Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Experimental summary for muon magnetic and electric dipole moment

Brendan Kiburg

Searching for Physics Beyond the Standard Models Using Charged Leptons

San Juan, Puerto Rico

22 May 2018

A Rich Discussion on MDMs and EDMs

Monday, 21 May

09:00 → 09:30 **Registration and Breakfast**

09:30 → 10:30 **Electron dipole moment "ACME"**

45 minutes talk and 15 minutes discussion

Speaker: Gerald Gabrielse (Northwestern University)

10:30 → 10:50 **Coffee Break**

10:50 → 11:50 **Neutrino electromagnetic properties**

45 minutes talk and 15 minutes discussion

Speaker: Prof. Jose Nieves (Universidad de Puerto Rico)

11:50 → 12:50 **Interpretation of Charged Lepton Flavor Violation and Connection to Neutrino Physics**

45 minutes talk and 15 minutes discussion

Speaker: Julian Heeck (Université Libre de Bruxelles)

12:50 → 13:50 **Lunch Break**

13:50 → 14:50 **Proton radius puzzle (electron versus muon measurements)**

45 minutes talk and 15 minutes discussion

Speaker: Jan Bernauer (MIT)

14:50 → 15:50 **Review of tau Physics**

45 minutes talk and 15 minutes discussion

Speaker: Emilie Passemar (Indiana University/JLab)

15:50 → 16:10 **Coffee Break**

16:10 → 17:10 **The Tau (g-2): Theory and Experiment**

45 minutes talk and 15 minutes discussion

Speaker: Jeffrey Berryman (Northwestern University)

Tuesday, 22 May

09:00 → 10:00 **Experimental summary for muon magnetic and electric dipole moment**

45 minutes talk and 15 minutes discussion

Speaker: Brendan Kiburg (Fermilab)

10:00 → 11:00 **g-2: Theory overview for muons**

45 minutes talk and 15 minutes discussion

Speaker: Andre De Gouvea (Northwestern University)

11:00 → 11:20 **Coffee Break**

11:20 → 12:15 **Reconciling lepton flavor violation and the muon anomalous magnetic moment**

40 minutes talk and 15 minutes discussion

Speaker: Moritz Platscher (Max-Planck-Institut, Heidelberg)

12:15 → 13:15 **Lunch Break**

13:15 → 14:10 **New hadronic corrections from e-mu scattering measurements**

40 minutes talk and 15 minutes discussion

Speaker: Clara Matteuzzi (Universita & INFN, Milano-Bicocca (IT))

14:10 → 14:30 **Coffee Break**

14:30 → 15:30 **Lattice: g-2 for muons**

45 minutes talk and 15 minutes discussion

Speaker: Thomas Blum (University of Connecticut)

15:30 → 16:30 **Dark Photons coupling to charge leptons: Theoretical overview on dark photons**

45 minutes talk and 15 minutes discussion

Speaker: Dr Yue Zhang (Northwestern University)

16:30 → 17:15 **Electroweak Baryogenesis with Lepton Flavor Violation**

35 minutes talk and 10 minutes discussion

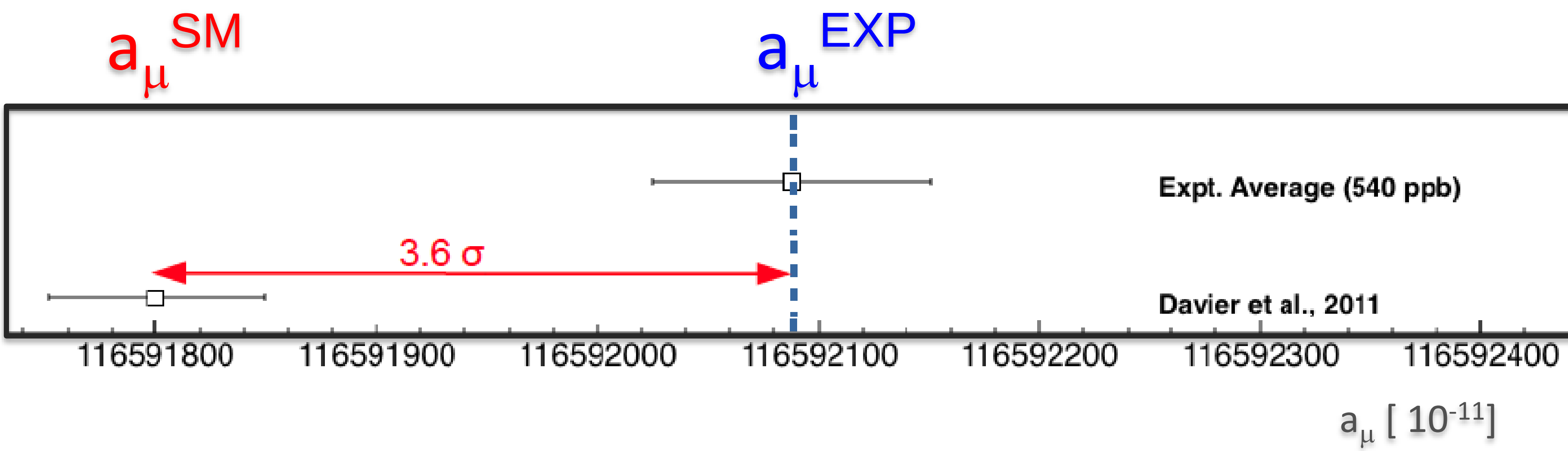
Speakers: Ms Kaori Fuyuto (University of Massachusetts Amherst), Kaori Fuyuto (Japan)

18:01 → 18:21 **Dinner**

Theory and Experiment Disagree on the Magnetic Moment

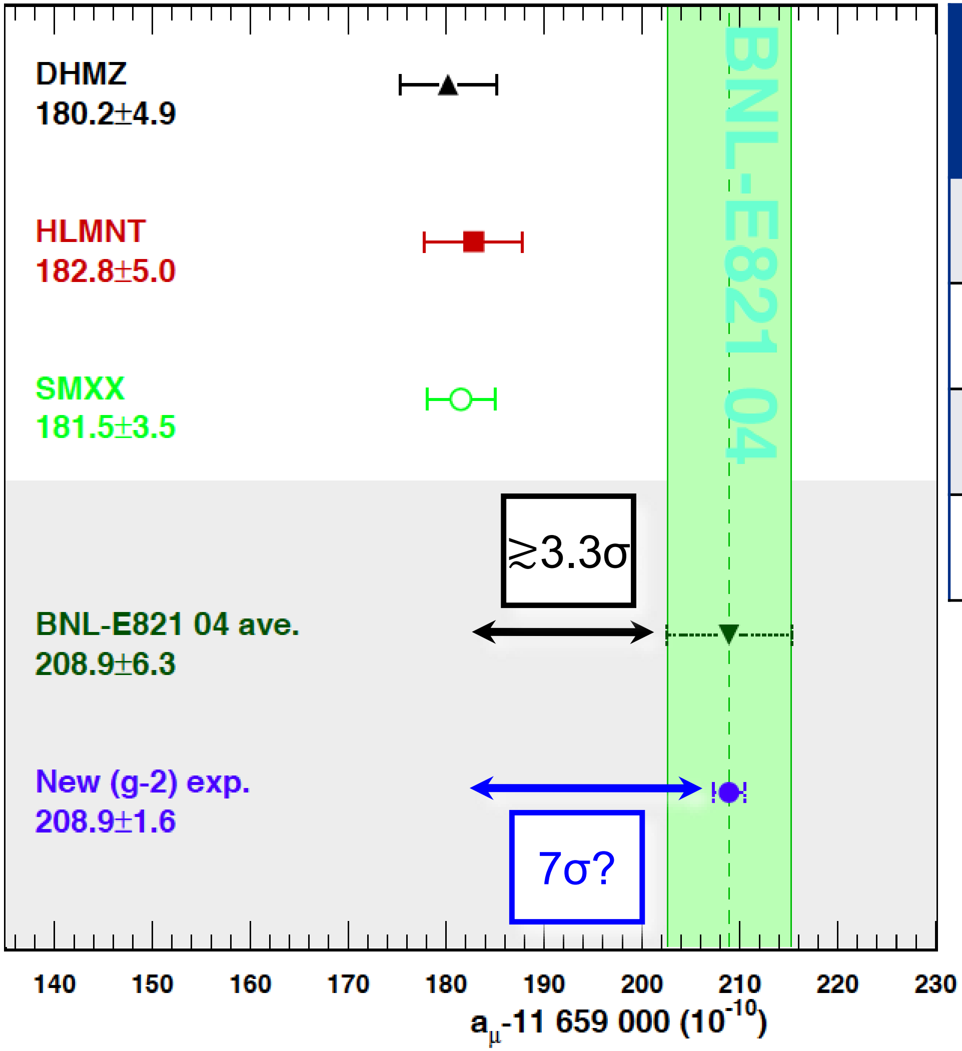
$$\vec{m} = g \frac{q}{2m} \vec{S}$$

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



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

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



[Blum et al., arXiv:1311.2198]

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

- Excited to hear latest updates in theory projections

Fermilab

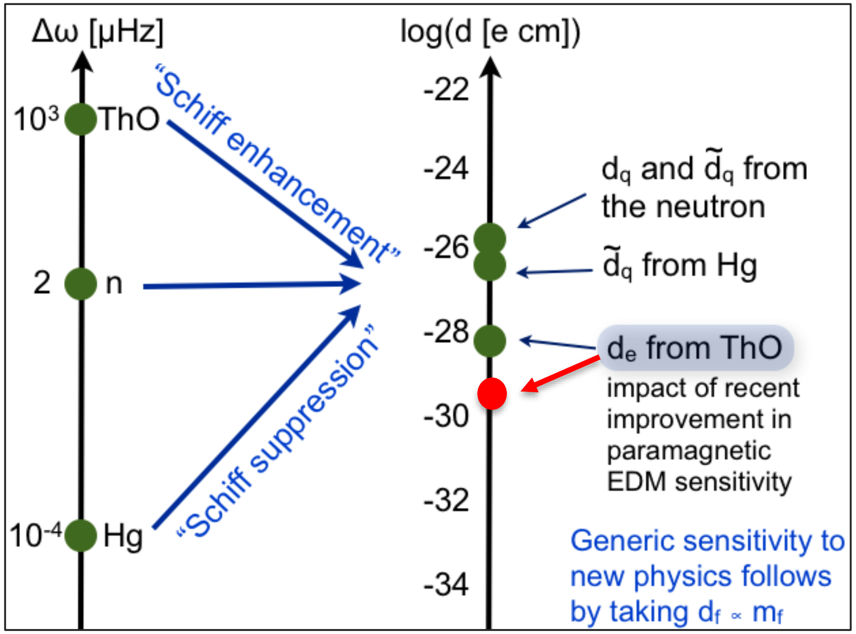
Experimental Summary of EDM bounds

SM EDM scales with lepton mass

SM pred ~10^-36 e-cm

Muons are curious

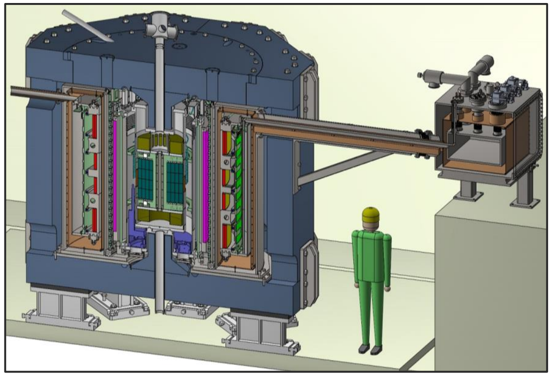
Source	d_μ Limit (e-cm)	Note
CERN III	< 1.05 x 10^-18	Bailey (1978)
BNL	< 1.8 x 10^-19	Bennett (2009)
FNAL	< ~10^-21	Projection
JPARC	< ~10^-21	Projection
eEDM	< 1.8 x 10^-26	Naïve SM scaling* from Baron (2014) ACME
eEDM	< ~1.8 x 10^-27	Gabrielse update (Projection assuming limit)

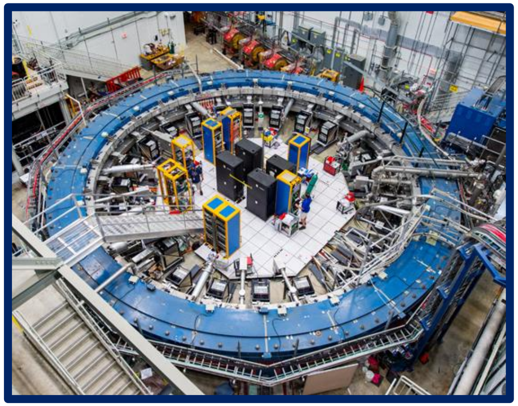


EDMs: Significant experimental progress in last few years

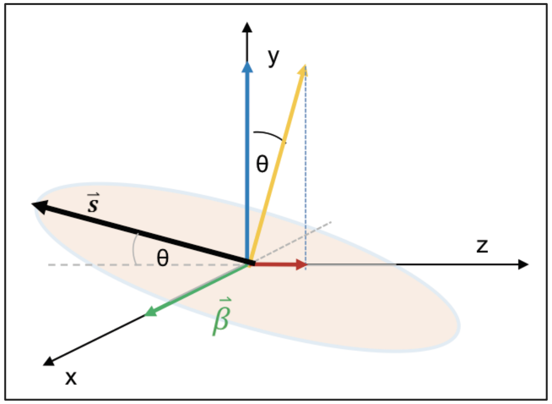
Courtesy: A. Ritz @ CIPANP 2015

Outline

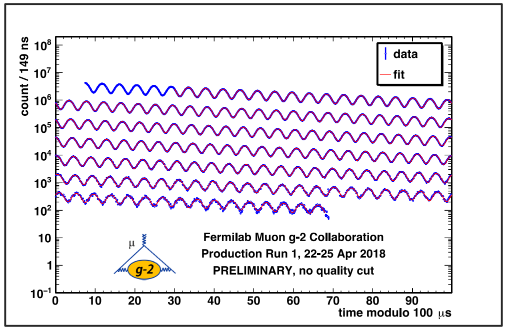




- ❖ Upcoming Experiments
- ❖ Experimental Technique

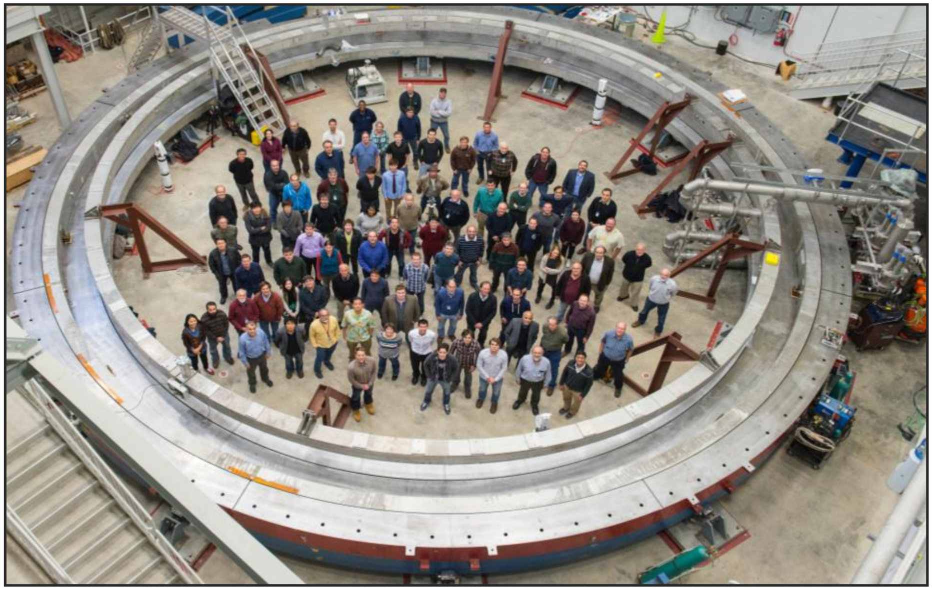


- ❖ EDM Dynamics
- ❖ Year One of Physics Running



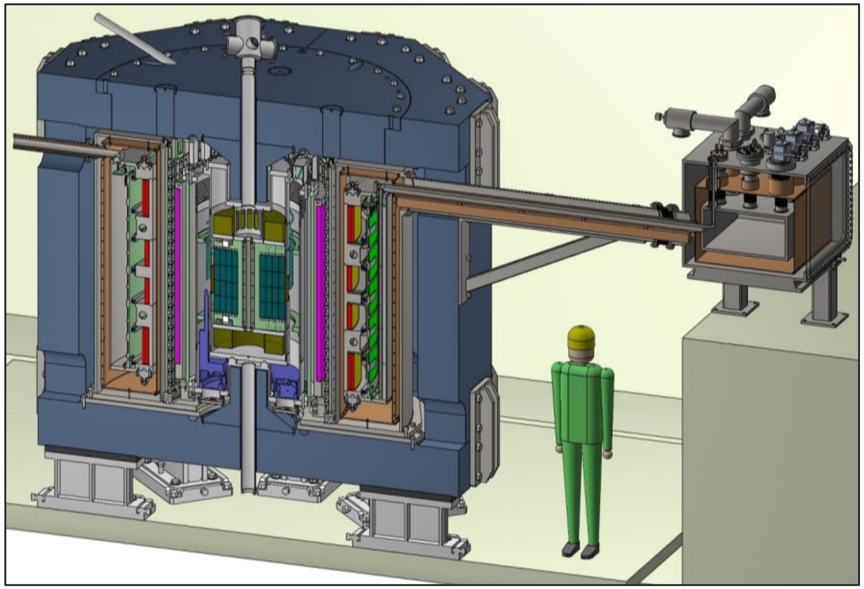
- ❖ Expectations for Results

Next-Generation Muon MDM+EDM Experiments



Fermilab (E989)

- High-rate 3.09 GeV/c muon beam
- Highly polarized (97%)
- 1.45 Tesla, 7-meter-radius storage ring

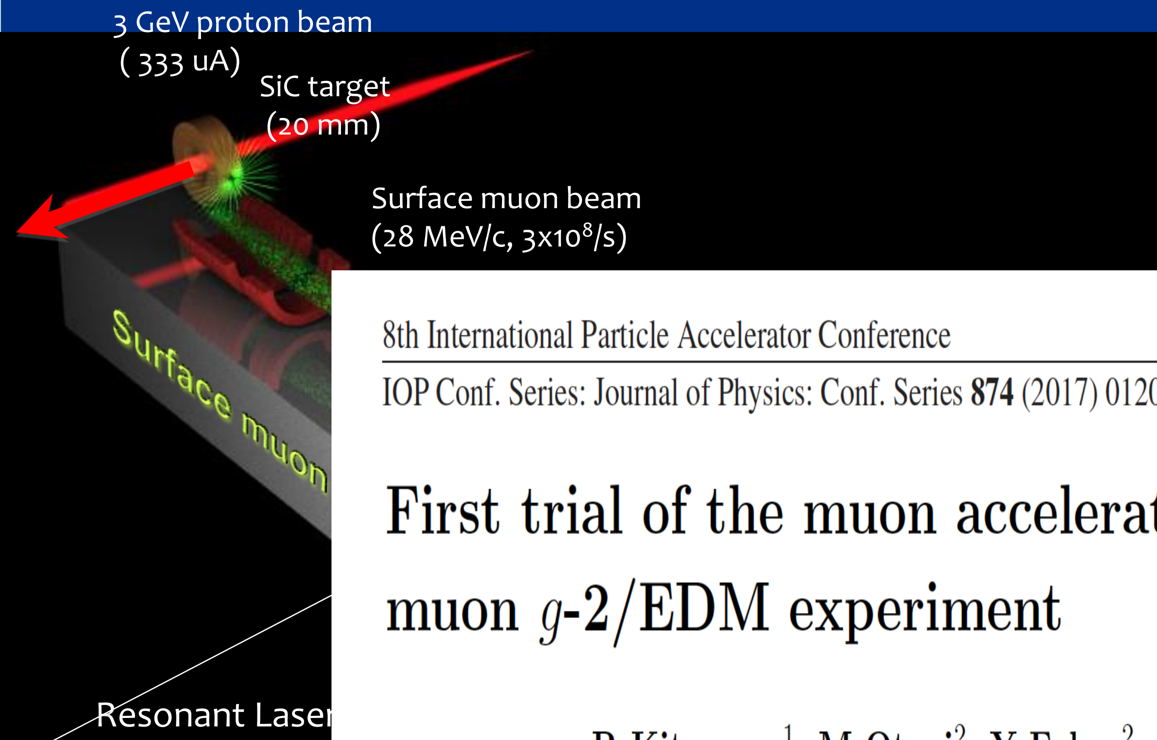


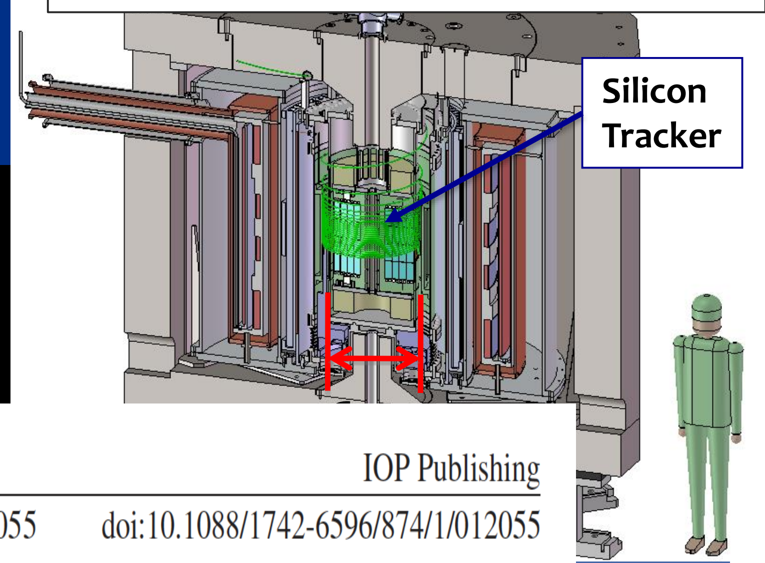
J-PARC (E34)

- Surface muon beam → muonium → 0.3 GeV/c muon beam
- Polarization ~ 50%
- 3 Tesla, 0.33-meter-radius storage ring

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

Slide from Ken-ichi Sasaki

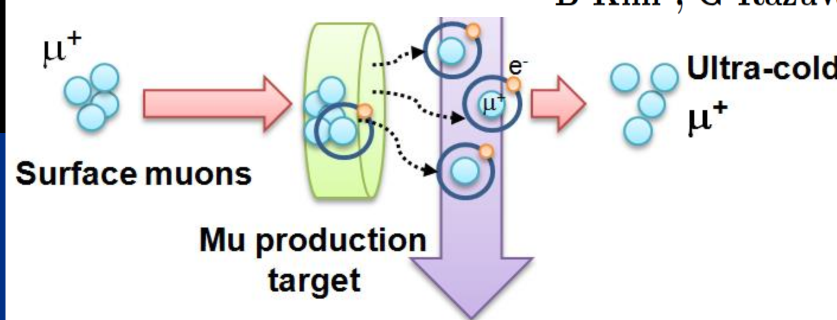




8th International Particle Accelerator Conference IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **874** (2017) 012055 doi:10.1088/1742-6596/874/1/012055

First trial of the muon acceleration for J-PARC muon *g*-2/EDM experiment

R Kitamura[1], M Otani[2], Y Fukao[2], N Kawamura[2], T Mibe[2], Y Miyake[2], K Shimomura[2], Y Kondo[3], K Hasegawa[3], S Bae[4], B Kim[4], G Razuvaev[5], H Iinuma[6], K Ishida[7] and N Saito[8]



Flux and Polarization

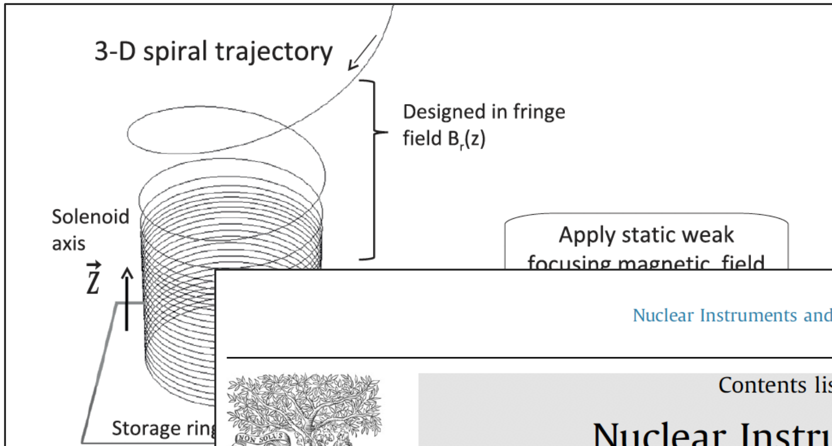


Fig. 2. Outline of ... deflects the vertic... nent. A pulsed rad... 10^{-5} rad, and the...

