The (new) muon g-2 experiment at Fermilab

- Introduction
- Experimental setup
- Theory calculation
- New experiment
- Status report
- Summary

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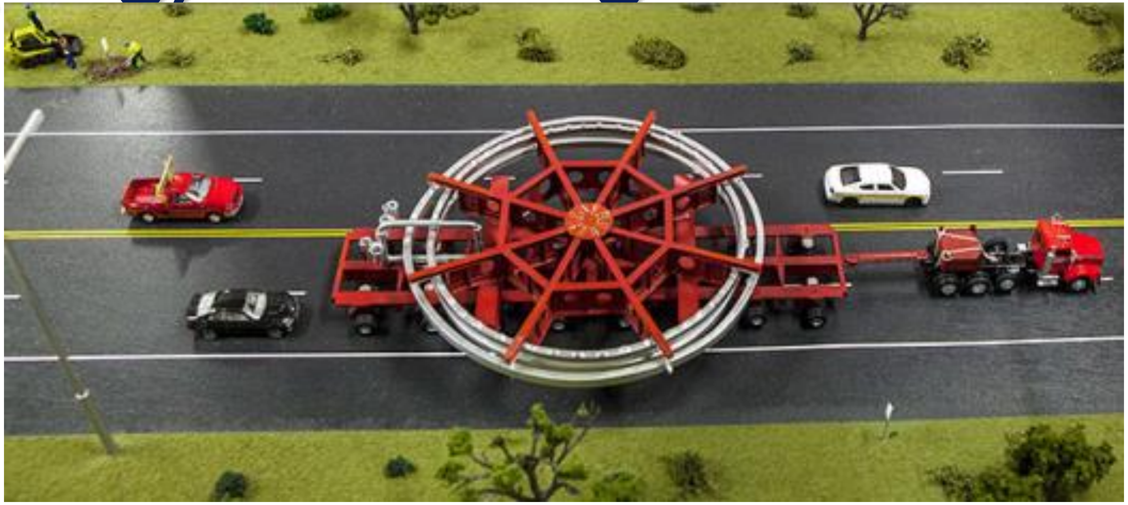
As many of you may have heard: Muon (ring) is moving…



Why move 600 ton, 15 meter wide metal ring half-way across U.S.?

- Why muons?
- What's muon g-2?
- What do we learn from it?
- Why we are moving it to Fermilab?
- How we are going to run the experiment?

It all starts from something simple…

Magnetic momentum, spin, g-factor

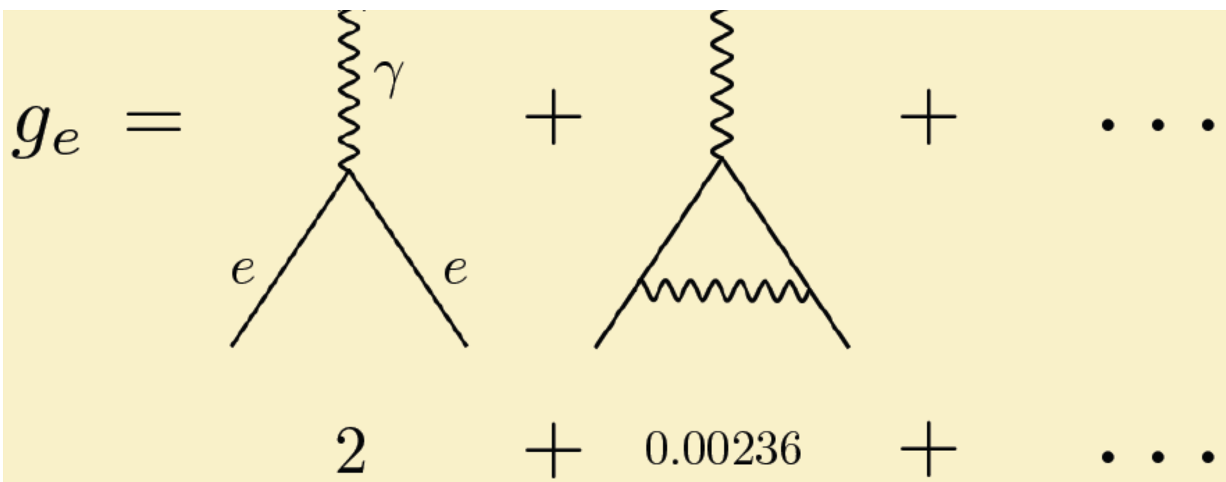
- Intrinsic magnetic momentum for any (charge) particle with spin S
- g-factor dictates the relationship between momentum and spin, tells something fundamental about the particle itself (and those interacting with it)
  - Classical system → g = 1
  - Elementary particles such as electrons → g = 2
  - Composite particles such as protons → g != 2
- It provides a unique prospective to analyze the particle without 'breaking' it: observe and learn!

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

Where is the fun part (anomaly)?

We physicists love ‘anomalies’

- **Electrons, do we really ‘see’ g=2 as predicted by Dirac?**
- **It is NOT! [1948 Kush and Foley measured $g_e = 2.00238(6)$]**
  - **Where does this 0.1% deviation comes from?**
  - **Empty space ?!**
- **As it turns out, the space is never ‘empty’, virtual particles pop in and out within short period – radiative corrections**



First order QED: beginning of QED and the Standard Model

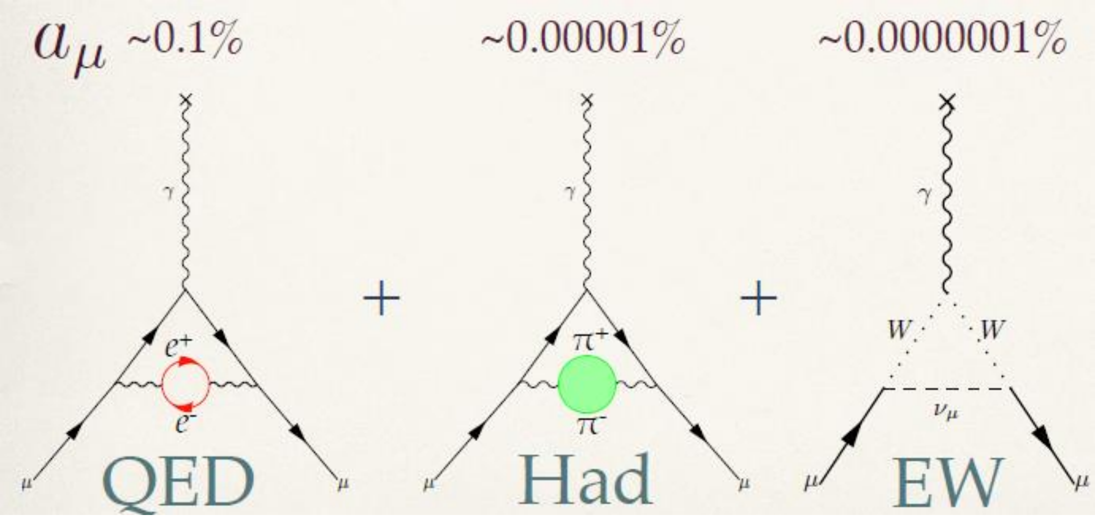
What about muons? $a = \frac{g-2}{2}$

A slight change of name: g → a

- **From 'empty space' → 'everything included'**
  - **Consider QED, hadronic, electroweak corrections…**

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

- **Muon is special**
  - **$m_u/m_e \sim 200$, sensitivity $\sim 200^2 \sim 10^4$ (effects on muons are much easier to be observed than electrons)**
  - **Easy to make ample production, life time (2.2μs) long enough**

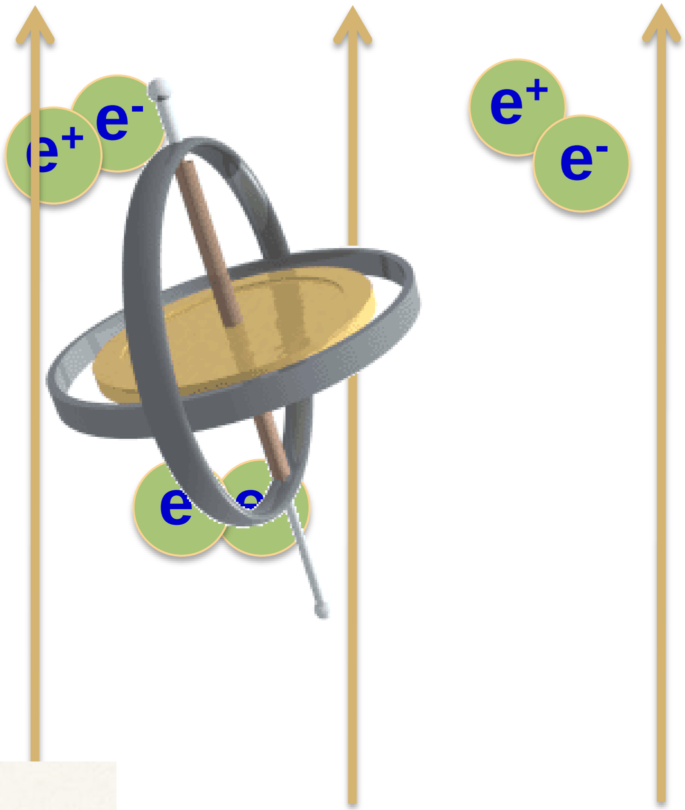


+ New correction beyond EW scale? beginning of the Beyond Standard Model?

How to measure?

