

# Muon g-2 and the Fermilab Program

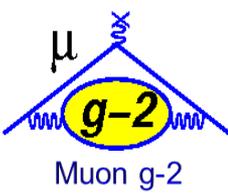
QuarkNet Workshop  
July 13, 2016

Chris Polly



U.S. DEPARTMENT OF  
**ENERGY**

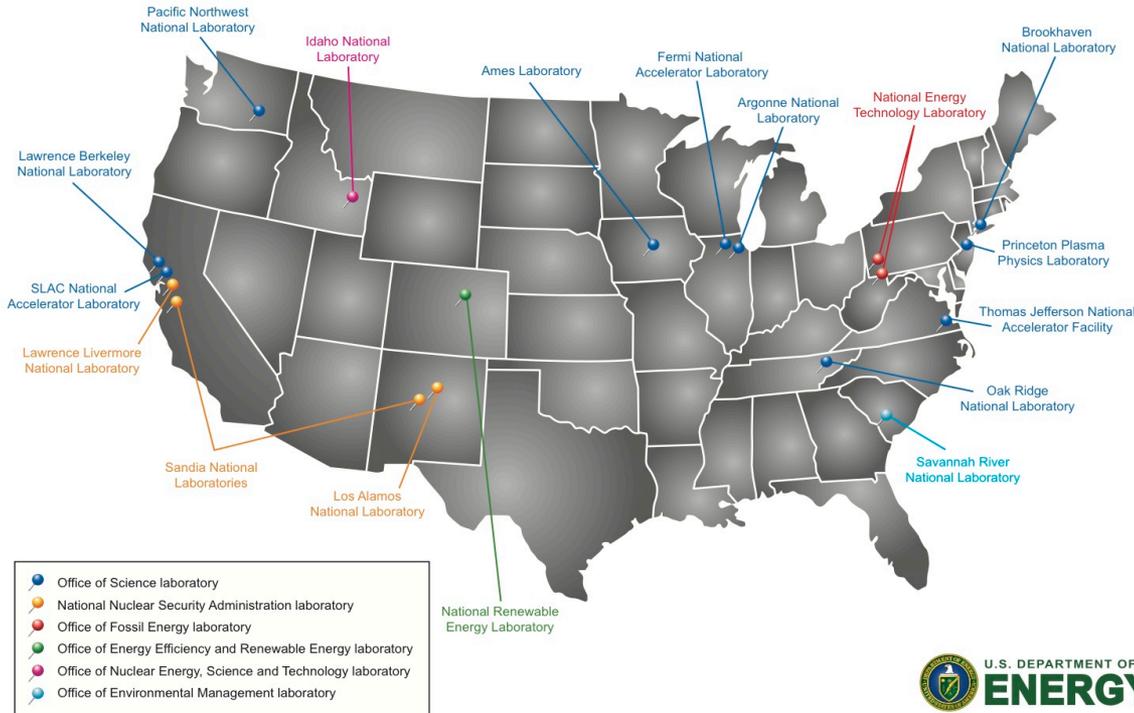
Office of  
Science



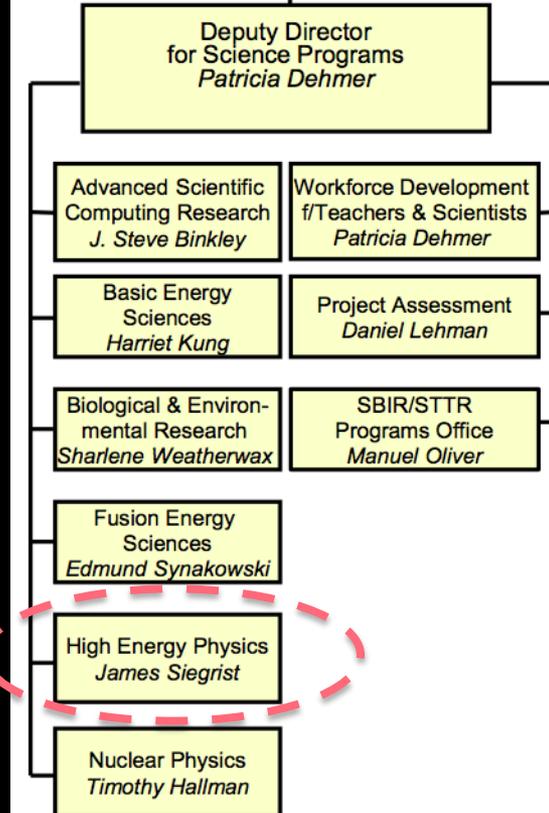
# Intro to Fermilab and the Muon Program

# Fermilab is one of 19 DOE National Laboratories

## Department of Energy National Laboratories

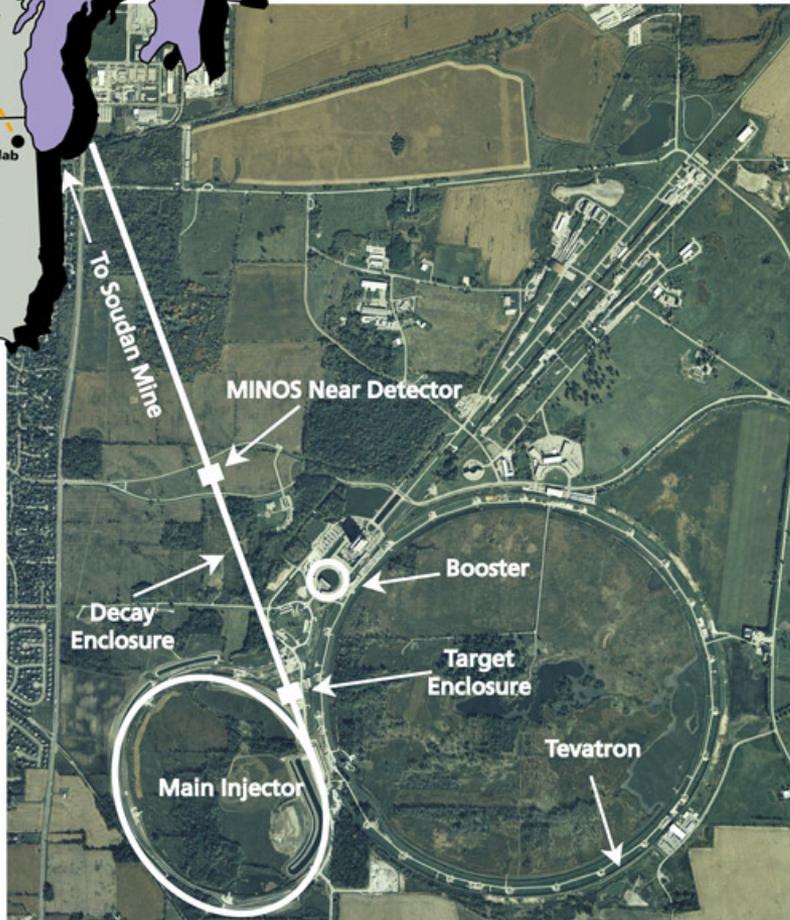
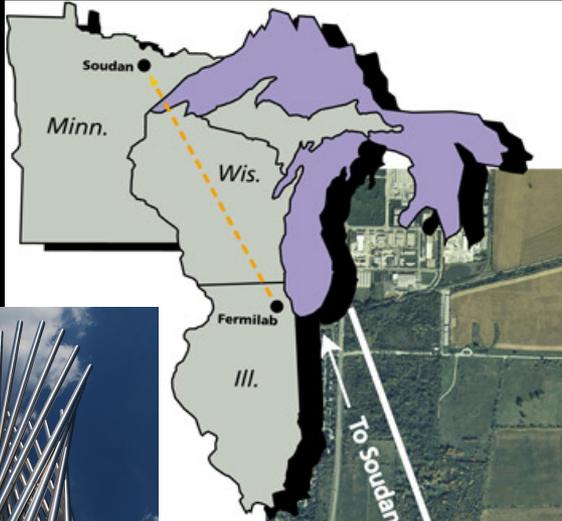


## Office of Science\*



\*DOE OS & NSF are the primary funding agencies for basic physical sciences in the US

# Fermilab unique



- Main laboratory for the Office of High Energy Physics

*"...explore the elementary constituents of matter and energy, the interactions between them, and the nature of space and time." - Mission Statement*

- Primary stewards of Accelerator Technology for the Office of Science
  - 30,000 operational accelerators in the world in various applications that arose from basic R&D
- 6800 acre completely open scientific facility
  - Prairie restoration project, bison farm, Wilson aesthetics

# So, what is our mission?

*The mission of the High Energy Physics program is to understand how our universe works at its most fundamental level. We do this by discovering the most elementary constituents of matter and energy, exploring the basic nature of space and time itself, and probing the interactions between them.*

We do this by

- building massive particle accelerators and advancing fundamental R&D
- employing world-class scientists and engineers that collaborate internationally on projects too big for one country to pursue alone
- developing experiments that test, expand upon, and occasionally discover the most fundamental laws of nature



**Senator John Pastore:** "Is there anything connected with the hopes of this accelerator that in any way involves the security of the country?"

**Physicist Robert Rathburn Wilson:** "No sir, I don't believe so."

**Pastore:** "Nothing at all?"

**Wilson:** "Nothing at all."

**Pastore:** "It has no value in that respect?"

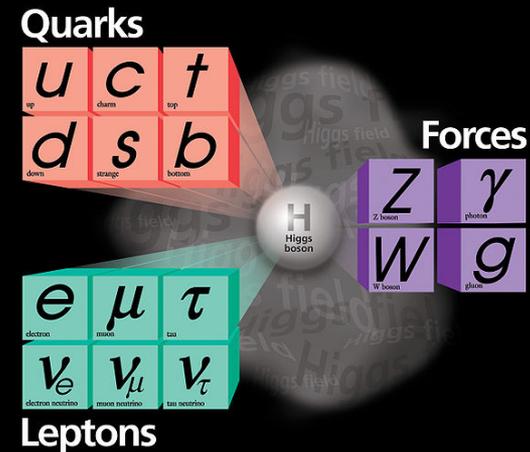
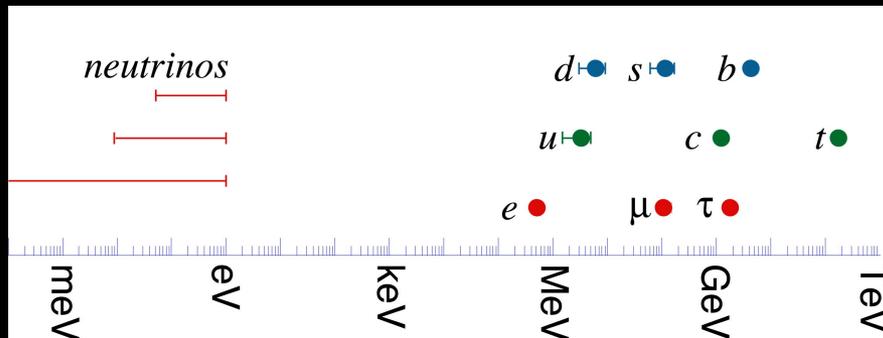
**Wilson:** "It has only to do with the respect with which we regard one another, the dignity of man, our love of culture. It has to do with: Are we good painters, good sculptors, great poets? I mean all the things we really venerate in our country and are patriotic about. It has nothing to do directly with defending our country except to make it worth defending."

- Robert Wilson, founding director of the National Accelerator Laboratory testifying to the Atomic Energy Commission in 1969

# Some of the big questions



- What is the source of the dark energy that is blowing the universe apart?
- What is the dark matter that appears to create 5x more mass in the universe than what we can explain?
- What happened to all the anti-matter?
- What is the mechanism that causes the Higgs mass to be so light?
- Why are neutrinos so weird? Mass scale & oscillations
- Are there other particles and forces yet to be discovered?



# What kind of people work at Fermilab? All kinds...

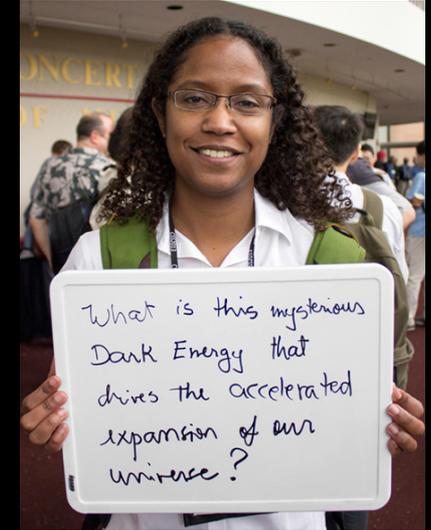


Particle Physicists

Accelerator Scientists

Astrophysicists

Scientists developing new technology



Computing



Theoretical Physicists



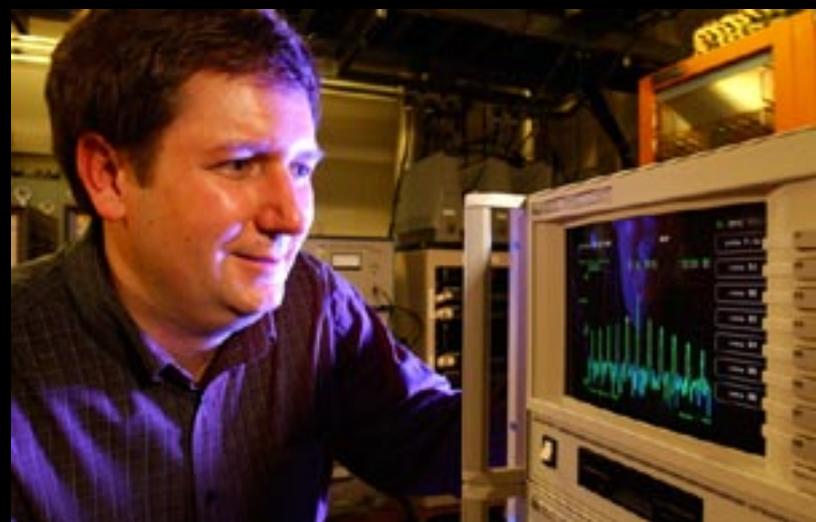
Scientists

# What kind of people work at Fermilab? 1700 of them... RF Engineers

Cryogenics



Civil



Electrical



Mechanical



# Engineers

# What kind of people work at Fermilab? Versatile...

Operators

Finance



Engineering  
Physicists



Mechanical/Electrical  
Technicians

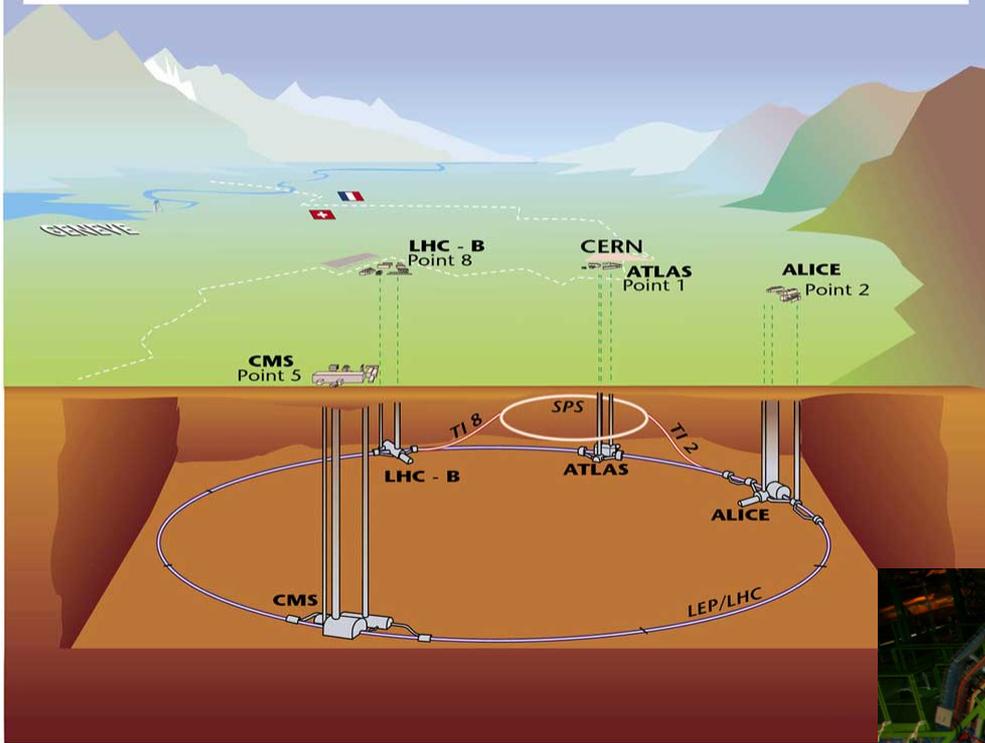


Managers

Technical Staff

# We work on many experiments...here and abroad

Overall view of the LHC experiments.

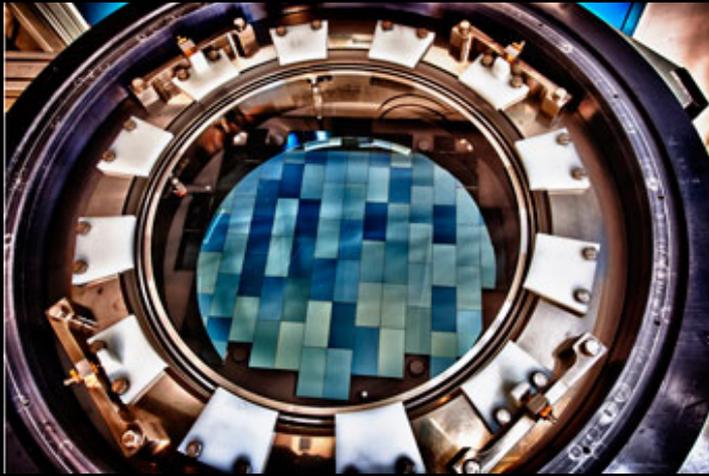


27 kilometers LHC – high energy accelerator in Europe

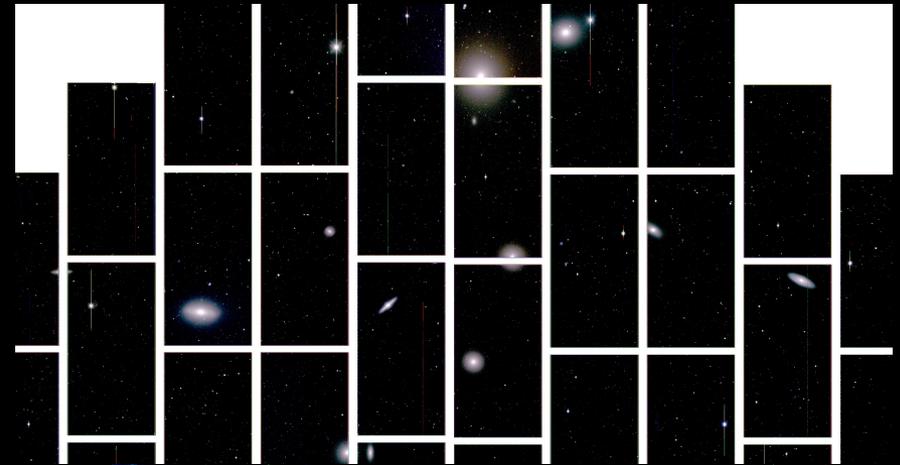
CMS detector – one of two experiments where the Higgs boson was definitively discovered



# Astrophysical Telescopes – Dark Energy Camera



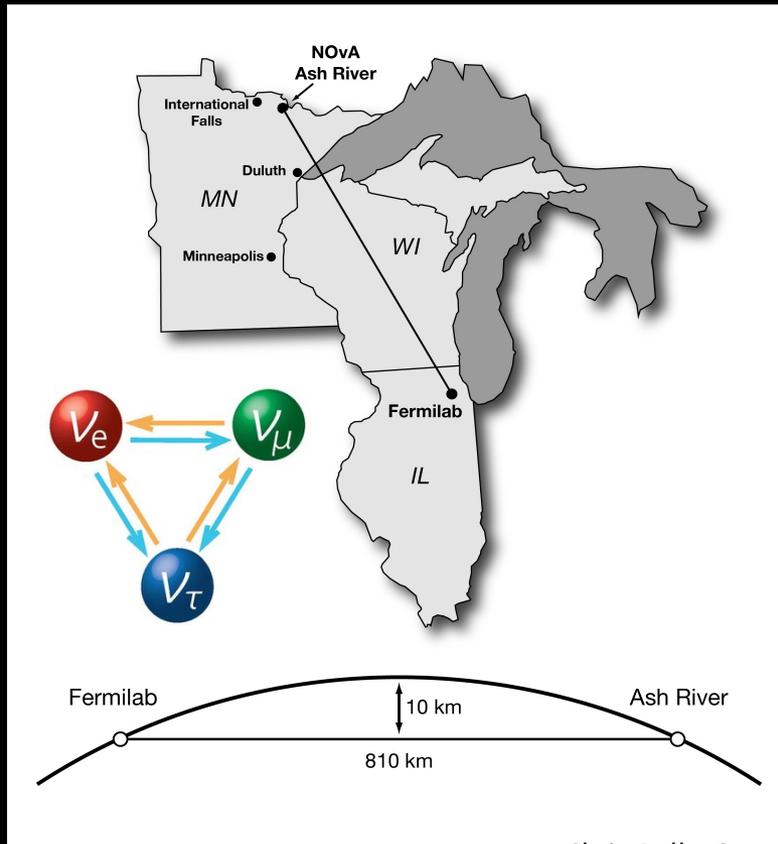
Constructed camera, now installed in telescope on mountain top in Chile...large angle survey will provide highest statistic, deepest samples to date on Supernovae, galaxy clusters, and lensing...all ingredients for understanding dark matter and E



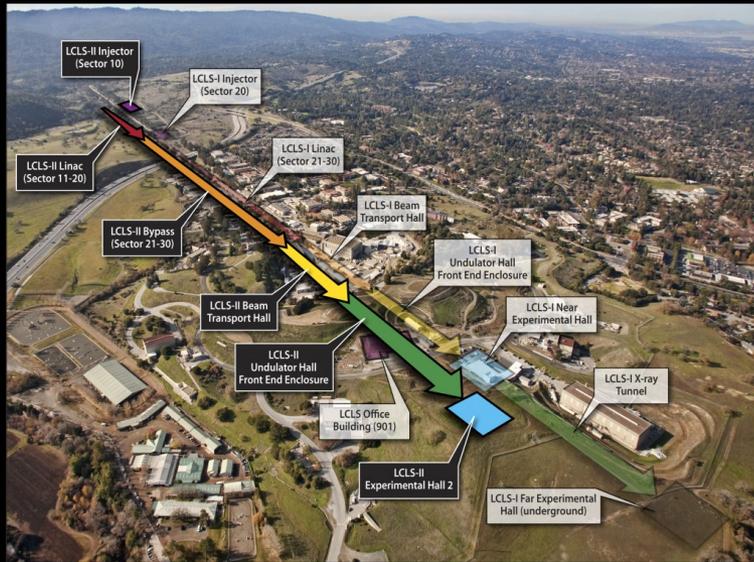
# Neutrino beams through the Earth

Over long distances, we know neutrinos oscillate and it has become a goal to make more precise measurements so that we might some day understand why

By long distances, I mean very long distances... will get to go underground later to see MINOS & NOvA beam and near detectors



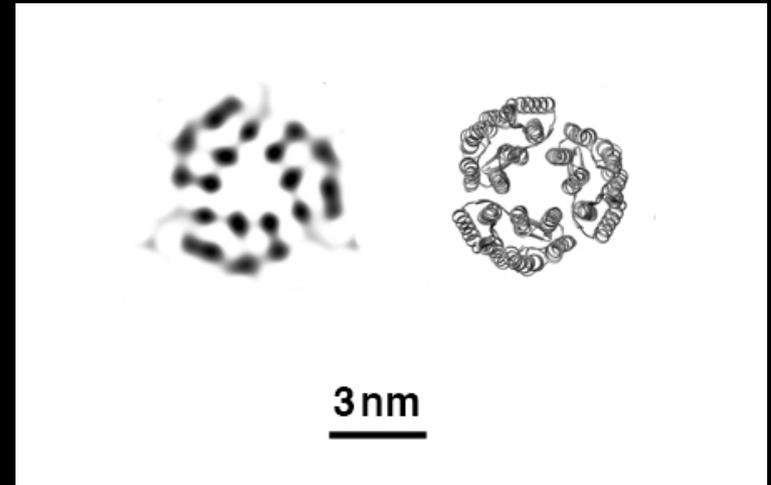
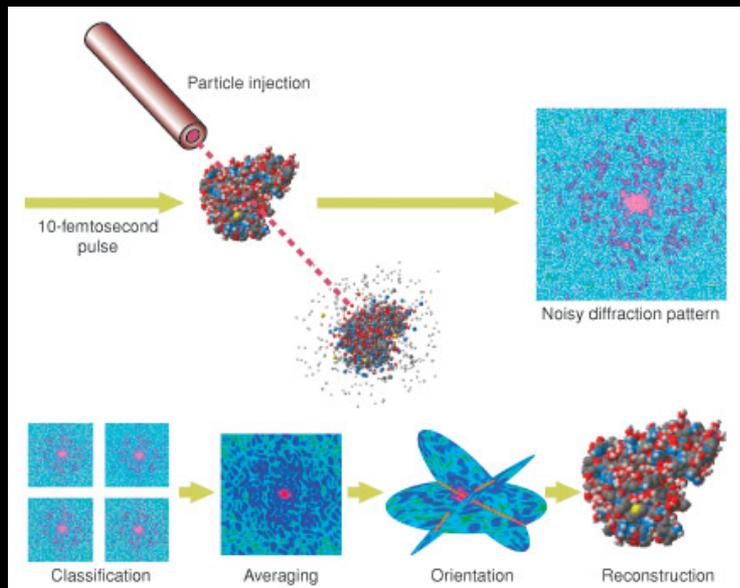
# Accelerators for the future



Due to Fermilab's expertise in building particle accelerators, we are often called upon

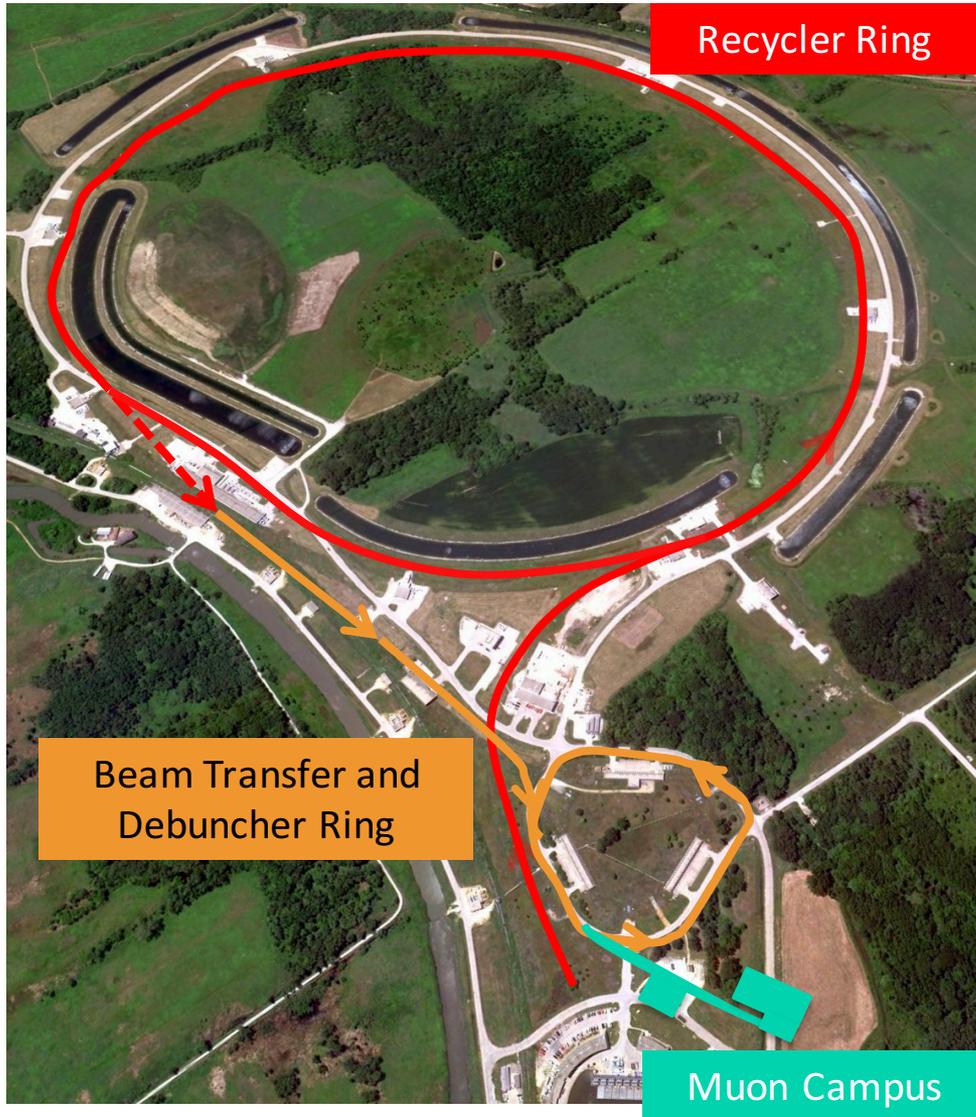
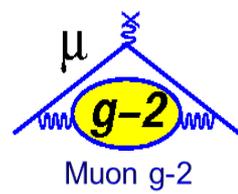
Building half of the SRF cavities needed for the next generation light source at Stanford

Light sources allow us to image molecules at resolution far greater than ever before





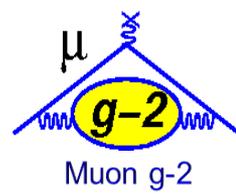
# The Fermilab Muon Program



- Starting in 2009, several groups started looking at what could be done at Fermilab after the impending shut down of the Tevatron
- Suddenly, several \$100M worth of equipment and accelerators available for first time in decades
- In particular, the facility use for generating the anti-matter proton ( $p\bar{b}ar$ ) beam could be used to make other particles, e.g. muons
- In 2011, the Tevatron saw its last collision, but the stage was set for the construction of a new muon program
- Muon Campus to house 2 new experiments
  - Mu2e
  - Muon g-2



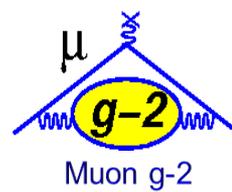
# Muon Campus vision, circa 2013



- New facility under construction
  - Two new experimental halls and the tunnel infrastructure to connect to the complex
  - Capability of produce and deliver high intensity customized muon beams



# Why muons?



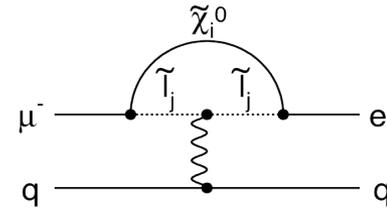
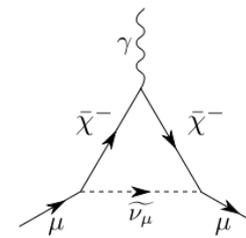
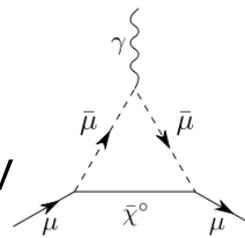
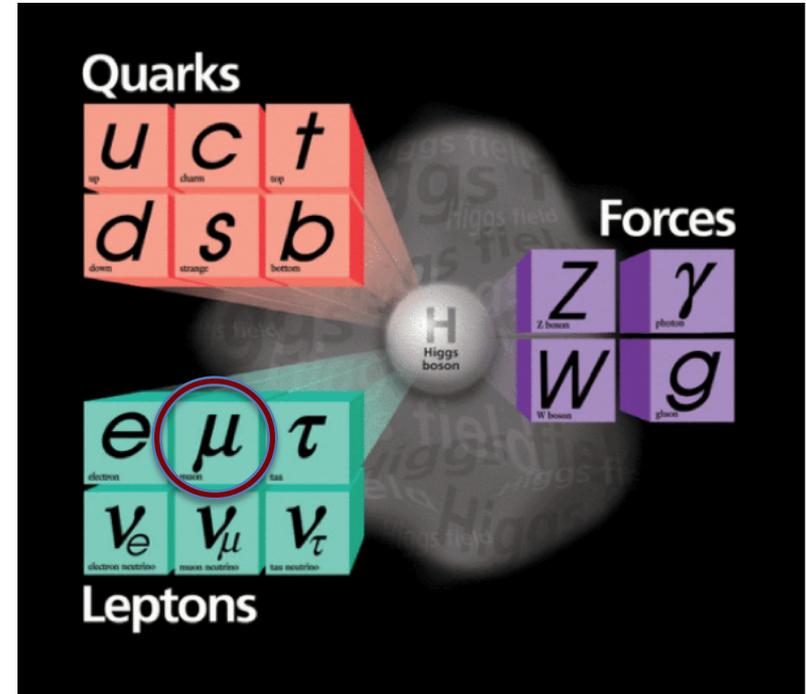
## Muons can be extremely good probes of the Standard Model

- Can be produced copiously  
 $BR(\pi^\pm \rightarrow \mu^\pm \nu) = 99.9877\%$
- Don't get ensnared by the strong force
- Relatively long life time  $2.2 \mu\text{s}$
- Relatively heavy  $(m_\mu/m_e)^2 = 40000$

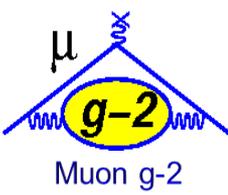
## Developing a program at Fermilab based on using muons as tools

- Muon g-2 experiment (data 2017)
- Mu2e experiment (data 2020)
- Future possibilities for other muon-based experiments, e.g. muon EDM, other CLFV channels

## The Standard Model



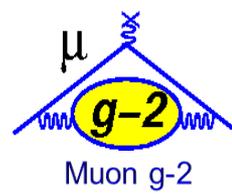
Windows into new physics...



