# Muon g-2 at Fermilab: Probing for BSM Physics

**Brendan Kiburg, Fermilab**

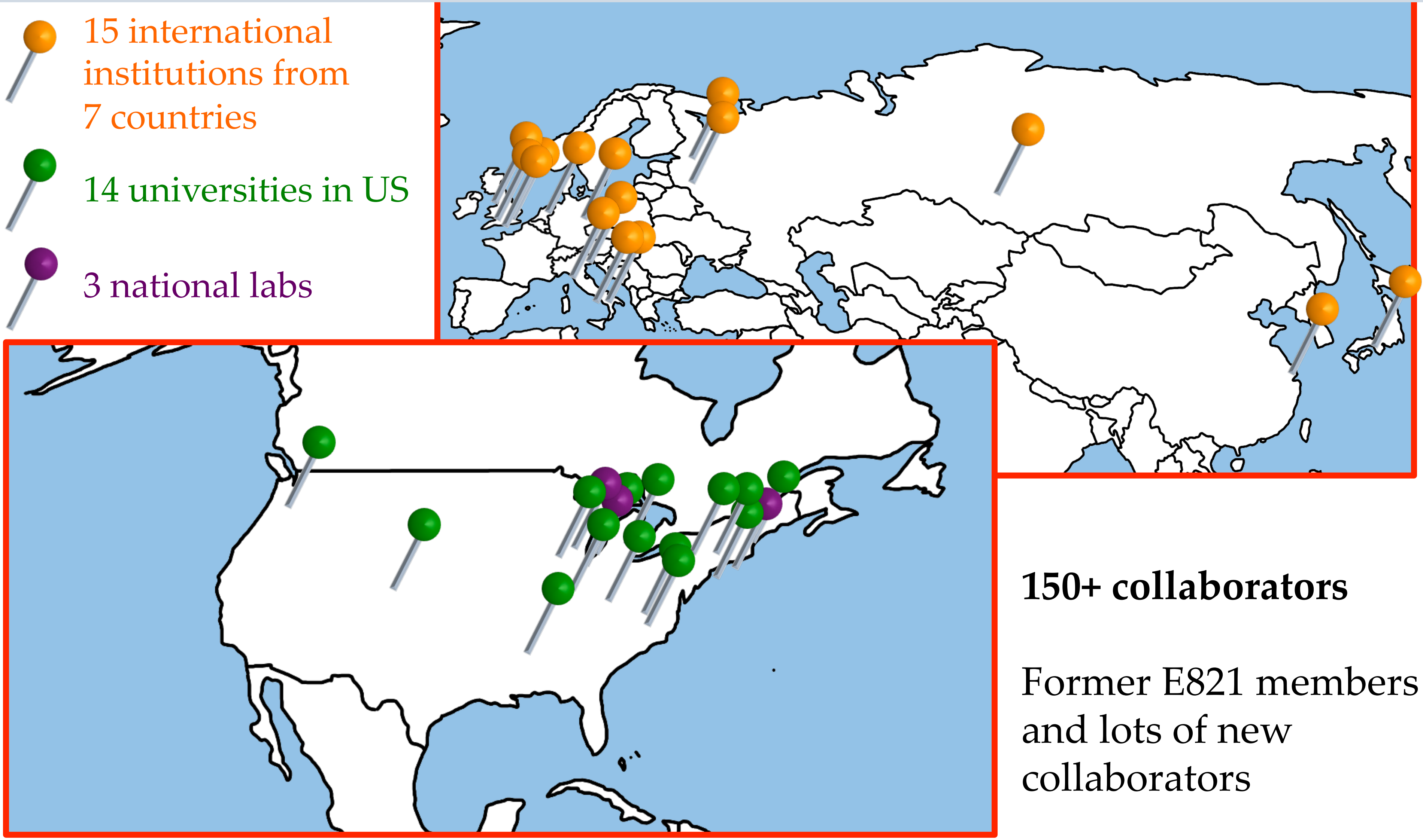
**DPF UC Santa Cruz**

**Physics Beyond the Standard Model**

**August 16, 2013**

# The E989 collaboration

- 15 international institutions from 7 countries
- 14 universities in US
- 3 national labs

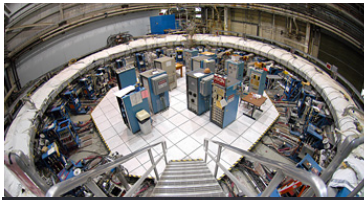
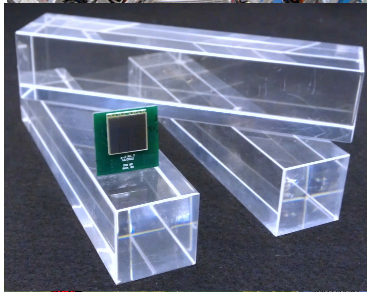


**150+ collaborators**

Former E821 members and lots of new collaborators

# Topics

- The Physics of Muon g-2
- Experimental Technique
- Fermilab Muon g-2
- The Ring Transport
- Outlook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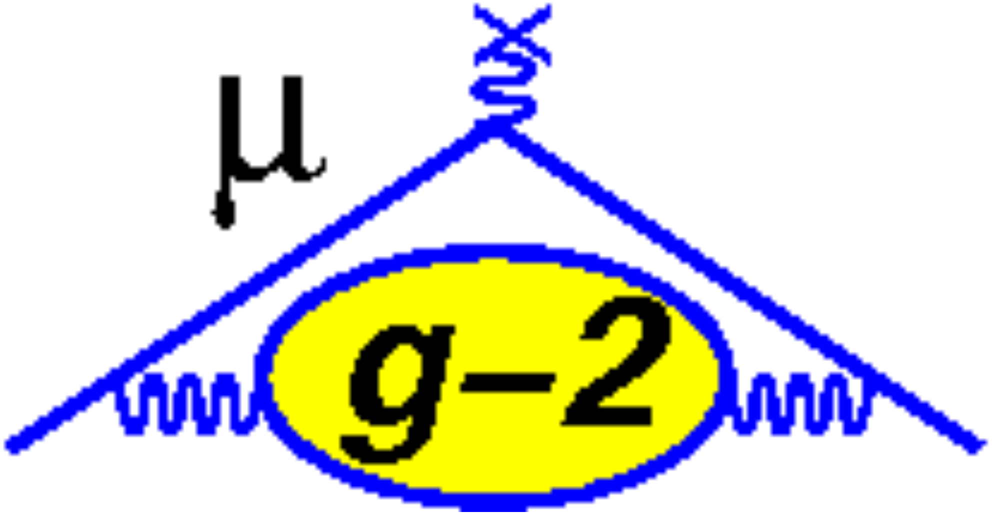
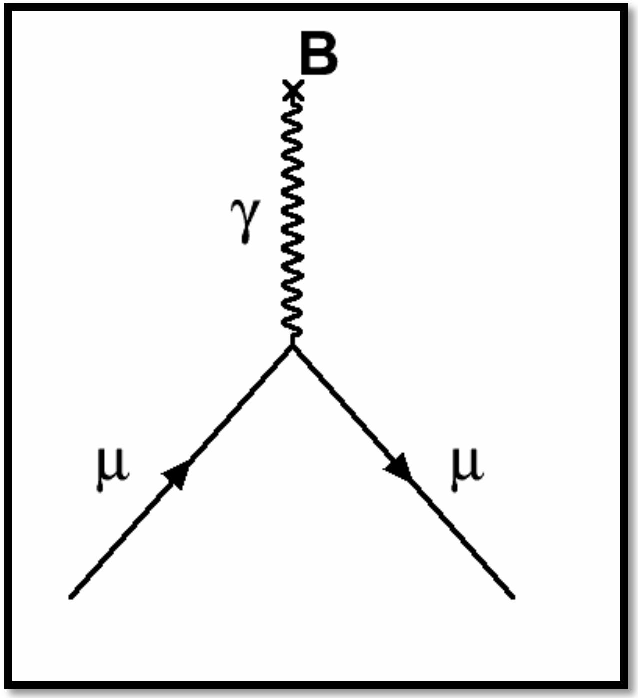


# The Magnetic Moment

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

- Dirac theory of charged, spin ½ elementary point particle:

$$g \equiv 2$$



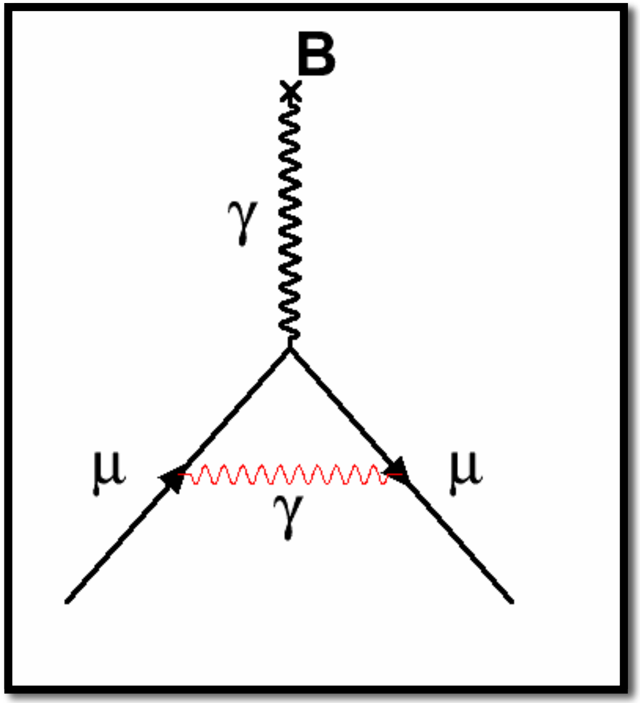
# The Magnetic Moment

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

- Dirac theory: $g \equiv 2$

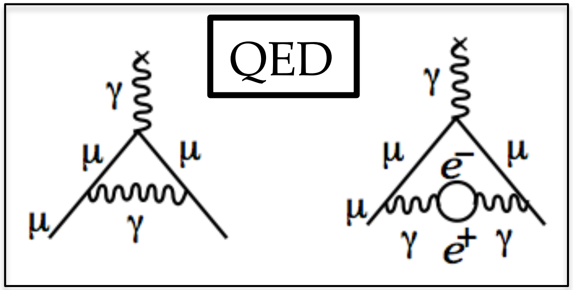
- $g \equiv 2 \rightarrow g = 2 + g^{QED(lo)}$