Nuclear Instruments and Methods in Physics Research A 832 (2016) 51–62

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Three-dimensional spiral injection scheme for the $g-2$/EDM experiment at J-PARC ☆

CrossMark

Hiromi Iinuma [a,*], Hisayoshi Nakayama [a], Katsunobu Oide [a], Ken-ichi Sasaki [a], Naohito Saito [a], Tsutomu Mibe [a], Mitsushi Abe [b]

[a] *High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba 305–0801, Japan*

[b] *Center of Technology Innovation-Energy, Hitachi, Ltd., Hitachi 319-1221, Japan*

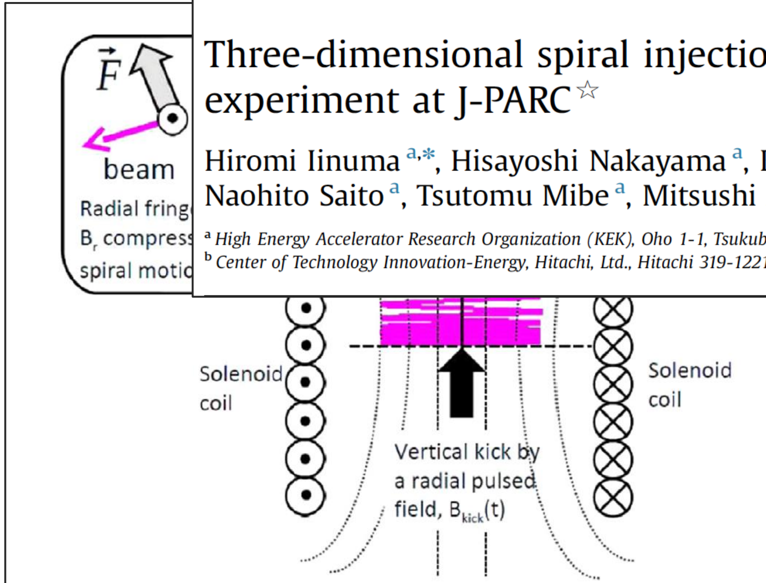


Fig. 3. Solenoid type storage magnet. The beam momentum is deflected vertically by a radial magnetic field, which will be built into the solenoid fringe field (B_r).

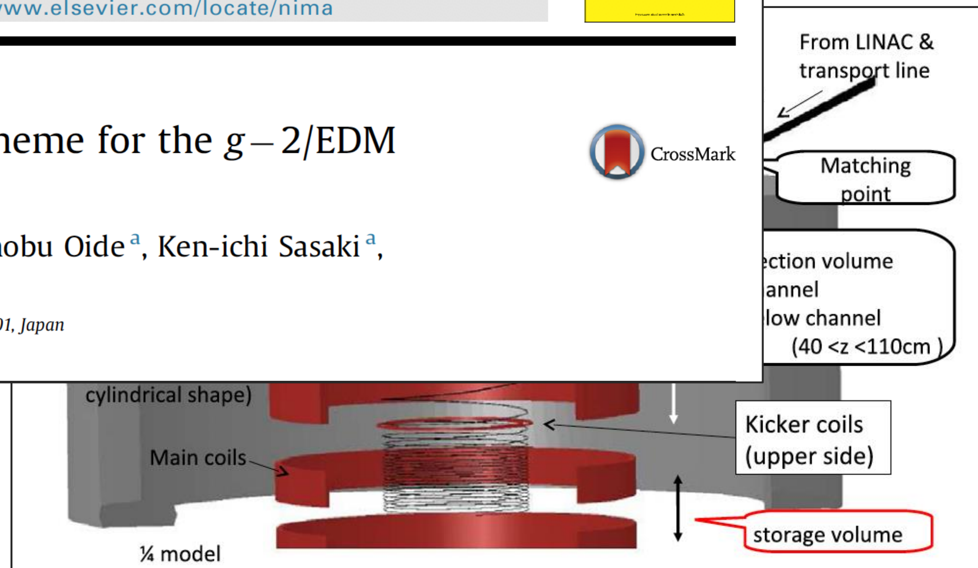


Fig. 4. One-quarter cut view of the storage magnet, with sample trajectories shown. The magnetic field is calculated by using OPERA-3D TOSCA. The beam enters through a hole in the return yoke iron (called the *channel*). Inside the magnet, two volumes are indicated by arrows: *the injection volume* and *the kick and storage volume*.

JPARC Experiment a promising new approach

- Community support and interest in the novel technique
- Some proof of principle measurements of beam production technique
- Support from the PAC → Updated design for detector
  - Still several years away from a measurement

Different design choices and different systematics to analyze

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

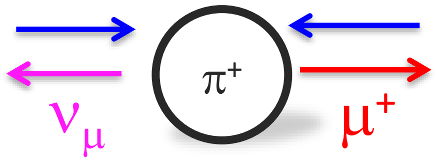
Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.5×10^{11}	8.1×10^{11}

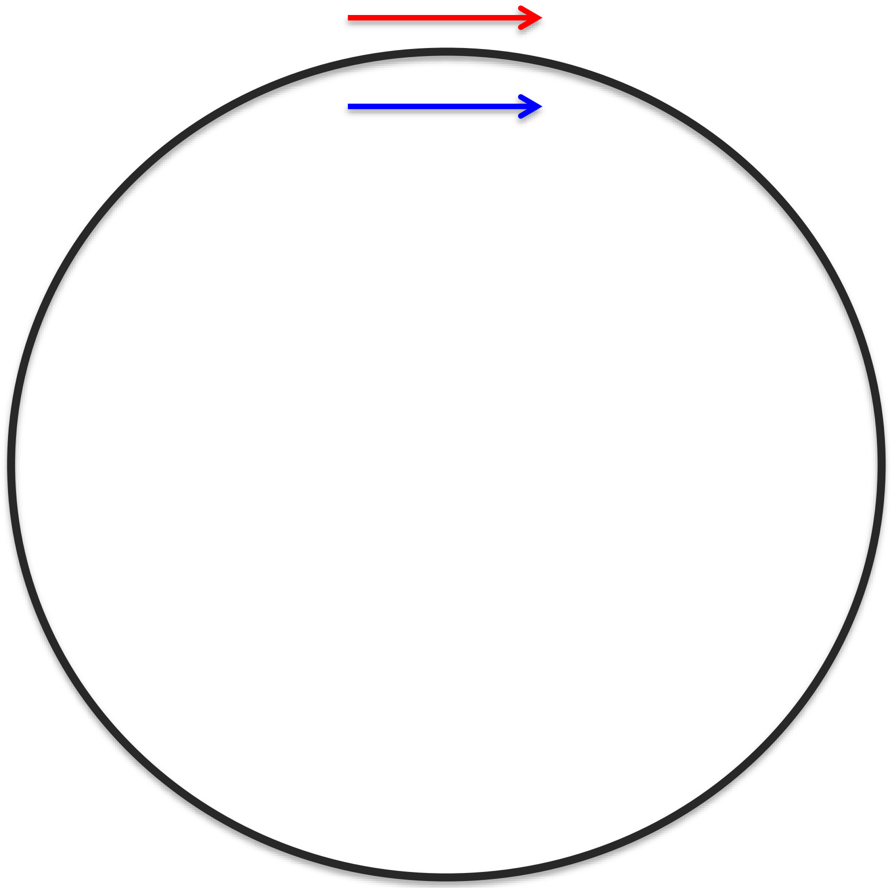
T. Gorringe and D. Hertzog, Prog. Part. Nucl. Phys. (2015).

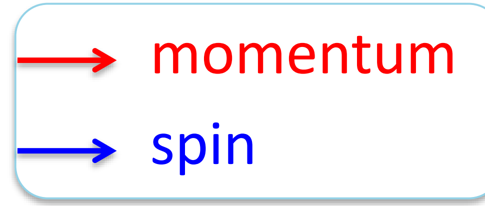
EXPERIMENTAL TECHNIQUE

Experiment Basics: Muons in a storage ring

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







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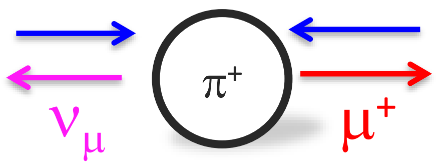


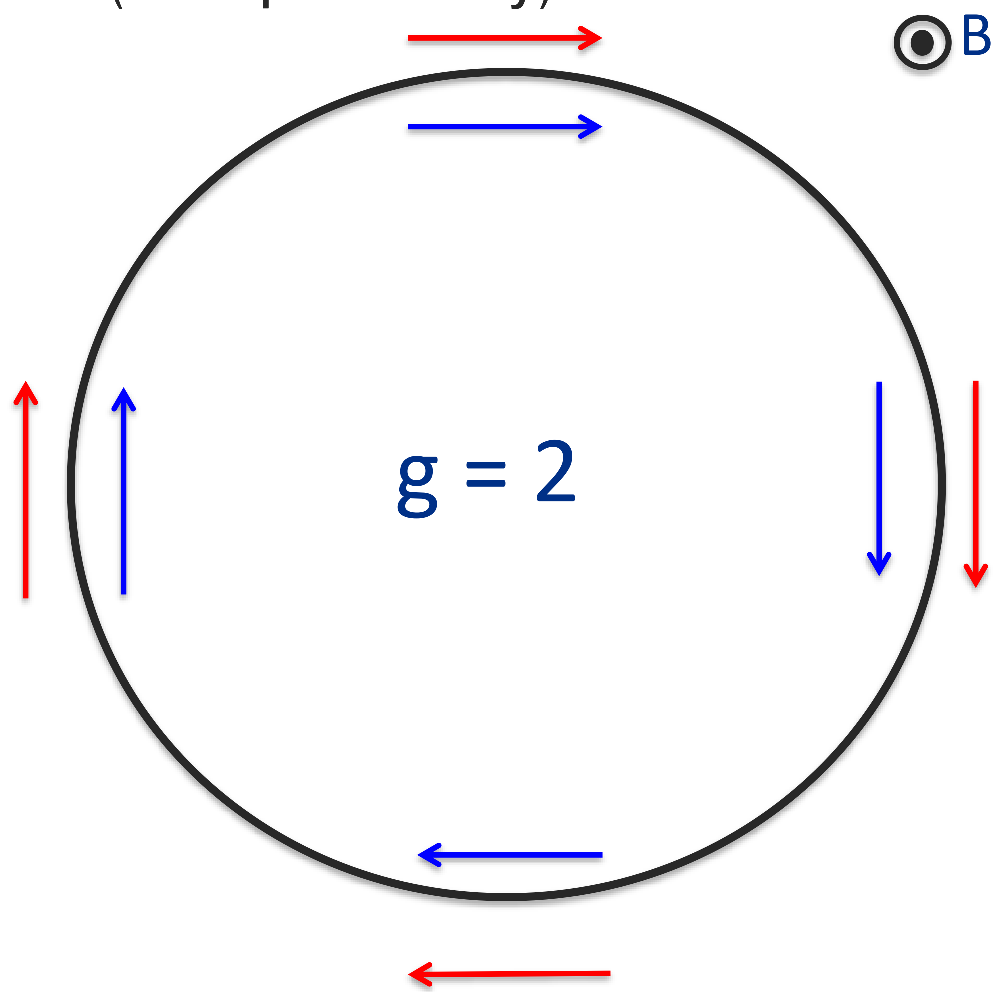
2. Cyclotron frequency :

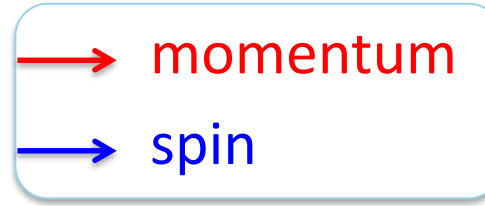
$$\omega_c = \frac{e}{m\gamma}B$$

3. Spin precession frequency :

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

Larmor + Thomas precession





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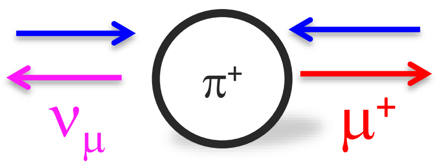

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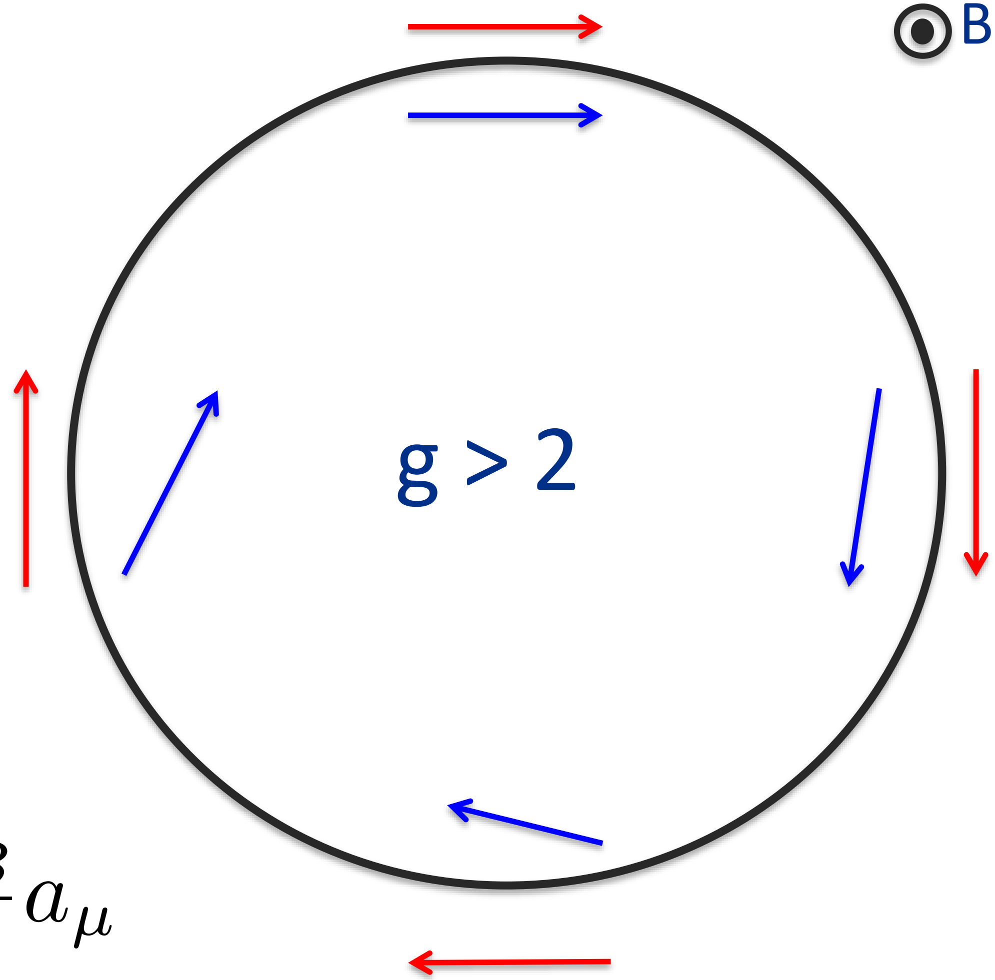


$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$

Muon g-2 Measurements

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

B via NMR → ω_p proton precession frequency,

$$a_\mu(Expt) \approx \frac{\omega_a}{\tilde{\omega}_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\mathrm{ppb}$$

$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\mathrm{ppb}$$

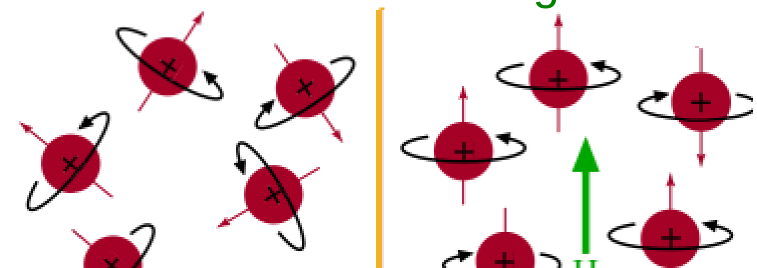
$$\delta\left(\frac{g_e}{2}\right) \sim 0.3\,\mathrm{ppt}$$

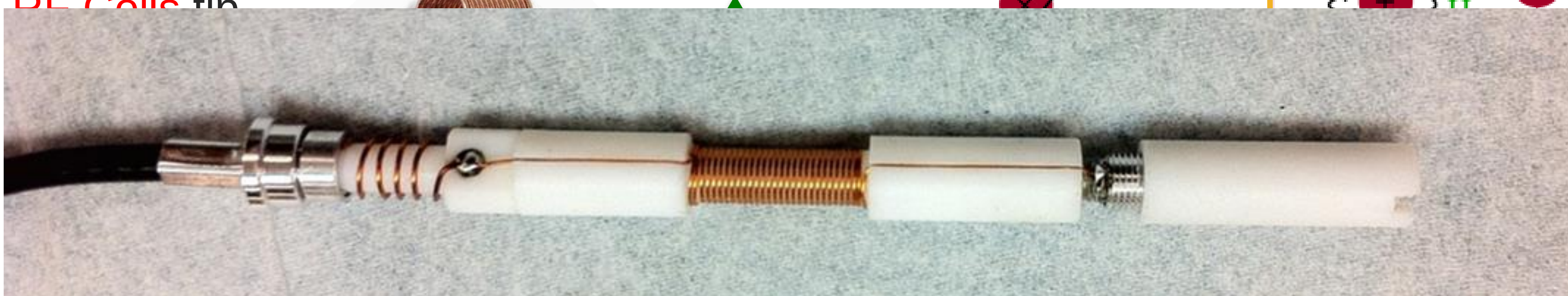
Proton Precession Frequency: How We Measure

- Nuclear Magnetic Resonance (NMR)
  - Extremely Precise (~10 ppb)
  - Measures Total Field

