Muon g-2: Views from the Field

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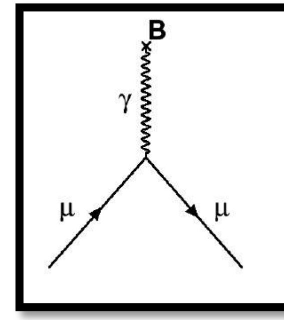
(for the Muon g-2 Collaboration)

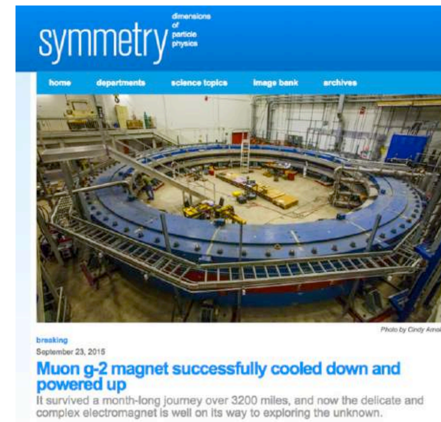
LNF Spring School

12/05/2016

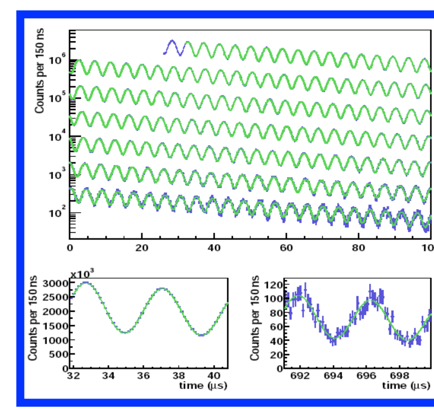
Outline



- ❖ Theoretical Background and Recent Progress


symmetry
dimensions of particle physics
home departments science topics image bank archives
Photo by Cindy Arnold
breaking
September 23, 2015
Muon g-2 magnet successfully cooled down and powered up
It survived a month-long journey over 3200 miles, and now the delicate and complex electromagnet is well on its way to exploring the unknown.

- ❖ Storage Ring Technique



- ❖ Experimental Progress and Details
- ❖ Measurements from the Field
- ❖ Outlook

