FERMILAB-SLIDES-18-095-PPD

The Muon g-2 Experiment

David Flay, University of Massachusetts, Amherst
on Behalf of the Muon g-2 Collaboration

Fermilab Users Meeting 2018

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Outline

Introduction

- The Magnetic Moment and the Anomaly

Experiment Overview

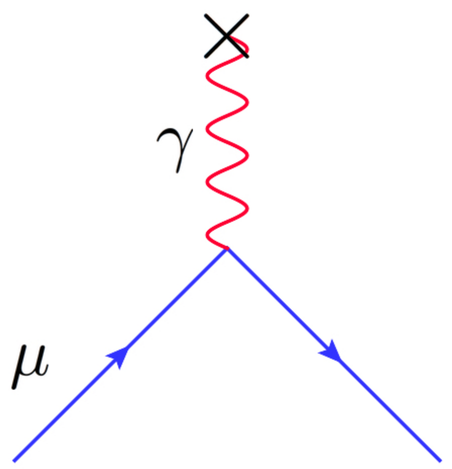
- Measuring the Anomaly
- Hardware Performance and Analysis Highlights
- Run Progress

Summary

The Magnetic Moment and The Anomaly

The Magnetic Moment

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



- Magnetic moment connected to spin via dimensionless g-factor
- Dirac: g = 2 for s = 1/2 particles (1928)
- g for electron found to differ from 2 in hyperfine structure experiments on hydrogen (Nafe, Nelson, Rabi 1947)
  - Anomalous contribution a_e
  - Interpretation: Schwinger's QED calculation of $a_e = \alpha/2\pi$ (1948)
  - Radiative corrections from virtual particles in loops

The Magnetic Moment and The Anomaly

The Magnetic Moment

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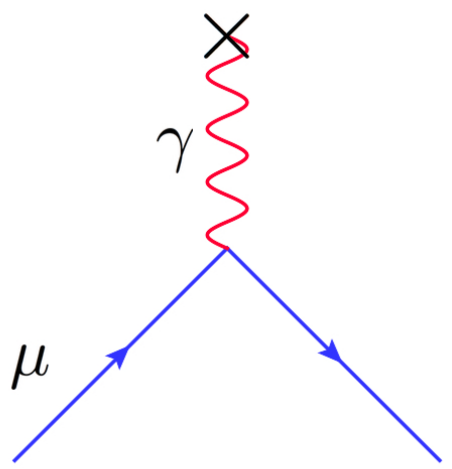

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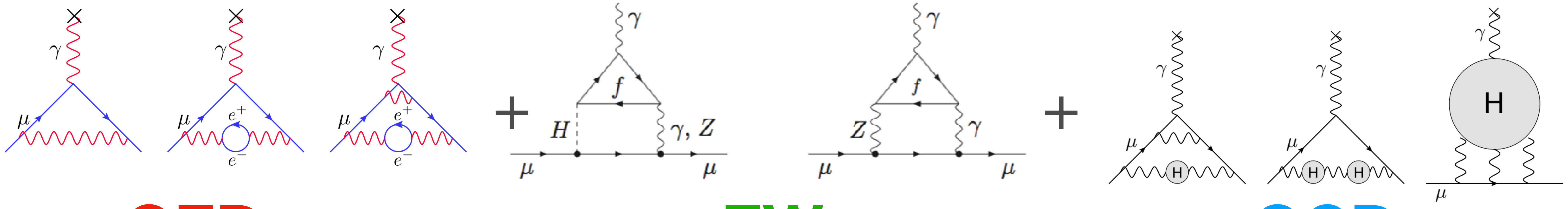
The Muon Anomaly a_μ

Schwinger $O(\alpha)$ Vacuum polarization $O(\alpha^2)$

$a_\mu =$



QED EW QCD

The Magnetic Moment and The Anomaly

The Magnetic Moment

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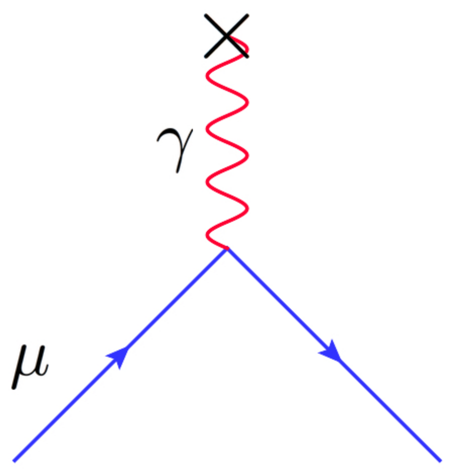

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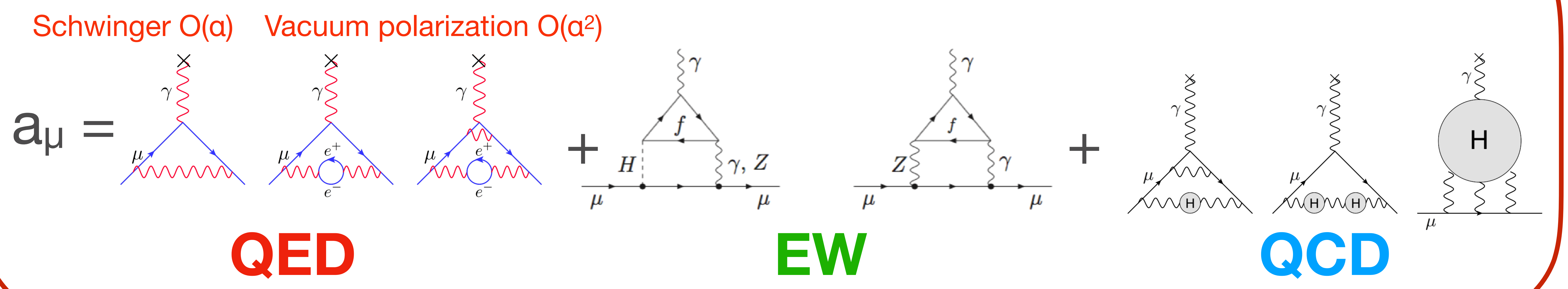
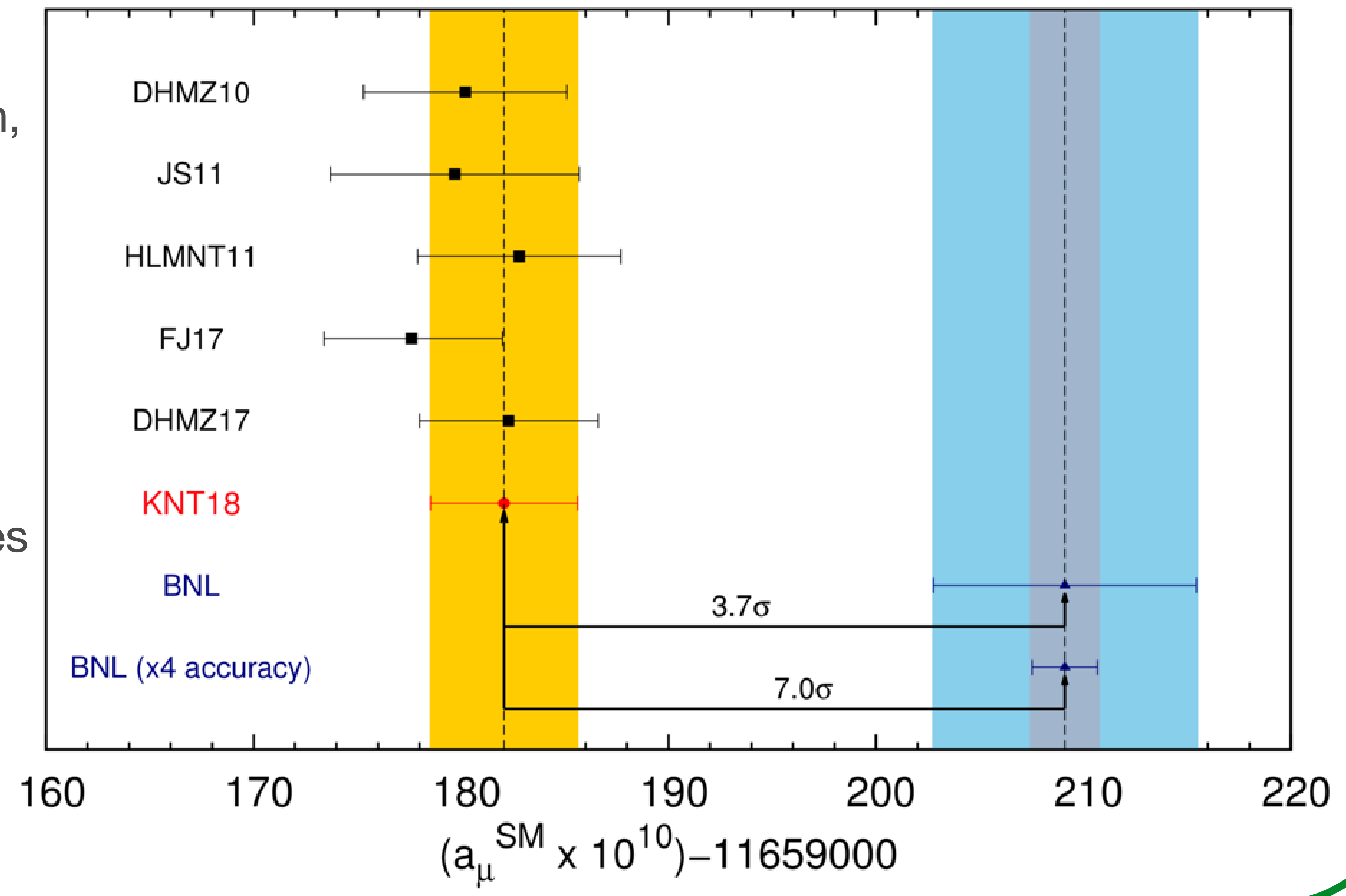
The Muon Anomaly a_μ



Current Status

- **Disagreement** between experiment and theory
  - Deviation is large compared to EW contribution, uncertainty on hadronic terms
  - Not at discovery threshold (5σ)
  - **Due to new physics?**
    - **SUSY, TeV-scale models, dark photon…**
- **Improvements** on both theory and experiment sides
  - **Experiment:** more statistics, reduce systematics
  - **Theory:** reduce uncertainties (HVP, HLbL). Lattice groups making big strides

arXiv:1802.02995 [hep-ph]



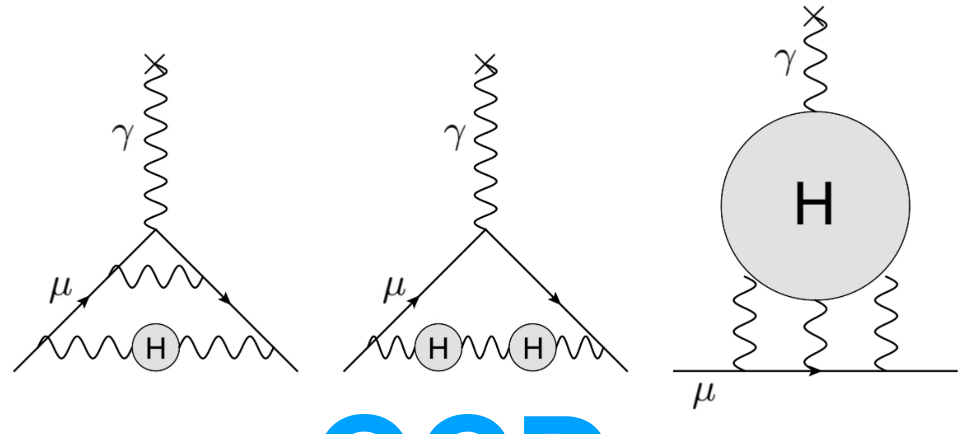
The Magnetic Moment and The Anomaly

The Magnetic Moment

$\vec{\mu}$ =

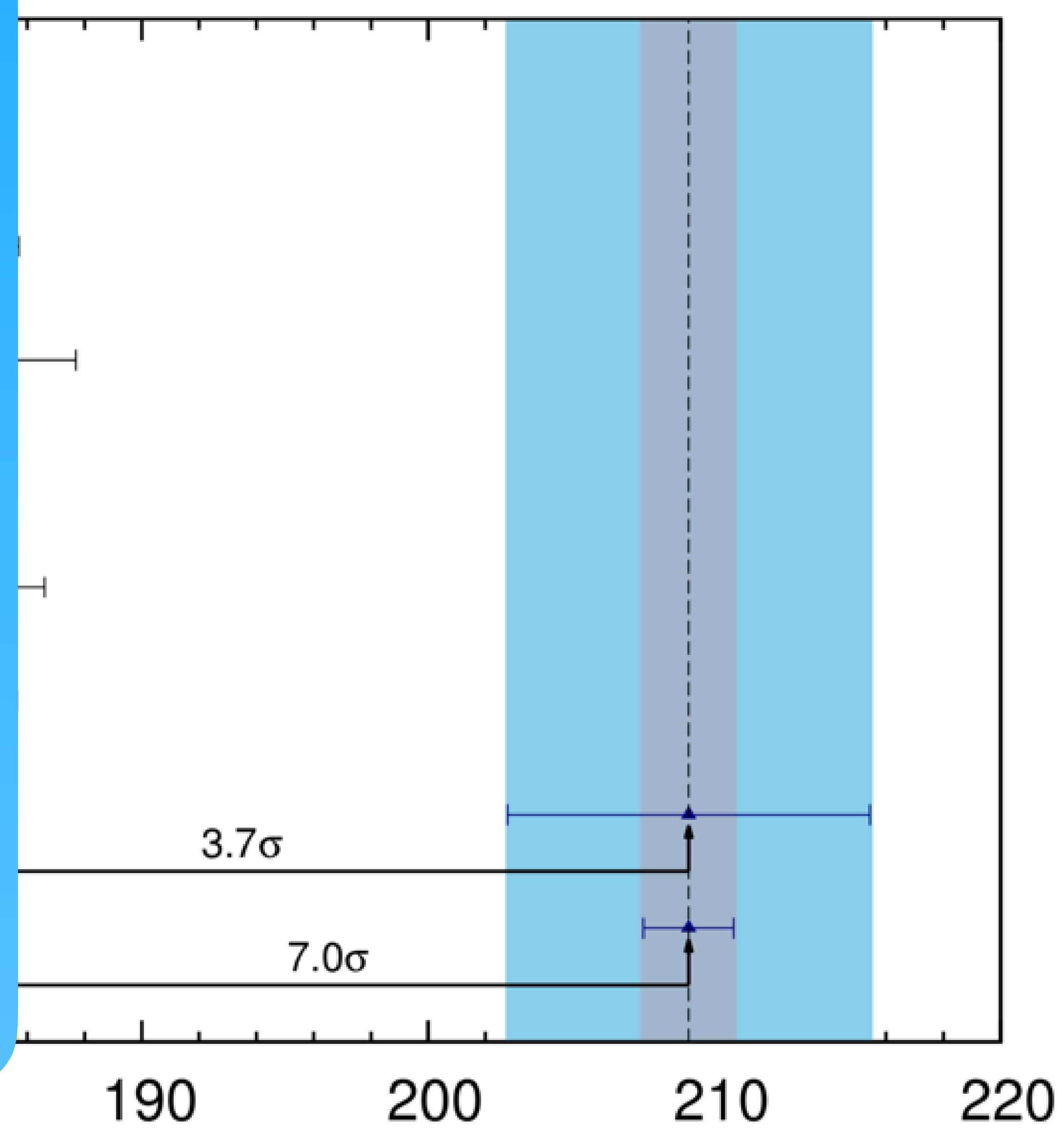
- Magn... spin
- Dirac (1928...
- g for... in hy... on hy... 1947
  - A...
  - I... c...
  - F... virtual particles in loops

The Muon Anomaly a_μ

+ 

QCD

arXiv:1802.02995 [hep-ph]



$(a_\mu^{SM} \times 10^{10}) - 11659000$

Theory: reduce uncertainties (HVP, HLbL): Lattice groups making big strides

Lattice groups making excellent progress (HVP LO, HLbL)

Hadronic vacuum polarization contribution to a_μ from full lattice QCD

Bipasha Chakraborty, C. T. H. Davies, P. G. de Oliveira, J. Koponen, G. P. Lepage, and R. S. Van de Water (HPQCD Collaboration)

Phys. Rev. D **96**, 034516 – Published 22 August 2017

Article | References | Citing Articles (7) | PDF | HTML | Export Citation

ABSTRACT

We determine the contri... hadronic vacuum polari... masses for the first time... at multiple values of the... include an analysis of fi... where the first error is fr... missing QED and isospi... implies a discrepancy b...

Calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment

T. Blum, P.A. Boyle, V. Gülpers, T. Izubuchi, L. Jin, C. Jung, A. Jüttner, C. Lehner, A. Portelli, J.T. Tsang

(Submitted on 22 Jan 2018)

We present a first-principles lattice QCD+QED calculation at physical pion mass of the leading-order hadronic vacuum polarization contribution to the muon anomalous magnetic moment. The total contribution of up, down, strange, and charm quarks including QED and strong isospin breaking effects is found to be $a_\mu^{\rm HVP\,LO} = 715.4(16.3)(9.2) \times 10^{-10}$, where the first error is statistical and the second is systematic. By supplementing lattice data for very short and long distances with experimental R-ratio data using the compilation of Ref. [1], we significantly improve the precision of our calculation and find $a_\mu^{\rm HVP\,LO} = 692.5(1.4)(0.5)(0.7)(2.1) \times 10^{-10}$ with lattice statistical, lattice systematic, R-ratio statistical, and R-ratio systematic errors given separately. This is the currently most precise determination of the leading-order hadronic vacuum polarization contribution to the muon anomalous magnetic moment. In addition, we present the first lattice calculation of the light-quark QED correction at physical pion mass.

Comments: 12 pages, 11 figures
Subjects: **High Energy Physics – Lattice (hep-lat)**; High Energy Physics – Phenomenology (hep-ph)
Cite as: arXiv:1801.07224 **[hep-lat]**
(or arXiv:1801.07224v1 **[hep-lat]** for this version)

The Magnetic Moment and The Anomaly

The Magnetic Moment

The Muon Anomaly a_μ

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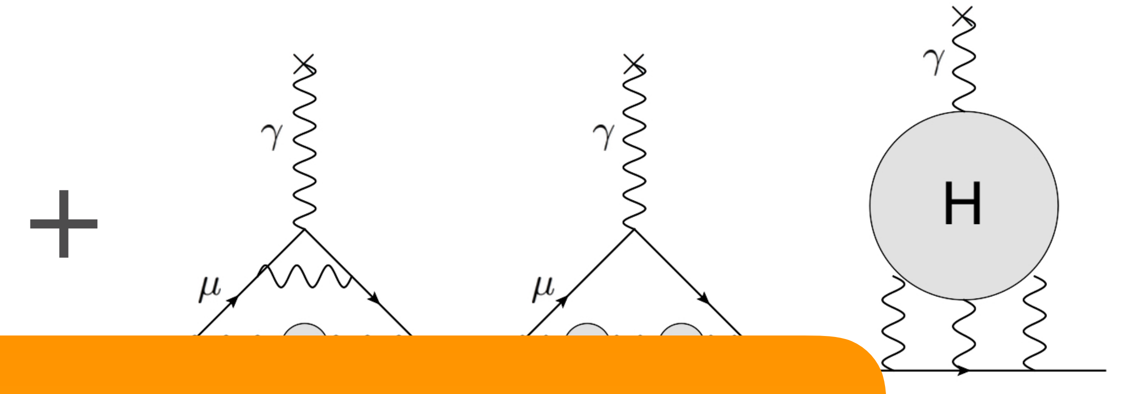
  - I... c...
  - F... virtual particles in loops

Theo... Lattic...



...ph]

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Lattice groups making excellent progress (HVP LO, HLbL)

Hadronic vacuum polarization contribution to a_μ from full lattice QCD

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(or arXiv:1801.07224v1 [h...

2nd g-2 Theory Initiative Meeting happening this week
Exciting to see the progress and results to come!

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Theory Group
Institute for Nuclear Physics

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Second Plenary Workshop of the Muon g-2 Theory Initiative

18 June 2018 - 22 June 2018

In the coming years, experiments at Fermilab and at J-PARC plan to reduce the uncertainties on the already very precisely measured anomalous magnetic moment of the muon by a factor of four. The goal is to resolve the current tantalizing tension between theory and experiment of three to four standard deviations. On the theory side the hadronic corrections to the anomalous magnetic moment are the dominant sources of uncertainty. They must be determined with better precision in order to unambiguously discover whether or not new physics effects contribute to this quantity.

There are a number of complementary theoretical efforts underway to better understand and quantify the hadronic corrections, including dispersive methods, lattice QCD, effective field theories, and QCD models. The Muon (g-2) Theory Initiative was formed in order to facilitate interactions between the different groups through organizing a series of workshops. The goal of this workshop is to bring together theorists from the different communities to discuss, assess, and compare the status of the various efforts, and to map out strategies for obtaining the best theoretical predictions for these hadronic corrections in advance of the experimental results.

First Circular
Second Circular
Indico website

Dates	June 18, 2018 - June 22, 2018
Timezone	GMT+2
Location	**Helmholtz-Institut Mainz** Staudinger Weg 18, 55128 Mainz, Ground Floor

The Muon g-2 Collaboration: 35 institutions, 180 members

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

- **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

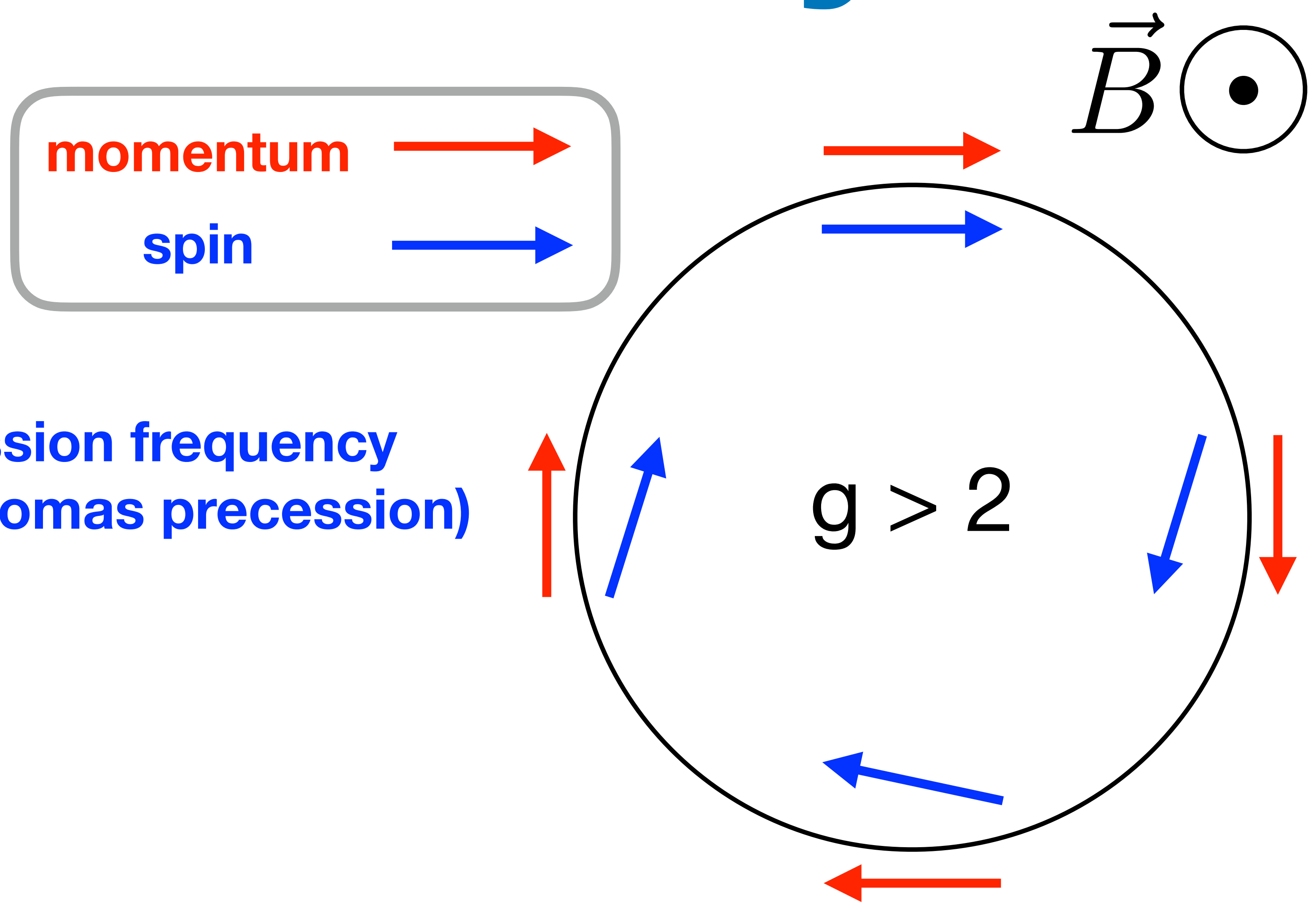
Measuring the Muon Anomaly

- Inject polarized muon beam into magnetic storage ring
- Measure **difference** between spin precession and cyclotron frequencies
- If g = 2, $\omega_a = 0$
- g ≠ 2, $\omega_a \cong (e/m_\mu) a_\mu B$
- Using $\hbar\omega_p = 2\mu_p|\vec{B}|$:

$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$ cyclotron frequency

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}\,(1 + \gamma a_\mu)$$ spin precession frequency (Larmor, Thomas precession)

$$\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_C$$

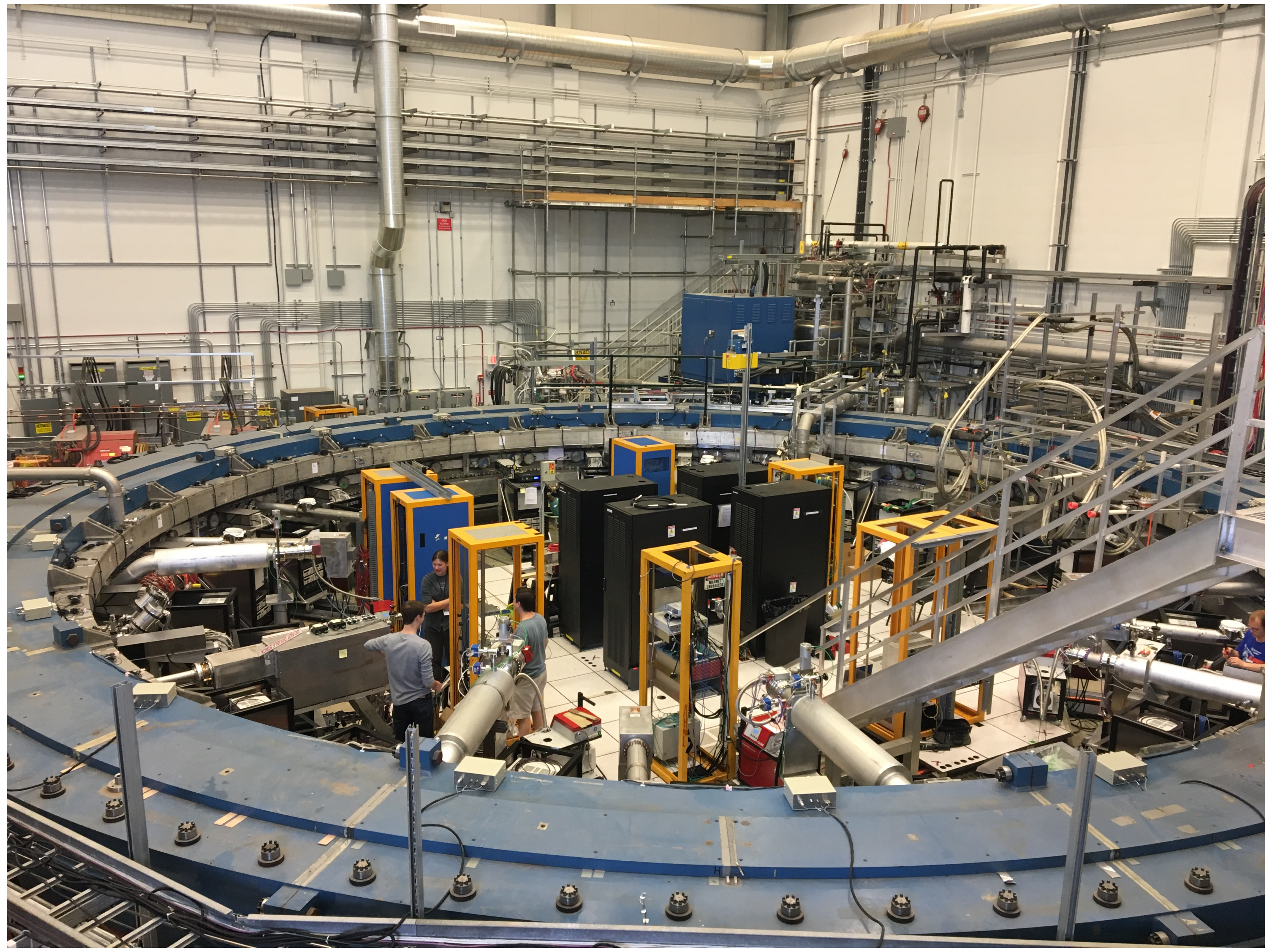


$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

3 ppb | 22 ppb | 0.3 ppt

- We measure ω_a and ω_p separately
  - Aiming for 70 ppb precision on each
- **Target: δa_μ = 140 ppb; factor of 4 improvement over BNL**

P. J. Mohr et al, Rev. Mod. Phys. **88**, 035009 (2016)

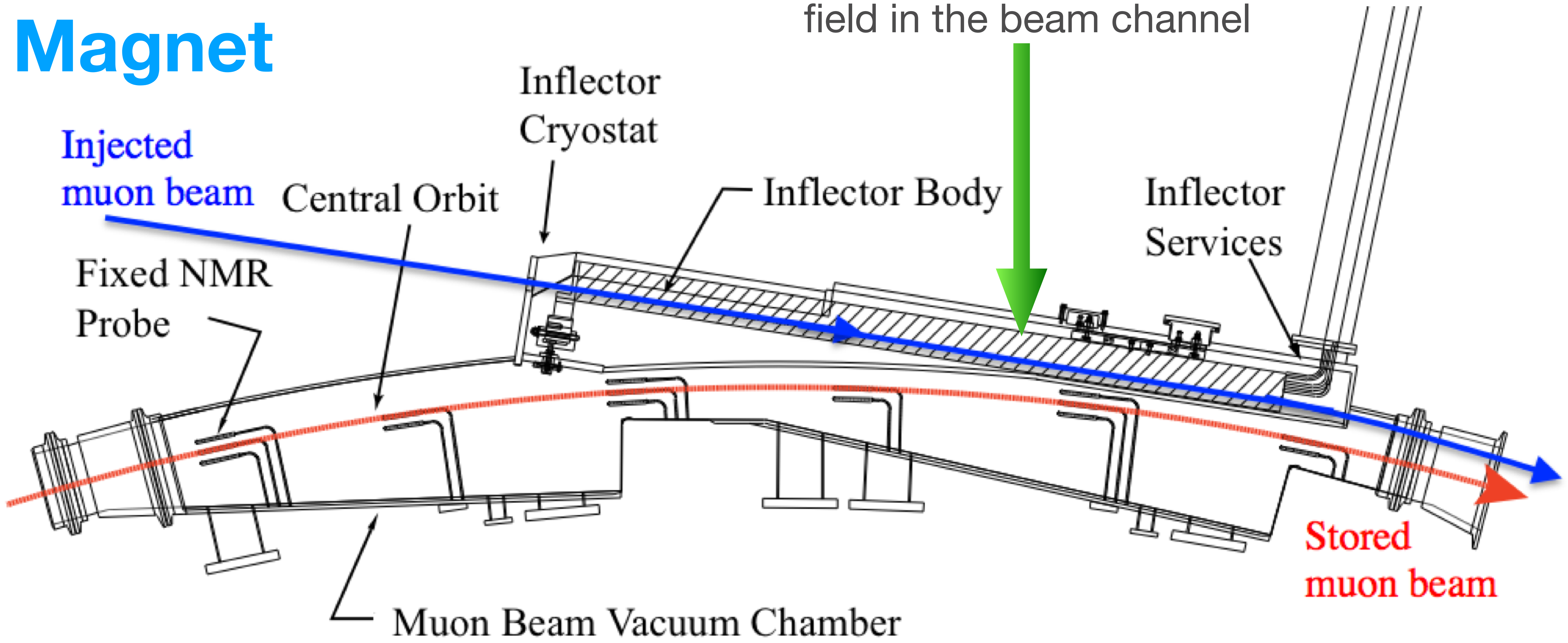


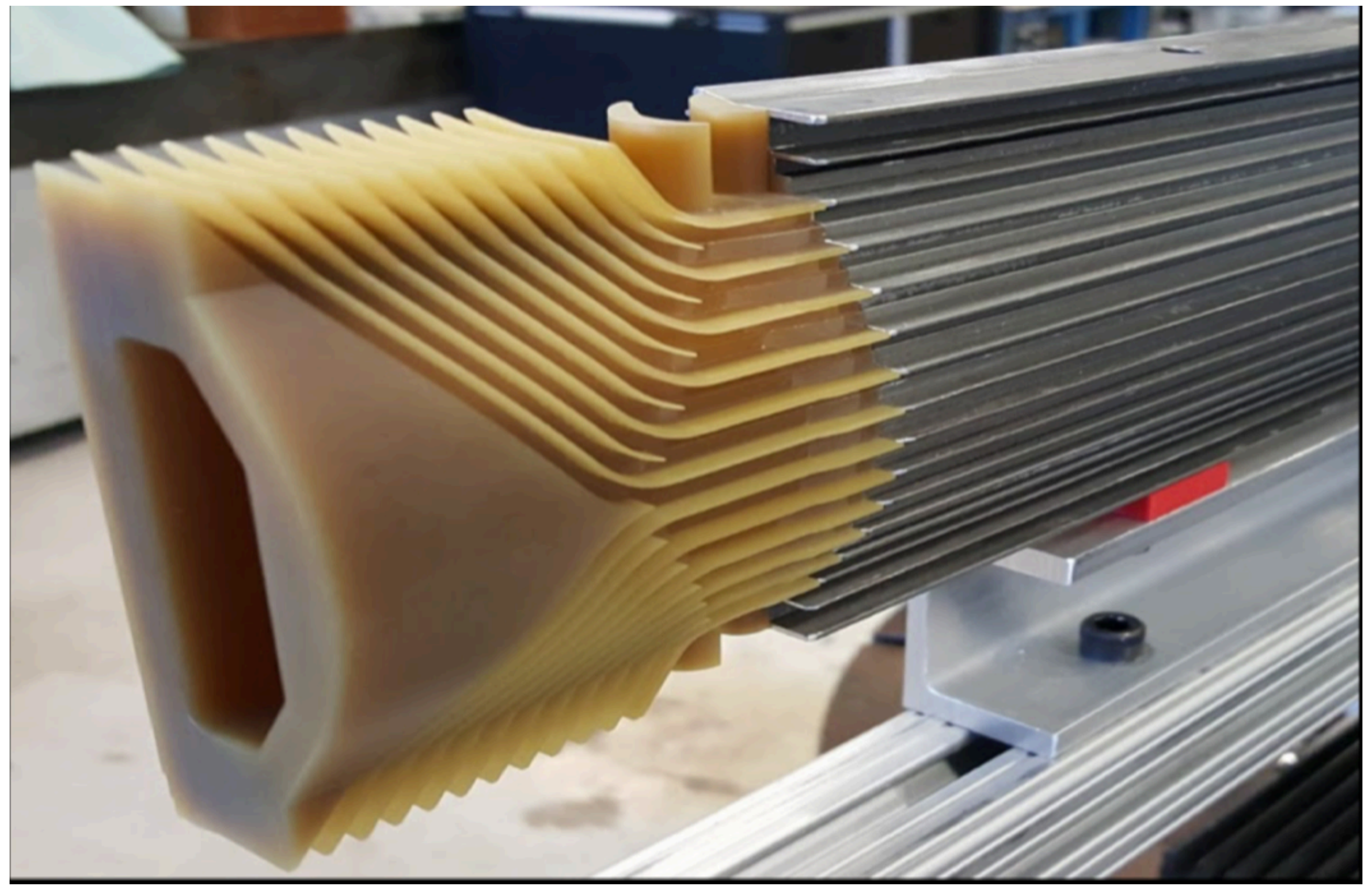
Muon Injection

Getting muons into ring: Inflector Magnet

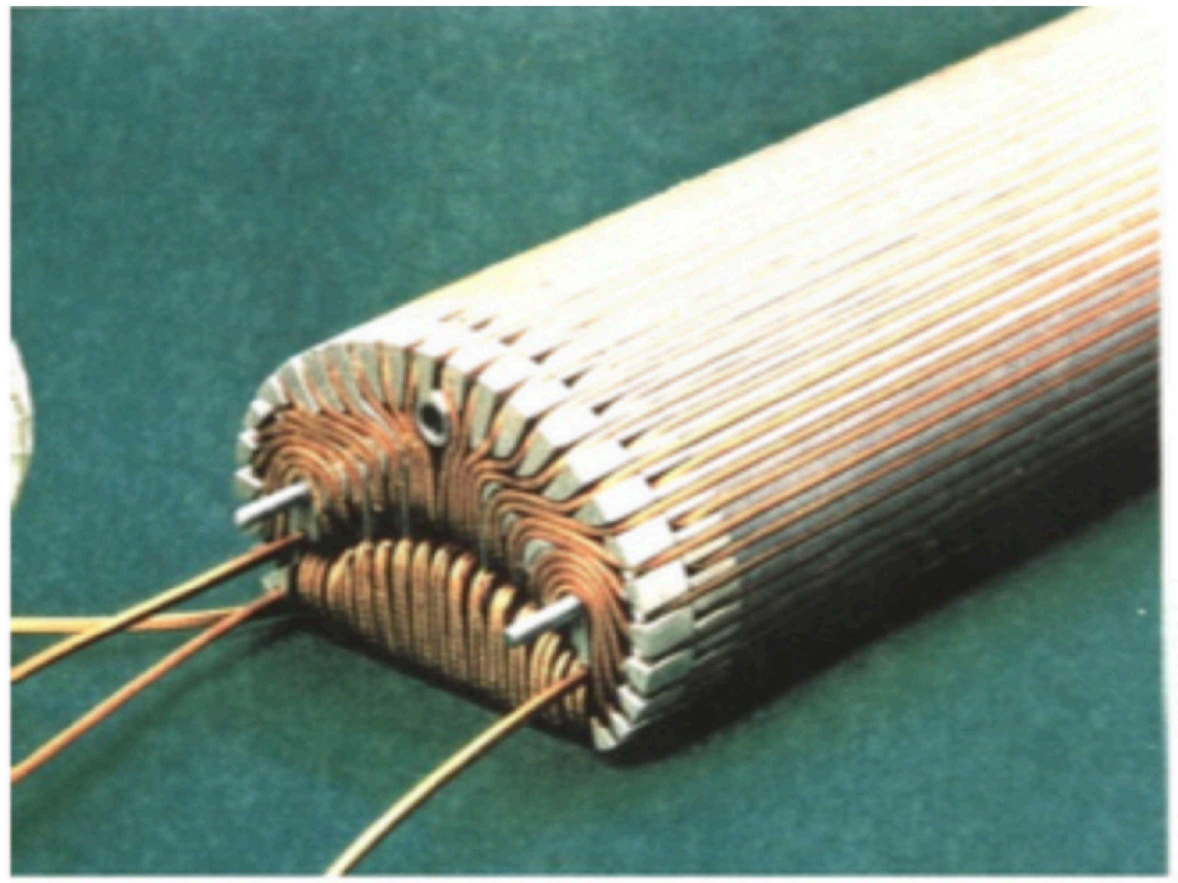
- Outside ring: B = 0 T, inside: B = 1.45 T
- Need to cancel field in order to get muons in (strong deflection otherwise)
- No perturbation to field outside shield
- New inflector design with higher transmission under development

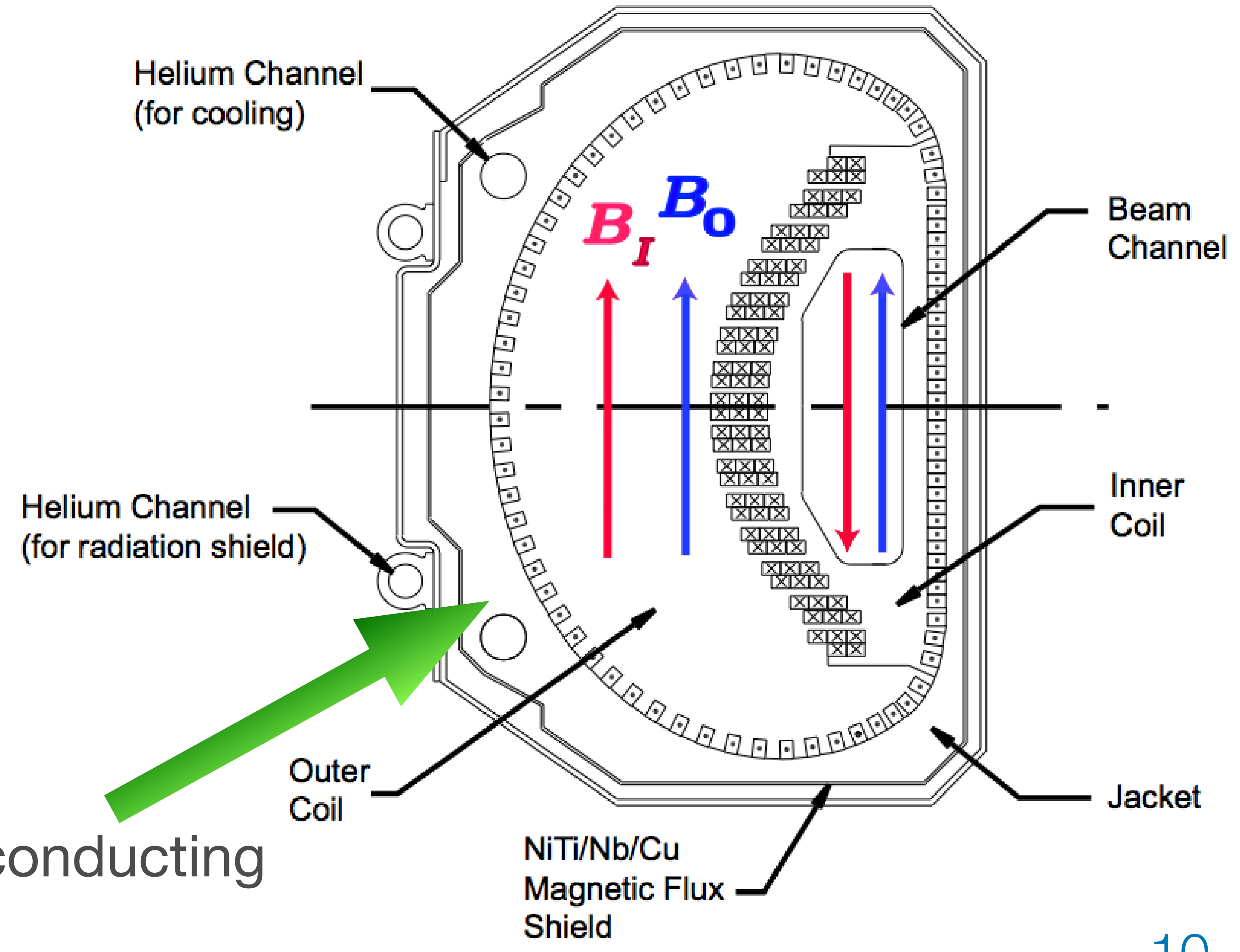
Energizing coils cancels the field in the beam channel