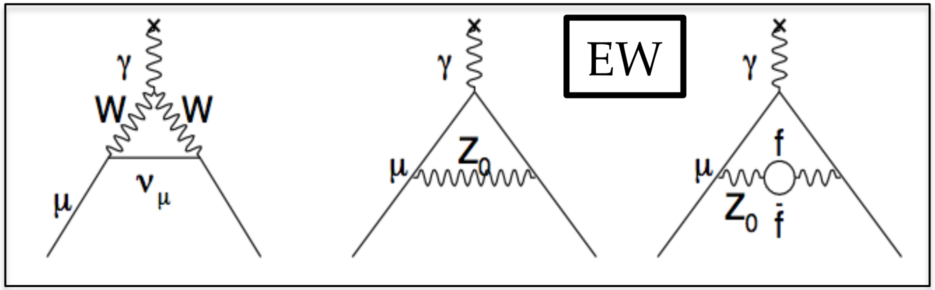
But, the vacuum is not empty space…

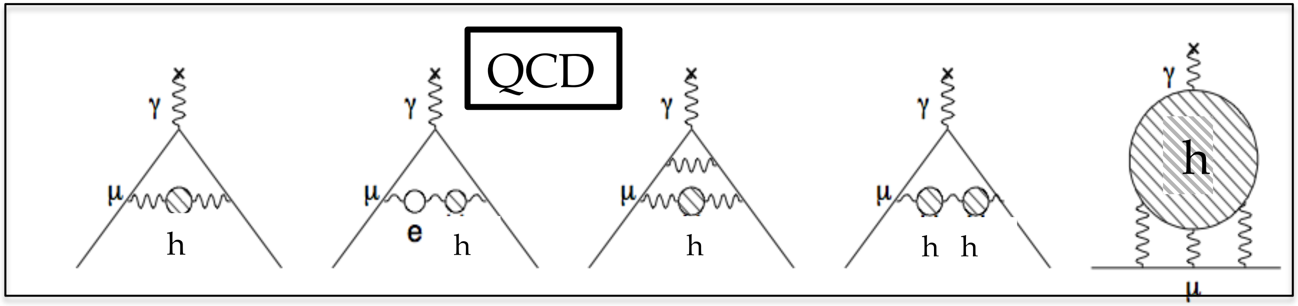


Schwinger term

# Add up all SM diagrams…



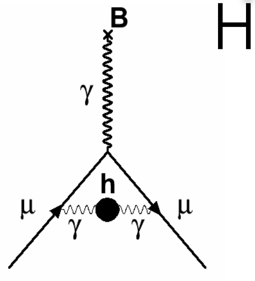




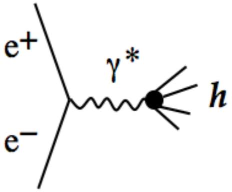
Anomalous magnetic moment: $a_\mu = (g_\mu - 2)/2$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

# $a_\mu^{SM}$ limited by hadronic terms



Hadronic Vacuum Polarization



- Ingredients:
  - Experimental determination:

$$R \equiv \frac{\sigma_{total}(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

  - Dispersion relation

$$a_\mu^{HVP} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \frac{R(s)K(s)}{s^2}$$

  - $\delta a_\mu^{HVP}$ **~ 0.36 part-per-million**

- Pending Improvements:
  - Data from BaBar, KLOE, BES-III…
  - Parallel lattice QCD efforts
  - Preliminary lQCD results match

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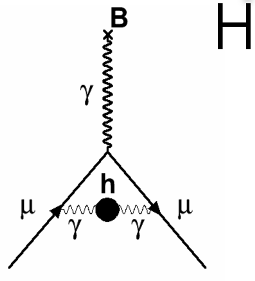
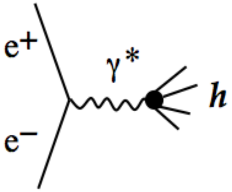


## Hadronic Vacuum Polarization



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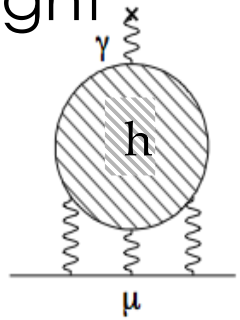
## Hadronic light-by-light scattering



- More complicated
  - Not expressed in terms of experimental quantities
  - Uncertainties are model-dependent
  - $\delta a_\mu^{HLBL}$ ~ **0.22 part-per-million**
- Early lattice calculations
  - Appear promising; results pending
  - Will require significant computing resources
  - Could encounter complications

# E821 result hints at BSM physics

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

$$\boxed{a_\mu^{Expt.} - a_\mu^{SM} = (260 \pm 78) \times 10^{-11} \quad (3.3\,\sigma)}$$

$$a_\mu^{Expt.} = a_\mu^{SM} + a_\mu^{New\ Physics}$$

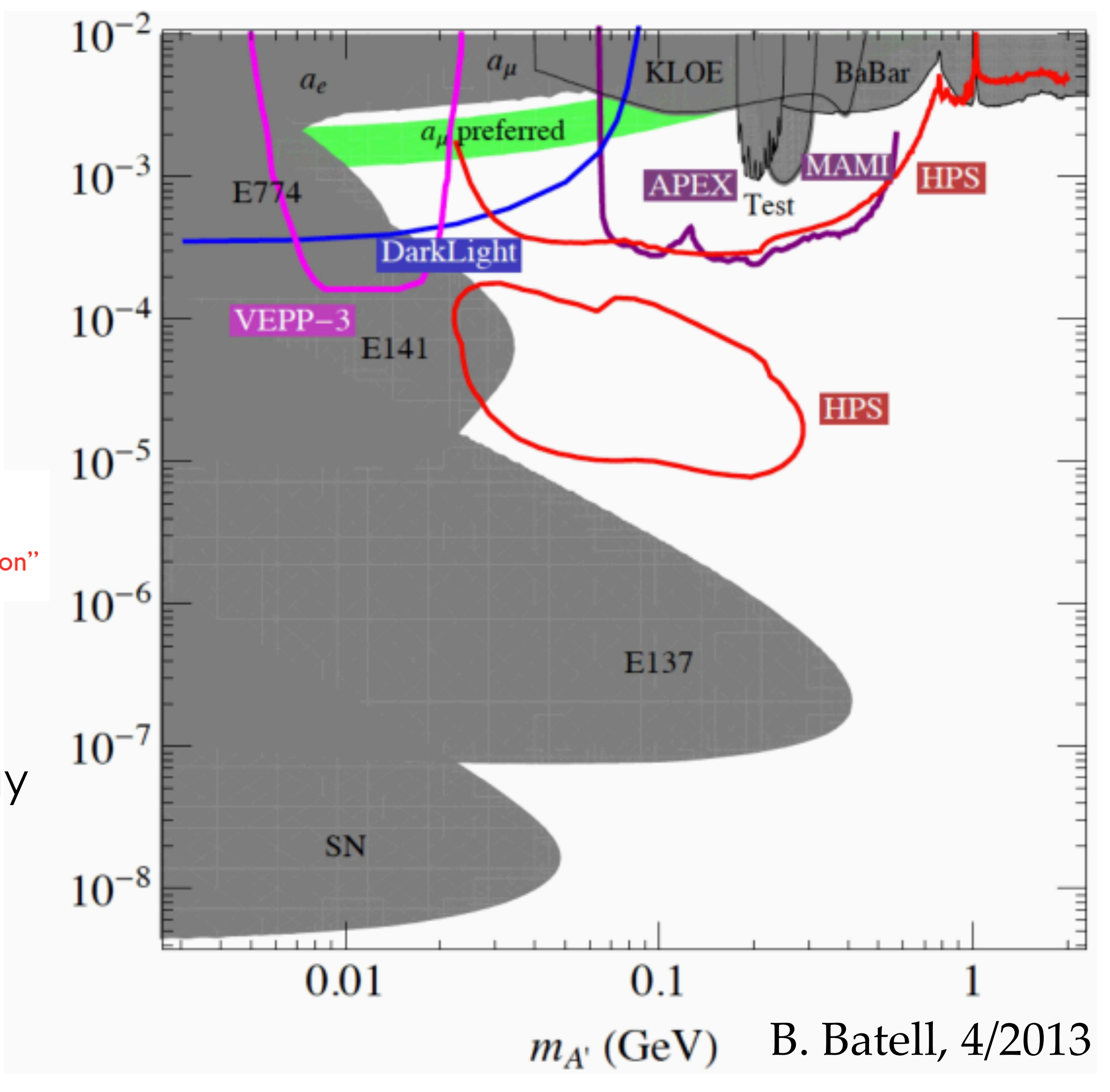
- New E989 experiment will reduce experimental uncertainty by a factor of 4 to $16 \times 10^{-11}$ (0.14 ppm)
- If current discrepancy remains this would yield $>5\sigma$
- Together with theory improvements could give $>8\sigma$

# BSM: SUSY, Dark Photons, … ?

Suppose a dark photon, A'

- Mediates a new force
- Weakly coupled to charged matter
- Kinetic mixing with the photon with strength ε via:

- If $m_{A'}$ ~ 1MeV -- 1GeV and this dark photon can decay to some light dark matter pair    ($2\, m_{\chi} < m_{A'}$)…



B. Batell, 4/2013

- The Physics of Muon g-2
- Experimental Technique
- Fermilab Muon g-2
- The Ring Transport
- Outlook

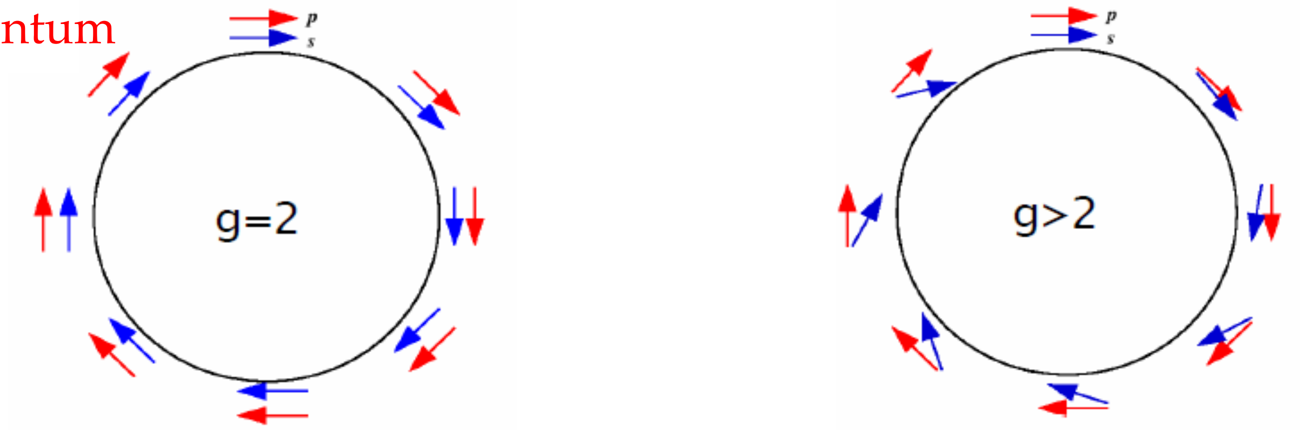
# Muons in a storage ring

1. Start with polarized muon beam (from pion decay)
2. Cyclotron frequency : $\omega_c = \dfrac{e}{m\,\gamma} B$
3. Spin precession frequency: $\omega_S = \dfrac{e}{m\,\gamma} B\,(1 + \gamma\, a_\mu)$