Muon g-2: The Basics

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

Eqn1

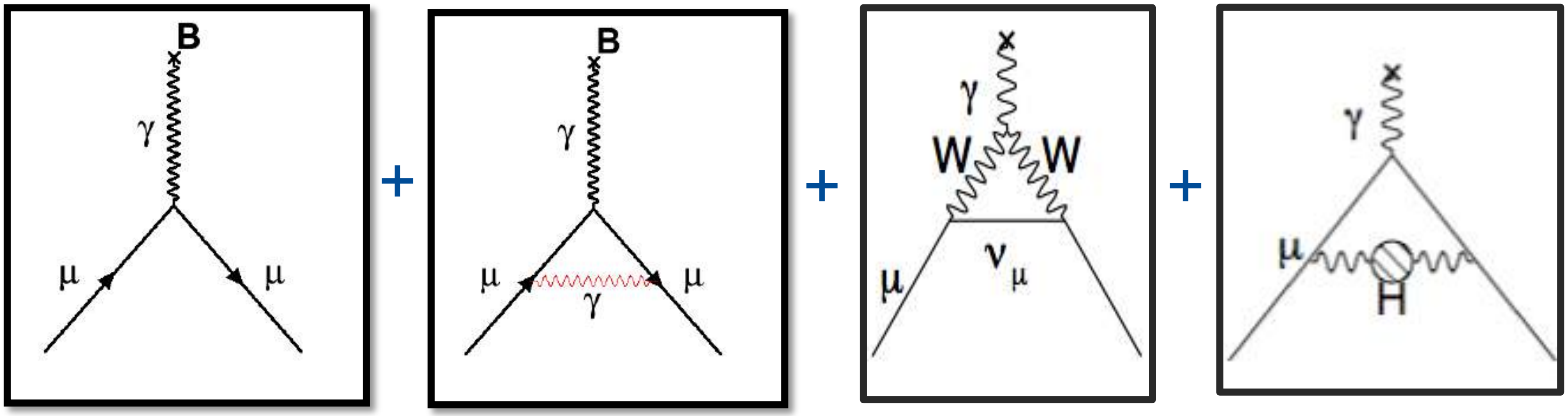
$g =$ 

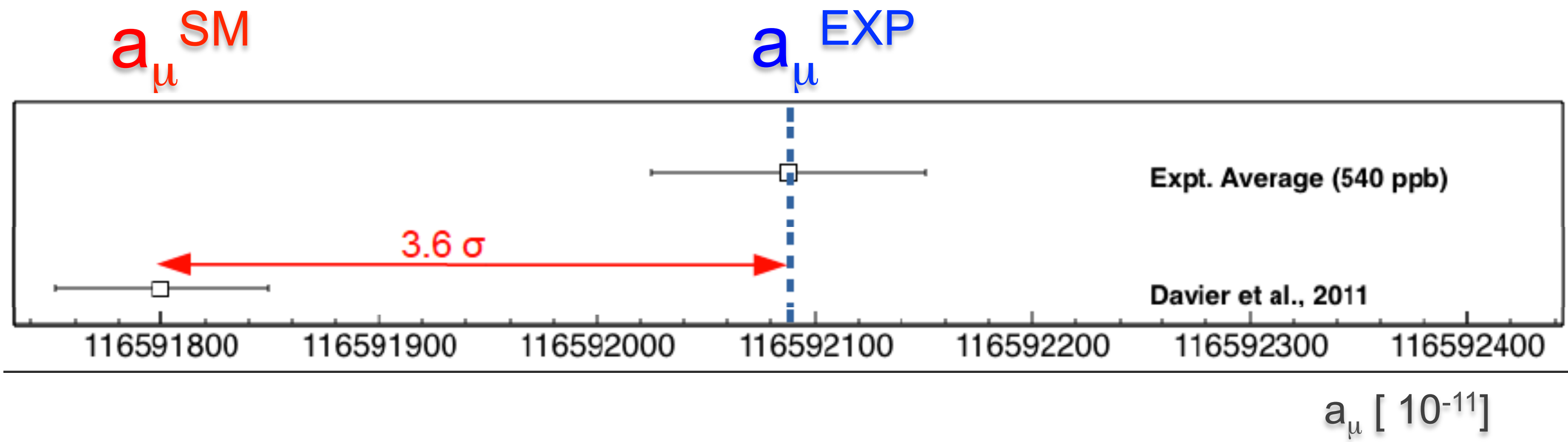
Fig1

$$g = 2 + O(10^{-3})_{QED} + O(10^{-9})_{EW} + O(10^{-7})_{QCD}$$

$$a_\mu^{SM} = (g_\mu^{SM}-2)/2 = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

Eqn2

Theory and Experiment Disagree



$$a_\mu^{EXP} - a_\mu^{SM} \stackrel{?}{=} a_\mu^{\text{New Physics}}$$

New Physics or missing systematics/statistics?

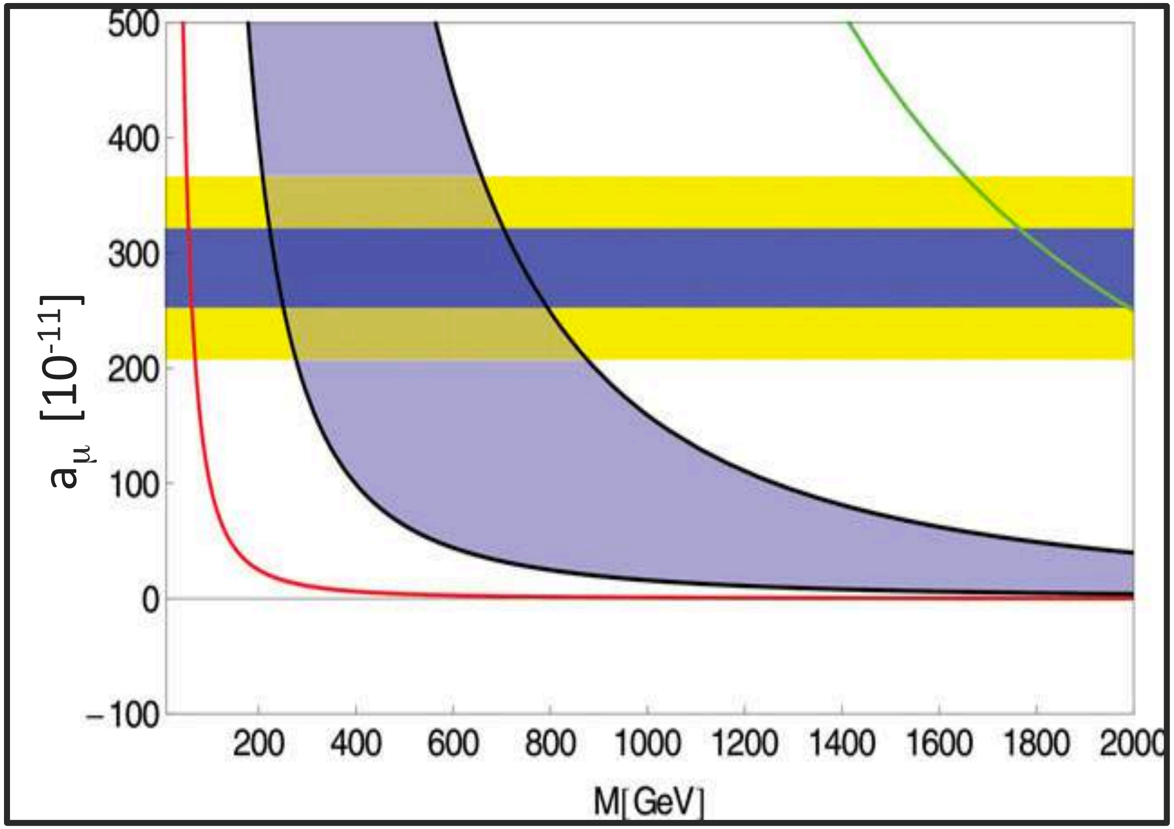
- Many Possible Models
  - SUSY (many variations)
  - Dark Photons
  - Any new model…

New Physics: TeV Scale Models

Z', W', Universal Extra Dimensions, Littlest Higgs (assumes typical weak coupling)

Radiative muon mass Generation

Unparticles, Extra Dimension Models, SUSY



D. Hertzog, Ann. Phys (Berlin) 2015., courtesy D. Stockinger (ref1)

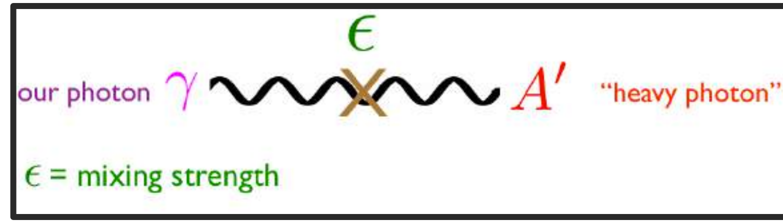
Difference b/w theory and experiment

Improvement with combined theory and experimental error

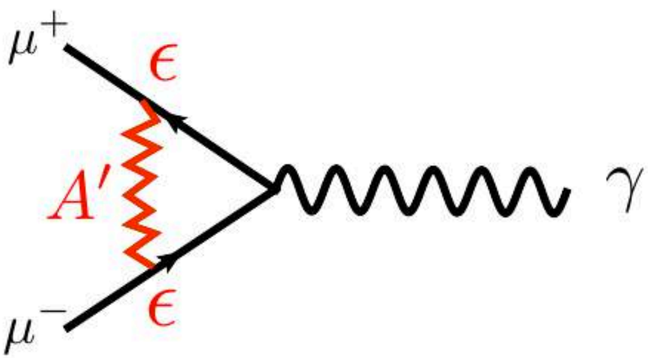
- Improved Precision will continue to constrain (or possibly validate!) the energy scale of the models