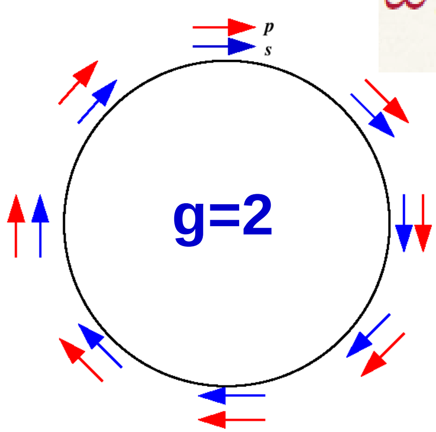
The name of game changes again: a → ω

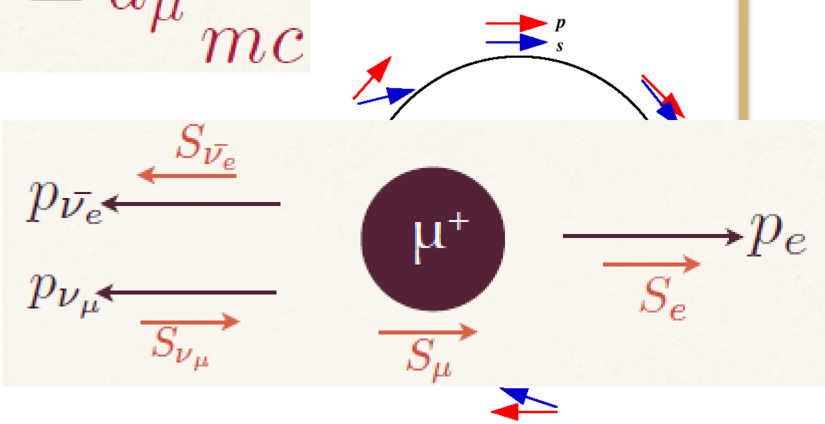
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

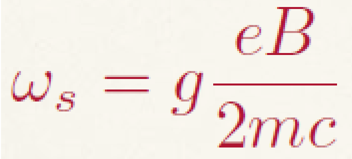


$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = a_\mu \frac{eB}{mc}$$







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

A slight complication…

The magic muon momentum

- **Muons make horizontal circular movement under influence of magnetic field B, what about vertical movement?**
  - **Need to use electrostatic quadruples to confine muons vertically, this brings additional complication**

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

- **How to measure E?**
  - **No need! choose $\gamma = 29.3$, then coefficient vanishes!**
  - **$\gamma = 29.3$ means $p_\mu = 3.09$ GeV (magic momentum)**

$$\omega_a = a_\mu \frac{eB}{mc}$$

A slight complication…

$$\omega_a = a_\mu \frac{eB}{mc}$$

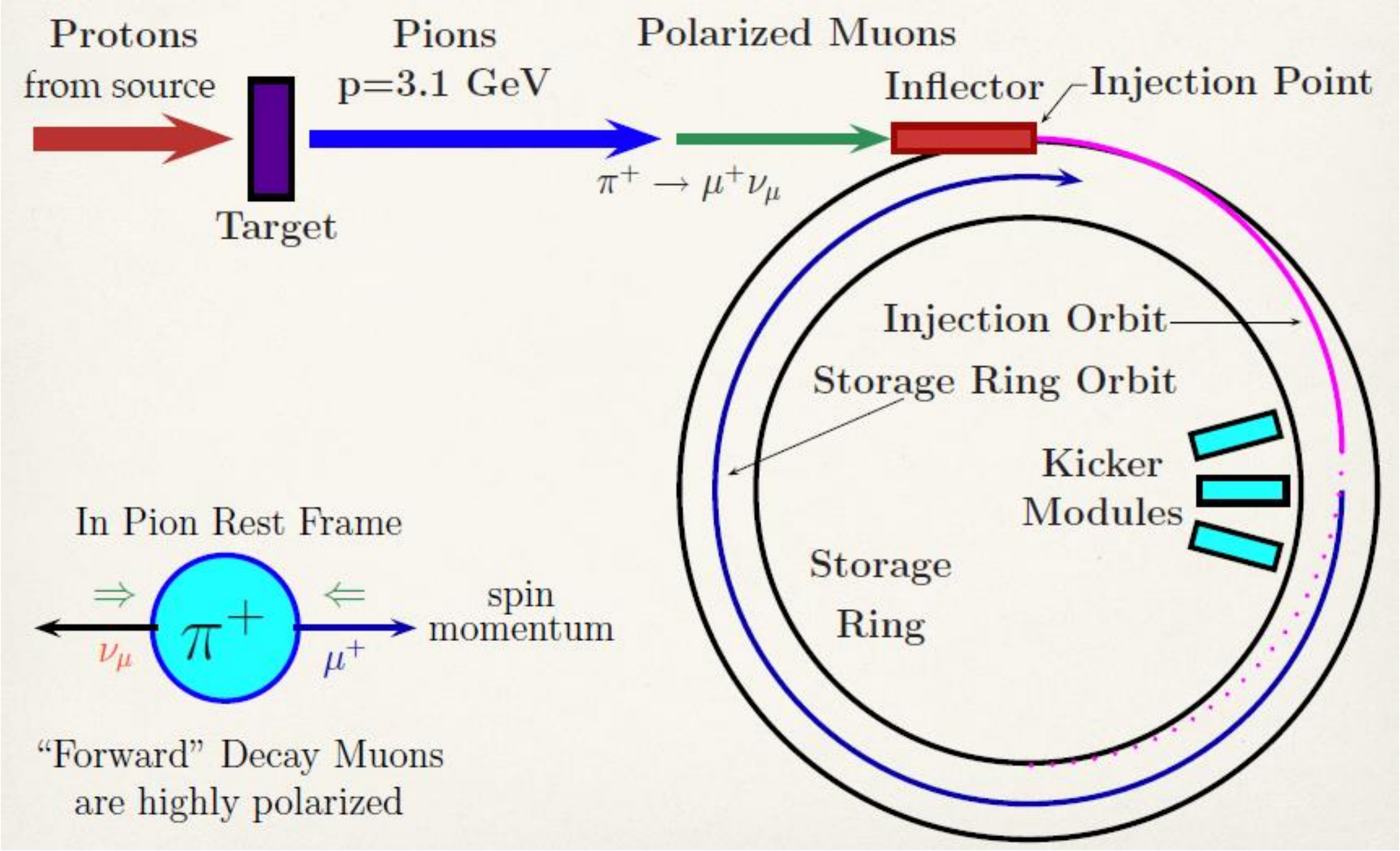
More name changing game

- **Avoid additional uncertainty from muon mass and charge**
  - **Use ratio of different frequencies instead**

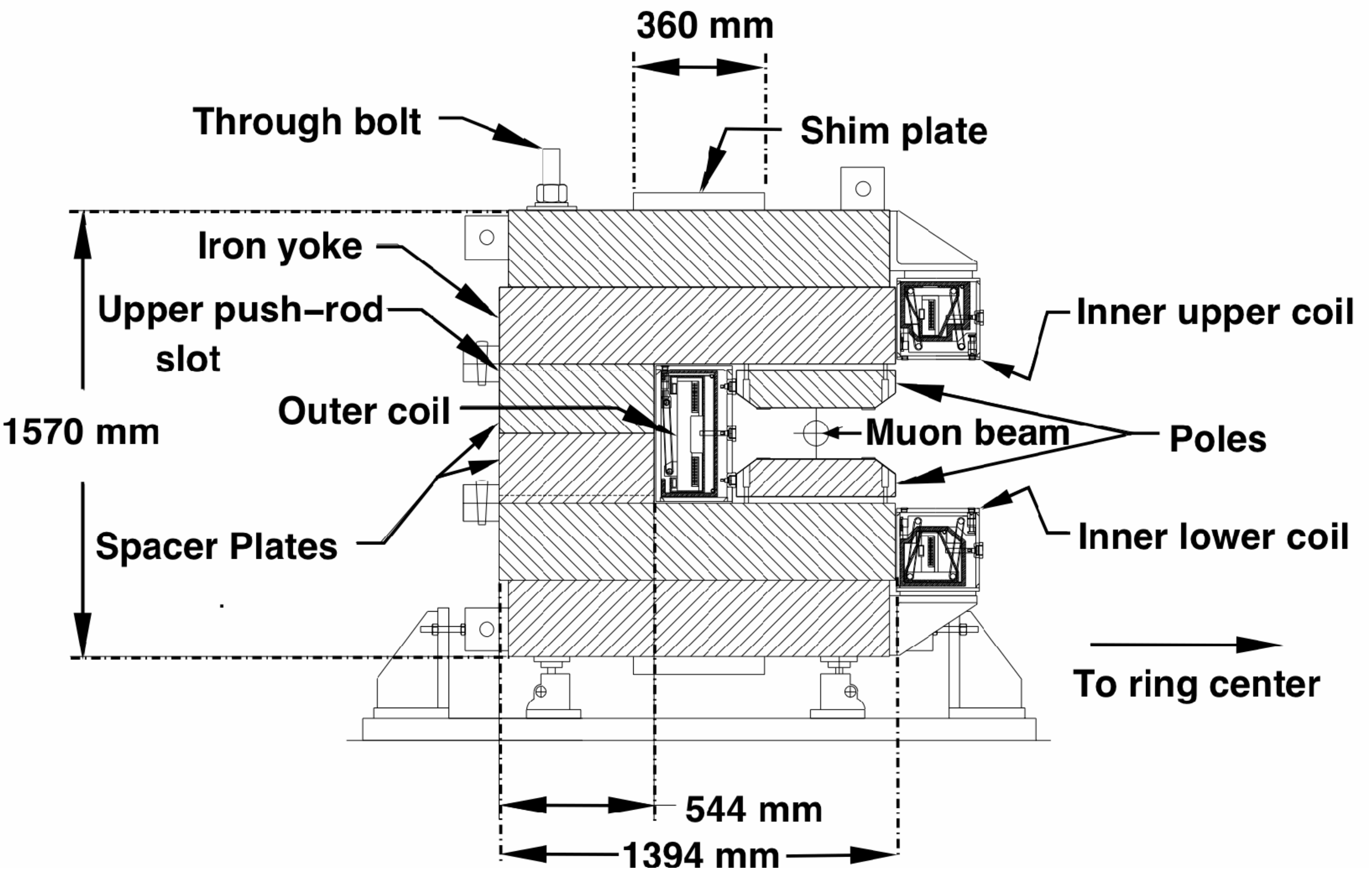
$$a_\mu = \frac{\mathcal{R}}{\lambda - \mathcal{R}} \qquad \mathcal{R} = \omega_a/\omega_p, \;\; \lambda = \mu_\mu/\mu_p$$

  - **ω_p is the proton precession frequency, ω_p ~ |B|**
  - **R is measured in this experiment**
  - **λ is determined by precision hyperfine muonium structure experiment**
- **Final measurements done in three steps**
  - **Inject muons into a ring with uniform magnetic field**
  - **Measure proton precession frequency ω_p**
  - **Measure muon frequency difference ω_a**
  - **The last two steps are done simultaneously and independently (blind analyses)**

