XXXIX International Conference on High Energy Physics – ICHEP2018

Recent Progress with Muon g-2 Experiment at Fermilab

Liang Li
Shanghai Jiao Tong University
On Behalf of Muon g-2 Collaboration

Muon g-2 Collaboration

7 Countries 34 Institutes
185 Members

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- North Central College
- Regis
- UT, Austin
- Virginia
- Washington

US National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- Frascati
- Molise
- Naples
- Pisa
- Rome 2
- Trieste
- Udine

China

- Shanghai

Germany

- Dresden

England

- Lancaster
- Liverpool
- University College London

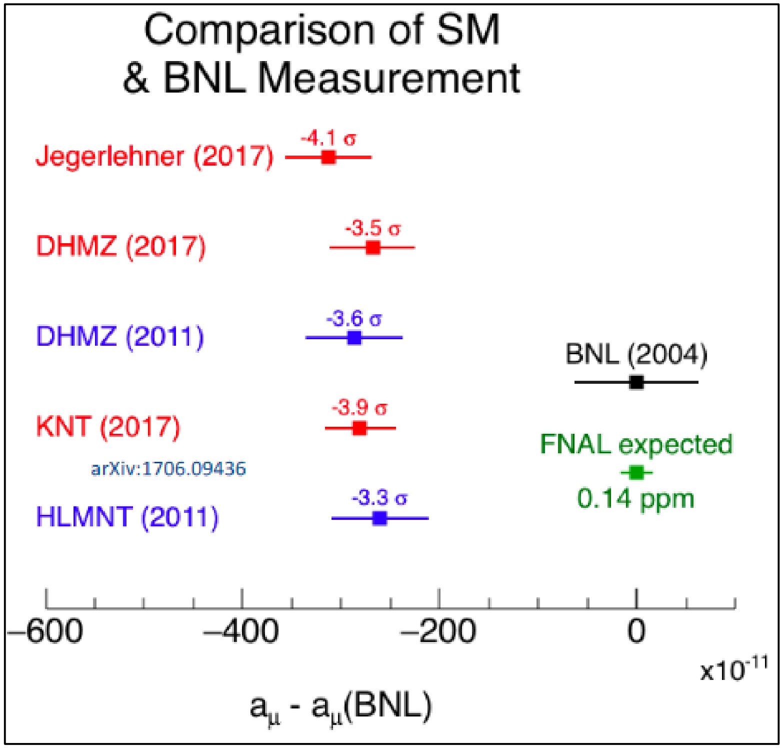
Korea

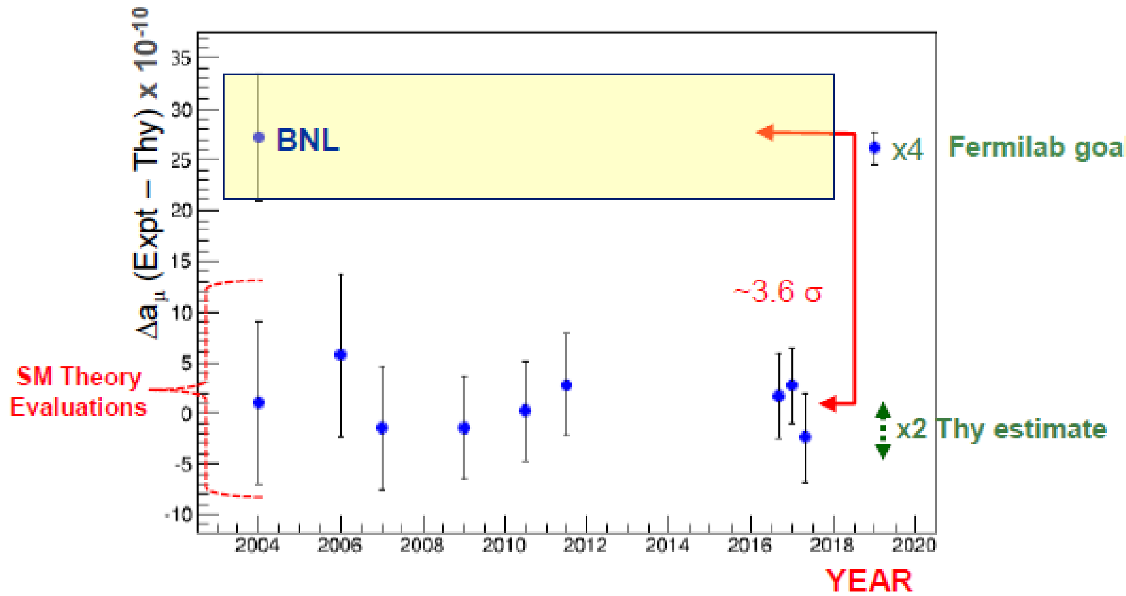
- CAPP/IBS
- KAIST

Russia:

- JINR/Dubna
- Novosibirsk

Today's Status about Muon g-2





D. Hertzog's projection map

3.3 σ – 4.1 σ difference depending on theory calculation

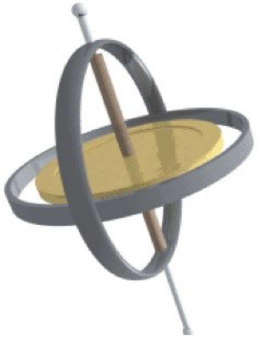
- **If the discrepancy sustains, strong indication of new physics!**
- **Even if not, Δa_μ tightly constraints new physics model**
- **Significant implications to interpret any BSM phenomena**

Pedagogical: What is (muon) g-2?

Spin, magnetic momentum, 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!

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



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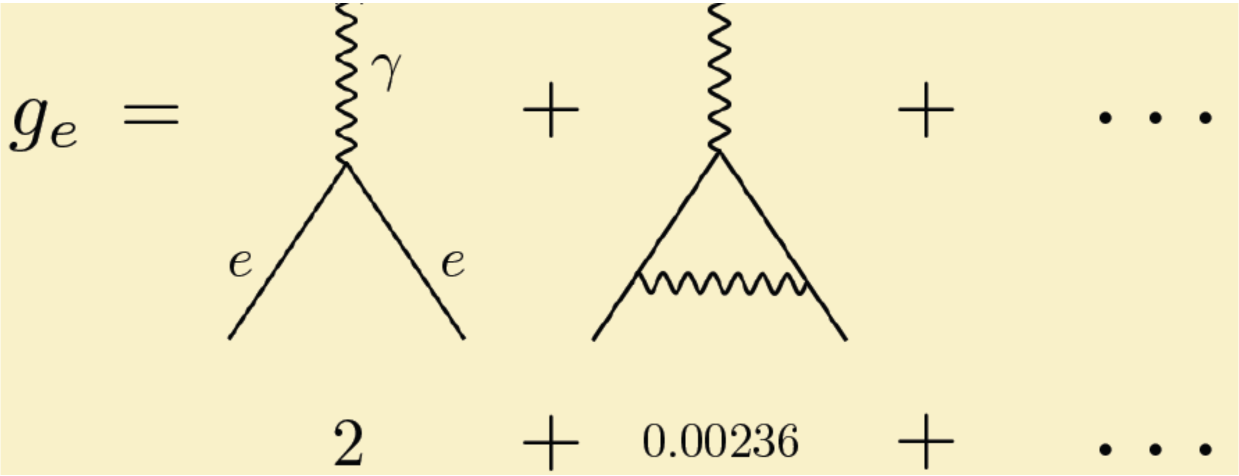

First order QED: beginning of QED and the Standard Model

From ‘beginning’ to ‘beyond’ of Standard Model

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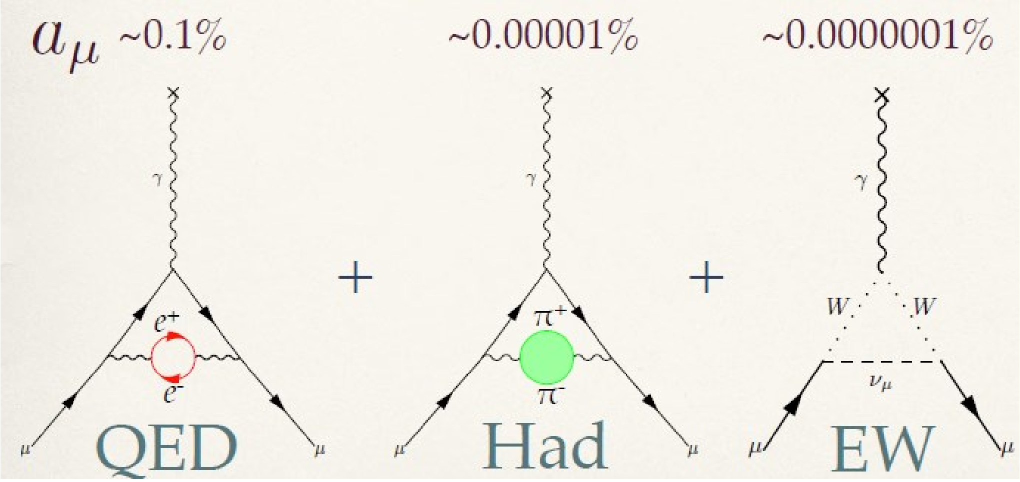

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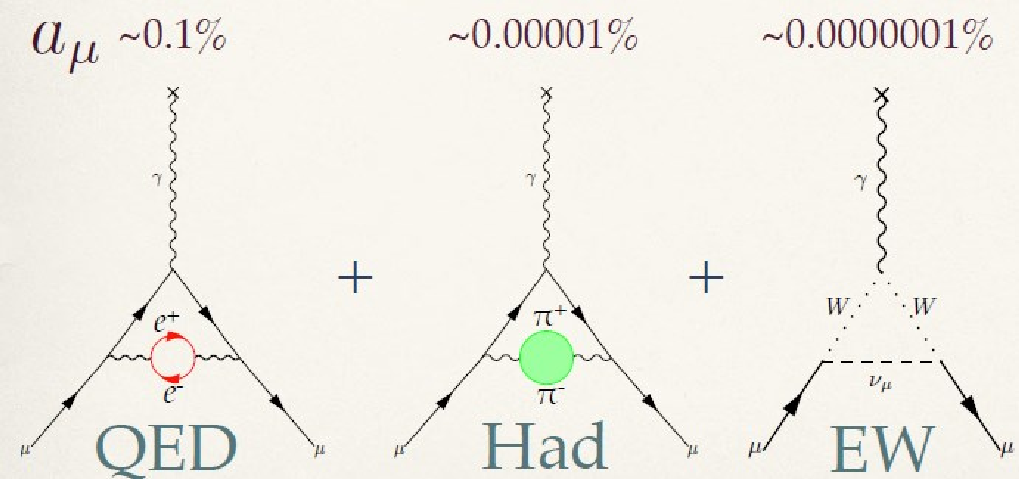

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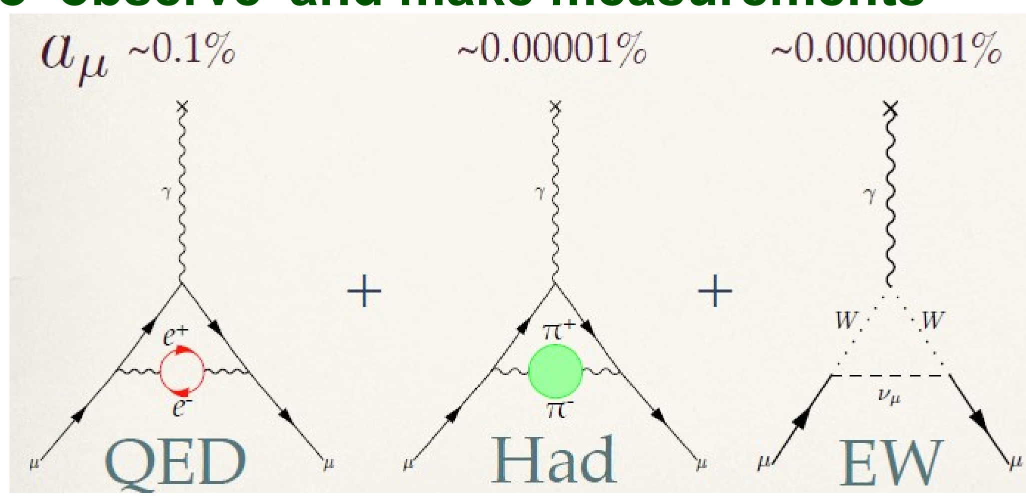
- **Muon is special**
  - **m_u/m_e ~ 200, sensitivity ~ 200^2 ~ 10^4 (effects on muons are much easier to be observed than electrons)**
  - **Easy to make ample production, life time (2.2μs) long enough to ‘observe’ and make measurements**



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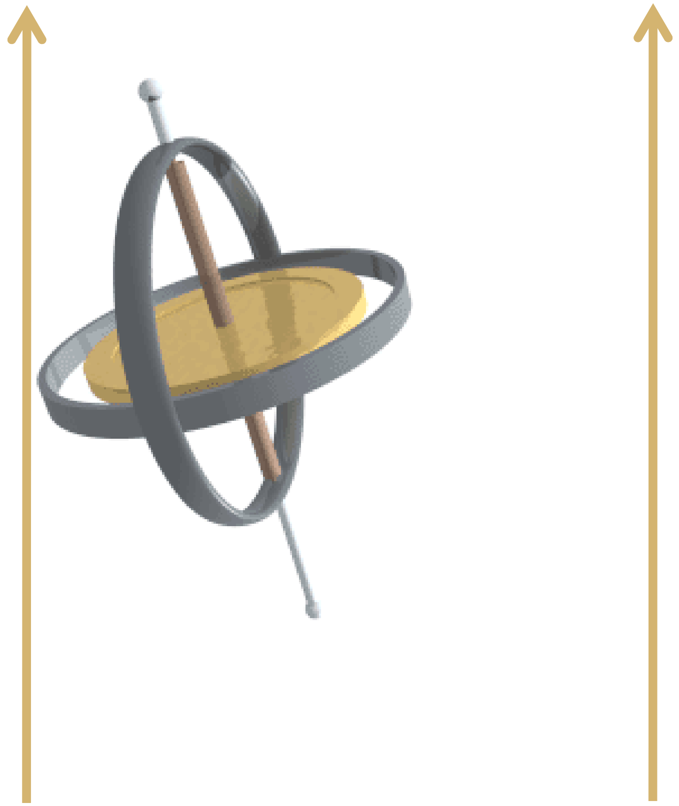

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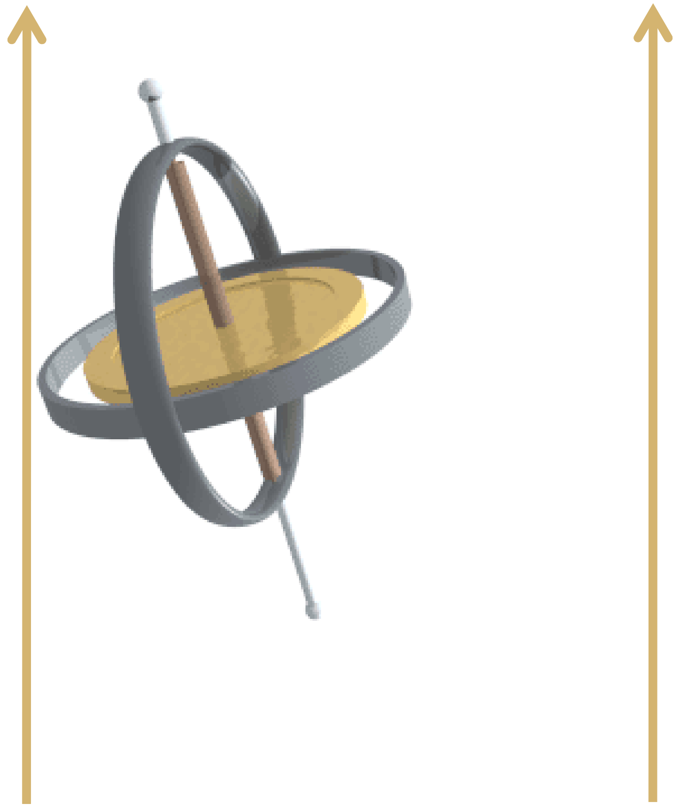

