Recent Progress on Muon g-2 Experiment at Fermilab

- Introduction
- Experimental setup
- Theory calculation
- Experiment at Fermilab
- Status report
- Summary

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On Behalf of Muon g-2 Collaboration

Muon g-2 Collaboration at Fermilab E989

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169 Members

US Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas, Austin
- Virginia
- Washington
- York College

US National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati
- Roma 2
- Udine
- Pisa
- Naples
- Trieste
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China
- Shanghai

Netherlands
- Groningen

Germany
- Dresden

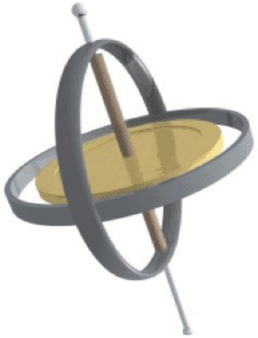
England
- University College
- London
- Liverpool

Korea
- CAPP/IBS & KAIST

Russia:
- Dubna
- Novosibirsk

What is (muon) g-2?

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



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!

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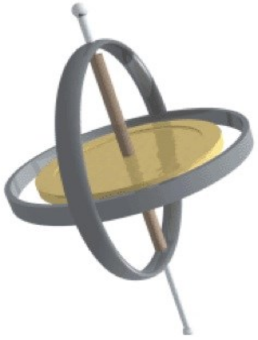

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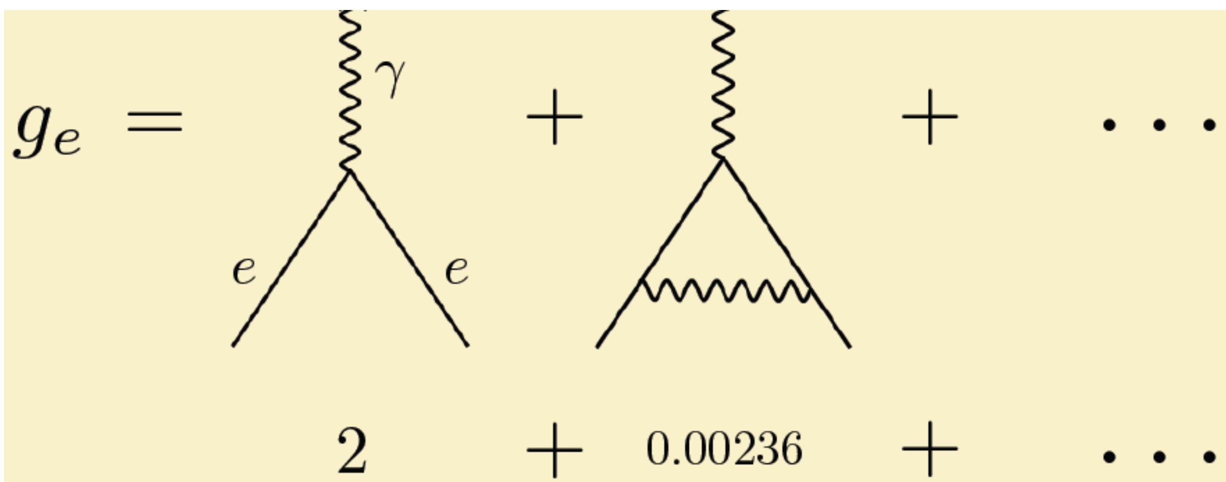

First order QED: beginning of QED and the Standard Model

From ‘beginning’ to ‘beyond’ of Standard Model

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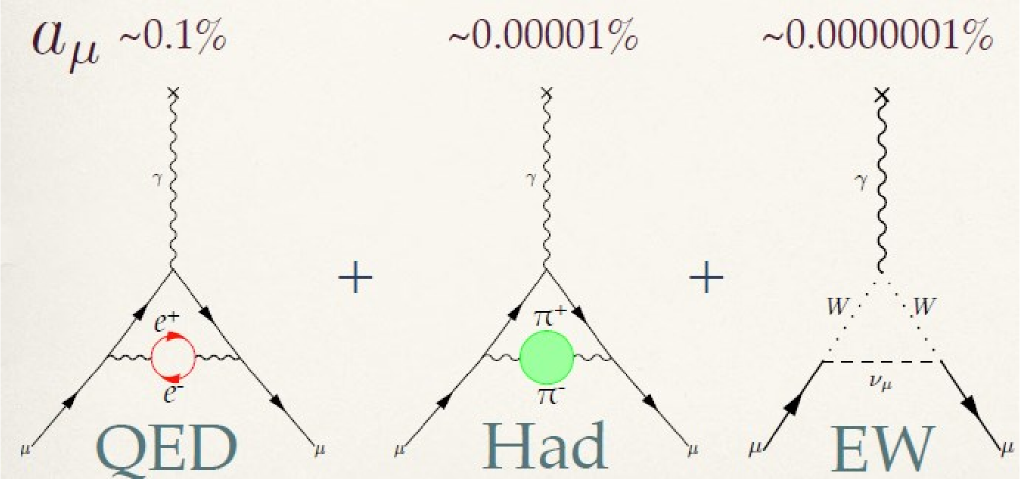

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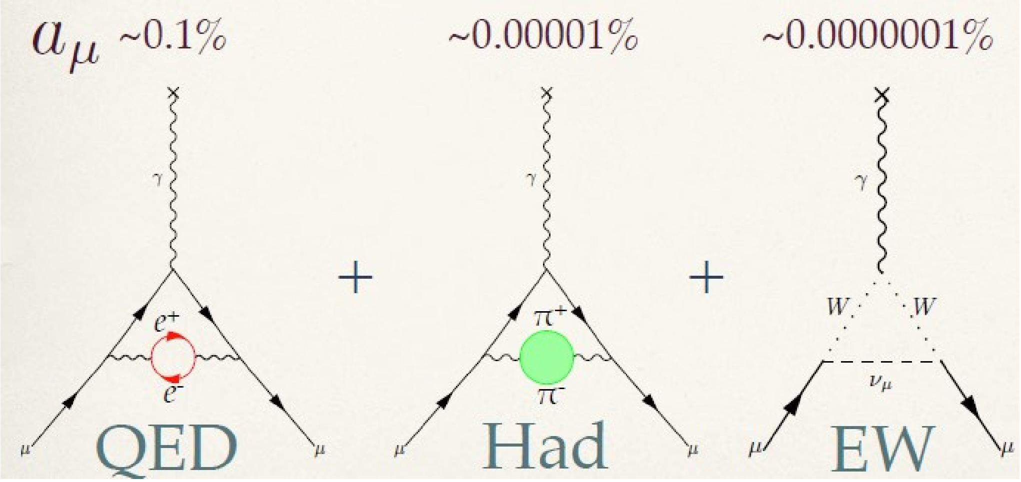

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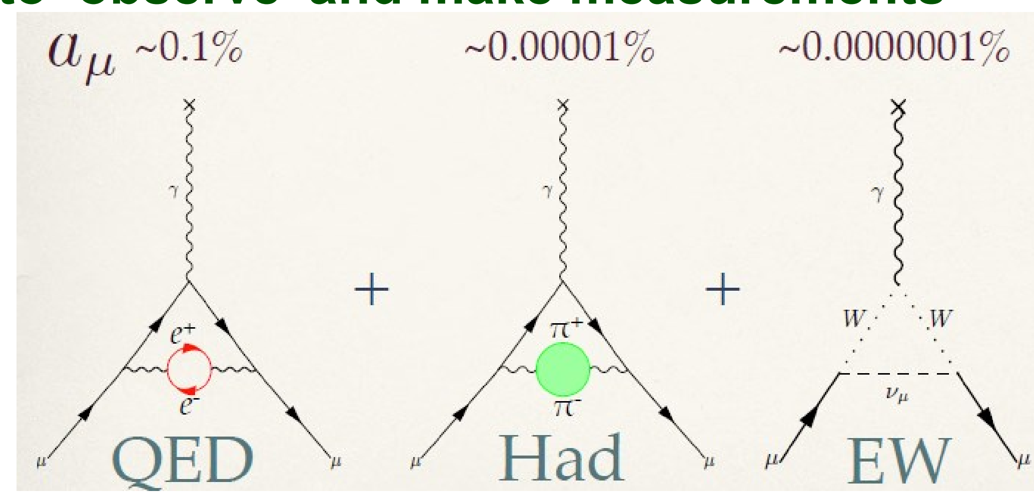
- **Muon is special**
  - **m_u/m_e ~ 200, sensitivity ~ 200^2 ~ 10^4 (effects on muons are much easier to be observed than electrons)**

  Easy to make ample production, life time (2.2μs) long enough to 'observe' and make measurements



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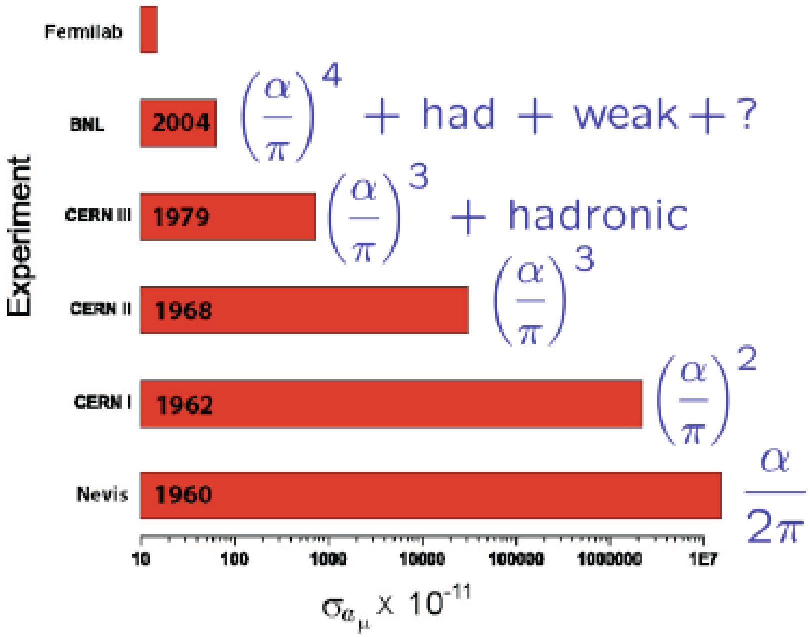

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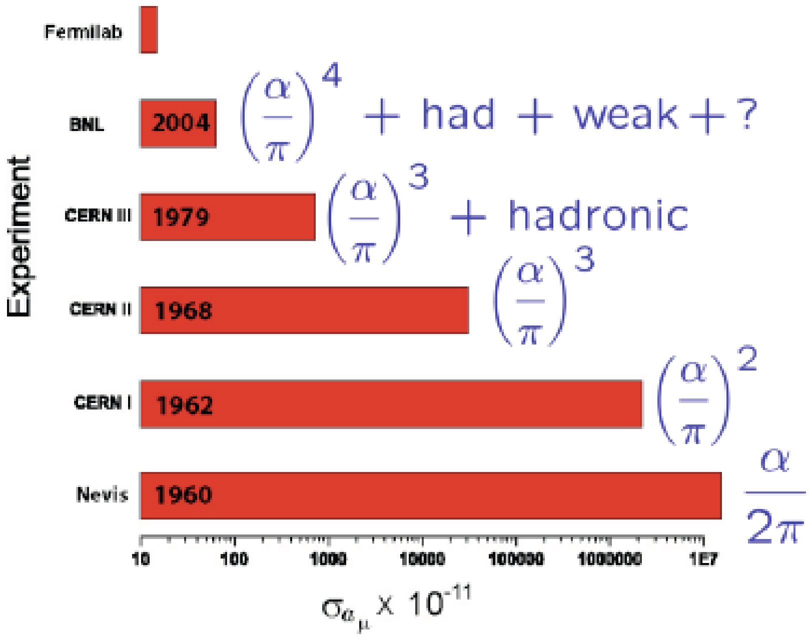

Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$
Columbia-Nevis(1957) [2]	μ^+	$g = 2.00 \pm 0.10$	
Columbia-Nevis(1959) [3]	μ^+	$0.001\,13^{+(16)}_{-(12)}$	12.4%
CERN 1(1961) [4]	μ^+	0.001 145(22)	1.9%
CERN 1(1962) [5]	μ^+	0.001 162(5)	0.43%
CERN 2(1968) [6]	$\mu^\pm$	0.001 166 16(31)	265 ppm
CERN 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

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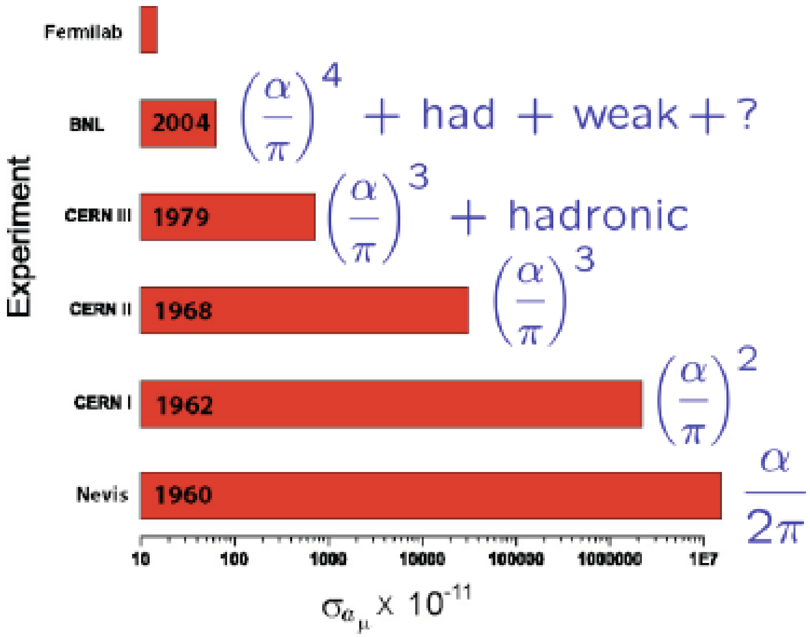

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Over 50 years of non-stopping improvement on δa_μ

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

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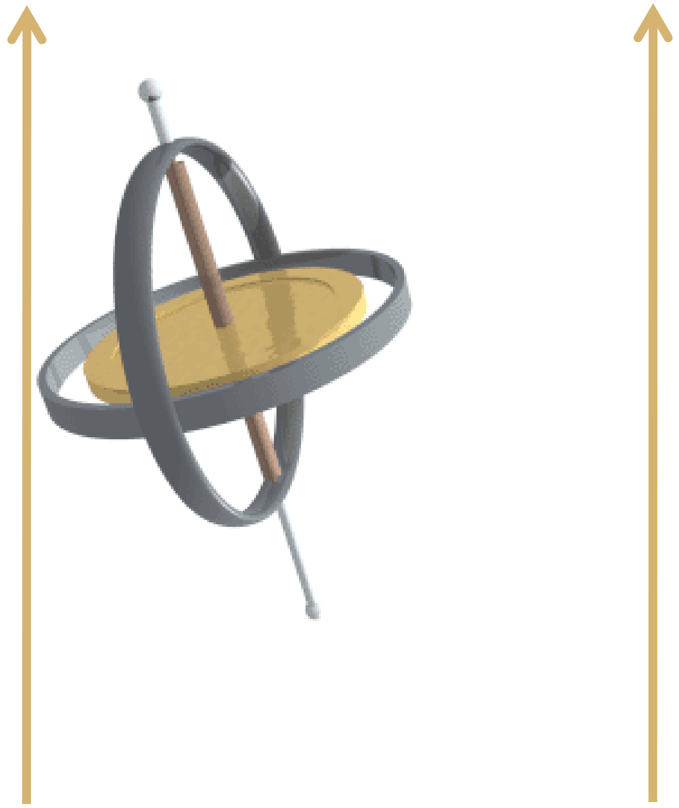

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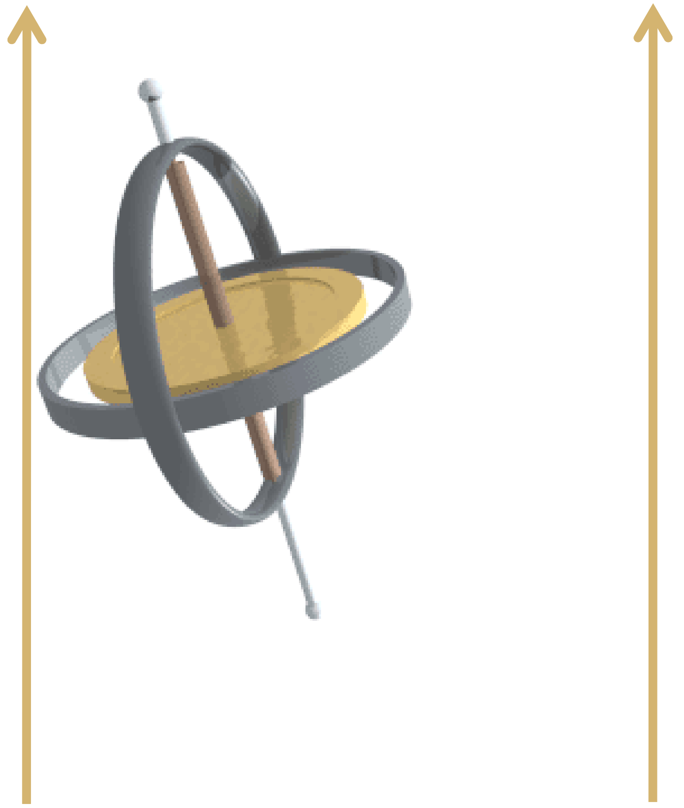

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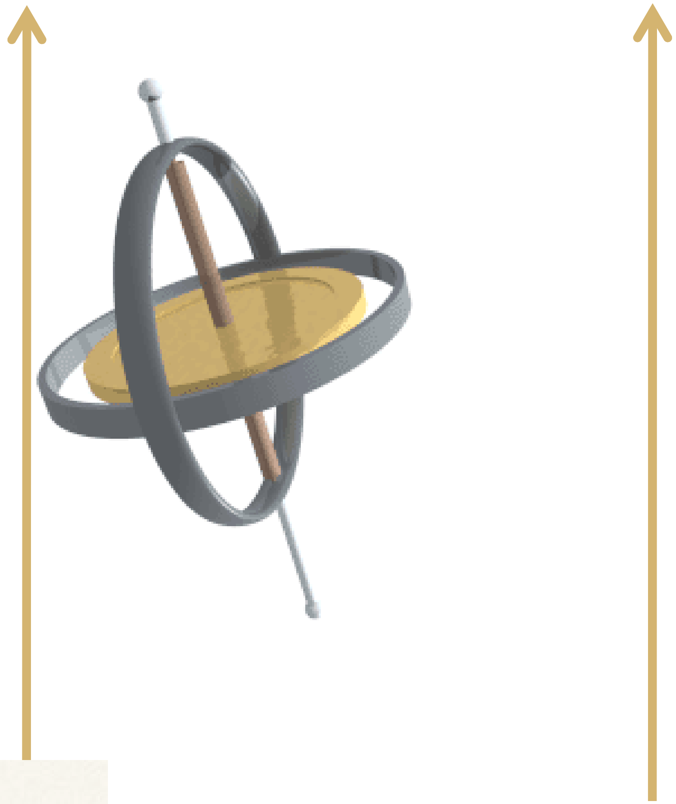

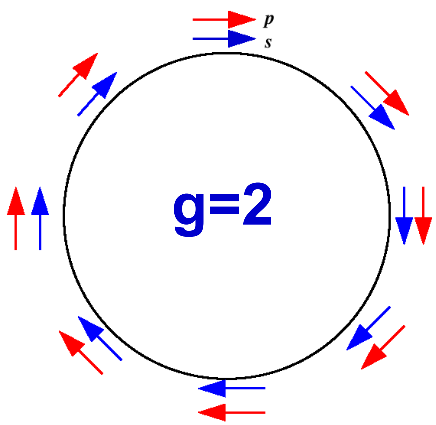

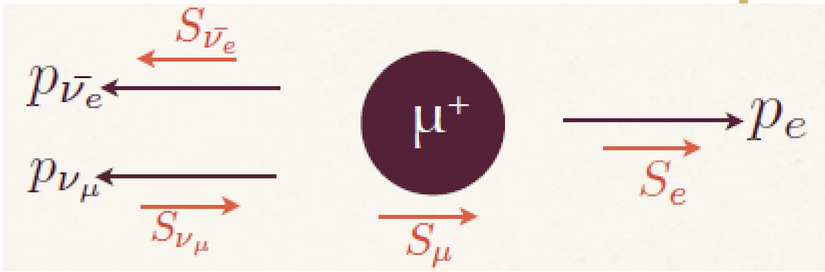

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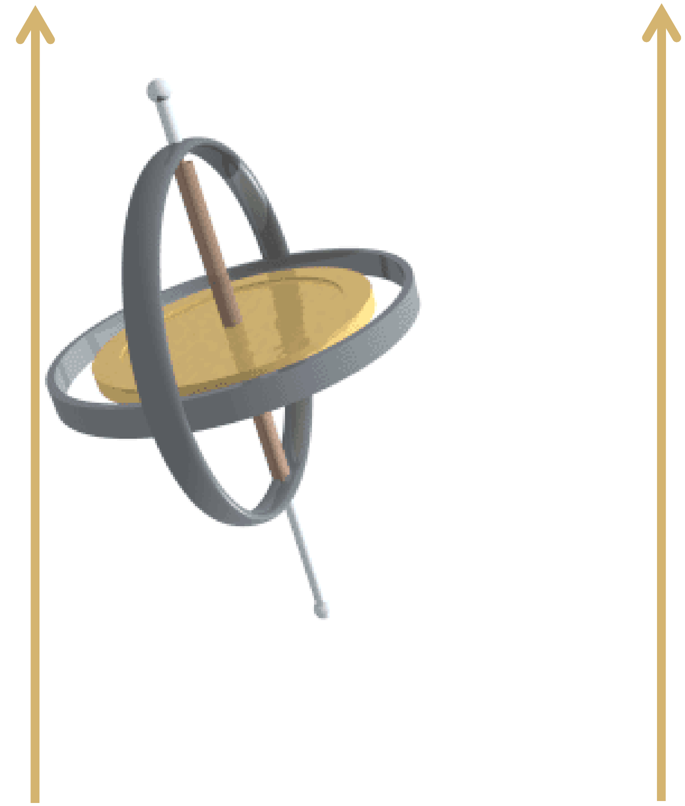

