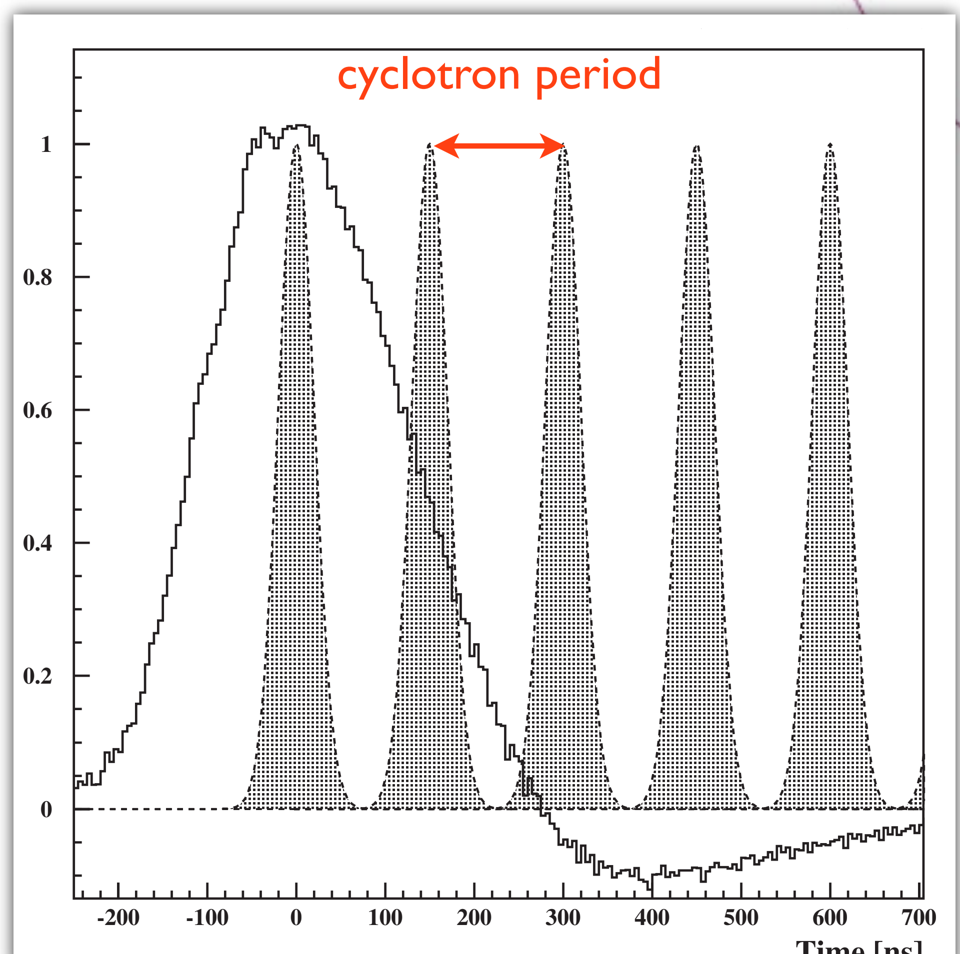

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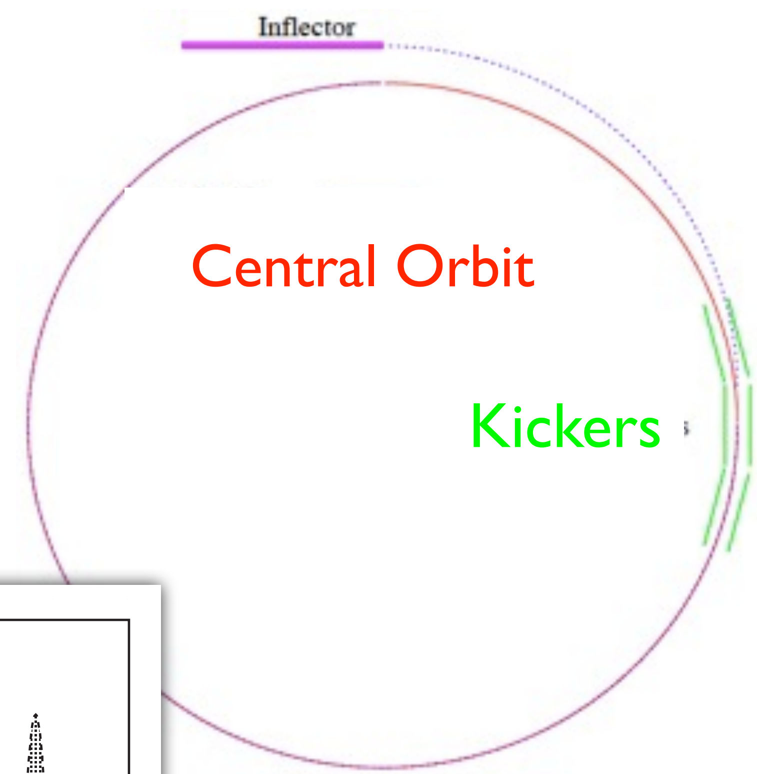
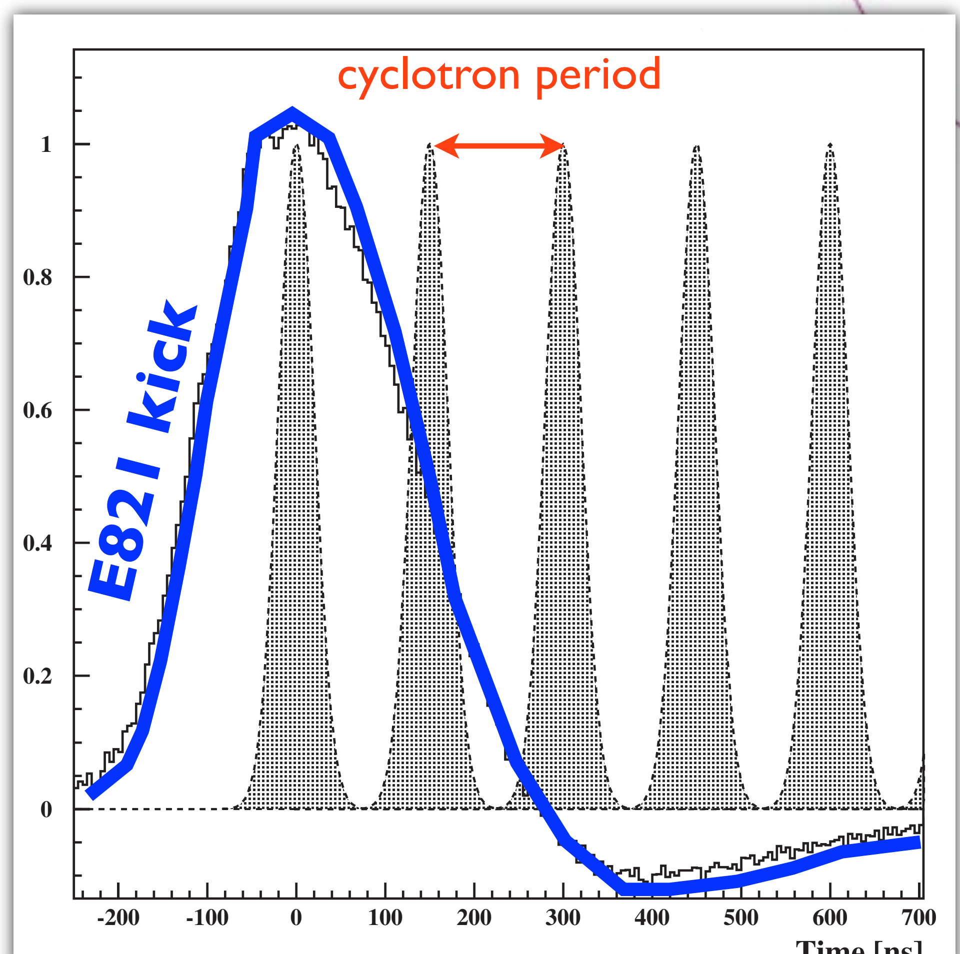
  - E821 dramatically underkicked muons

    → lost muons and large betatron oscillations





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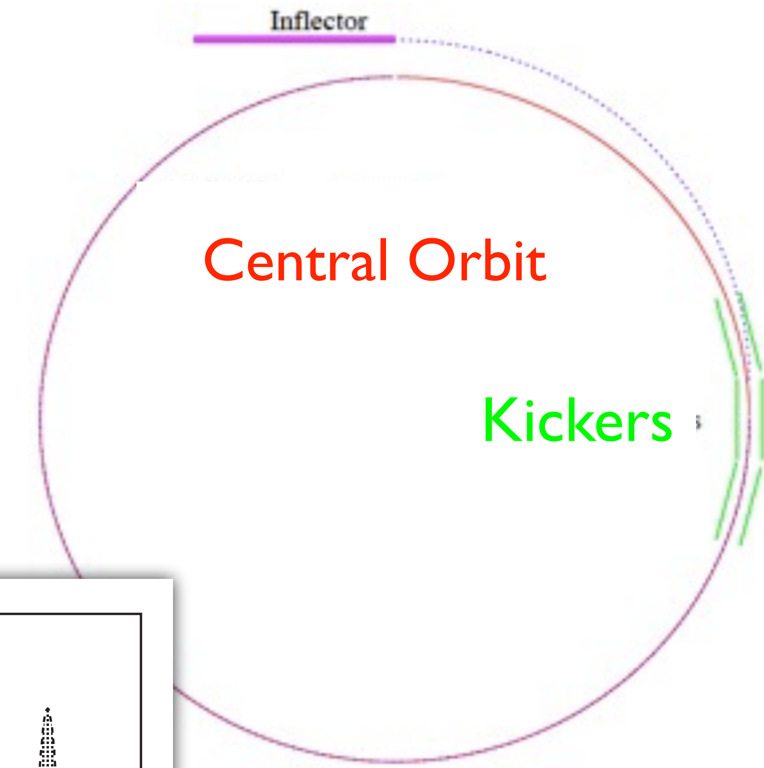
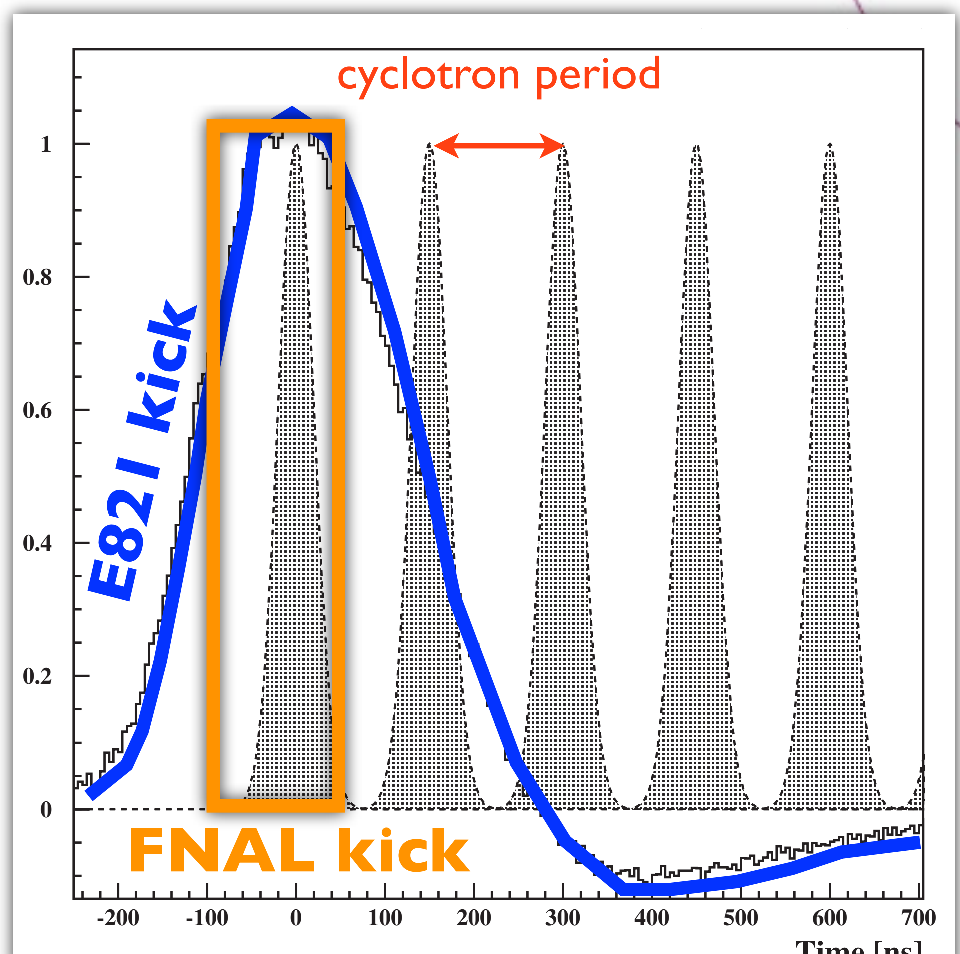
  - **FNAL** kicker uses a fast blumlien pulser