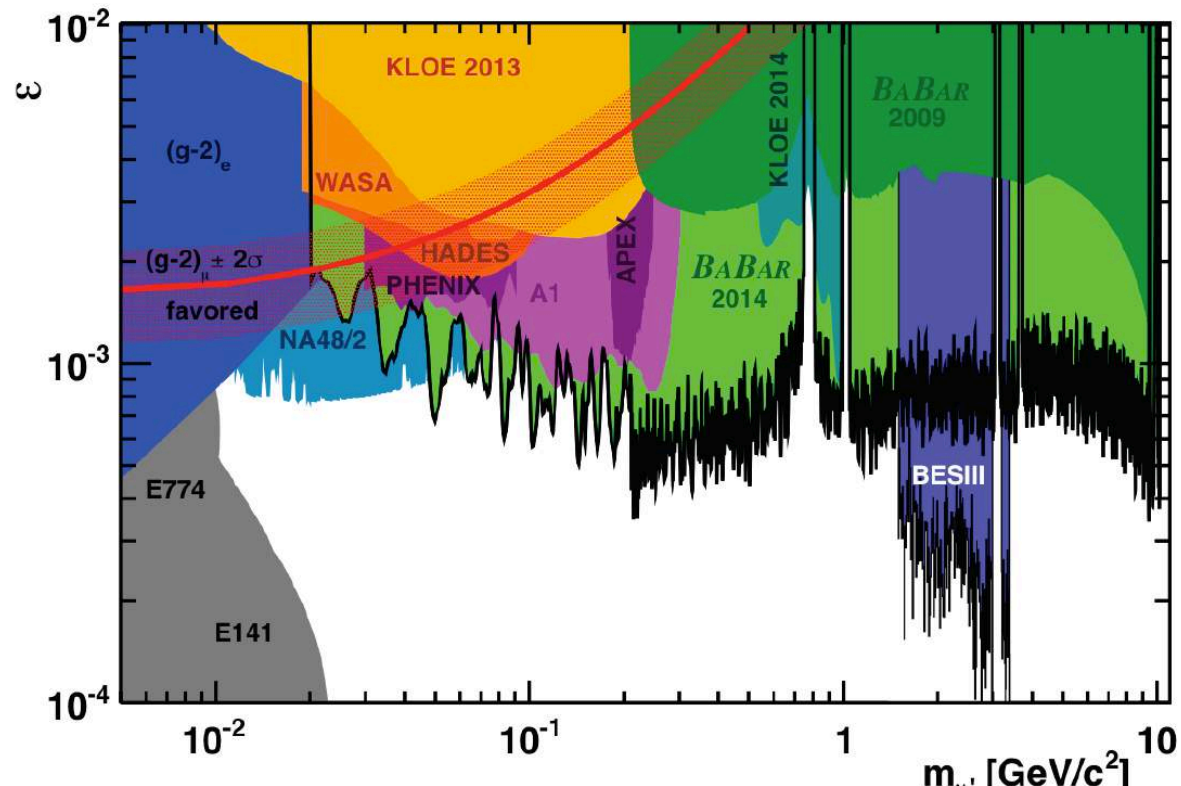
New Physics Possibilities: Essig's W&C Jan-2012

- A new U(1)' symmetry
- Dark Photon A'



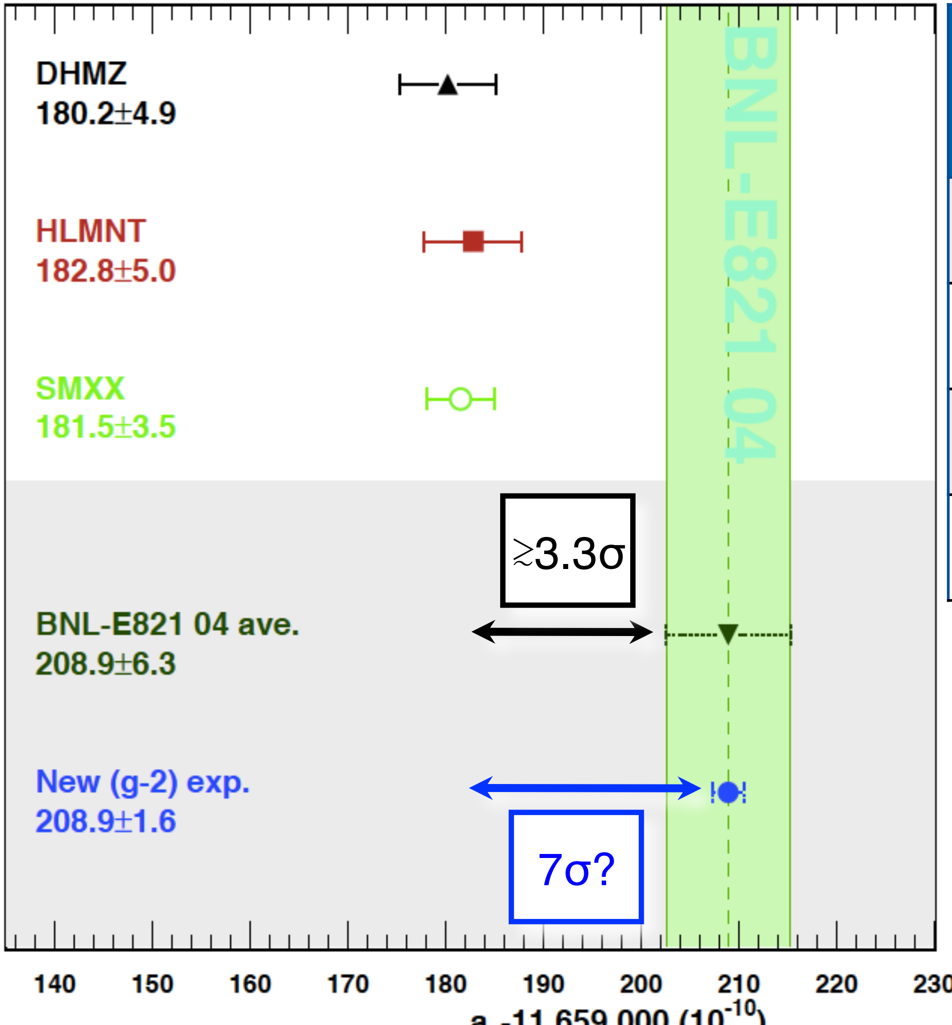
Limit on mixing strength from various experiments ($e^- e^+$)