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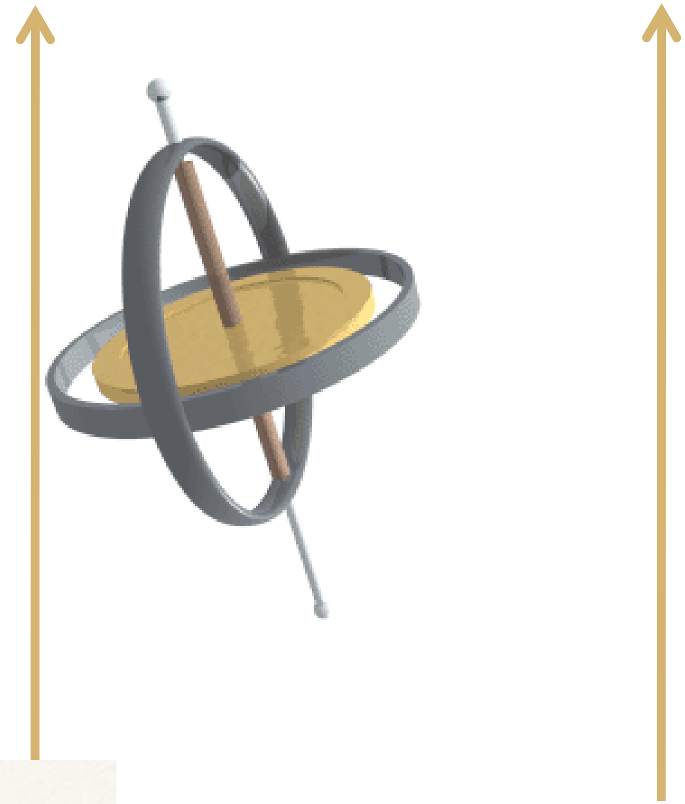

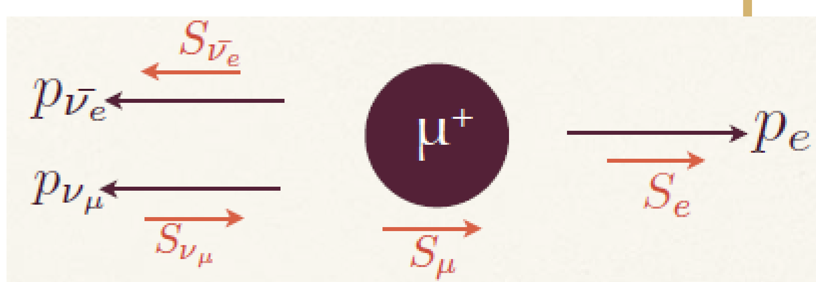

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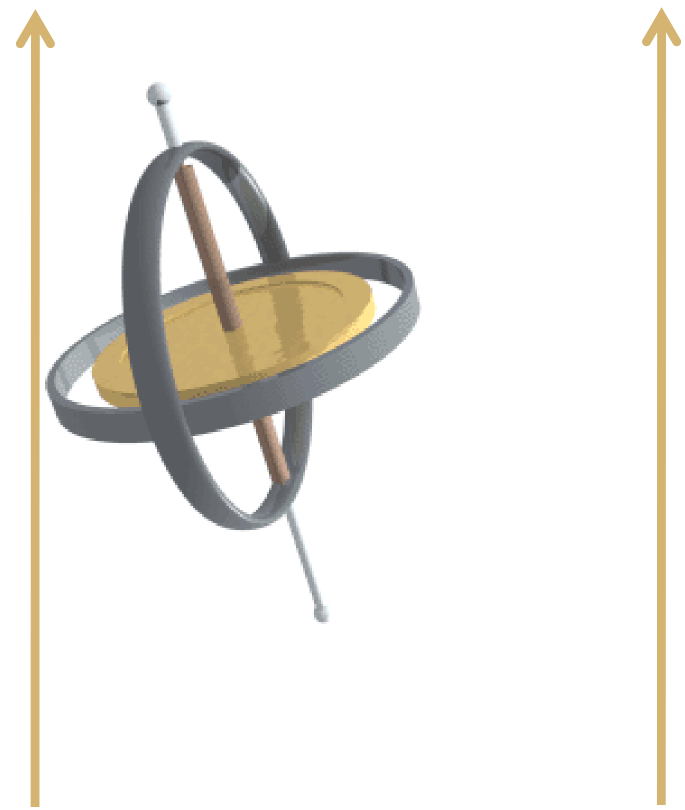

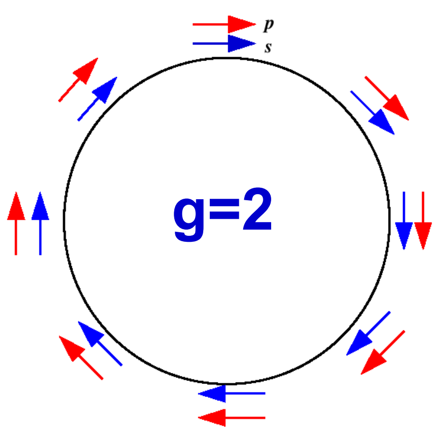

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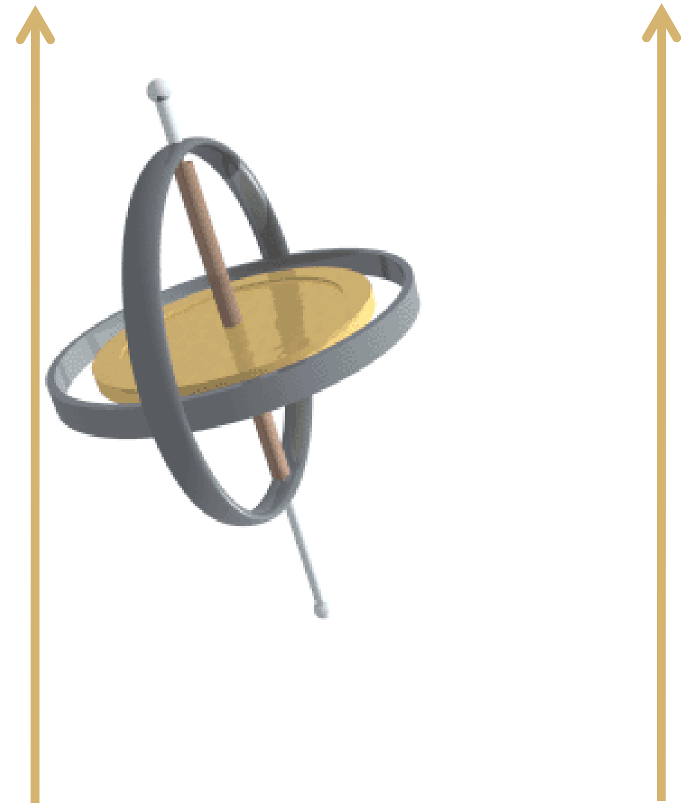
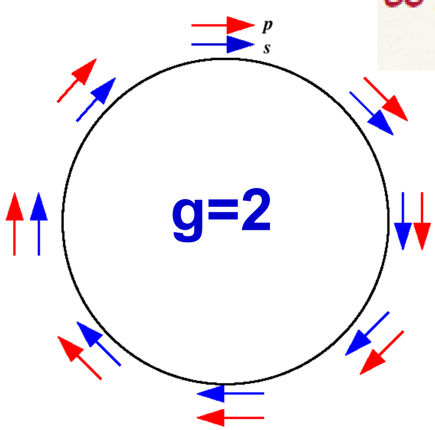


$$\omega_a = \omega_s - \omega_c$$

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



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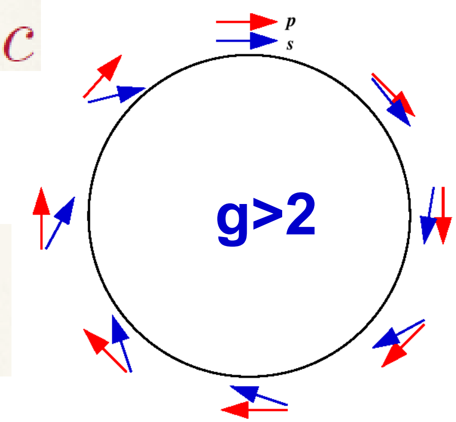

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Frequency Measurements

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- **Measure frequency ratio and extract from several measurements**

$$a_\mu \sim \frac{\omega_a}{<B>} = \frac{g_e}{2} \frac{\omega_a}{\varpi_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$$

  - **ω_p is the proton precession frequency (ω_p ~ |B|)**
  - **ϖ_p is the weighted magnetic field folded with muon distribution**
  - **All other values from Committee on Data for Science and Technology (CODATA), uncertainty < 25 pb**
    - E.g. muon-to-electron mass ratio by muonium hyperfine structure experiment

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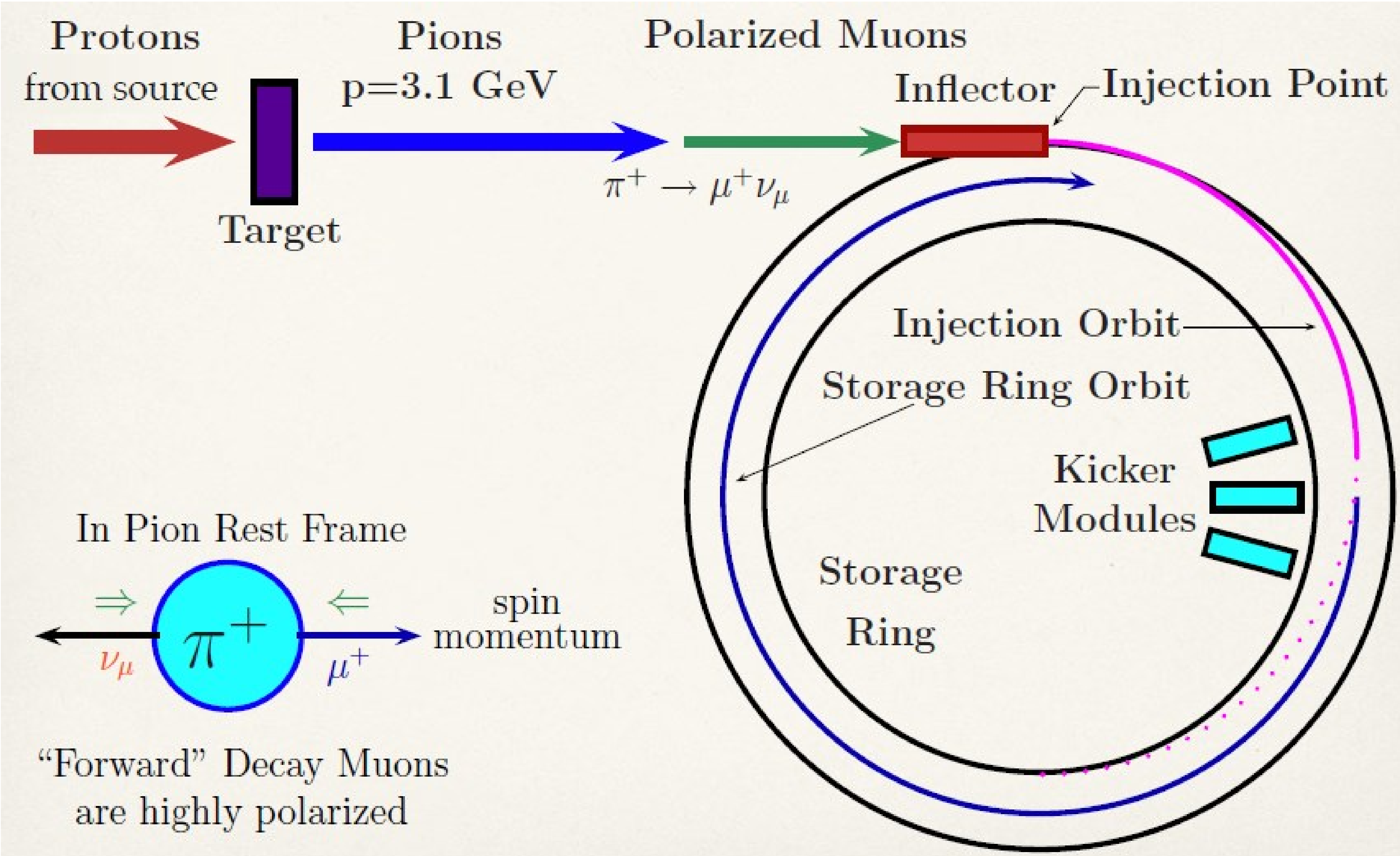
- **Final measurements done in three steps**
  - Inject muons into a ring with uniform magnetic field
  - Measure proton precession frequency ω_p
  - Measure muon frequency difference ω_a
  - The last two steps done simultaneously and independently (blind analyses)

Experiment setup



Measuring ω_p, namely the B field

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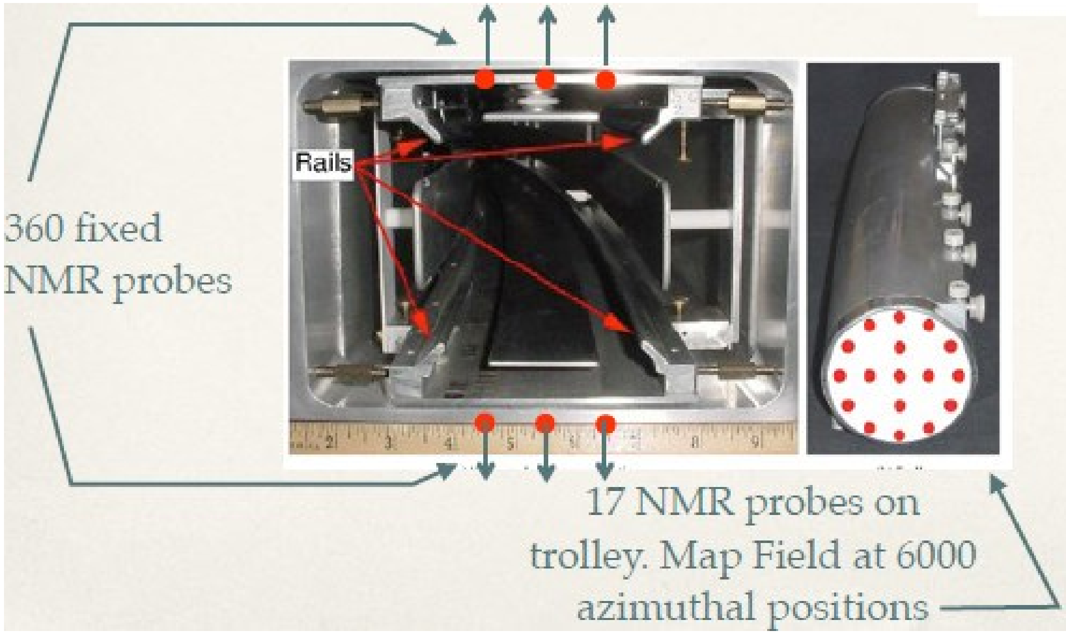

Use trolley and high precision (~10ppb) nuclear magnetic resonance (NMR) probes

- **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**
- **Shimming techniques to better produce uniform B field**