# Magnetic moments



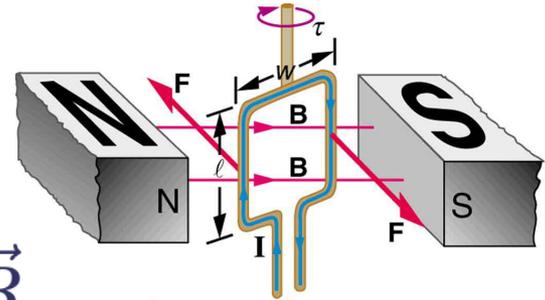
# Magnetic moments...classical



- Magnetic moments have been an invaluable tool for probing basic physics for a very long time!
- For a system of classical charged particles...

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c} \vec{L}_i$$

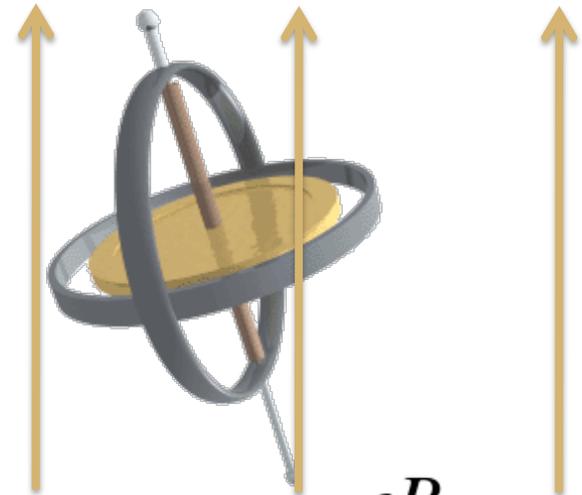
$$\vec{\tau} = \vec{\mu} \times \vec{B}, \quad U = -\vec{\mu} \cdot \vec{B}$$



- For particles with spin

$$\vec{\mu} = g \frac{q\hbar}{4mc} \vec{\sigma}, \quad \vec{S} = \frac{\hbar}{2} \vec{\sigma}$$

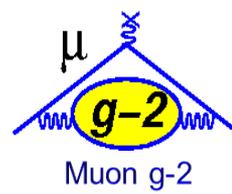
- The Landé g factor is a proportionality constant describing the strength of the magnetic moment and how rapidly a particle will Larmor precess



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

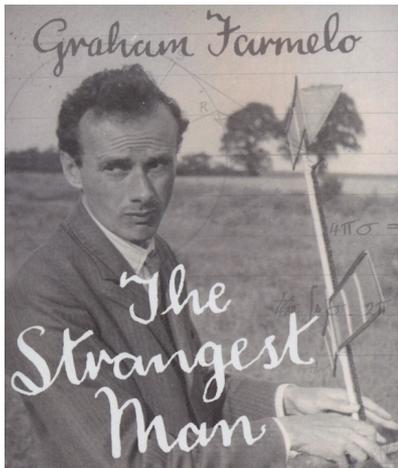


# Magnetic moments...classical to quantum

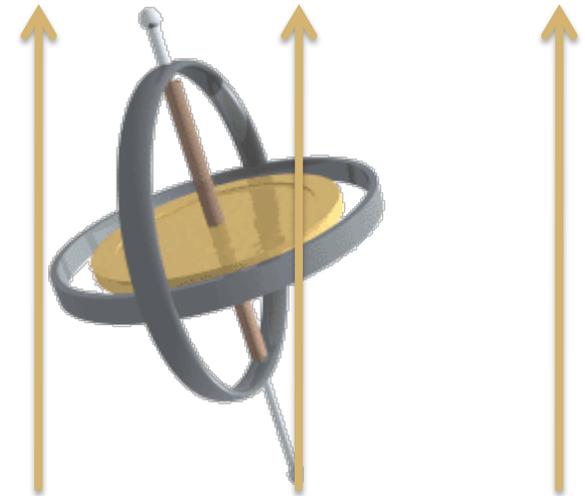


- For a spin  $\frac{1}{2}$  point particle, classically the expectation is  $g = 1$
- With Stern-Gerlach and atomic spectroscopy experiments in the 1920s, it became apparent that  $g_e = 2$ .
- An electron (or muon) precesses twice as fast
- Solution to the  $g$  problem appeared in 1926 with a relativistic treatment by Thomas
- Incorporated in Dirac's famous equation by 1928

$$\left( \frac{1}{2m} (\vec{P} + e\vec{A})^2 + \frac{e}{2m} \vec{\sigma} \cdot \vec{B} - eA^0 \right) \psi_A = (E - m) \psi_A$$

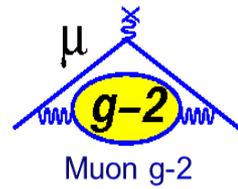


So, for an elementary spin  $\frac{1}{2}$  particle in Dirac's theory,  $g=2$ !



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

# Moments have been testing BSM for decades



- The success of Dirac's theory got people excited about making a measurement of the g-factor for the proton
- Stern and Estermann set out to make the measurement in 1933

*"Don't you know the Dirac theory? It is obvious that  $g_p=2$ ."*, Pauli to Stern

$$g_p \approx 5.6$$



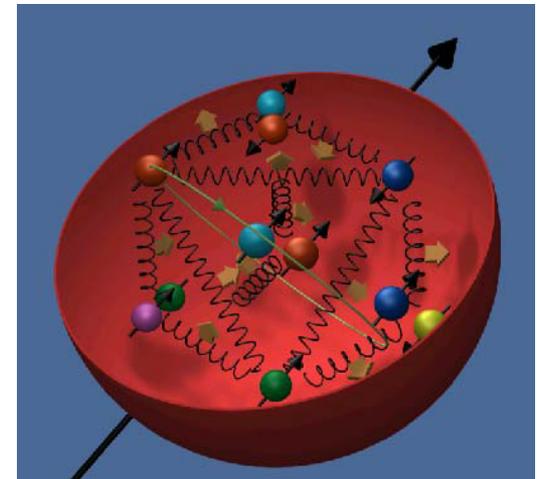
The first 'anomalous' magnetic moment!

- Same year, Rabi inferred  $g_n = -3.8$  from measurements on the deuteron



How does a neutral particle develop a magnetic moment?

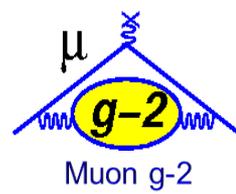
30 more years to develop quark model



Can see how powerful magnetic moments are for exploring new physics!



# Proof that nature abhors a vacuum



- At least for the electron, things were in good shape with Dirac's new theory until 1948 when gains in precision revealed another 'anomaly'
- Kusch and Foley employed atomic spectroscopy to precisely measure  $g_e$

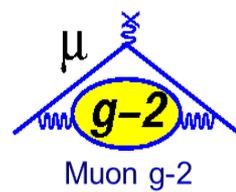


Thus the anomalous magnetic moment was discovered, fractionally  $g$  differs from 2 by  $(g-2)/2 = 0.1\%$

$$g_e = 2.00238(6)$$

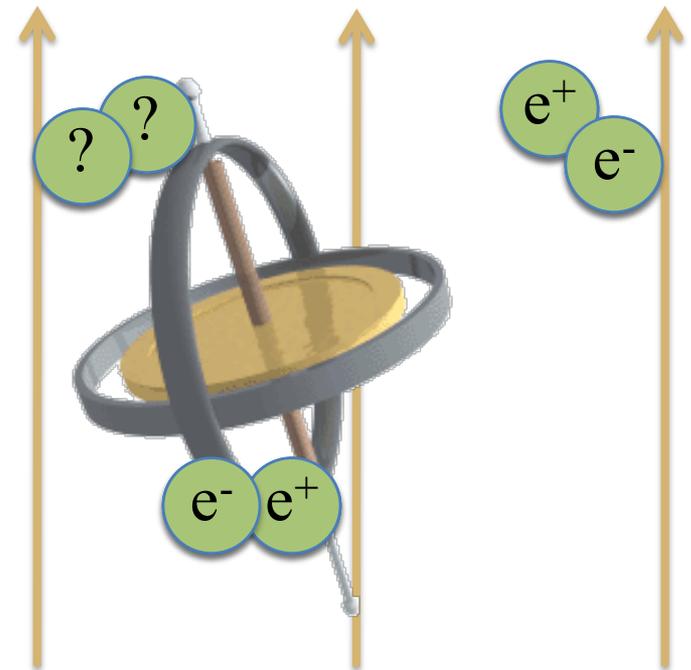


# Enter the world of phantom particles



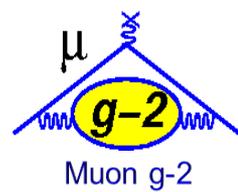
- In reality, particles are never really alone...virtual particles continually fluctuate in and out of the vacuum
- In fact, the more massive the particle, the more mass it has to lend and the probability for friends appearing unexpectedly is enhanced
- These virtual particles effectively screen the magnetic field and alter the bare muon's interaction, changing the g factor
- The extent to which g differs fractionally from 2 is what we call the anomalous magnetic moment

$$a_{\mu} = \frac{g-2}{2}$$



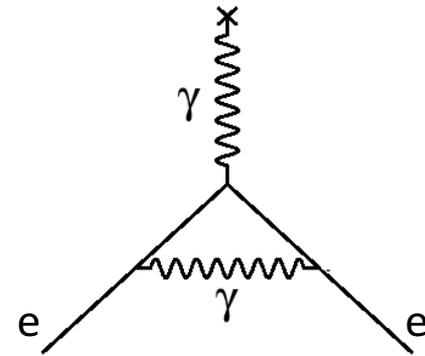


# QED discovered



- Schwinger takes one look at the anomaly in the g-factor and immediately knows what's up

$$g_e = 2.00238(6)$$



Schwinger term describing 1<sup>st</sup> order electron self-interaction

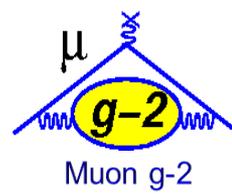
$$g_e \approx 2\left(1 + \frac{\alpha}{2\pi}\right) \approx 2.00232$$

Calculation agrees well with experiment, and that is how we build confidence in new physics models!





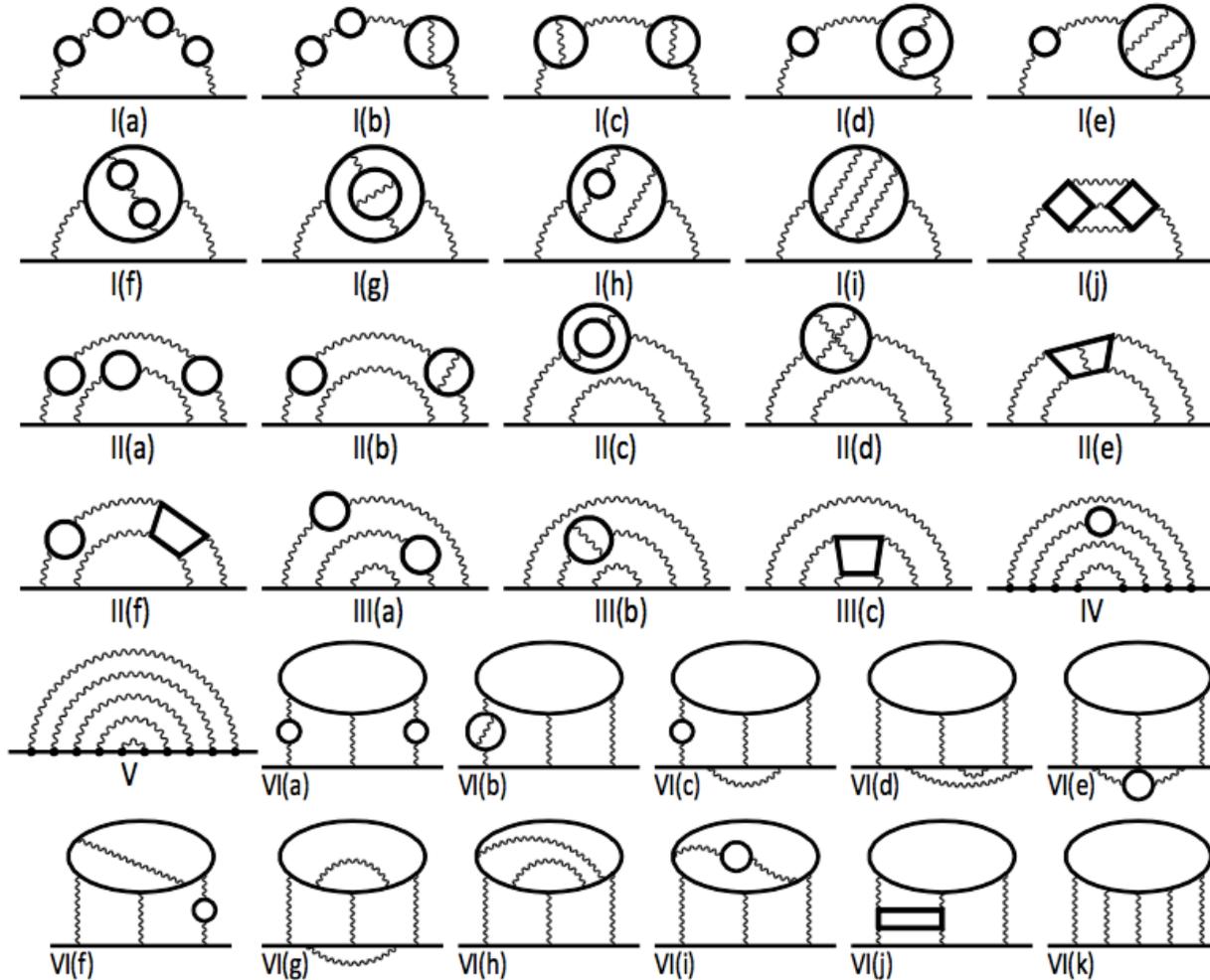
# QED calculation now out to 5 loops



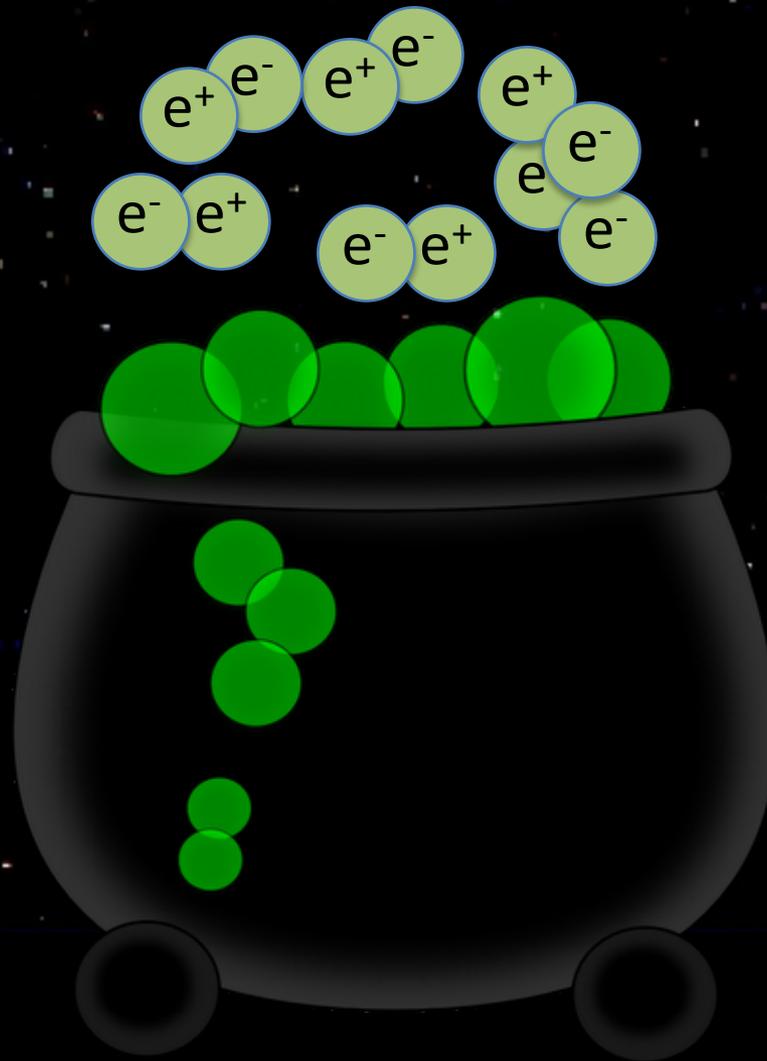
Muon  $g-2$

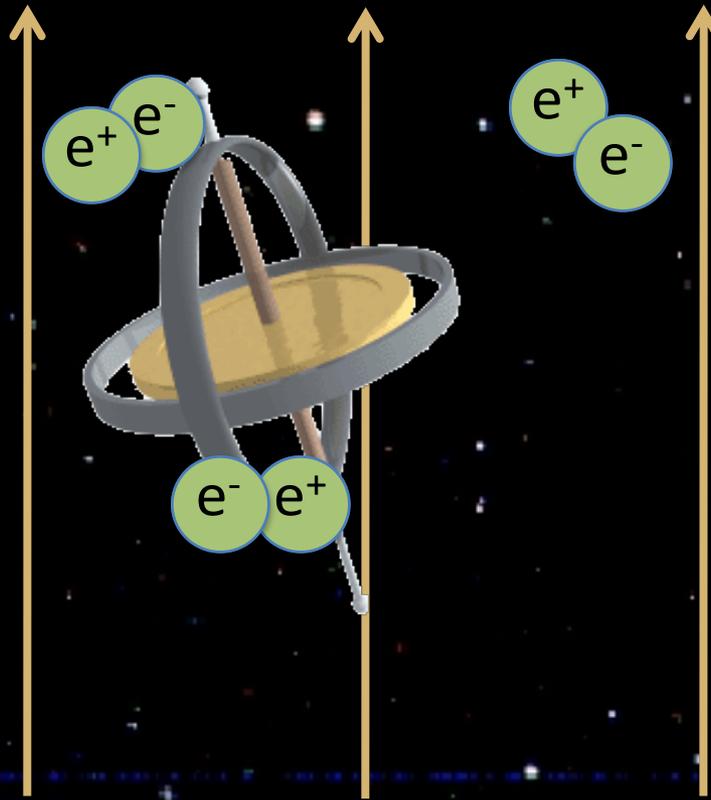
T. Aoyama, M. Hayakawa,  
T. Kinoshita, M. Nio (PRLs, 2012)

10<sup>th</sup>  
12672  
diagrams



To fairly high precision (unlike the proton and neutron) the  $g$ -factor of the electron is consistent with the QED expectation





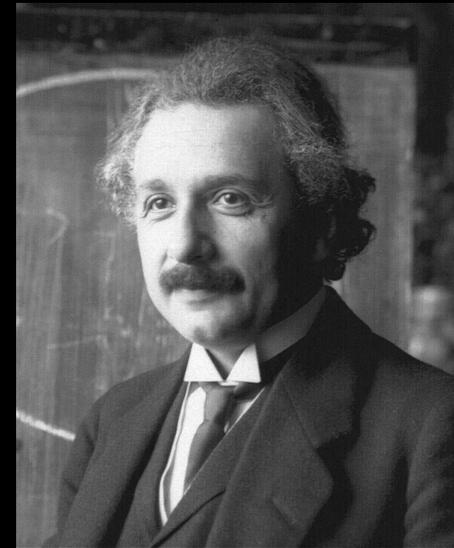
“ $g \sim$  gyromagnetic ratio”

$g(\text{expt})$  2  
 $g(\text{theory})$  2



$$\left( \frac{1}{2m} (\vec{P} + e\vec{A})^2 + \frac{e}{2m} \vec{\sigma} \cdot \vec{B} - eA^0 \right) \psi_A = (E - m) \psi_A$$

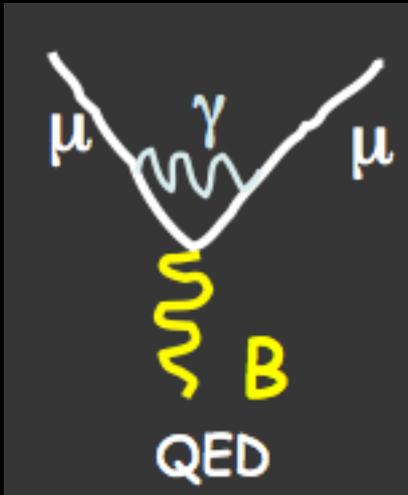
Quantum mechanics meets  
relativity -> anti-matter





$g(\text{expt})$  2.00  
 $g(\text{theory})$  2.00

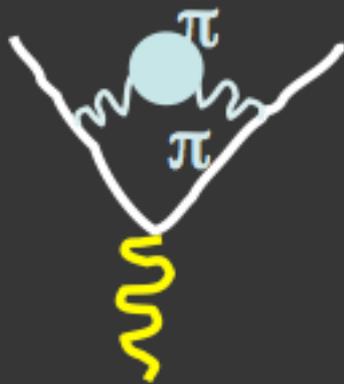
$g(\text{expt})$  2.002331  
 $g(\text{theory})$  2.002331



Quantum  
Electrodynamics  $\rightarrow$   
Electricity &  
Magnetism



$g(\text{expt})$  2.00233184  
 $g(\text{theory})$  2.00233183

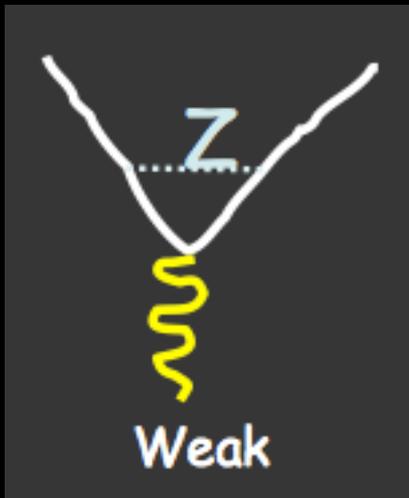


Had VP

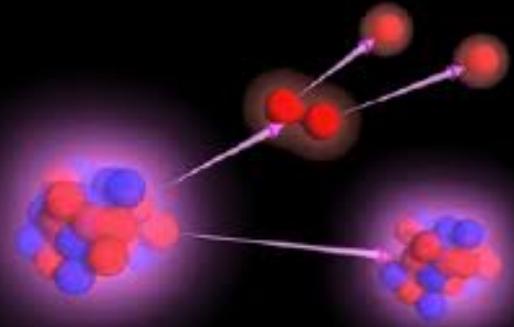
Quantum  
Chromodynamics  $\rightarrow$   
Strong force that  
binds nuclei



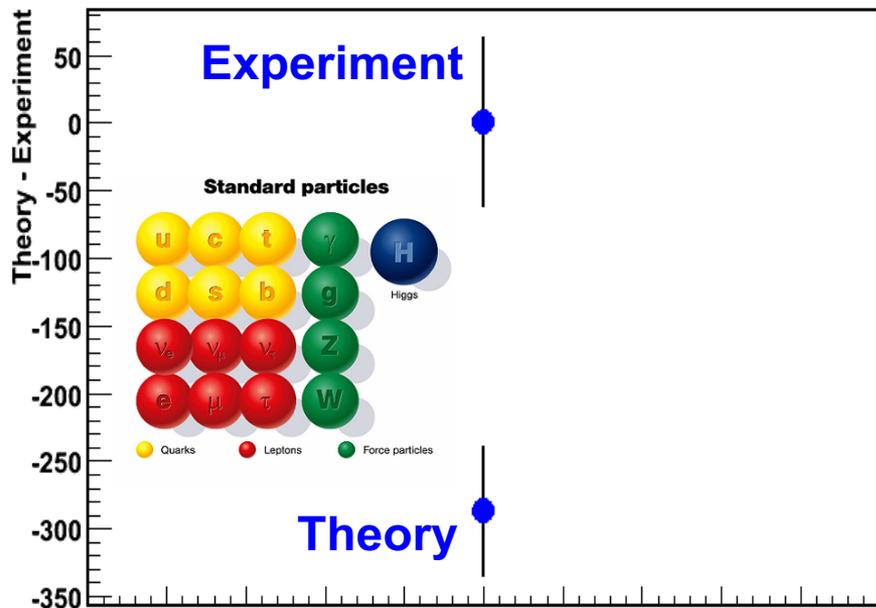
$g(\text{expt})$  2.002331841  
 $g(\text{theory})$  2.002331836



Electroweak Theory->  
Weak force that  
makes nuclei (and  
muons) unstable



$g(\text{expt})$  2.00233184178  
 $g(\text{theory})$  2.00233183630



# Recap...the physics of muon $g-2$

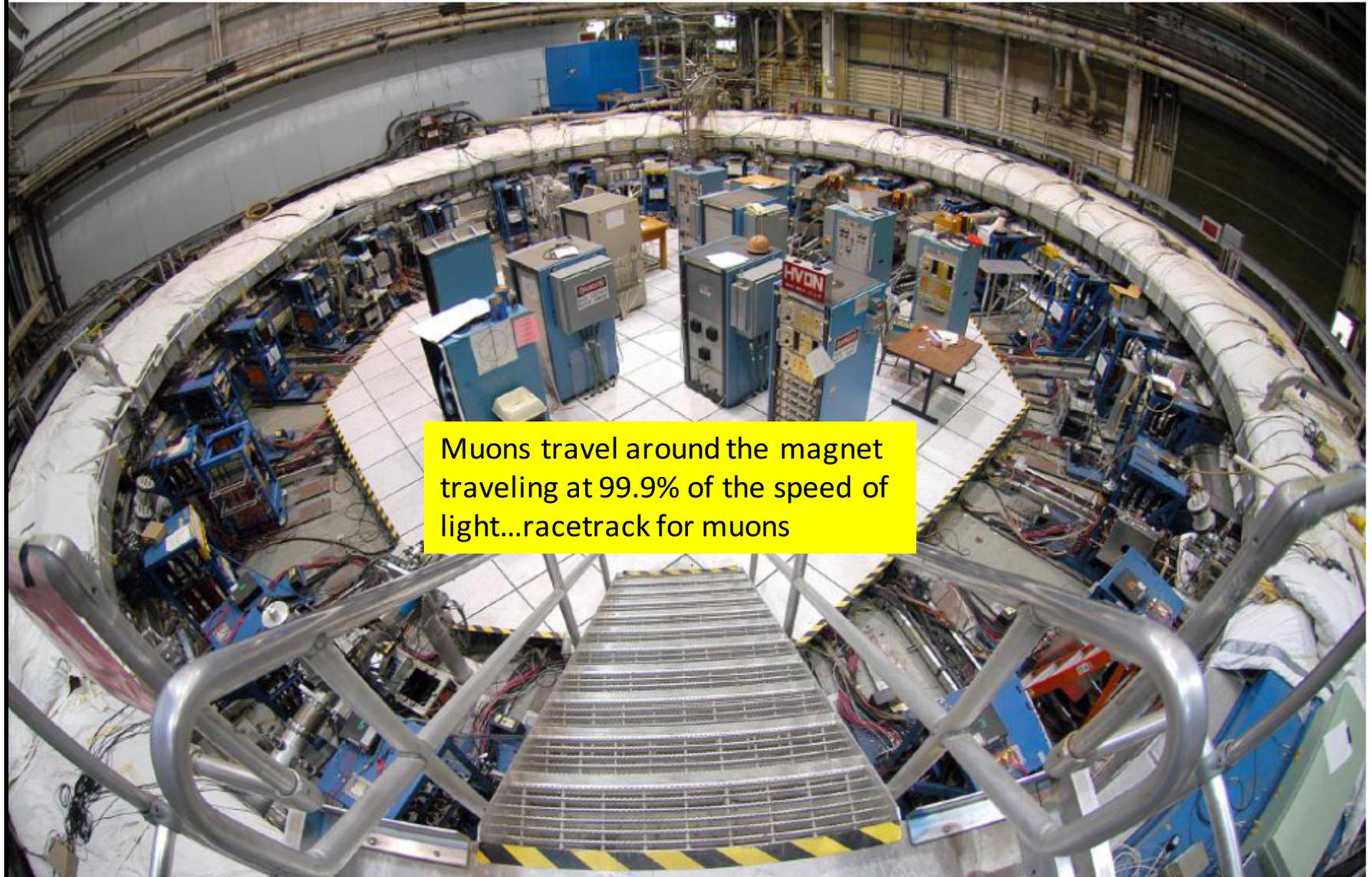
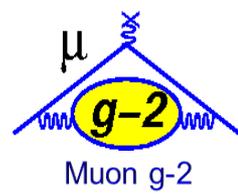
- Special relativity
- Quantum mechanics
- Electricity and magnetism (QED)
- Strong force (QCD)
- Weak force (EW theory)
- Supersymmetry?
- Dark Matter?