New inflector coil winding mount

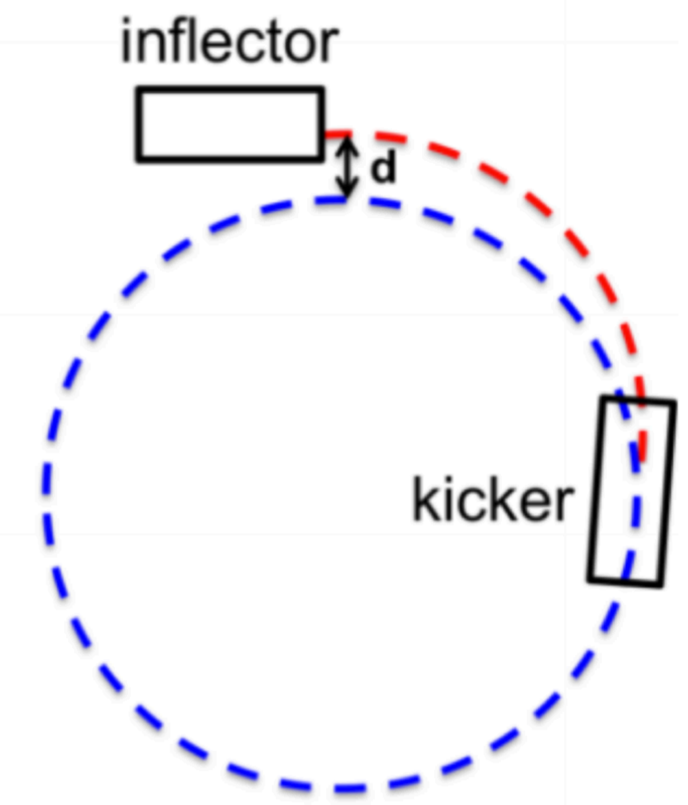


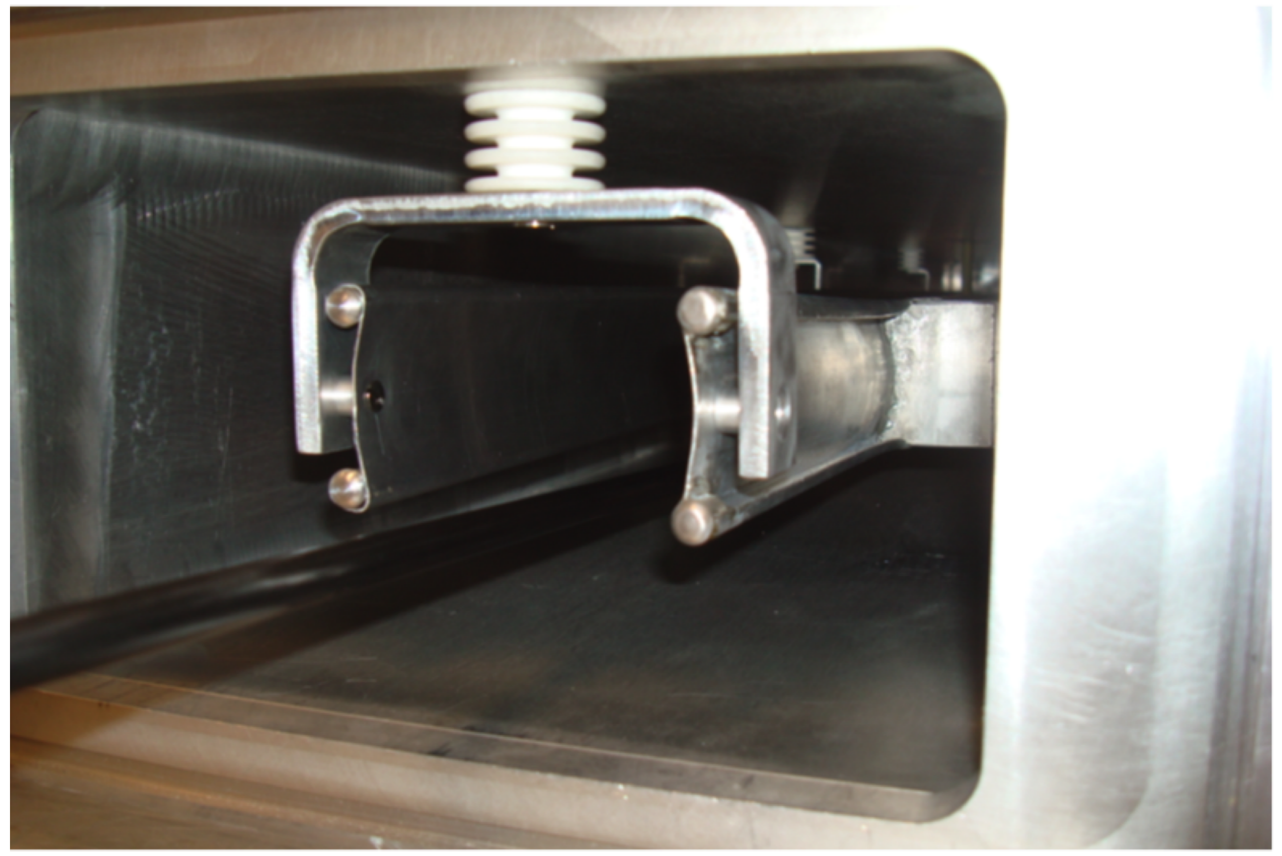


Eddy currents in passive superconducting shield prevents flux leakage

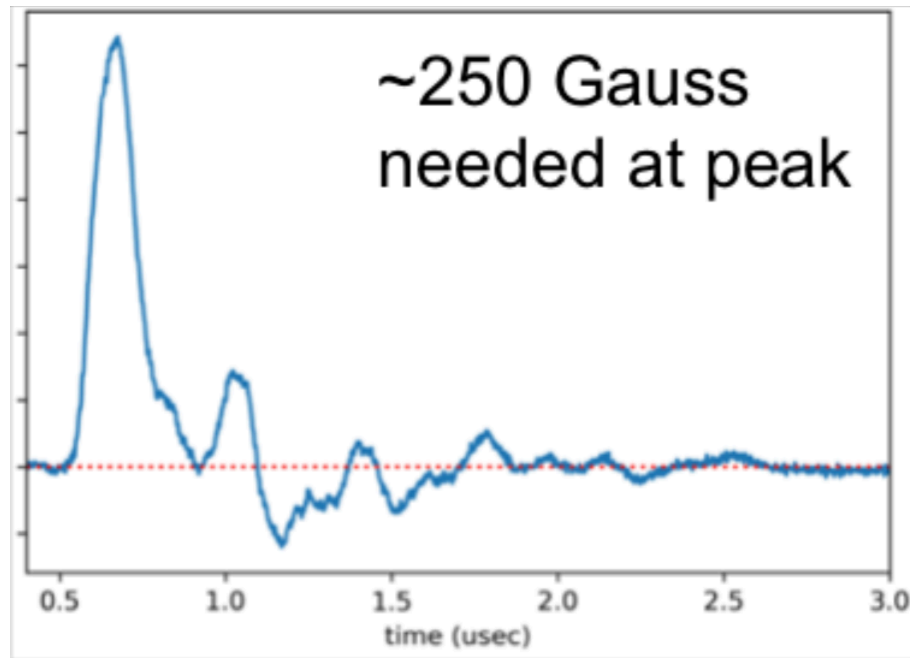
Muon Storage & Focusing

Kicker: Moving muons onto closed orbit





- After inflector, muons enter storage region at r = 77 mm outside central closed orbit
- Muons cross ideal orbit 90 deg later in azimuth, angle is off by 10.8 mrad
- Operating time: < 149 ns at f = 100 Hz (peak), 12 Hz (avg)
- 3 x 1.7 m stripline kickers, Blumlein pulse-forming network



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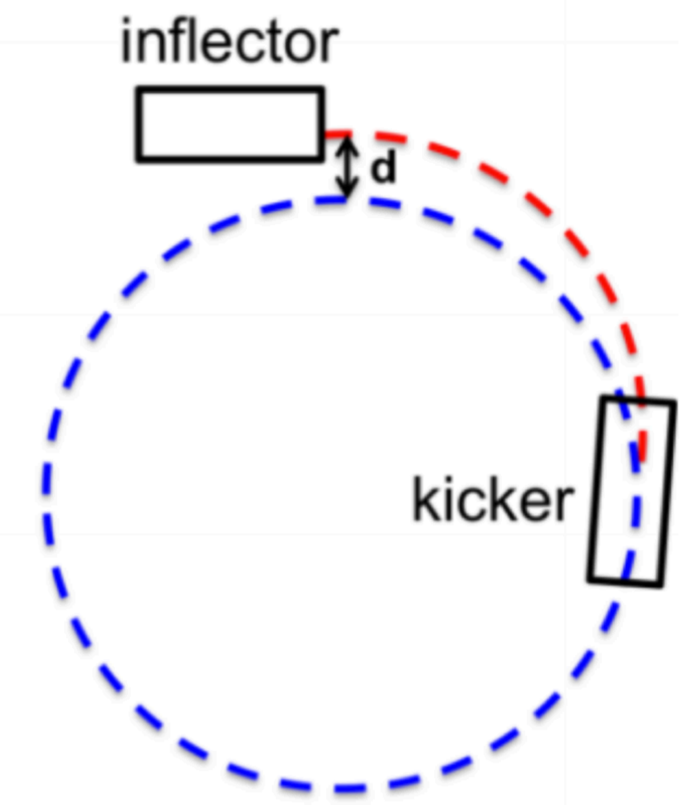

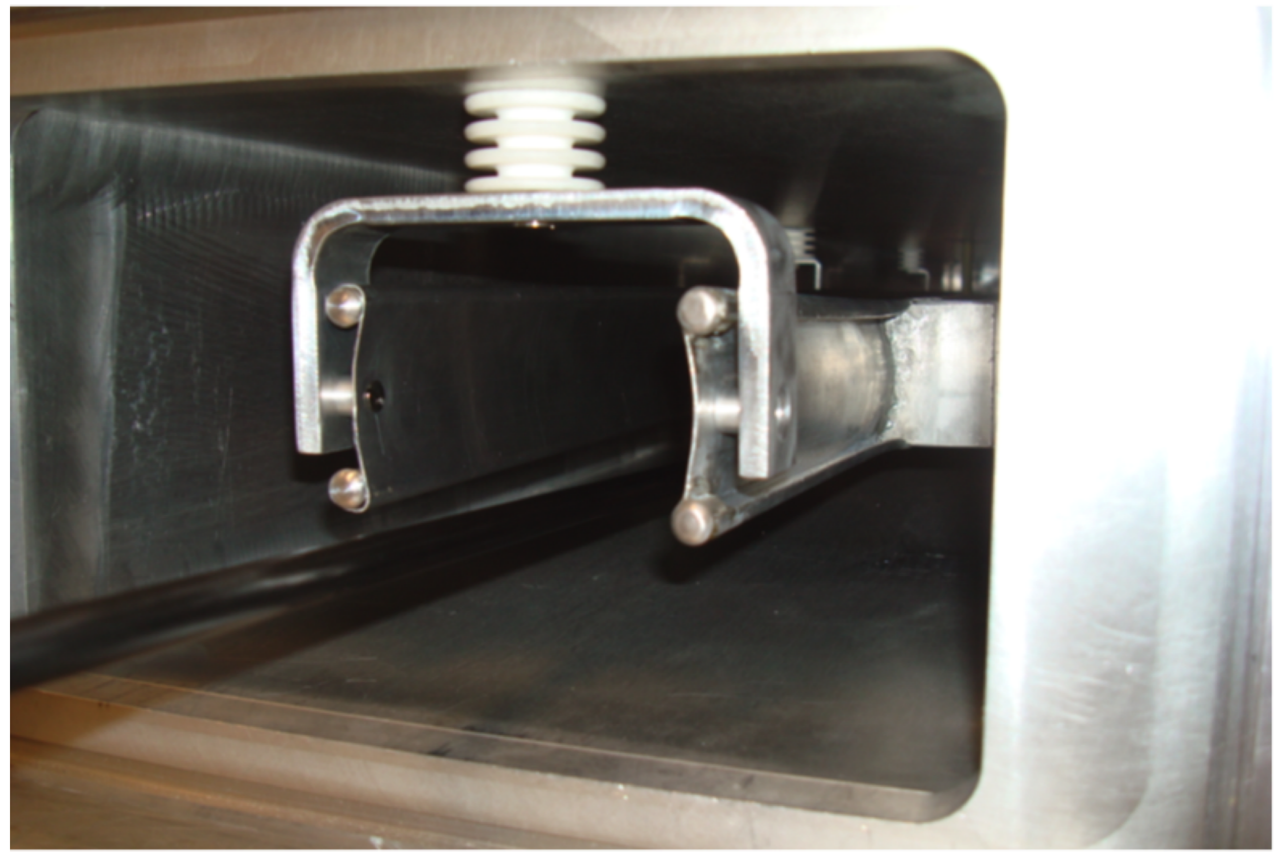

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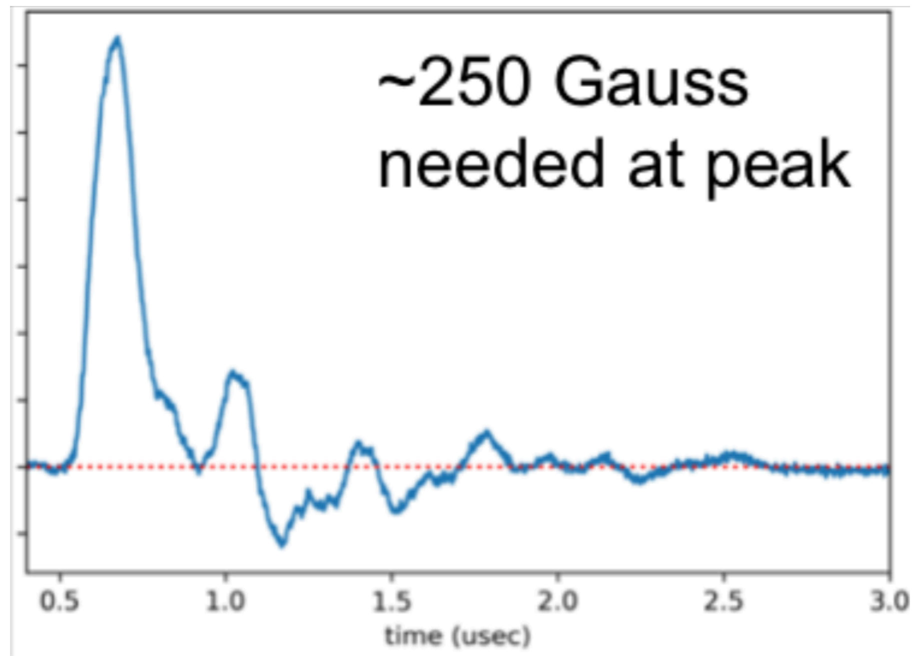
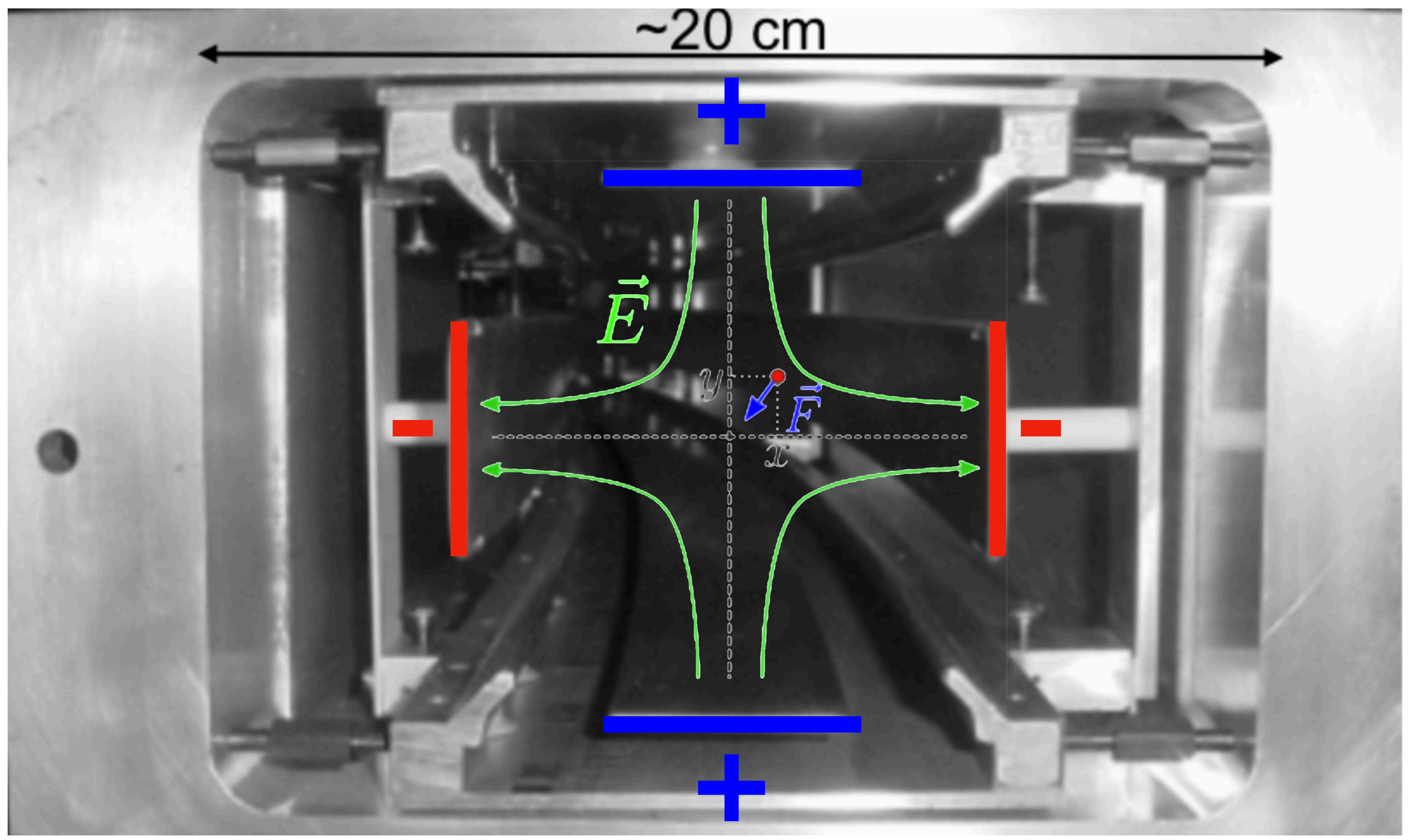


Electrostatic Quadrupoles: Vertical beam focusing



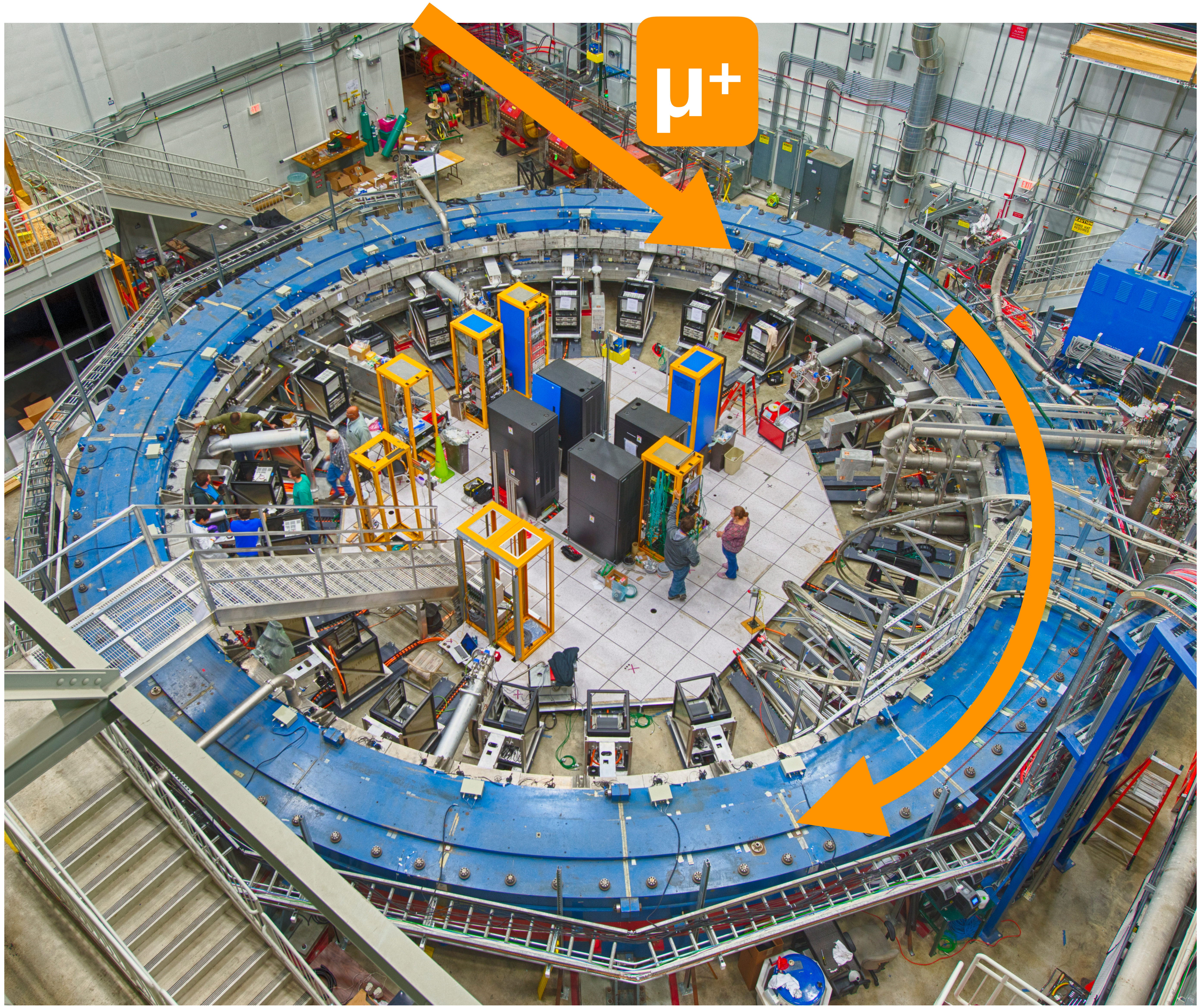
0 for γ = 29.3 muons

μ momentum pitched relative to B
=> measure vertical beam position

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

- Drives the muons towards the central part of storage region vertically
- 4-fold symmetry around the ring — minimizes beam “breathing”, improves muon orbit stability
- Aluminum electrodes cover ~43% of total circumference

Measuring Muon Spin Precession (ω_a)



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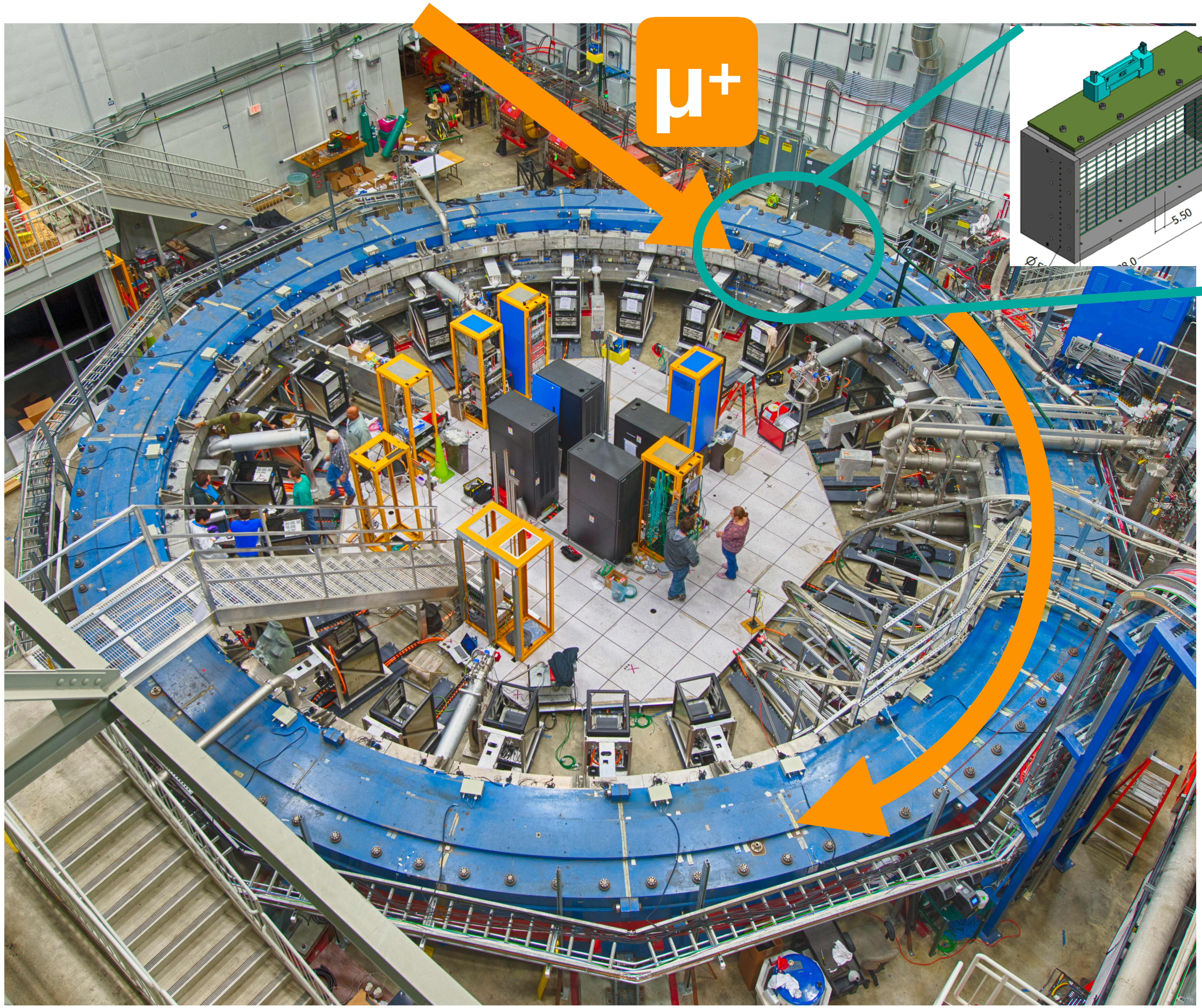
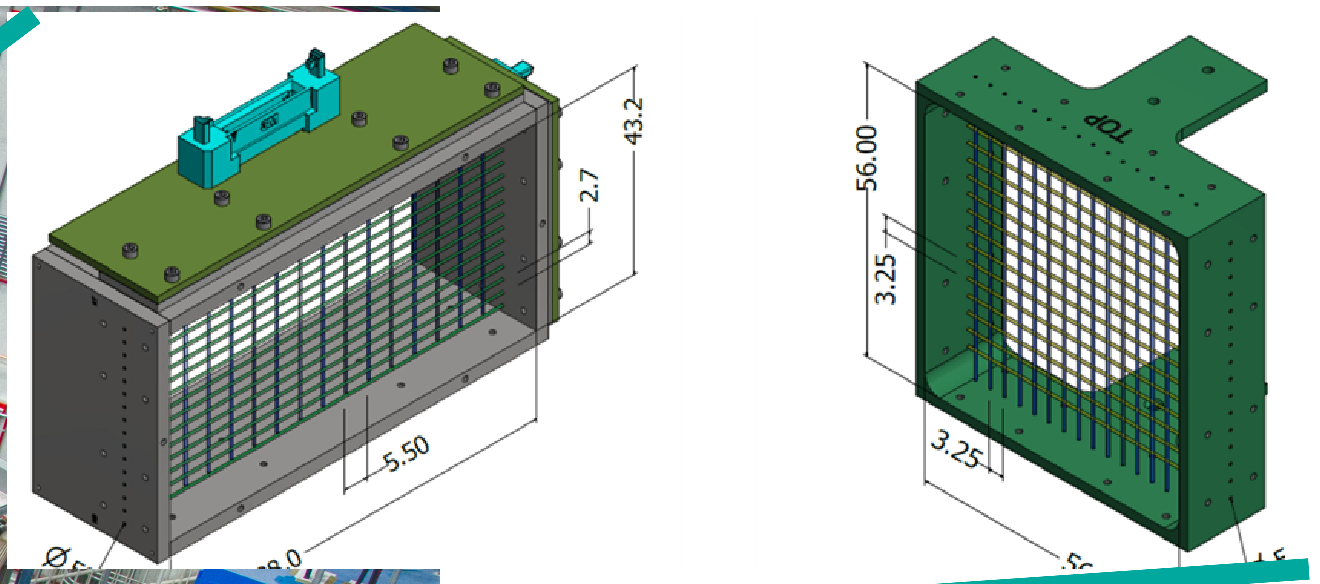
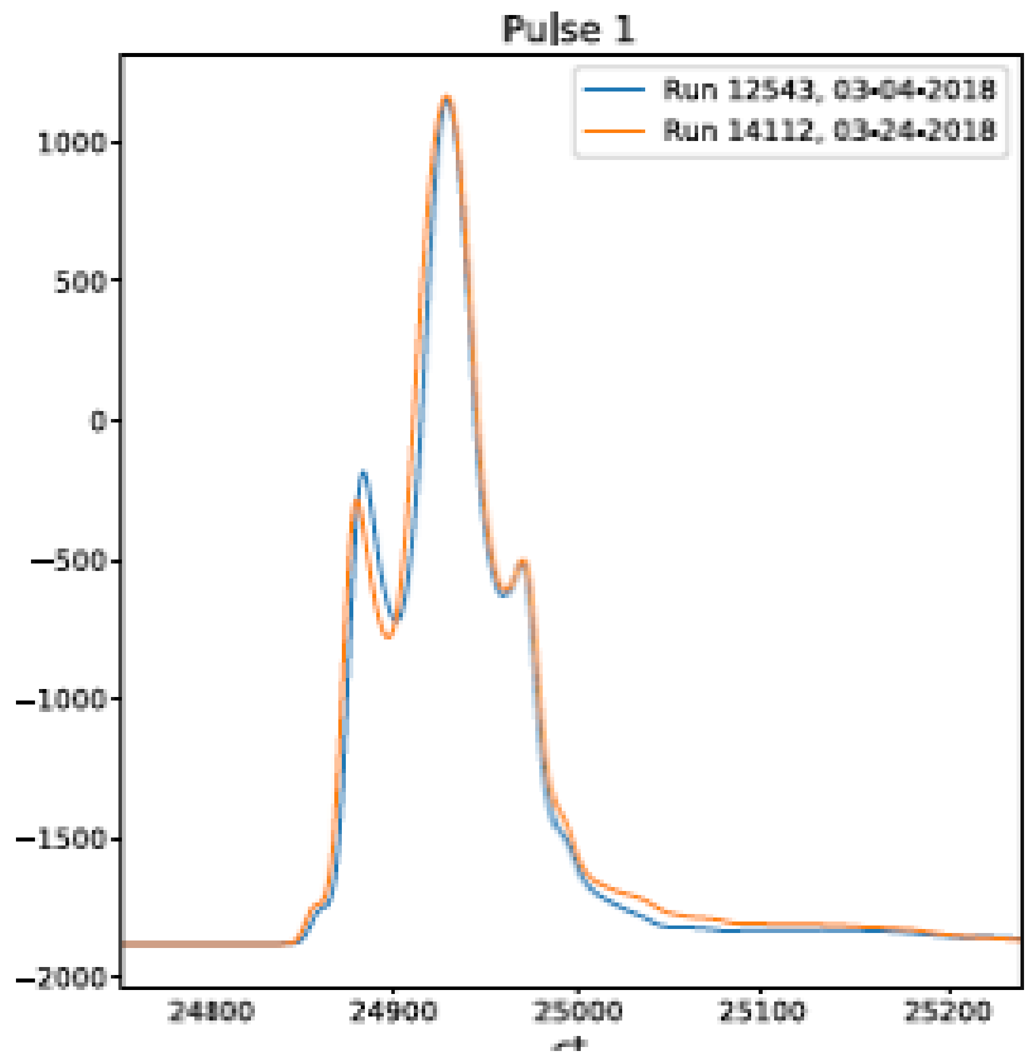


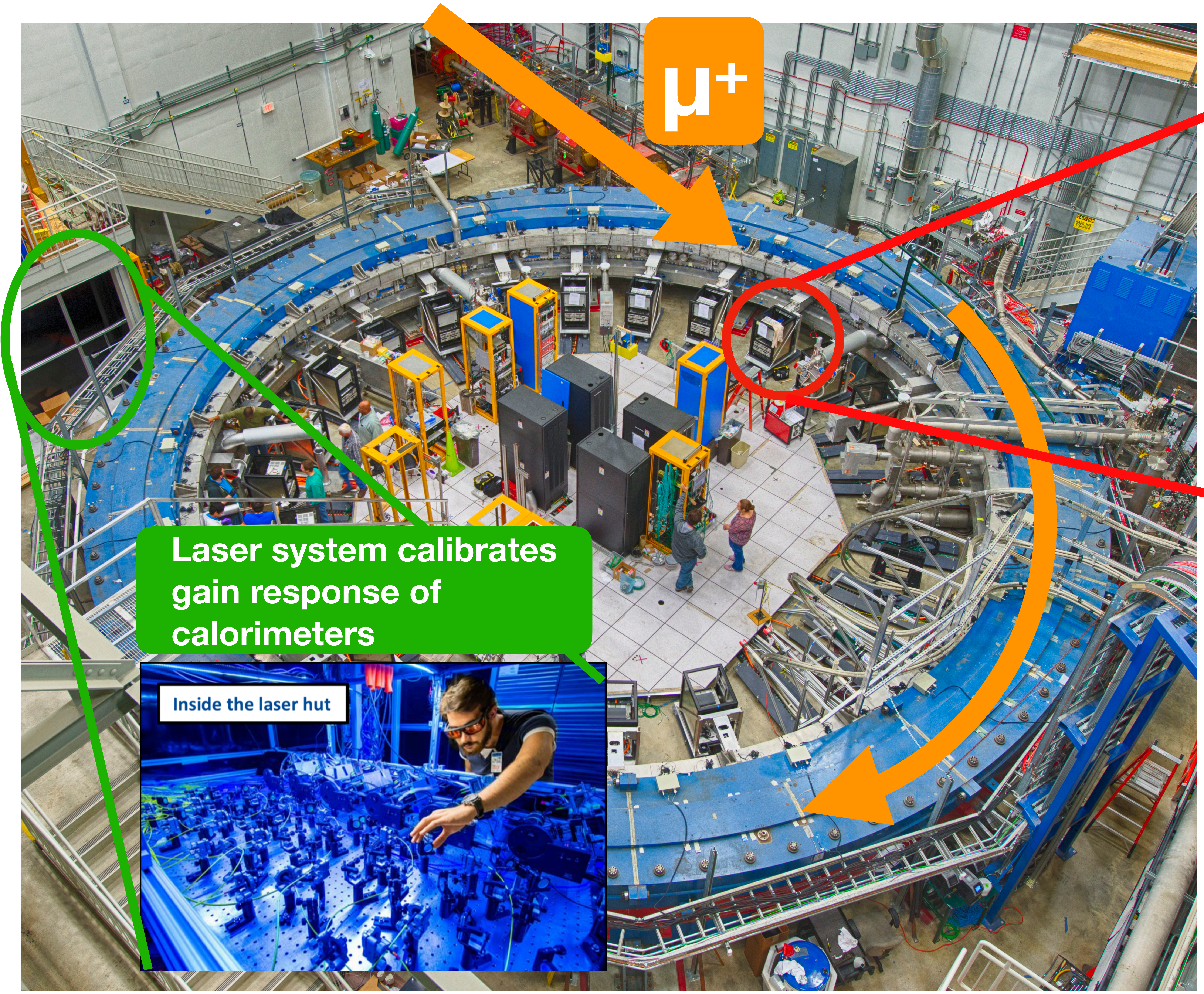


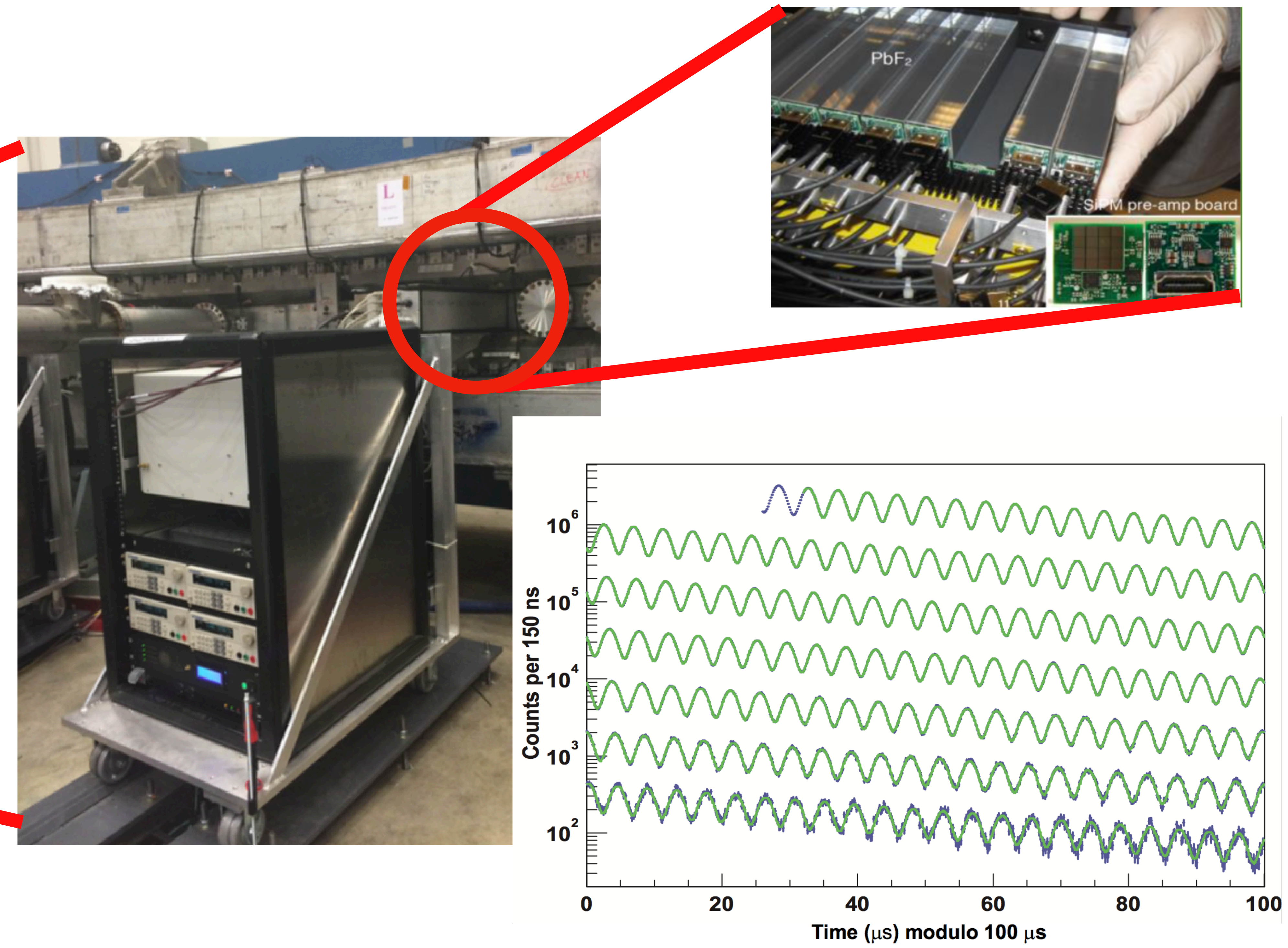


Monitoring the Incoming Muon Beam

- **Scintillating Paddles**: Monitoring temporal distribution
- **Scintillating Fibers**: Map of transverse profile, guides μ tuning into the ring

Measuring Muon Spin Precession (ω_a)

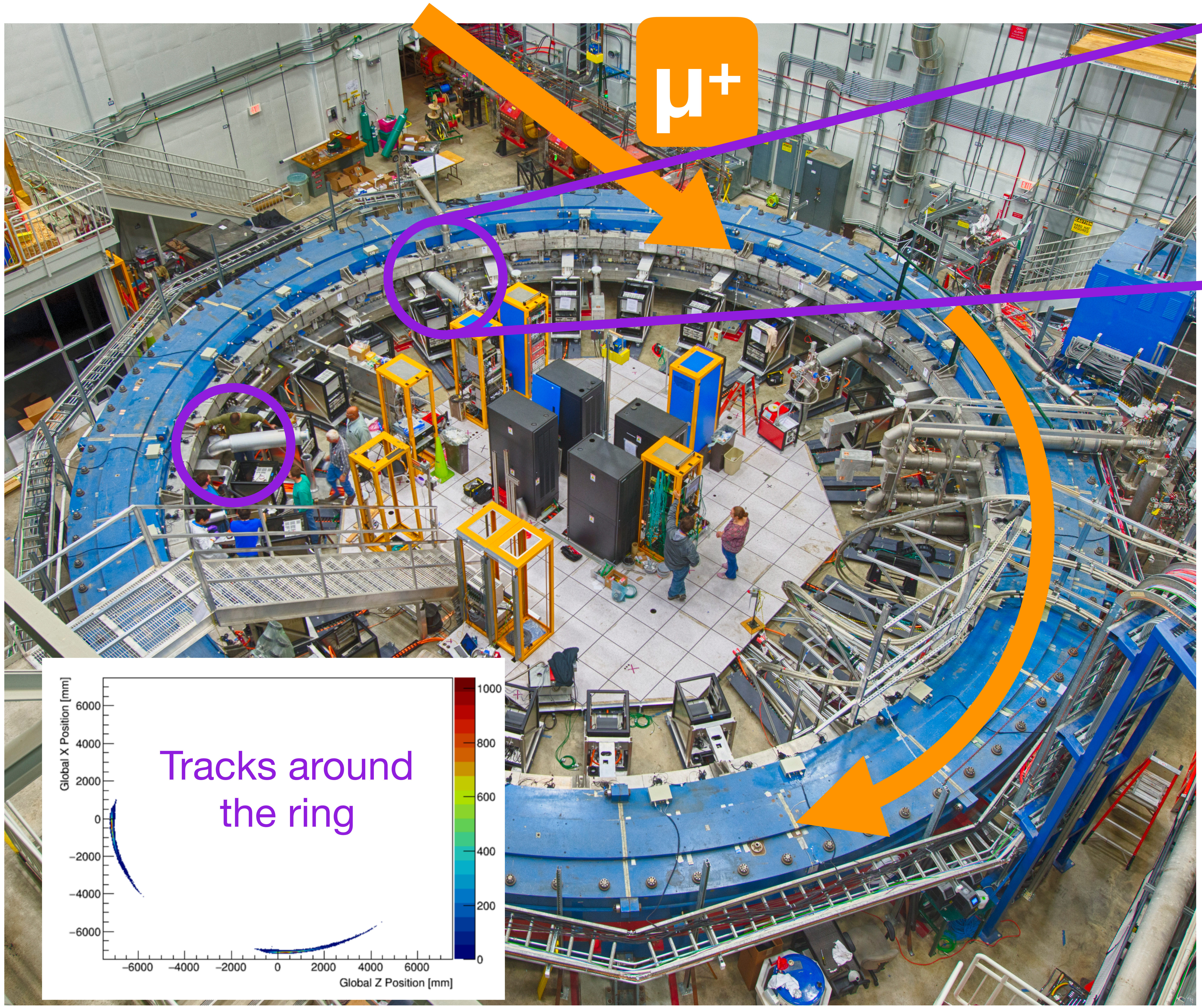




24 finely-segmented PbF_2 crystal calorimeters

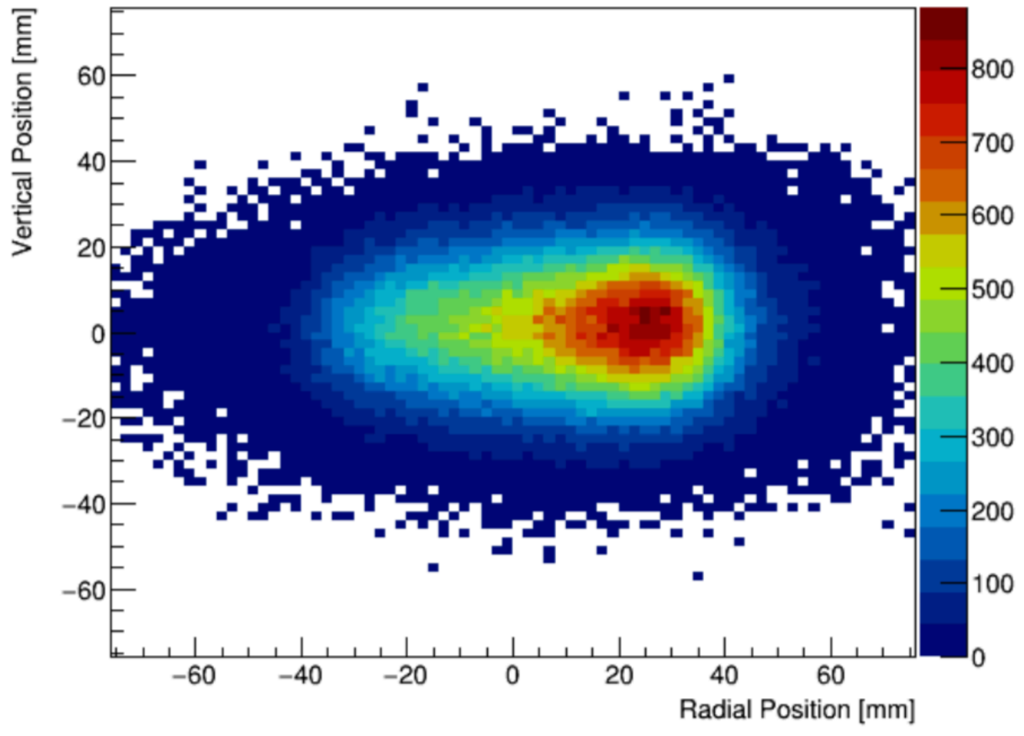
- Self-analyzing decay: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$
- Highest-energy e^+ emitted preferentially along muon spin
- Results in sinusoidally-oscillating arrival time of these e^+ in calorimeters

Measuring Muon Spin Precession (ω_a)