Larmor + Thomas precession

→ momentum

→ spin

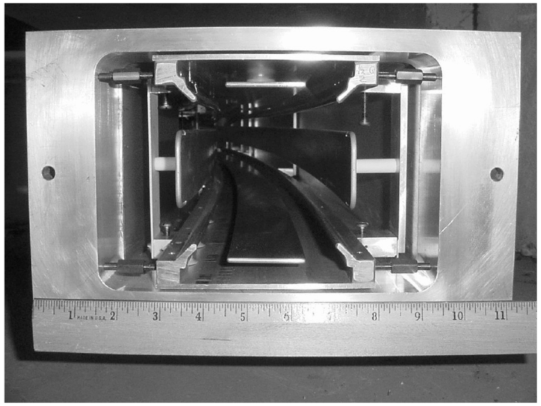


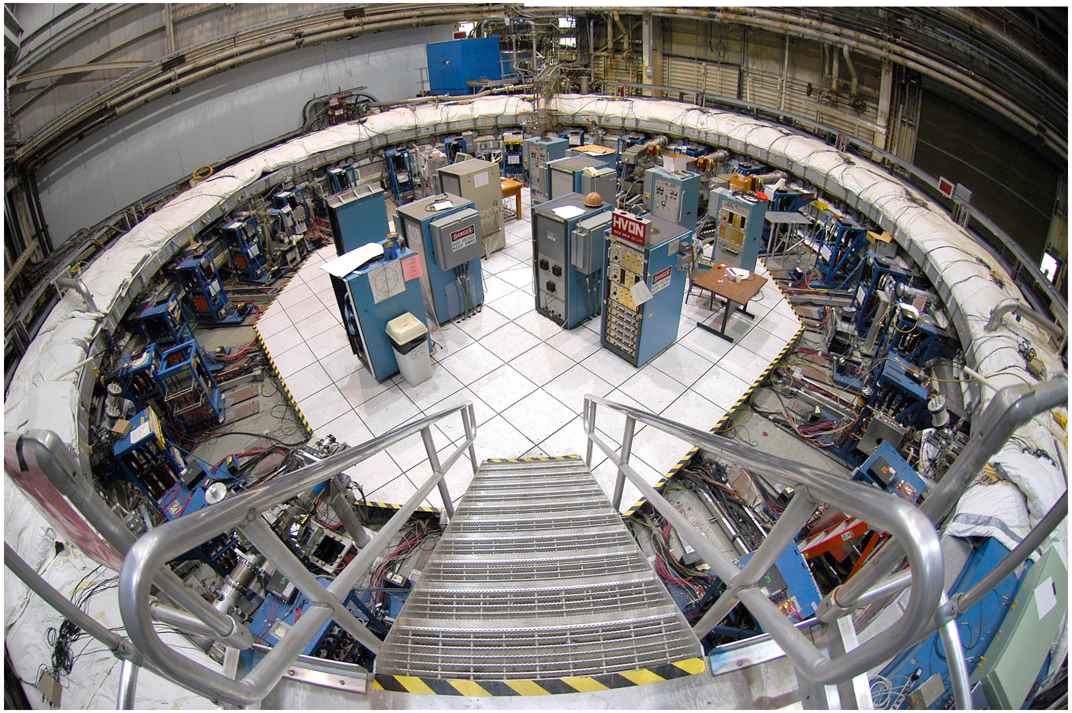
$$\boxed{\omega_a = \omega_S - \omega_C = e/m\ a_\mu\ B}$$

# Storage Ring

Need to contain beam

Electrostatic quadrupoles





- Muons see E field as a B field in their rest frame

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

- Choose $\gamma = 29.3$

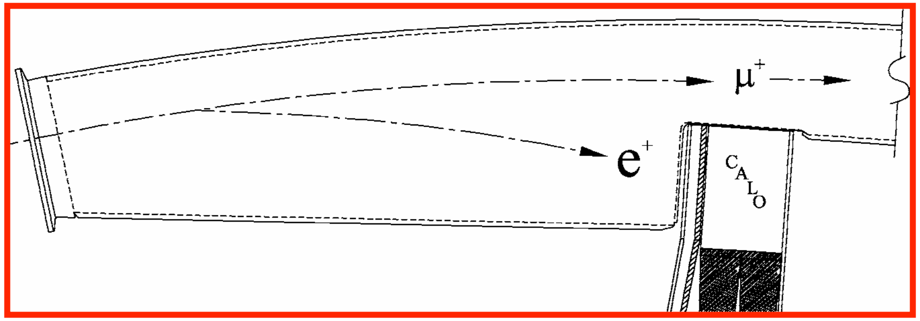
  $(p_\mu = 3.09 \text{ GeV/c})$
- E-field contribution vanishes

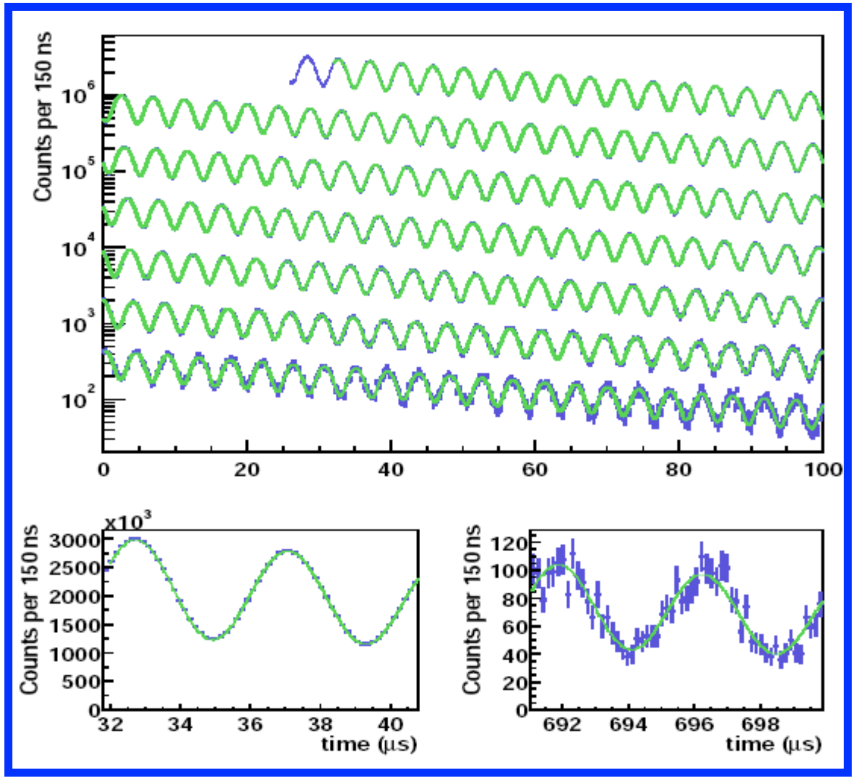
# Muons in a storage ring

$$\omega_a = e/m\ a_\mu\ B$$

Measuring the anomalous moment $a_\mu$ requires both

1. the spin precession frequency $\omega_a$





- Polarized muons from pion decay
- Muon decay self-analyzing : Higher energy positrons emitted preferentially in direction of muon spin

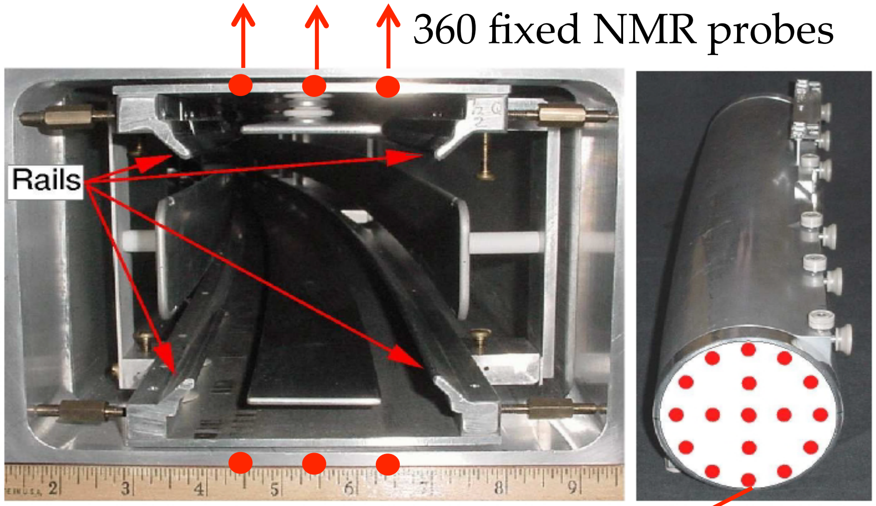
# Muons in a storage ring

$$\boxed{\omega_a = e/m\; a_\mu\; B}$$

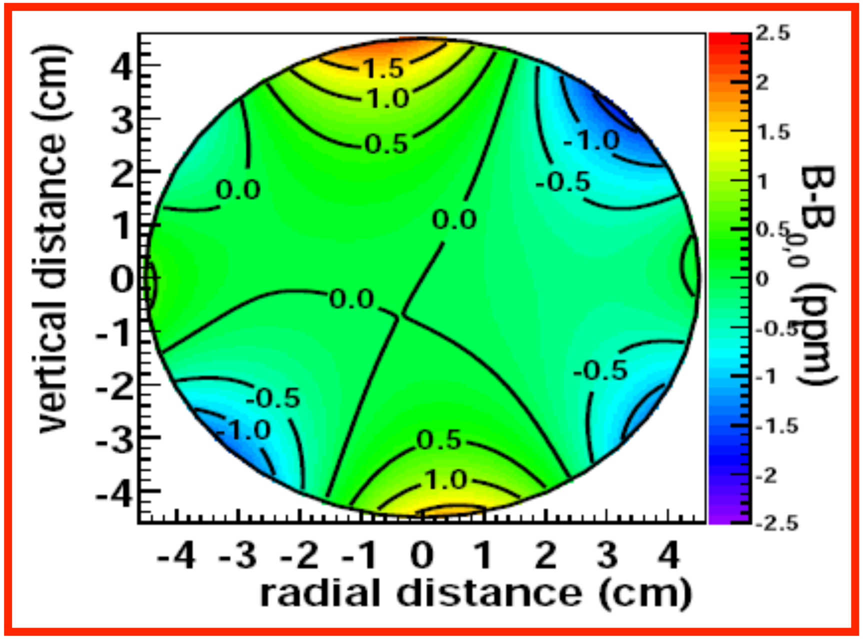
Measuring the anomalous moment **$a_\mu$** requires both