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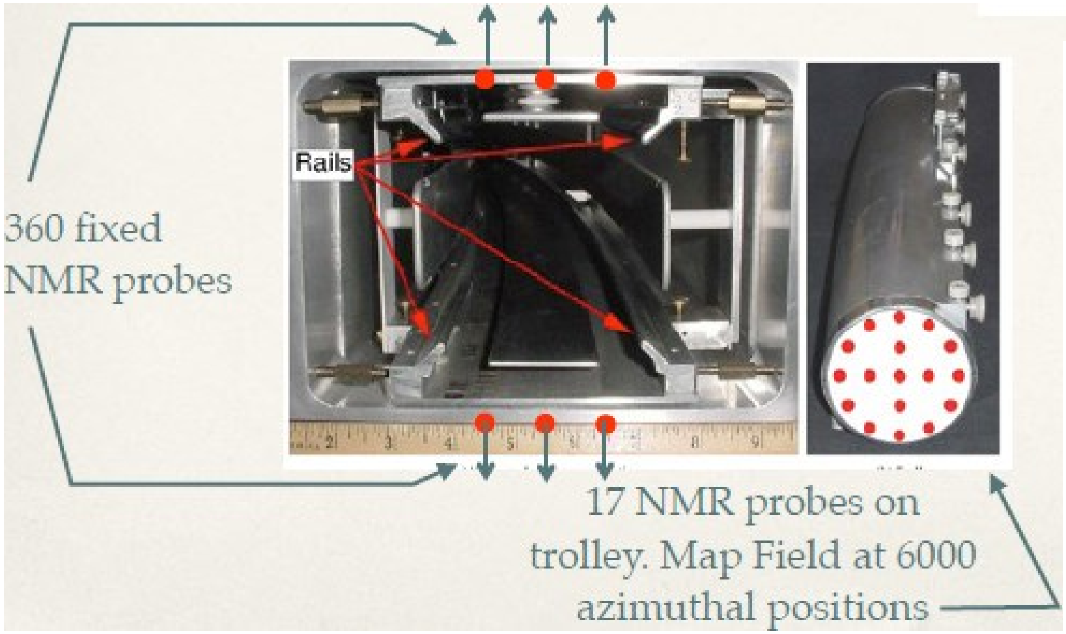

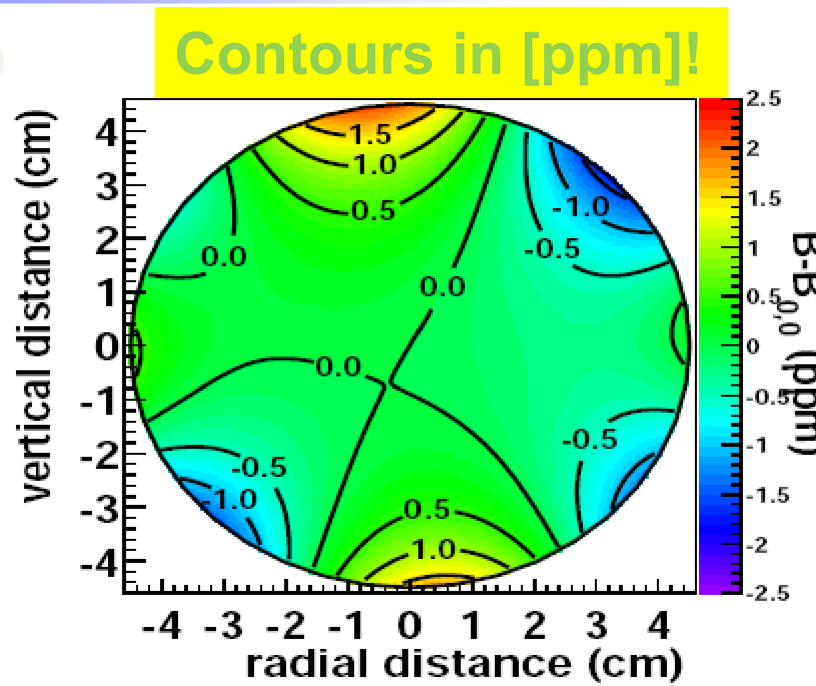

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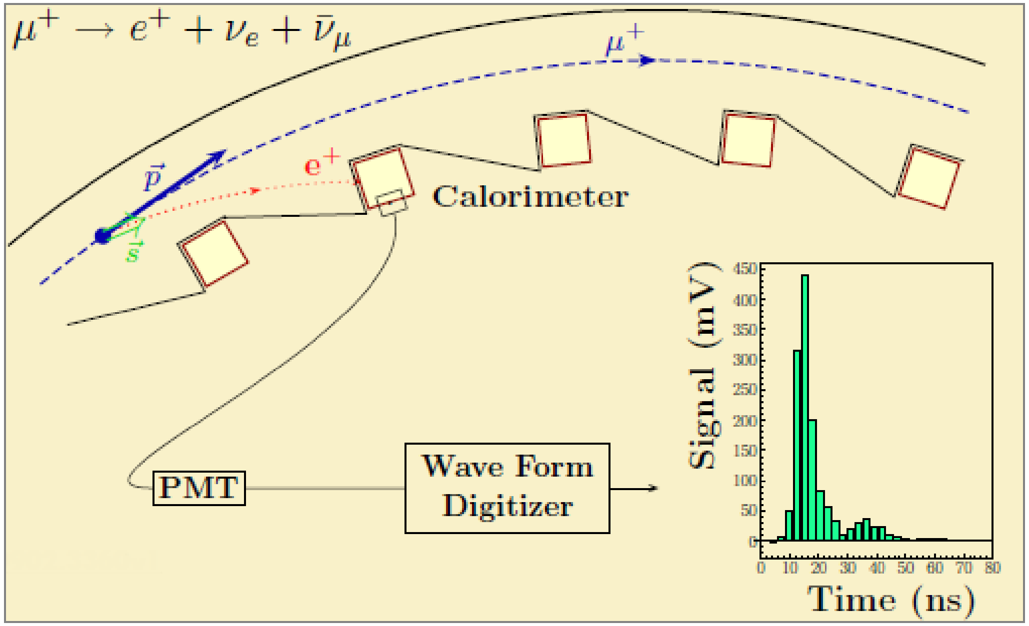

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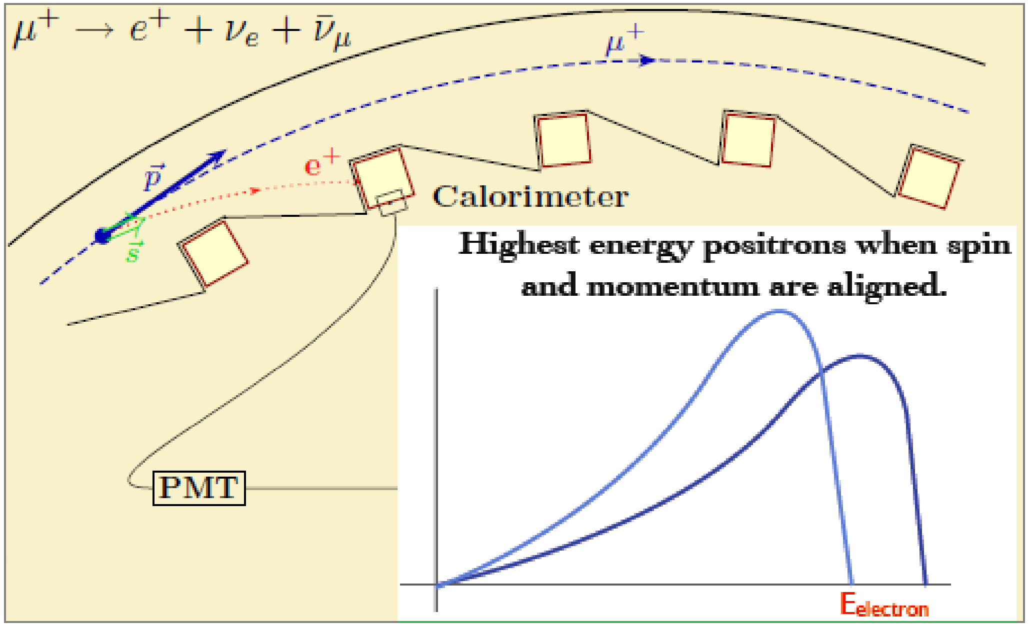

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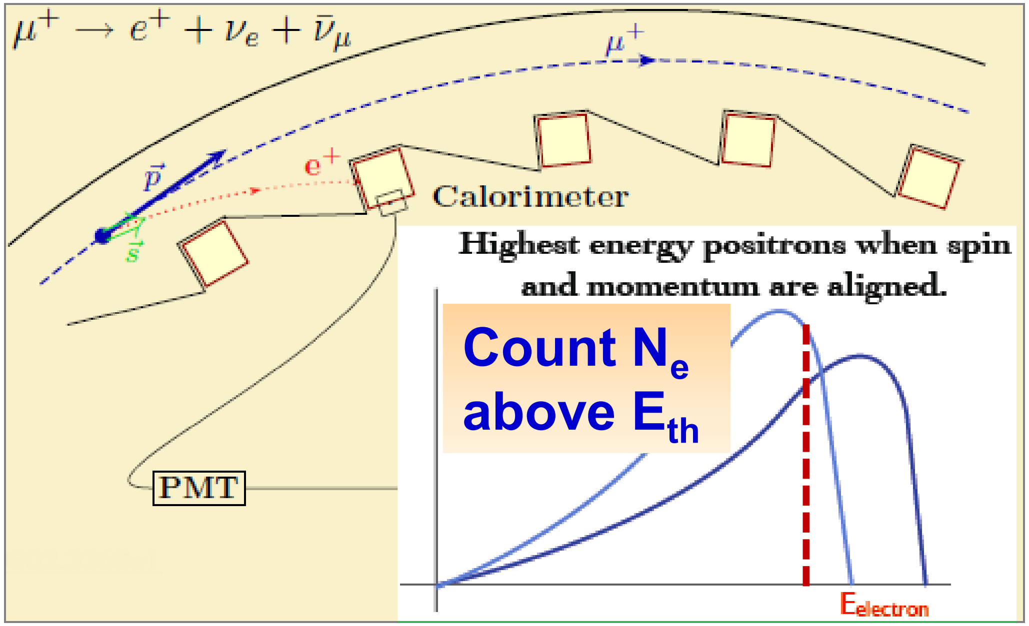

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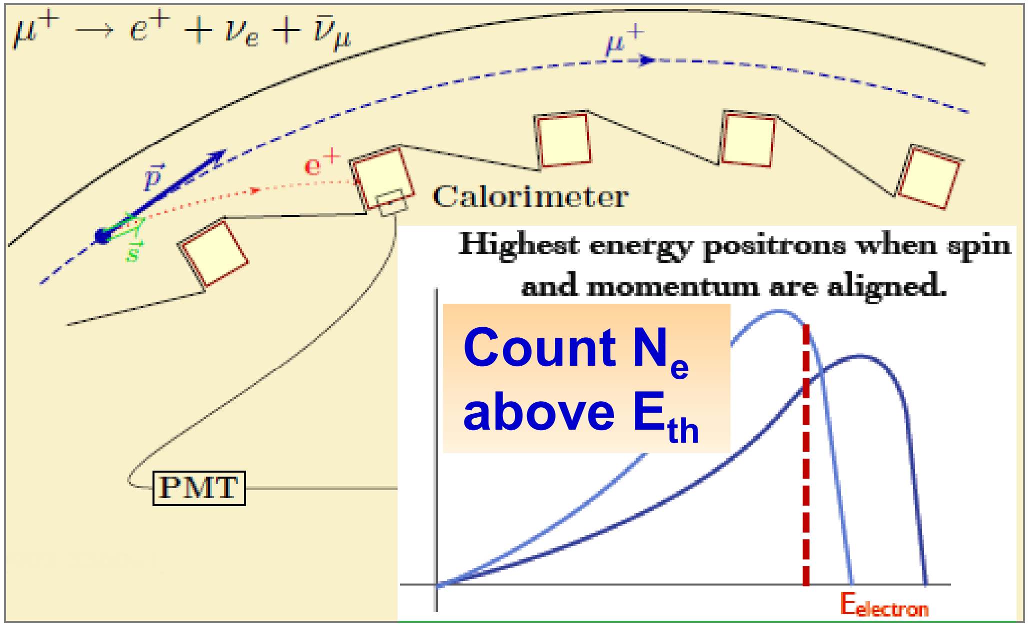

The integrated number of electrons (above E_{th}) modulated at ω_a

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

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

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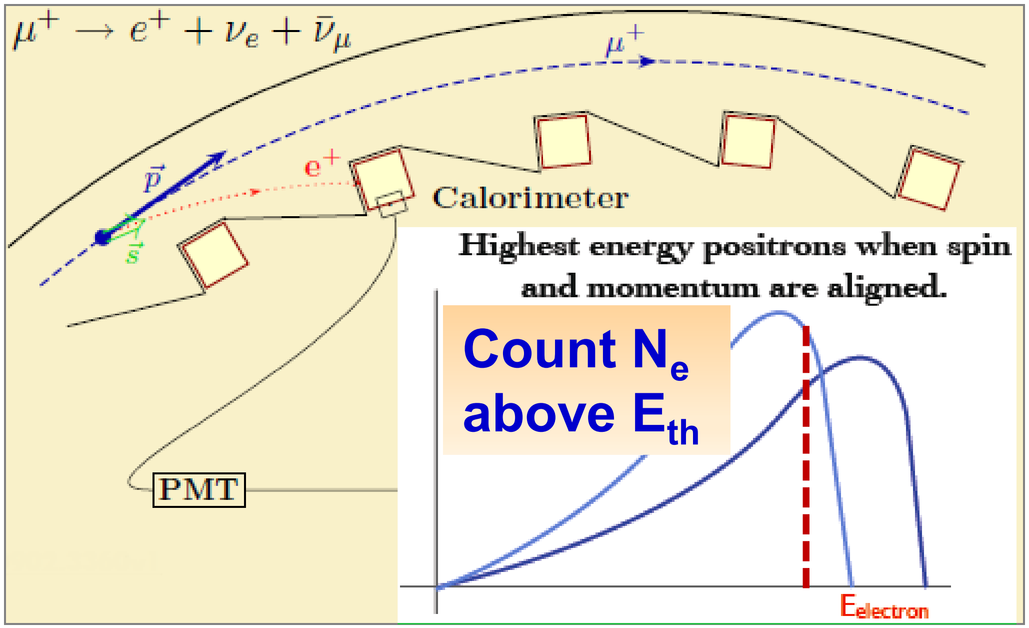

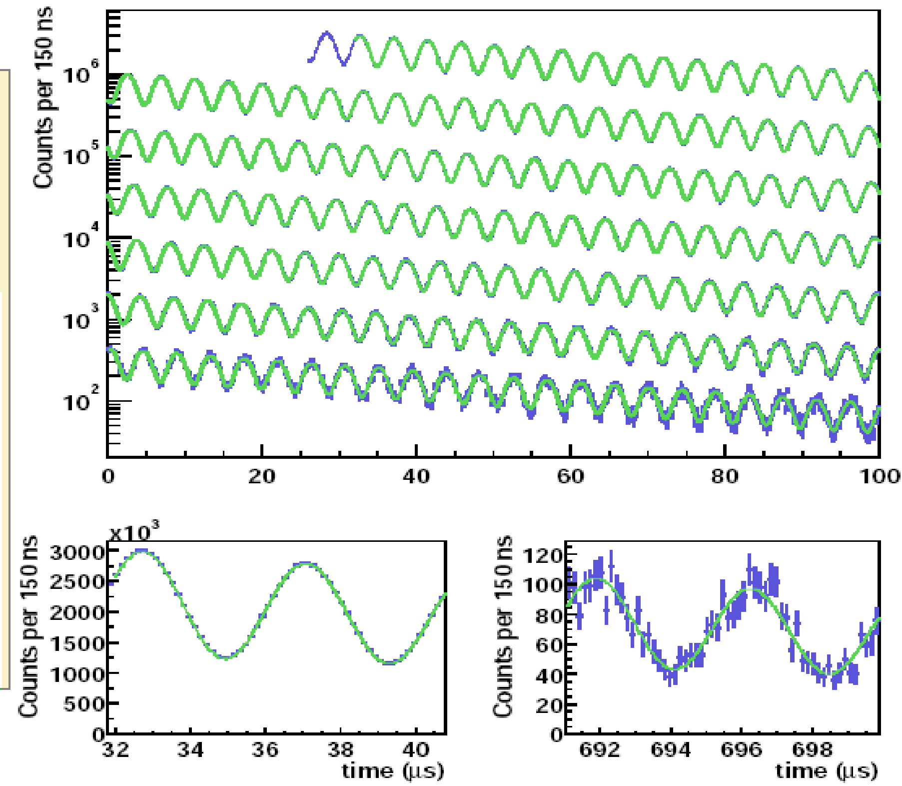

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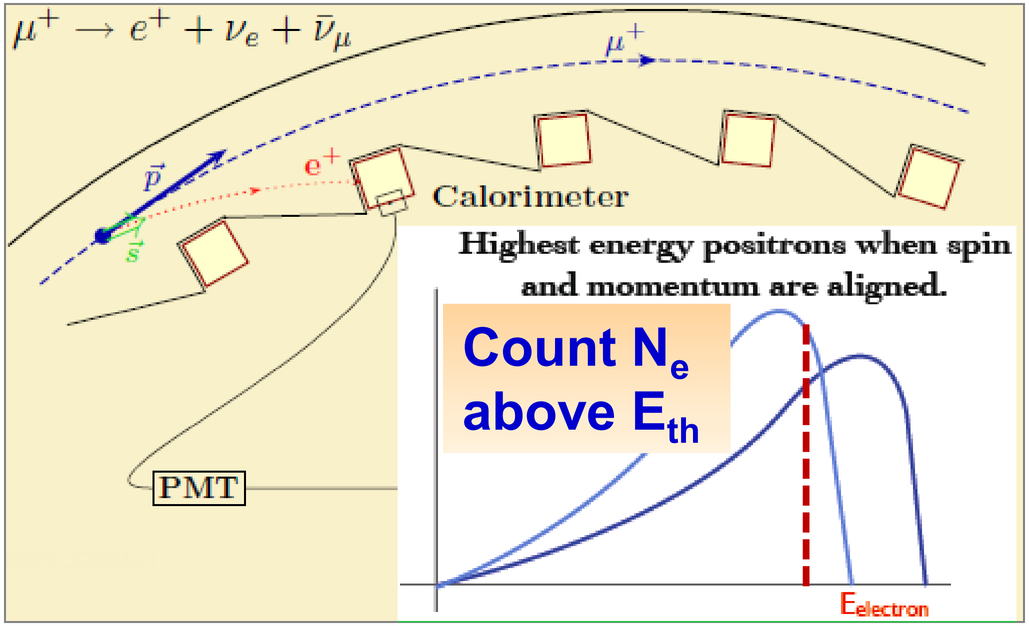