A. Soffer http://arxiv.org/abs/1507.02330 Jul-2015 (ref2)

More precise comparison of SM and experimental values of g-2 needed to reveal new physics



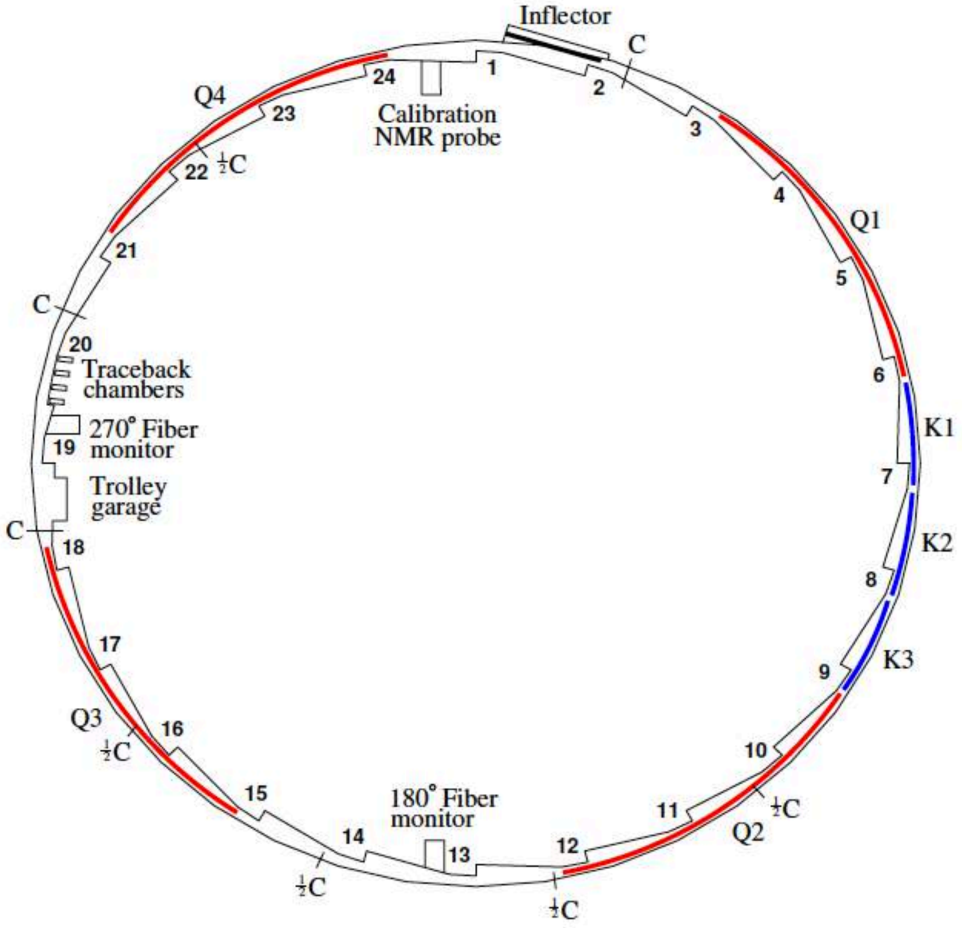
[Blum et al.,arXiv:1311.2198 (ref3)]