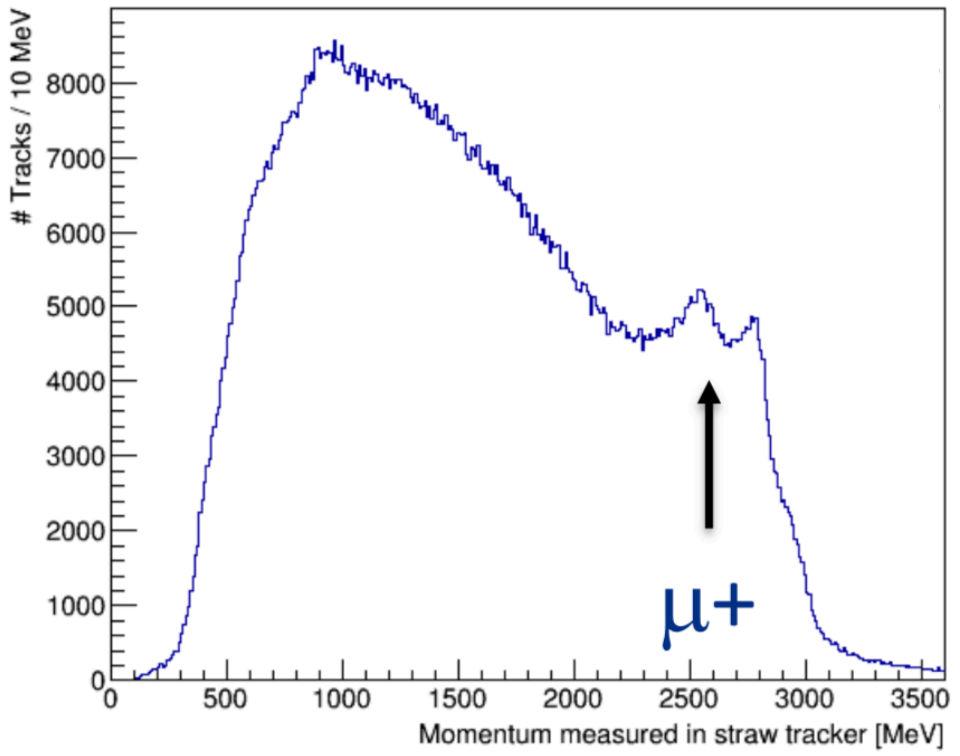


Muon's view of the storage region

Transverse Distribution



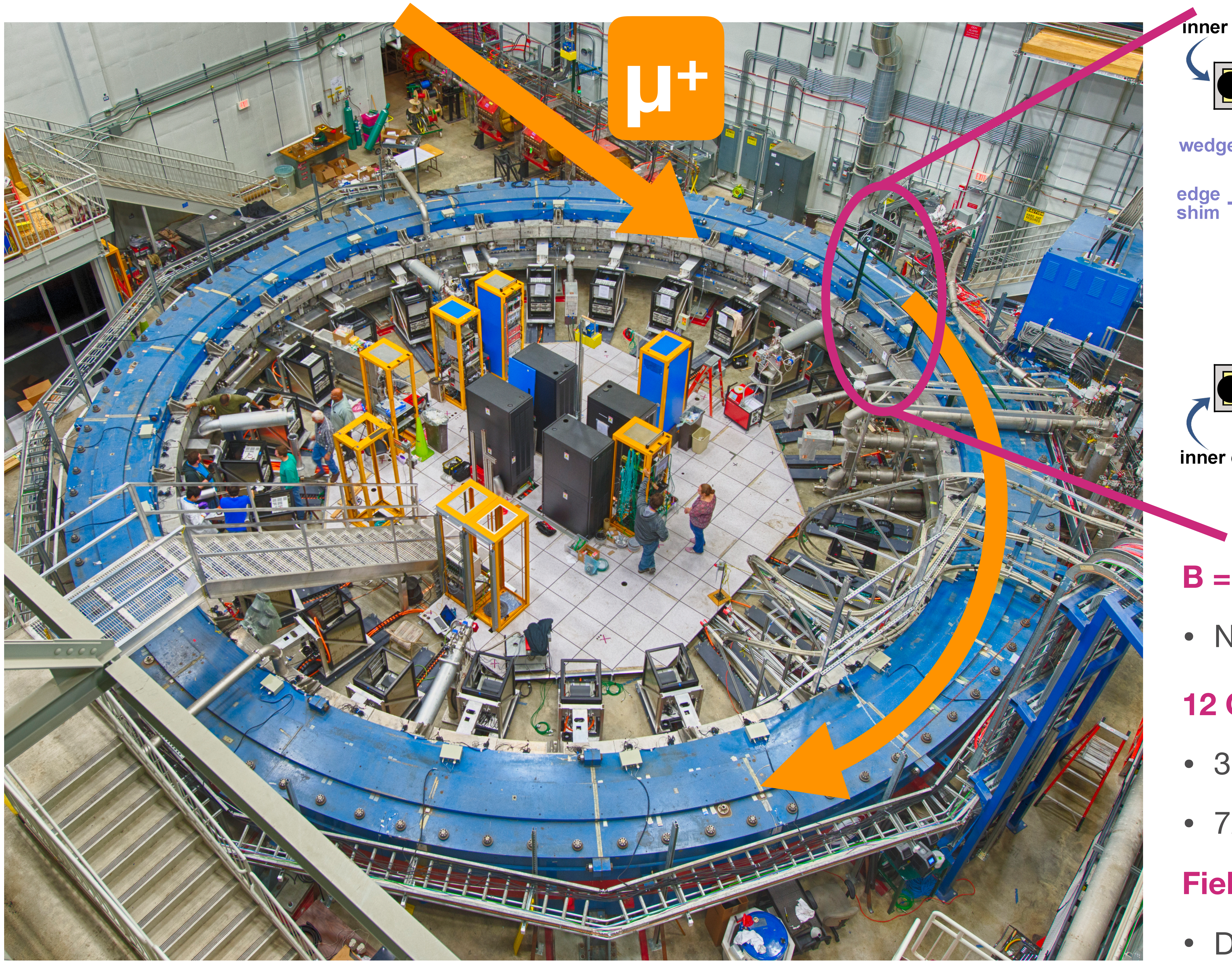
e^+ momentum distribution

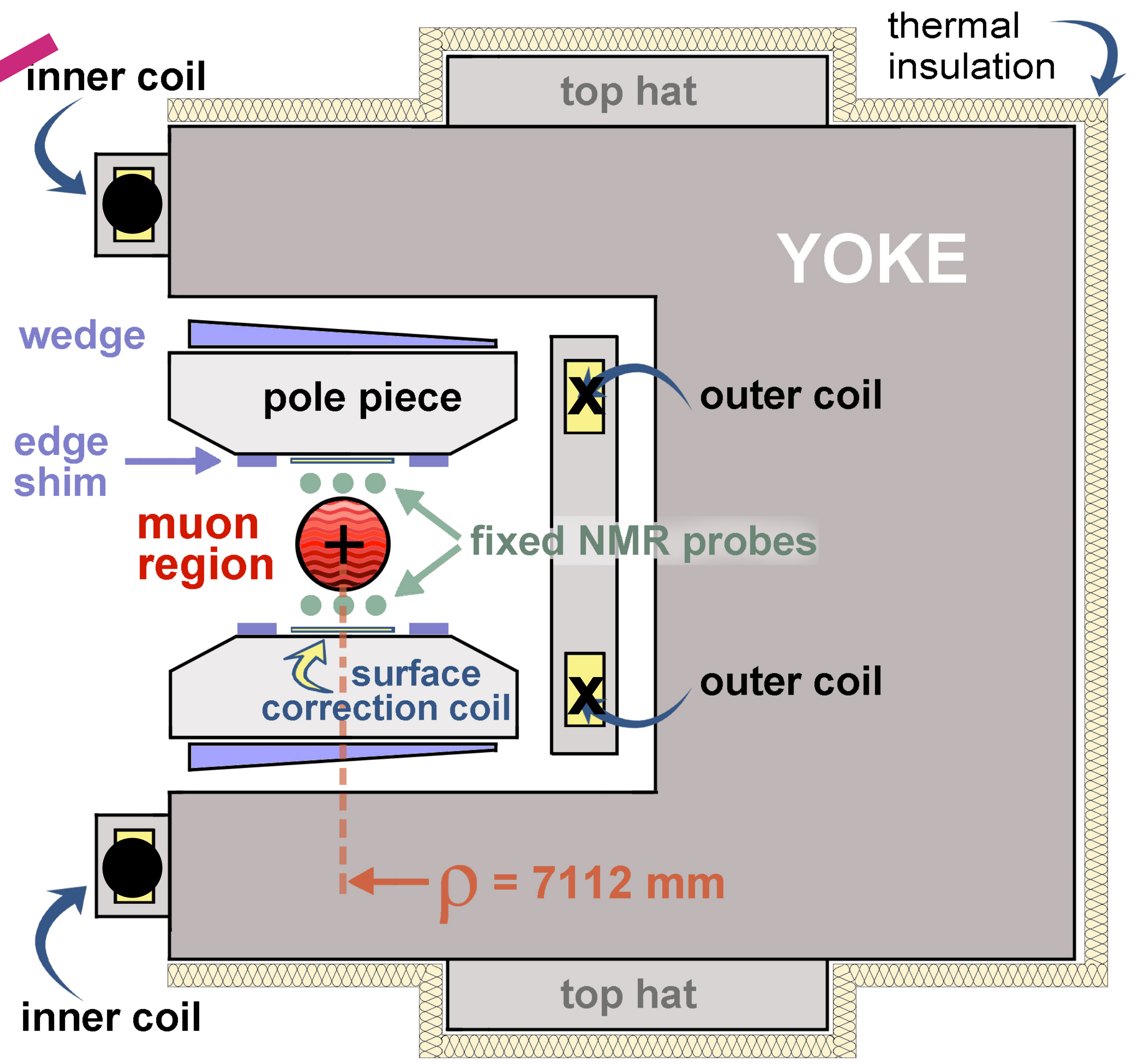


Two straw-tracker stations

- Reconstruct the muon beam distribution from e^+ hits
- Tracker module: 128 straws/module
- 8 modules per station

Magnet Anatomy





Current direction indicated by ● and x

g-2 Magnet in Cross Section

B = 1.45 T (~5200 A)

- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

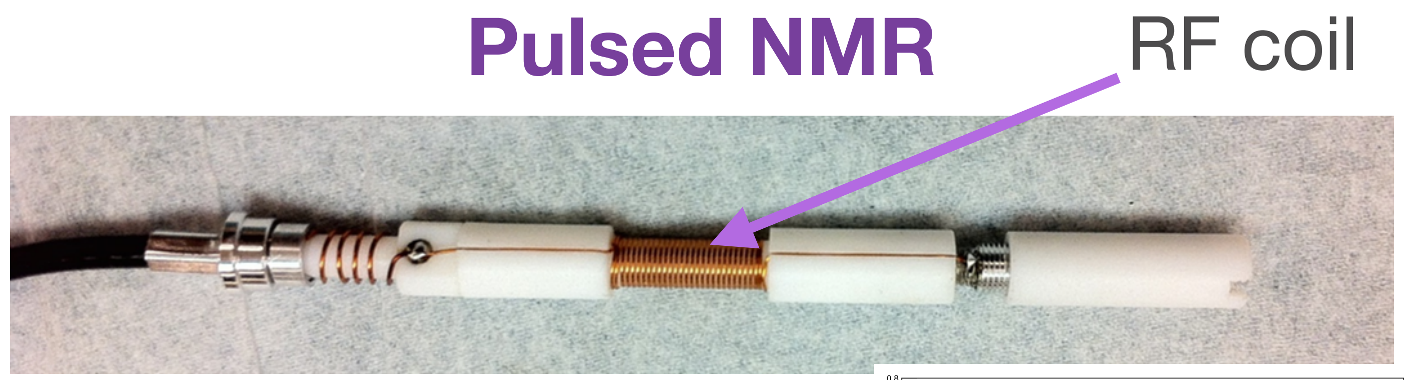
- 3 upper and 3 lower poles per yoke
- 72 total poles

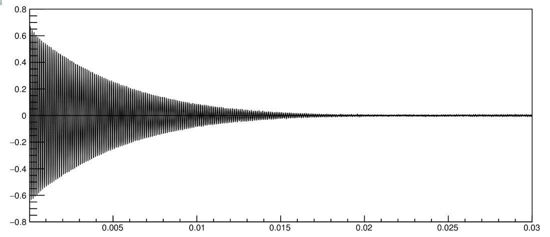
Field Shape

- Determined by positioning of pole pieces, wedge-shaped pieces of steel, programmable surface coils

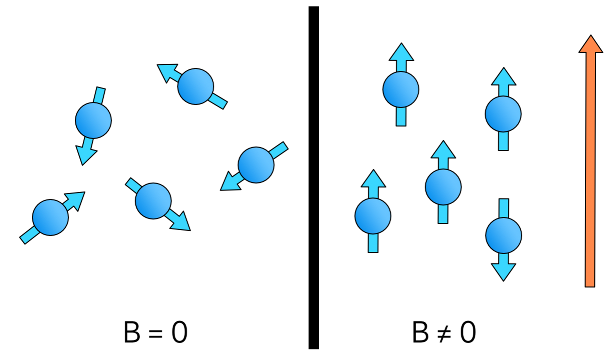
Monitoring and Mapping the Magnetic Field

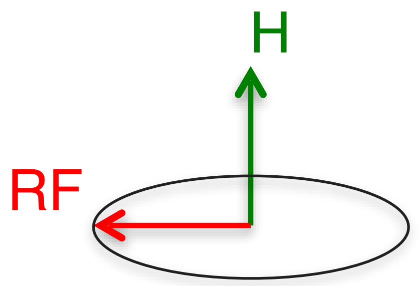
Pulsed NMR





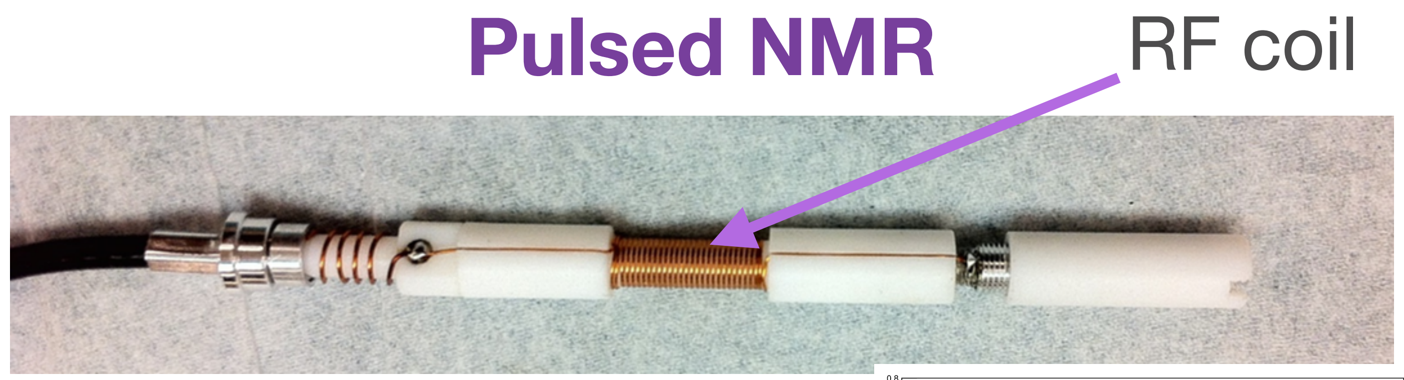
- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID

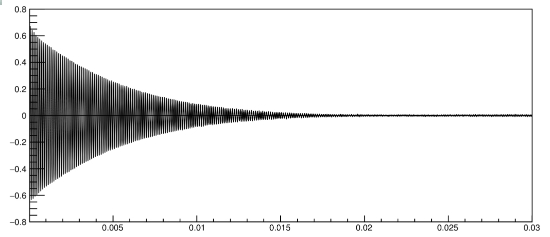




Monitoring and Mapping the Magnetic Field

Pulsed NMR





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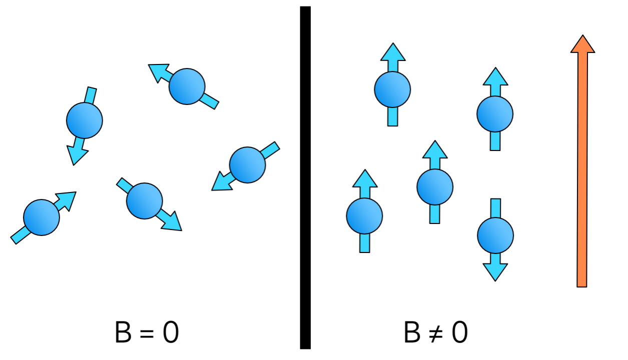
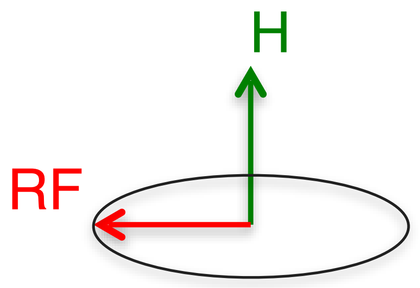
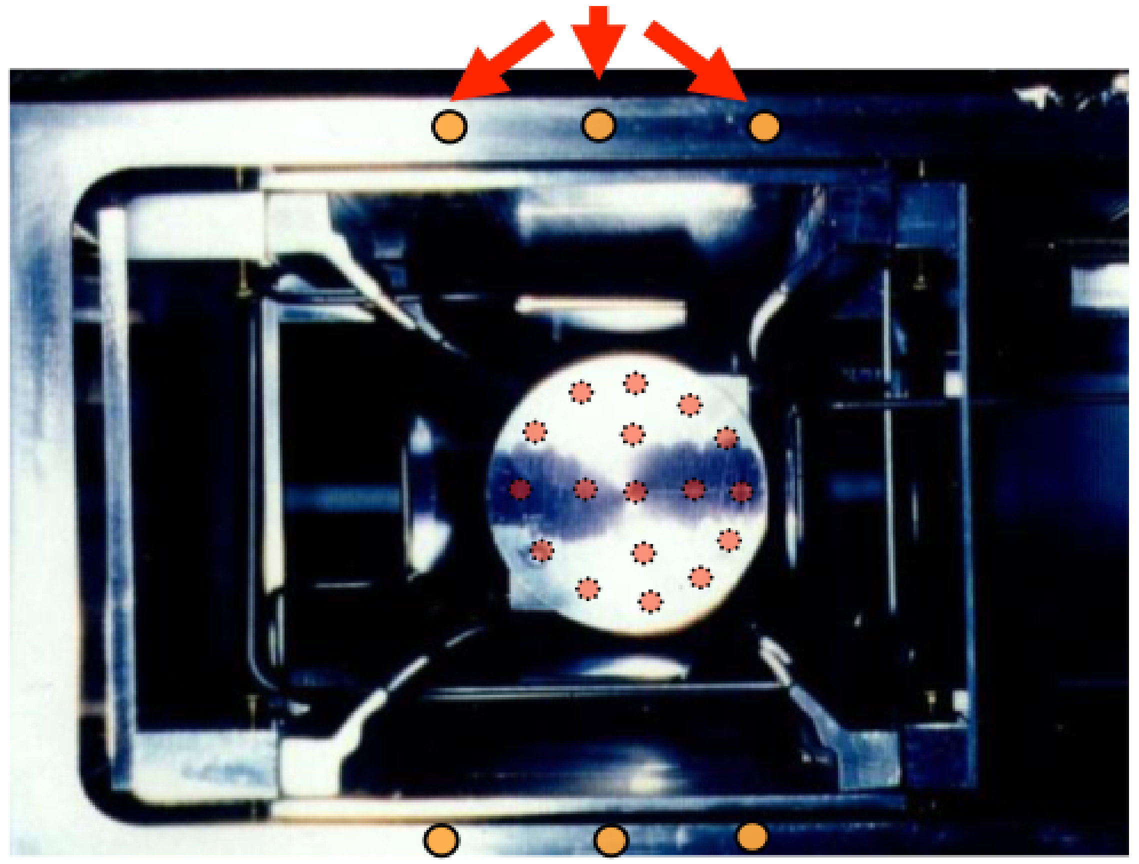




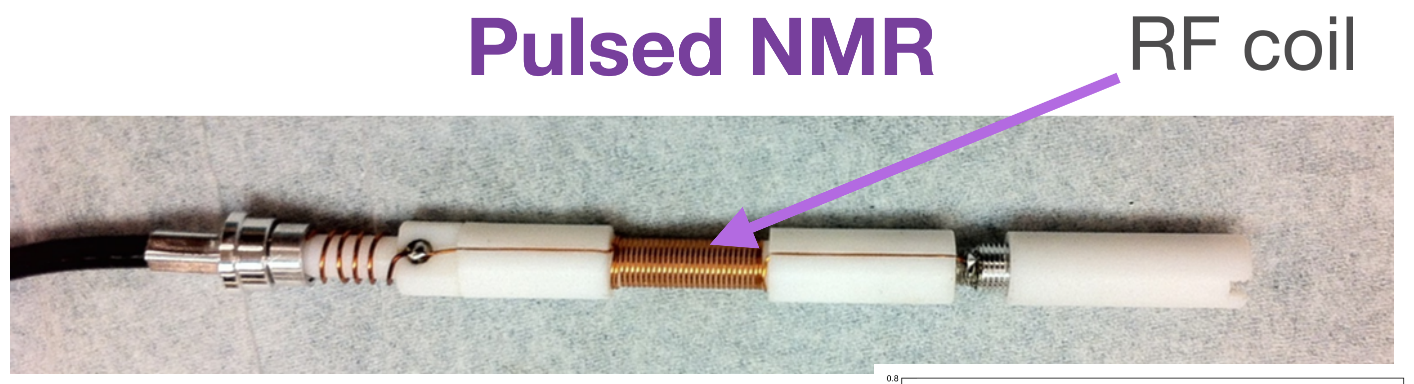
Fixed probes on vacuum chambers

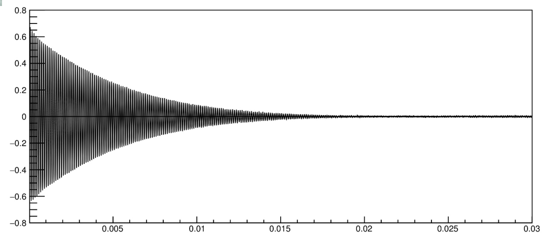


- Measure field while muons are in ring — 378 probes **outside** storage region

Monitoring and Mapping the Magnetic Field

Pulsed NMR





- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
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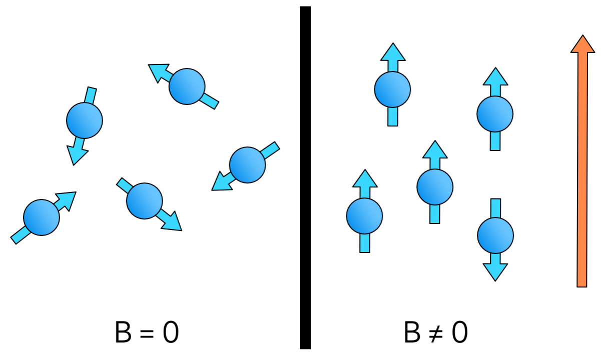

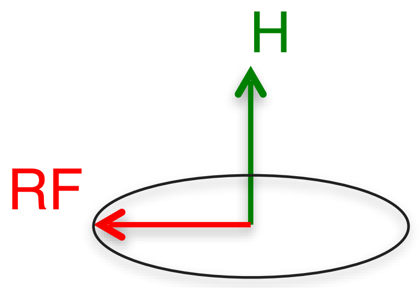

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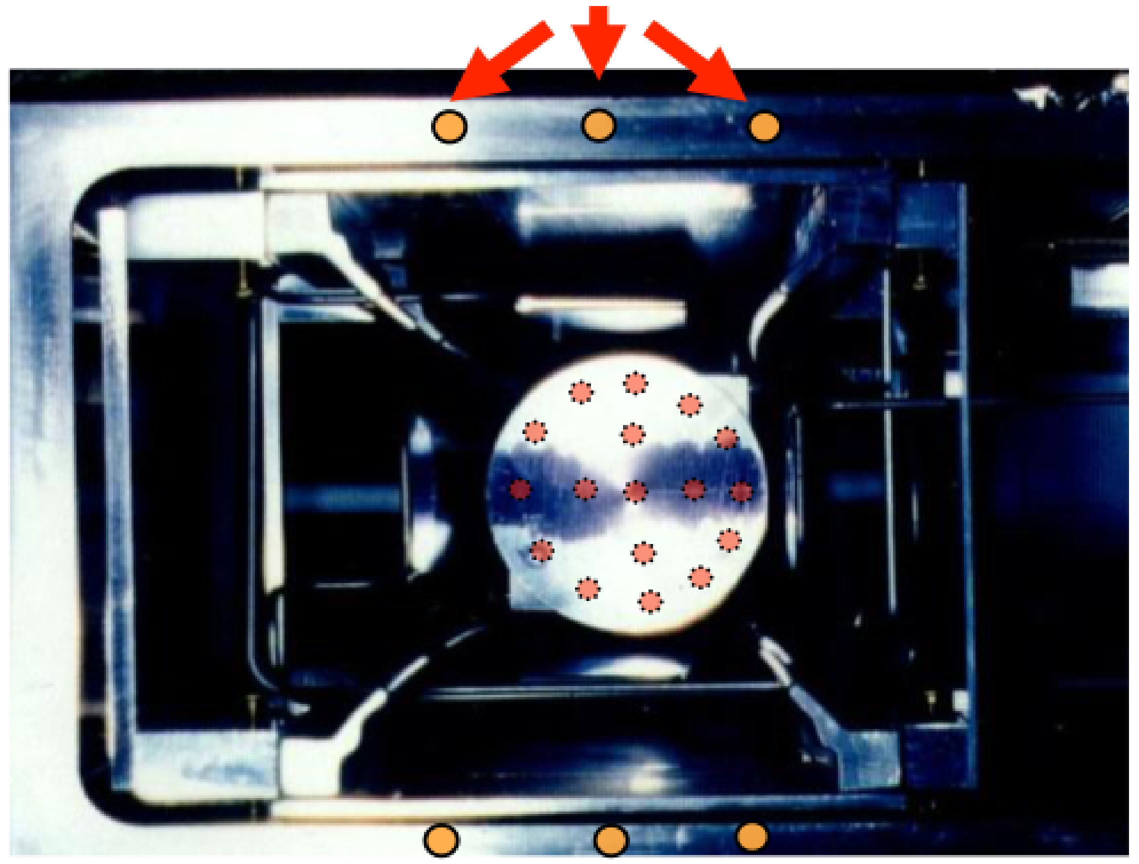

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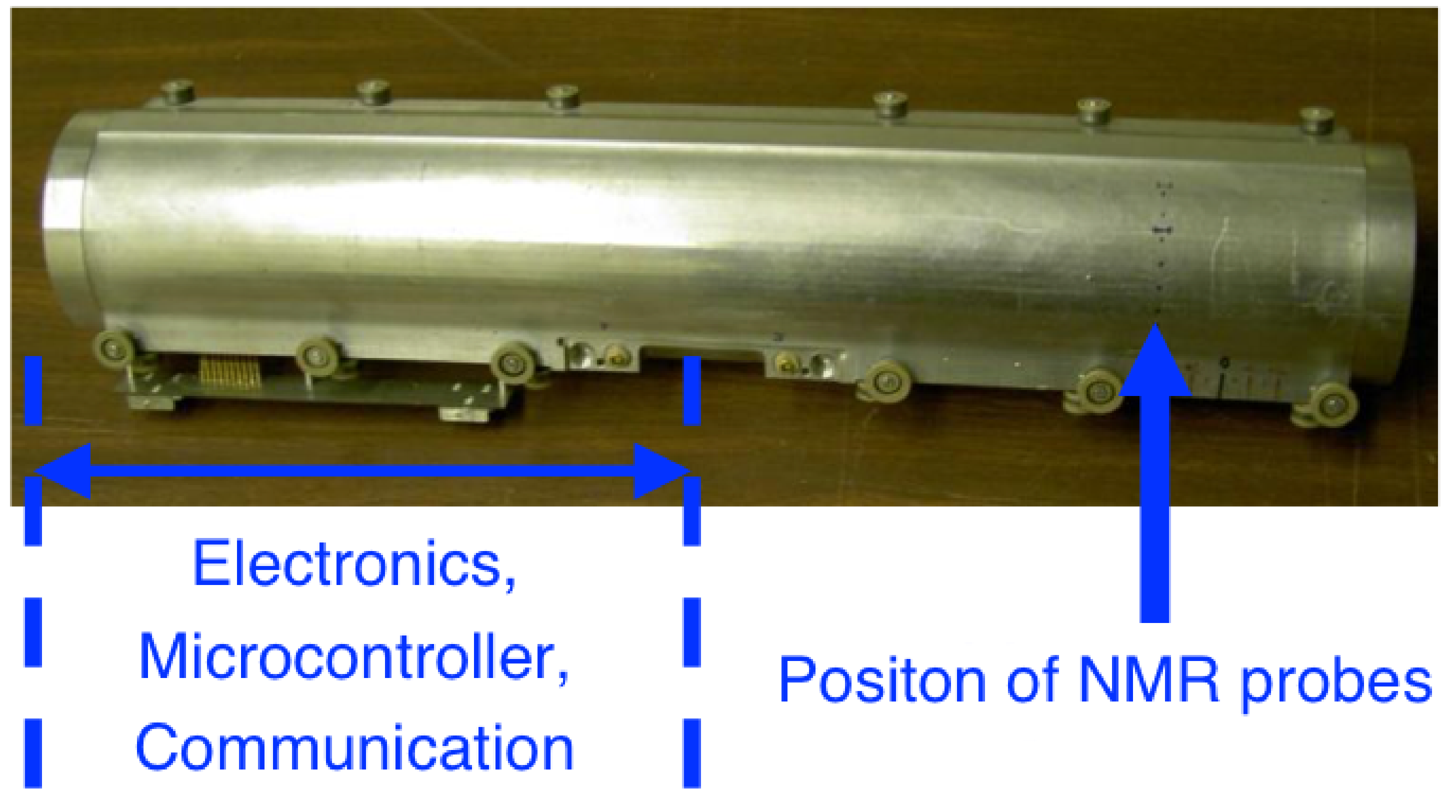
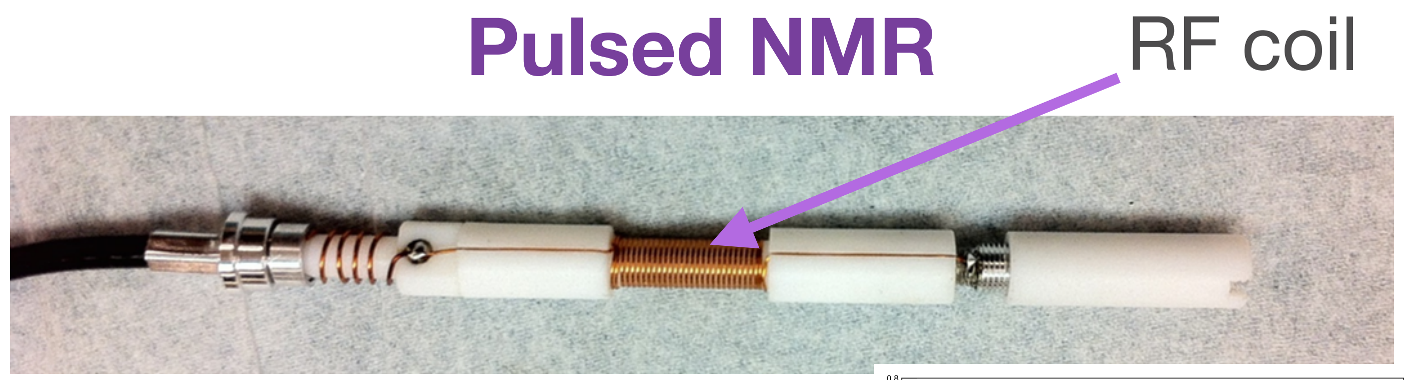
Trolley matrix of 17 NMR probes

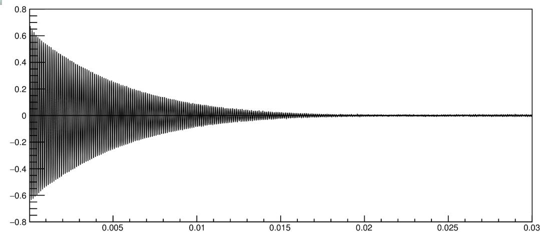


- Measure field in storage region during **specialized runs** when **muons are not being stored**
- Map the field every 3–4 days

Monitoring and Mapping the Magnetic Field

Pulsed NMR





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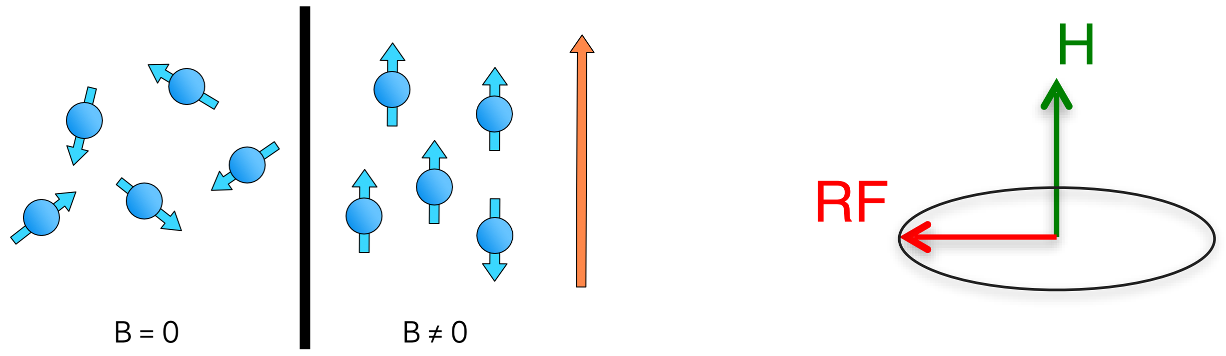

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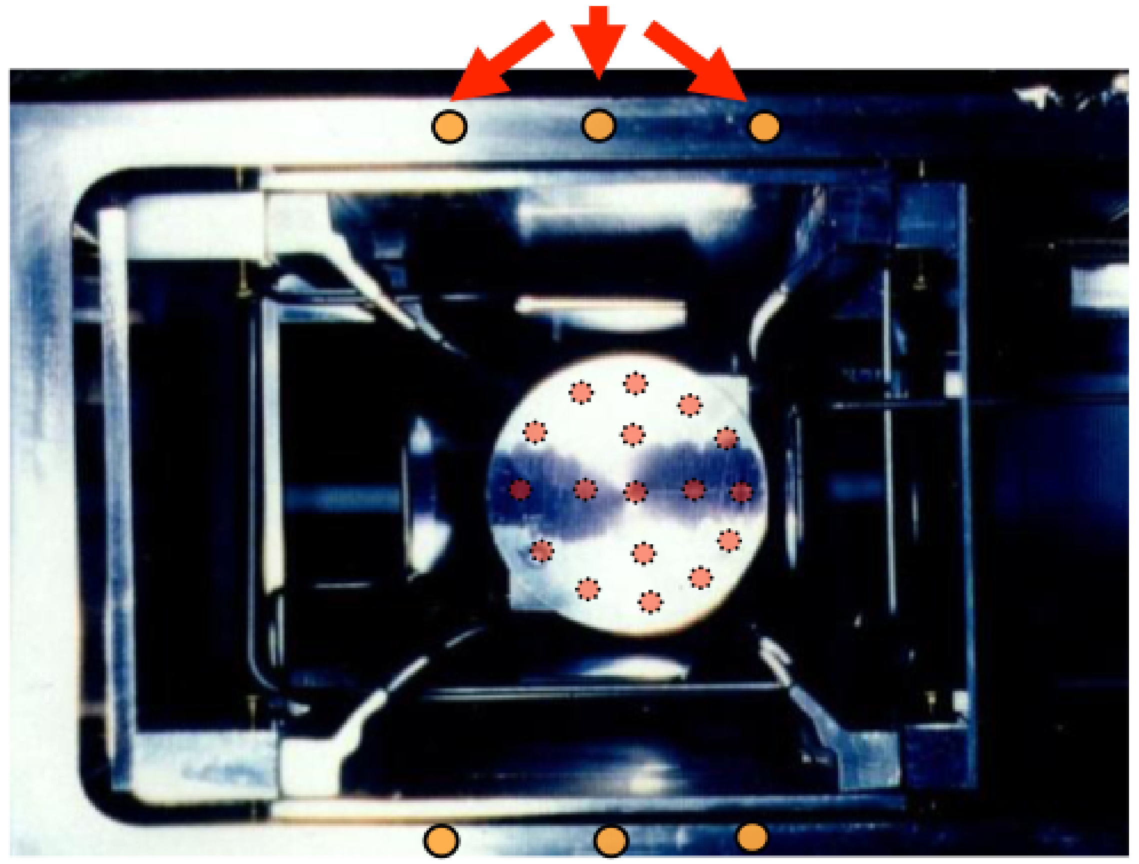

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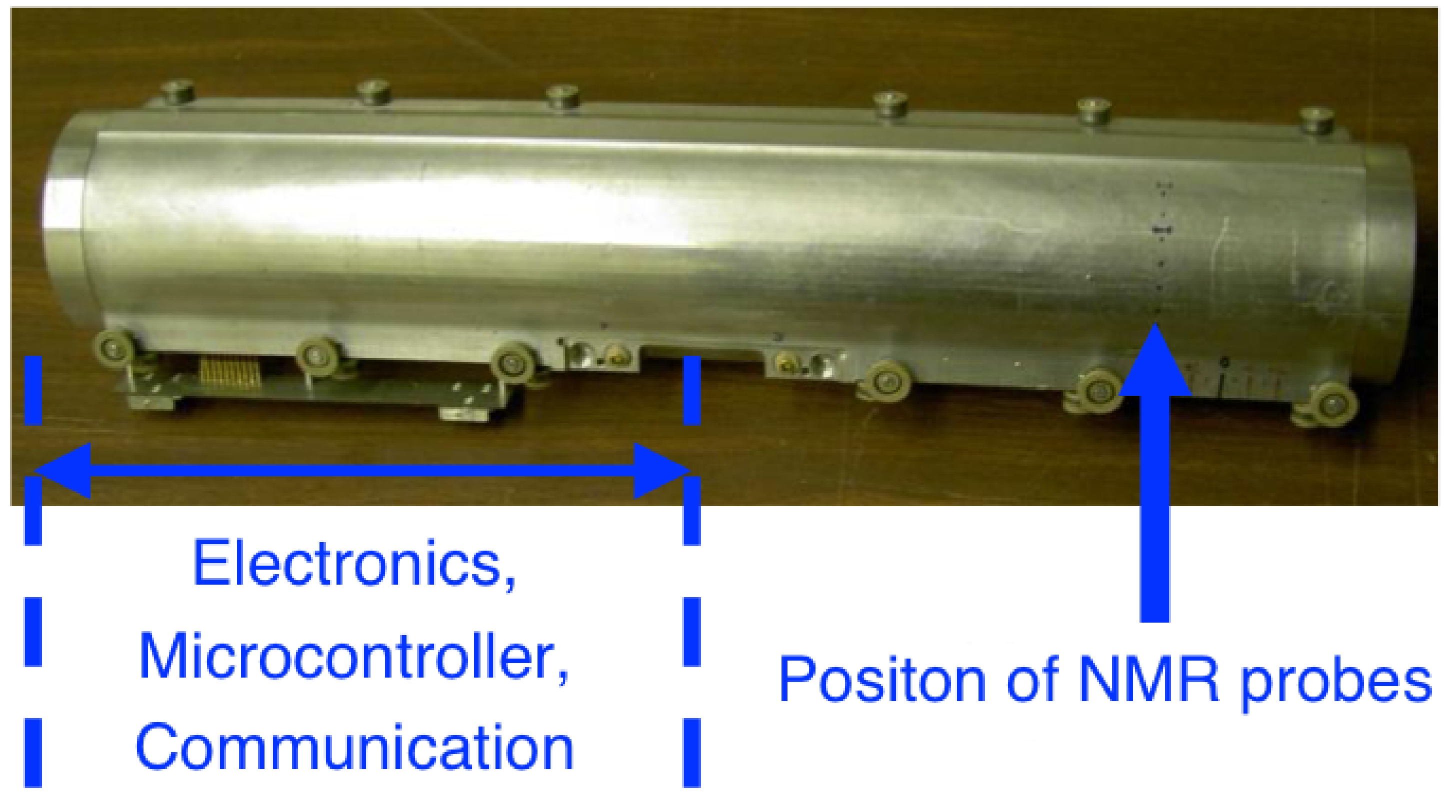
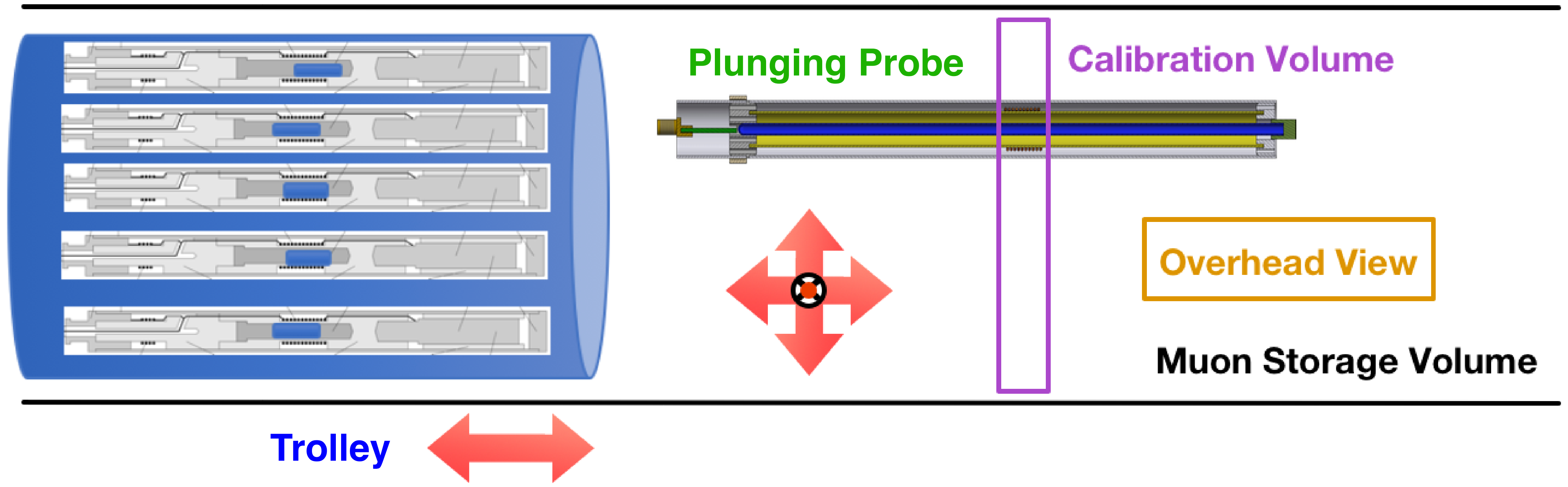


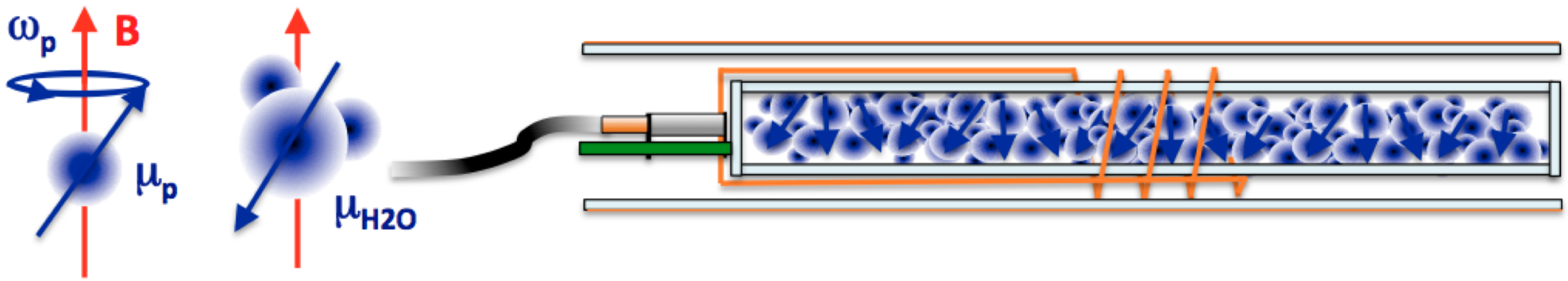
- Measure field in storage region during **specialized runs** when **muons are not being stored**
- Map the field every 3–4 days

- **Trolley** probes **calibrated to free-proton Larmor frequency**
  - Calibrate trolley probes using a special probe that uses a water sample
  - Measurements in specially-shimmed region of ring



Calibration of the Magnetic Field

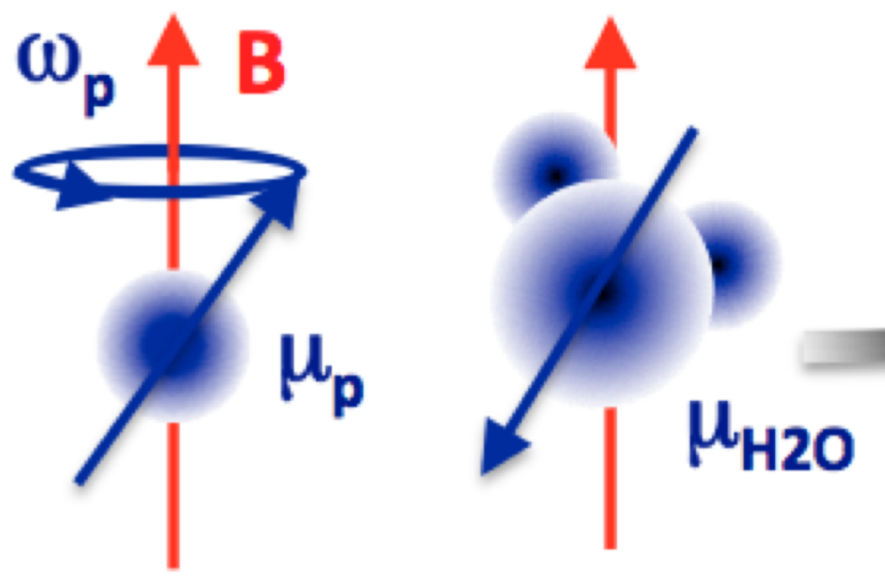
- In the experiment, need to extract ω_p; however, we don't have free protons — need a calibration

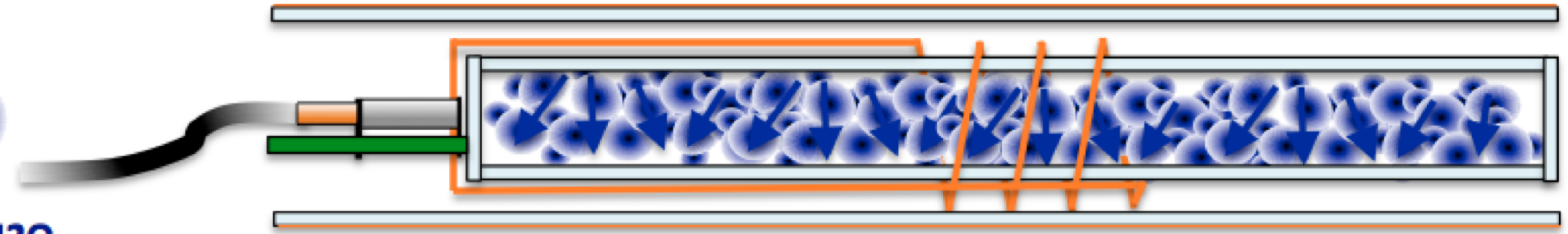


$$\omega_p^{\mathrm{meas}} \approx \omega_p^{\mathrm{free}}$$

Calibration of the Magnetic Field

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





$$\omega_p^{\mathrm{meas}} = \omega_p^{\mathrm{free}} \left[1 - \sigma \left(\mathrm{H_2O}, T \right) \right]$$

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)]

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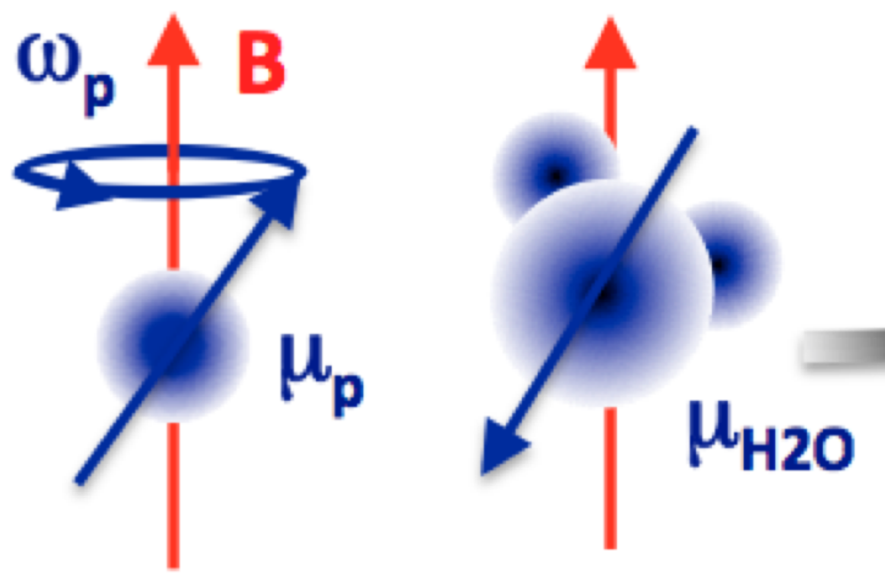

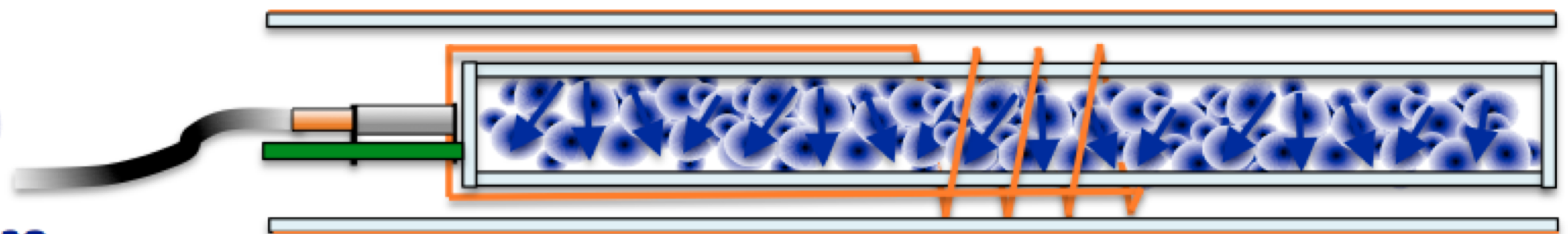

$$\omega_p^{\text{meas}} = \omega_p^{\text{free}} \left[1 - \sigma\left(H_2O, T\right) - \left(\varepsilon - \frac{4\pi}{3}\right) \chi\left(H_2O, T\right) \right]$$