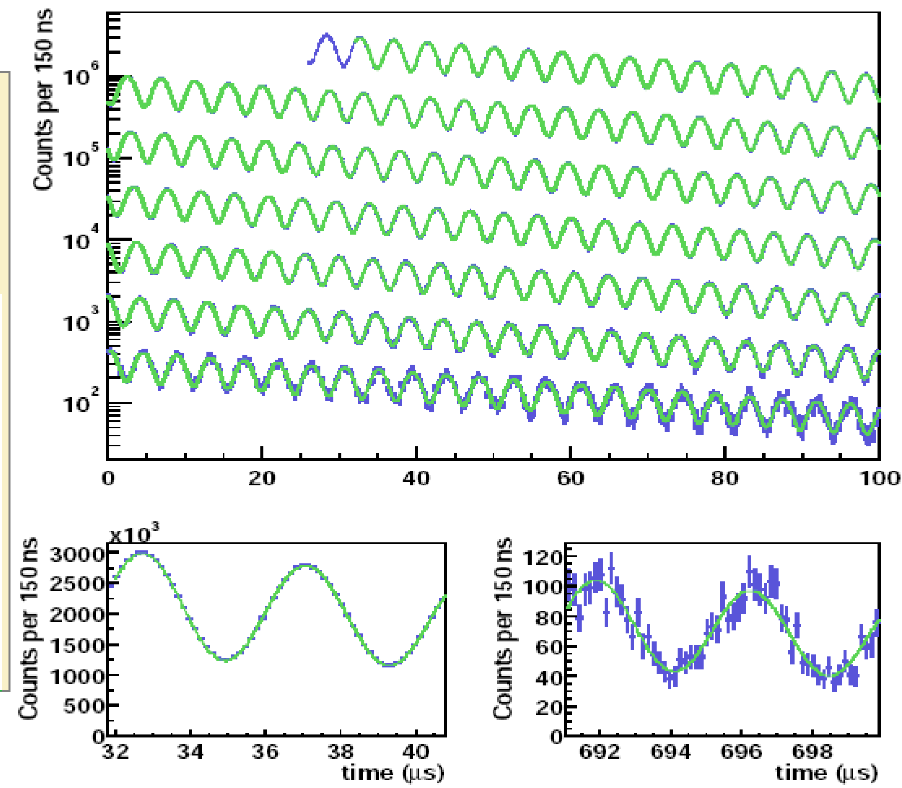

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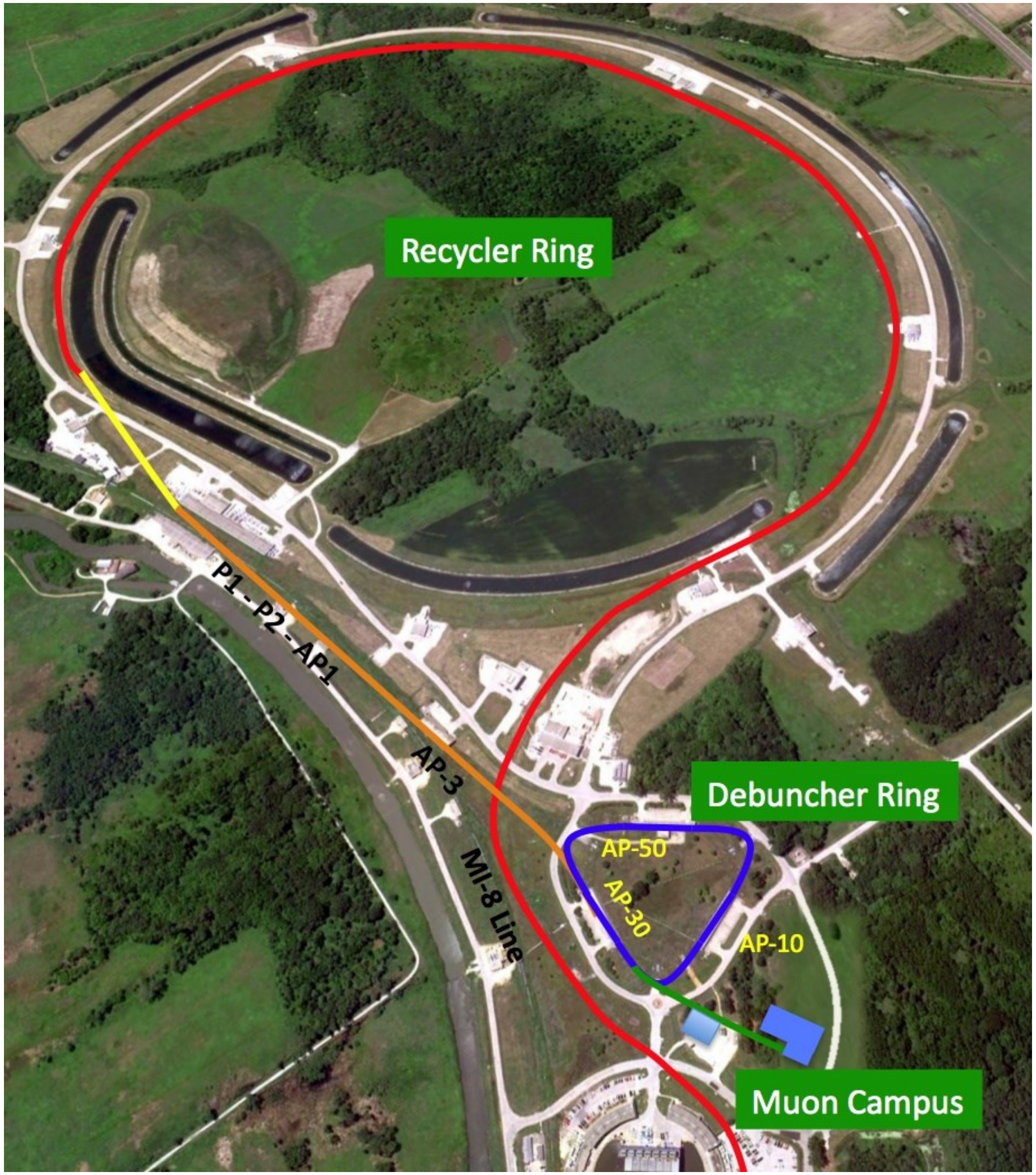
- **Pileup**
- **Gain (energy scale) changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**
- **E-field and pitch corrections**

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

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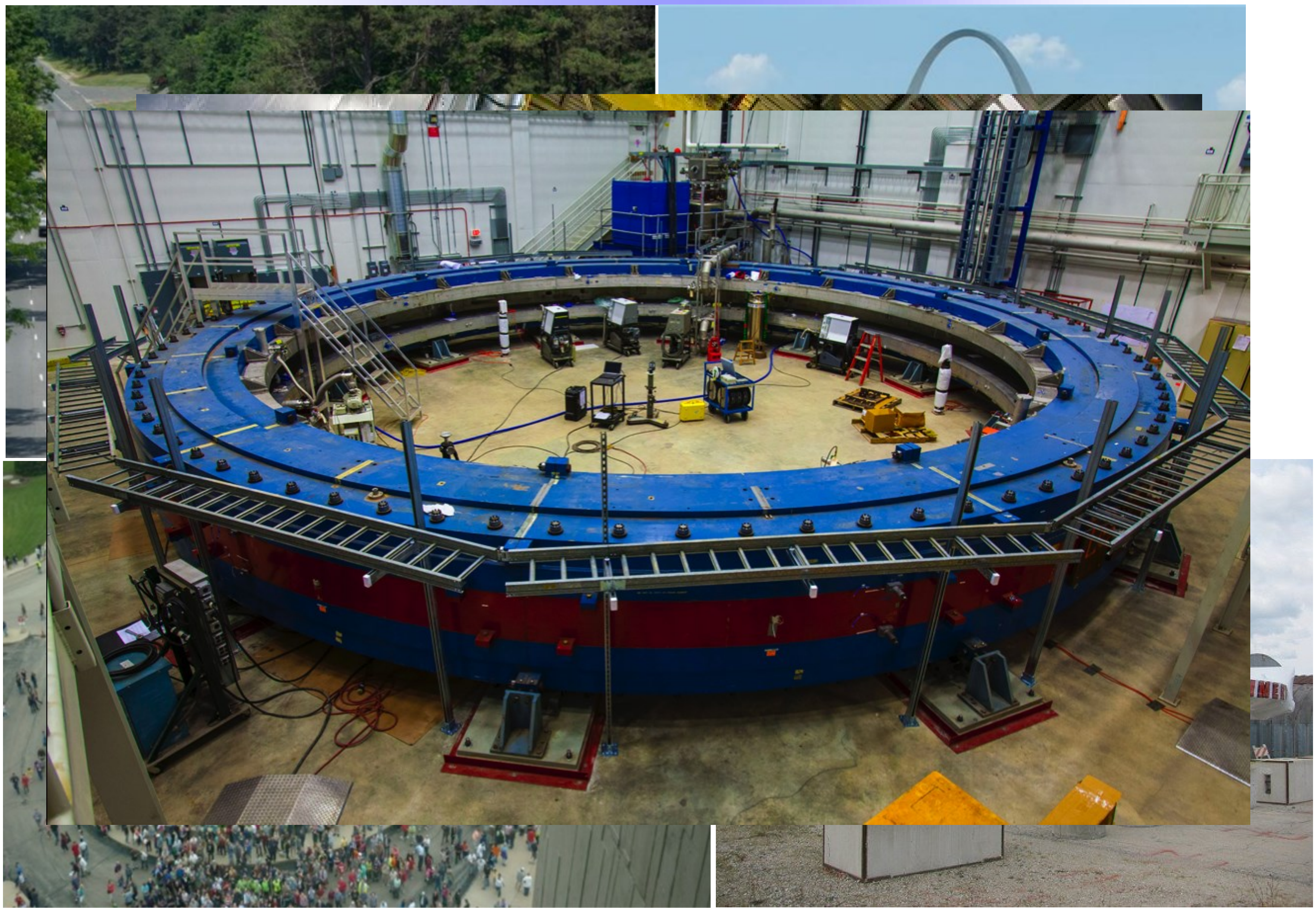

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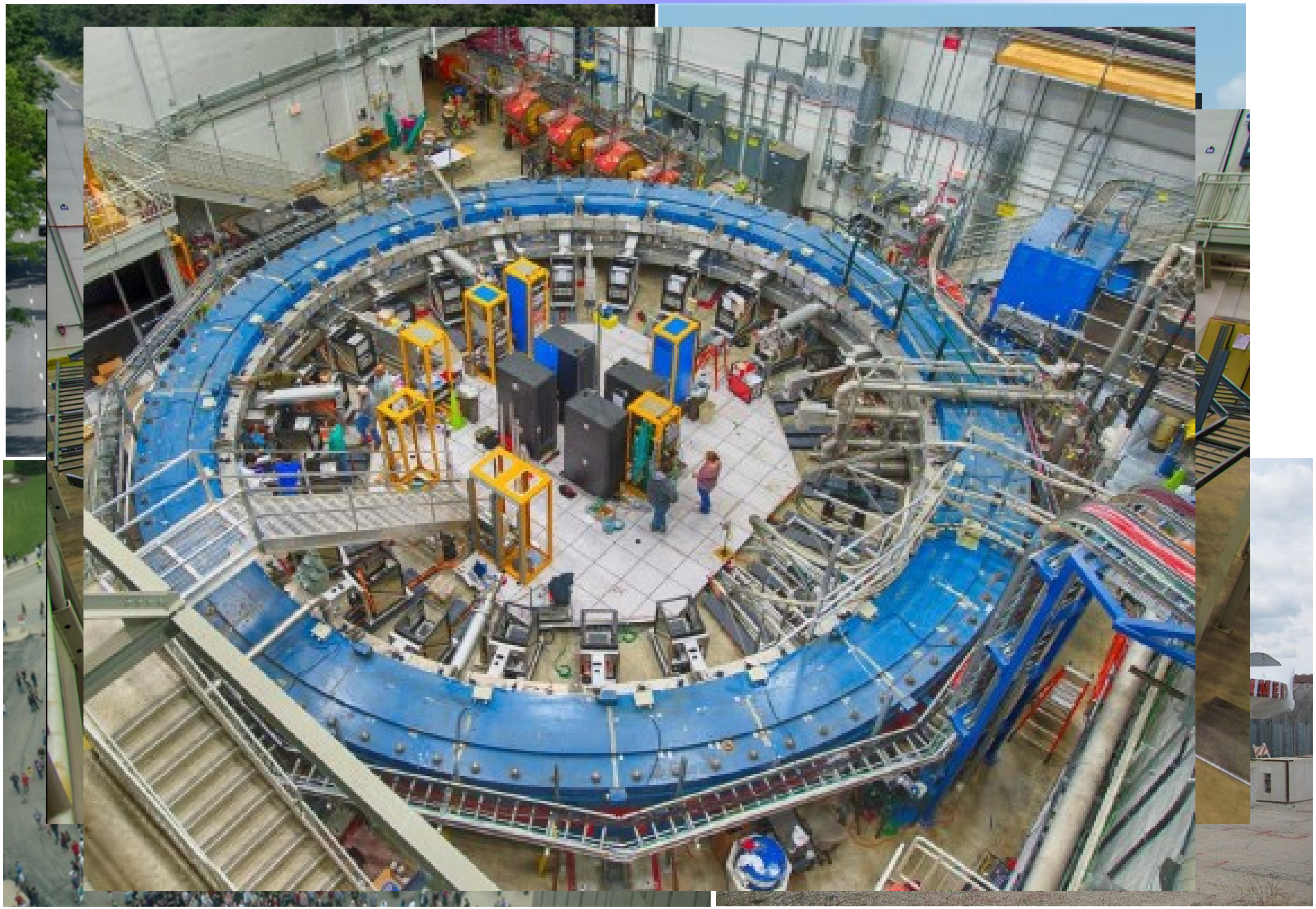