2. the magnetic field **B**

360 fixed NMR probes



17 NMR probes on trolley to map 6000 azimuthal locations



Measure field without muon beam
Monitor field with fixed probes
Extract field experienced by muons

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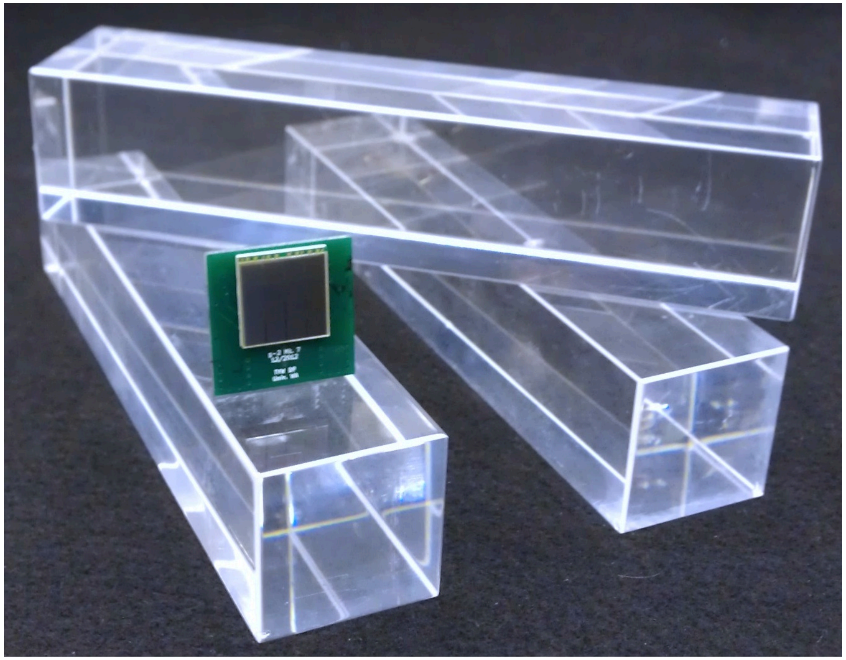
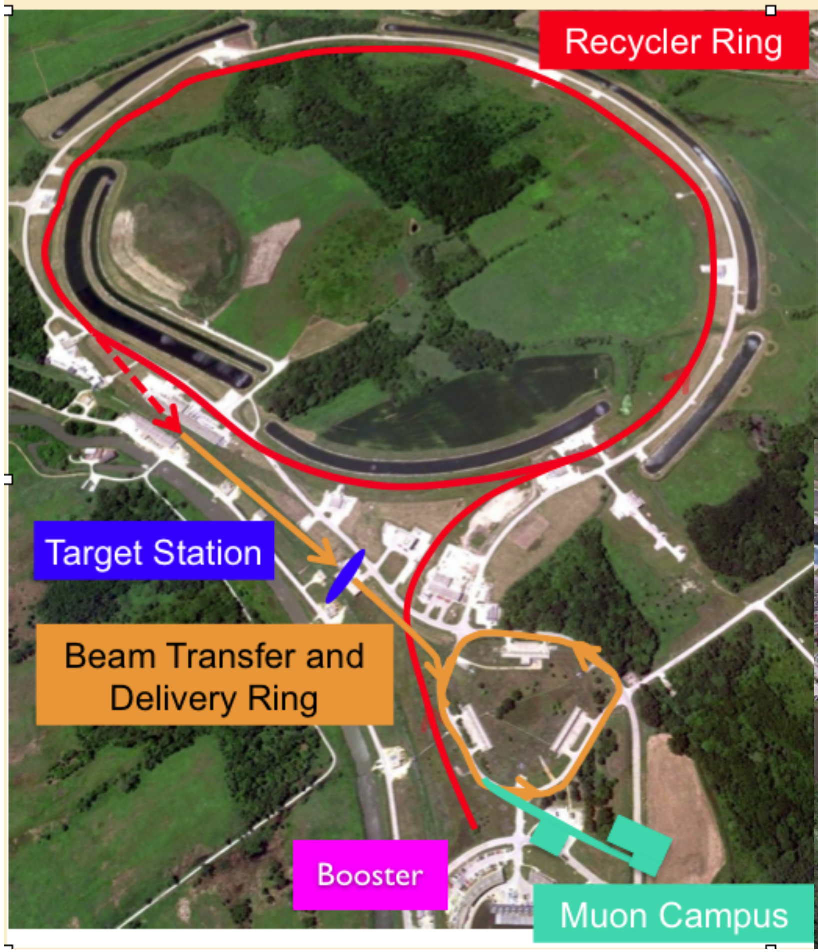


# Goal: 4x improvement in $\delta a_\mu^{exp} \rightarrow 16 \times 10^{-11}$ (0.14 ppm)

✓ Transport storage ring to Fermilab

1. Accelerator upgrades
   - Brookhaven experiment ended statistics-limited
   - Factor 20 increase in statistics at Fermilab (0.1 ppm)
   - Synergetic developments with mu2e experiment
2. Improve $\omega_a$ systematics (0.07 ppm)
   - Low-mass tracker to measure decay positron trajectories
   - Segmented calorimeter
3. Improve B-field systematics (0.07 ppm)
   - Better temperature control, B-field stability
   - Better shimming kit and modeling to improve azimuthal uniformity

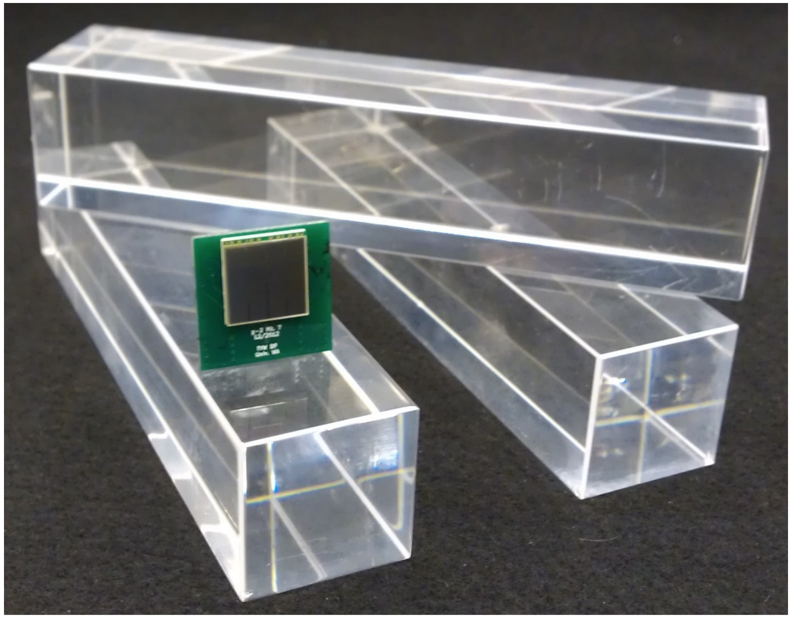
# Upgrade to infrastructure



Some Examples :

- More frequent proton batches
- Longer decay channel for pions, can separate hadronic background

# Calo: Segmented $PbF_2$ Cerenkov with SiPM



- PbF2 is dense
- Segmentation helps with pileup
- SiPM operate in magnetic fields
- Need very stable bias voltage

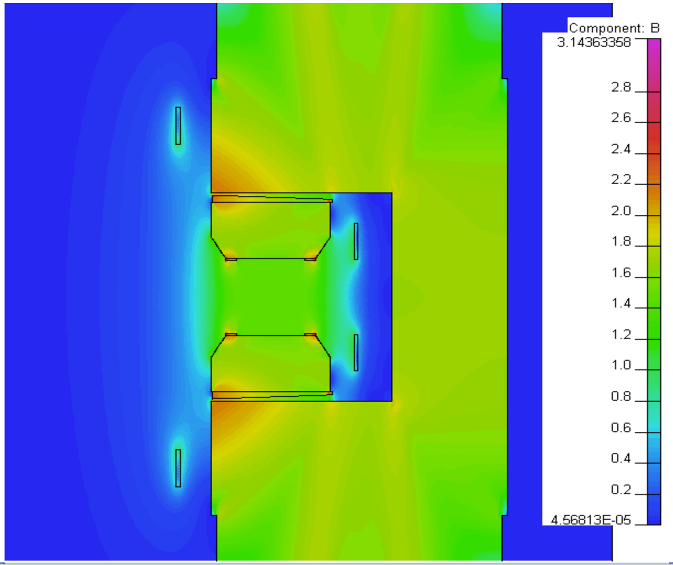
- Beam Tests
  - Fermilab 2012
  - SLAC 2014

| | |
|---|---|
| Size | 2.5 x 2.5 cm |
| Thickness | 14 cm (> 15 $X_0$) |
| Segmentation | 6 x 9 |
| Radiation length | 0.93 cm |
| Moliere radius $R_M$ | 2.2 cm |
| Moliere radius $R_M$ (Cerenkov) | 1.8 cm |

# Improvements for measuring the B field in E989

- Refurbish most of the existing NMR probes and equipment
- Add full waveform digitization of NMR signal
- Improve homogeneity of field with passive and active shims
- Better temperature control in new building

