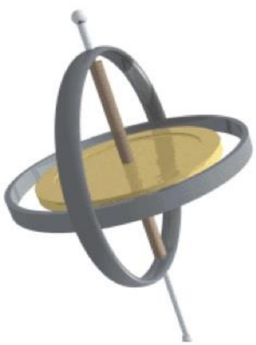
The First Physics Run of Muon g-2 Experiment at Fermilab



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

$$a = \frac{g-2}{2}$$

Liang Li 李亮

Shanghai Jiao Tong University 上海交通大学

Muon g-2 Collaboration

US Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Northern Illinois
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

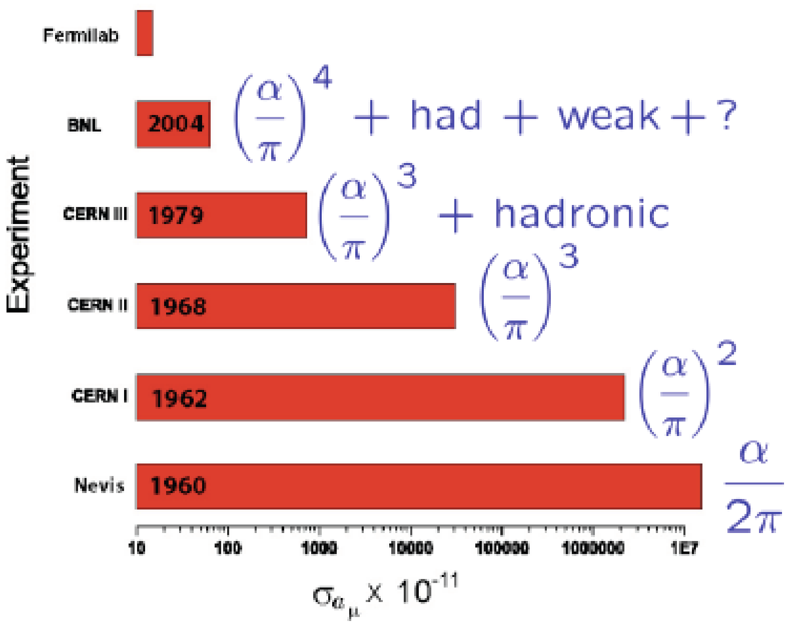
Korea
- CAPP/ISB
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

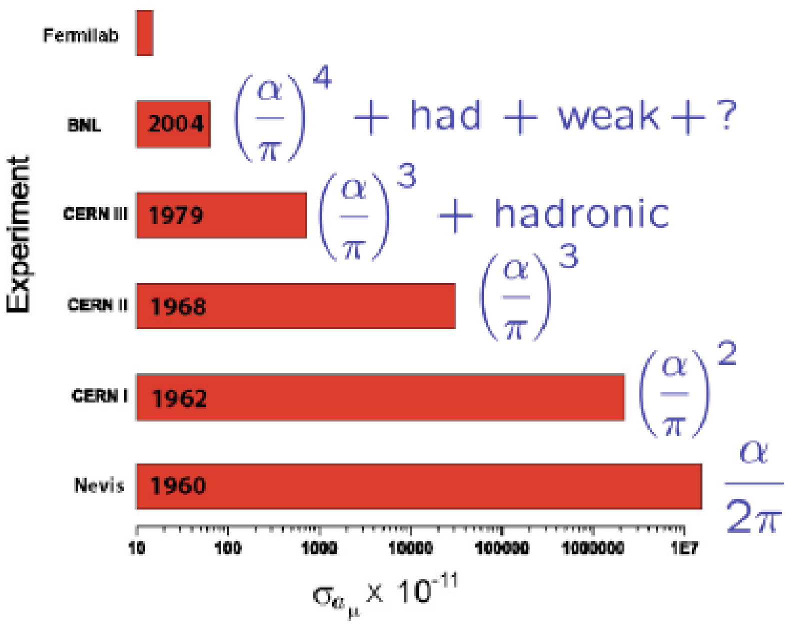
May 27-31, 2019
Elba Collaboration Meeting

Muon g-2 Experiment



Over 50 years of non-stopping improvement on δa_μ

Muon g-2 Experiment

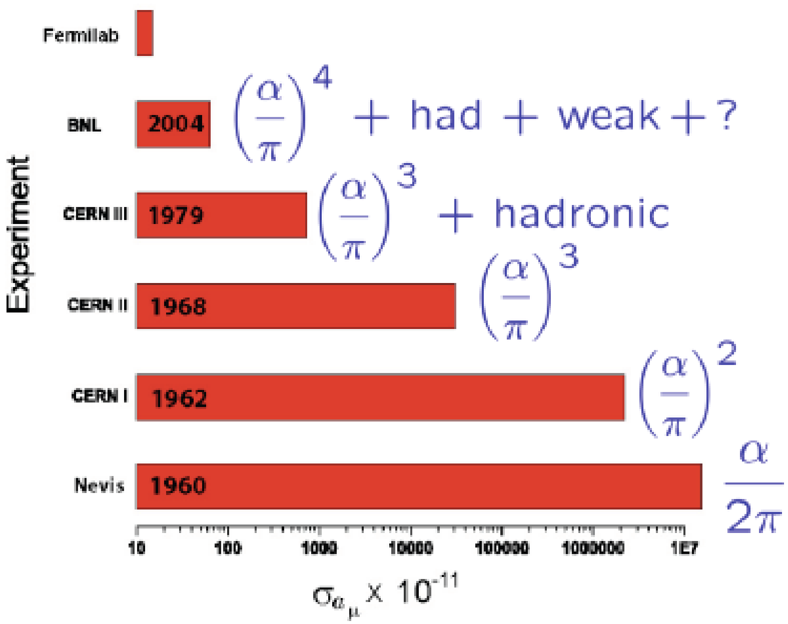


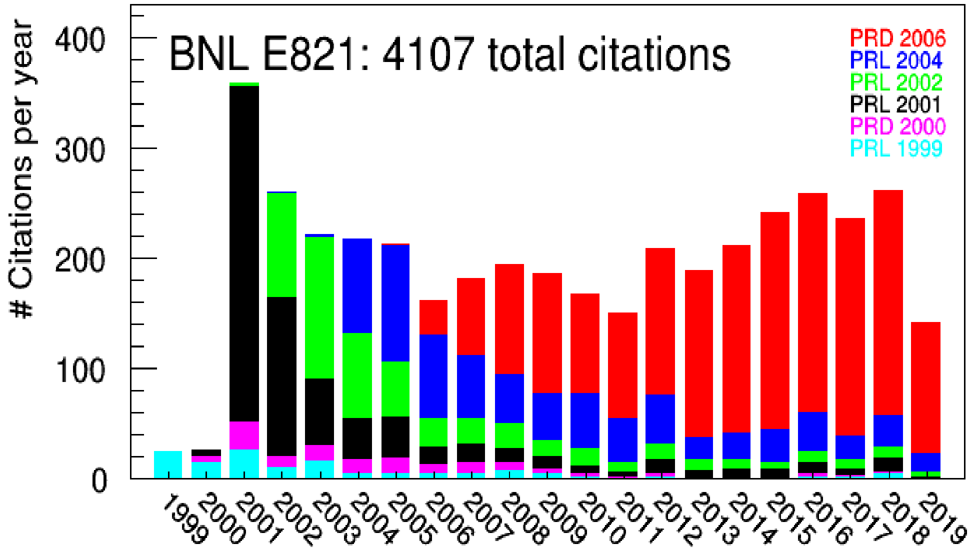
Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$
Columbia-Nevis(1957) [2]	μ^+	$g = 2.00 \pm 0.10$	
Columbia-Nevis(1959) [3]	μ^+	$0.001\,13^{+(16)}_{-(12)}$	12.4%
CERN 1(1961) [4]	μ^+	0.001 145(22)	1.9%
CERN 1(1962) [5]	μ^+	0.001 162(5)	0.43%
CERN 2(1968) [6]	$\mu^\pm$	0.001 166 16(31)	265 ppm
CERN 3(1975) [7]	$\mu^\pm$	0.001 165 895(27)	23 ppm
CERN 3(1979) [8]	$\mu^\pm$	0.001 165 911(11)	7.3 ppm
BNL E821(2000) [9]	μ^+	0.001 165 919 1(59)	5 ppm
BNL E821(2001) [10]	μ^+	0.001 165 920 2(16)	1.3 ppm
BNL E821(2002) [11]	μ^+	0.001 165 920 3(8)	0.7 ppm
BNL E821(2004) [12]	μ^-	0.001 165 921 4(8)(3)	0.7 ppm
World Average(2004) [12,13]	$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm

Over 50 years of non-stopping improvement on δa_μ

- **Pushing both theoretical and experimental frontend**
- **Last measurement from BNL E821 (2004) came with 0.54ppm**

Muon g-2 Experiment

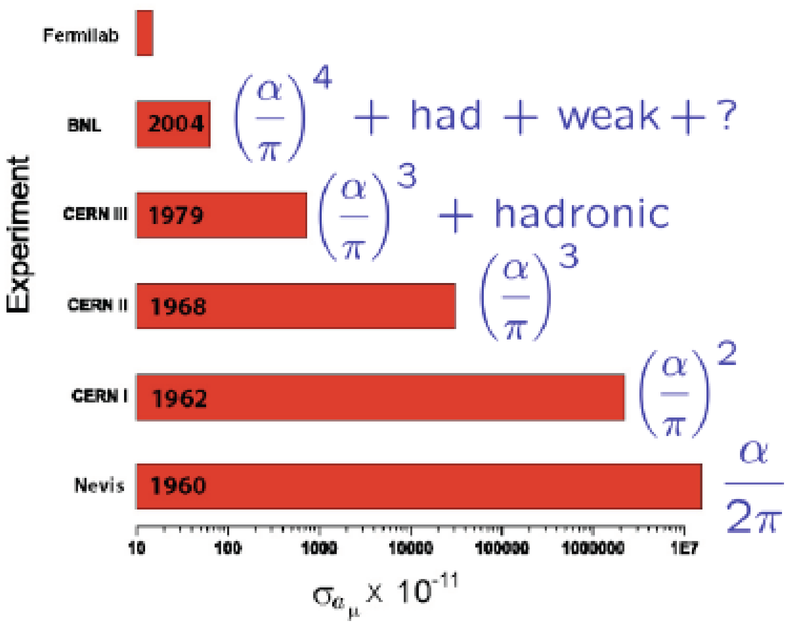




Over 50 years of non-stopping improvement on δa_μ

- **Pushing both theoretical and experimental frontend**
- **Last measurement from BNL E821 (2004) came with 0.54ppm**

Muon g-2 Experiment



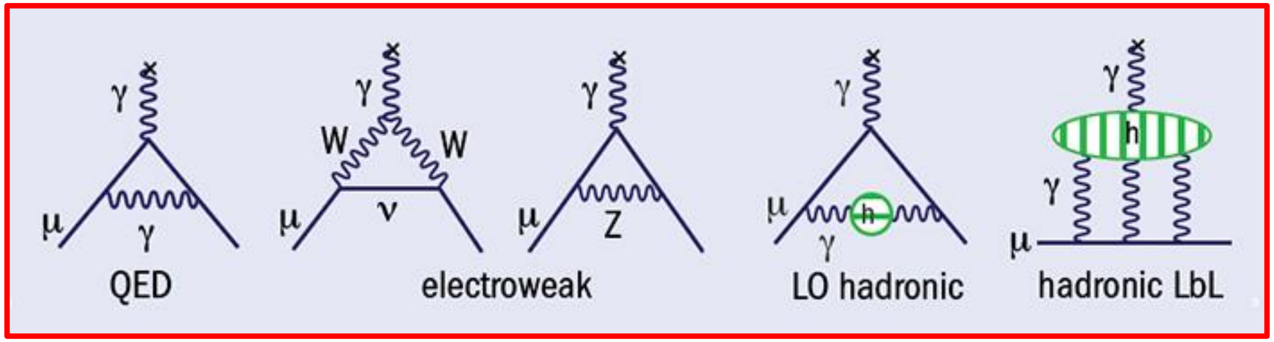
Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$
Columbia-Nevis(1957) [2]	μ^+	$g = 2.00 \pm 0.10$	
Columbia-Nevis(1959) [3]	μ^+	$0.001\,13^{+(16)}_{-(12)}$	12.4%
CERN 1(1961) [4]	μ^+	0.001 145(22)	1.9%
CERN 1(1962) [5]	μ^+	0.001 162(5)	0.43%
CERN 2(1968) [6]	$\mu^\pm$	0.001 166 16(31)	265 ppm
CERN 3(1975) [7]	$\mu^\pm$	0.001 165 895(27)	23 ppm
CERN 3(1979) [8]	$\mu^\pm$	0.001 165 911(11)	7.3 ppm
BNL E821(2000) [9]	μ^+	0.001 165 919 1(59)	5 ppm
BNL E821(2001) [10]	μ^+	0.001 165 920 2(16)	1.3 ppm
BNL E821(2002) [11]	μ^+	0.001 165 920 3(8)	0.7 ppm
BNL E821(2004) [12]	μ^-	0.001 165 921 4(8)(3)	0.7 ppm
World Average(2004) [12,13]	$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm

Over 50 years of non-stopping improvement on δa_μ

- **Pushing both theoretical and experimental frontend**
- **Last measurement from BNL E821 (2004) came with 0.54ppm**
- **New muon g-2 experiment at Fermilab aim at 0.14ppm**
- **Very exciting and highly expected measurement!**

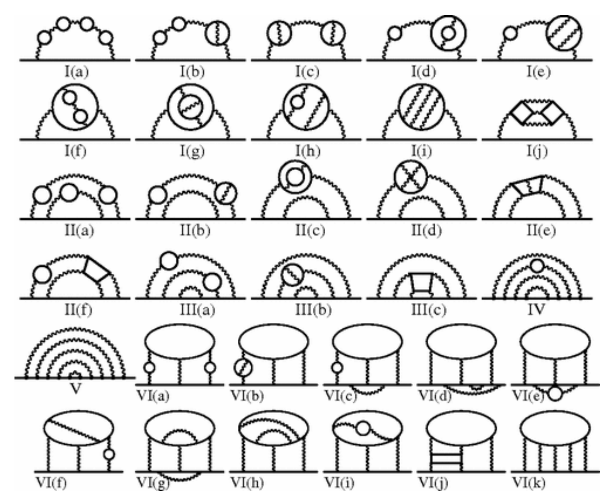
Muon g-2 Theory: QED

$$a_m^{SM} = a_m^{QED} + a_m^{EW} + a_m^{Had}$$



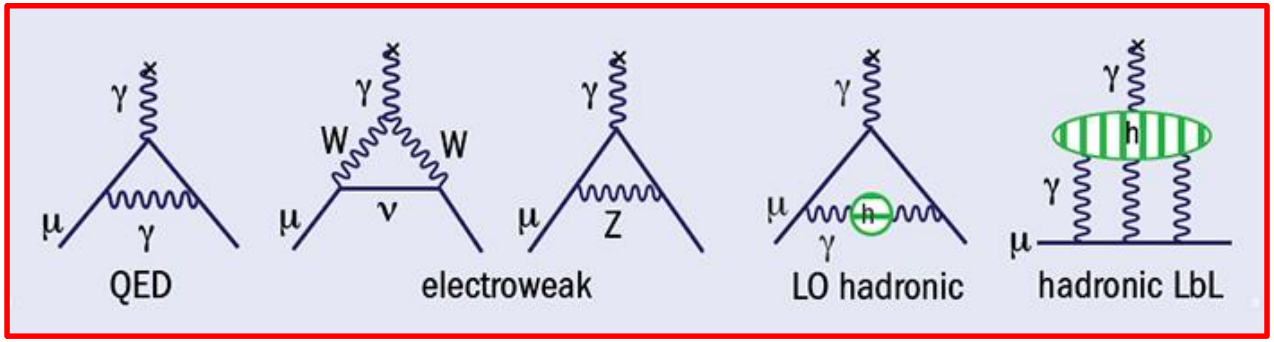
- **Includes all photonic and leptonic loops**
- **Largest contribution to a_μ (99.99%)**
- **Most precise calculation (~10^{-9} precision!)**
  - **Calculated through 10th order!**

Aoyama, Kinoshita, Nio Phys.Rev. D97 (2018) 036001.



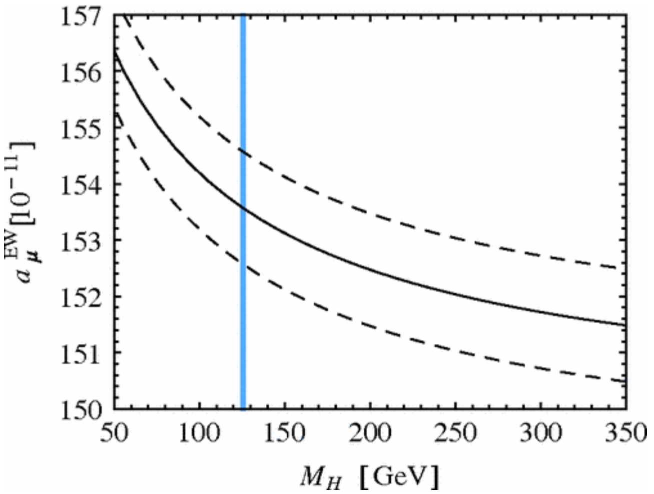
Muon g-2 Theory: EW

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



- **Includes all W, Z or Higgs loops**
- **Calculated to two loops and re-evaluated using the LHC value of the Higgs mass**
- **Small contribution (0.0001%)**

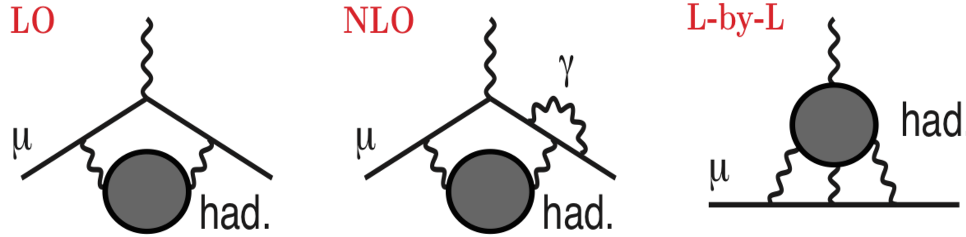
Gnendiger, Stockinger, Stockinger-Kim, Phys.Rev. D88, (2013) 053005.



Muon g-2 Theory: QCD

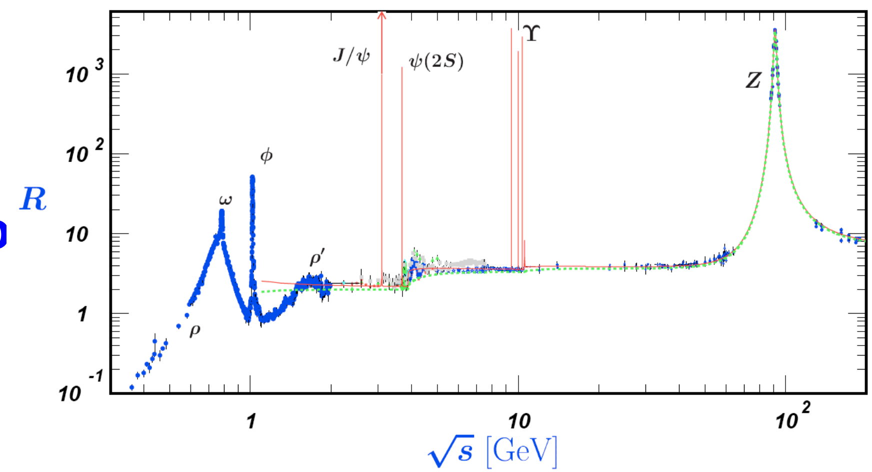
$$a_m^{SM} = a_m^{QED} + a_m^{EW} + a_m^{Had}$$

Hadronic Vacuum Polarization (HVP)



Hadronic Light-by-Light Scattering (HLbL)

- **Includes quark and gluon loops**
- **Small contribution with dominant so of theoretical uncertainties**
- **Hadronic Vacuum Polarization**
- **Hadronic Light-by-Light scattering**
- **Three approaches**
  - **Dispersion relationships**
  - **Hadronic models**
  - **Lattice**
    - **Fast progress but not yet competitive**



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

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

Muon g-2 Theory: Summary

	2011		2018	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 (2.60)	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 (2.46)	**Phys. Dev. D 97 (2018) 114025**
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	**Phys. Dev. D 97 (2018) 114025**
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	**Phys. Dev. D 97 (2018) 114025**
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	**Phys. Dev. D 97 (2018) 114025**
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	**Phys. Dev. D 97 (2018) 114025**

[KNT18: Phys. Rev. D 97 (2018) 114025]

Muon g-2 Theory: Summary

	2011		2018	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 (2.60)	[EPJ Web Conf. 118 (2016) 01016]
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	**~0.35%**
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 (2.46)	**Phys. Dev. D 97 (2018) 114025**
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	**Phys. Dev. D 97 (2018) 114025**
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	**Phys. Dev. D 97 (2018) 114025**
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	**Phys. Dev. D 97 (2018) 114025**
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	**Phys. Dev. D 97 (2018) 114025**

[KNT18: Phys. Rev. D 97 (2018) 114025]

Muon g-2 Theory: Summary

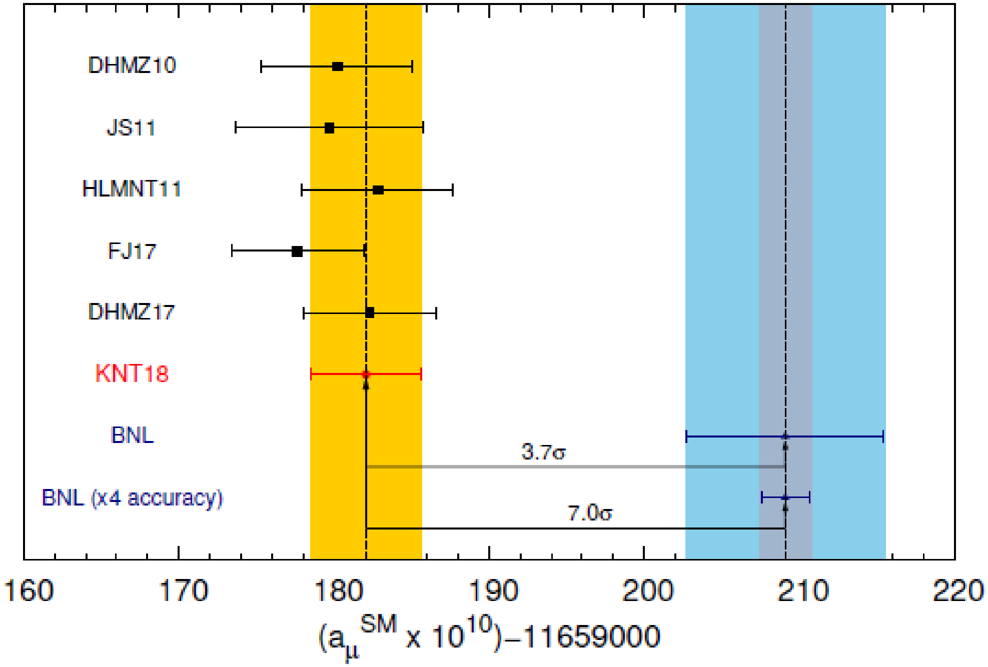
	2011		2018	
QED	11658471.81 (0.02)	$\longrightarrow$	11658471.90 (0.01)	[arXiv:1712.06060]
EW	15.40 (0.20)	$\longrightarrow$	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	$\longrightarrow$	9.80 (2.60)	[EPJ Web Conf. 118 (2016)] ~ 26%
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]
	HLMNT11		**KNT18**	~0.35%
LO HVP	694.91 (4.27)	$\longrightarrow$	693.27 (2.46)	Phys. Dev. D 97 (2018) 114025
NLO HVP	-9.84 (0.07)	$\longrightarrow$	-9.82 (0.04)	Phys. Dev. D 97 (2018) 114025
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144]
Theory total	11659182.80 (4.94)	$\longrightarrow$	11659182.05 (3.56)	Phys. Dev. D 97 (2018) 114025
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	$\longrightarrow$	27.1 (7.3)	Phys. Dev. D 97 (2018) 114025
Δa_μ	3.3σ	$\longrightarrow$	3.7σ	Phys. Dev. D 97 (2018) 114025

[KNT18: Phys. Rev. D 97 (2018) 114025]

Muon g-2 Experiment vs. Theory

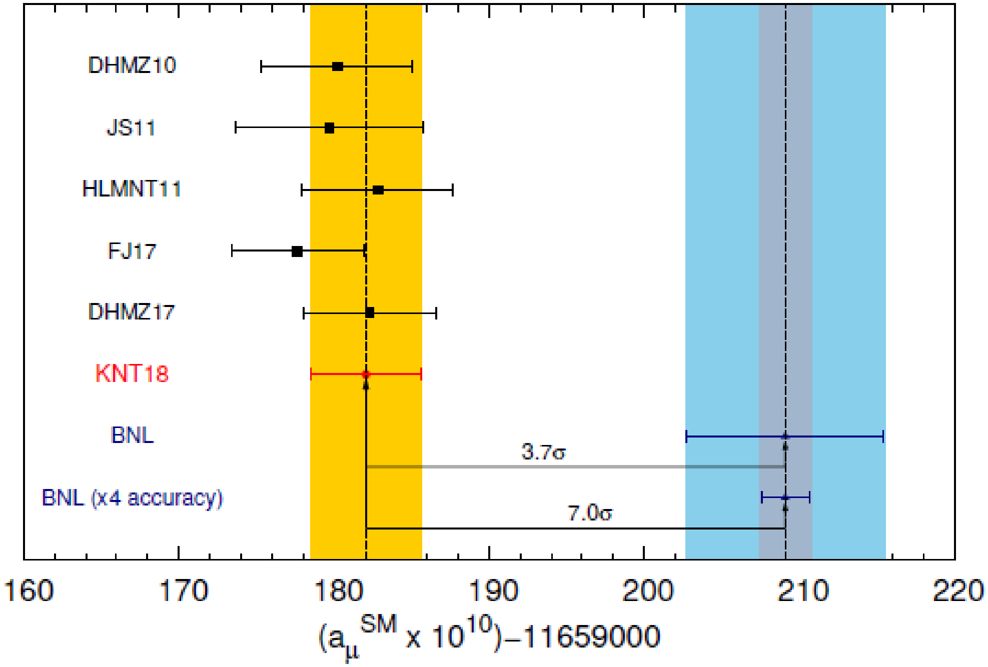
Muon g-2 Experiment vs. Theory

Comparison as of July 2018

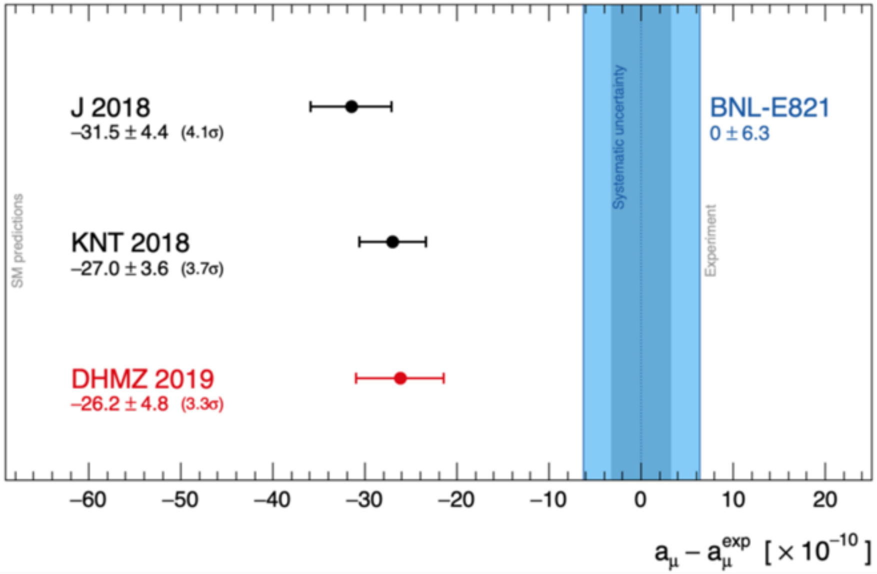


Muon g-2 Experiment vs. Theory

Comparison as of July 2018

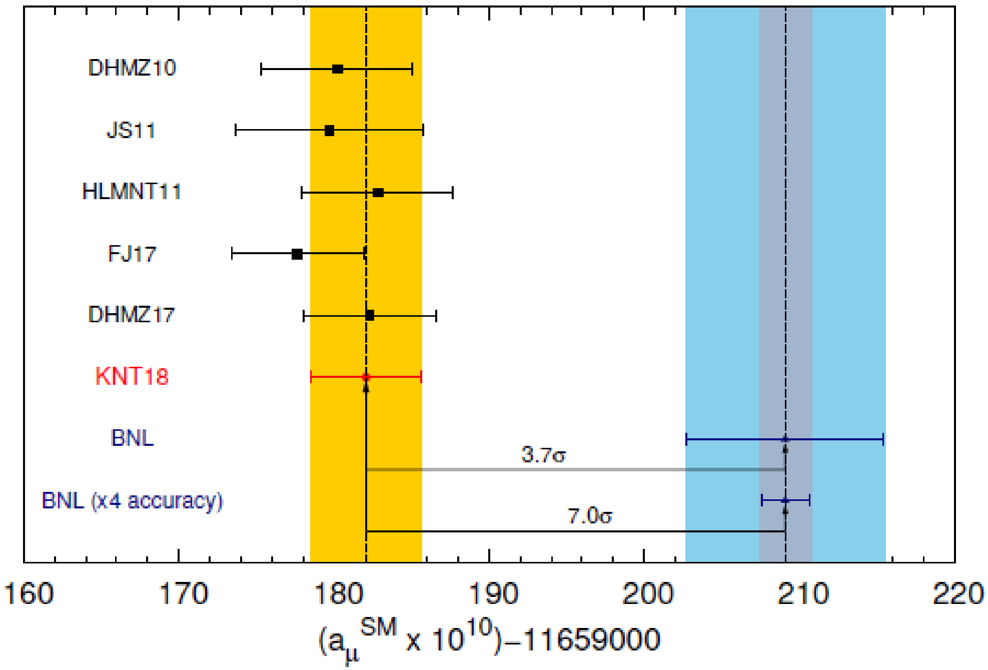


Davier, Hoecker, Malaescu, Zhang 2019

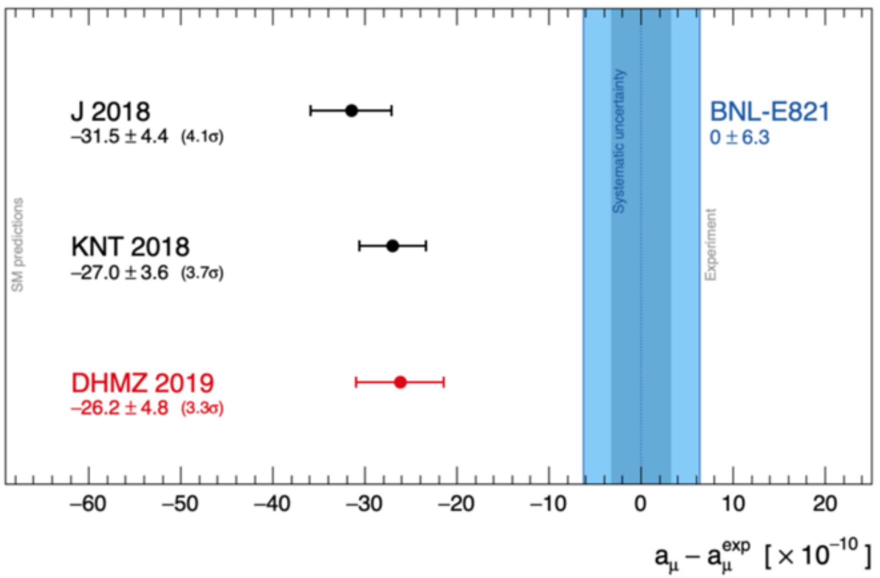


Muon g-2 Experiment vs. Theory

Comparison as of July 2018



Davier, Hoecker, Malaescu, Zhang 2019

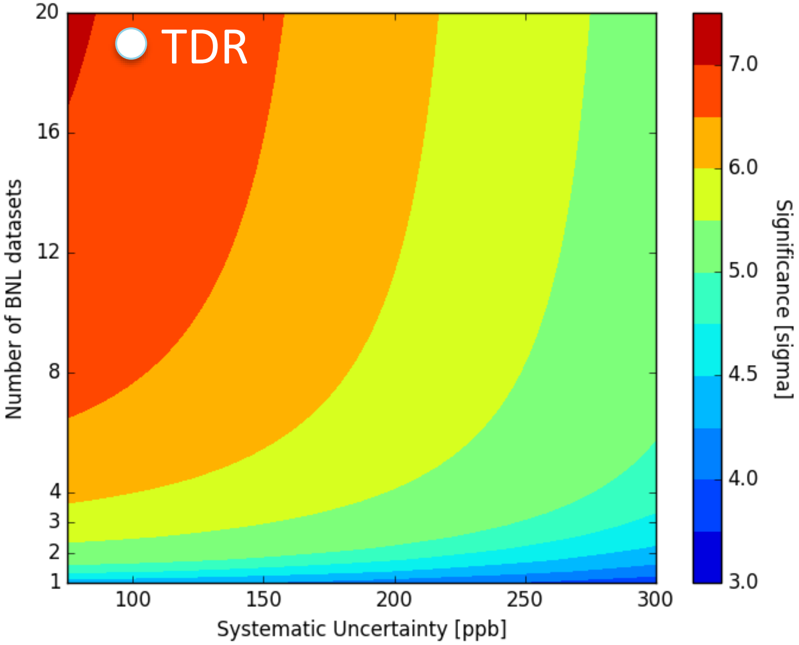


Latest comparison gives 3.3-4.1 σ difference

- **Variations in theory model does NOT seem to explain the difference**
- **Hint of BSM physics**
- **With improvements in theory calculation and experiment measurements, muon g-2 as a fundamental property can serve as a benchmark test for any new physics**