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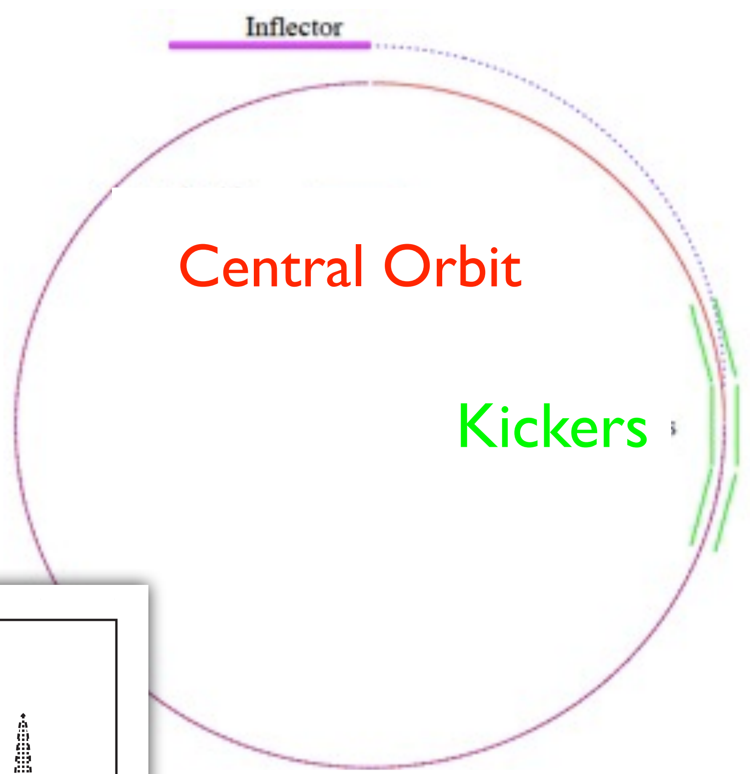
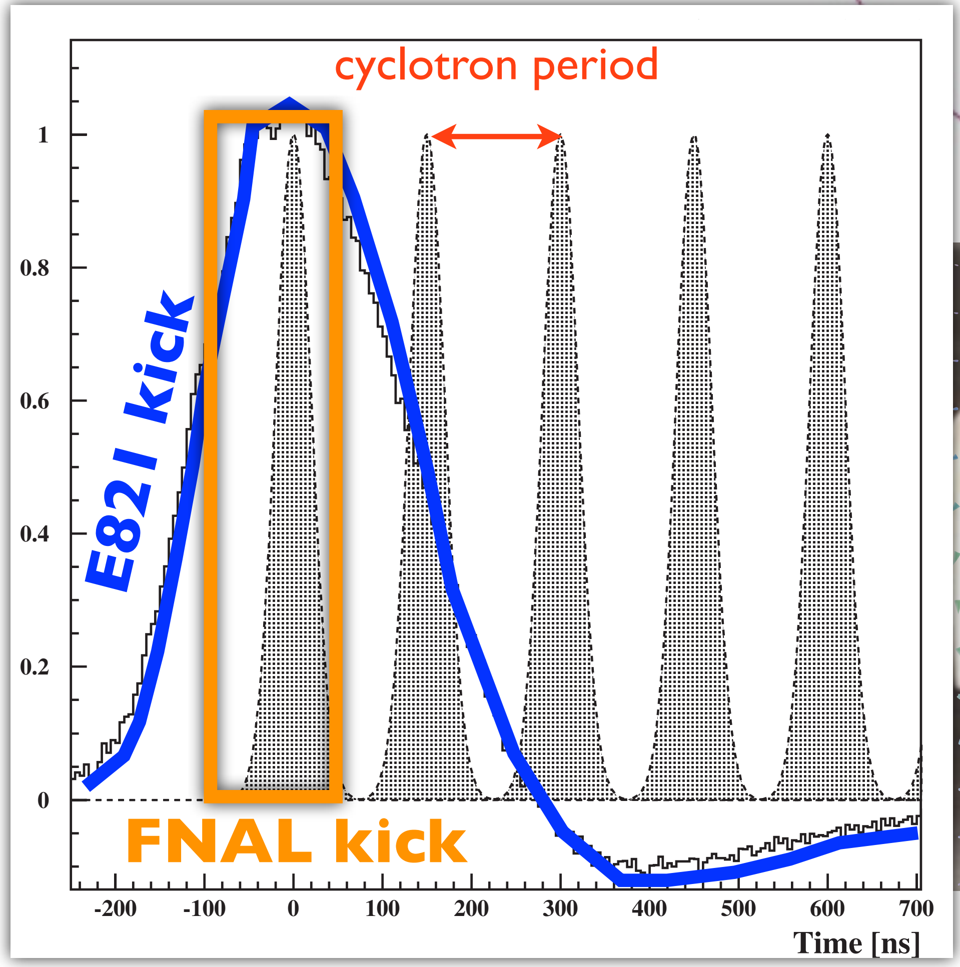
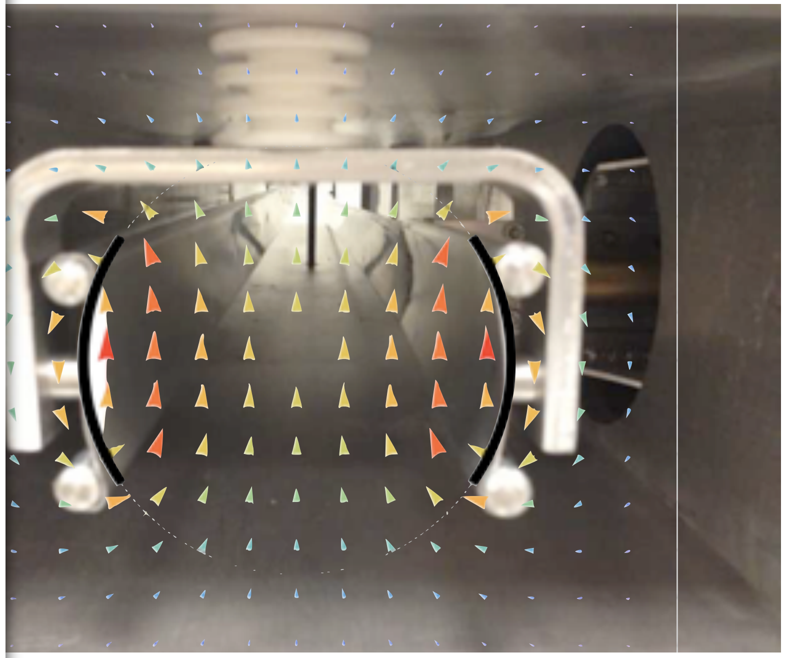
  - FNAL kicker uses a fast blumlien pulser
  - Curved kicker plates allow for higher fields



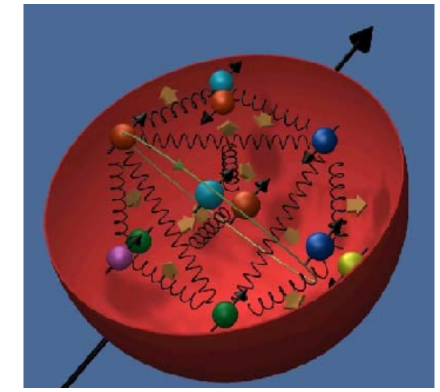




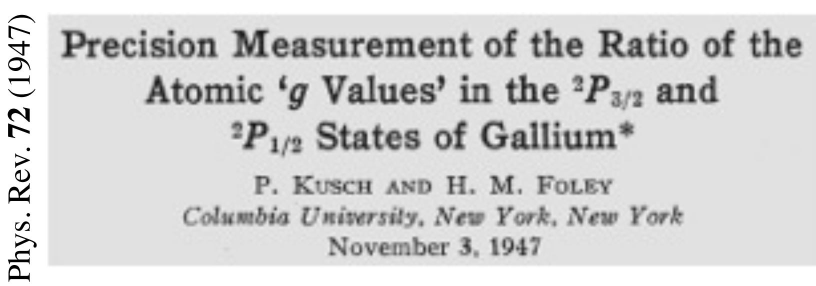
Field Goals

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; more calibration probes; better electronics	35
Trolley probe calibrations	90	3-axis motion of plunging probe; better position accuracy of probe active volumes; more frequent calib, better shimming	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	30
Muon distribution	30	Move trolley probes to 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
Others †	100	Improved trolley power supply; reduced temperature effects on trolley; measure/reduce kicker field transients	30
Total syst. unc. on ω_p	170		70

g Does Not Equal 2



- The 1930's saw two unanticipated results for the g-factor of the proton ($g_p \approx 5.6$) and the neutron ($g_n \approx -3.8$).
  - Strongly suggests nucleon substructure.
- In the late 1940's another breakthrough measurement was made at Columbia by Kusch and Foley.



Phys. Rev. **72** (1947)

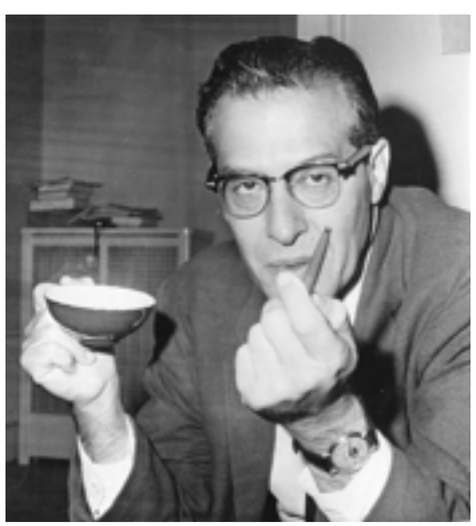
Precision Measurement of the Ratio of the Atomic '*g* Values' in the $^2P_{3/2}$ and $^2P_{1/2}$ States of Gallium*

P. Kusch and H. M. Foley
Columbia University, New York, New York
November 3, 1947

→

$$g_e = 2.00229(8)$$

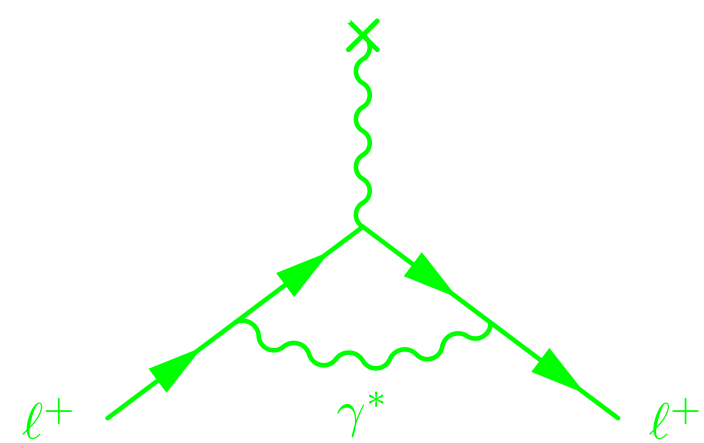
- Swinger showed this result to be consistent with QM + 1 loop correction.



$$g_e = 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$$

D. Hanneke, S. Fogwell, and G. Gabrielse
PRL 100, 120801 (2008)

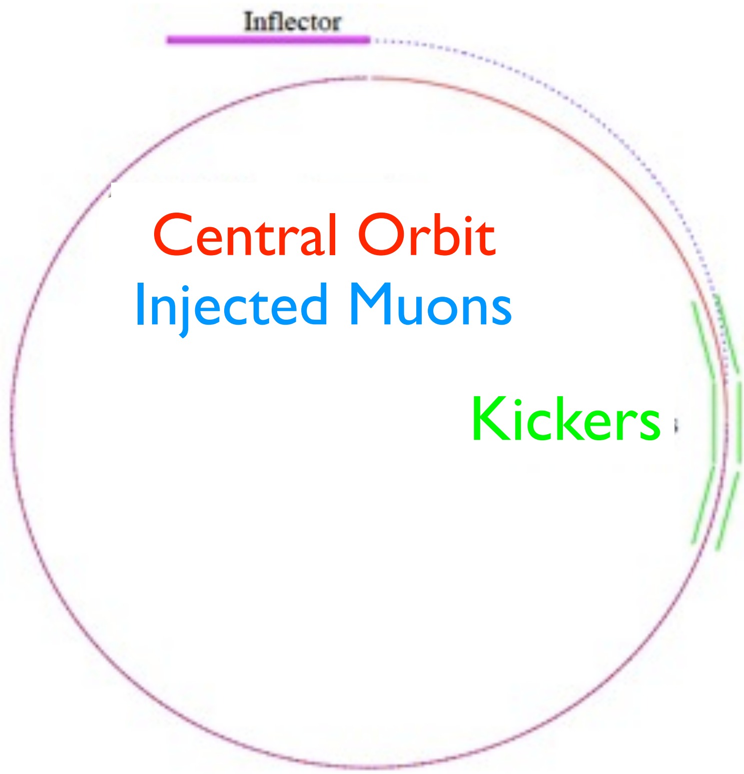
$$g_e/2 = 1.001\ 159\ 652\ 180\ 73(28)$$