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	**140**

STORAGE RING TECHNIQUE

Experiment Basics: Muons in a storage ring

1. Start with polarized muon beam (from pion decay)



Experiment Basics: Muons in a storage ring

1. Start with polarized muon beam (from pion decay)

2. Cyclotron frequency :

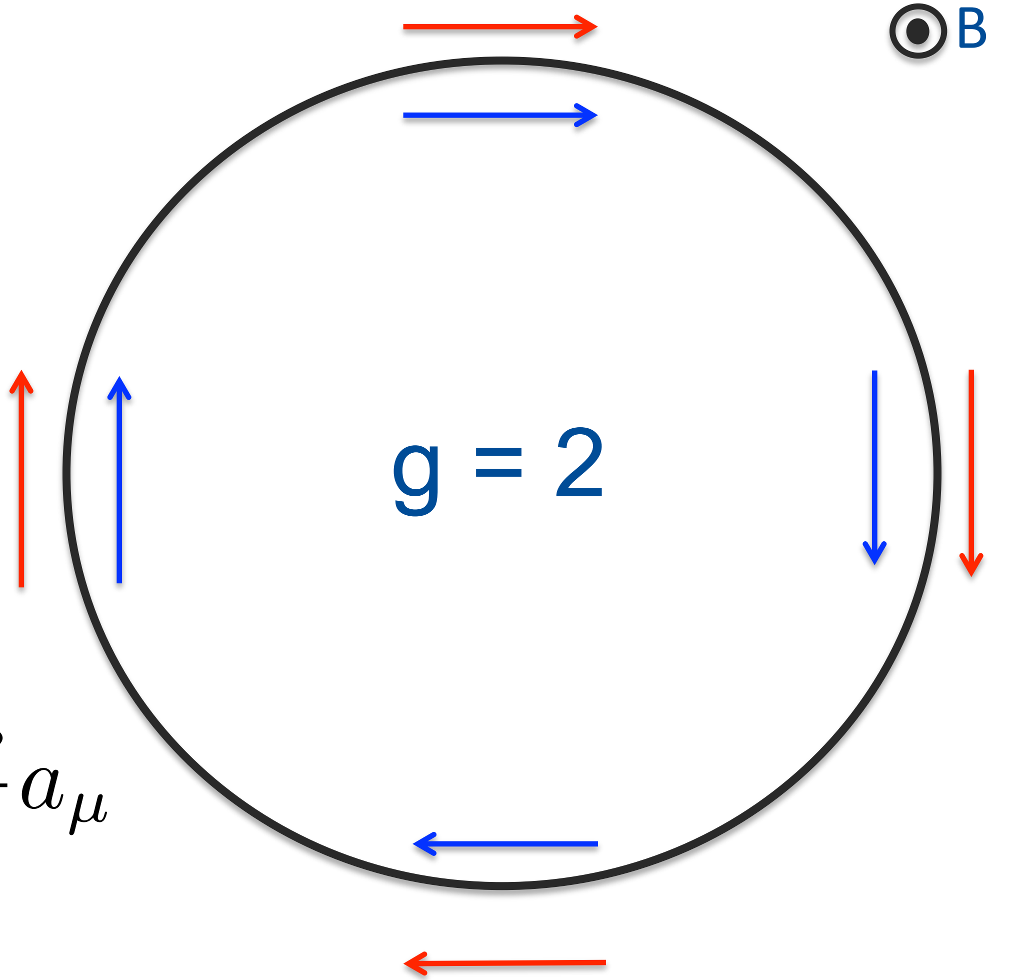
$$\omega_c = \frac{e}{m\gamma} B$$

3. Spin precession frequency :

$$\omega_S = \frac{e}{m\gamma} B \left(1 + \gamma a_\mu\right)$$

Larmor + Thomas precession

$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$



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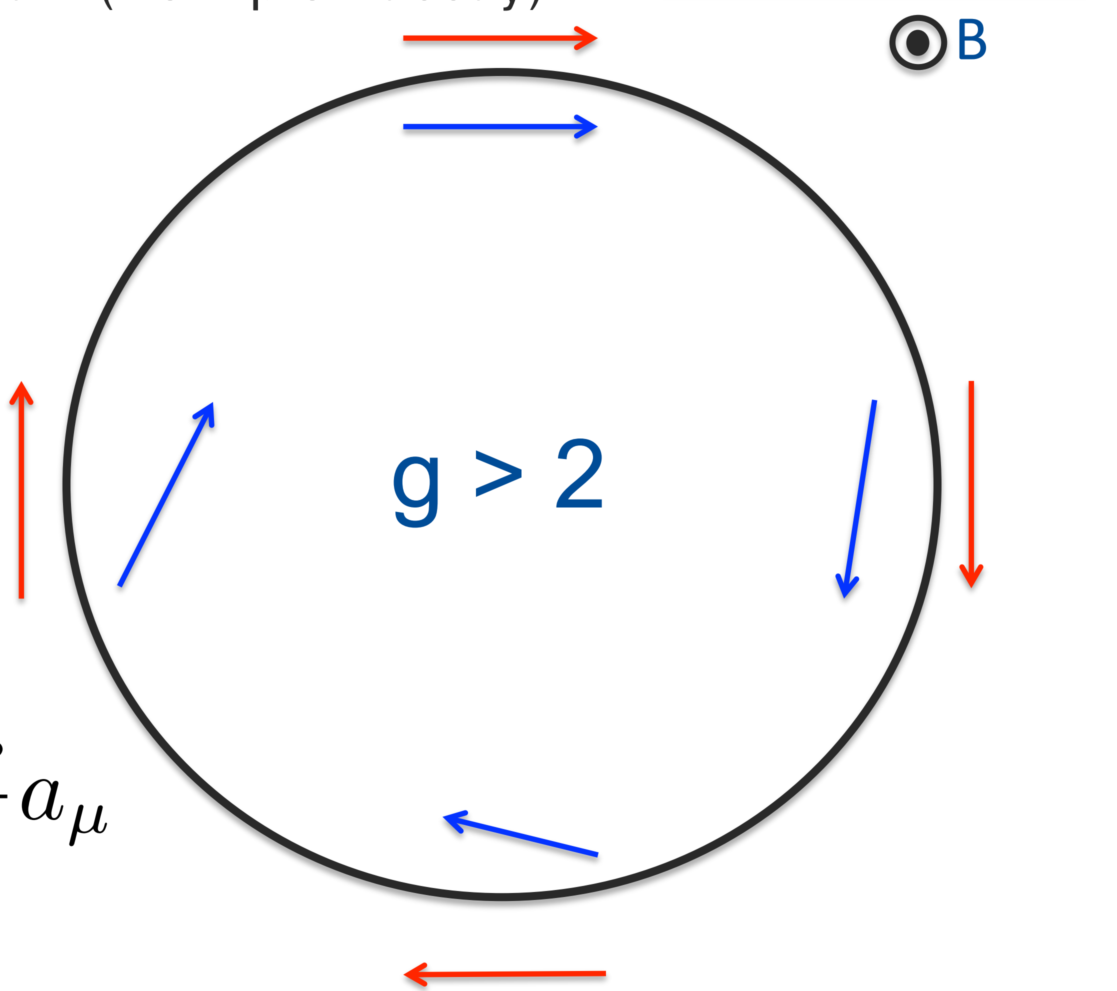
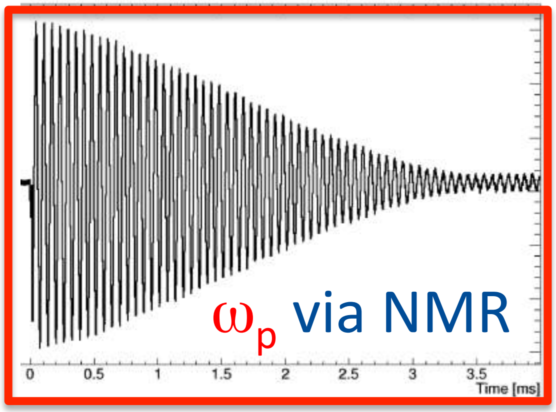


