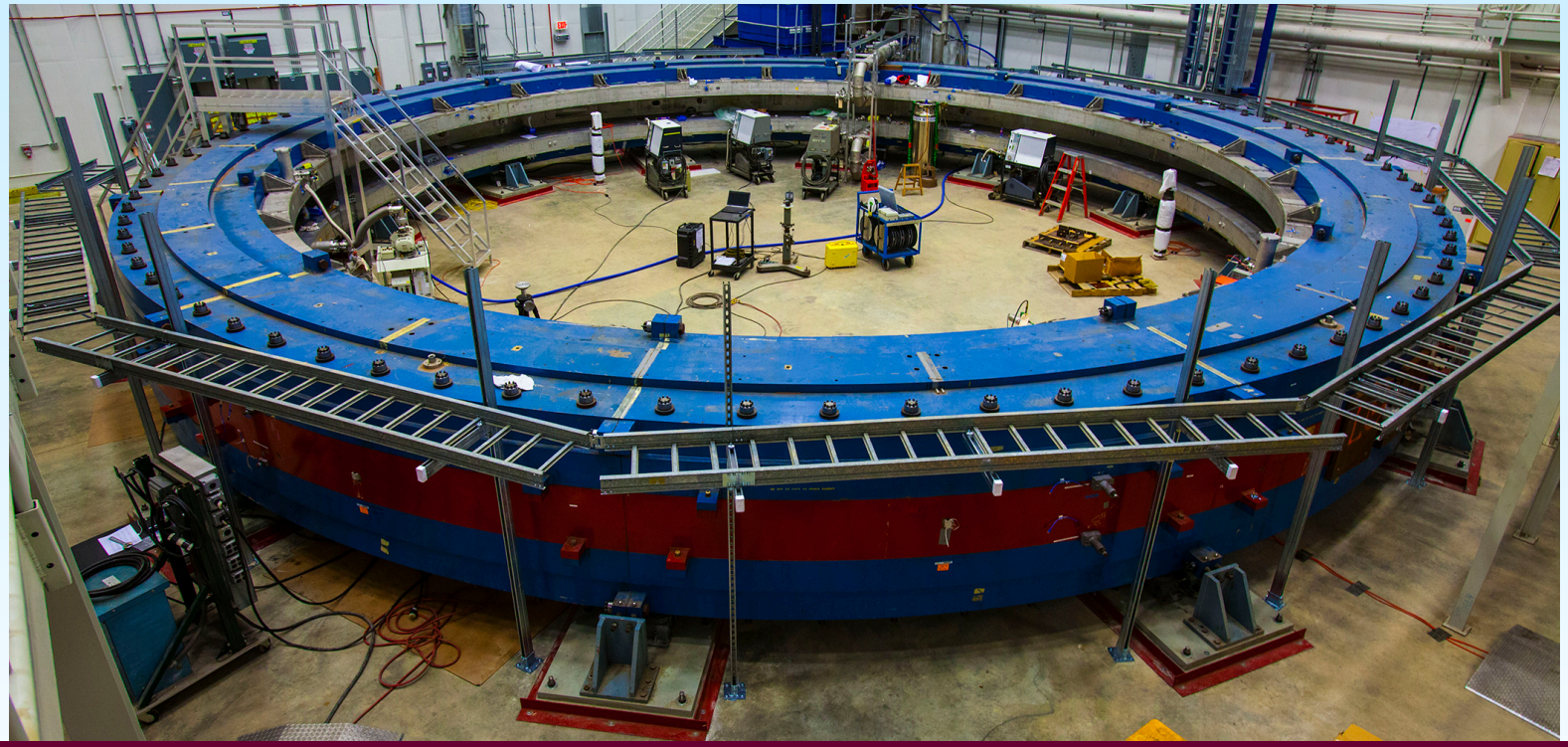
The New Muon g-2 experiment at Fermilab (E989)

G. Venanzoni

(for the E989 Collaboration)

LNF/INFN Frascati



European Physical Society
Conference on High Energy Physics 2015

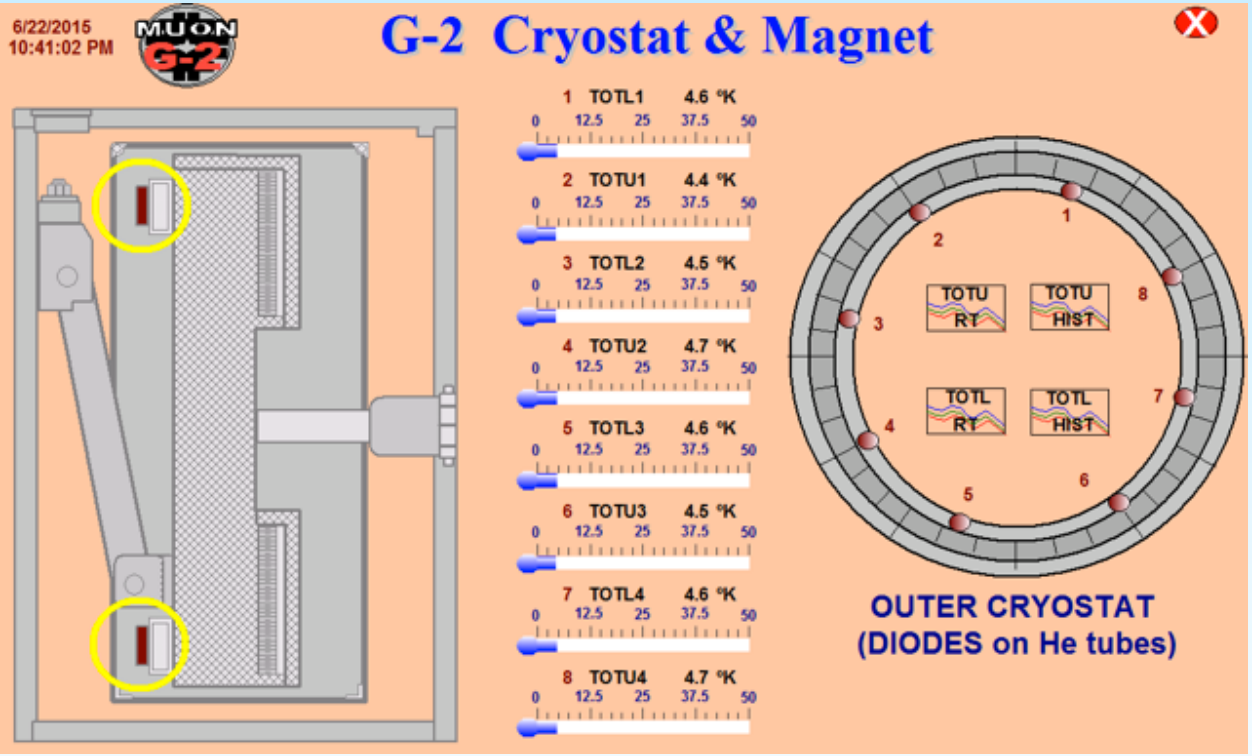
22-29 July 2015
Vienna, Austria

June 2015

After 14 dormant years

The RING is Cold

And the Power is about to be turned ON



- Magnet has been energized to 20% of full current!

- Anticipate full power over next few days!