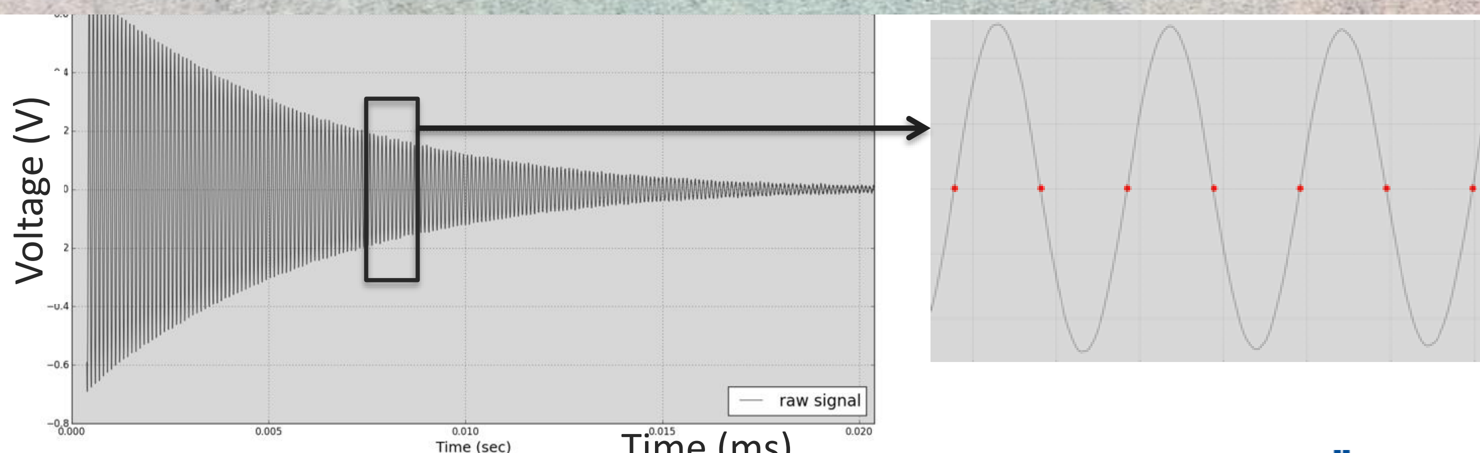
Proton-rich sample

- Turn on magnetic field





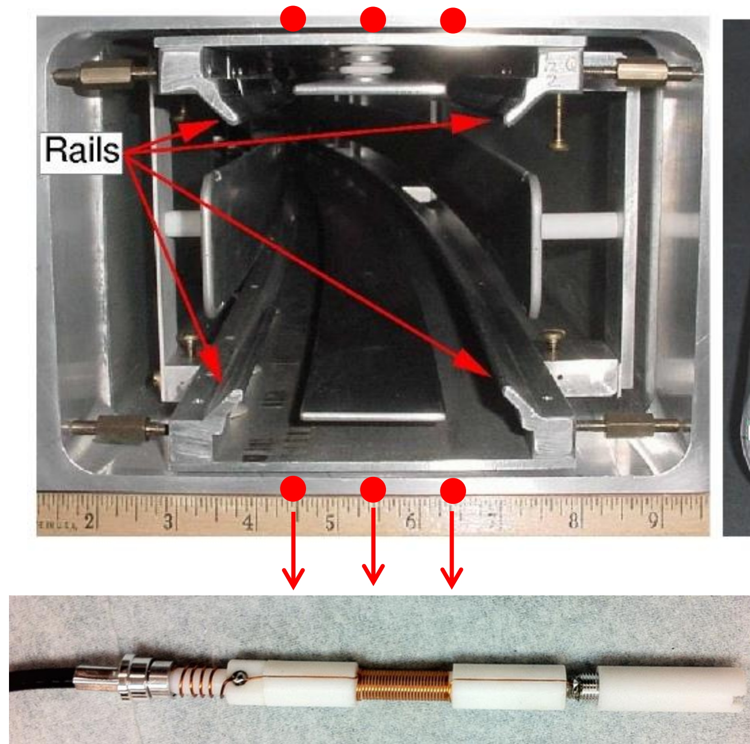
Digitize to extract ω_p



Measurement principle for the magnetic field

- Map the storage field regularly during beam off periods with trolley
- Monitor the field with 400 fixed NMR probes around the ring
- Use a spherical water-based probe for absolute calibration (~30ppb accuracy)

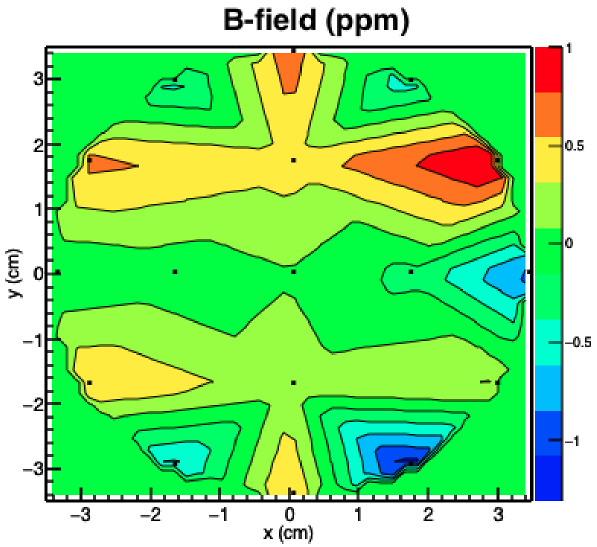
Calibration probe



Fixed NMR probes

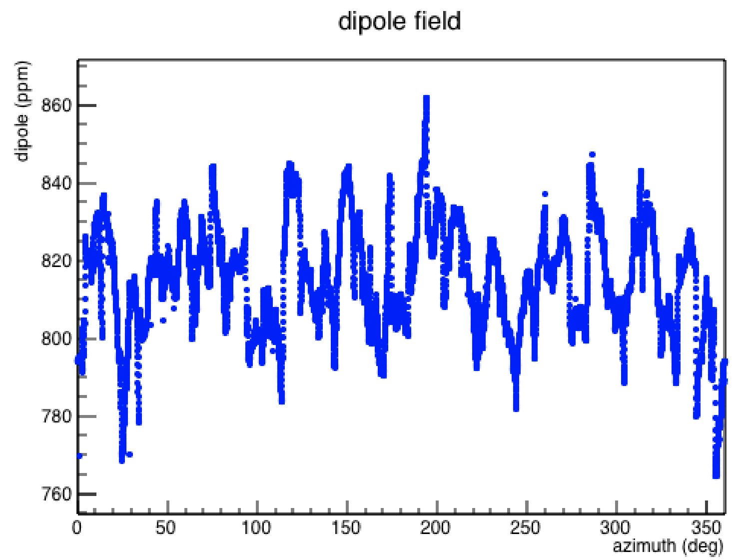
trolley

Field: Production Trolley Runs



	Norm	Skew
Quad	-0.19	0.28
Sext	0.05	0.27
Octu	-0.07	0.25
Decu	0.23	0.07
Dipole	-0.0	

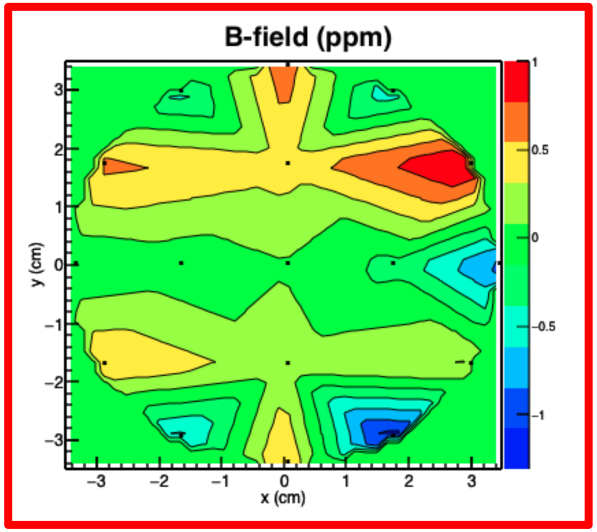
100 ppm



- Moments all < 0.28 ppm! Goal was < 0.5 ppm
- Variation of field +/-1ppm over storage region
- BNL +/-2 ppm

- **Dipole RMS =14.2 ppm**
- BNL RMS = 29 to 39 ppm

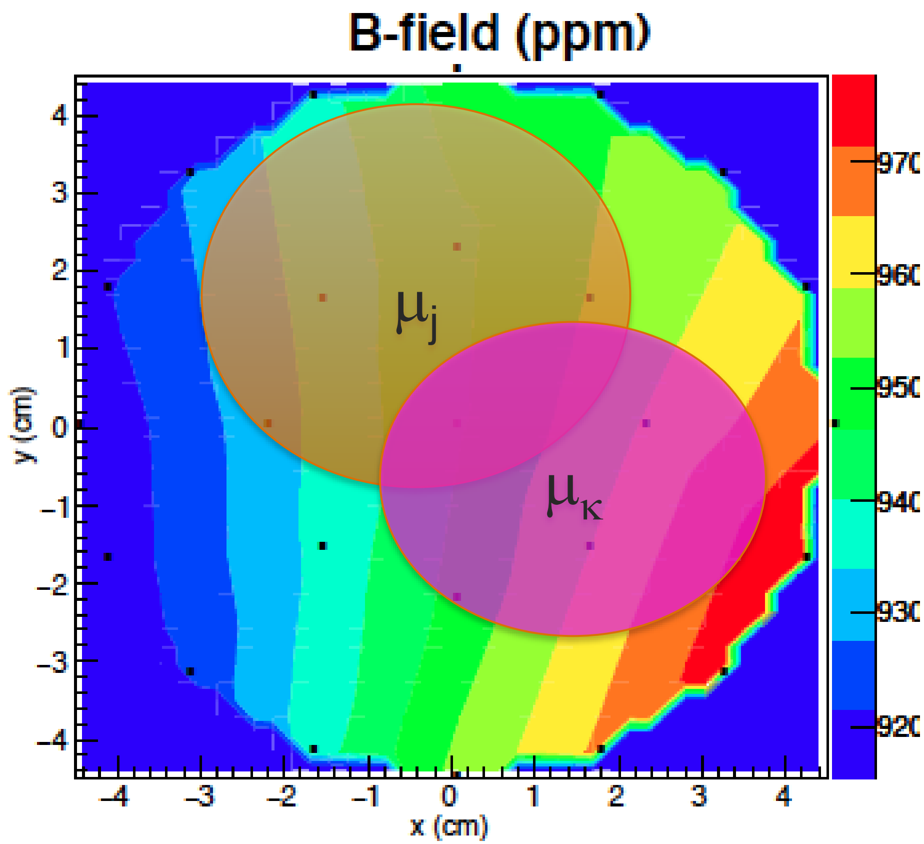
Muon g-2 Measurements



ω_p via NMR

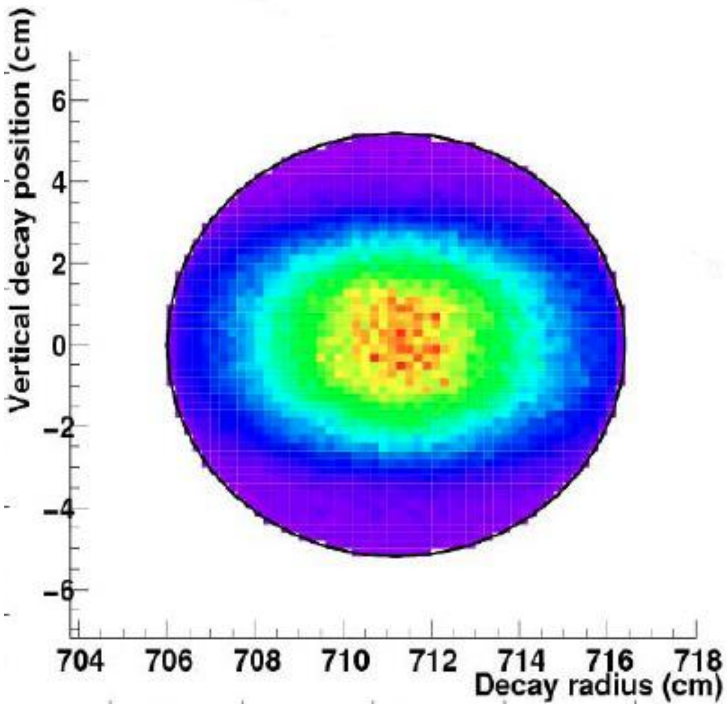
$$a_\mu\,(Expt) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$

Muon distribution

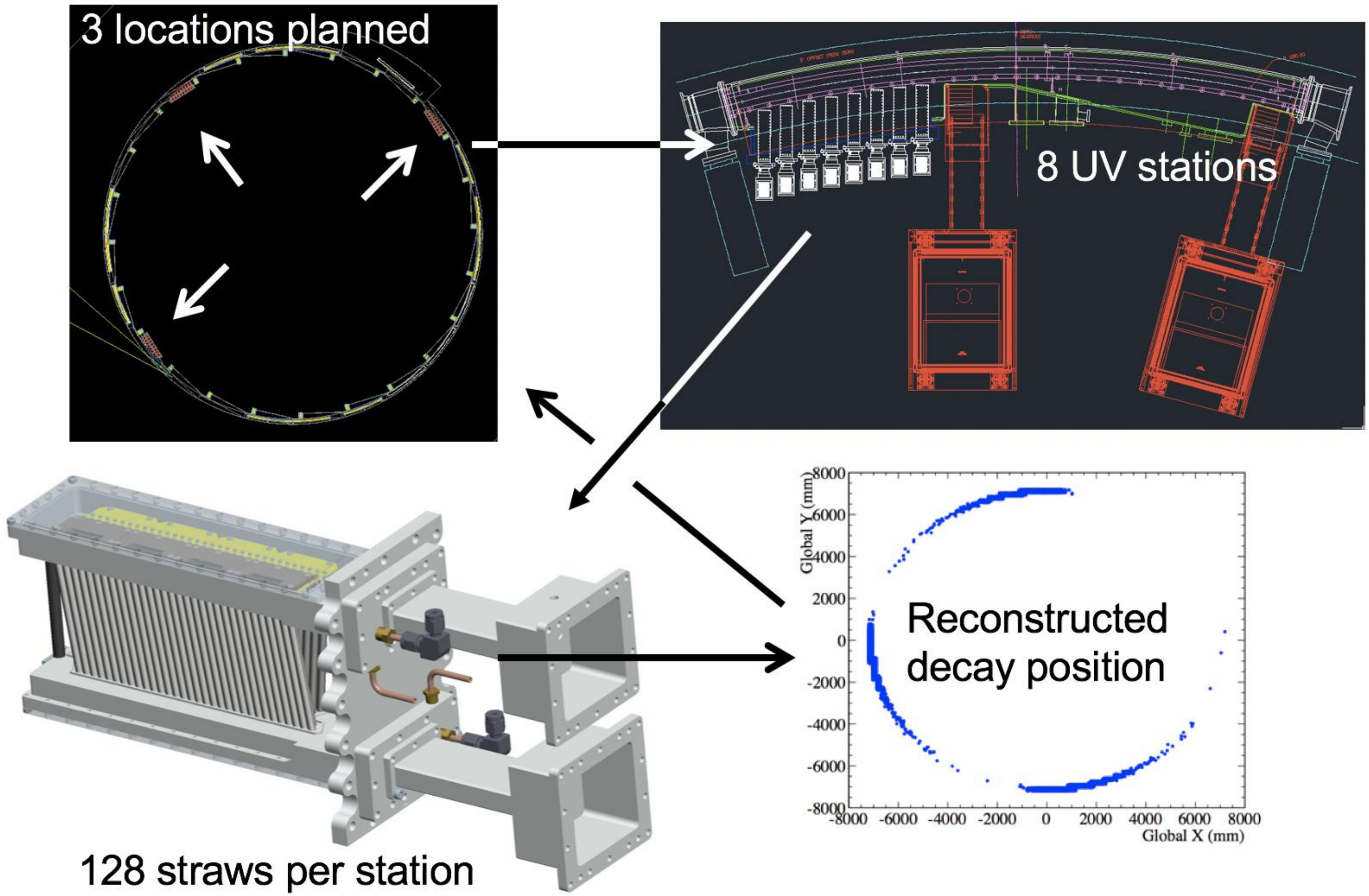


Arbitrary field distribution

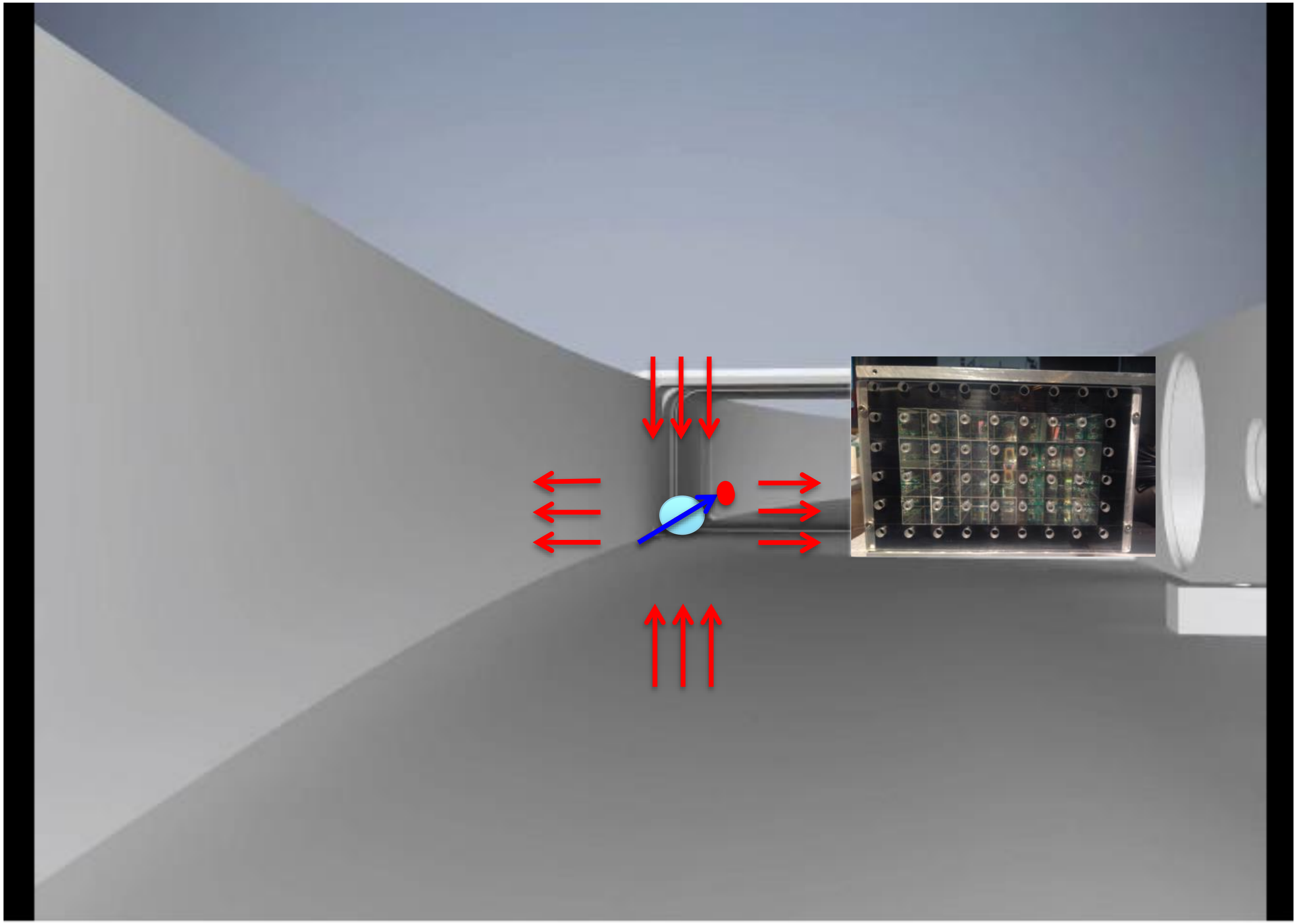
- B-field not perfect
- Weight field by muon distribution



In-vacuum Trackers are used to reconstruct decay electron tracks at two locations

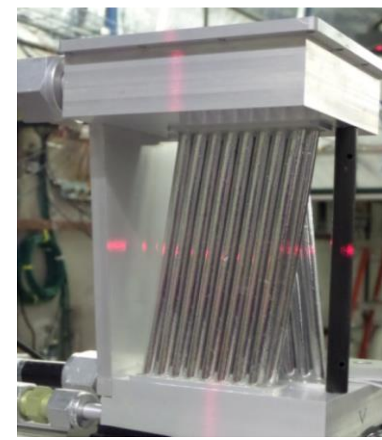


Our Muons' Racetrack



Electrostatic Quadrupoles

Tracker



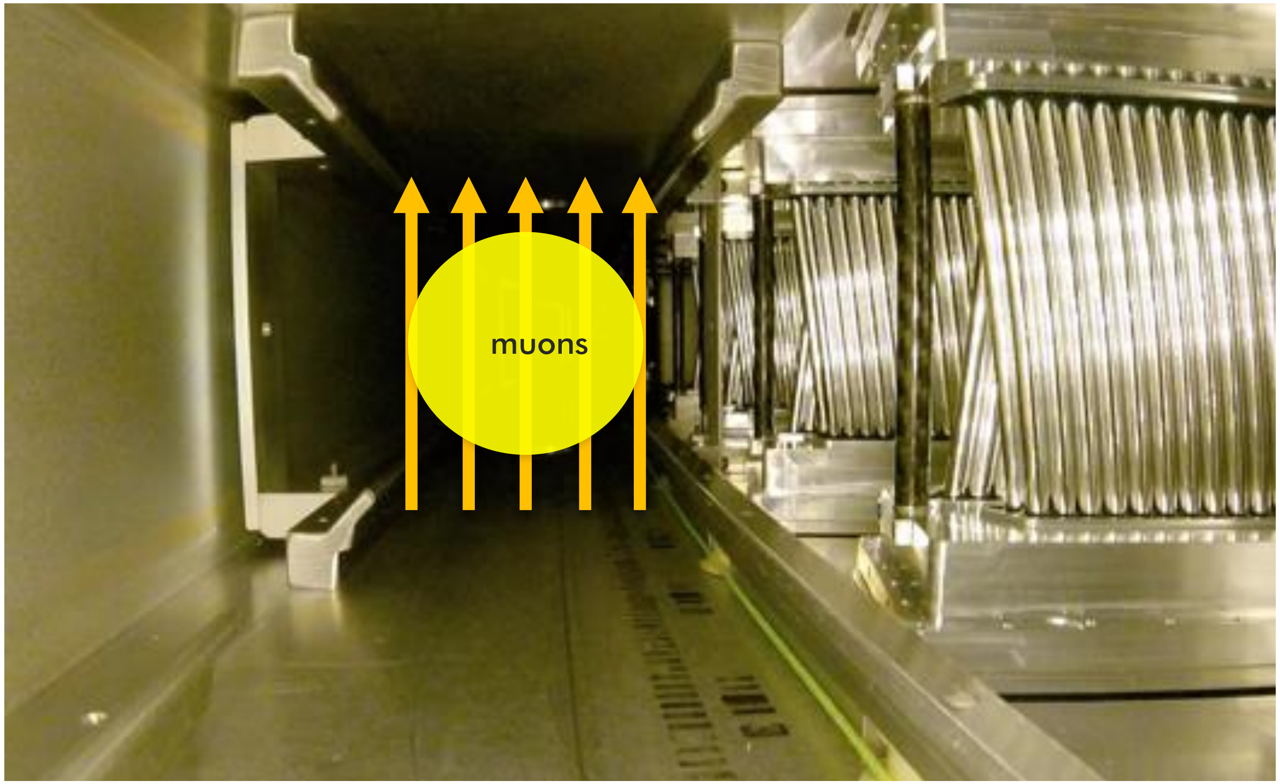
Rendering: W. Turner
Model: J.Kaspar

Ensemble of muons precess about vertical B-Field

$$a_\mu\,(Expt) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$

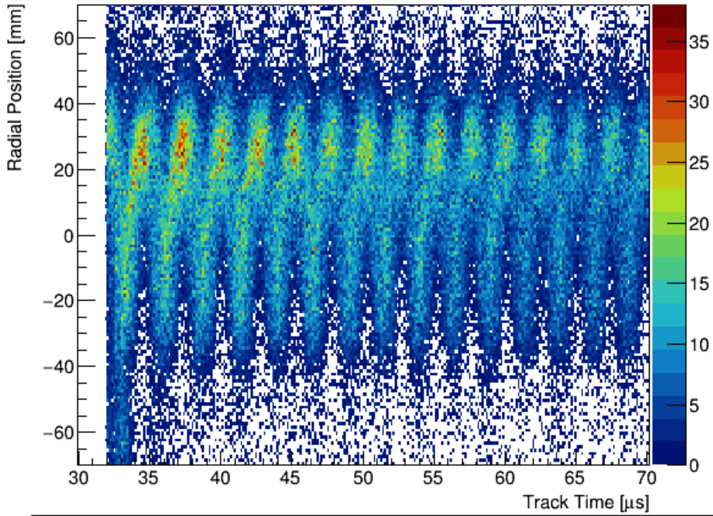
B-field = 1.45 T

Tracking detectors measure the muon beam.