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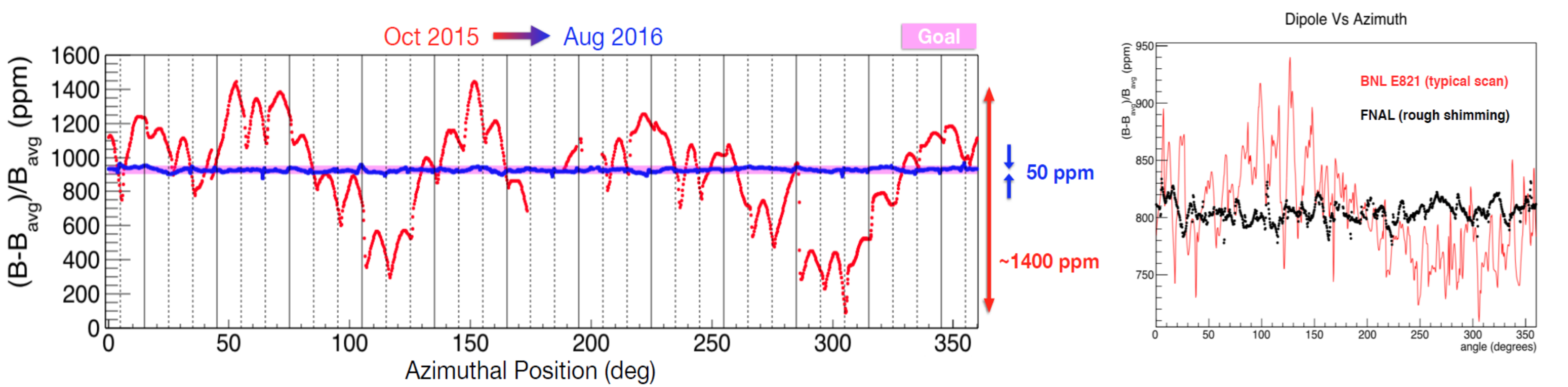

Shim 1.45 T field to high uniformity and measure it vs time

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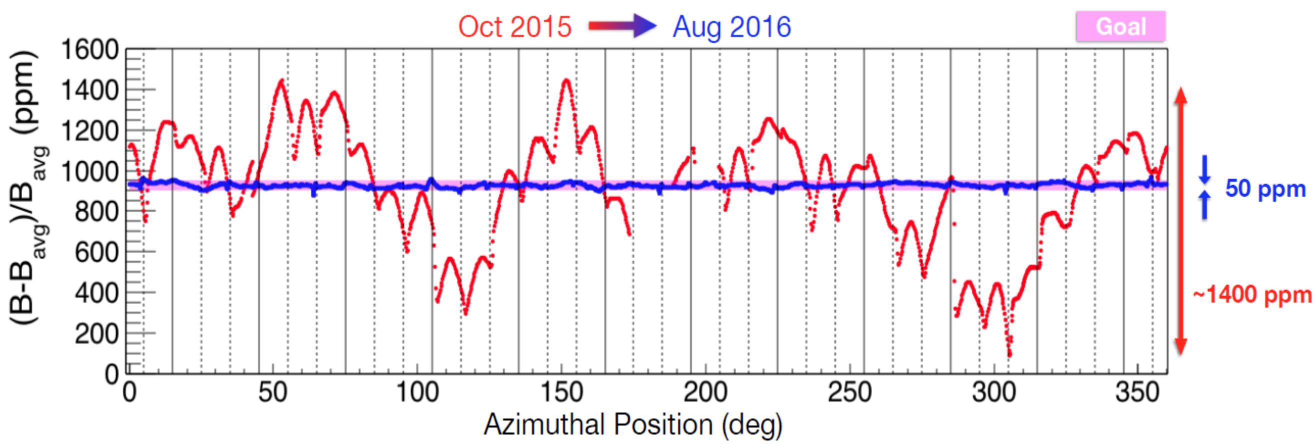

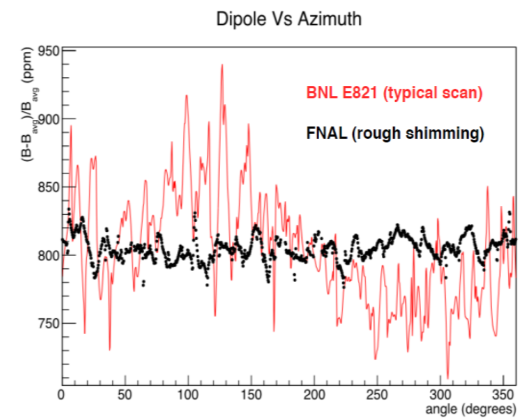

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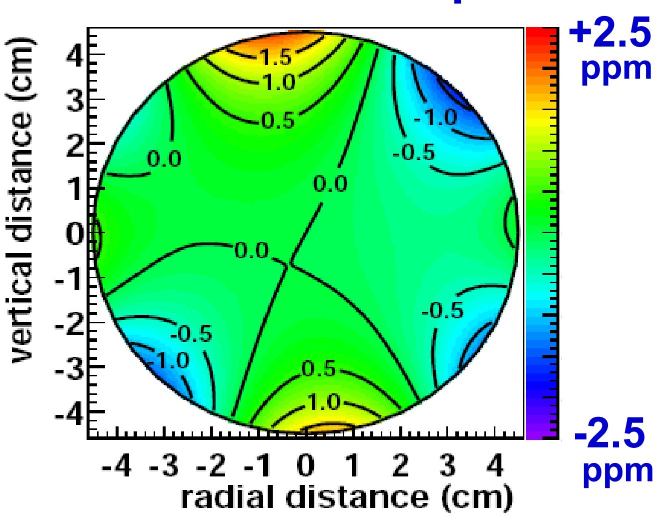
BNL Field Map



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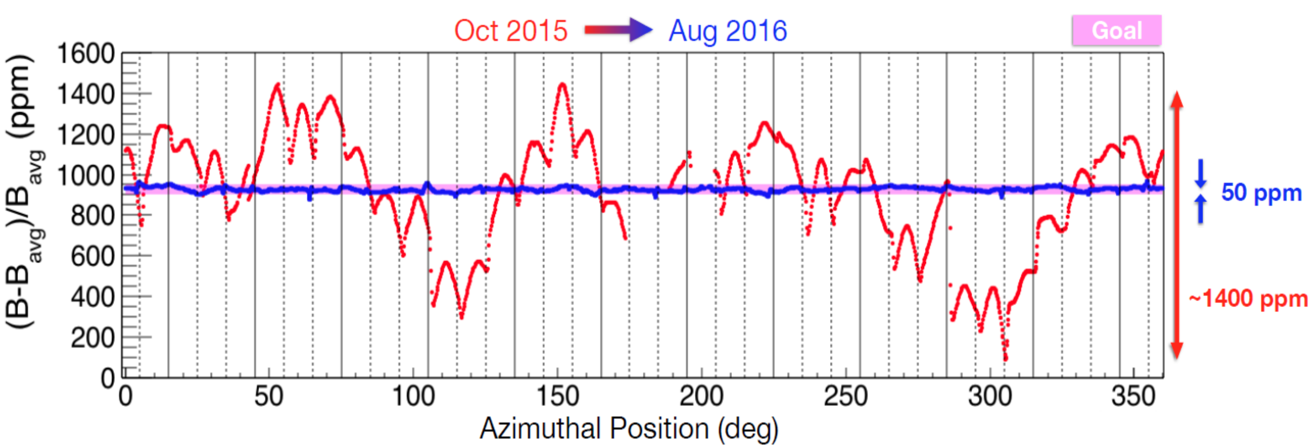

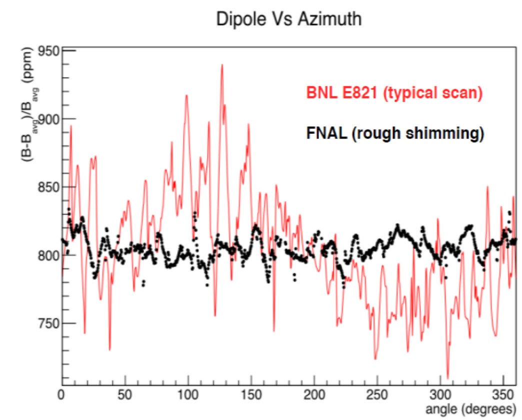

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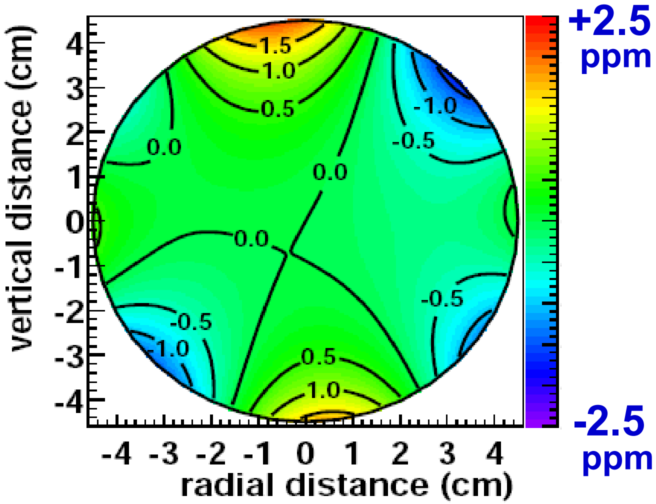
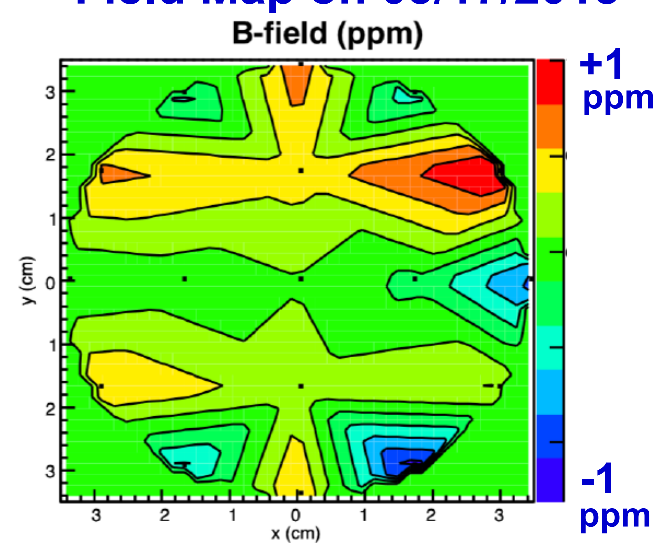


Averaged over azimuth: Shimmed to $\pm$1 ppm level

Field Map on 03/17/2018



Detector performance: calorimeter

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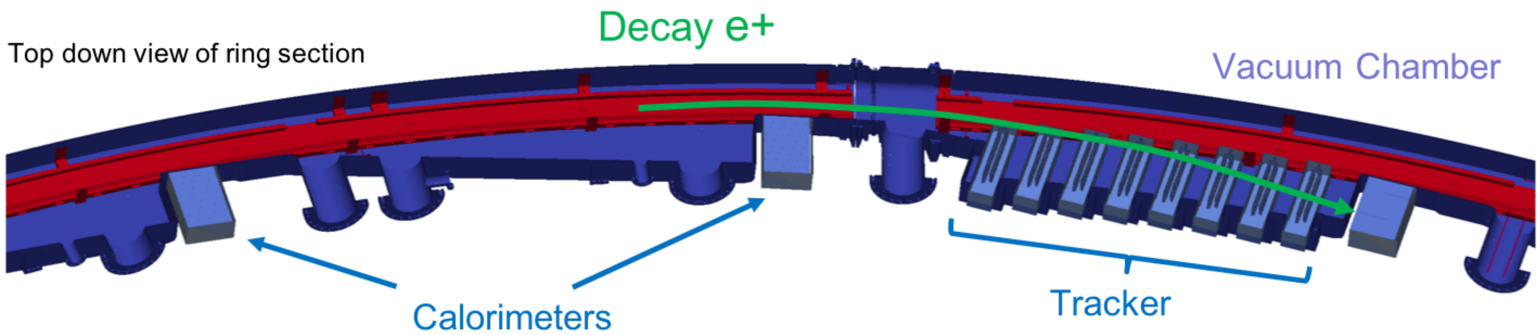

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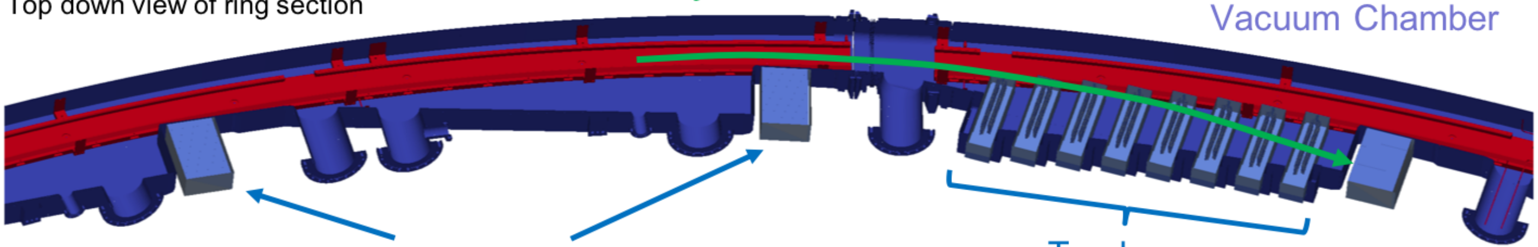

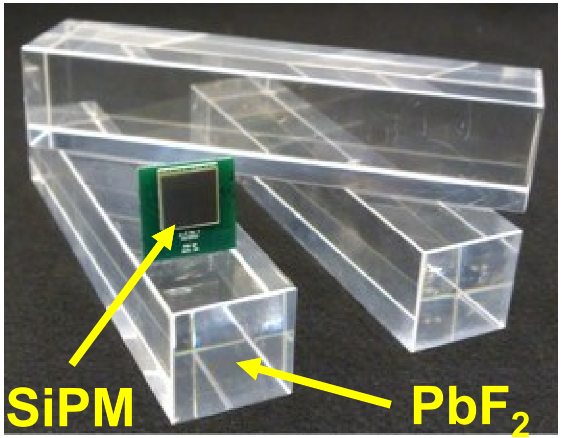

Segmented, fast response, crystal calorimeter (9X6 array)

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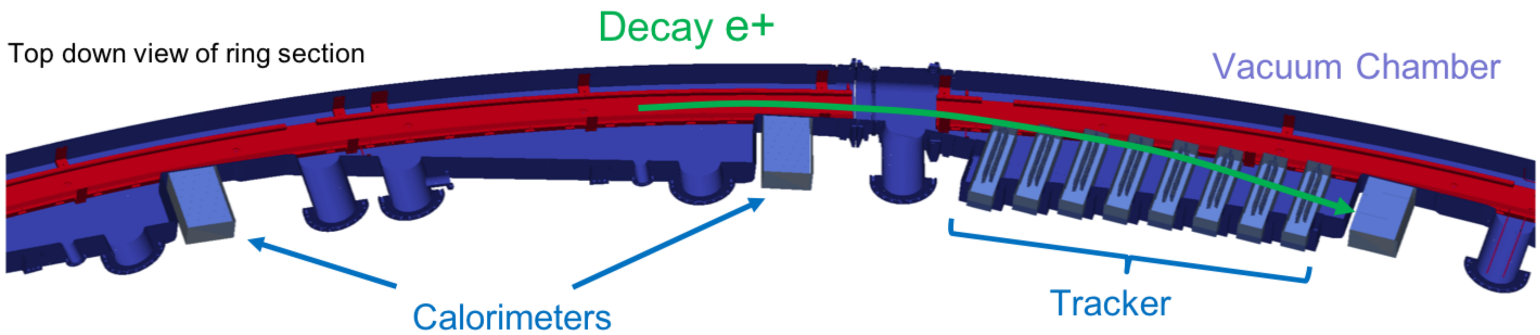
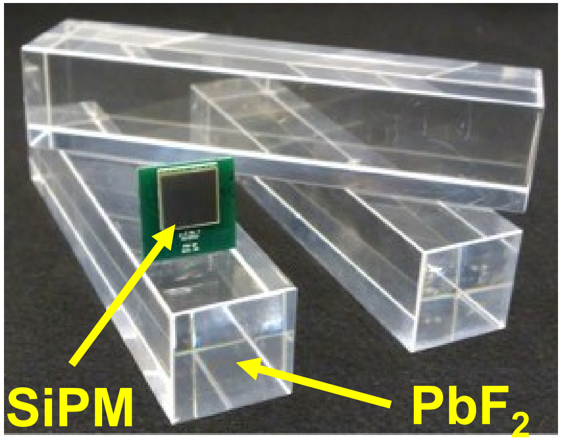
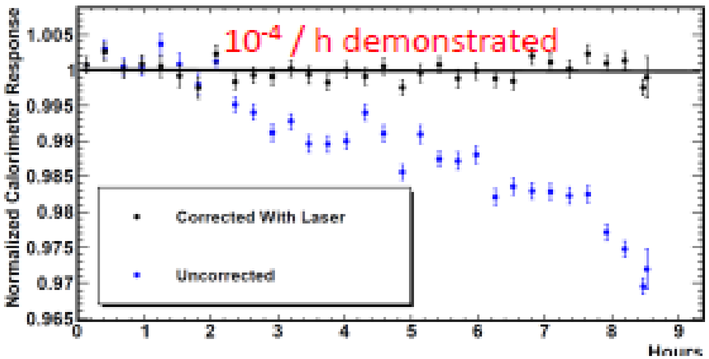