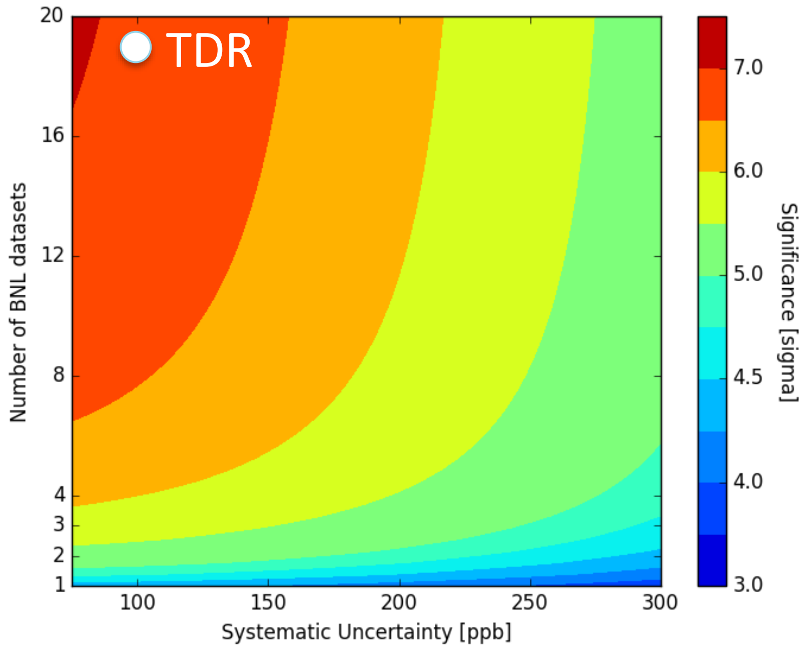
Muon g-2 Discovery Potential

Muon g-2 Discovery Potential

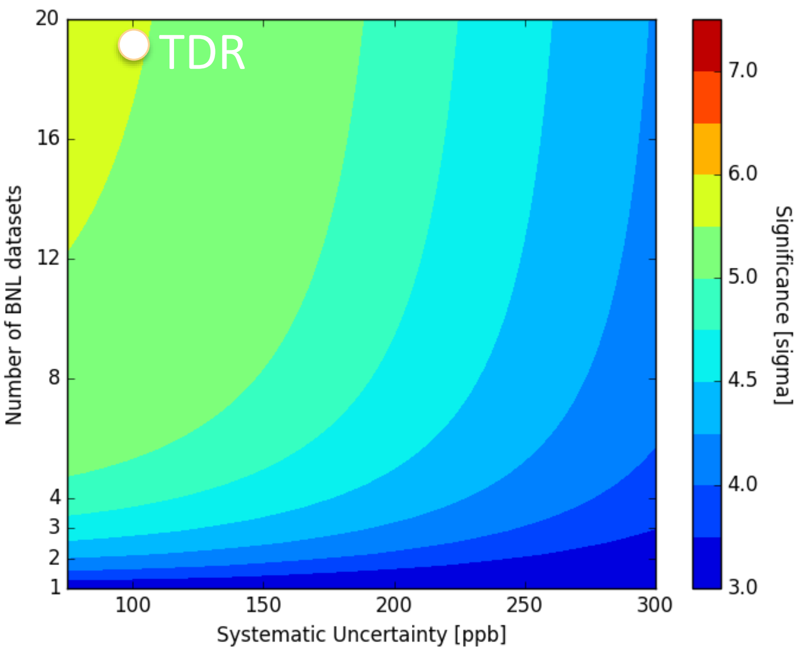


With theory and experiment central values unchanged, achieving target errors → 6.9σ discrepancy with KNT18

Muon g-2 Discovery Potential

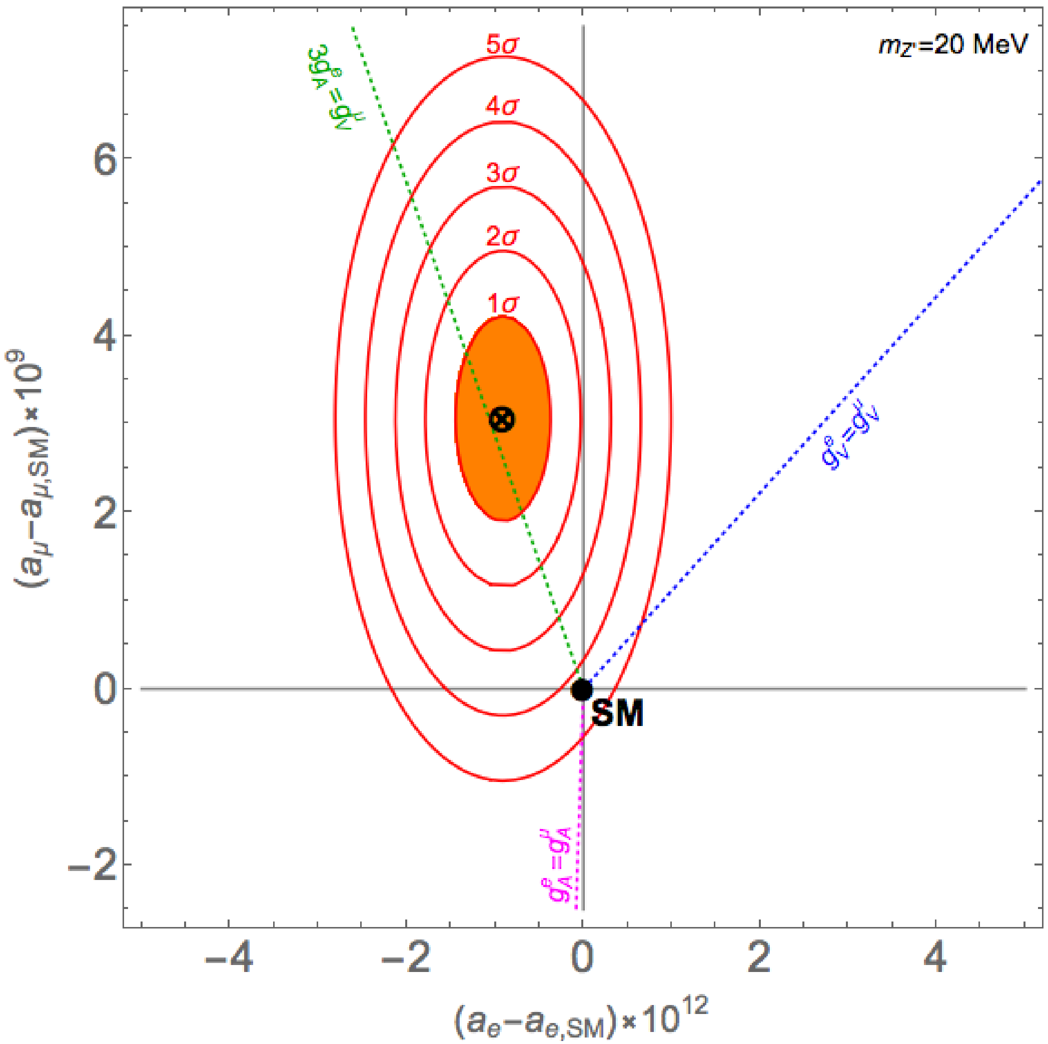


With theory and experiment central values unchanged, achieving target errors → 6.9σ discrepancy with KNT18

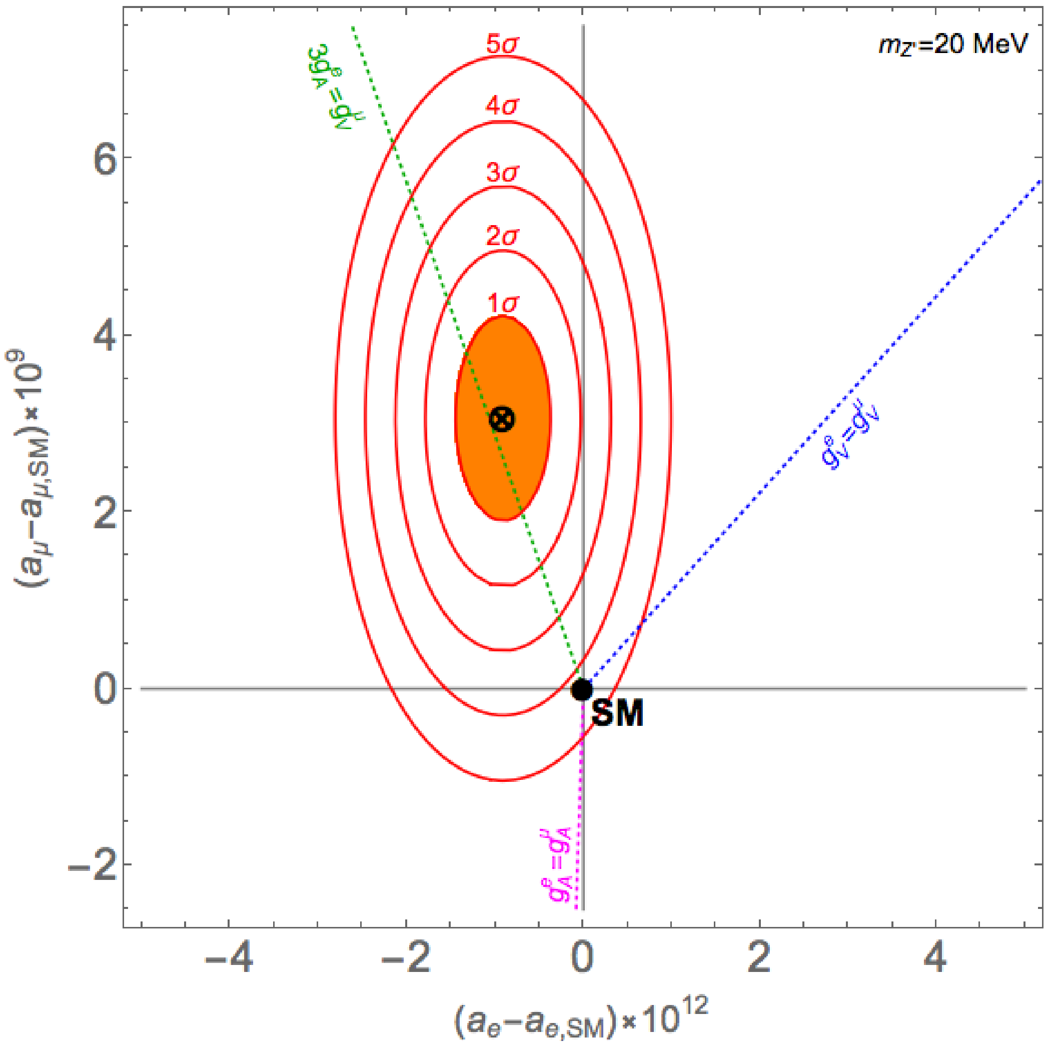


If experiment moves 1σ towards theory → 5.6σ discrepancy with KNT18

g-2 Discovery Potential



g-2 Discovery Potential



Two g-2 anomalies!

- **2.5σ for a_e**
- **~3.5σ for a_μ**
- **Combined deviation from SM > 4σ**

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.

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…**
  - $\delta_{<B>(\omega_p)}$ = 0.17 ppm → 0.07 ppm

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…**
  - $\delta_{<B>(\omega_p)}$ = 0.17 ppm → 0.07 ppm

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

Experimental: How to Measure?

Experimental: How to Measure?

The name of game changes: a → ω

- **Put (polarized) muons in a magnetic field and measure precession f.q.**

Experimental: How to Measure?

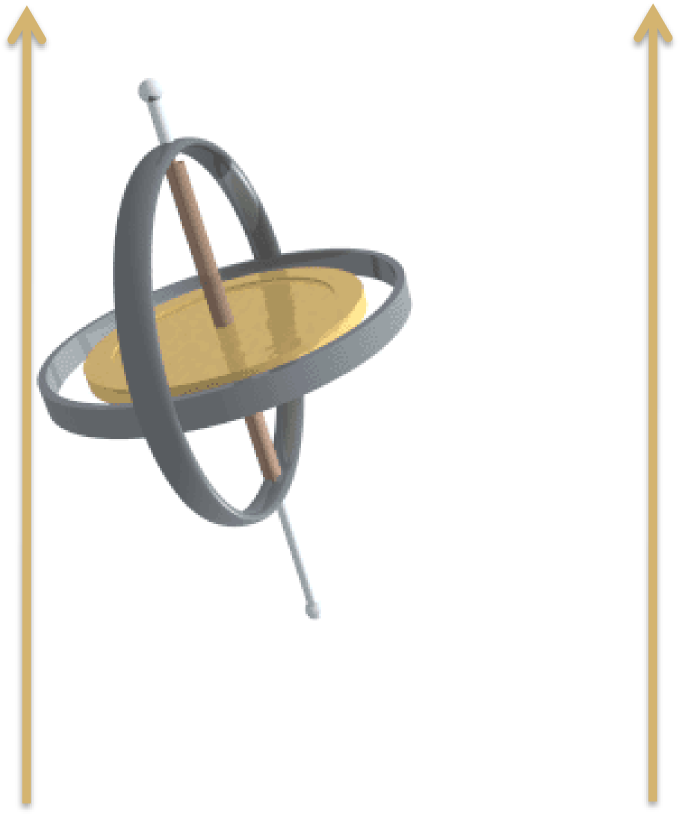
The name of game changes: a → ω

- **Put (polarized) muons in a magnetic field and measure precession f.q.**

Experimental: How to Measure?

The name of game changes: a → ω

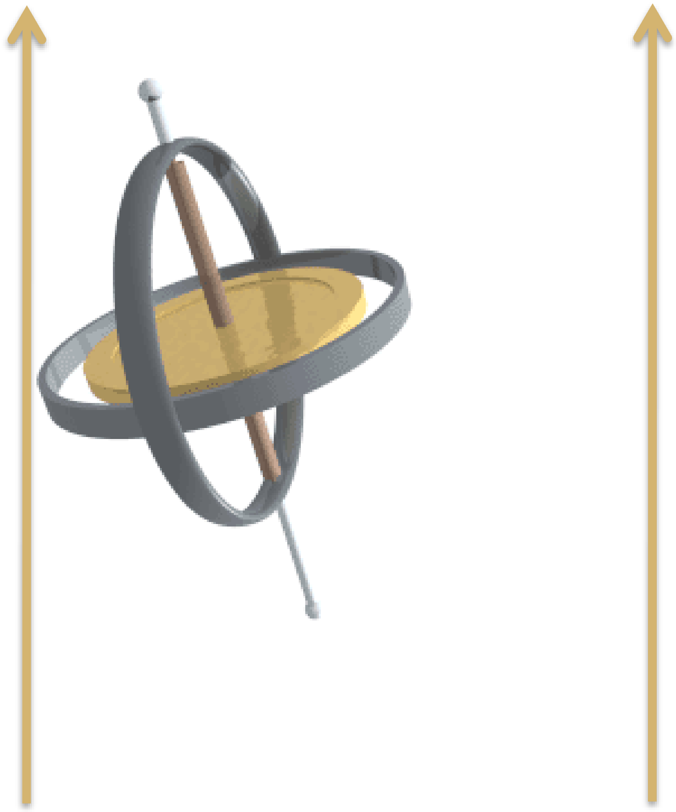
- **Put (polarized) muons in a magnetic field and measure precession f.q.**



Experimental: How to Measure?

The name of game changes: a → ω

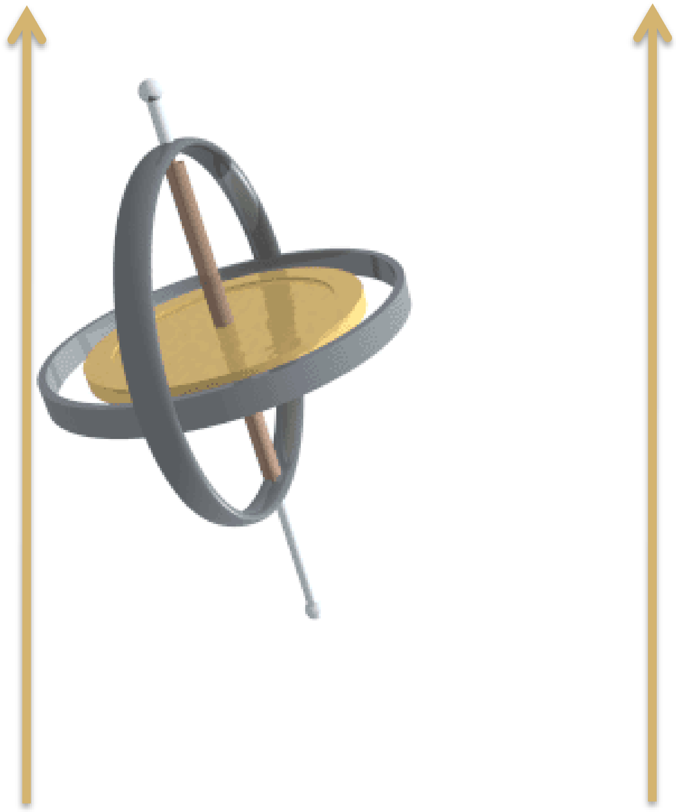
- **Put (polarized) muons in a magnetic field and measure precession f.q.**



Experimental: How to Measure?

The name of game changes: a → ω

- **Put (polarized) muons in a magnetic field and measure precession f.q.**

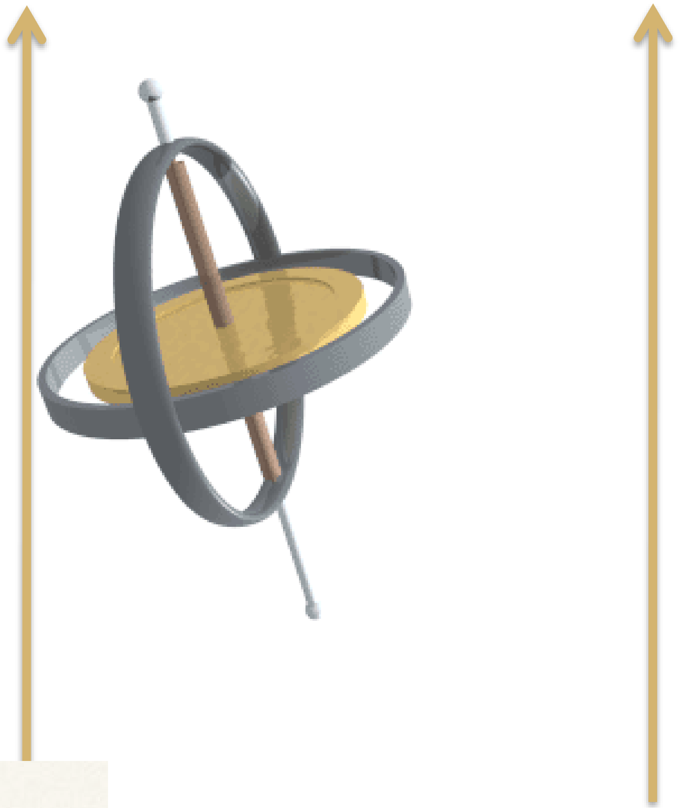


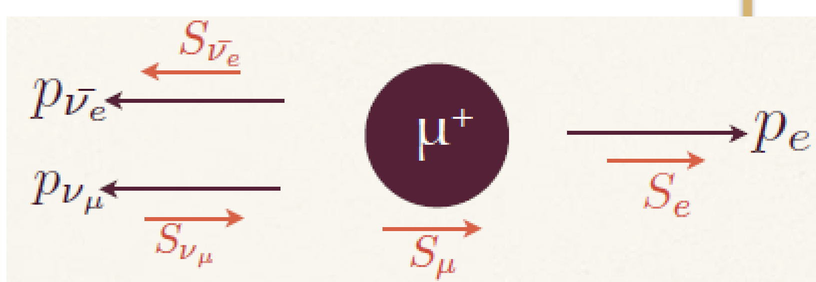
$$\omega_s = g\frac{eB}{2mc}$$

Experimental: How to Measure?

The name of game changes: a → ω

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



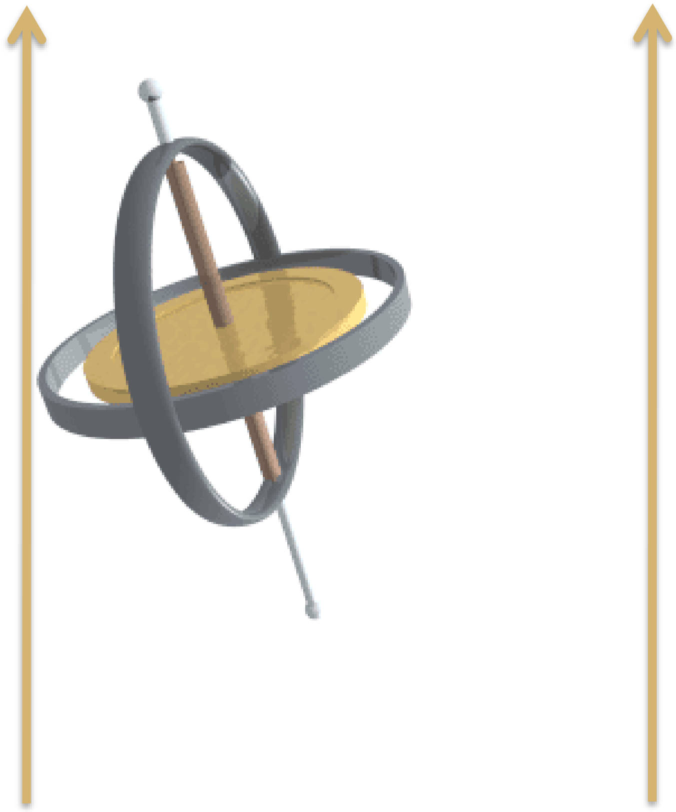


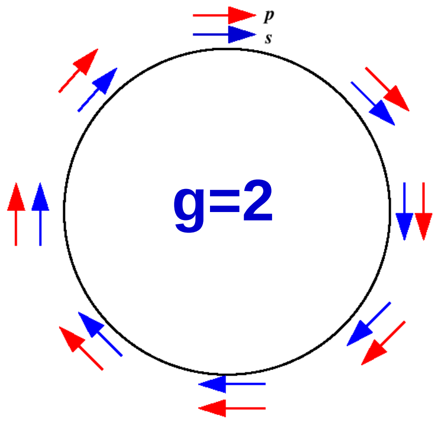
$$\omega_s = g\frac{eB}{2mc}$$

Experimental: How to Measure?

The name of game changes: 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**





$$\omega_c = \frac{eB}{mc}$$

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

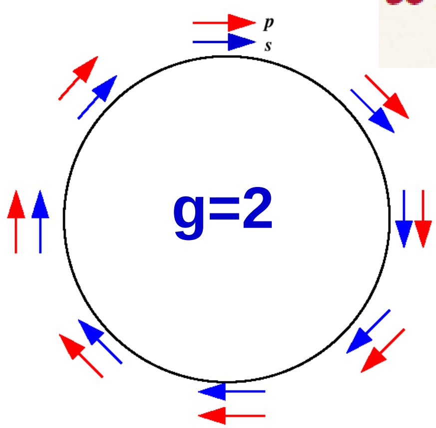
Experimental: How to Measure?