Improvements with E821

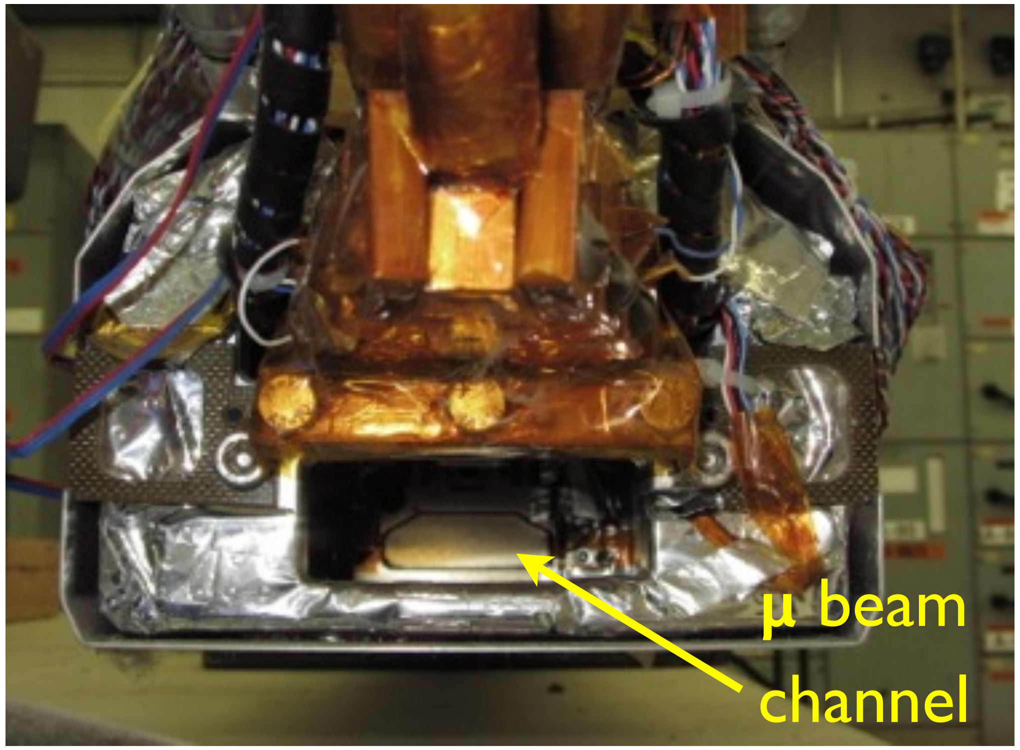
Muon Injection

- Previous experiments inject pions into storage ring. Only fraction of pion decays create "storable" muons.
- Direct muon injection also greatly reduces hadronic flash background on detectors.
- Requires fast **kicker** to place muons onto stable orbit.



Superconducting Inflector Magnet

- Novel double cosine theta septum magnet creates field free region for injected muons.
- Avoids large gap in main magnet.
- Key design feature: traps its own fringe field using a SC shield.



Spin and Its Observable Effects

- In the Standard Model (SM), the **muon** is a point-like particle with precisely measured properties.

- The muon is a spin ½ particle and with spin comes a magnetic dipole moment (MDM).

$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$

  - Dirac explained in 1928 that **g = 2** for the electron. →

The Quantum Theory of the Electron.

By P. A. M. Dirac, St. John's College, Cambridge.

- Dirac also postulated the existence of an electric dipole moment (EDM) of strength.

$$\vec{d} = \eta\frac{q}{2mc}\vec{s}$$

- The EDM of the electron, if present, is many orders of magnitude weaker than the MDM.

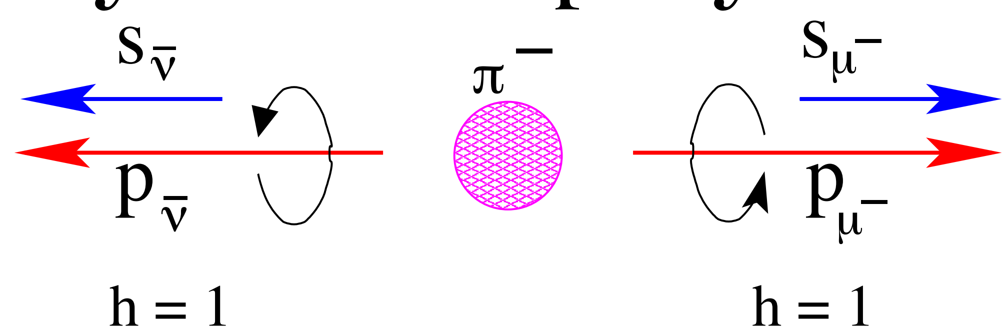
$$|d_e| < 8.7 \times 10^{-29} e \cdot cm$$

ACME Electron EDM (arXiv:1310.7534)

Measurement Technique

1. Source of Polarized Muons
(i.e., $\hat{s} \cdot \hat{p} \approx 1$)

Lucky break from parity violation



2. Magic Momentum Muons
(i.e., γ = 29.3 → p = 3.094 GeV/c)

Vertical focusing w/ E field adds new term to oscillation frequency

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

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

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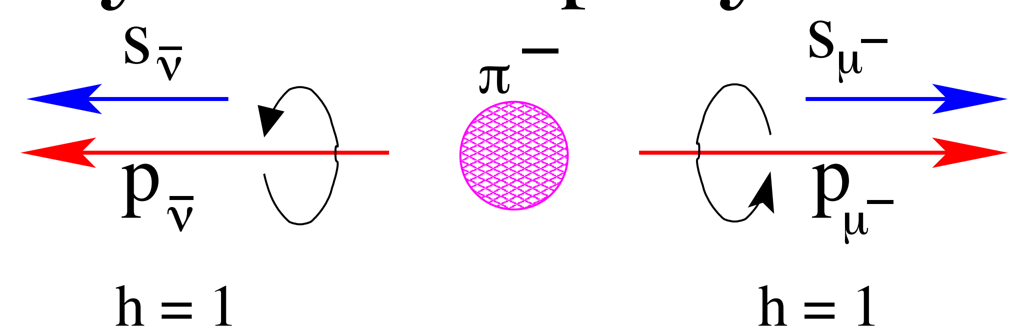

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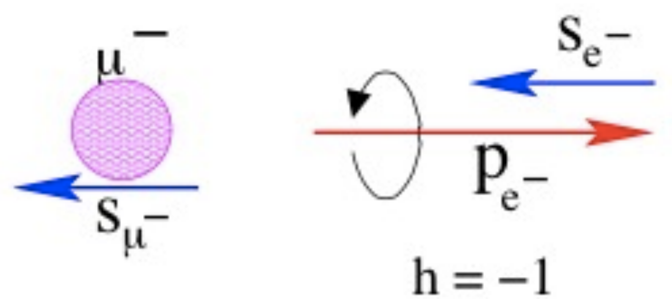
0

3. Measure Electron Energy

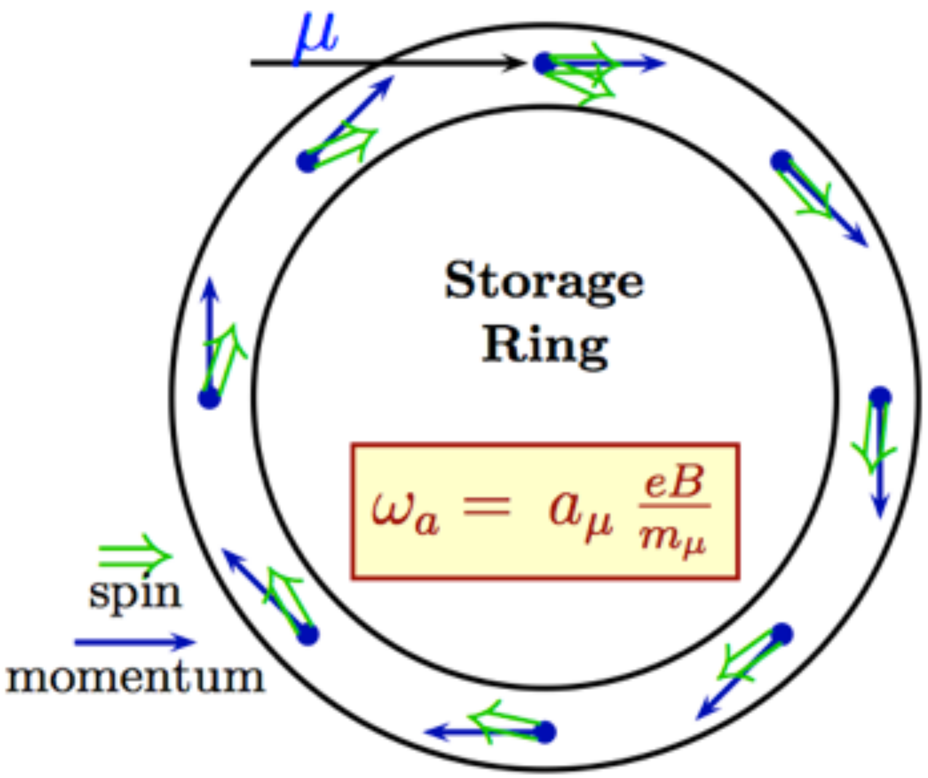
Another lucky break from parity violation



Electron spin follows muon spin

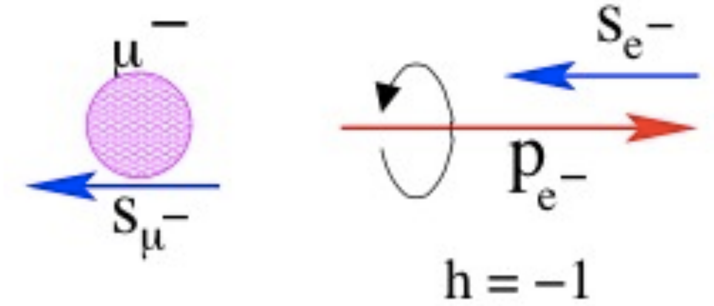
Measurement Technique

Spin precesses because $g_\mu \neq 2$

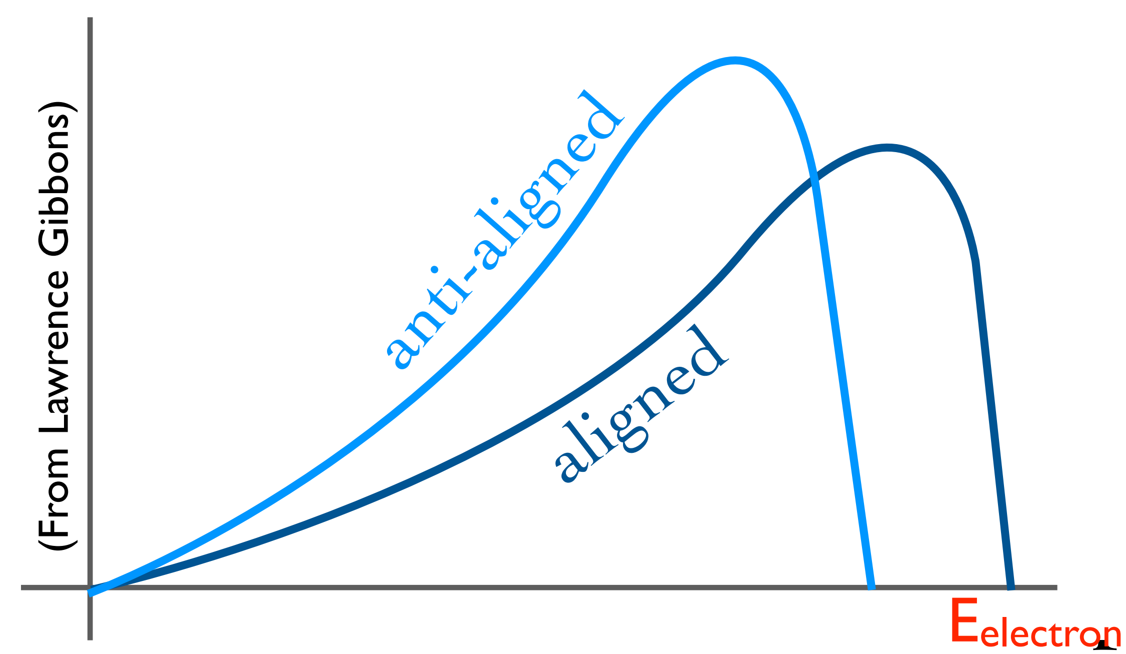


actual precession × 2

3. Measure Electron Energy



Harder electron spectrum when spin and momentum are aligned



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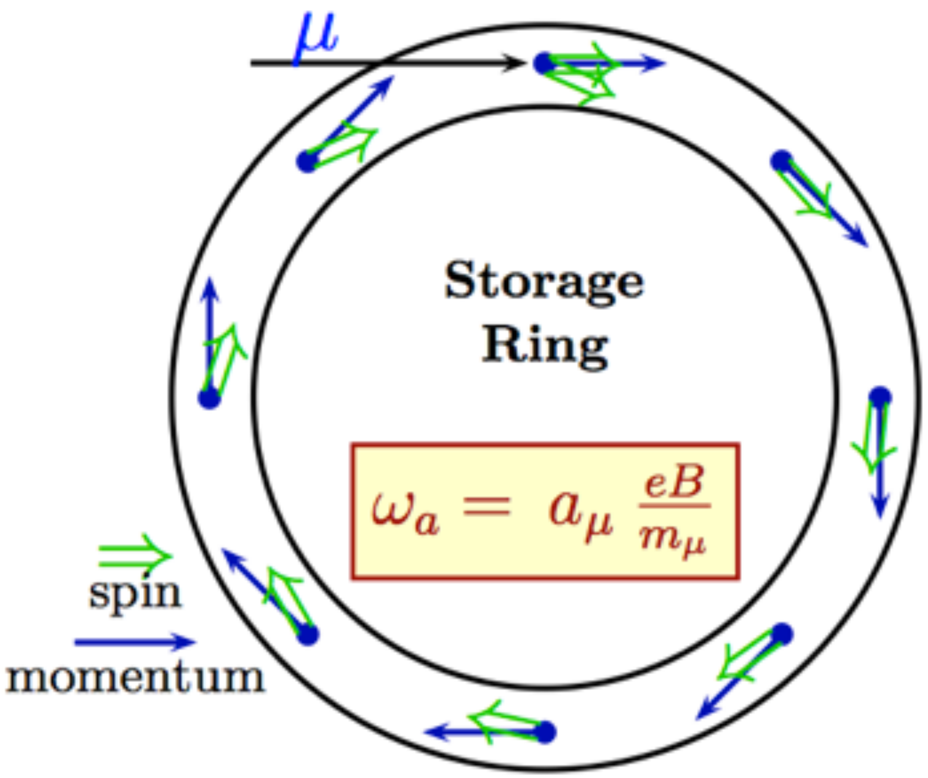