**Not bad for a single number!**

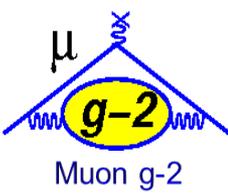
**Goal at FNAL: Repeat with 20x muons**



For perspective, this is the device at BNL



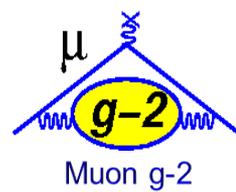
Muons travel around the magnet traveling at 99.9% of the speed of light...racetrack for muons



# Principles of Muon $g-2$ Expt



# Muon spin dynamics in a storage ring



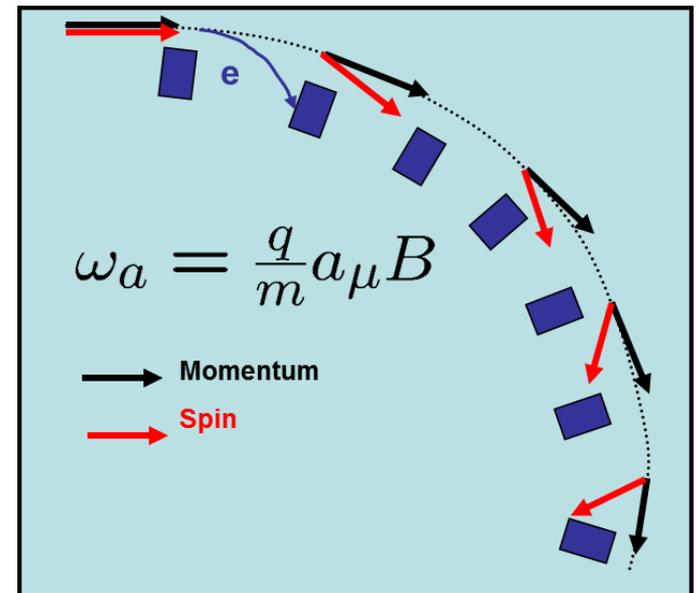
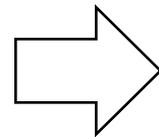
$$\omega_S = \frac{geB}{2mc} + (1 - \gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

The **Spin** frequency relative to the **Cyclotron** frequency is the “anomalous precession frequency”,  $\omega_a$

Does NOT depend on  $\gamma$  !

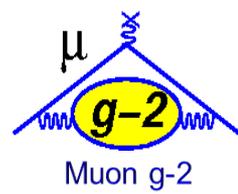
Proportional to  $g - 2$  and  $B$  !

$$\begin{aligned} \omega_a &= \omega_S - \omega_C \\ &= \left(\frac{g-2}{2}\right) \frac{eB}{mc} = a \frac{eB}{mc} \end{aligned}$$





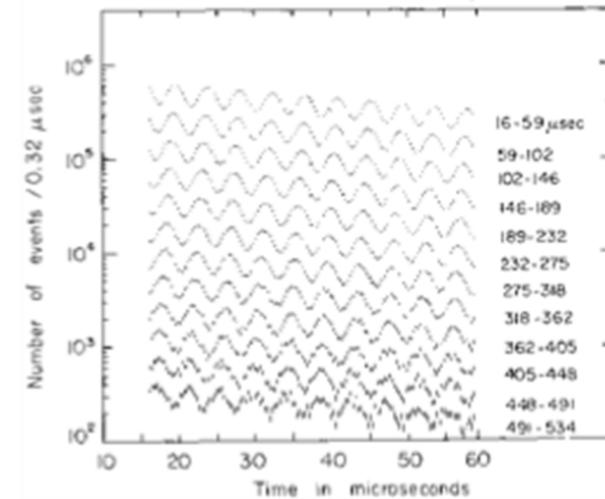
# E field needed for vertical focussing



But ... it looks like a B field to a moving particle !

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

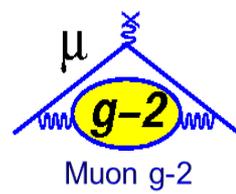
The CERN III Miracle : choose  $\gamma = 29.3$  ( $P_\mu = 3.094$  GeV/c)



$a_\mu = 0.001\,166\,924(8.5) (\pm 7 \text{ ppm})$   
(sensitive to HVP)

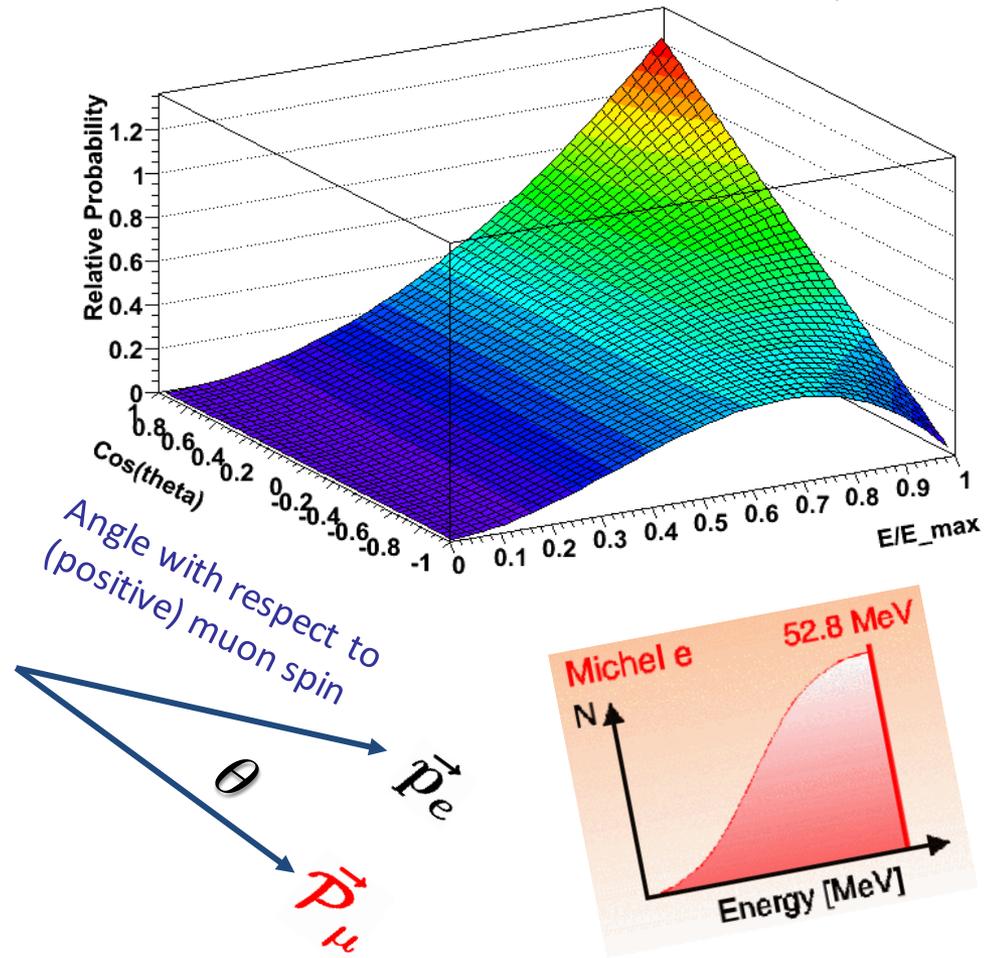


# Analyzing the muon spin



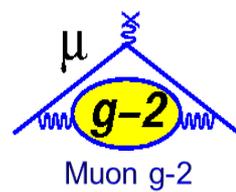
Primary decay  $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

- Parity violation in muon decay  $\rightarrow$  highest energy decay electron emitted in direction of muon spin
- When spin is aligned with momentum, the boost adds, anti-aligned and the decay electron energy is reduced in the lab frame
- Results in a modulation of the energy spectrum at the g-2 frequency





# Recap the four key elements



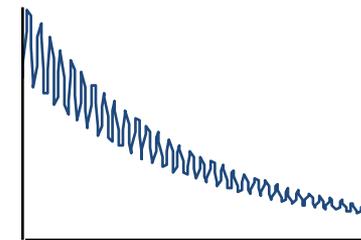
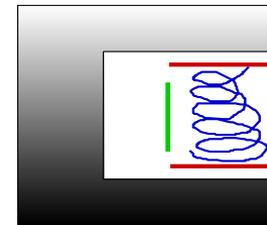
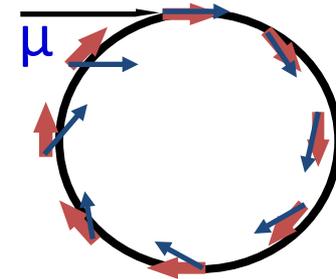
(1) Polarized muons

~97% polarized for forward decays

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

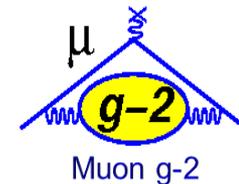
(3)  $P_\mu$  magic momentum = 3.094 GeV/c

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





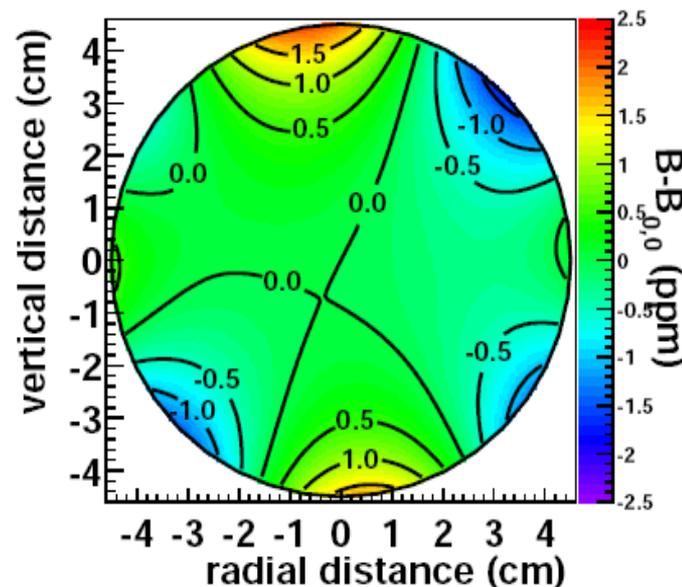
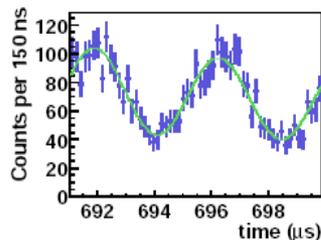
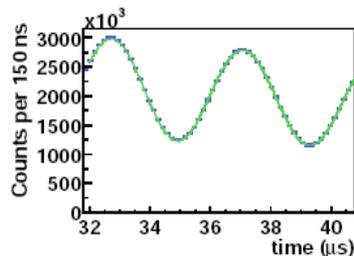
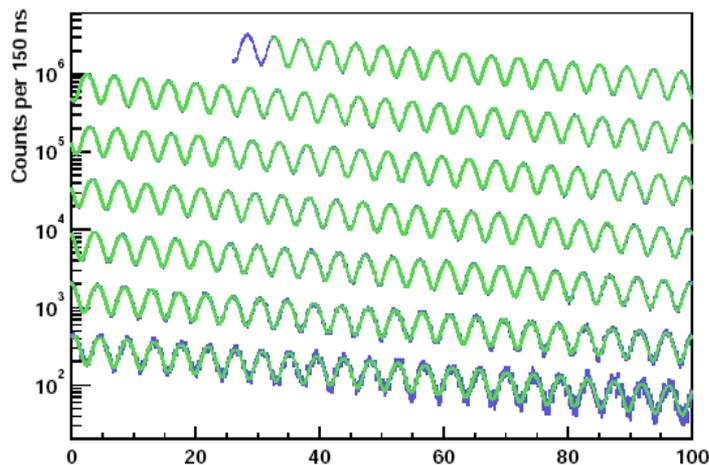
# Extracting $a_\mu$ from experiment



$\lambda$   
taken from muonium  
hyperfine

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

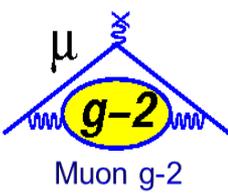
$$dN / dt = N_0(t) e^{-t/\tau} [1 + A(t) \cos(\omega_a t + \phi_a(t))]$$



	2001 [ppm]	2000 [ppm]
Total Syst Error	0.27	0.39
Statistical Error	0.66	0.62
Total Error	0.71	0.73

At BNL stat error dominant!

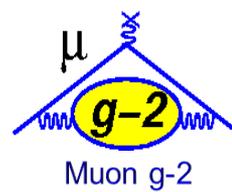
Combined total error on  $a_\mu$  0.54 ppm



# Muon g-2 at Fermilab



# Who we are...



## Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

## National Labs

- Argonne
- Brookhaven
- Fermilab



## Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste



## China:

- Shanghai



## The Netherlands:

- Groningen



## Germany:

- Dresden



## Russia:

- Dubna
- Novosibirsk

D.W. Hertzog, Co-Spokesperson  
 B.L. Roberts, Co-Spokesperson  
 C. Polly, Project Manager



## England

- University College London
- Liverpool
- Oxford



## Korea

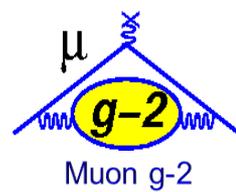
KAIST



- 33 institution, 150 members



# What we need to do...

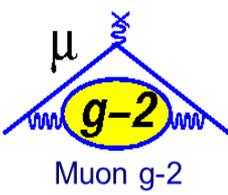


- 4 Major Steps

- Transport BNL storage ring and associated equipment to Fermilab ✓
- Construct a new experimental hall to house the storage ring ✓
- Modify anti-proton complex to provide a high-purity, intense beam of 3.094 GeV/c muons
- Upgrade various subsystems (injection devices, field monitoring, detectors & DAQ) to meet requirements for rates and systematics

- Overall plan to achieve a factor of four improvement in precision

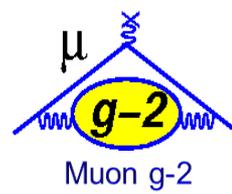
- Increase statistics by x 21 to reduce stat error from 0.46 ppm to 0.1 ppm
- Reduce systematics on  $\omega_a$  from 0.2 ppm to 0.07 ppm
- Reduce systematics on  $\omega_p$  from 0.17 ppm to 0.07 ppm



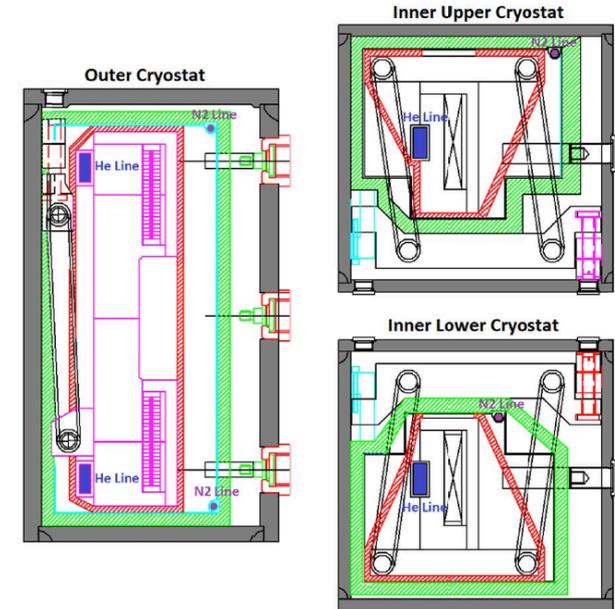
# The transport



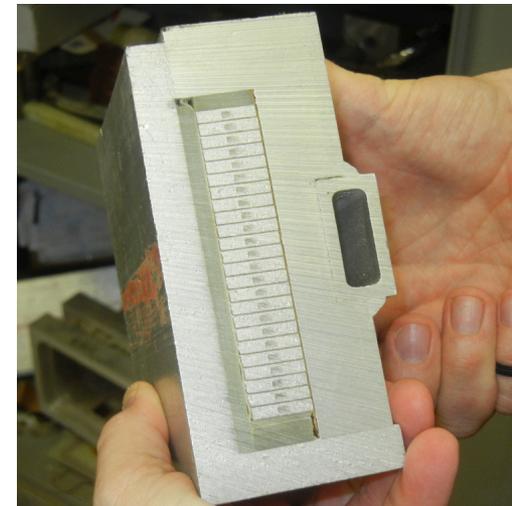
# Getting storage ring to FNAL was a challenge



Muon g-2



- The big pieces of steel (return yoke) come apart
  - Ship one 26T piece/flatbed
- The superconducting coils do not
  - Can't be cut and can't be unwound
  - \$20M and 2 year delay to make from scratch



Can ship by barge most of the way...this is actual GPS during transport

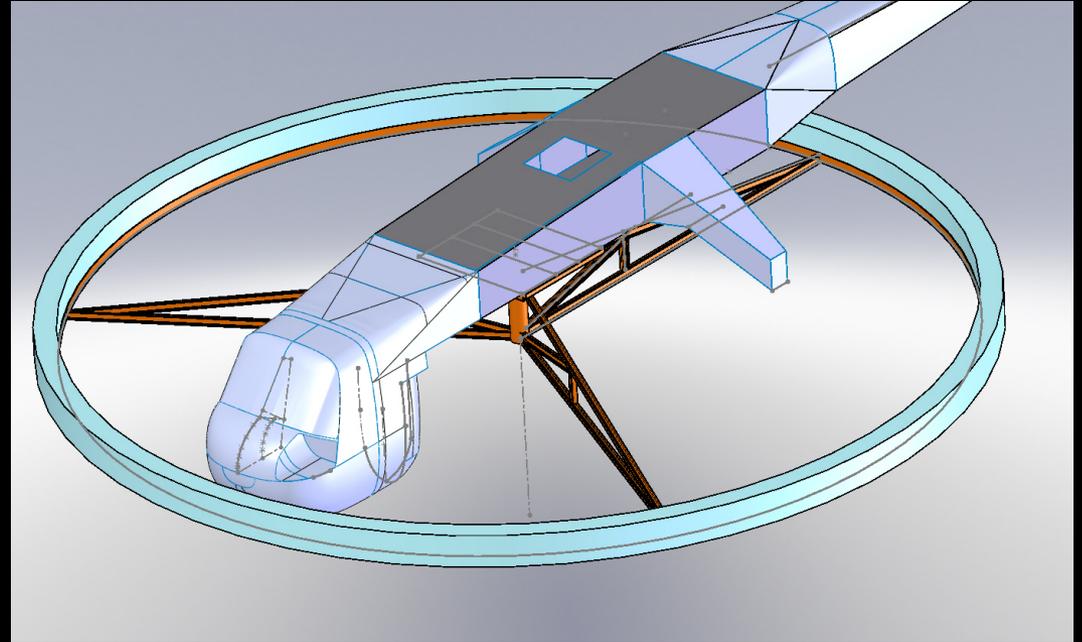




Easiest way to get to Chicago is by barge,  
but how to get from lab to barge?



First solution considered...



Took helicopter concept through full feasibility study. High risk due to vibrations, need to keep fixture light but coils rigid, and fact that helicopter needs 300 ft clear path (no humans)

# 1992 UFO?



“Nope, no UFOs at Brookhaven”,  
Symmetry, July 2009



It was tough to give up on the flying the magnet dream..



# Instead we hired Emmert International..



Family started business 40 yrs ago

World leader in specialized hauling

Might have seen them on TV a couple of years ago moving the rock through LA



# Moving 50 ft diameter Al rings without flexing by $>1/8''$



# The barge deck flexed by way more than the spec on rings



# Offloading in Lemont, IL...30 miles from FNAL



# Closing two interstates in Chicago...



# Enthusiasm...



3 July 2016

Chris Polly, QuarkNet Workshop

After the crowds left...



# Science as art



Photo Credit: Connie Sieh

Our local brewery, Two Brothers, created a special beer for the occasion



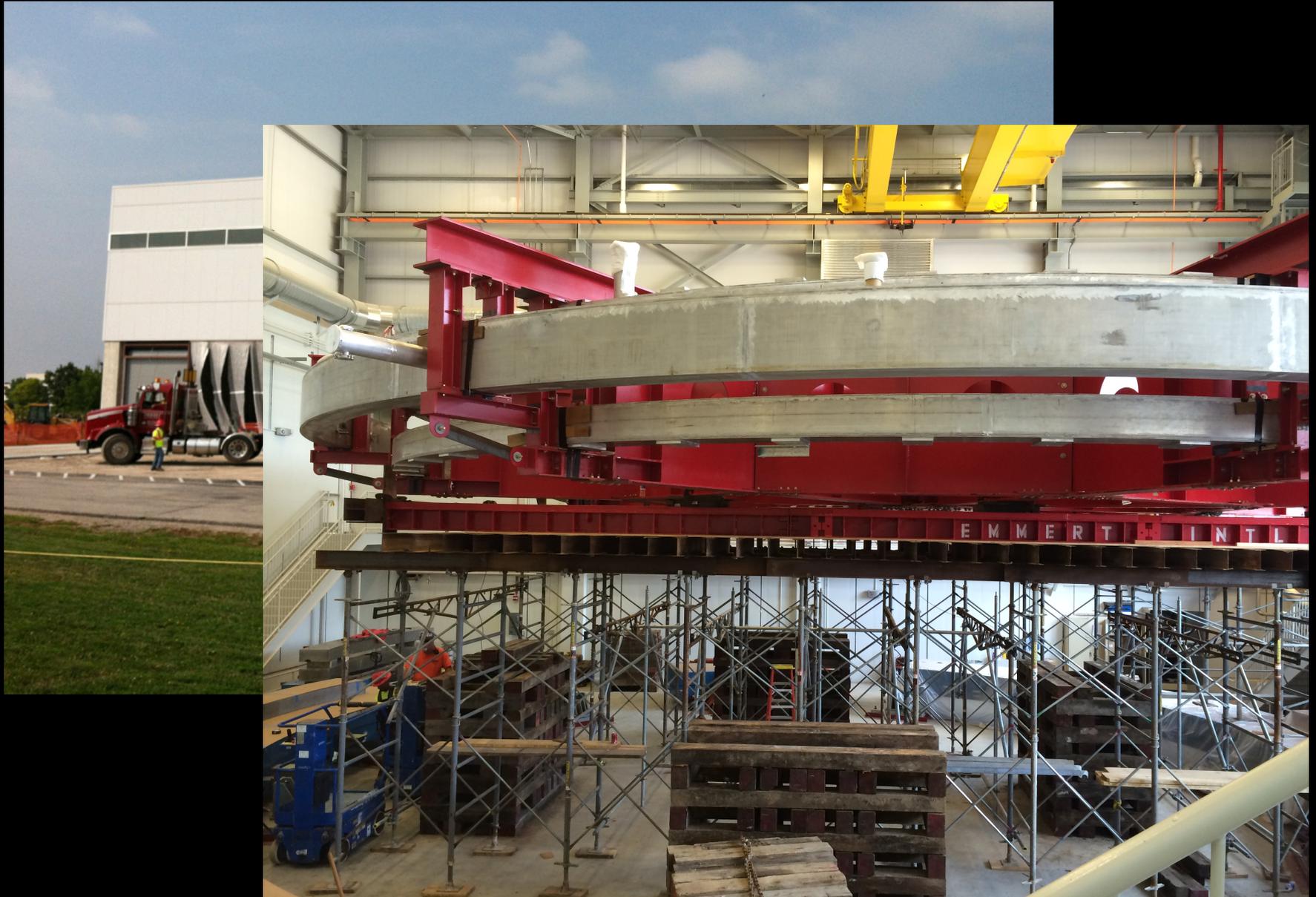
# About one year later...the building finished



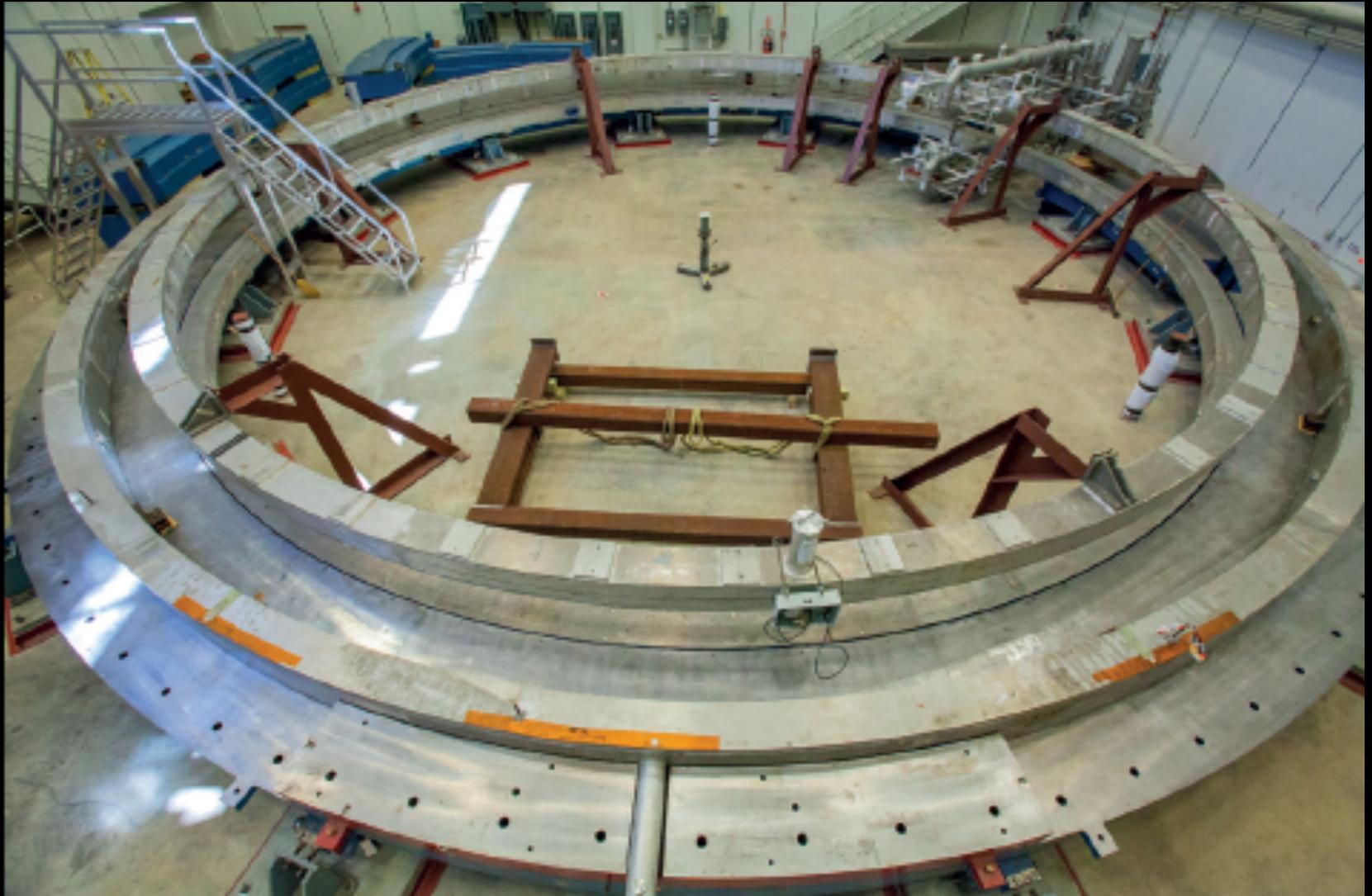
The MC1 Building at Fermilab

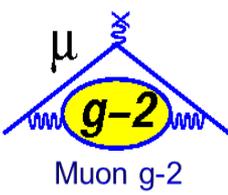


# About one year later...the building



# Coils installed last July

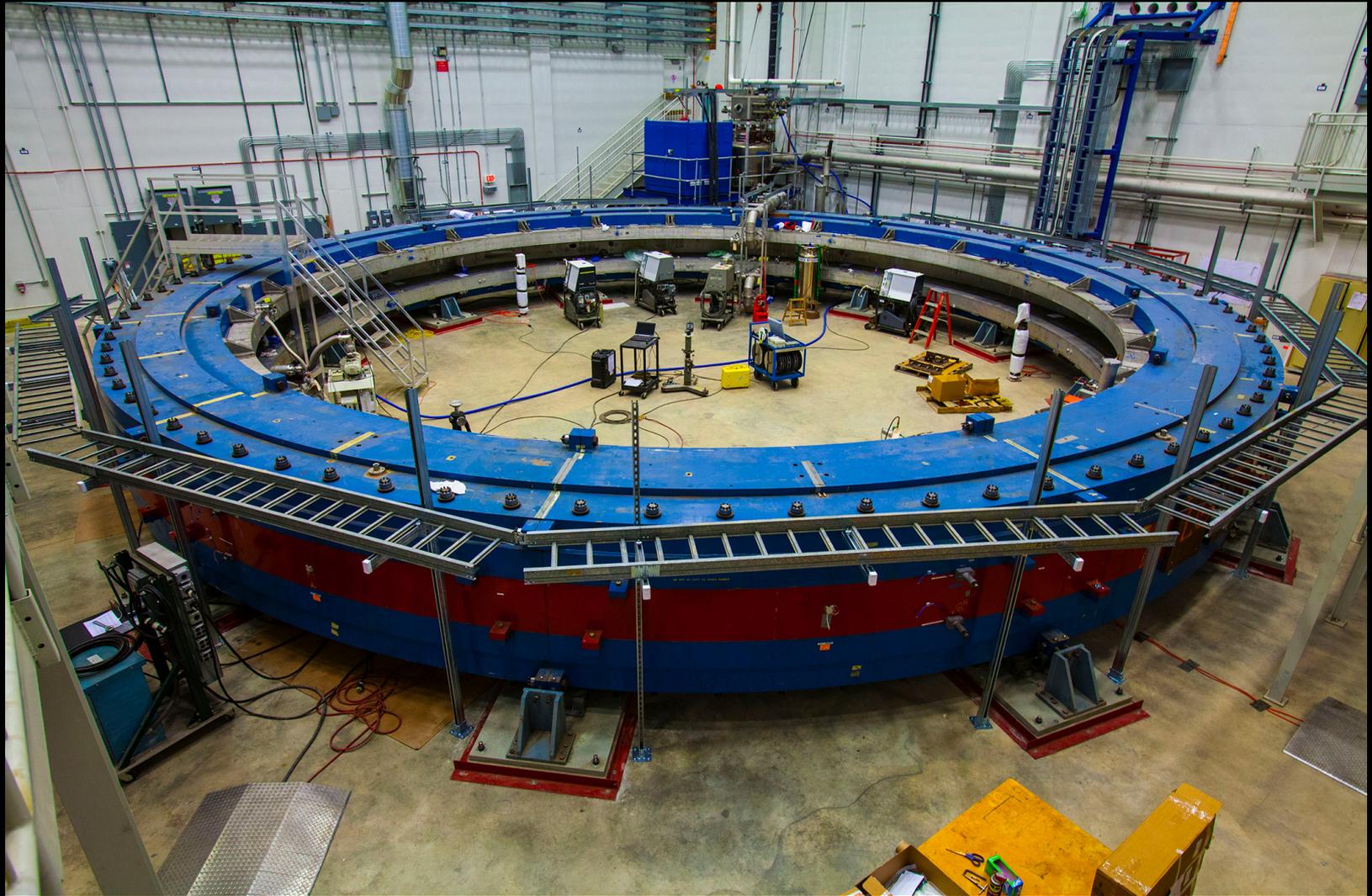




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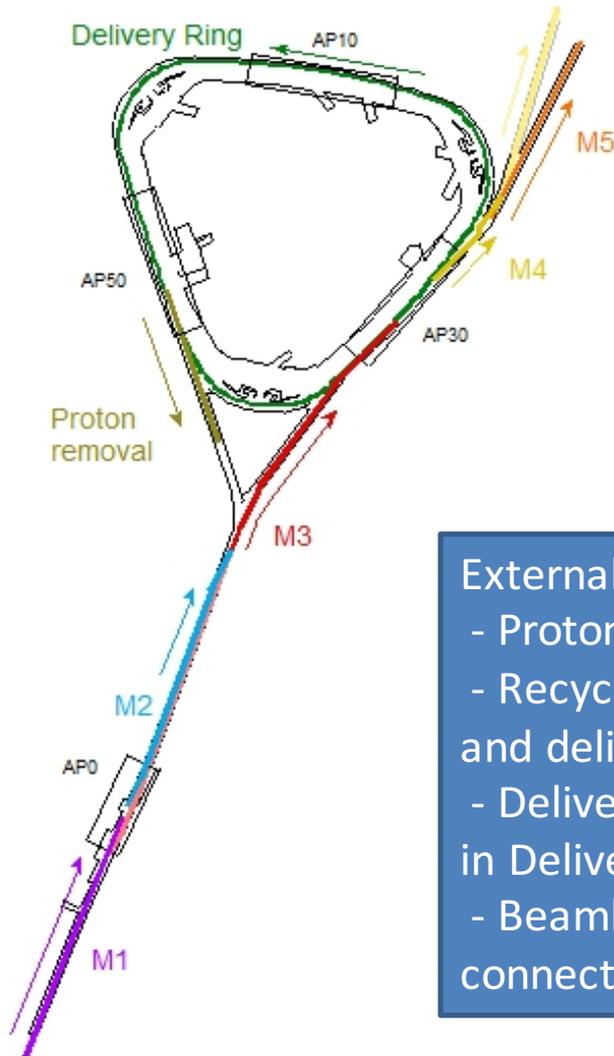
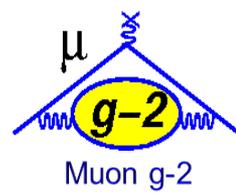
The end...thank you!