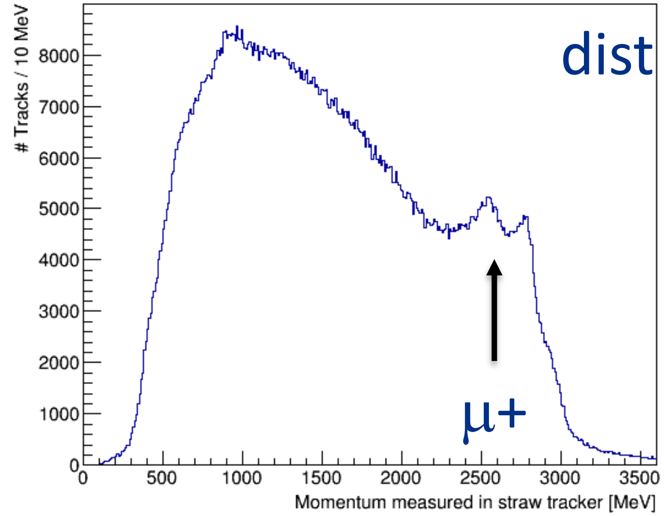


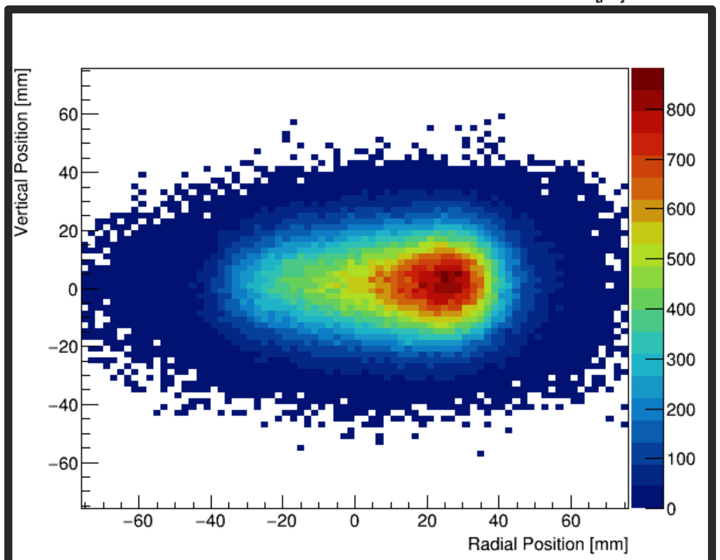
Slide From T. Walton

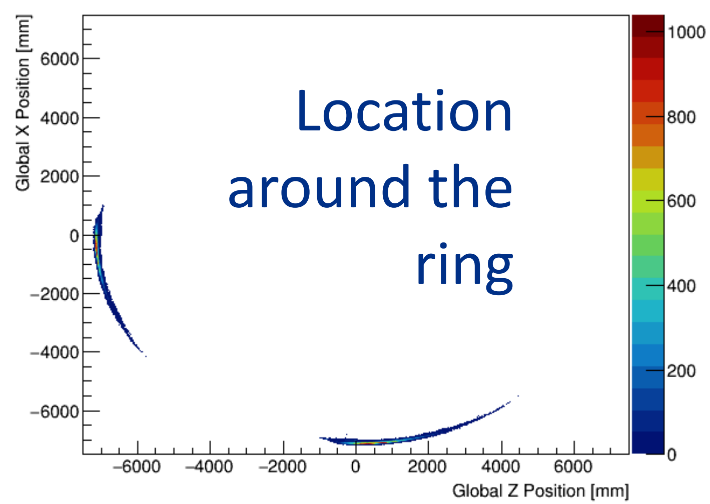
Detector: Offline+OnlineTrackers Plots from Sun Mar 25th PM running



e+ momentum dist



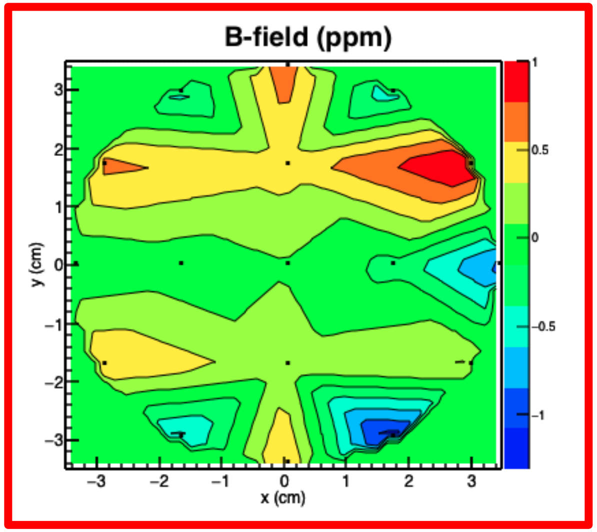




Location around the ring

Plots from J. Mott

Muon g-2 Measurements



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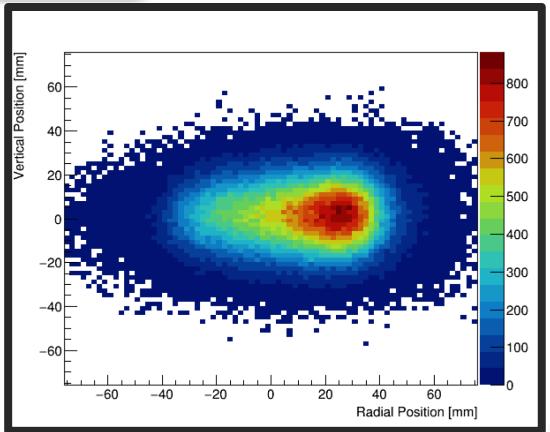
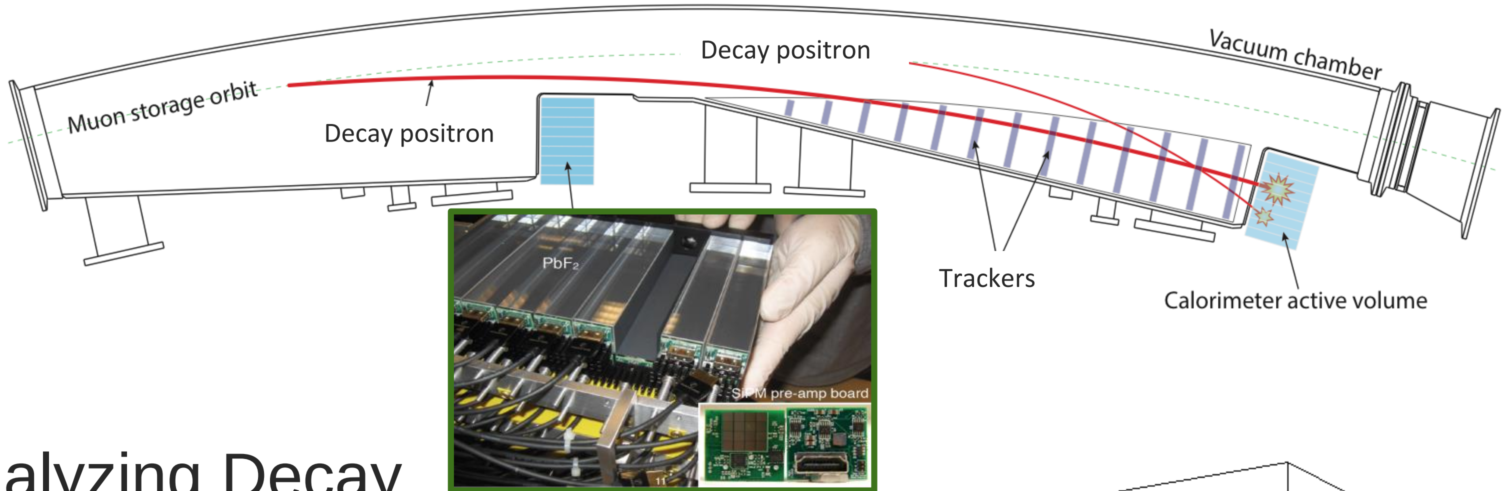
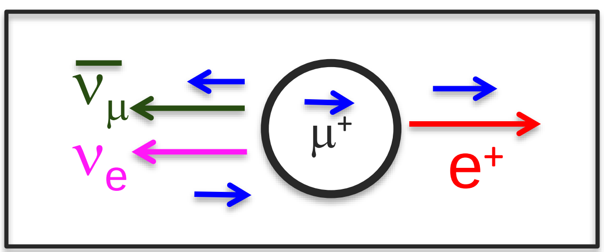


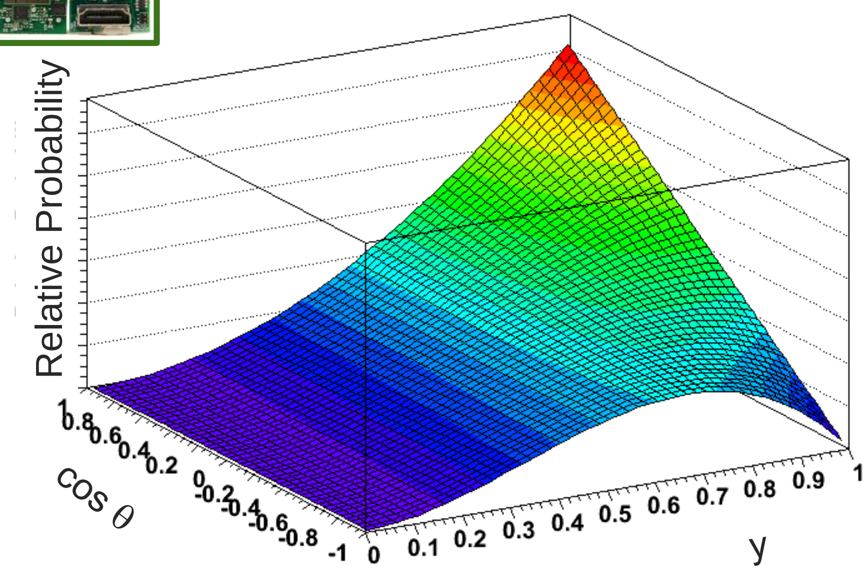
Muon spin precession frequency



Self-Analyzing Decay

- Energy Direction Correlation



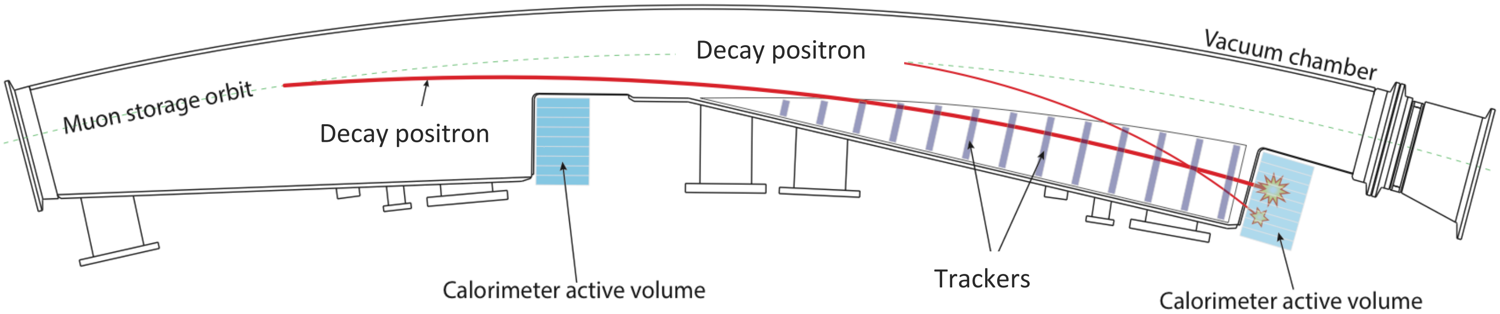


$$dP(y,\theta) \propto n(y)[1 \pm A(y)cos\theta]dyd\Omega$$

$$\theta = \cos^{-1}(\hat{p}_e \cdot \hat{s})$$

$$y = E_e/E_e\mathrm{max}$$

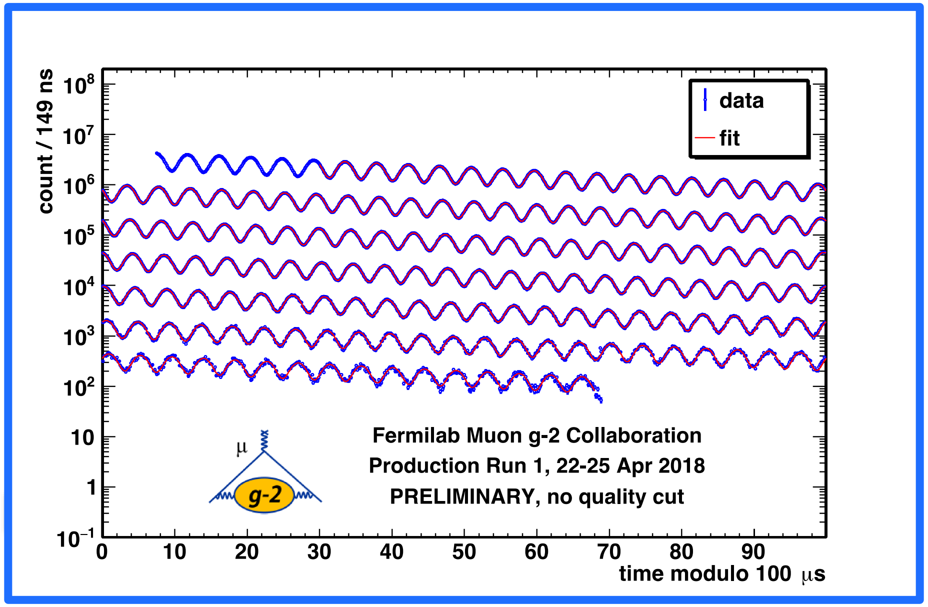
Muon spin precession frequency

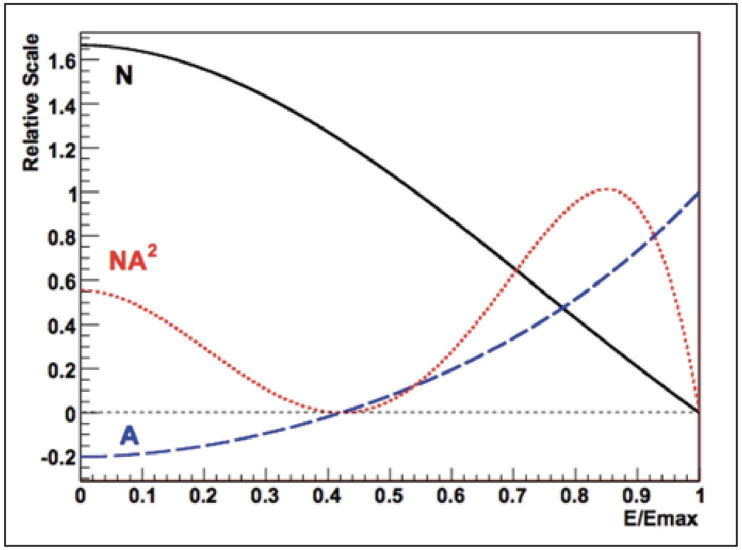


E821 data: e^+ with E > 1.8 GeV

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

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





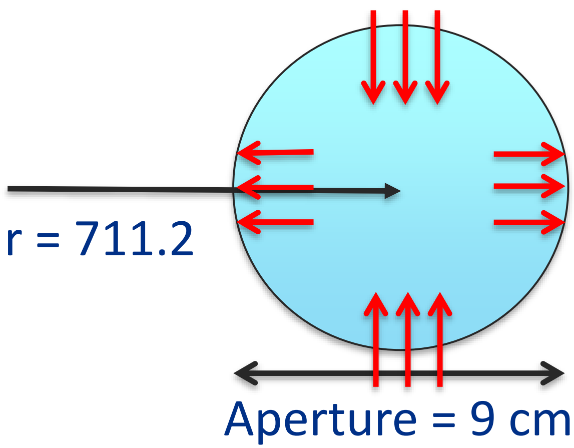
More Complete Muon Precession

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

Choose $\gamma = 29.3$ → coefficient vanishes

Electrostatic quads needed to contain particles vertically

Muon momentum pitched wrt horizontal plane
- affects $\boldsymbol{\omega}_a$
- measure vertical beam position



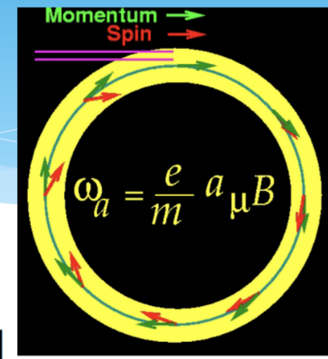
Ring Acceptance = $\delta p/p \sim 0.15\%$
- need to correct $\boldsymbol{\omega}_a$ since higher p and lower p muons feel net E field

JPARC will take a different approach

muon g-2 and EDM measurements

by T. Mibe

- Target
  - Statistical uncertainty on a_μ: 0.1 ppm
  - Statistical uncertainty on d_μ: 1E-21 e•cm



In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0

general form of spin precession vector:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

FNAL E989

J-PARC approach
E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

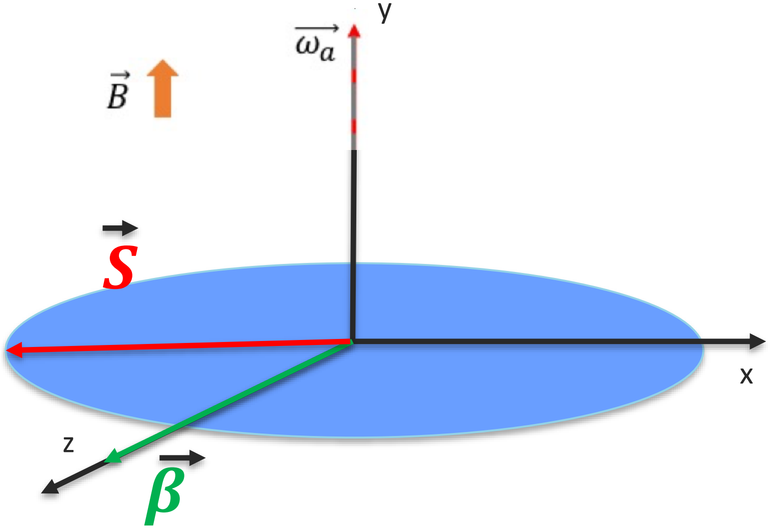
J-PARC E34

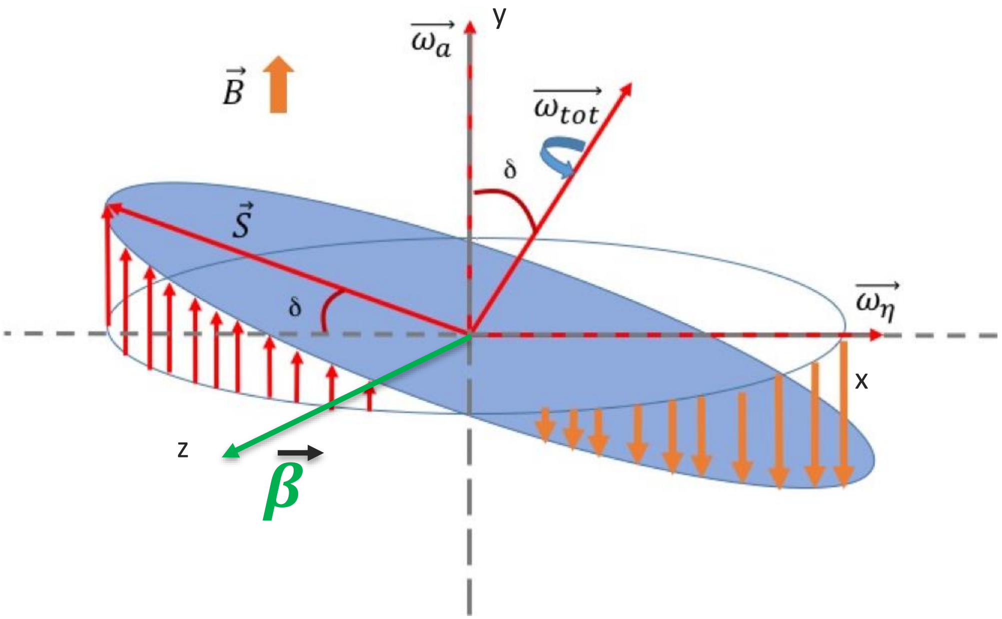
8

An EDM modifies the muon precession

$$\boldsymbol{\omega}_{tot} = \boldsymbol{\omega}_a + \boldsymbol{\omega}_\eta = \frac{e}{mc}\left[a_\mu \boldsymbol{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\boldsymbol{\beta} \times \boldsymbol{E}\right] + \eta \frac{e}{2m}\left[\frac{\boldsymbol{E}}{c} + \boldsymbol{\beta} \times \boldsymbol{B}\right]$$