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Magnetic susceptibility of water gives shape-dependent perturbation

- $\varepsilon = 4\pi/3$ (perfect sphere)
- $\varepsilon = 2\pi$ (infinite cylinder) when probe is perpendicular to B
- χ_{H_2O} = -720(3) x 10^{-9} [B. H. Blott and G. J. Daniell, Meas. Sci. Technol. **4,** 462 (1993)]

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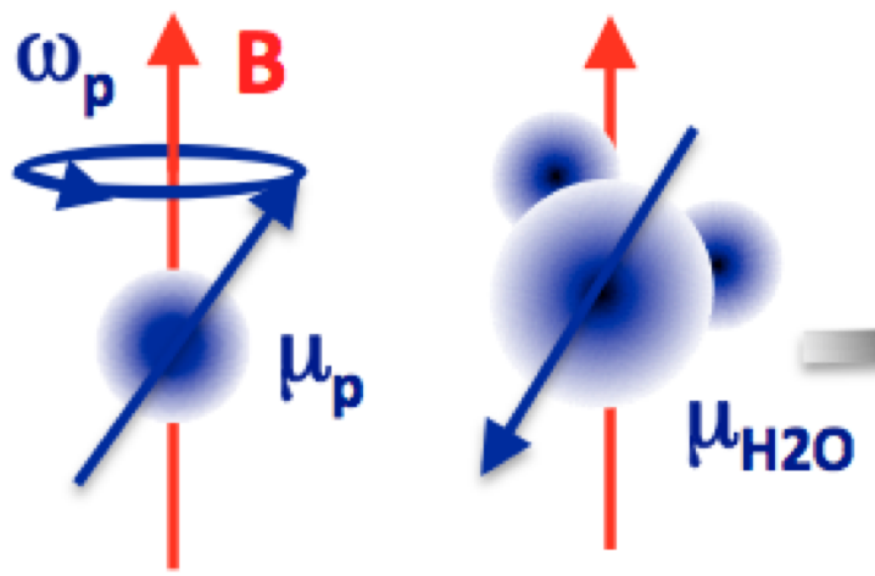

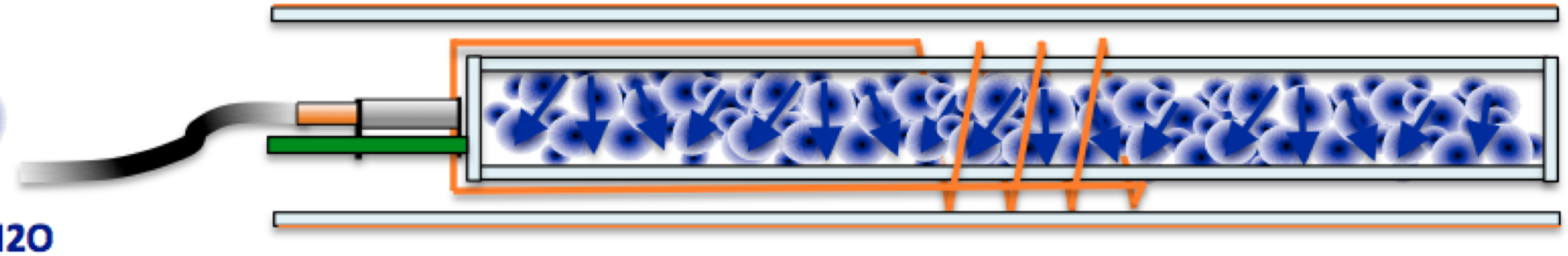

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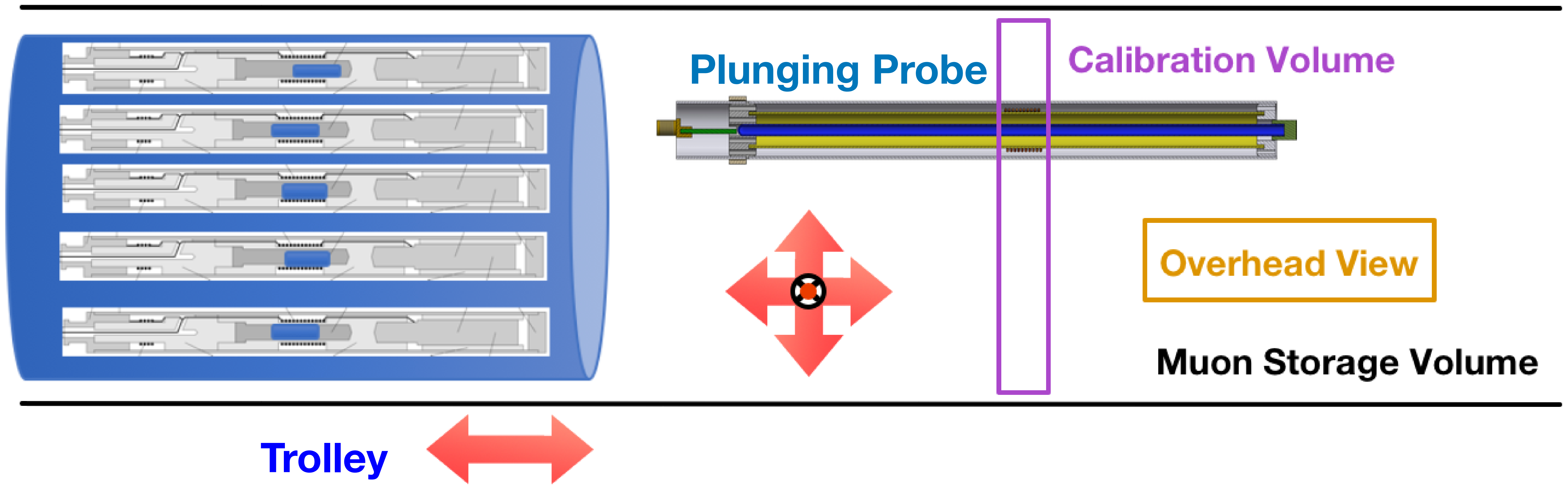
Magnetization of probe materials perturbs the field at site of protons

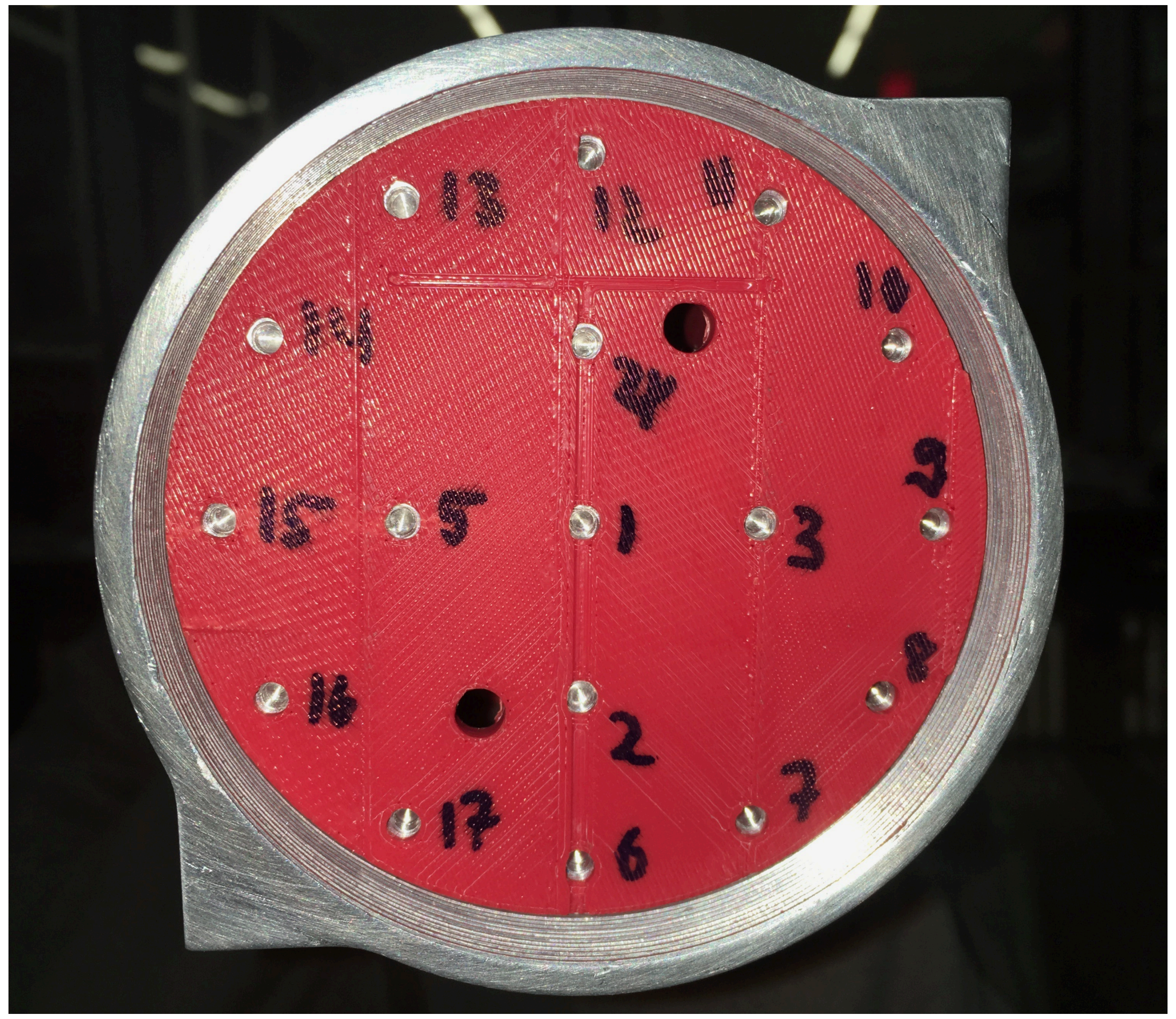
➡ Goal: Determine total correction to ≤ 35 ppb accuracy

Calibrating the Trolley

Procedure

- Select **trolley** probe to calibrate





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- Select **trolley** probe to calibrate
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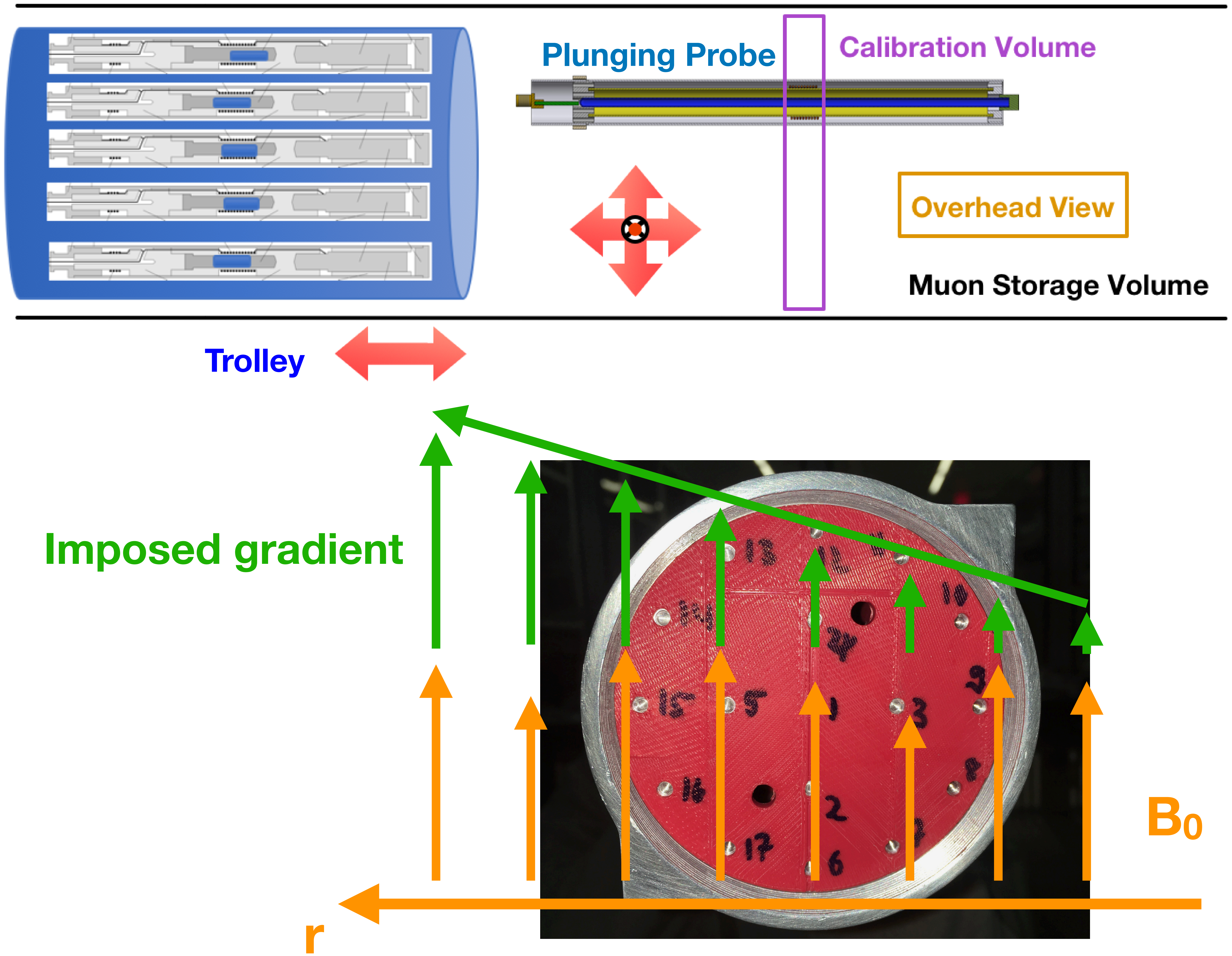

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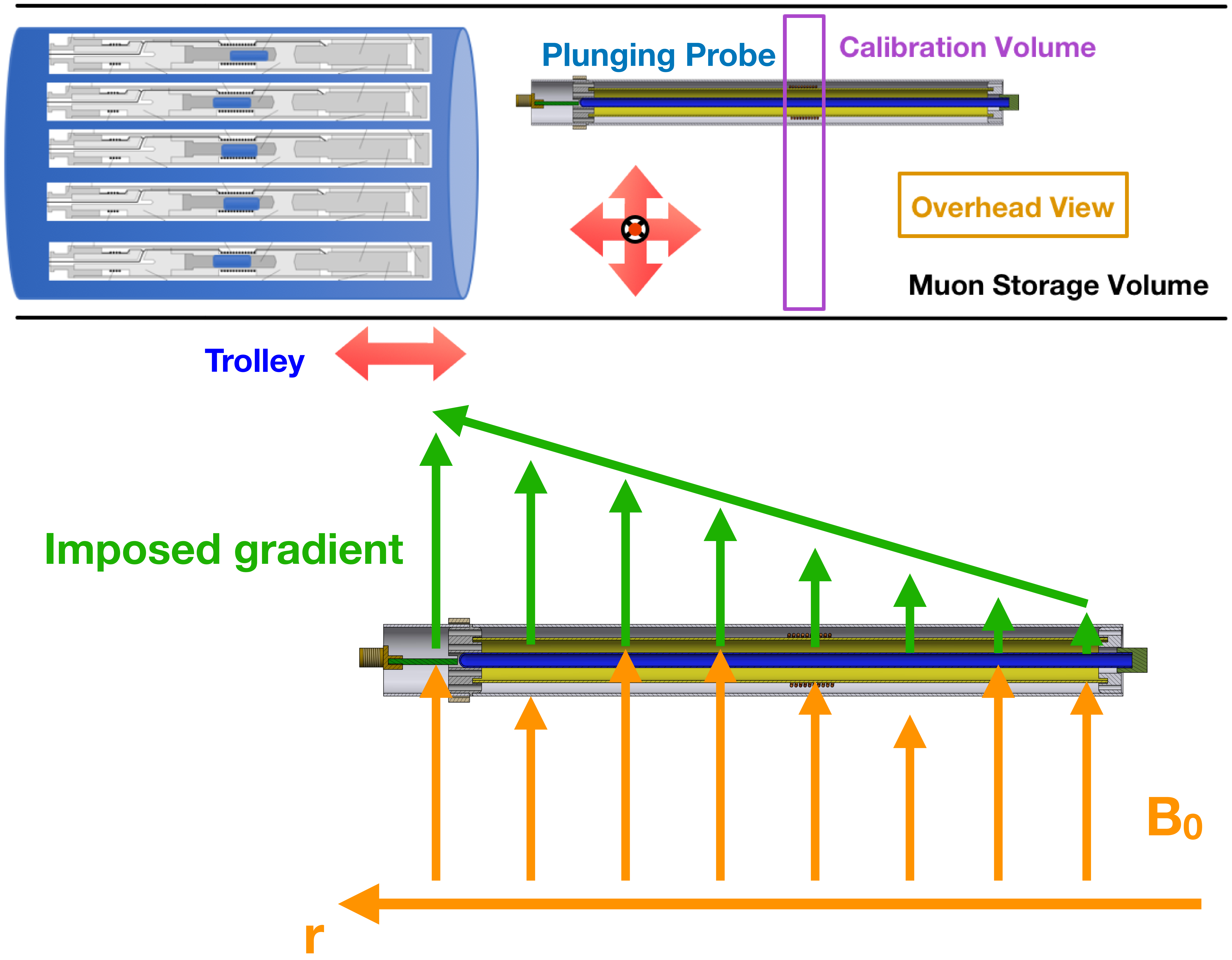

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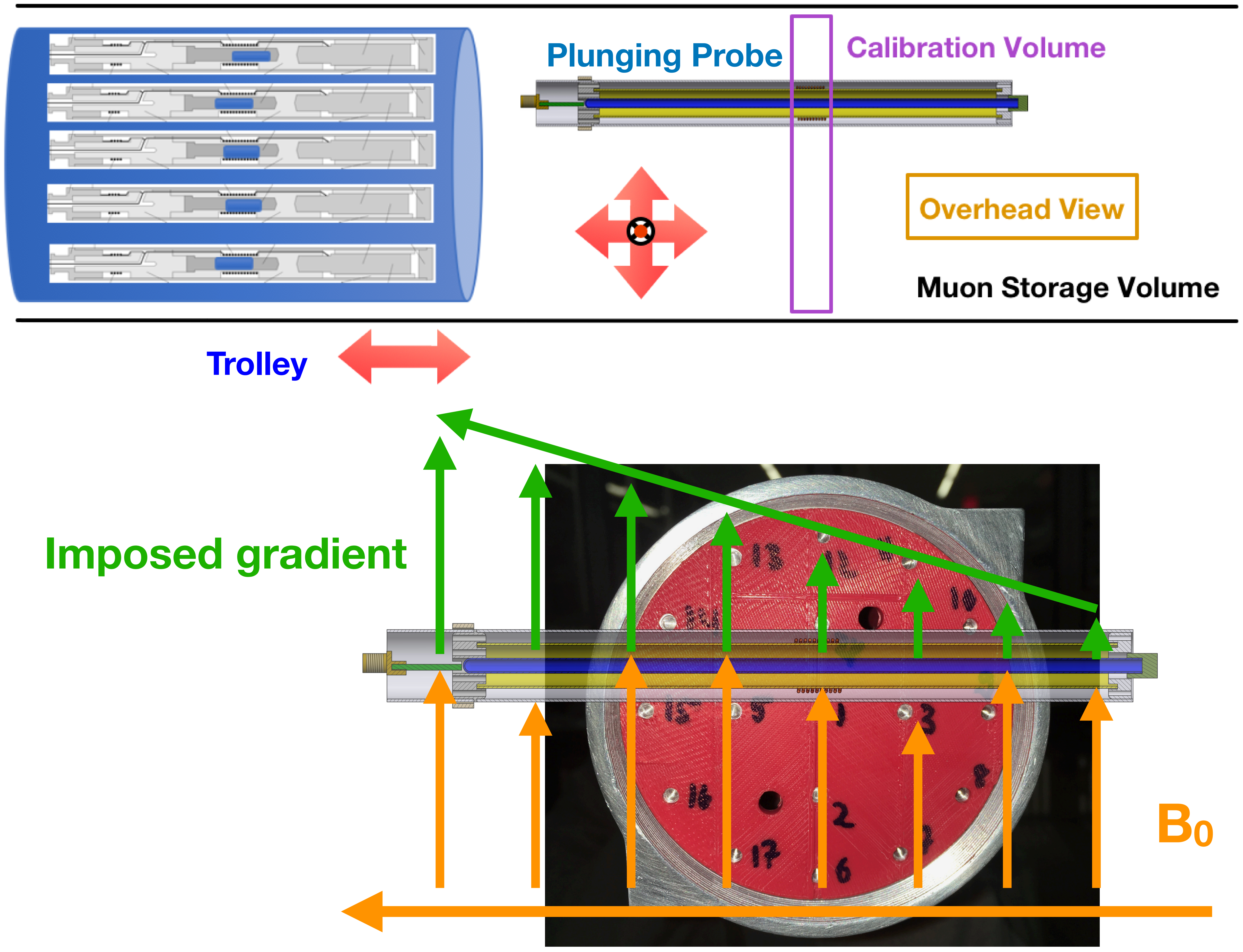
- Iterate until **plunging probe** ΔB matches **trolley** probe ΔB
- Perform for radial, vertical, azimuthal coordinates



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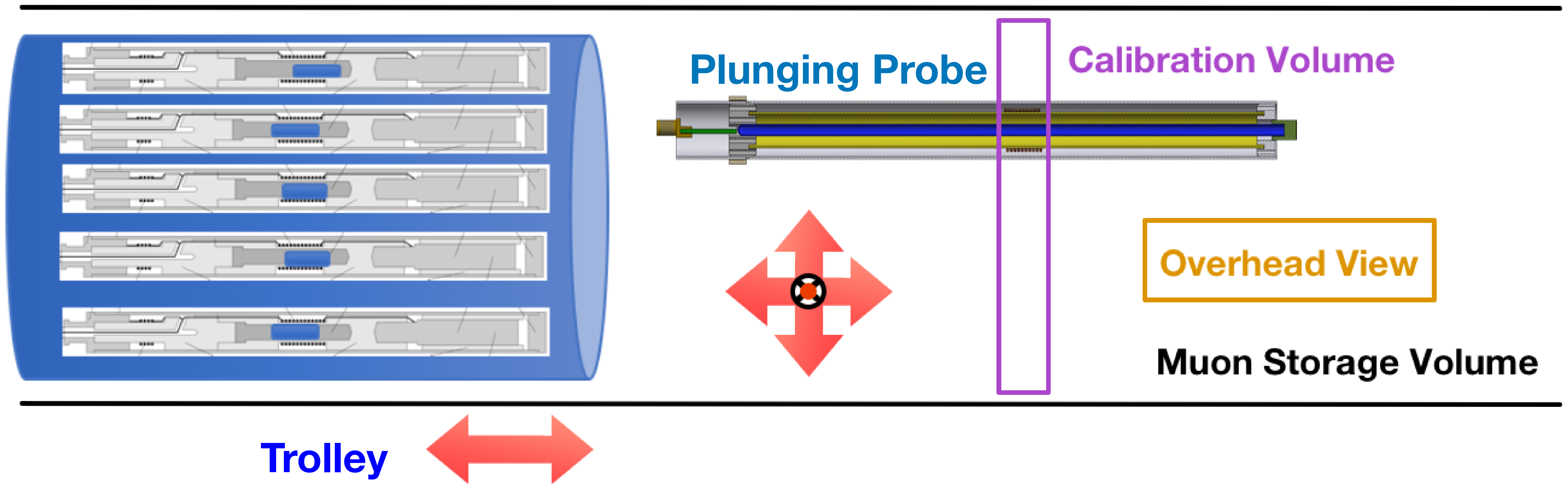
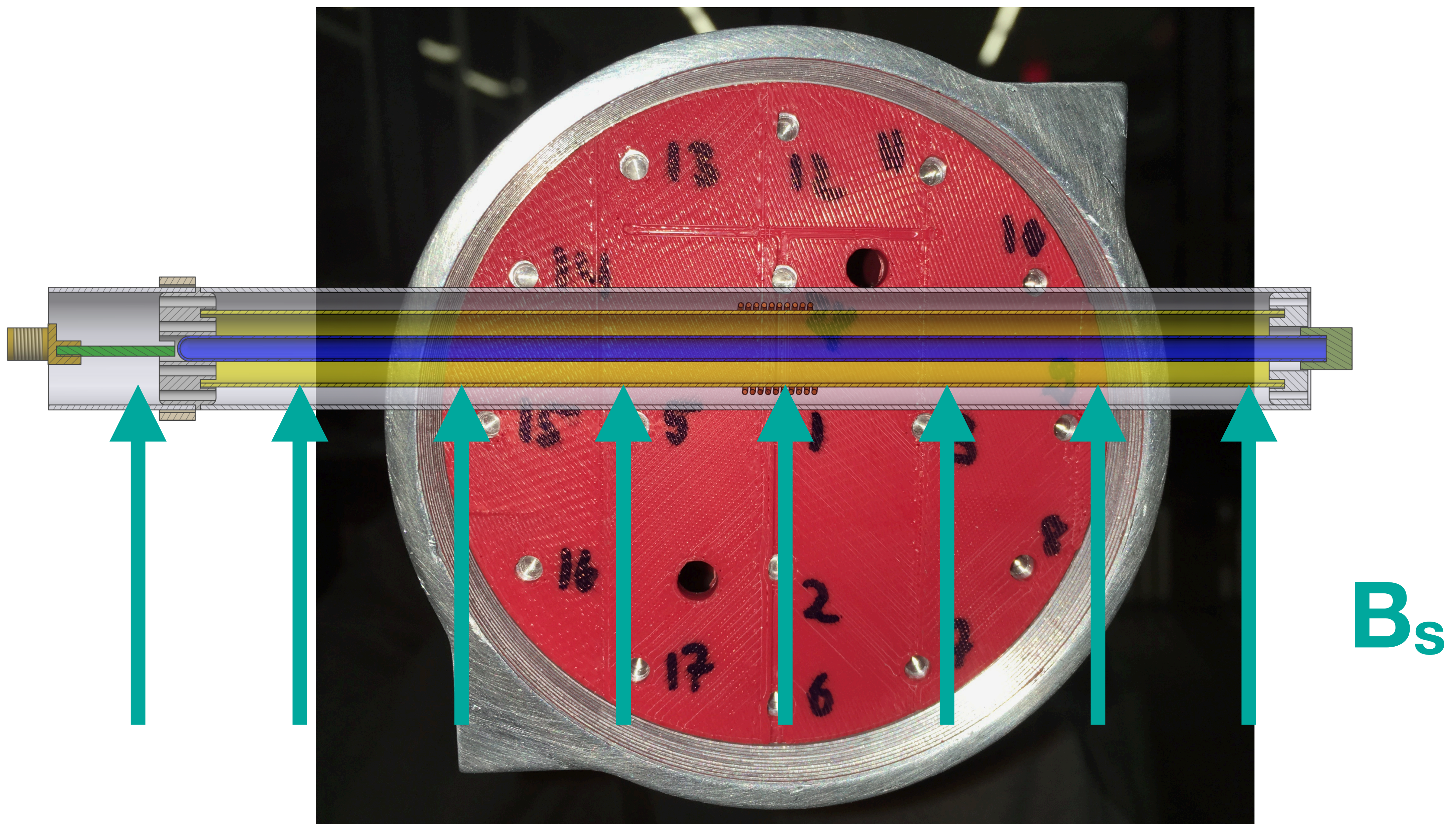
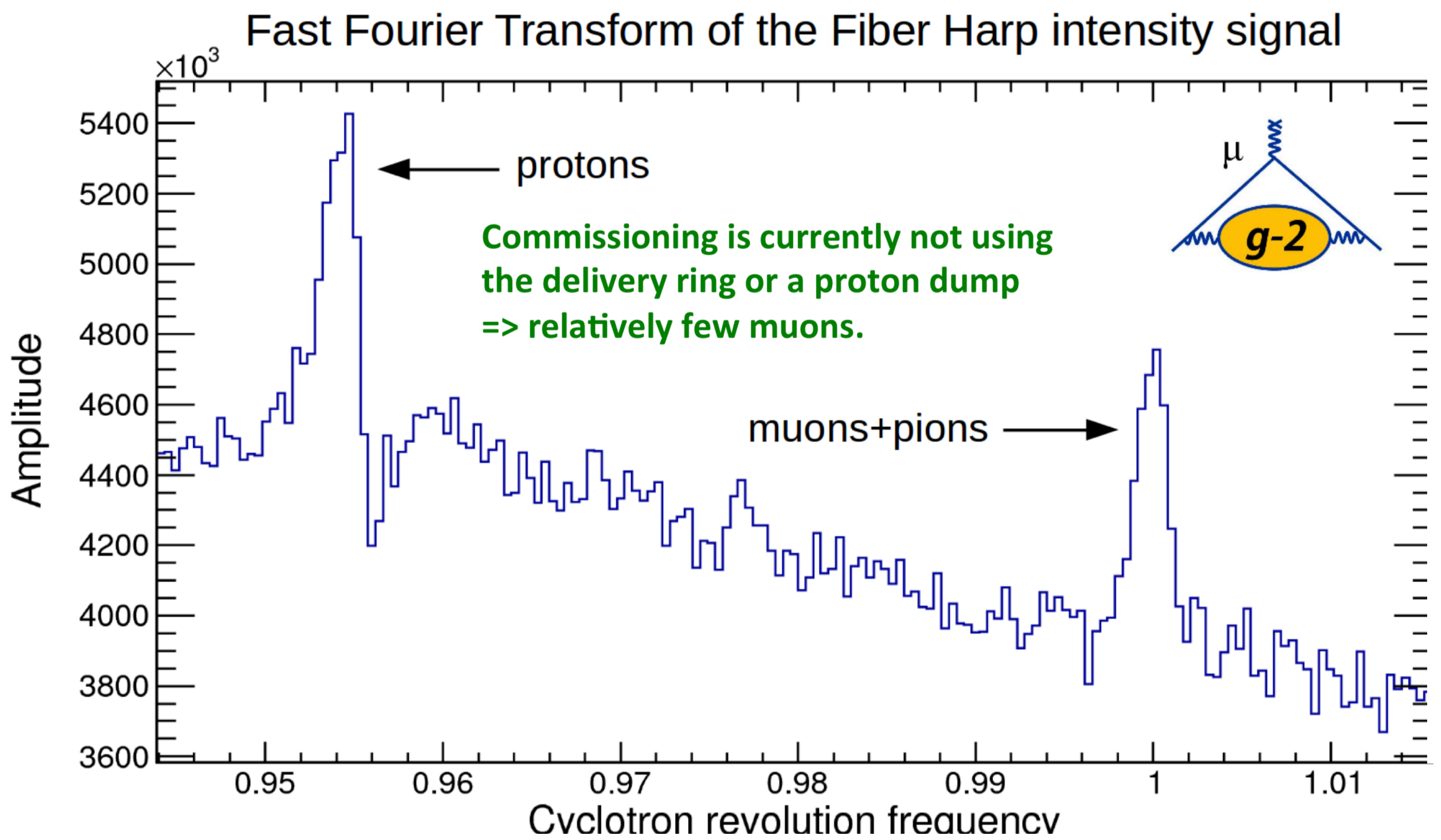
- Iterate until **plunging probe** ΔB matches **trolley** probe ΔB
- Perform for radial, vertical, azimuthal coordinates
- Shim the field to be **highly uniform**, and measure using the **PP** and the **trolley** (rapid swapping)



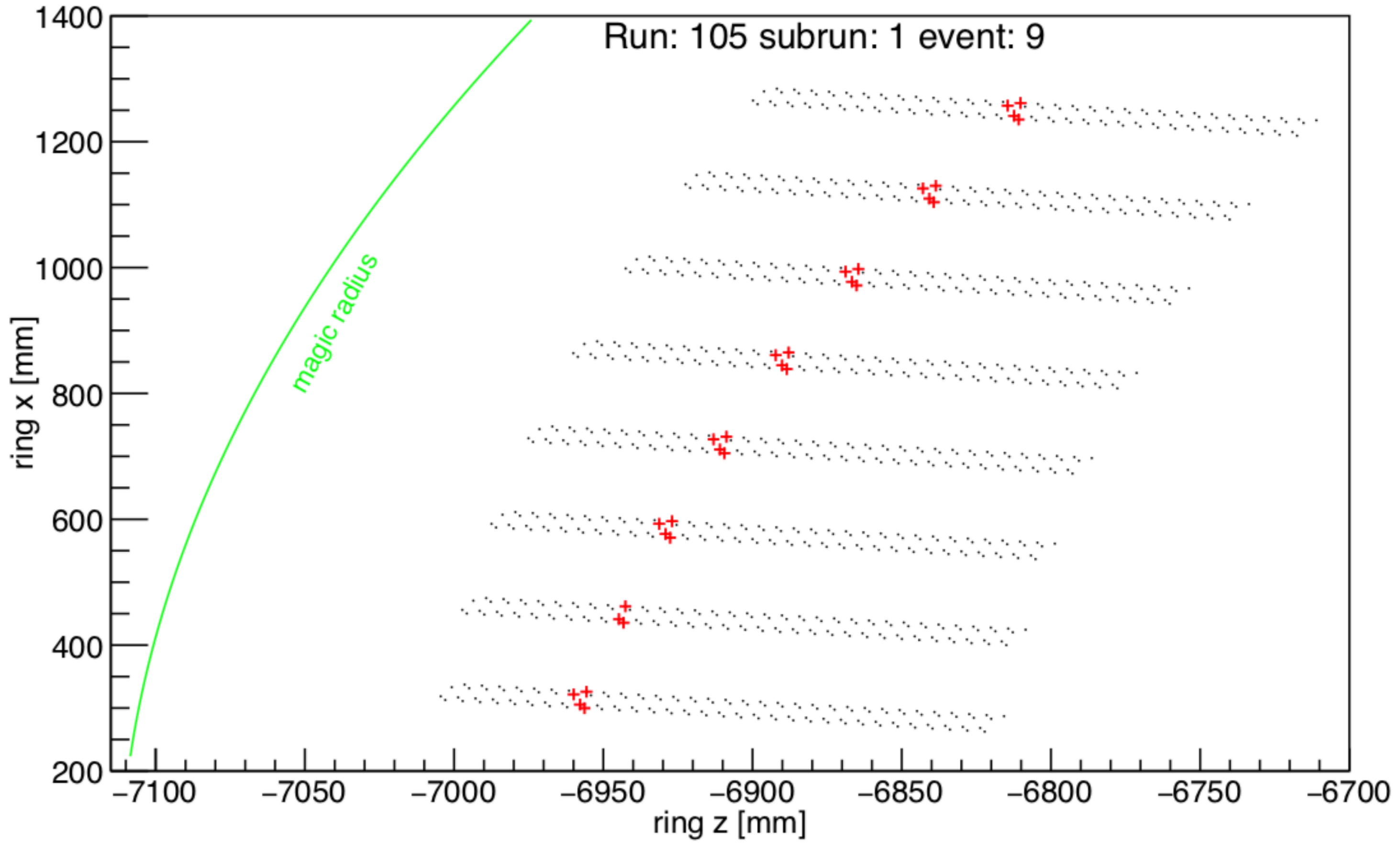


Where Were We A Year Ago? (June 2017)

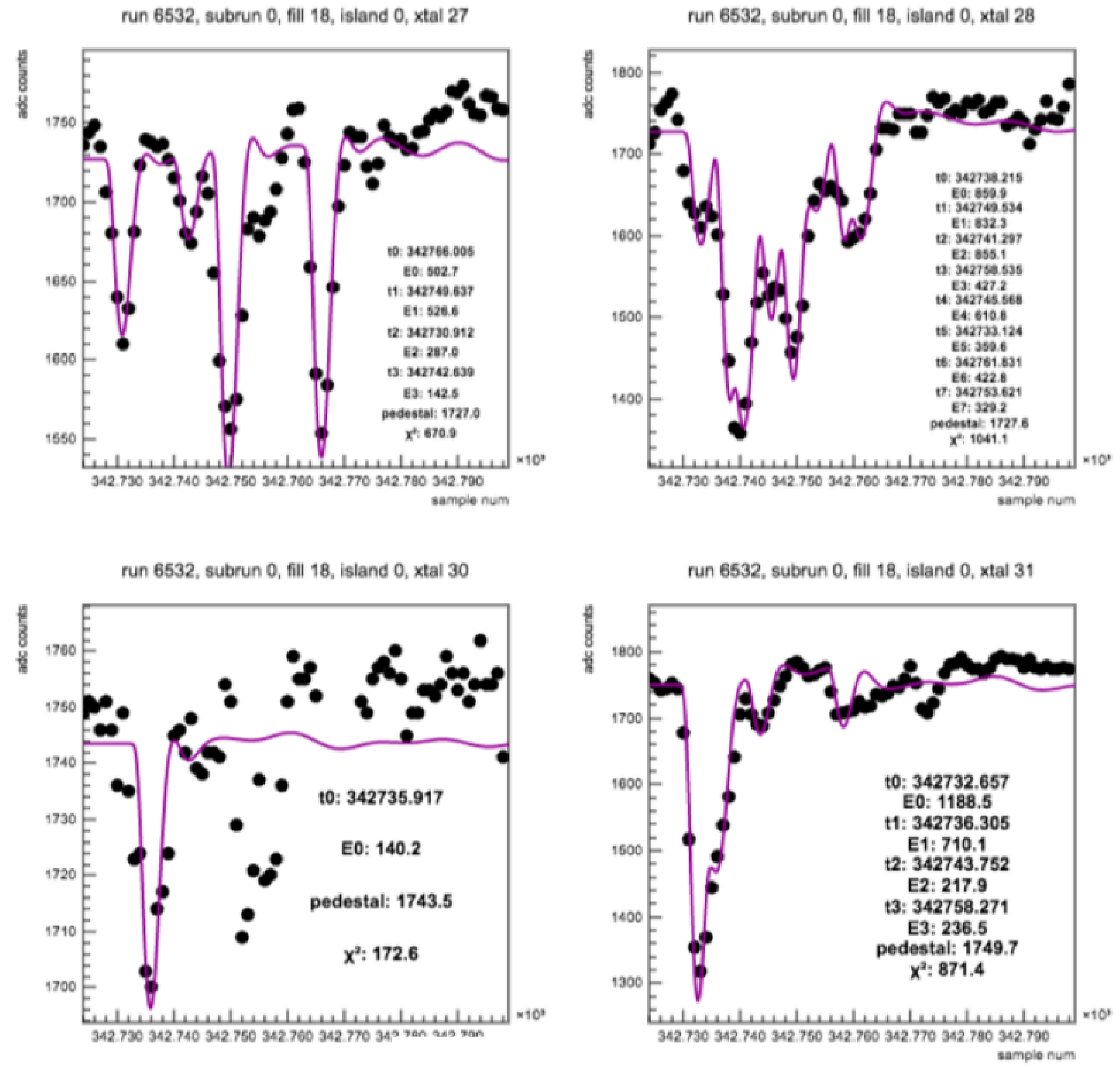
Beam: (mostly) protons, some muons



Straw Trackers starting to produce tracks

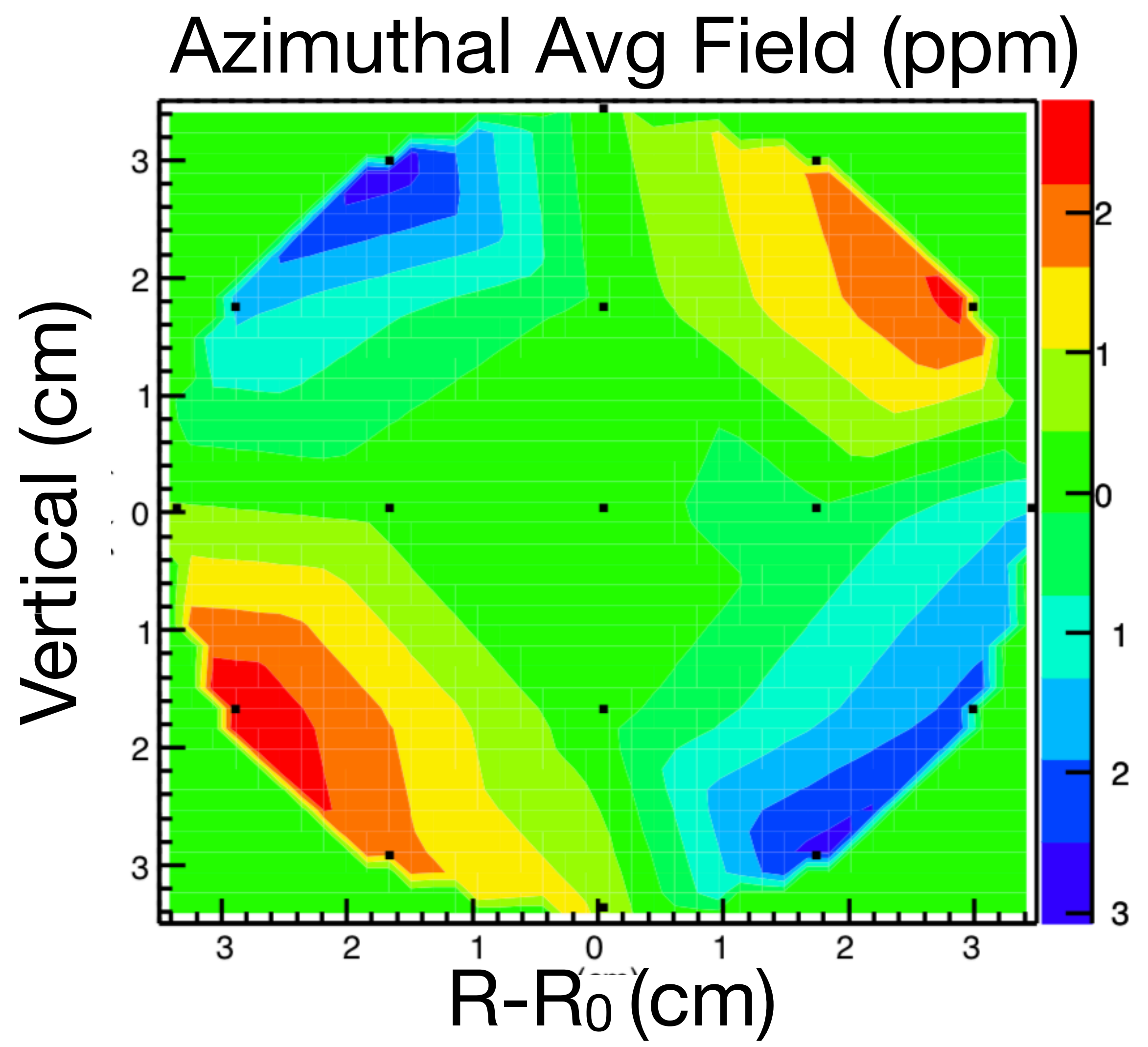


Starting to see first splashes of beam on the calorimeters

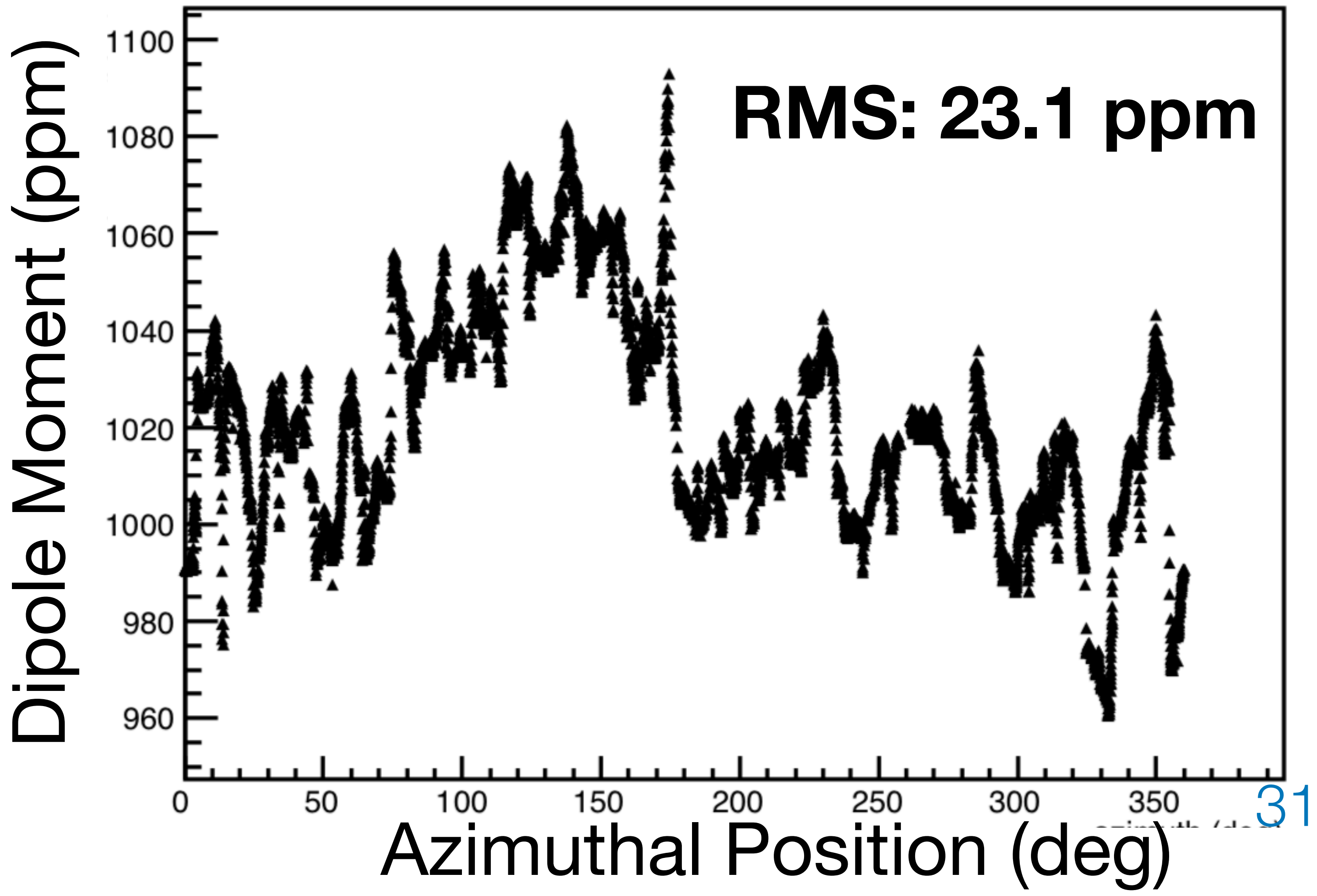


Magnetic Field:

- Starting to take in-vacuum **trolley** runs
- Had some large multipole moments to correct
- Learning how to optimize **Surface Coils** to minimize higher-order moments



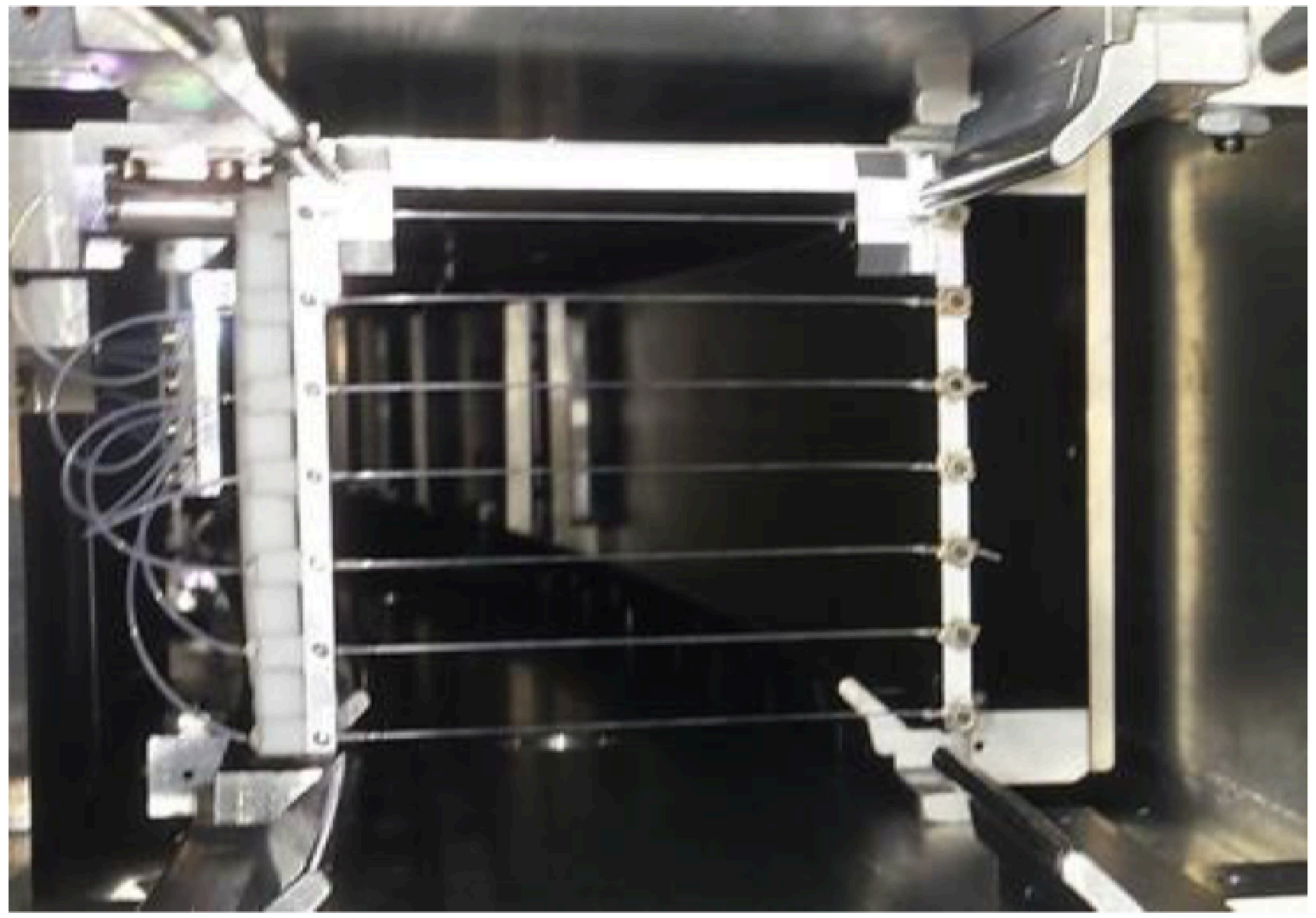
	Norm	Skew
Quad	-0.63	-0.21
Sext	-0.07	4.47
Octu	-0.71	0.36
Decu	0.35	-0.20
Dipole	-0.0	

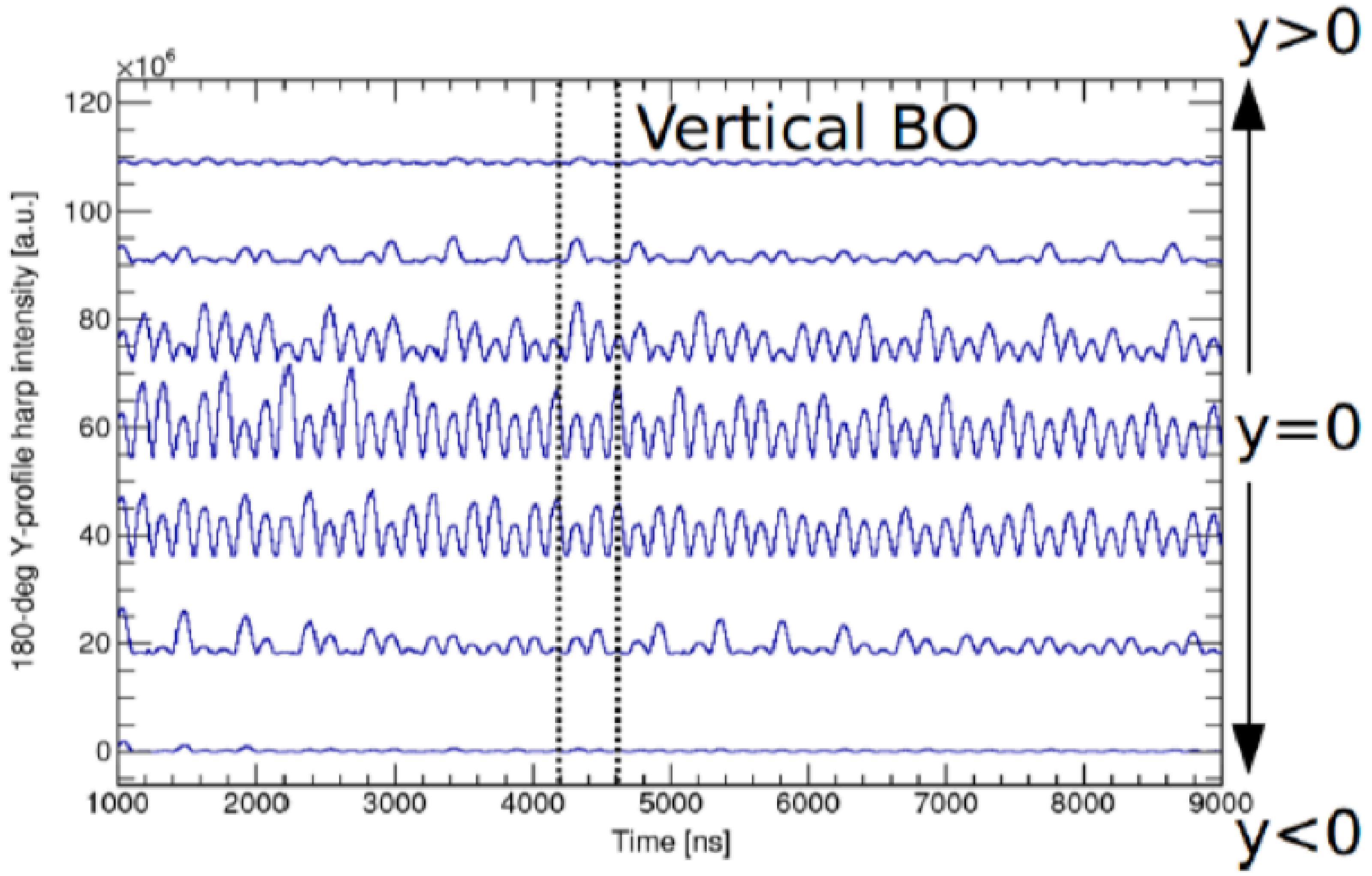


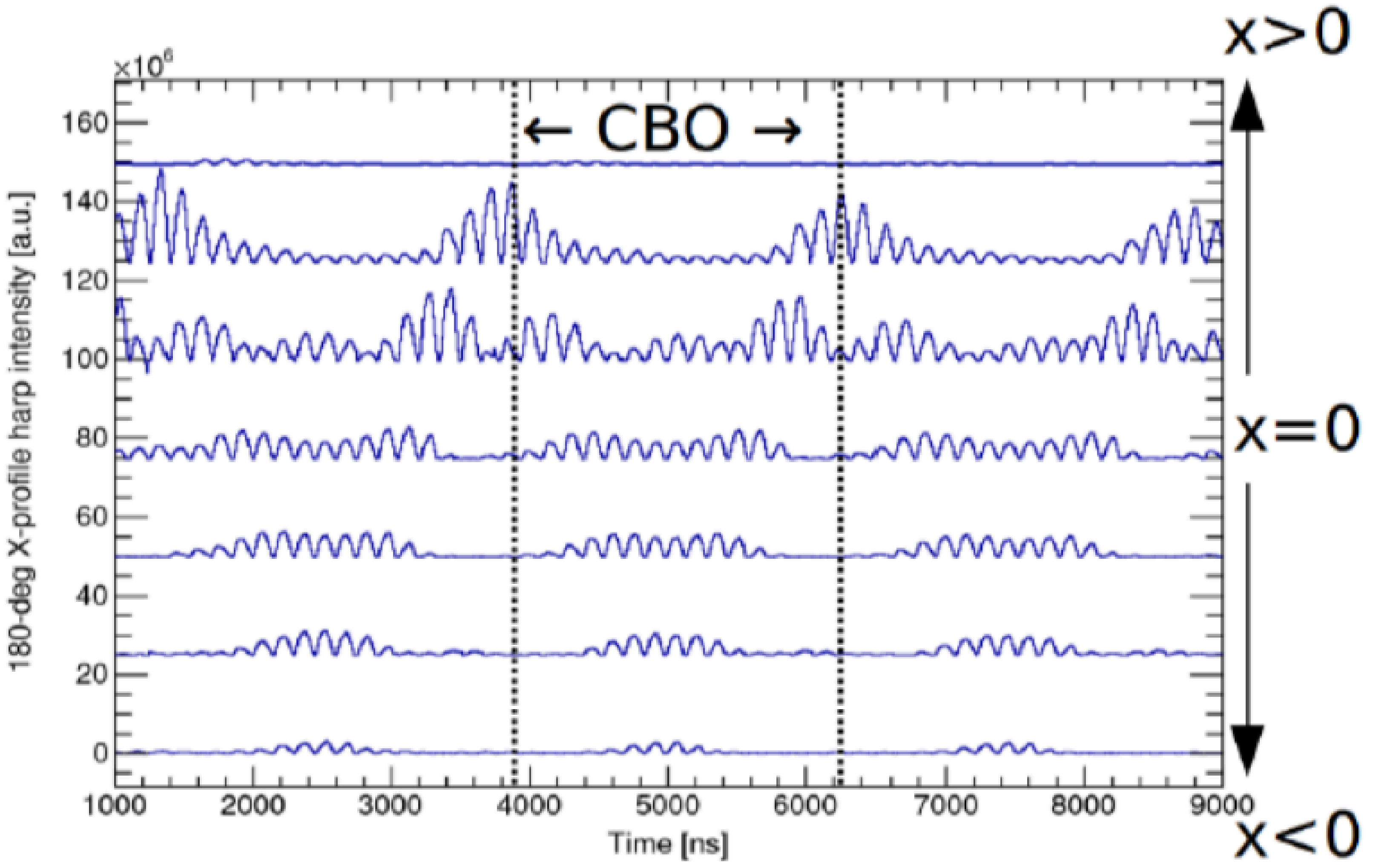
Detectors: What's New in the Past Year?

Taking and storing muon beam

- Deploy **Fiber Harps** to learn how the muons behave
- Measure beam flux as a function of time
- Study important characteristics: vertical, radial motion







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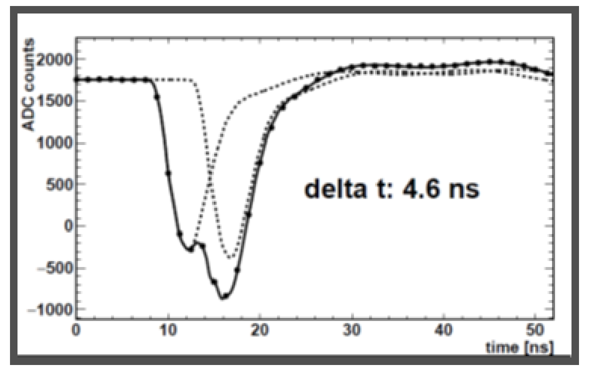

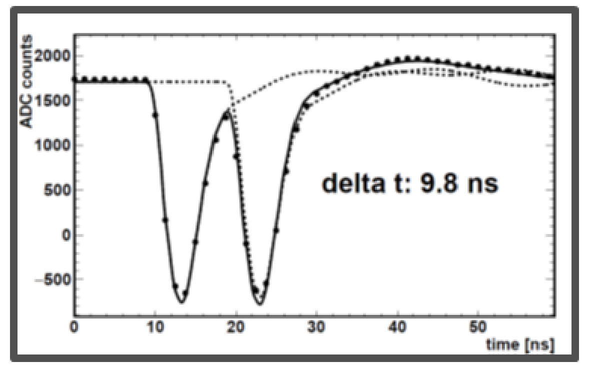

- **Calorimeters** showing excellent performance
- Fitting two pulses separated at tens of nanosecond scale, overlapped pulses

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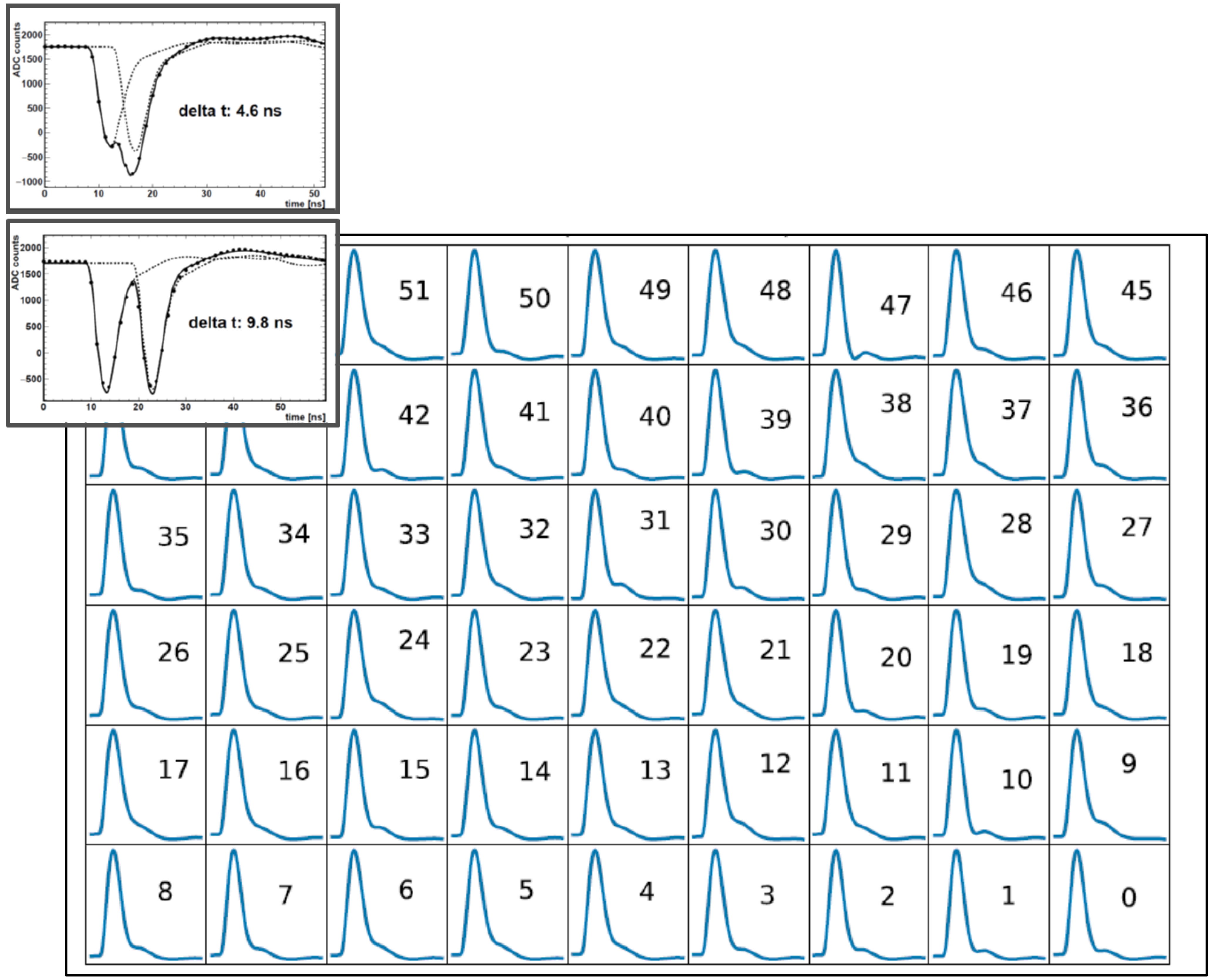

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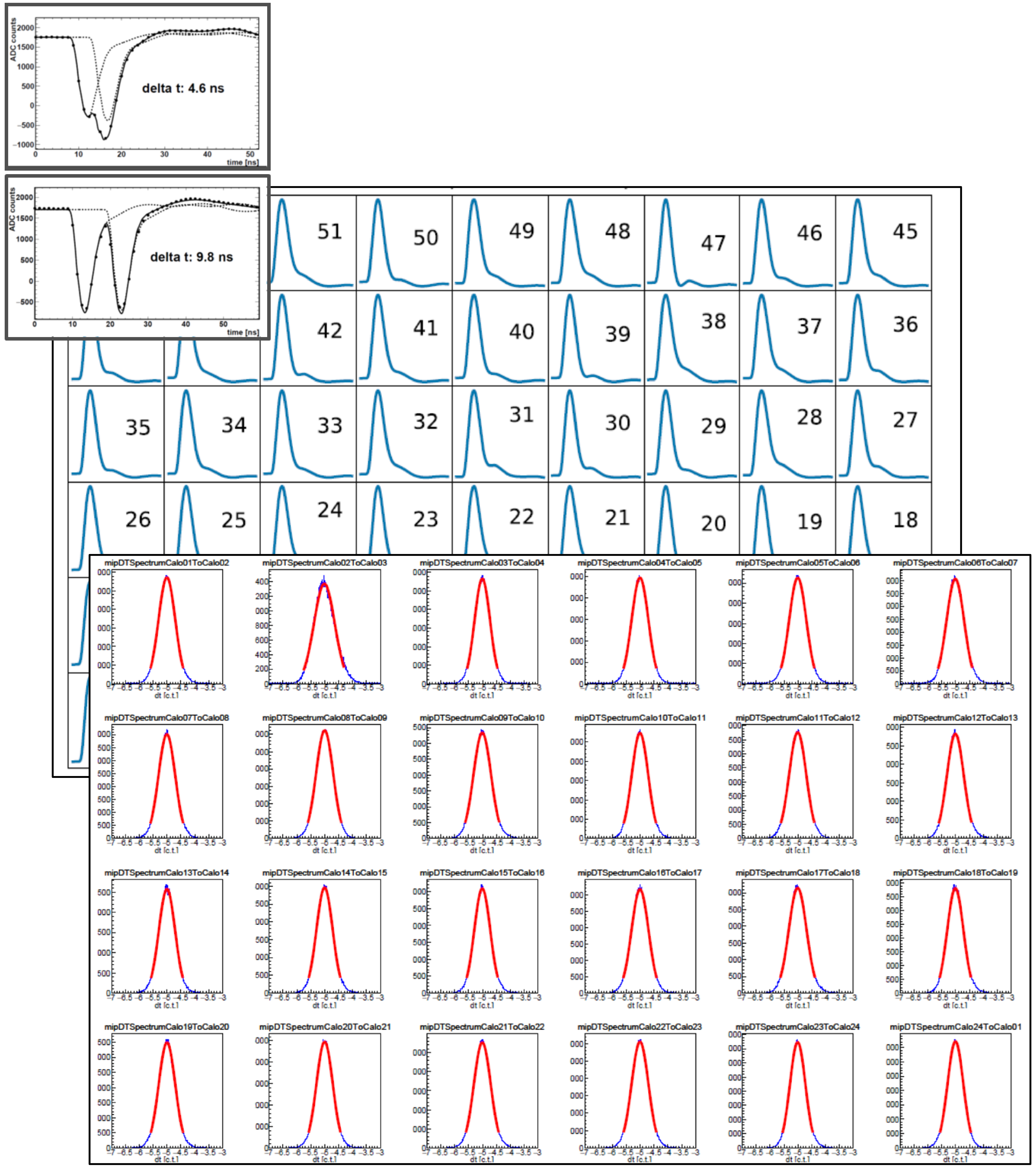

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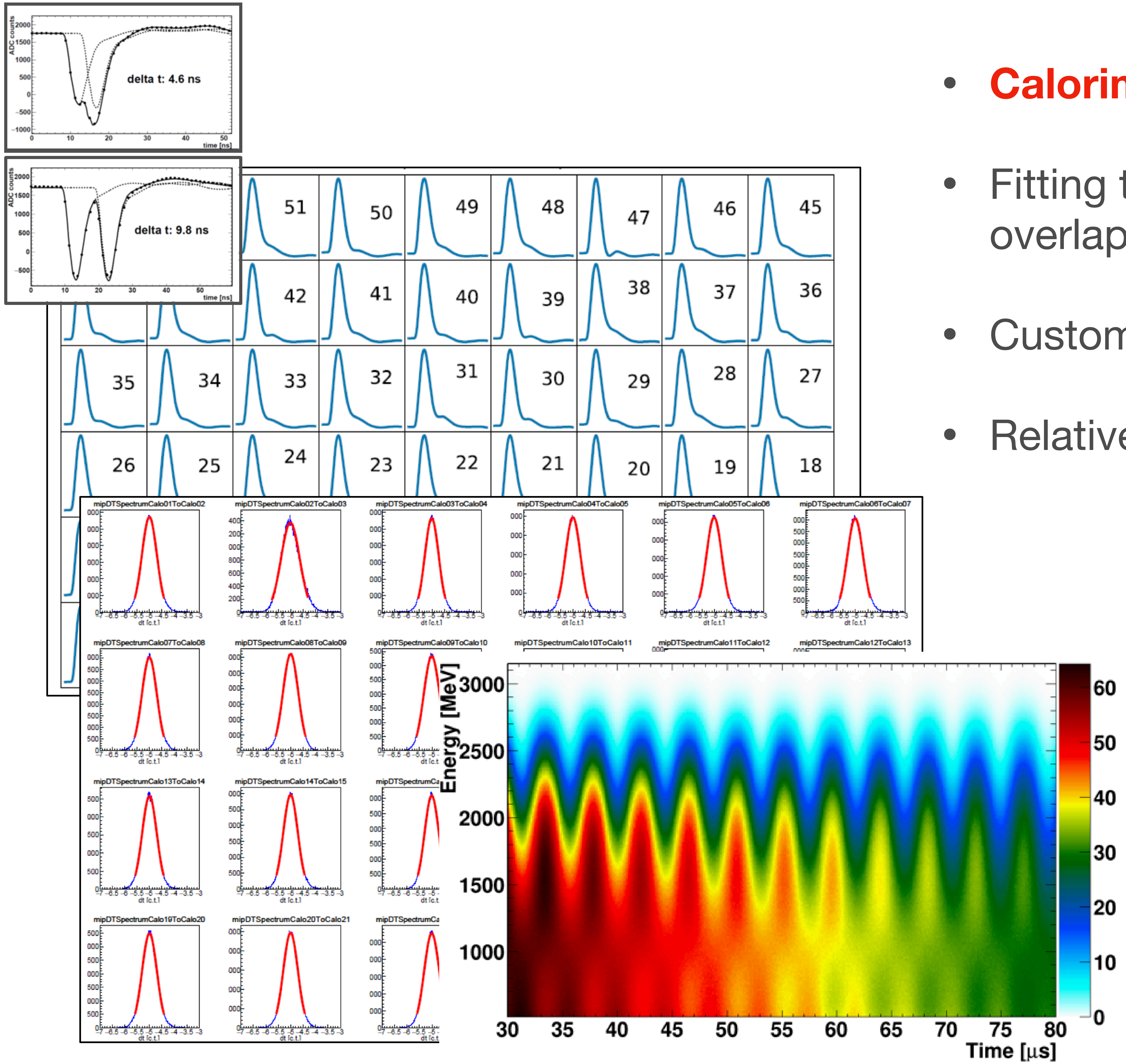

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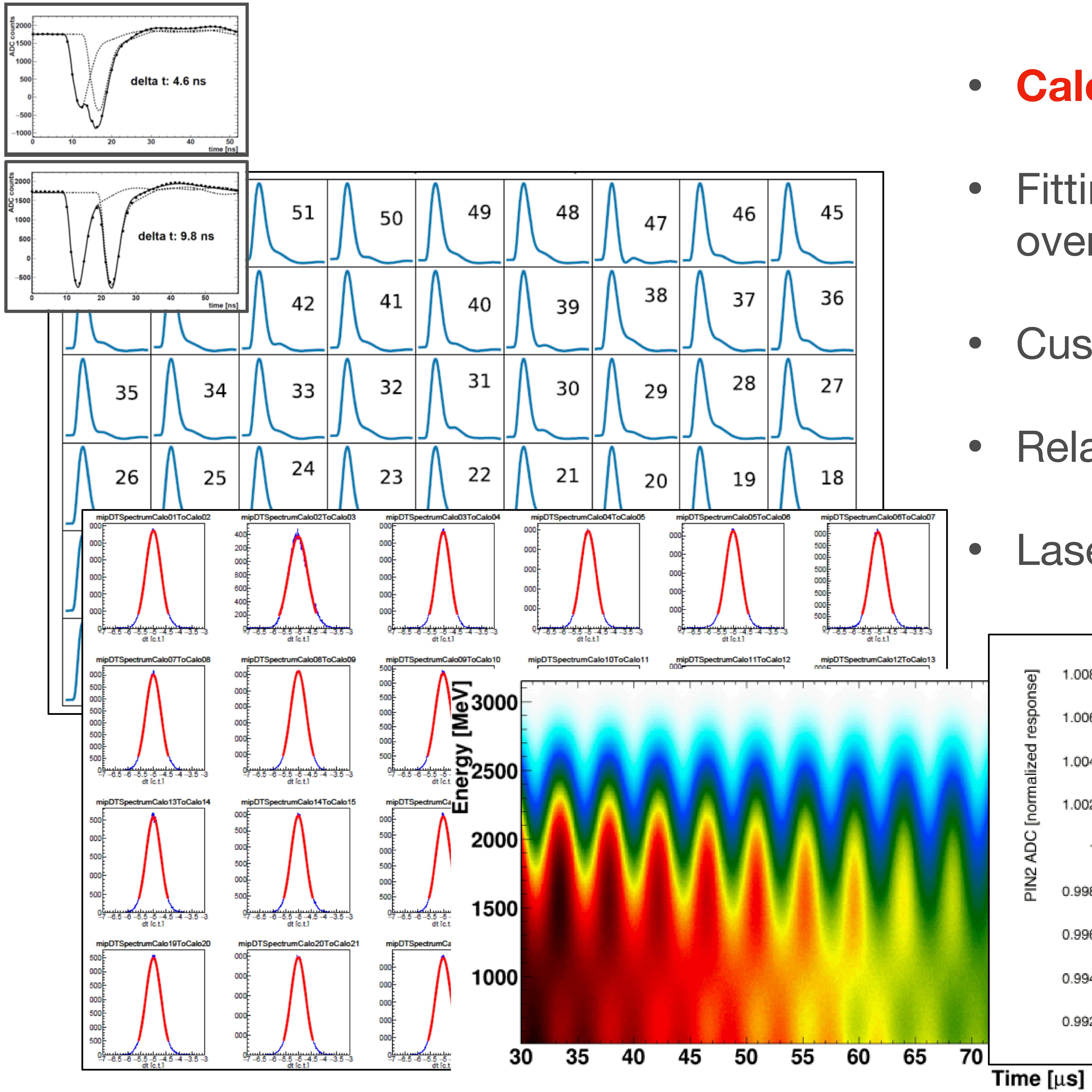
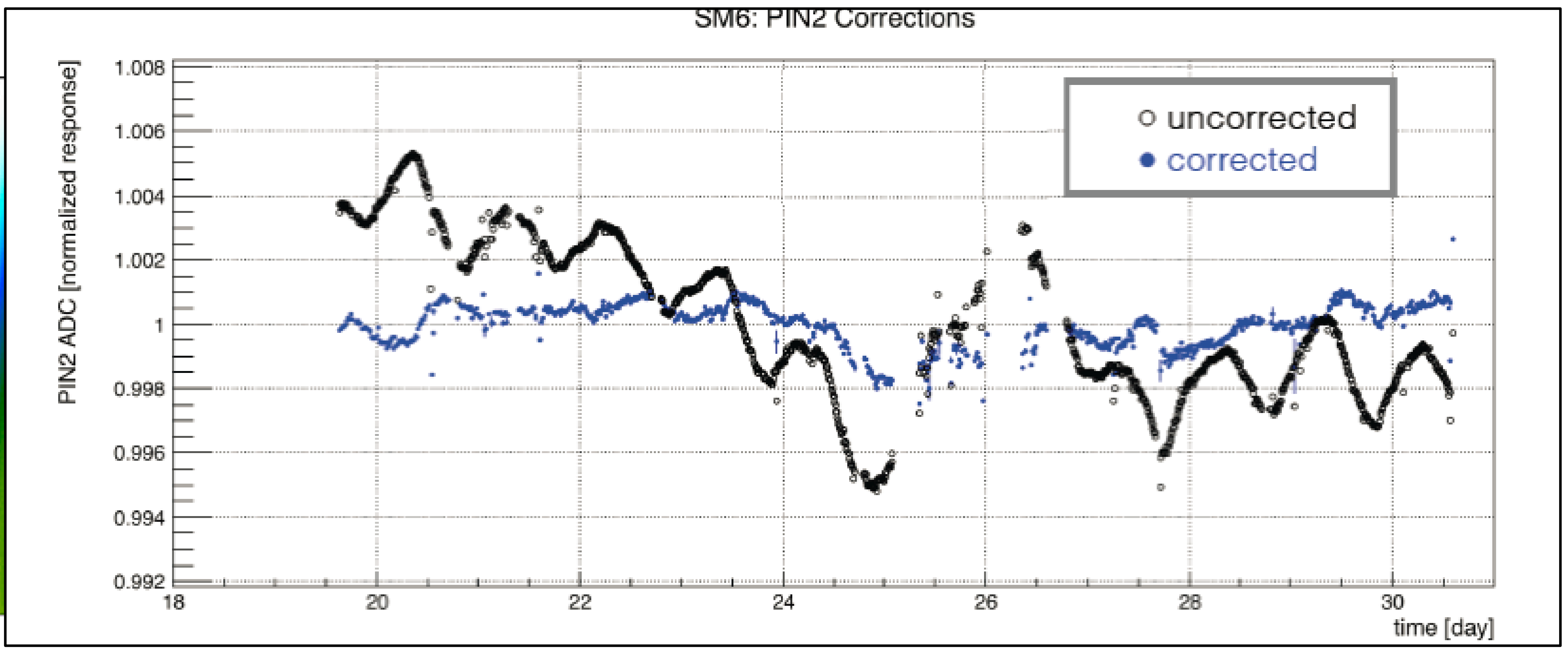
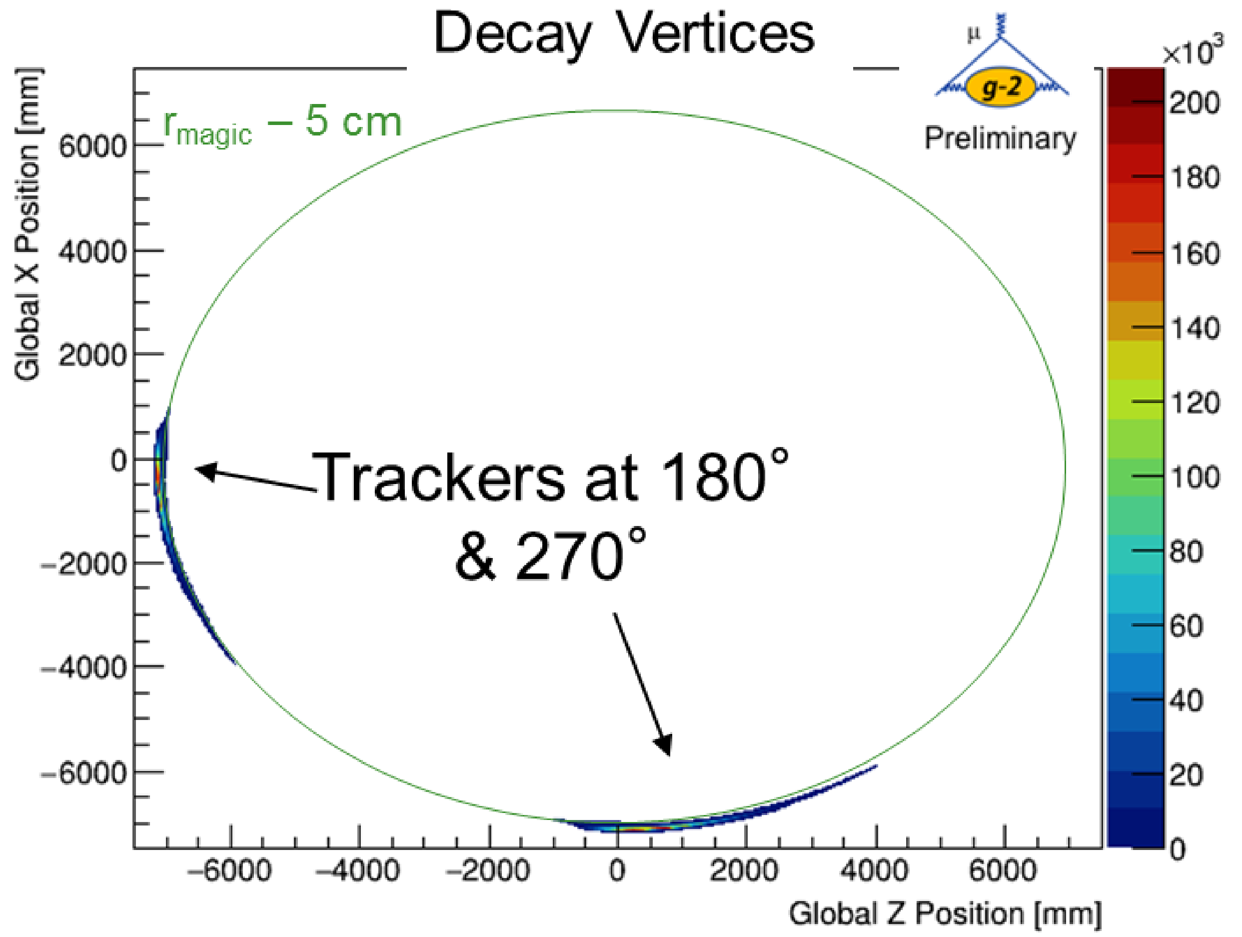


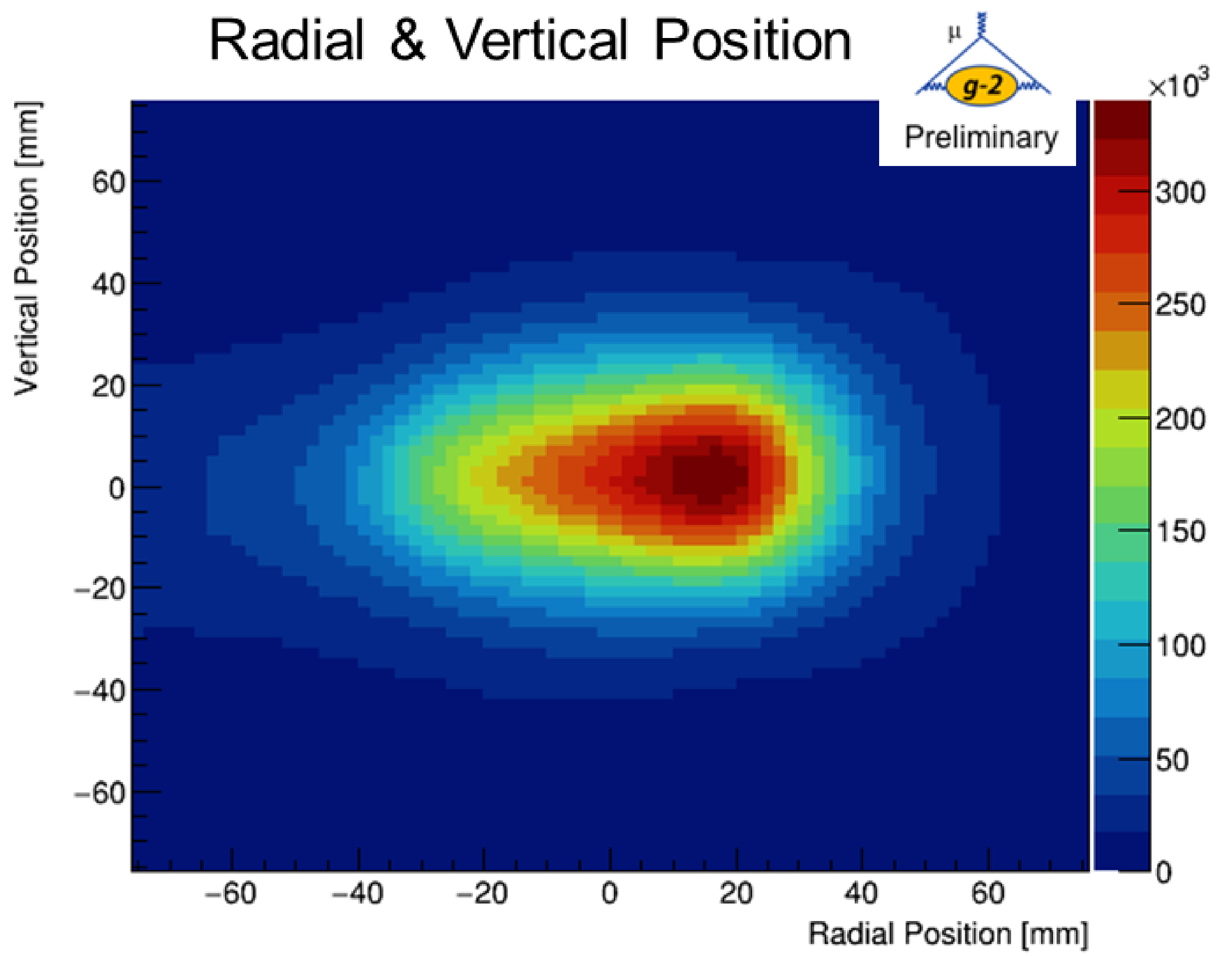
- **Calorimeters** showing excellent performance
- Fitting two pulses separated at tens of nanosecond scale, overlapped pulses
- Custom shapes for all crystals
- Relative time alignment to 5 ps
- Laser system stabilizes gain to ~ 10^{-4}

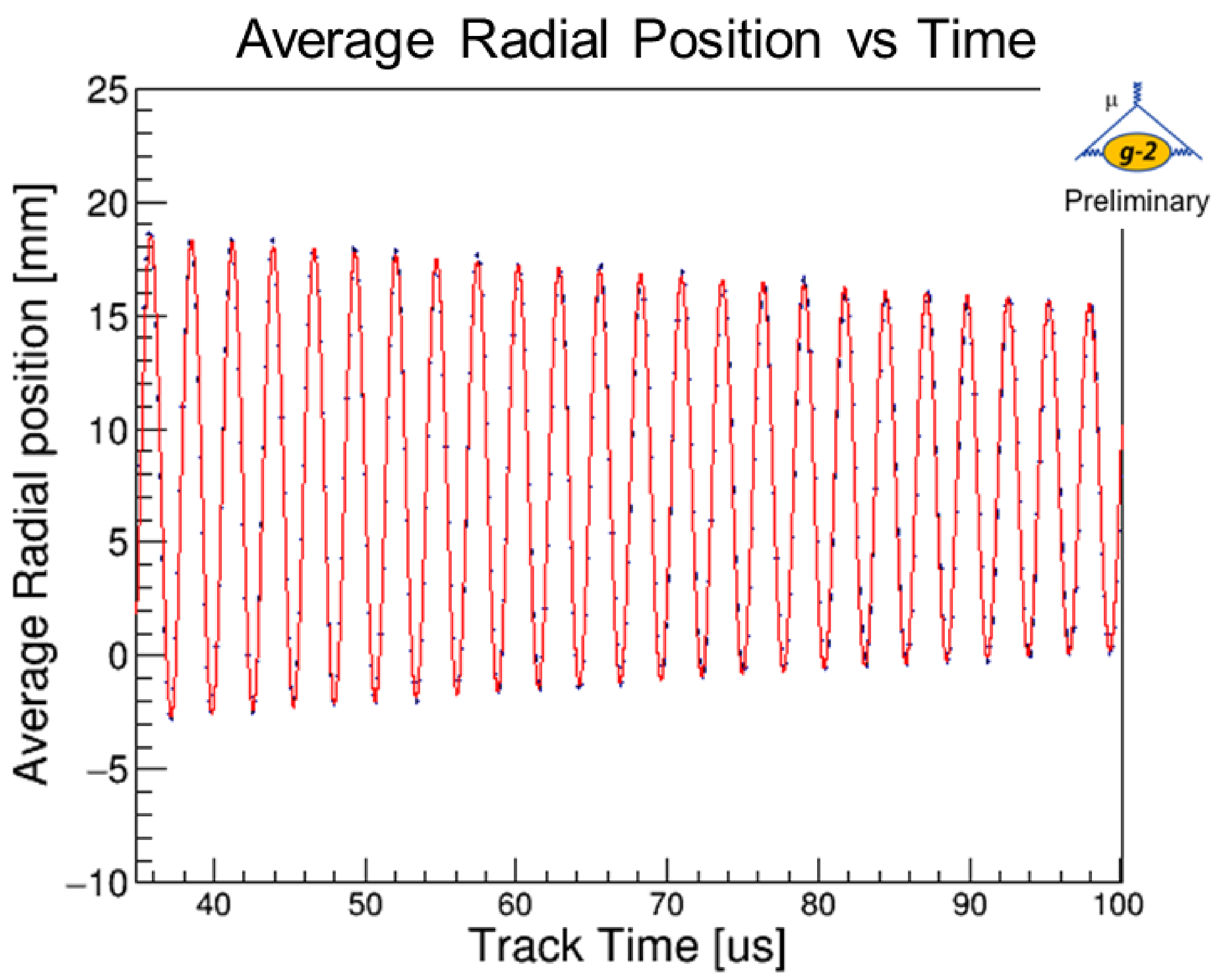


Detectors: What's New in the Past Year?