" … we confirmed that the resistance is 0.1 +- 0.5 micro-ohm, consistent with being superconducting ! " *Hogan Nguyen, L2 Ring Team* 6/23/2015

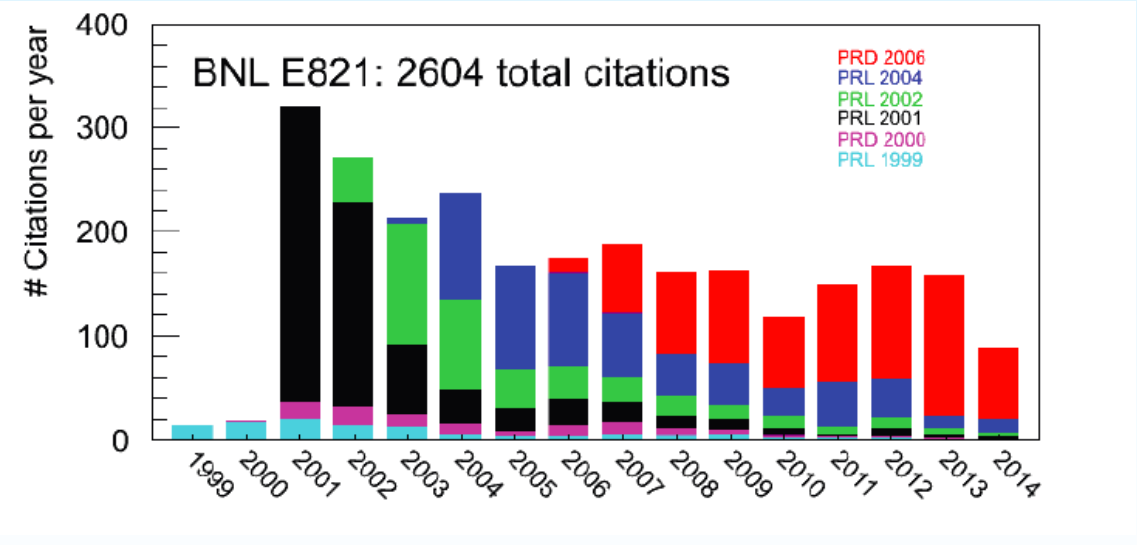
$(g\text{-}2)_\mu$: summary of present status

E821 experiment at BNL has generated enormous interest

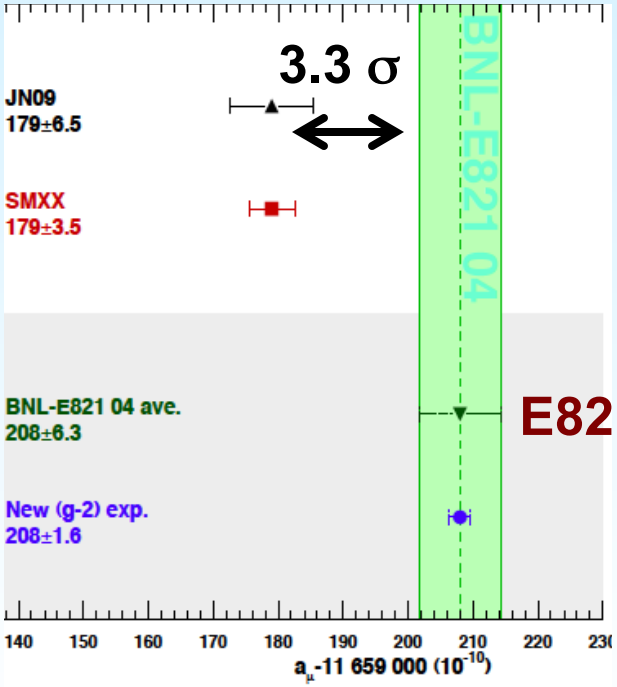
Tantalizing deviation with SM (persistent since>10 years) is ~3σ

Current discrepancy limited by experimental uncertainty (BNL)

BNL E821 citations



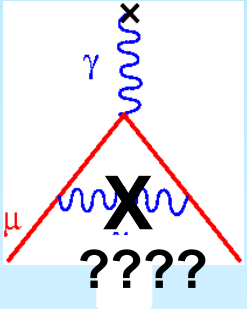
>2600 citations



$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(63)(49)\times10^{-11}$

New Physics?

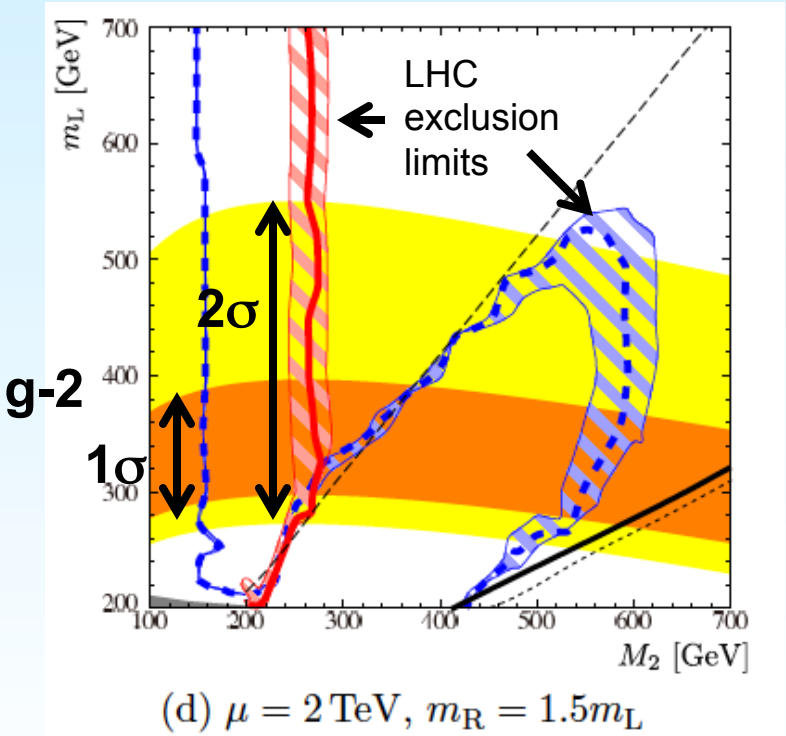
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$



$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(63)(49)\times10^{-11} \sim 2\, a_\mu^{Weak}\ (154\times10^{-11})$

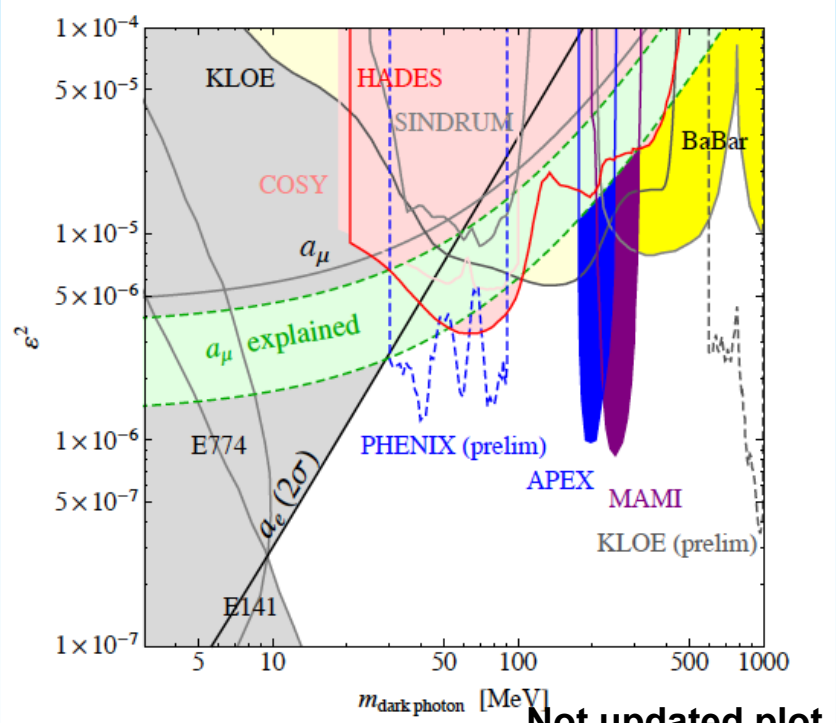
(BNL)(SM)

SUSY?