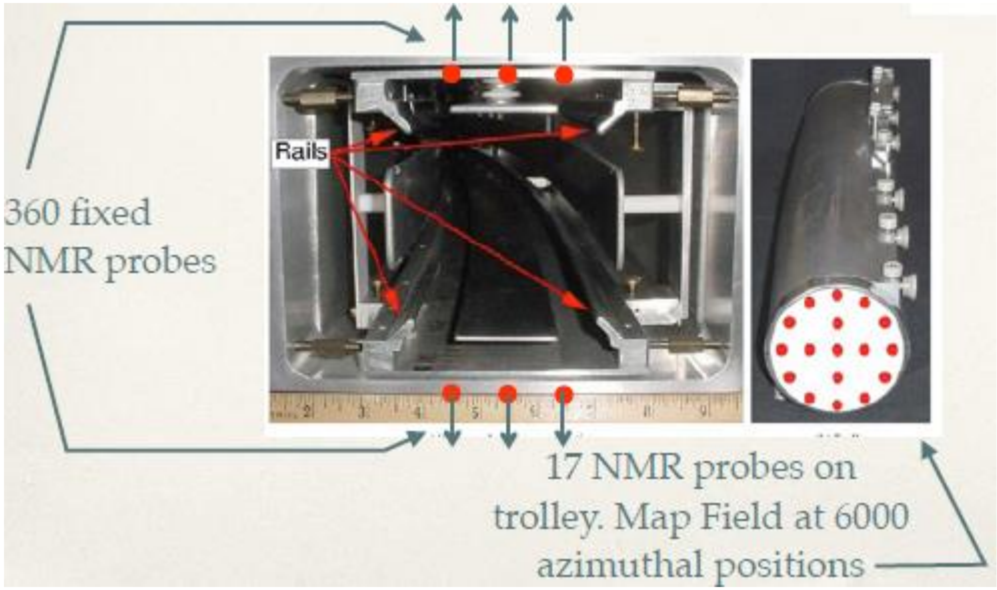
The experiment setup

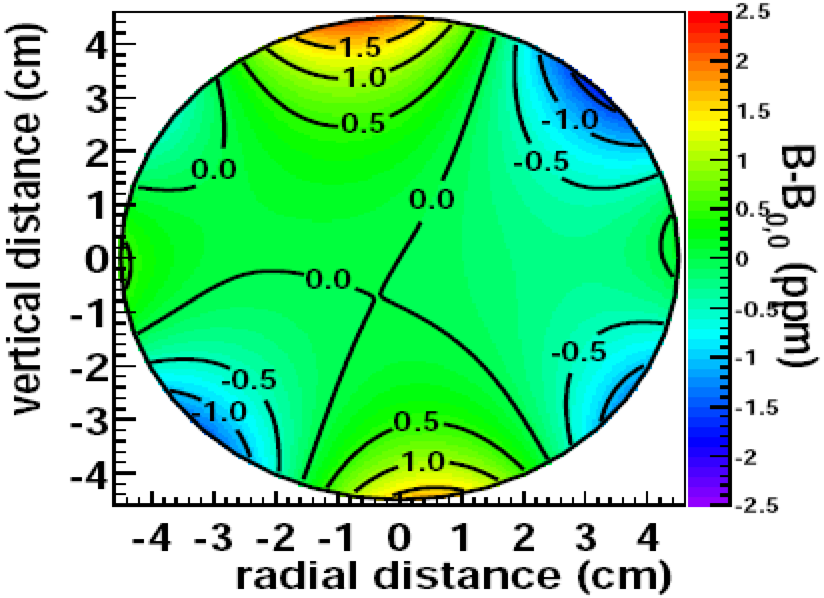


Injection into the muon storage ring



Measuring ω_p, namely the B field

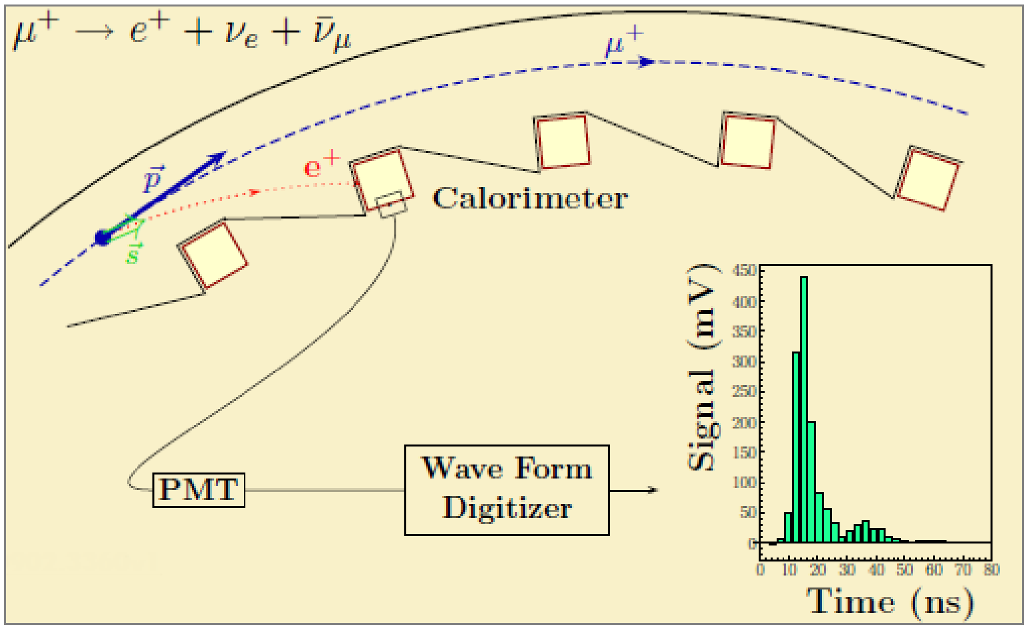


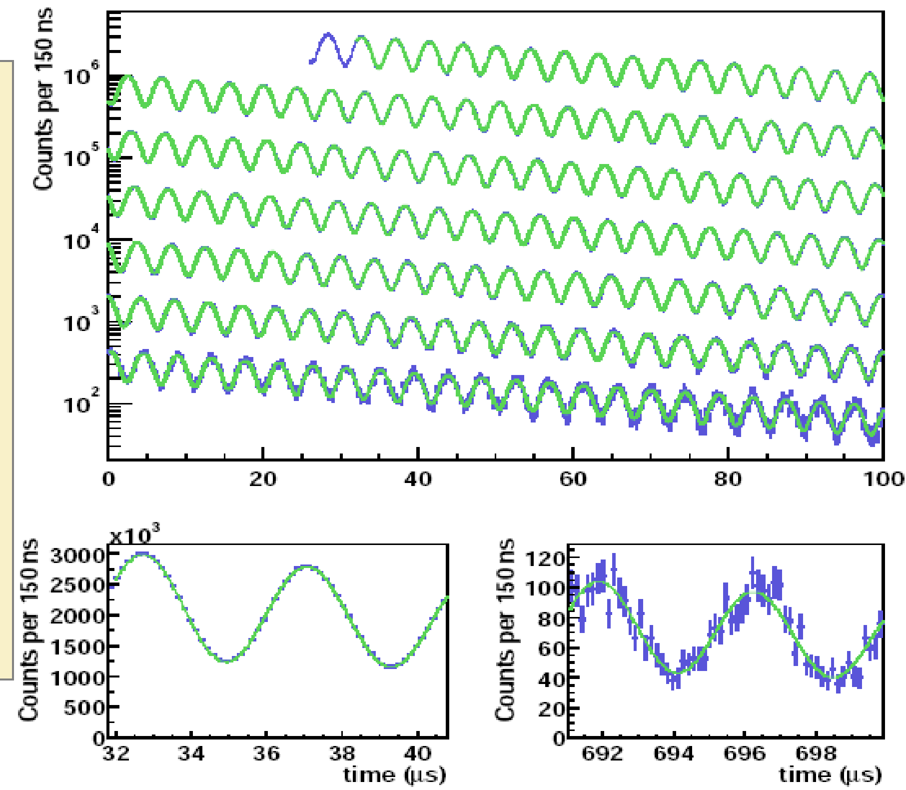


Use trolley and high precision (~10ppb) nuclear magnetic resonance (NMR) probes

- Monitoring the field and provide feedback to the storage ring power supply during data taking
- Mapping the storage ring field when the beam is off
- Absolute and cross calibration of all probes
- Use shimming techniques to better produce uniform B field

Measuring ω_a





The integrated number of electrons (above E_{th}) modulated at ω_a

- **Angular distribution of decayed electrons correlated to muon spin**
- **Five parameter fit to extract ω_a**

$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

Systematics

Category	E821 [ppm]	Main E989 Improvement Plans	Goal [ppm]
Absolute field calibra-	0.05	Special 1.45 T calibration magnet	0.035
nal magnetic fields		fields; simulations of impact; active	
on ω_p			

Category	E821 [ppm]	E989 Improvement Plans	Goal [ppm]
Gain changes	0.12	Better laser calibration	
		low-energy threshold	0.02
Pileup	0.08	Low-energy samples recorded	
		calorimeter segmentation	0.04
Lost muons	0.09	Better collimation in ring	0.02
CBO	0.07	Higher n value (frequency)	
		Better match of beamline to ring	< 0.03
E and pitch	0.05	Improved tracker	
		Precise storage ring simulations	0.03
Total	0.18	Quadrature sum	0.07

E821: a_μ^{exp} = 116 592 089 (63) X 10^{-11}, 0.46 ppm stat., 0.28 ppm syst.