The name of game changes: a → ω

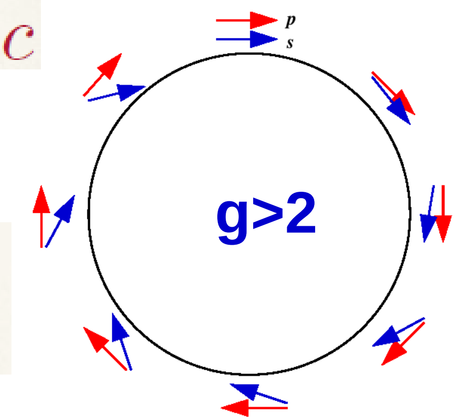
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

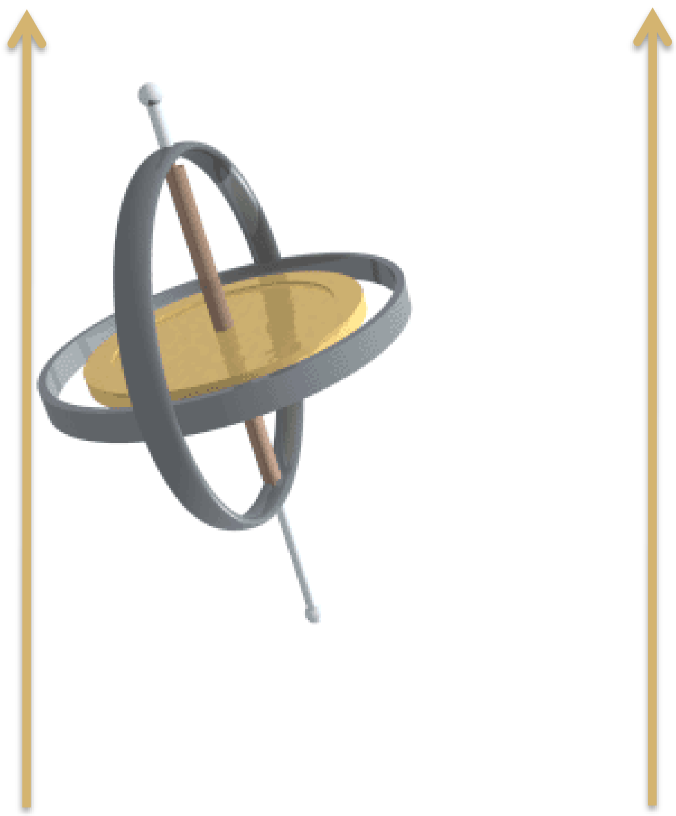
$$\omega_a = \omega_s - \omega_c$$

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



$$\omega_c = \frac{eB}{mc}$$





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

Frequency Measurements

Frequency Measurements

Frequency measurements can be done in very high precision

Frequency Measurements

Frequency measurements can be done in very high precision

Frequency Measurements

Frequency measurements can be done in very high precision

- **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 ($\omega_p \sim |B|$)**
  - **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**

Frequency Measurements

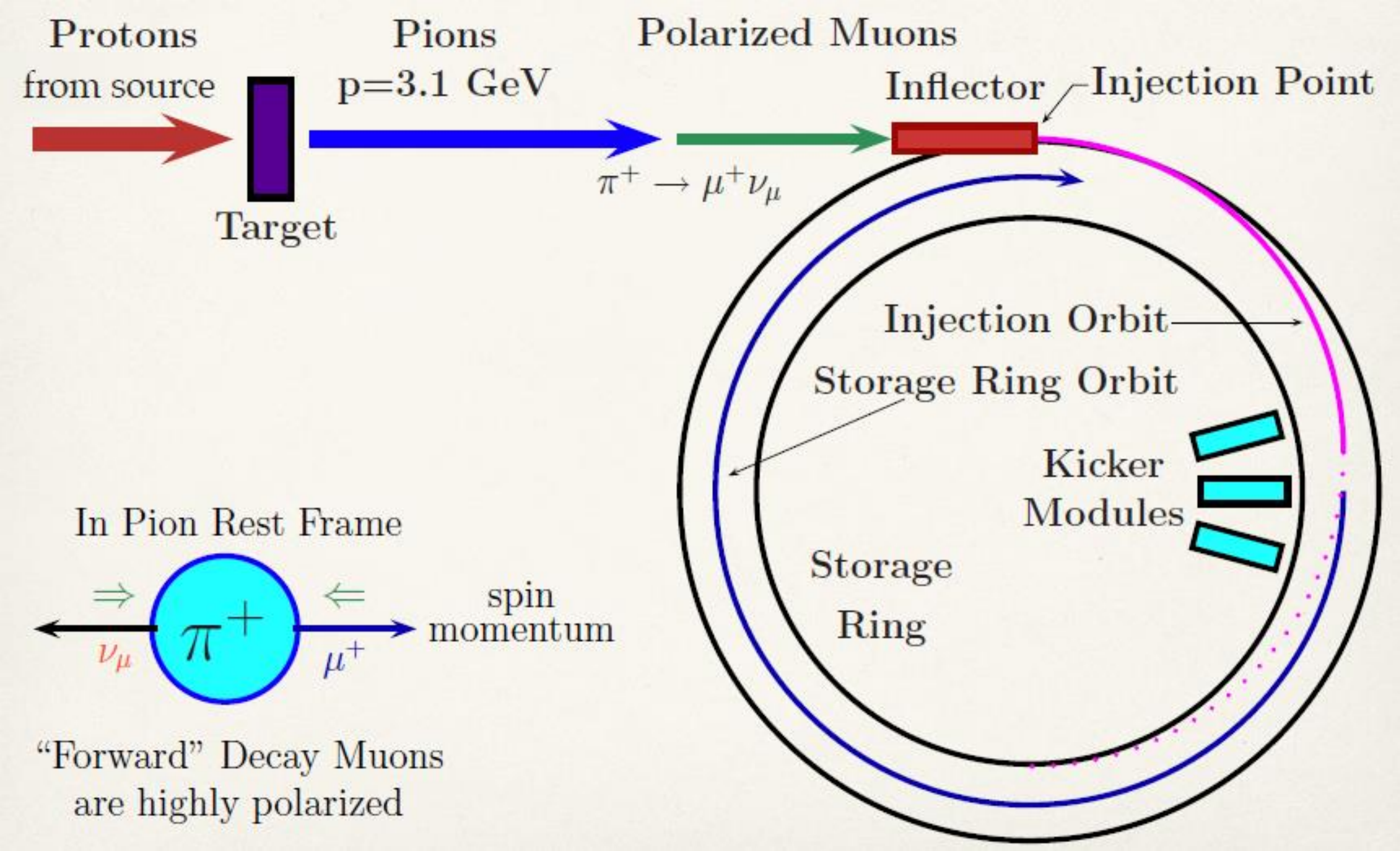
Frequency measurements can be done in very high precision

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

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

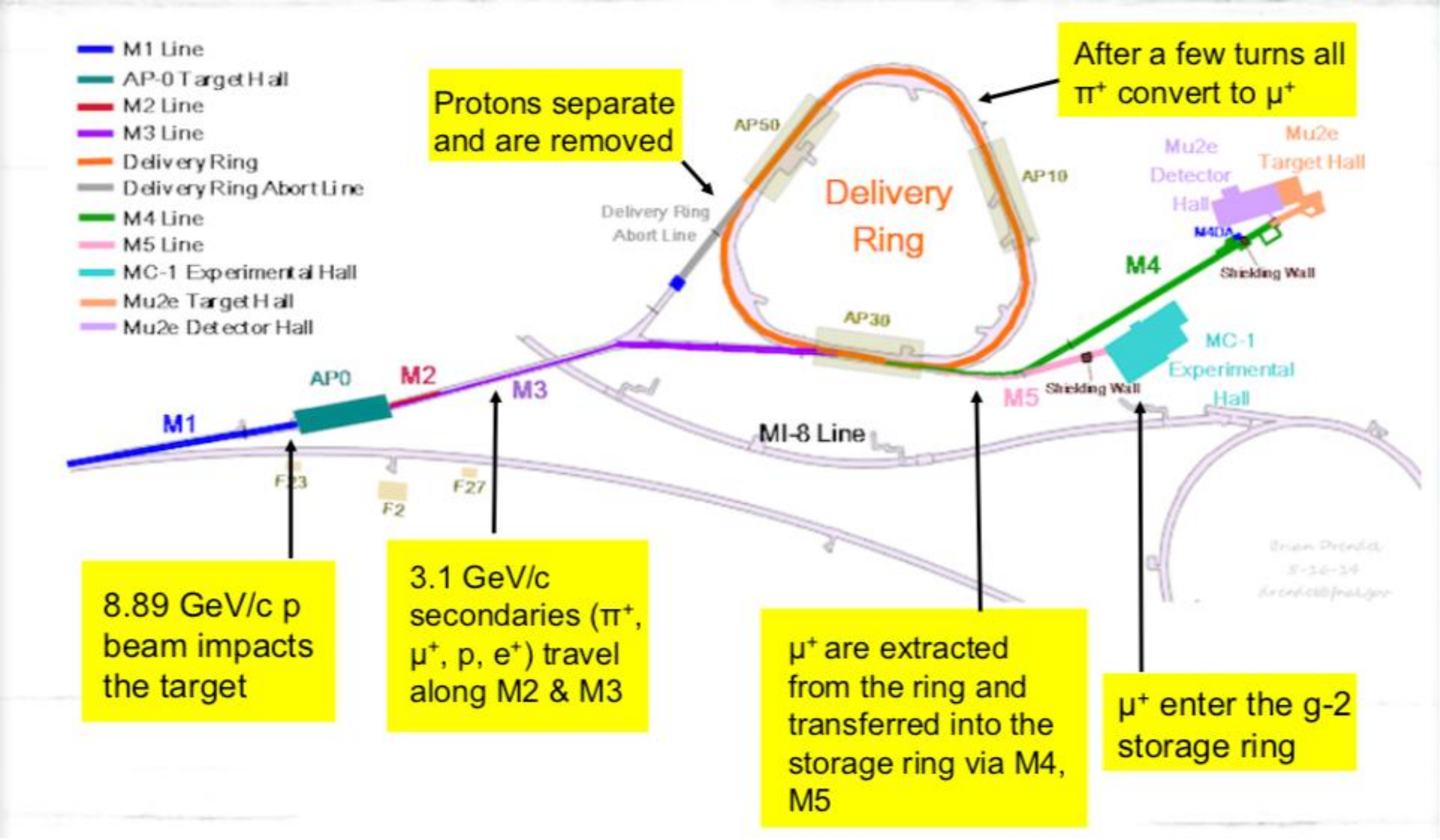
  - ω_p is the proton precession frequency ($\omega_p \sim |B|$)
  - ϖ_p is the weighted magnetic field folded with muon distribution
  - All other values from Committee on Data for Science and Technology (CODATA), uncertainty < 25 pb
    - E.g. muon-to-electron mass ratio by muonium hyperfine structure experiment
- **Final measurements done in three steps**
  - Inject ~3 GeV 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