$$\vec{d}_\mu = \frac{\eta}{2}\frac{e\,\hbar}{2m_\mu c}\vec{S}$$



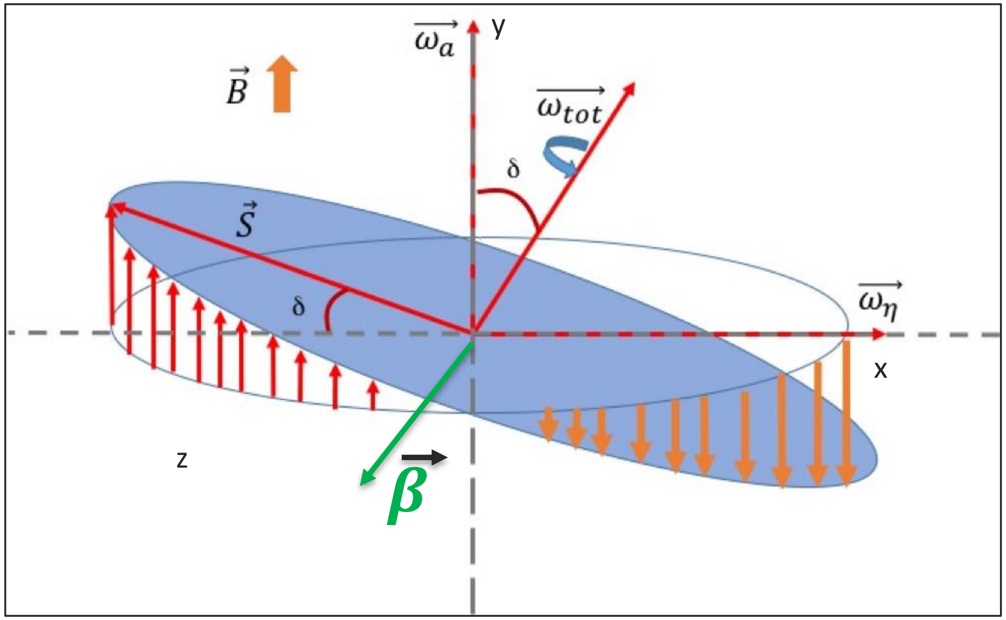


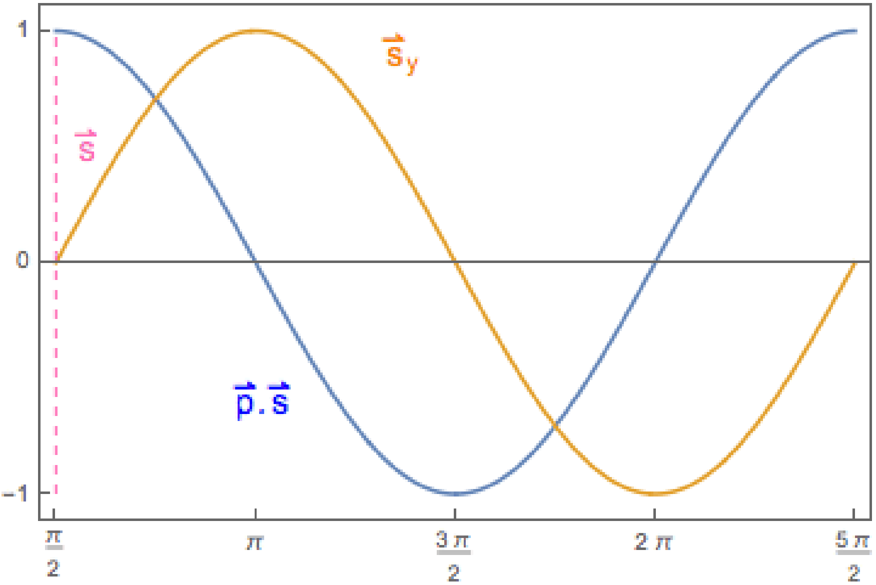
- With just MDM in uniform B field, the spin precesses around B field

- An EDM tips the spin precession plane, modifies $\boldsymbol{\omega}_{tot}$

EDM Signal

- Muon polarization has vertical component S_y
  - Maximized when $\boldsymbol{\beta} \cdot \boldsymbol{S} = 0$





EDM signal: an oscillation with in the average vertical angle of the e+ that:

- has frequency ω_{tot} (~ ω_a)
- is 90° out of phase with g−2 oscillation
- has amplitude ∝ EDM magnitude

Effect	Error(μm)
Detector Tilt	6.1
Vertical Spin	5.1

Detection Techniques

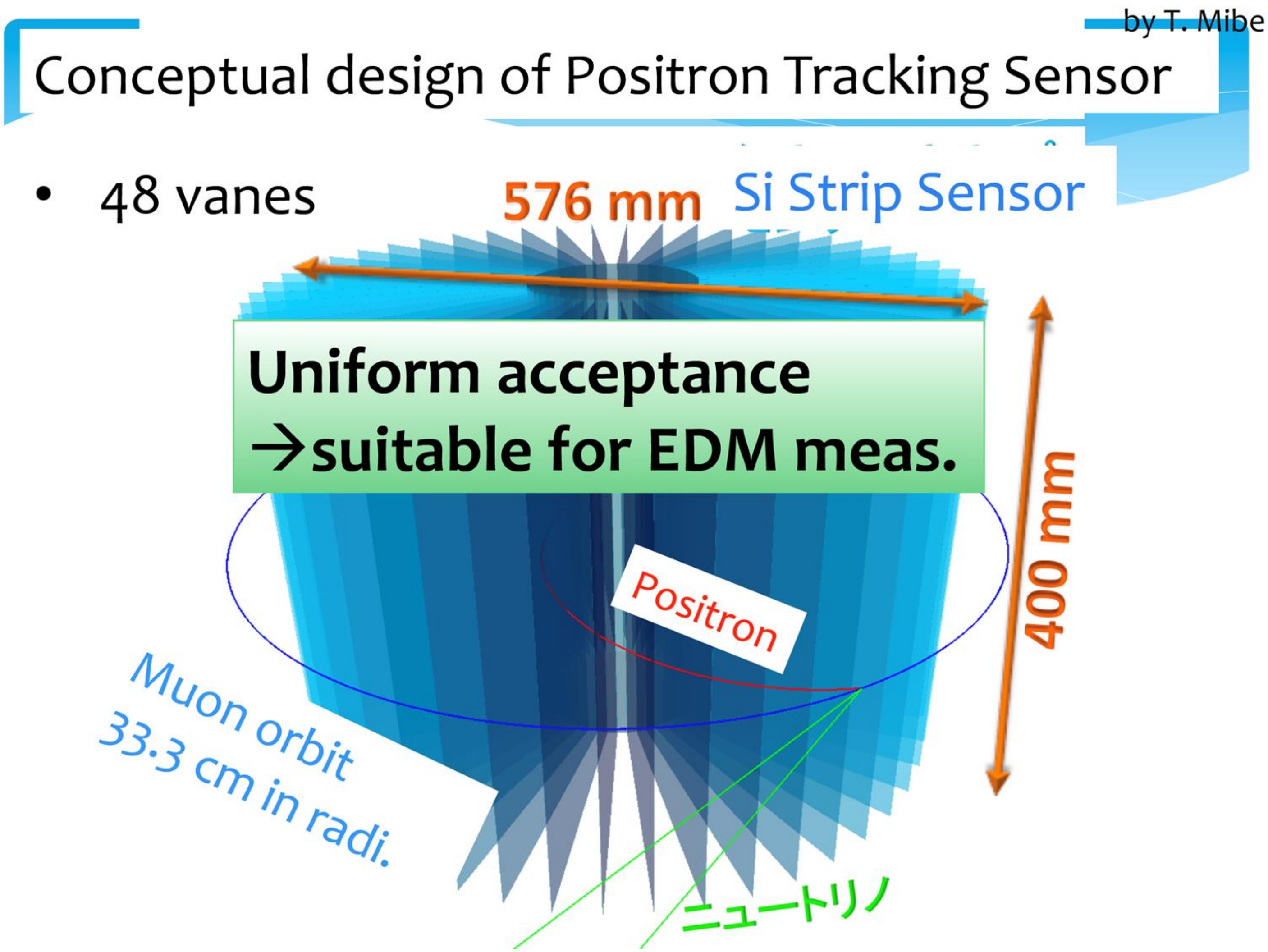
- A non-zero muon EDM introduces an oscillation in the average vertical angle of the emitted decay e+

1. Vertical Position Oscillations
   - Measure time evolution of vertical distribution on calos
   - Vulnerable to alignment
2. Vertical phase asymmetry
   - More outward going decays in top half of calo, and more inward decays in bottom half of calo
   - Vulnerable to alignment, tilt, radial field
3. Vertical decay angle
   - More direct measurement using trackers
   - Statistically limited

Improvements:
- Calo
  - Increased segmentation
  - Lower energy resolution
- Trackers
  - In-vacuum location increases geometric acceptance
  - Increase number
- Increase number of muons
  - → x1000 increase in stats
  - → Should improve EDM limit x10 relatively quickly, x100 eventually

Effect	Error(μrad)
Radial Magnetic Field	0.13
Acceptance Coupling	0.3
Horizontal CBO	0.3
Phase Fit	0.01
Precession Period	0.01
Total Systematic	0.44
Statistical	4.4
Total Uncertainty	4.4

JPARC Experiment Detector



EXPERIMENTAL PROGRESS AND DETAILS: YEAR ONE OF PHYSICS RUNNING

E989 Collaboration: 35 Institutes; 180 Members

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

National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

England
University College London

Liverpool

Oxford

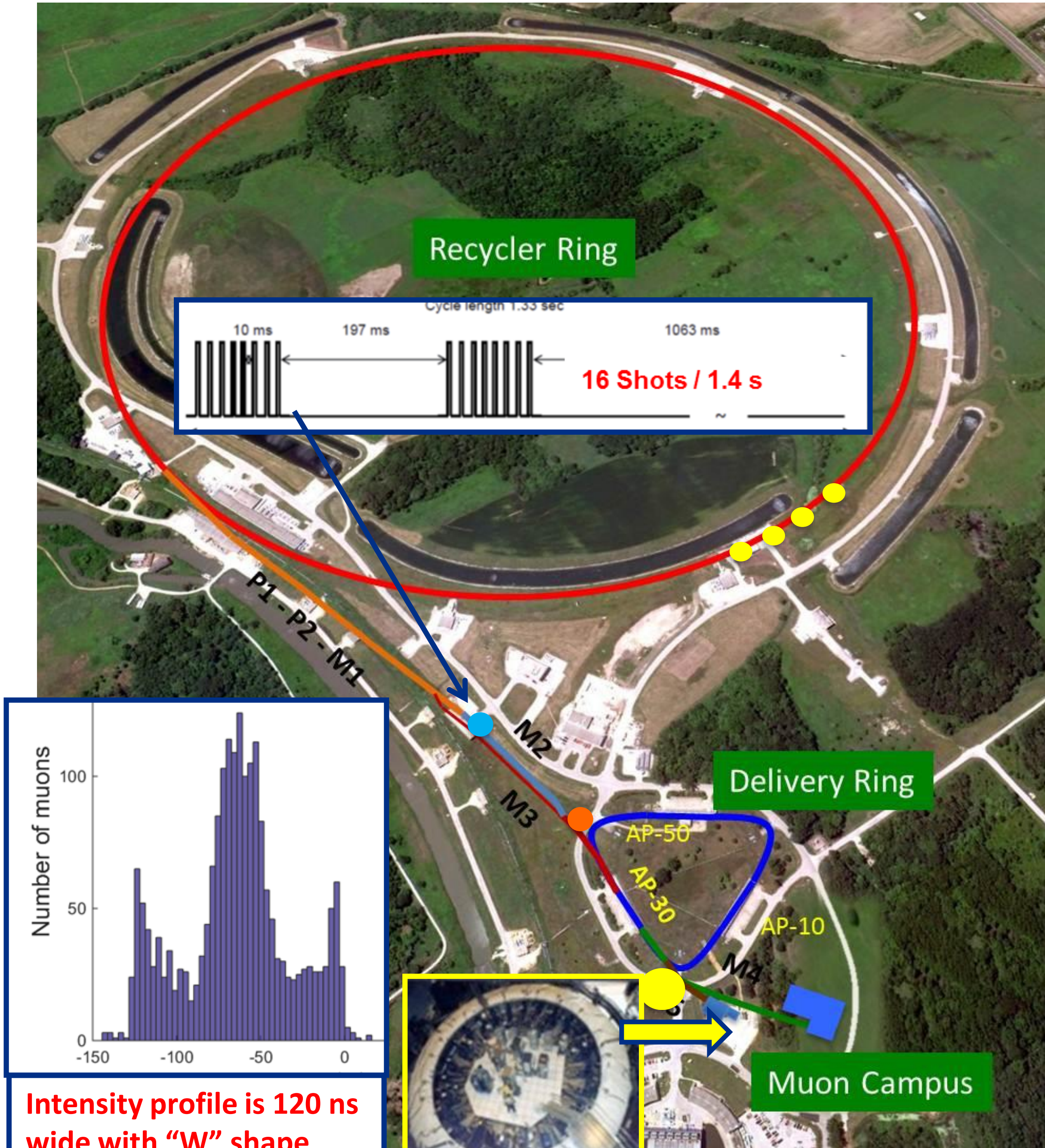
Korea
KAIST

CAPP

The Experimental Approach

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	240
HVP	360	215
HLbL	225	100
Total Exp.	540	**140**
Stat	460	100
ω_a	180	70
ω_p	170	70

- Previous effort statistically limited → x21 improvement
  - Facility Upgrades
  - Improved Muon Storage

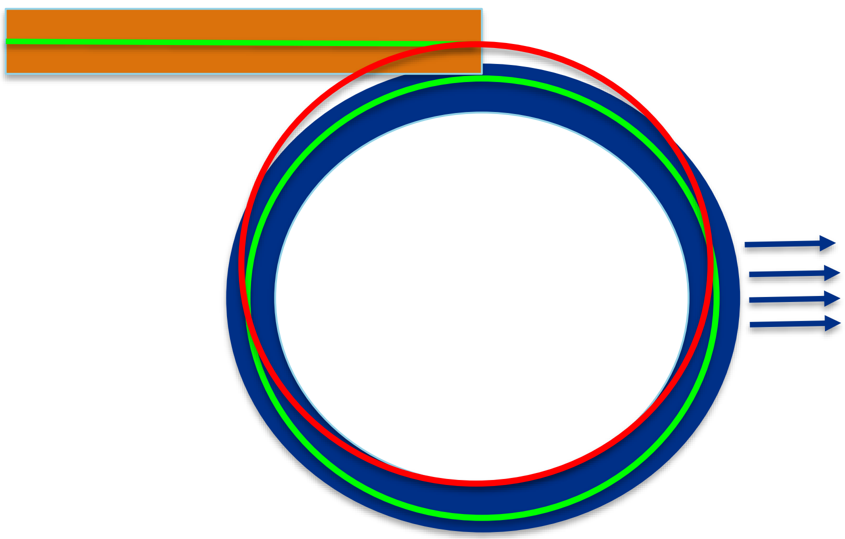


Creating the Muon Beam for g-2

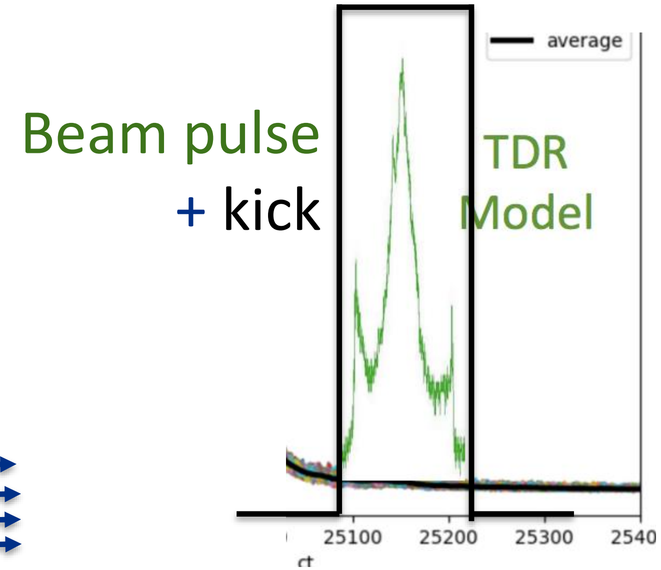
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract each bunch to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- **~10,000 μ stored in ring per pulse (goal)**

(Ideal) Blumlein Kickers and Beam Pulse

- Take the incoming beam pulse on the displaced orbit and kick it on the central orbit



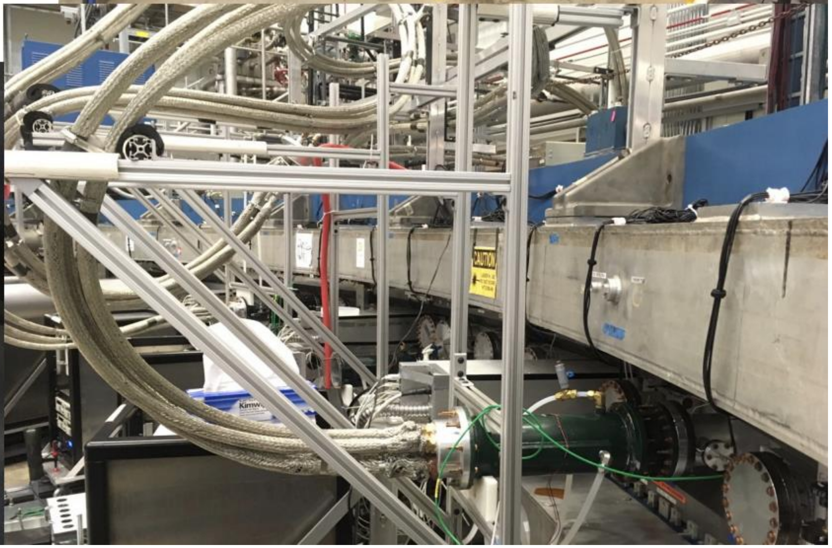
Orbit time is 149 ns

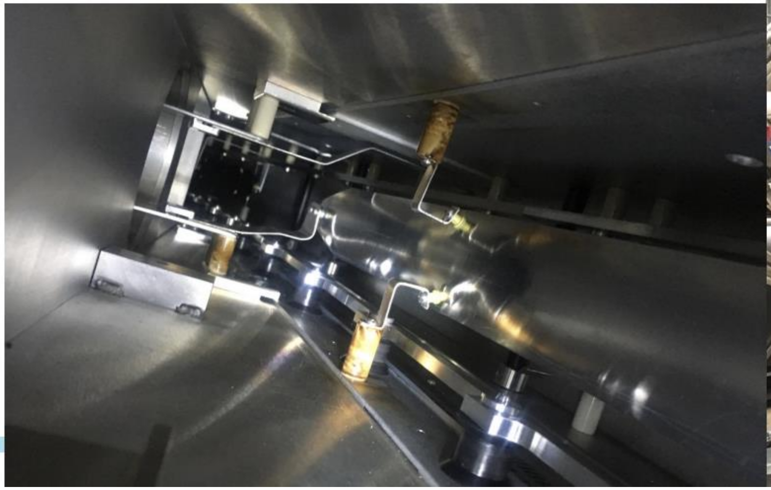


- Each incoming muon receives ideal 10.8 mrad kick
- Kicker is off for subsequent orbits

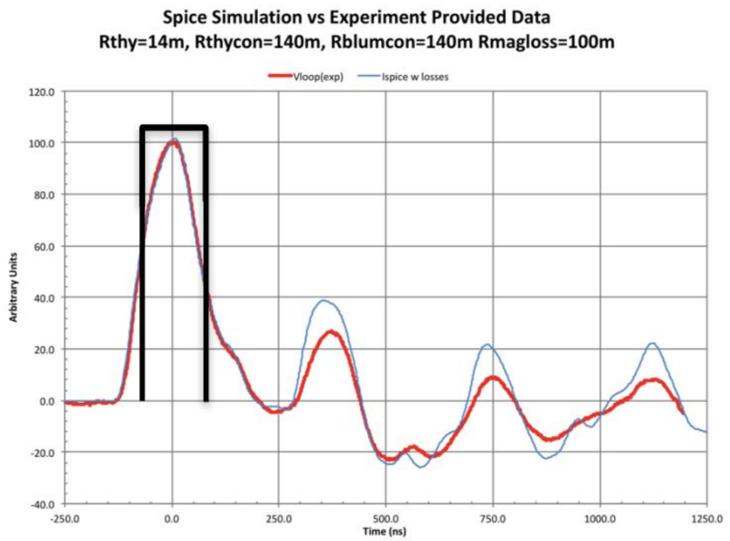
How do our Blumlein kickers work?