actual precession × 2

Count N(e) above fixed threshold. Oscillation rate ∝ a_μ

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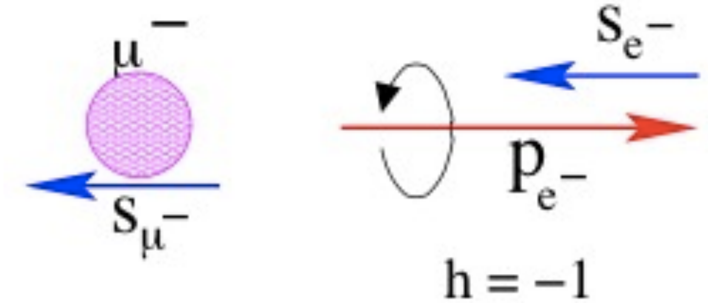

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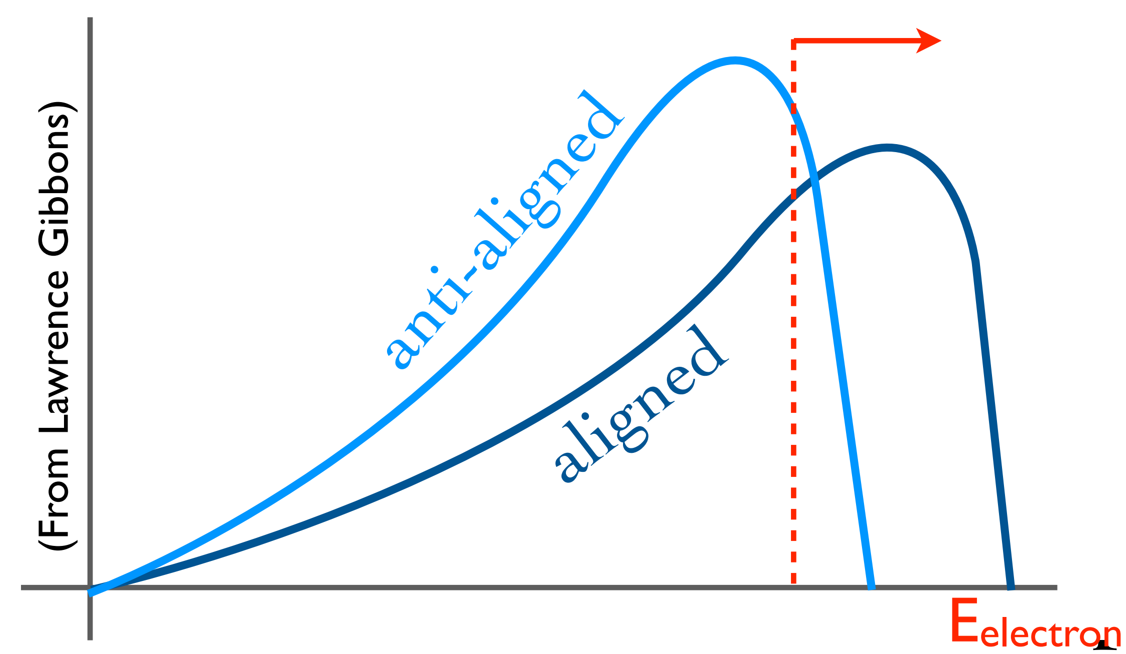
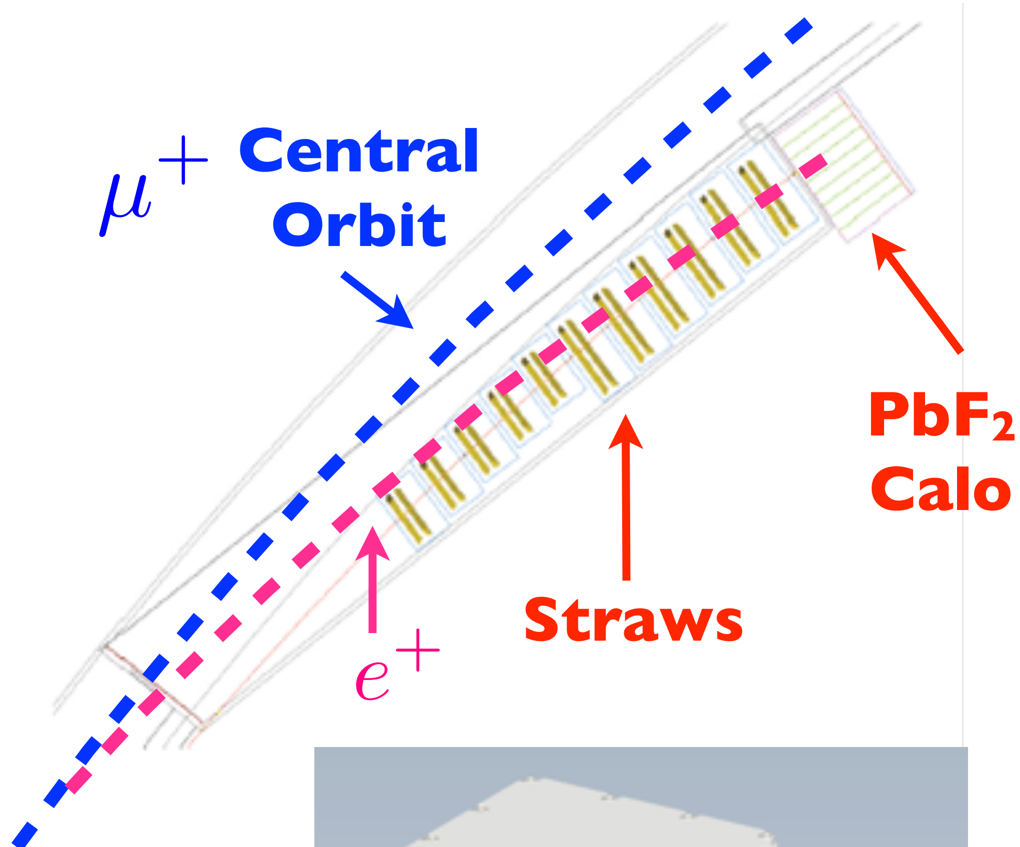
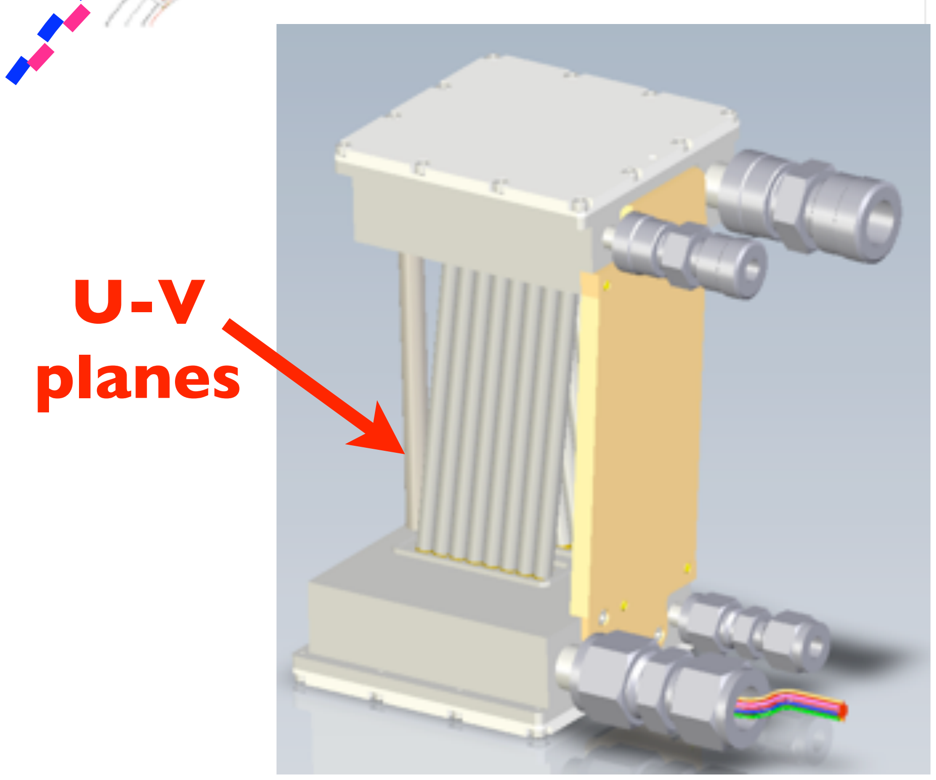


New Detector Elements

- Straw Tracking System
  - Two straw wire tracking chambers will record positrons before hitting the calorimeters.
- Allows non-destructive beam profile measurements
  - Reconstruct muon decay vertex.
  - Assist in pileup determination.