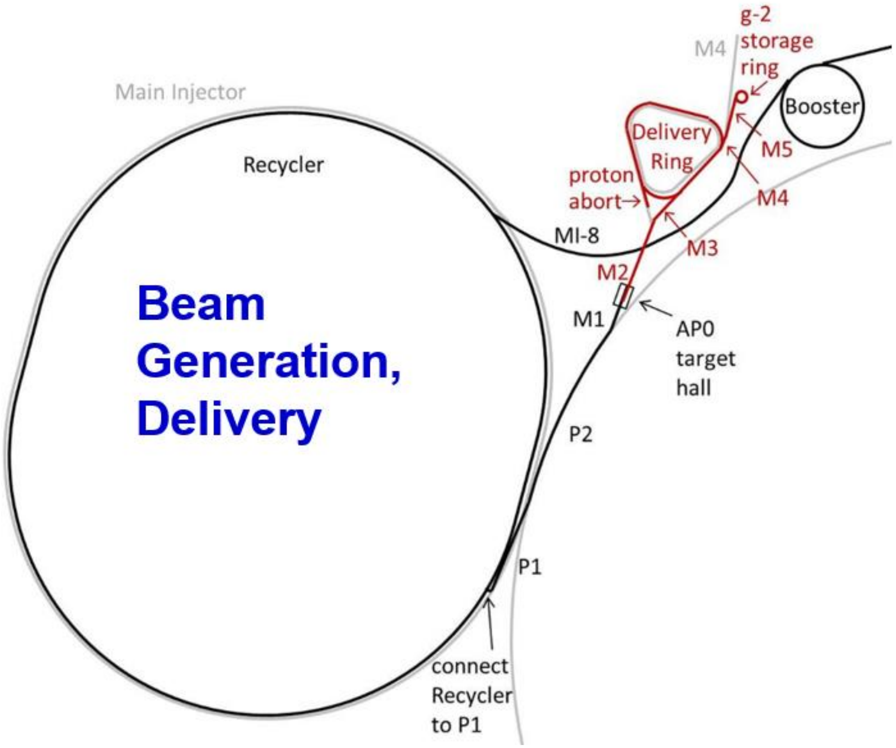


Muon Storage and Measurement

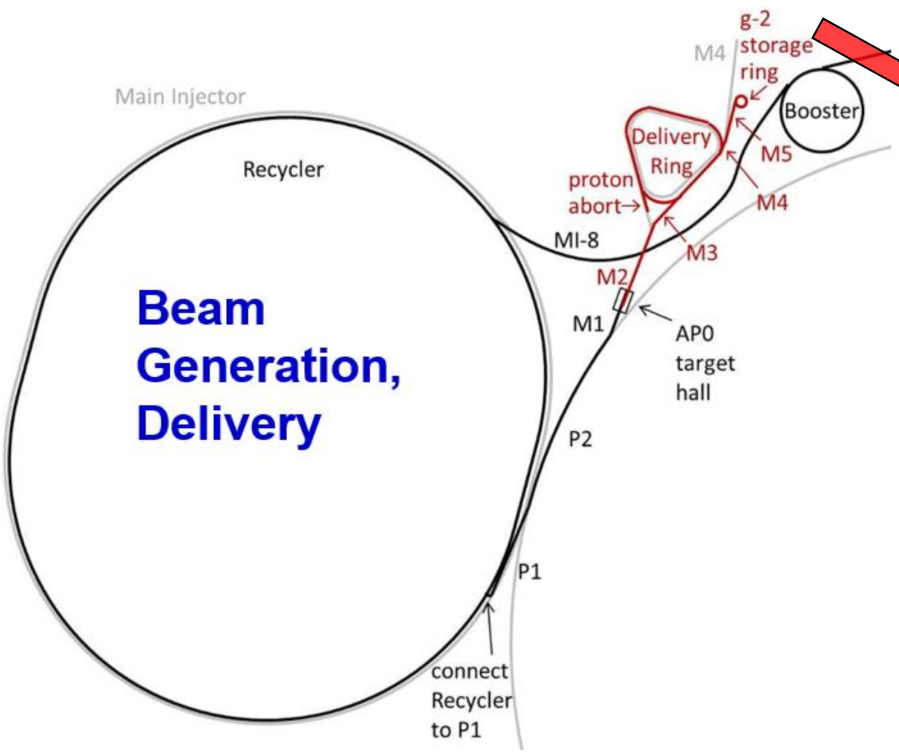
Muon Storage and Measurement



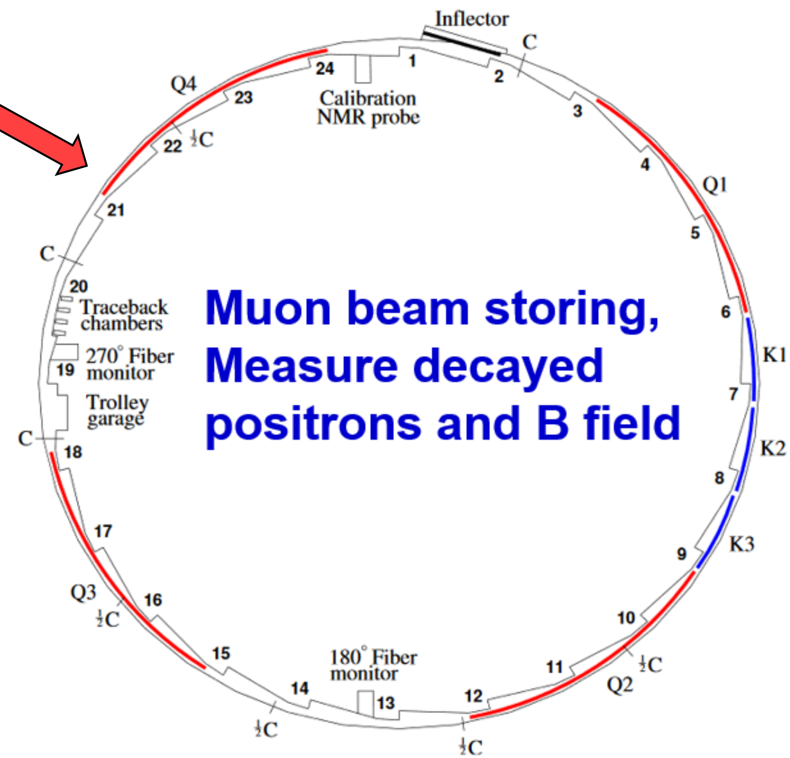
Muon Storage and Measurement



Muon Storage and Measurement

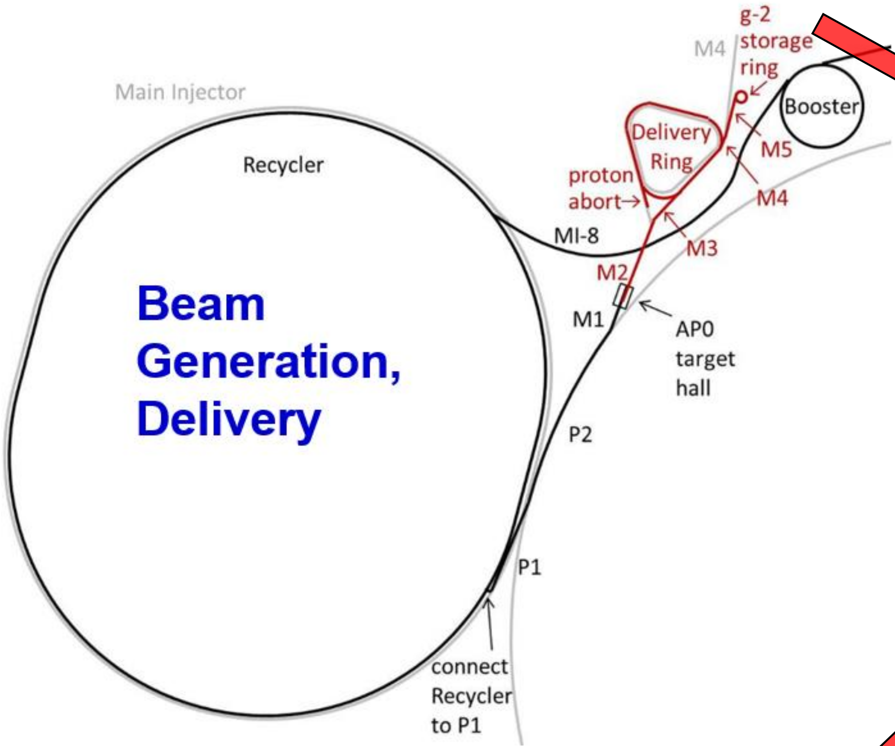


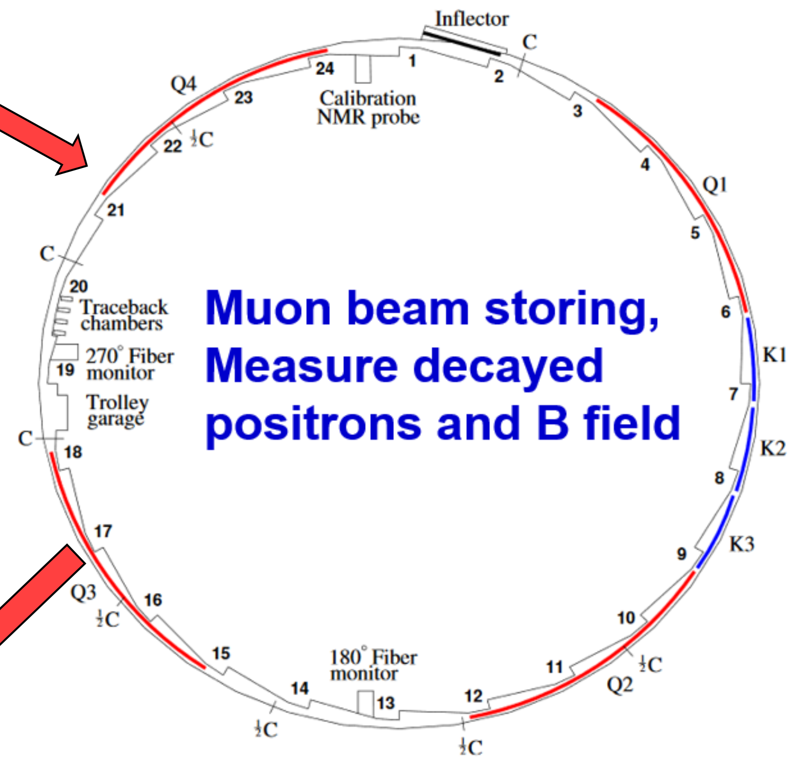
Beam Generation, Delivery

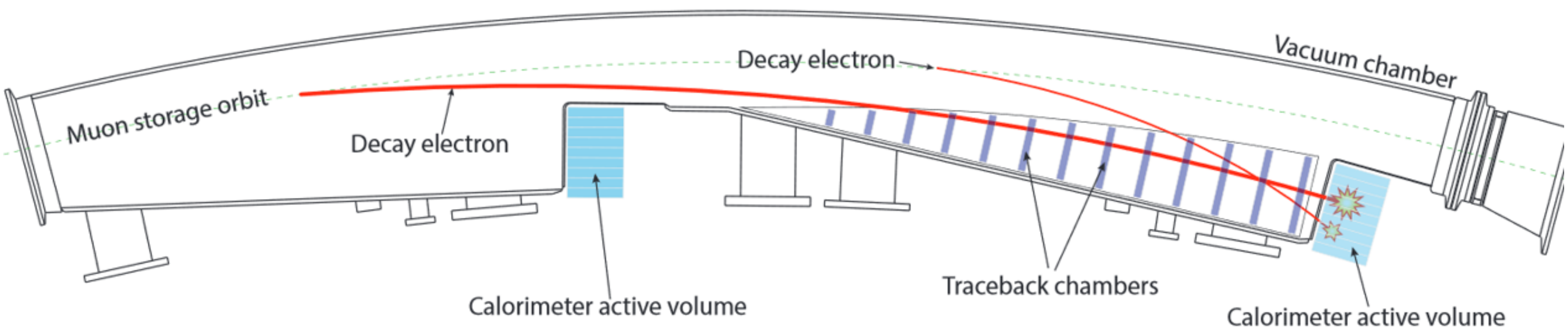


Muon beam storing, Measure decayed positrons and B field

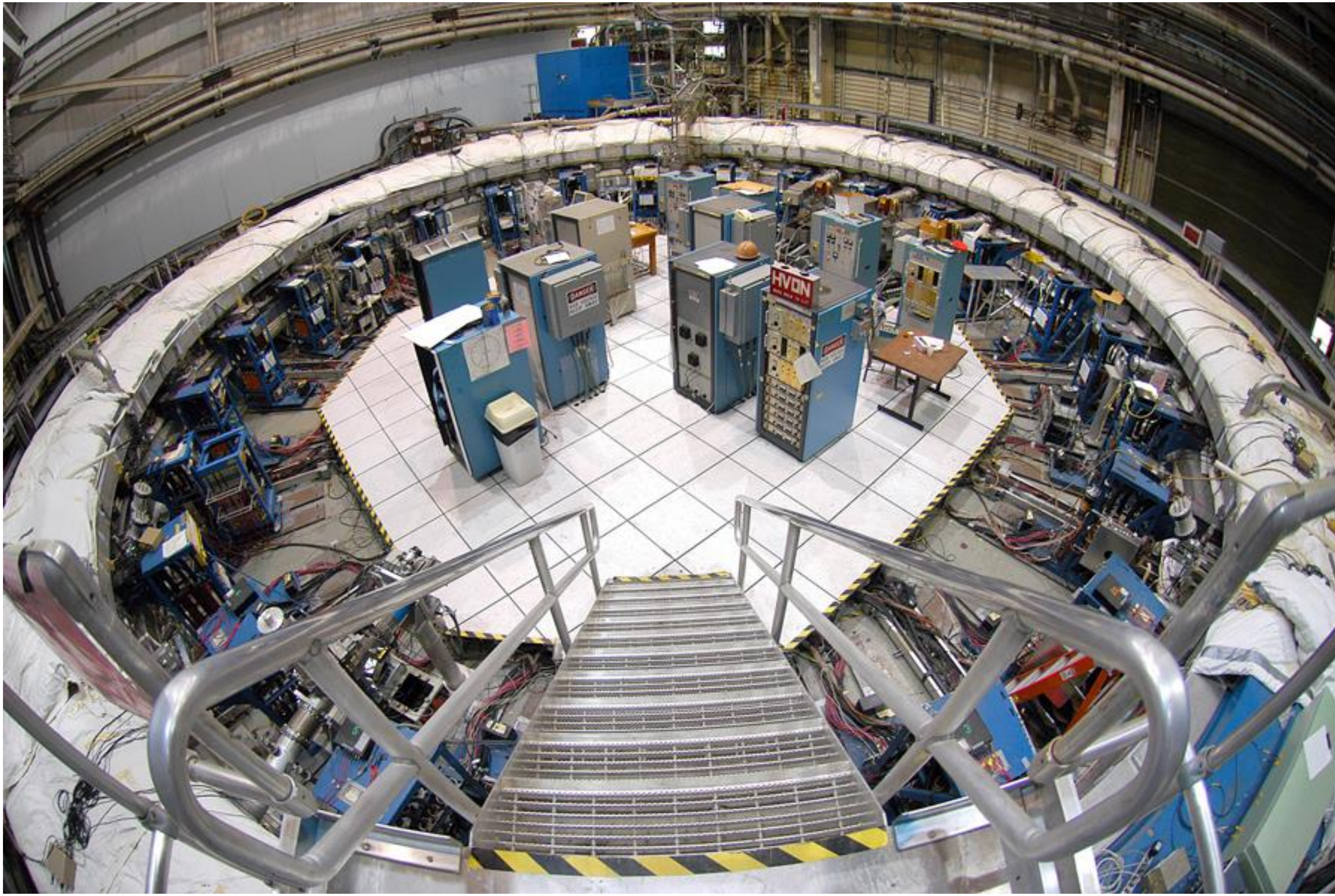
Muon Storage and Measurement



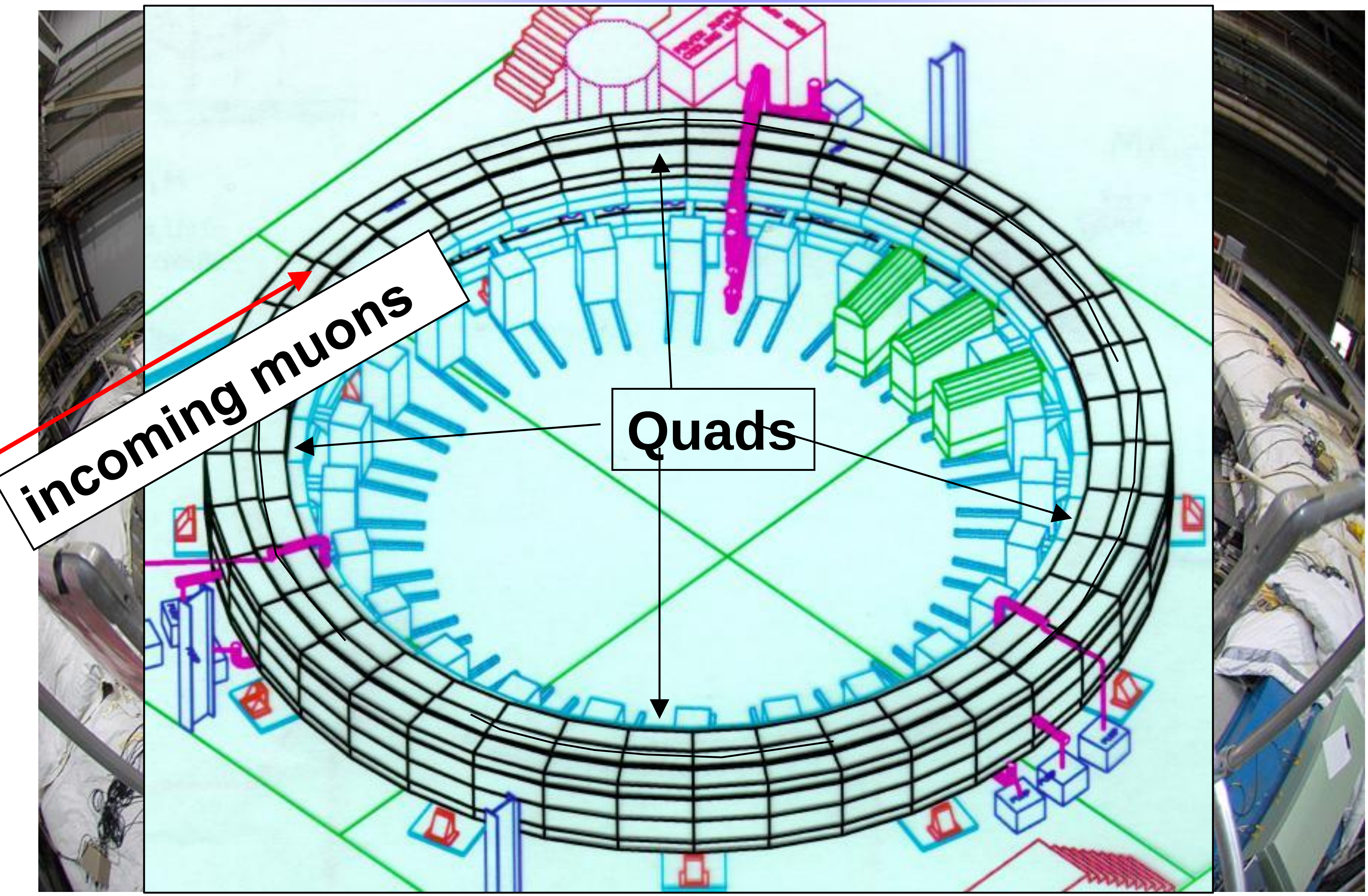




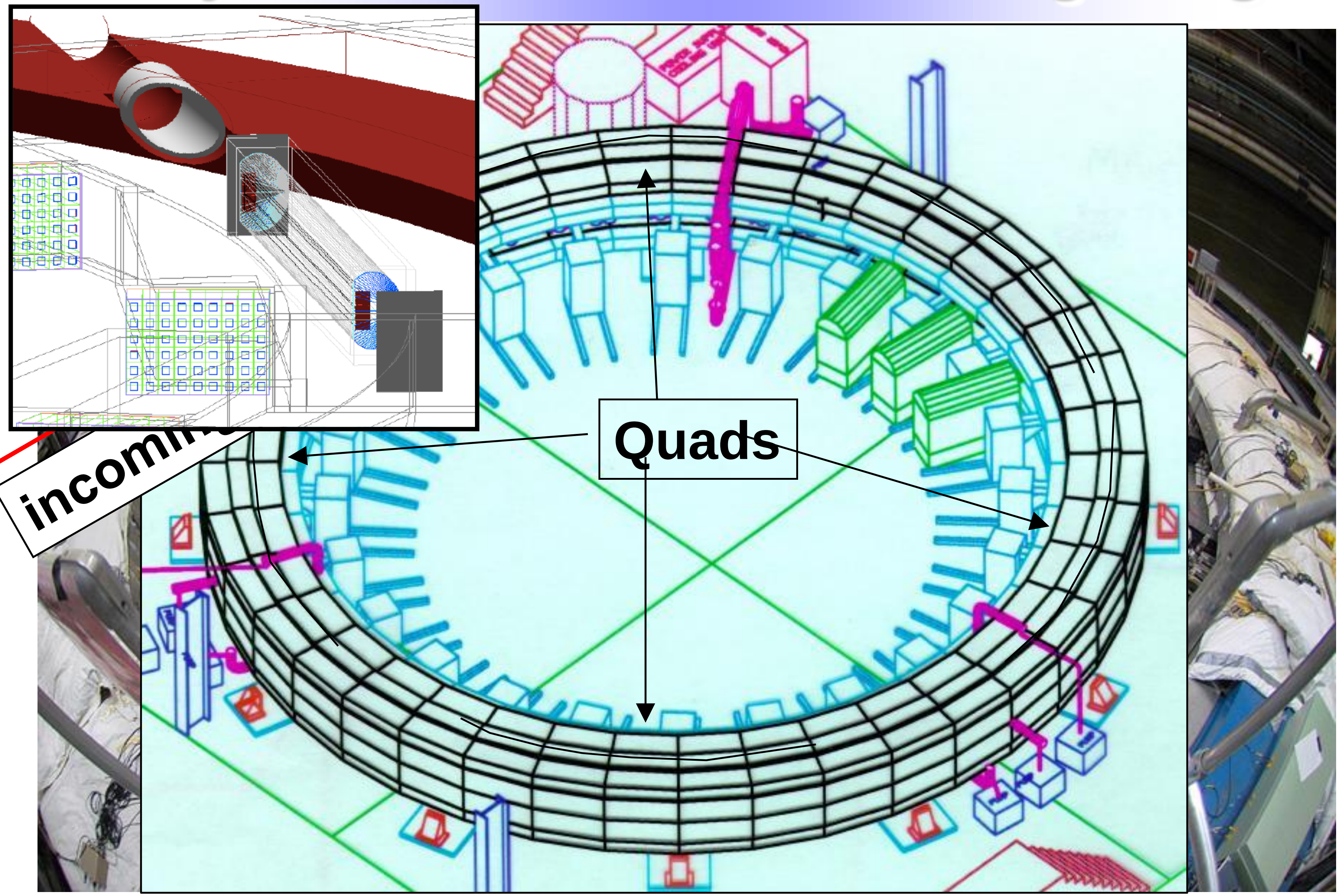
Injection into the muon storage ring



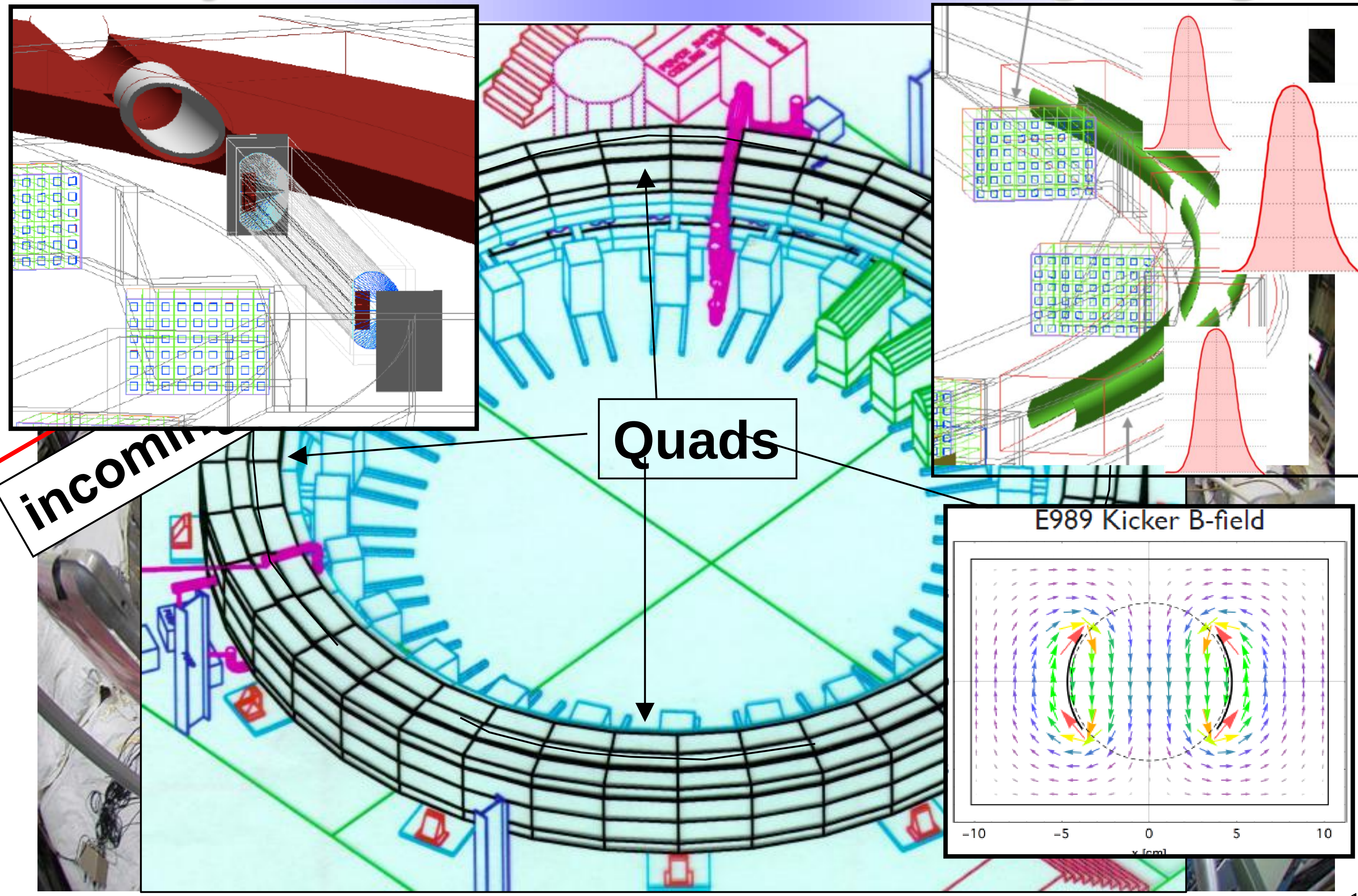
Injection into the muon storage ring



Injection into the muon storage ring



Injection into the muon storage ring



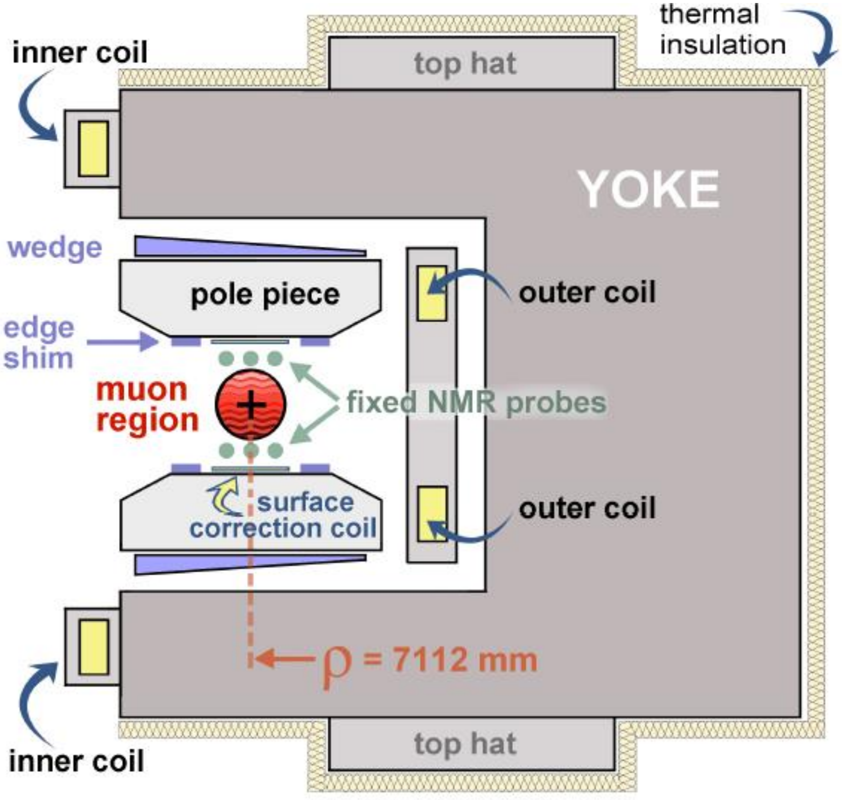
Magnetic Shimming

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

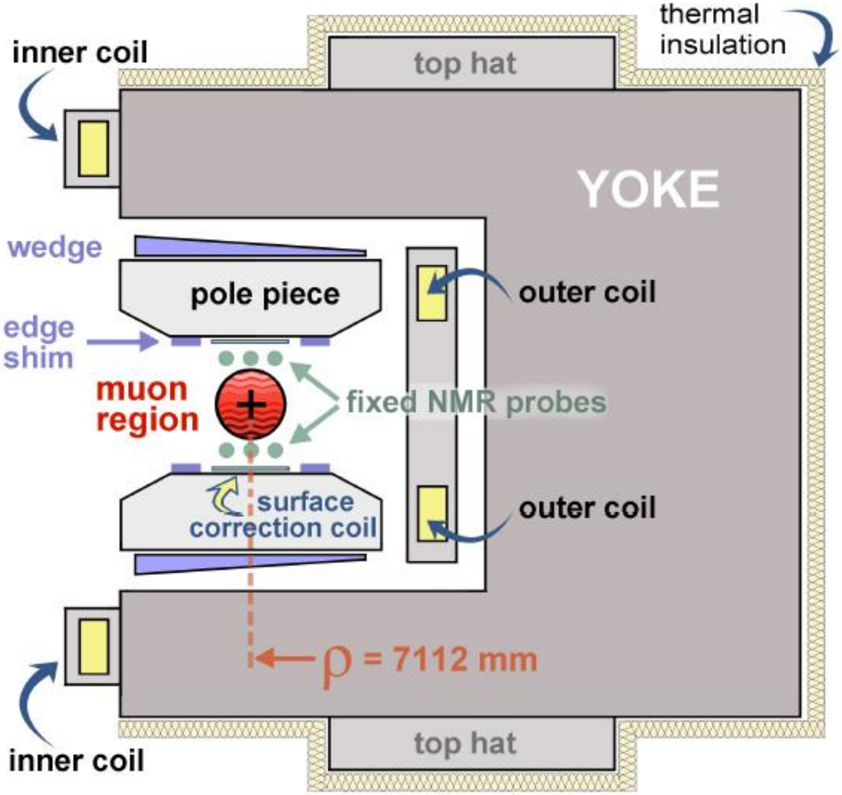


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- 1 B field ~ 1.45T

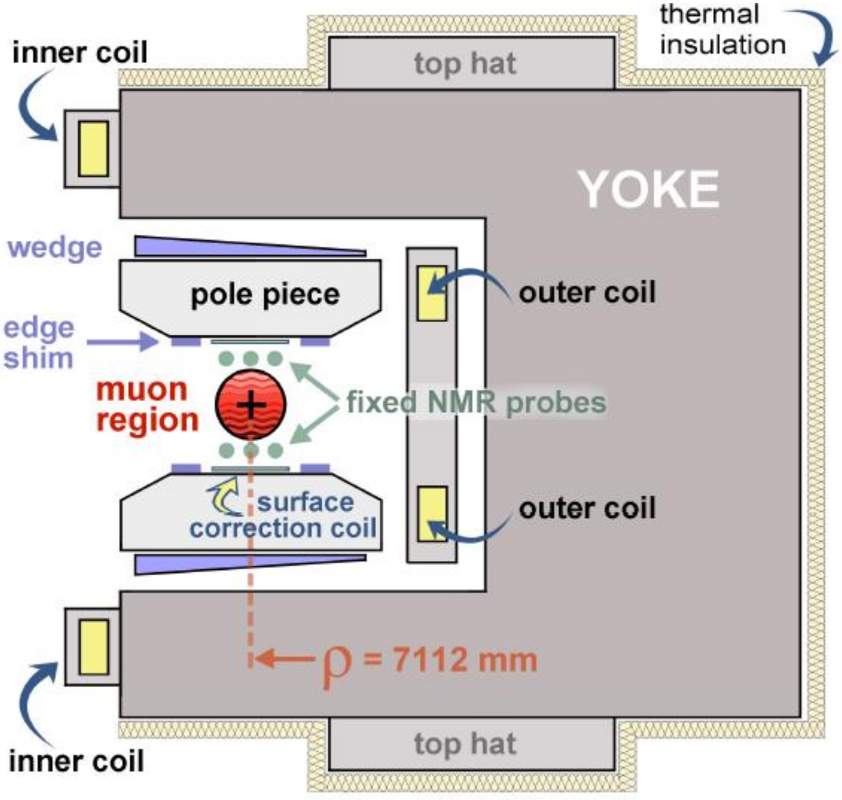


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- **1 B field ~ 1.45T**

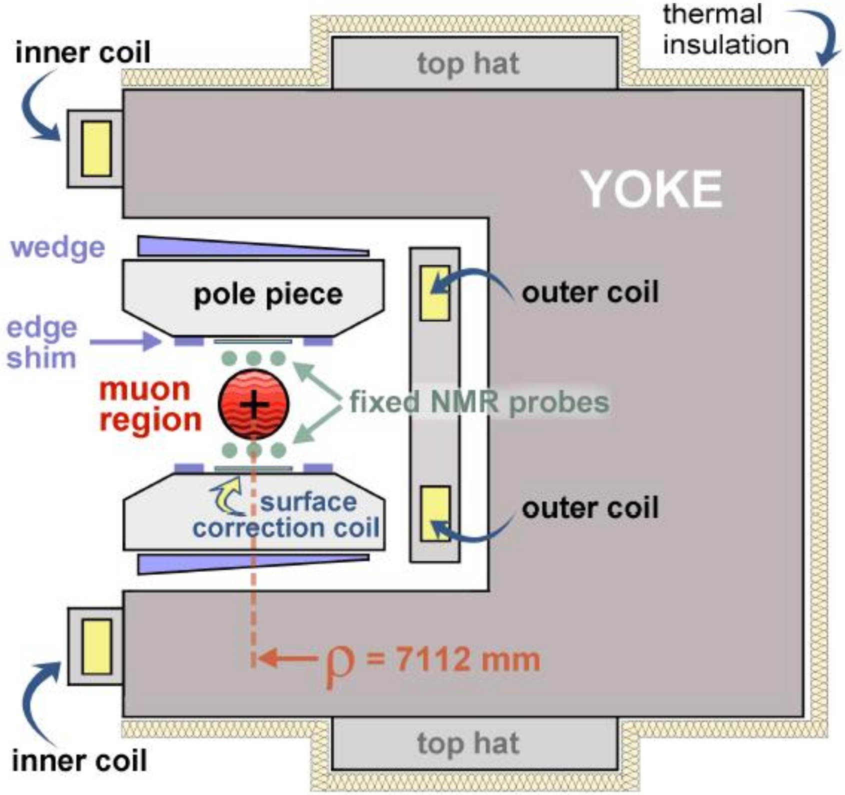


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- **1 B field ~ 1.45T**
- **12 C shape flux return yokes**

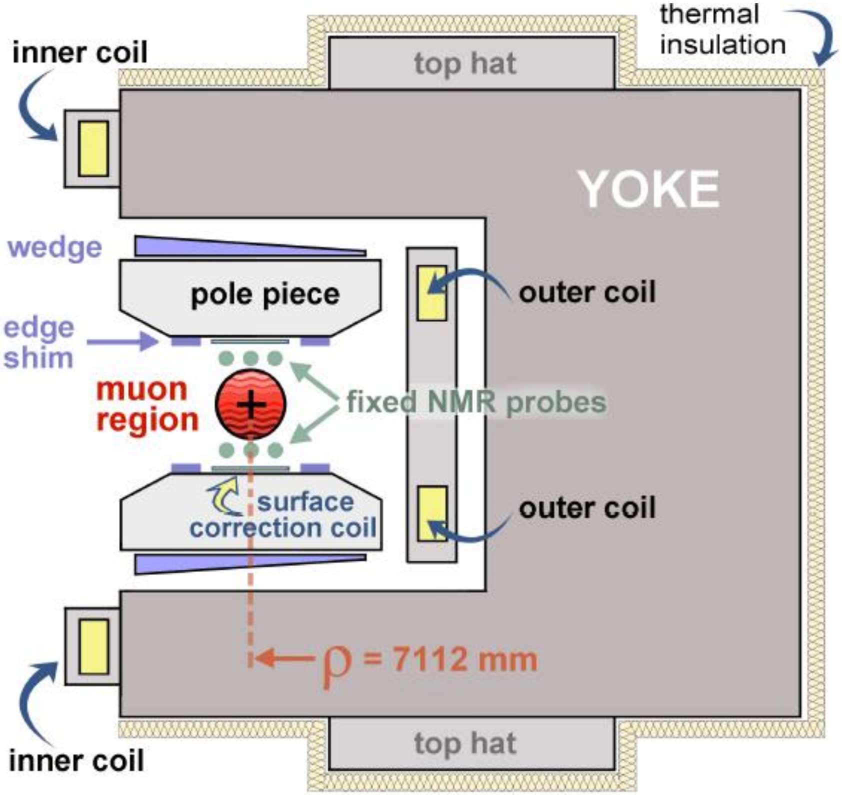


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T

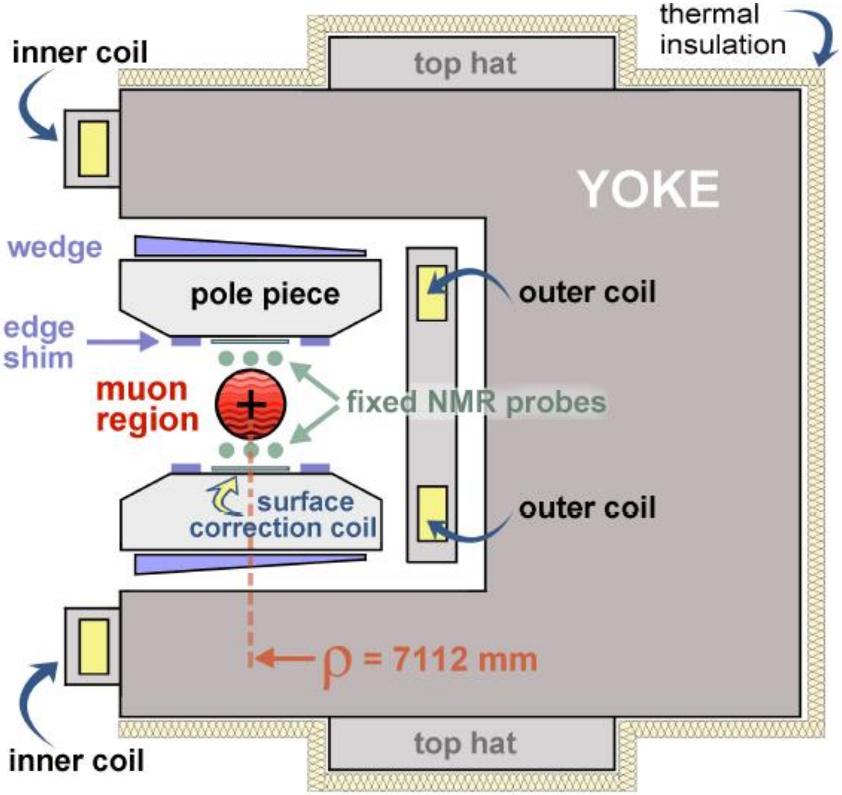


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- **1 B field ~ 1.45T**
- **12 C shape flux return yokes**
- **72 poles**
  - **Minimizing higher-order multipoles**
  - **Dipole moment ~ 1.45T**

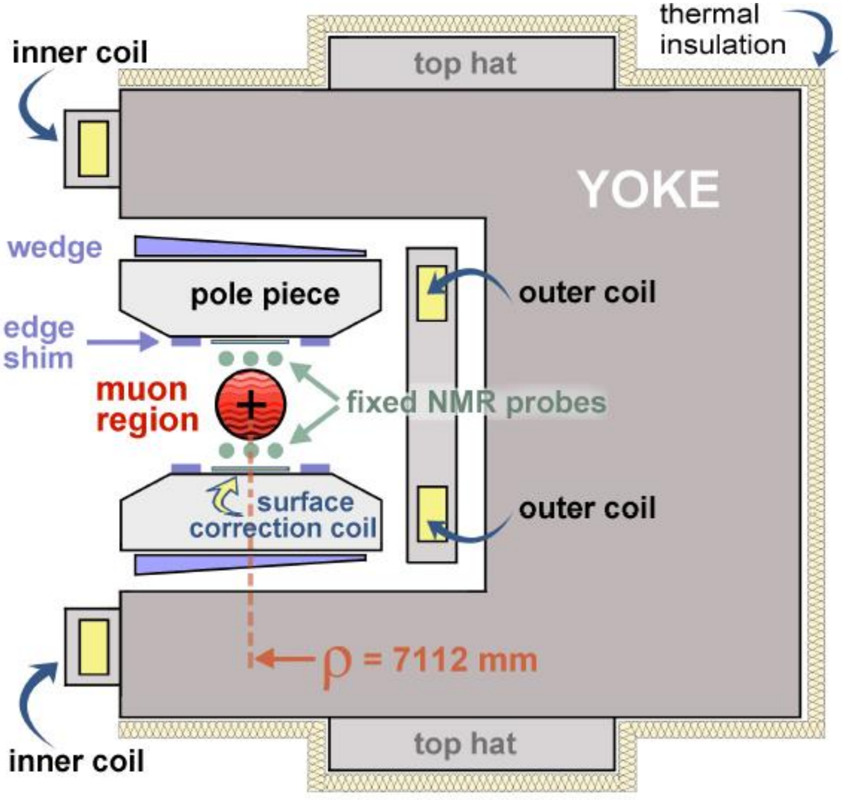


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T
- Field Shimming

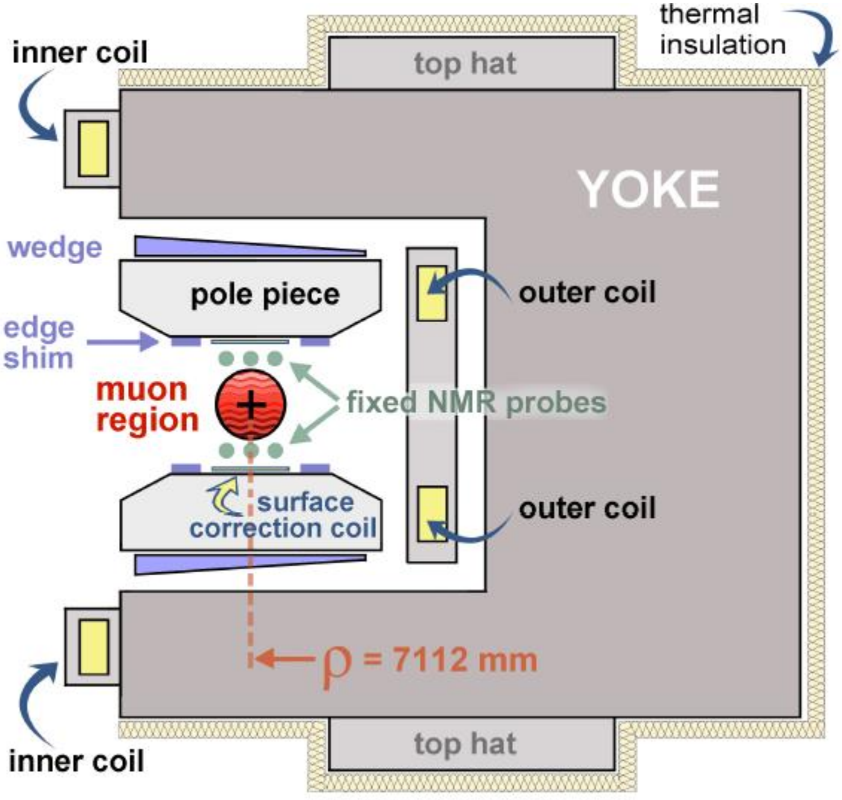


g-2 Magnet in Cross Section

Magnetic Shimming

Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T
- Field Shimming
  - Passive shim method (geometry)
    - 24 iron top hats
    - 864 wedges: angle quadrupole
    - >1000 edge shims: sextapole
    - >8000 surface iron foils

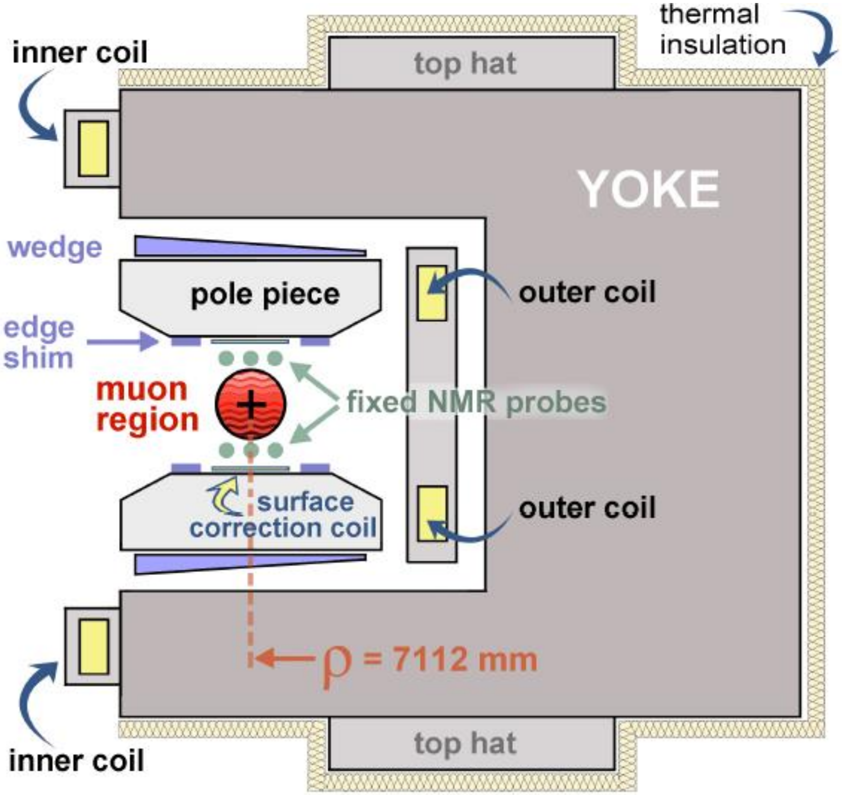


g-2 Magnet in Cross Section

Magnetic Shimming

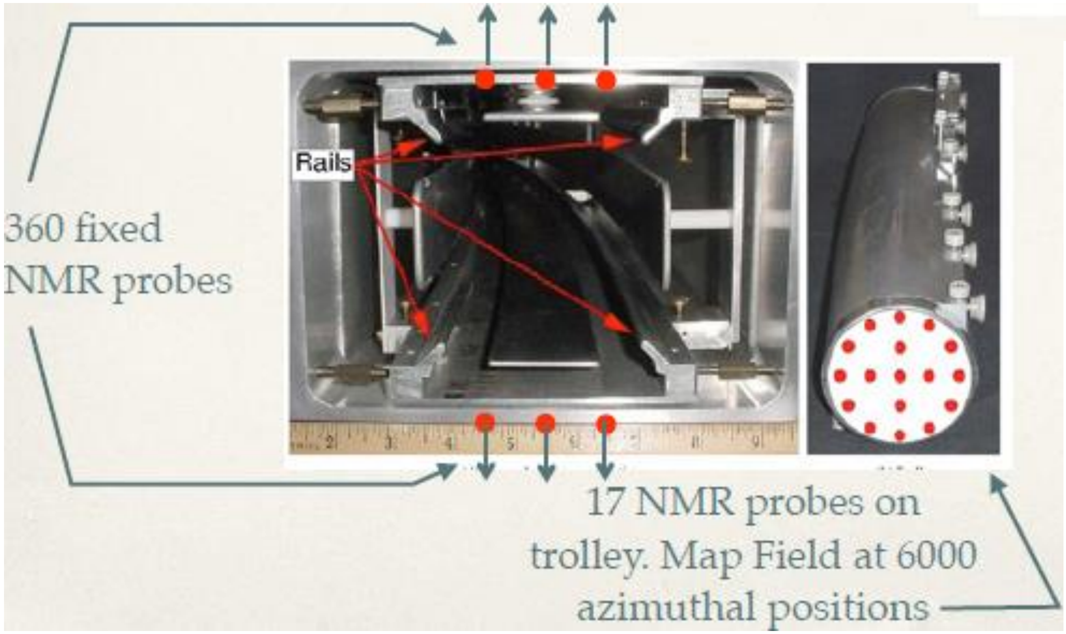
Magnetic field need to be uniform to ±1 ppm level averaged over azimuth

- 1 B field ~ 1.45T
- 12 C shape flux return yokes
- 72 poles
  - Minimizing higher-order multipoles
  - Dipole moment ~ 1.45T
- Field Shimming
  - Passive shim method (geometry)
    - 24 iron top hats
    - 864 wedges: angle quadrupole
    - >1000 edge shims: sextapole
    - >8000 surface iron foils
  - Active shim method (current)
    - Surface correction coil
    - Power supply feedback

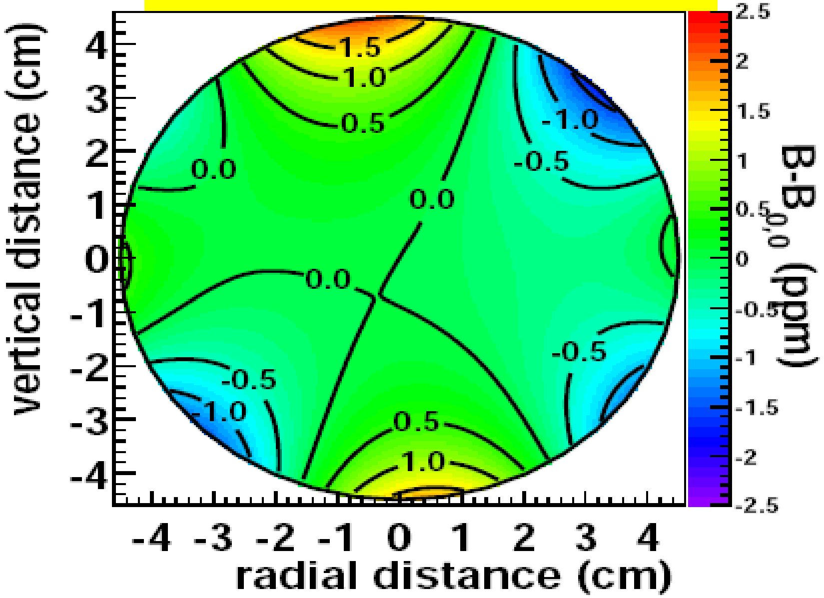


g-2 Magnet in Cross Section

Measuring ω_p, namely the B field



Contours in [ppm]!