- **Trackers** are advanced, giving vital information on radial beam motion

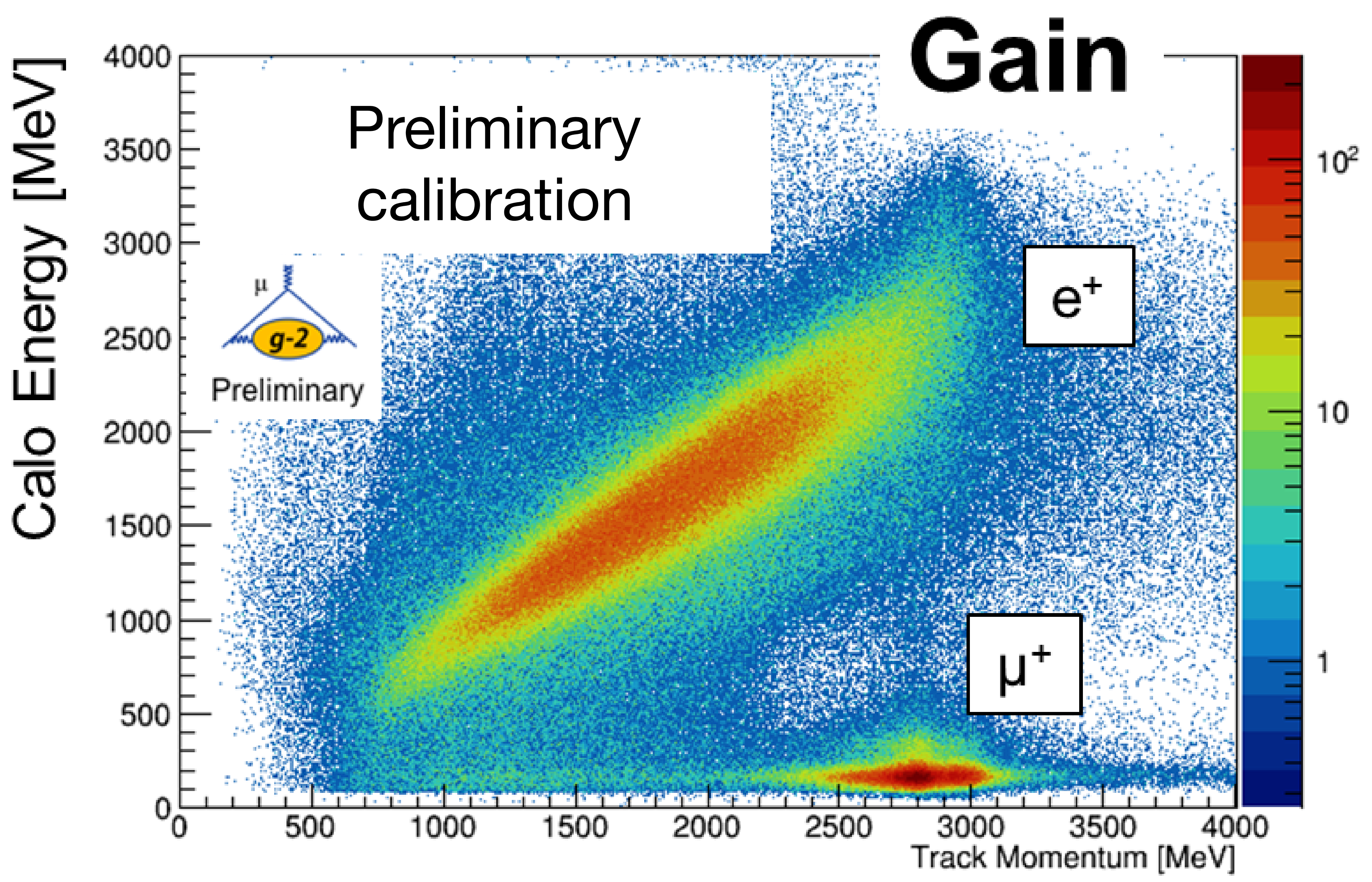


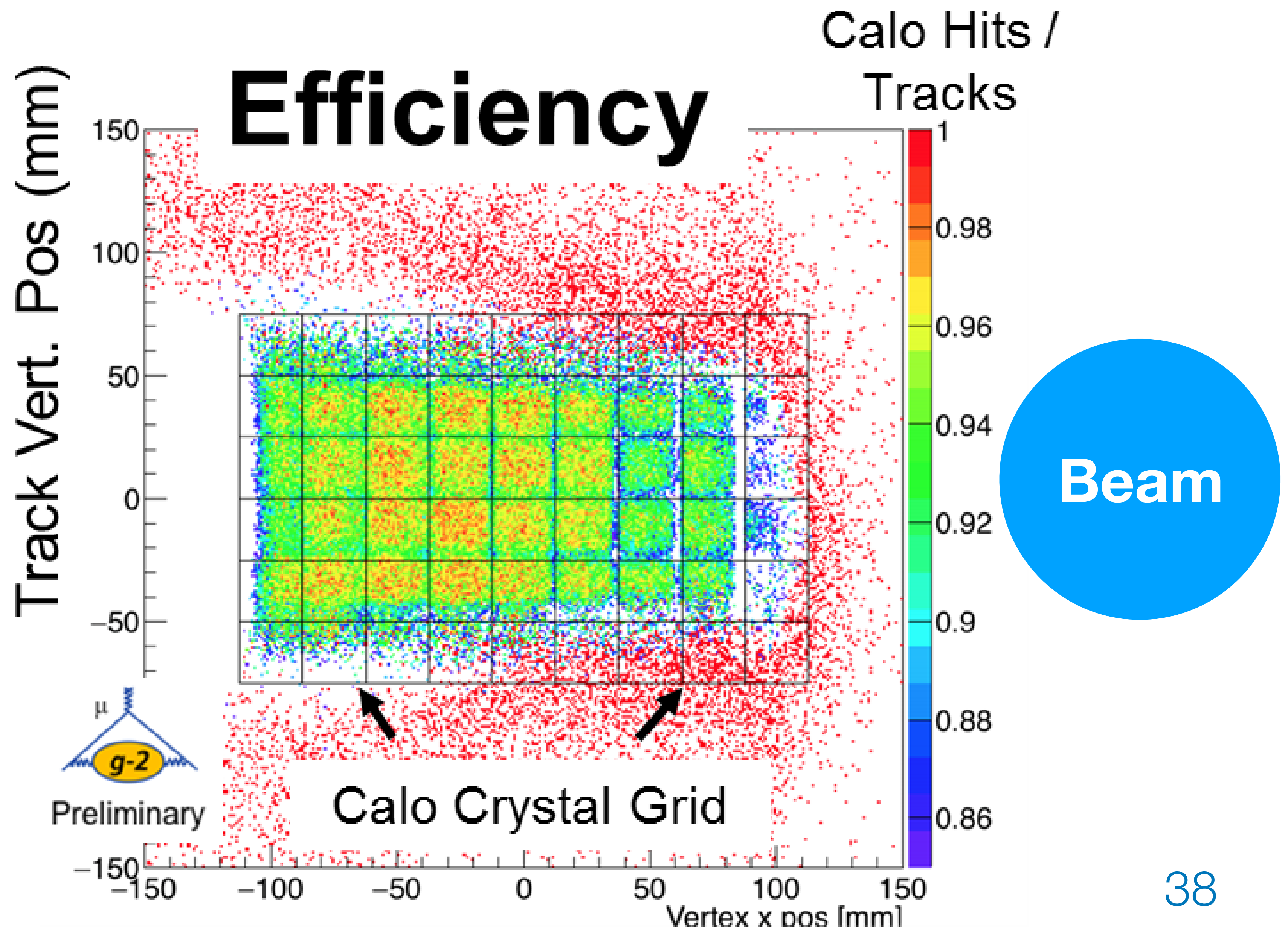




- Combined with **calos**, show excellent particle identification capabilities

- Imaging of calorimeters

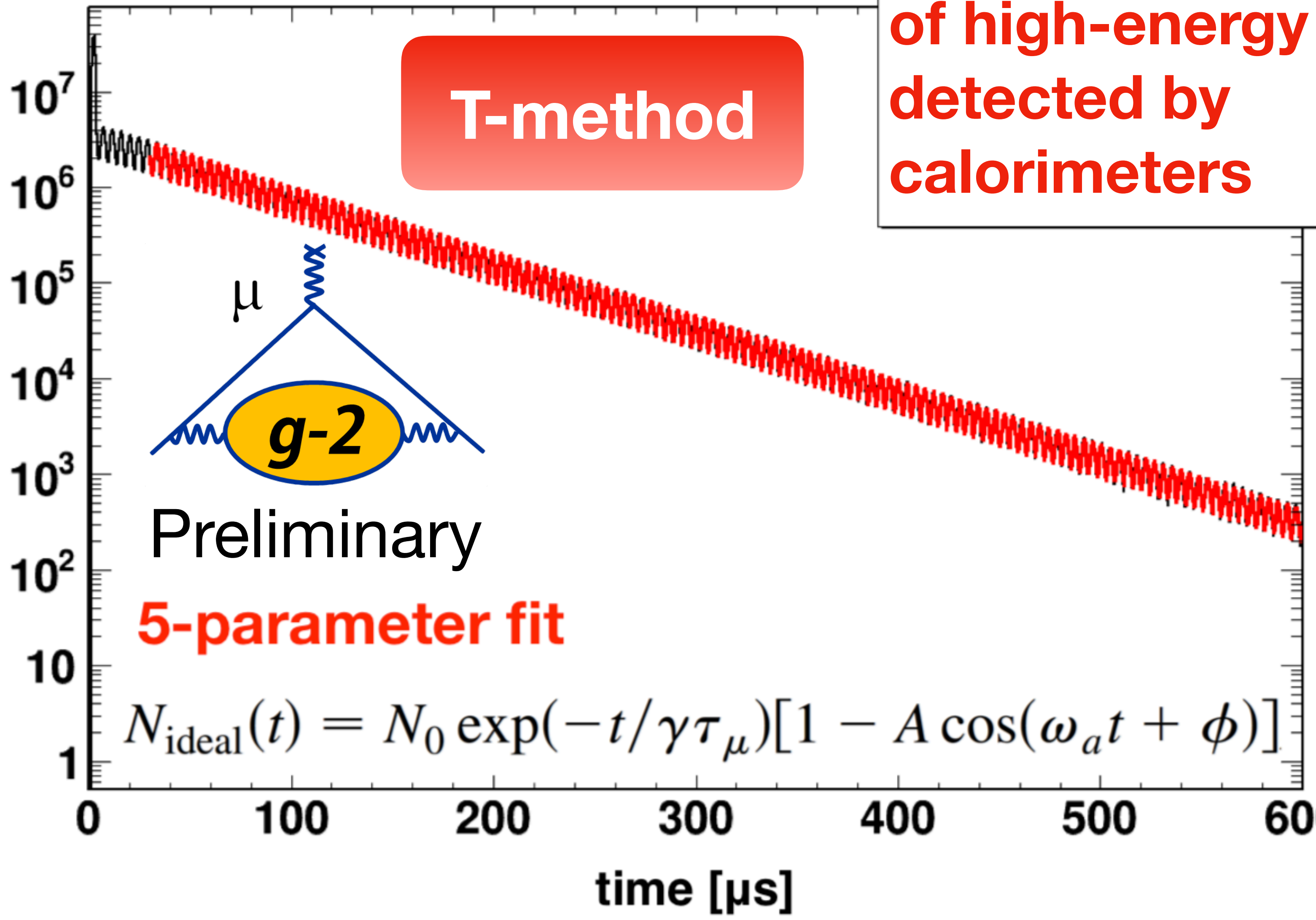


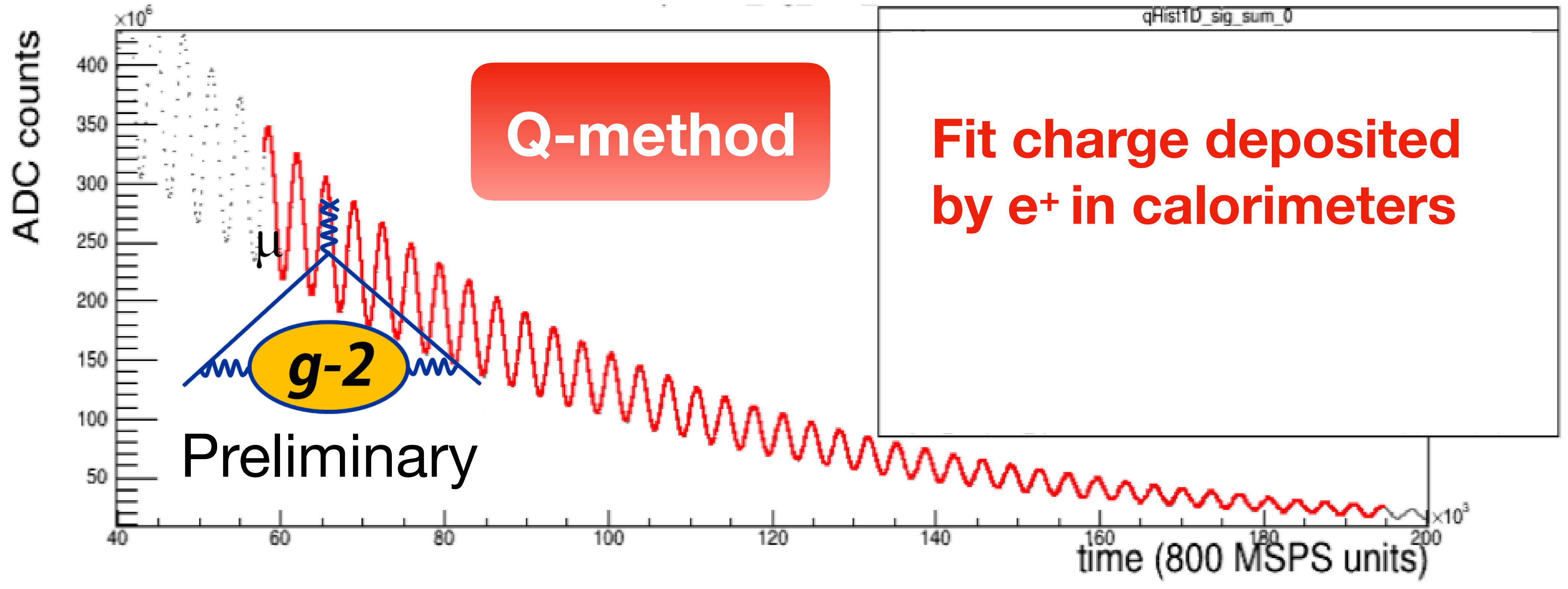


ω_a Analysis Highlights

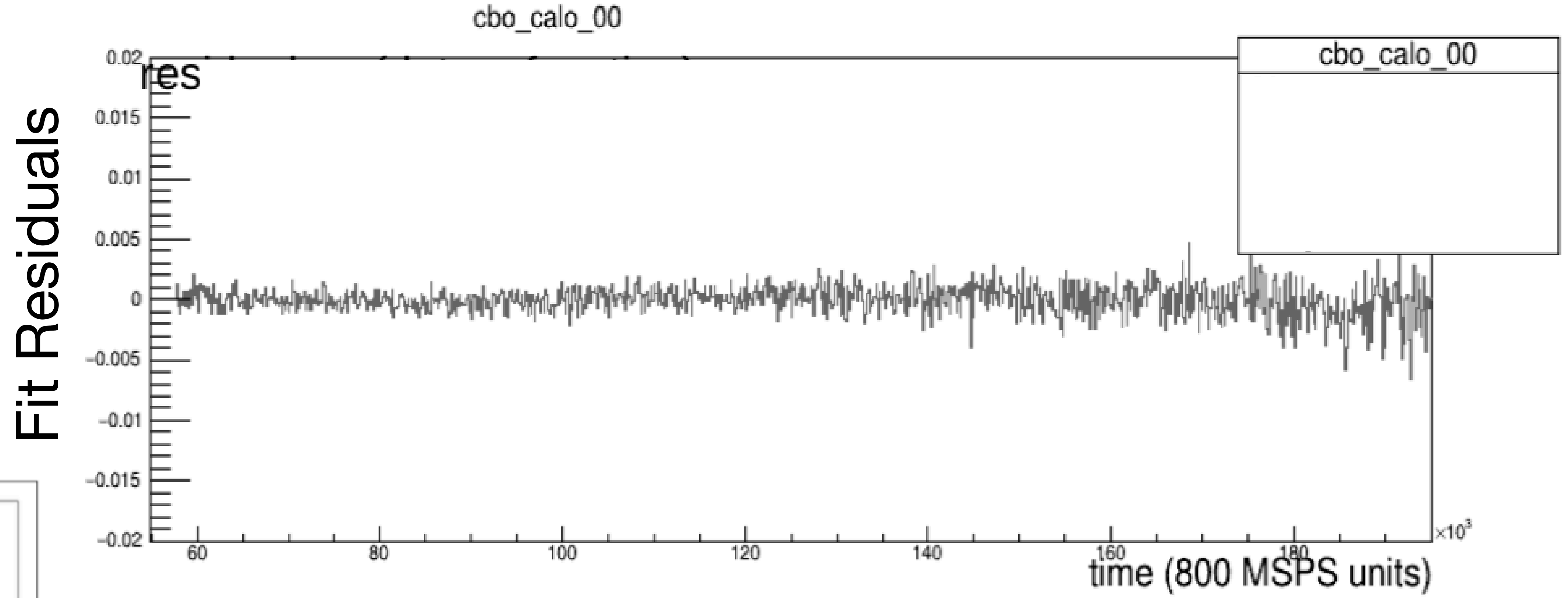
- Advanced fitting algorithms accounting for systematics
- Multiple analysis techniques — more than what's shown here!

Fit time spectrum of high-energy e+ detected by calorimeters

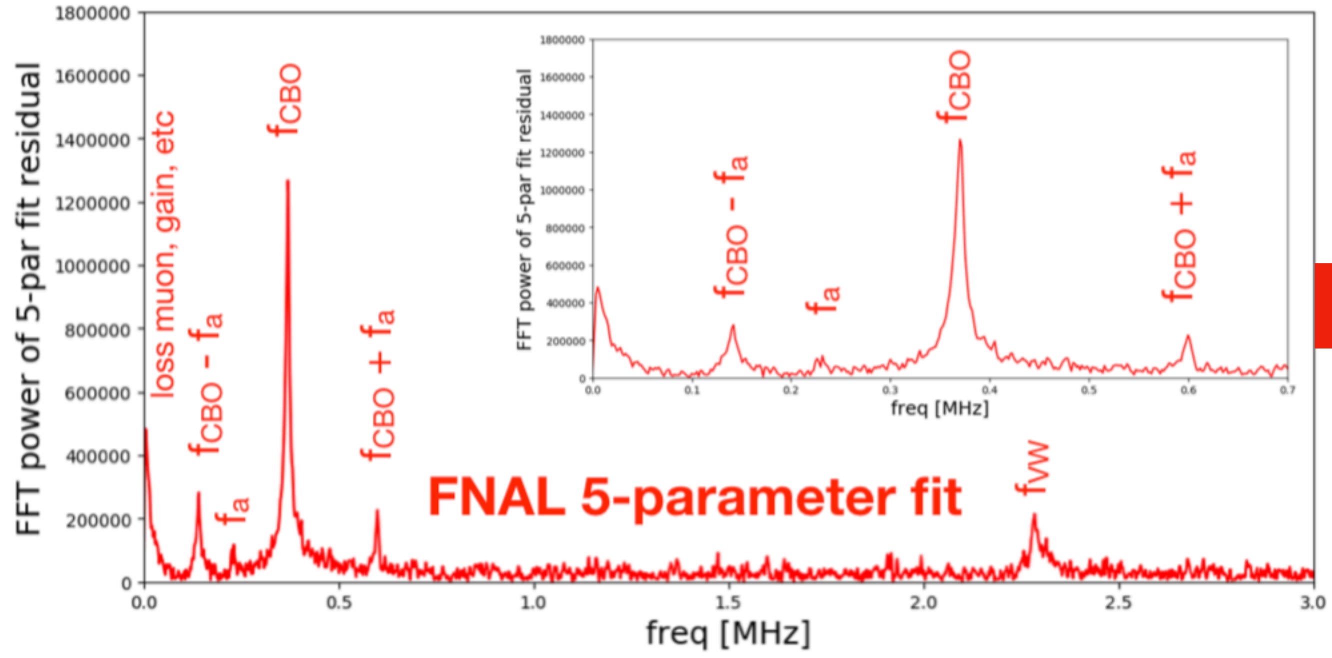


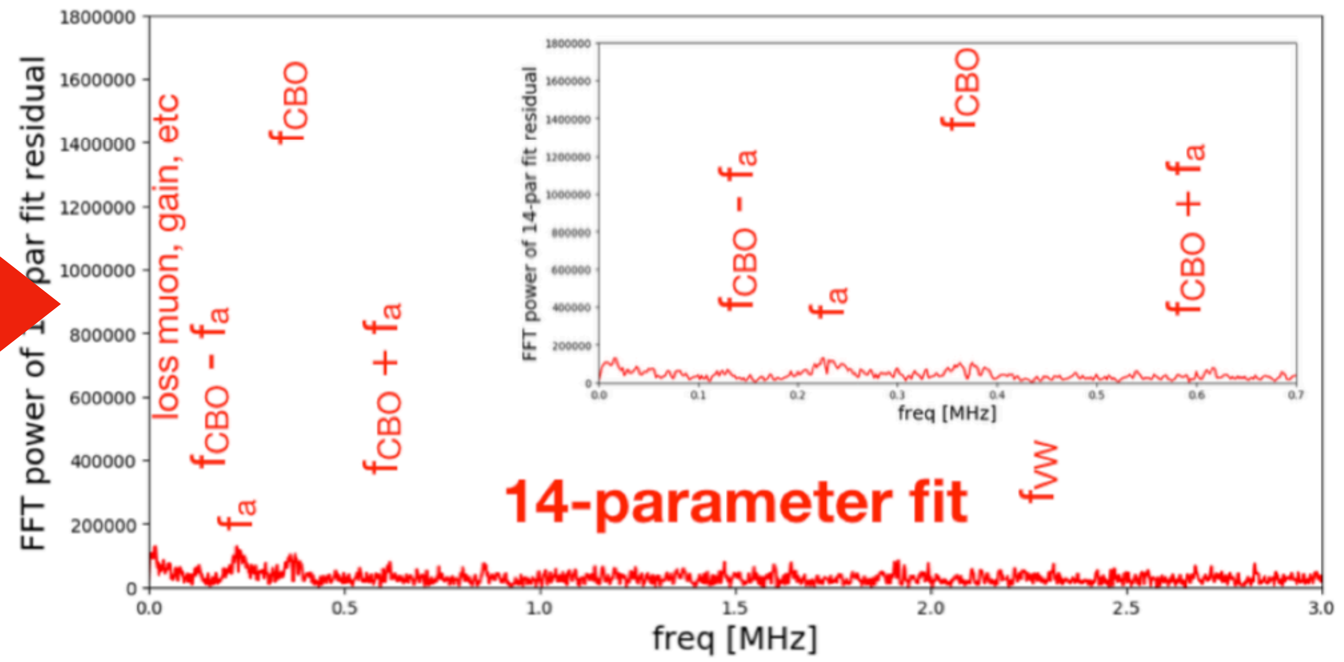


Fit charge deposited by e+ in calorimeters



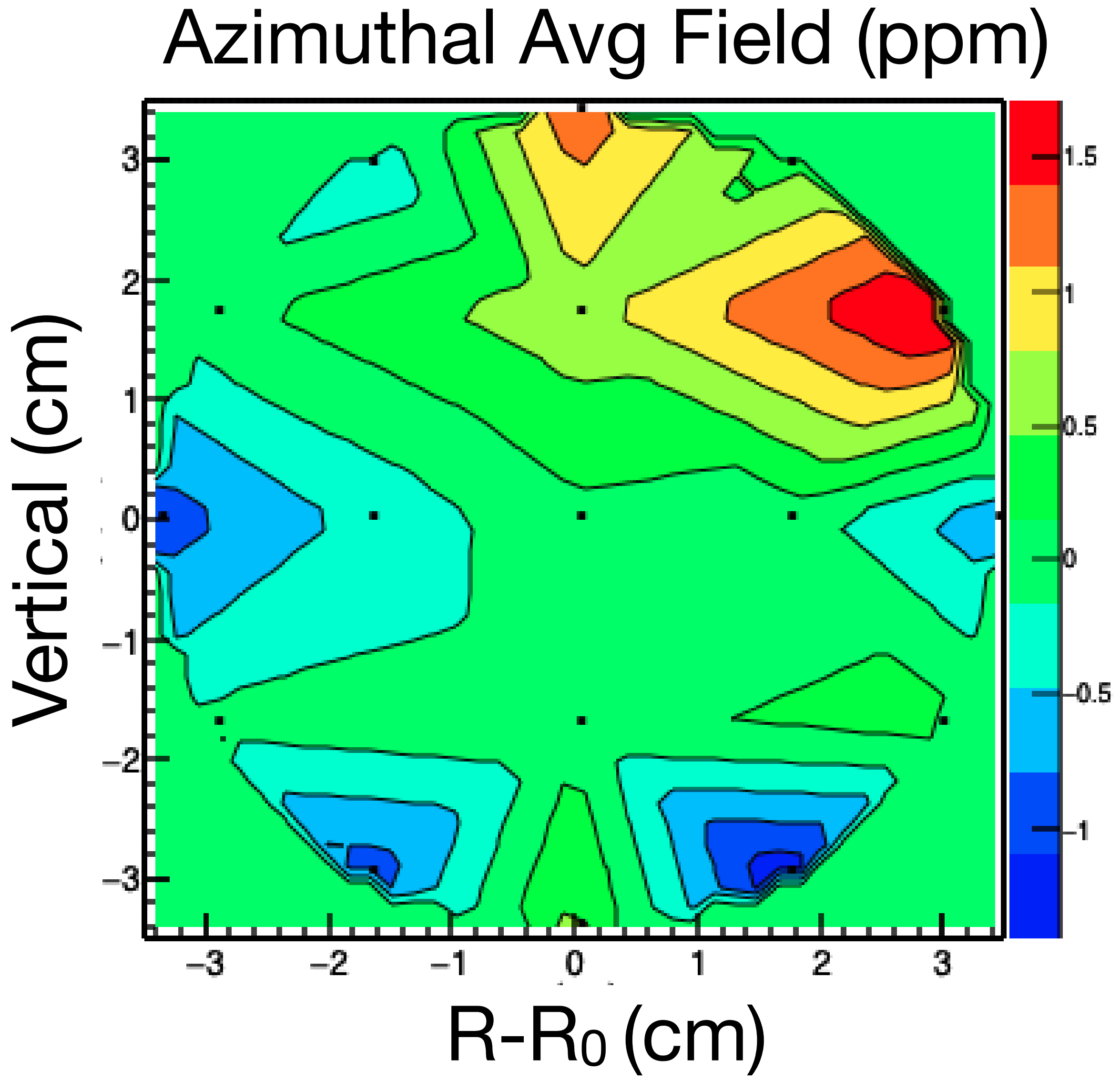
T-method: FFT of fit residuals: Big improvements when accounting for CBO, lost muons,…





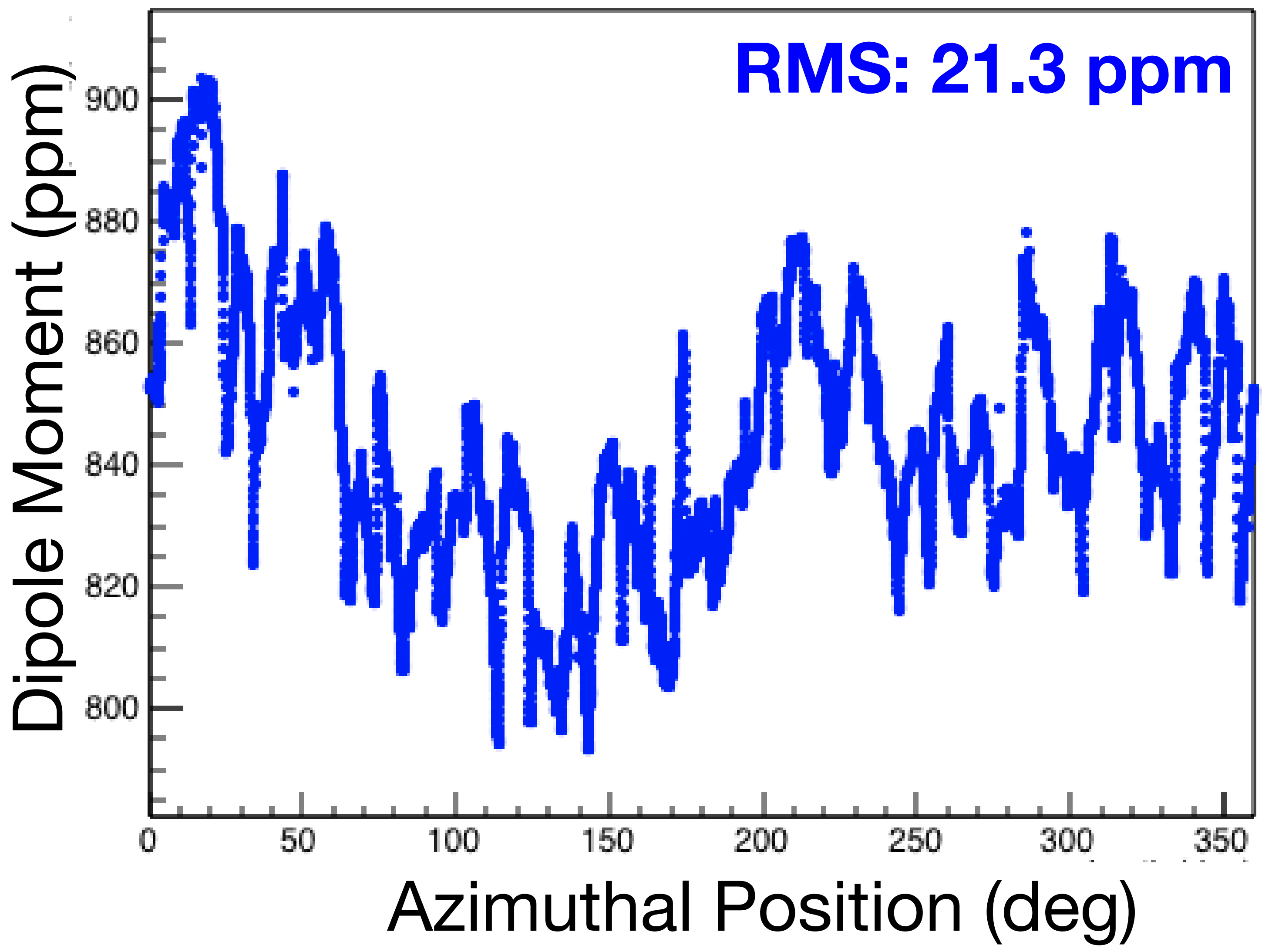
Magnetic Field: What's New in the Past Year?

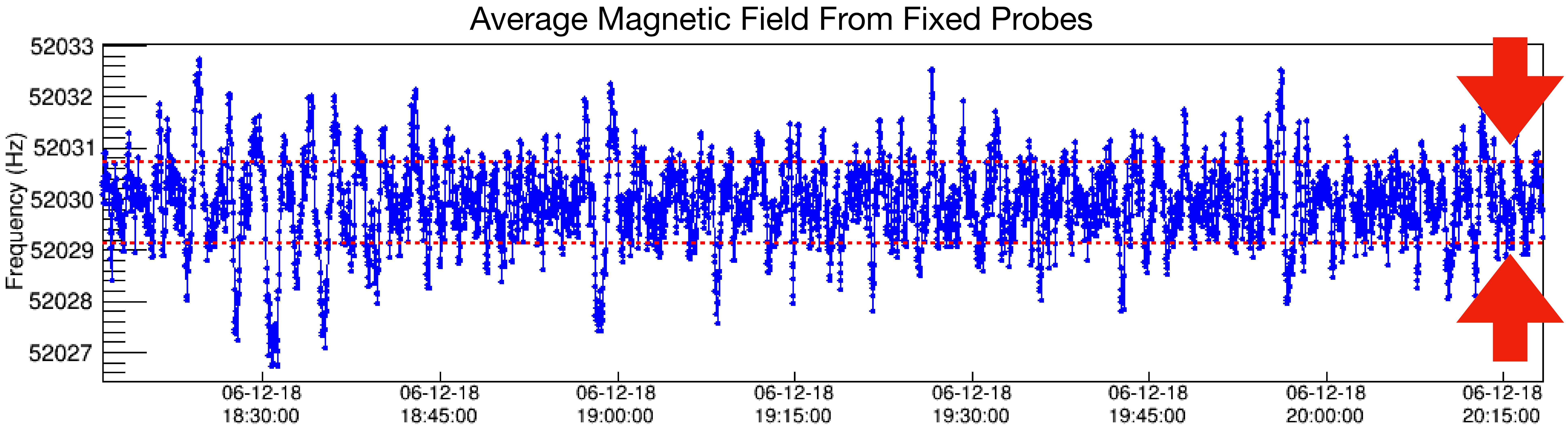
- **25+** **trolley** runs mapping the magnetic field
- Optimized **Surface Coil** configuration for both shimming and beam storage
- Started **calibrating** the **Trolley** using the **Plunging Probe**
- **PS Feedback** stabilizing the field to **± 15 ppb**



	Norm	Skew
Quad	0.50	0.76
Sext	-0.43	0.63
Octu	-0.07	0.35
Decu	0.23	0.08
Dipole	-0.0	

Preliminary

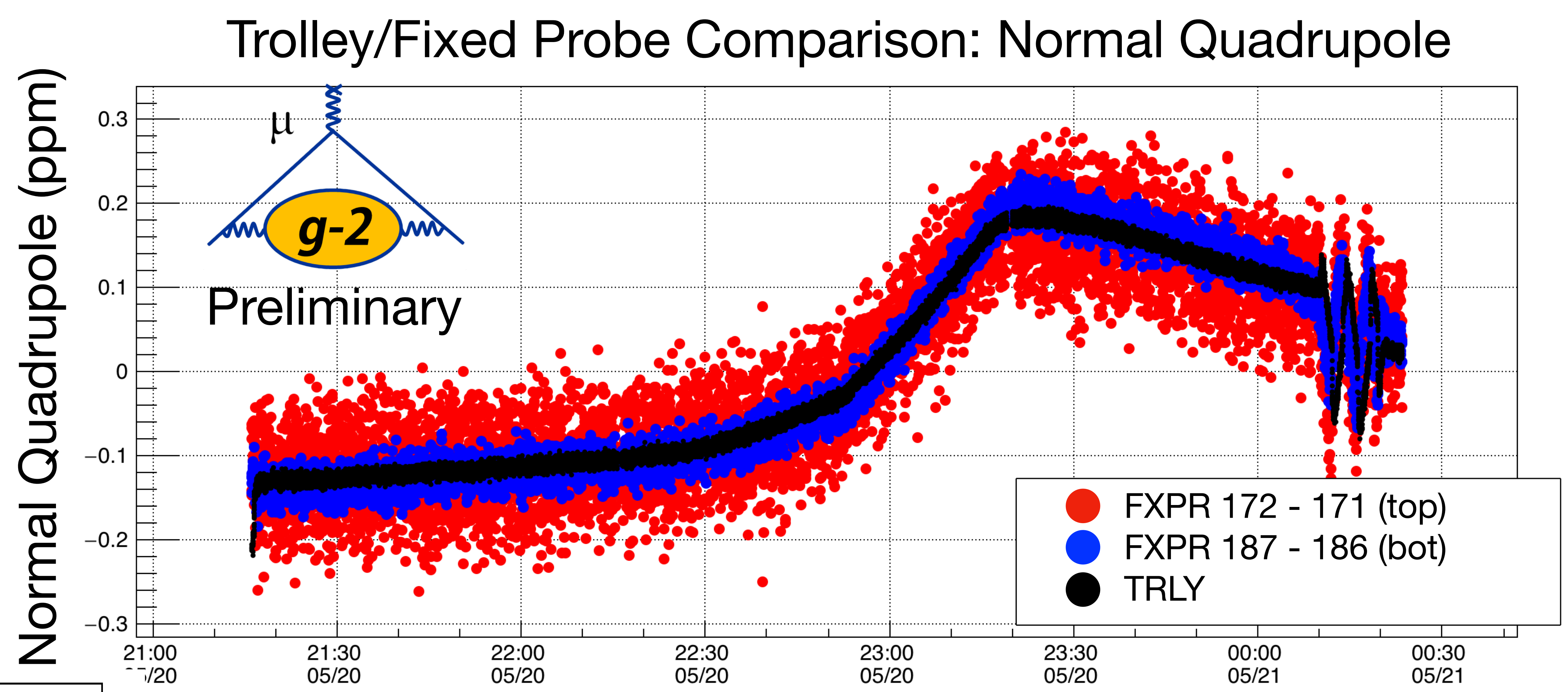


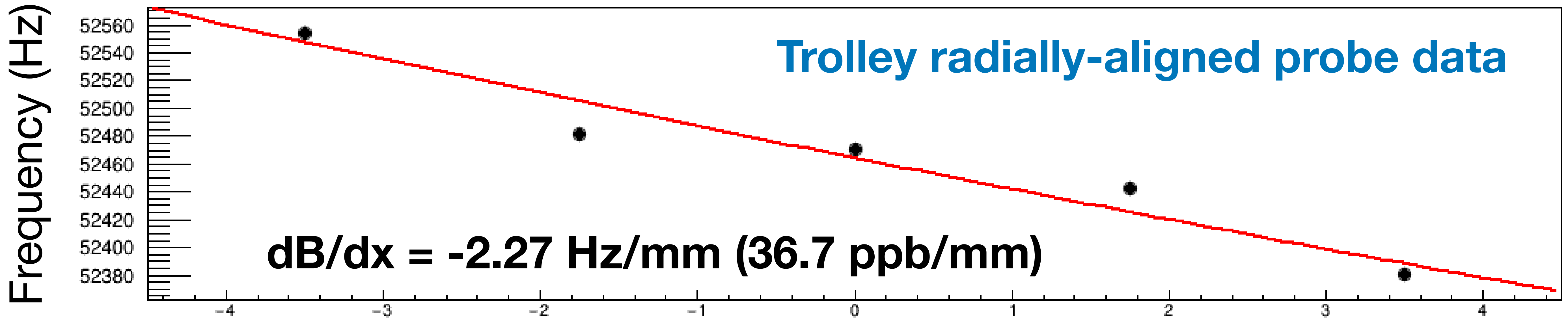


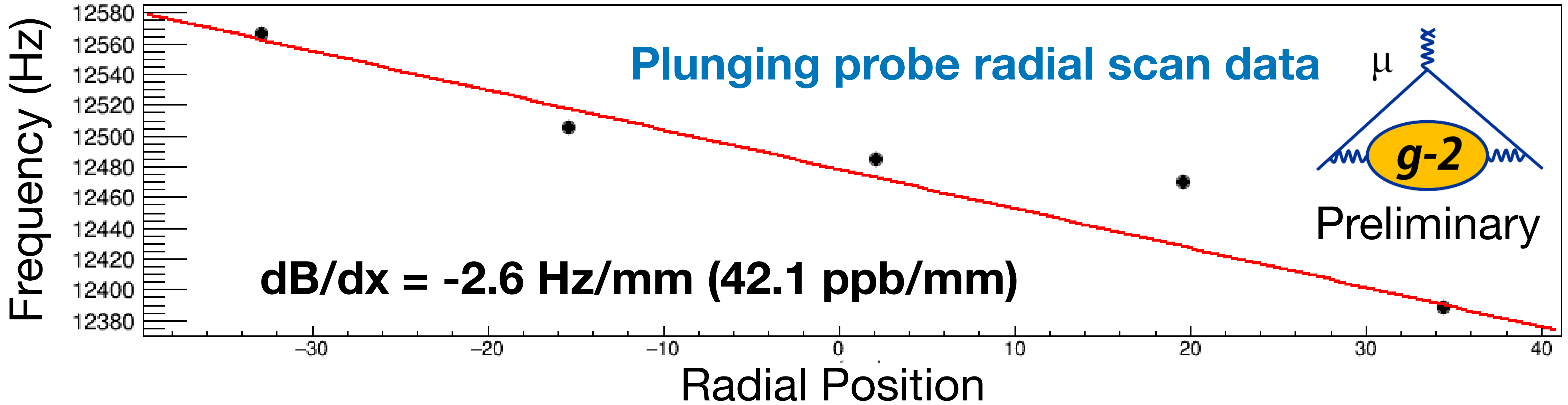
± 0.8 Hz (15 ppb)

ω_p Analysis Highlights

- Analyzing trolley multipole evolution as a function of time, temperature
- Trolley/fixed probe correlations
- Tracking multipoles with fixed probes







- Trolley calibration: scans using PP showing similar gradients seen by trolley => evidence that trolley probe calibration offsets are similar
- Important for understanding how our field maps convolute with muon beam distribution(s)

Run Progress: Major Gains in Last Months

Started off slow, but steady

- **3/17 start of production**
- Typical run conditions ~ 230 e^+/fill
- After a few weeks of continuous running, 25% of BNL statistics

Early April: Systematic efforts to increase e^+/fill

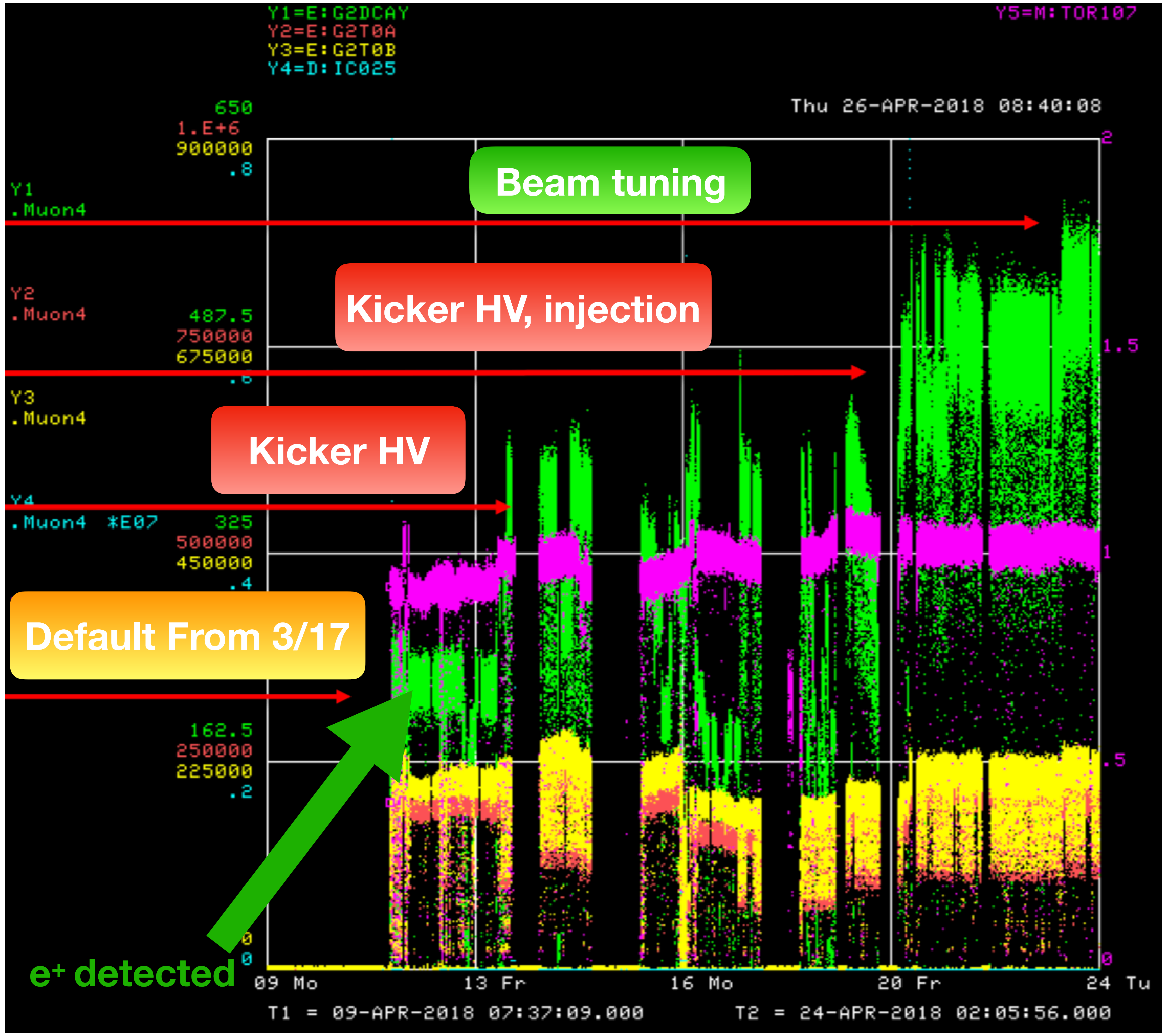
- Tuning beam parameters: optimization of dipole/quadrupole magnets (M5)
- Varying the kicker strength: Looking for the turnover of e^+/fill with increasing voltage — still hadn't hit the maximum yet
- Statistics at ~ 35% BNL

Late April: **Major progress**

- Beam tuning, injection optimized
- Kicker HV increases
- **Up to ~ 50% BNL**

May–June: Stable running (some downtime here and there), accumulating statistics…

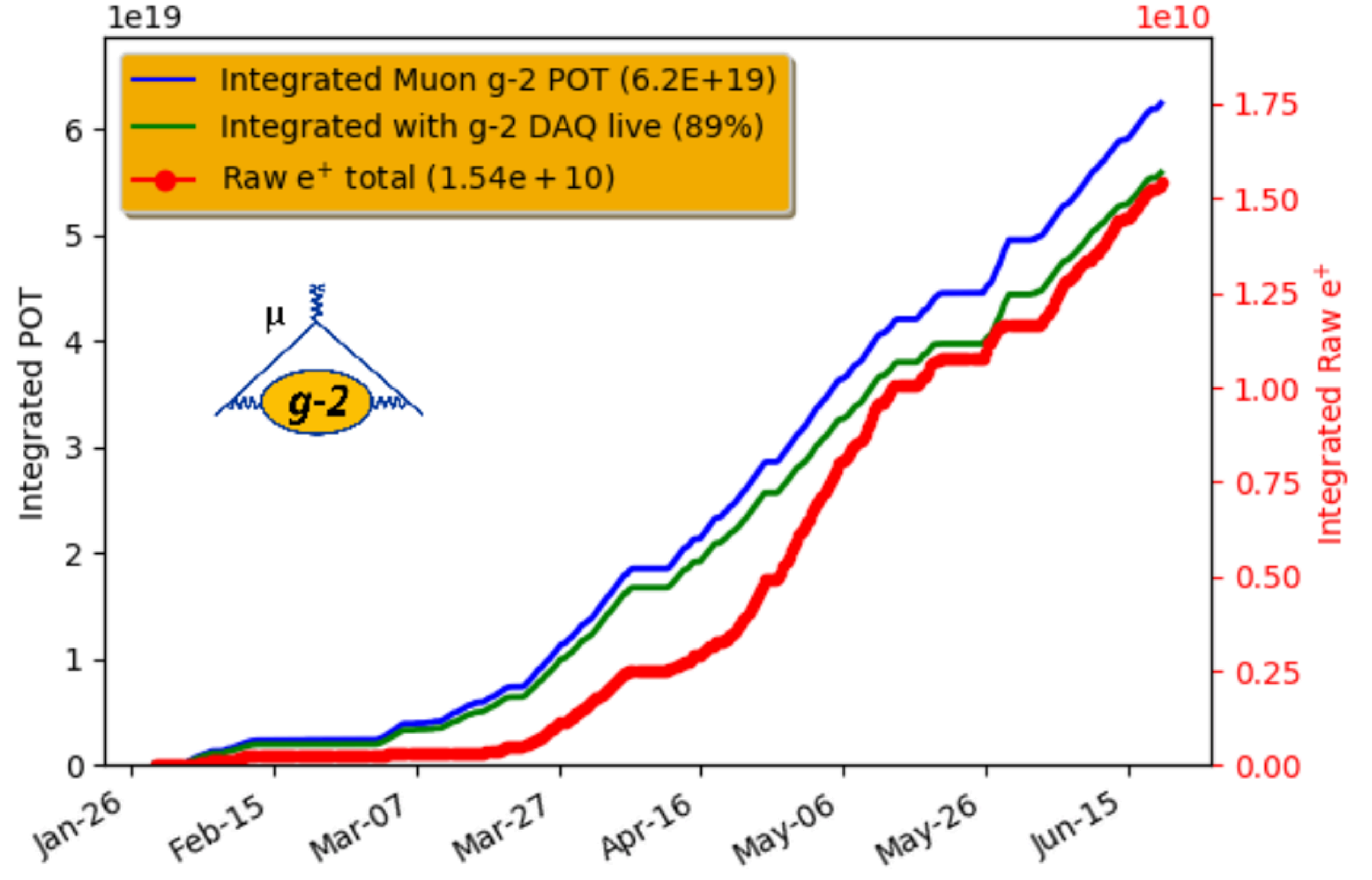
4/24 ACNET History



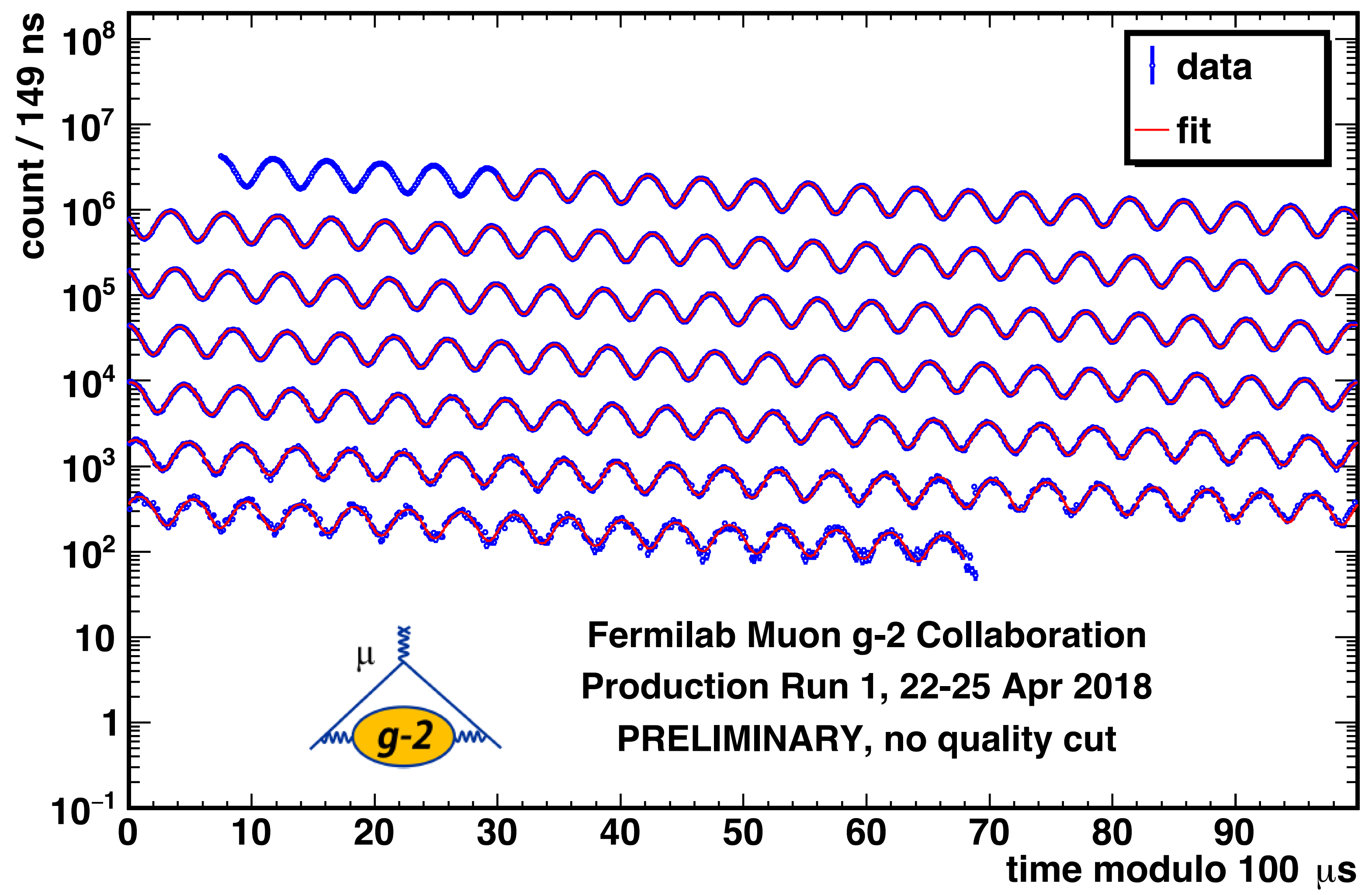
Summary: Where Are We Now?