OPERA-2D simulation



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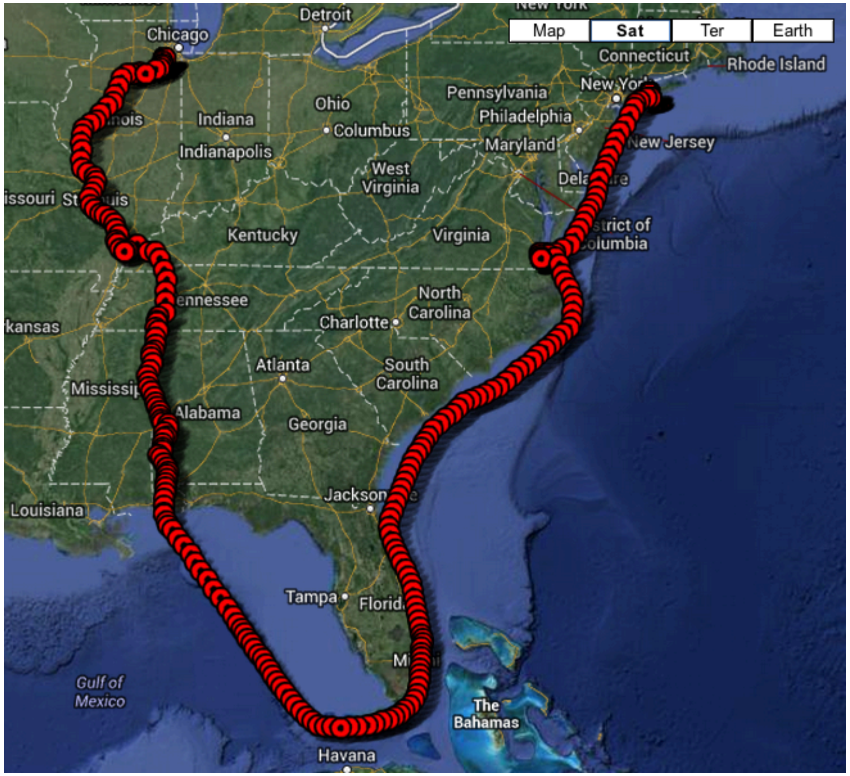
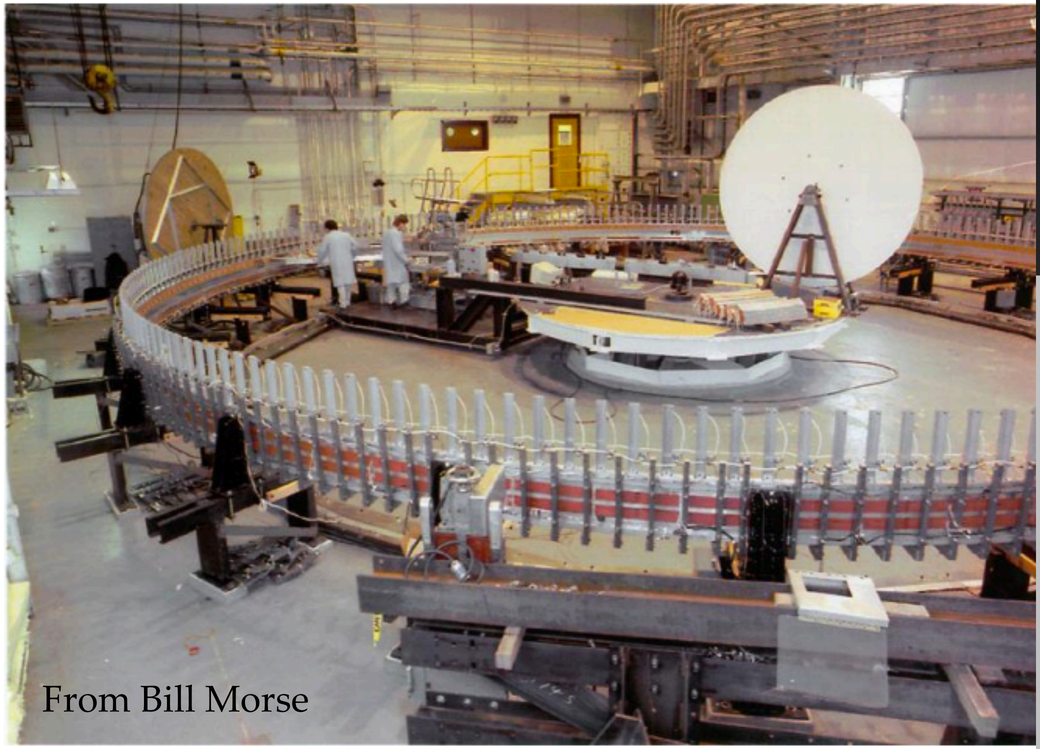
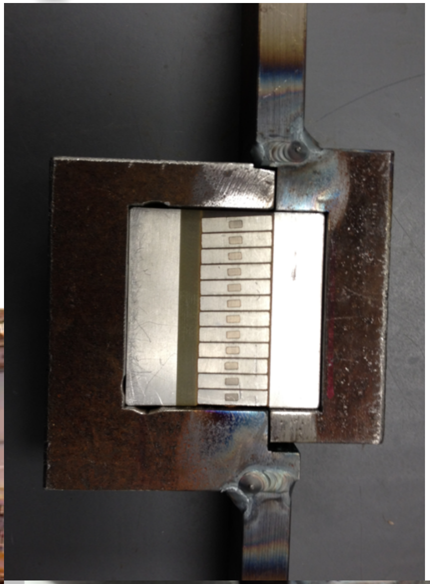


# The delicate requirements

- Largest SC coil by factor 10 in 1990s
- **Continuous winding** around 50 ft diameter
- Transporting much **more cost effective** than rebuilding


From Bill Morse

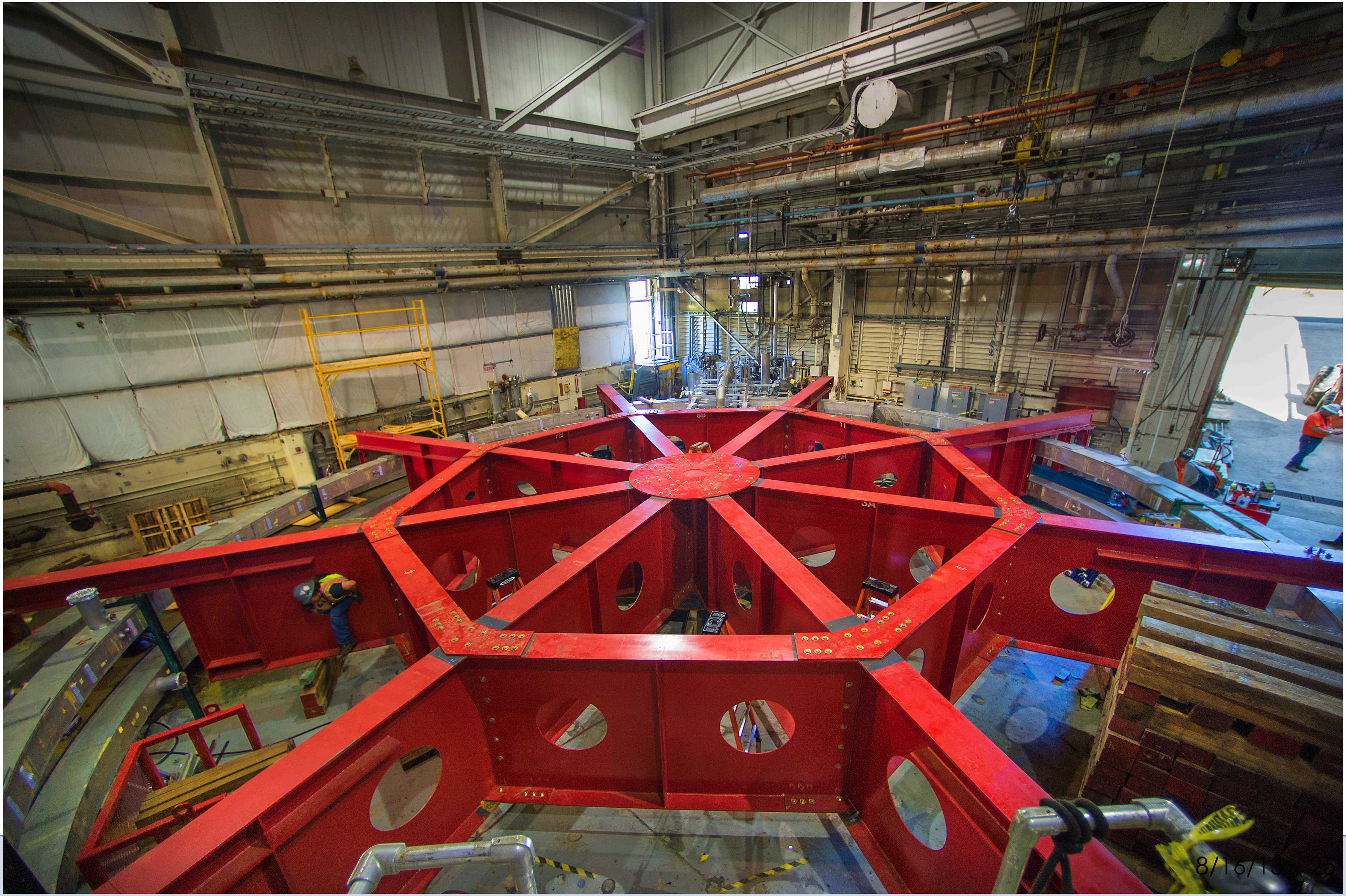

Shear tests + calculations divided by a safety factor set the deflection spec. (**3mm out of plane / twisting**)


**Wave analysis** to understand forces endured at sea

# Preparing for transport

- Rigid structure to fix ring
- Three point mount

# Fixture in place



# Not a spaceship

# Not a spaceship

A long time ago in a galaxy far, far away...

A little time ago on an island, 3,200 miles away ...