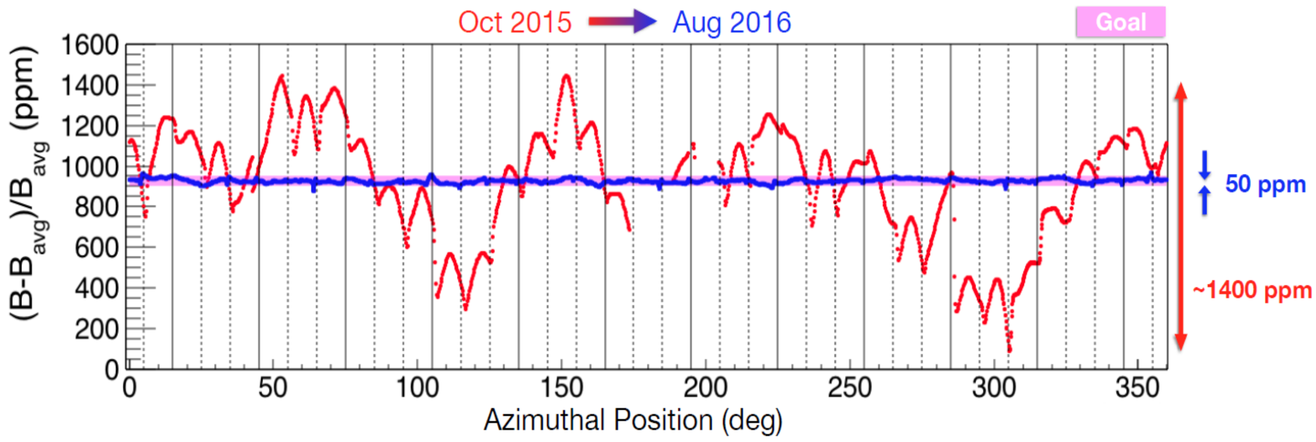


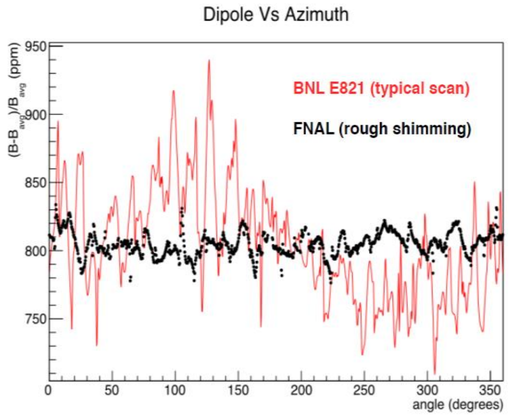
Use trolley and high precision (~10ppb) nuclear magnetic resonance (NMR) probes

- **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: trolley run**
- **Absolute and cross calibration of all probes**
- **Shimming techniques to better produce uniform B field**

B Field Measurements

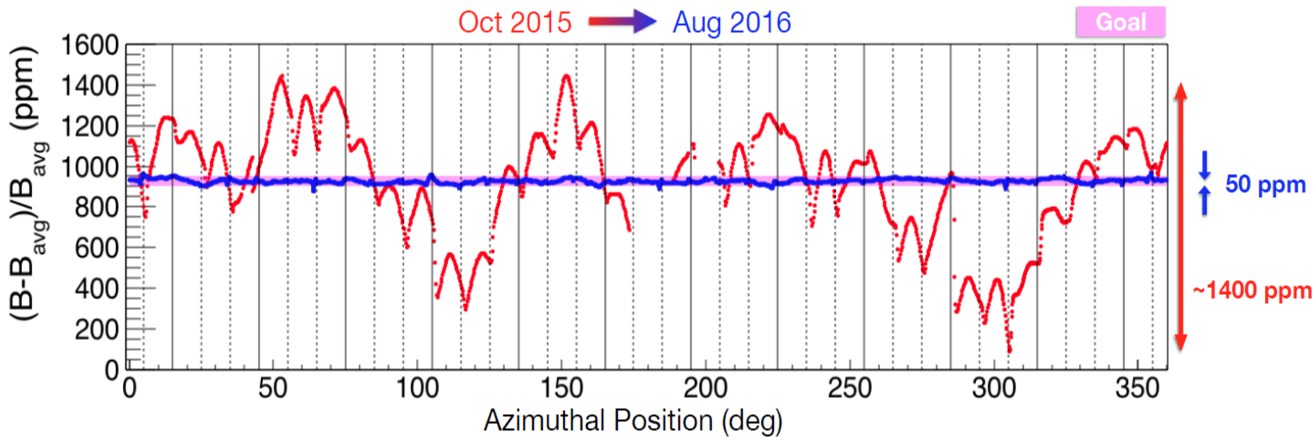
B Field Measurements

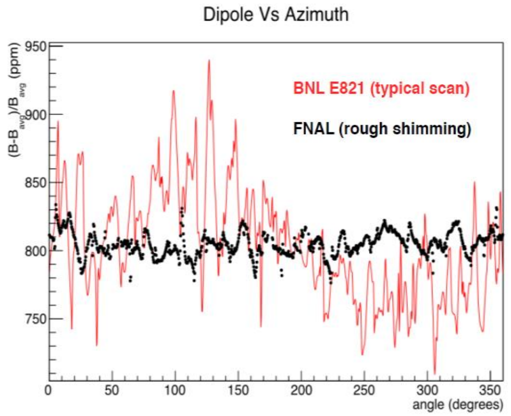




Shim 1.45 T field to high uniformity and measure it vs time

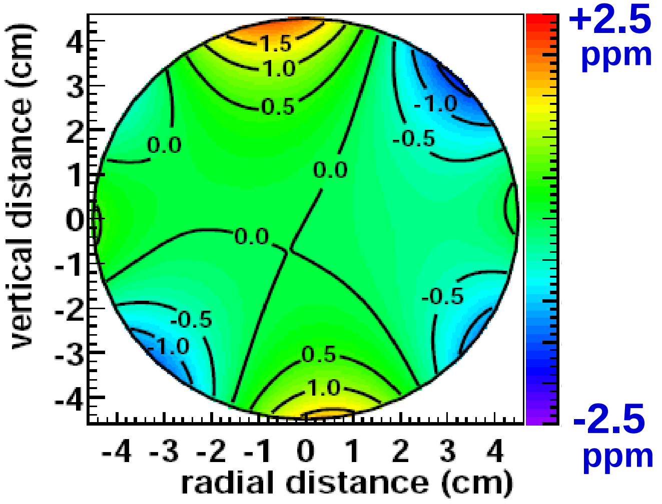
B Field Measurements



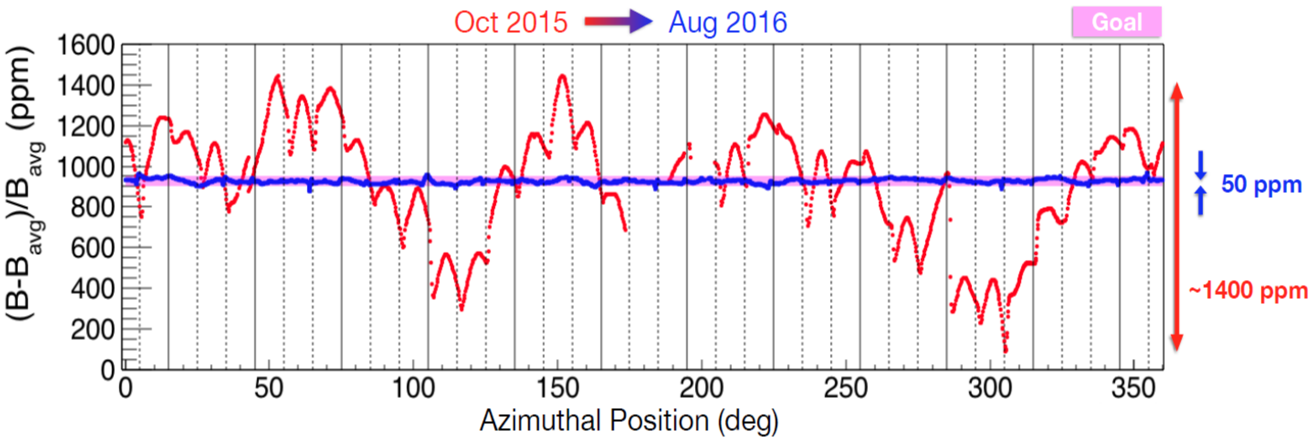


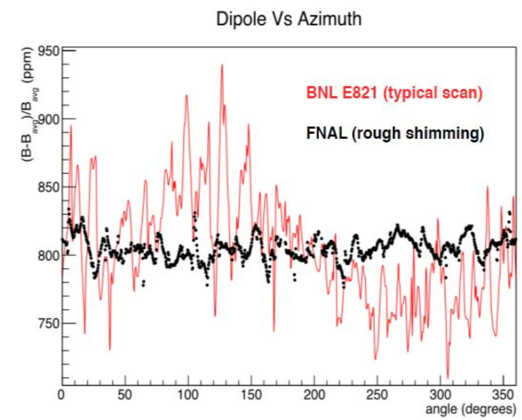
Shim 1.45 T field to high uniformity and measure it vs time

BNL Field Map



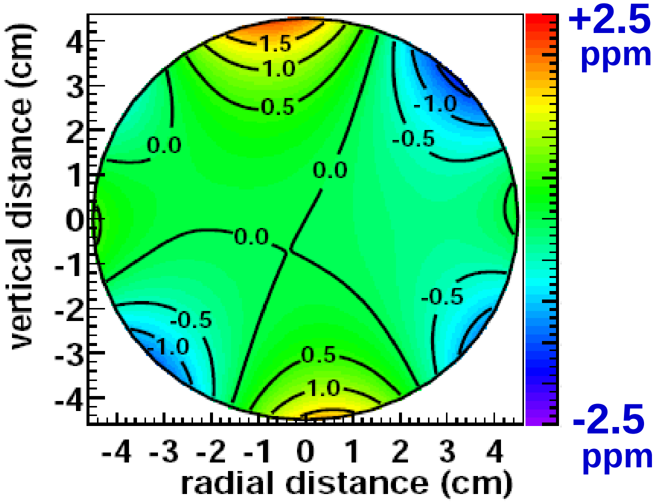
B Field Measurements





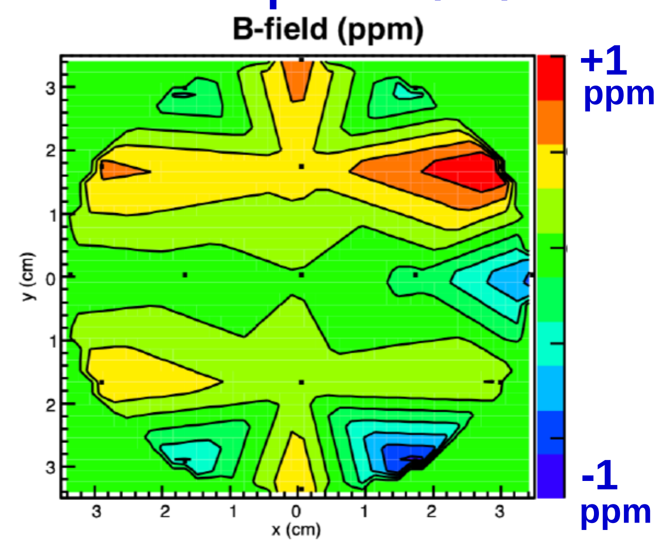
Shim 1.45 T field to high uniformity and measure it vs time

BNL Field Map



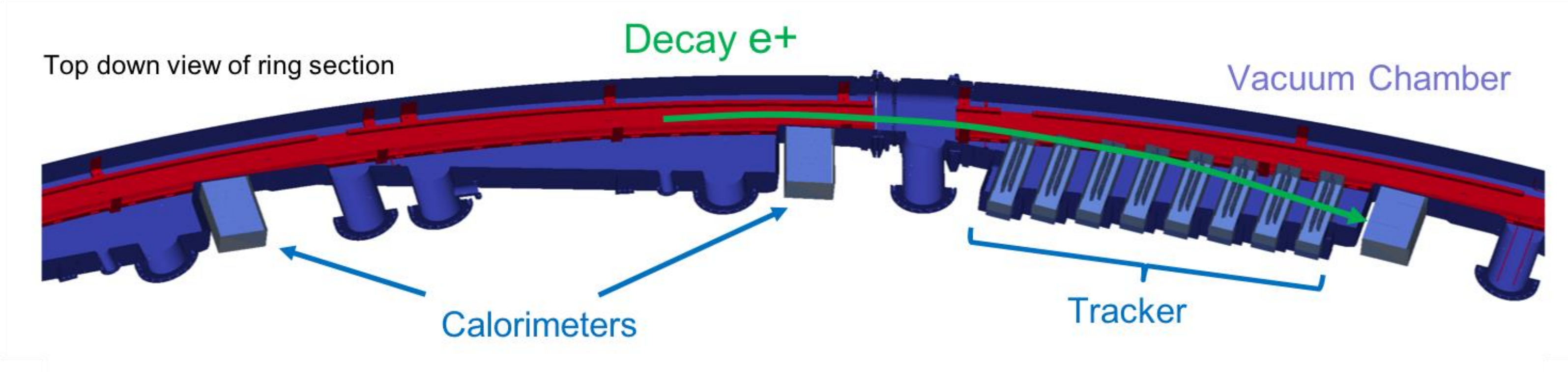
Averaged over azimuth: Shimmed to ±1 ppm level

Field Map on 03/17/2018

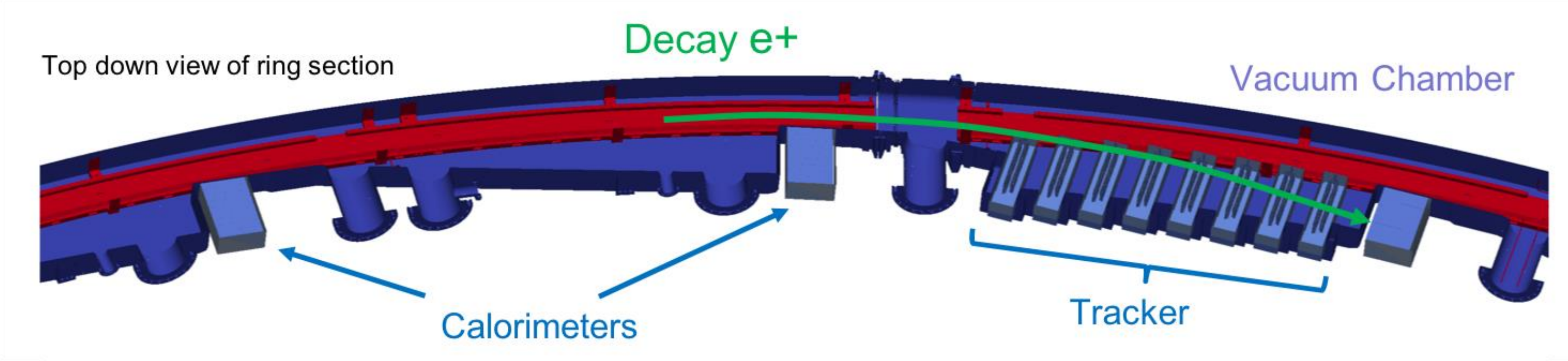


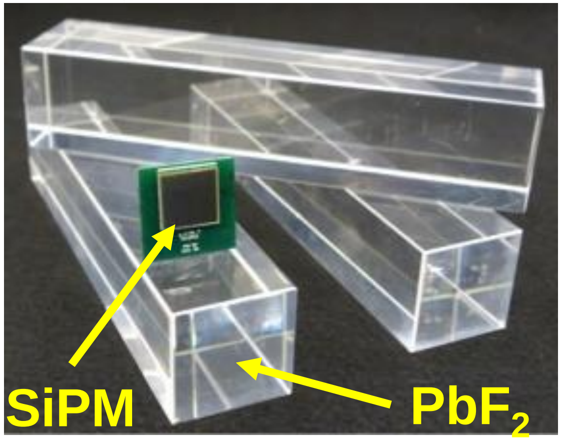
Detector performance: calorimeter

Detector performance: calorimeter



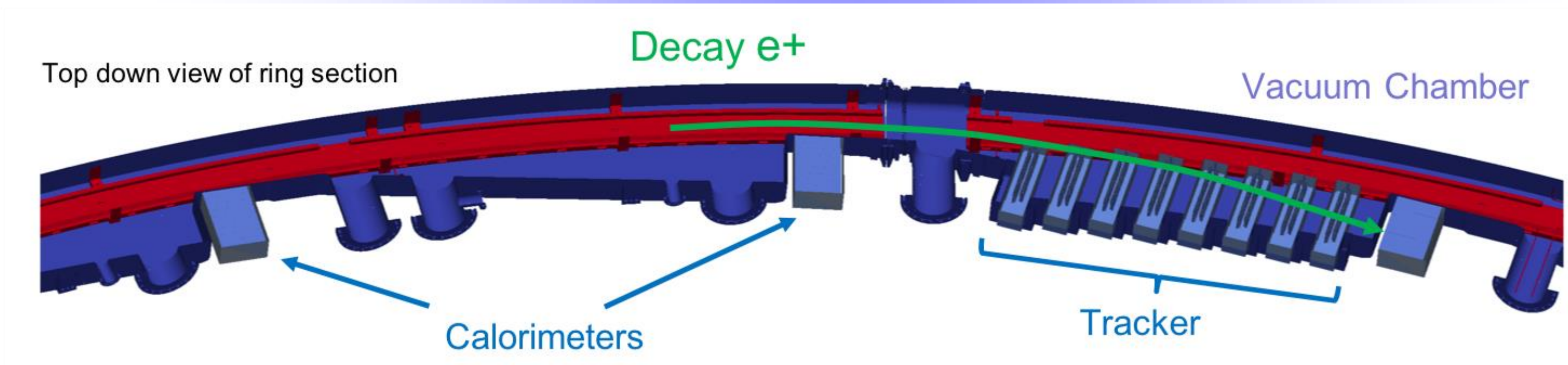
Detector performance: calorimeter

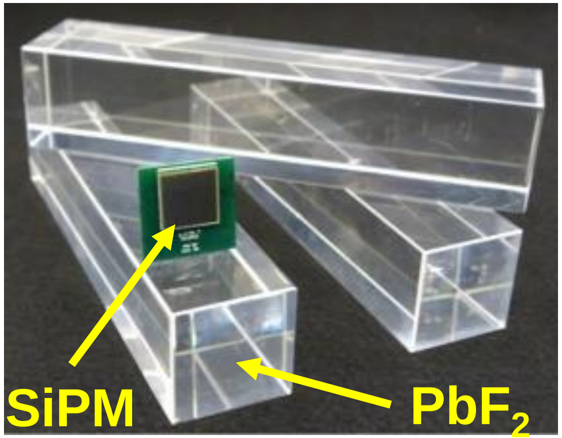


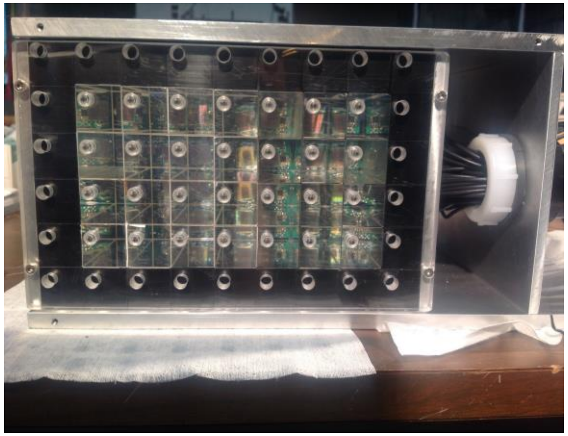


Segmented, fast response, crystal calorimeter (9X6 array)

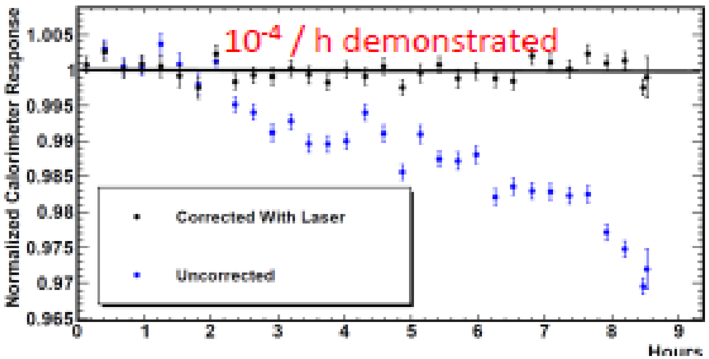
Detector performance: calorimeter





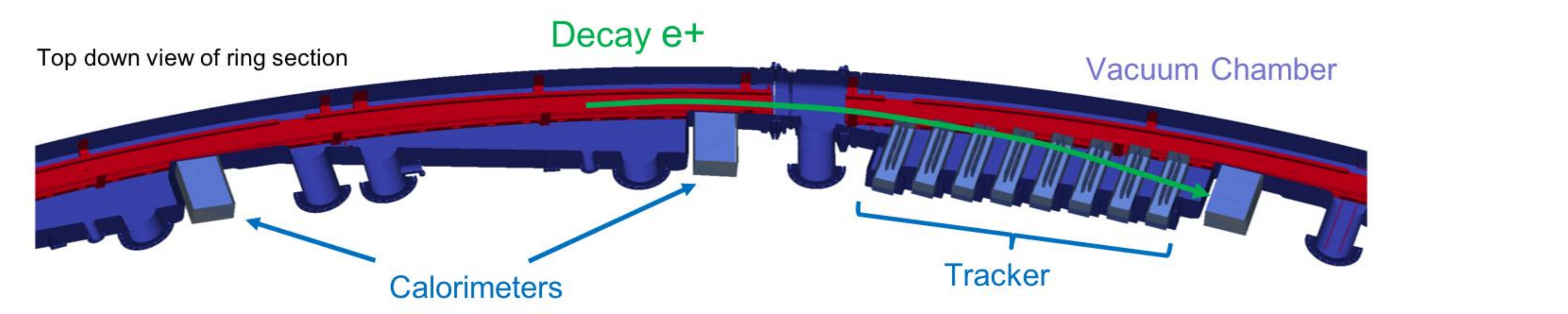


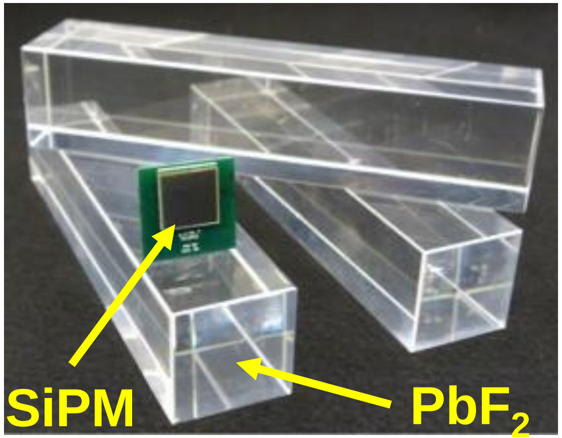
SLAC Test beam: 2013,2014,2016

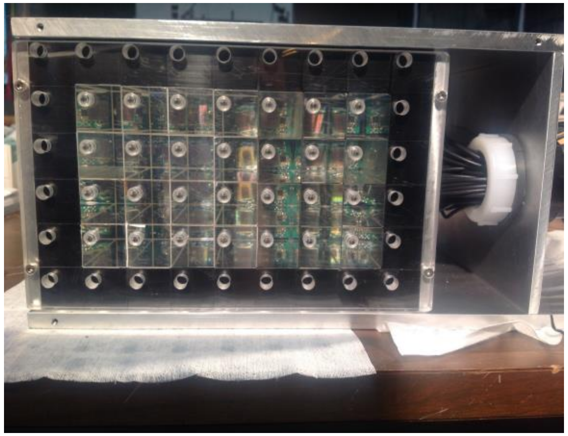


Segmented, fast response, crystal calorimeter (9X6 array)

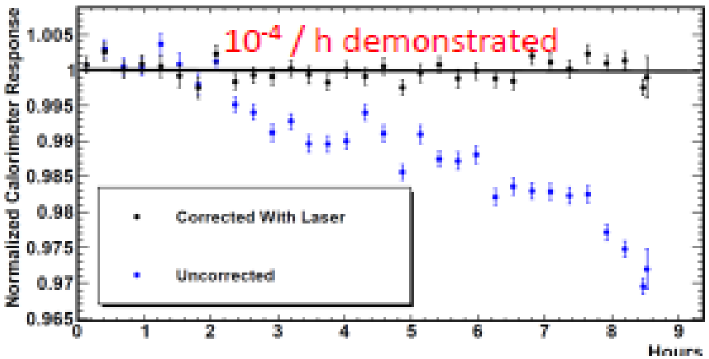
Detector performance: calorimeter







SLAC Test beam: 2013,2014,2016

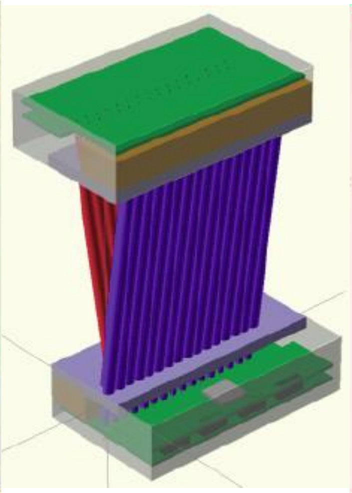


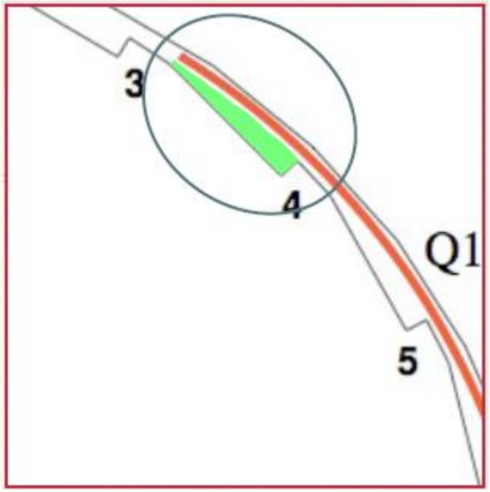
Segmented, fast response, crystal calorimeter (9X6 array)

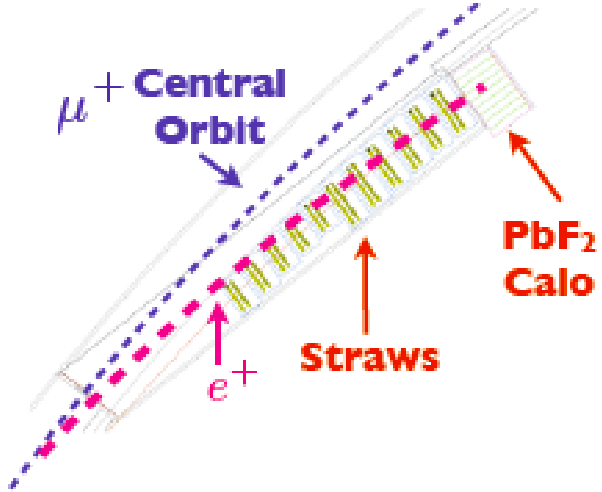
- **Lead-floride Cherenkov crystal (PbF_2) can reduce pileup**
  - **Resolution (2.3% at 3 GeV) better than requirement (5%)**
- **Silicon photomultiplier (SiPM) directly on back of PbF_2**
  - **No disturbing magnetic field, avoid long light guides**

Detector performance: tracker

Detector performance: tracker

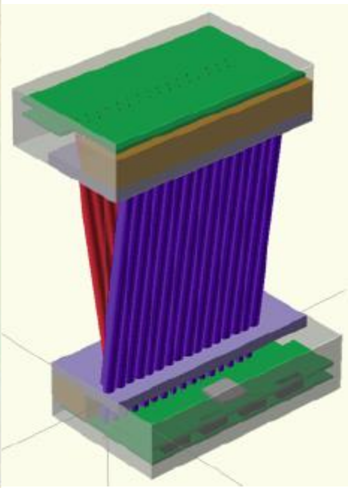


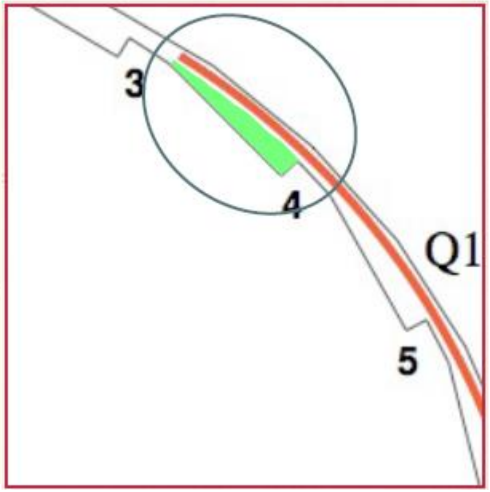


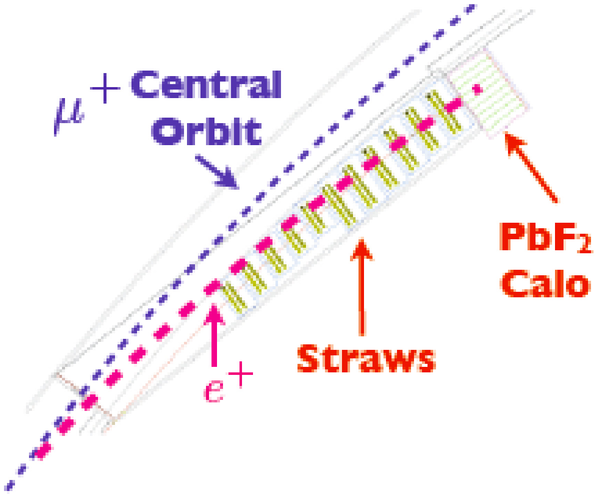


Doublet of UV straw chambers

Detector performance: tracker



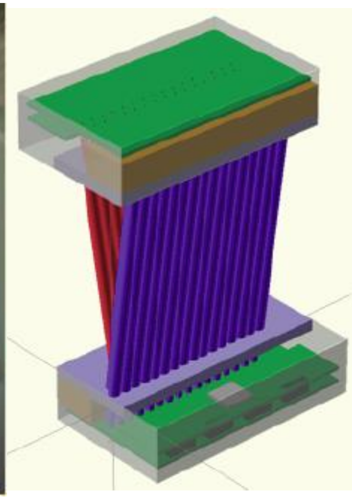


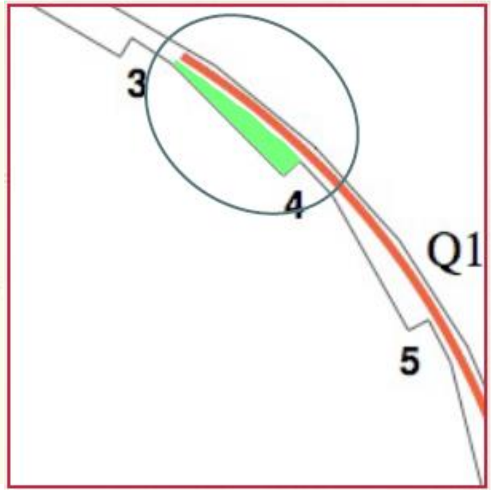


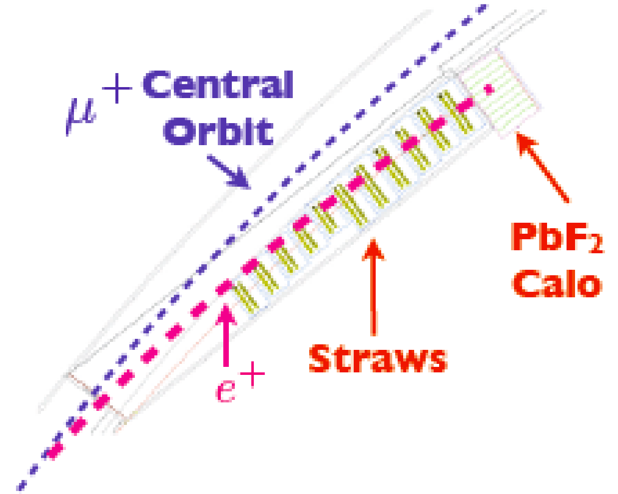
Doublet of UV straw chambers

New straw tracking detector

Detector performance: tracker



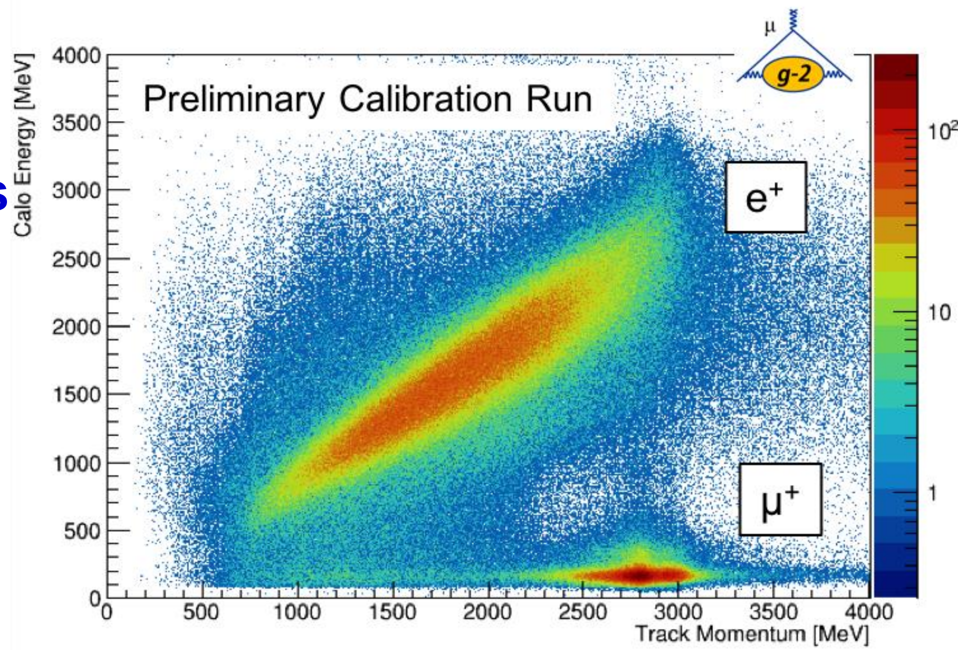




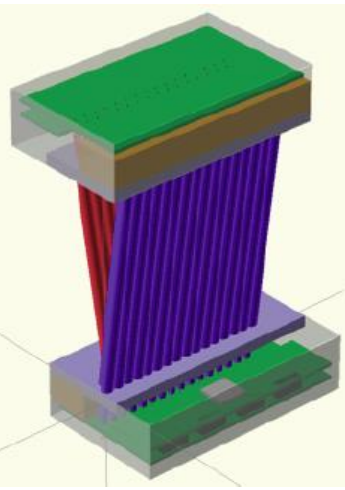
Doublet of UV straw chambers

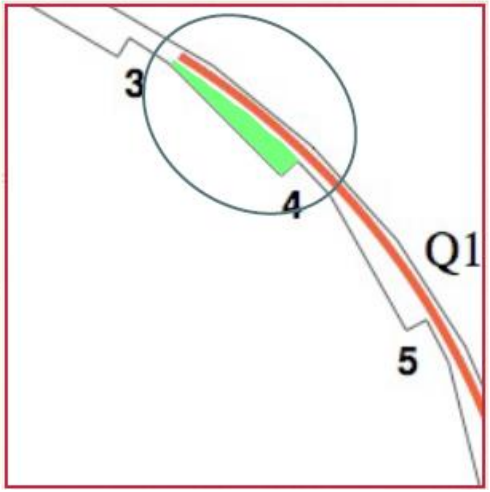
New straw tracking detector

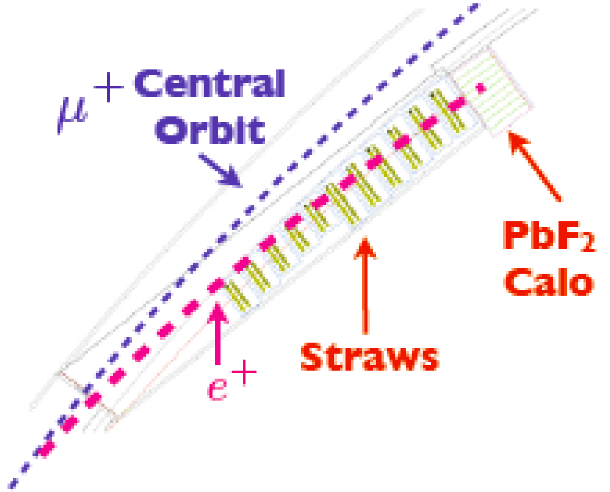
- **Two stations installed, 1024 straws**
- **Measure muon decay vertex and momentum**