How it looks today...operational by next month





# Accelerators



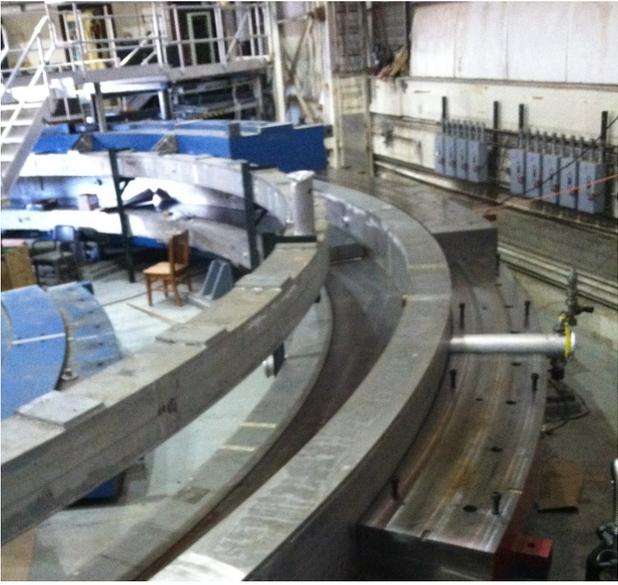
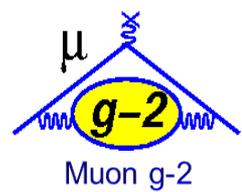
- Convert anti-proton source to a custom muon source
  - Largely reuse of AP0 target hall as-is with some modification and repairs to run at g-2 rep rate
  - Installation of M2, M3, M4, and M5 beamlines to efficiently capture muons and transport to experimental hall
  - Circulation in Delivery Ring for to enough turns (4-7) to remove protons from muon beam
  - Appropriate controls, instrumentation, and safety systems to monitor and steer the beam

## External Dependencies:

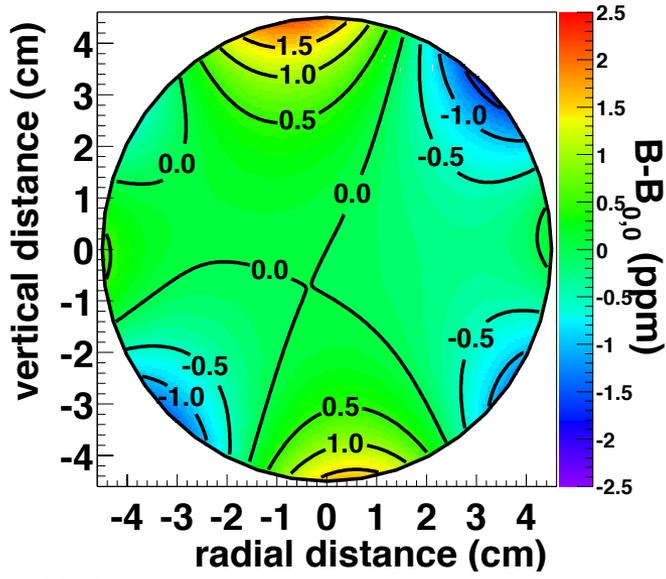
- Proton Improvement Plan to upgrade Booster to 15 Hz
- Recycler RF and Beam Transport AIPs rebunch Booster beam and deliver to M1 line
- Delivery Ring AIP providing common g-2/Mu2e components in Delivery Ring
- Beamline Enclosure GPP constructs new tunnel system to connect Delivery Ring to g-2 and Mu2e halls



# Ring



- Reassembly of E821 storage ring,
- Design, construct, and install upgraded subsystems
  - Refurbishment of ring and modernization to FNAL-compatible controls
  - Upgrades to electromagnetic kickers and electrostatic quadrupoles
  - Reuse of superconducting inflector
    - A new inflector was explored for CD-2 and would provide many benefits. However, due to funding constraints it has been moved into our contingency spend plan
  - Improvements in field monitoring equipment and shimming of magnetic field to attain high uniformity

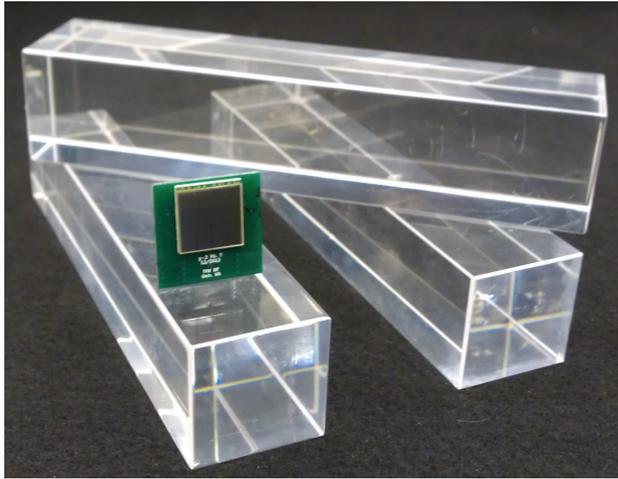
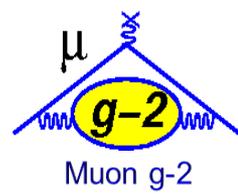


External Dependencies:

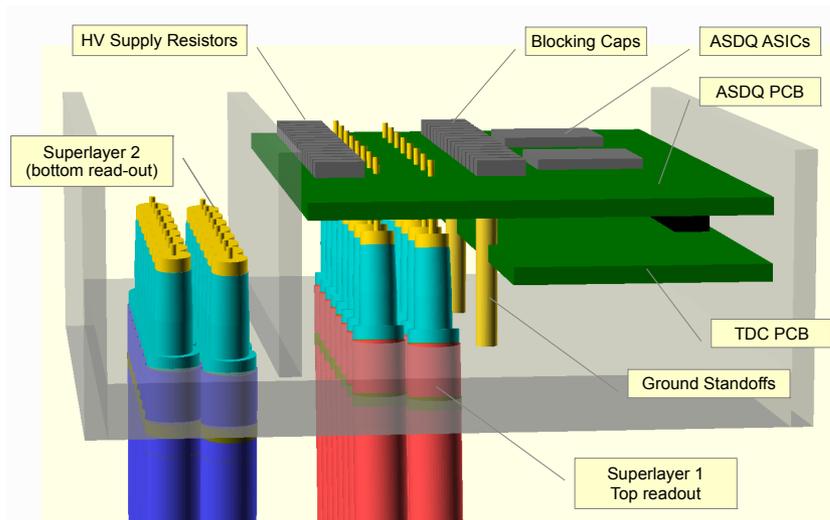
- MC-1 Building GPP to house storage ring
- Muon Campus Cryo Plant to provide liquid He and N cryogens for storage ring and inflector



# Detectors



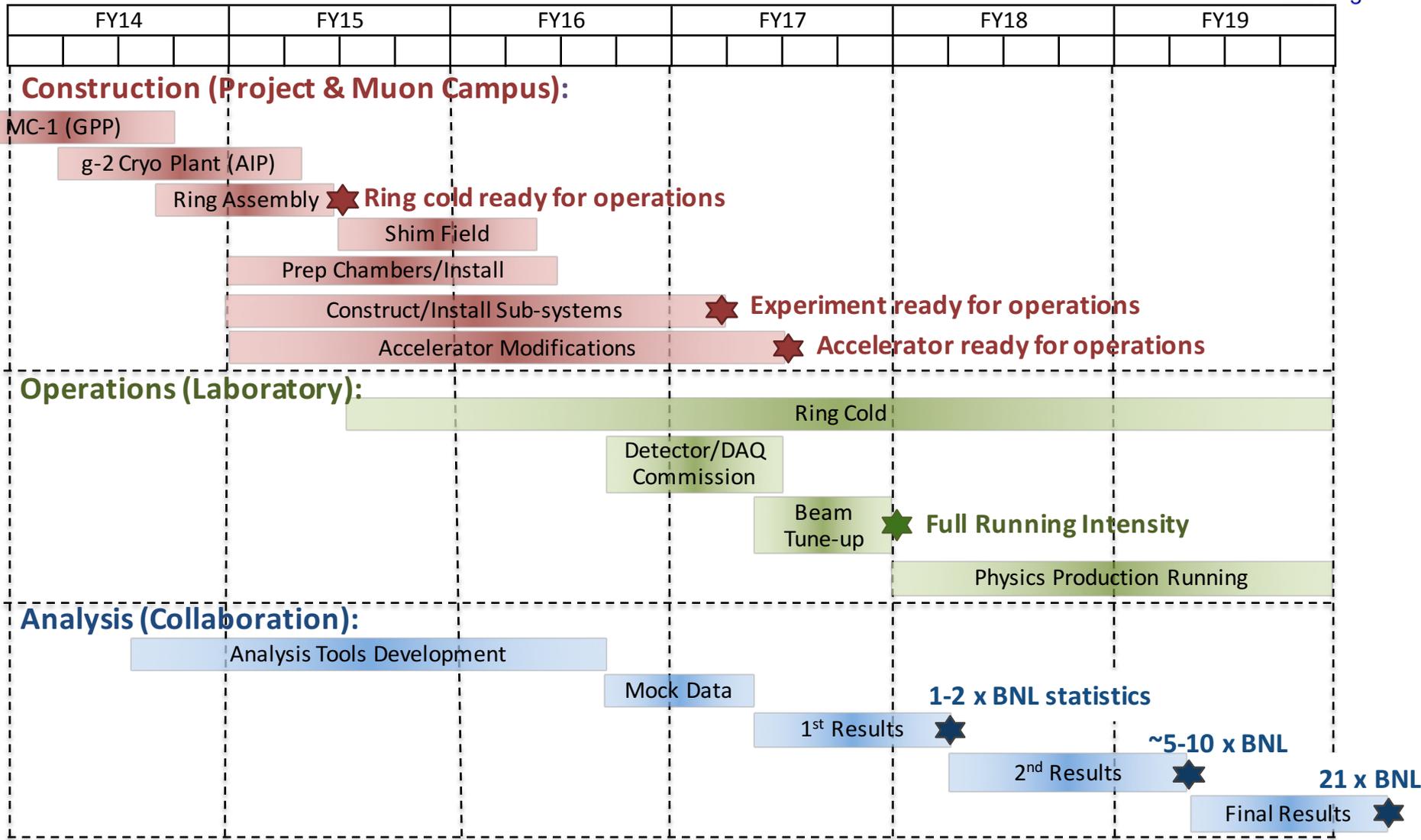
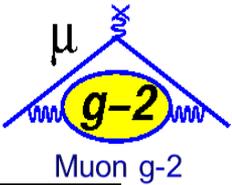
- Calorimeters 24 6x9 PbF2 crystal arrays with SiPM readout
- New electronics and DAQ
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons
- Auxiliary detectors and slow controls to monitor beam properties and environmental conditions



## External Dependencies:

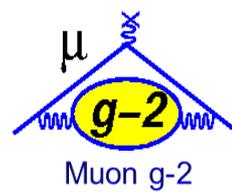
- Calorimeters, DAQ, and electronics primarily NSF funded with laser calibration from INFN
- Trackers funded by Early Career and UK contributions

# Big Picture Schedule-Project/Ops/Analysis





# First challenge...getting the statistics



Item	Estimate
Protons per fill on target	$10^{12}$ p
Positive-charged secondaries with $dp/p = \pm 2\%$	$4.8 \times 10^7$
$\pi^+$ fraction of secondaries	0.48
$\pi^+$ flux entering FODO decay line	$> 2 \times 10^7$
Pion decay to muons in 220 m of M2/M3 line	0.72
Muon capture fraction with $dp/p < \pm 0.5\%$	0.0036
Muon survive decay 1800 m to storage ring	0.90
Muons flux at inflector entrance (per fill)	$4.7 \times 10^4$
Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$	$0.10 \pm 0.04$
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$
Positrons accepted per fill (factors 0.15 x 0.63)	$444 \pm 180$
Number of fills for $1.8 \times 10^{11}$ events	$(4.1 \pm 1.7) \times 10^8$ fills
Time to collect statistics	$(13 \pm 5)$ months
Beam-on commissioning	2 months
Dedicated systematic studies periods	2 months
Net running time required	$17 \pm 5$ months

Achieving required statistics is a primary concern

- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

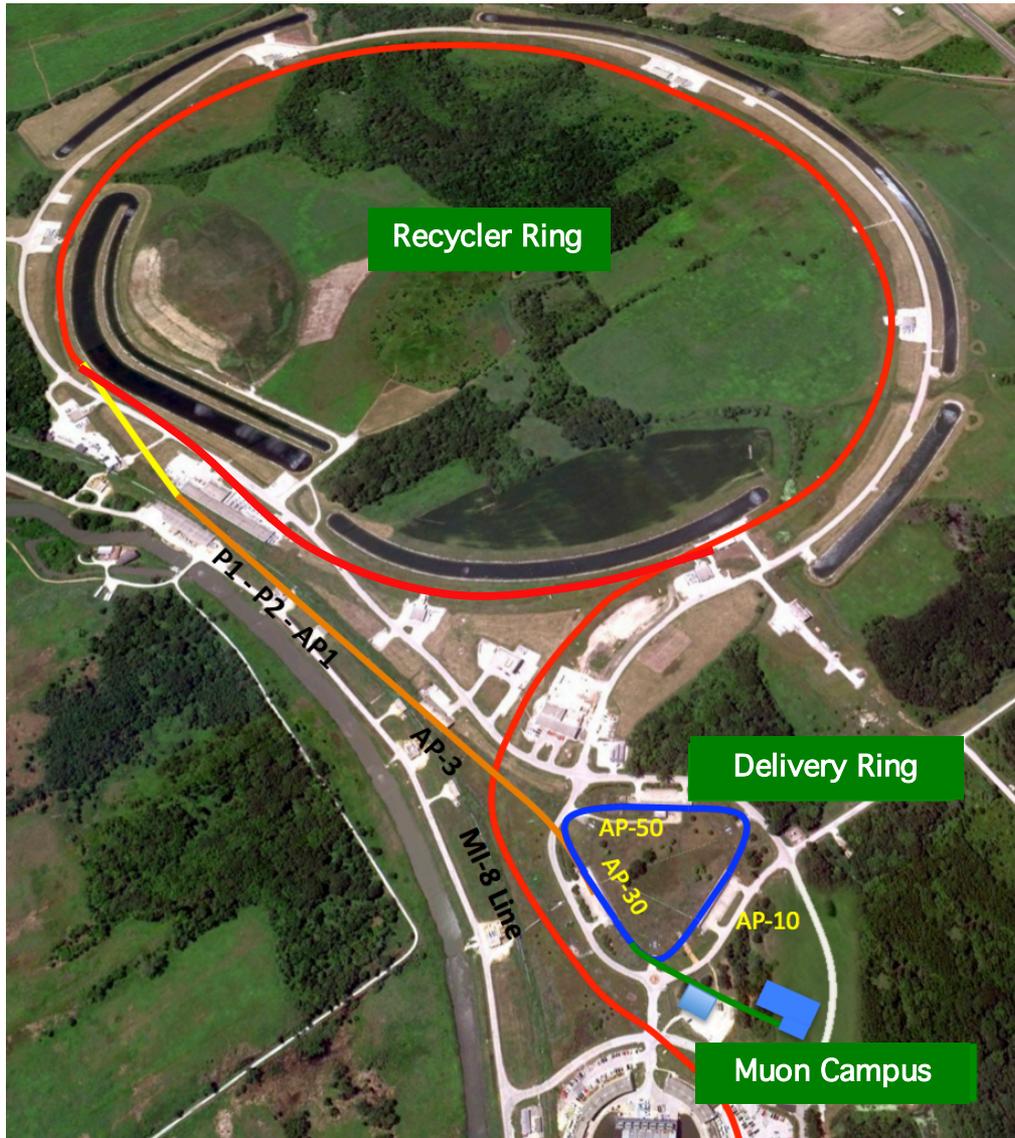
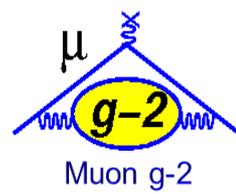
Need a factor of 85 improvement in integrated beam coming from many other factors

Ratio of beam powers BNL/FNAL:

$$\frac{4e12 \text{ protons/fill} * (12 \text{ fills} / 2.7s) * 24 \text{ GeV}}{1e12 \text{ protons/fill} * (16 \text{ fills} / 1.3s) * 8 \text{ GeV}} = 4.3$$



# First challenge...getting the statistics



Achieving required statistics is a primary concern

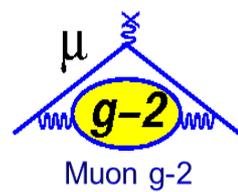
- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

Need a factor of 85 improvement in integrated beam coming from many other factors

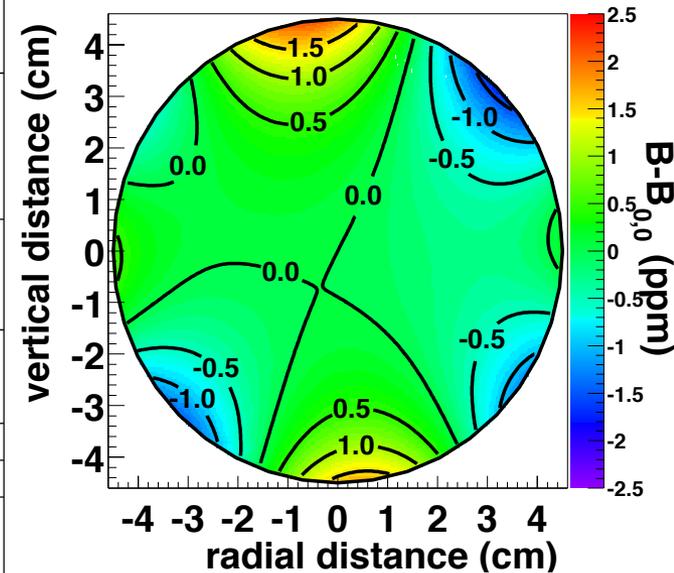
- Collection of pions from lens
- Capture of decay muons in FODO channel
- $p_{\pi}$  closer to magic momentum
- Longer decay channel
- Increased injection efficiency
- Earlier start time of fits
- Longer runtime



# Second challenge...controlling $\omega_p$ systematic



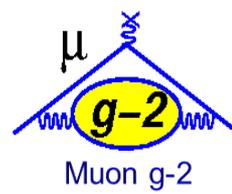
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved $T$ stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, <b>higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients</b> , smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of $B_0$	50	Reduced/measured rail irregularities; <b>reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients</b>	30
Fixed probe interpolation	70	<b>Better temp. stability of the magnet</b> , more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce $O_2$ and image effects	30
Total syst. unc. on $\omega_p$	170		70



- 3 part plan to achieve 70 ppb
  - Start by making magnetic fields as uniform and stable as possible
  - Continuously monitor the magnetic field with proton NMR
  - Absolutely calibrate the proton NMR



# Field stability and uniformity improvements



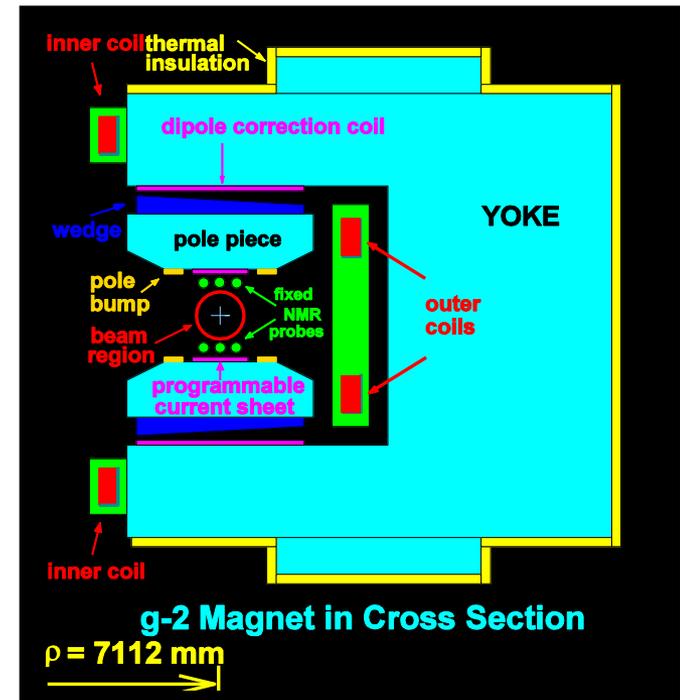
- Environmental

- 2'9" heavily-reinforced floor installed on 12' deep excavation of undisturbed soil
- Temperature control to +/- 1C

- Construction tolerances

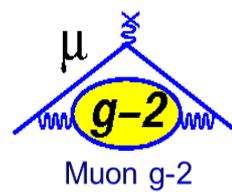
- 26 ton pieces of yoke steel (30 of them) placed to 125 micron tolerance
- Pole pieces aligned to 25 micron

- 9 months of interactively shimming B-field with bits of steel and current loops (starts in July)

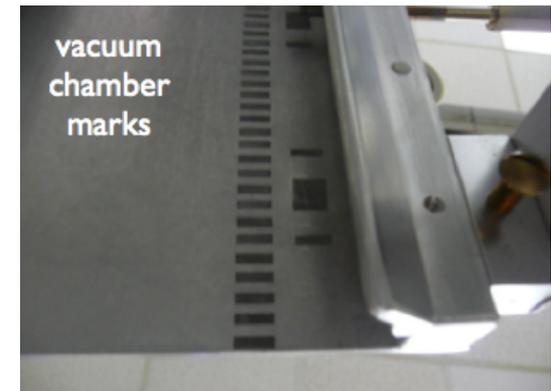
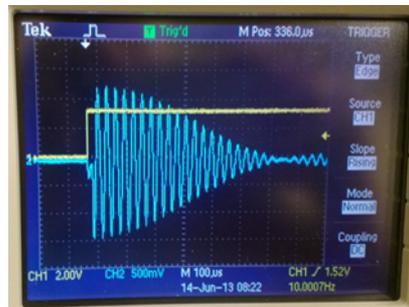
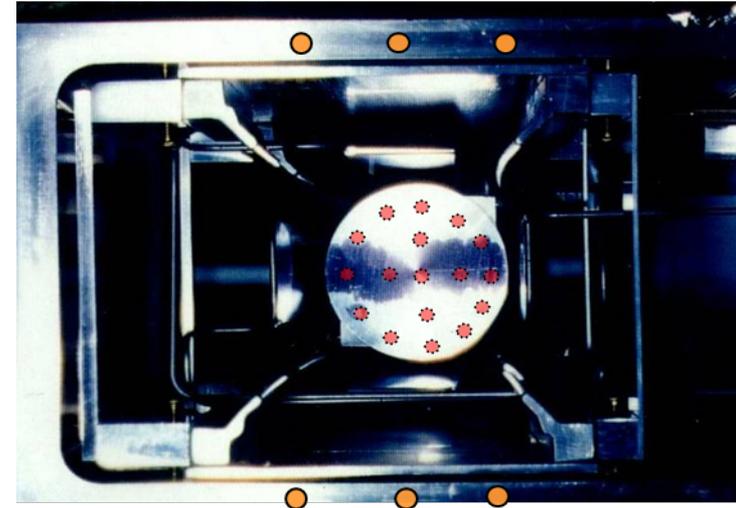




# Monitoring magnetic field

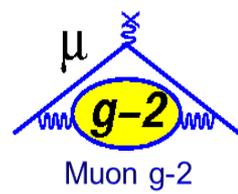


- Fixed probes track field at top/bottom of vacuum chamber monitor field 24/7
  - Only half of 400 were used in BNL (primarily due to being in gradients that were too large) → building better NMR probes and in some case adjusting positions
- NMR trolley pulls out of garage every day or two and maps field where muons live
  - More frequent trolley runs (every 2-3 days) to reduce extrapolation error
  - Optical encoders for better position resolution
- Digitizing FID signals

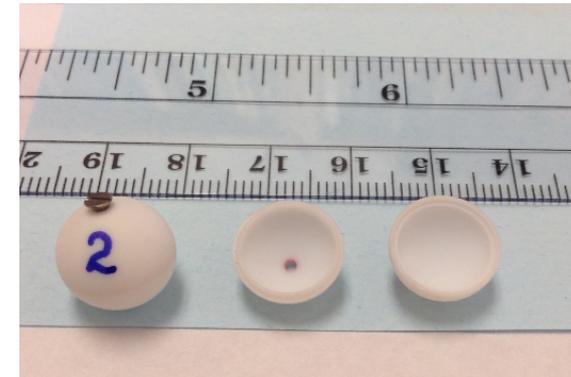




# Absolute calibration

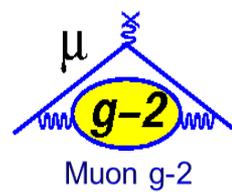


- Setting up a dedicated test facility at ANL to study and develop improved absolute calibration tests
- Learning how to make better spheres... water diamagnetic shielding is 26 ppm
- Developing He3 magnetometry





# Third challenge..controlling $\omega_a$ systematic

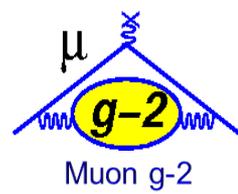


Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration low-energy threshold	20
Pileup	80	Low-energy samples recorded calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher $n$ value (frequency) Better match of beamline to ring	< 30
$E$ and pitch	50	Improved tracker Precise storage ring simulations	30
Total	180	Quadrature sum	70

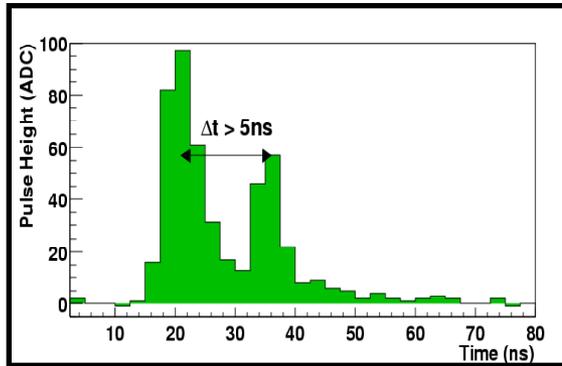
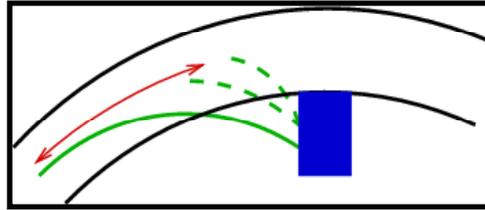
- Tackling each of the major systematic errors with knowledge gained from BNL E821



# Example...pileup



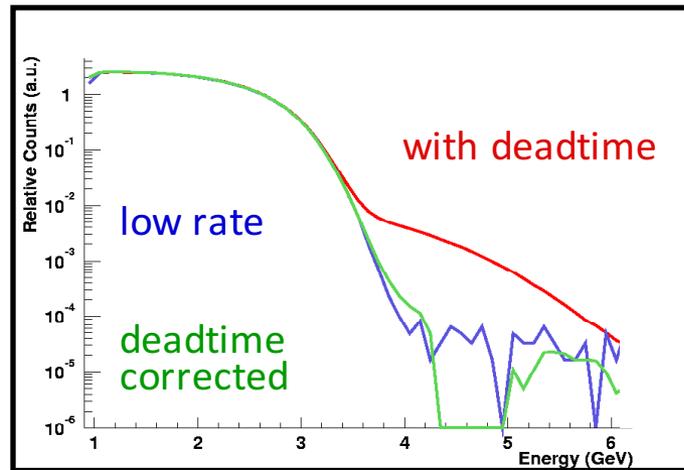
2 “below-threshold” events  
conspire to make one “above-  
threshold” event → with a **different  
average phase & ^%\$**