- Accumulated ~ 1.5x BNL statistics so far. Few weeks to go in the run to accumulate more statistics
- To date: 25+ trolley runs mapping the magnetic field
- ω_a, ω_p analyses becoming more mature
- Plans in place for summer shutdown (optimizations, upgrades)

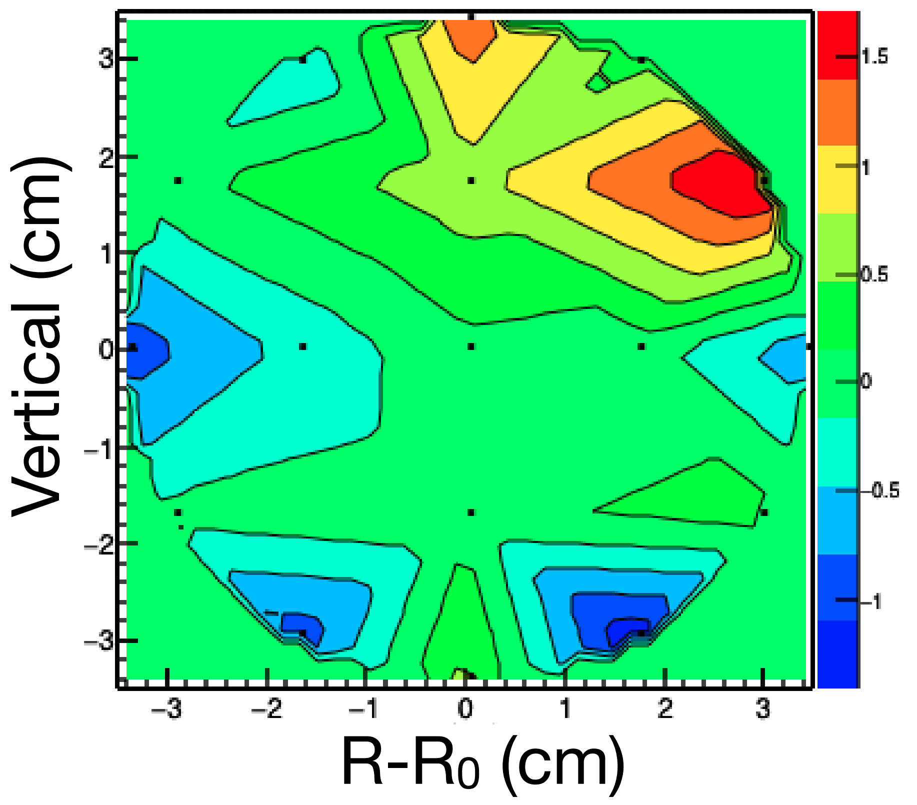
Accumulated statistics



ω_a analysis well underway



Recent trolley run



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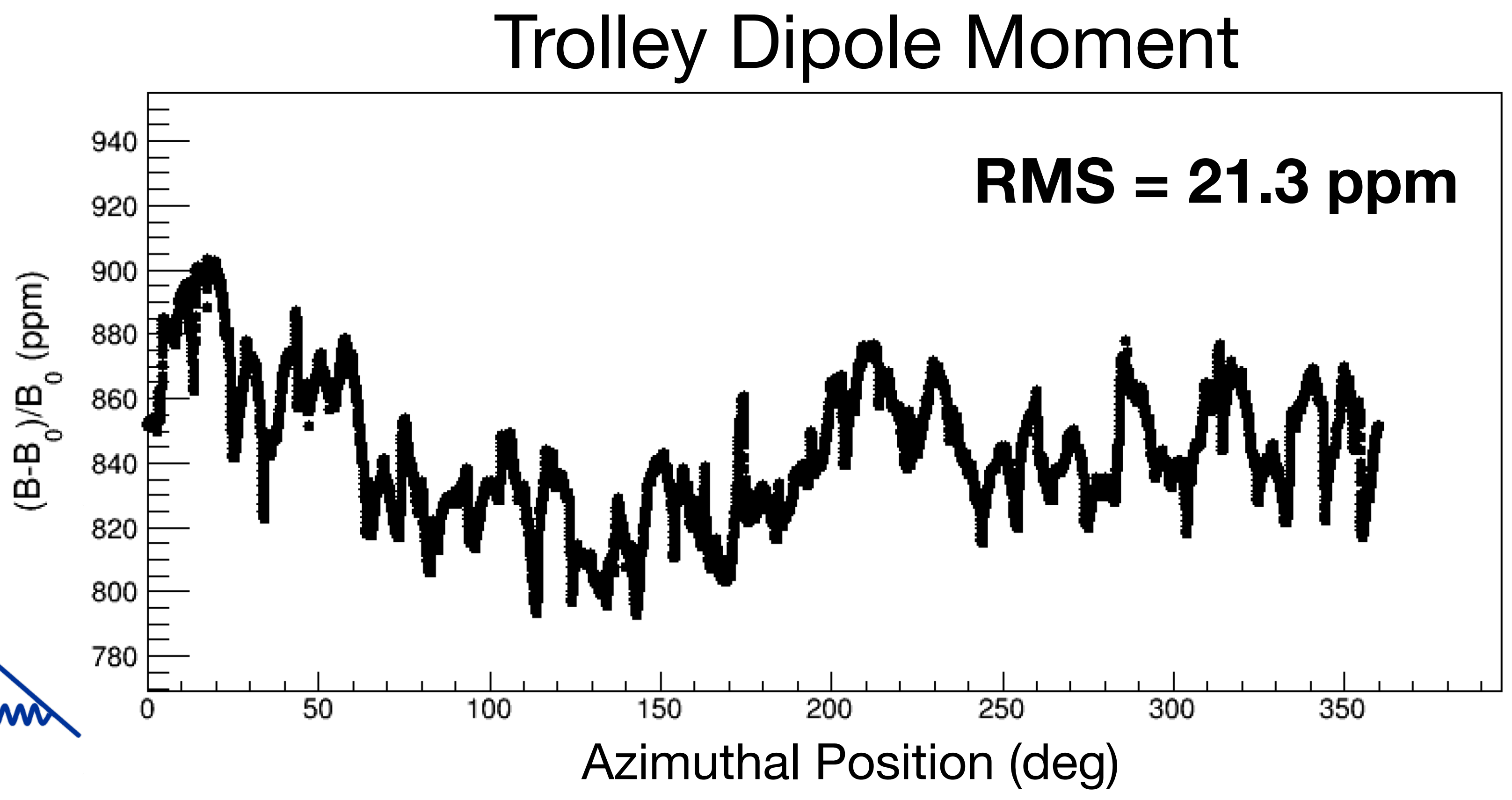


Thank You!

Backup

Systematic Uncertainties: Improvements Over E821

Reduce ω_a systematic uncertainties by a factor of 3

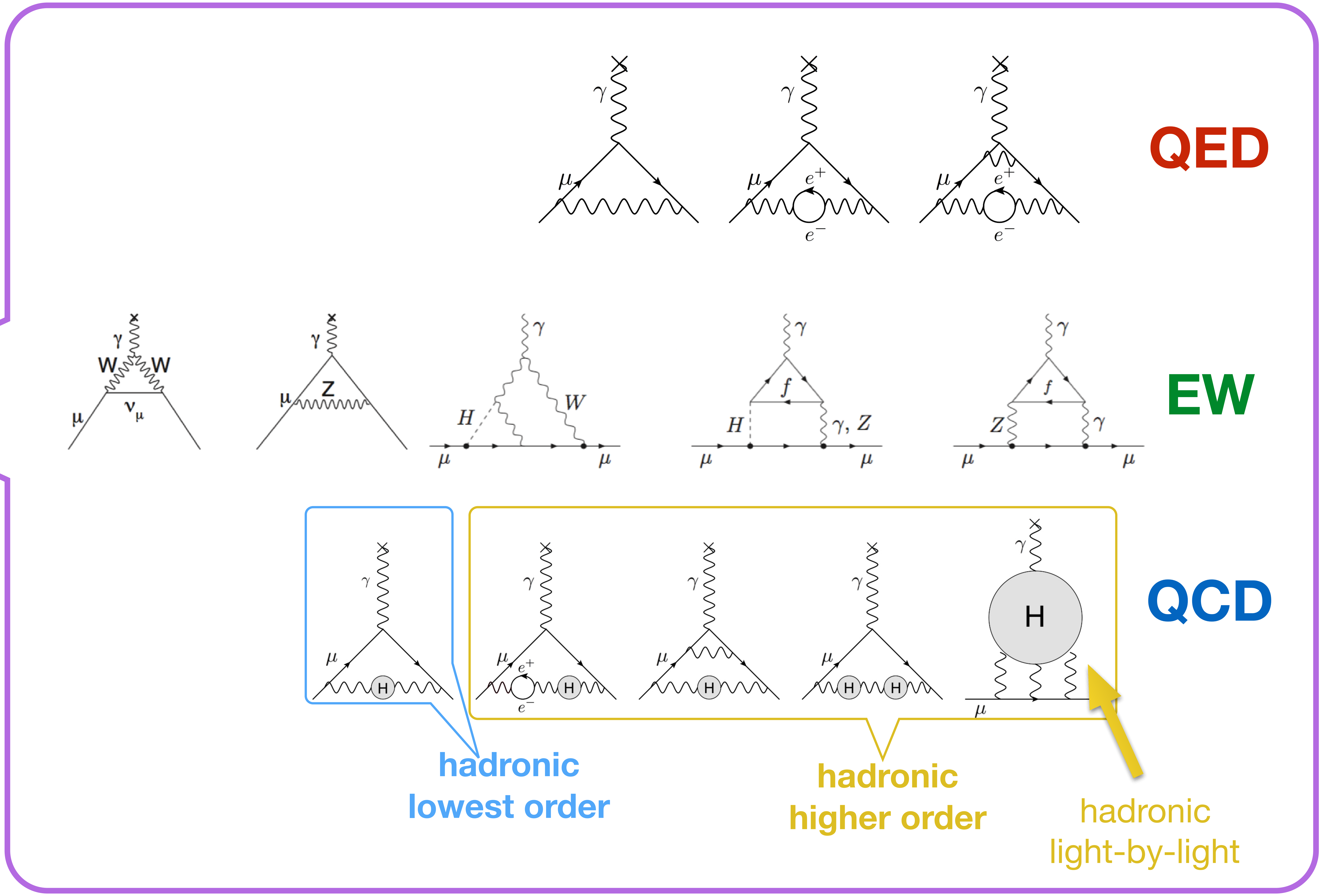
E821 Error	Size (ppb)	E989 Improvements	Goal (ppb)
Gain Changes	120	Better laser calibration; low-energy threshold, temperature stability, no hadronic flash	35
Lost Muons	90	Less scattering due to material at injection; muons reconstructed by calorimeters	30
Pileup	80	Low-E samples recorded; calo segmentation; trackers cross-calibrate pileup efficiencies	30
Coherent Betatron Oscillations	70	Higher n-value, straw trackers to determine parameters	10
E-field/pitch	60	Straw trackers to reconstruct muon distribution, better collimators, better kick	30
Diff. Decay	50	Better kicker, tracking simulation	20
Total	**200**		**70**

Reduce ω_p systematic uncertainties by a factor of 2.5

E821 Error	Size (ppb)	E989 Improvements	Goal (ppb)
Field Calibration	50	Dedicated test solenoid, more probes, better electronics	35
Trolley Measurements	50	Reduced rail irregularities, field gradients	30
Fixed Probe Interpolation	70	More trolley runs, fixed probes; better temperature stability of magnet	30
Muon Convolution	30	Improved field uniformity, muon tracking	10
Time-Dependent Fields	–	Direct measurements of external fields, active feedback	5
Others	100	Improved electronics, reduced temperature dependence, kicker transients	50
Total	**170**		**70**

SM Contributions to a_μ

$$g_\mu \equiv 2\,(1 + a_\mu)$$

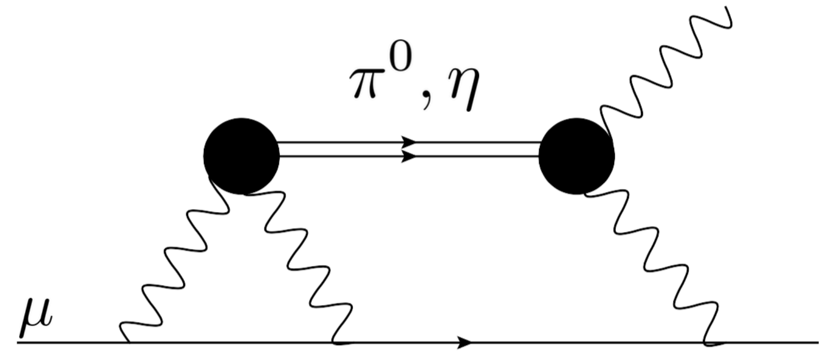


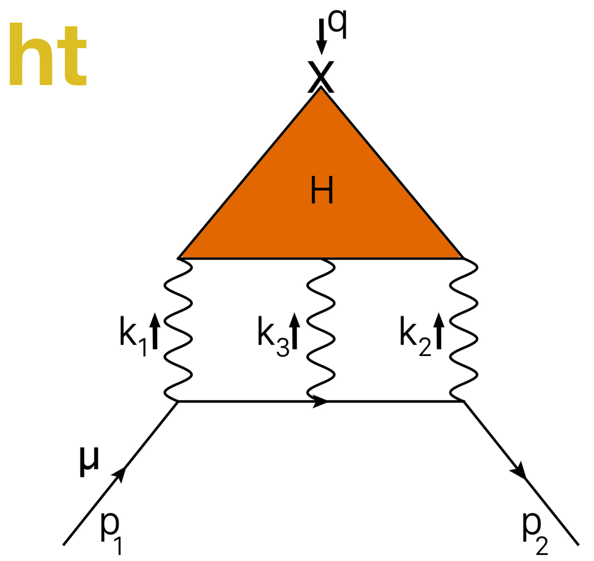
Contributions from **quantum electrodynamics**, **electroweak**, and **quantum chromodynamics**

SM Contributions to a_μ

Source	Value (x 10^{-10})	Uncertainty (x 10^{-10})	Reference
QED	11658471.895	0.008	Kinoshita et al., 2012
EW	15.36	0.10	Czarnecki, Marciano, Stöckinger et al., 2013
HVP (LO)	693.1	3.4	Davier et al., 2017
HVP (LO)	694.9	4.3	Hagiwara et al., 2011
HVP (HO)	-0.984	0.007	Hagiwara et al., 2011
HLbL	10.5	0.26	Prades et al., 2010
Total	11659182.3	4.3 (368 ppb)	
	11659182.8	5.0 (430 ppb)	

HLbL: Hadronic Light-by-Light





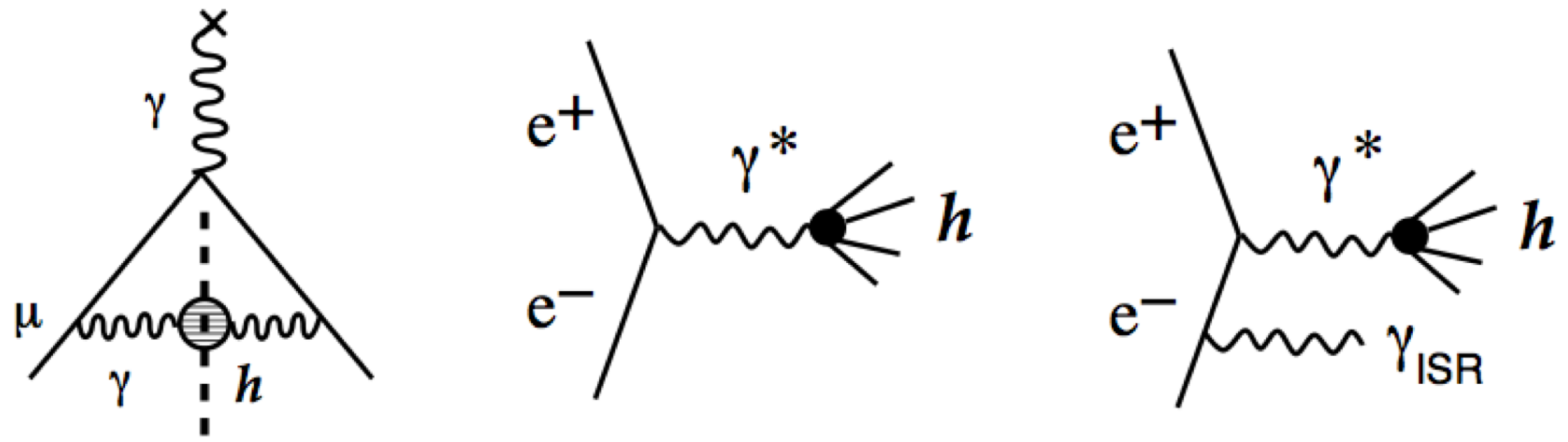
- Model dependent: based on χPT + short-distance constraints (operator product expansion)
- Difficult to relate to data like HVP (LO); γ* physics, π^0 data (BESIII, KLOE) important for constraining models
- **Theory Progress**: New dispersive calculation approach; extend the lattice (finite volume, disconnected diagrams); Blum et al. making excellent progress

HVP (LO): Lowest-Order Hadronic Vacuum Polarization

- **Critical input** from e^+e^- colliders (data from SND, CMD3, BaBar, KLOE, Belle, BESIII), δa_μ^{HVP} ~ 0.5%; extensive physics program in place to reduce δa_μ^{HVP} to ~ 0.3% in coming years
- **Progress on the lattice**: Calculations at physical π mass; goal: δa_μ^{HVP} ~ 1—2% in a few years (cross-check with e^+e^- data)

$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

$$R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



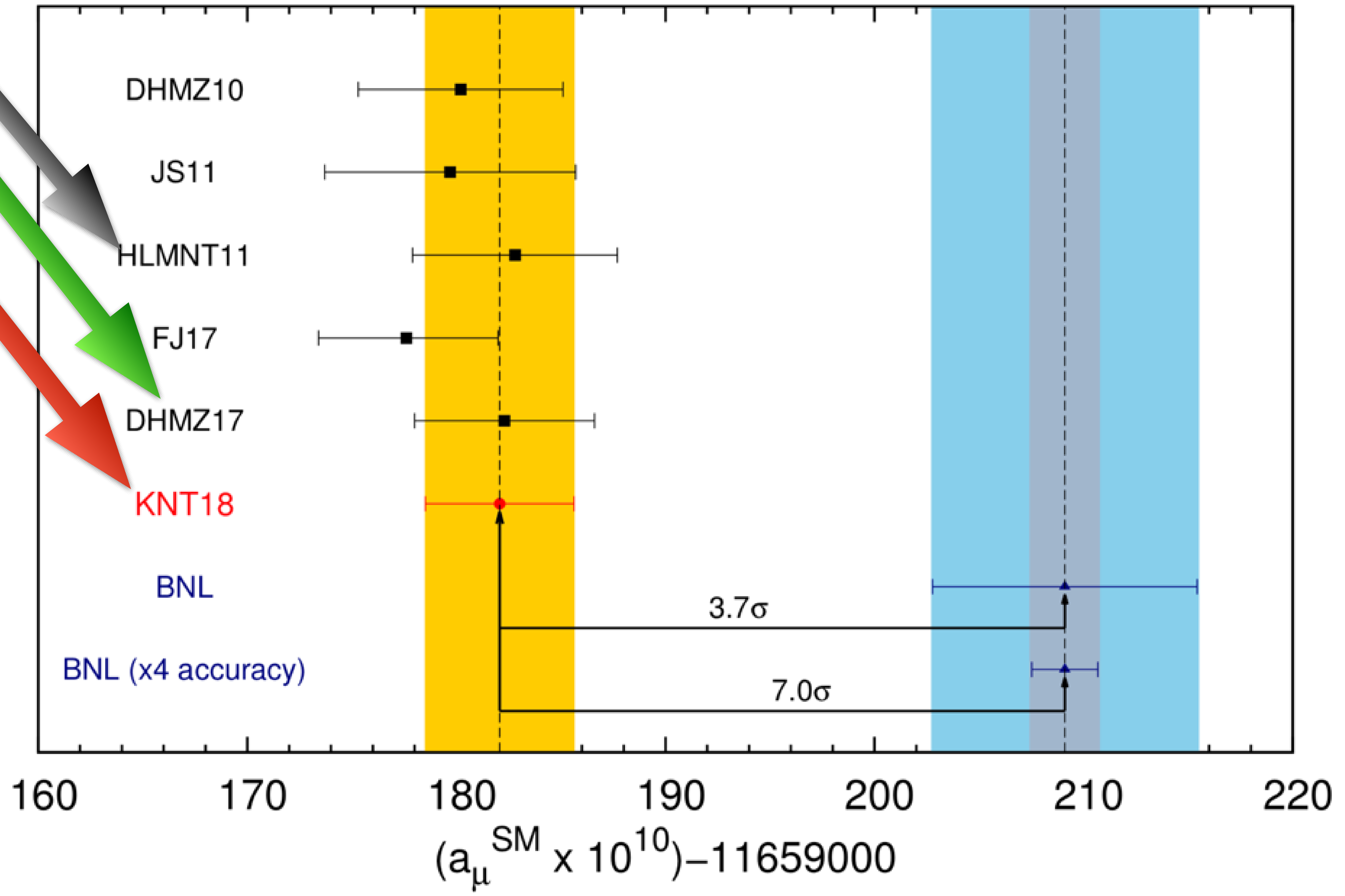
a_μ Current Status

a_μ (Exp) - a_μ (SM) = 26.3 ± 8.0 (3.3σ)
a_μ (Exp) - a_μ (SM) = 26.8 ± 7.6 (3.5σ)
a_μ (Exp) - a_μ (SM) = 27.0 ± 7.3 (3.7σ)

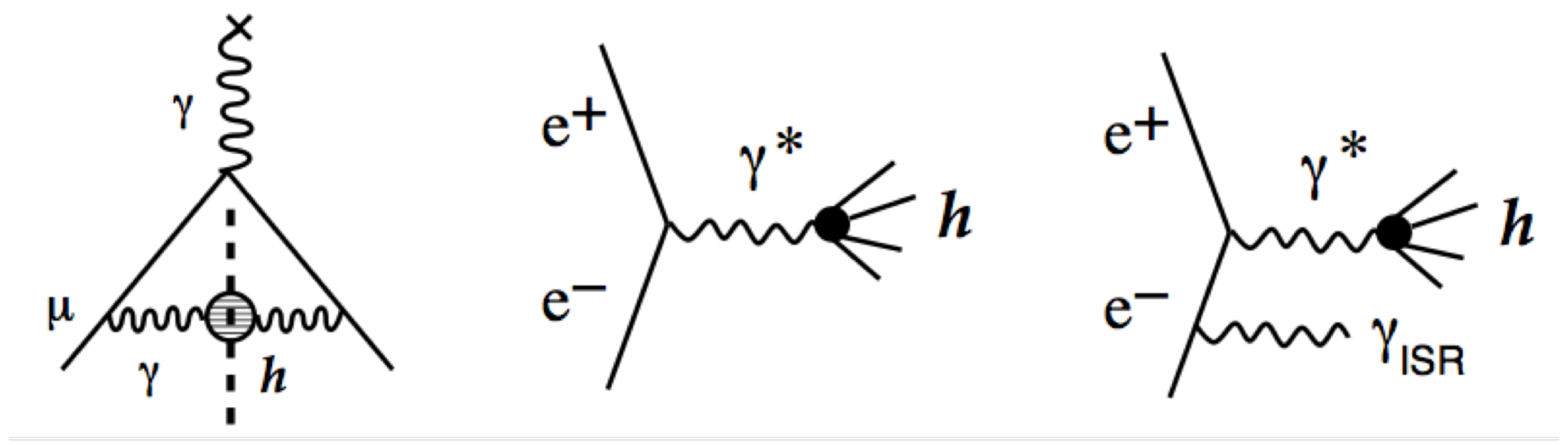
- **Disagreement** between experiment and theory
  - Deviation is large compared to EW contribution, uncertainty on hadronic terms
  - Not at discovery threshold (5σ)
  - **Due to new physics? SUSY, TeV-scale models, dark photon…**
- **Improvements** on both theory and experiment sides
  - **Experiment**: more statistics, reduce systematics
  - **Theory**: reduce uncertainties (HVP, HLbL)

Uncertainty Source δa_μ	Status 2018 (ppb)	Projected after E989 (ppb)
HVP	242	215
HLbL	260	225
Total Theory	356	310
Total Experiment	540	140

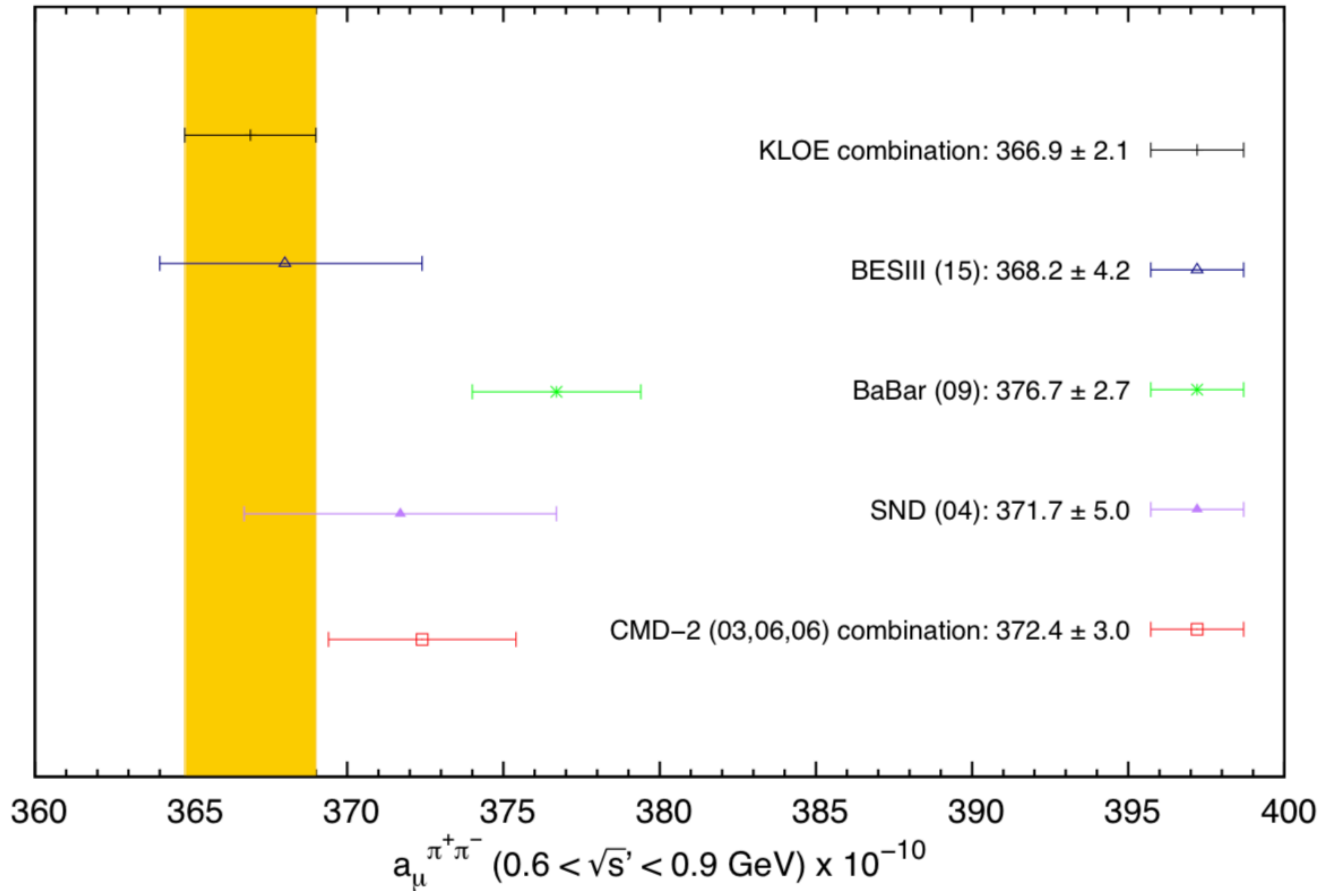
arXiv:1802.02995 [hep-ph]



Hadronic Vacuum Polarization

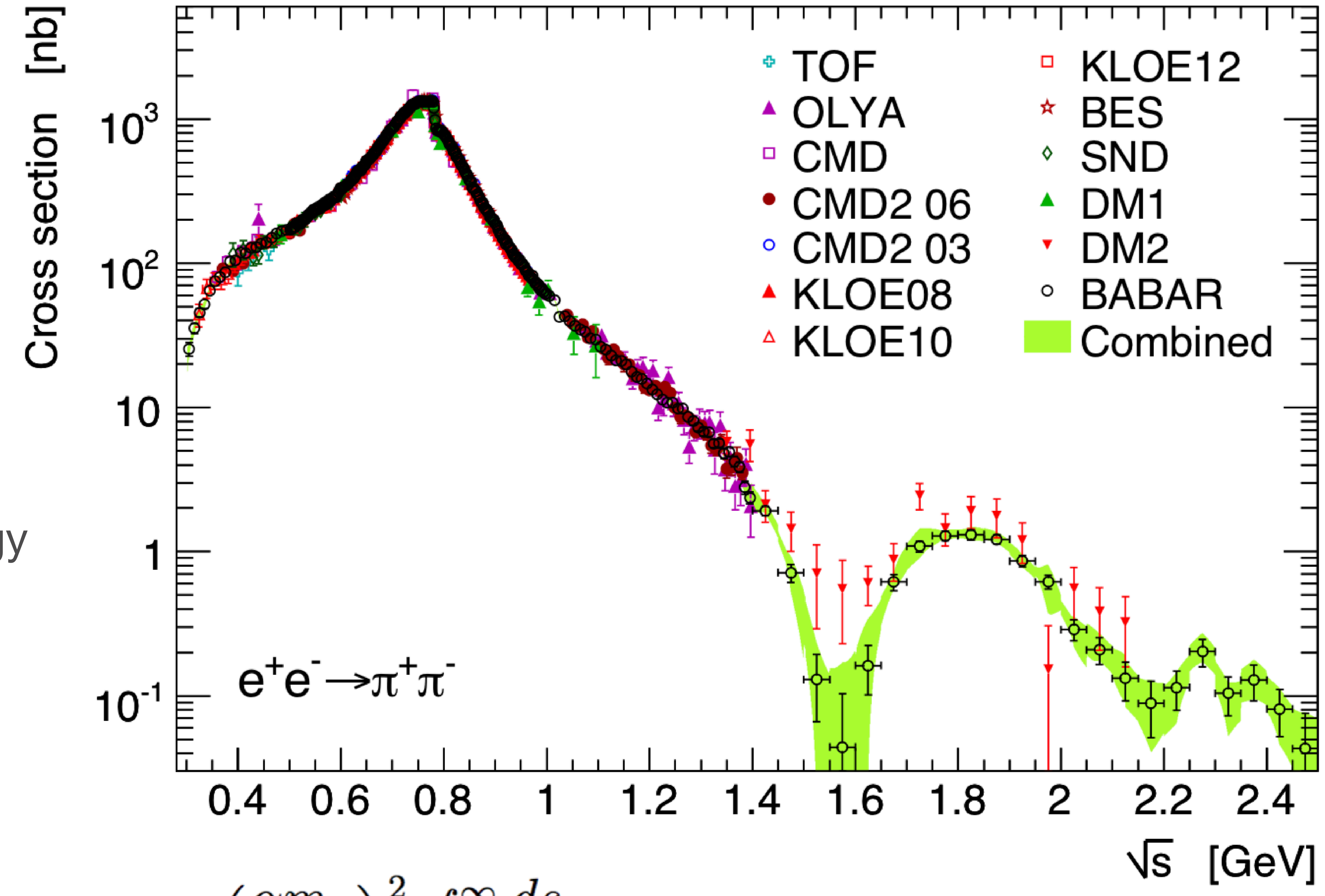


- **Critical input to HVP** from e+e- colliders (SND, CMD3, BaBar, KLOE, Belle, BESIII)
- **BESIII:** 3x more data available, luminosity measurement improvements
- **VEPP-2000:** Aiming for 0.3% (fractional) uncertainty; radiative return + energy scan
- **CMD3:** Will measure up to 2 GeV (energy scan, ISR — good cross check)



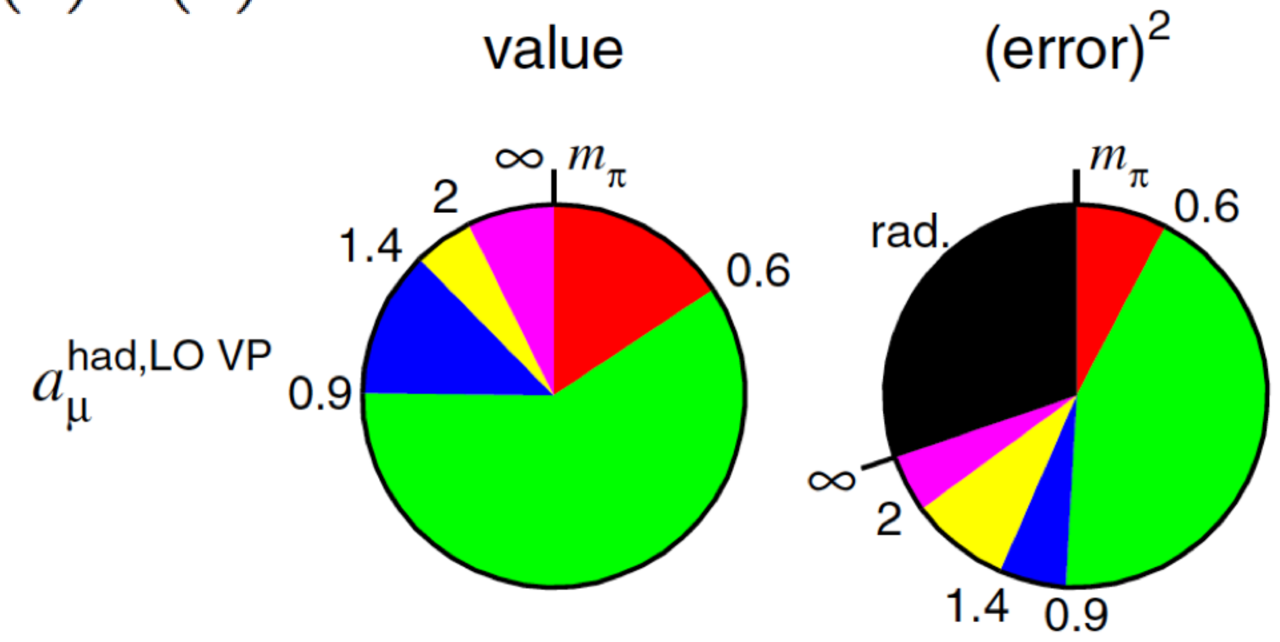
A. Anastasi et al., arXiv:1711.03085 [hep-ex]

M. Davier et al., arXiv:1706.09436 [hep-ph]



$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

$$R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

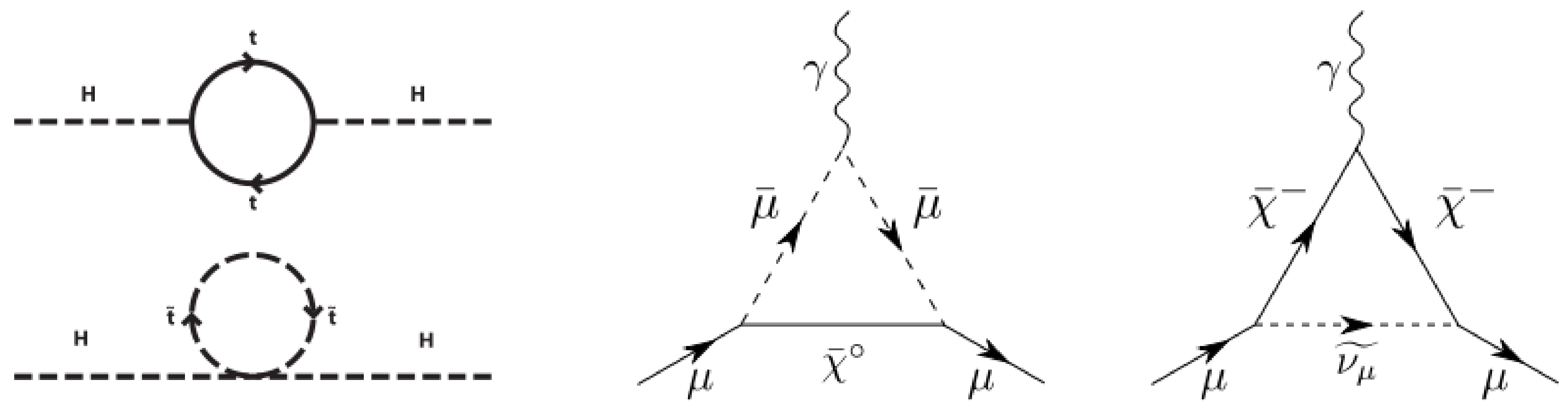


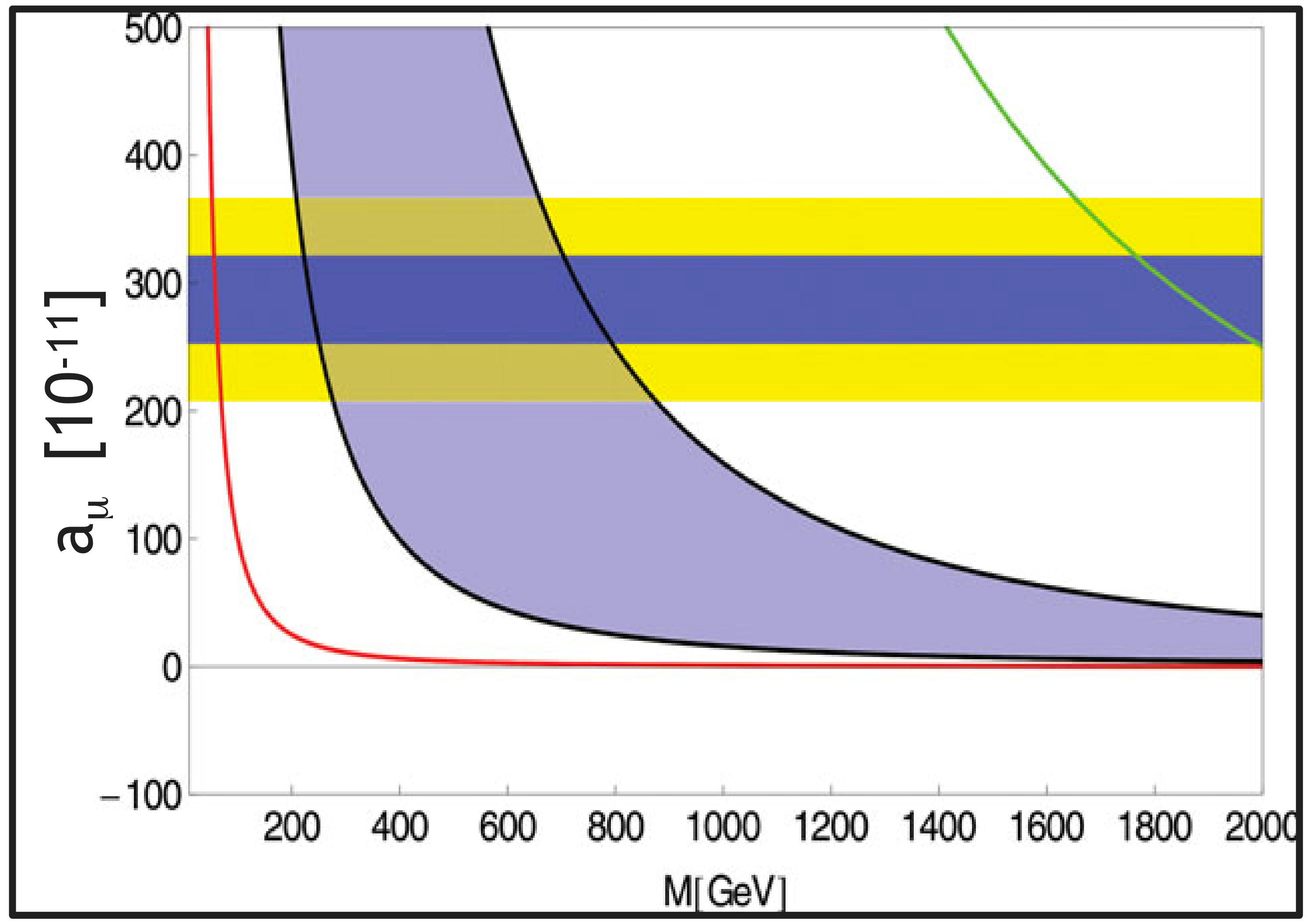
- **Lattice calculations** of a_μ^{HVP} to 1% possible, 30% for HLbL in 3—5 years

Physics Beyond SM?