SLAC Test beam: 2013,2014,2016



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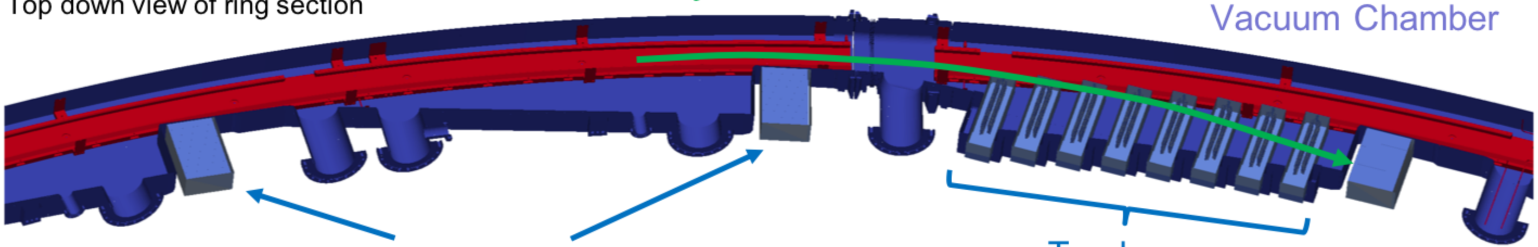
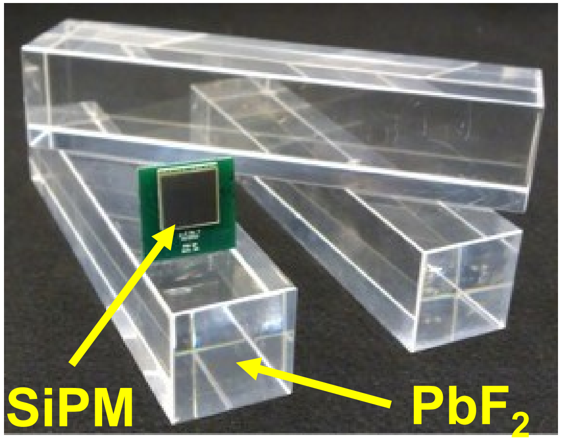
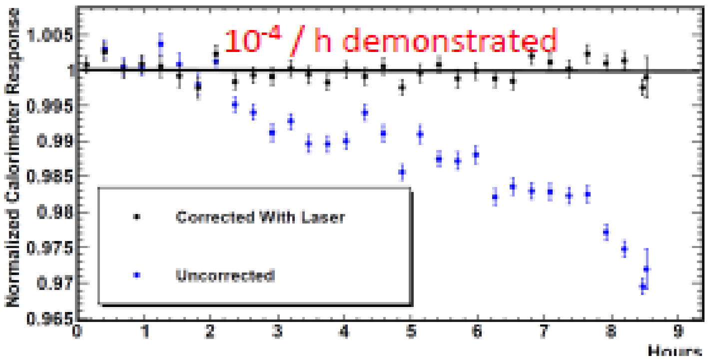




SLAC Test beam: 2013,2014,2016



Segmented, fast response, crystal calorimeter (9X6 array)

- **Lead-floride Cherenkov crystal (PbF_2) can reduce pileup**
  - **Resolution (2.3% at 3 GeV) better than requirement (5%)**
- **Silicon photomultiplier (SiPM) directly on back of PbF_2**
  - **No disturbing magnetic field, avoid long light guides**

Detector performance: tracker

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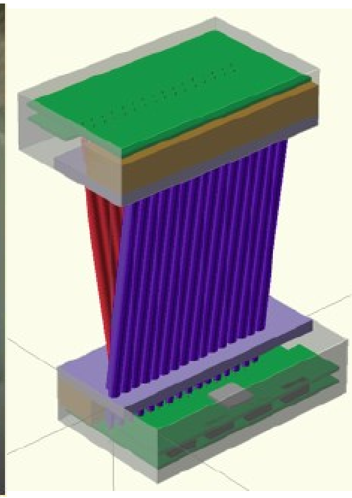
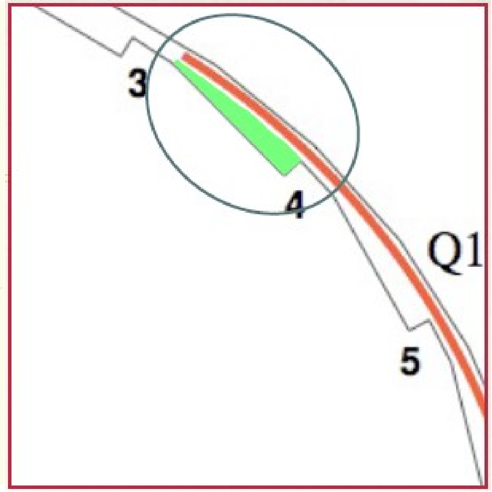
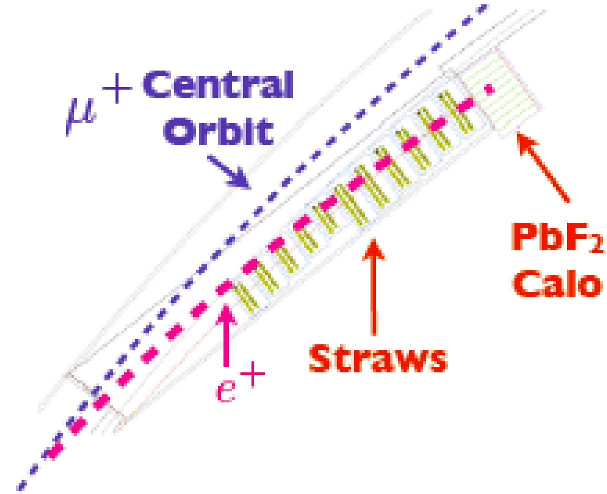
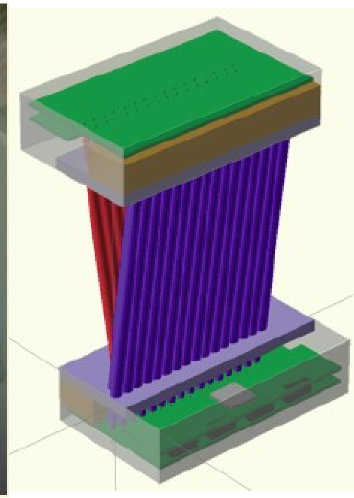


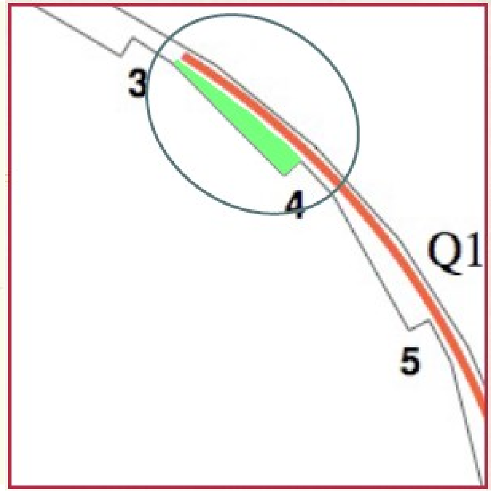


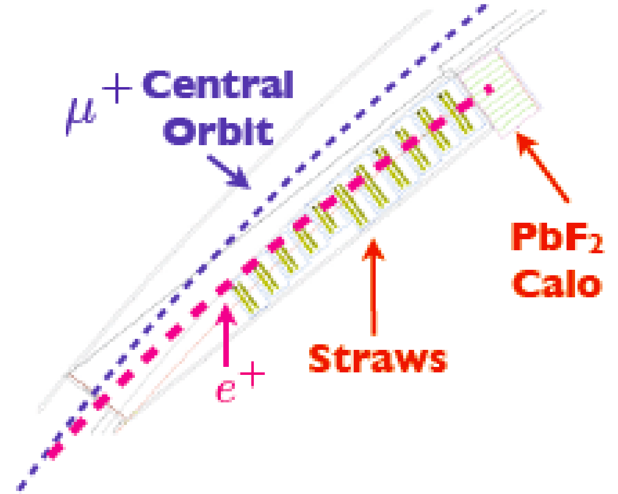


Doublet of UV straw chambers

Detector performance: tracker



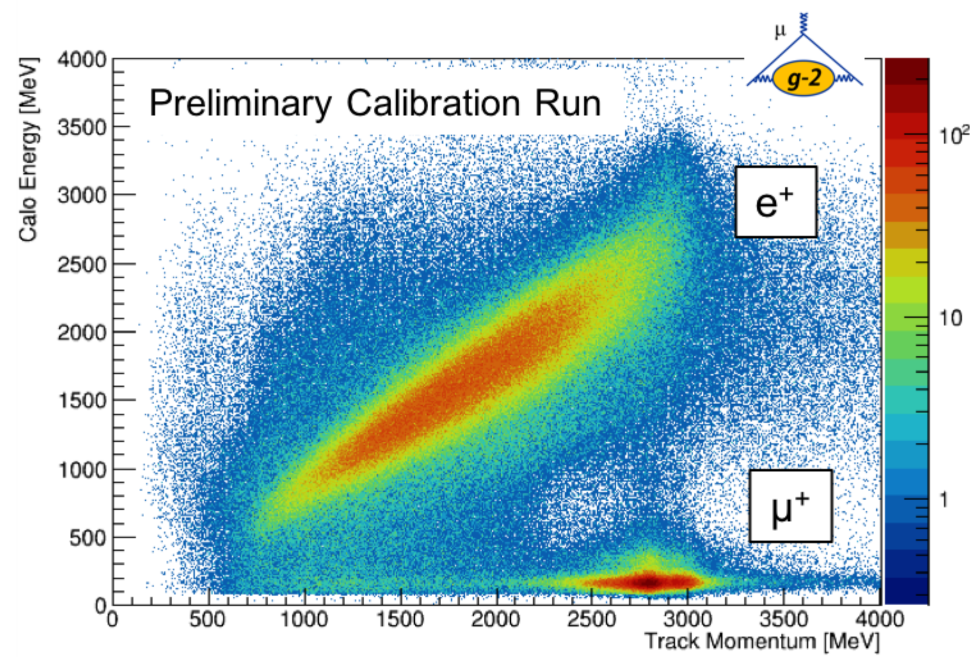




Doublet of UV straw chambers

New straw tracking detector

- Measure muon decay vertex and momentum



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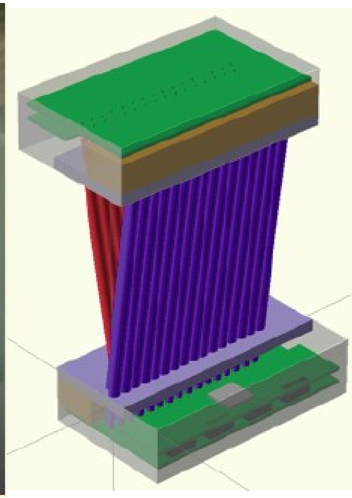

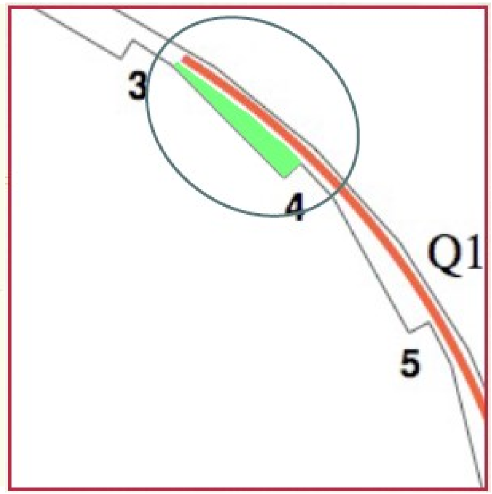

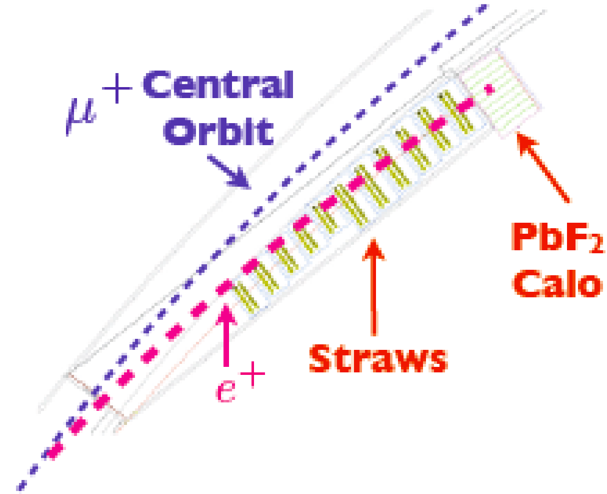

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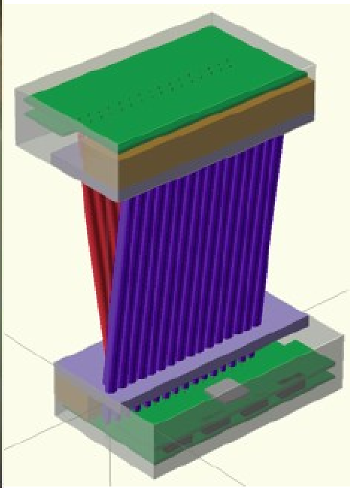