# Ready for the transport

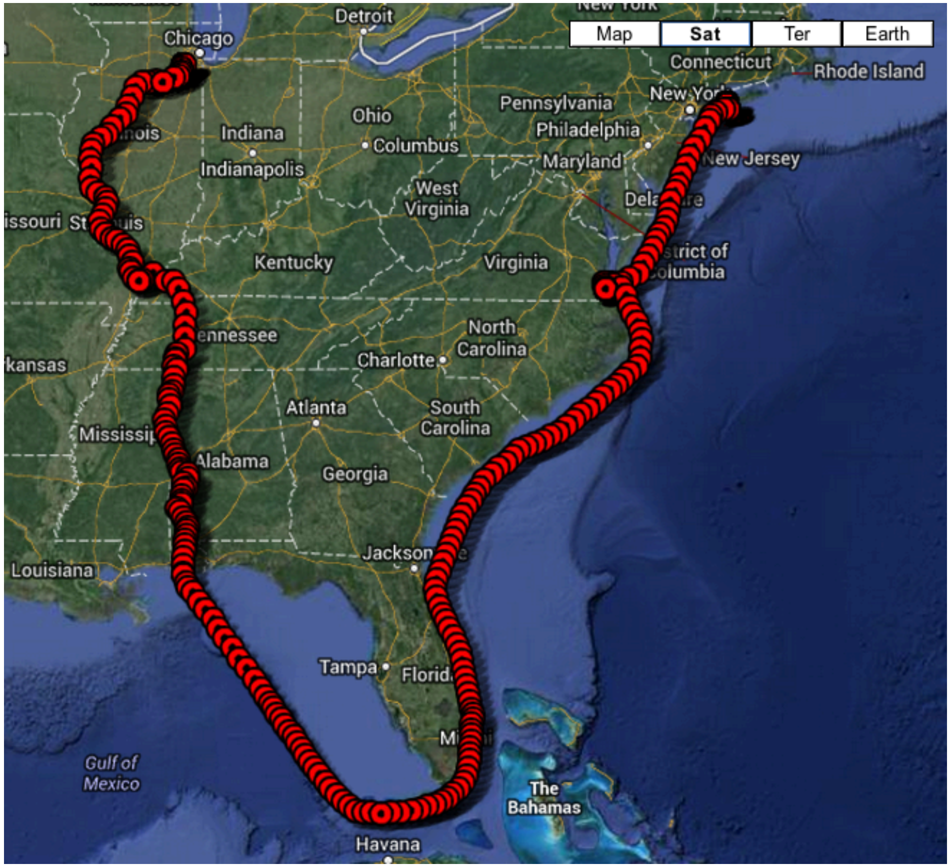
# Added shrink wrap & ready to roll

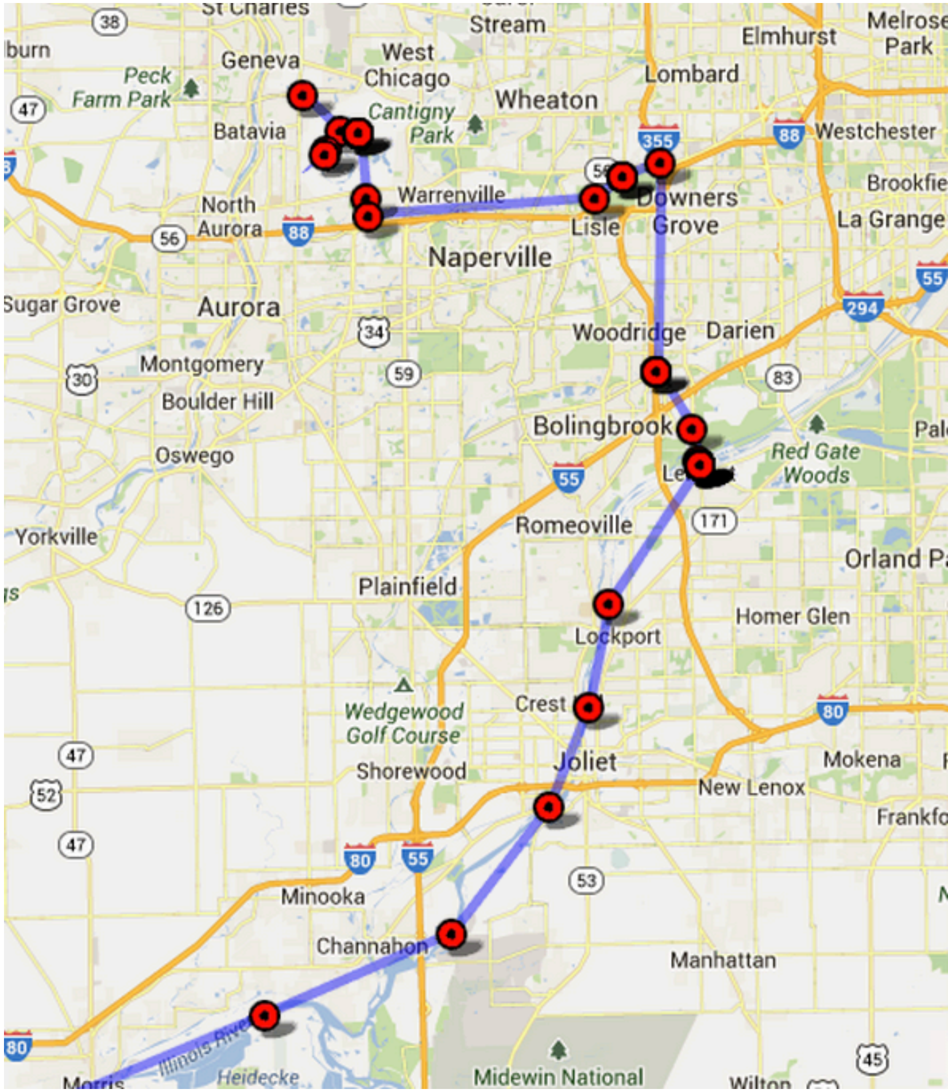
# Rolling Roadblocks

# Craned off of the trailer

# And onto the barge

# The journey





For photos and more info :
http://muon-g-2.fnal.gov/bigmove/

# Changing Tugboats in Mobile Bay July 12

Darin Clifton

Ocean Tug: Trident

River Tug: Miss Katie

# Passing through Illinois locks

Reidar Hahn

Reidar Hahn

# Arriving at Lemont July 20th, 2013

# No traffic on the interstate ☺

# July 26, 2013

- ❖The Physics of Muon g-2
- ❖Experimental Technique
- ❖Fermilab Muon g-2
- ❖The Ring Transport
- ❖**Outlook**

# Going forward

- ✓ Ring is at Fermilab
- Plan to start installation in the new building during the next six months
- Re-assemble yoke, coils, pole pieces and start the shimming procedure

- Simultaneous accelerator upgrades
- Beam in 2016…

Wilson Hall

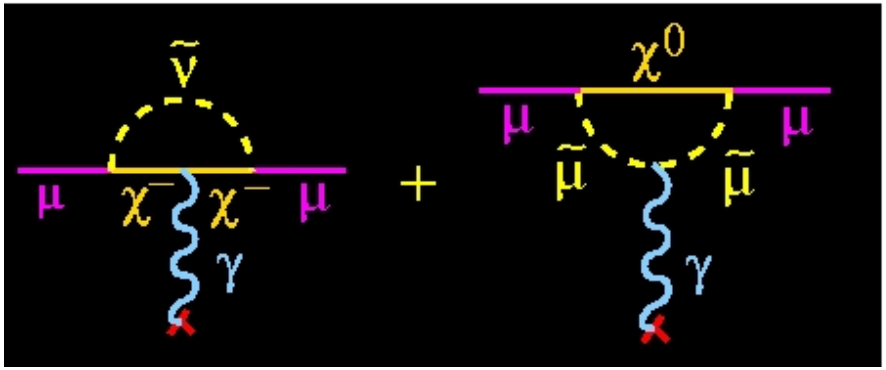
Forest of Dark Photons ?

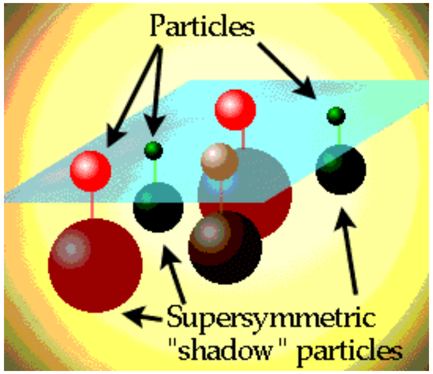
sWilson Hall?

# Backup Slides

# What about the new physics?

**One example: SUSY**



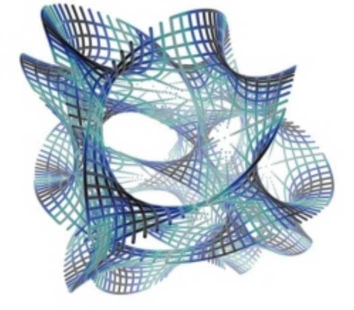


$$a_\mu(\mathrm{SUSY}) \simeq \boxed{(\mathrm{sgn}\mu)}\, 130\times10^{-11}\, \boxed{\tan\beta} \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

**difficult to measure at LHC**

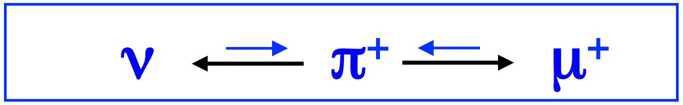
**Another example: Universal Extra Dimensions**

$$a_\mu(\mathrm{UED}) \approx -13 \times 10^{-11}$$



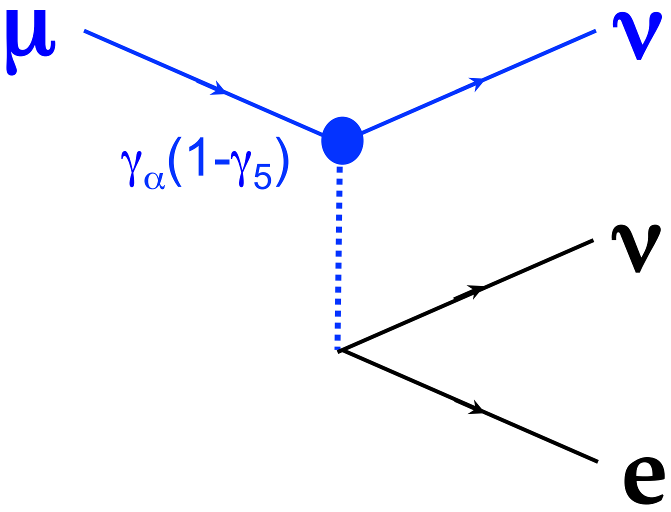
# Two important ingredients

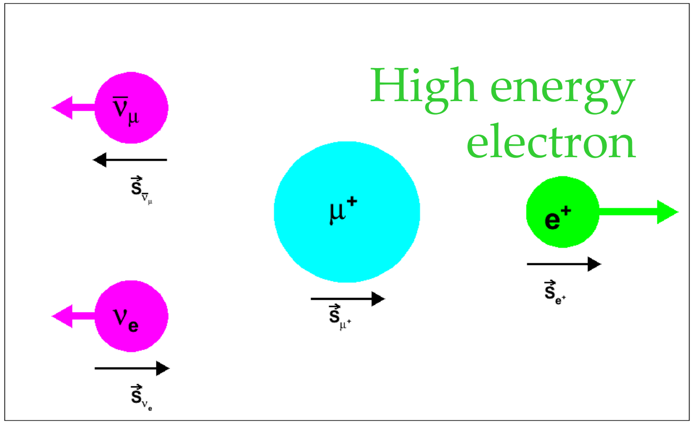
1. Polarized muons from pion decay



2. Muon decay is self-analyzing

$\mu \rightarrow e\,\nu\,\nu$





# $a_\mu^{SM}$ limited by hadronic terms

## Hadronic Vacuum Polarization

- Ingredients:
  - Experimental determination:

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  - Dispersion relation

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  - $\delta a_\mu^{HVP}$ ~ 0.36 part-per-million
- Pending Improvements:
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  - Parallel lattice QCD efforts
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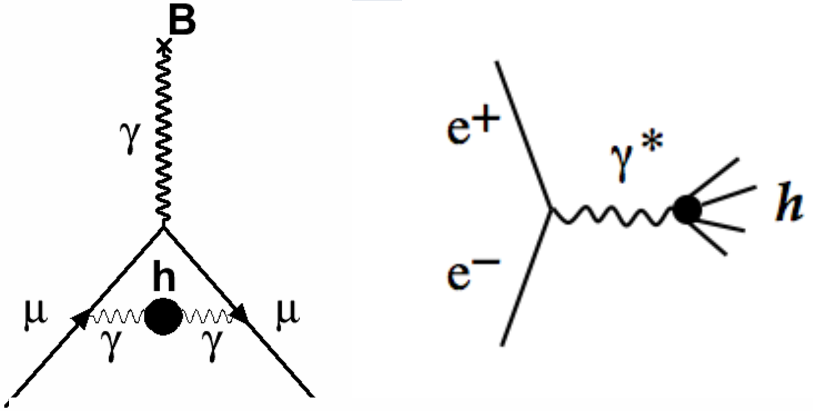
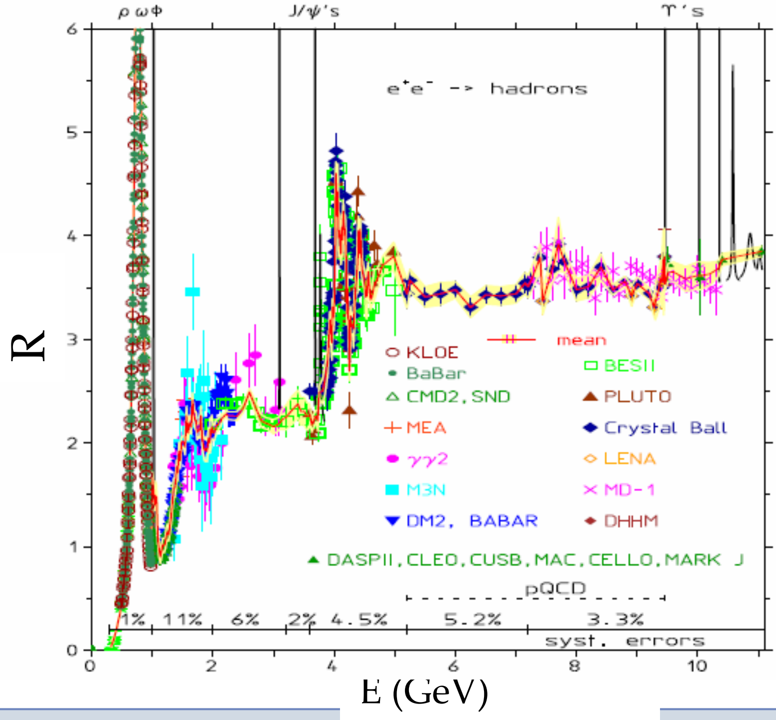
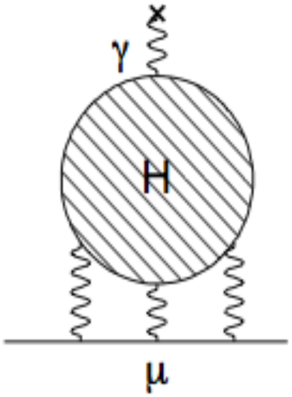




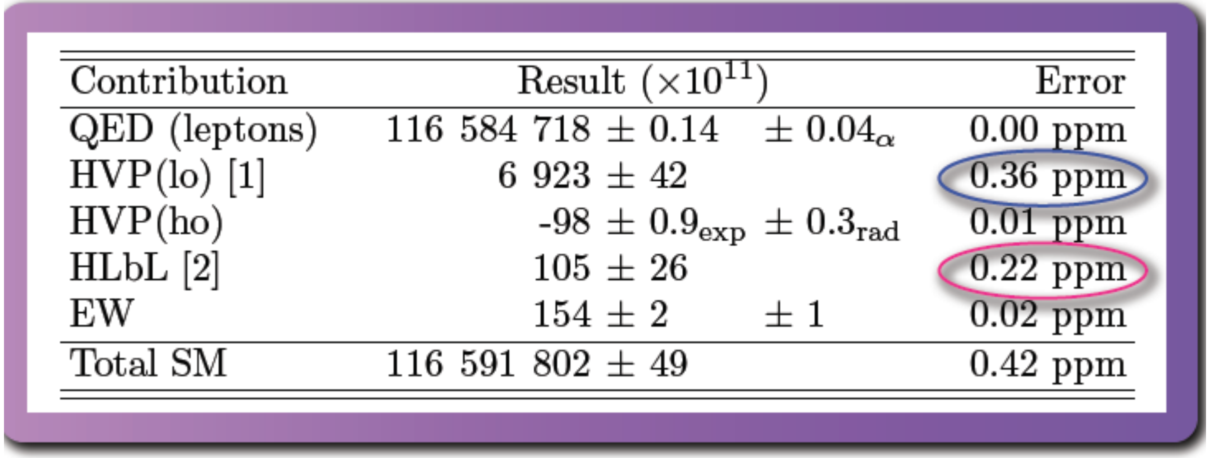
# $a_\mu^{SM}$ limited by hadronic terms

- Hadronic light by light scattering
  - More complicated
  - Not expressed in terms of experimental quantities
  - Uncertainties are model-dependent



  - Early lattice calculations appear promising
  - Will require significant computing resources

From R. Van de Water

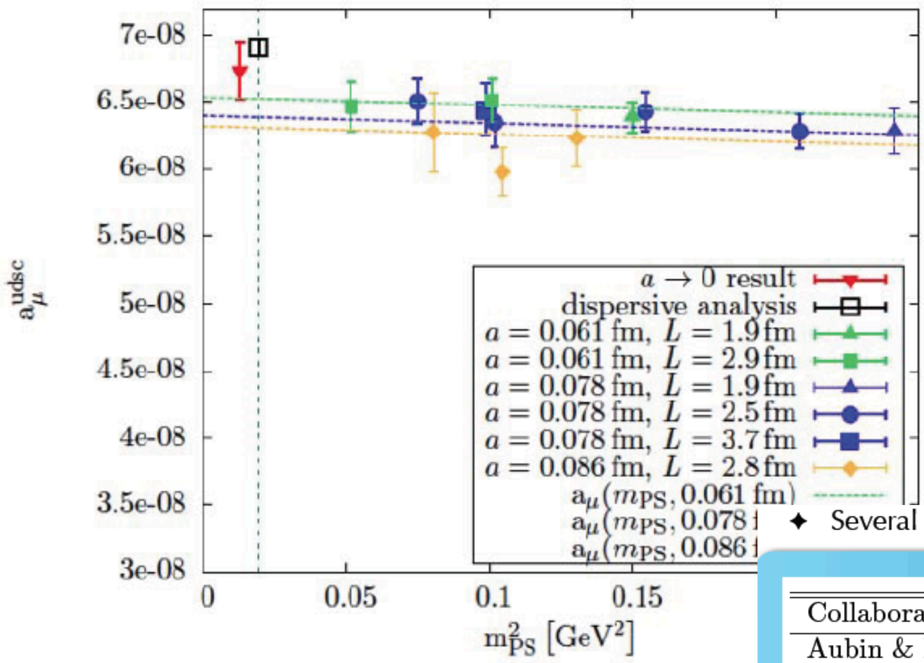


| Contribution | Result ($\times 10^{11}$) |  | Error |
|---|---|---|---|
| QED (leptons) | 116 584 718 ± 0.14 | $\pm 0.04_\alpha$ | 0.00 ppm |
| HVP(lo) [1] | 6 923 ± 42 |  | 0.36 ppm |
| HVP(ho) | $-98 \pm 0.9_{\text{exp}}$ | $\pm 0.3_{\text{rad}}$ | 0.01 ppm |
| HLbL [2] | 105 ± 26 |  | 0.22 ppm |
| EW | 154 ± 2 | ± 1 | 0.02 ppm |
| Total SM | 116 591 802 ± 49 |  | 0.42 ppm |

All plots from Ruth Van de Water @ Snowmass, Aug 2013

# First four-flavor result (PRELIMINARY)

[G. Hotzel for ETM Collaboration, Lattice 2013]



$$a_\mu^{HVP} = 6.74(21)_{stat}(18)_{sys} \times 10^{-10}$$

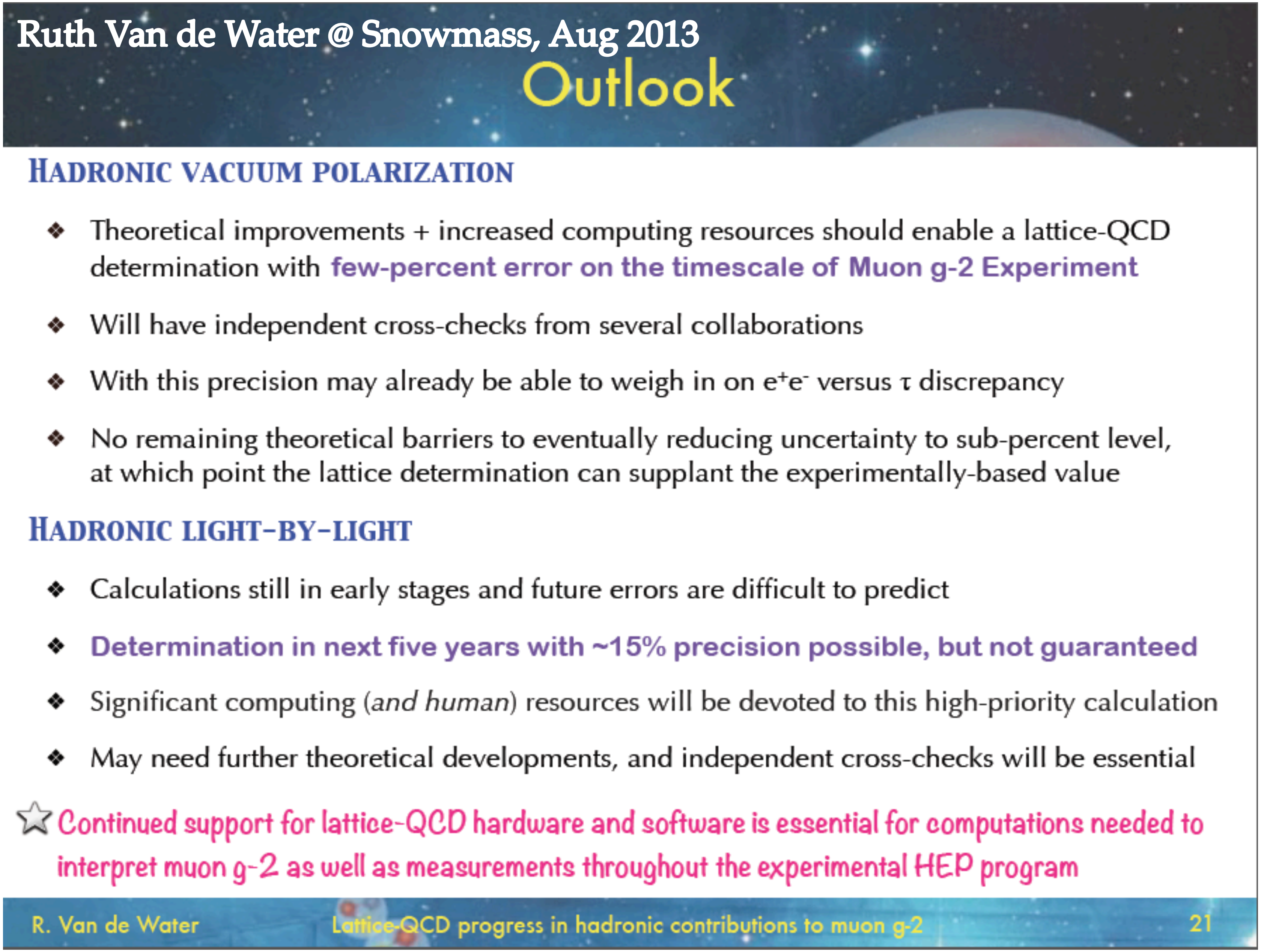
- Error estimate does not yet include sea-quark mass mistuning (small) or quark-disconnected contributions (as much as ~10%?)
- Several independent efforts ongoing