Muon g-2 Measurements

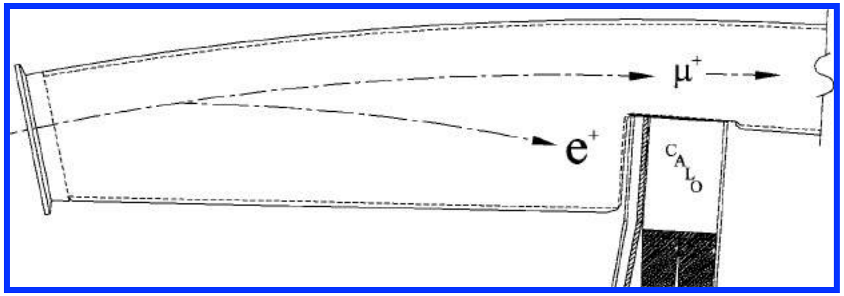
$$\omega_a = \frac{eB}{m} a_\mu$$

Measure B → via NMR → recast a_μ in terms of proton precession frequency, ω_p



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

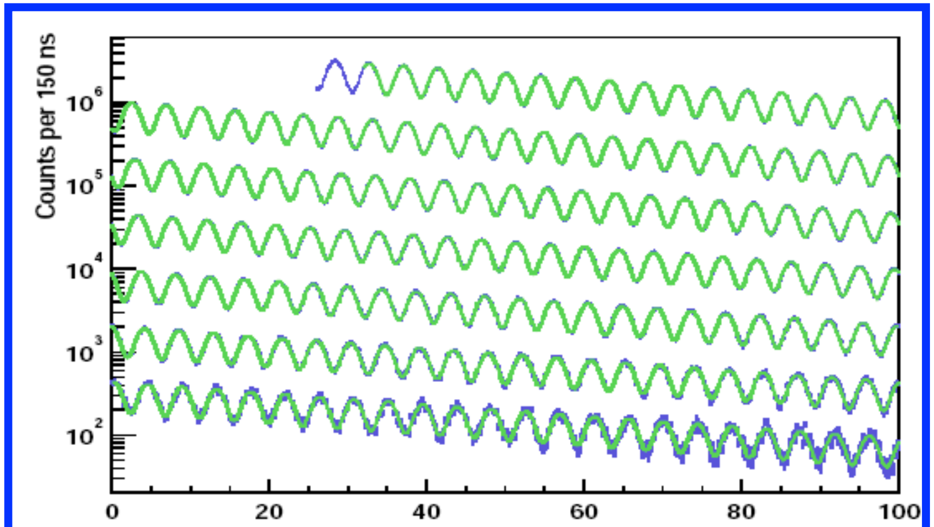
Muon spin precession frequency



E821 data: e^+ with E > 1.8 GeV

$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$

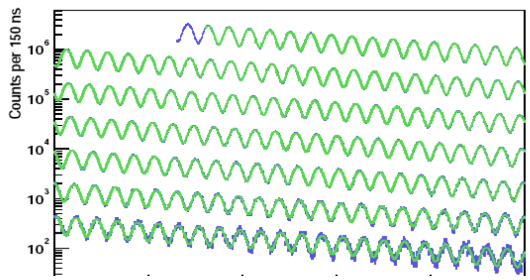
- Decay self-analyzing:
  - Higher energy positrons emitted preferentially in direction of muon spin



$$N(t) = N_0 e^{-t/\tau} (1 + A cos(\omega_a t + \phi))$$

- Spectrum distortions from
  - Pileup, gain stability
  - Beam Effects, Losses

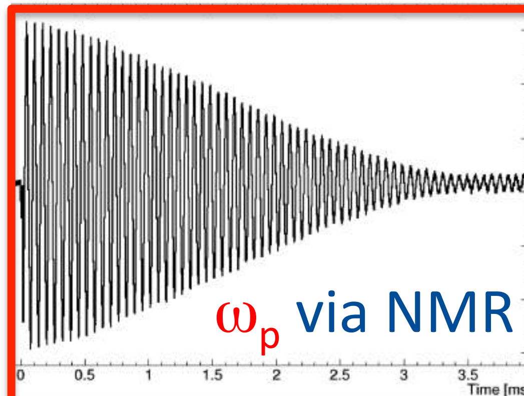
Muon g-2 Measurements



ω_a via positrons

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

Measure B → via NMR → recast a_μ in terms of proton precession frequency, ω_p



ω_p via NMR

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

EXPERIMENTAL PROGRESS AND DETAILS

E989 Collaboration: 35 Institutes; 155 Members

Domestic Universities

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

England

University College London

Liverpool

Oxford

Korea

KAIST

The Experimental Approach

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Total Theory	420	310
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Total Exp.	540	**140**
Stat	460	100
ω_a	180	70
ω_p	170	70