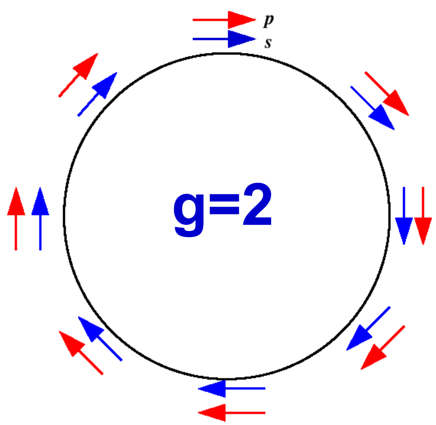

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$$\omega_a = \omega_s - \omega_c$$

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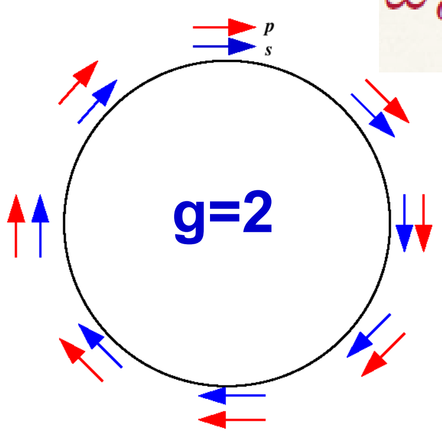

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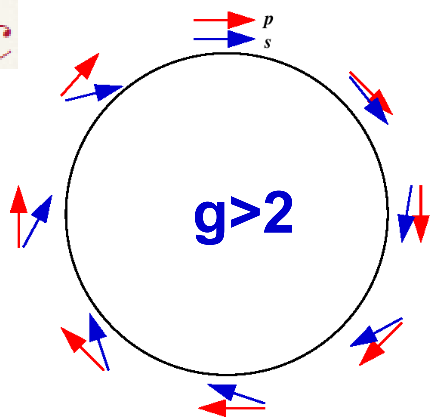

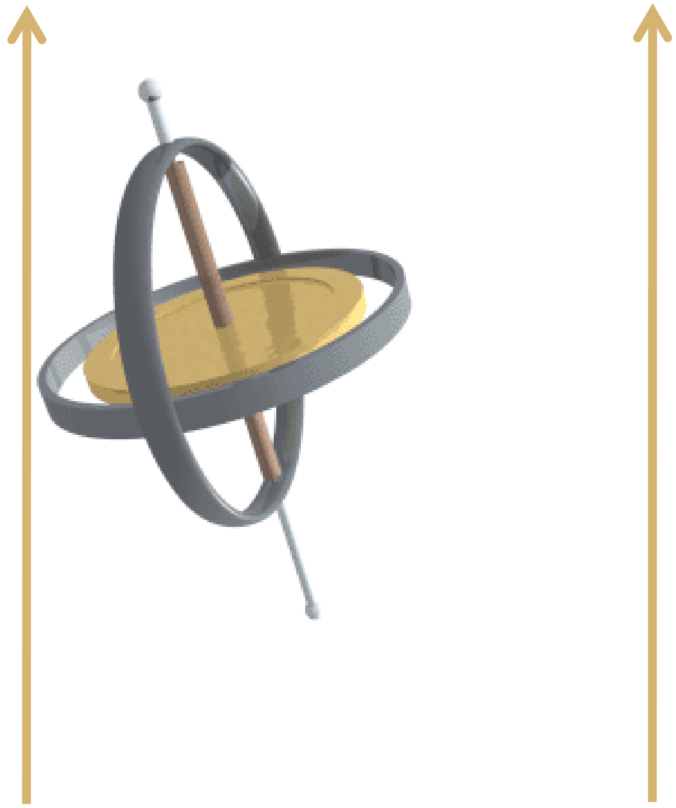

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$$a_\mu \sim \frac{\omega_a}{<B>} = \frac{g_e}{2} \frac{\omega_a}{\varpi_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_e}$$

  - ω_p is the proton precession frequency, $\omega_p \sim |B|$
  - ϖ_p is the weighted magnetic field folded with muon distribution
  - For other values: recommended by 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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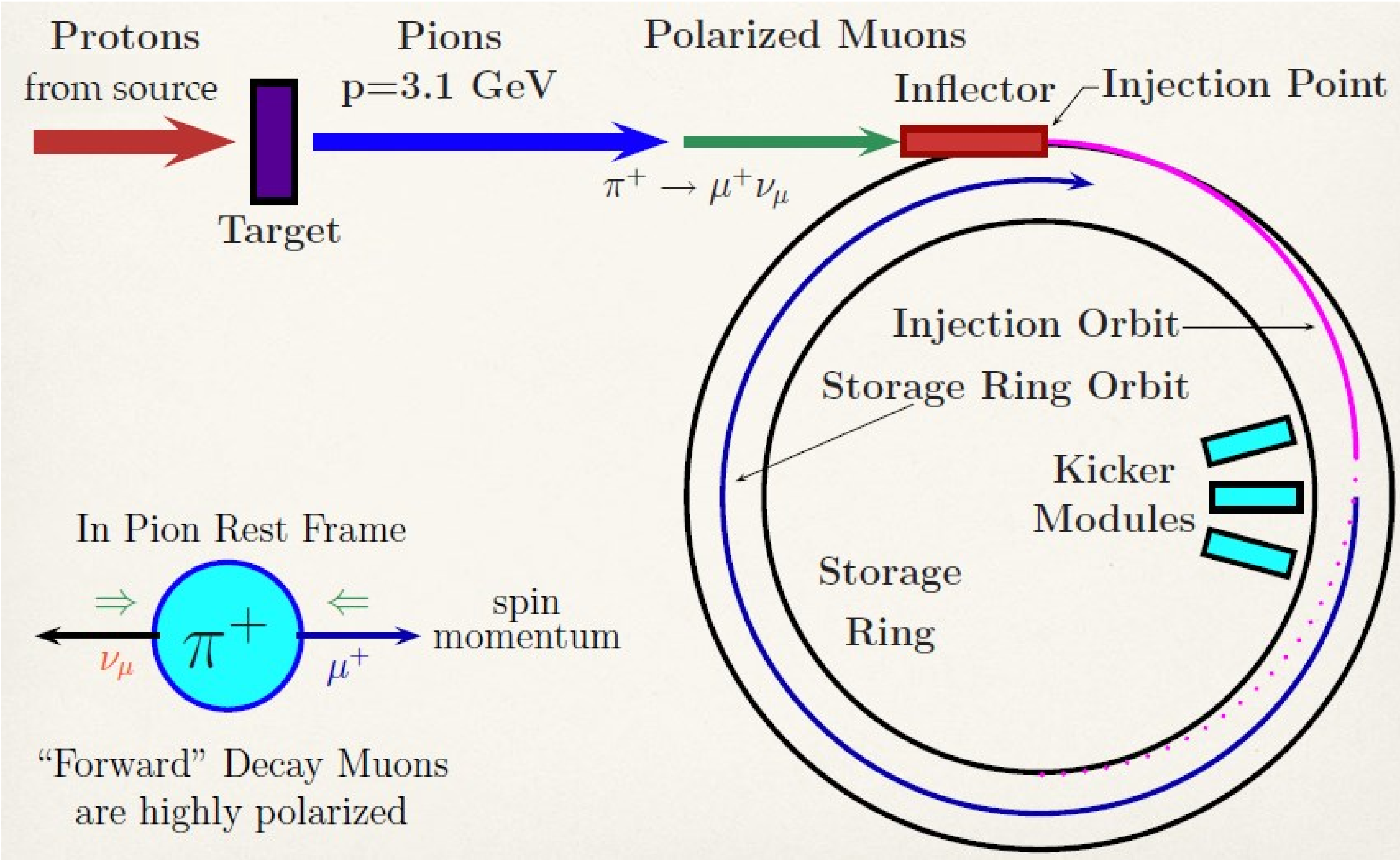
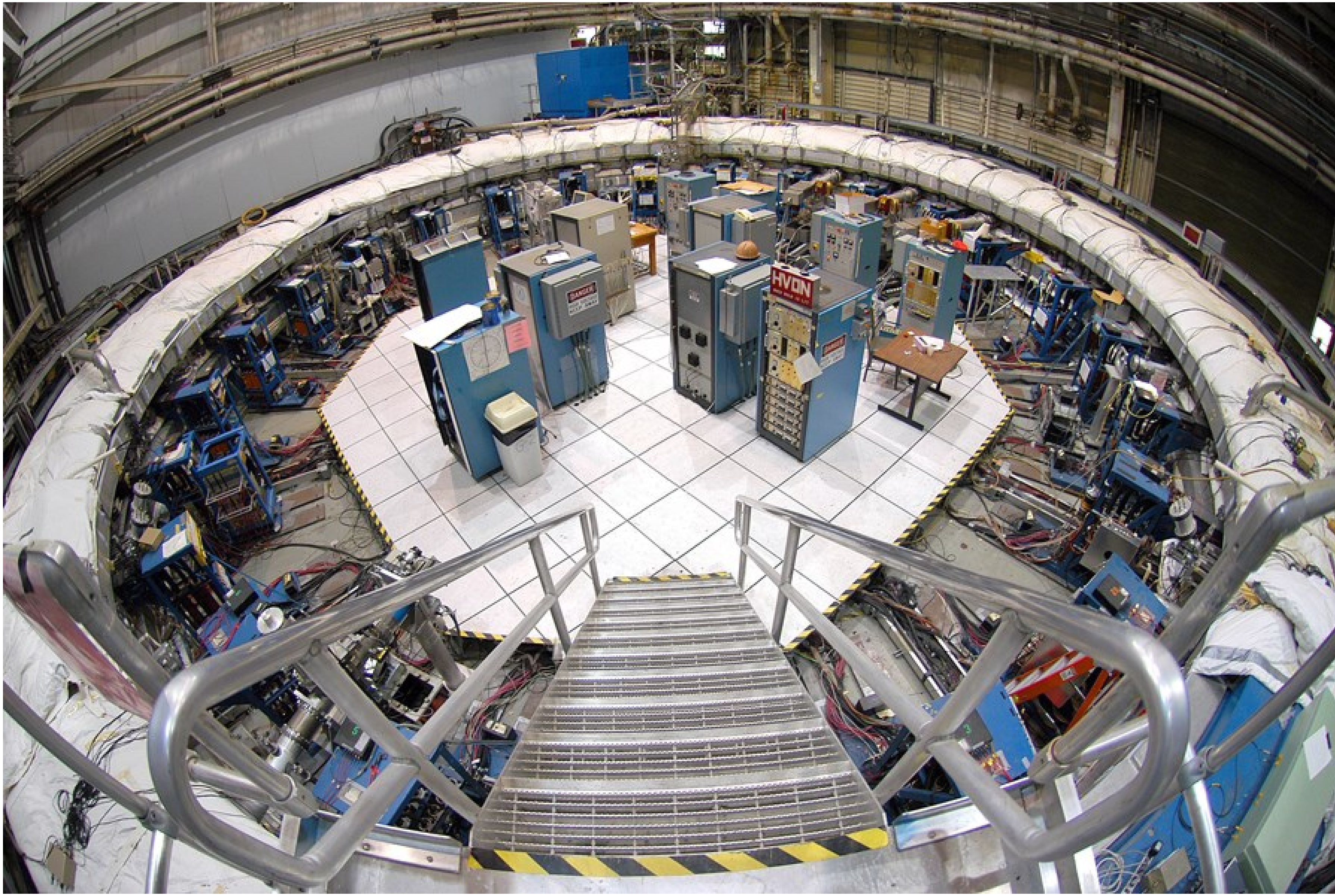
- **Final measurements done in three steps**
  - Inject muons into a ring with uniform magnetic field
    Measure proton precession frequency ω_p
  - Measure muon frequency difference ω_a
  - The last two steps are done simultaneously and independently (blind analyses)

Experiment setup



Injection into the muon storage ring



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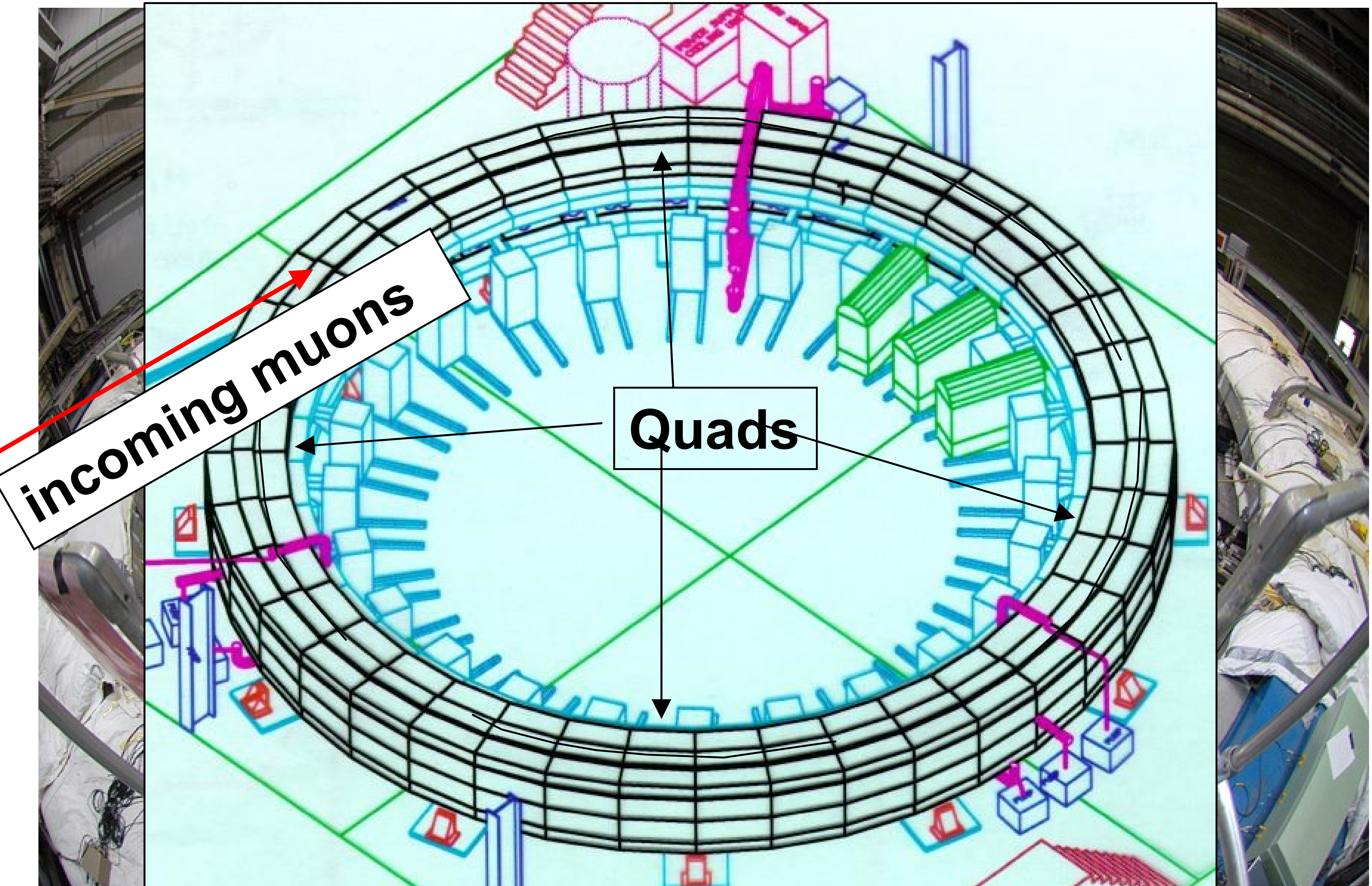

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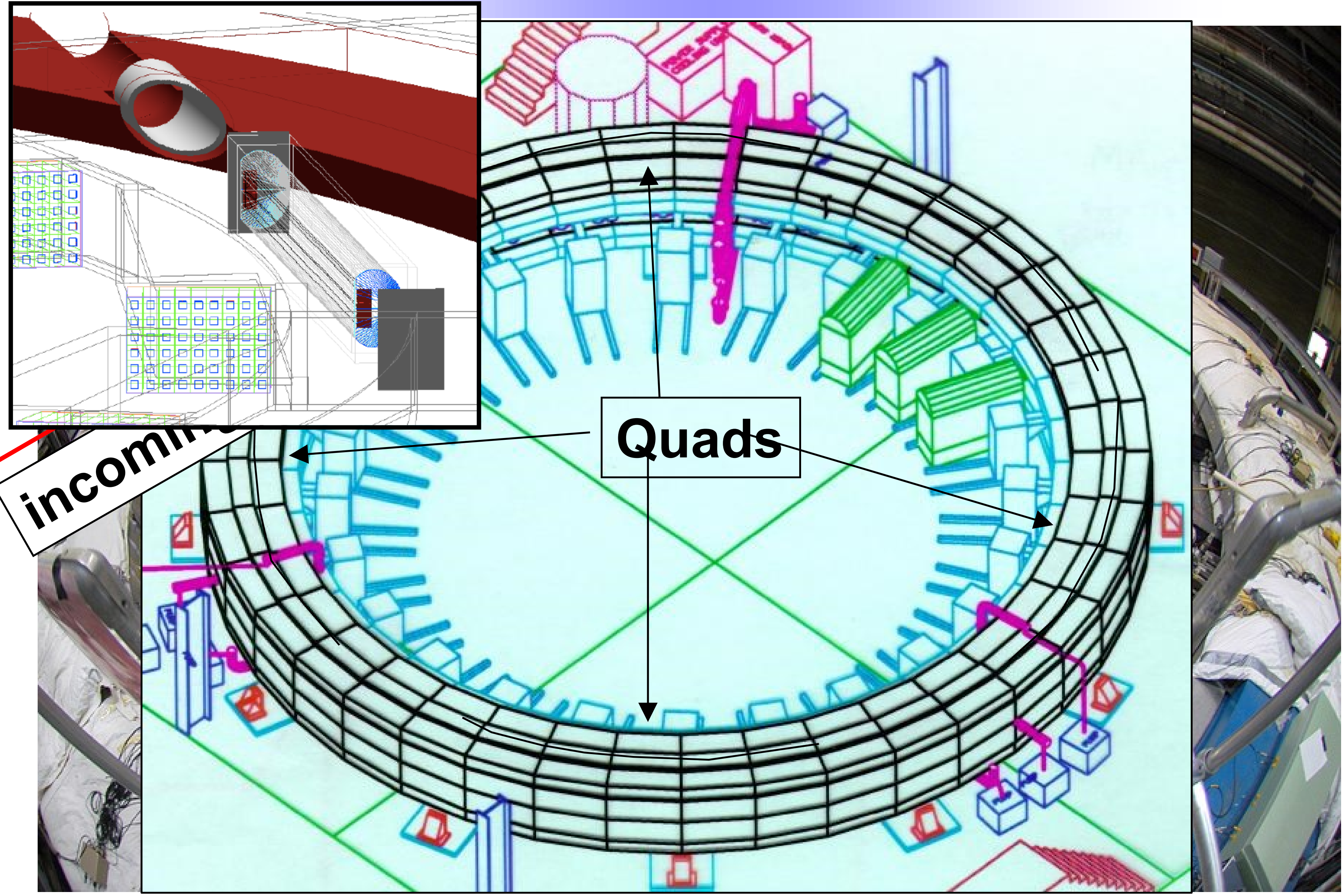

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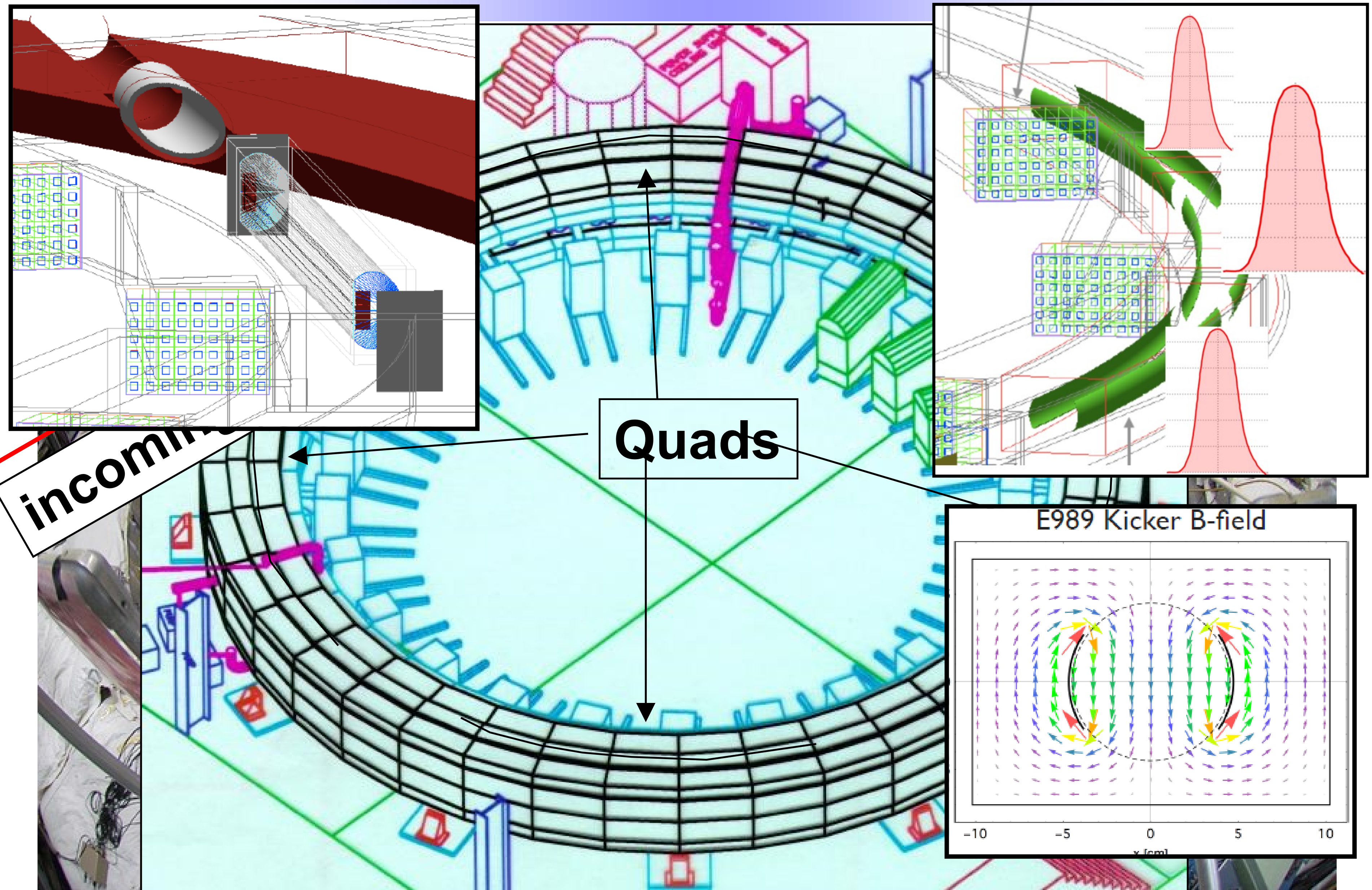