| Collaboration | $N_f$ | Fermion action | $a_\mu^{HVP} \times 10^{10}$ |
|---|---|---|---|
| Aubin & Blum | 2+1 | Asqtad staggered | $713(15)_{stat}(31)_{\chi PT}(??)_{other}$ |
| ETMC | 2 | twisted-mass | $572(16)_{total}$ |
| ETMC (*preliminary*) | 2+1+1 | twisted-mass | $674(21)_{stat}(18)_{sys}(??)_{disc}$ |
| Edinburgh | 2+1 | domain-wall | $641(33)_{stat}(32)_{sys}(??)_{disc}$ |
| Mainz | 2 | $\mathcal{O}(a)$ improved Wilson | $618(64)_{stat+sys}(??)_{disc}$ |

R. Van de Water   Lattice-QCD progress in hadr

| Contribution | Result ($\times 10^{11}$) | Error |
|---|---|---|
| QED (leptons) | $116\ 584\ 718 \pm 0.14 \pm 0.04_\alpha$ | 0.00 ppm |
| HVP(lo) [1] | $6\ 923 \pm 42$ | 0.36 ppm |
| HVP(ho) | $-98 \pm 0.9_{exp} \pm 0.3_{rad}$ | 0.01 ppm |

# Ruth Van de Water @ Snowmass, Aug 2013



## Outlook

### HADRONIC VACUUM POLARIZATION

- Theoretical improvements + increased computing resources should enable a lattice-QCD determination with **few-percent error on the timescale of Muon g-2 Experiment**
- Will have independent cross-checks from several collaborations
- With this precision may already be able to weigh in on $e^+e^-$ versus $\tau$ discrepancy
- No remaining theoretical barriers to eventually reducing uncertainty to sub-percent level, at which point the lattice determination can supplant the experimentally-based value

### HADRONIC LIGHT-BY-LIGHT

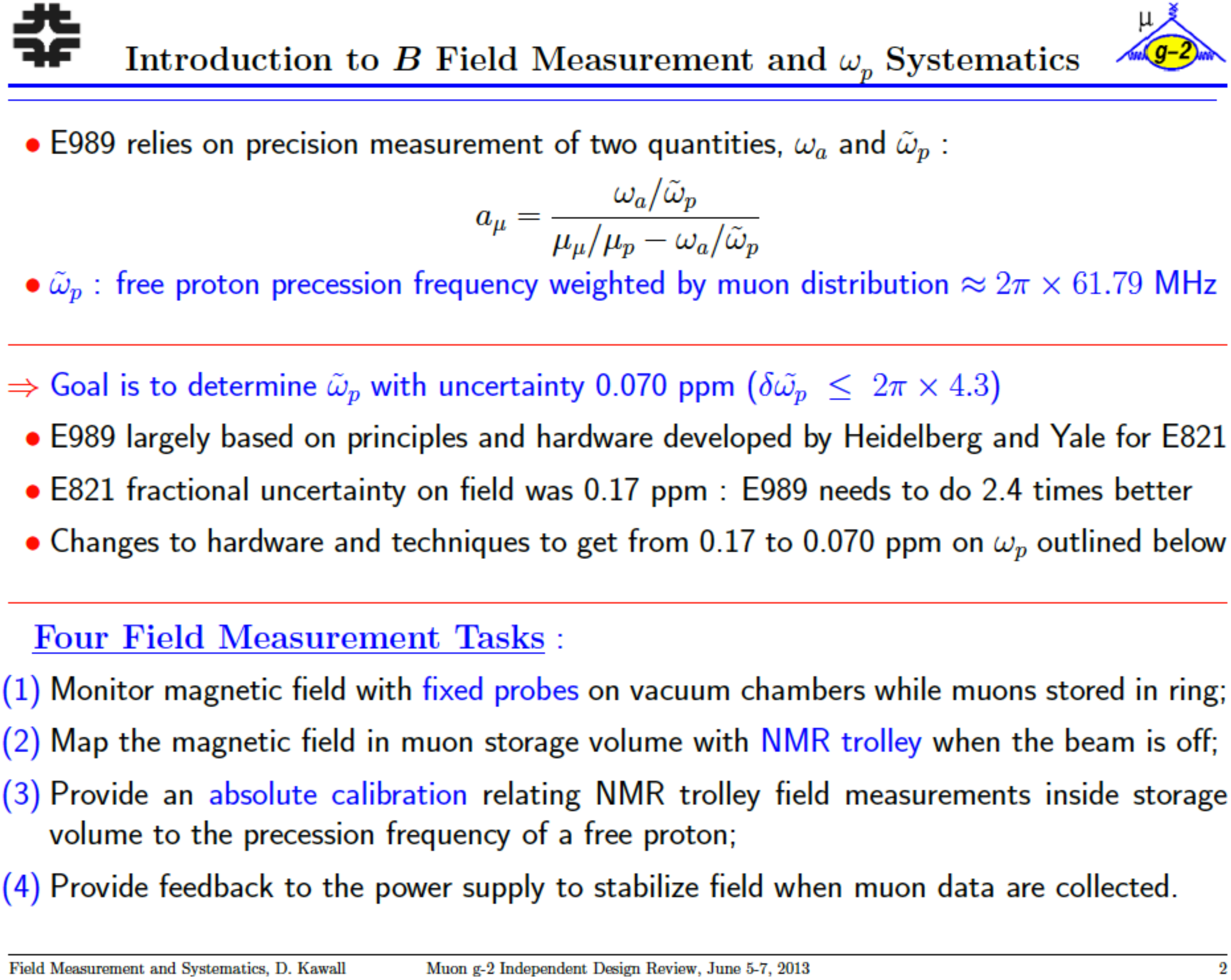
- Calculations still in early stages and future errors are difficult to predict
- **Determination in next five years with ~15% precision possible, but not guaranteed**
- Significant computing (*and human*) resources will be devoted to this high-priority calculation
- May need further theoretical developments, and independent cross-checks will be essential

☆ Continued support for lattice-QCD hardware and software is essential for computations needed to interpret muon g-2 as well as measurements throughout the experimental HEP program

# Current status of $a_\mu$ in Standard Model

| | Value ($\times 10^{-11}$) |
|---|---|
| QED | 116 584 718.951 ± 0.009 ± 0.019 ± 0.007 ± 0.077 |
| HVP (lo) | 6949 ± 42 |
| HVP (ho) | -98.4 ± 0.7 |
| HLBL | 105 ± 26 |
| EQ | 154 ± 1 |
| Total SM | 116 591 802 ± 49 |

$$\boxed{a_\mu^{\text{Expt.}} - a_\mu^{\text{SM}} = (260 \pm 78) \times 10^{-11} \quad (3.3\,\sigma)}$$



## Introduction to $B$ Field Measurement and $\omega_p$ Systematics

- E989 relies on precision measurement of two quantities, $\omega_a$ and $\tilde{\omega}_p$ :

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

- $\tilde{\omega}_p$ : free proton precession frequency weighted by muon distribution $\approx 2\pi \times 61.79$ MHz

⇒ Goal is to determine $\tilde{\omega}_p$ with uncertainty 0.070 ppm ($\delta\tilde{\omega}_p \ \leq \ 2\pi \times 4.3$)

- E989 largely based on principles and hardware developed by Heidelberg and Yale for E821
- E821 fractional uncertainty on field was 0.17 ppm : E989 needs to do 2.4 times better
- Changes to hardware and techniques to get from 0.17 to 0.070 ppm on $\omega_p$ outlined below

### Four Field Measurement Tasks :

(1) Monitor magnetic field with fixed probes on vacuum chambers while muons stored in ring;

(2) Map the magnetic field in muon storage volume with NMR trolley when the beam is off;

(3) Provide an absolute calibration relating NMR trolley field measurements inside storage volume to the precession frequency of a free proton;

(4) Provide feedback to the power supply to stabilize field when muon data are collected.

Field Measurement and Systematics, D. Kawall Muon g-2 Independent Design Review, June 5-7, 2013 2

# Main E989 Improvements in Field Measurement

| Category | E821 [ppm] | Main E989 Improvement Plans | Goal [ppm] |
|---|---|---|---|
| Absolute field calibration | 0.05 | Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics | 0.035 |
| Trolley probe calibrations | 0.09 | Smaller abs cal probe to calibrate all trolley probes; better position accuracy by physical stops and/or optical survey; more frequent calib, better shimming | 0.03 |
| Trolley measurements of $B_0$ | 0.05 | Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients | 0.03 |
| Fixed probe interpolation | 0.07 | More frequent trolley runs; more fixed probes; better temp. stability of the magnet, correct for $\Delta I$ | 0.03 |
| Muon distribution | 0.03 | Additional probes at larger radii; improved field uniformity; improved muon tracking | 0.01 |
| Time-dependent external magnetic fields | – | Direct measurement of external fields; simulations of impact; active feedback | 0.005 |
| Others † | 0.10 | Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients | 0.03 |
| Total syst. unc. on $\omega_p$ | 0.17 | | 0.07 |

# Shrink wrap