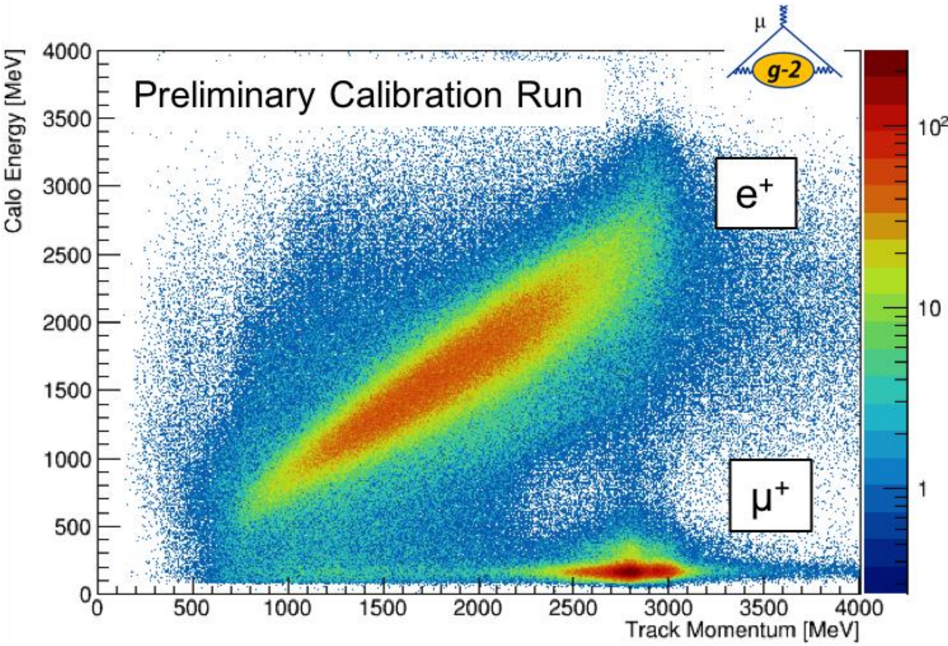
Detector performance: tracker







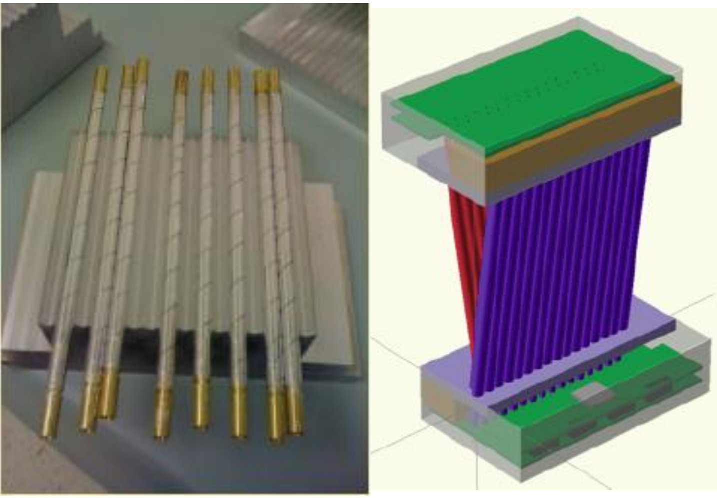
Doublet of UV straw chambers

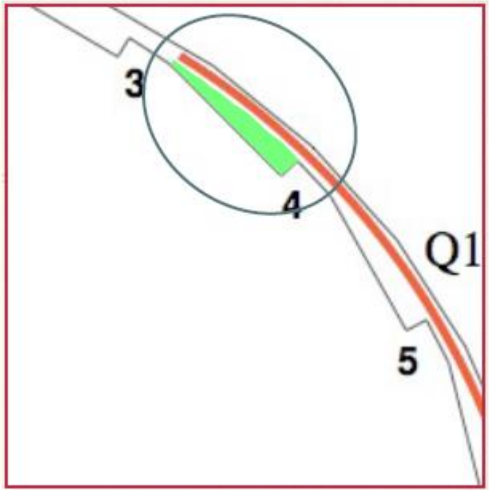


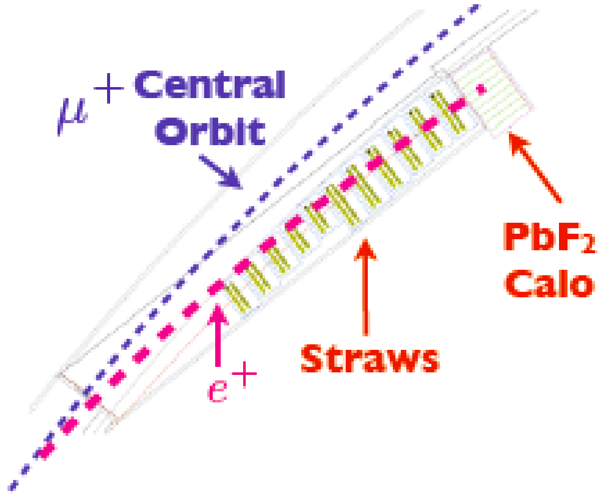
New straw tracking detector

- Two stations installed, 1024 straws
- Measure muon decay vertex and momentum

Detector performance: tracker



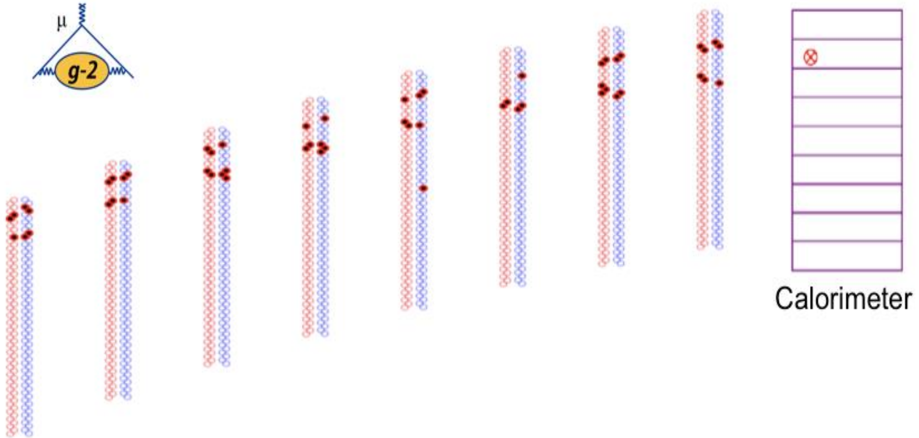




Doublet of UV straw chambers

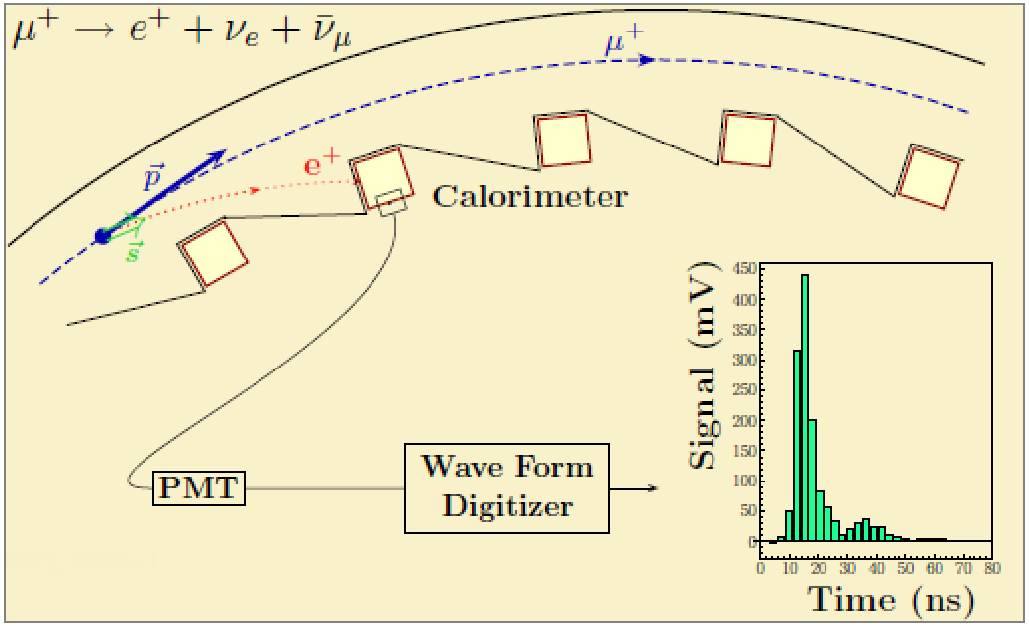
New straw tracking detector

- **Two stations installed, 1024 straws**
- **Measure muon decay vertex and momentum**
- **Calibrate beam dynamics parameters, better control of systematics**
- **Dedicated EDM measurement**

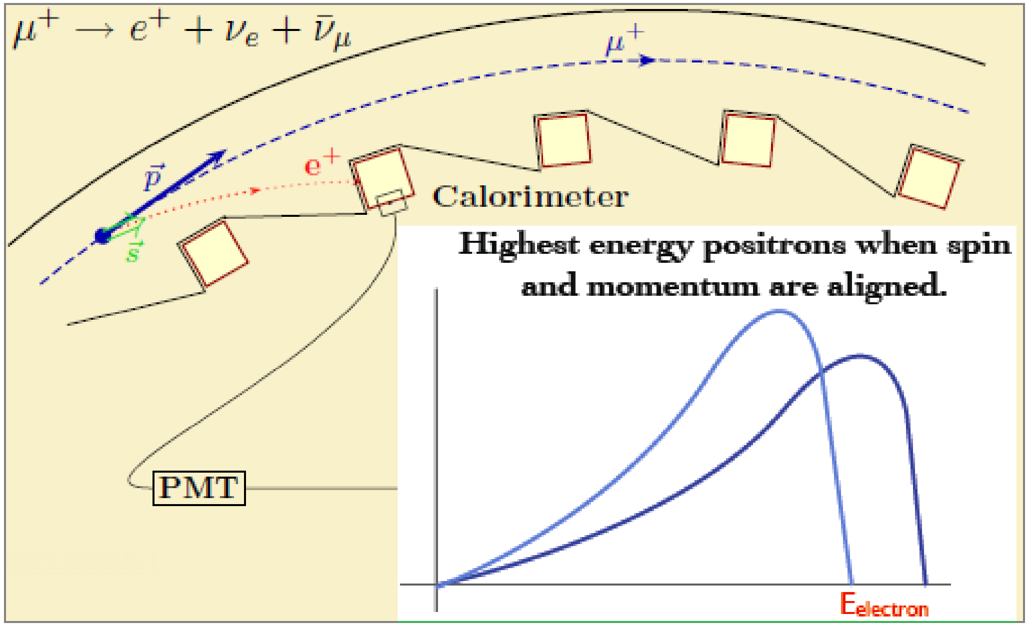


Measuring ω_a

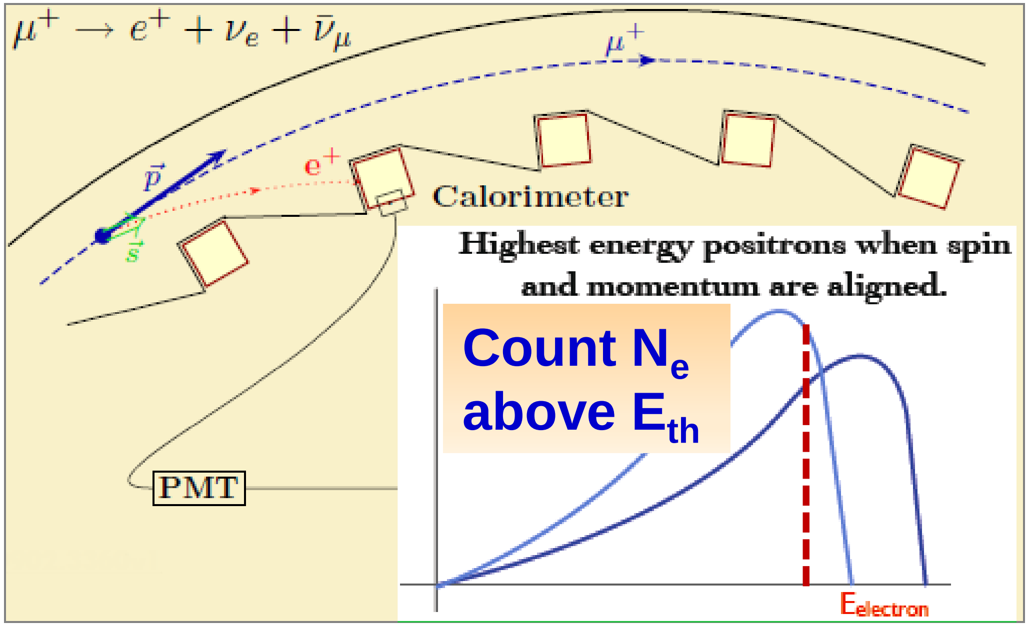
Measuring ω_a



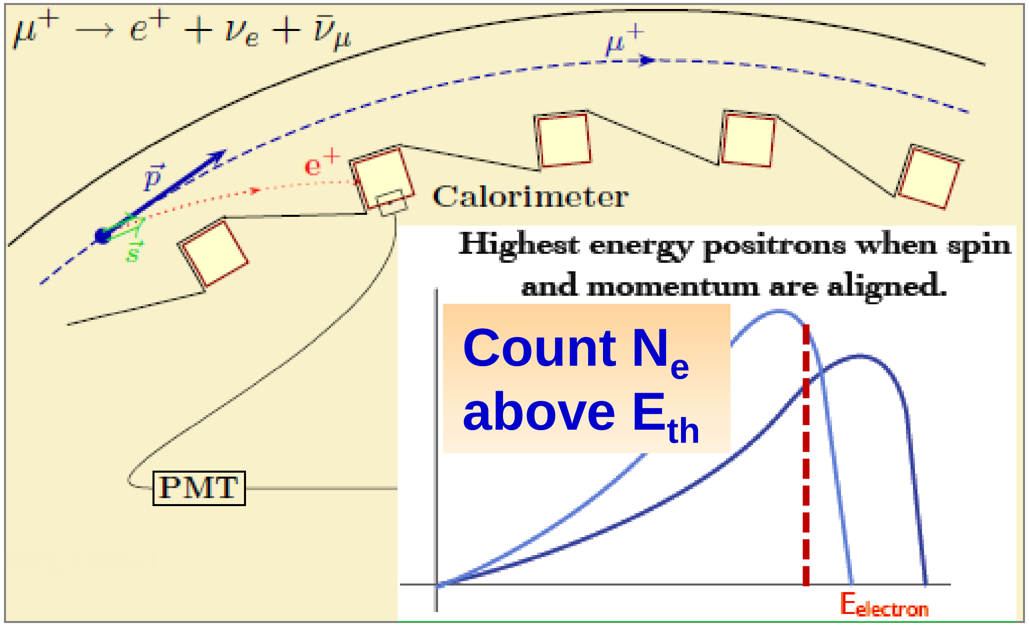
Measuring ω_a



Measuring ω_a



Measuring ω_a

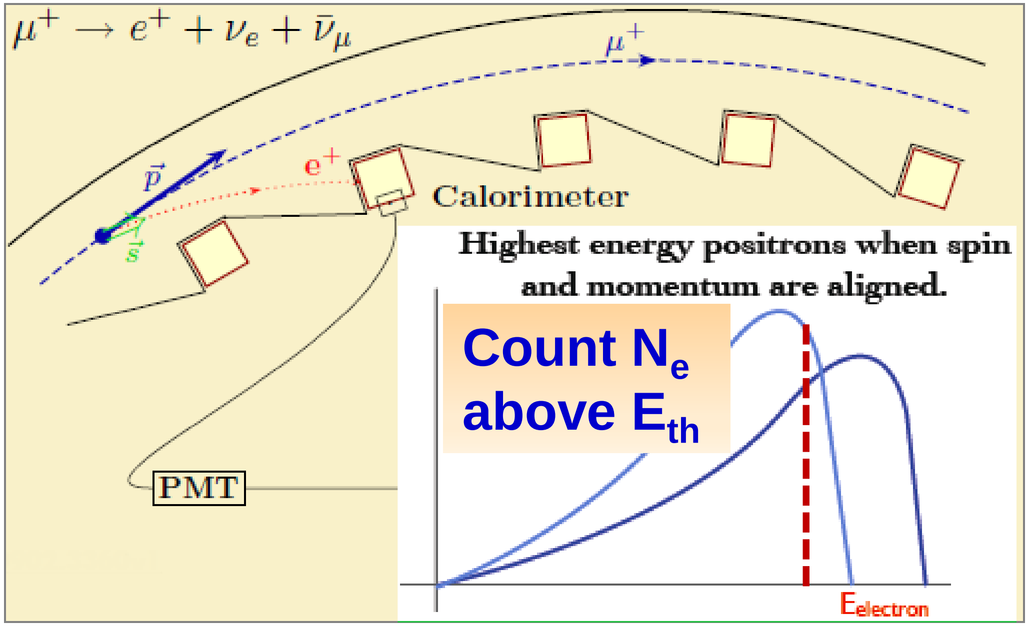


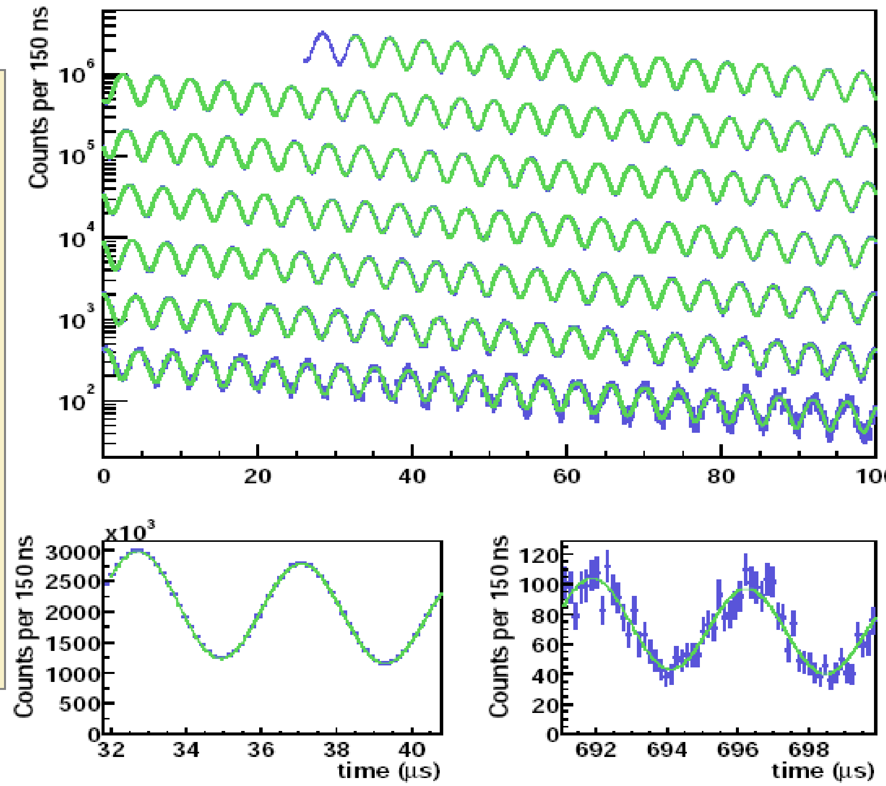
The integrated number of electrons (above E_{th}) modulated at ω_a

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

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

Measuring ω_a



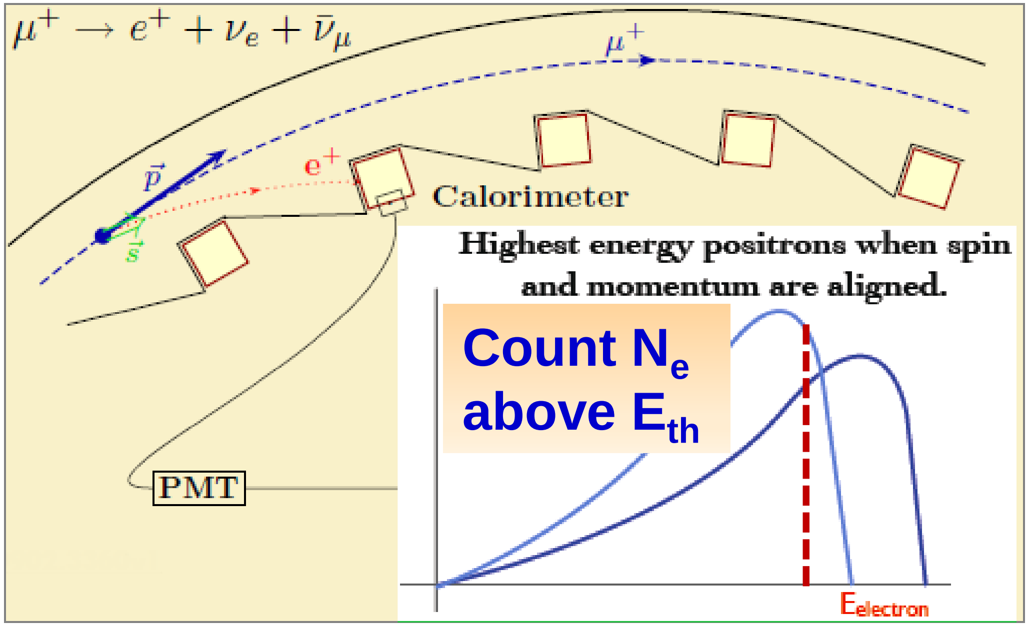


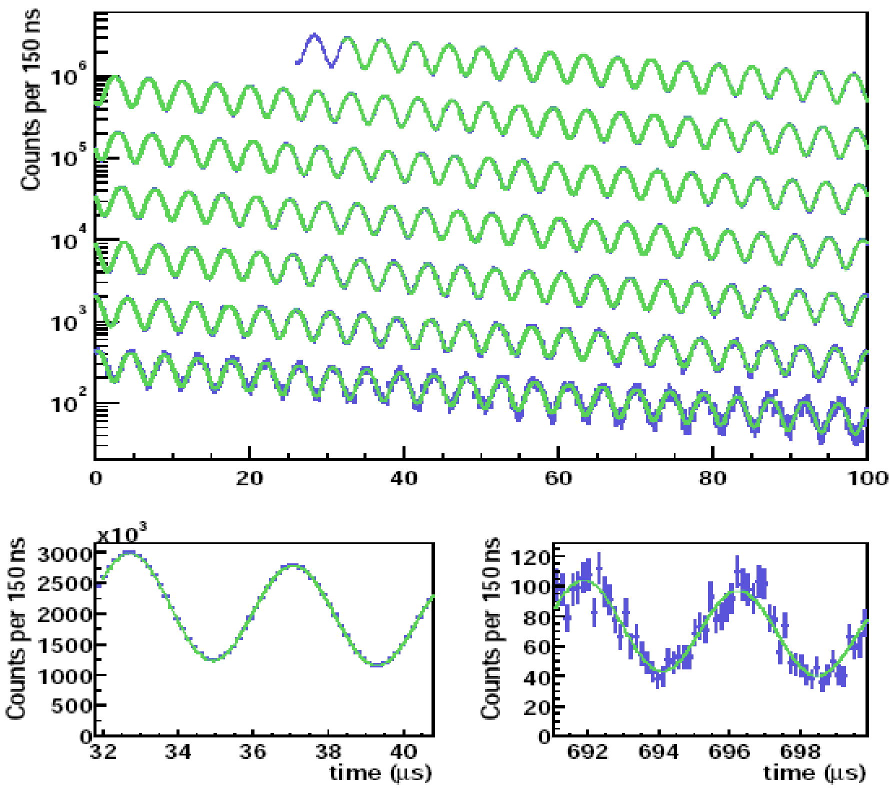
The integrated number of electrons (above E_{th}) modulated at ω_a

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

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

Measuring ω_a





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

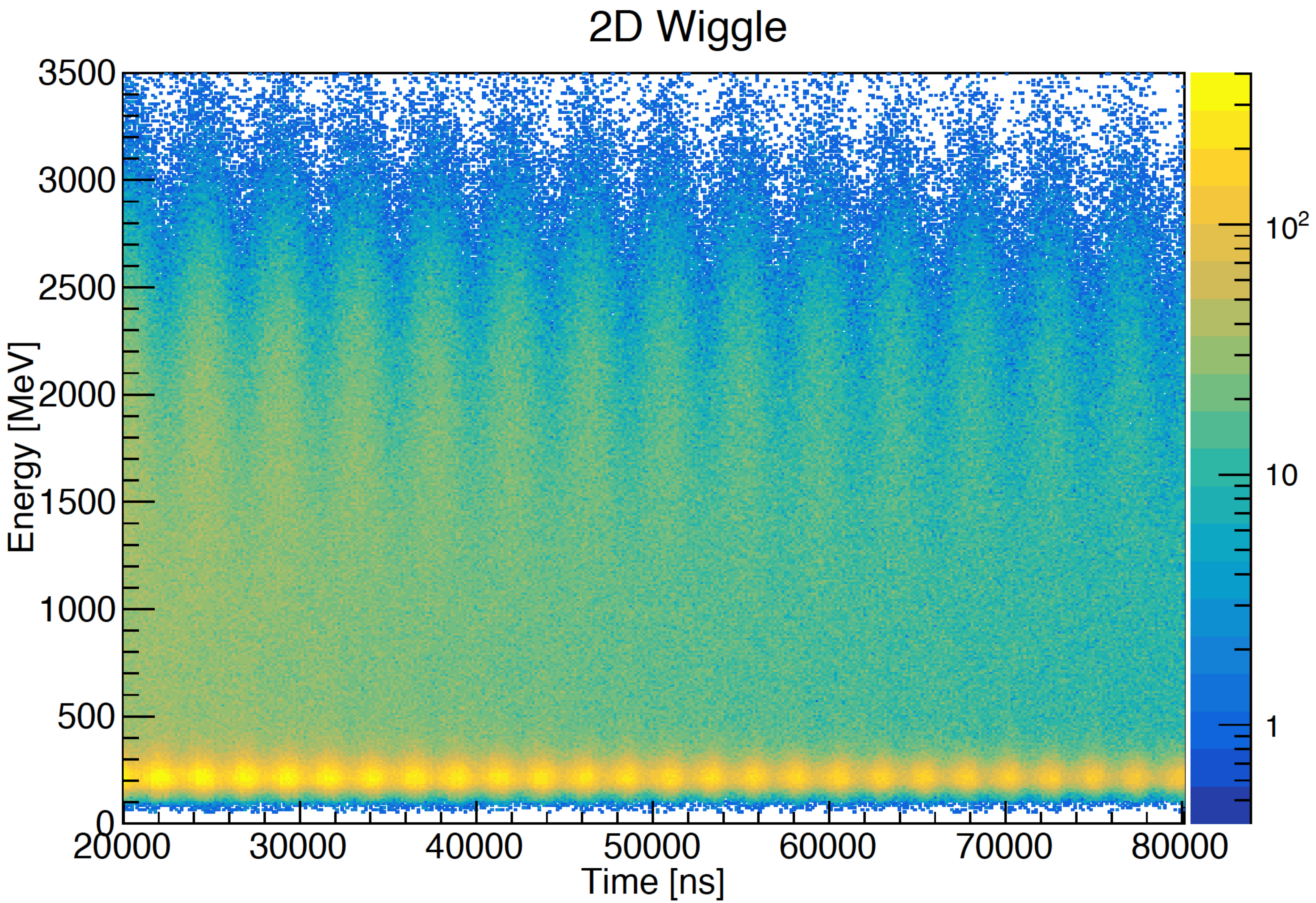
- **Angular distribution of decayed electrons correlated to muon spin**
- **Five parameter fit to extract ω_a**