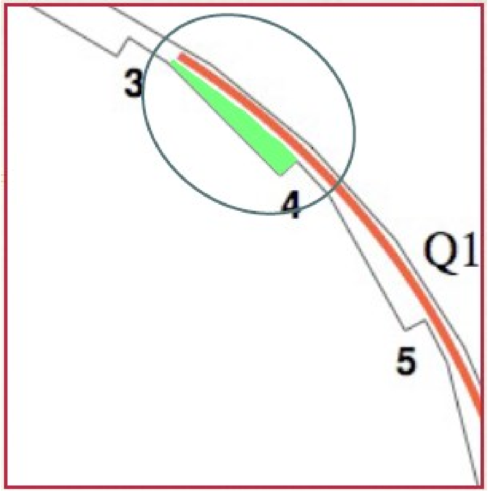

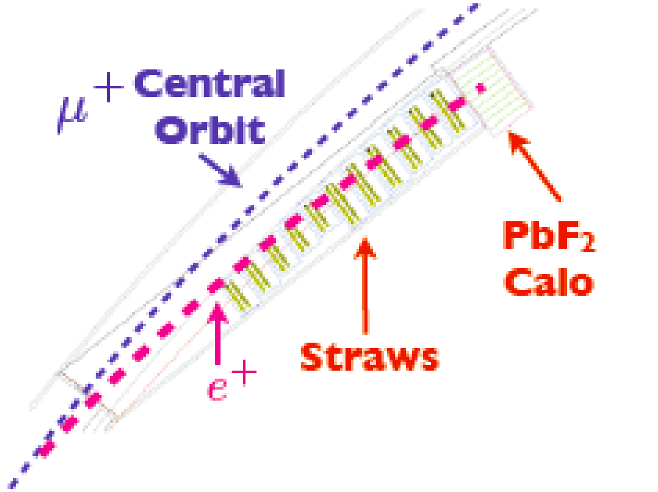

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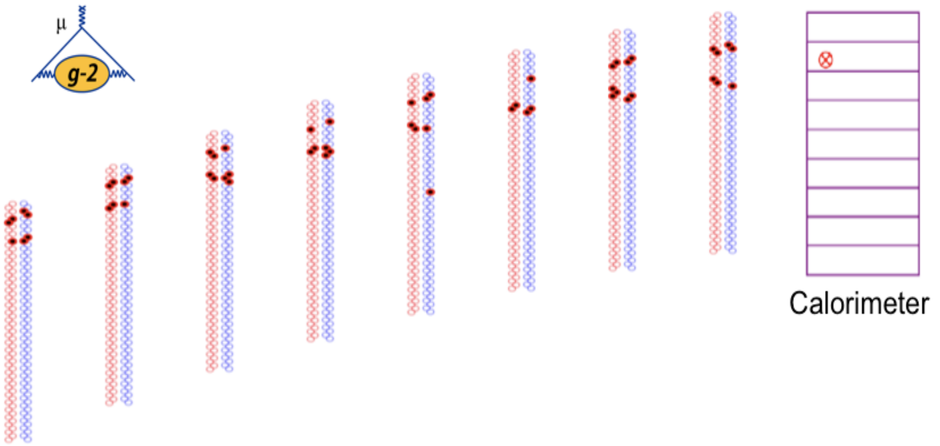

Wiggle, Wiggle, Wiggle…

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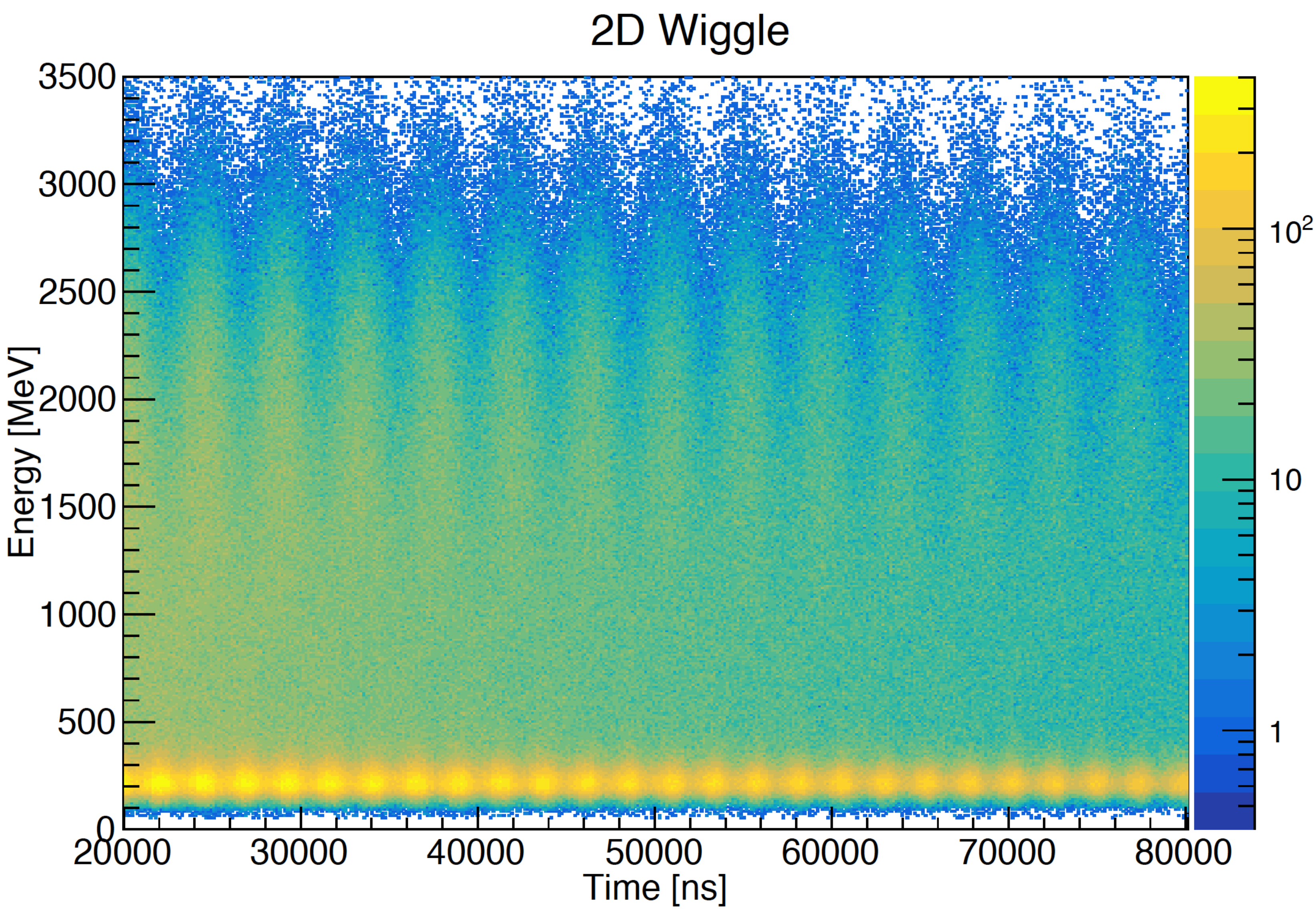
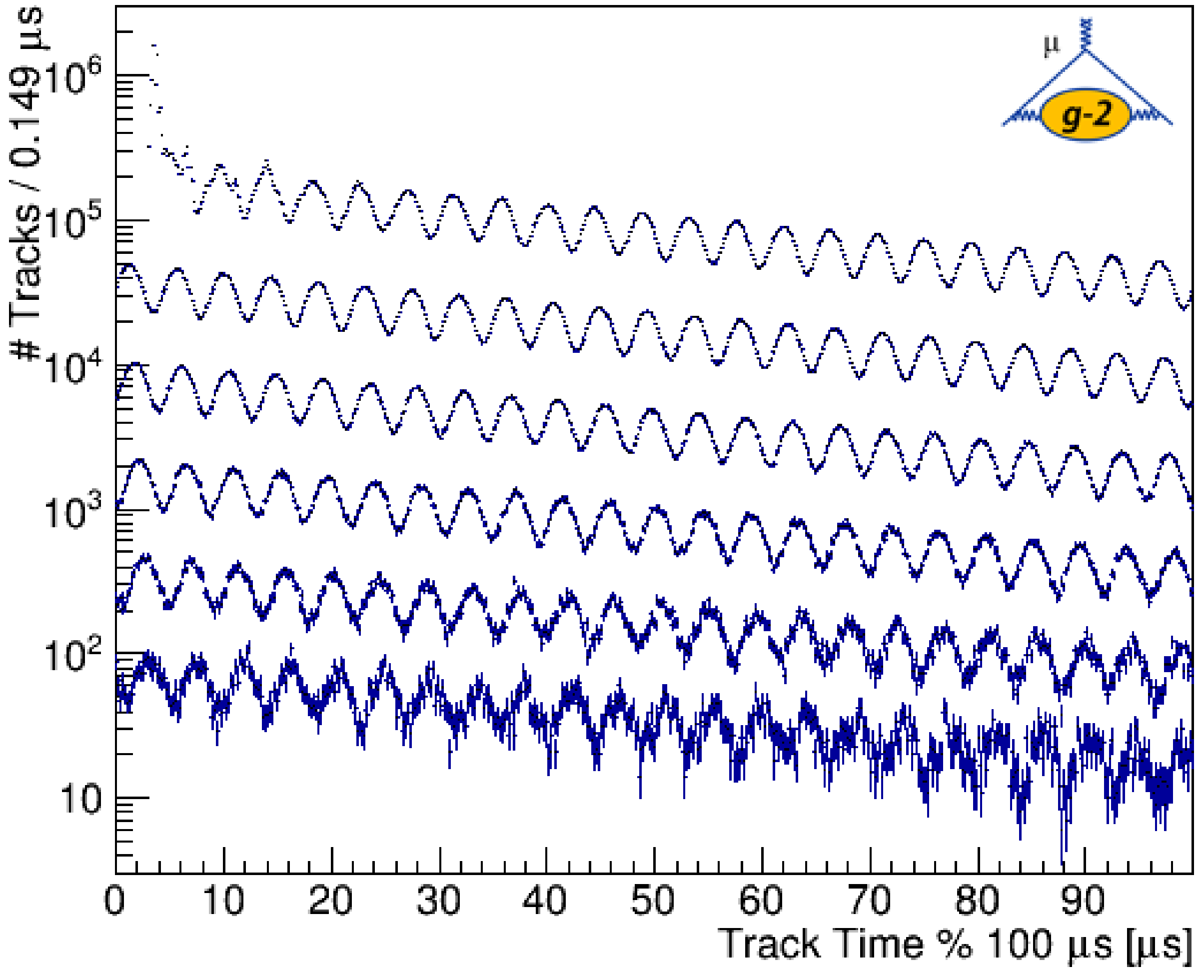


Energy vs. Time seen by calorimeters

Wiggle, Wiggle, Wiggle…



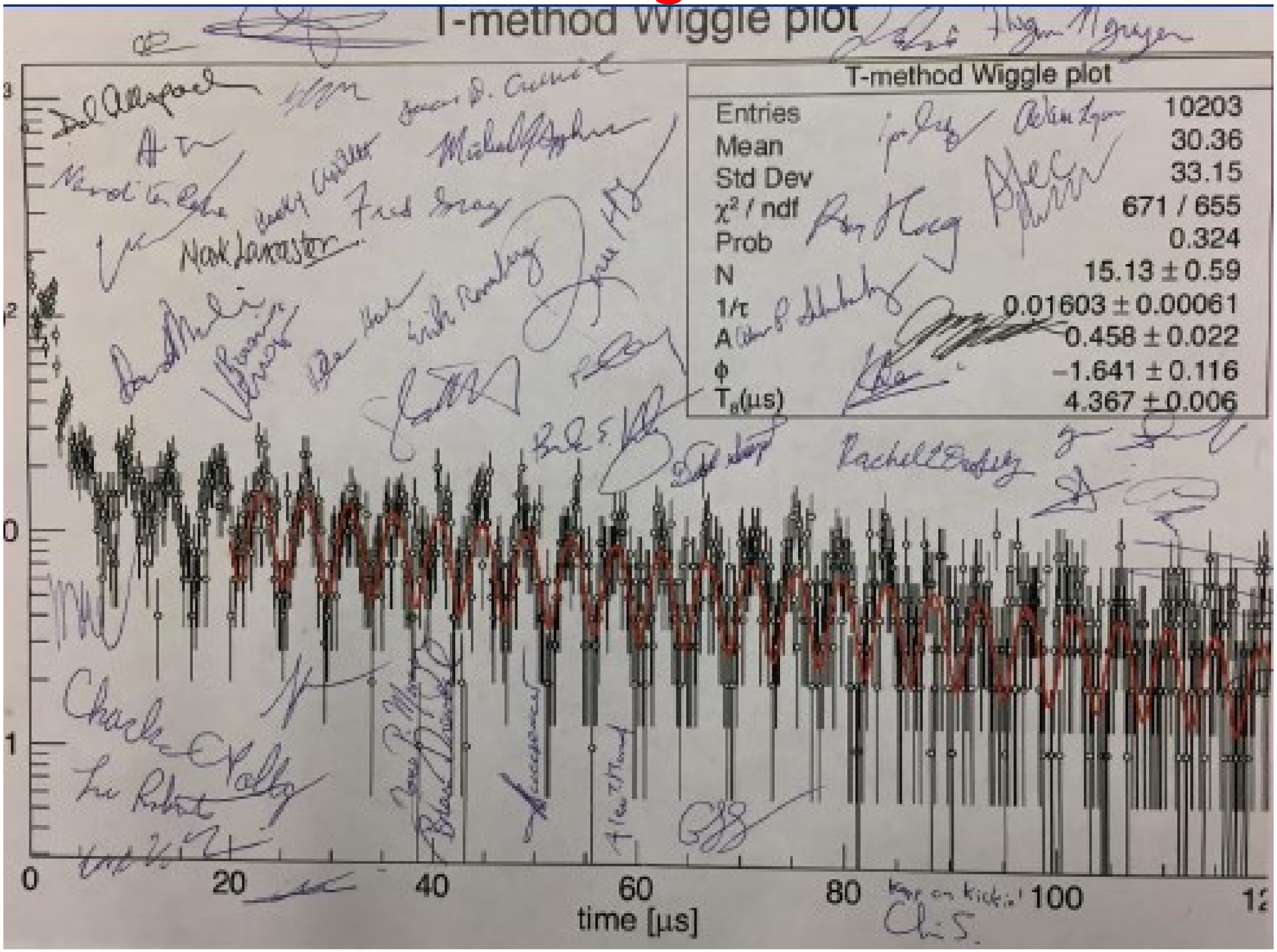
Track vs. Time seen by trackers (momentum greater than 1.8 GeV)

Wiggle, Wiggle, Wiggle…

Wiggle, Wiggle, Wiggle…

Wiggle, Wiggle, Wiggle…

First commissioning run: June 2017



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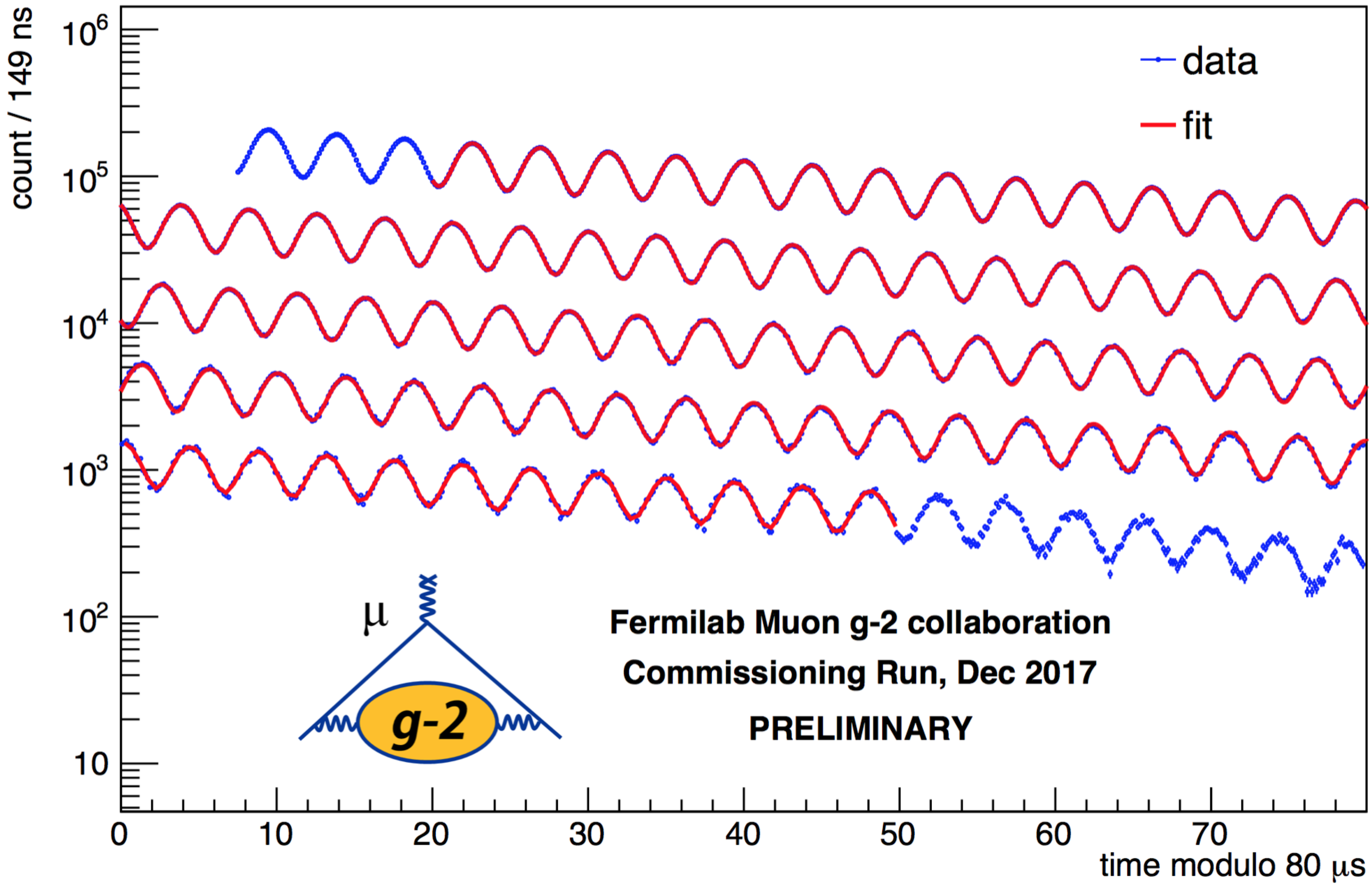