E989: experimental uncertainty ~ 16 X 10^{-11}

Theory calculation

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

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [47]	$6\,923 \pm 42$
HVP(lo) [48]	$6\,949 \pm 43$
HVP(ho) [48]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [47]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [48]	$116\,591\,829 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 45_{\text{tot}})$

[47] DHMZ, Eur.Phys.J.C72:1874 (2012)

[48] HLMNT, J.Phys.G38,085003 (2011)

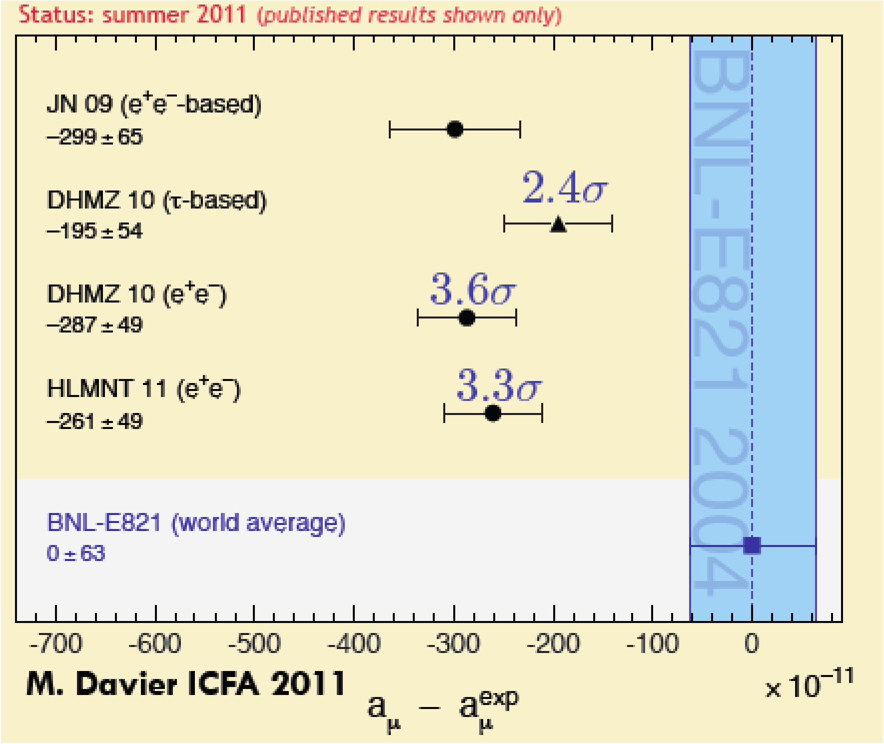
$\Delta a_\mu = (286 \pm 80) \times 10^{-11}$ [47]

$\Delta a_\mu = (260 \pm 78) \times 10^{-11}$ [48]

Dominating theoretical uncertainties are hadronic components

- **Most from low energy non-perturbative QCD regime**
- **The hadronic vacuum polarization (HVP) is related to the cross section for hadron production $e^+e^- \rightarrow$ hadrons**
- **The hadronic light by light (HLbL) is model specific (cannot be determined from data directly), much less known (25% error)**
- **Lattice QCD is starting to get involved, could be a big help**

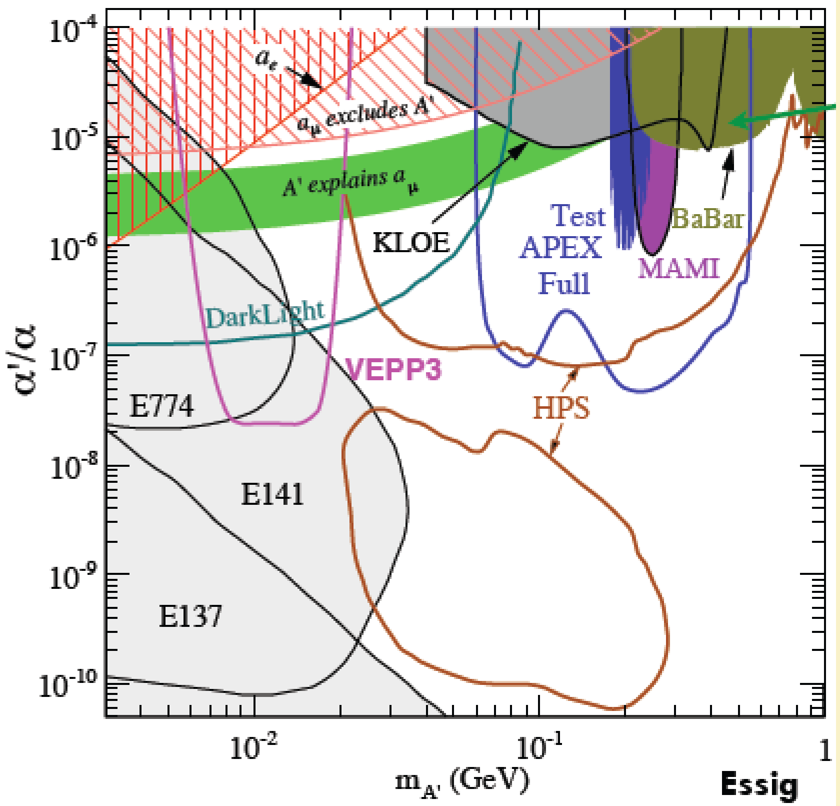
Comparison

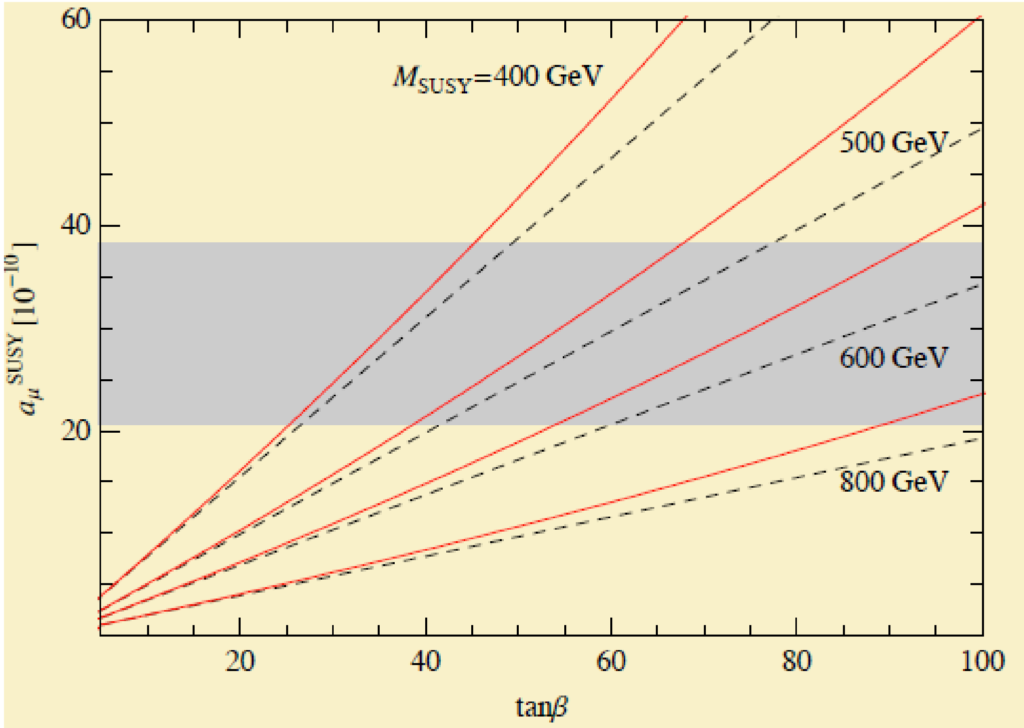


3.3 σ – 3.6 σ difference depending on HVP LO contribution

- **If the discrepancy between the theory and the experimental result sustains, it can point to new physics**
- **More importantly, Δa_μ tightly constraints new physics models and has significant implications to interpret any new phenomena**

New physics?



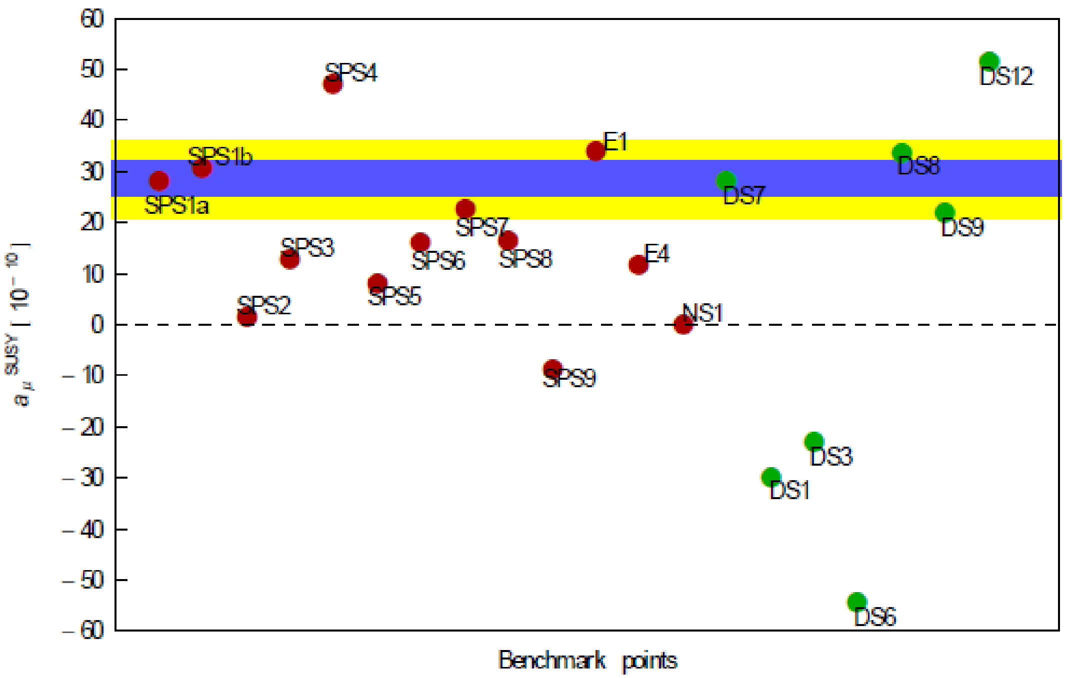


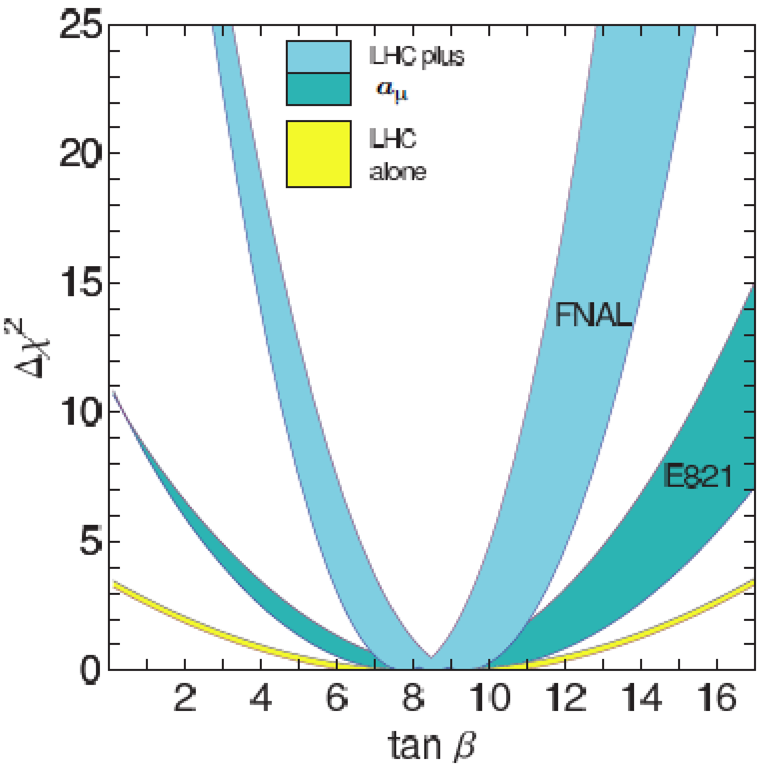
Dark photons?