Measuring ω_p, namely the B field

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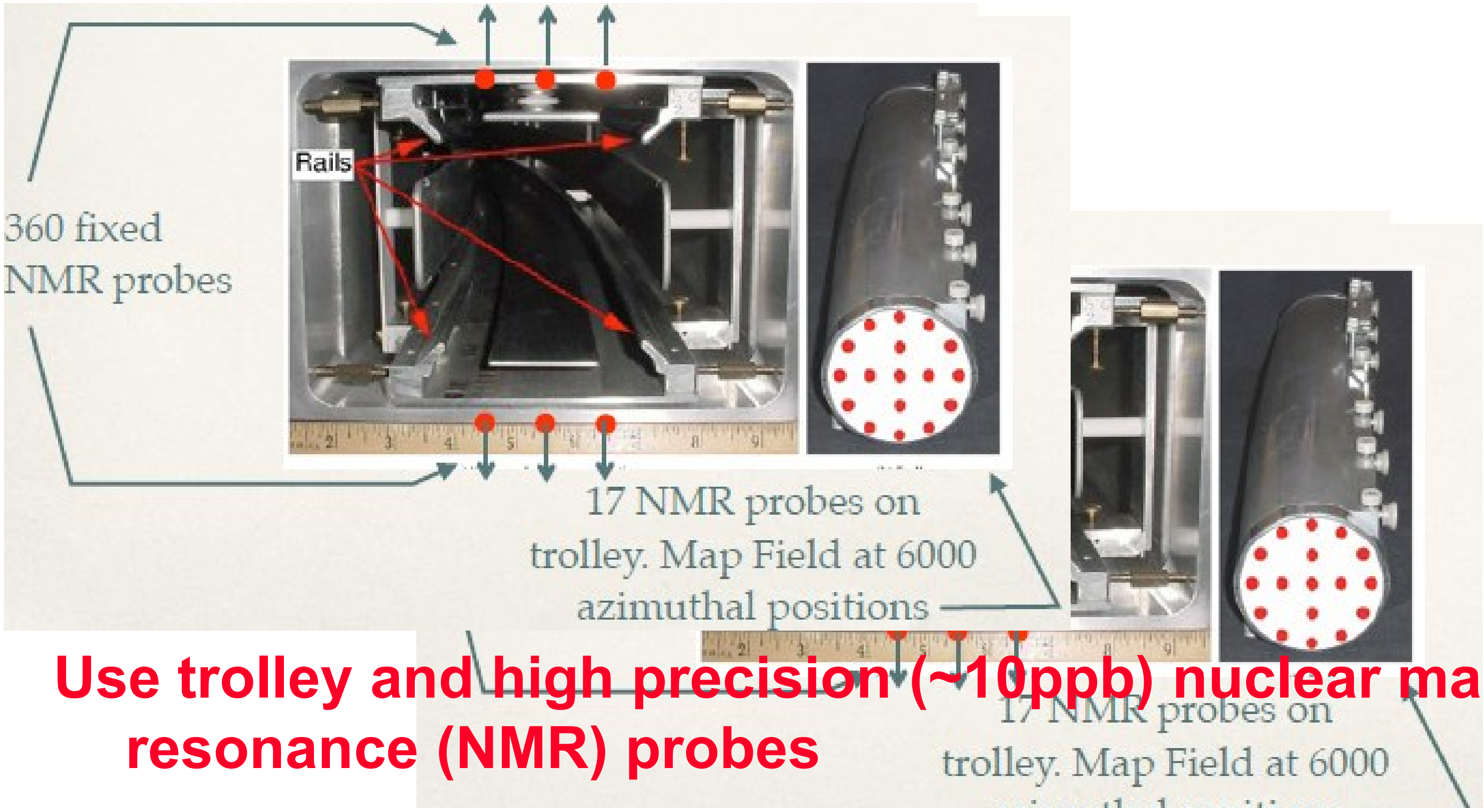

Use trolley and high precision (~10ppb) nuclear magnetic resonance (NMR) probes

- **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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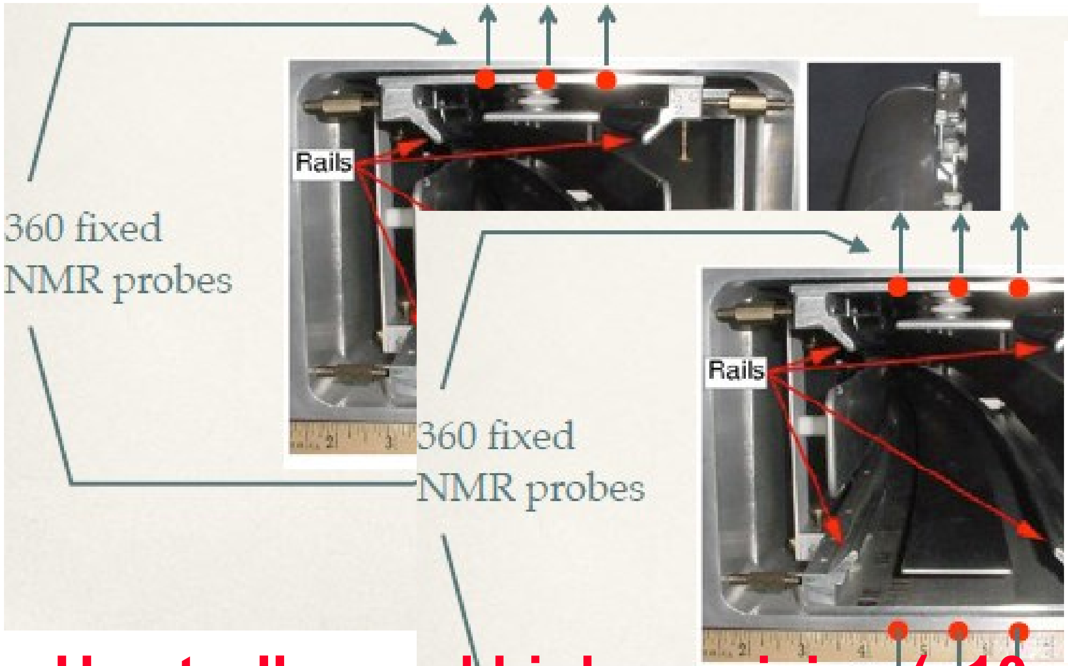

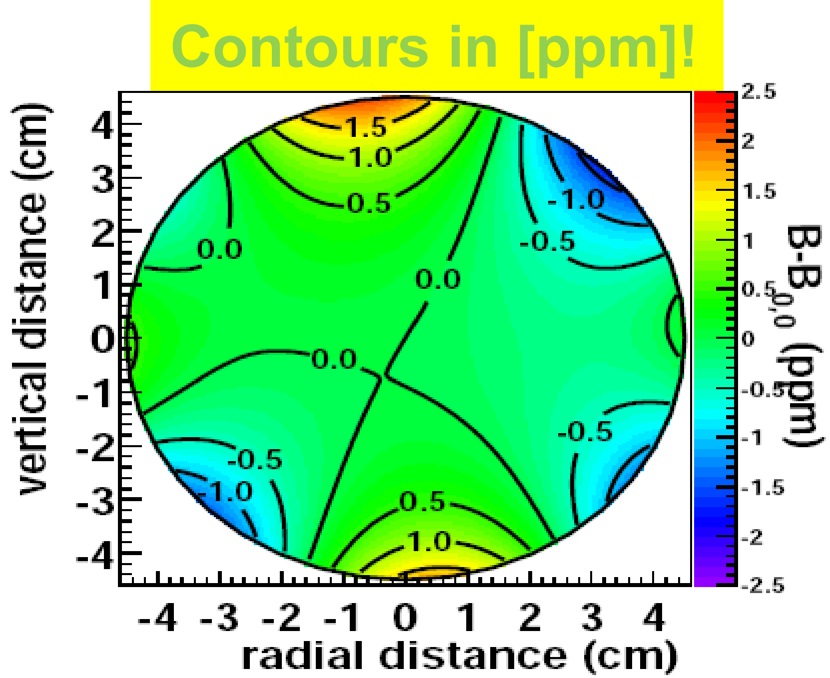

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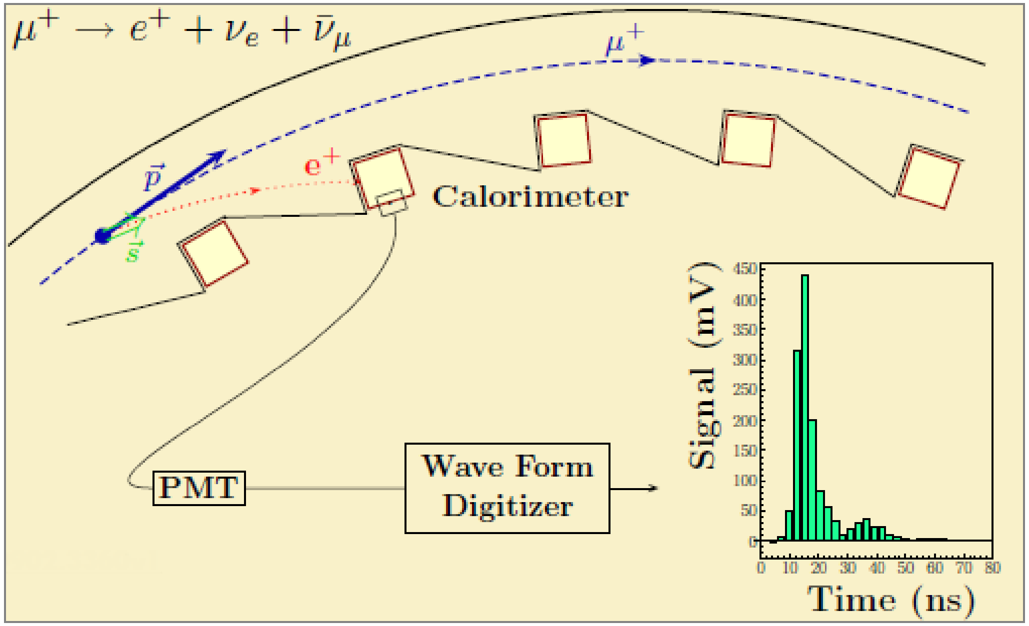

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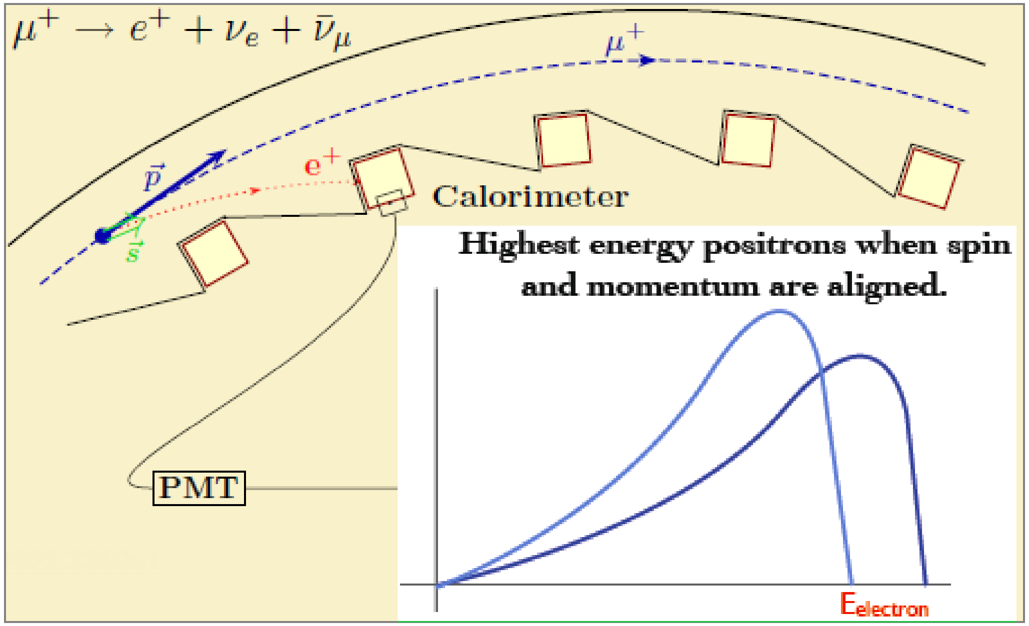

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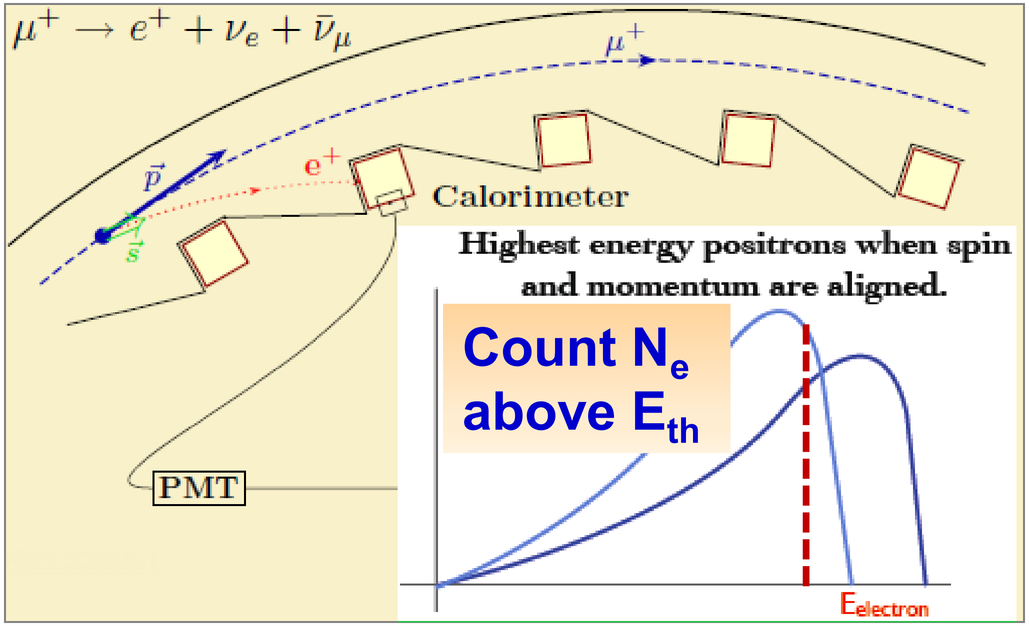

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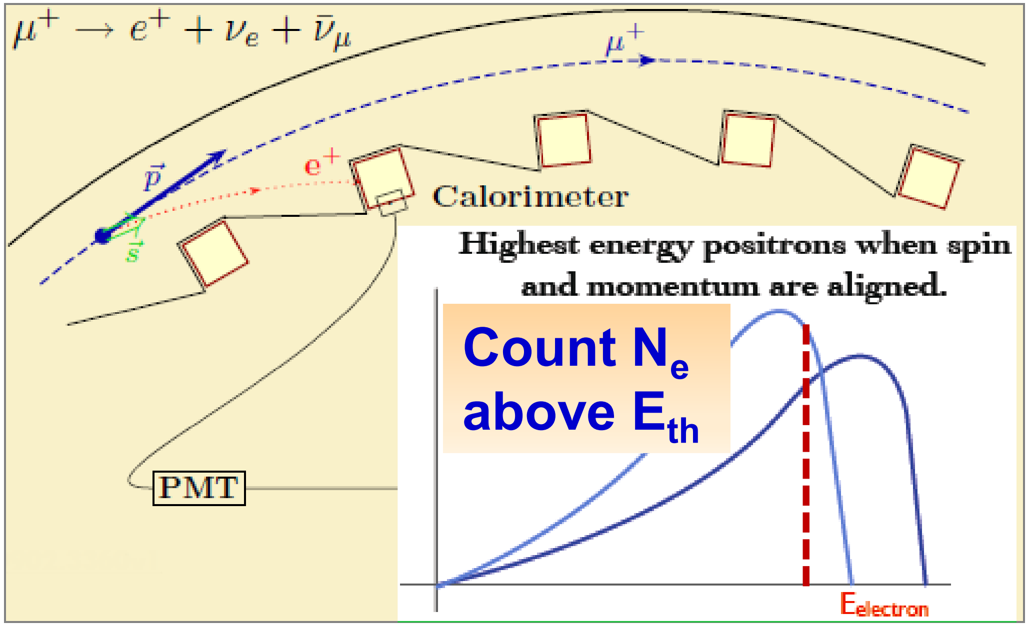

The integrated number of electrons (above E_{th}) modulated at ω_a

- **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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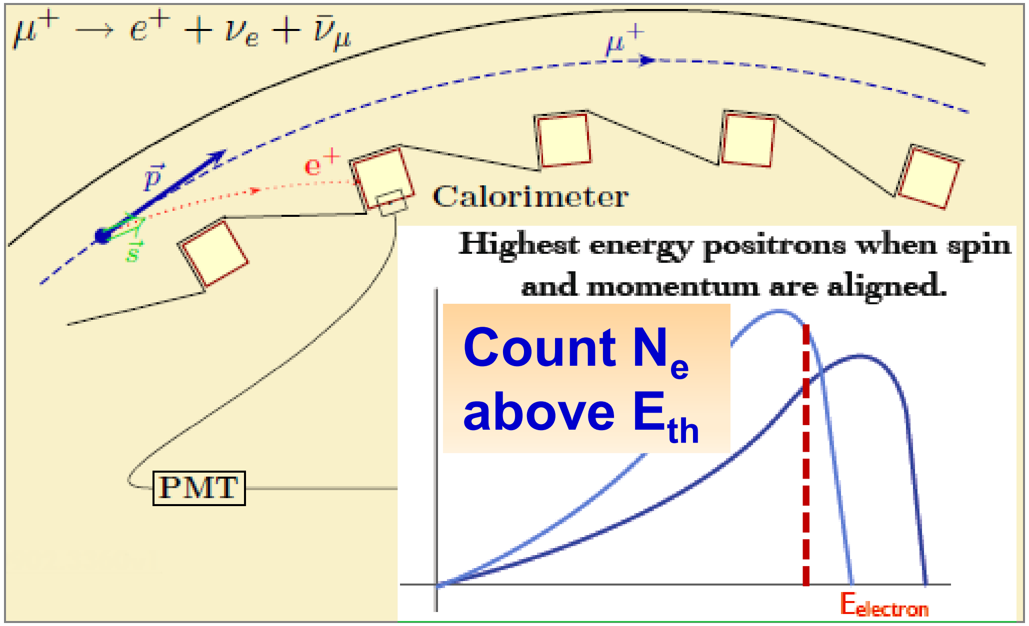

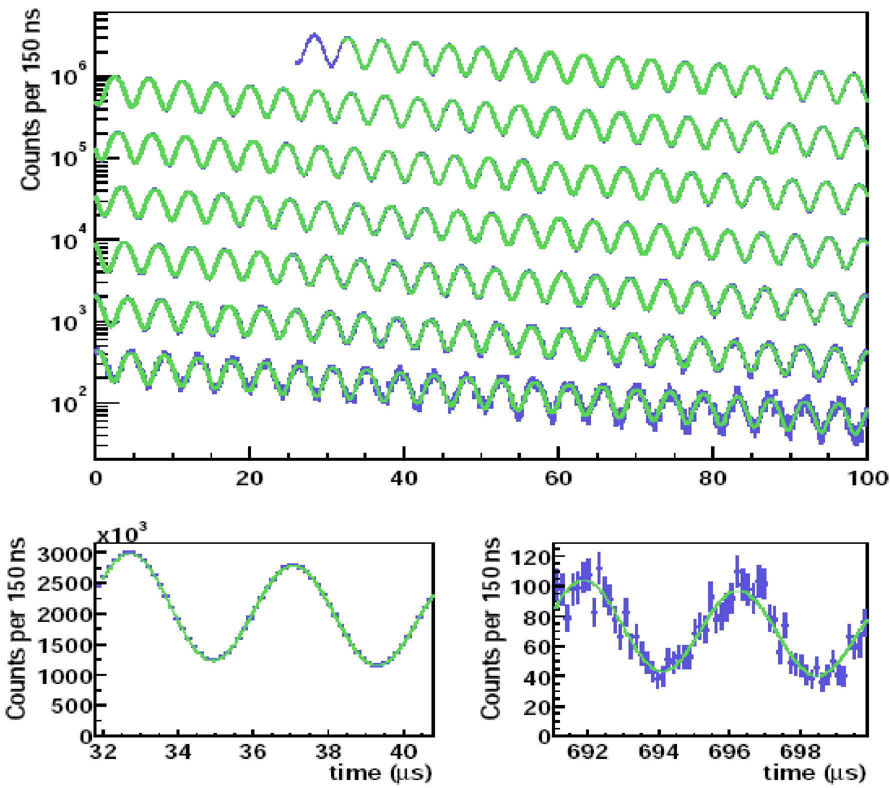

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- **Pileup**
- **Gain (energy scale) changes**
- **Coherent Betatron Oscillations**
- **Muon Losses**