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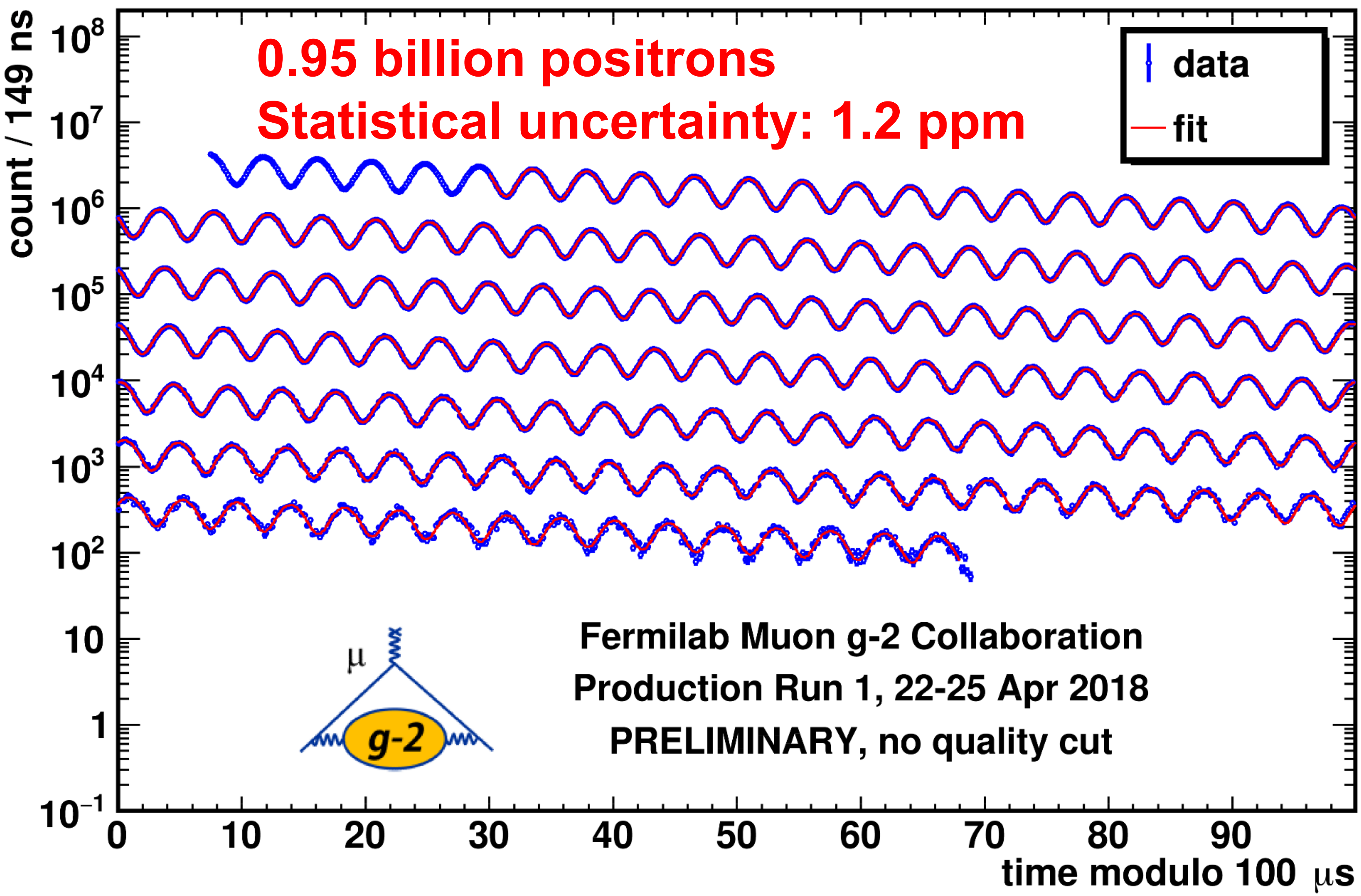

Summary

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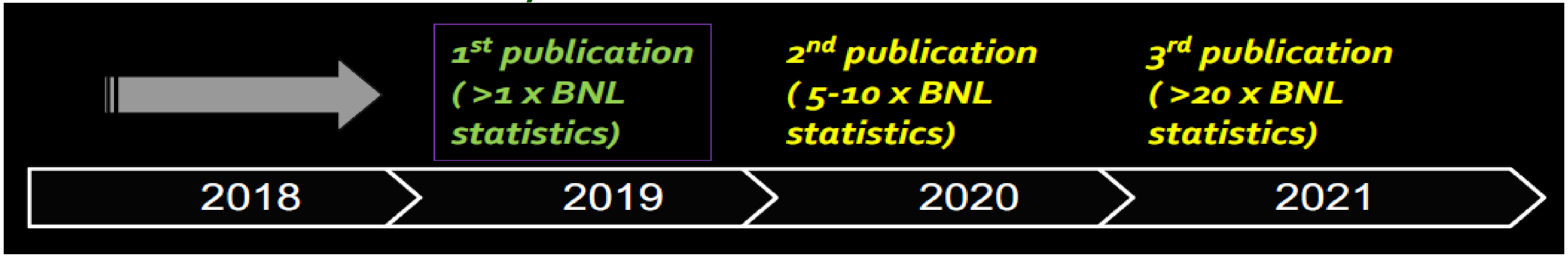


Backup

E821(BNL) vs. E989(Fermilab)

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

Goal: reduce experimental uncertainty by a factor of 4

- 21 times more statistics: powerful Fermilab particle source
  - δ_{stat} = 0.46 ppm → 0.1 ppm
- New segmented calorimeters, straw wire tracker, fast muon kicker…
  - $\delta\omega_a$ = 0.21 ppm → 0.07 ppm
- Long shimming period, magnet temperature stability, more/better in-situ calibrations, more probes, modern instrumentation…
  - $\delta_{\langle B\rangle(\omega_p)}$ = 0.17 ppm → 0.07 ppm

E989 (Fermilab) experimental uncertainty:
0.14ppm ~ 16 X 10^{-11}
> 5σ deviation with the same central value

Theory calculation

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

	Contribution	Result in 10^{-11} units
a_μ^{QED}	QED (leptons)	$116\,584\,718.09 \pm 0.15$
a_μ^{Had}	HVP(lo)[e+e-]	$6\,923 \pm 42$
	HVP(ho)	-98.4 ± 0.7
	HLbyL	105 ± 26
a_μ^{EW}	EW	153 ± 1
	Total	$116\,591\,801 \pm 49$

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, no big "shift" seen in early results compared to models: potential to improve in systematics**

ω_a Systematics

Category	E821 [ppb]	E989 Improvement Plans	E989 [ppb]
Gain changes	120	• Better laser calibration • Low-energy threshold	20
Pileup	80	• Recording low-energy samples • Segmented Calorimeters	40
Lost muons	90	• Better collimation in ring	20
CBO	70	• Higher n value • Better match of beamline to ring	< 30
E and pitch corrections	50	• Improved tracker • High precision storage ring simulation	30
Total	180	Quadrature Sum for $\delta\omega_a$ (syst.)	70

Detector Team

Ring Team

Detector Team

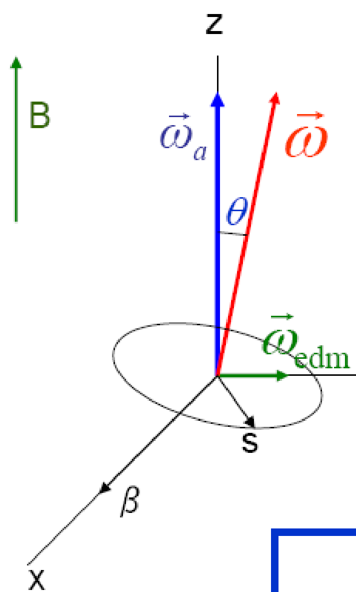
Systematics error < 70 ppb: x 3 improvement !

ω_p Systematics

Category	E821 (ppb)	E989 (ppb)	Methods
Absolute probe calibration	50	35	More uniform field for calibration
Trolley probe calibration	90	30	Better alignment between trolley and the plunging probe
Trolley measurement	50	30	More uniform field, less position uncertainty
Fixed probe interpolation	70	30	More stable temperature
Muon distribution	30	10	More uniform field, better understanding of muon distribution
Time dependent external magnetic field	-	5	Direct measurement of external field, active feedback
Others*	100	30	More uniform field, trolley temperature monitor, etc
total	170	70	

Systematics error < 70 ppb: x 2 improvement !

Muon EDM

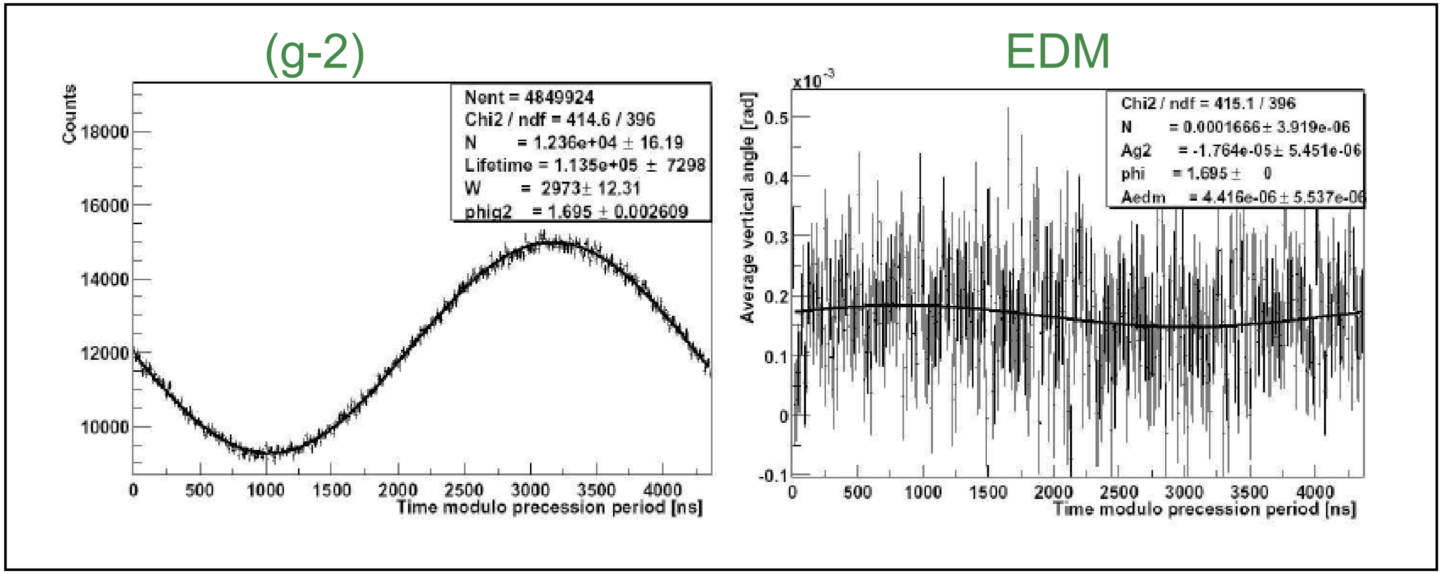


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

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

Muon EDM

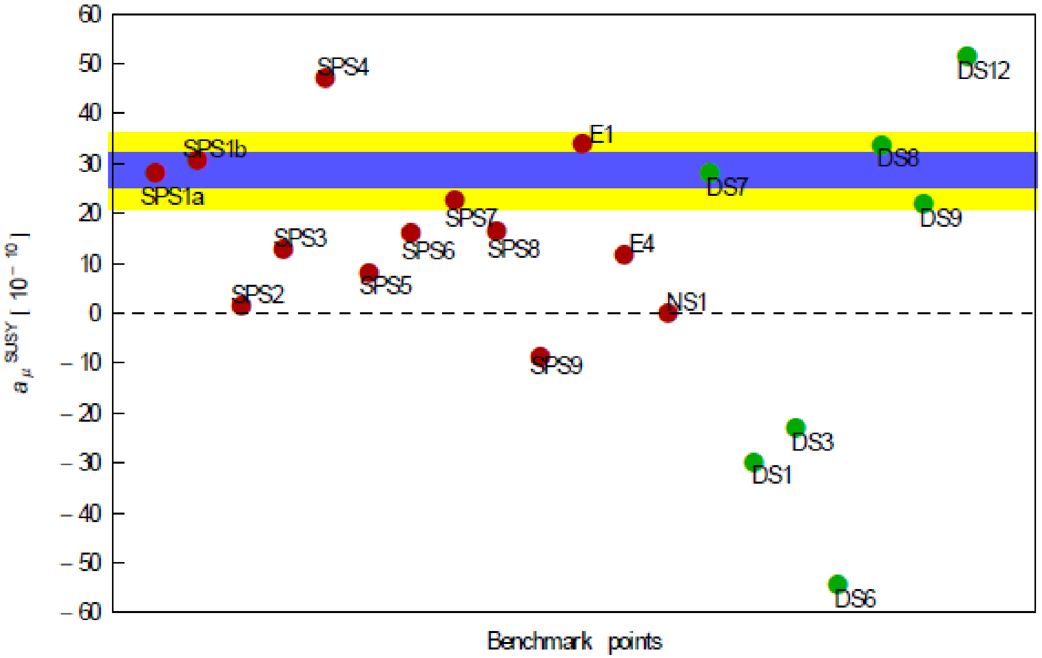


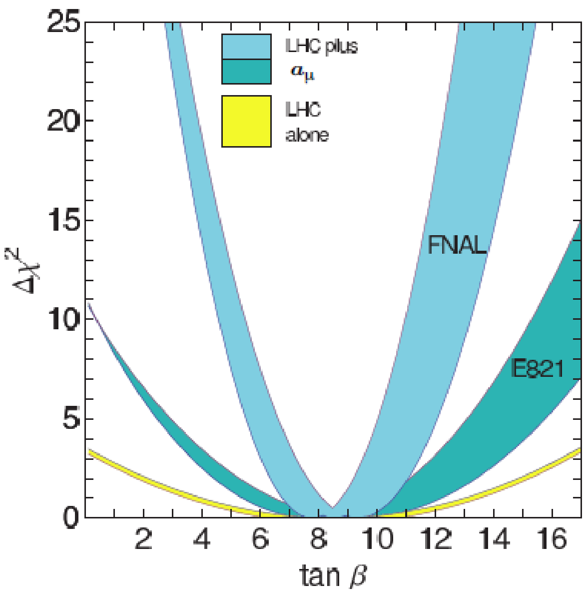
(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

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

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

New Physics?





SUSY?

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

- **Strong discriminating power from improved measurements**
- **Complementary to LHC**
- **Invisible decay connected to dark sector**

Dark Sector?