SUSY?

$$a_\mu^{\rm SUSY} \approx 13 \times 10^{-10}\, \mathrm{sign}(\mu) \left(\frac{100\ \mathrm{GeV}}{m_{\rm SUSY}} \right)^2 \tan\beta$$

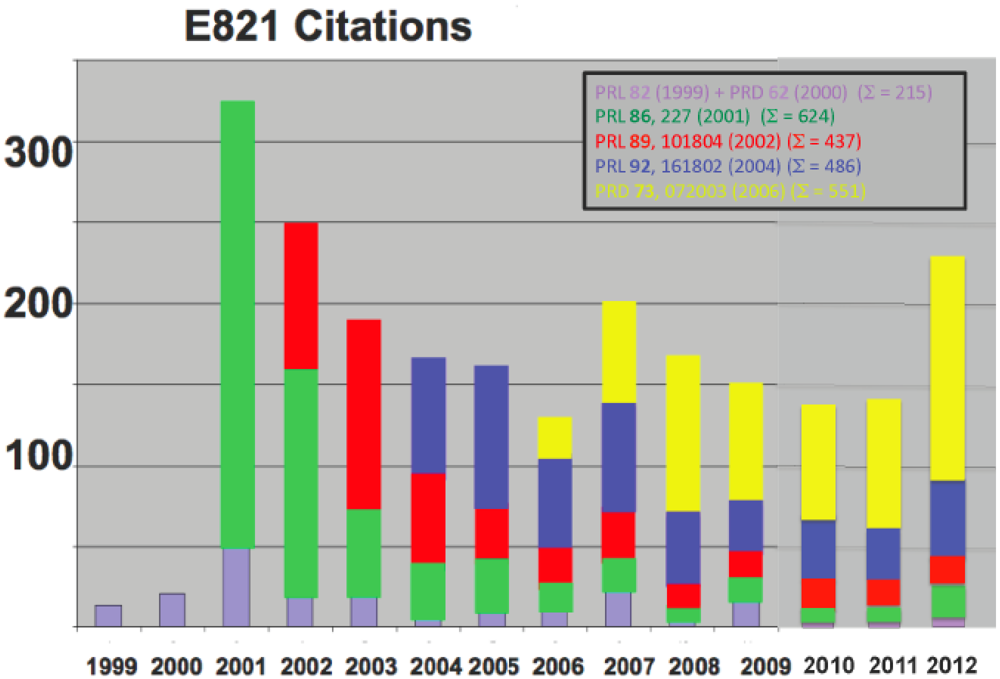
New physics?

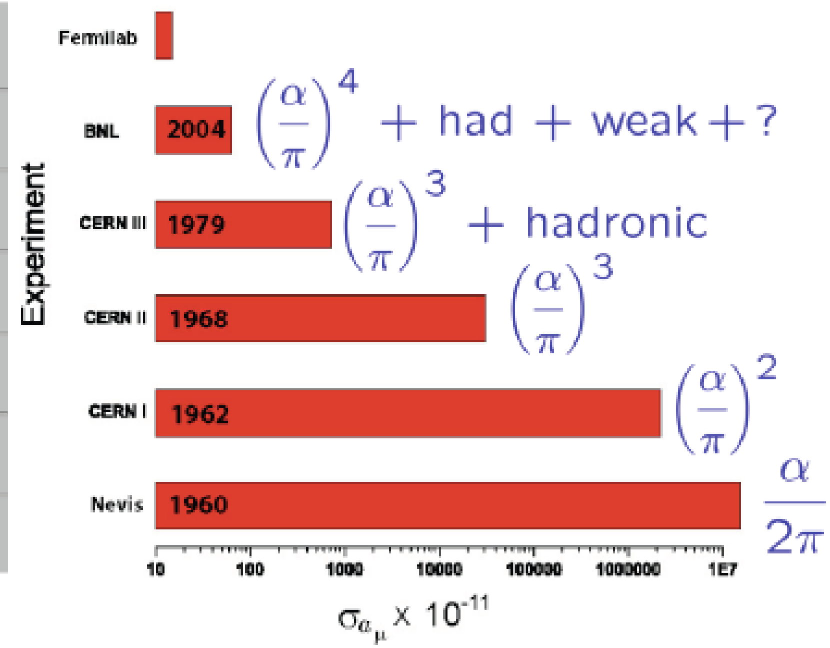




- **Strong discriminating power from improved measurements**
- **Complementary to LHC**

From old to new

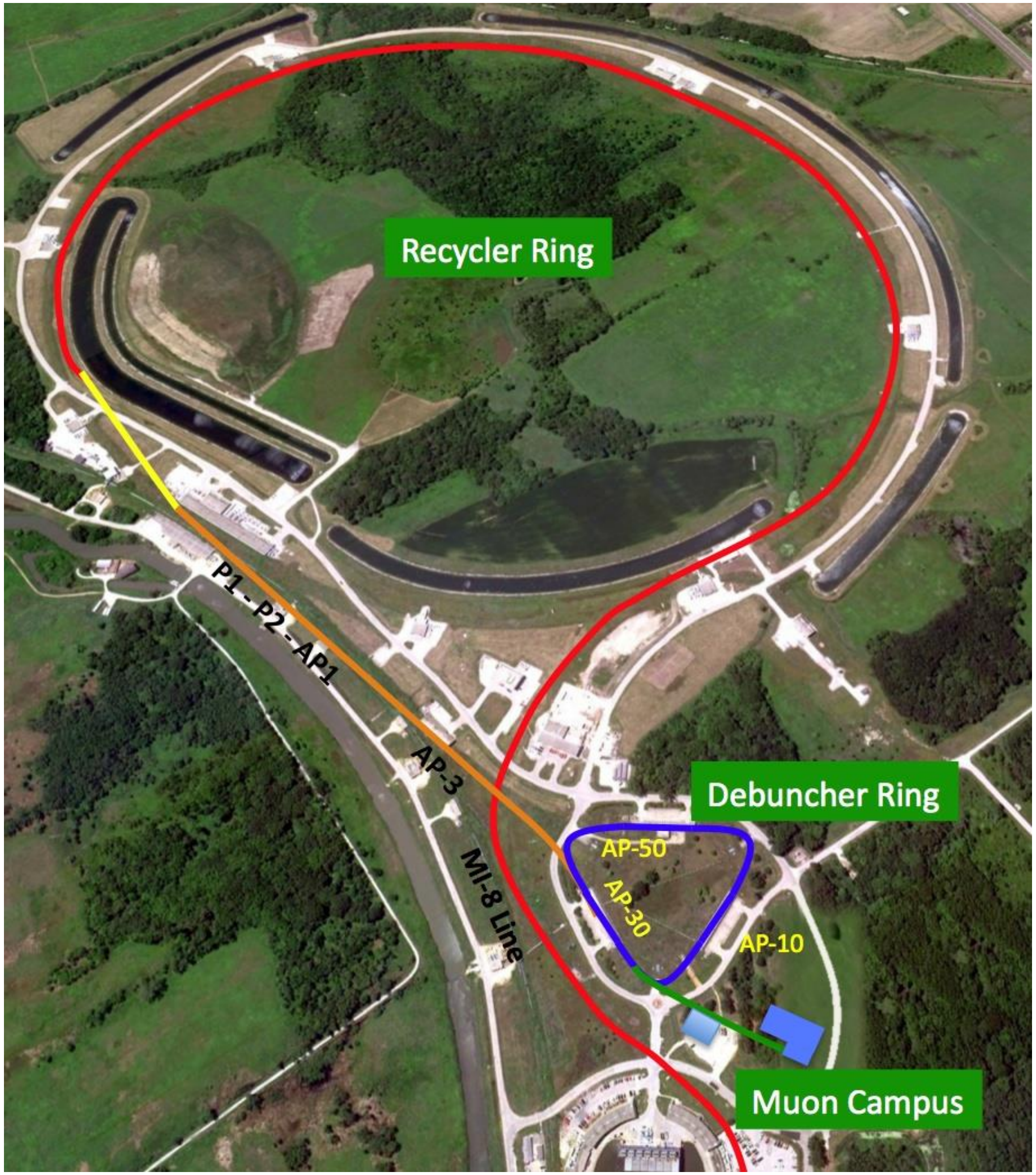




E989 Goal: 0.14 ppm, 0.10 ppm stat., 0.07 ppm for both ω_a and ω_p

- **Move to Fermilab, a part of newly established muon campus!**
  - **Increase statistics by 20 times**
  - **Long beam line, no pion background, hadronic flash**