- Previous effort statistically limited → x21 more muons
  - ❖ Facility Upgrades
  - ❖ Improved Muon Storage

Muon Beam Preparation for 21x BNL statistics

- Efficiency
  - Improved pion collection
  - Long decay channel to produce muons
- Delivery Ring to get rid of protons
  - Eliminate background early
  - Start fits earlier
- Fermilab structure
  - 12 Hz rep rate (3 batches)
- ~10,000 muons per pulse successfully injected
- Run Time: 18-24 months

Preparing Existing Tunnels, Building new ones,

Modest improvements to the muon precession systematics

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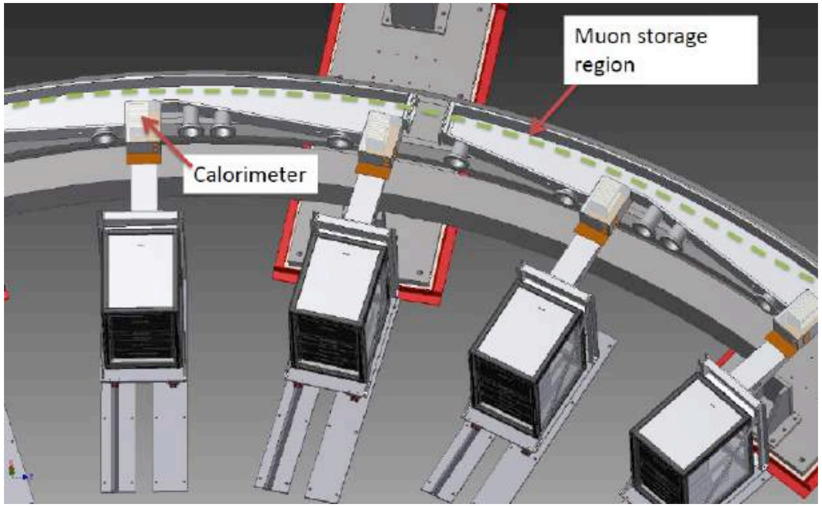
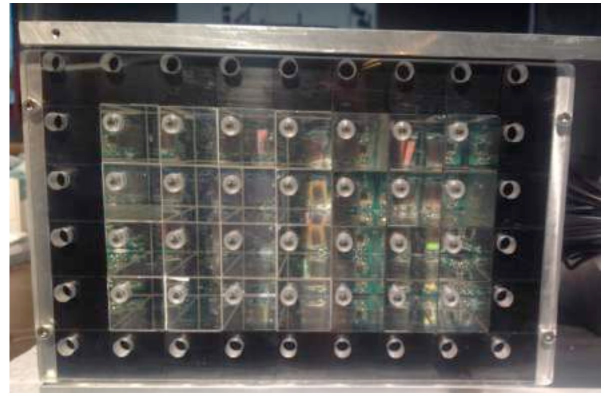
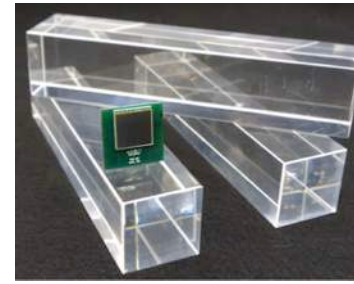
- Calorimeter
  - Resolve multiple particles
  - Gain stability – Italian group
- Tracker
  - Improved positron tracking
  - Informs muon beam dynamics