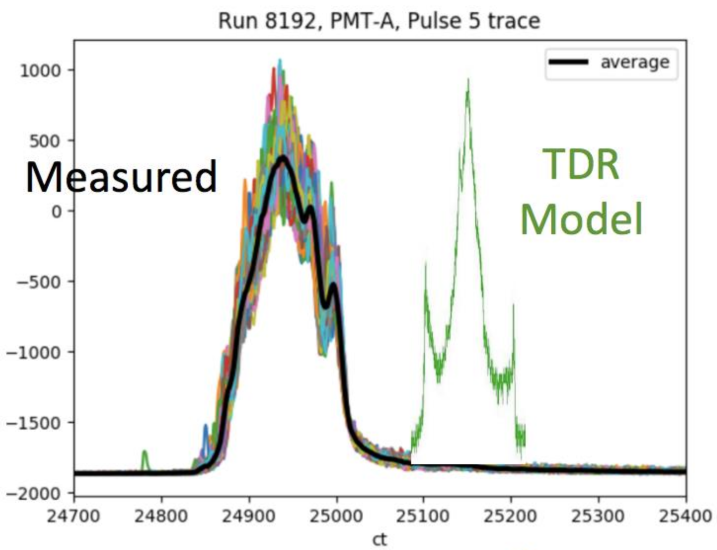
- a *charging power supply* charges up
- *capacitor back* to low voltage (700 V) that is discharged
- through a *transformer* into
- a *Blumlein*, which is a HV capacitor (55 kV), that is discharged through
- four *50 Ohms resistors*, which convert high voltage into high current into
- in-vacuum *plates*, where the current generates magnetic field that rotates momentum vector of muons



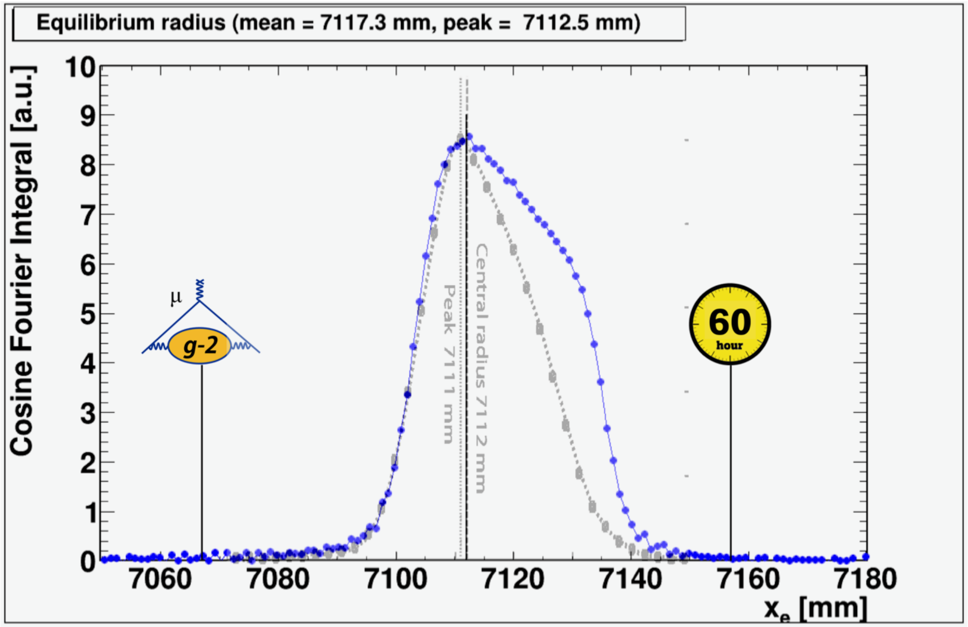


Real Kickers and beam





- Started out with wider kicker pulse, smaller amplitude, and wider beam pulse
- Simulations indicate max storage efficiency (0.40 overall): shape, ringing, beam width

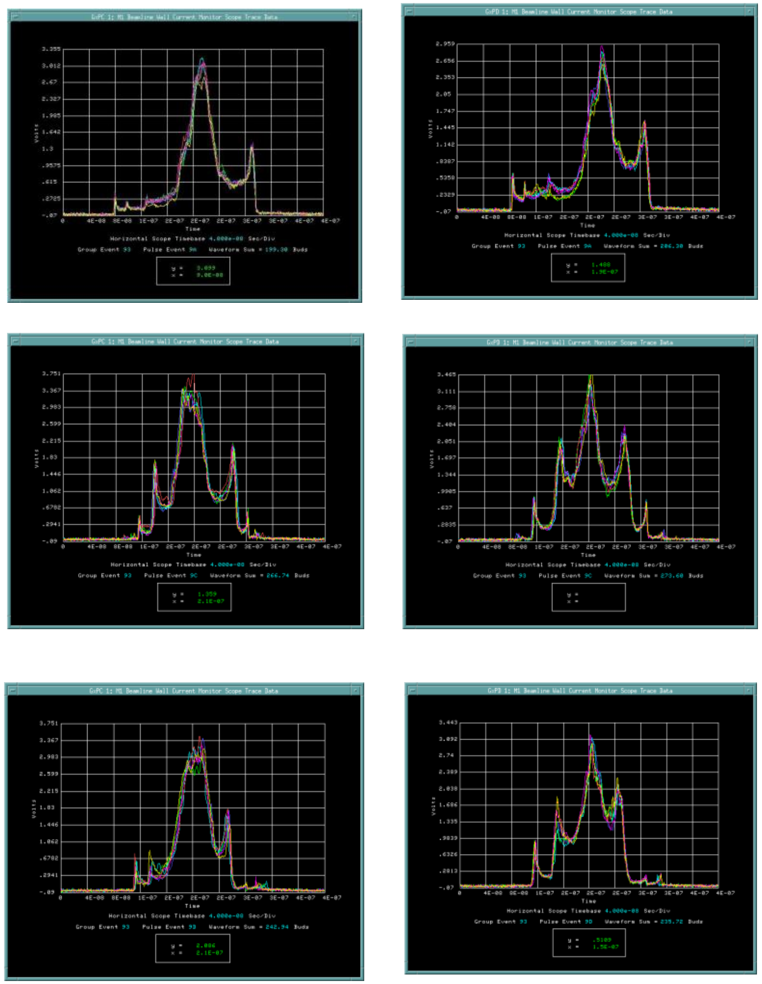


- Mismatched momentum distribution in ring → larger E-field corrections than anticipated → solution is to fix the kick

Fermilab

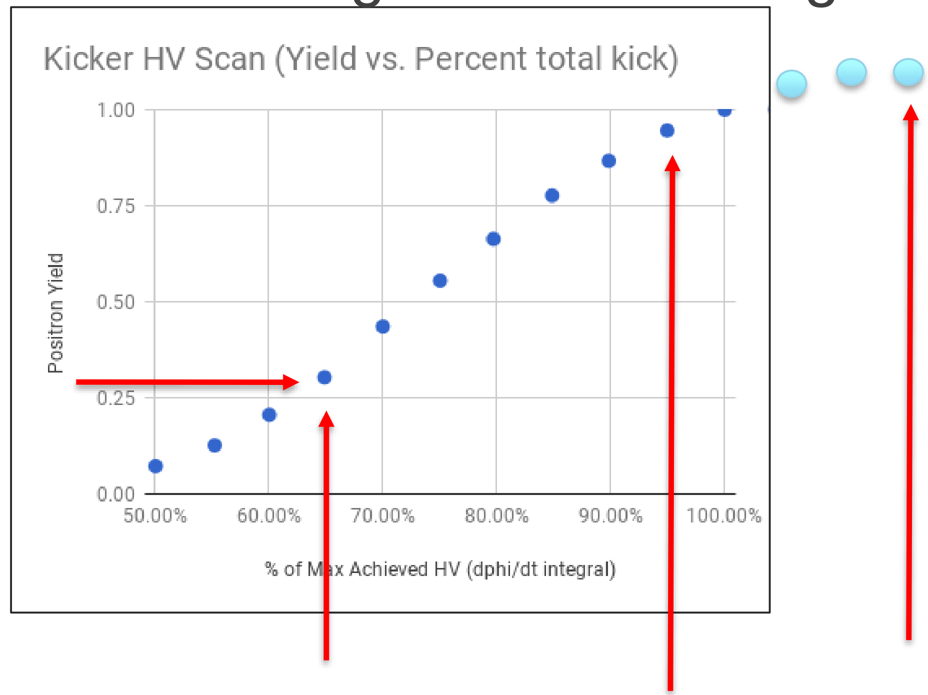
This winter we learned how to improve our injection

Before (left) and After (right) RF Tuning



Each pulse has its own personality

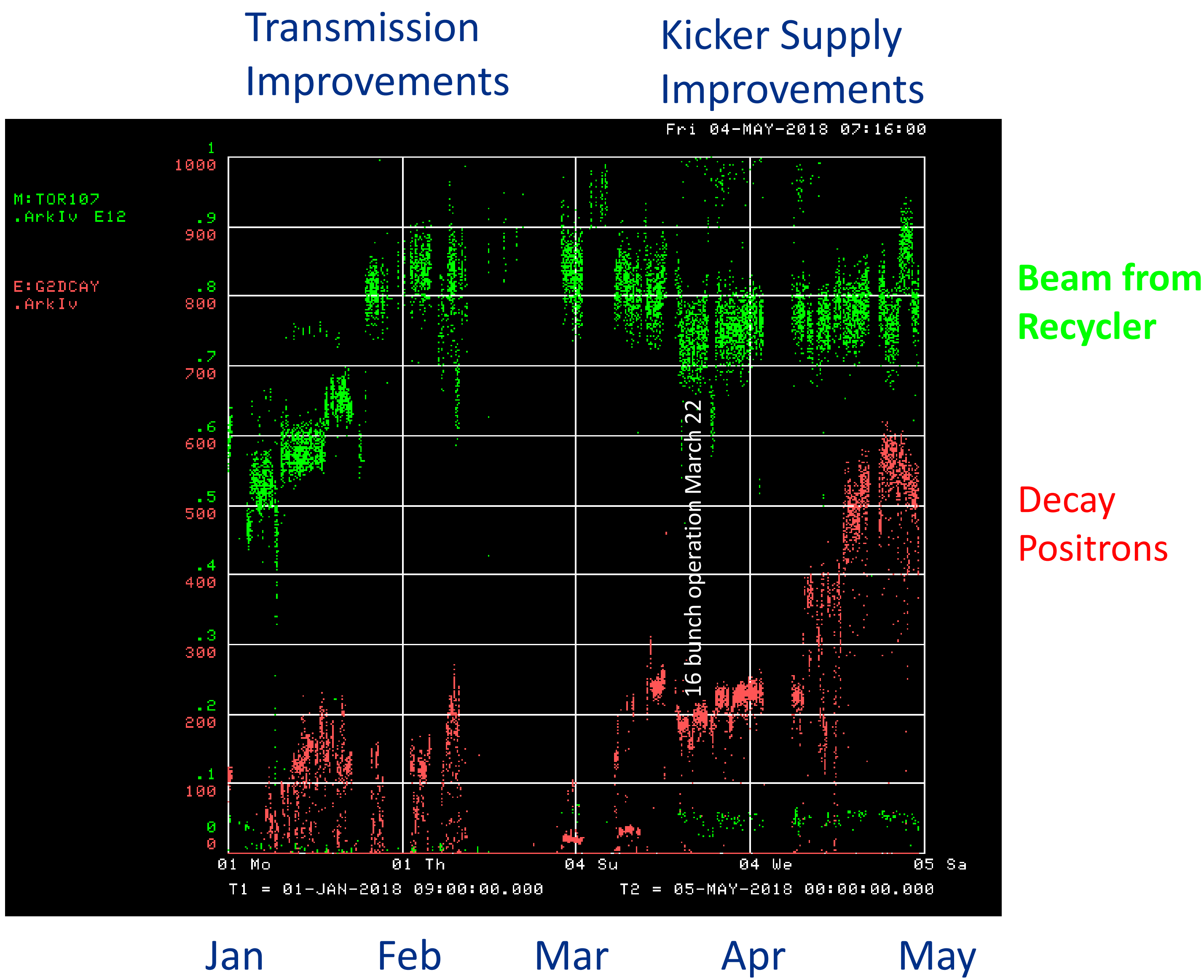
- Kick strength affects storage



Jan – Feb Apr-May Future

Worked to understand/improve charging supplies of fast blumlein kicker

Beam to g-2 since January



Modest improvements to the muon precession systematics

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140
Stat	460	100
ω_a	180	70
ω_p	170	70

Previous effort statistically limited

→ x21 improvement

Facility Upgrades

Improved Muon Storage

ω_a – Muon Precession

Segmented Calorimeters

In-Vacuum Trackers

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration low-energy threshold	20
Pileup	80	Low-energy samples recorded calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency) Better match of beamline to ring	< 30
E and pitch	50	Improved tracker Precise storage ring simulations	30
Total	180	Quadrature sum	70

Fermilab

Modest improvements to the proton precession systematics

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140
Stat	460	100
ω_a	180	70
ω_p	170	70

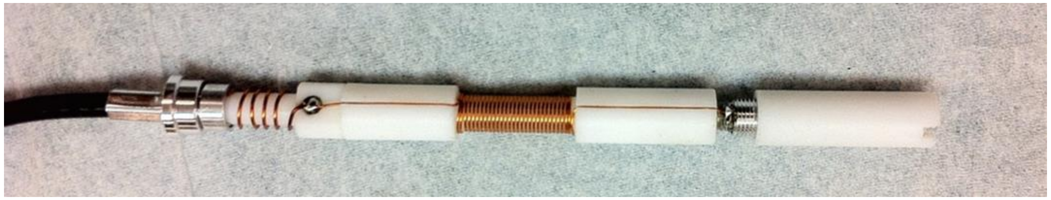
Previous effort statistically limited
→ x21 improvement
- Facility Upgrades
- Improved Muon Storage

ω_a – Muon Precession
- Segmented Calorimeters
- In-Vacuum Trackers

ω_p – Proton Precession
- Absolute Calibration
- More Uniform Field

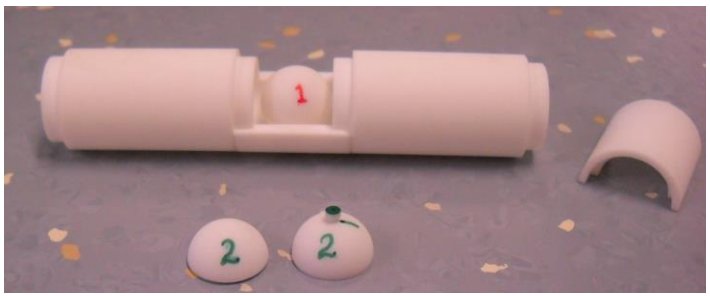
ω_p Instrumentation Upgrades

Low-noise electronics

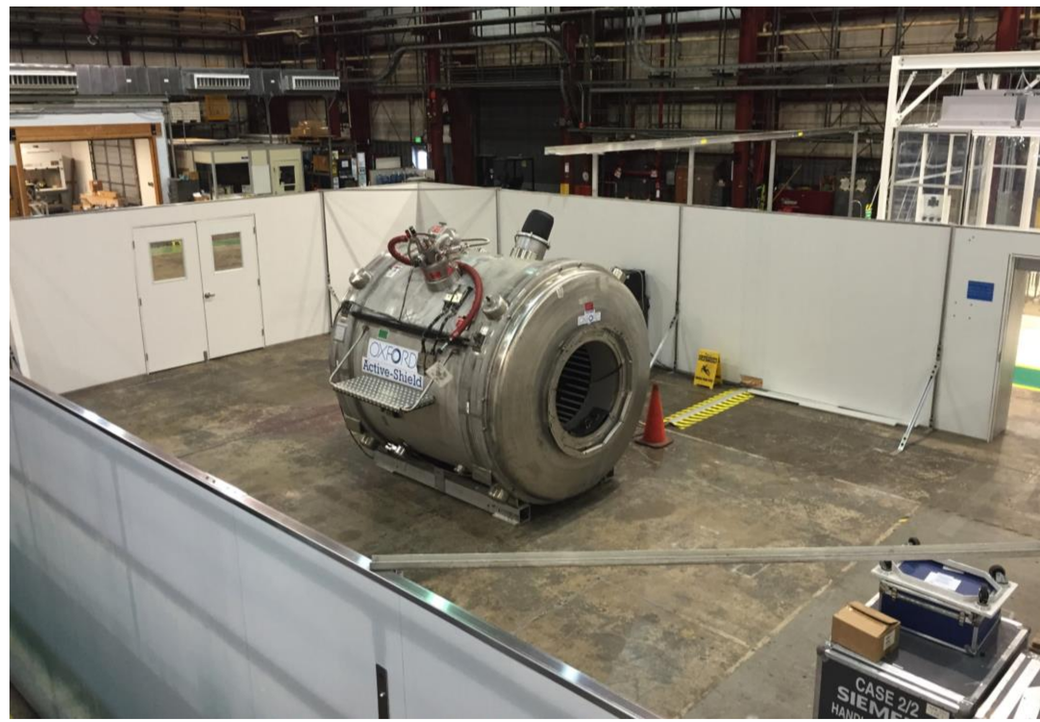


400 New Tunable NMR Probes

68-cm bore MRI magnet w/ high stability

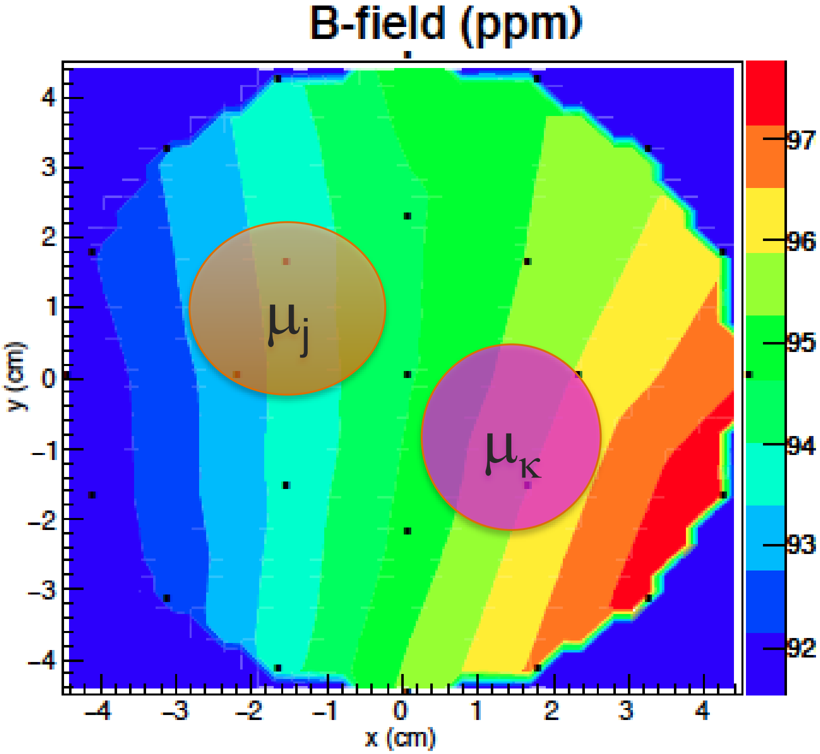


Absolute Calibration Probes



Maximize Field Uniformity

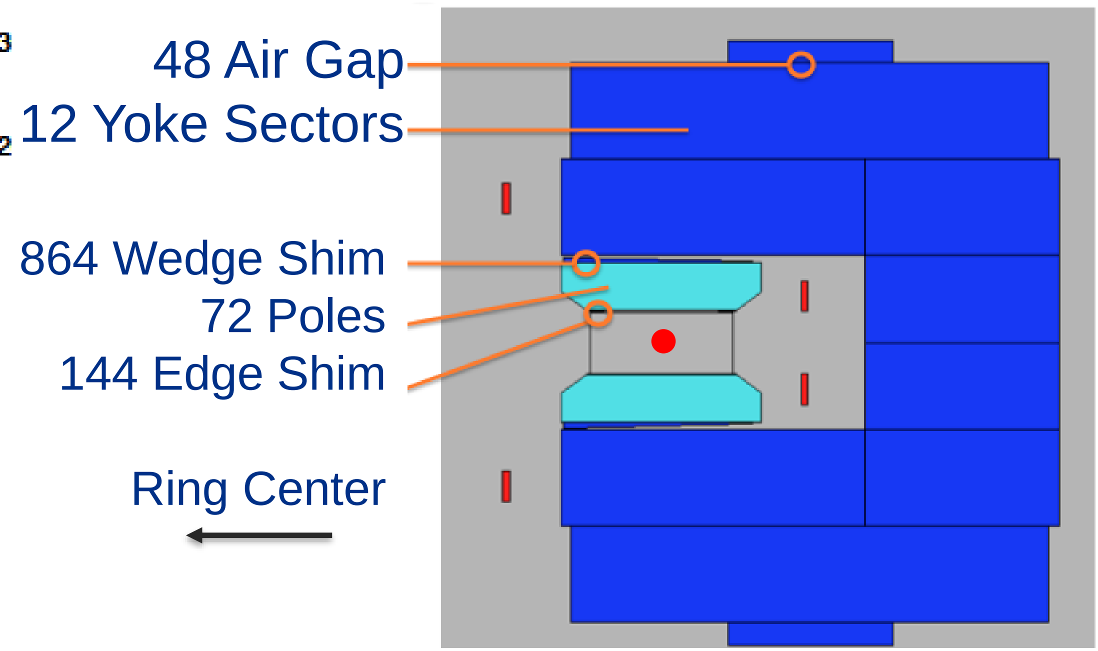
$$a_\mu(\text{Expt}) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$



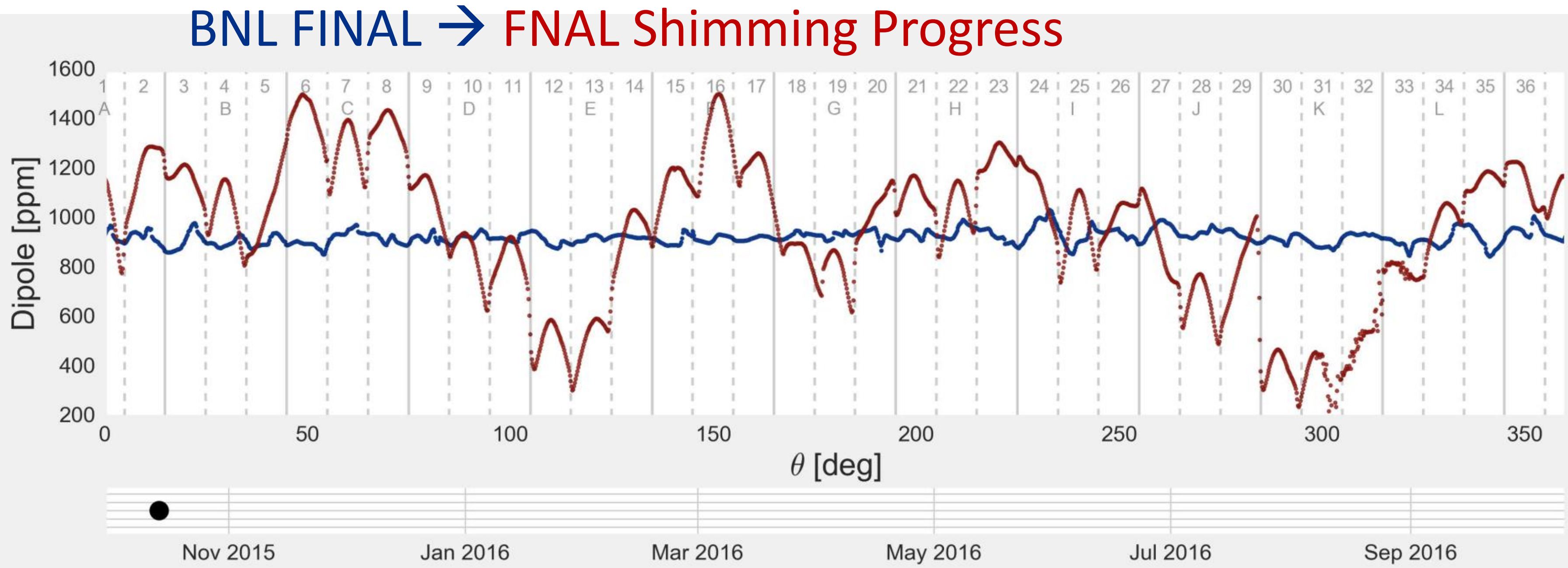
(Sample field distribution)