[Endo,Hamaguchi,Iwamoto,Yoshinaga '13]

Dark Photons?



Not updated plot

New Physics?

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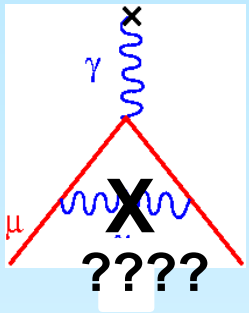
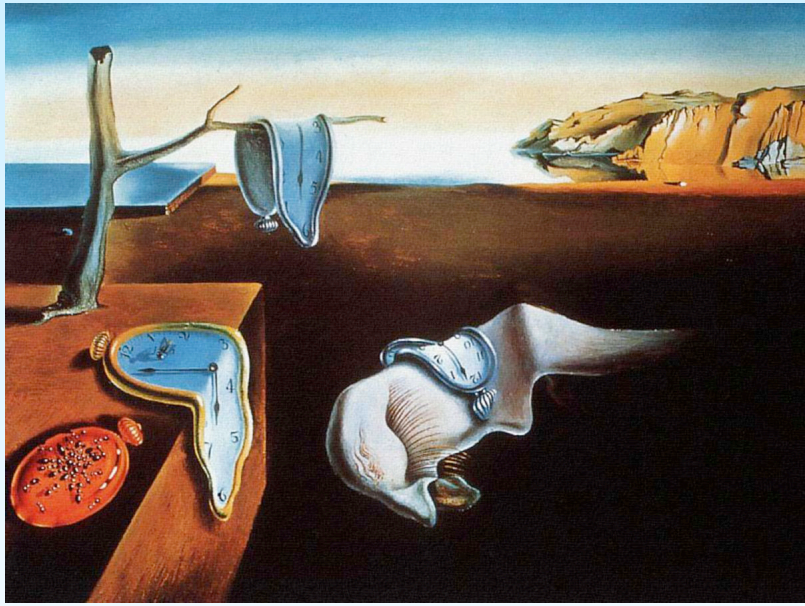


Maybe an unknow "unknown" ?



In any case 3σ are not enough to claim a discovery.

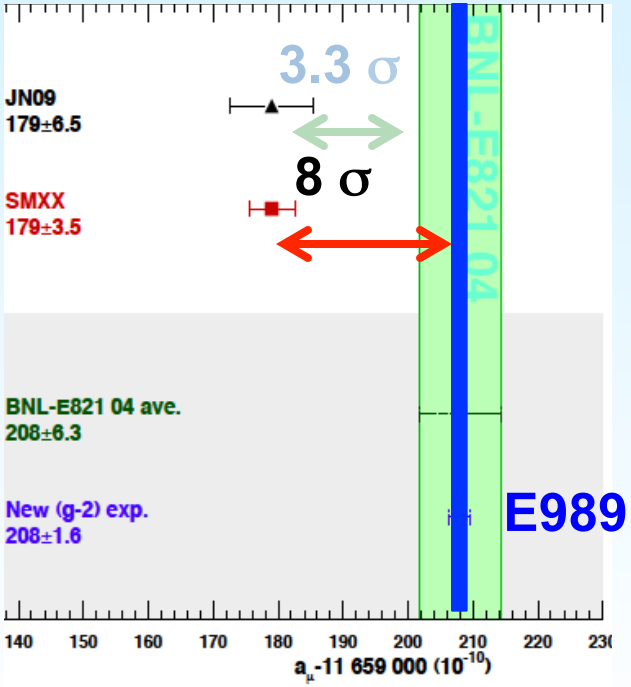
We need a new (possible more) experiment with better precision!

$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat.** w.r.t. E821. Relocate the BNL storage ring to FNAL.

$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)

If the central value remains the same ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)



***Depending on the progress on Theory**

Thomas Blum; Achim Denig; Ivan Logashenko; Eduardo de Rafael; Lee oberts, B.; Thomas Teubner; Graziano Venanzoni (2013). "The Muon (g-2) heory Value: Present and Future". arXiv:1311.2198 [hep-ph].

Alternative proposal at JPARC in progress [H. Iinuma JPC 295 (2011) 012032]

4 key elements for E989 at FNAL

- Consolidated method
- More muons (x20)
- Reduced systematics (ring and detector)
- New crew

- **E821 at Brookhaven**

$$\left.\begin{array}{l}\sigma_{\text{stat}} = \pm 0.46 \text{ ppm} \\ \sigma_{\text{syst}} = \pm 0.28 \text{ ppm}\end{array}\right\} \sigma = \pm 0.54 \text{ ppm}$$

- **E989 at Fermilab**

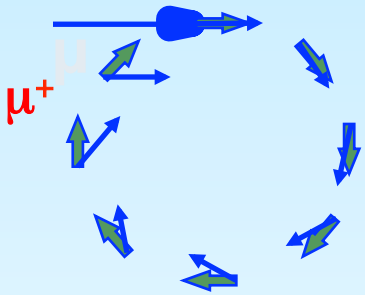
$$\left.\begin{array}{l}\sigma_{\text{stat}} = \pm 0.1 \text{ ppm} \\ \sigma_{\text{syst}} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

How to precisely measure g-2 in a storage ring

(1) Polarized muons

~97% polarized for forward decays

(2) Precession proportional to (g-2)