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

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

Wiggle, Wiggle, Wiggle…

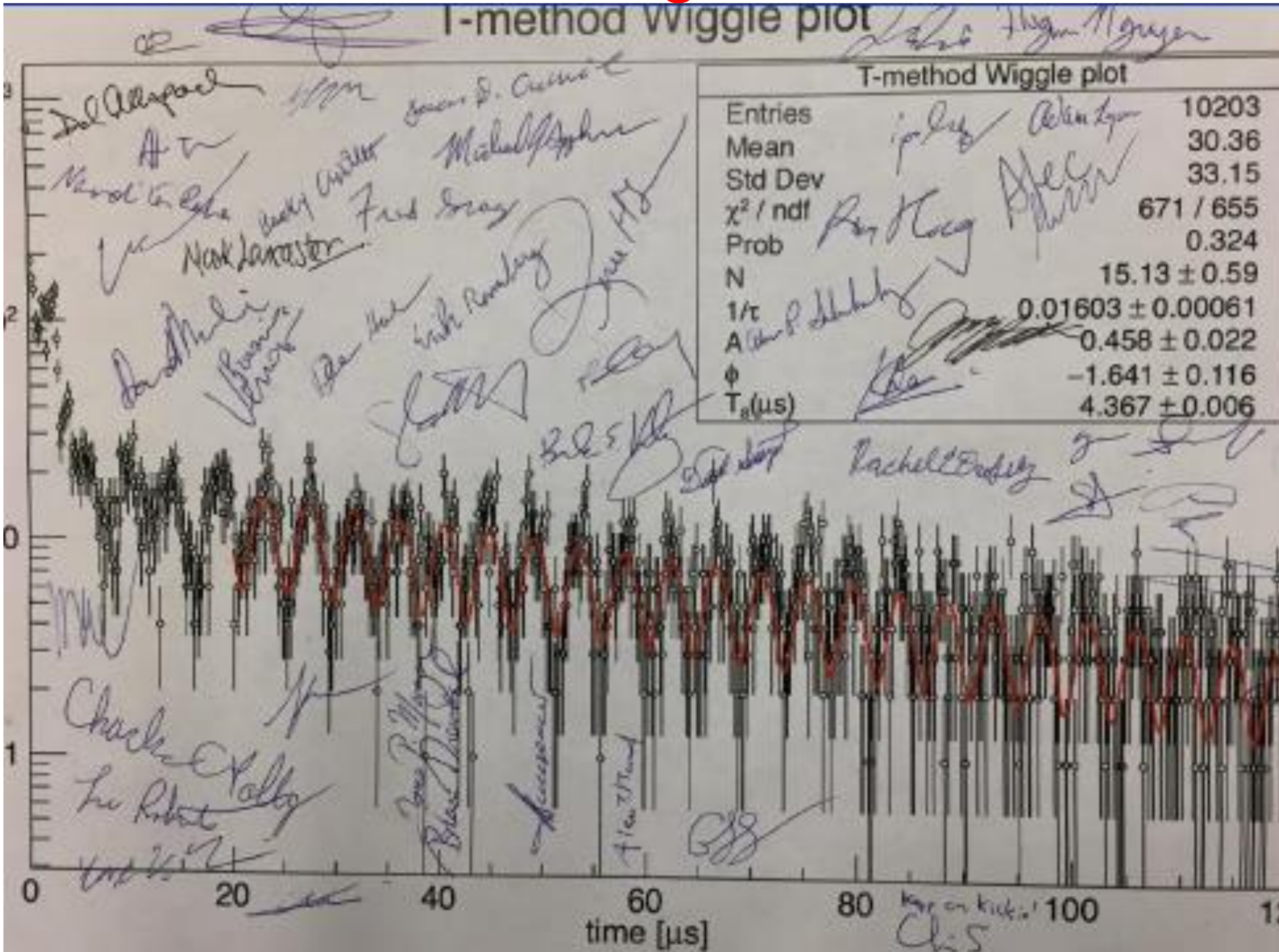
Wiggle, Wiggle, Wiggle…



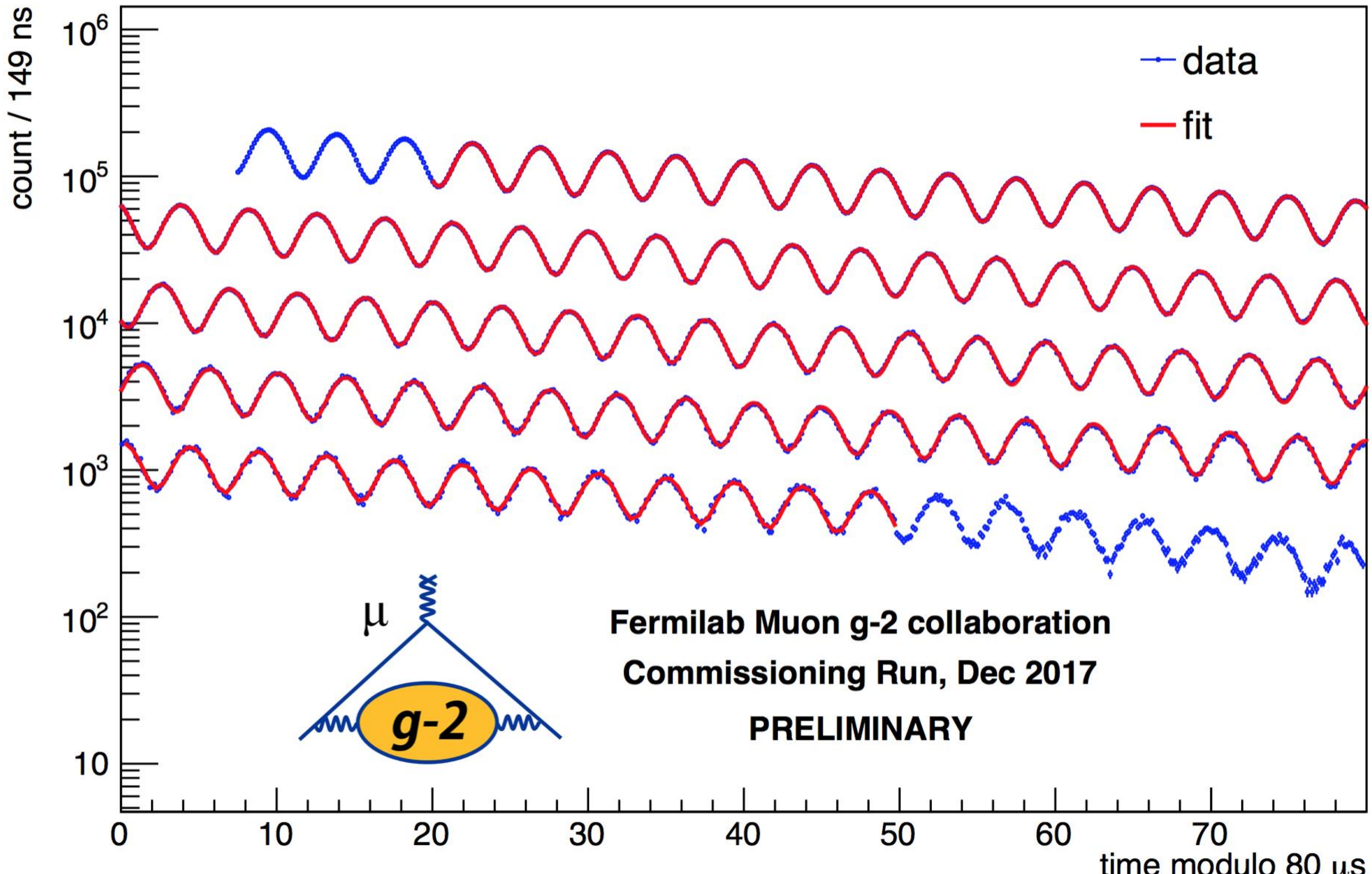
Energy vs. Time seen by calorimeters

Wiggle, Wiggle, Wiggle…

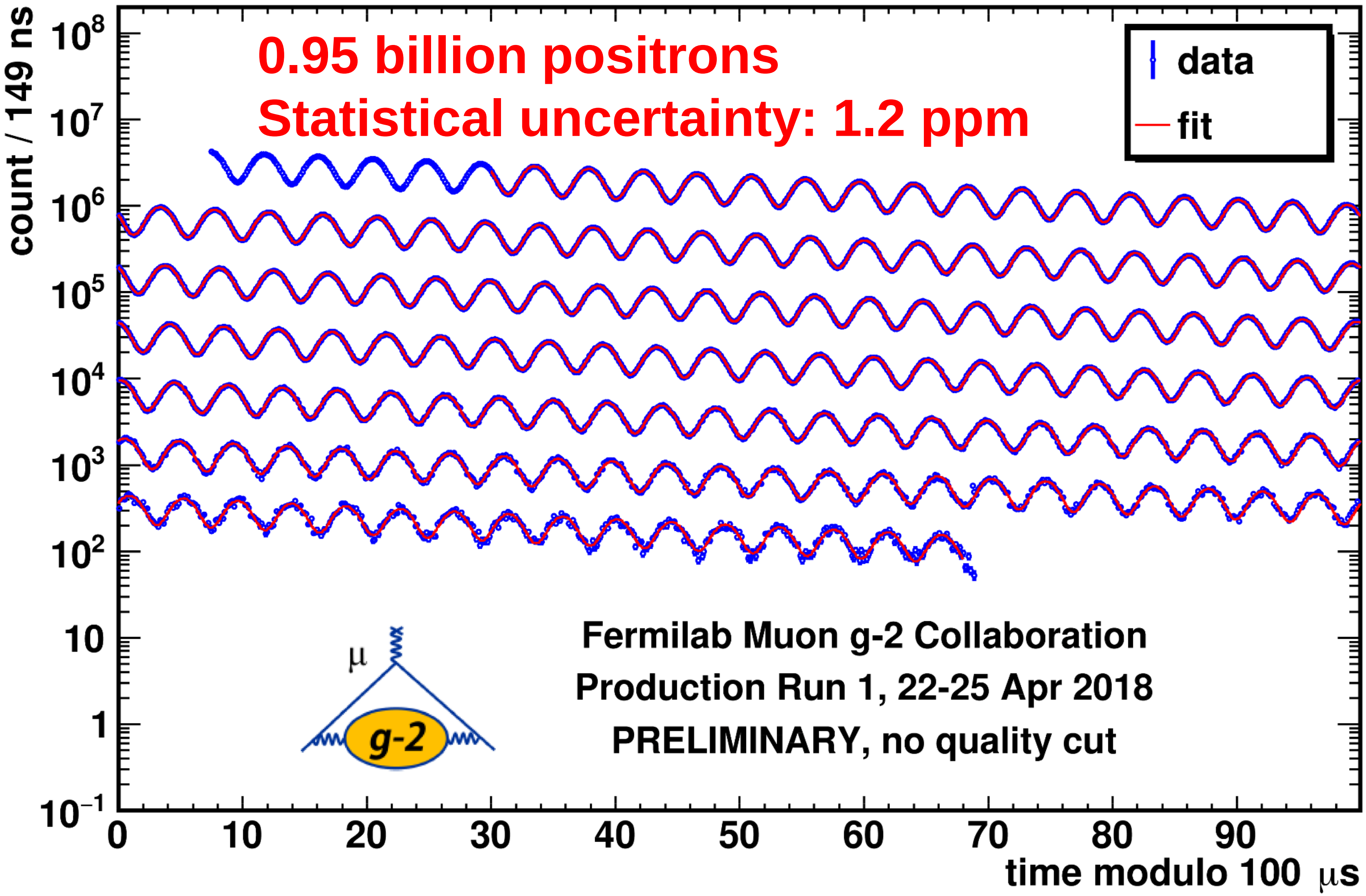
First commissioning run: June 2017



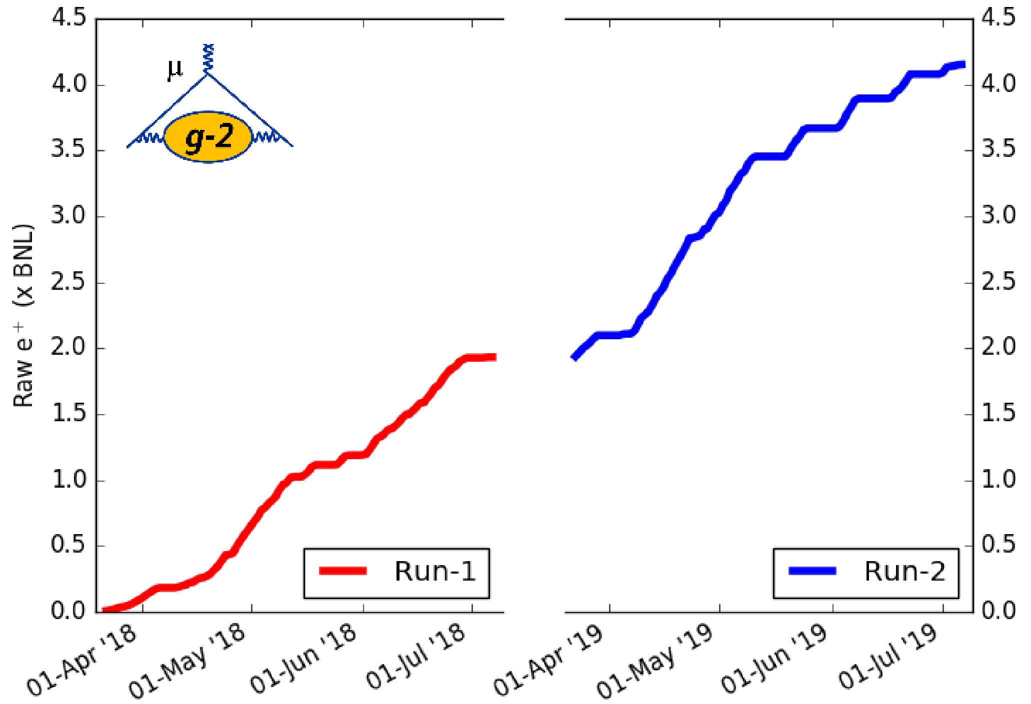
Wiggle, Wiggle, Wiggle…



Wiggle, Wiggle, Wiggle…



Current Muon g-2 Experiment Status

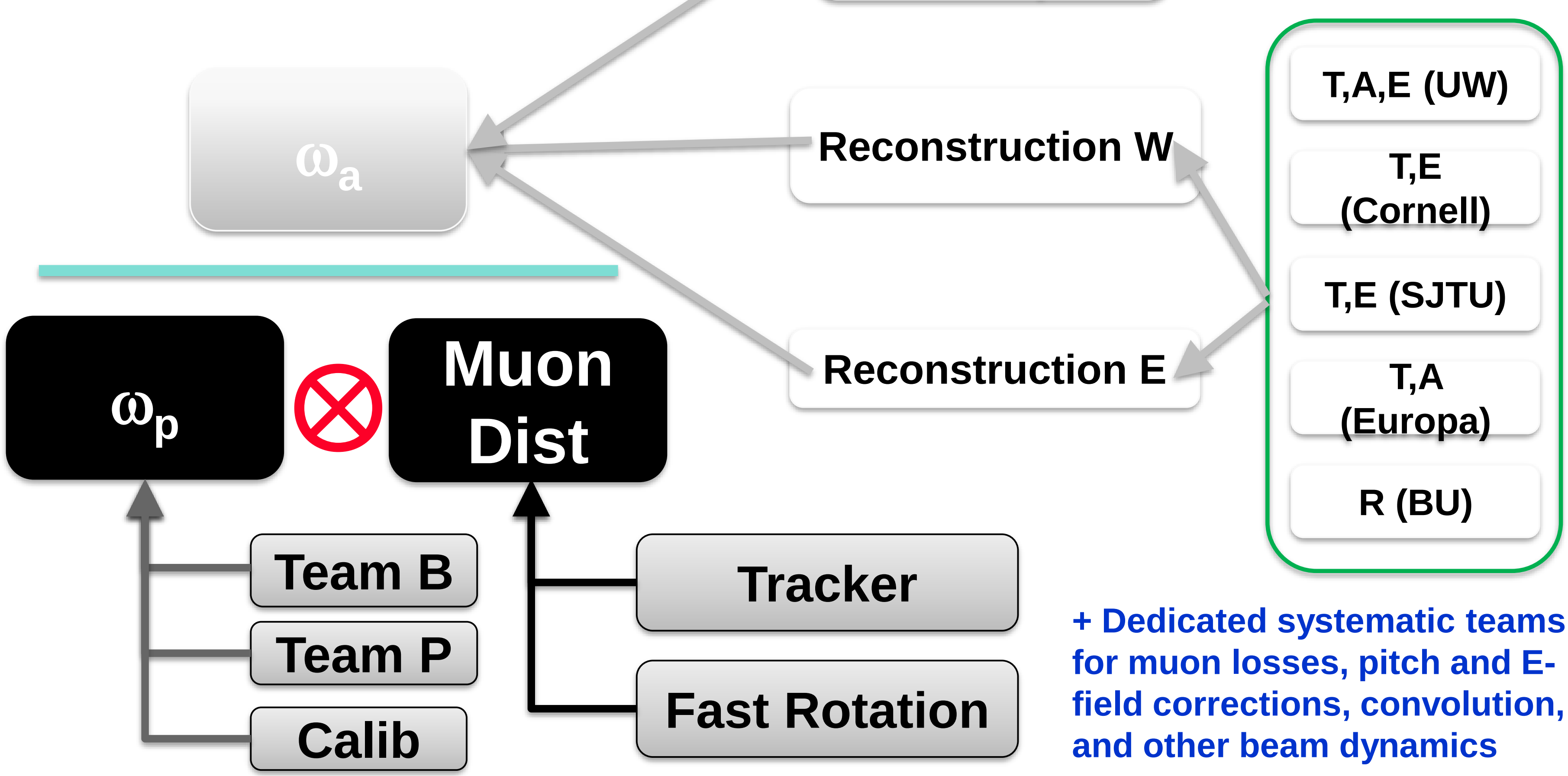


Already collected 4X BNL dataset (raw size)

- **Run 1 completed in 2018 with 1.9X BNL dataset (effective size 1.5X)**
  - **17.5 billion e^+ → δ_{stat} = 0.41 ppm**
- **Run 2 just finished in July 2019: ~2.2X Run 1 → δ_{stat} = 0.35 ppm**
- **Now in shutdown preparing for Run 3 starting in November**

Data Analyses

$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$



+ Dedicated systematic teams for muon losses, pitch and E-field corrections, convolution, and other beam dynamics

Blinded Analysis

Avoid possible bias during analysis

- **Credibility is the key**

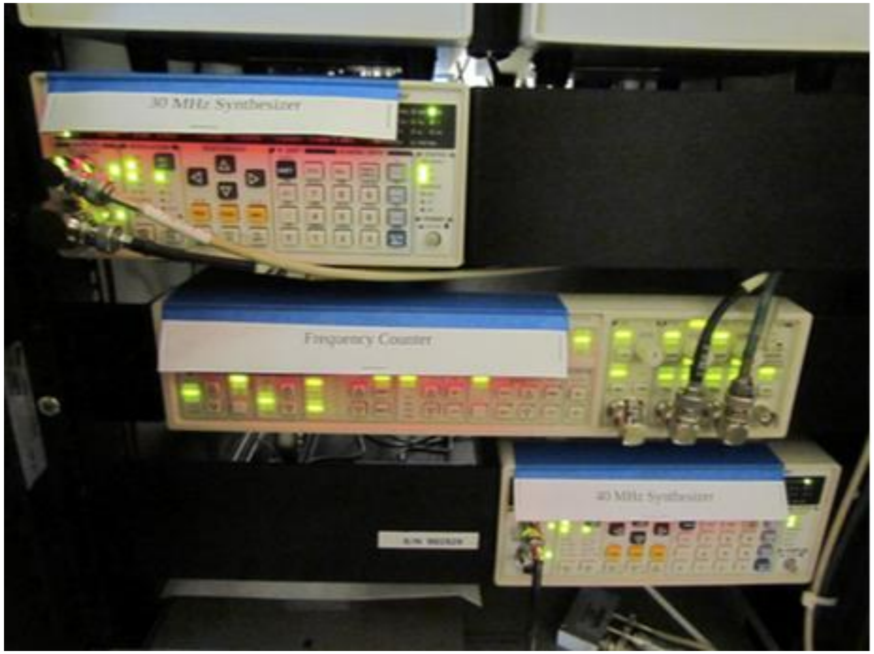
Blinded Analysis

Avoid possible bias during analysis

- **Credibility is the key**

Hardware Blinding

- **Perturb the clocks from the nominal frequency of 40 MHz → 39.XX MHz**



Blinded Analysis

Avoid possible bias during analysis

- **Credibility is the key**

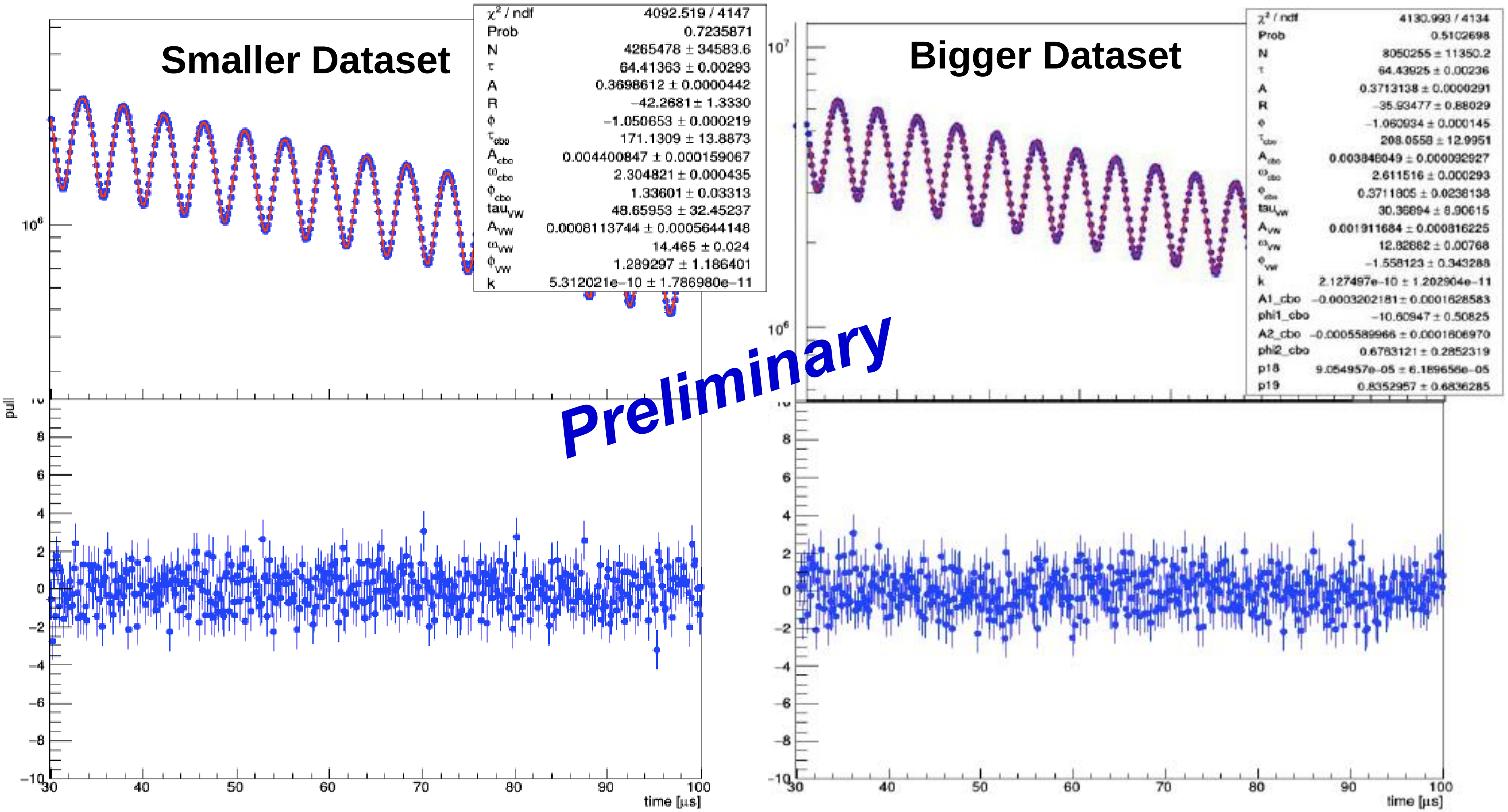
Hardware Blinding

- **Perturb the clocks from the nominal frequency of 40 MHz → 39.XX MHz**

Software Blinding

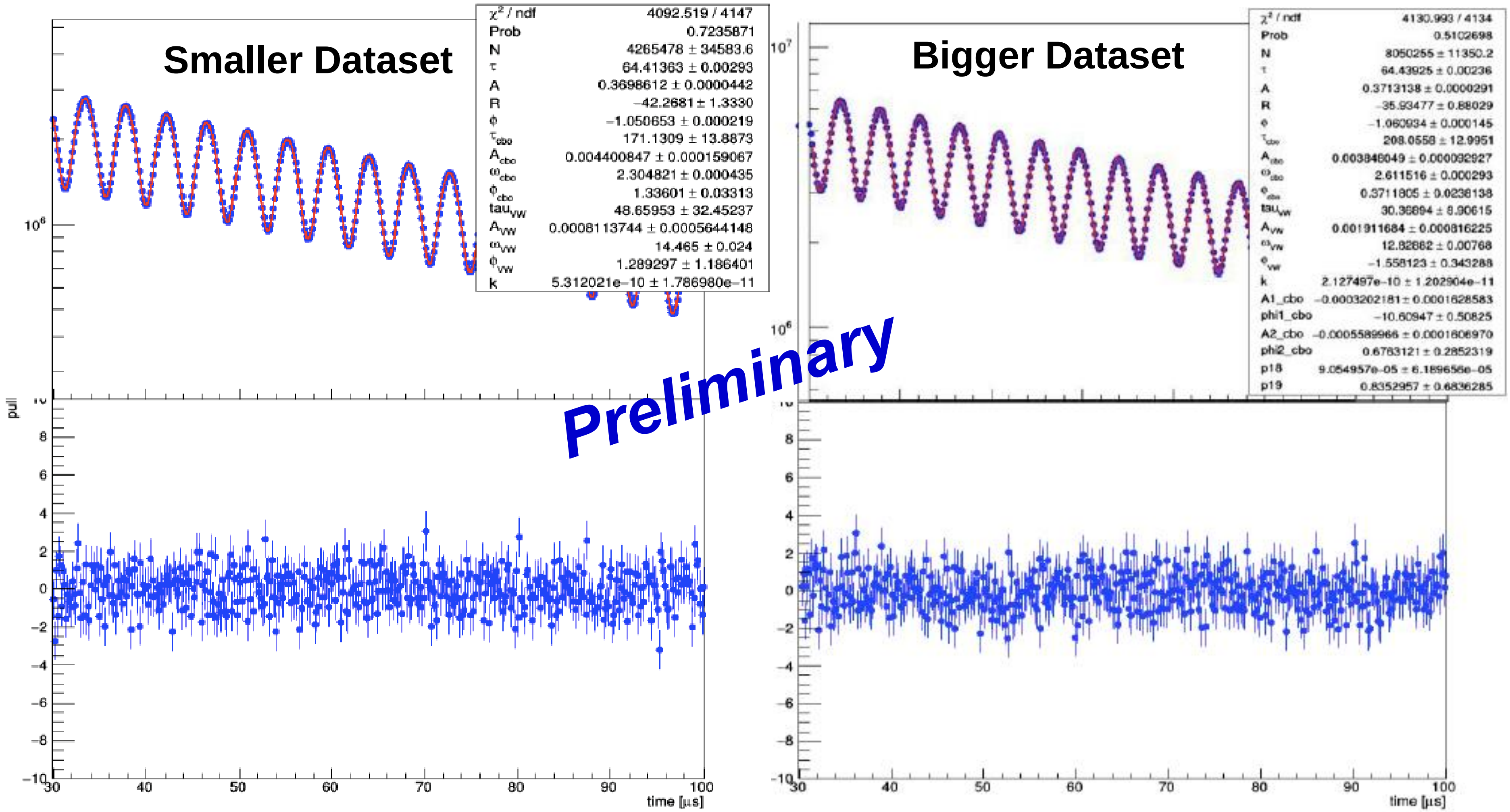
- **Software package to apply individual offsets to fit results to ensure independence of analyses**
- $\omega_a \rightarrow \omega_a \pm \Delta$ **ppm**
- **Unblinding can be done in different stages and cross check**