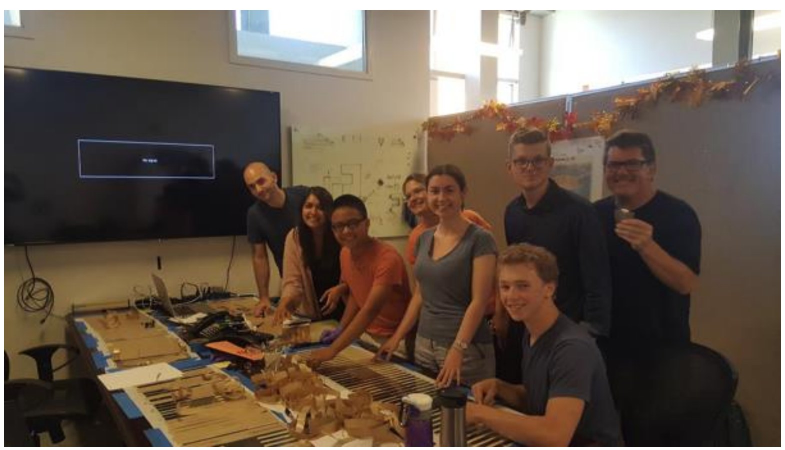
- Weight B by muon distribution
- Maximize the uniformity of B

- 1000s of knobs help control different non-uniformities

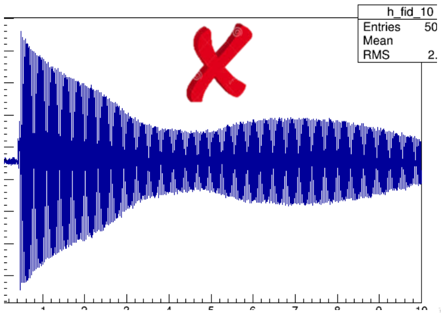


Recent Successes: Muon g-2 Shimming

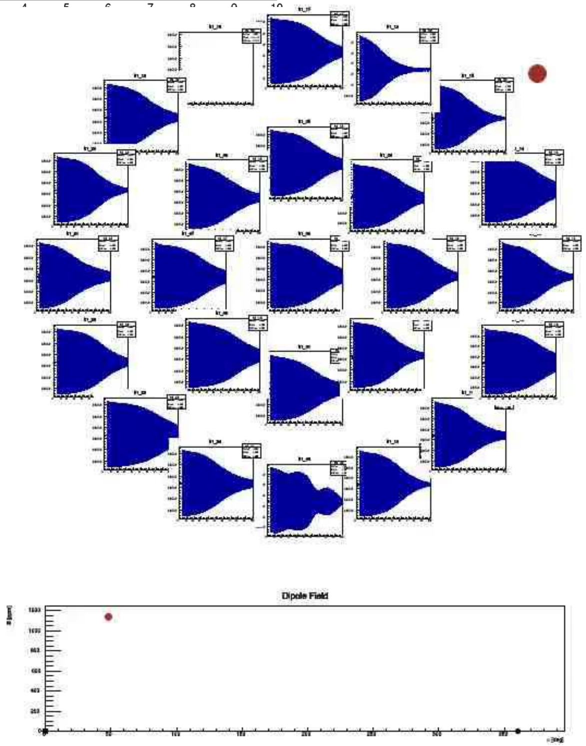


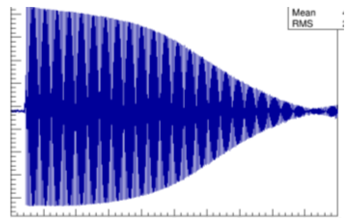


Representative Runs Improved from Nov 2015 → Sep 2016

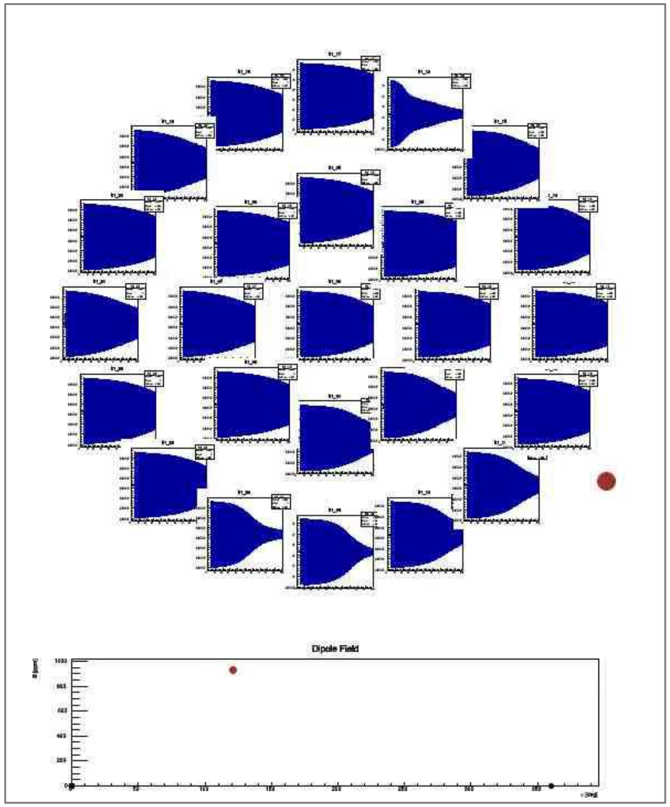


Large gradients





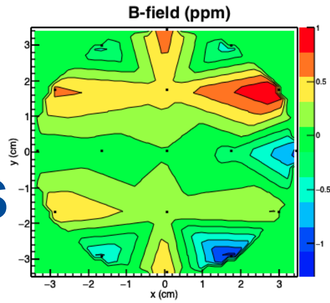
Small gradients



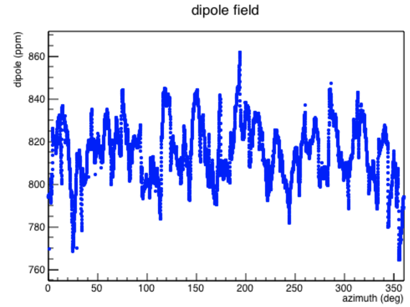
Fermilab

Production Trolley Runs

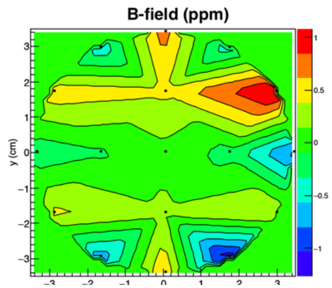
Dates



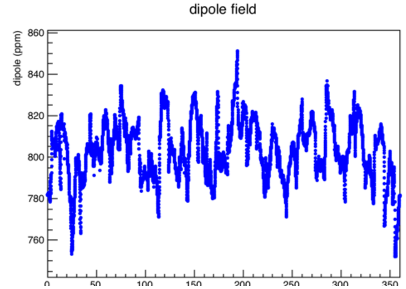
	Norm	Skew
Quad	-0.19	0.28
Sext	0.05	0.27
Octu	-0.07	0.25
Decu	0.23	0.07
Dipole	-0.0	



(3/17)

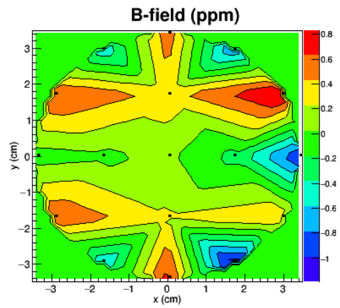


	Norm	Skew
Quad	-0.07	0.30
Sext	-0.00	0.30
Octu	-0.07	0.26
Decu	0.23	0.05
Dipole	-0.0	

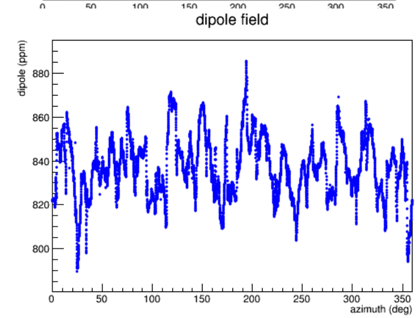


(3/19)

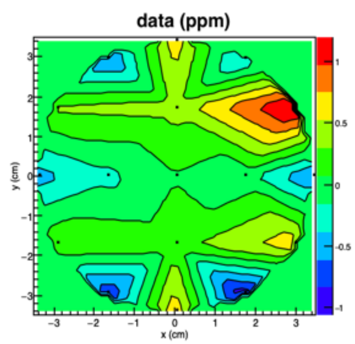
Small changes



	Norm	Skew
Quad	-0.29	0.10
Sext	0.06	0.19
Octu	-0.06	0.25
Decu	0.25	0.05
Dipole	-0.0	

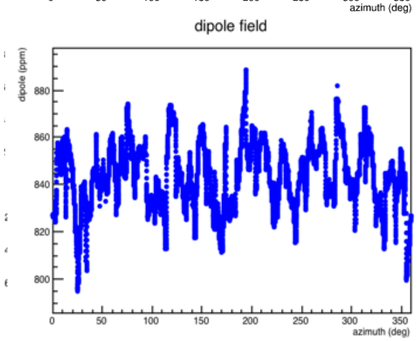


(3/21)

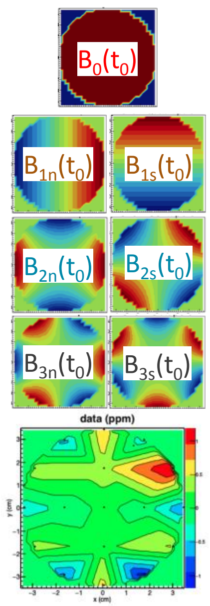


	Norm	Skew
Quad	0.21	0.20
Sext	0.02	0.23
Octu	-0.07	0.26
Decu	0.25	0.06
Dipole	-0.0	

Run 3483



(3/25)

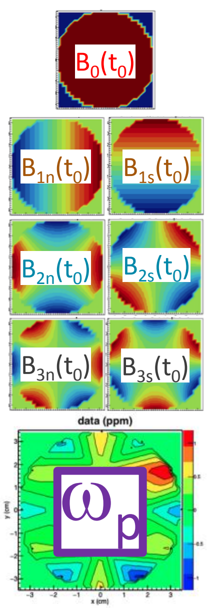


dipole: B_0
normal quad: B_{1n}
skew quad: B_{1s}
normal sext.: B_{2n}
skew sext.: B_{2s}
normal oct.: B_{3n}
skew oct.: B_{3s}

Field Maps

Systematic uncertainty entry includes:

- Precision of extracted multipoles
- Correlations
- Influence of higher multipoles
- Longitudinal and radial fields
- Drift correction



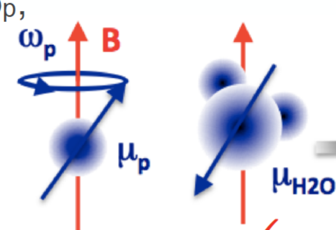
Trolley Calibration

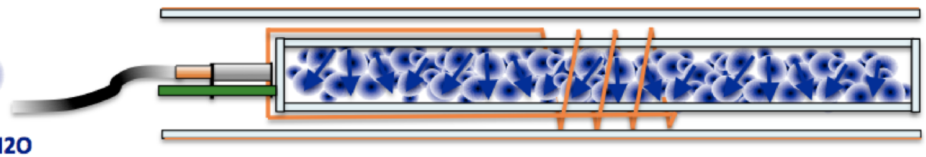
Systematic uncertainty entry includes:

- Gradients * position uncertainty
- Drift correction
- Temperature drift
- …

Calibrating the Magnetic Field

- In the experiment, need to extract ω_p; however, don't have free protons
  - Need a calibration
- Field at the proton differs from the applied field





$$\omega_p^{\mathrm{meas}} = \left[1 - \sigma\left(\mathrm{H_2O}, T\right) - \left(\varepsilon - \frac{4\pi}{3}\right)\chi\left(\mathrm{H_2O}, T\right) - \delta_s\right]\omega_p^{\mathrm{free}}$$

Protons in H_2O molecules, diamagnetism of electrons screens protons => local B changes

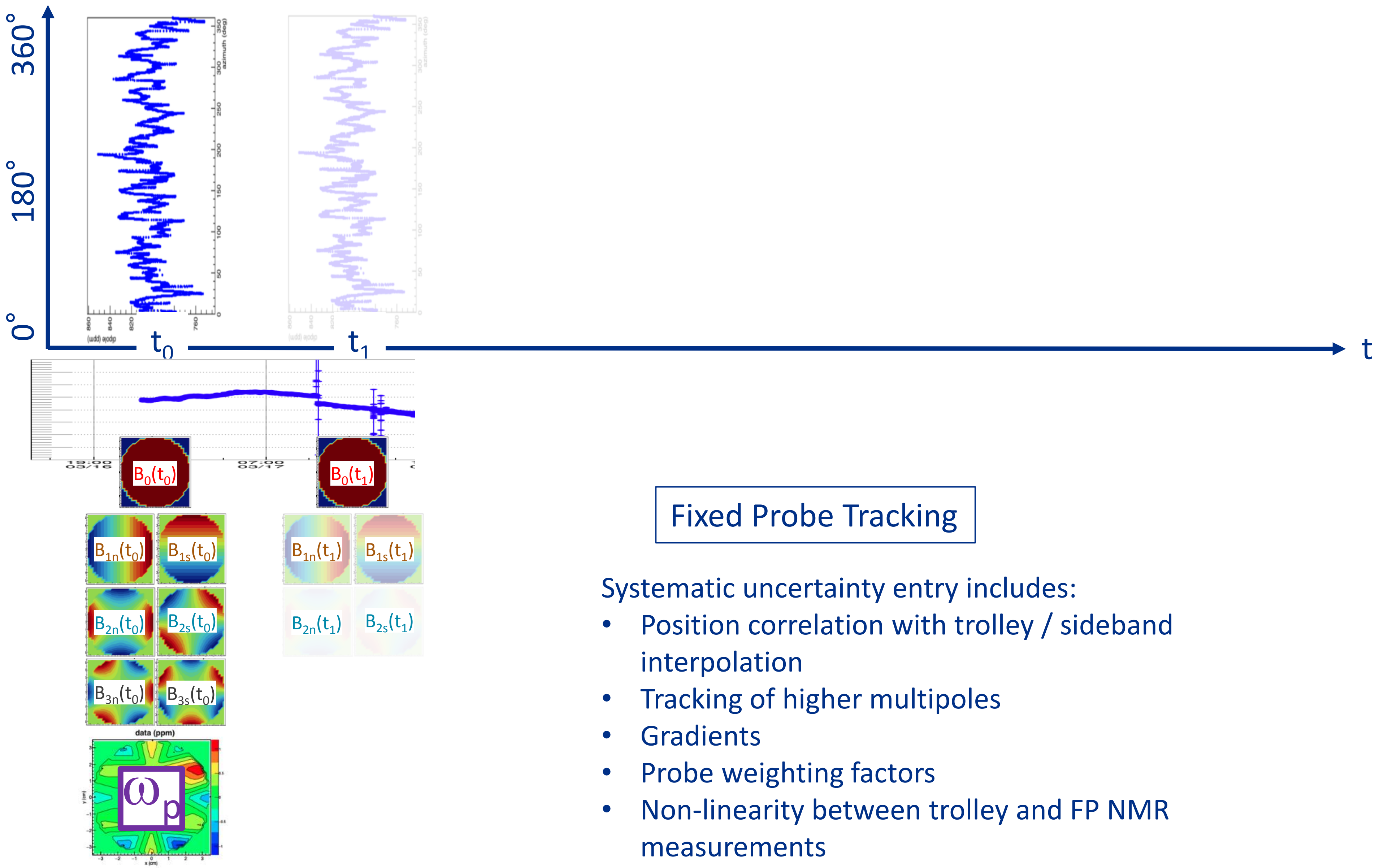
- σ = 25 680(2.5) x 10^{-9} at 25 deg C [Y. Neronov and N. Seregin, Metrologia **51**, 54 (2014)]

Magnetic susceptibility of water gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (sphere), 2π (cylinder) when probe is perpendicular to B
- $\chi_{H_2O} \cong$ -720(2) x 10^{-9} [J. Schenck, Med. Phys. **23**, 815 (1996)]

Magnetization of probe materials perturbs the field at site of protons

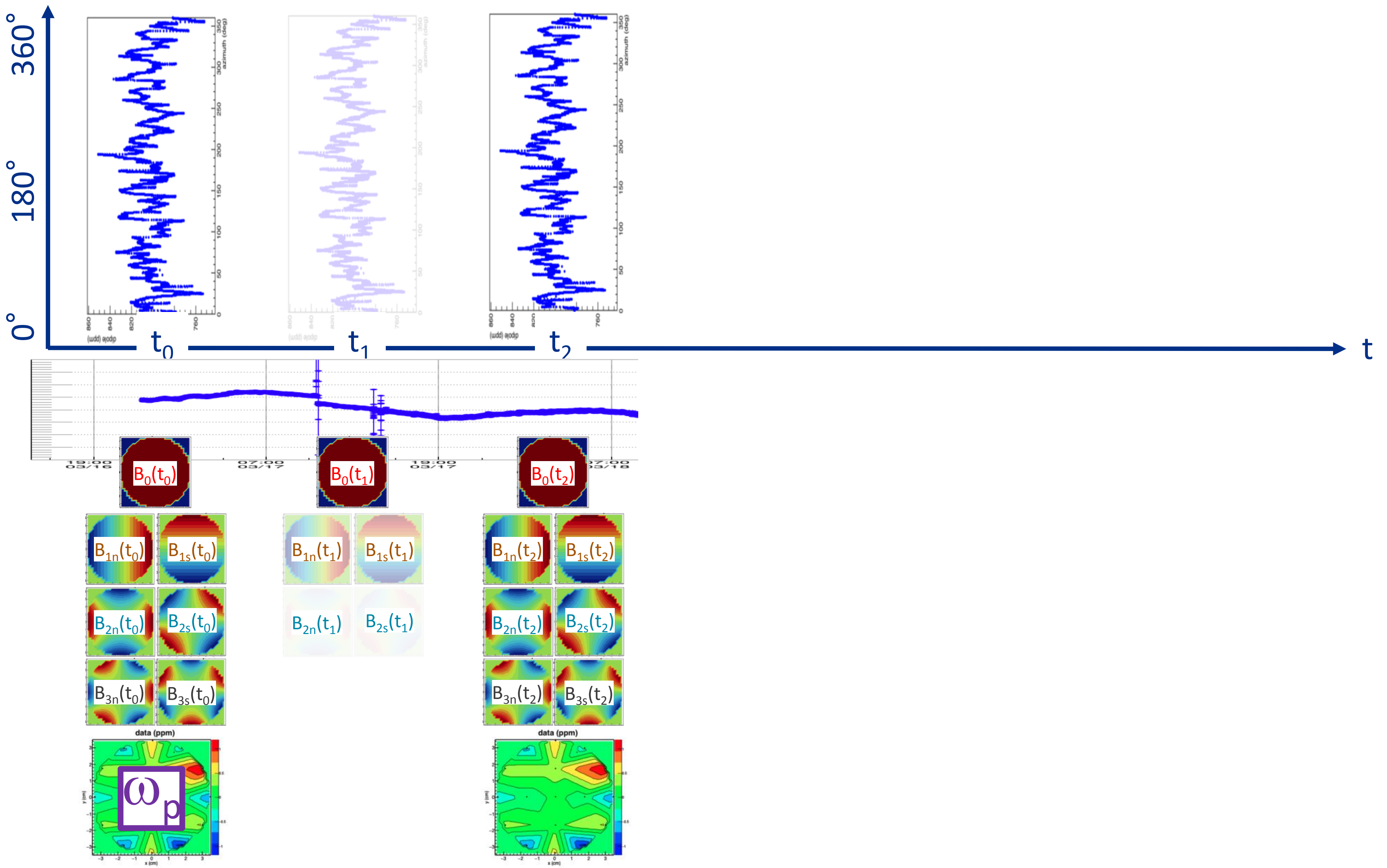
Goal: Determine total correction to ≤ 35 ppb accuracy