$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

measure

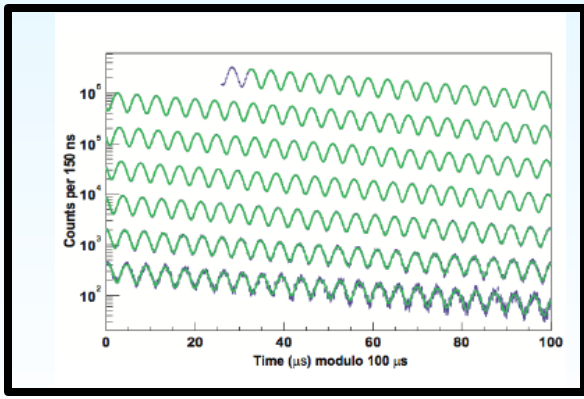
(3) P_μ magic momentum = 3.094 GeV/c

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

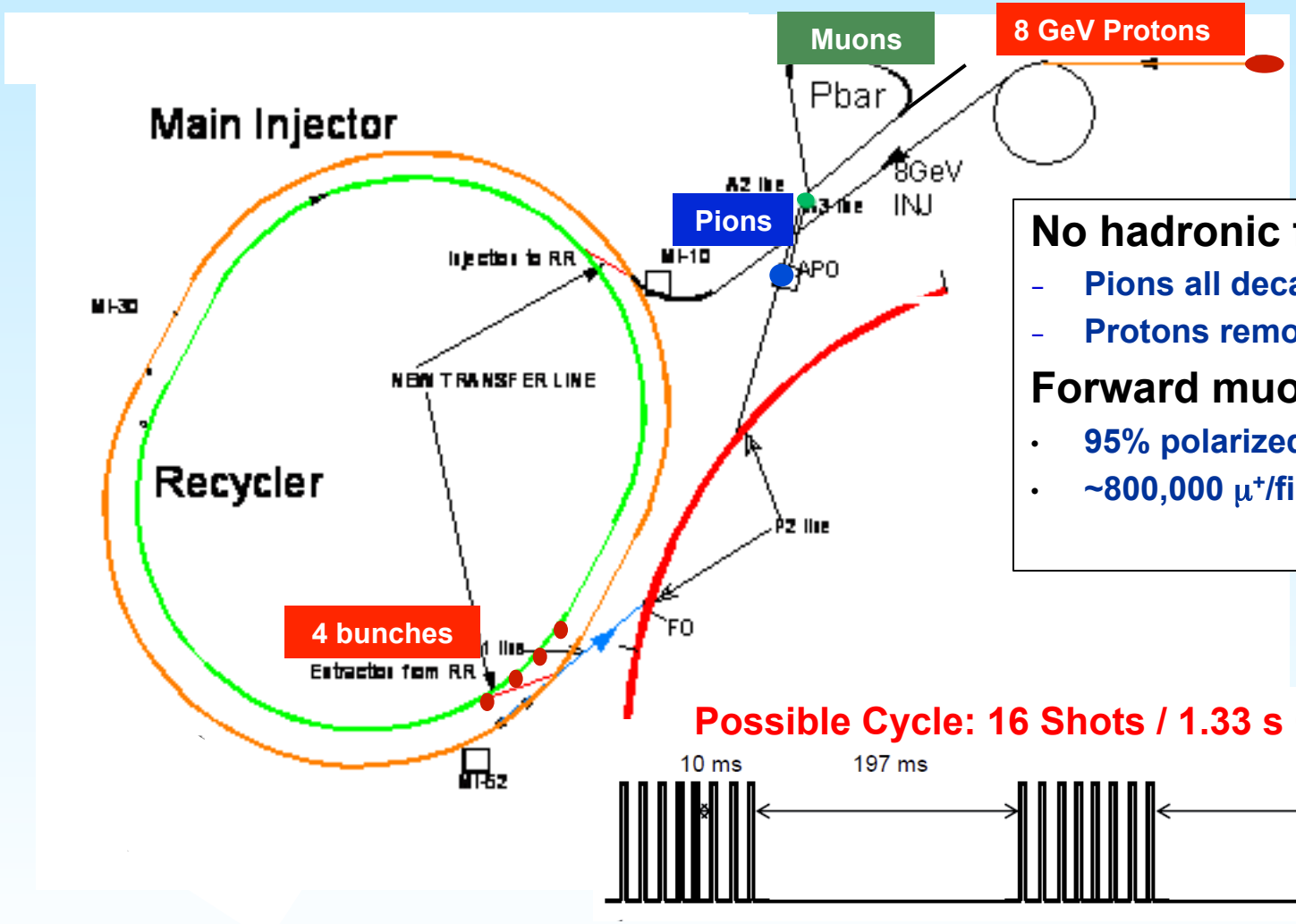
E field doesn't affect muon spin when γ = 29.3

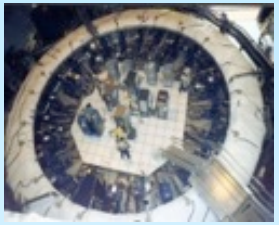
(4) Parity violation in the decay gives average spin direction

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \longrightarrow \omega_a$$



The FNAL beamline is very long so it provides a pure muon flux, to be complemented by a much better Kicker





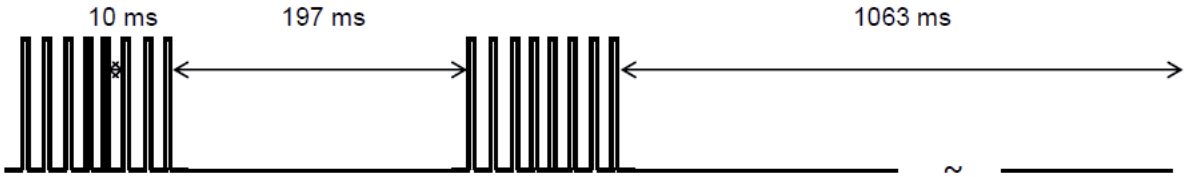
No hadronic flash

- Pions all decay
- Protons removed by a DR kicker

Forward muons collected

- 95% polarized
- ~800,000 μ^+/fill ($\delta P/P$ 2%) at ring

Possible Cycle: 16 Shots / 1.33 s Cycle



All protons are "excess" from those used for NOvA ν Program

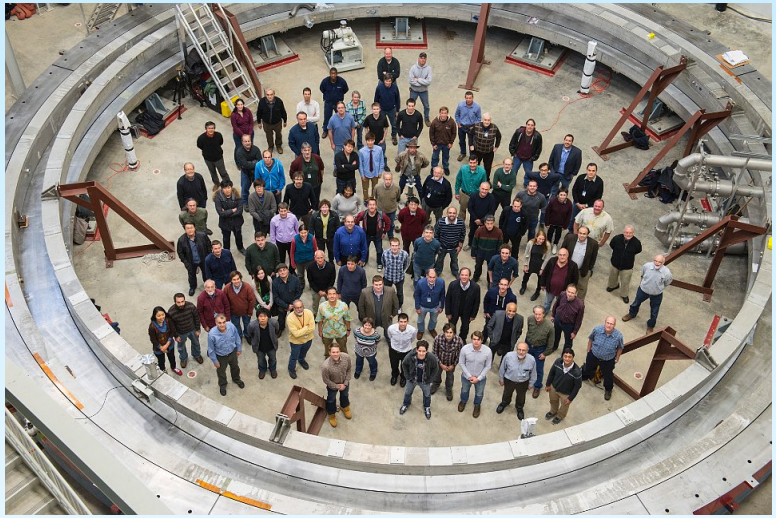
The New Muon Campus at FNAL is taking shape

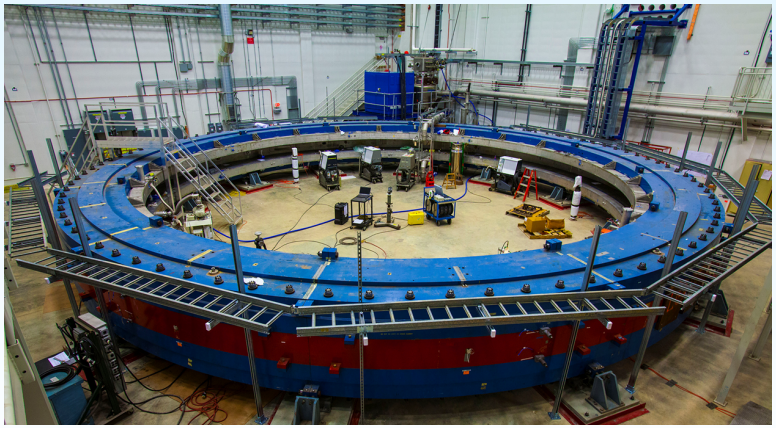
Last two years

- Moved ring from BNL two summers ago
- Started ring installation in new building last summer