Data Analyses Ongoing …



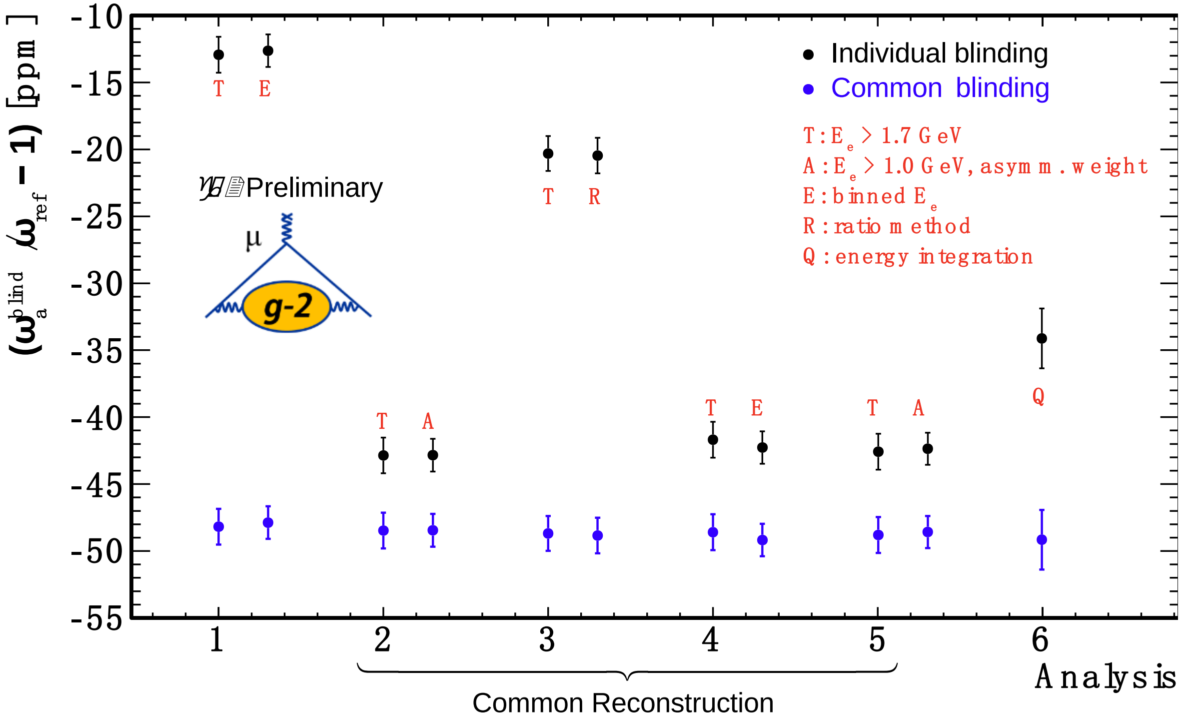
$$N(t) = N_0 \cdot \Lambda(t) \cdot N_{1\mathrm{CBO}}(t) \cdot N_{2\mathrm{CBO}}(t) \cdot N_{VW}(t) \cdot N_{VO}(t)$$
$$\cdot\, e^{-t/\tau} \left[1 + A_0 \cdot A_{1\mathrm{CBO}}(t) \cdot \cos(\omega_a(R) \cdot t + \phi_0 + \phi_{1\mathrm{CBO}}(t))\right]$$

Data Analyses Ongoing …



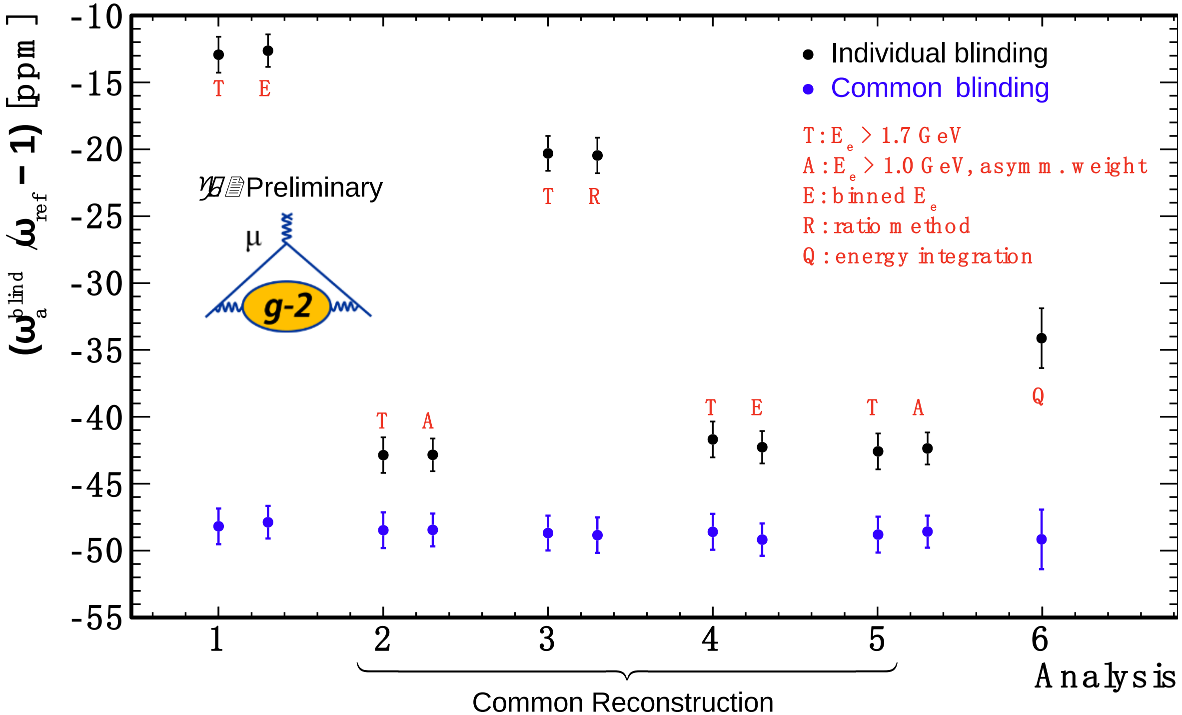
- **Very good fitting χ^2 and clean residuals**
- **Statistical uncertainty of blinded ω_a improves after including more data**

Data Analyses Ongoing …



- **6 independent ω_a analysis groups with multiple methods blinded from each other**
- **Relative unblinding performed for analysis consistency check**

Data Analyses Ongoing …



- **6 independent ω_a analysis groups with multiple methods blinded from each other**
- **Relative unblinding performed for analysis consistency check**
- **Several datasets separated due to different running conditions**
- **A-weighted method extract more information from high energy positrons**
- **Estimated statistics uncertainty: δ_{stat} = 0.41 ppm < 0.46 ppm (BNL)**

Data Analyses Ongoing …

Run 1 systematics estimation well underway

- ω_a analysis: δ_{stat} ~ 0.41 ppm, $\delta_{syst.}$ ~ 0.05 ppm
- ω_p analysis: $\delta_{syst.}$ ~ 0.10-0.20 ppm
- Beam dynamics corrections: $\delta_{syst.}$ ~ 0.05 ppm
- Overall systematics: $\delta_{syst.}$ ~ 0.15-0.25 ppm

Data Analyses Ongoing …

Run 1 systematics estimation well underway

- ω_a analysis: δ_{stat} ~ 0.41 ppm, $\delta_{syst.}$ ~ 0.05 ppm
- ω_p analysis: $\delta_{syst.}$ ~ 0.10-0.20 ppm
- Beam dynamics corrections: $\delta_{syst.}$ ~ 0.05 ppm
- Overall systematics: $\delta_{syst.}$ ~ 0.15-0.25 ppm

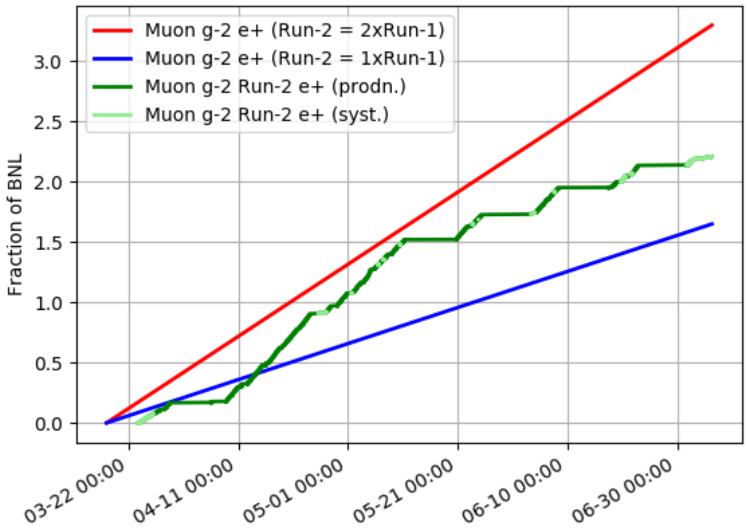
Additional systematics studies still ongoing

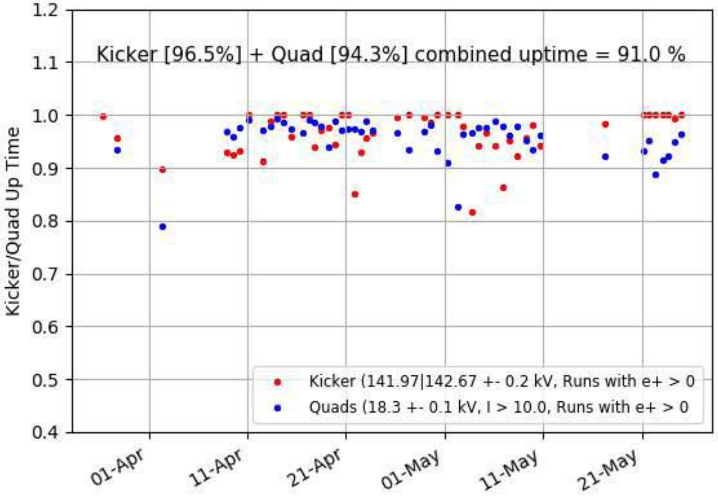
- Muon loss phase
- Systematic error due to failed quad resistors
- Evaluating if there are sources of short timescale (<1 ms) field perturbations, e.g. pulsed quads, accelerator complex

Expect Run 1 results with similar precision with BNL (E821)

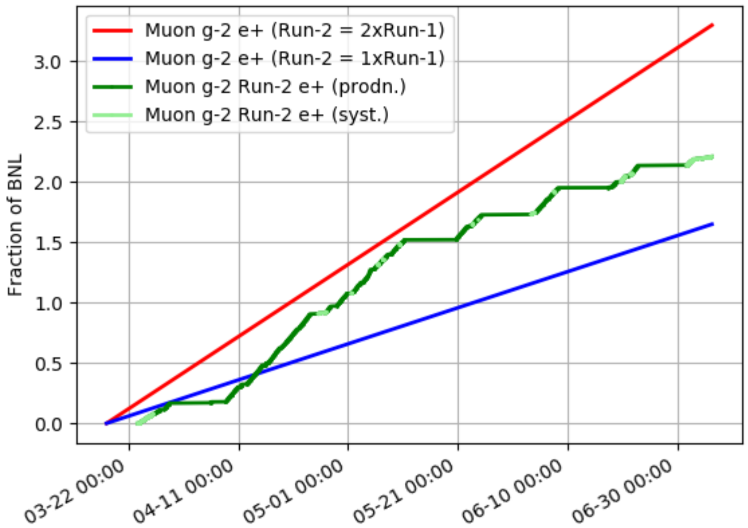
- Statistics uncertainty dominated

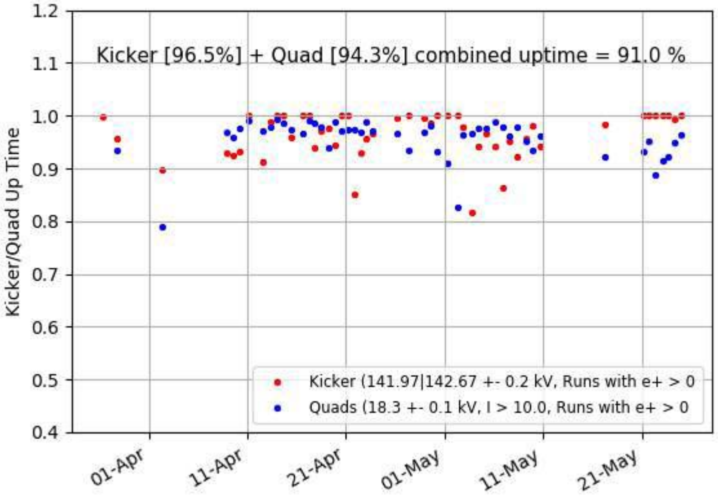
From Run 1 to Run 2





From Run 1 to Run 2





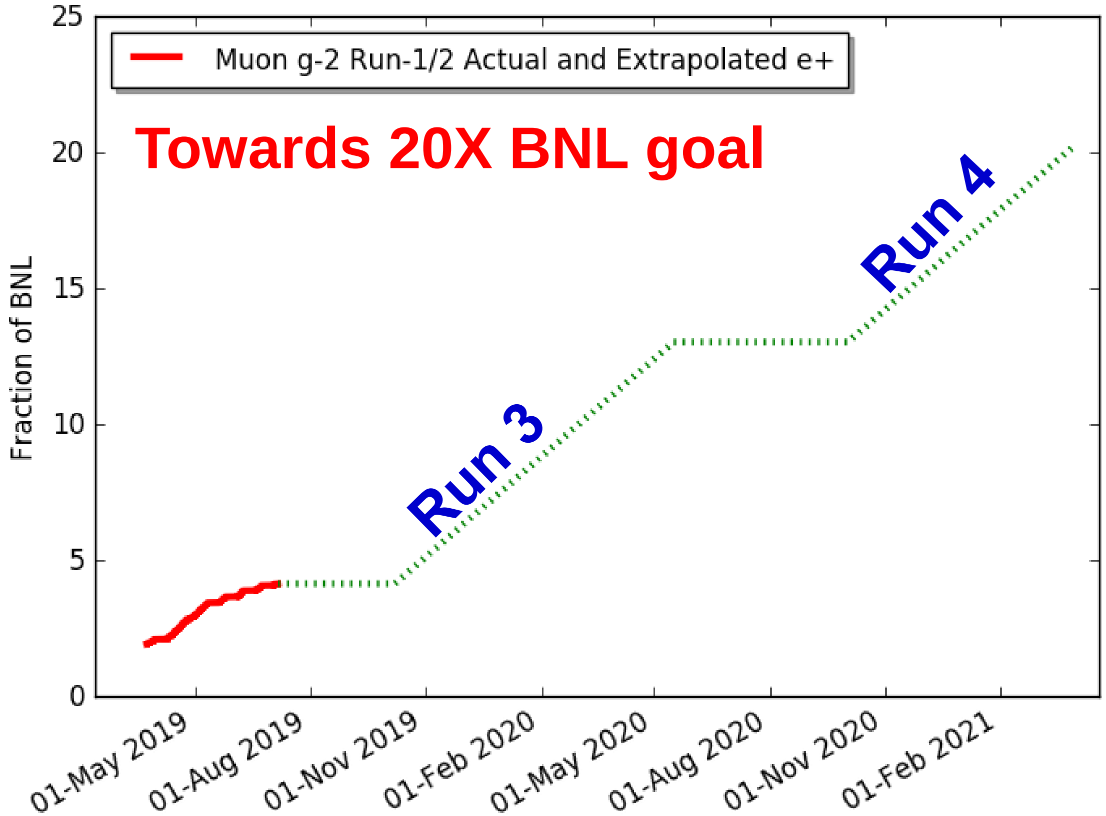
Various Run 1 issued addressed during last year shutdown

- **Kick was too low**
- **Kicker had significant downtime**
- **Quad sparks**
- **Magnet downtime due to cryogenic issues**

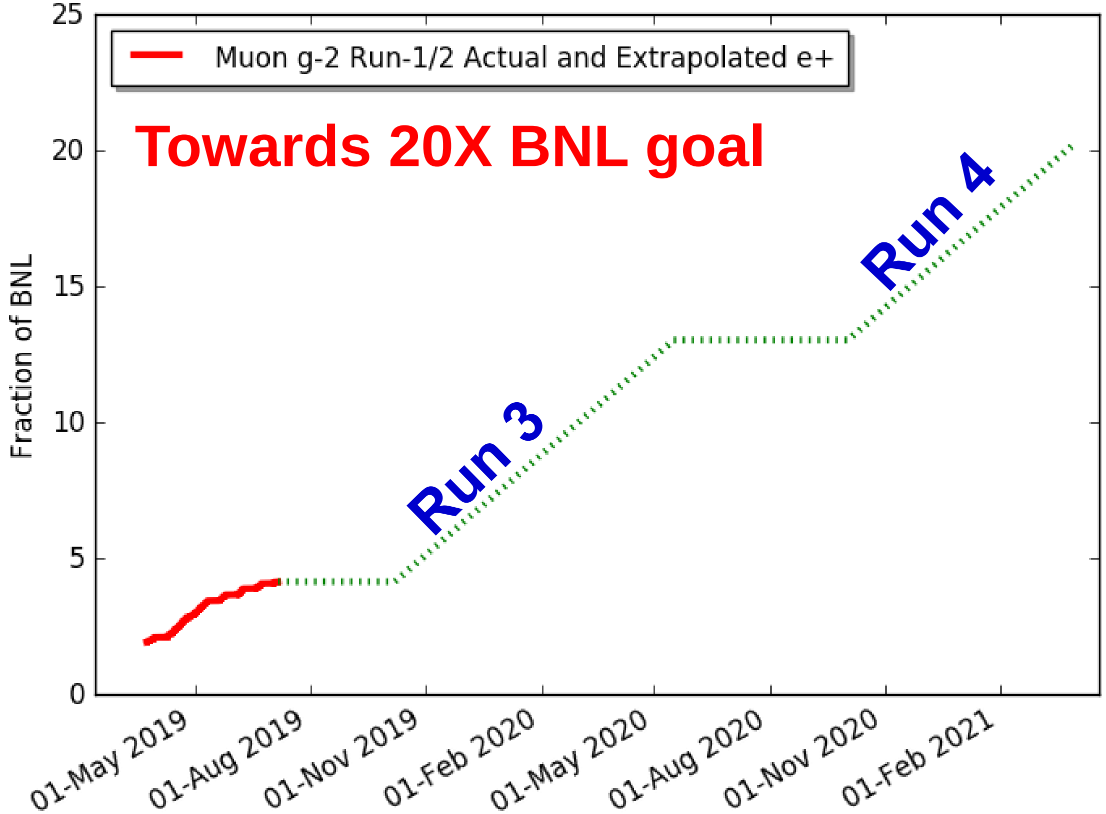
Run 2 condition not yet optimum: reduced beam intensity & down time

- **During stable running condition: collect 4% BNL stat. per running day**

Run 3 and Beyond



Run 3 and Beyond



Run 3 and Run 4 beam time projection

- **Run 3 (FY20) starting next month, Run 4 (FY21) runs 6 months**
- **Running beyond FY21 contingent on how Mu2e schedule evolves and initial g-2 results**
- **20X BNL statistics expected**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - **Potential to achieve 5-7σ significance measurement**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - **Potential to achieve 5-7σ significance measurement**
- **Very sensitive way to explore physics beyond the SM**
  - **High precision measurements and high order calculations**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - **Potential to achieve 5-7σ significance measurement**
- **Very sensitive way to explore physics beyond the SM**
  - **High precision measurements and high order calculations**
- **Publication plan**
  - **Expect to publish first physics result by end of 2019 or early 2020 (~ BNL dataset statistics)**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - **Potential to achieve 5-7σ significance measurement**
- **Very sensitive way to explore physics beyond the SM**
  - **High precision measurements and high order calculations**
- **Publication plan**
  - **Expect to publish first physics result ~~by end of 2019 or~~ early 2020 (~ BNL dataset statistics)**

Summary

Fermilab muon g-2 experiment completed Run 1 and Run 2

- **Run 2 was taken under much more stable conditions**
  - **Expect higher quality Run3/4 with 1 BNL dataset each month**
- **Aiming to reduce experimental uncertainty by a factor of 4**
  - **Potential to achieve 5-7σ significance measurement**
- **Very sensitive way to explore physics beyond the SM**
  - **High precision measurements and high order calculations**
- **Publication plan**
  - **Expect to publish first physics result ~~by end of 2019 or~~ early 2020 (~ BNL dataset statistics)**
- **Stay tuned!**

1st publication (~ BNL statistics)

2nd publication (5-10 x BNL statistics)

3rd publication (>20 x BNL statistics)

CY18 | CY20 | CY21 | CY22

Backup

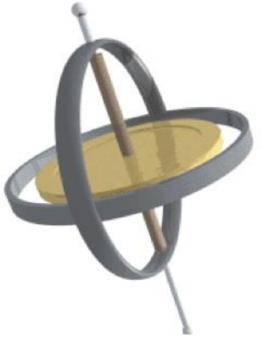
Pedagogical: What is (muon) g-2?

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!

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

$$a = \frac{g-2}{2}$$



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**

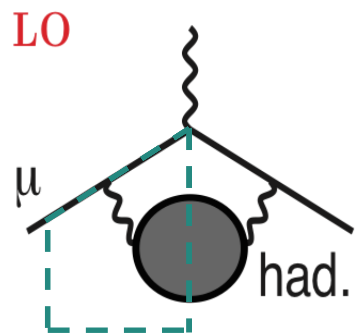
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

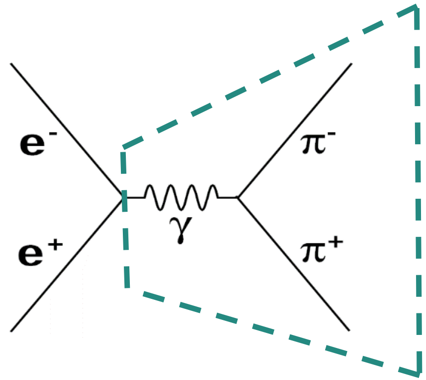
- **How to measure E?**
  - **No need! choose $\gamma = 29.3$, then coefficient vanishes!**
  - **$\gamma = 29.3$ means $p_\mu = 3.09$ GeV (magic momentum)**

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

Muon g-2 Theory: QCD

LO



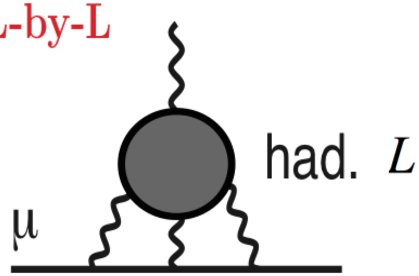


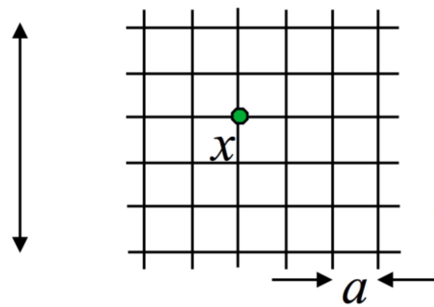
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

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

- Dispersion relation connects rate of $e^+e^-\rightarrow$hadrons to HVP
- More experimental data across the energy spectrum, better understanding of the data determines the uncertainty.

L-by-L





$$a_\mu^{\text{had, LO VP}} = \frac{\alpha^2}{\pi^2}\int dq^2 w(q^2)\hat{\Pi}(q^2)$$

$$a_\mu^{\text{HLbL}} = -e^6 \int \frac{d^4q_1}{(2\pi)^4}\frac{d^4q_2}{(2\pi)^4}\frac{\sum_{i=1}^{12}\hat{T}_i(q_1,q_2;p)\hat{\Pi}_i(q_1,q_2,-q_1,-q_2)}{q_1^2q_2^2(q_1+q_2)^2[(p+q_1)^2-m_\mu^2][(p-q_2)^2-m_\mu^2]}$$

- Lattice HVP determinations improving with more computing time
- Traditionally HLbL calculation only by hadronic models
- Lattice and dispersive HLbL approach agree with models and are crucial to drastically reduce uncertainties
- HVP and HLbL (absolute) uncertainties are now comparable

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

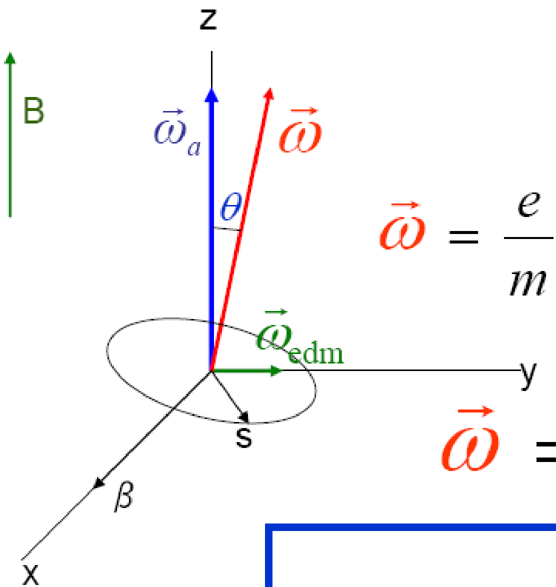
Systematics error < 70 ppb: x 3 improvement !

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

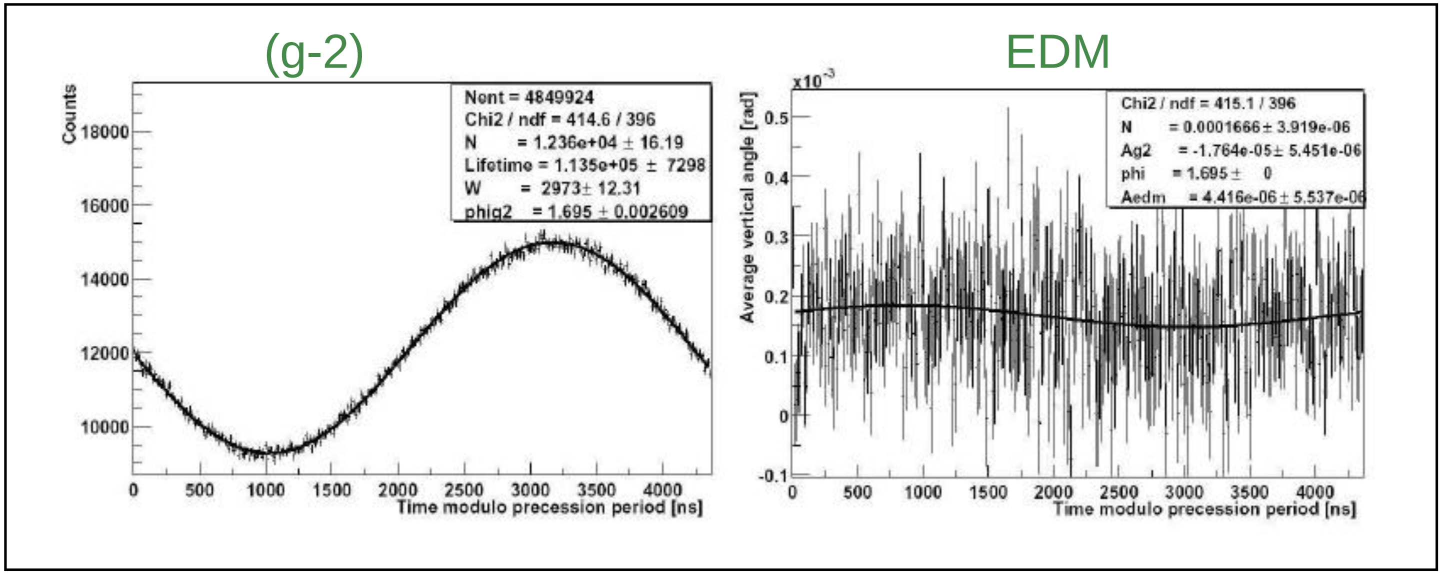


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

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

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

Muon EDM

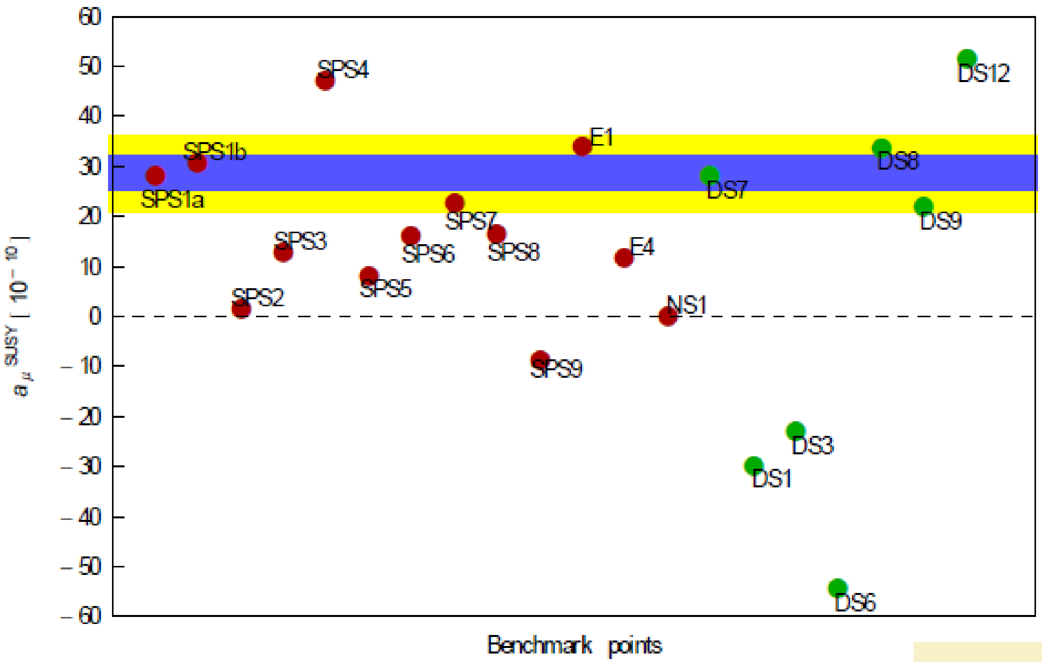


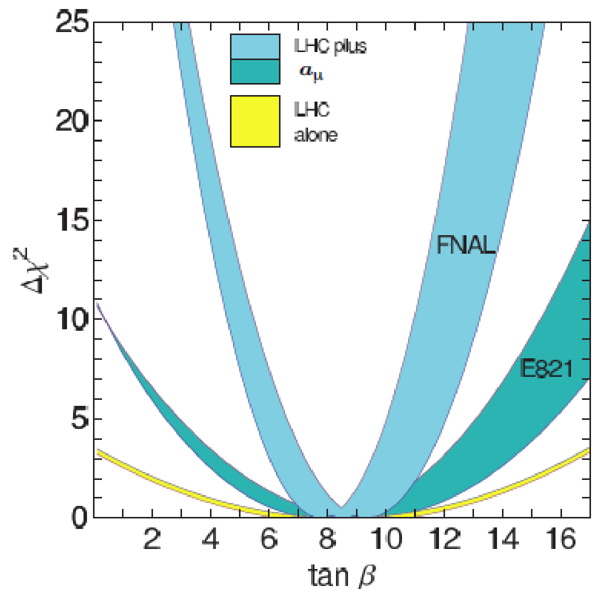
(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

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

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

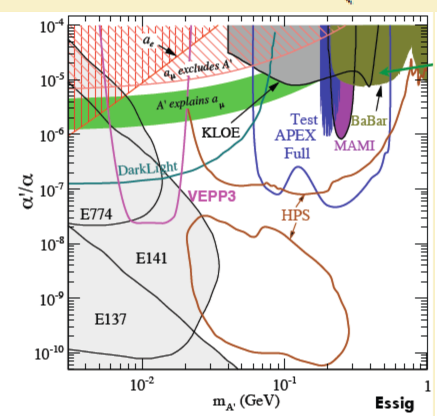
New Physics?





SUSY?

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



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