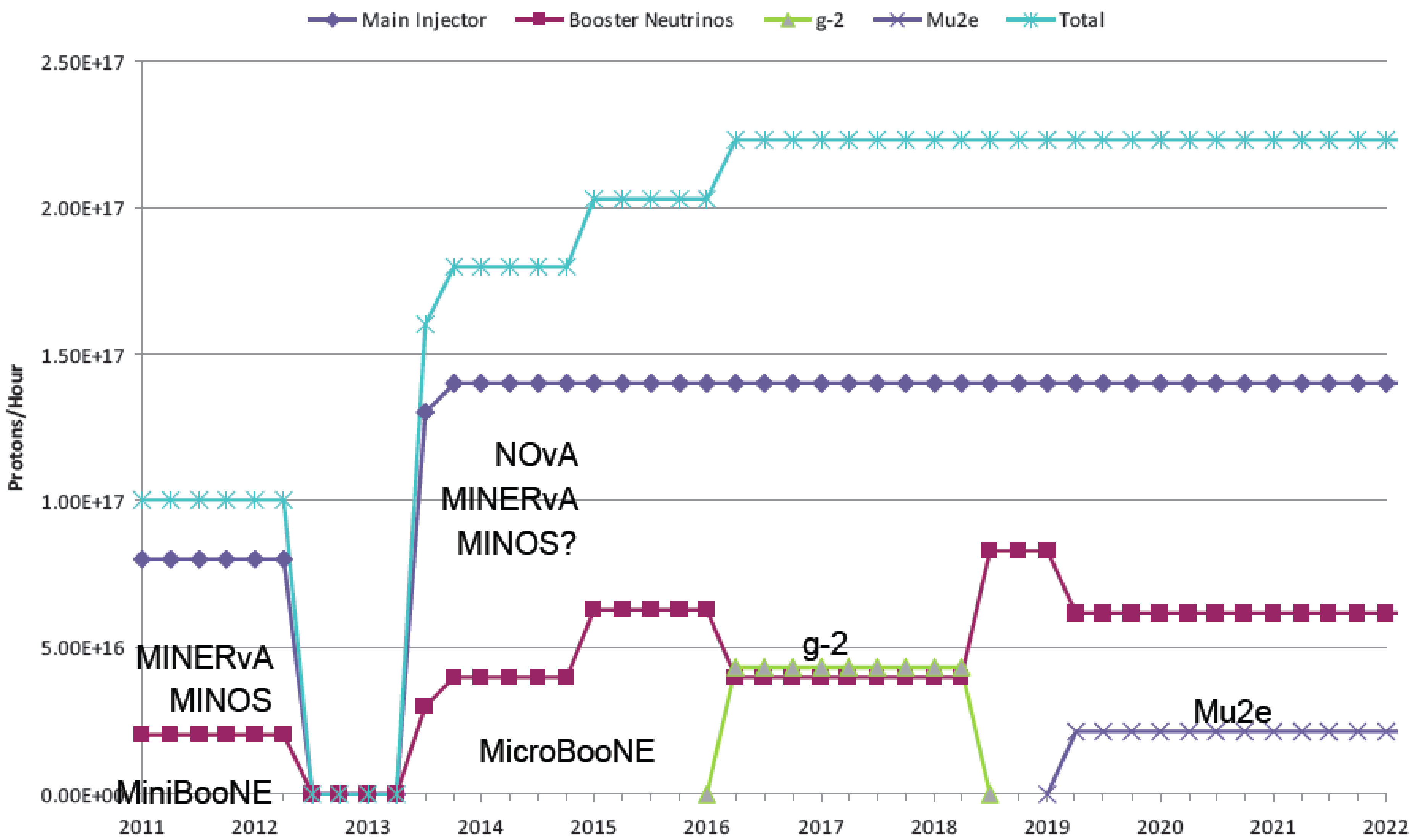
Fermilab Muon Campus



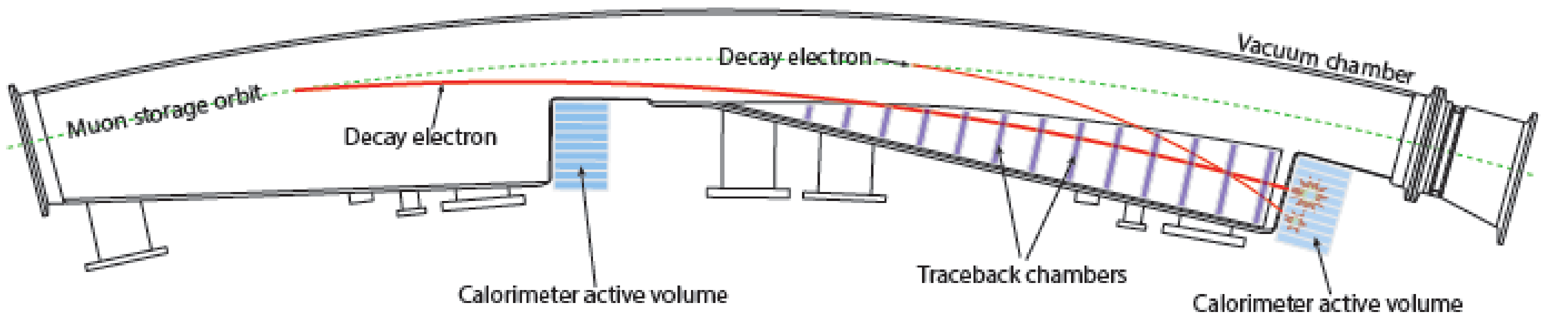
- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

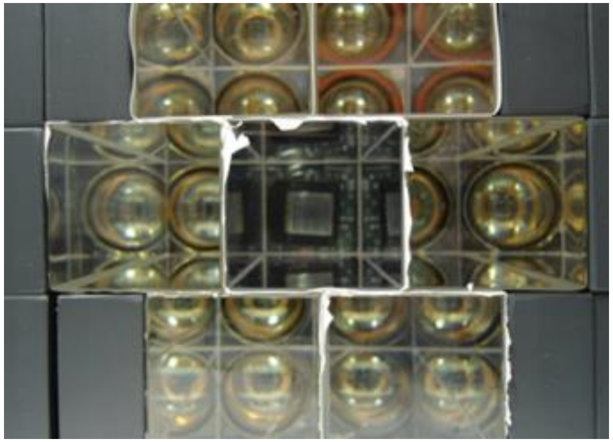
Fermilab Muon Campus

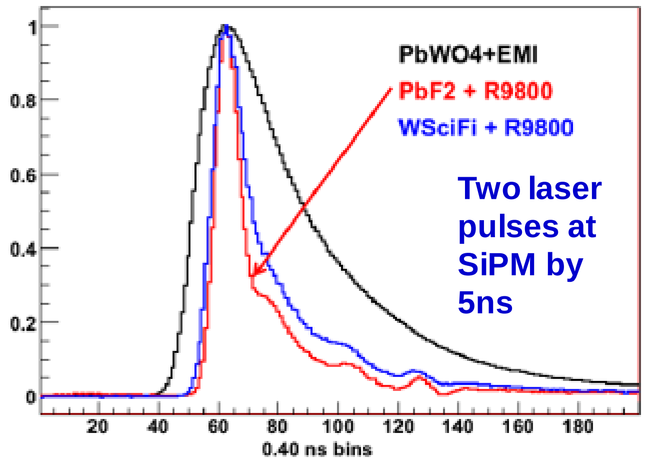
Share the beam

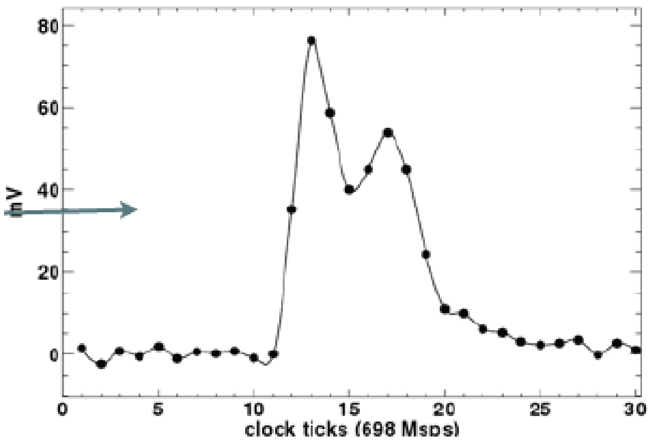


Detector upgrade: calorimeter





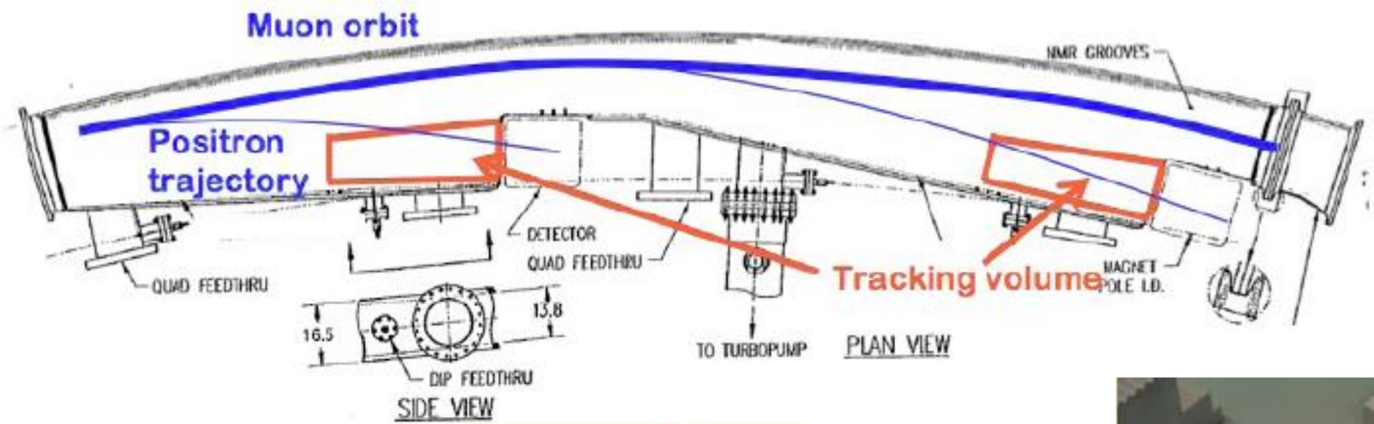


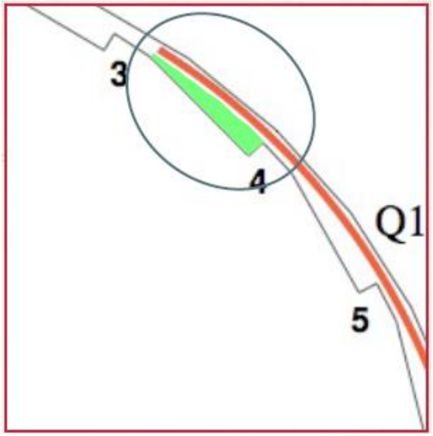


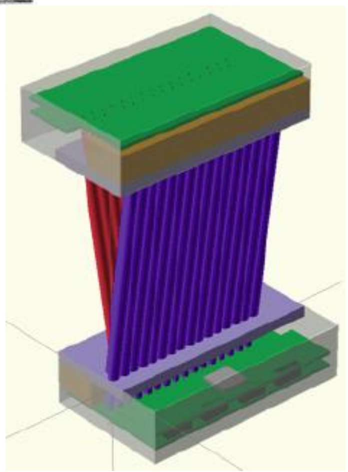
Segmented, fast response, crystal calorimeter

- Lead-floride Cherenkov crystal (PbF_2) can reduce pileup
- Silicon photomultiplier (SiPM) directly on back of PbF_2
  - Not disturb magnetic field, avoid long lightguides