Separate by good  
timing

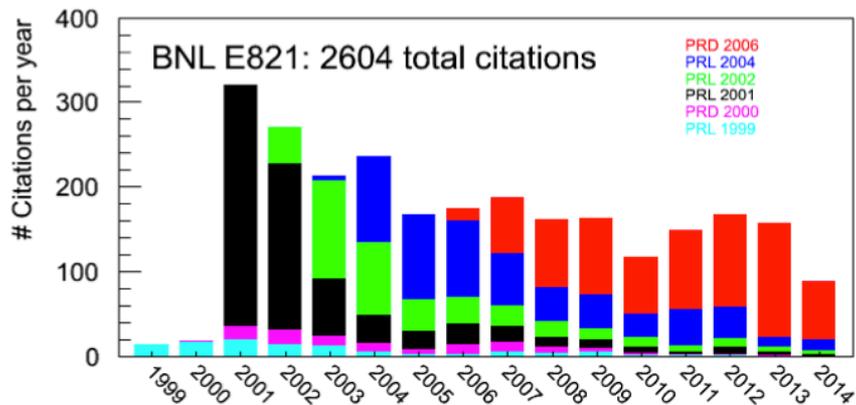
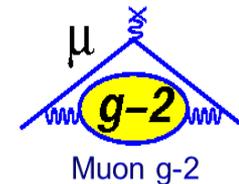
$$dN / dt = N_0(t) e^{-\frac{t}{\tau}} [1 + A(t) \cos(\omega_a t + \phi_a(t))]$$

Build artificial pileup  
events from other fills  
and subtract

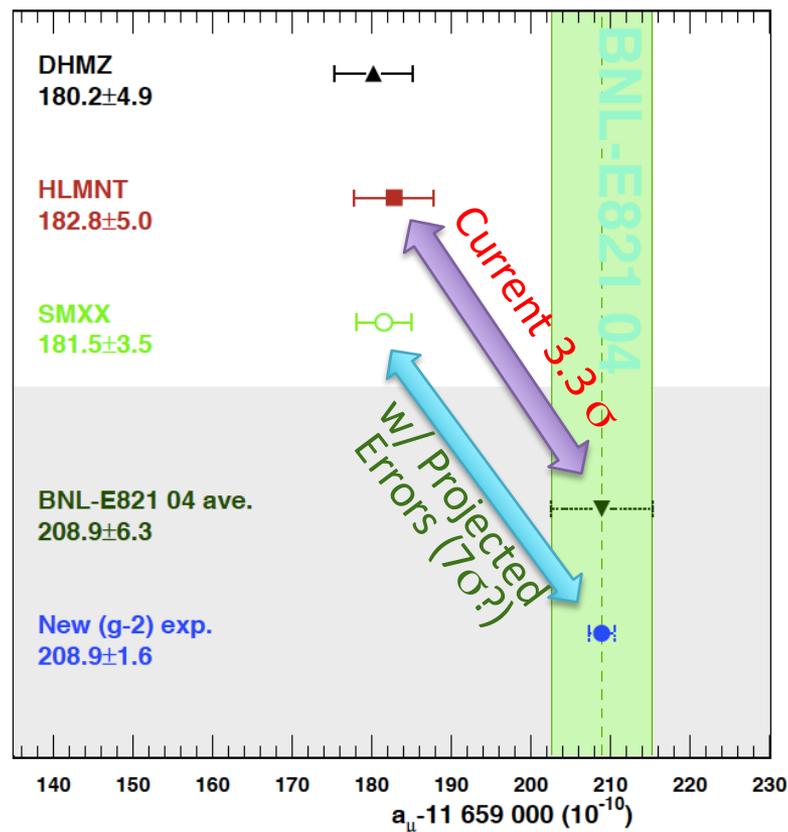




# Conclusion



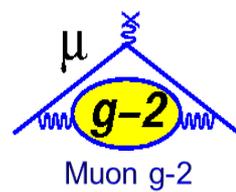
<http://arxiv.org/pdf/1311.2198v1.pdf>



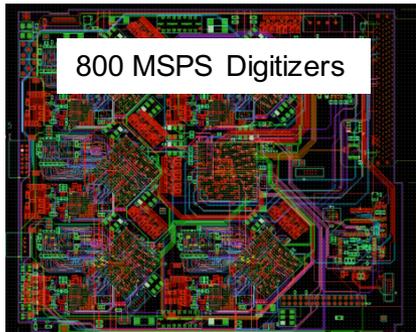
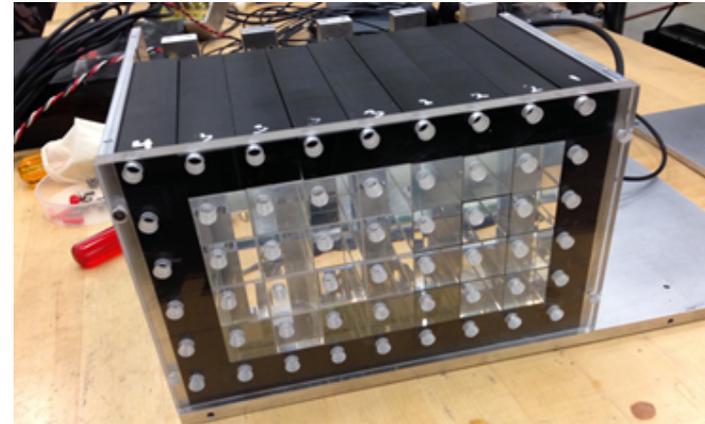
- Muon g-2 remains one of the most highly cited experimental results in particle physics
  - Provides constraints orthogonal to many other experiments in the quest for new physics
- The theoretical error will continue to improve over the next few years
  - 30% reduction from e+e- with high hopes for lattice QCD
- A new muon g-2 is under constructions now....stayed tuned for first result in 2018!



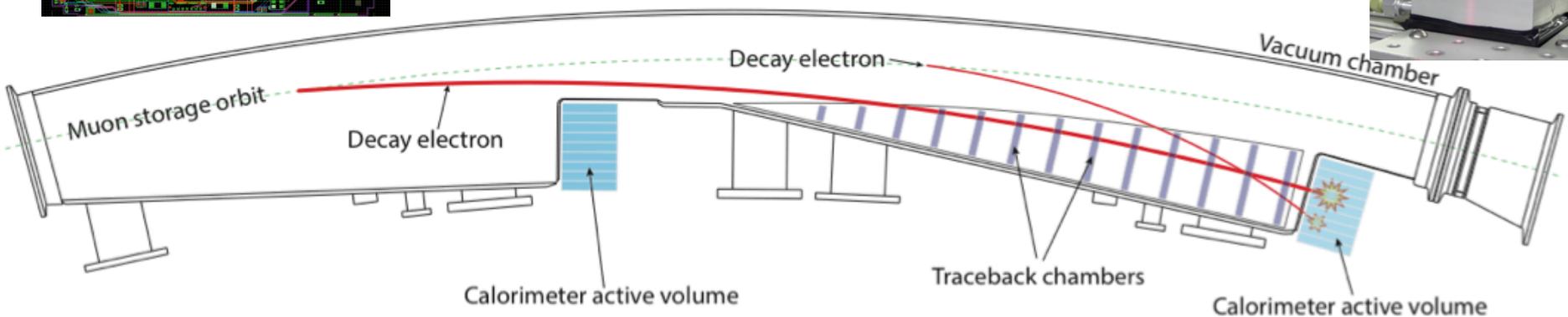
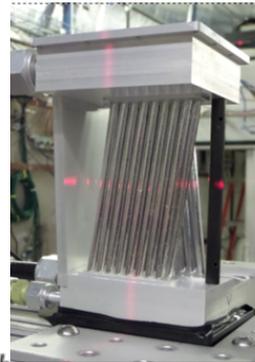
# Improvements to deal with pileup

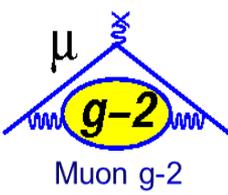


- PbF2 calorimeters constructed with spatial segmentation read out with individual SiPMs
- Faster 800 MSPS digitizers
- Keeping pulses down to much lower threshold – 2 PB/year
- Installing straw trackers in front of 3/24 calorimeters



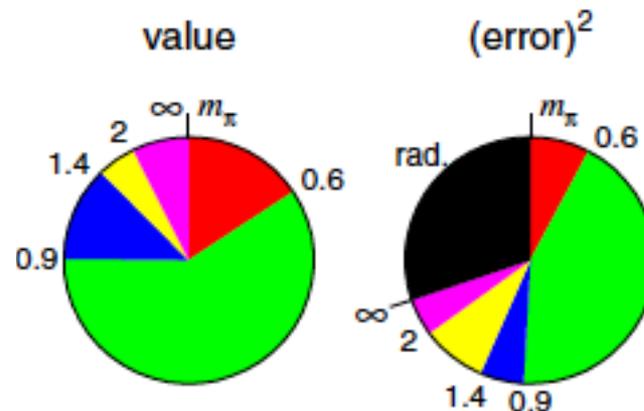
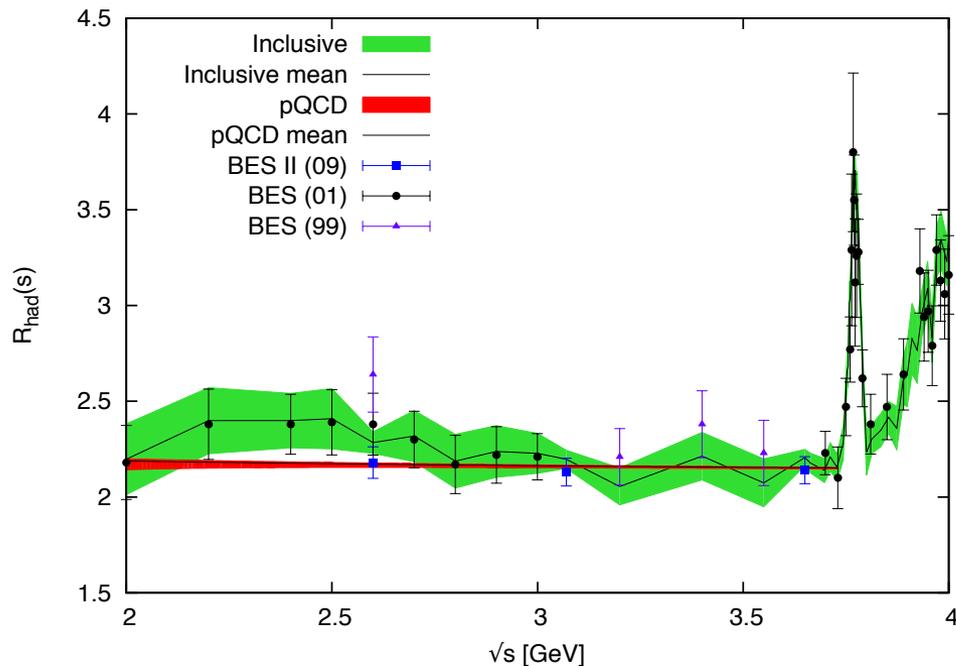
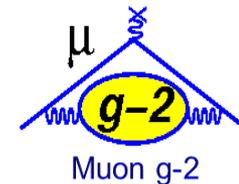
Top view of 1/12 vacuum chambers





# Backup Slides

# LO hadronic contributions at $\sqrt{s} > 2$ GeV

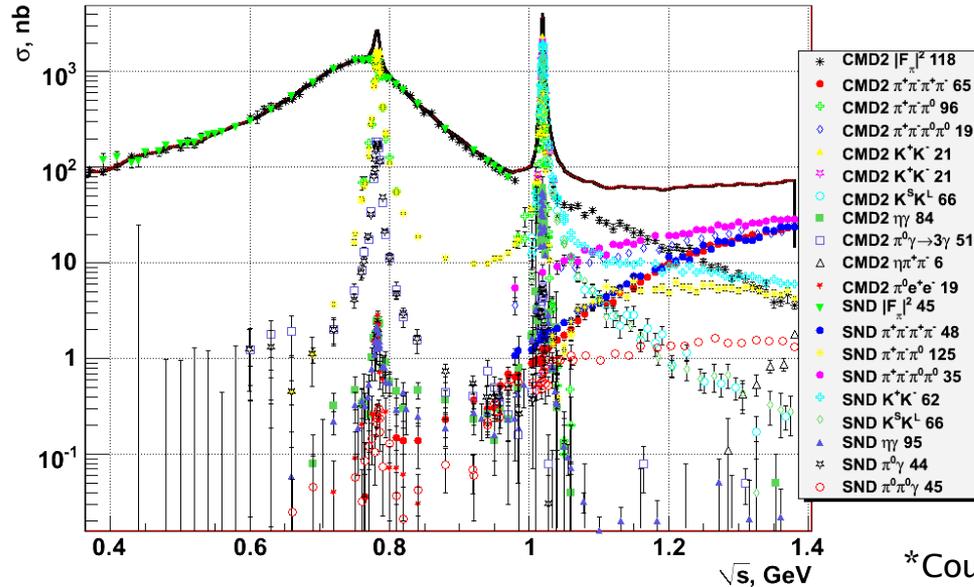
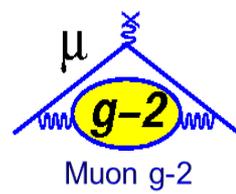


\*from Hagiwara et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 085003

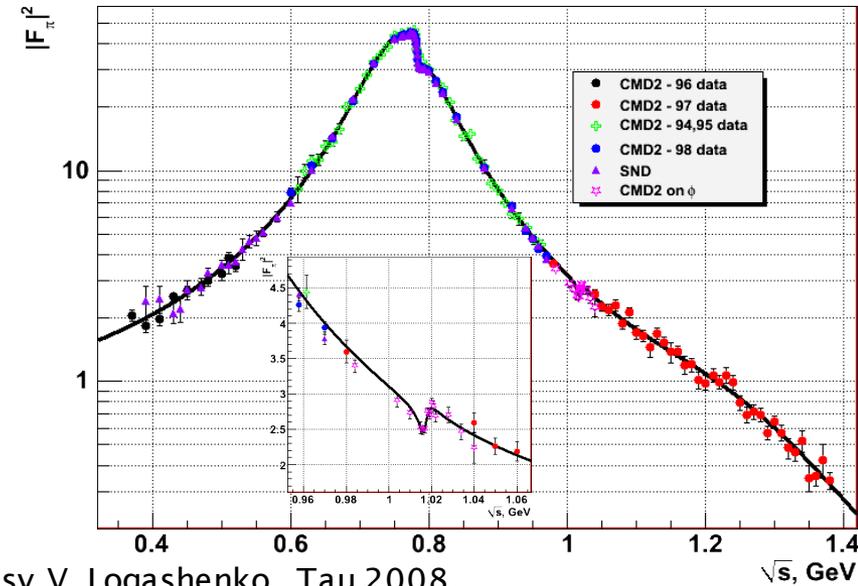
- At larger center-of-mass energies perturbative QCD can be used to calculate  $e^+e^-$  cross-section
  - BES data confirms pQCD calculation in transition region, different groups have slightly different regions where they switch from using data to pQCD (1.8 – 2.4 GeV)
  - Looking forward to higher statistics and center of mass energies from BES III data
- Below 2 GeV, we rely on exclusive measurements, with two pion channel especially important (green portion of pi charts)



# Hadronic contributions at lower sqrt(s)



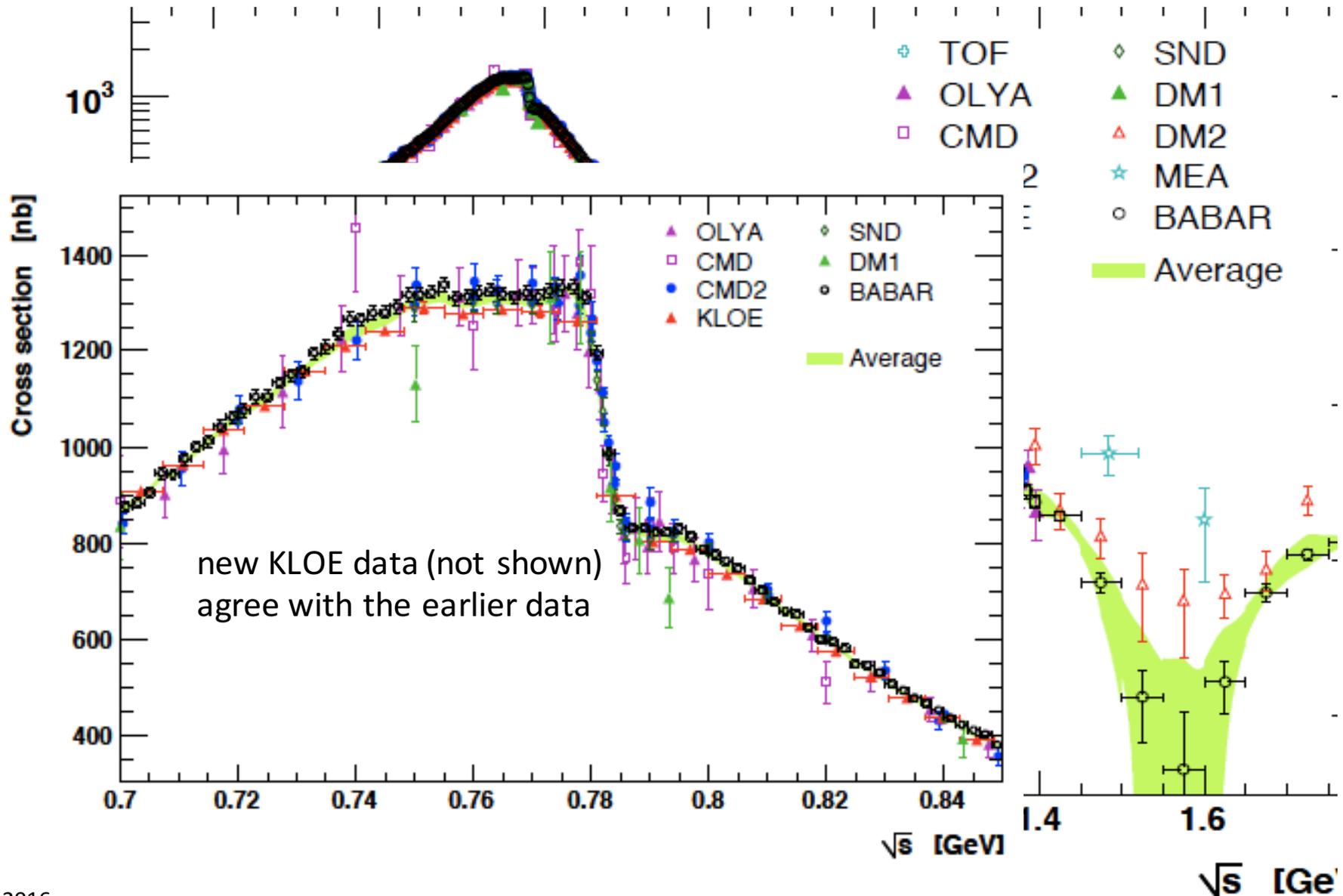
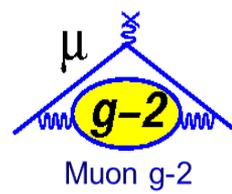
\*Courtesy V. Logashenko, Tau 2008



- At the time the BNL data were being analyzed, the only  $e^+e^-$  data with came from Novosibirsk beam energy scans
- Since then, KLOE and Babar have used radiative return to produce very high statistics data sample
- Can see the  $\rho$ - $\omega$  mixing peak (2 pion channel) that dominates spectrum along with the turn on of many exclusive channels

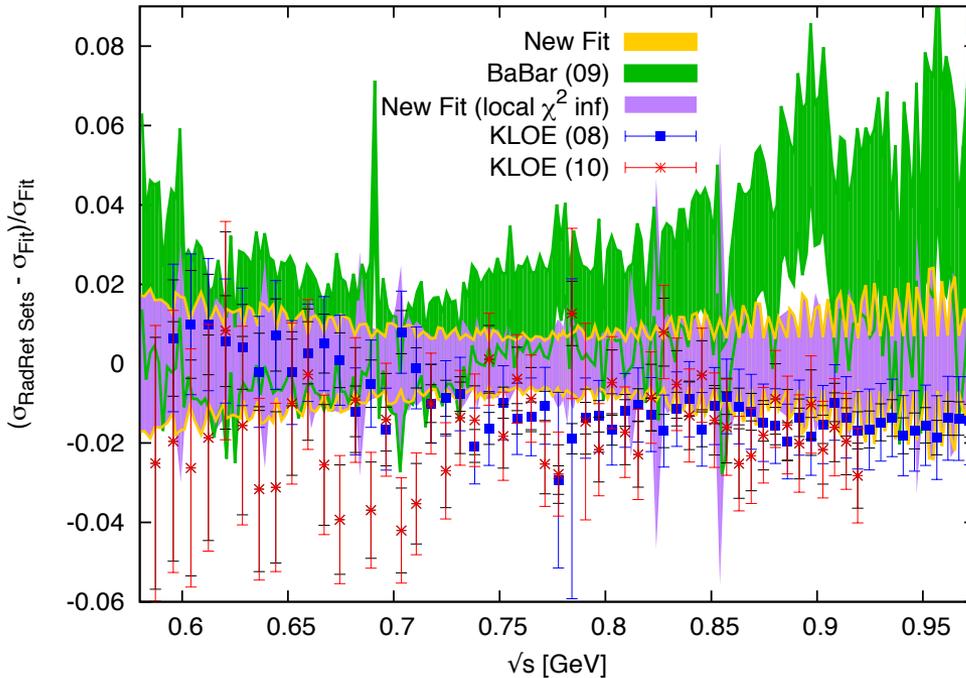
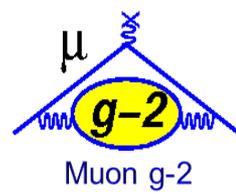


# Results from the 2 pion channel





# Outlook for $\rho$ - $\omega$ mixing region



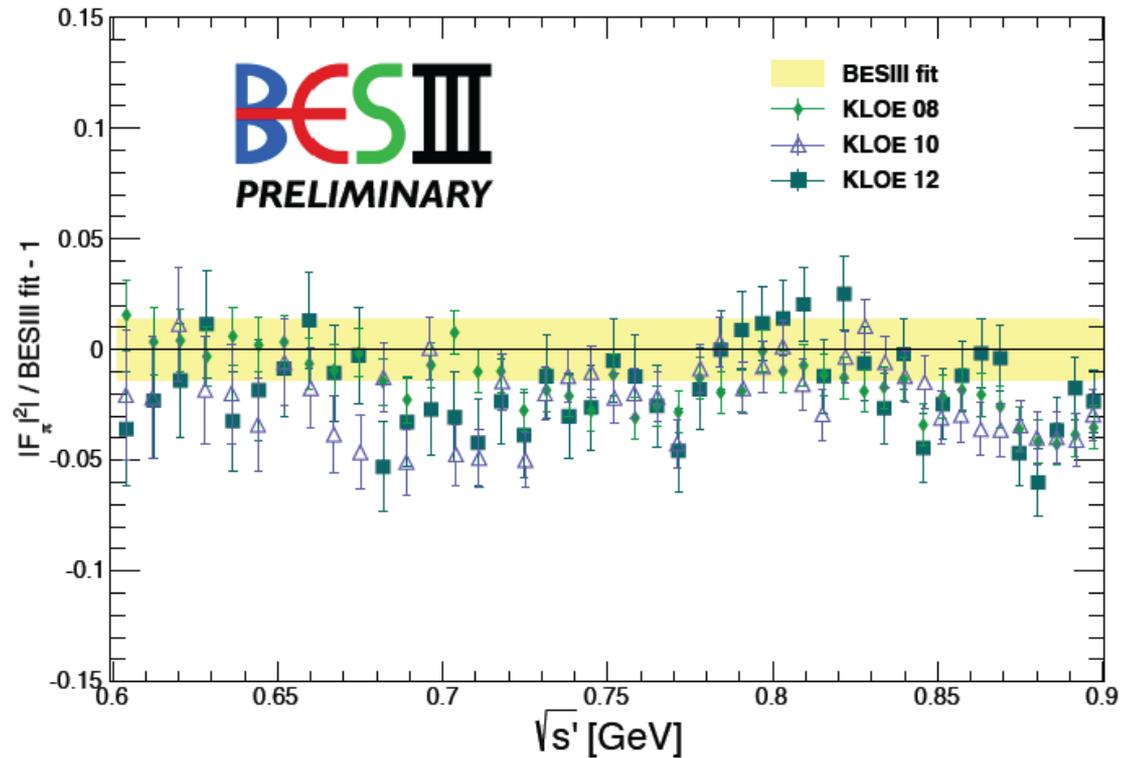
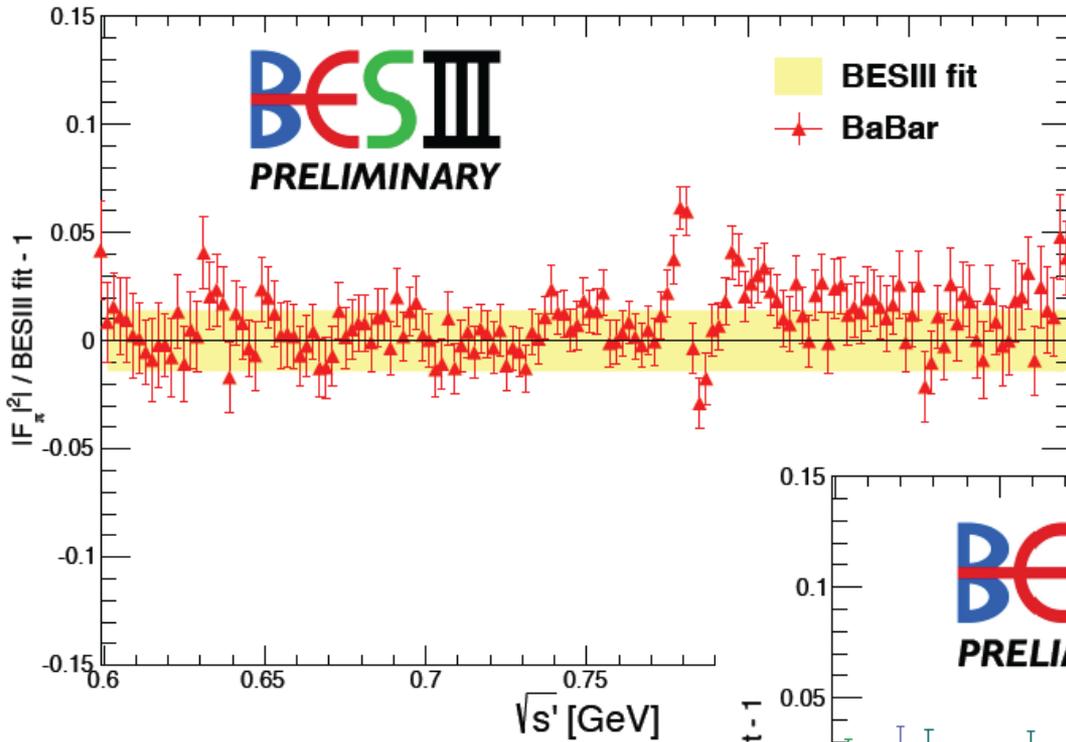
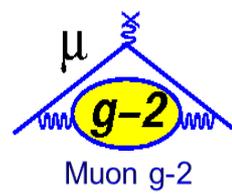
- Can see tension between Babar and KLOE data
- Prevents full reduction in errors from combination

- Avenues for improvement...