Muon precession

ω_a Instrumentation Upgrades

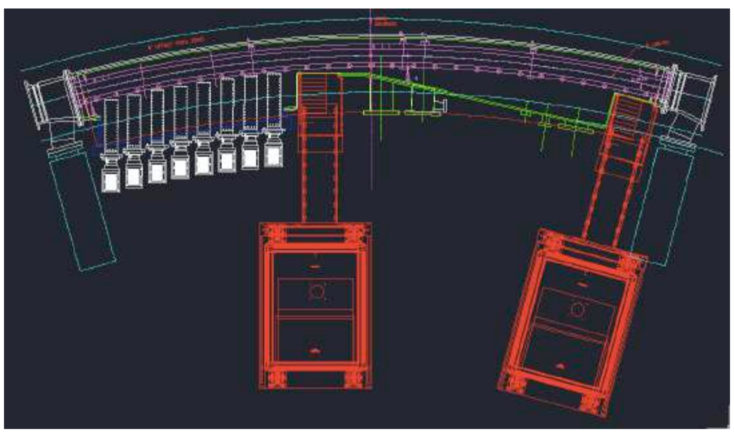




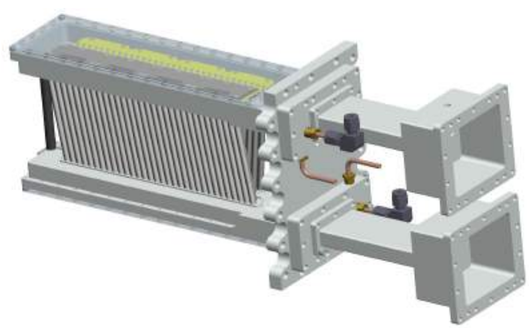


Segmented compact PbF2 Cherenkov

~3 cm and ns spatial/temporal separation



Thin straws



Precision positron tracking

Modest improvements to the proton precession systematics

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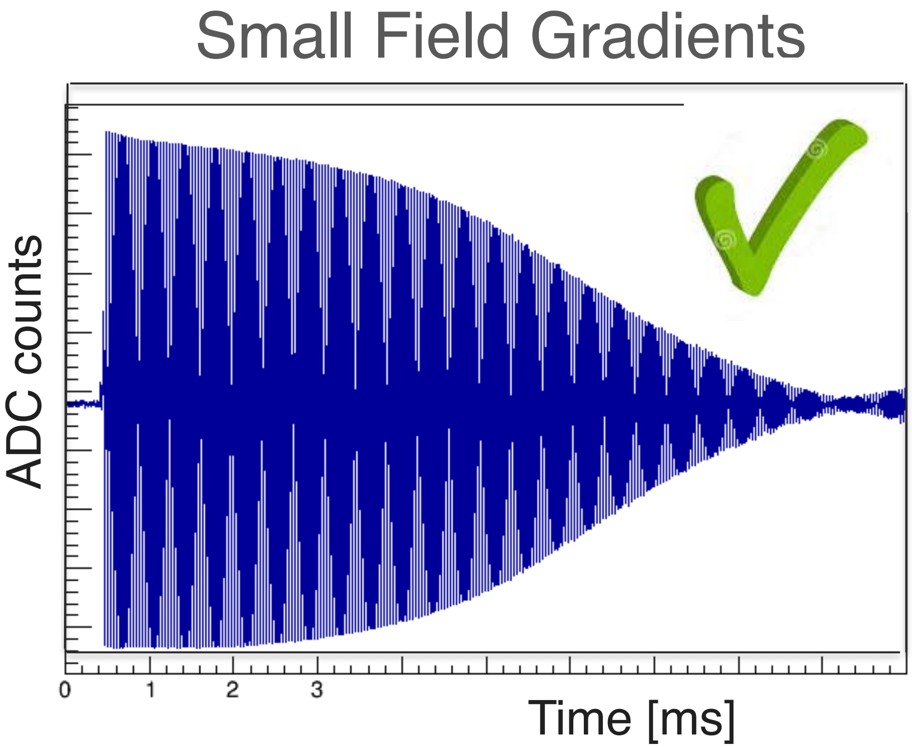
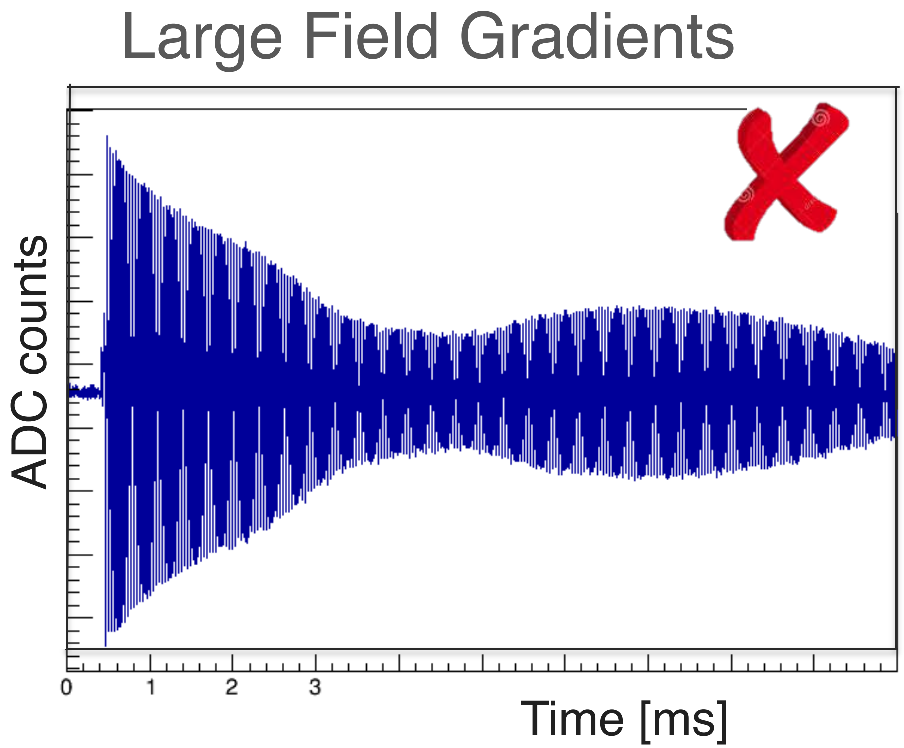
- New set of NMR probes
- Generate a more uniform field

Proton precession

Signal Shape informs us about gradients

- Improved NMR techniques
- Improved Shimming of magnets

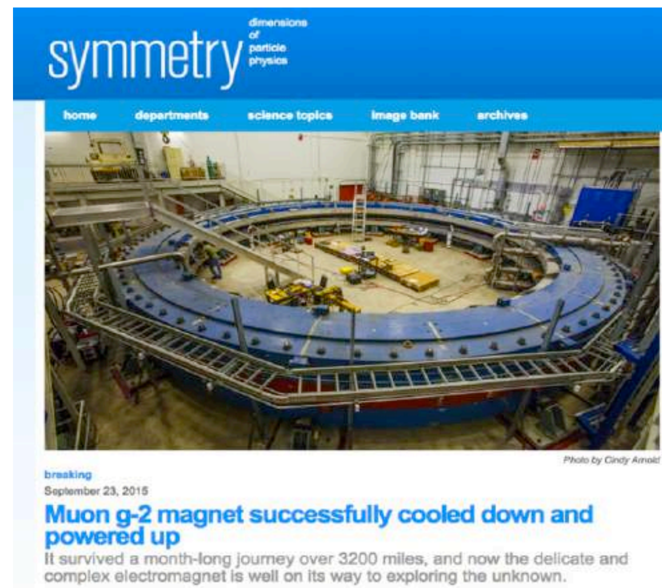




Signal degrades more quickly in high gradients

Summary

- Significant Theory Efforts
  - e^+e^- measurements improving HVP uncertainty
  - Significant Progress on the Lattice
- Fermilab experiment is cold and powered
  - Magnetic field measurements 2015
  - Systematic shimming through Spring
  - Installation in 2nd half of 2016
  - Muons in 2017
- These are exciting times!



Thank You!