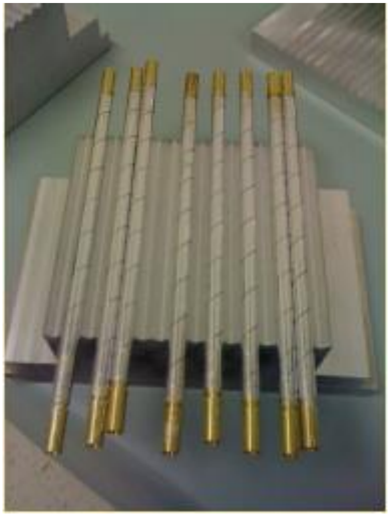
Detector upgrade: tracker







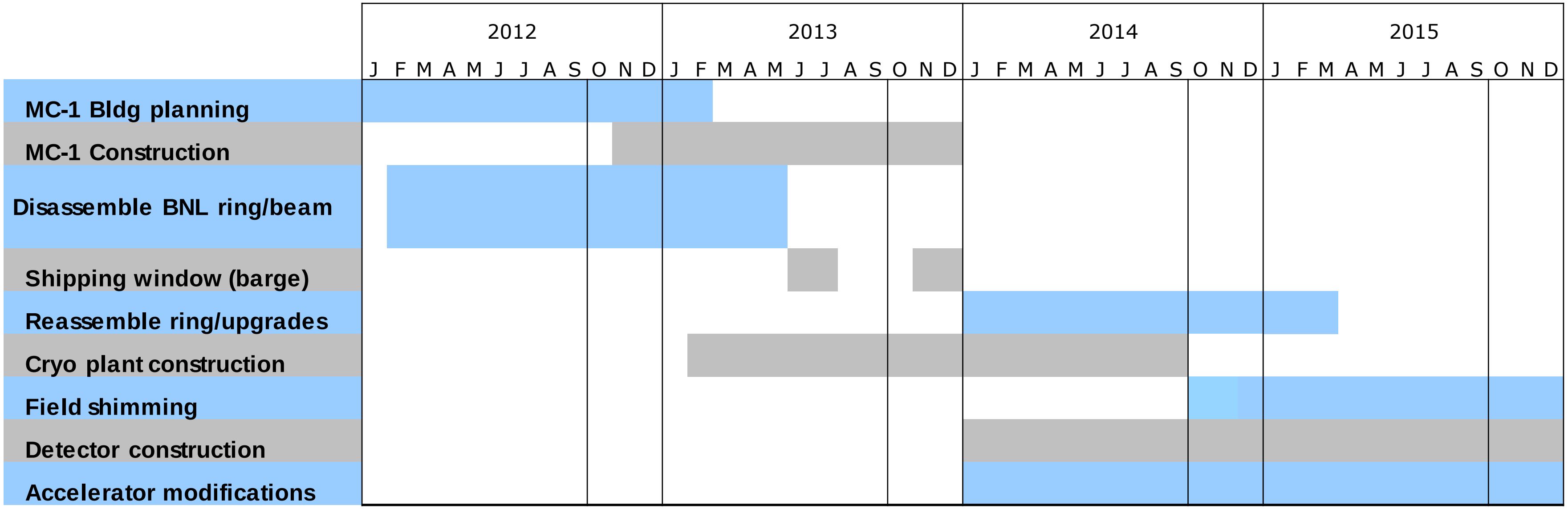
Doublet of UV straw chambers



New tracking traceback detector

- Calibrate beam dynamics, better control of systematics
- Better measurement of the pileup (multiple positrons)

Status



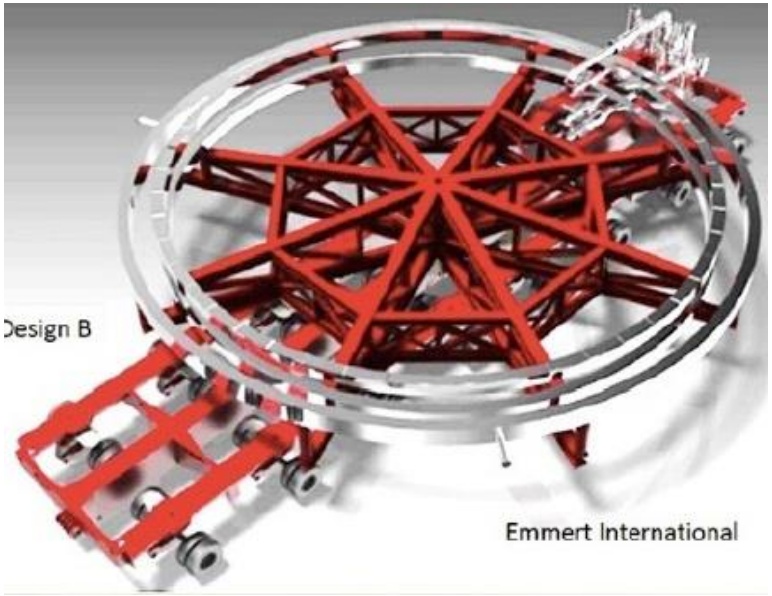
On schedule to start data taking in 2016!

- **Received DOE CD-0 approval in September 2012**
- **Construction started with site preparation**
- **Disassembly of BNL site finished**
- **"Big ring" starts to move in 5 days (June 10th)**

Independent Design Review (IDR) starts today (June 5th) !

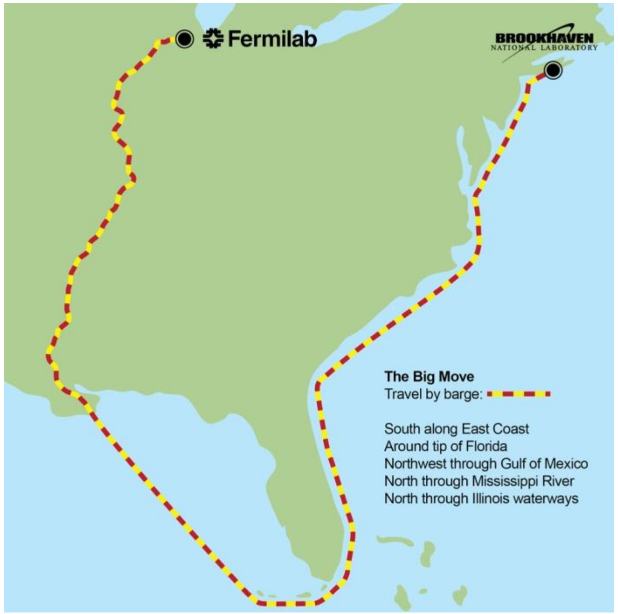
The ring is moving…

Disassembly



The Big Move

Expect to arrive at end of July



Fermilab g-2 Collaboration (Fermilab E989)