Theory calculation

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

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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 $e^+e^- \to$ hadrons**
- **The hadronic light by light (HLbL) is model specific (cannot be determined from data directly), much less known (25% error)**
- **Lattice QCD is starting to get involved, could be a big help**

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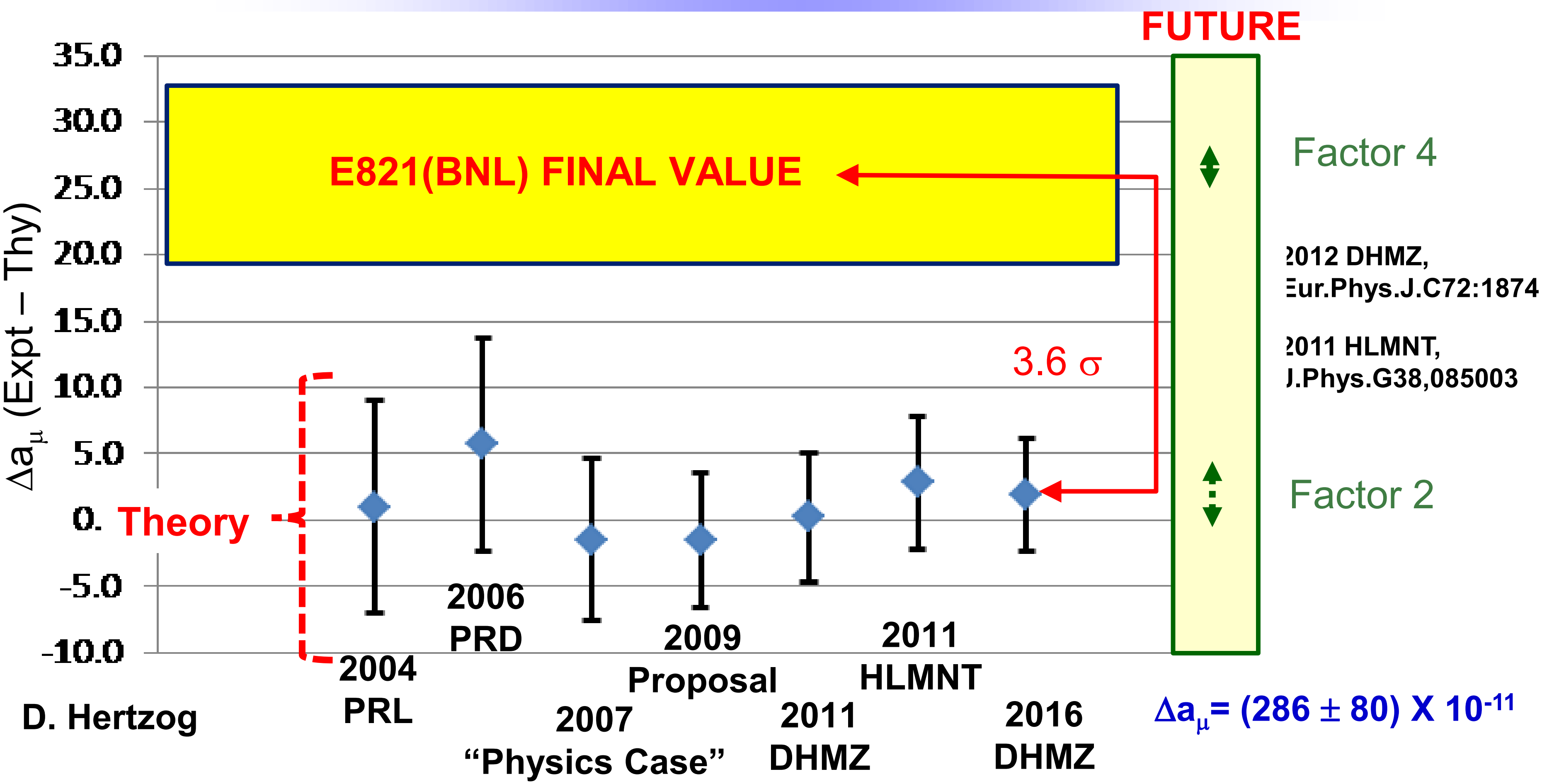

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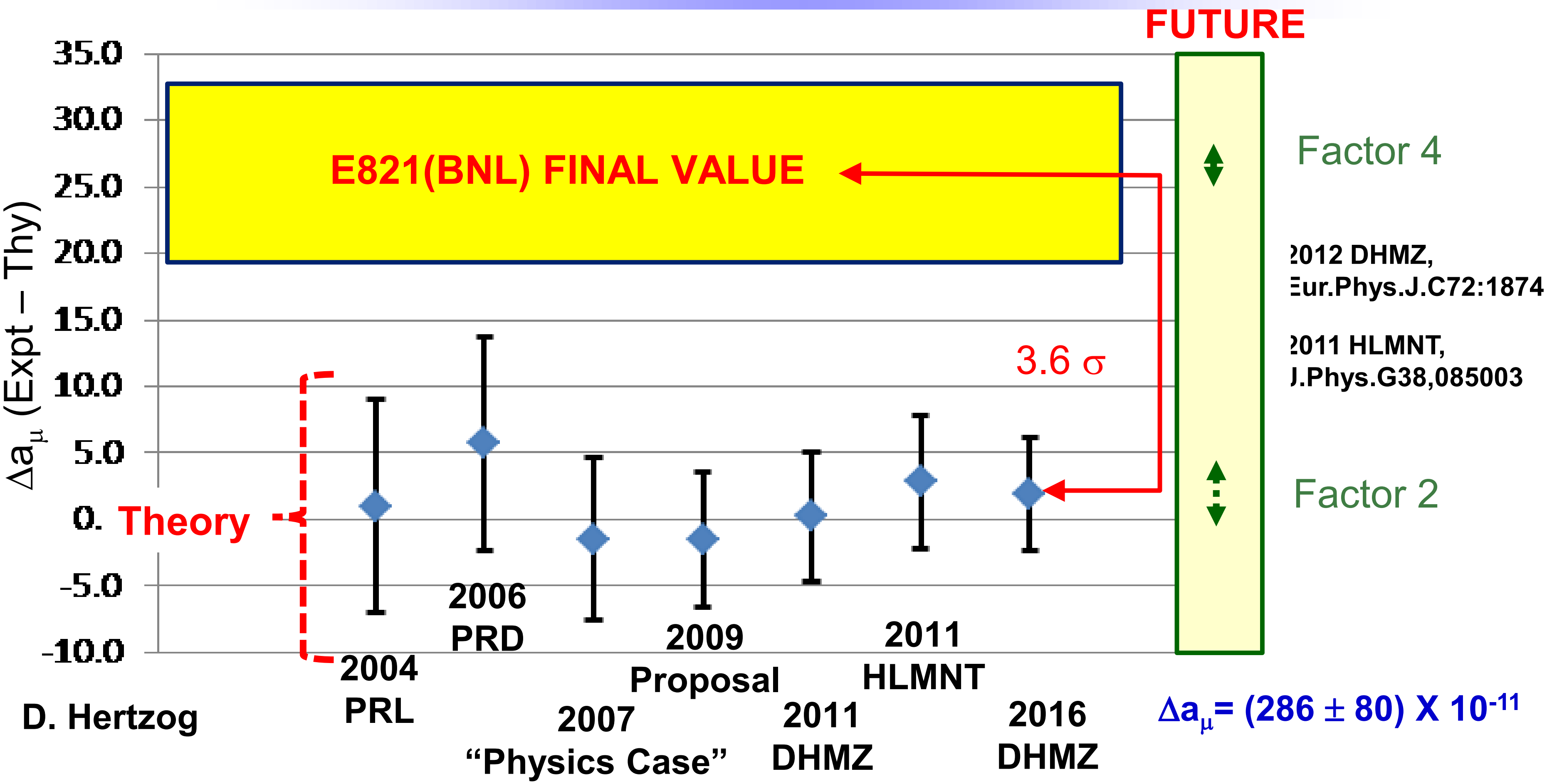

3.3 σ – 3.6 σ difference depending on HVP LO contribution

- **If the discrepancy sustains, it can point to new physics**
- **Δa_μ tightly constraints new physics models: significant implications to interpret any new phenomena**

E821(BNL) vs. E989(Fermilab)

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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}
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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

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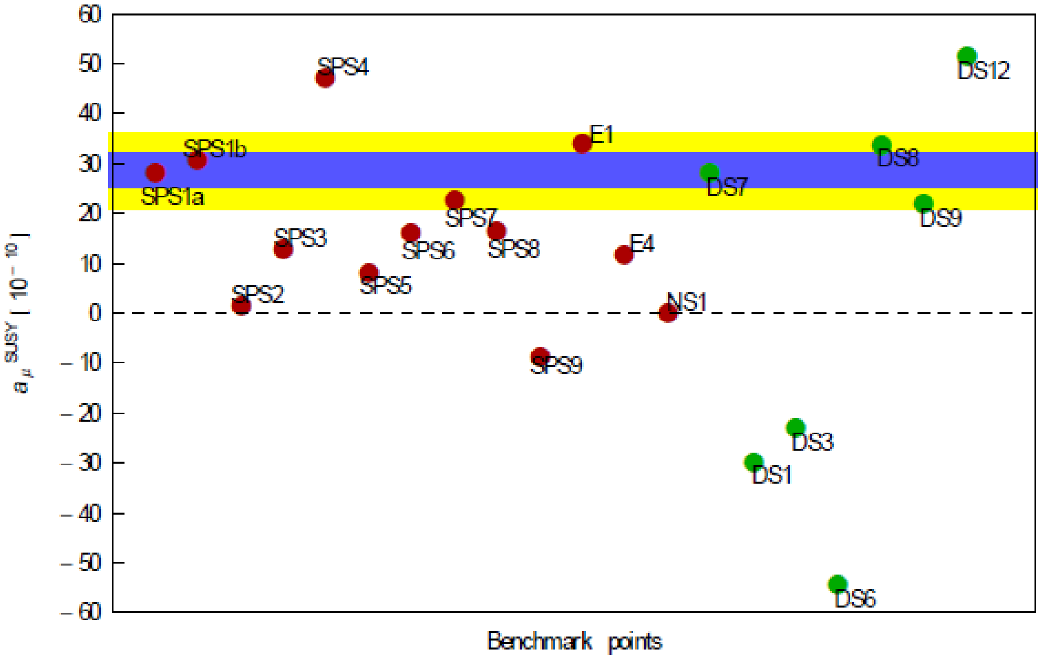
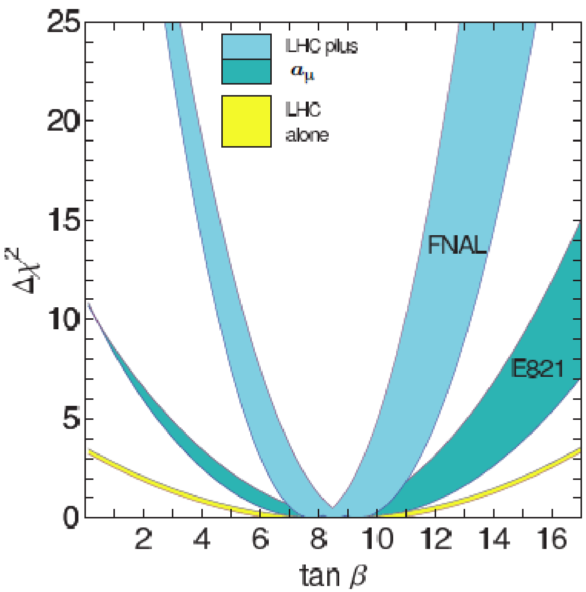
E989 (Fermilab) experimental uncertainty:
0.14ppm ~ 16 X 10 $^{-11}$
> 5σ deviation if with the same central value

New Physics?



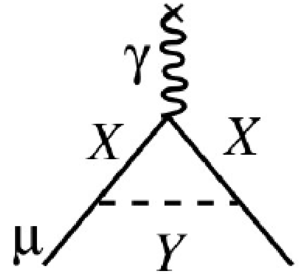


SUSY?

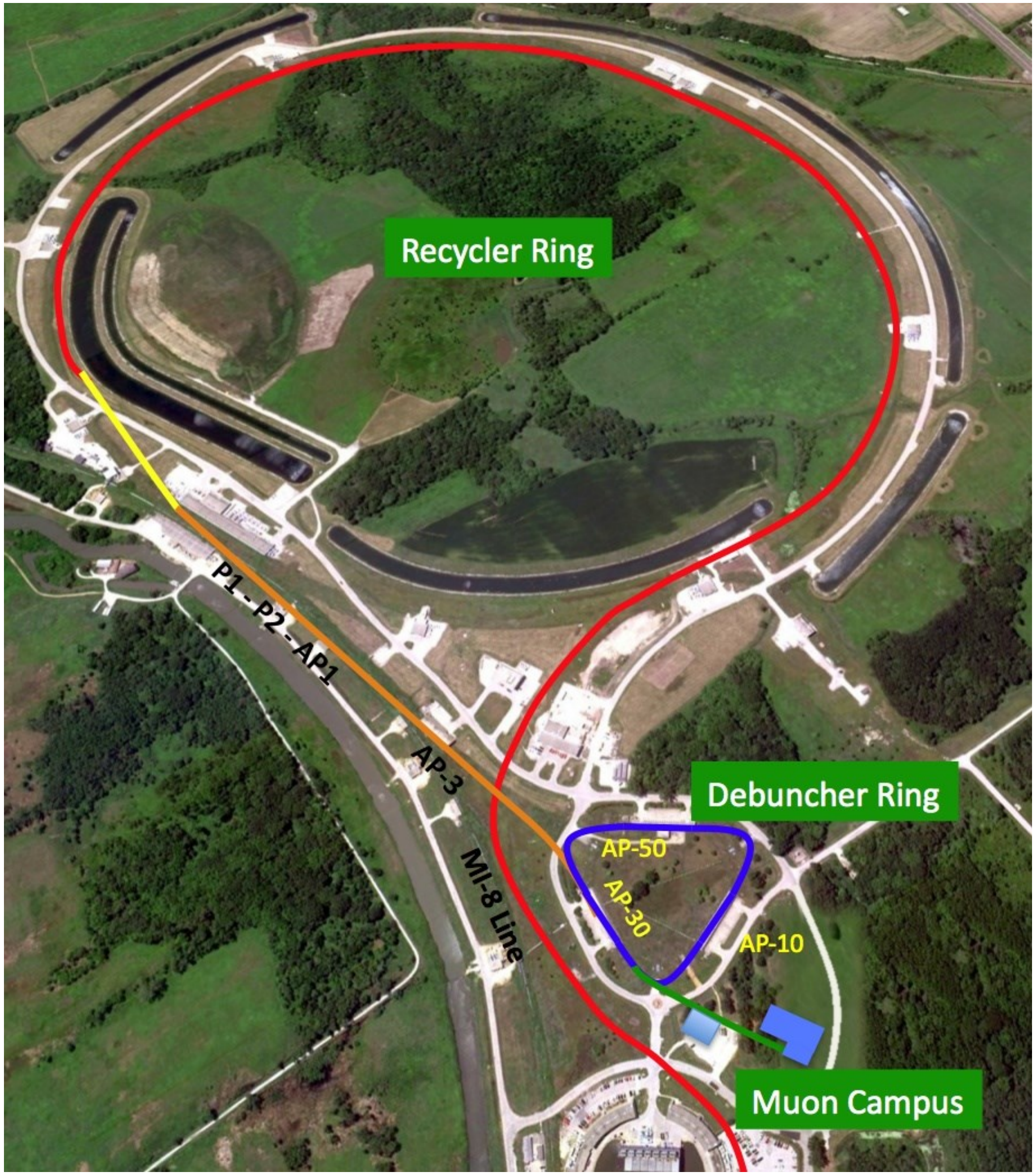
$$a_\mu^{\rm SUSY} \approx 13 \times 10^{-10}\,{\rm sign}(\mu)\left(\frac{100\ {\rm GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

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

Dark Sector?



Fermilab Muon Campus



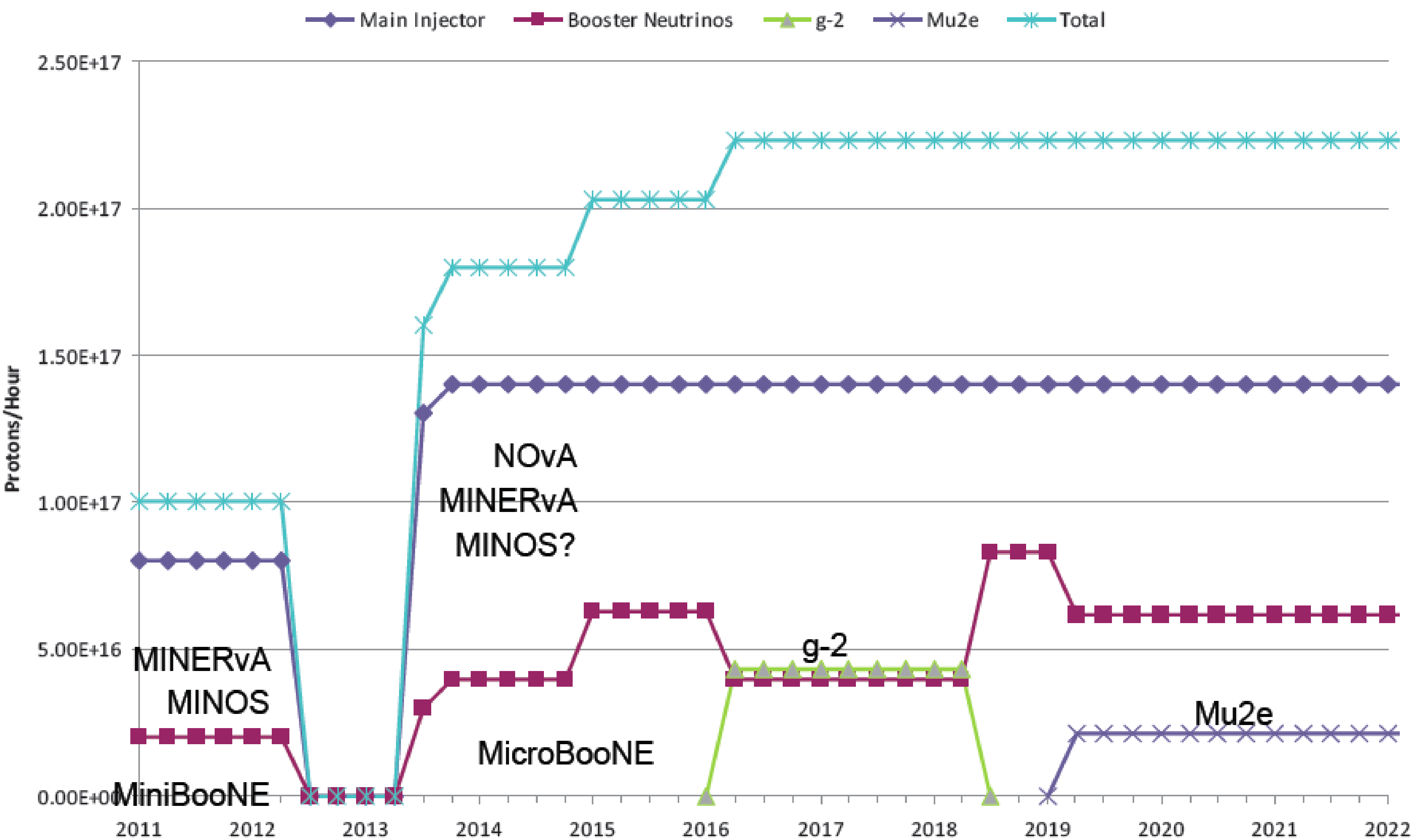
- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - 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

Fermilab Muon Campus

Fermilab Muon Campus

Share the beam



Detector upgrade: calorimeter

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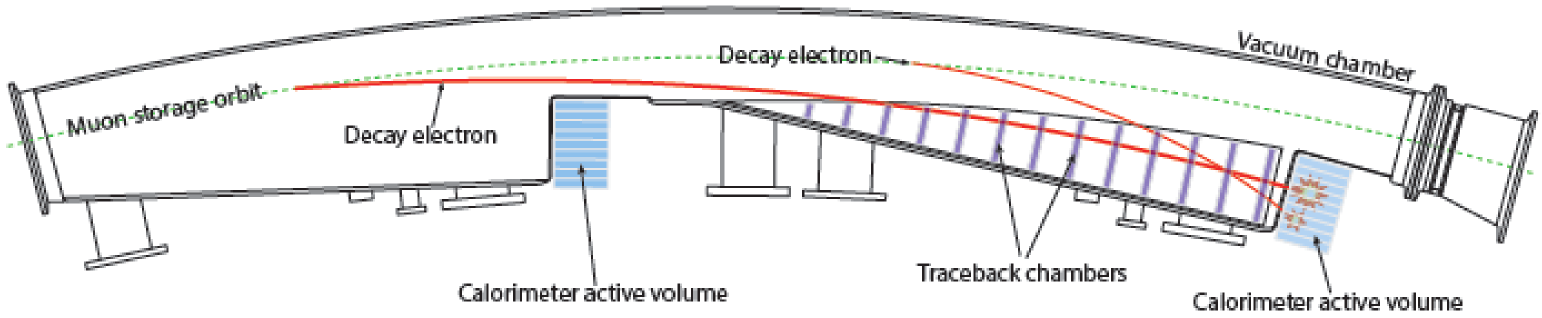