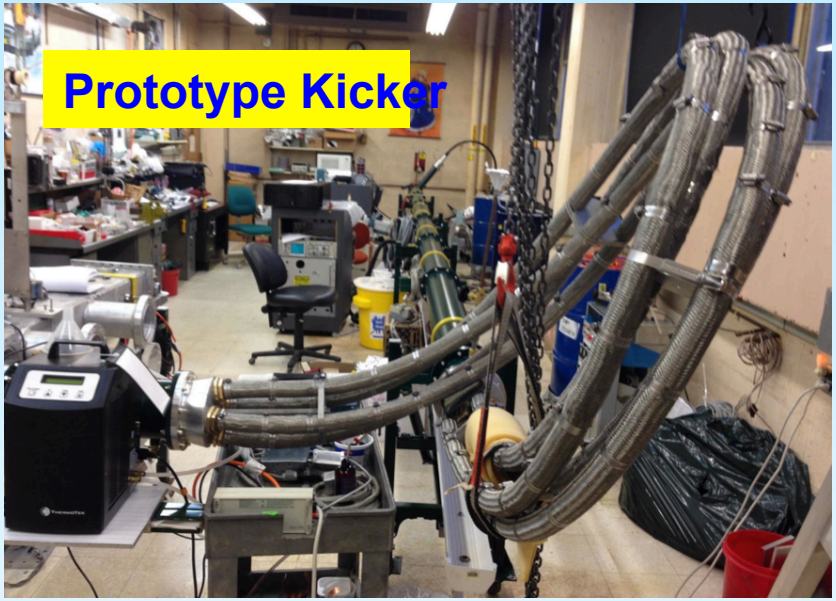
Major Installations

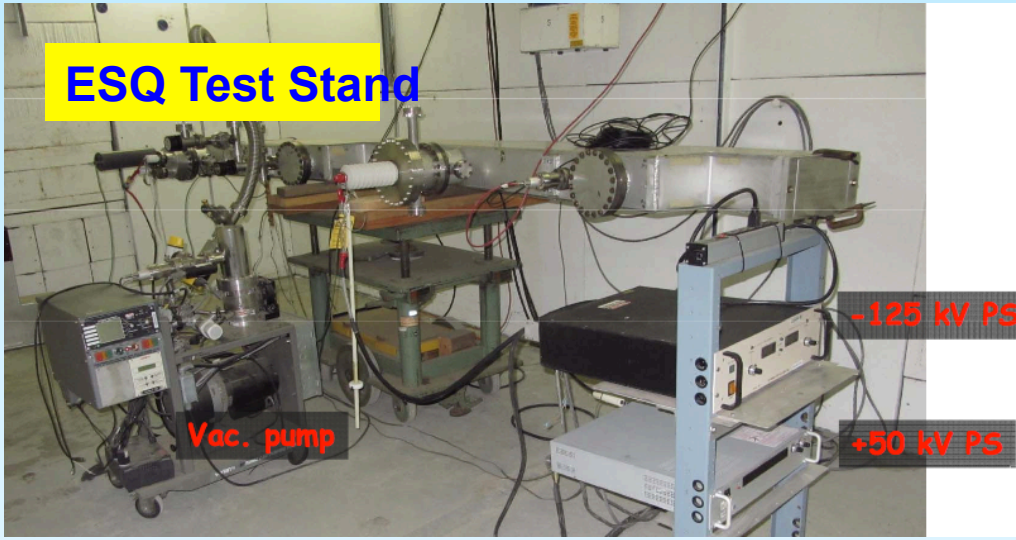
- MC-1 complete and occupied
  - Temp stability ±1 C;
  - Floor stability for magnet
  - Counting room; Electronics; Meeting area/Prep area; Services
- Ring re-assembled and cold
  - Alignment successes
  - Solved cold-cryostat leak from BNL
  - Power supplies on
  - Rough Field shimming starting imminently
    - team on site working now