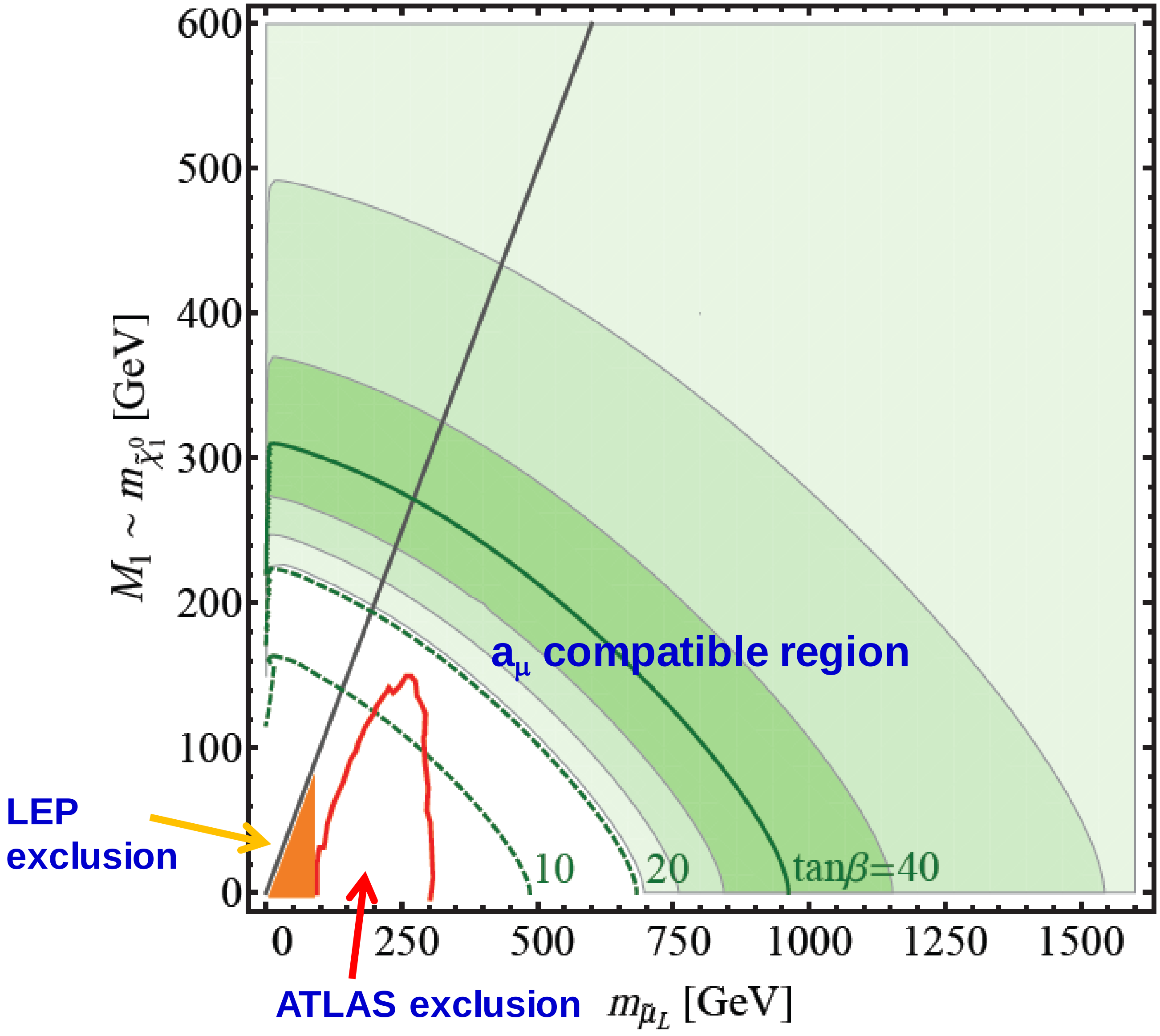
Summary

Fermilab muon g-2 program is well underway

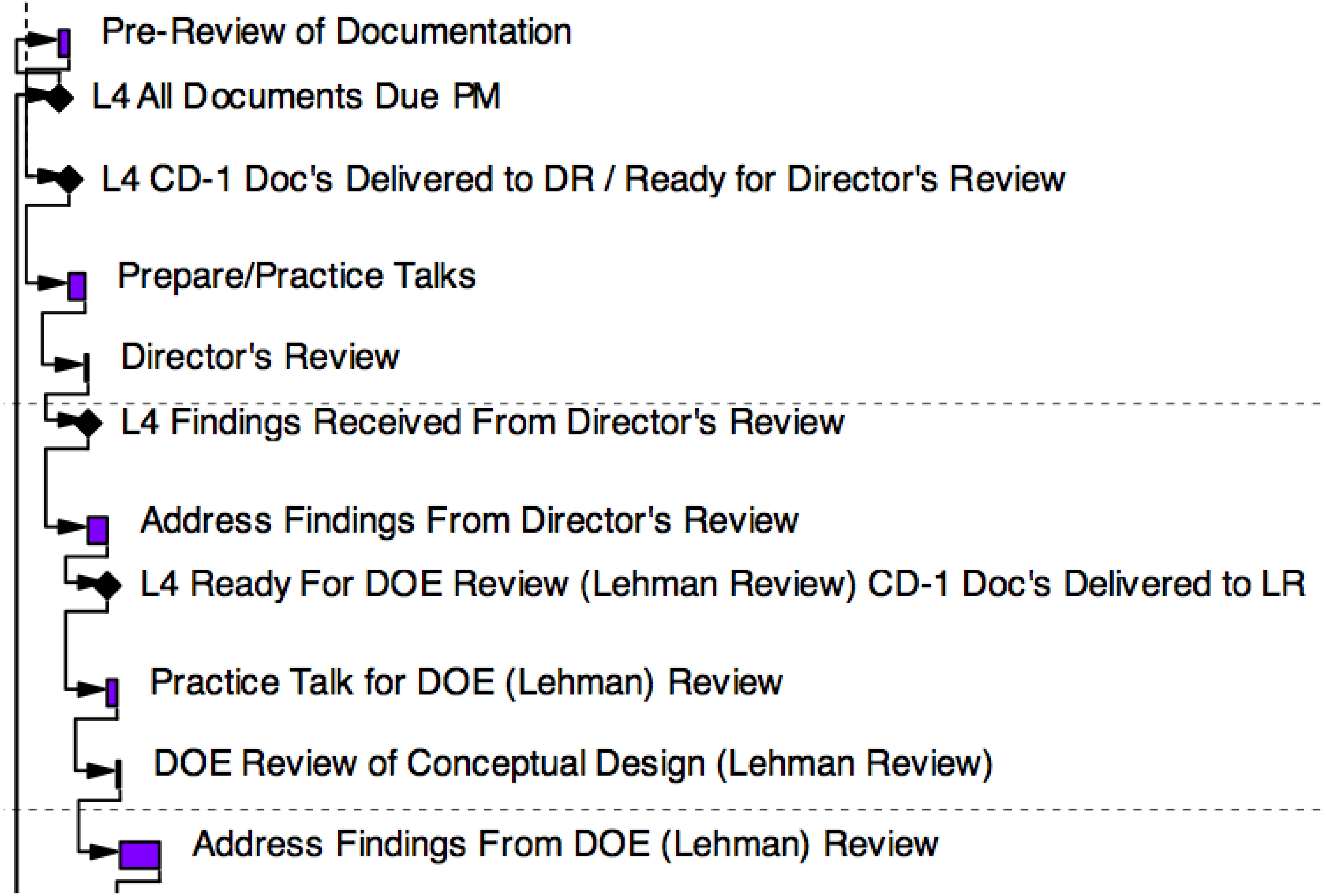
- **Flagship project within Fermilab muon campus**
  - Received Mission Need approval
  - g-2 is extremely sensitive to new physics and high order calculations, correction
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - Theoretical uncertainty also expected to reduce by a factor of 2
  - Could achieve 5.6 σ deviation with the same central value
- **Great discovery potential and bright future in line with Fermilab muon / Project-X programs**

Backup

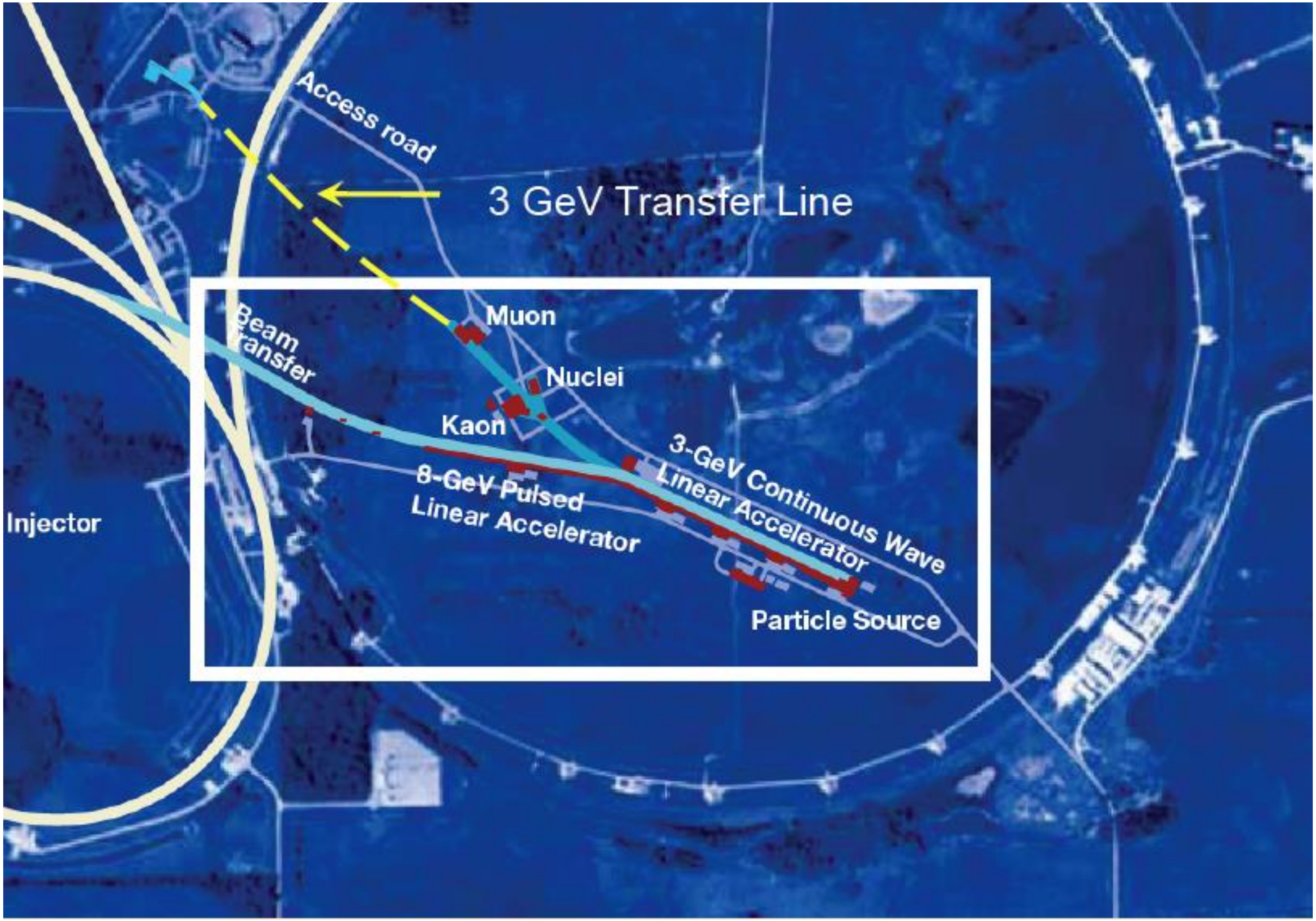
New SUSY Limits



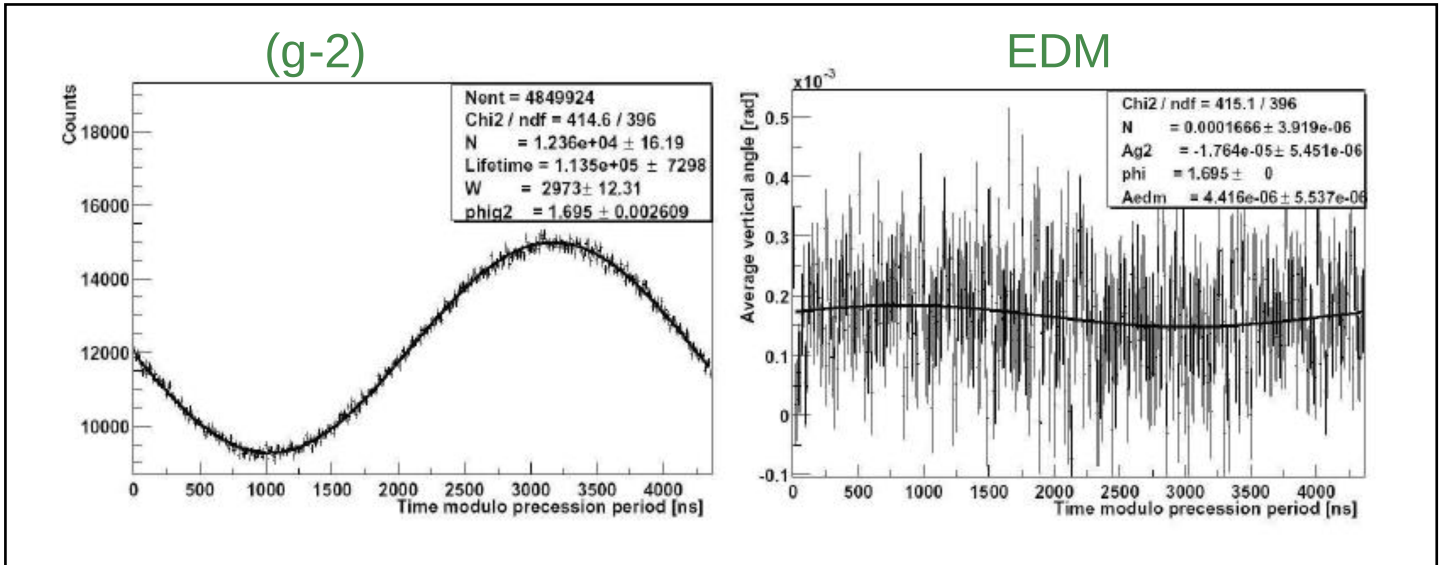
Review Schedule



Project-X scenario



Muon EDM



(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

EDM Signal: Average vertical angle modulo g-2 period. Out-of-phase by 90° from g-2; this is the EDM signal

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

$$\text{from E821} \quad d_\mu < 1.8 \times 10^{-19}\, e\,\text{cm} \rightarrow \sim \text{ few } 10^{-21}$$