- Understand source of tension, radiative return corrections
- Bring in more data sets
  - BESIII data already coming in
  - Novosibirsk upgrade to run up to higher center-of-mass energies
- Calculate LO HVP on the lattice

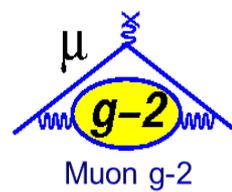


# Comparison to BaBar/KLOE

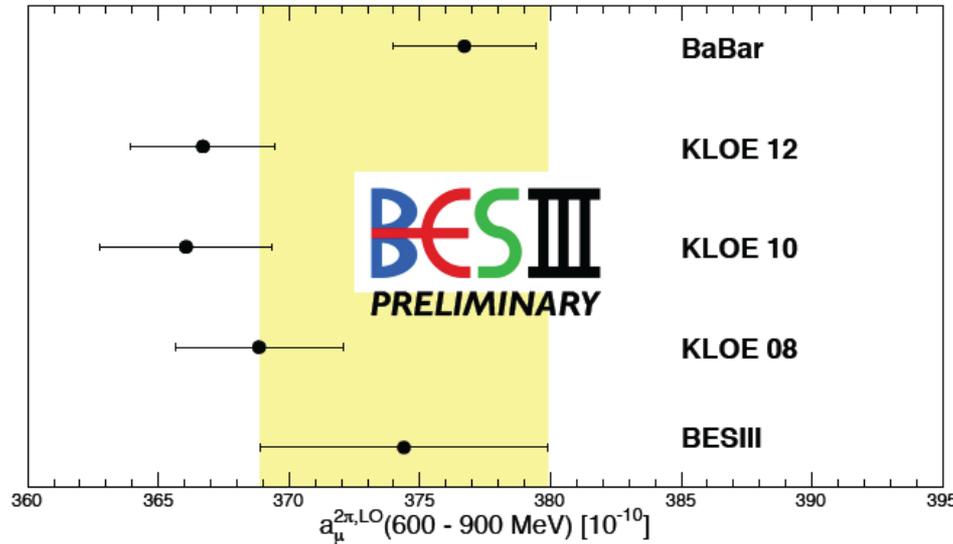




# Initial results confirm BaBar/KLOE



## Result for (g-2)

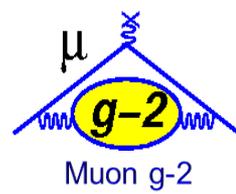


- 3x data already collected
- Anticipate initial publication with 30% smaller errors
- So far, landing right between BaBar and KLOE

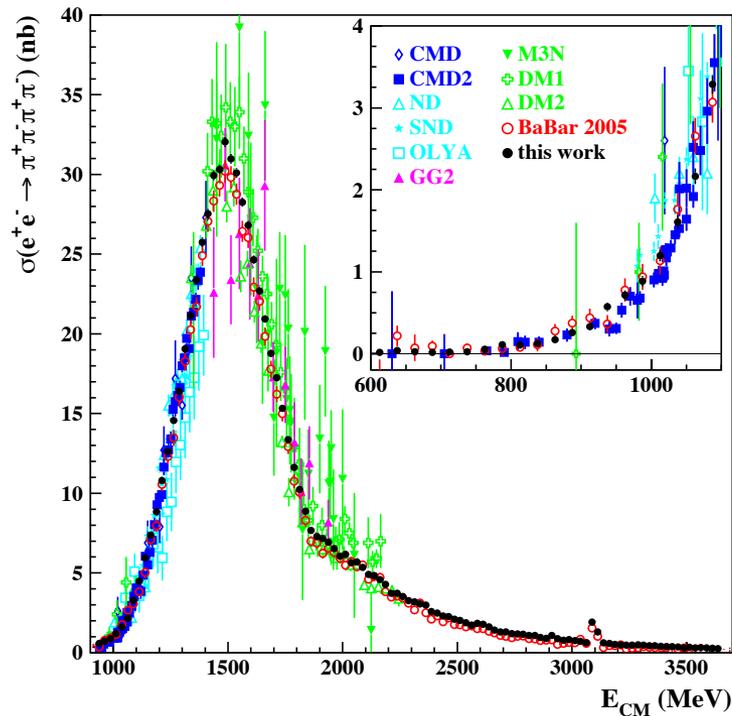
Experiment	$a_\mu^{2\pi,LO}(600 - 900 \text{ MeV}) [10^{-10}]$
BaBar	$376.7 \pm 2.0_{\text{stat}} \pm 1.9_{\text{sys}}$
KLOE 08	$368.9 \pm 0.4_{\text{stat}} \pm 2.3_{\text{sys,exp}} \pm 2.2_{\text{sys,theo}}$
KLOE 10	$366.1 \pm 0.9_{\text{stat}} \pm 2.3_{\text{sys,exp}} \pm 2.2_{\text{sys,theo}}$
KLOE 12	$366.7 \pm 1.2_{\text{stat}} \pm 2.4_{\text{sys,exp}} \pm 0.8_{\text{sys,theo}}$
BESIII (preliminary)	$374.4 \pm 2.6_{\text{stat}} \pm 4.9_{\text{sys}}$



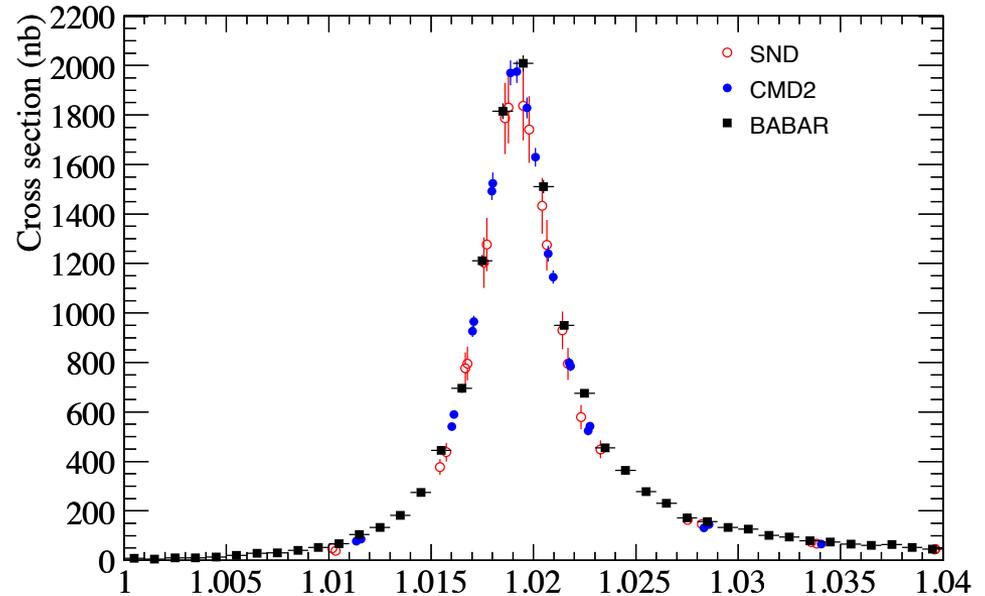
# Recent data from multi-hadron channels



## $K^+K^-(\gamma)$ from BaBar



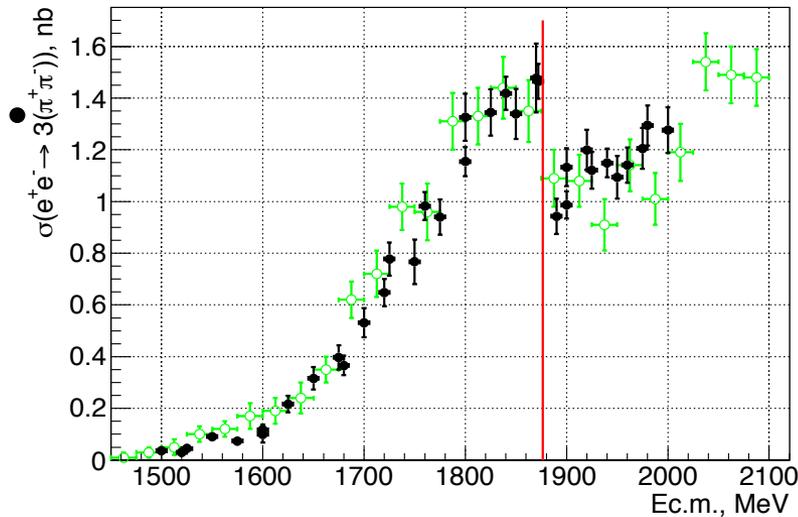
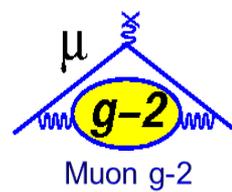
## $2\pi^+2\pi^-(\gamma)$ from BaBar



- In region from  $2\pi$  threshold to 2 GeV...many exclusive channels are used
- More precise measurements coming from BaBar, Belle, & Novosibirsk

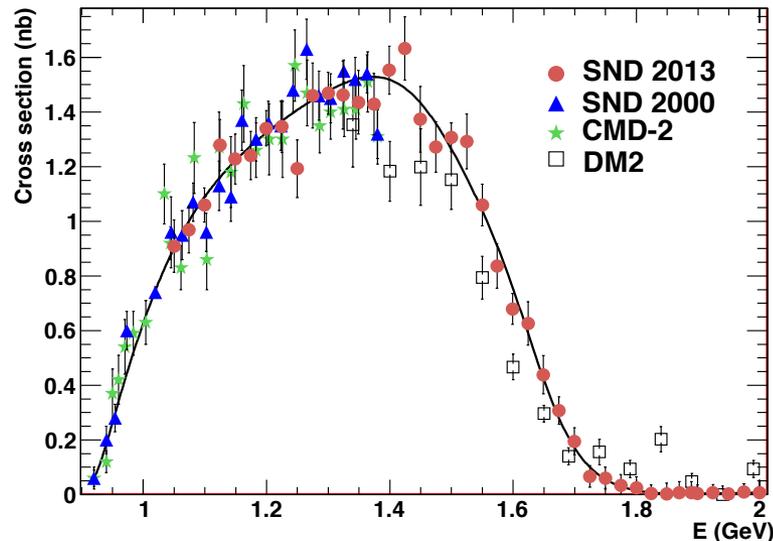


# Novosibirsk recently upgrade to 2 GeV sqrt(s)



## CMD-3 $6\pi$ charged PLB723(2013)82

- solid black: CMD-3, open green: BaBar
- full analysis will include  $2(\pi^+\pi^-\pi^0)$

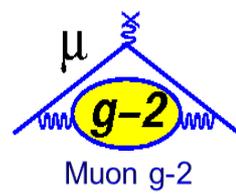


## SND $\omega\pi^0$ , arXiv:1303.5198

- many more analyses reported with preliminary results, incl.  $3\pi$ ,  $4\pi(2\eta)$
- looking forward to rich harvest from SND and CMD-3



# Out look for LOHVP data-driven approach



- Much more data coming in from b-factories
- Upgrades to BES and Novosibirsk allowing access to multi-hadron channels with unprecedented precision
- Work has started to reanalyze how BaBar and KLOE handle radiative corrections
- Lattice calculation looks very promising as well.

Thomas Teubner's opinion...echoes sentiment of the community

My personal '5 year prognosis':

[expected improvement in error]

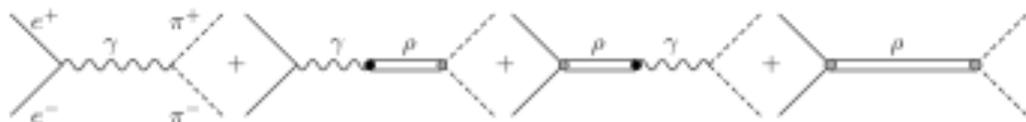
- $2\pi$ : error down by about 30-50%
- **subleading channels**: by factor 2-3
- $\sqrt{s} > 2 \text{ GeV}$ : by about a factor 2

➔ I believe we can half the HVP error

# Another 'puzzle': Use of **tau** spectral function data?

- Use CVC (iso-spin symmetry) to connect  $\tau^- \rightarrow \pi^0 \pi^- \nu_\tau$  spectral functions to  $e^+e^- \rightarrow \omega, \rho \rightarrow \pi^+\pi^-$  but have to apply **iso-spin corrections**
- Early calculations by [Alemany, Davier, Hoecker](#): use of  $\tau$  data complementing  $e^+e^-$  data originally resulted in an improvement w.r.t. use of  $e^+e^-$  data alone; discrepancy smaller with tau data; later increased tension between  $e^+e^-$  and  $\tau$
- Recent compilation by [Davier et al](#) in [BaBar's PRD86,032013](#):

- [Jegerlehner+Szafron](#): crucial role of  **$\gamma$ - $\rho$  mixing**:

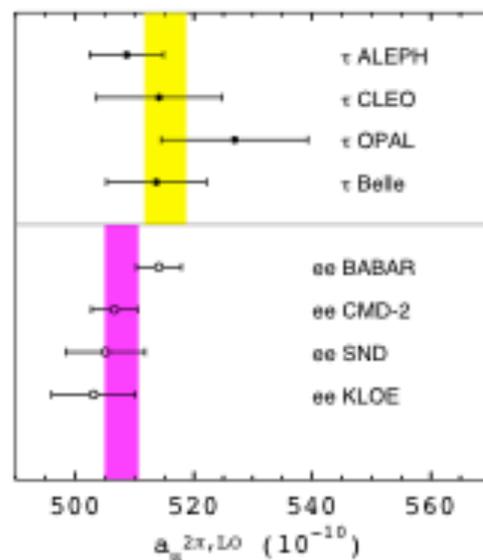


- They found discrepancy gone but  $\tau$  data improved  $e^+e^-$  analysis only marginally, however [BaBar](#)  $\pi^+\pi^-$  data not used

- Analyses by [Benayoun et al](#): combined fit of  $e^+e^-$  and  $\tau$  based on **Hidden Local Symmetry (HLS)**: no big tension betw.  $e^+e^-$  and  $\tau$ , but w. [BaBar](#), hence not used; **increased  $\Delta a_\mu$  of  $\sim 4.5\sigma$**

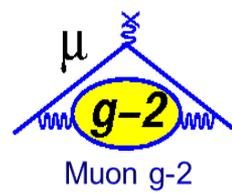
- [Davier+Malaescu](#) refute criticism, claim fair agreement betw. [BaBar](#) and their  $\tau$  comp.

- **HLMNT**: stick to  $e^+e^-$  (and do not use  $\tau$  data). With  $e^+e^-$  (incl. [BaBar](#)) discrepancy of **3-3.5 $\sigma$**





# The 'Glasgow Consensus'



- Major effort from quite a few experts over the last two decades to produce reliable (but still model-dependent) calculations

Some results for the various contributions to  $a_\mu^{\text{LbyL;had}} \times 10^{11}$ :

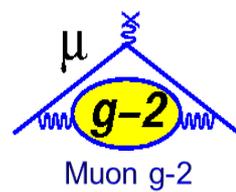
Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
$\pi^0, \eta, \eta'$	$85 \pm 13$	$82.7 \pm 6.4$	$83 \pm 12$	$114 \pm 10$	—	$114 \pm 13$	$99 \pm 16$	$84 \pm 13$
axial vectors	$2.5 \pm 1.0$	$1.7 \pm 1.7$	—	$22 \pm 5$	—	$15 \pm 10$	$22 \pm 5$	—
scalars	$-6.8 \pm 2.0$	—	—	—	—	$-7 \pm 7$	$-7 \pm 2$	—
$\pi, K$ loops	$-19 \pm 13$	$-4.5 \pm 8.1$	—	—	—	$-19 \pm 19$	$-19 \pm 13$	—
$\pi, K$ loops +subl. $N_C$	—	—	—	$0 \pm 10$	—	—	—	—
other	—	—	—	—	—	—	—	$0 \pm 20$
quark loops	$21 \pm 3$	$9.7 \pm 11.1$	—	—	—	$2.3$	$21 \pm 3$	$107 \pm 48$
Total	$83 \pm 32$	$89.6 \pm 15.4$	$80 \pm 40$	$136 \pm 25$	$110 \pm 40$	$105 \pm 26$	$116 \pm 39$	$191 \pm 81$

BPP = Bijmens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijmens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

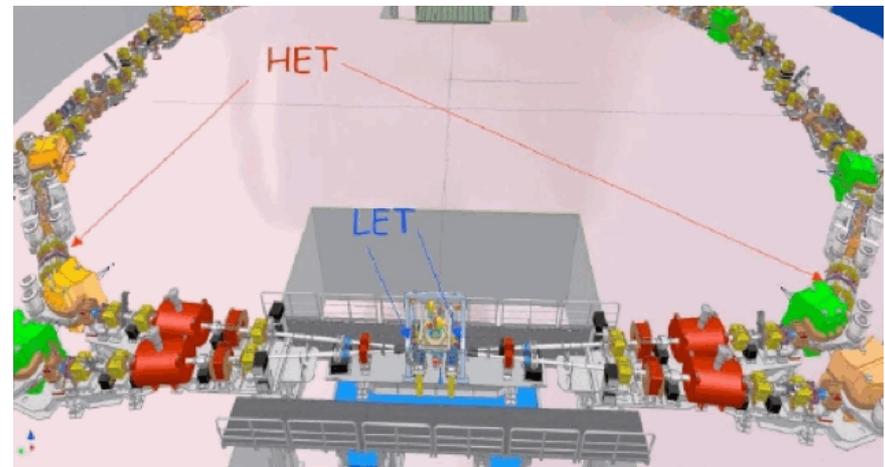
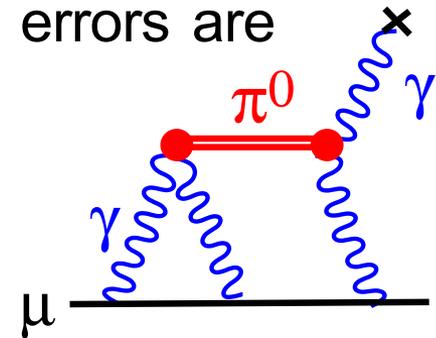
- Terrible name...sounds like the theorists got together and voted
- In reality, at Glasgow workshop they got together and did a careful comparison of what components each had calculated
- They found that within errors all of their calculations were in agreement
- Established the recommended valued of  $105 (26) \times 10^{-11}$



# HLBL Outlook



- It is worth noting that the modelers would have to be really wrong to explain the BNL discrepancy with HLBL
  - Contribution would have to be 350% larger
  - Based on their understanding of errors, would have to be off by  $10-12\sigma$
- Nevertheless, the question of how well the model errors are understood remains
- Possible improvements
  - Low angle scattering detectors installed at KLOE 2 and BESIII
  - Measurement of  $\gamma\gamma^* \rightarrow \text{hadrons}$  relates to  $\sim 70\%$  of HLBL
  - $\pi^0 \rightarrow \gamma\gamma$  life-time (from PrimEx at JLab) help to constrain models
- Real hope for future is that HLBL will come from lattice



## Importance of various 'channels'

[Numbers from HLMNT, 'local error infl.',  $\cdot 10^{-10}$ ]

- Errors contributions to  $a_\mu$  from leading and subleading channels (ordered) up to 2 GeV

Purely from data:

channel	error
$\pi^+\pi^-$	3.09
$\pi^+\pi^-\pi^0\pi^0$	1.26
$3\pi$	0.99
$2\pi^+2\pi^-$	0.47
$K^+K^-$	0.46
$2\pi^+2\pi^-2\pi^0$	0.24
$K_S^0K_L^0$	0.16

'Higher multiplicity' region from 1.4 to 2 GeV  
with use of isospin relations for some channels:

[Use of old inclusive data disfavoured.]

Channel	contr. $\pm$ error
$K\bar{K}2\pi$	$3.31 \pm 0.58$
$\pi^+\pi^-4\pi^0$	$0.28 \pm 0.28$
$\eta\pi^+\pi^-$	$0.98 \pm 0.24$
$K\bar{K}\pi$	$2.77 \pm 0.15$
$2\pi^+2\pi^-\pi^0$	$1.20 \pm 0.10$

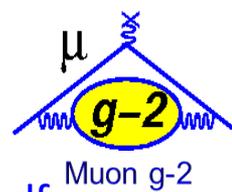
- 'Inclusive' region from 2 to  $\sim 11$  GeV:  **$41.19 \pm 0.82$**

Can be 'squeezed' by using pQCD (done by DHMZ from 1.8 GeV);

region from 2 to 2.6 GeV:  $15.69 \pm 0.63 \rightarrow 14.49 \pm 0.13$ , only small changes for higher energies.

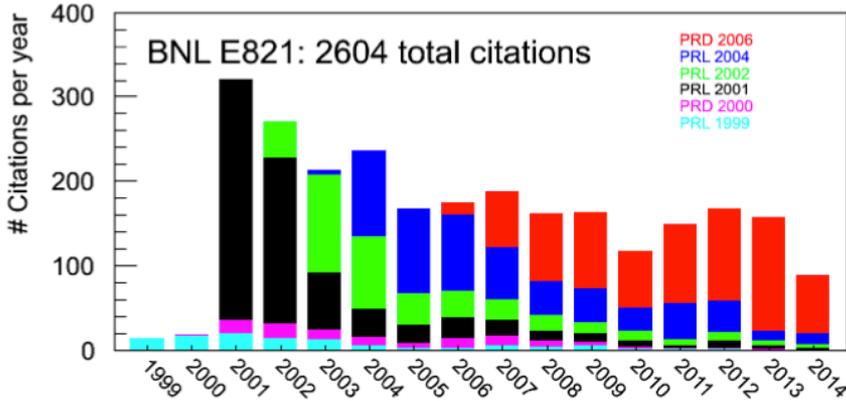


# Mission Need & Scientific Requirements

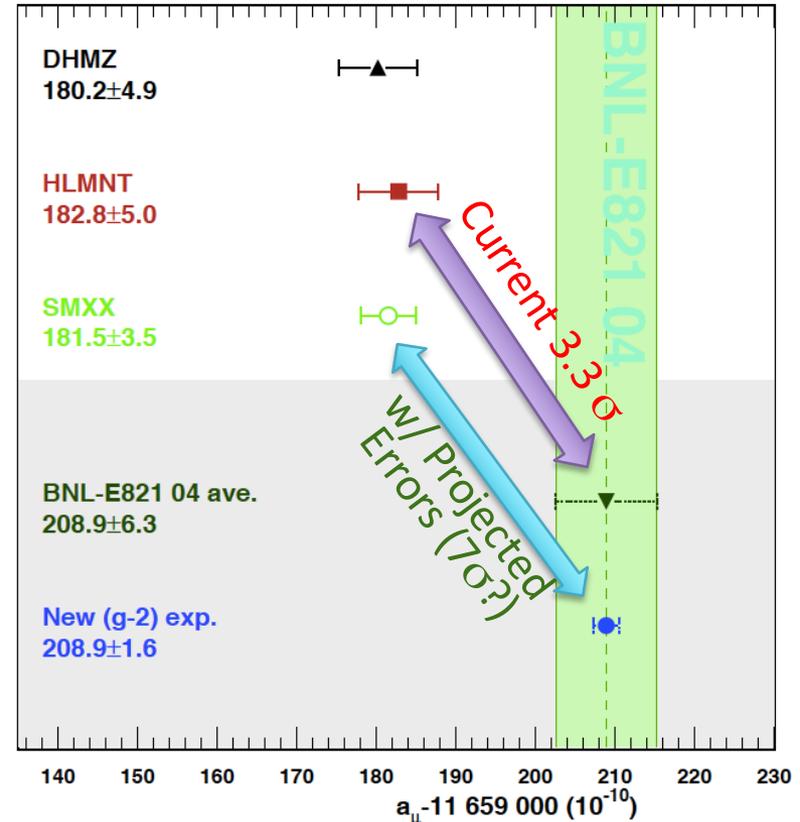


Muon g-2

<http://arxiv.org/pdf/1311.2198v1.pdf>

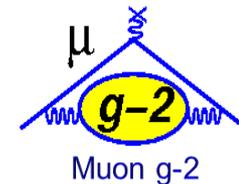


- The BNL E821 experiment remains one of the highest cited results in particle physics
  - Applicable to a wide range of theories
  - $3\sigma$  discrepancy intriguing



- FNAL E989 experiment granted Mission Need from OHEP on Sep 18, 2012 to develop an experiment that could confirm or refute the BNL result by reducing the experimental error by a factor of 4
  - If current discrepancy persists, significance will be pushed beyond  $5\sigma$  discovery threshold
  - Anticipated theoretical improvement could lead to  $>7\sigma$

# Strong mix of E821 and new collaborators



## Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Mississippi
- Kentucky
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

## • National Labs

- Argonne
- Brookhaven
- Fermilab

## • Consultants

- Muons, Inc.



## Italy

- Frascati
- Roma 2
- Udine
- Naples
- Trieste



## China:

- Shanghai



## The Netherlands:

- Groningen



## Germany:

- Dresden



## Japan:

- Osaka



## Russia:

- Dubna
- PNPI
- Novosibirsk



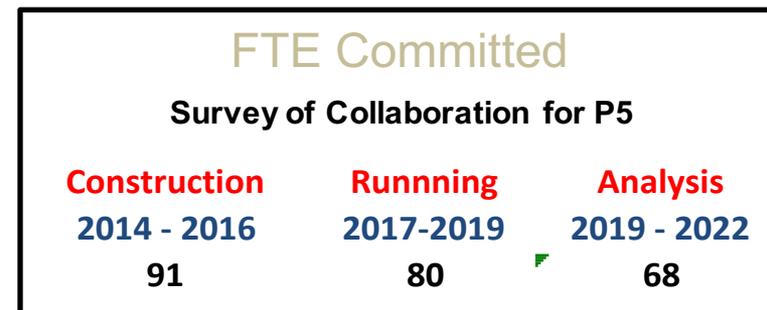
## England

- University College London
- Liverpool
- Oxford
- Rutherford Lab



## Korea

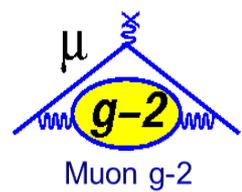
- KAIST



Co-spokespersons: David Hertzog, Lee Roberts  
Project Manager: Chris Polly



# $\omega_a$ Systematic Requirements



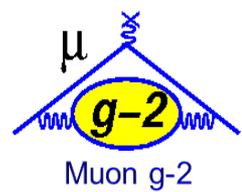
E821 Error	Size [ppm]	Plan for the E989 $g - 2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher $n$ -value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher $n$ -value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05 <sup>1</sup>	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

Overall,  $\omega_a$  systematics need to be reduced by a factor of 3

- Some errors were data-driven, precision of corrections scales with statistics
- Environmental improvements by changing run conditions, e.g. no hadronic flash
- Many hardware and analysis-driven improvements detailed in parallel sessions



# $\omega_p$ Systematic Requirements

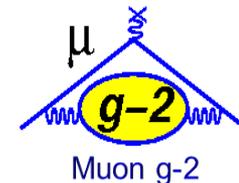


E821 Error	Size [ppm]	Plan for the E989 $g - 2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	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 temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B 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	0.05
Total	0.17		0.07

Overall,  $\omega_p$  systematics need to be reduced by a factor of 2.5

- Better run conditions, e.g. temperature stability of experimental hall, more time to shim magnetic field to high uniformity, smaller stored muon distribution
- Also many hardware and simulation driven improvements detailed in parallel sessions

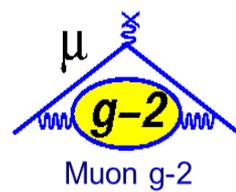
# Domestic Collaborators & Responsibilities



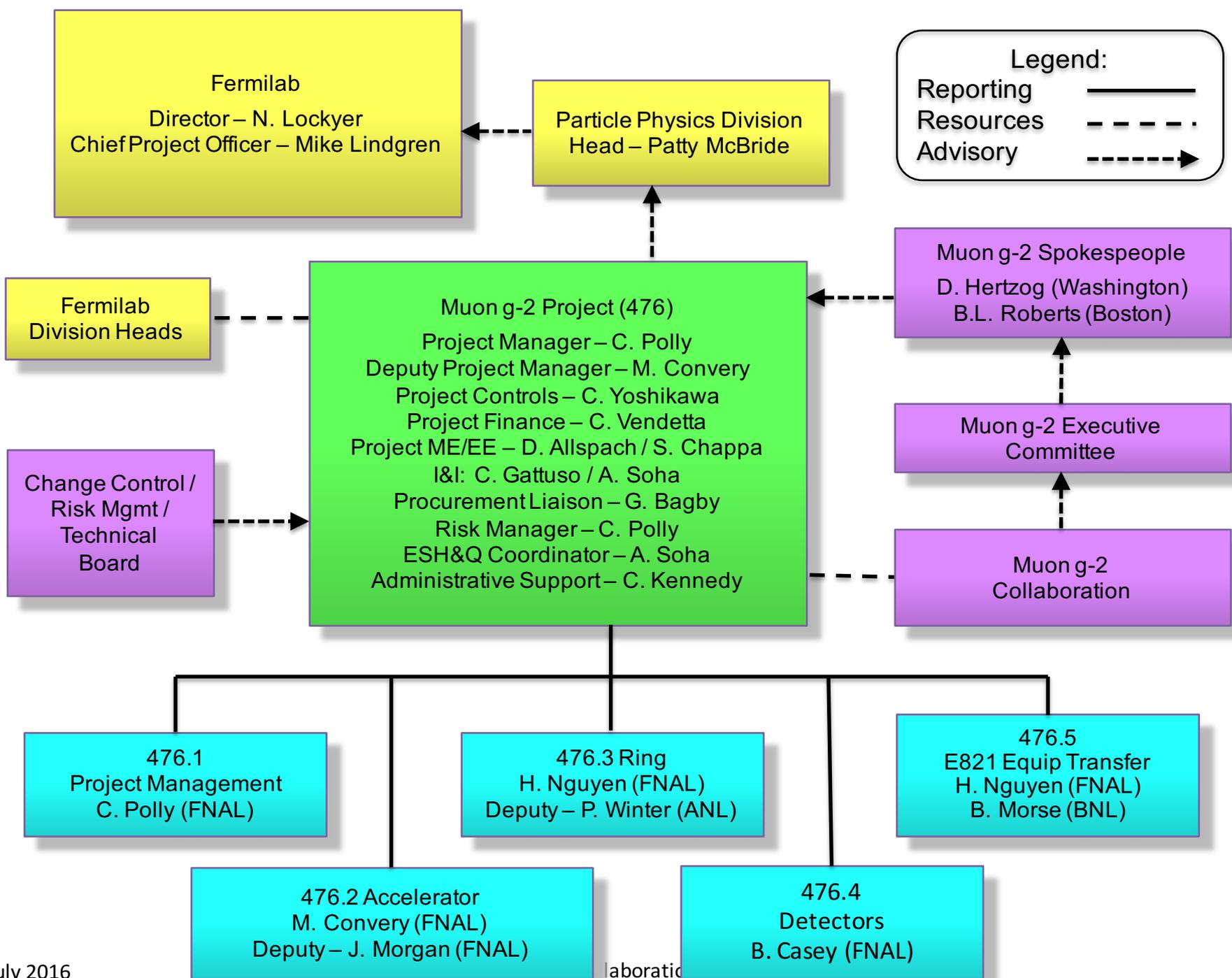
- Argonne
  - Slow controls; Field DAQ; NMR Trolley
- Boston
  - Straw electronics; Fast rotation; Inflector
- Brookhaven
  - Quads, Storage Ring; DAQ, Analysis methods
- Cornell
  - New Kicker; Waveform digitizers; Simulations
- Fermilab
  - Storage Ring, Accelerator, Traceback Straws, Beam Dynamics, Inflector; Simulations
- Illinois
  - Beam dynamics; Clocks and controls
- James Madison
  - Bias distribution
- Massachusetts
  - Magnetic Field
- Kentucky
  - DAQ
- Michigan
  - Magnetic Field
- Michigan State University
  - End-to-end Simulation
- Mississippi
  - Muon beam instrumentation
- Muons, Inc.
  - Beam and target design simulations
- Northern Illinois University
  - Straws and Ring Transport
- Northwestern
  - Tracking; Theory
- Regis
  - Fiber harp monitor; Analysis
- Virginia
  - Bias distribution; Clock distribution; simulations
- Washington
  - Calorimeter, Beam dynamics, Magnetic field
- York College
  - Storage ring simulation

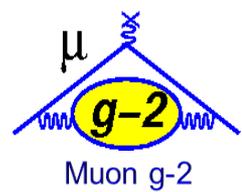


# International Collaborators & Responsibilities



- **Italy**
  - Frascati,
  - Naples
  - Roma 2,
  - Udine
  - Trieste
    - Calorimeter calibration system, test beam, KLOE
- **China:**
  - Shanghai
    - Calorimeter crystals and simulations
- **The Netherlands:**
  - KVI
    - Magnetic field
- **Germany:**
  - Dresden
    - Theory
- **Japan:**
  - Osaka
    - SiPM studies
- **Russia:**
  - Dubna
  - PNPI
  - Novosibirsk
    - TBD
- **England**
  - University College London
  - Liverpool
  - Oxford
  - Rutherford
    - Straws, Inflector, Theory
- **KOREA**
  - KAIST

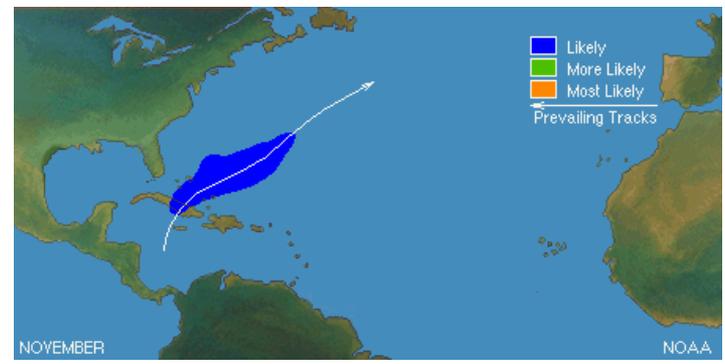
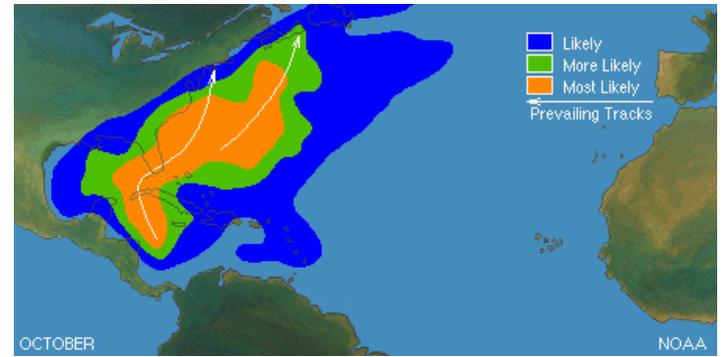
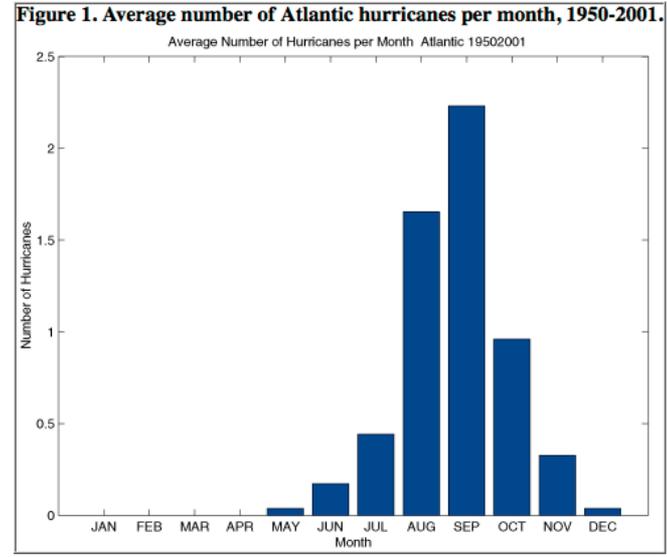




Muon g-2

### Annual Cycle of Atlantic Hurricanes

The peak of the Atlantic hurricane season happens during the months of August to September, as seen in Figure 1, which shows the average number of hurricanes in the Atlantic per month from 1950-2001. The official hurricane season is defined from June to November, but hurricanes occasionally form in other months.