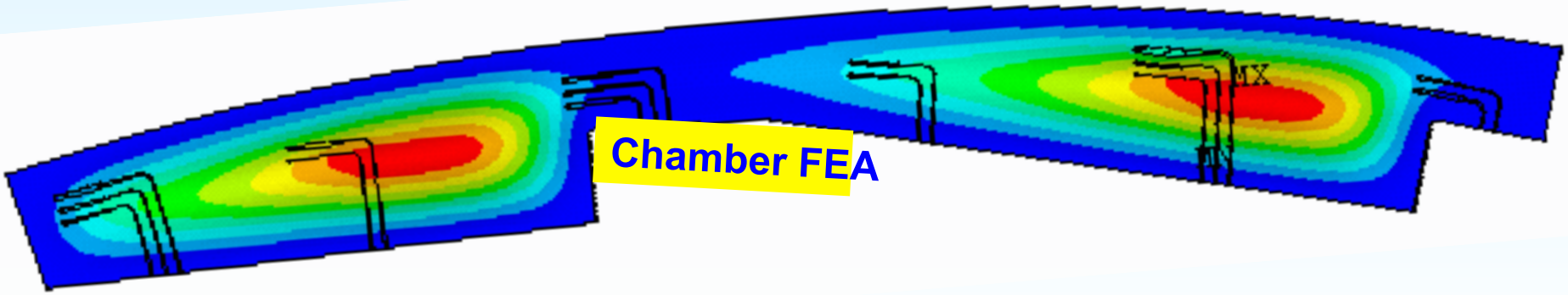




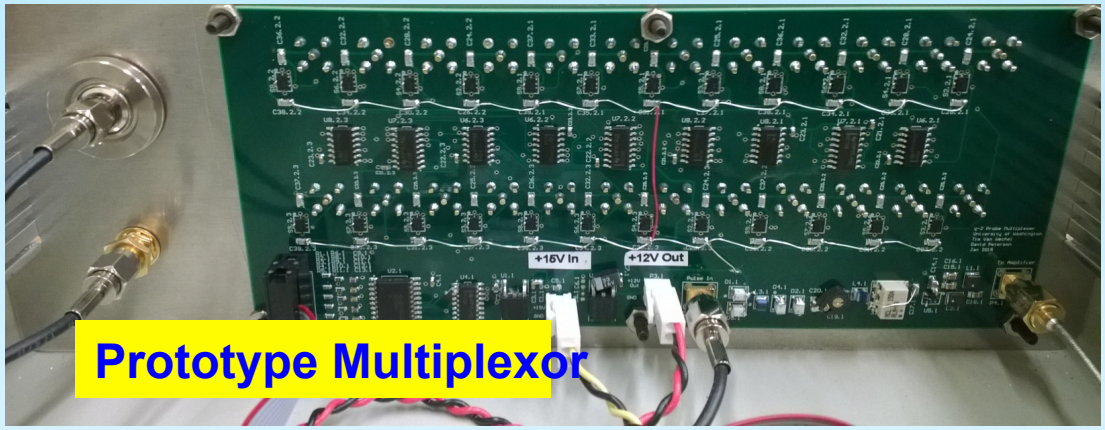
Upgrades: Ring

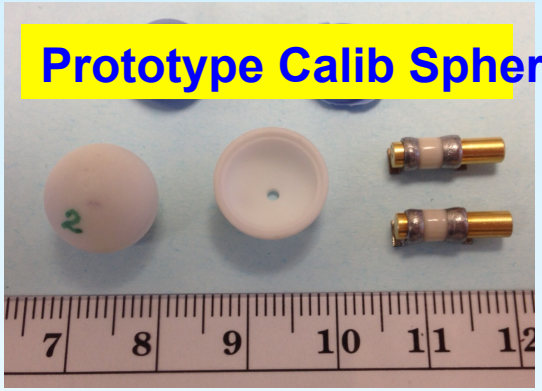


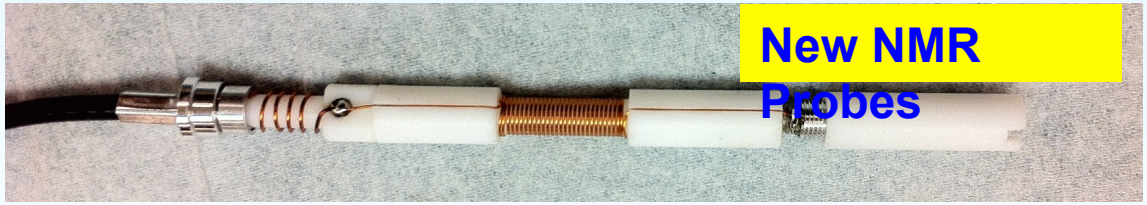




Upgrades: Magnetic Field

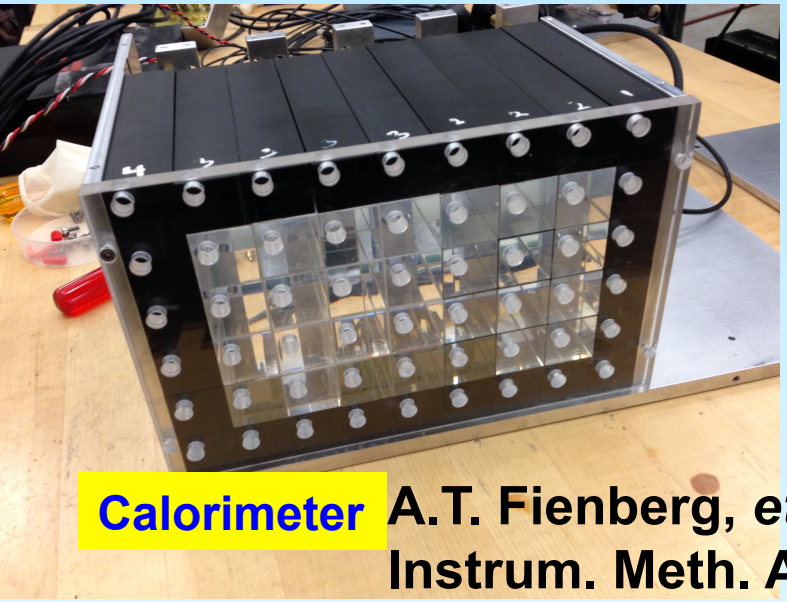






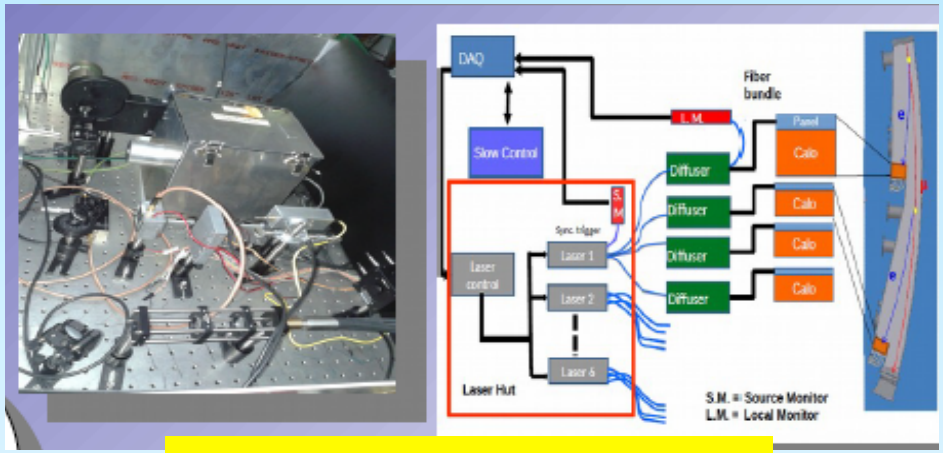
Upgrades: Detector

A. Anastasi, *et. al.*, Nucl. Instrum. Meth. A 788 (2015) 43

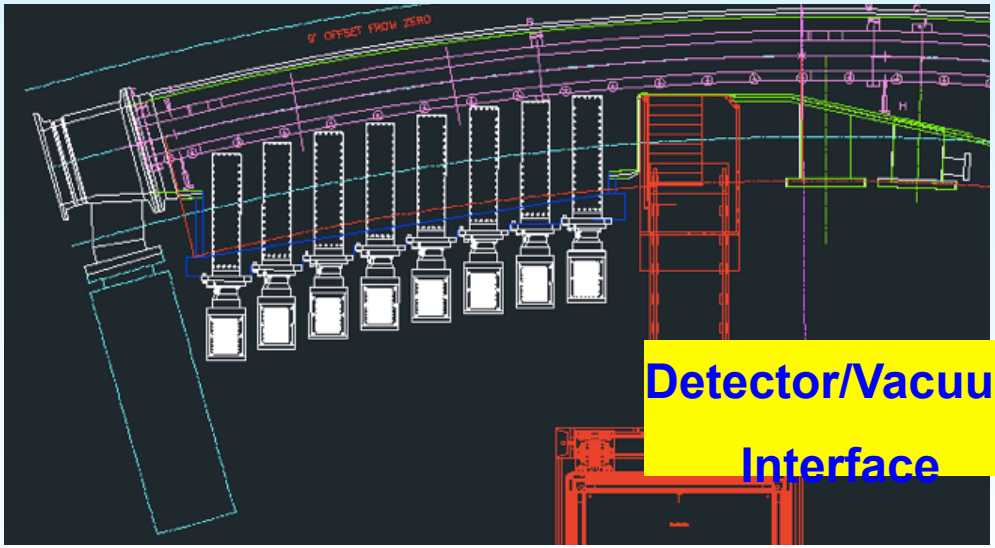


Calorimeter

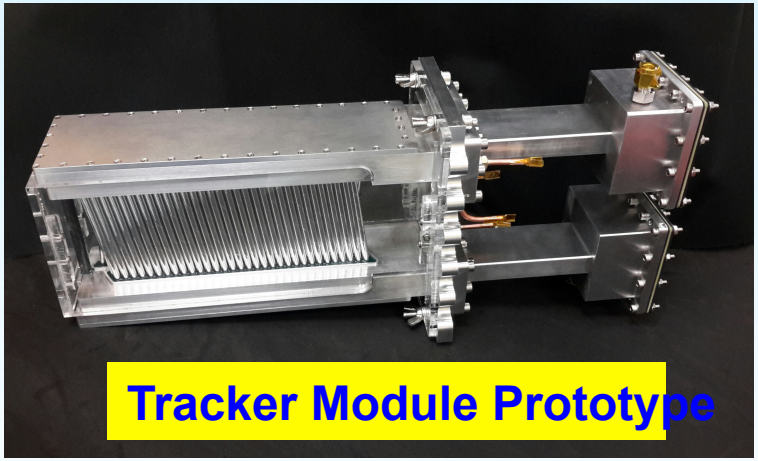
A.T. Fienberg, *et. al.*, Nucl. Instrum. Meth. A 783 (2015) 12