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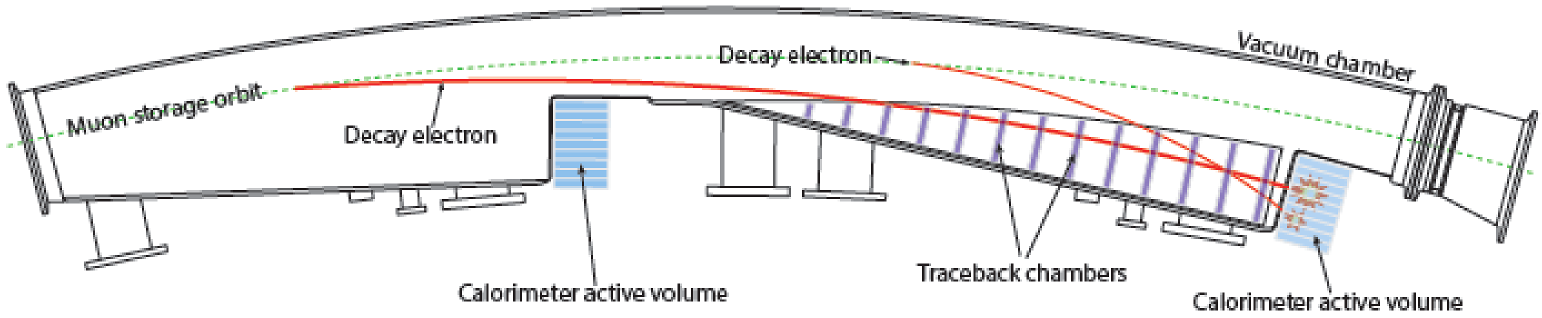
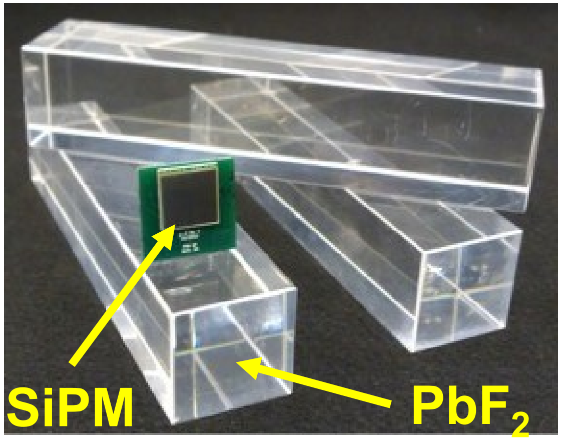
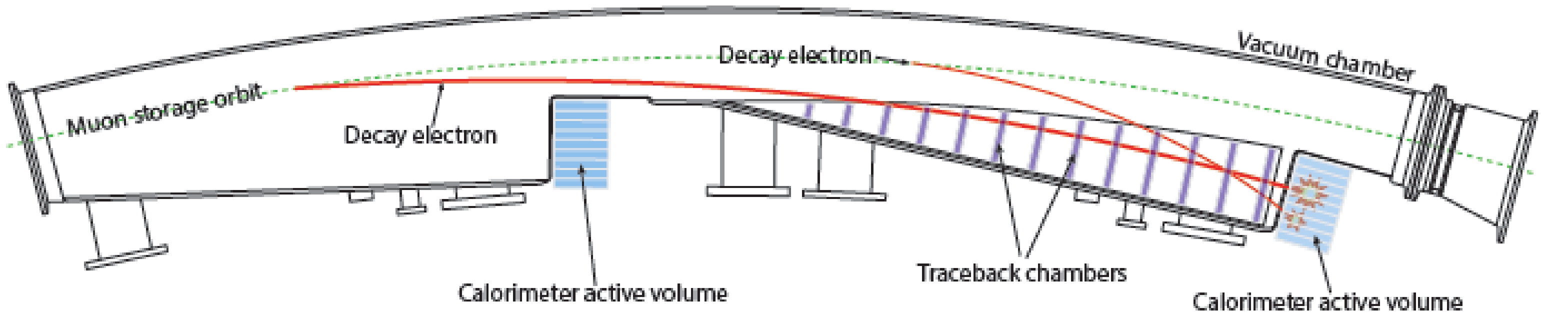
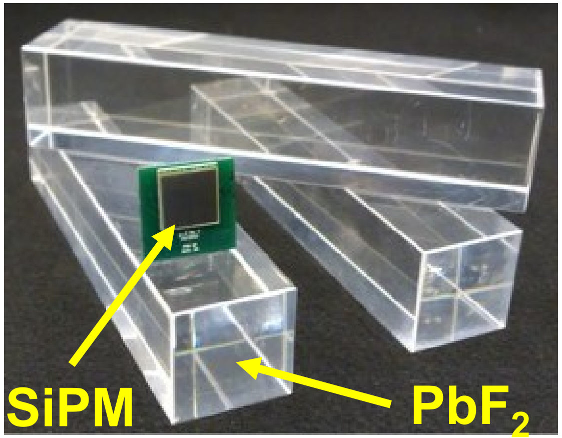


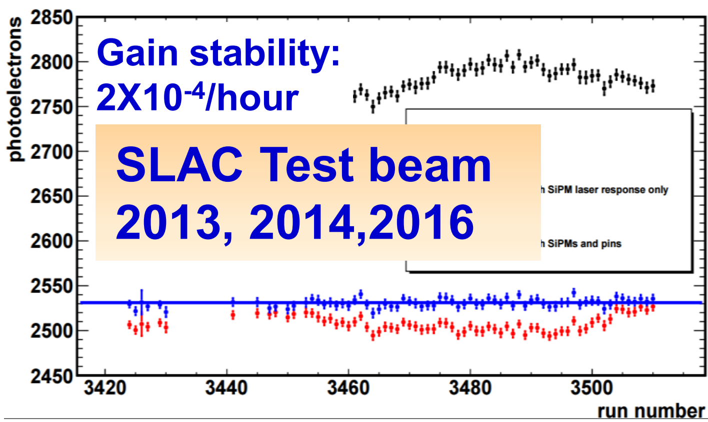


Segmented, fast response, crystal calorimeter (9X6 array)

Detector upgrade: calorimeter







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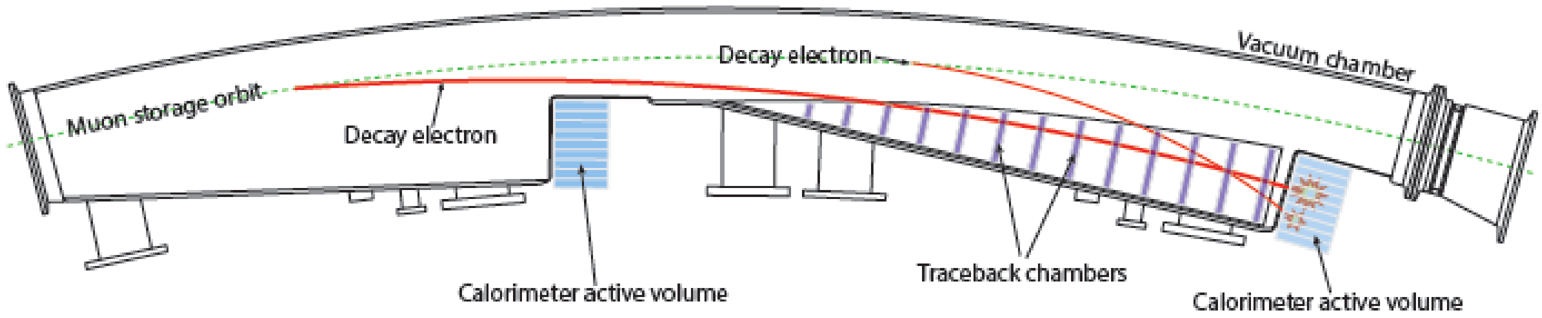

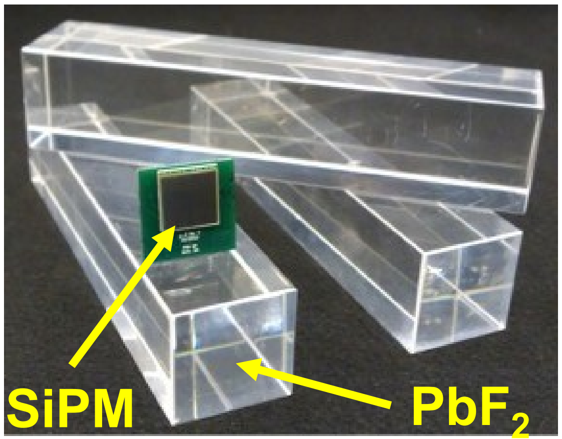

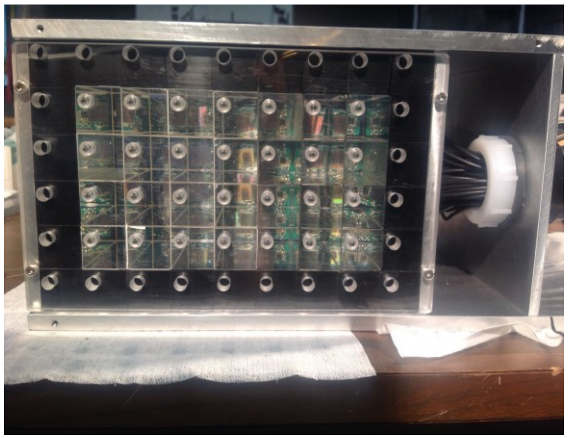

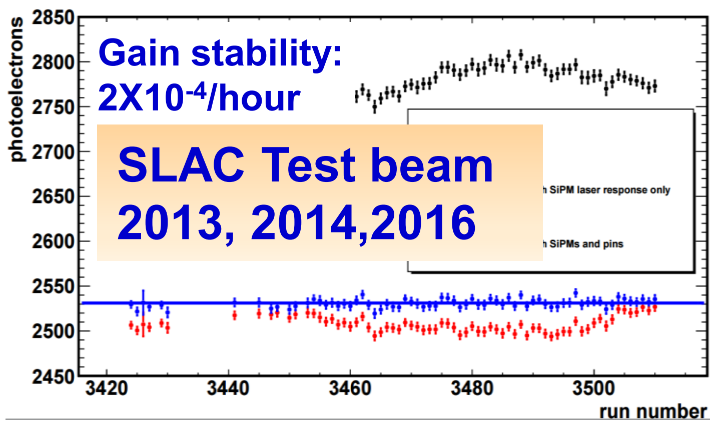

Segmented, fast response, crystal calorimeter (9X6 array)

- **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 upgrade: tracker

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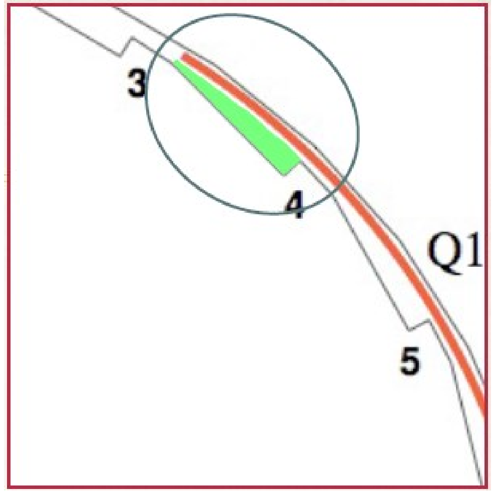

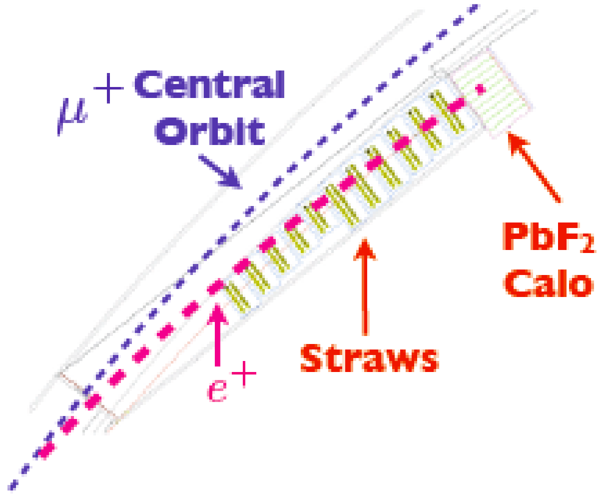

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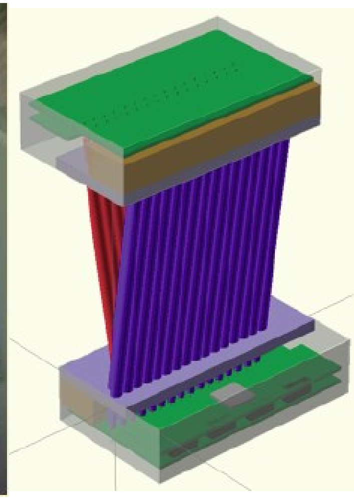
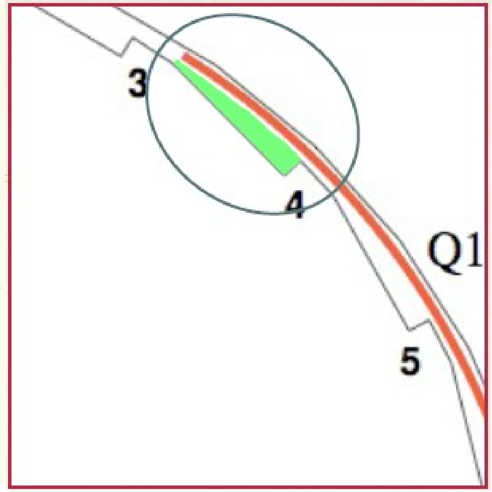
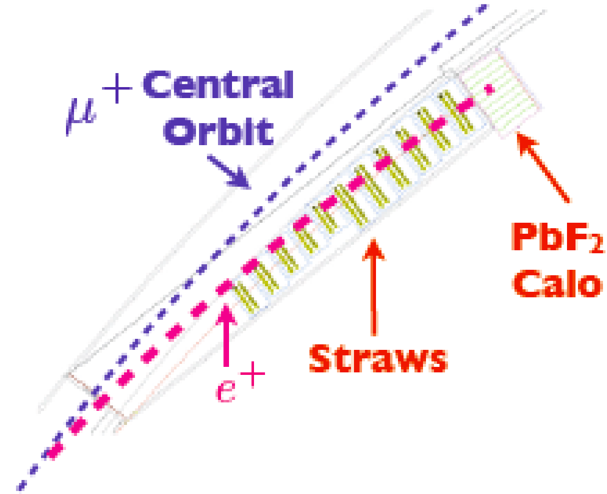
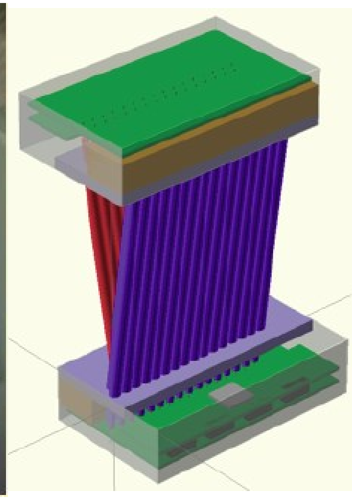
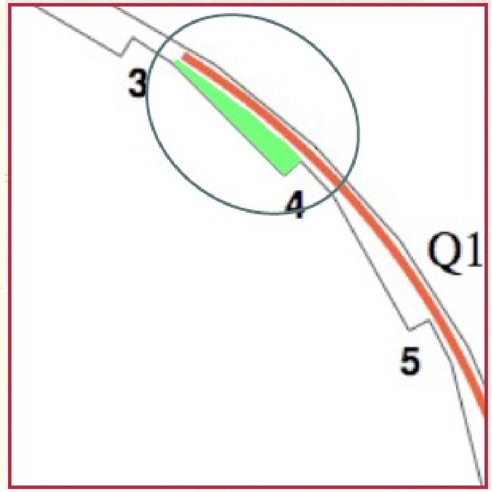



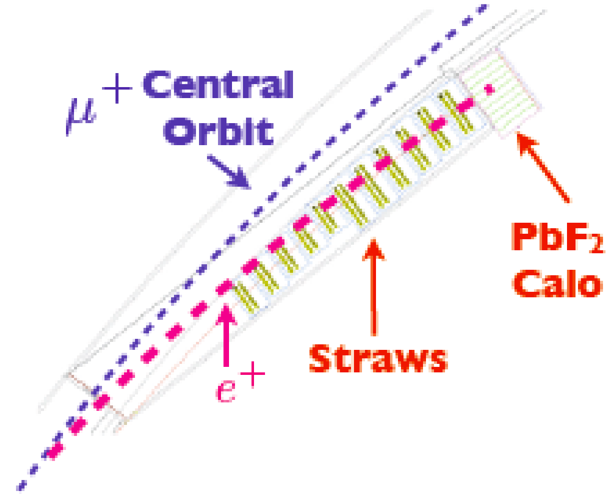


Doublet of UV straw chambers

Detector upgrade: tracker







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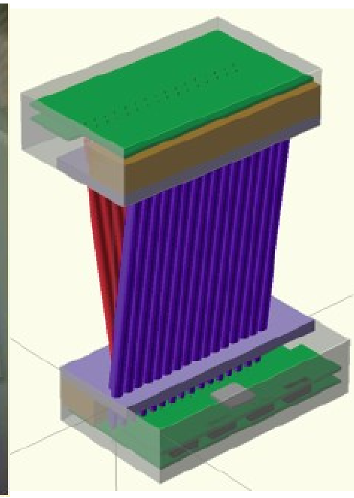
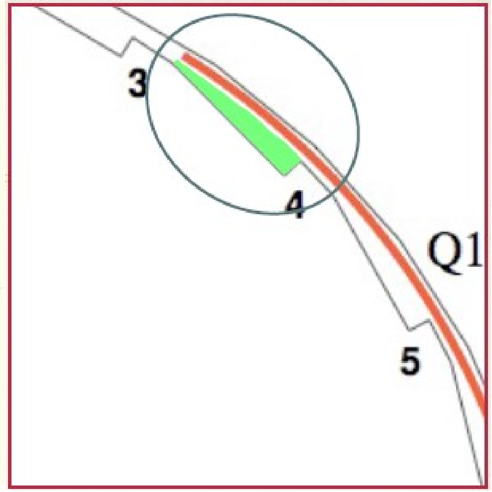
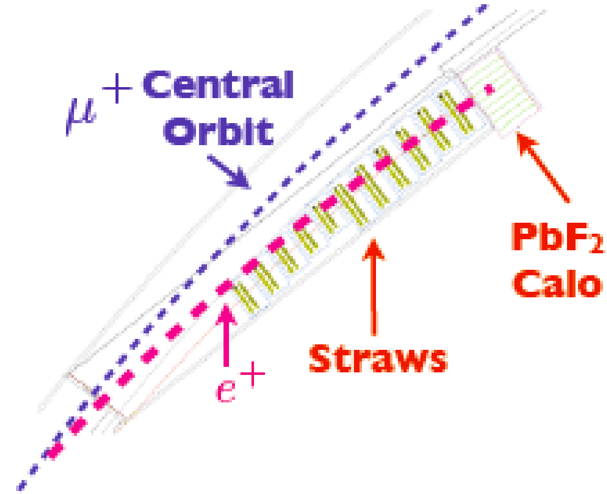
New straw tracking detector

- Measure muon decay vertex and momentum
- Calibrate beam dynamics, better control of systematics
- Better measurement of the pileup (multiple positrons)

Detector upgrade: tracker



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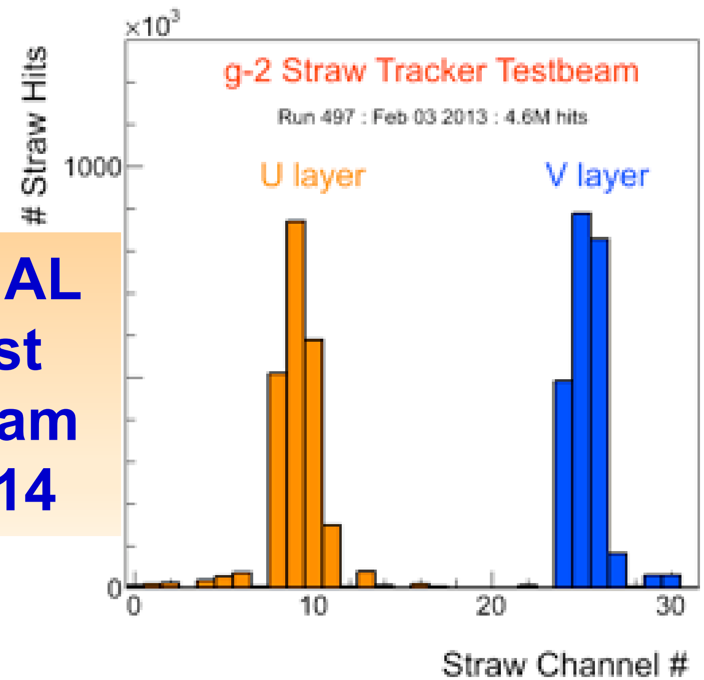
FNAL Test beam 2014



Simulation & Reconstruction

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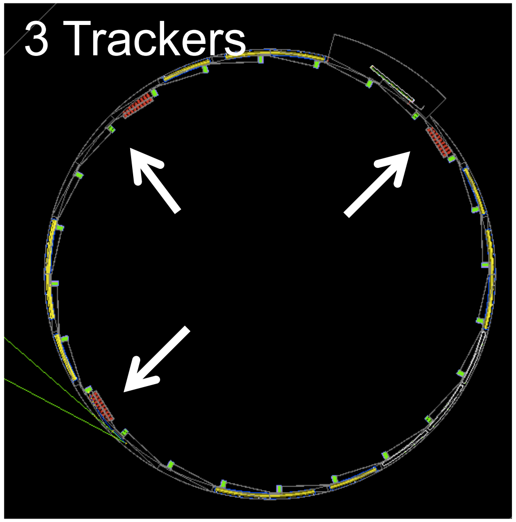