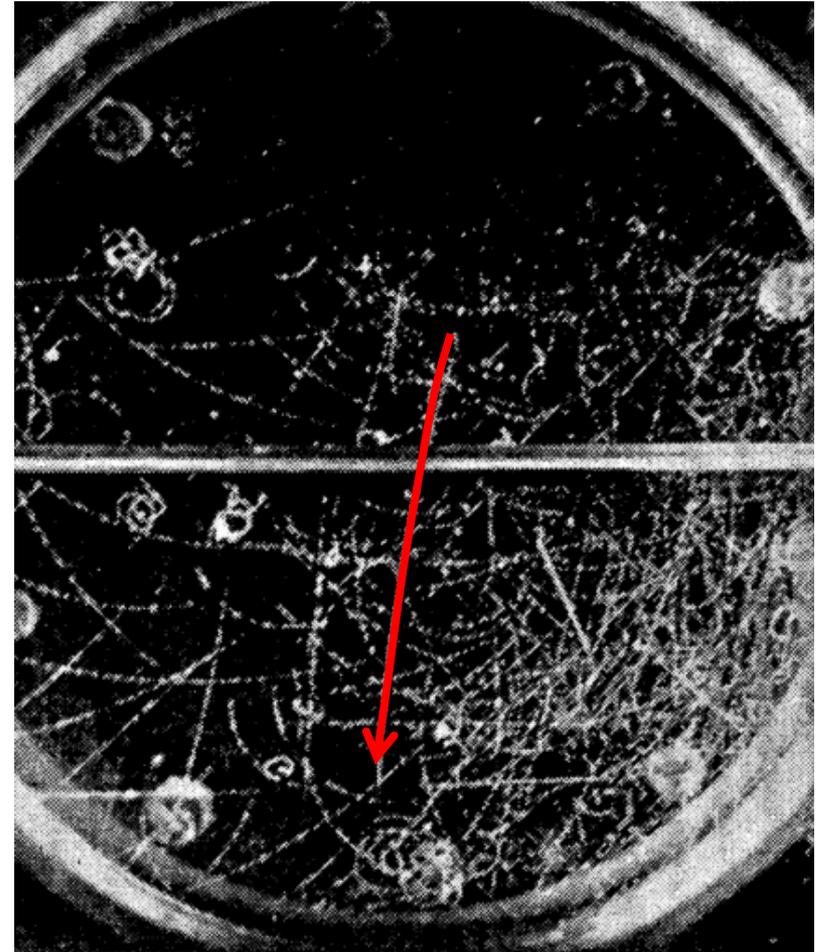
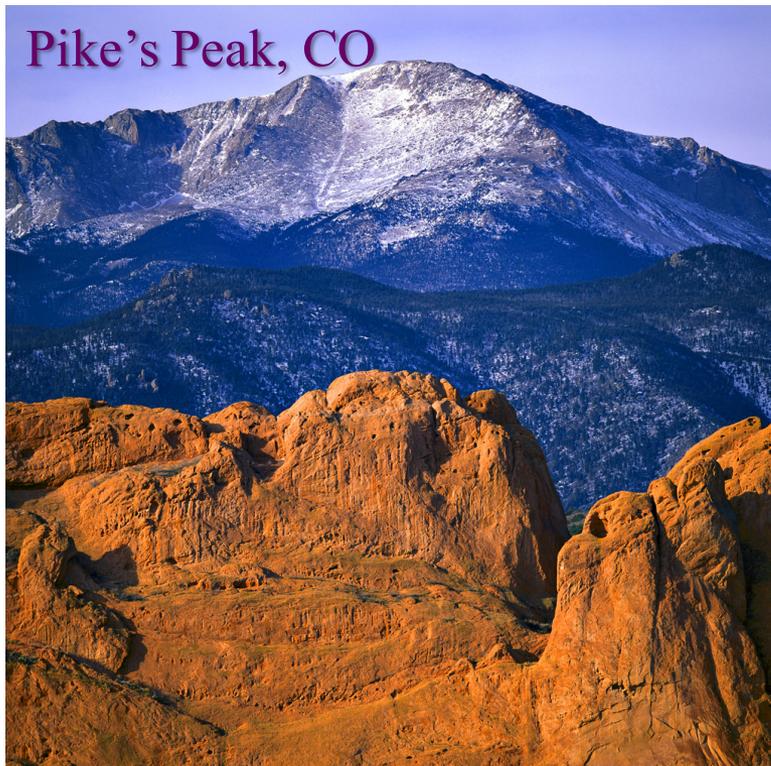
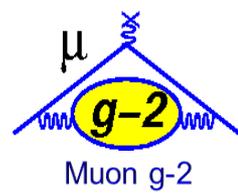


About one year later...the building finished





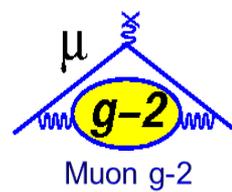
# Muon discovered in 1936



Immediately people were interested in determining its magnetic moment



# First $g_\mu$ measurements



## 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

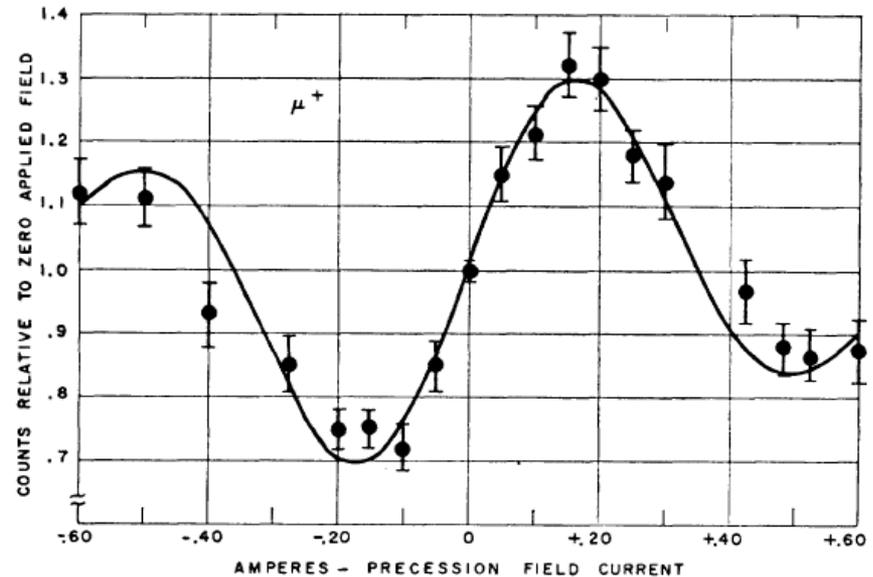
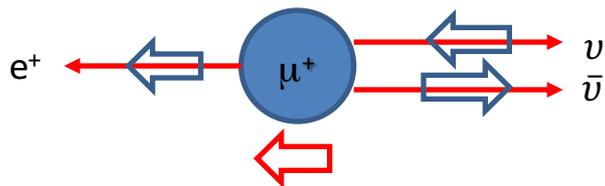
*Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York*

(Received January 15, 1957)

LEE and Yang<sup>1-3</sup> have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the “weak” interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the  $\tau-\theta$  puzzle,<sup>4</sup> was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \quad (1)$$

$$\mu^+ \rightarrow e^+ + 2\nu. \quad (2)$$



- Place polarized muons in a B-field and make two discoveries
  - Parity violation in the muon decay
  - $g_\mu = 2.01 \pm 0.01$
- More precise results followed which confirmed muons really are like ‘heavy’ electrons

# What is dark matter?

$v$  (km/s)

100

50

observed

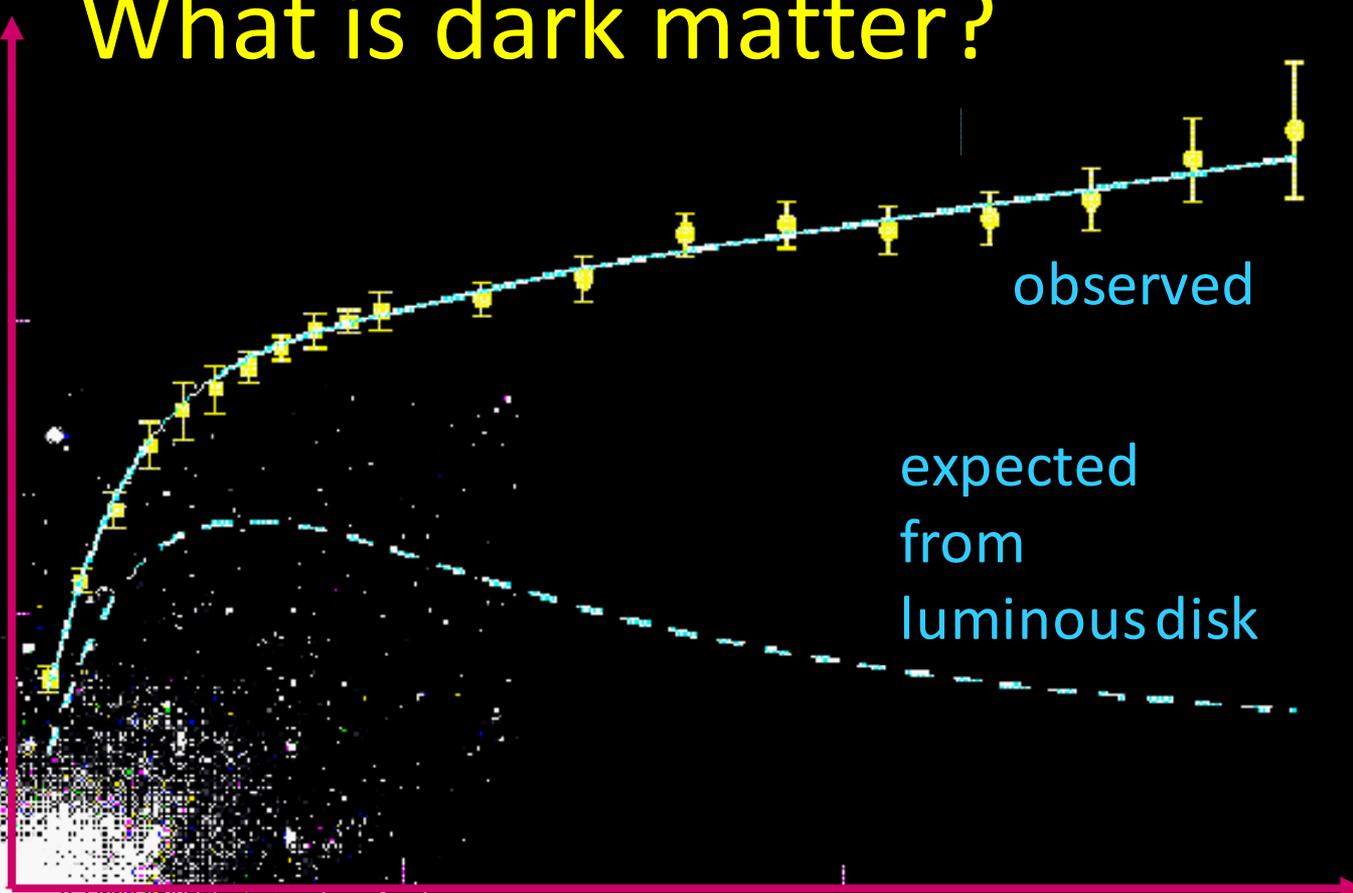
expected  
from  
luminous disk

5

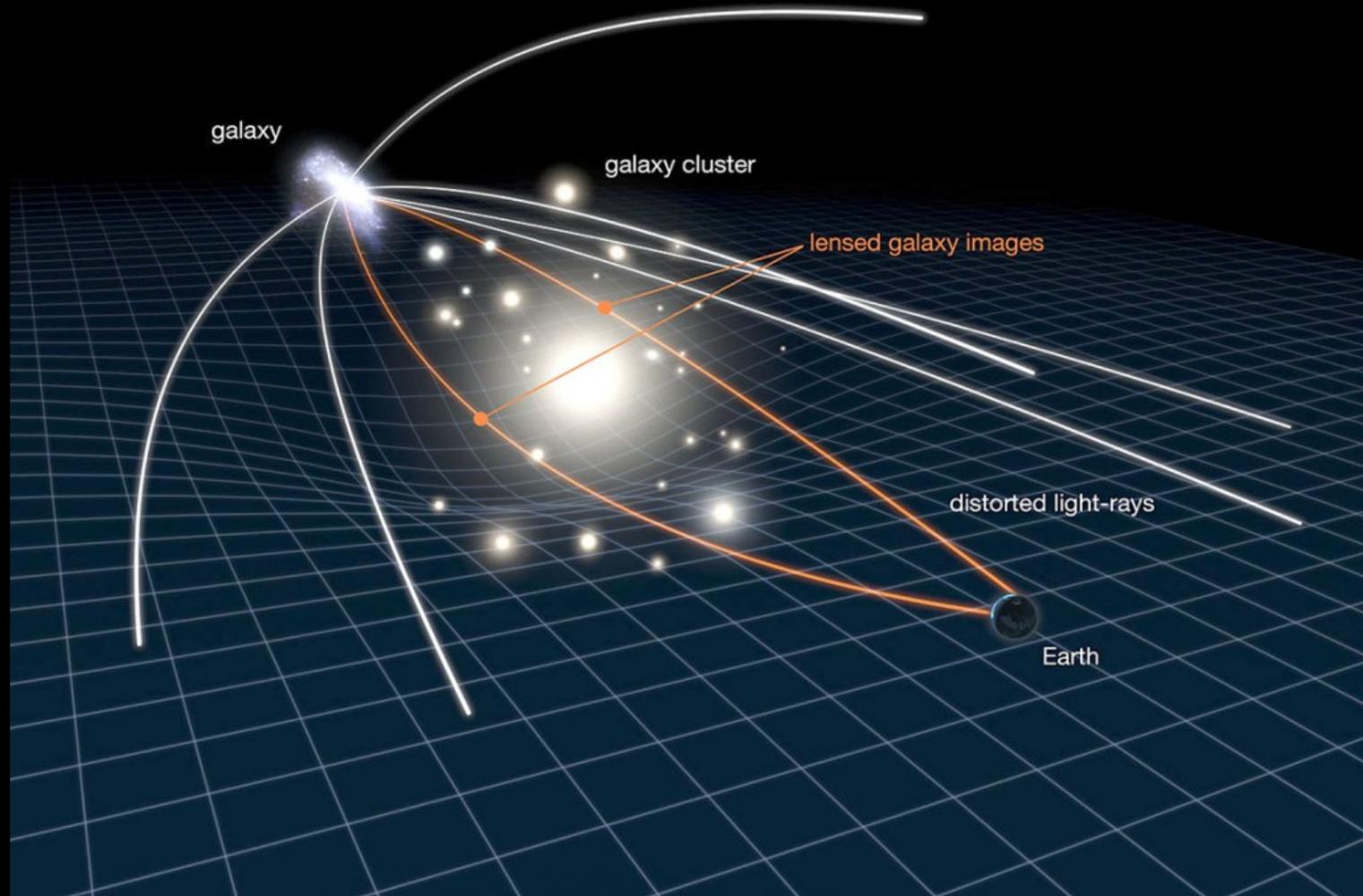
10

$R$  (kpc)

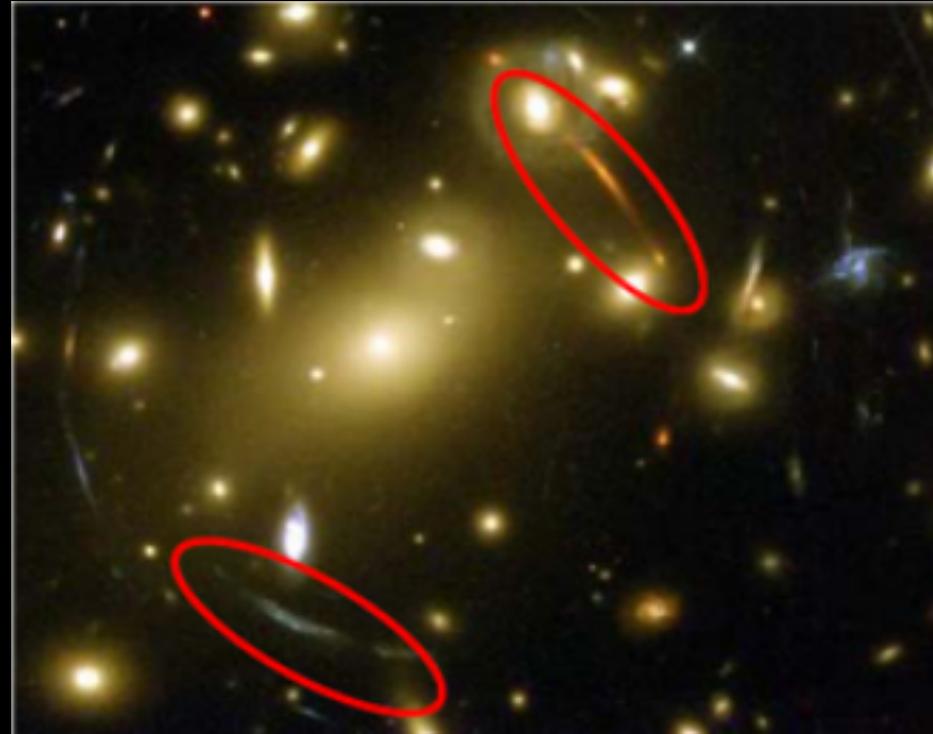
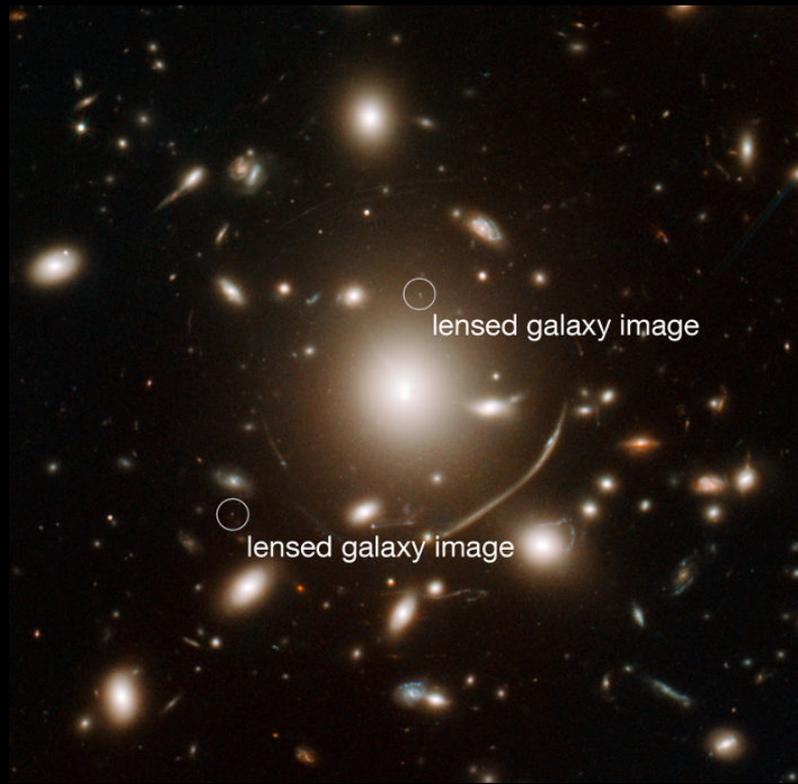
M33 rotation curve  
Courtesy R. Kolb



# Evidence for dark matter confirmed by gravitational lensing observations!



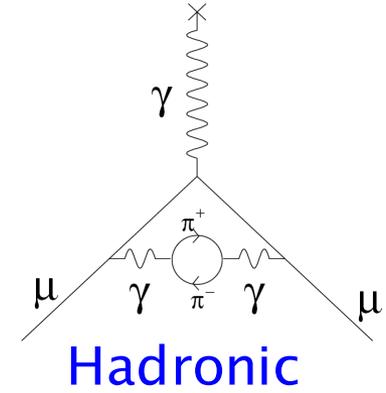
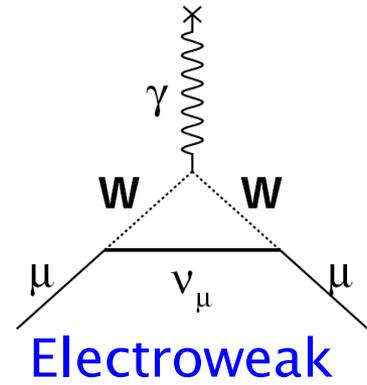
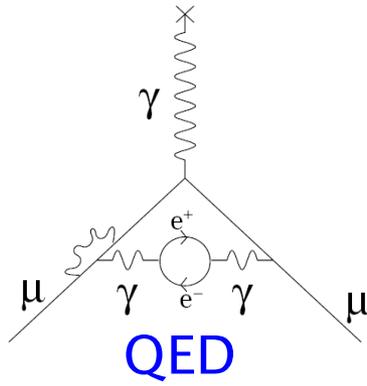
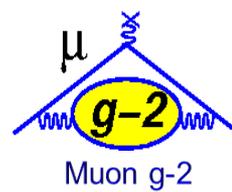
# Gravitational lensing



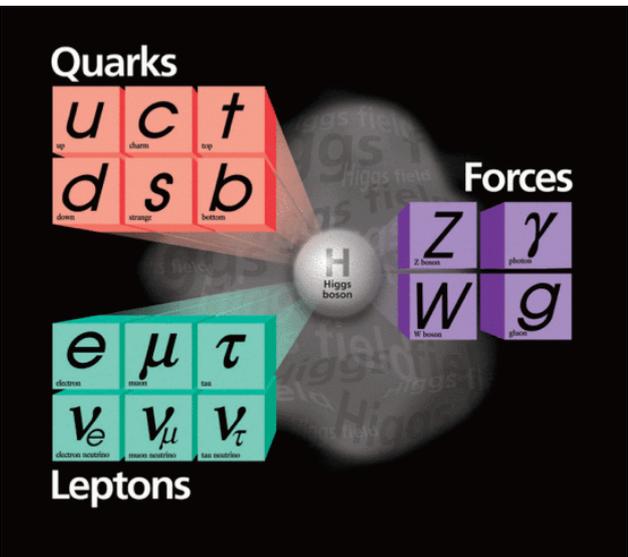
The amount of lensing provides a measurement of the mass between the Earth and the lensed object in the foreground...confirms more mass than can be explained



# The motivation for muon g-2 today



$$a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{EW} + a_{\mu}^{HLBL} + a_{\mu}^{HVP} + a_{\mu}^{HOHVP}$$

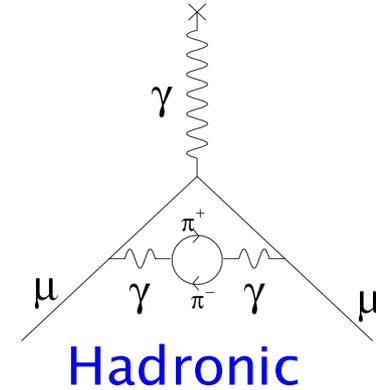
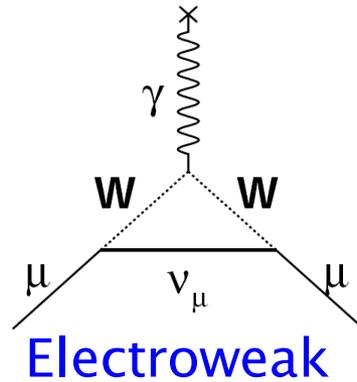
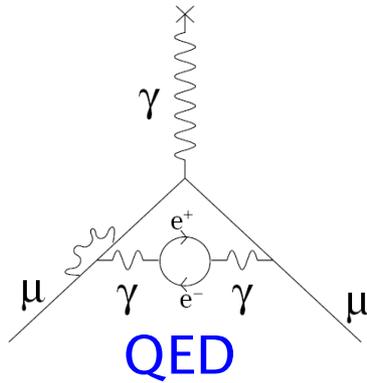
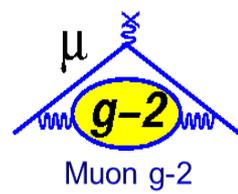


- Any Standard Model particle can contribute
- It is customary to break the calculation into QED, weak, and hadronic impacts on  $a_{\mu}$
- Because the muon is more massive, it is easier for higher mass particles to appear in the loops

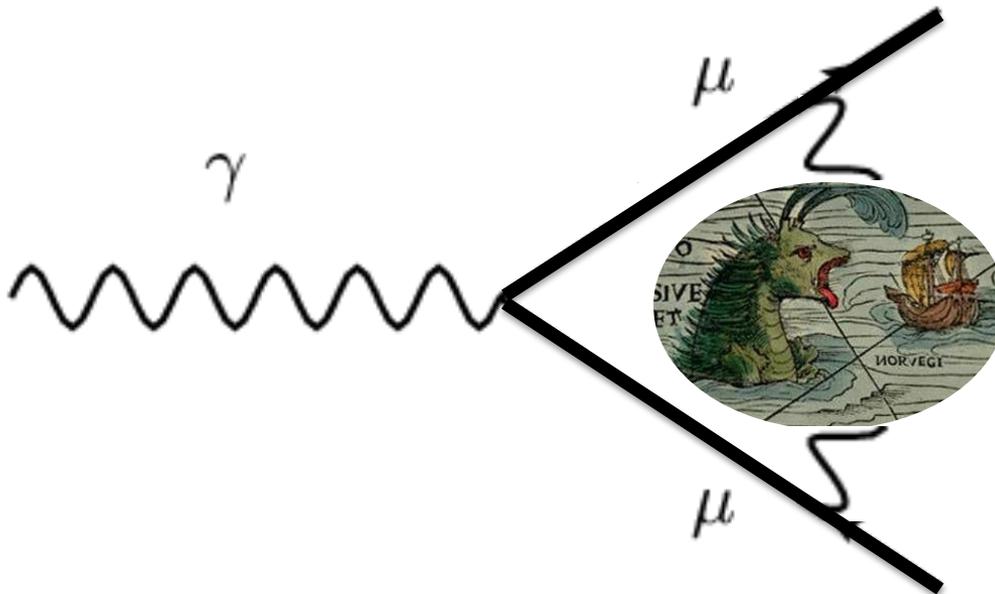
$$\lambda_{sens} \propto \left( \frac{m_{\mu}}{m_e} \right)^2 \approx 40,000$$



# Calculating $a_\mu$ (thy)



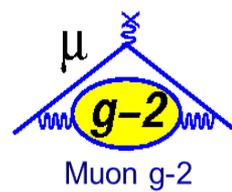
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$



- What we really want to know is if there are any new monsters lurking in the loops

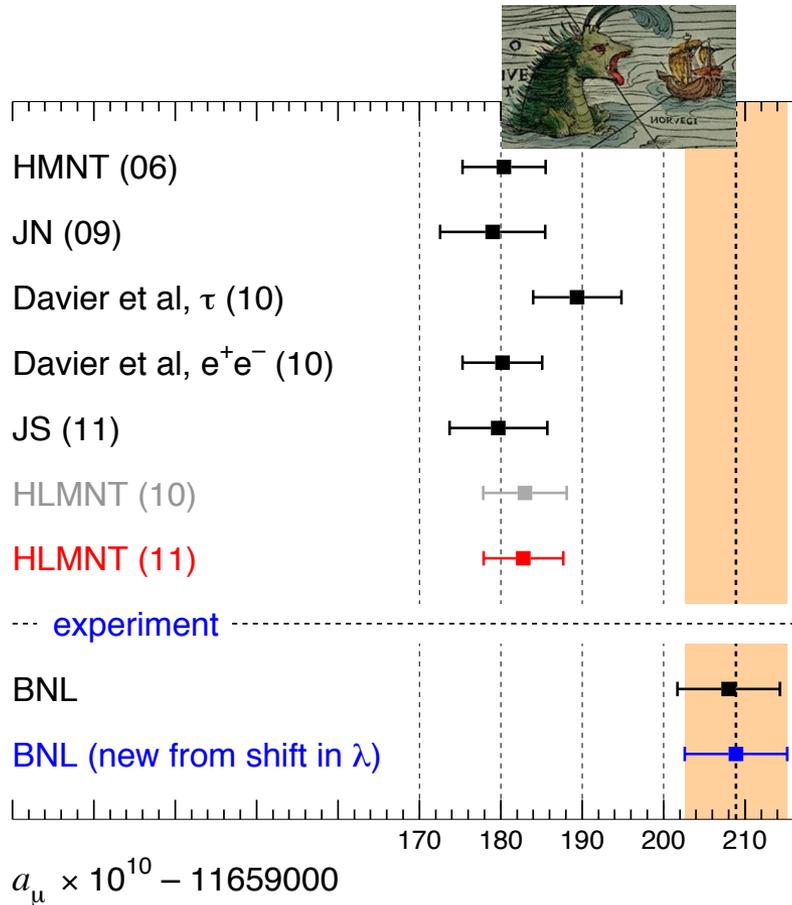


# Progress on the hunt, thus far...



$$a_\mu(\text{exp}) = 116\,592\,089(63) \times 10^{-11} \text{ (0.54 ppm)}$$

$$a_\mu(\text{thy}) = 116\,591\,802(49) \times 10^{-11} \text{ (0.42 ppm)}$$



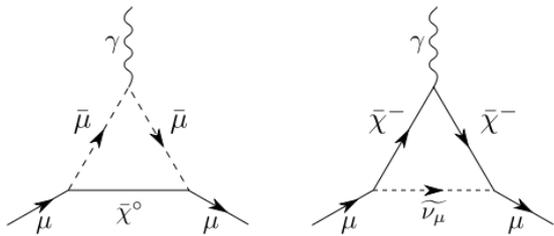
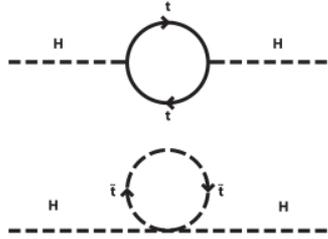
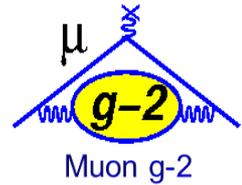
- The last  $a_\mu$  experiment ended at BNL in 2001
- $3\sigma$  discrepancy with the theoretical expectation
- Goal of FNAL g-2 is to reduce the experimental error by a factor of 4