Laser calibration system



Detector/Vacuum Interface



Tracker Module Prototype

E989 Collaboration: 35 Institutes; >150 Members

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern (thy)
- Regis
- Texas (joined, 2015)
- Virginia
- Washington
- York College

US National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

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

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden (thy)

England

University College London

Liverpool

Oxford

Rutherford Lab

Korea

KAIST

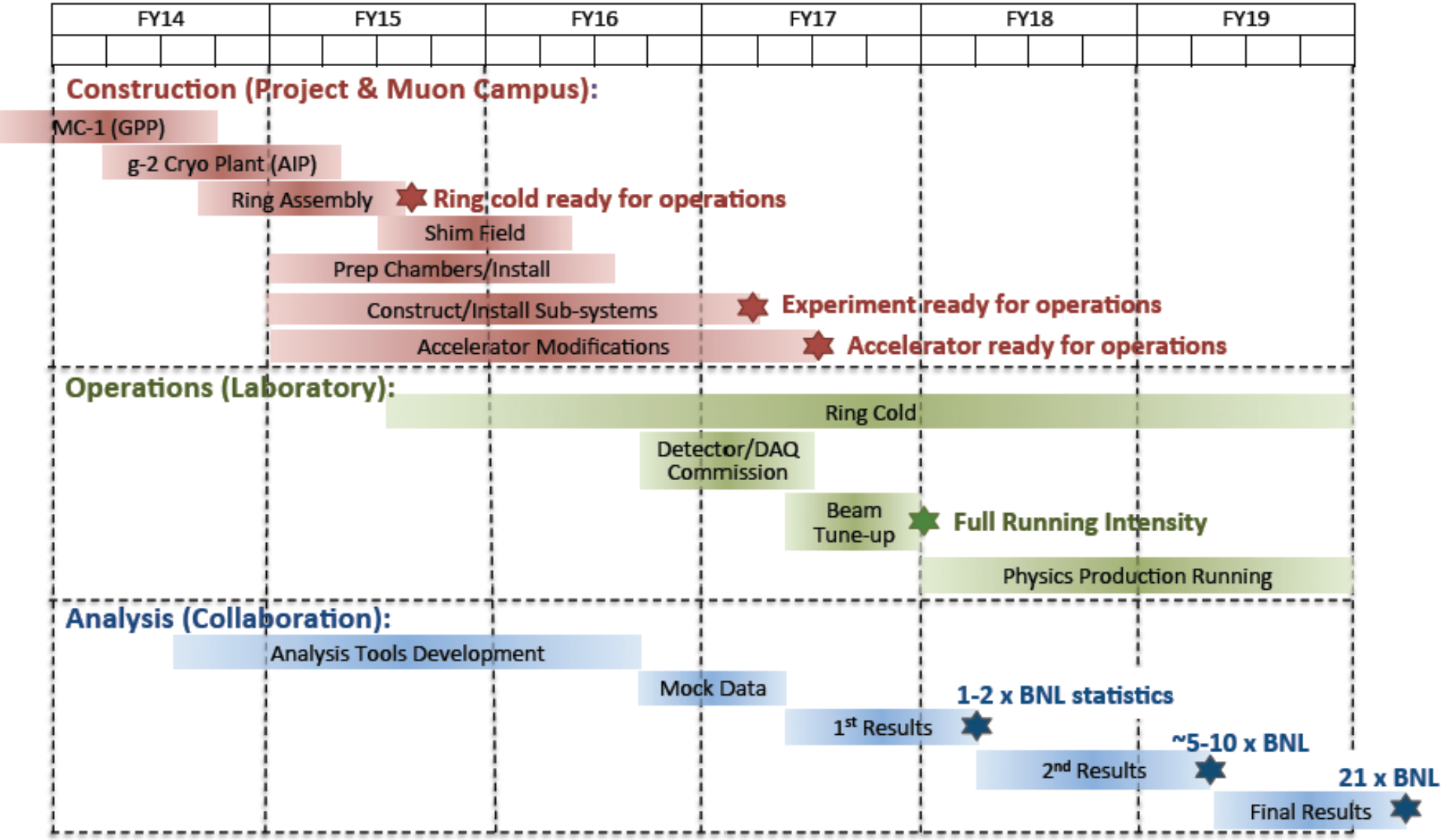
Russia:

Dubna

Novosibirsk

Co-spokespersons:	**David Hertzog, Lee Roberts**
Project Manager:	**Chris Polly**
Deputy PM:	**Mary Convery**
Institutional Board:	Mike Eads, chair
Talks Committee:	Lawrence Gibbons, chair
Publication Committee:	Graziano Venanzoni, chair
g-2 Notes Editor:	Bill Morse
Collaboration Secretary:	Liang Li

Schedule overview



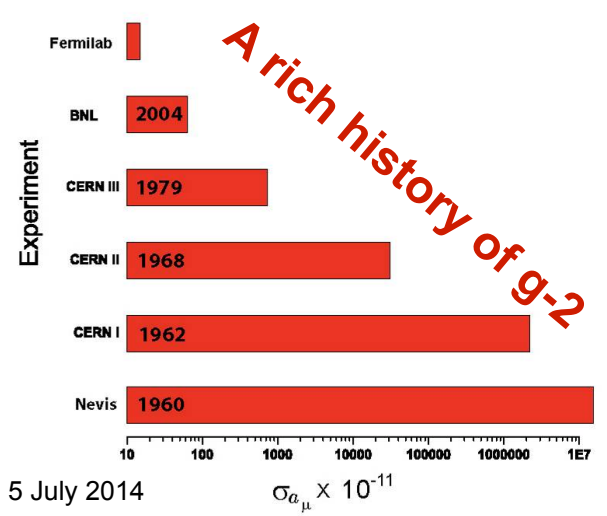
Conclusion

- During the last ten years the muon (g-2) provided one of the strongest tests of the SM, thanks to the impressive accuracy of BNL experiment (δa_μ^{EXP} = 0.54 ppm). Important interplay with LHC!

- At present a discrepancy of more than 3 "standard deviations" between SM and Experiment; uncertainty dominated by BNL experiment. Possible sign of New Physics?

- New $(g\text{-}2)_\mu$ experiment at Fermilab with a fourfold reduction δa_μ^{EXP} = 0.14 ppm . Data taking expected in 2017.

Stay Tuned!



SPARES

Construction of Campus accelerator goes on

Construction has of the tunnel that connects g-2/Mu2e to the accelerator complex has started

More muons with less systematic errors!