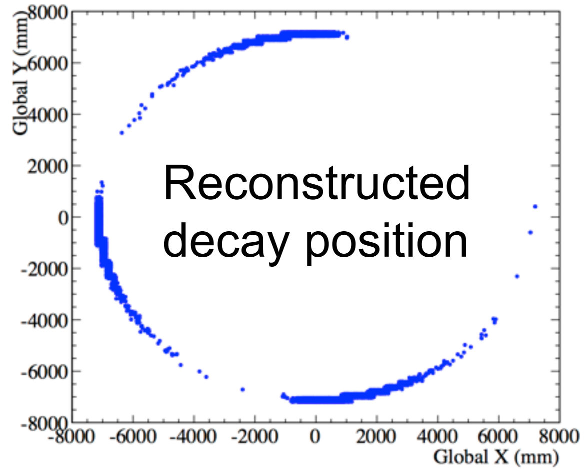

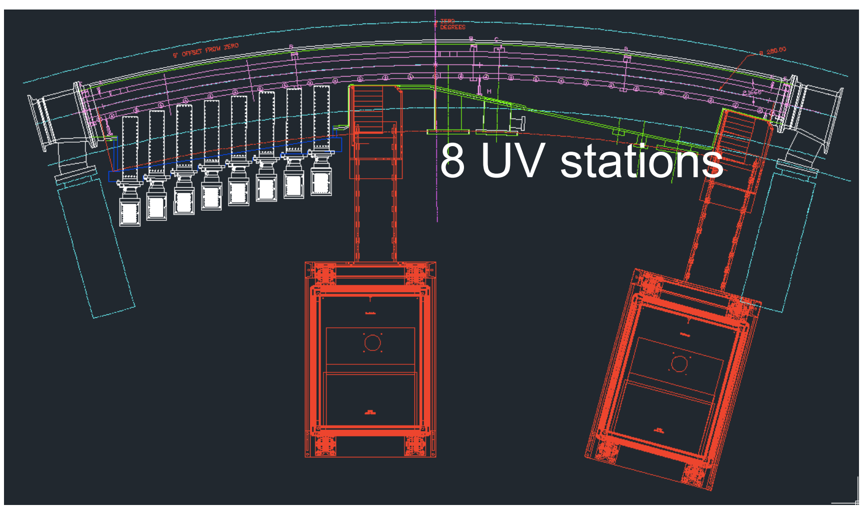

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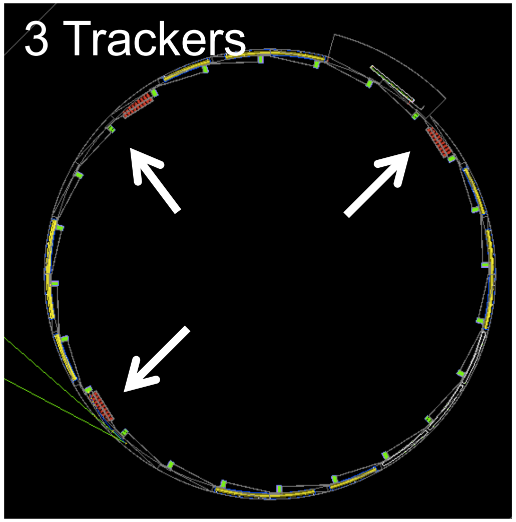
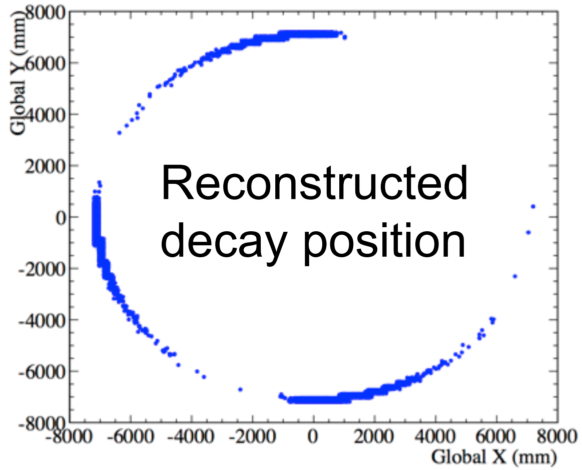
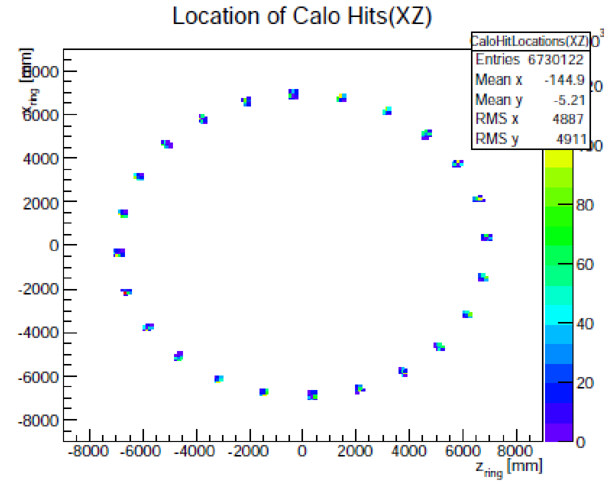
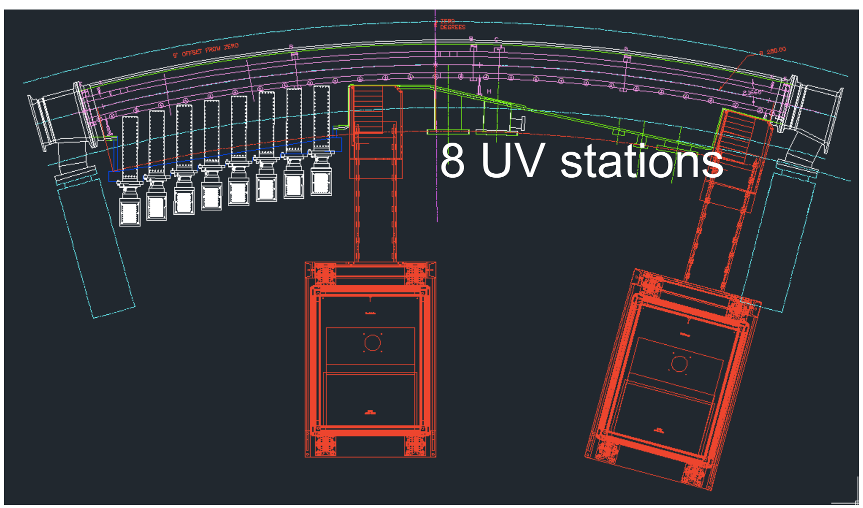
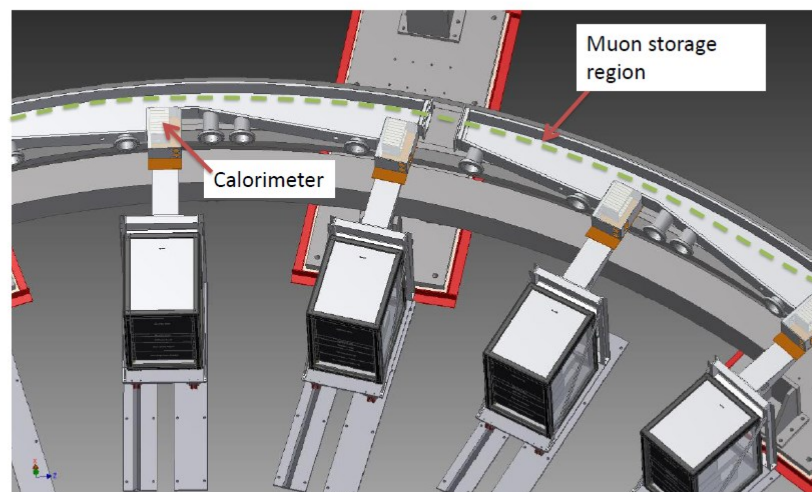






24 calorimeters placed around the ring





The Big Move of The Big Ring

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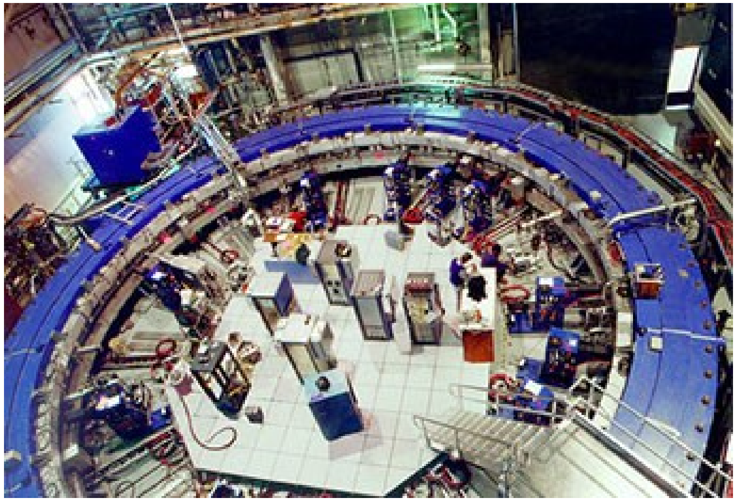

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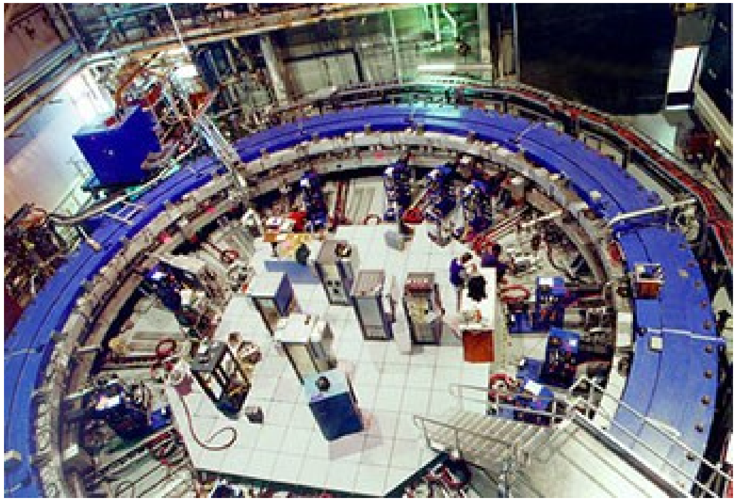

Disassembly

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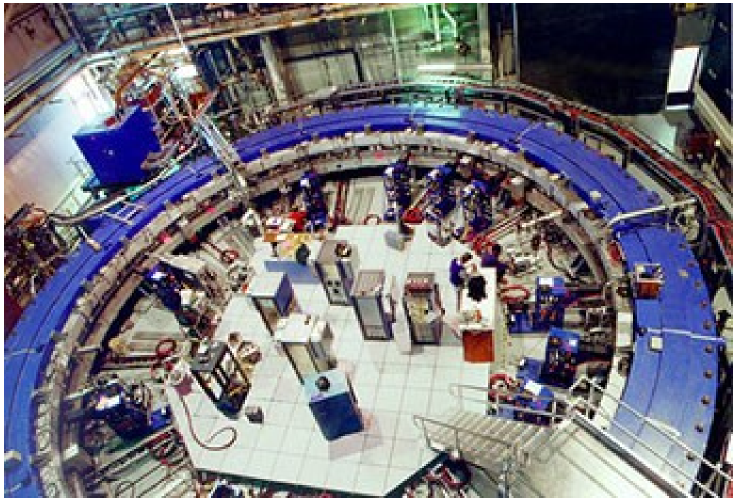

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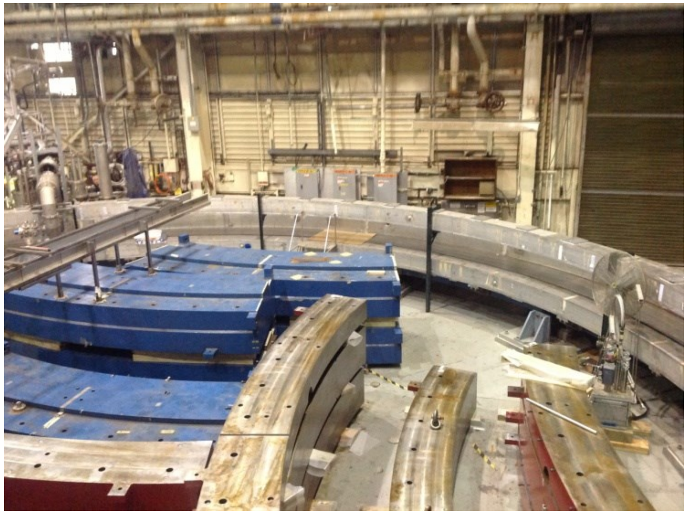

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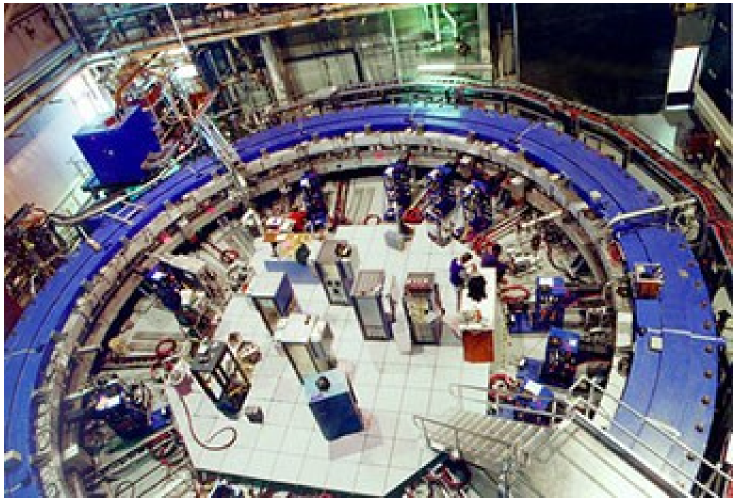

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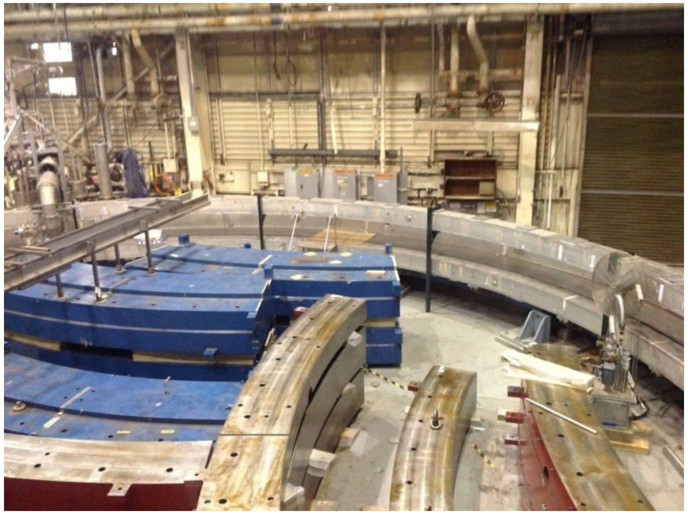

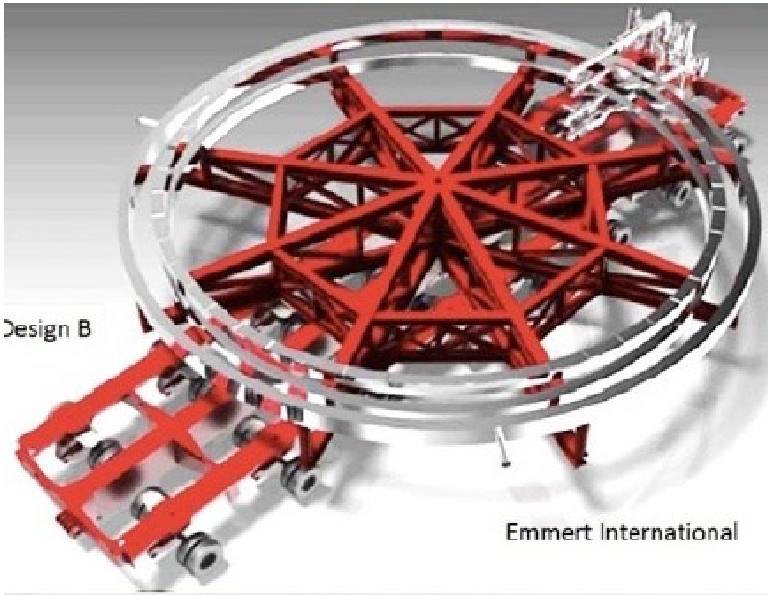

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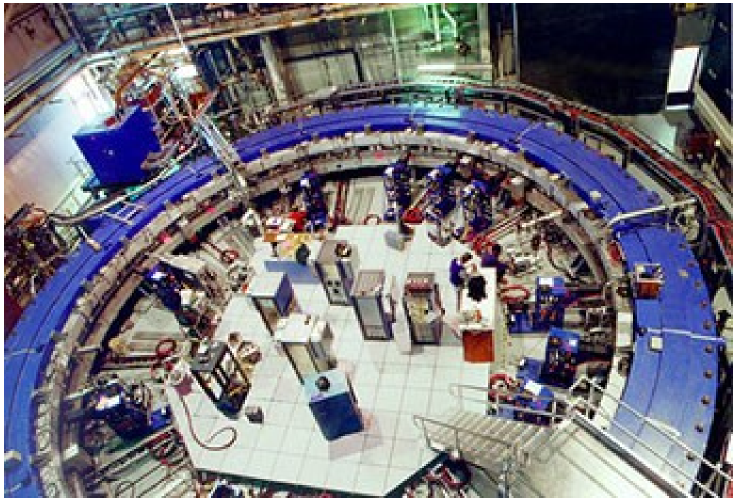

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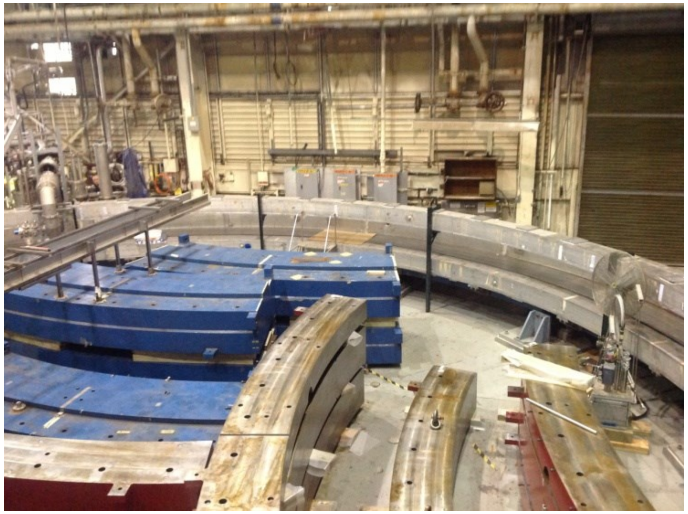

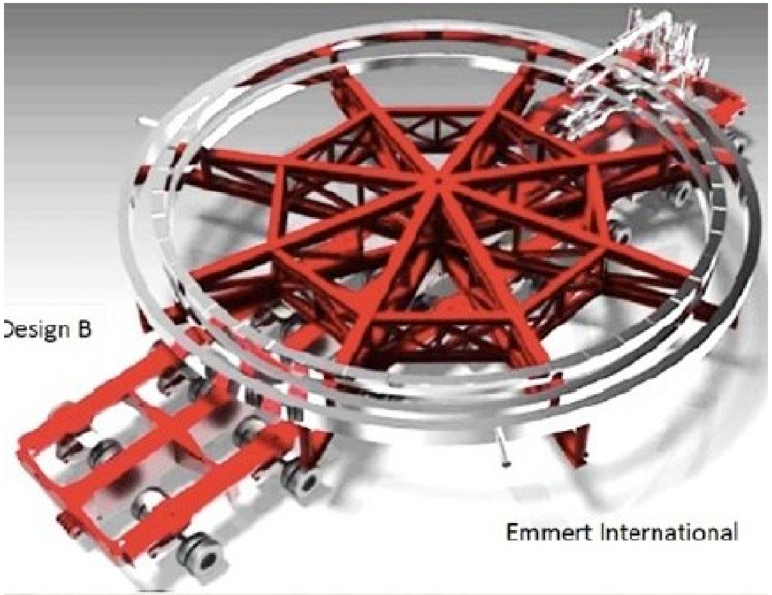

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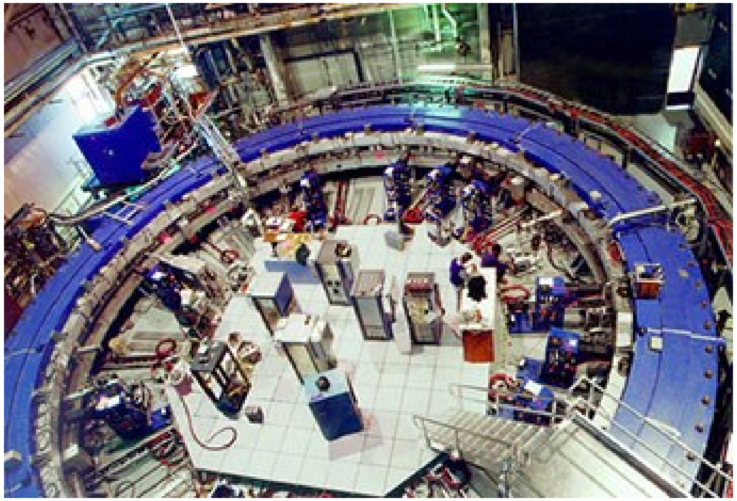

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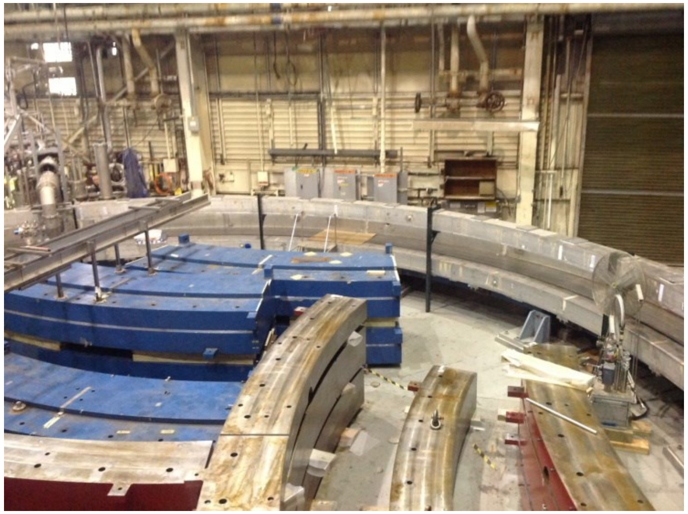