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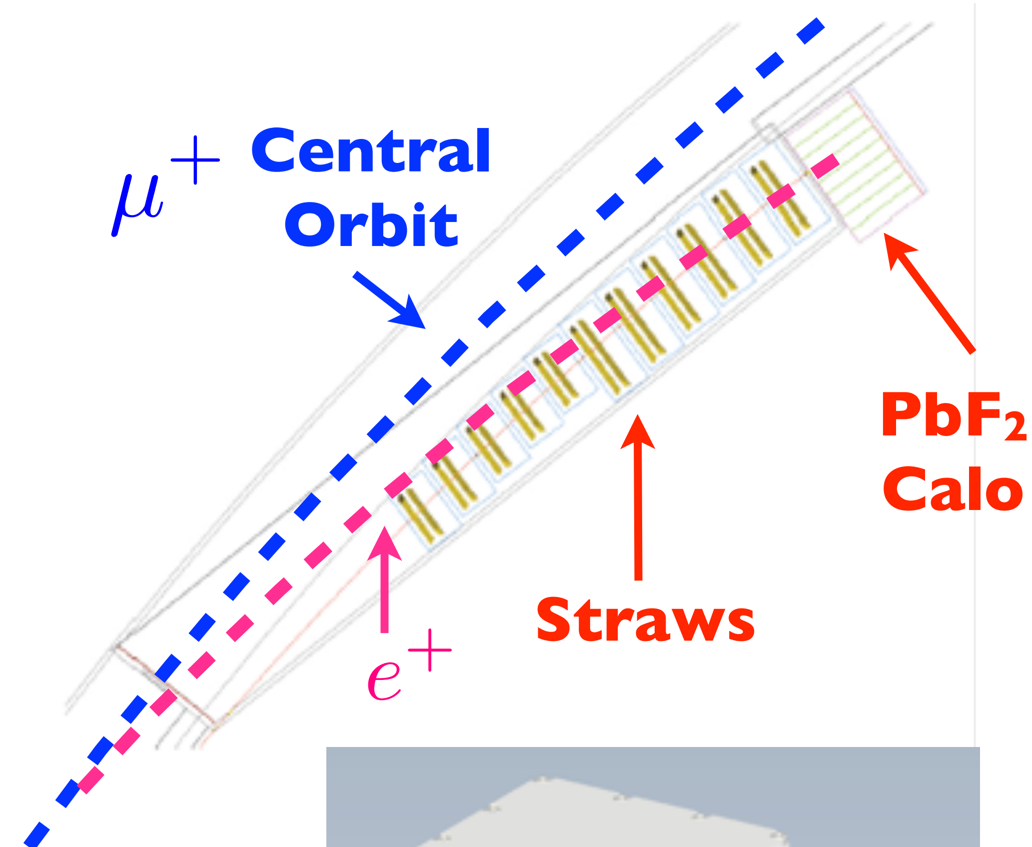
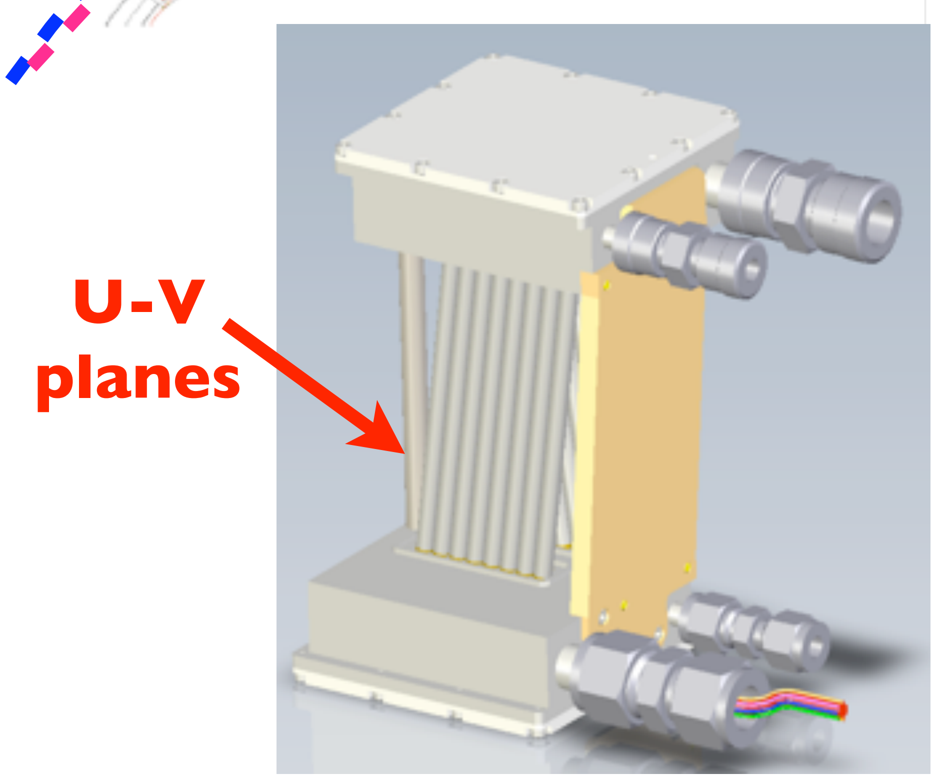
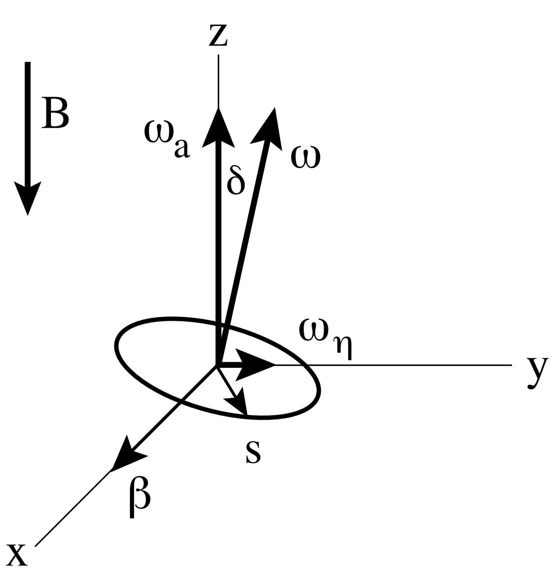




- Allows Muon EDM Measurement

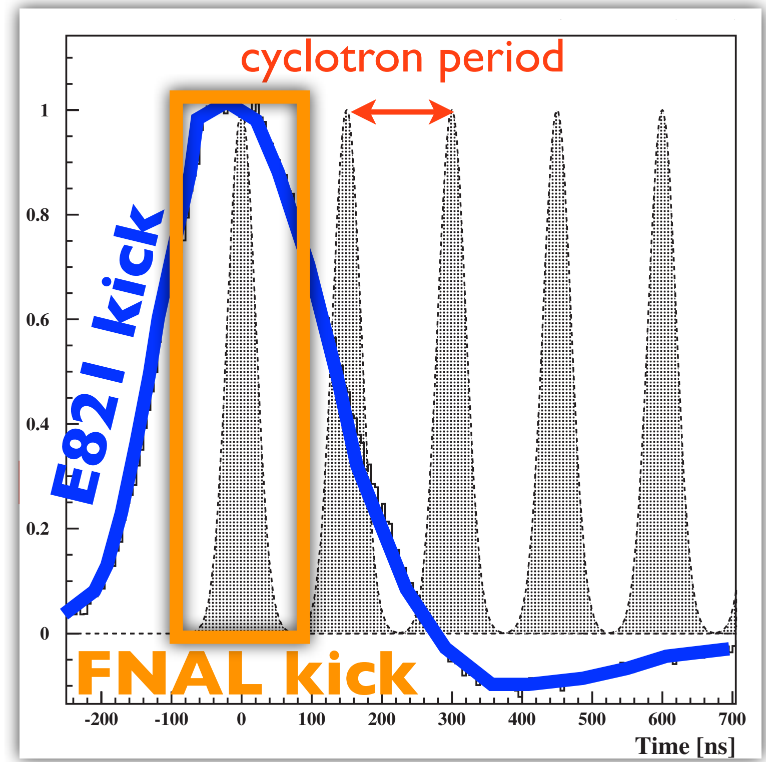


EDM tilts oscillation plane

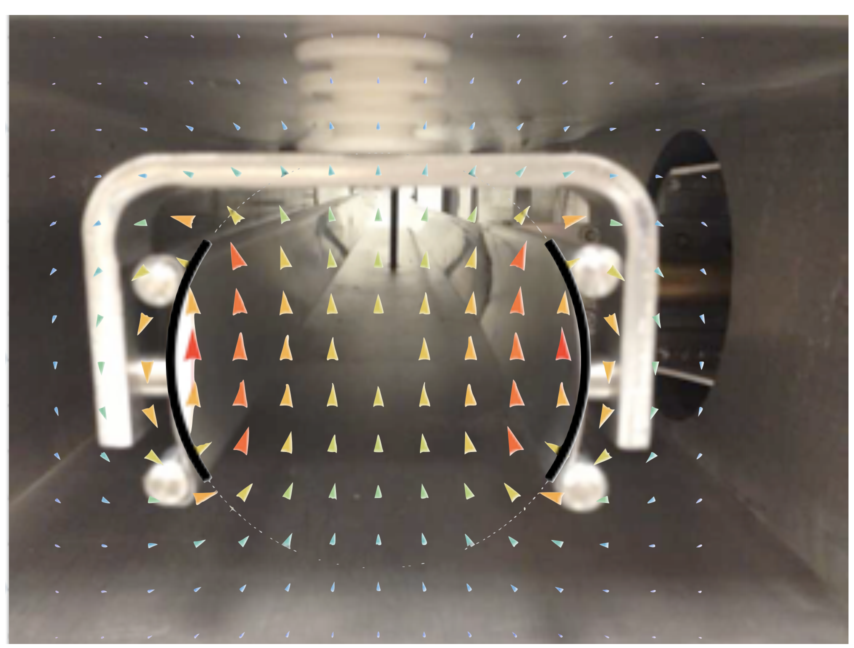
→ Induces up-down asymmetry in positron spectrum

New Ring Elements

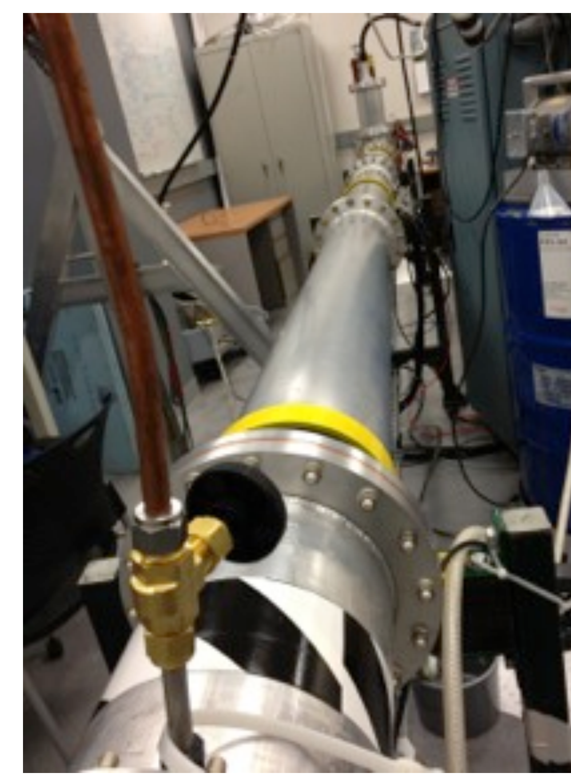
- New fast electrostatic kicker
  - Requirement: Produce a fast (<150 ns) ≈11 mrad kick. Otherwise, muon bunch will hit the inflector up return.
  - Requirement: Can not perturb precision field.



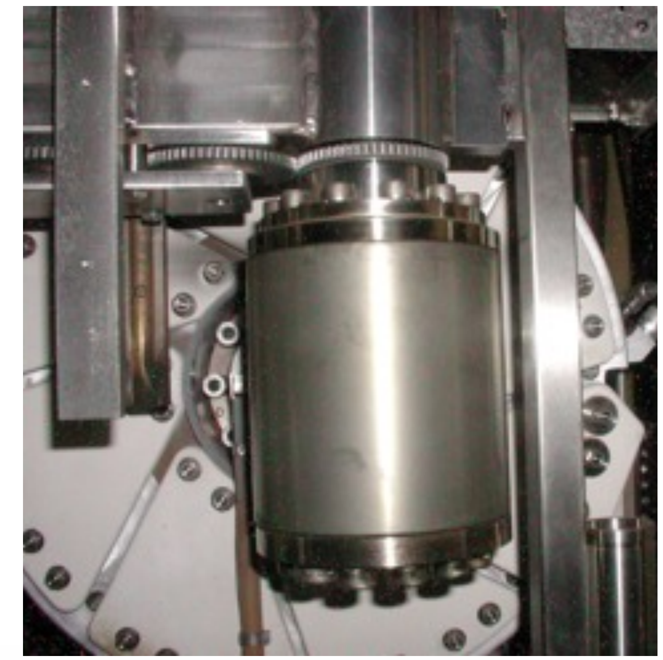
- E821 design produced insufficient kick
  - Result: Lost muons and large betatron oscillations.



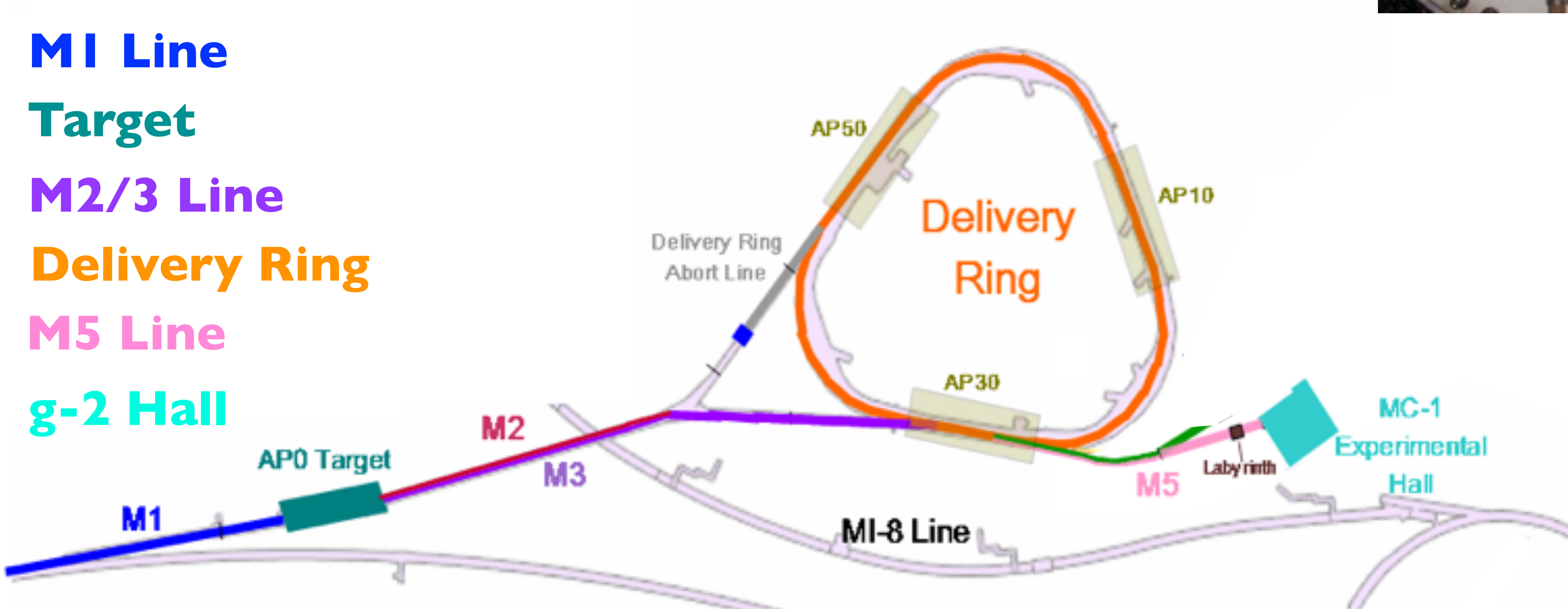
- New design creates a fast square pulse using 3 Blumleins. →
- Curved kicker plates generate larger field / pulse. ←



Fermilab Muon Campus



- Fermilab will produce pions using 8.9 GeV protons impacting the former antiproton production target
  - Yield is $\approx 10^{-5}$ π/POT within 2% of P_{magic} = 3.094 GeV.
- Pions travel through M2/M3 lines (900 m“decay pipe”) to delivery ring (DR) and accumulating muons ($\pi \rightarrow \mu$).
  - Nearly pure muon beam in DR (big improvement over E821).