- Take advantage of Fermilab beam structure:
  - Higher proton rate, less proton per bunch than at BNL:
    - BNL 4 X 10^{12} p/fill: repetition rate 4.4 Hz
    - FNAL 10^{12} p/fill: repetition rate 15 Hz
  - 900 m pion decay line (BNL 80 m) using antiproton ring:
    - 20 times **<u>less</u>** pion flash at injection than BNL
  - 0° muons:
    - ~5-10x increase μ/p over BNL
  - Can run parasitic to main injector experiments (e.g. to NOVA)
- Improved detectors against pileup, new electronics, better shimming to reduce B-field variation, more improvement over BNL:
  - Expect x3 reduction of syst. error on ω_a
  - Expect x2 reduction of syst. error on B-field

E989 Approved in Jan 2011. Expected data early 2017

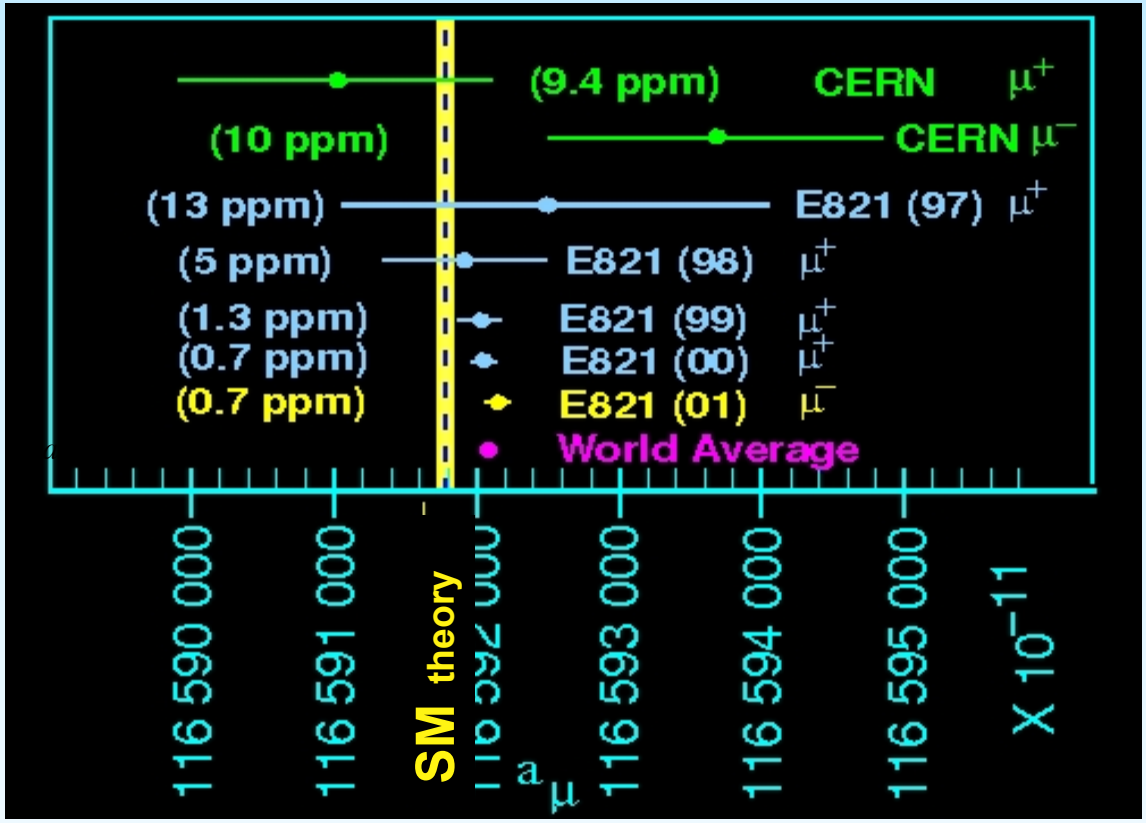
$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot} \times 10^{-11}$$

(0.54 ppm!)

A factor 15 improvement in accuracy respect to CERN!

~3.5 "standard deviations" with SM

Error dominated by experimental uncertainty!



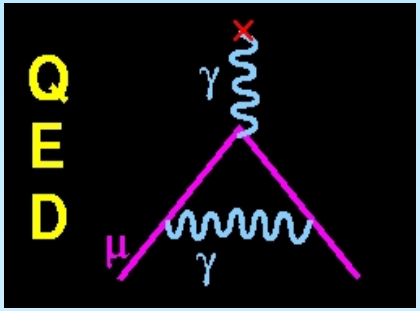
$$a_\mu^{SM} = 116\,591\,802 \pm 49 \times 10^{-11}$$

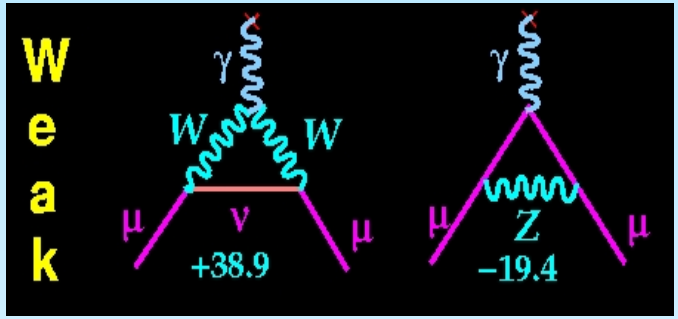
M. Davier et al. 2011

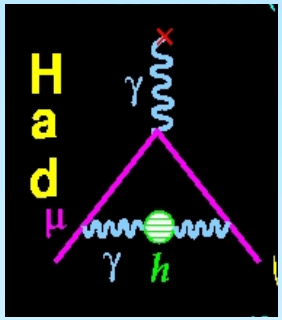
$$a_\mu^{E821} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11} \; (3.6\,\sigma)$$

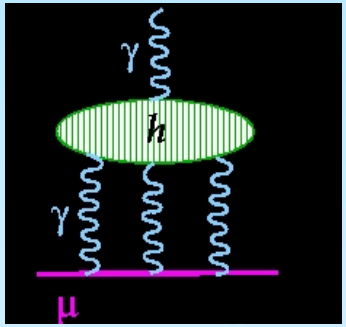
Hint of new physics?

The SM Value for a_μ









well known

significant work ongoing

Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\ 923 \pm 42$
HVP(ho)	-97.9 ± 0.9
HLxL	105 ± 26
EW	$154 \pm 2_{Higgs} \pm 1_{had}$
Total SM	$116\ 591\ 802 \pm 42 \pm 26 \pm 2(49_{tot})$

We have reached a 0.6 ppm accuracy!

$\sigma_{\rm exp} = \pm 63$

(E821 @ BNL)

More muons with less systematic errors!

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  - proton bunch structure:
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  - Can run parasitic to main injector ex (e.g. to NOVA) or take all the boo

Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

Stored Muons / POT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 $\pm$ 0.5 mr	forward	3
$\delta p_\pi/p_\pi$ pion momentum band	$\pm$0.5%	$\pm$2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

Expected data taking beginning of 2017

Improving ω_a

E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

Systematic uncertainty on ω_a expected to be reduced by 1/3 at E989 (compared to E821) thanks to **reduced** pion contamination,the **segmented** detectors, and an **improved** storage ring kick of the muons onto orbit.

Improving ω_p

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11 **->0.07**

Systematic uncertainty on ω_p expected to be reduced by a factor 2 thanks to **better** shimming (uniformity of B), **relocations** of critical NMR probes, and **other** incremental changes