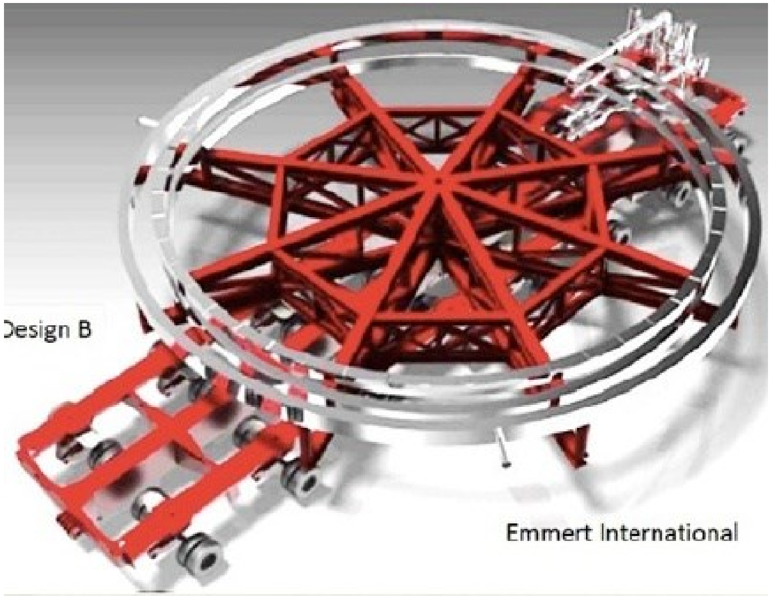

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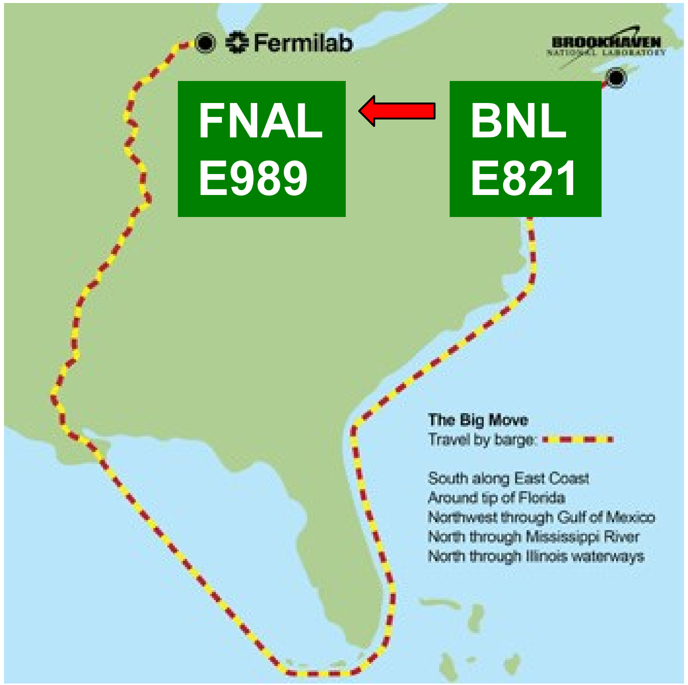

Arrived at Fermilab

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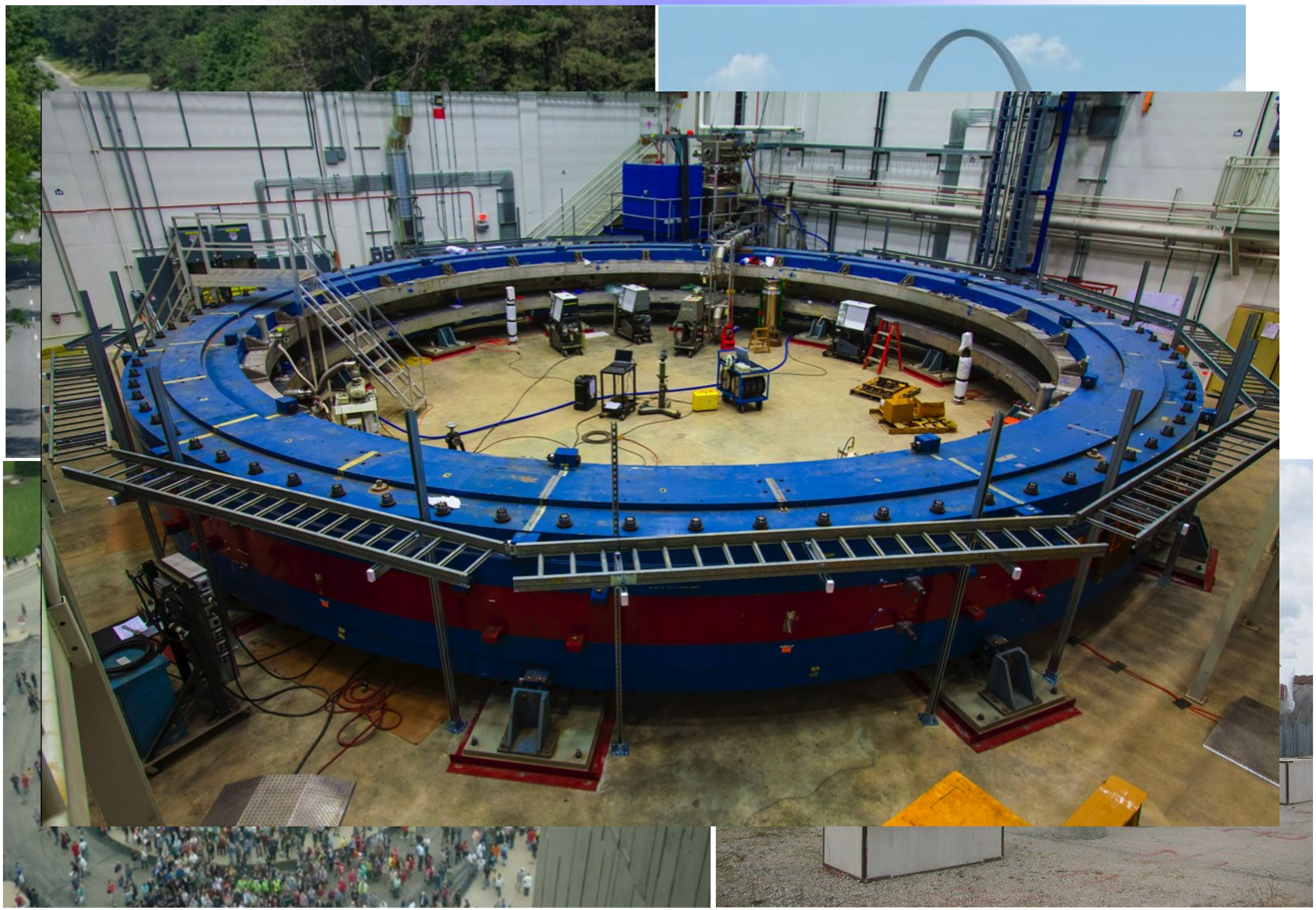

B Field Measurement Improvements

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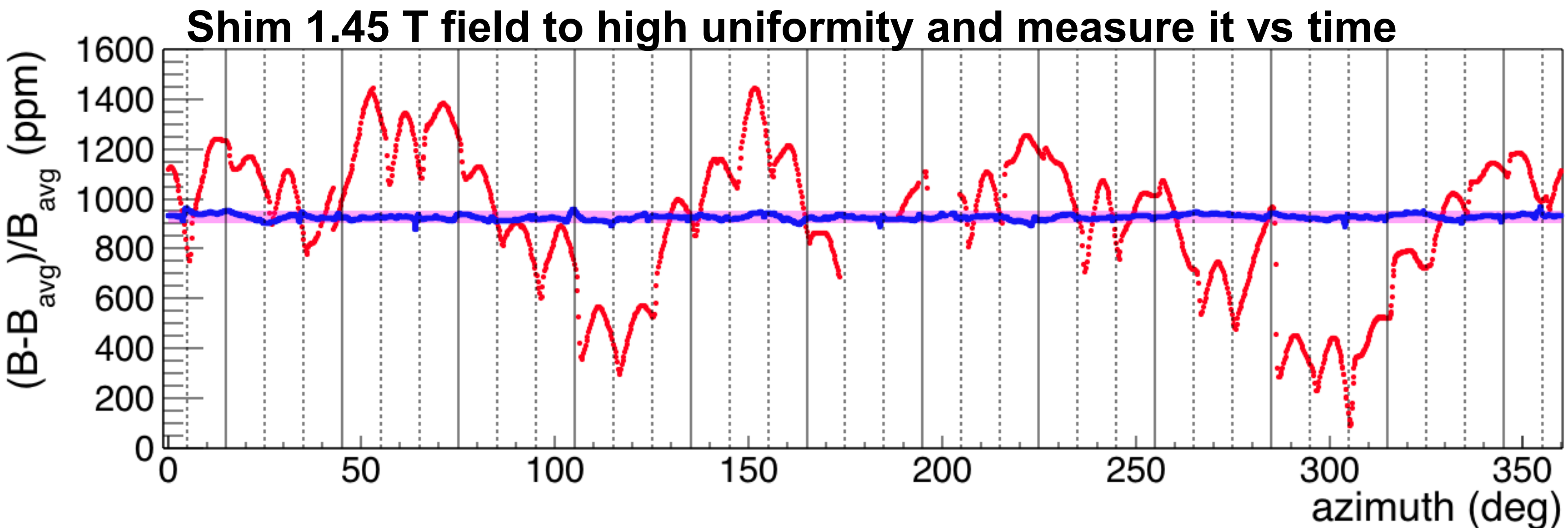
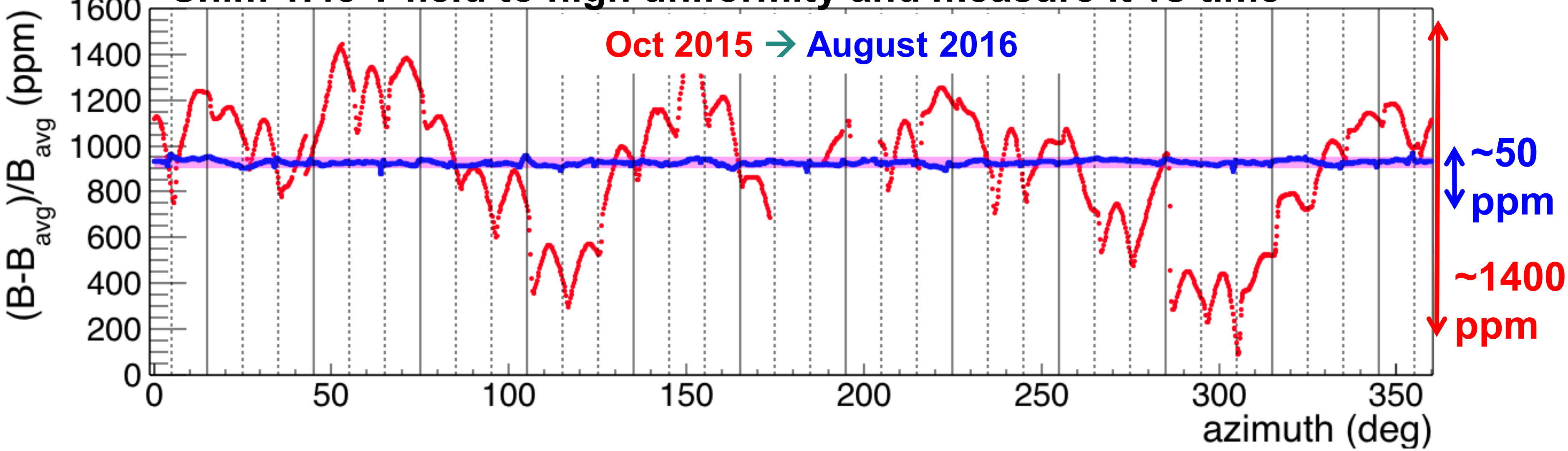


B Field Measurement Improvements

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



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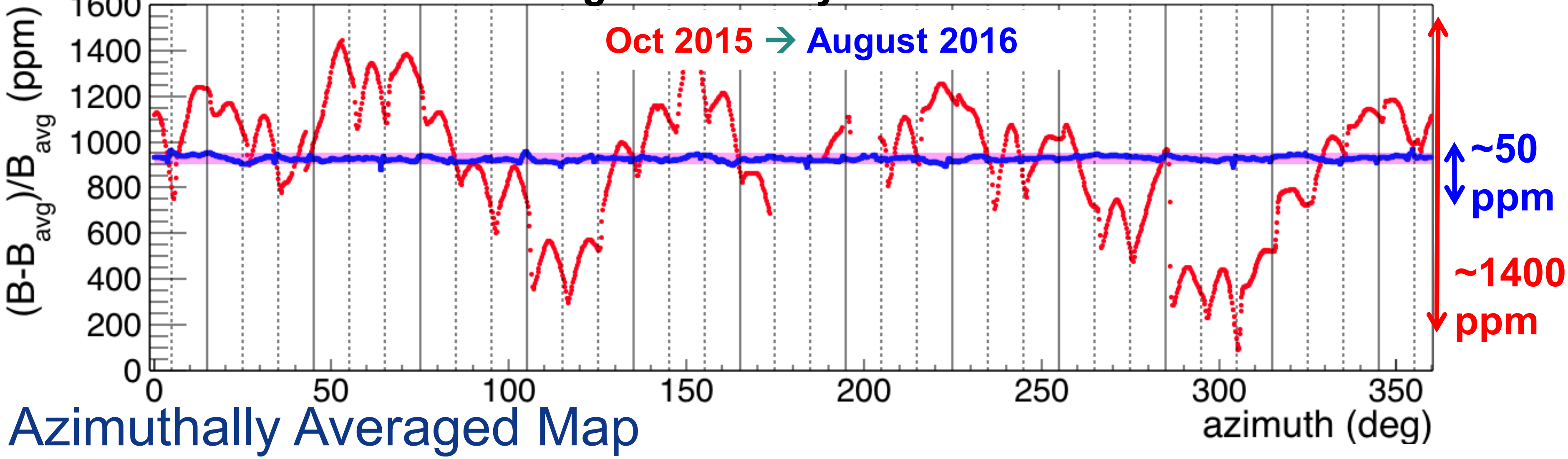
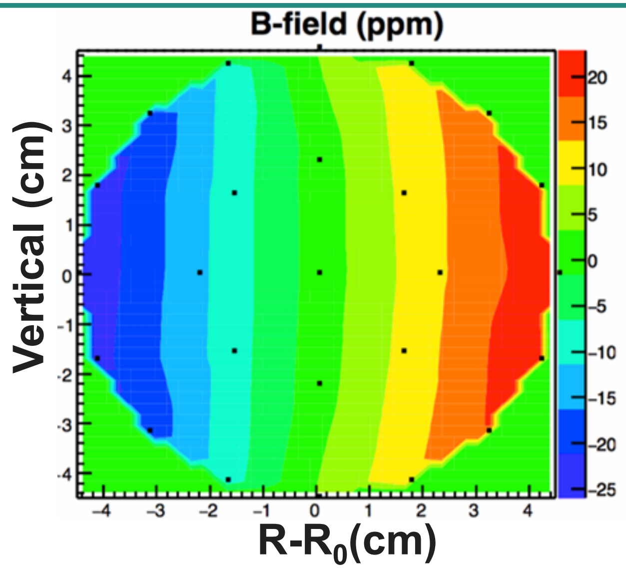


Azimuthally Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

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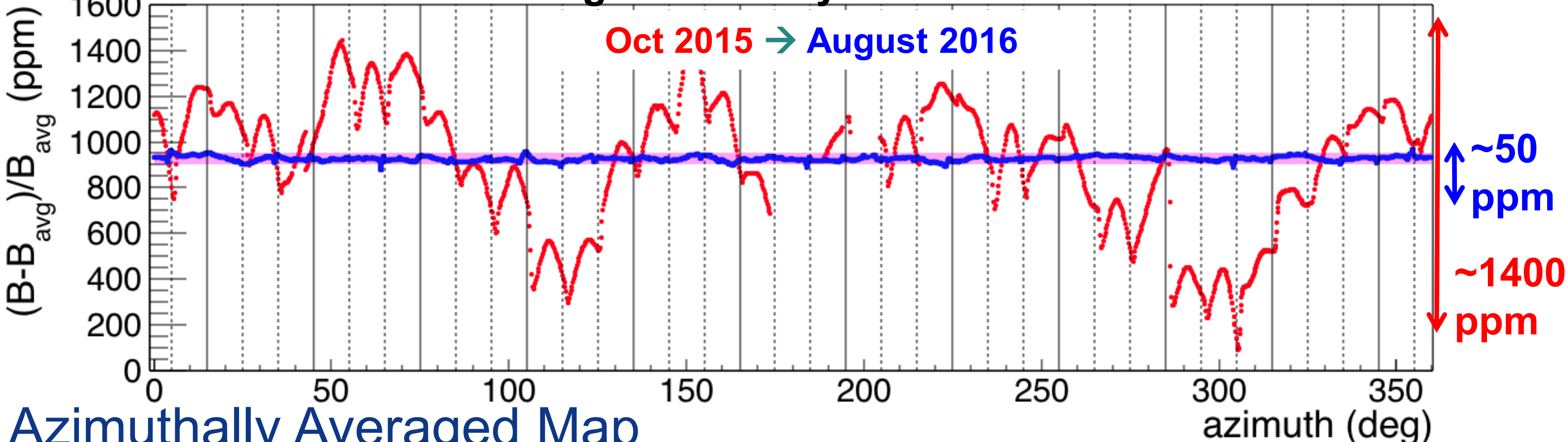

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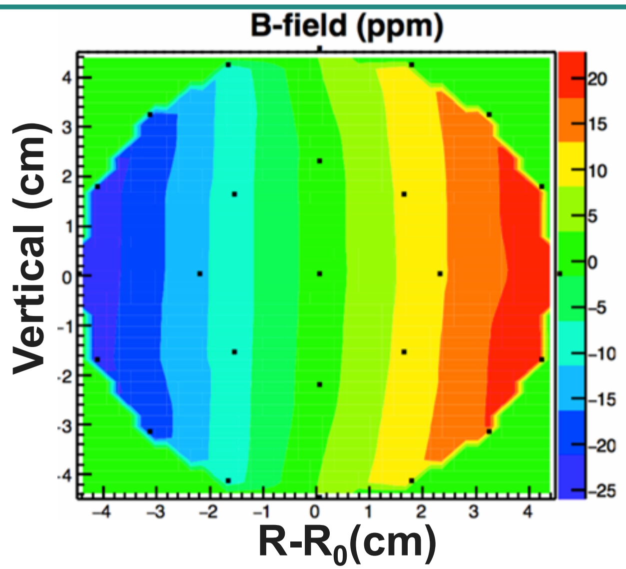

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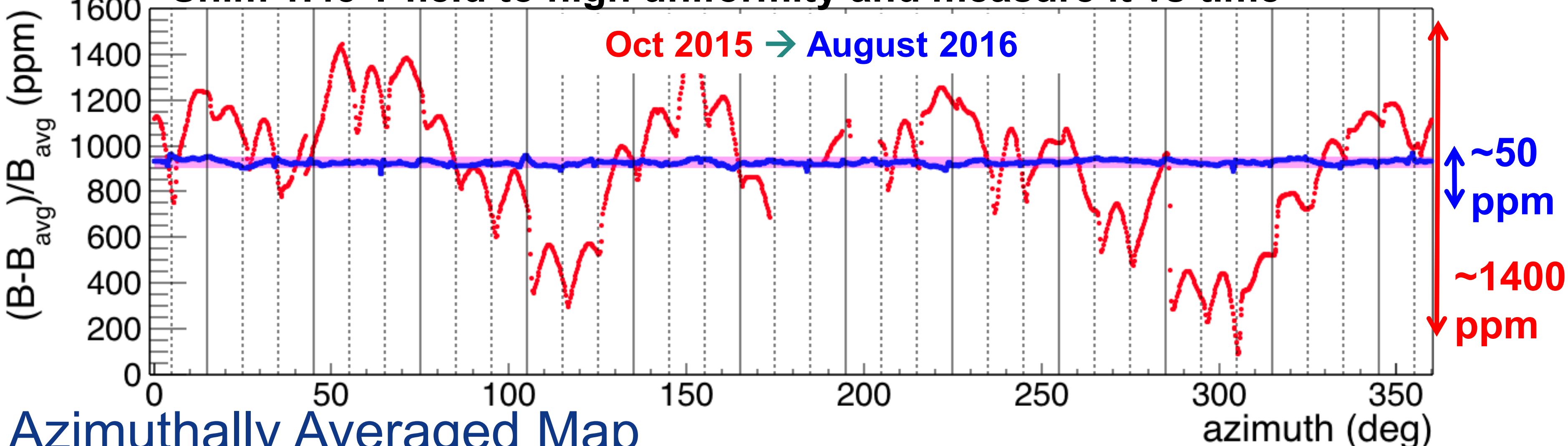

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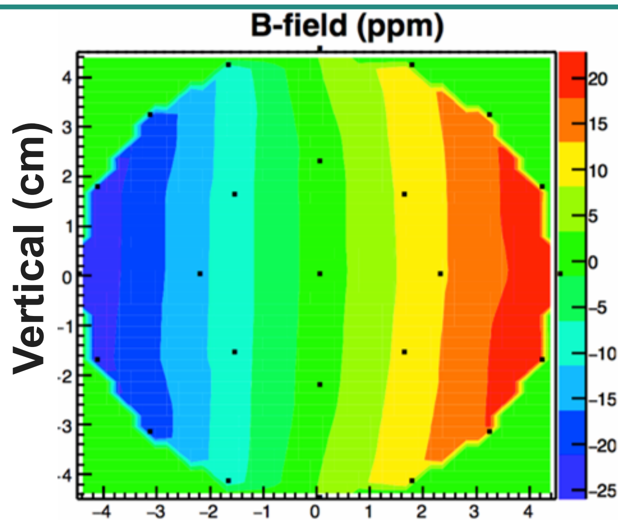