- After several turns in DR (to remove beam protons), muons are kicked into M5 beamline and into g-2 experimental hall.

Fermilab Muon Campus

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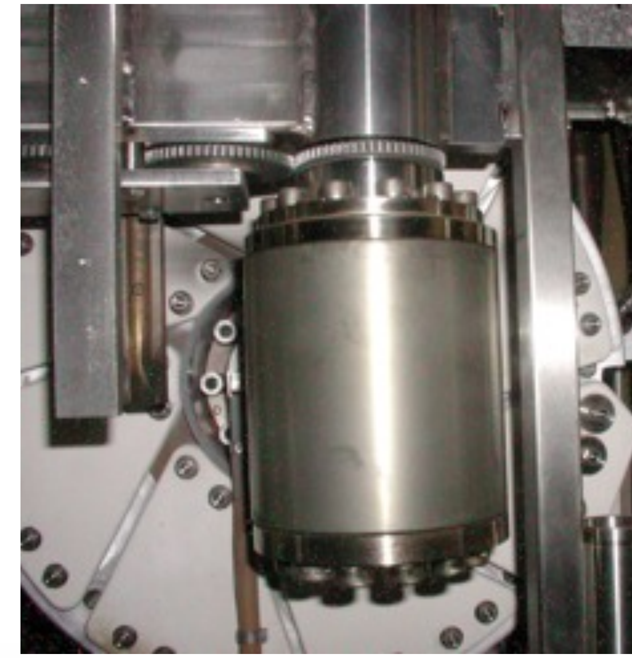
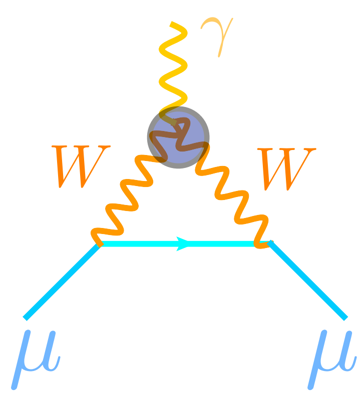


New Physics?

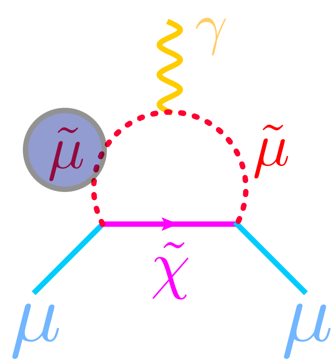
- Standard Model calculation is ok. We are just seeing new physics.

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}} + \boxed{a_\mu^{\mathrm{NP}}}$$

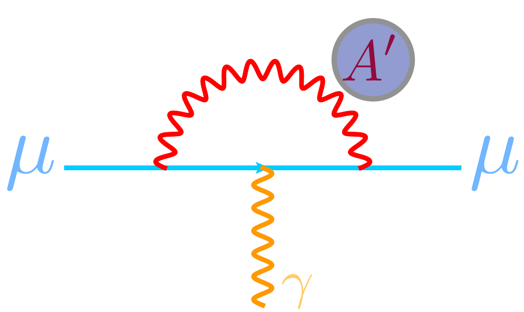
aTGC $WW\gamma$



SUSY



Dark Photons



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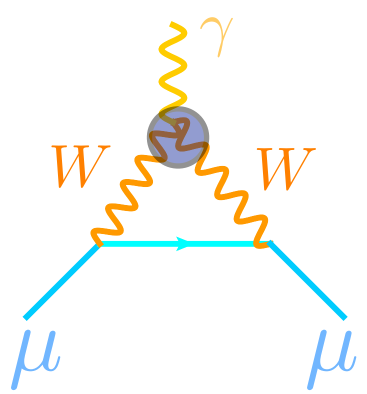

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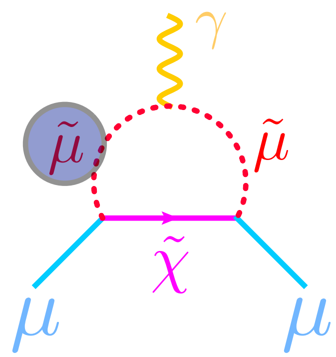

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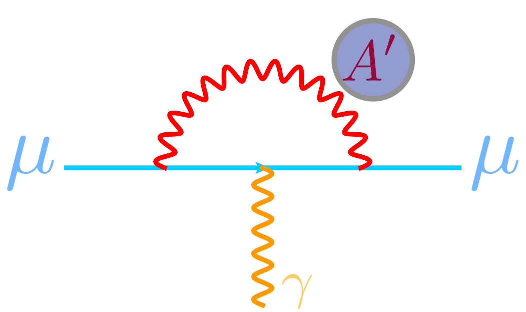
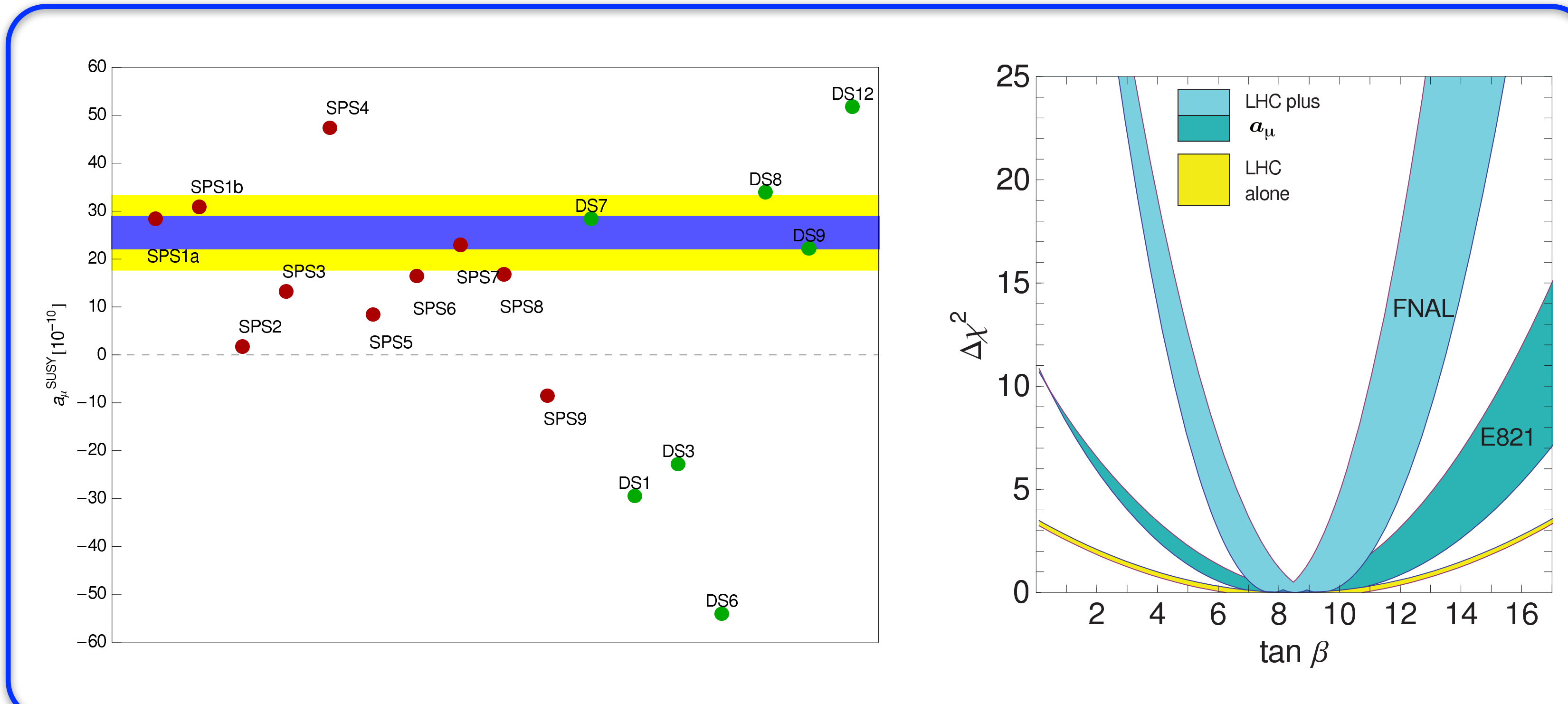


g-2 can disentangle allowed SUSY models



- A precise g-2 measurement is very complimentary to a future LHC discovery.

Understanding The Muon

- There is a rich history of muon g-factor measurements starting in the 1950's at Nevis.

$$g_\mu = 2(10\%)$$

  - Evidence that the muon is just a heavy electron.

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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

(Received January 15, 1957)

Phys. Rev. 105, 1415–1417 (1957)

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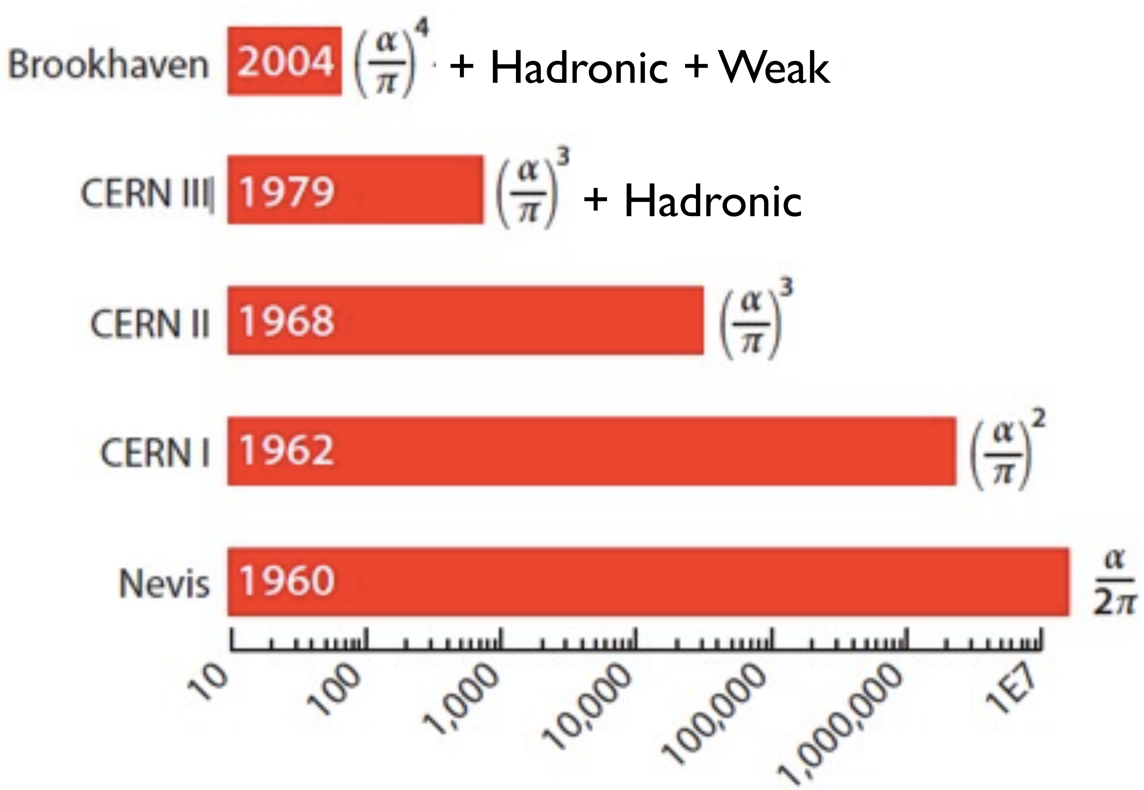