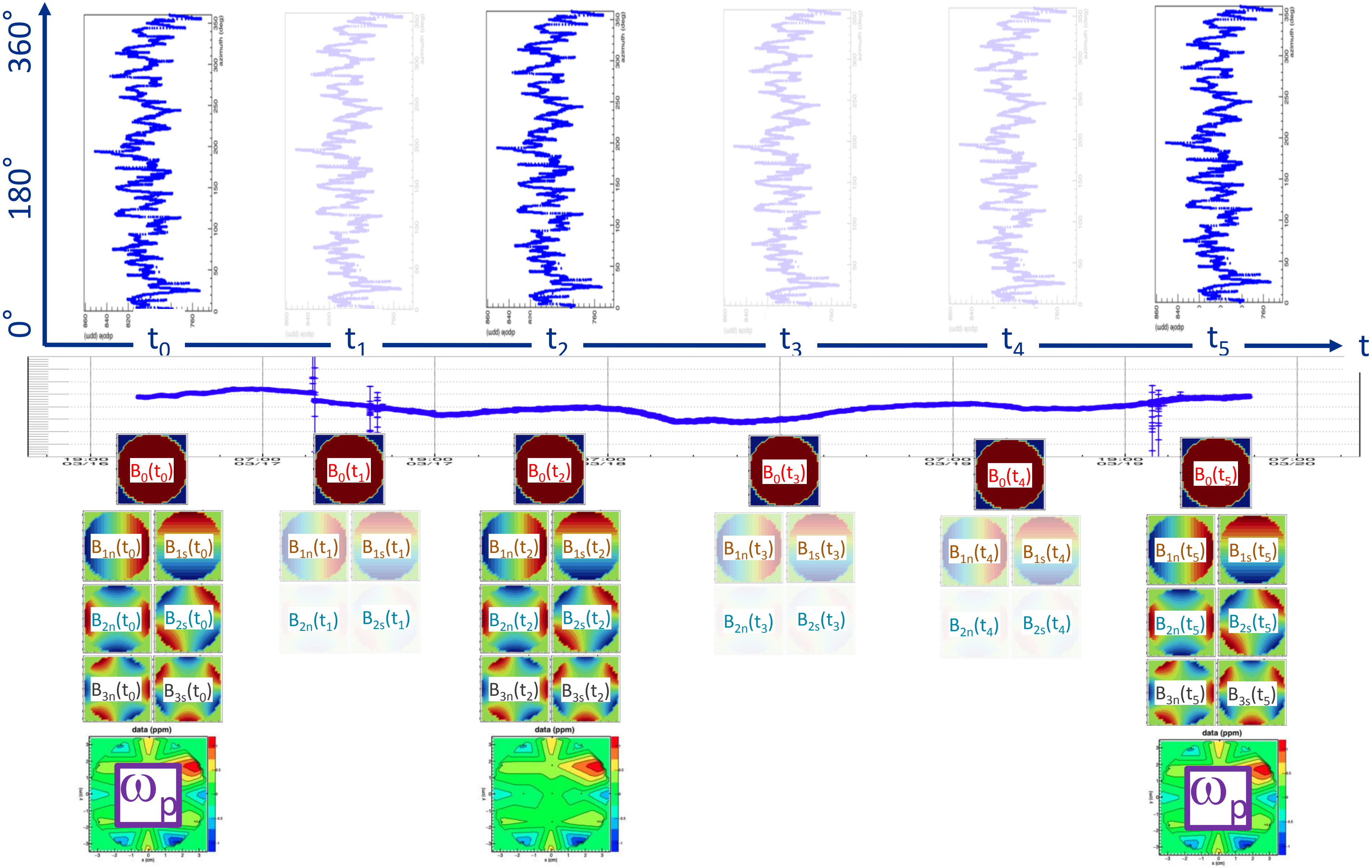


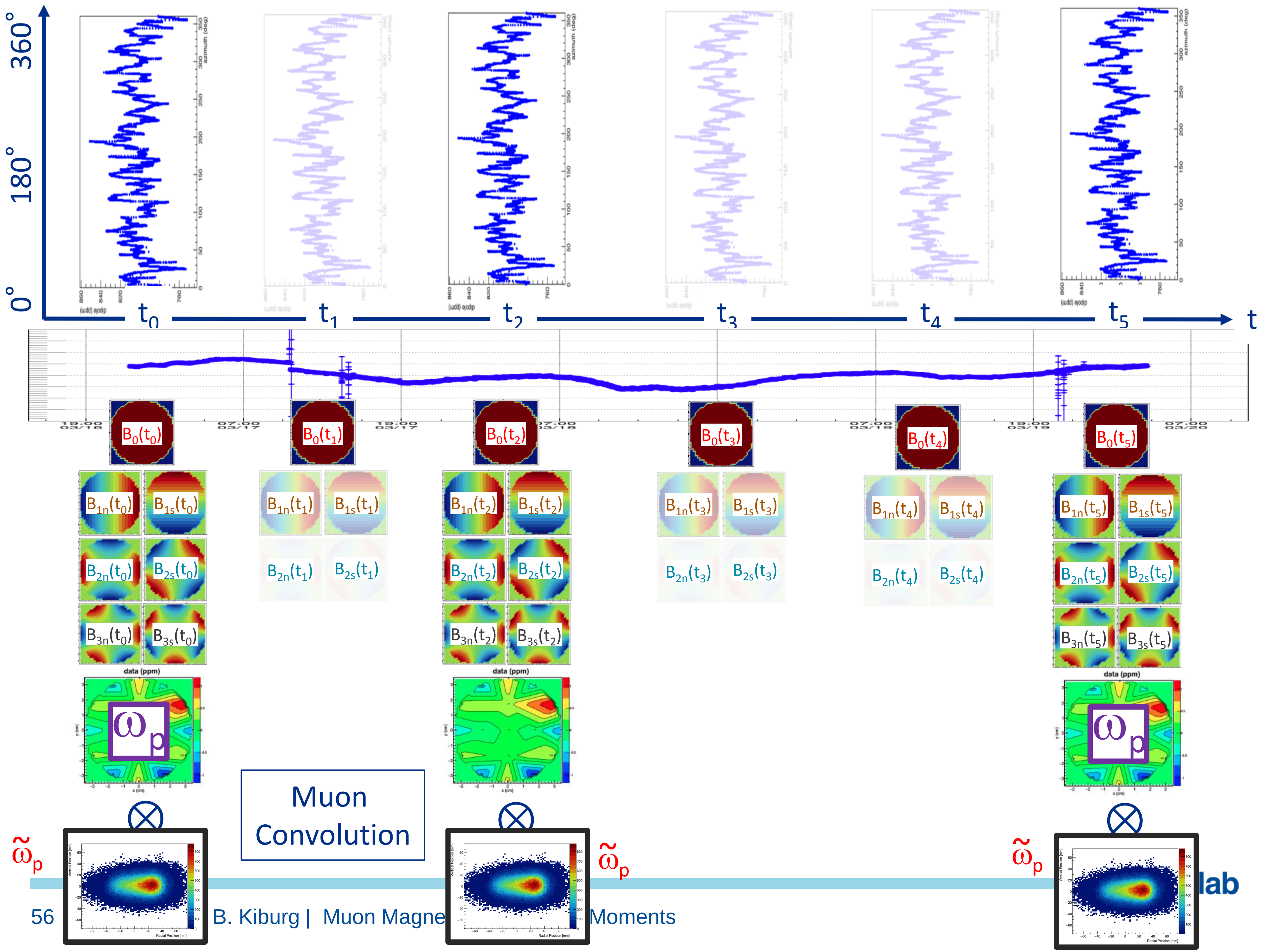
Fixed Probe Tracking

Systematic uncertainty entry includes:

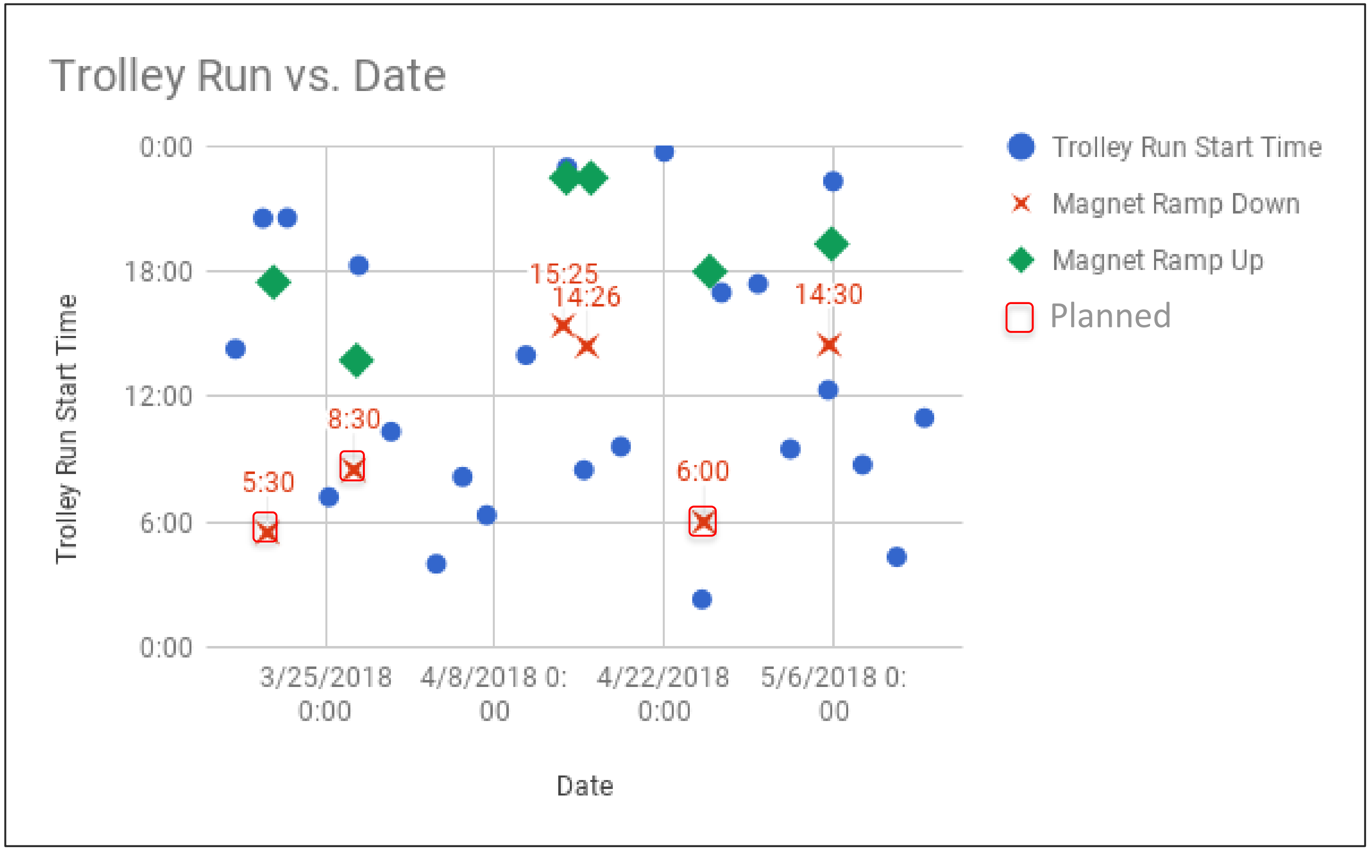
- Position correlation with trolley / sideband interpolation
- Tracking of higher multipoles
- Gradients
- Probe weighting factors
- Non-linearity between trolley and FP NMR measurements
- Temperature drift
- ....


360°
180°
0°
t0
t1
t2
t
B0(t0)
B0(t1)
B0(t2)
B1n(t0)
B1s(t0)
B1n(t1)
B1s(t1)
B1n(t2)
B1s(t2)
B2n(t0)
B2s(t0)
B2n(t1)
B2s(t1)
B2n(t2)
B2s(t2)
B3n(t0)
B3s(t0)
B3n(t2)
B3s(t2)
data (ppm)
ωp
data (ppm)


360°
180°
0°
t_0 t_1 t_2 t_3 t_4 t_5 t
B_0(t_0) B_0(t_1) B_0(t_2) B_0(t_3) B_0(t_4) B_0(t_5)
B_1n(t_0) B_1s(t_0) B_2n(t_0) B_2s(t_0) B_3n(t_0) B_3s(t_0)
B_1n(t_1) B_1s(t_1) B_2n(t_1) B_2s(t_1)
B_1n(t_2) B_1s(t_2) B_2n(t_2) B_2s(t_2) B_3n(t_2) B_3s(t_2)
B_1n(t_3) B_1s(t_3) B_2n(t_3) B_2s(t_3)
B_1n(t_4) B_1s(t_4) B_2n(t_4) B_2s(t_4)
B_1n(t_5) B_1s(t_5) B_2n(t_5) B_2s(t_5) B_3n(t_5) B_3s(t_5)
data (ppm)
ω_p


360°
180°
0°
t0
t1
t2
t3
t4
t5
t
B0(t0)
B0(t1)
B0(t2)
B0(t3)
B0(t4)
B0(t5)
B1n(t0) B1s(t0)
B2n(t0) B2s(t0)
B3n(t0) B3s(t0)
B1n(t1) B1s(t1)
B2n(t1) B2s(t1)
B1n(t2) B1s(t2)
B2n(t2) B2s(t2)
B3n(t2) B3s(t2)
B1n(t3) B1s(t3)
B2n(t3) B2s(t3)
B1n(t4) B1s(t4)
B2n(t4) B2s(t4)
B1n(t5) B1s(t5)
B2n(t5) B2s(t5)
B3n(t5) B3s(t5)
data (ppm)
ωp
⊗
Muon Convolution
ω̃p

Trolley Runs Vs Time

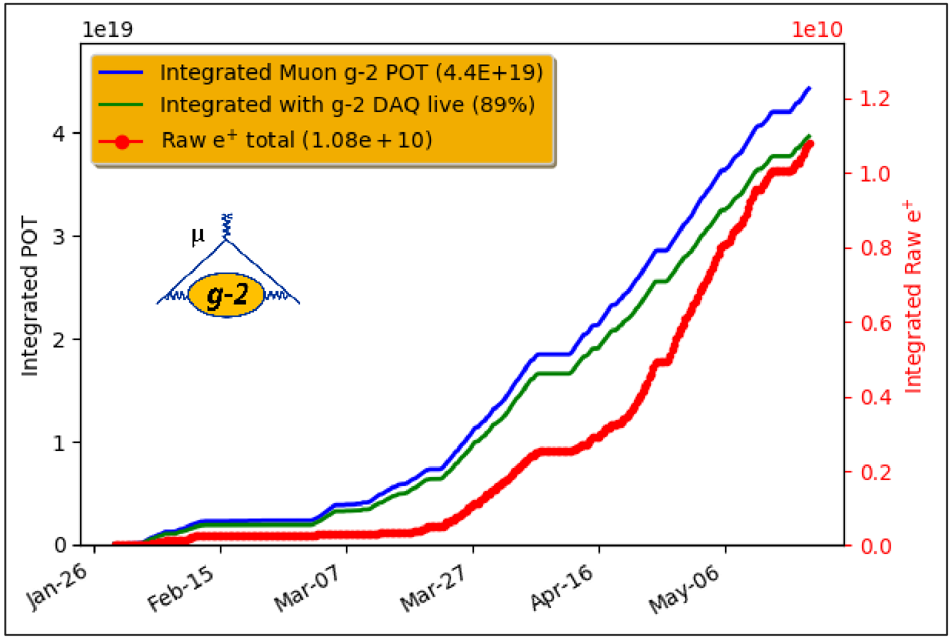


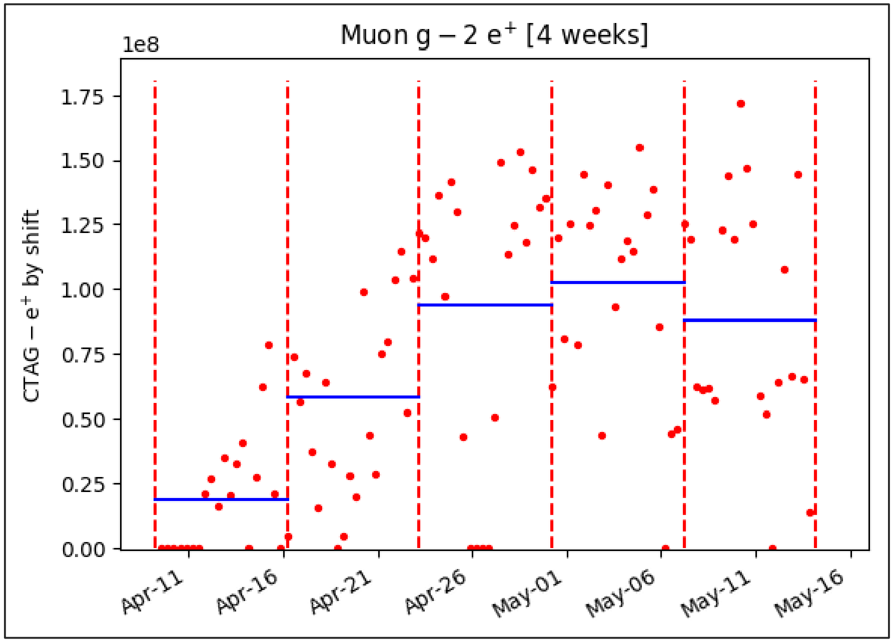
Every ~3 days or so to capture magnet/conditions drifts

Pseudorandom to capture external conditions (temperature, equipment, etc)

Bookend every magnet ramp period

Performance

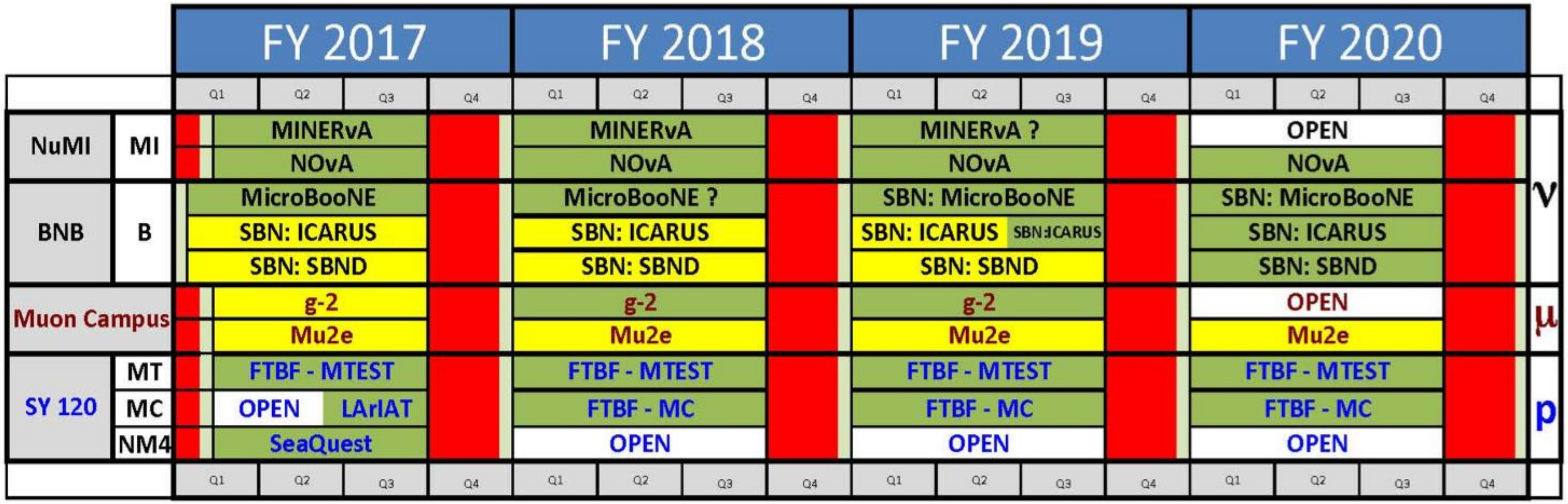




- Started 16-pulse running w/ all systems installed Mar 22 2017
- Accumulated 1.08e10 raw decay positrons!
  - BNL 0.939e10 total w/ quality cuts [raw e^+ now 1.15 x BNL]
- Still plenty of growing pains and operational issues, but our good shifts are still improving

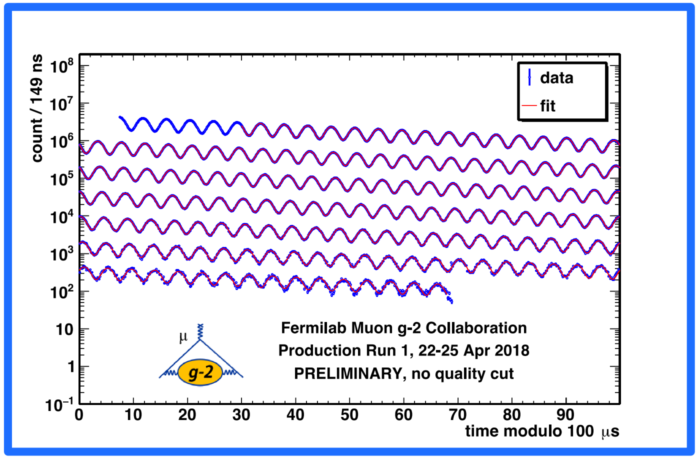
Muon g-2 Running Outlook

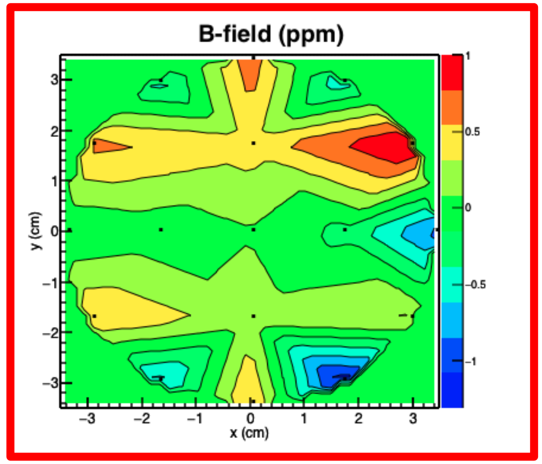
- Will need FY2020 running
- Running about 50% of design rate, making great progress

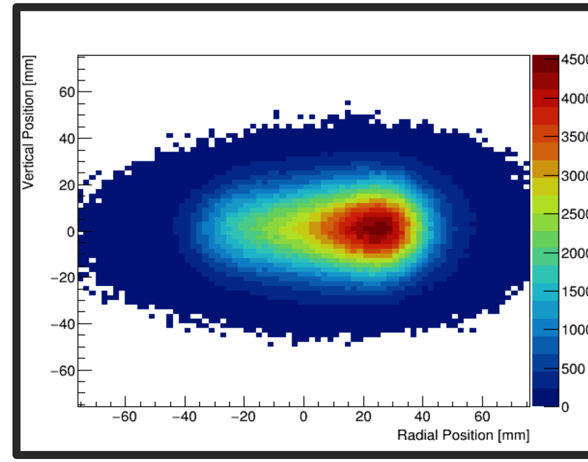


Summary

$$a_\mu(\mathrm{Expt}) \approx \frac{\omega_a}{\omega_p \otimes \rho(r)}$$







- Two Experiments to improve MDM x4, EDM x100 have been designed
  - FNAL E989 has started, and collected raw stats > 1.15 x BNL
  - 6 more weeks of data collection → Anticipate ~2.5 x BNL raw
  - Analyses are well underway
  - Projected first results this winter
- We are very excited to hear updates on the theory progress

Thank You!