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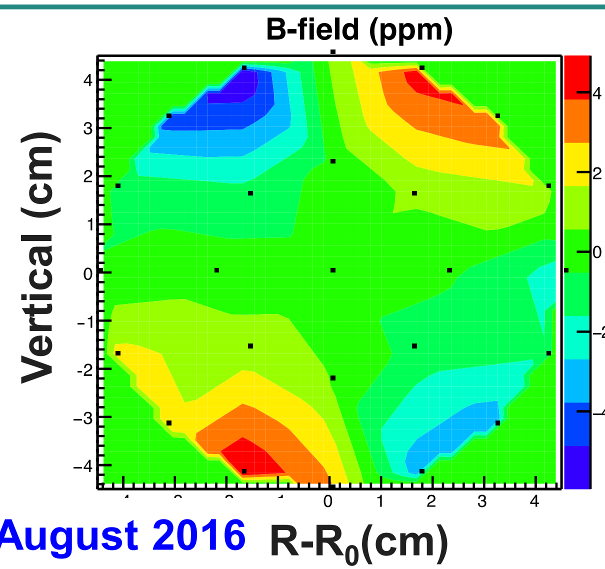
Oct 2015 → August 2016



Norm	Skew
-0.02	-0.57
-0.70	3.84
-0.76	0.56
0.44	-1.61

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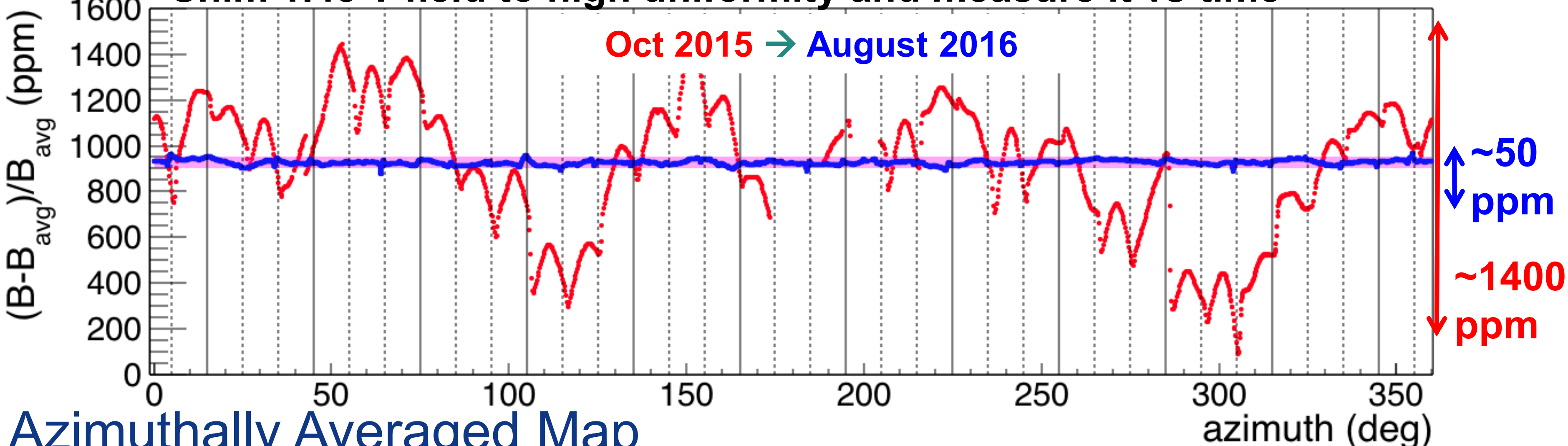

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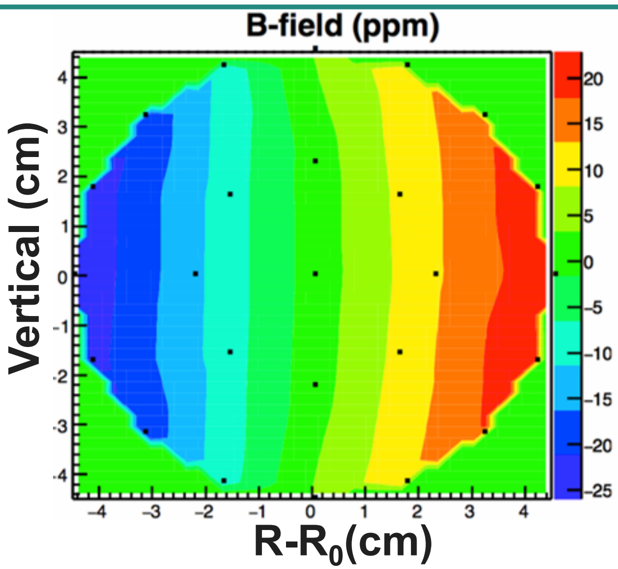

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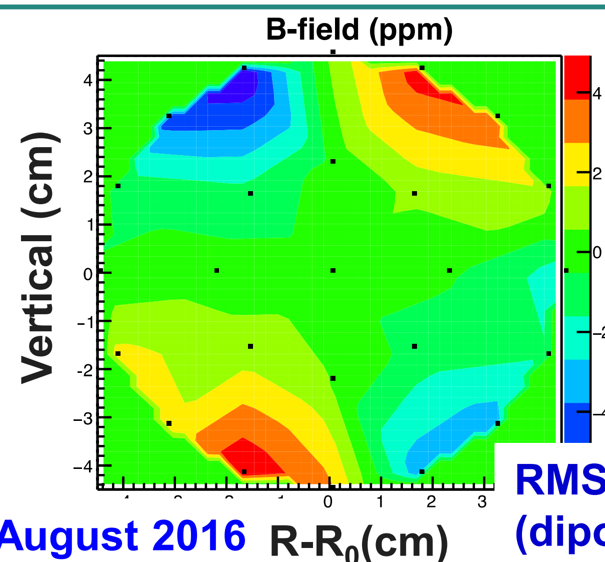
Decu	0.95	-0.07

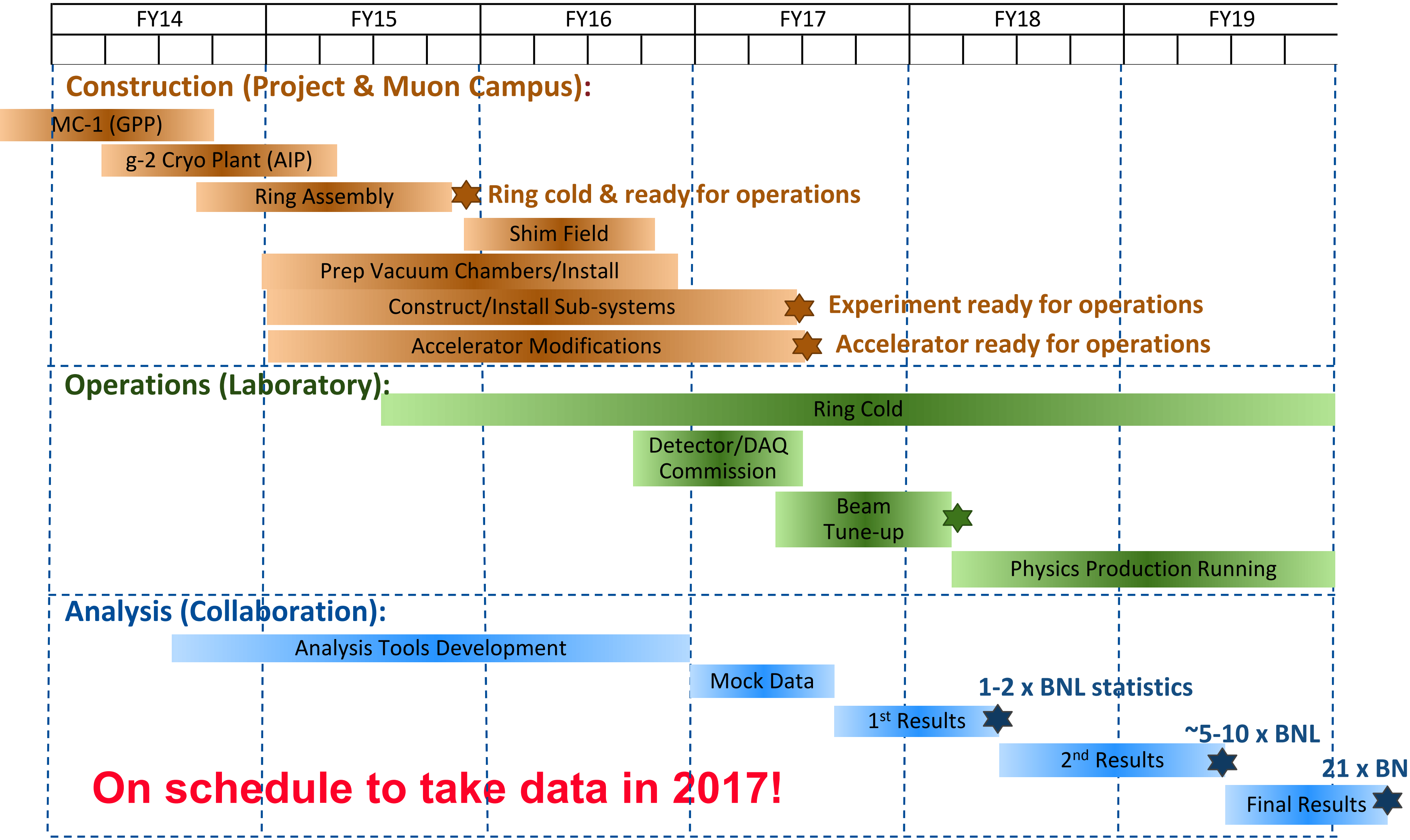
Oct 2015 → August 2016



Norm	Skew
-0.02	-0.57
-0.70	3.84
-0.76	0.56
0.44	-1.61

RMS is 10 ppm (dipole)
BNL was ~ 35 ppm

Current Status



On schedule to take data in 2017!

Summary

Fermilab muon g-2 is in the commissioning phase, preparing for incoming data next year!

- Flagship project at Fermilab muon campus
  - World wide international collaboration
  - Implementation and construction phase, Ring installed!
  - Beam expected in early 2017
  - g-2 is extremely sensitive to new physics and high order calculations & corrections
- Aiming to reduce experimental uncertainty by a factor of 4
  - Theoretical uncertainty also expected to reduce by a factor of 2
  - Could achieve 5.5-7.5 σ significance if the central value stays
- Great discovery potential and bright future in line with Fermilab Intensity Frontier programs

Backup

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**

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

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- How to measure E?

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

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

ω_a Systematics

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

Detector Team

Ring Team

Detector Team

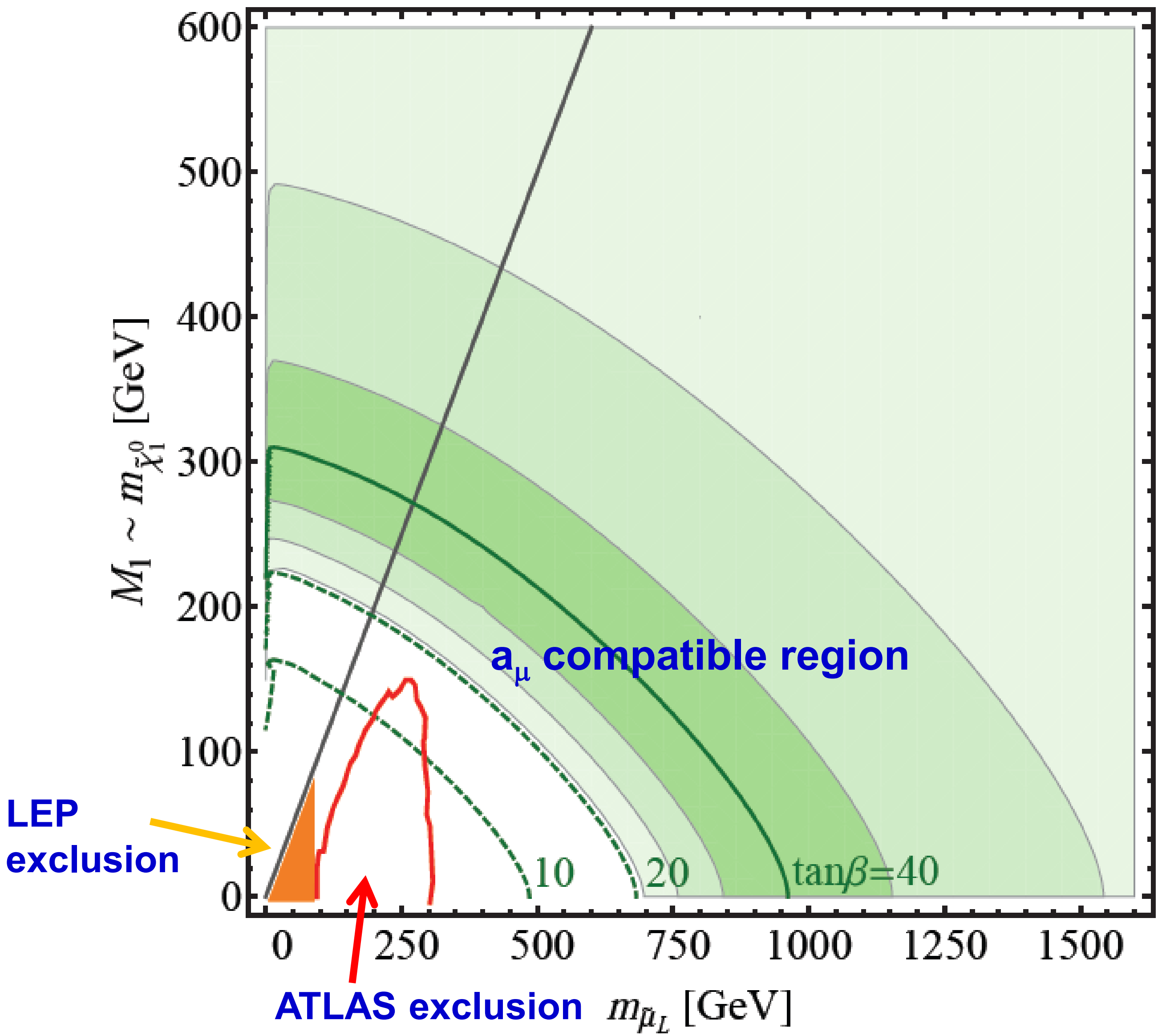
Systematics error to 70 ppb (x 3 improvement)

ω_p Systematics

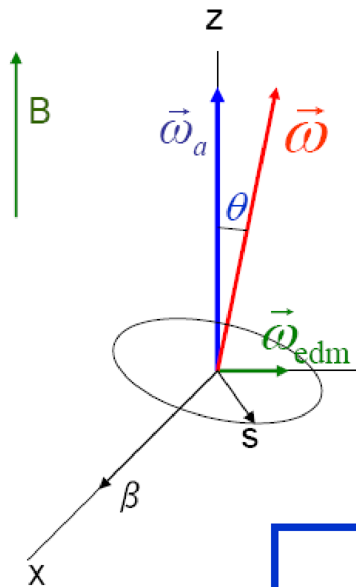
Category	E821 [ppm]	Main E989 Improvement Plans	Goal [ppm]
Absolute field calibration	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	0.03
Fixed probe interpolation	0.07	Better temperature stability of the magnet; more frequent trolley runs	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others †	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.03
Total systematic error on ω_p	0.17		0.07

Systematics error to 70 ppb (x 2 improvement)

New SUSY Limits



Muon EDM

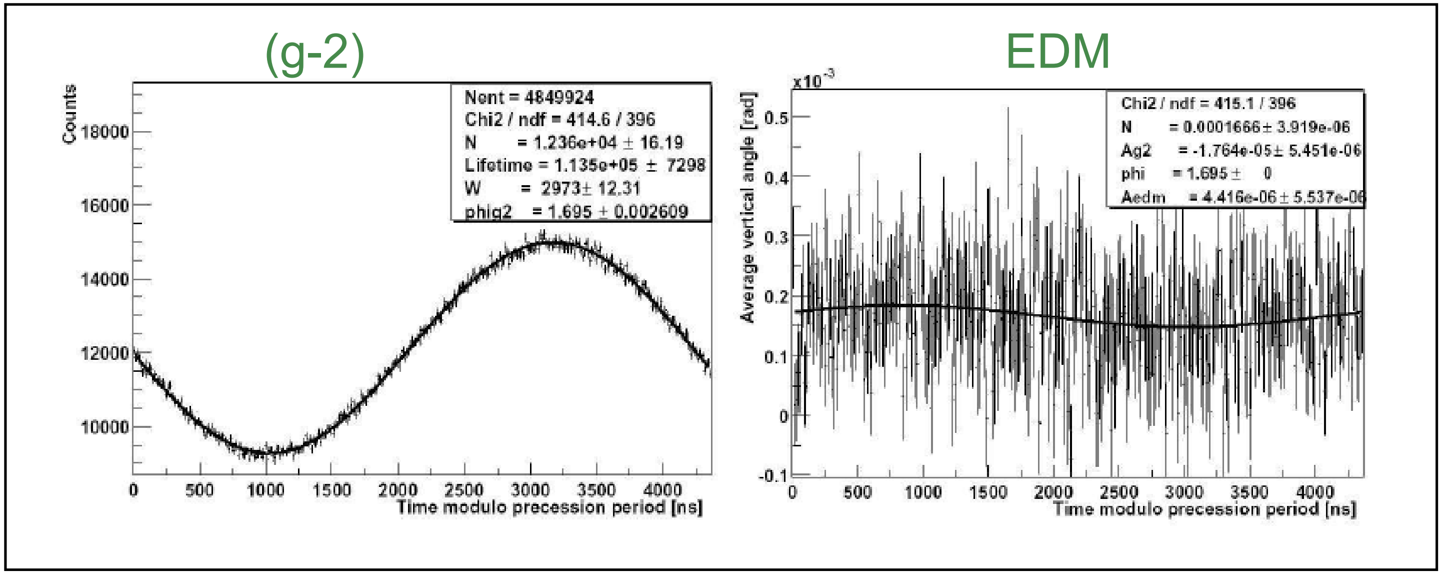


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

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

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

Muon EDM



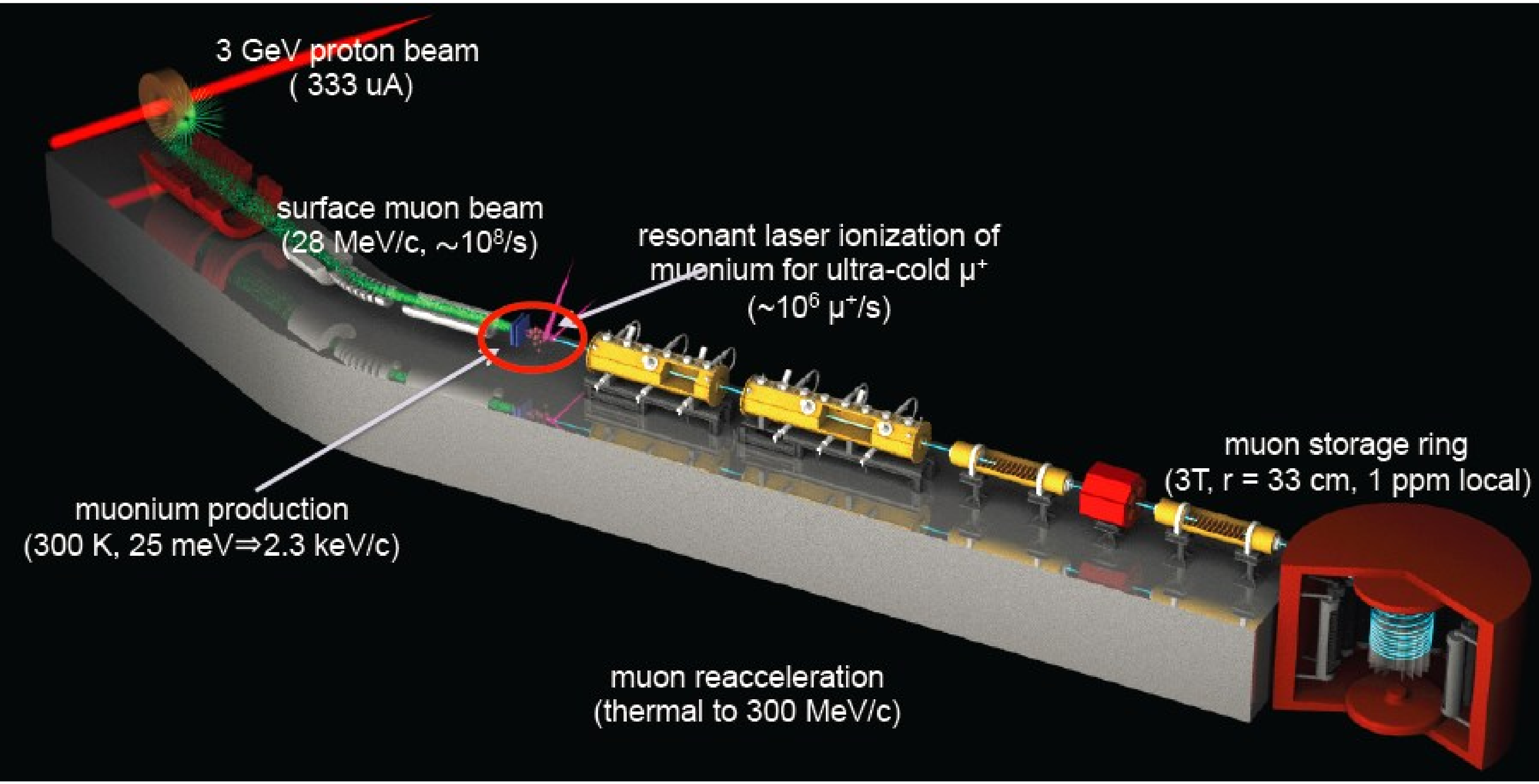
(g-2) signal: # Tracks vs time, modulo g-2 period, in phase.

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

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

The J-PARC approach*

***Slides derived from talk by Glen Marshall, July 2015**



What makes them different?

Eliminate electric focusing removes β x E term

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

Do need ~zero P_T to store muons

→ Not constrained to run at the "magic momentum"

Create "ultra-cold" muon source; accelerate, and inject into compact storage ring.

Consequences are quite interesting …

- Smaller magnet; intrinsically more uniform
- Issues related to needed counts

Aim for BNL level precision as an important check

Fermilab vs. J-PARC

$$\delta\omega_a/\omega_a = \frac{1}{\omega_a \gamma \tau_\mu} \sqrt{\frac{2}{NA^2 \langle P \rangle^2}},$$

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

Gorringe and Hertzog, Progress in Nuclear and Particle Physics, *Volume 84 (2015) September 2015*