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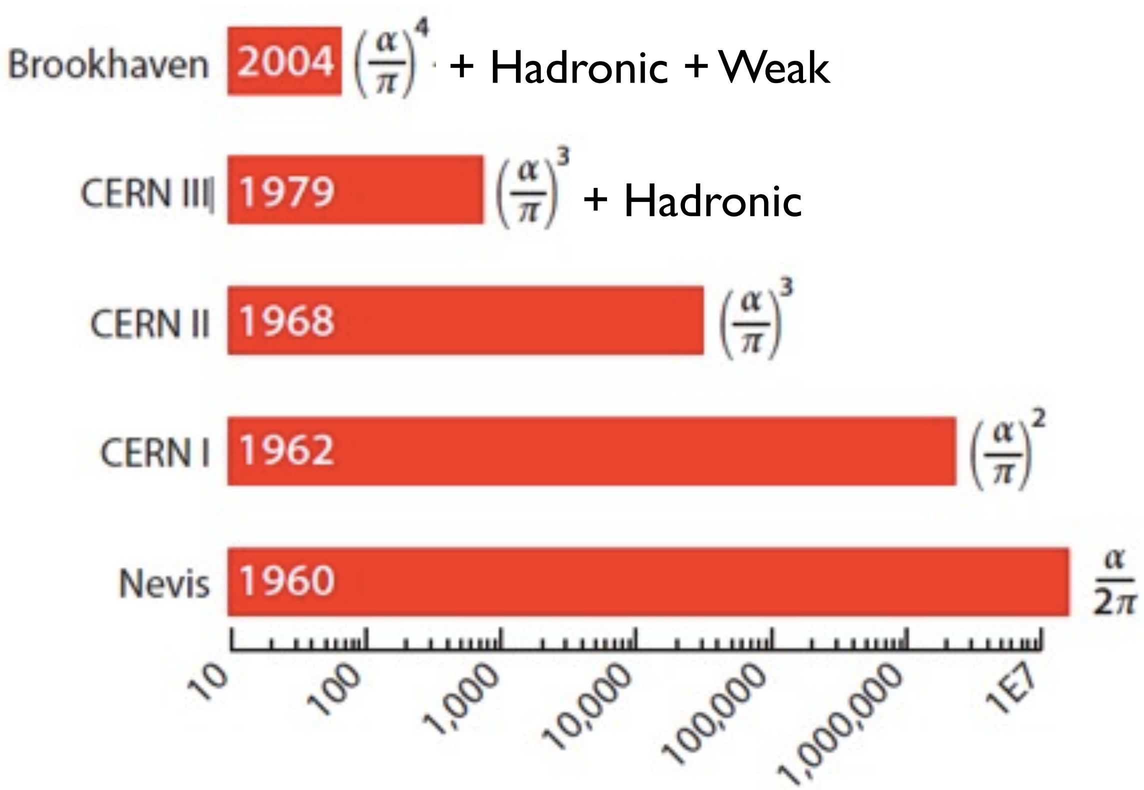
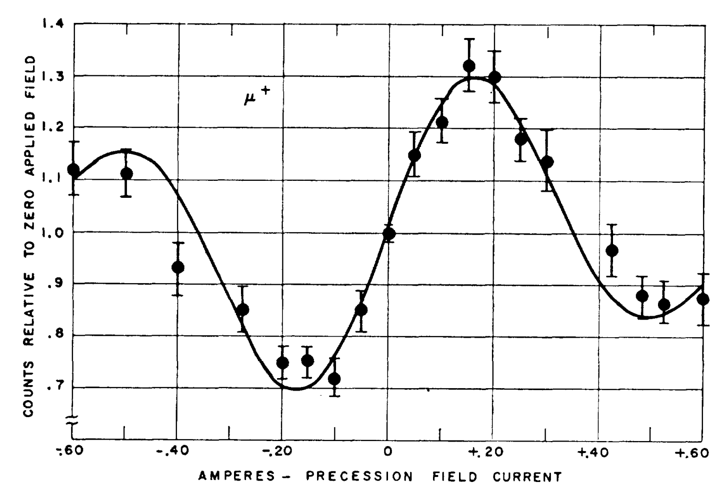
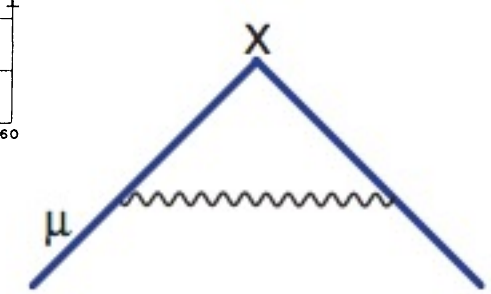


Nevis





Muon spin rotation in magnetic field

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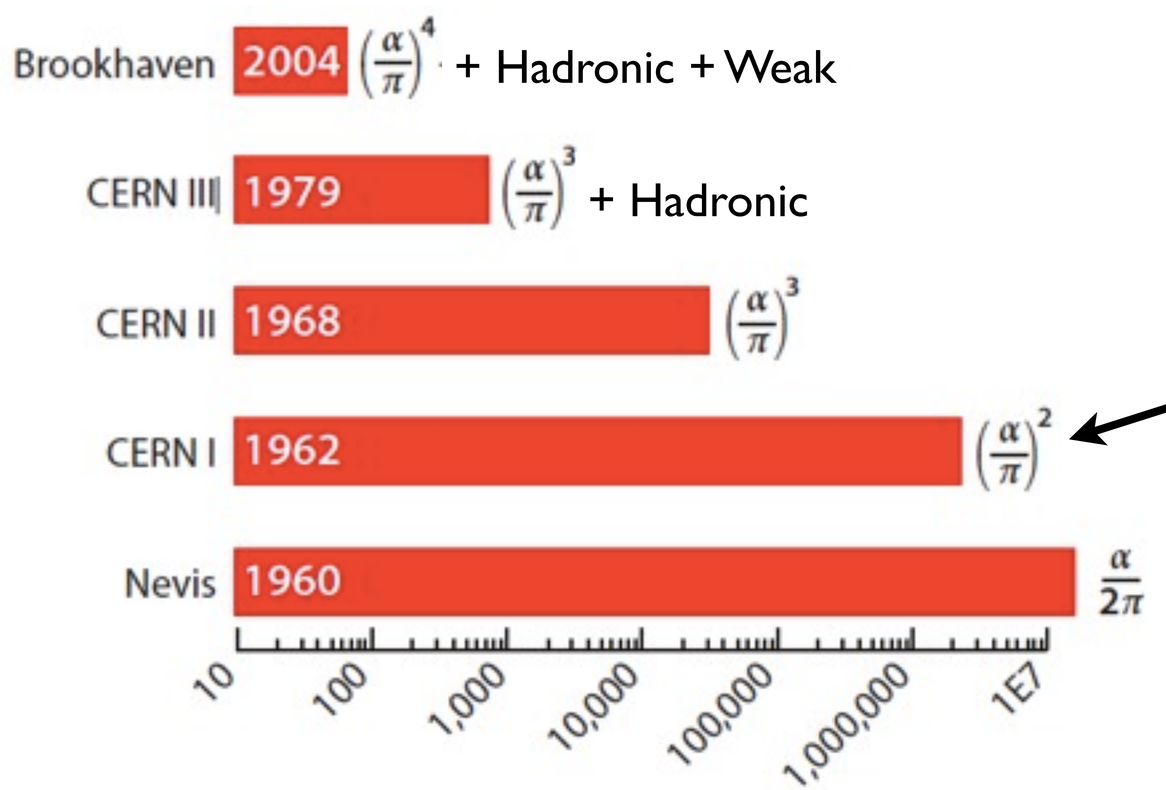

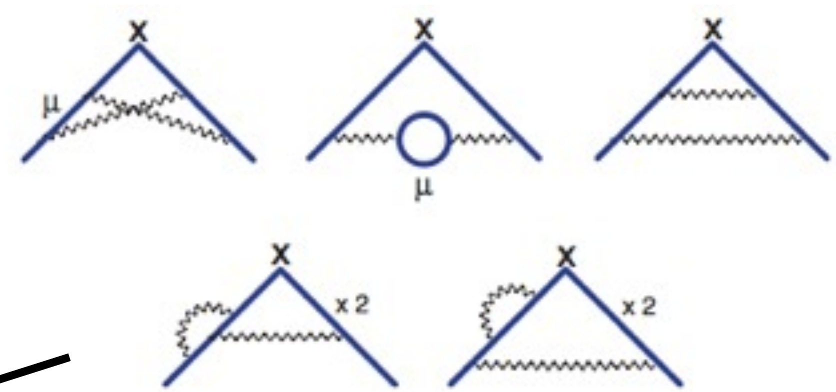

Muon in circular obits, spin precession relative to cyclotron frequency.

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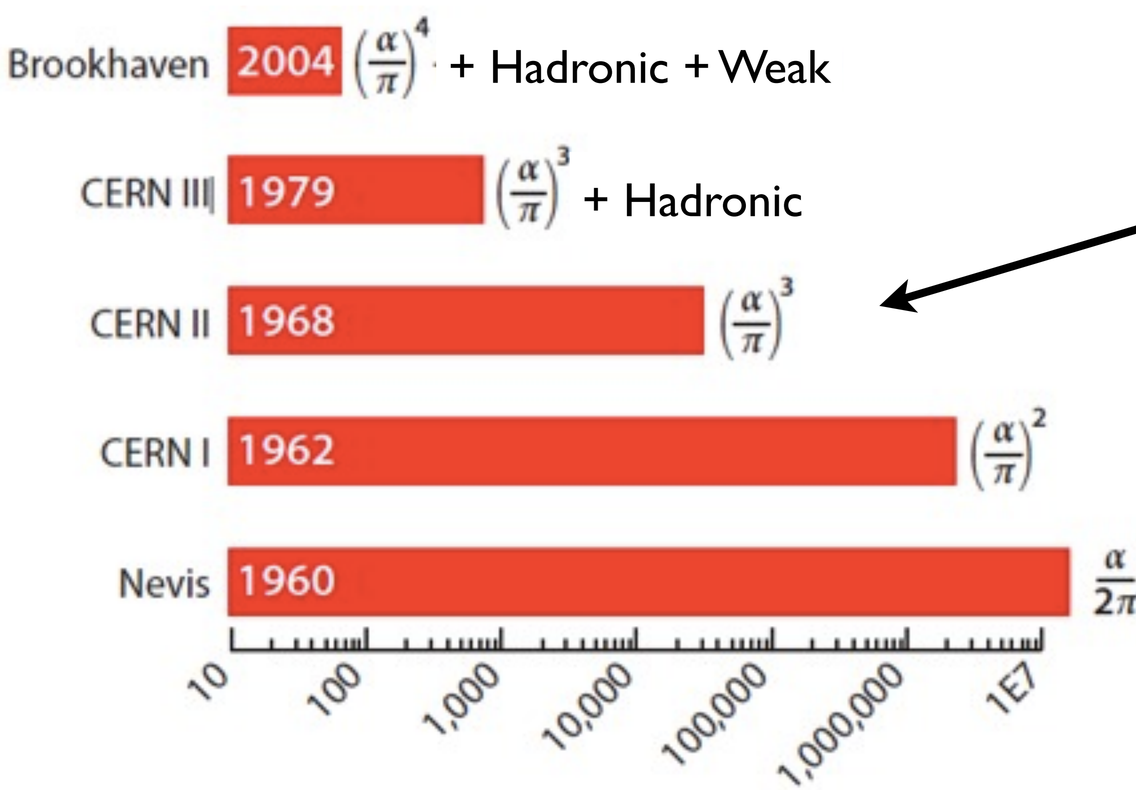