Theoretical evaluations

Last experimental result from BNL

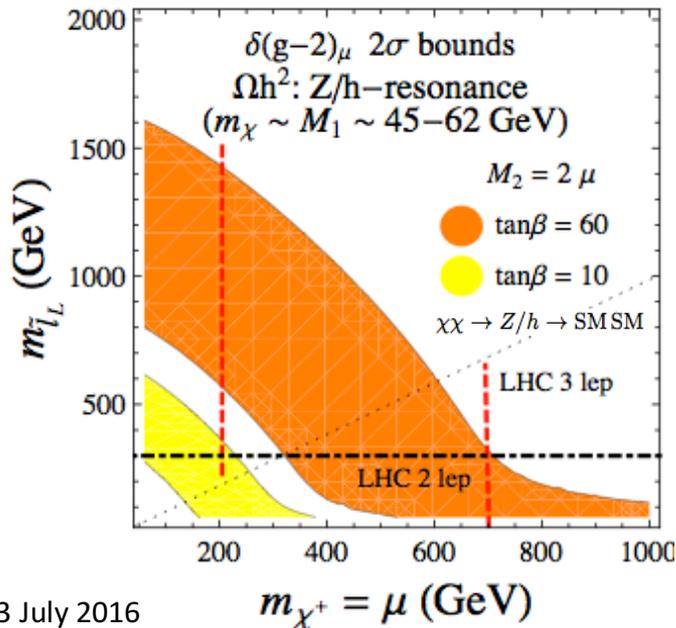


# What monsters might there be? SUSY



- The Higgs mass has now been measured at the LHC (and predicted long before that due to precision electroweak fits) to be  $\sim 125$  GeV
- Theoretically, expectation is that the Higgs should acquire a much heavier mass from loops with heavy SM particles, e.g. top quark
- Supersymmetry postulates a new class of particles who can enter the loops and effectively cancel the

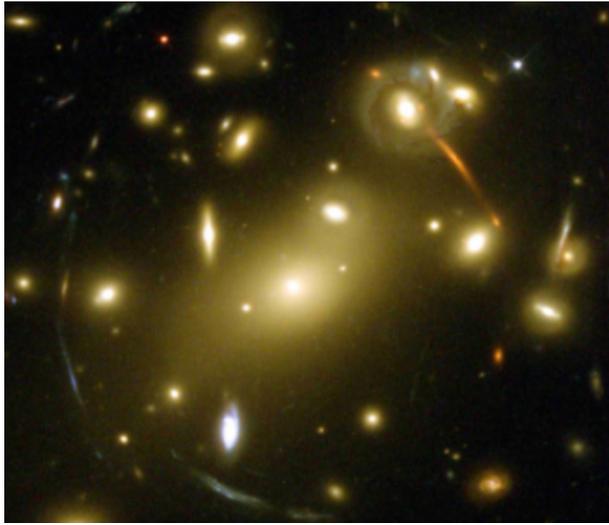
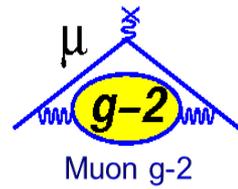
arXiv:1503.08219v1



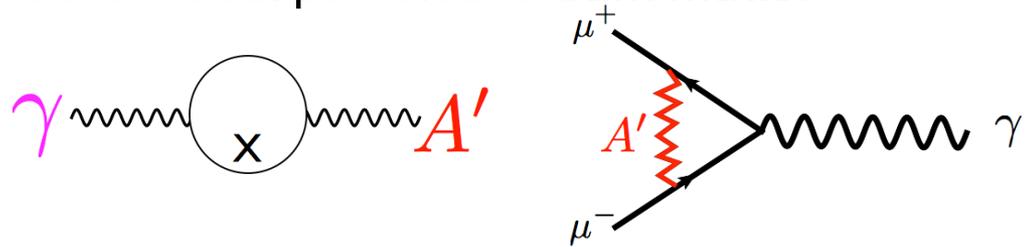
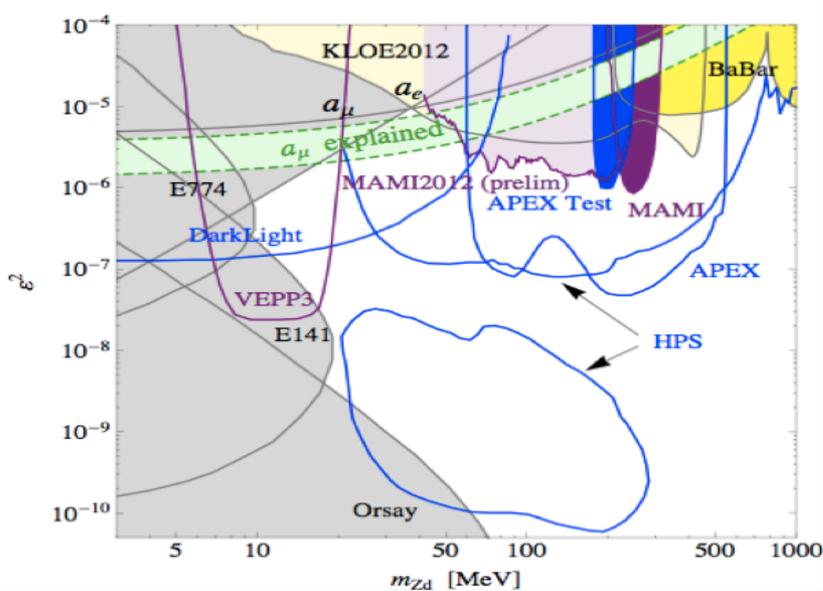
$$a_\mu(\text{SUSY}) \approx (\text{sgn}\mu) 130 \times 10^{-11} \tan\beta \left( \frac{100\text{GeV}}{\tilde{m}} \right)^2$$

- Complementary to direct searches at the LHC
  - Sensitive to  $\text{sgn}\mu$  and  $\tan\beta$
  - Contributions to  $g-2$  arise from charginos and sleptons while LHC direct searches are most sensitive to squarks and gluinos

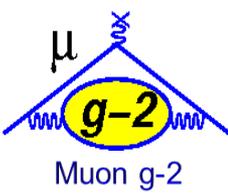
# What monsters might there be? Dark Matter



- Through cosmological observations, e.g. galaxy rotation curves, lensing, there appears to be much more mass in the universe than expected
- Many theories arising to explain the dark matter
- One example is the dark photon, which is a new U(1) gauge symmetry that would weakly couple standard model particles to dark matter



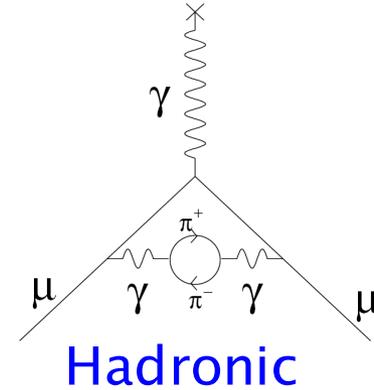
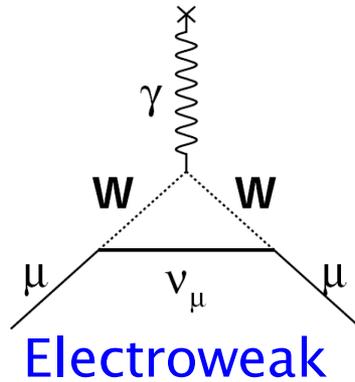
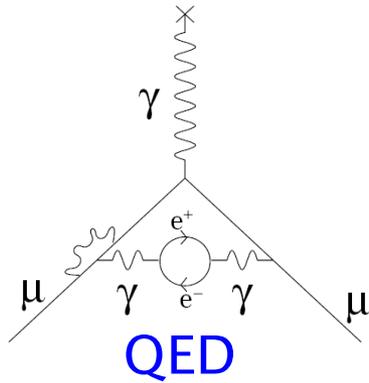
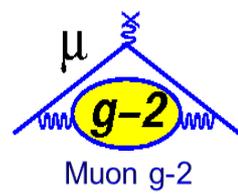
- Dark photon can also impact the magnetic moment of the muon
- Many search underway for direct production



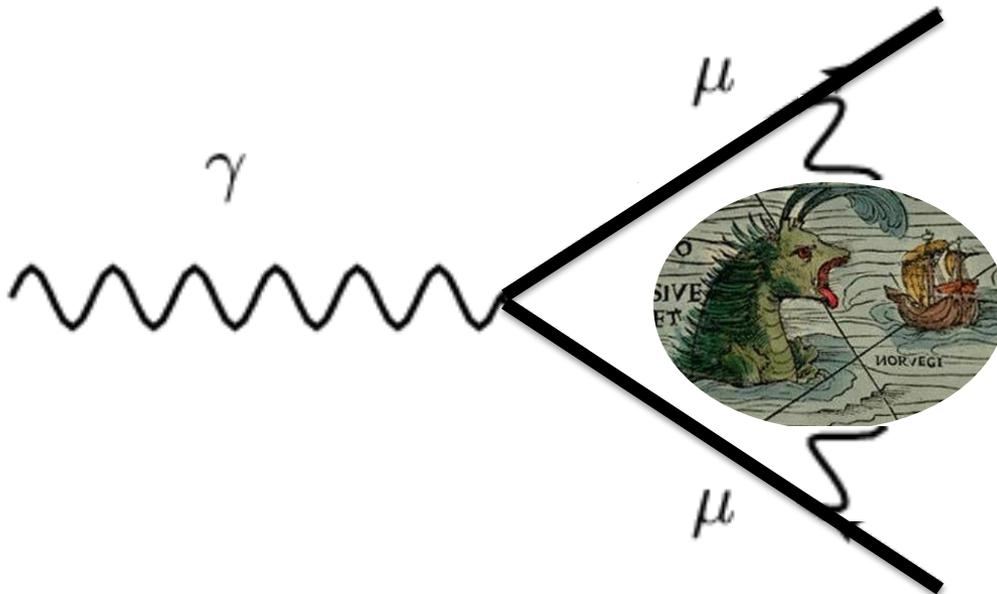
# Standard Model Calculation



# Calculating $a_\mu$ (thy)



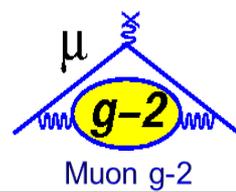
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$



- To determine if there are any new monsters in the loops we first need to understand what the normal creatures contribute



# Standard Model contributions to $a_\mu$



Muon g-2

	VALUE ( $\times 10^{-11}$ ) UNITS
QED ( $\gamma + \ell$ )	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	$-98.4 \pm 0.7$
H-LBL <sup>†</sup>	$105 \pm 26$
EW	$153.6 \pm 1.0$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$

- Theoretical contribution is dominated by QED component
- Error is dominated by hadronic terms (loops with quarks)
- For comparison, the discrepancy is...

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (261 - 287 \pm 80) \times 10^{-11}$$

\*Davier et al, Eur. Phys. J. C (2011) 71:1515

\*\*Hagiwara et al, J. Phys. G38, 085003 (2011).



# QED contributions to $a_\mu$ by order

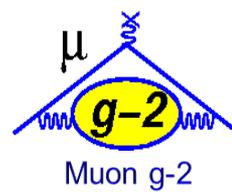


Table:  $a_\mu(\text{QED})$  at each order  $2n$ , scaled by  $10^{11}$

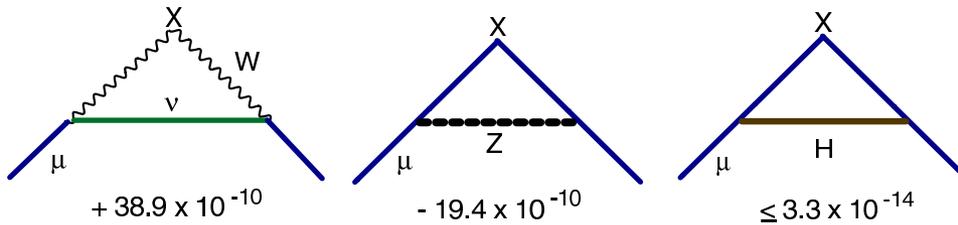
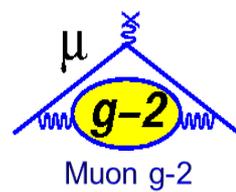
order $2n$	using $\alpha(\text{Rb})$	using $\alpha(a_e)$
2	116 140 973.318 (77)	116 140 973.213 (30)
4	413 217.6291 (90)	413 217.6284 (89)
6	30 141.902 48 (41)	30 141.902 39 (40)
8	381.008 (19)	381.008 (19)
10	5.0938 (70)	5.0938 (70)
sum	116 584 718.951 (80)	116 584 718.846 (37)



- Standard Model QED has now been calculated out to 5 loops...12672 Feynman diagrams
- Non-controversial since the QED is so exact



# Electroweak contributions to $a_\mu$



$$a_\mu^{\text{EW}(1)} = 195 \times 10^{-11}$$

- 2-loop calculation completed  $a_\mu^{\text{EW}(1+2)} = (154 \pm 2) \times 10^{-11}$
- Higgs mass now determined...thanks LHC!

$$a_\mu^{\text{EW}(1+2)} = (153.6 \pm 1.0) \times 10^{-11}$$

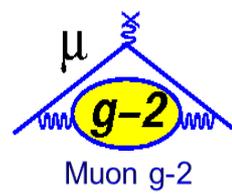
- Error completely negligible
- Interesting to note that discrepancy between SM and BNL result is nearly double the weak contribution



→ Plenty of room for monsters!



# Now for the hadronic terms

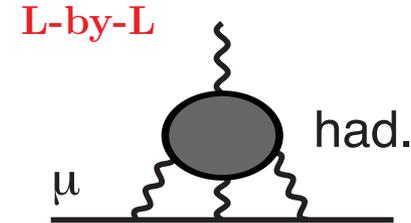
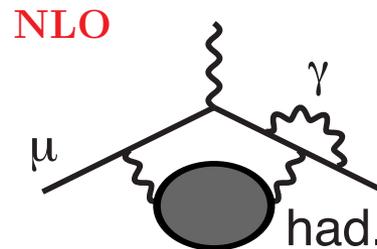
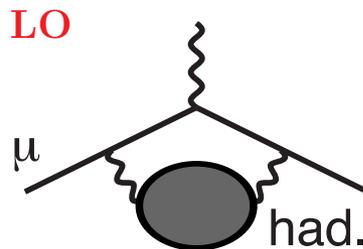


VALUE ( $\times 10^{-11}$ ) UNITS

QED ( $\gamma + \ell$ )	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
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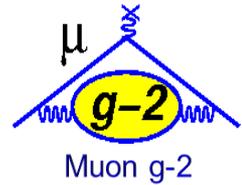
- Hadronic contributions divided into 3 terms

$$= a_{\mu}^{\text{had,VP LO}} + a_{\mu}^{\text{had,VP NLO}} + a_{\mu}^{\text{had,Light-by-Light}}$$





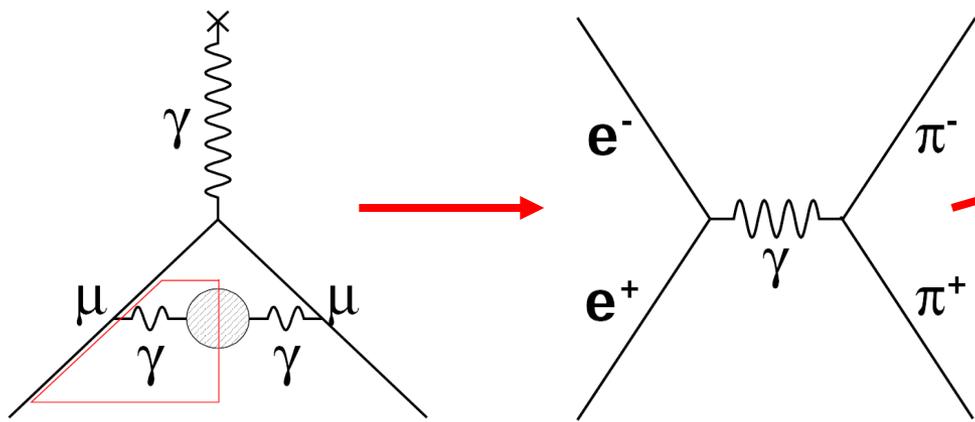
# LO hadronic contributions



- Due to non-perturbative nature of QCD at low energies, an analytical calculation is not possible
- Instead, we rely on using the optical theorem and a dispersion integral to calculate the contribution from direct measurements of  $e^+e^- \rightarrow \text{hadrons}$
- Contribution heavily weight to low  $\sqrt{s}$

$$\text{had.} = \int \frac{ds}{\pi(s-q^2)} \text{Im had.}$$

$$2 \text{Im had.} = \sum_{\text{had.}} \int d\Phi \left| \text{had.} \right|^2$$

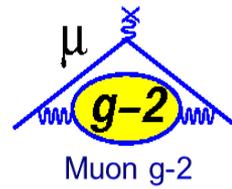


$$a_{\mu}^{had,1} \propto \int_{2m_{\pi}}^{\infty} ds \frac{K(s)}{s} R(s)$$

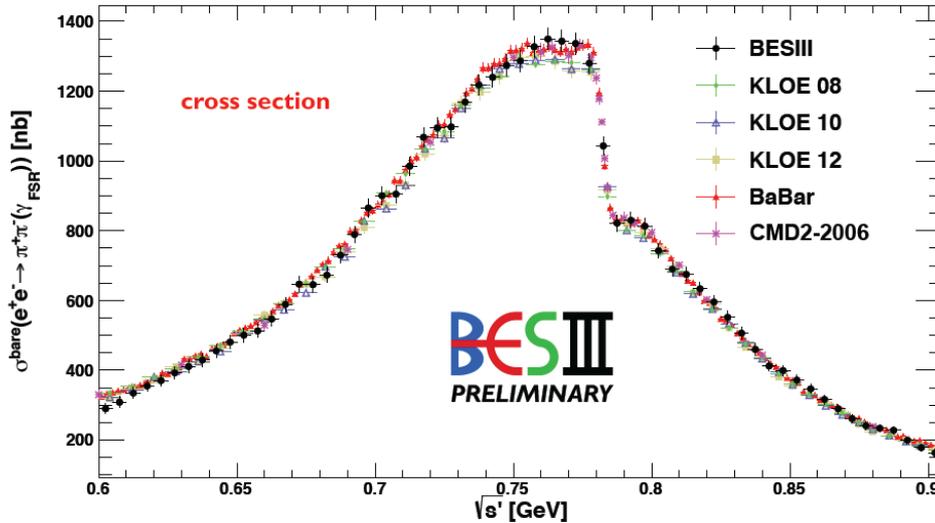
$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \text{muons})}$$

Error is dominated by how well we have determined the cross sections

# The 'theory' error on the LOHVP is actually exp

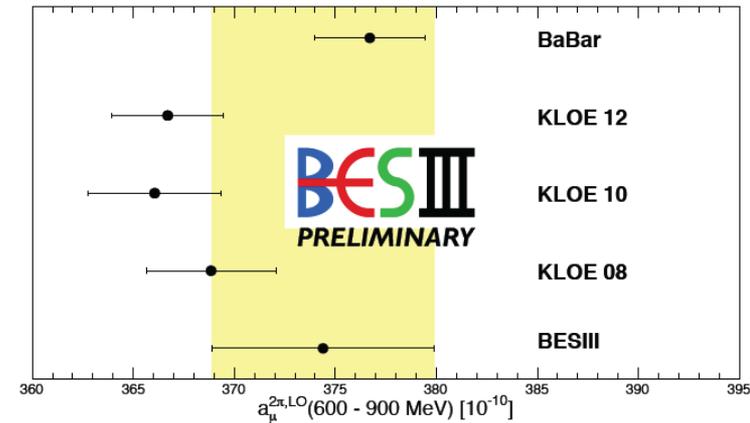


## Comparison to other experiments



- Examples of  $e^+e^- \rightarrow \pi\pi$  data, recent development where BESIII upgraded collider is starting to produce data
- Other data coming from upgrade machines at Novosibirsk, KLOE and Belle

## Result for (g-2)

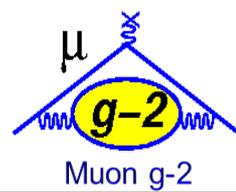


Experiment	$a_\mu^{2\pi, LO} (600 - 900 \text{ MeV}) [10^{-10}]$
BaBar	$376.7 \pm 2.0_{\text{stat}} \pm 1.9_{\text{sys}}$
KLOE 08	$368.9 \pm 0.4_{\text{stat}} \pm 2.3_{\text{sys,exp}} \pm 2.2_{\text{sys,theo}}$
KLOE 10	$366.1 \pm 0.9_{\text{stat}} \pm 2.3_{\text{sys,exp}} \pm 2.2_{\text{sys,theo}}$
KLOE 12	$366.7 \pm 1.2_{\text{stat}} \pm 2.4_{\text{sys,exp}} \pm 0.8_{\text{sys,theo}}$
BESIII (preliminary)	$374.4 \pm 2.6_{\text{stat}} \pm 4.9_{\text{sys}}$





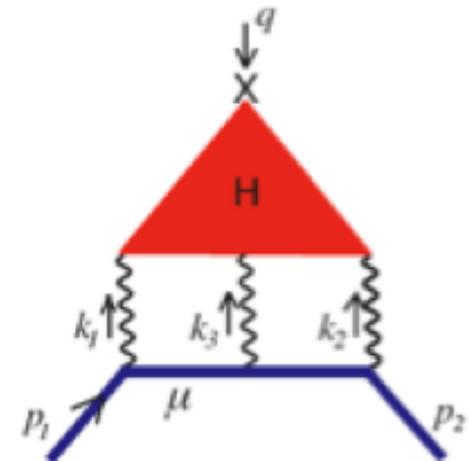
# Hadronic light-by-light



VALUE ( $\times 10^{-11}$ ) UNITS

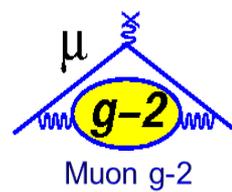
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EW	$153.6 \pm 1.0$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$

- 2<sup>nd</sup> largest error in SM calculation
- Cannot be directly related to data in the same way as the LOHVP
- Calculations are model-dependent based on Chiral Perturbation Theory plus short distance constraints
- Probably the limiting term in the future theory, but hope that lattice QCD will be able to produce a first principles calculation

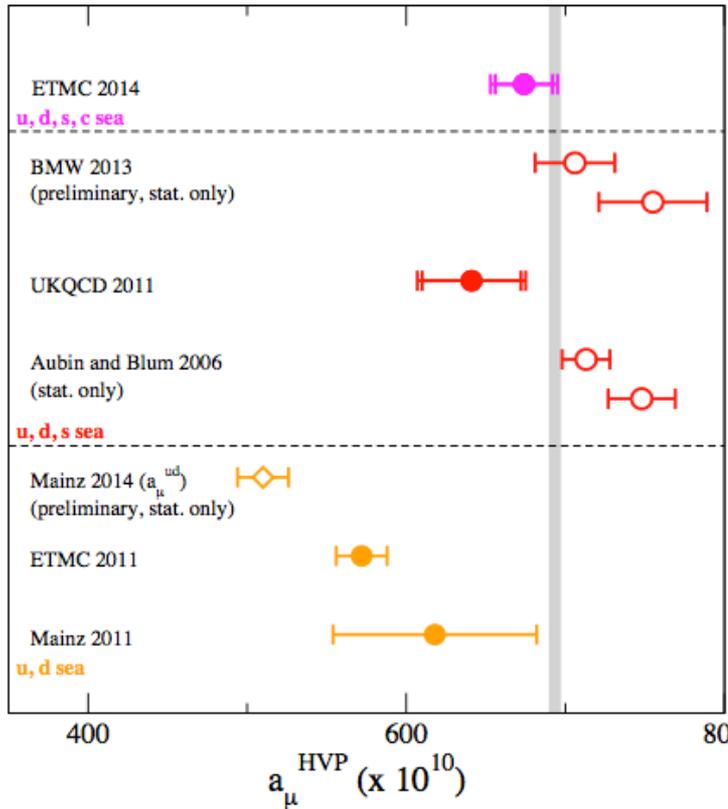




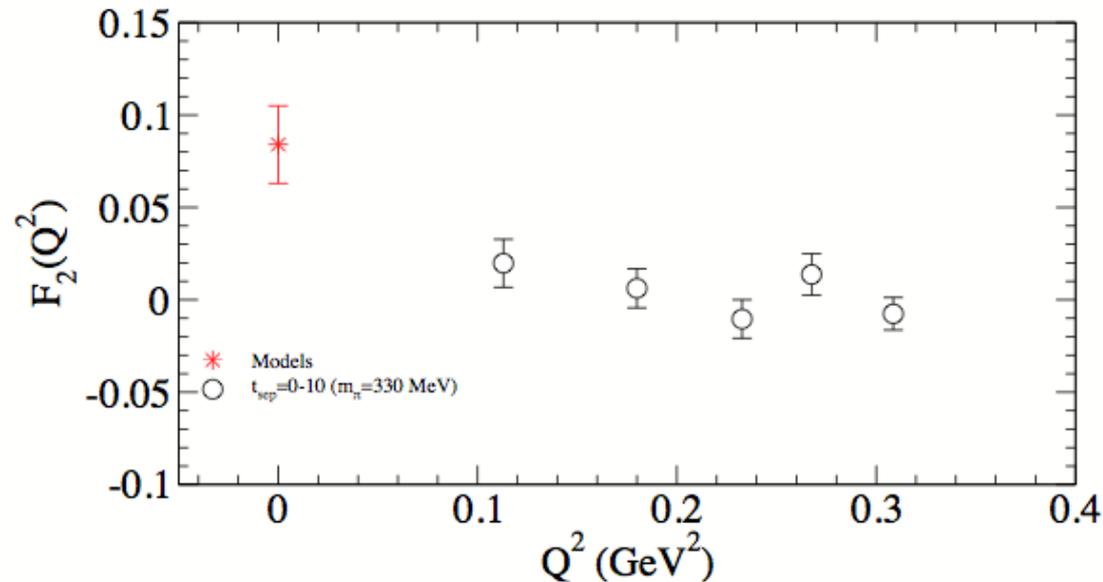
# Lattice calculation of g-2



$e^+e^-$  (Davier 2011)



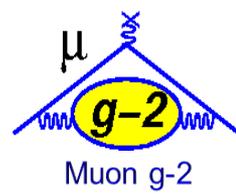
Blum et al. Phys.Rev.Lett. 114 (2015)



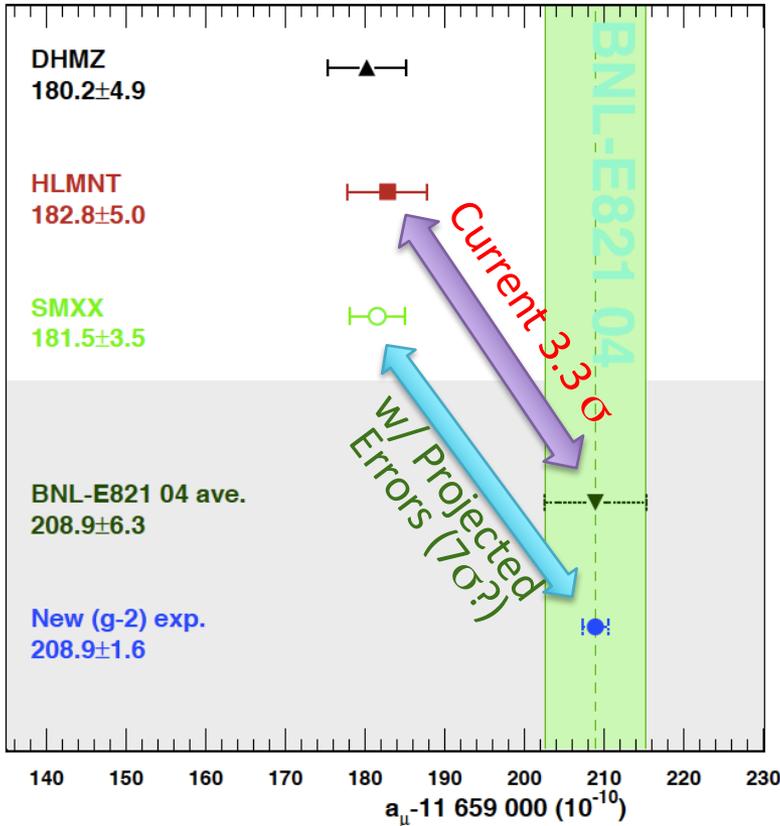
- Can see from plot on left that the LOHVP calculations are converging...expectation is that they will become competitive with  $e^+e^-$
- On right some initial attempts from Tom Blum to calculate HLBL by factorizing the QED part
- For both LOHVP and HLBL, results from the lattice would have a profound impact



# Projections



<http://arxiv.org/pdf/1311.2198v1.pdf>



- With new  $e+e- \rightarrow$  hadrons data samples coming from upgraded machines, it is anticipated that the theory error will come down by about 30% in the next 5 years
- Lattice community getting heavily involved with avenues to independent calculations
- Goal of the new muon  $g-2$  experiment at Fermilab is to reduced the experimental error by a factor of 4
  - If current discrepancy persists, significance will be pushed beyond  $5\sigma$  discovery threshold
  - Anticipated theoretical improvement could lead to  $>7\sigma$

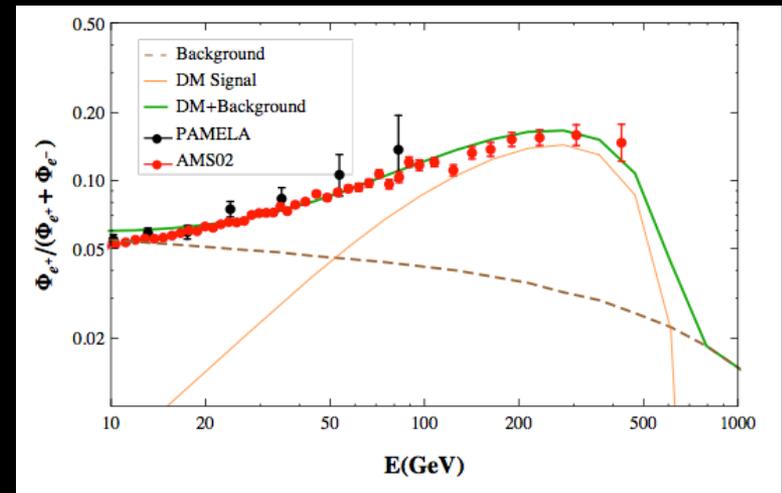
# Cover of the Rolling Stone!



**Muon g-2 moves  
on to a new life**

Ironically, there is a GREAT new archive article out that relates dark matter and the AMS positron excess to muon g-2

arXiv:1501.06193 [hep=ph]



$$\Delta a_\mu = 2.9 \times 10^{-9}$$