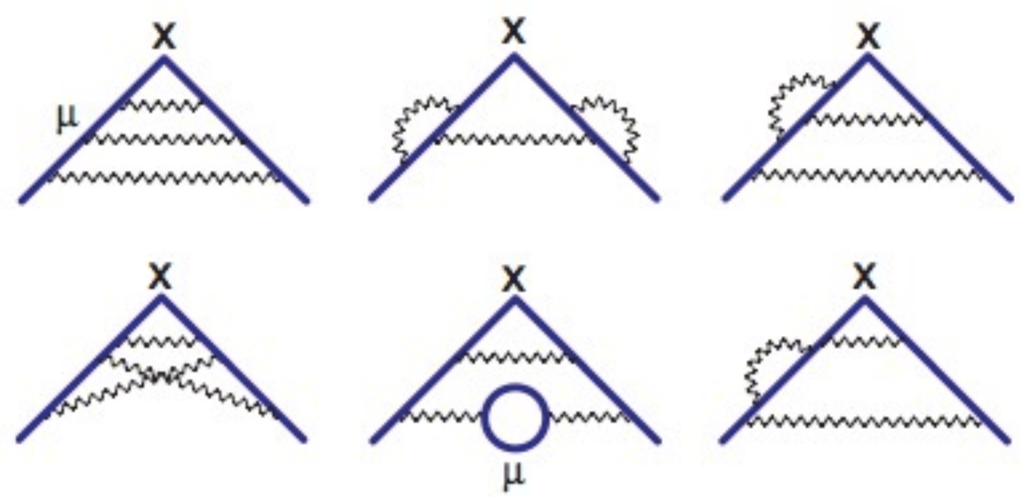

Storage ring w/ vertical focusing + tying a_μ to hyperfine splitting in muonium

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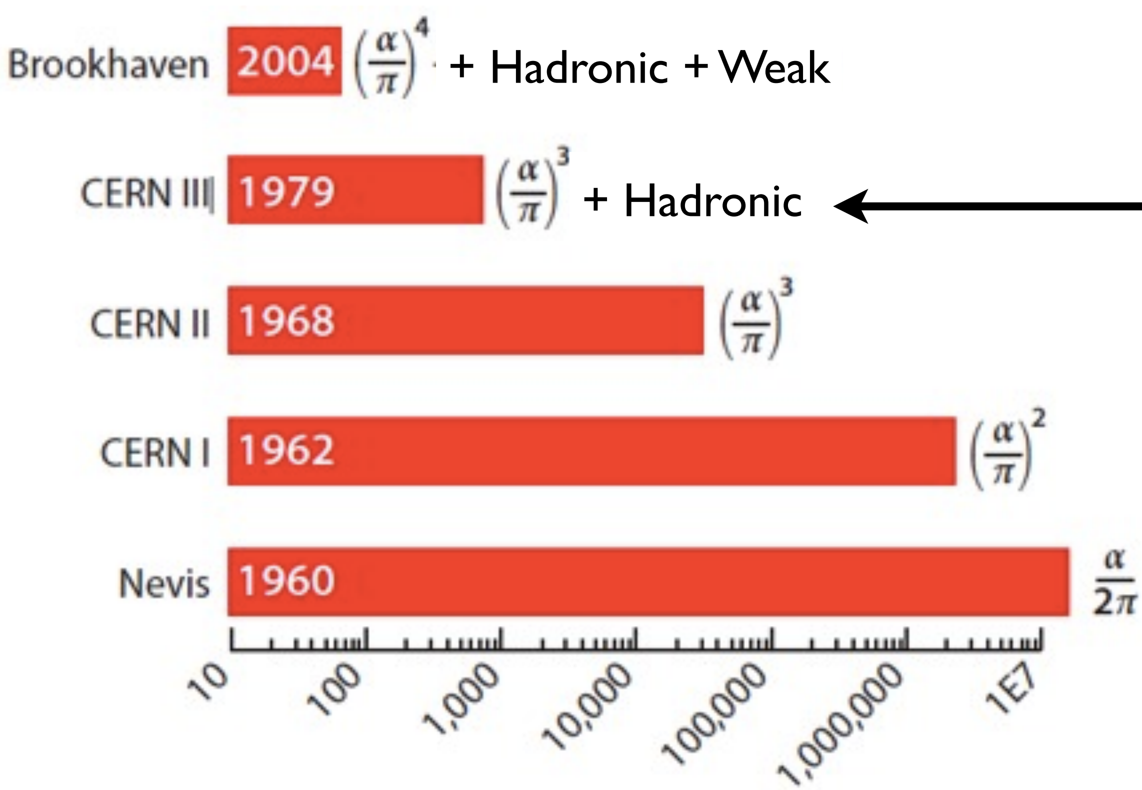

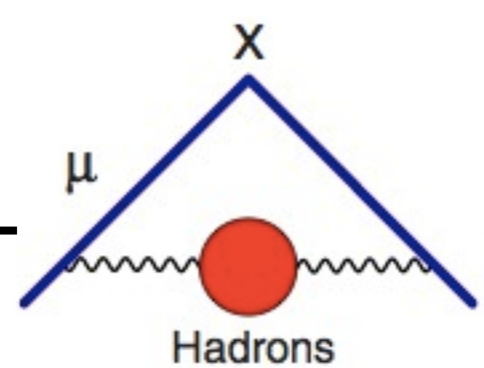

CERN III

Electrostatic focusing w/ "Magic momentum" muons w/ $\gamma = 29.3$

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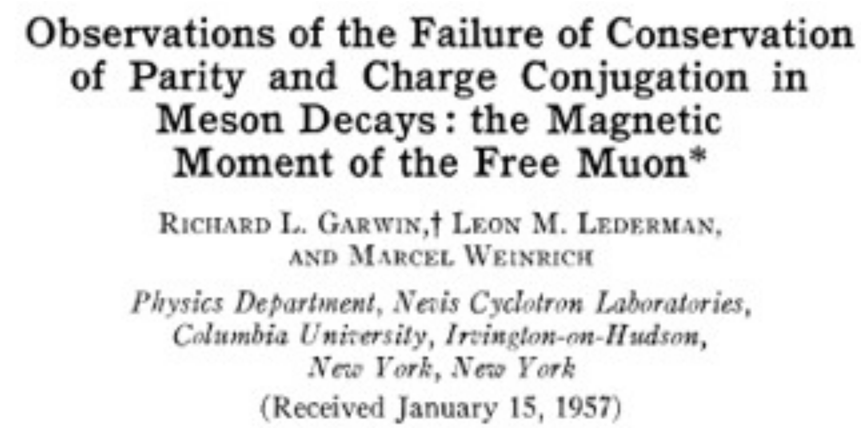
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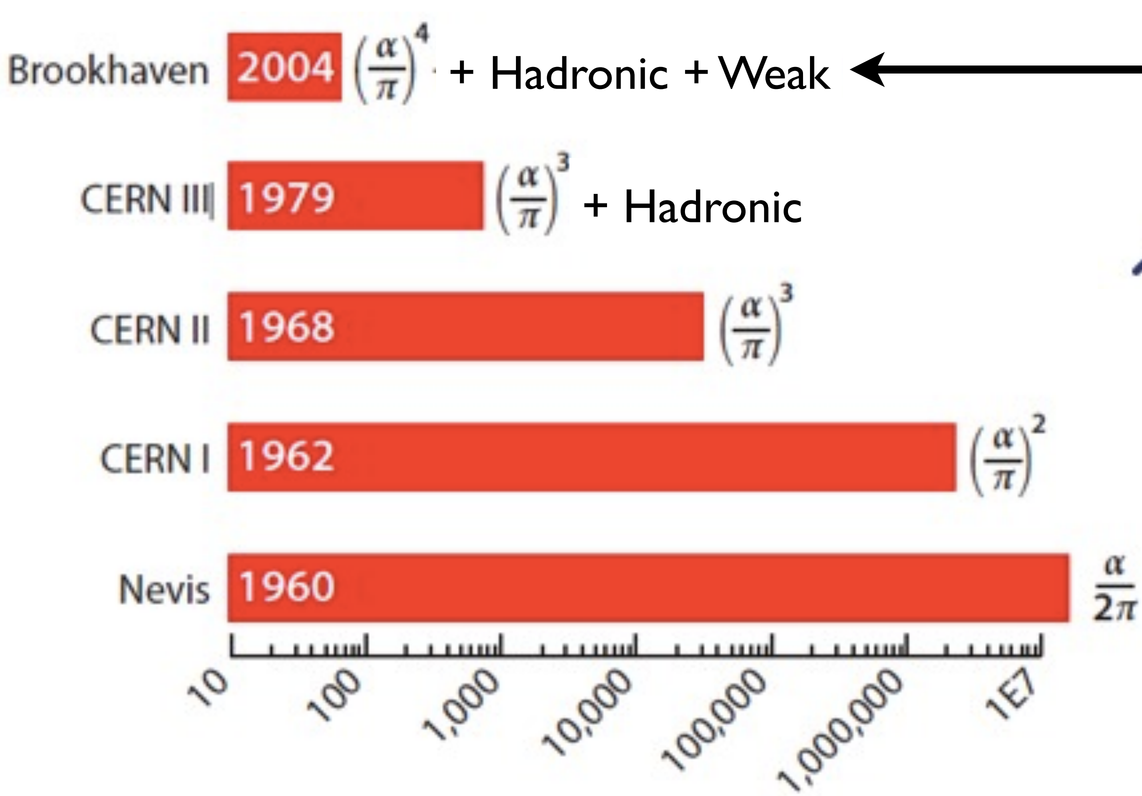
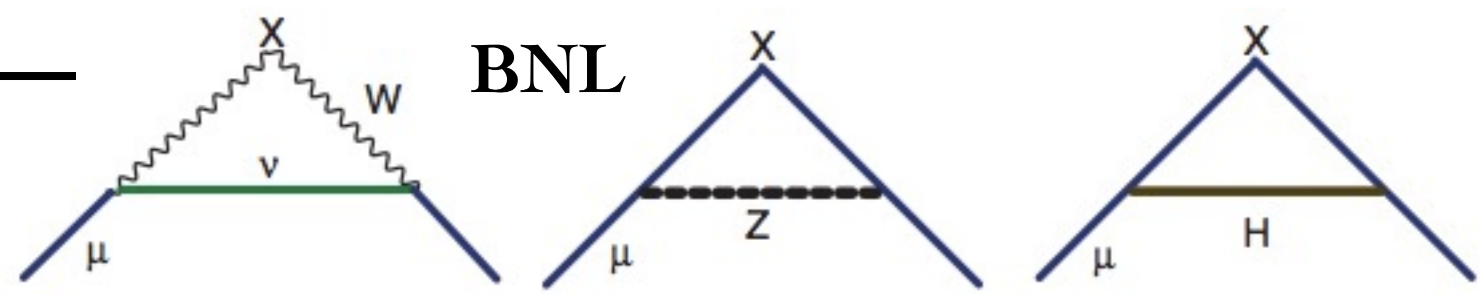
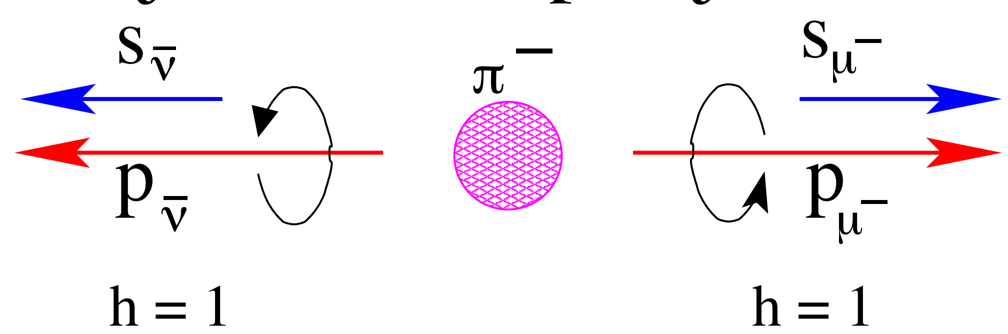




Measurement Technique

1. Source of Polarized Muons
(i.e., $\hat{s} \cdot \hat{p} \approx 1$)

Lucky break from parity violation



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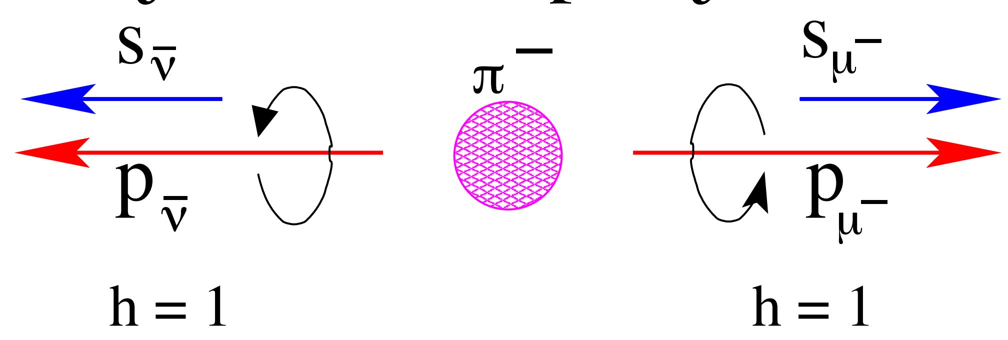

2. Vertical Focusing
(i.e., trapped muons)

Using quad E field adds new term to oscillation frequency

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

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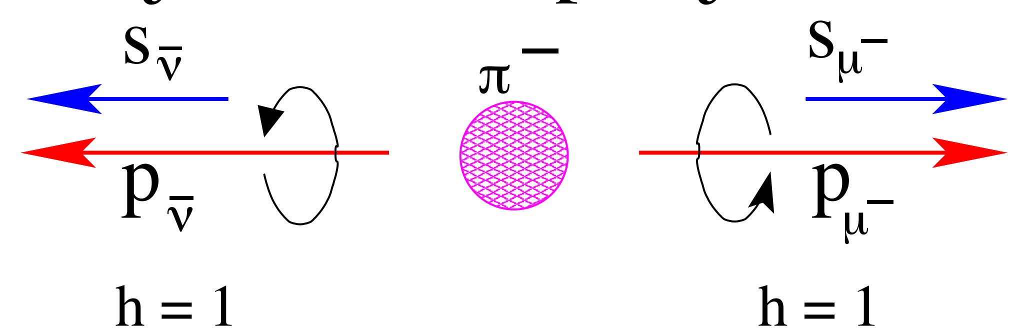

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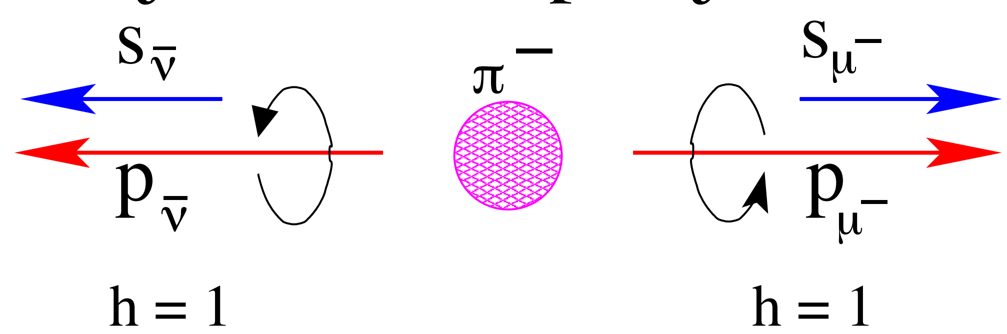

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3. Measure Muon
Spin Precession

Weak decay correlates muon spin and electron momentum