SUSY, TeV-Scale Models

- Higgs measured at the LHC to be ~125 GeV
- Theory: Higgs should acquire much heavier mass from loops with heavy SM particles (e.g., top quark)
  - **Supersymmetry: new class of particles** that enters such loops and **cancels this contribution**





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

- **Complementary to direct searches at the LHC**
  - Sensitivity to sgn(μ), tan(β)
  - Contributions to a_μ arise from charginos, sleptons
  - LHC searches sensitive to squarks, gluinos

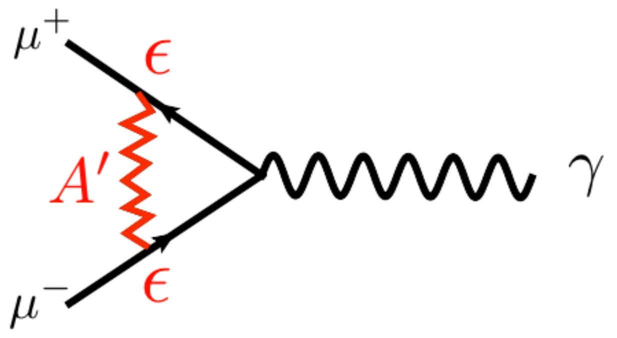
Z’, W’, UED, Littlest Higgs
- Assumes typical weak coupling

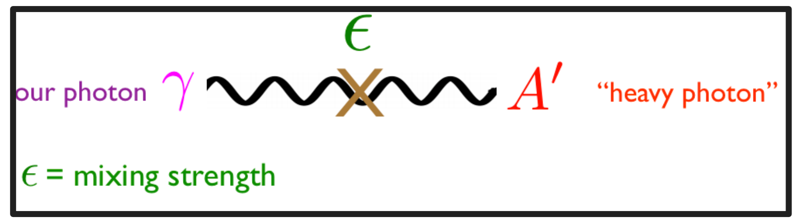
Radiative muon mass generation

Unparticles, Extra Dimension Models, SUSY (tan β = 5 to 50)

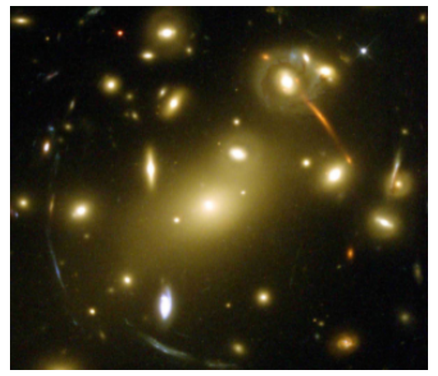
Dark Matter

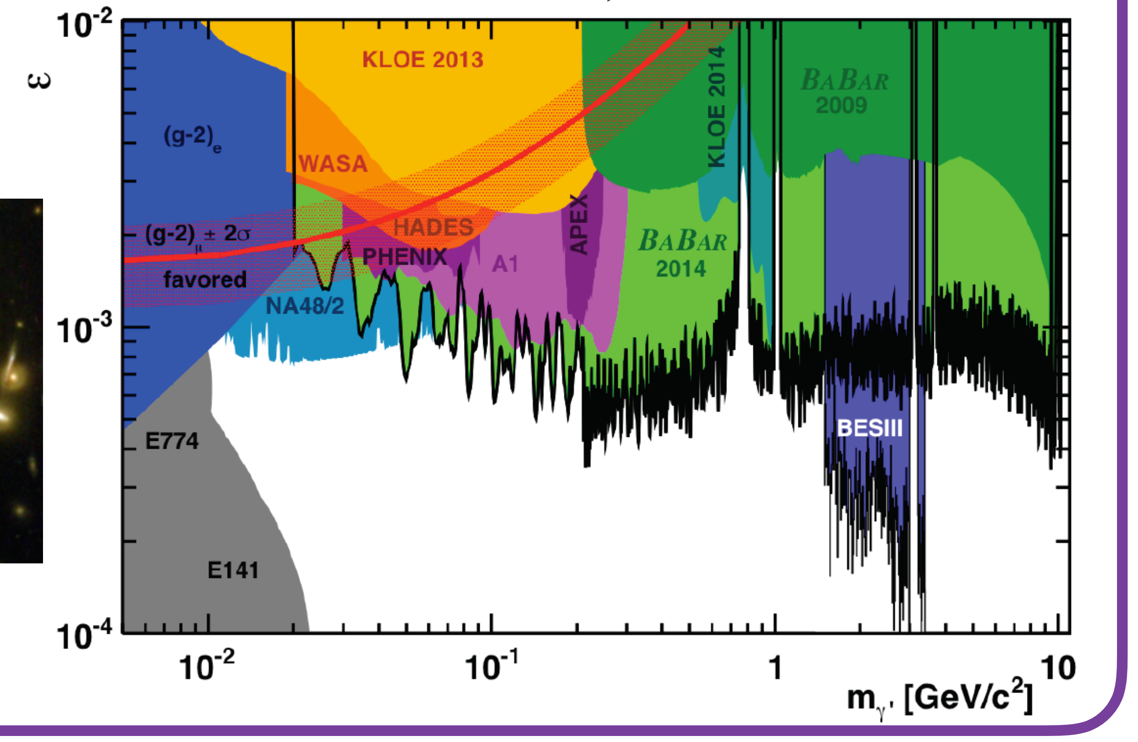
- **Cosmological observations** (galaxy rotation curves, lensing) point to much **more mass in the universe** than expected
- Many **theories** to explain dark matter
- **A new U(1)’ symmetry: dark photon A’**
  - Could impact the muon’s magnetic moment
  - Many direct-detection searches underway





A. Soffer, arXiv:1507.02330





Improved precision on a_μ will continue to constrain (or validate!) the energy scale of new models

Muon Beam: From Protons to Muons

Recycler

- Rebunches 8 GeV protons from booster

Target Station

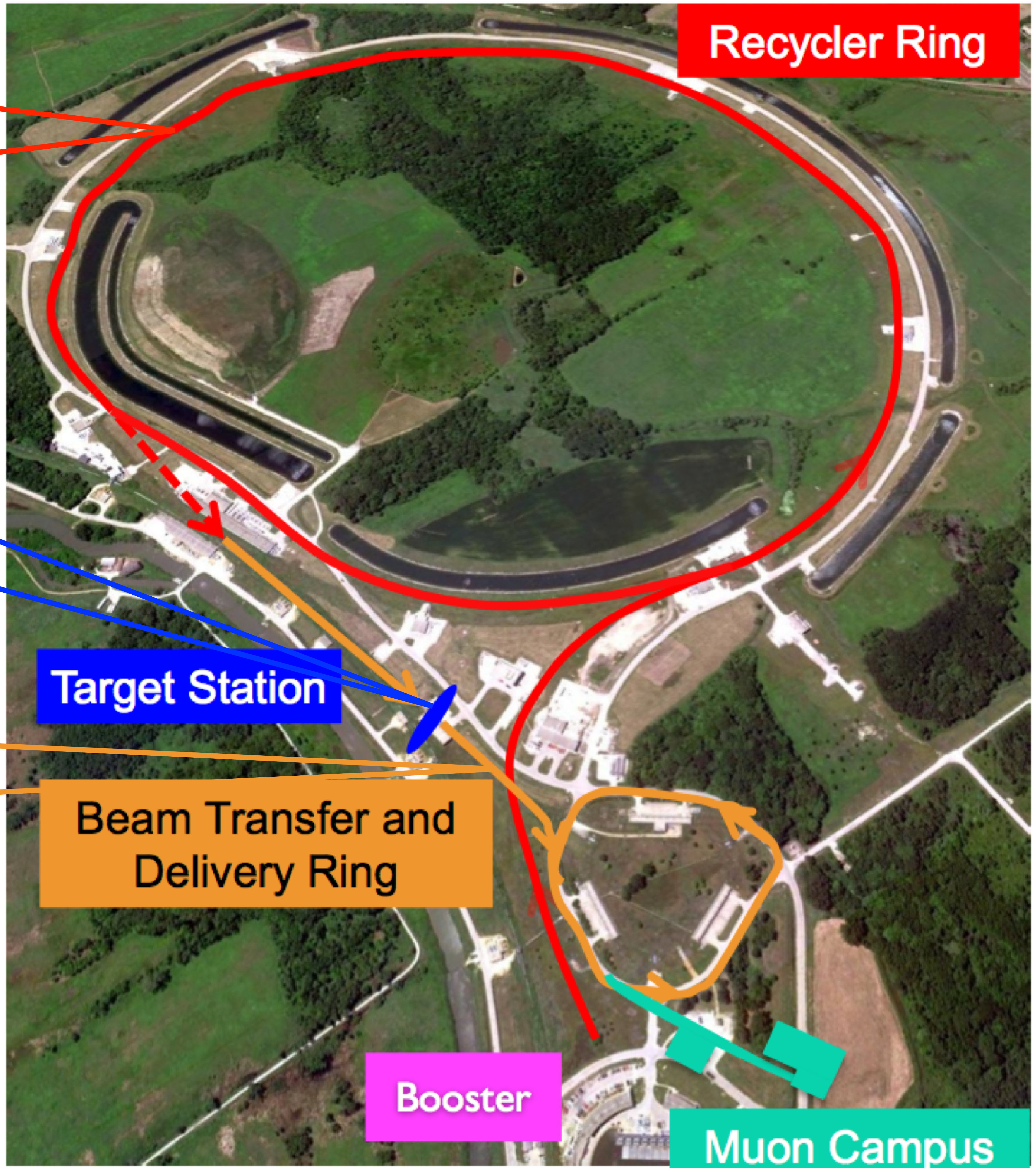
- Protons impinge upon Inconel target
- Focusing lens captures pions

Beam Transfer and Delivery

- Straight section: capture muons from forward-decaying pions (polarized)
- Remove protons by time-of-flight
    - Reduce number of pions and protons in ring

Characteristics

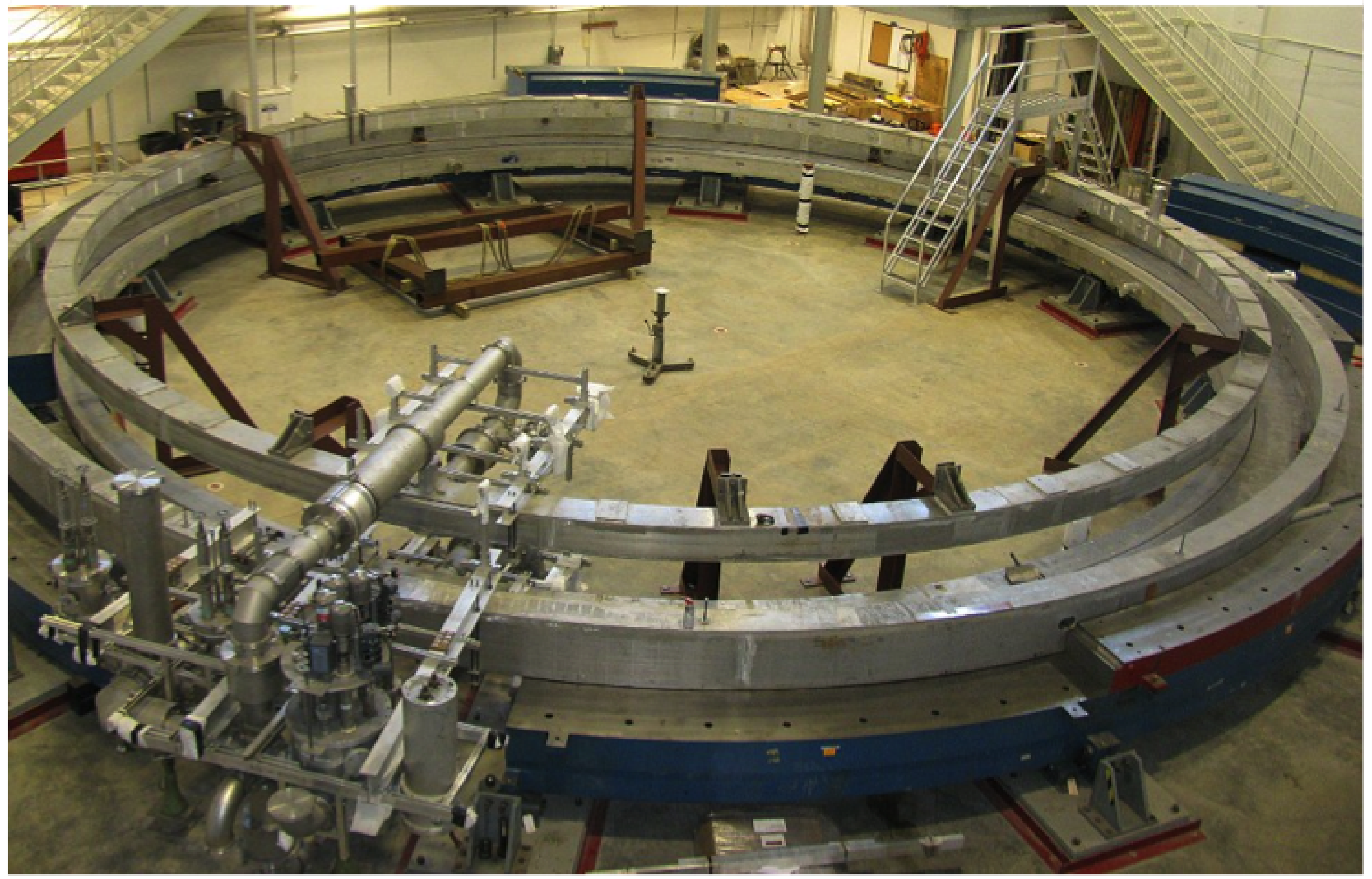
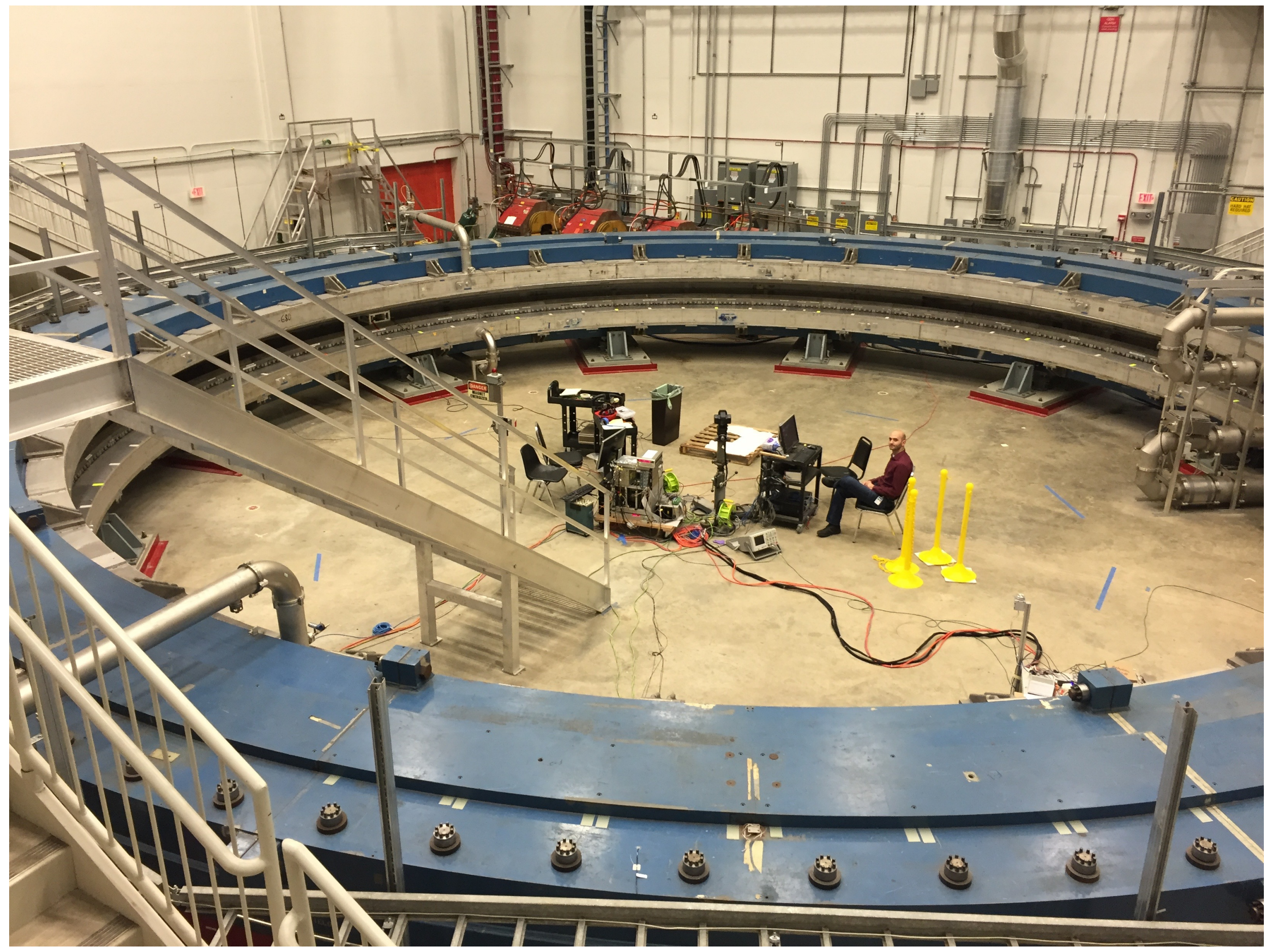
- Fill storage ring 16 times/1.4 sec (2x muons/fill compared to BNL)
- Expect 21x more statistics than BNL



The Big Move

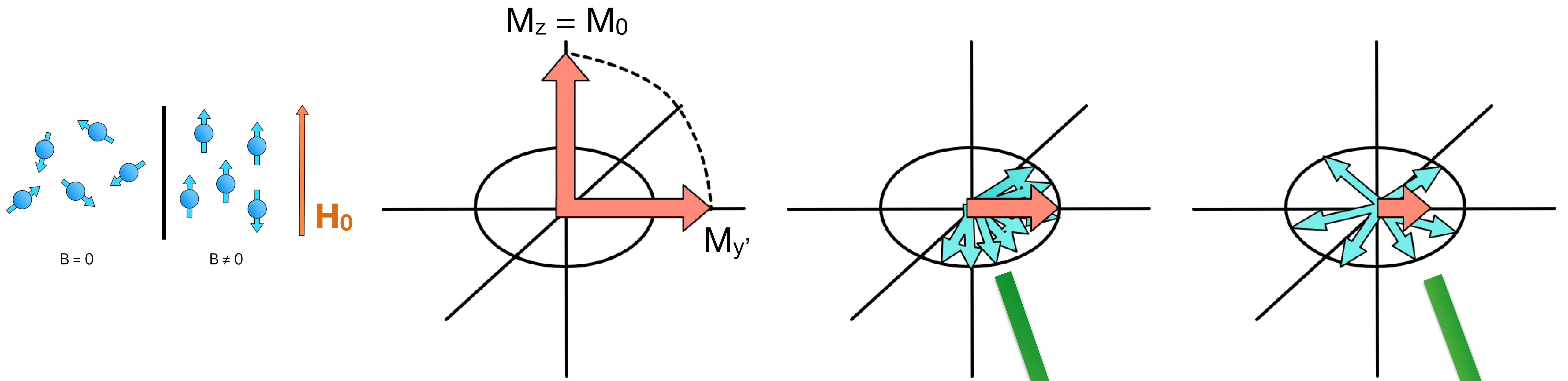
Relocating the Ring from BNL to FNAL


- June 2013—June 2015
- Ring deconstructed at BNL, transported by barge/flatbed trailer
- Reassembled at FNAL

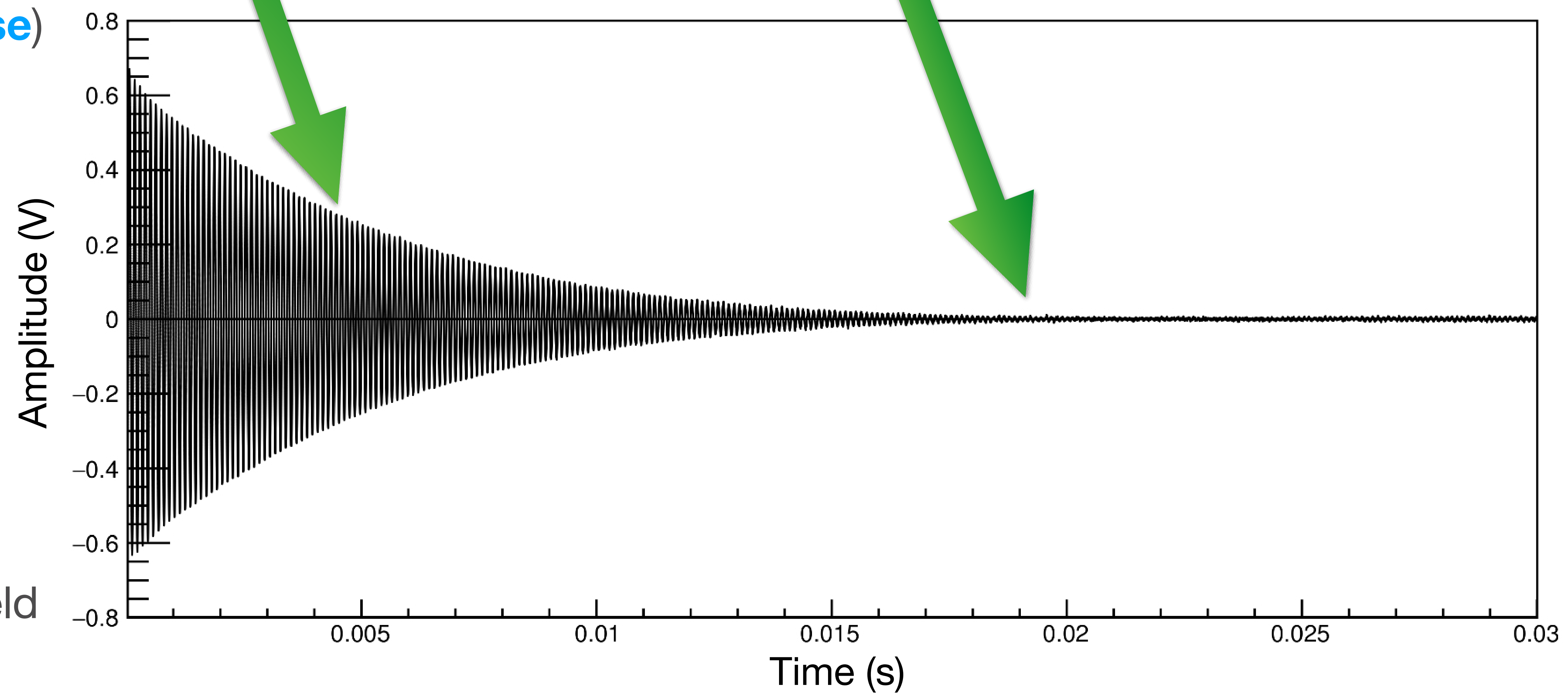




Ring successfully cooled and powered to 1.45 T in September 2015 — remarkable achievement!

Measuring the Field: Pulsed Nuclear Magnetic Resonance



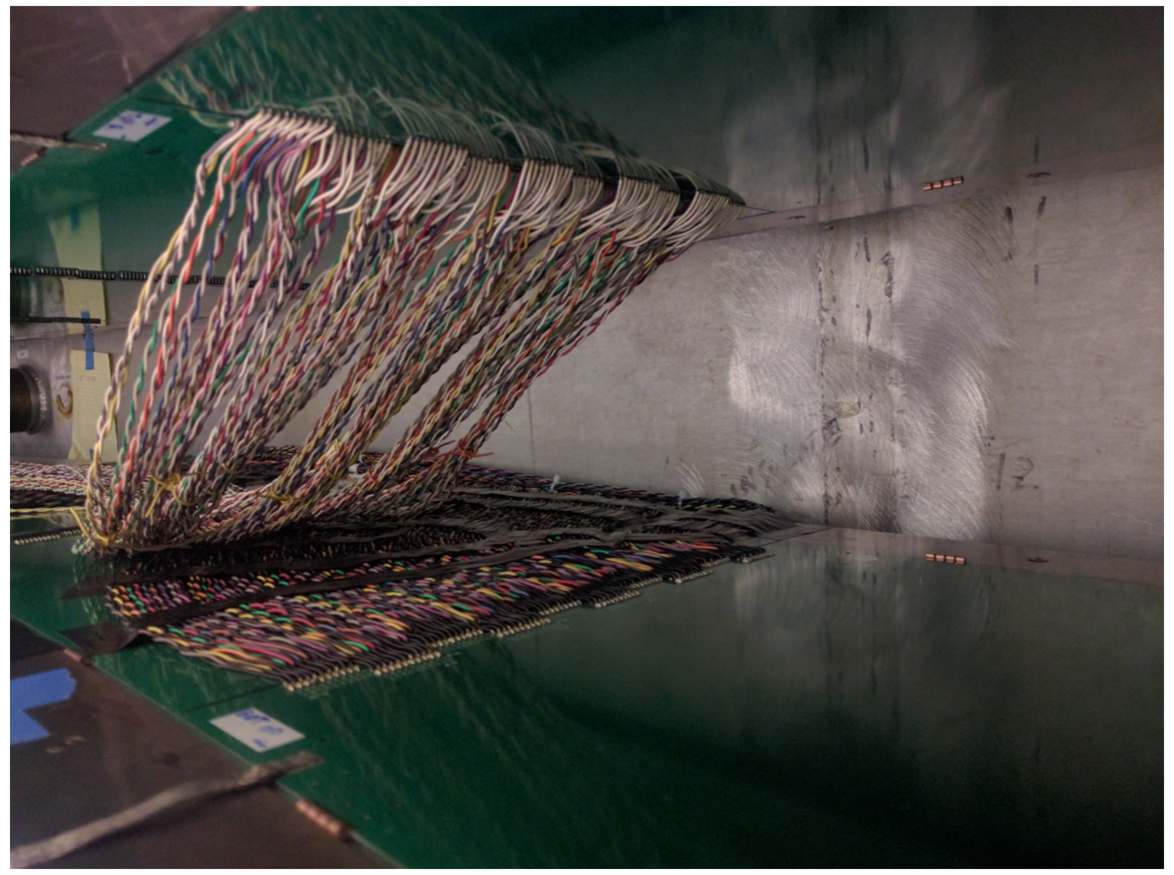
- Apply an RF pulse for a short time to the sample at Larmor frequency — tips spins perpendicular to external B field (**π/2 pulse**)
- Spin precession induces an EMF in the pickup coil
    - So-called **Free-Induction Decay** (**FID**)
- Decay of signal driven by:
    - Spin-spin interactions (dephasing) (pure T_2)
    - Field inhomogeneities (T_2^*)
    - Simultaneously, spins relax back to alignment with holding field (spin-lattice relaxation, T_1)

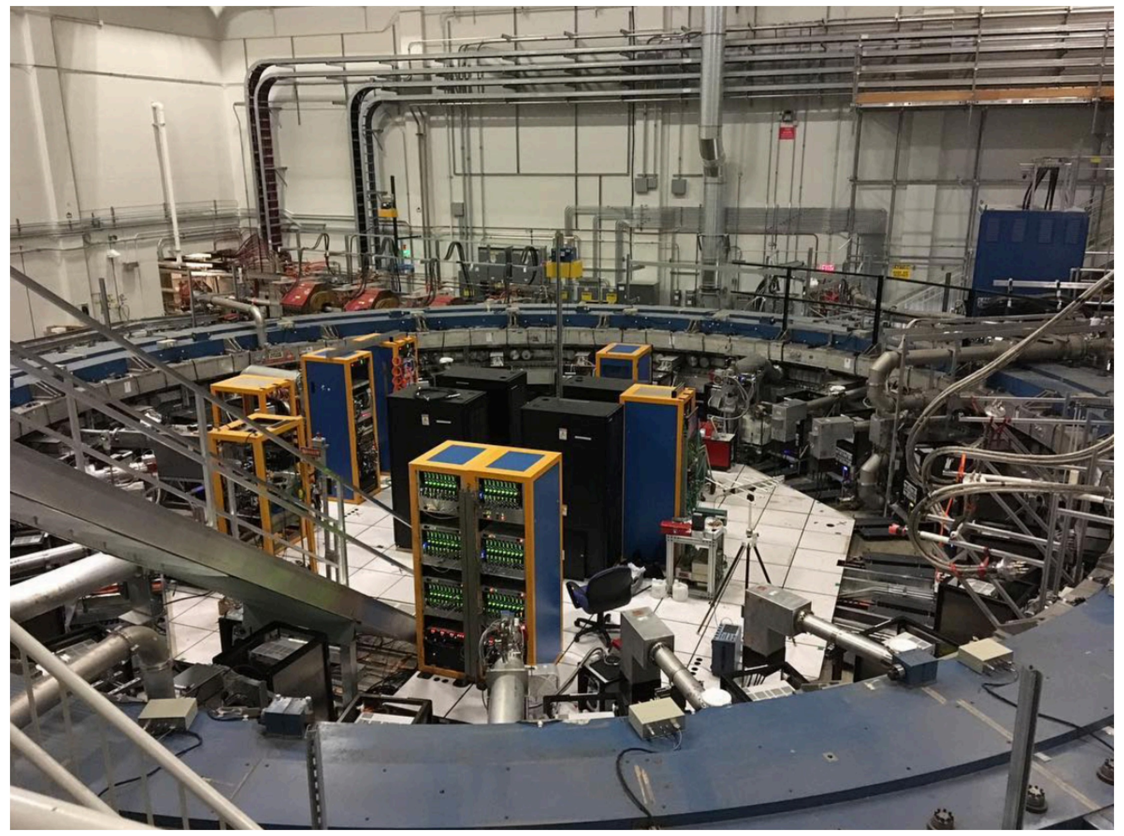


Auxiliary Field Systems

Surface Correction Coils

- Continuous PCB traces going around the ring on pole surfaces
- 100 concentric traces on upper poles, 100 on lower poles
- Current range: ± 2.5 A
- Used to cancel higher-order multipole moments in the magnetic field (on average)





Power Supply Feedback

- Programmable current source with a range of ± 200 mA
- Uses data from **fixed probe** system to stabilize the field at a specified set point

Fluxgates

- Measure (x,y,z) components of transient fields in the hall
- Sensitive down to 10^{-9} T (DC or AC) fields
- Bandwidth up to 1 kHz

Magnetic Circuits

- Recall the electromotive force:

$$\mathcal{E} = \oint \vec{f}_s \cdot d\vec{\ell} = V = IR$$

Can write a similar equation for magnets

$$\mathcal{F} = \oint \vec{H} \cdot d\vec{\ell} = NI$$

Magnetomotive Force (mmf)

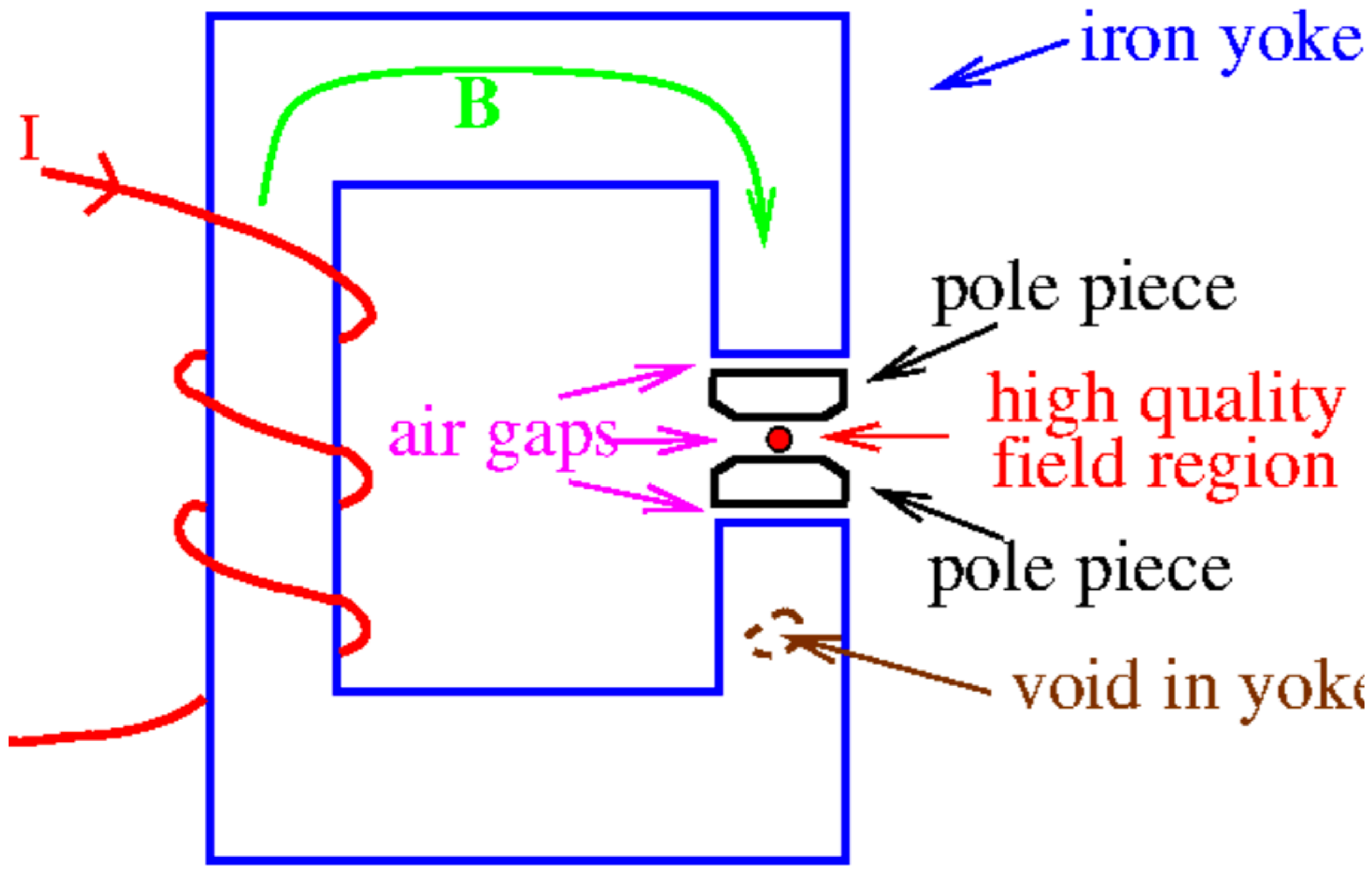
$$\vec{B} = \mu_0 (1 + \chi_m) \vec{H} = \mu \vec{H}$$

Rewrite H in terms of B

$$\Phi = \vec{B} \cdot \vec{A} = \mu \vec{H} \cdot \vec{A}$$

Consider magnetic flux

$$\Phi \oint \frac{d\ell}{\mu A} = \mathcal{F} \Rightarrow \boxed{\mathcal{R} = \oint \frac{d\ell}{\mu A} = \frac{\mathcal{F}}{\Phi}}$$



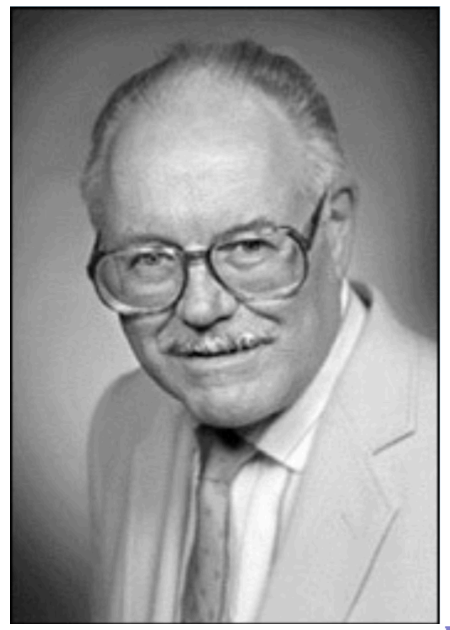
Magnetic Reluctance

$$\boxed{V = IR \Leftrightarrow \mathcal{F} = \Phi \mathcal{R}}$$

- Analogous to resistance in an electrical circuit
- Current flows along a path of least resistance while field lines will take a path of least reluctance
- While the emf drives electric charges (Ohm's Law), the mmf "drives" magnetic field lines (Hopkinson's Law)

Magnet Anatomy

- For E821, Gordon Danby had a brilliant magnet design



B = 1.45 T (~5200 A)

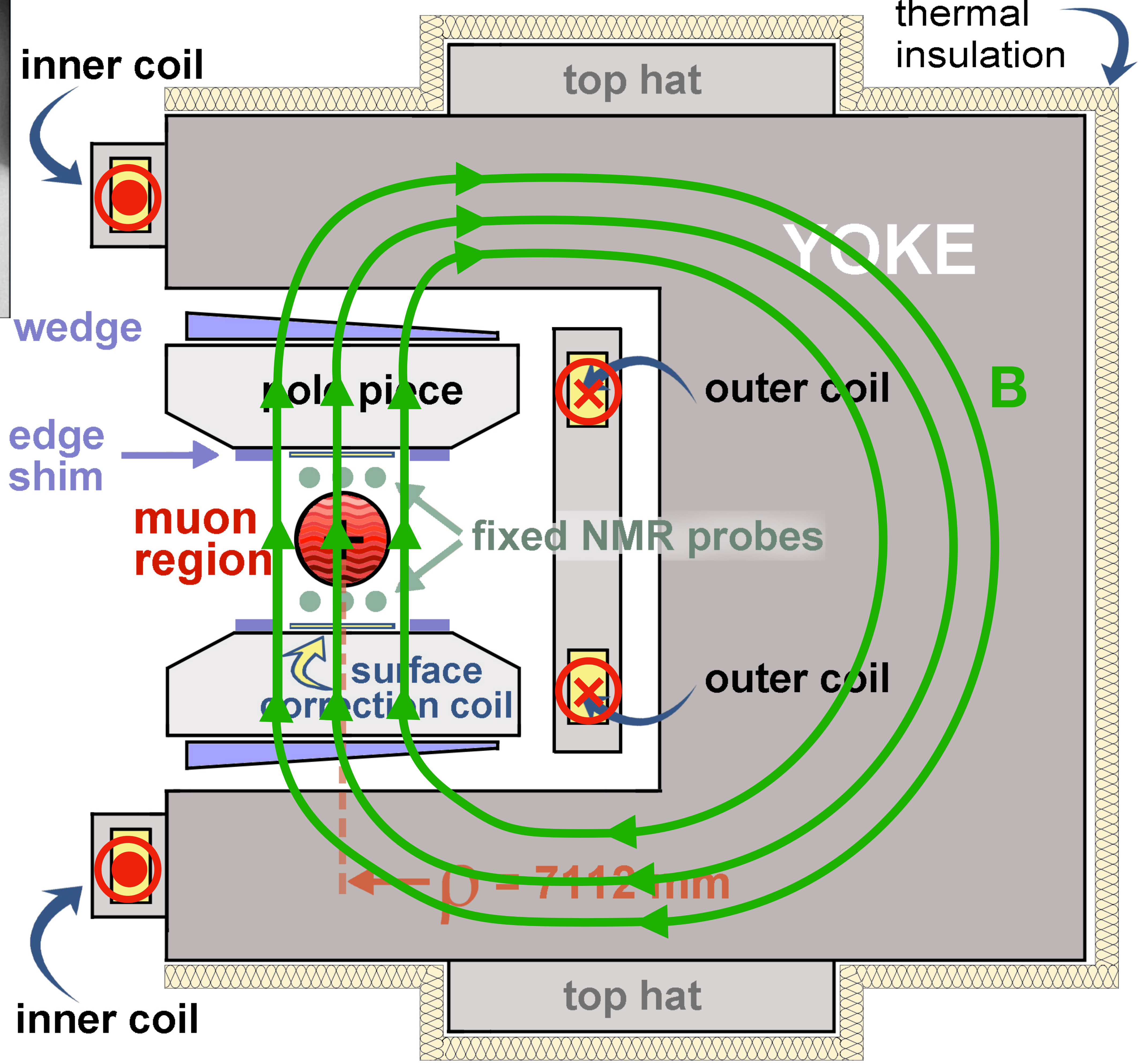
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 upper and 3 lower poles per yoke
- 72 total poles

Shimming knobs

- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (30 deg effect, dipole)
- Wedges (10 deg effect, dipole, quadrupole)
- Edge shims (10 deg effect, dipole, quadrupole, sextupole)
- Laminations (1 deg effect, dipole, quadrupole, sextupole)
- Surface coils (360 deg effect, quadrupole, sextupole,…)

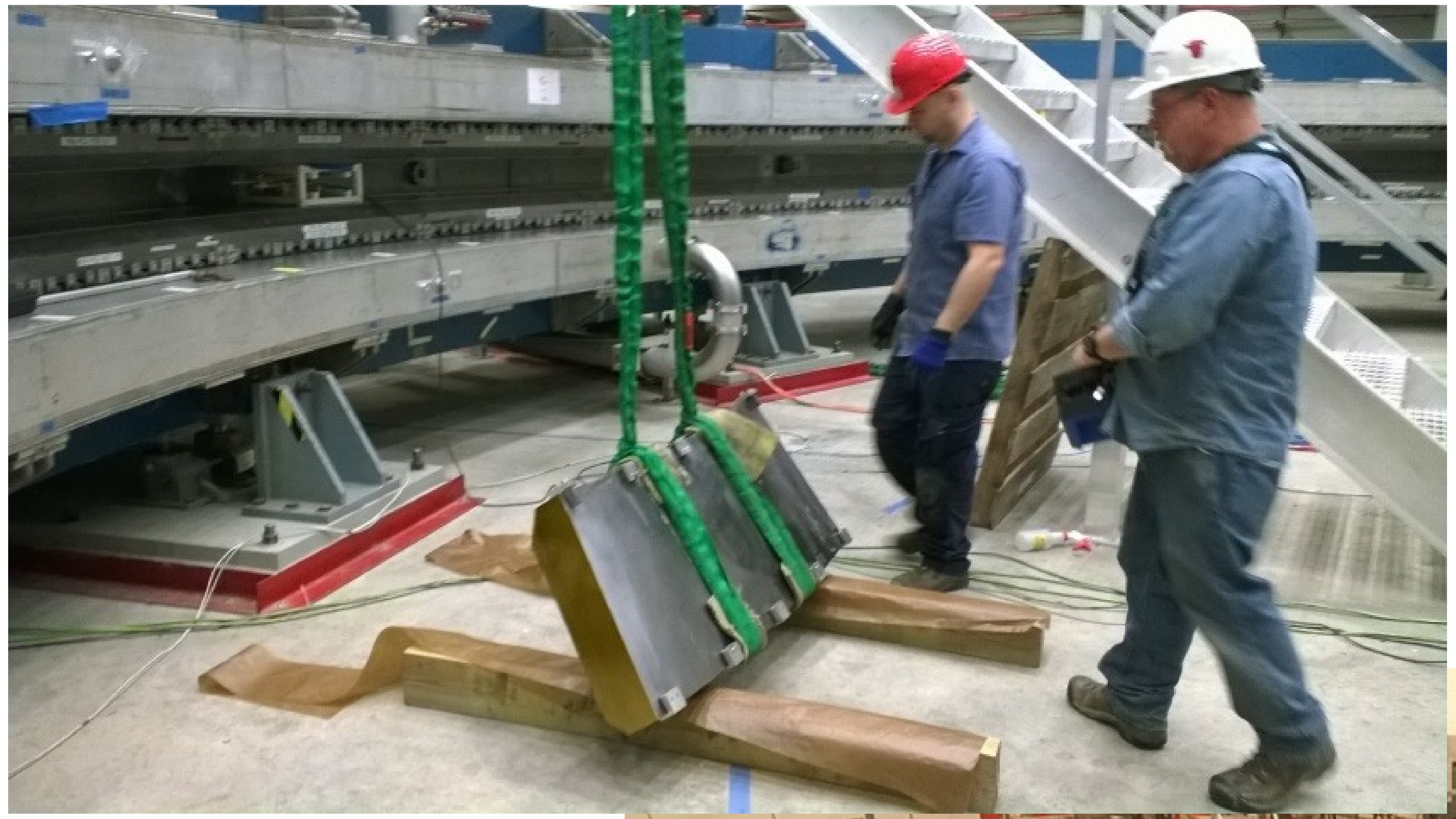


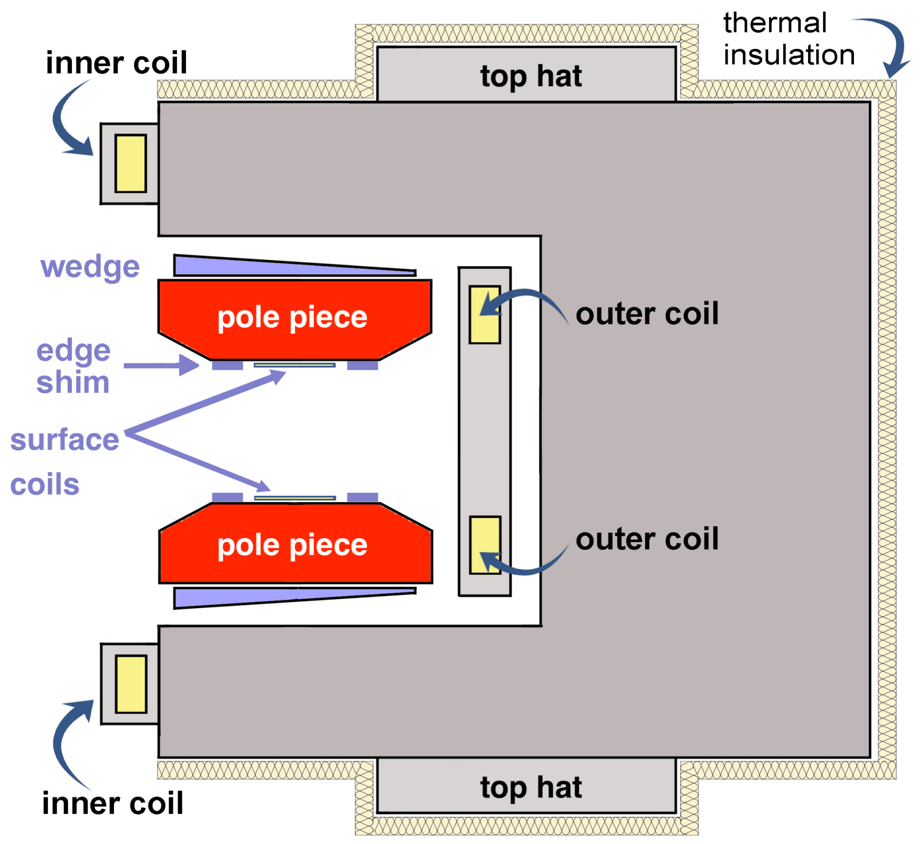
g-2 Magnet in Cross Section

Current direction indicated by red markers

Optimizing the Dipole Moment

- Want to optimize the vertical component of the field
- Step and tilt discontinuities in pole surfaces yield large variations in the field
- To reduce/remove such effects, make adjustments to pole feet, which changes the magnet gaps and tilts
  - Use 0.001—0.010” thick shims
  - Requires removal of poles from the ring
- Informed by a computer model that optimizes the pole configurations
  - Requires global continuity between pole surfaces
  - Allows only three adjacent poles to be moved at a time (preserves alignment)





Minimizing the Quad, Sext, Octu

Calibrated shimming knobs

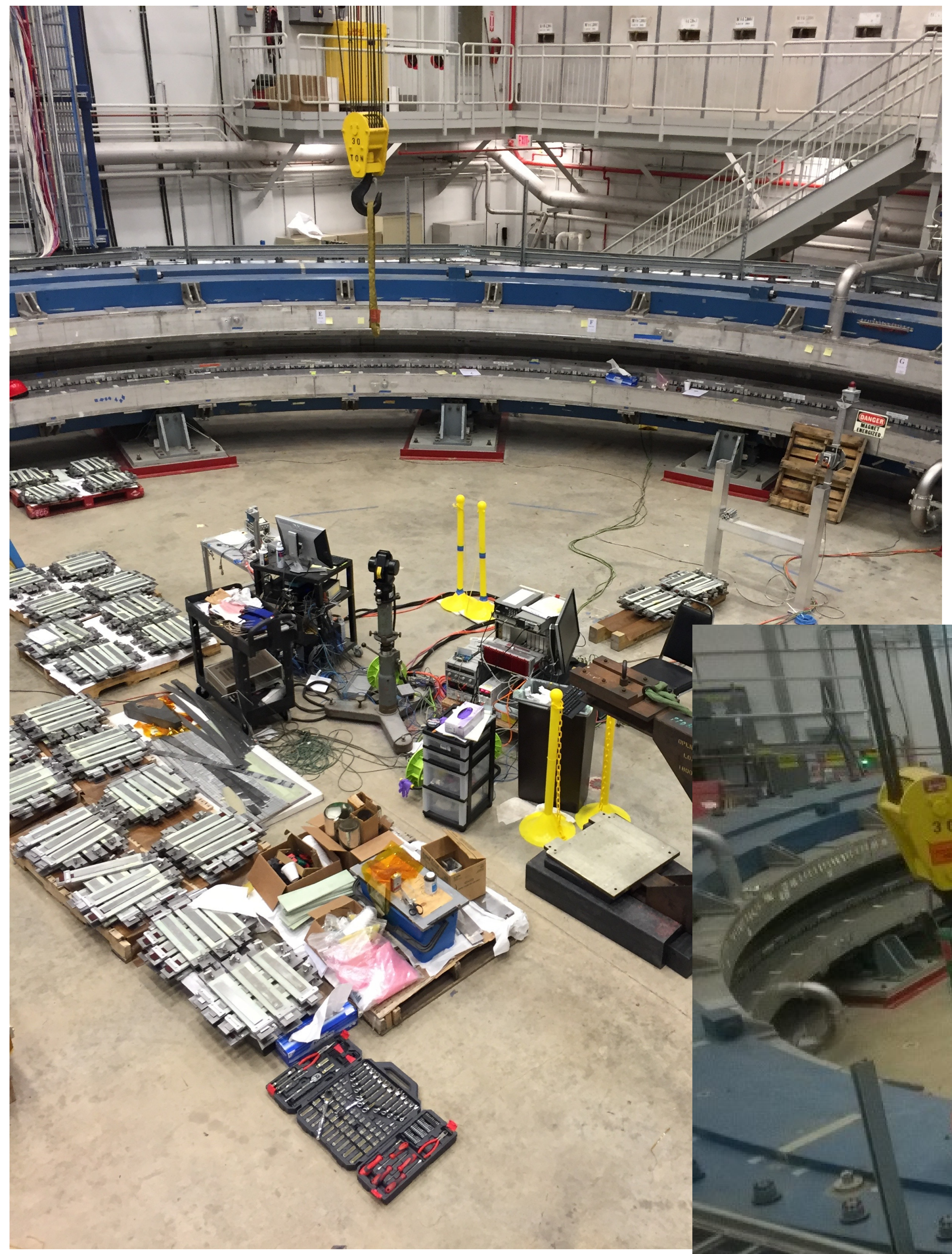
- 48 top hats
- 864 wedges
- ~8400 iron foils (on pole surfaces)

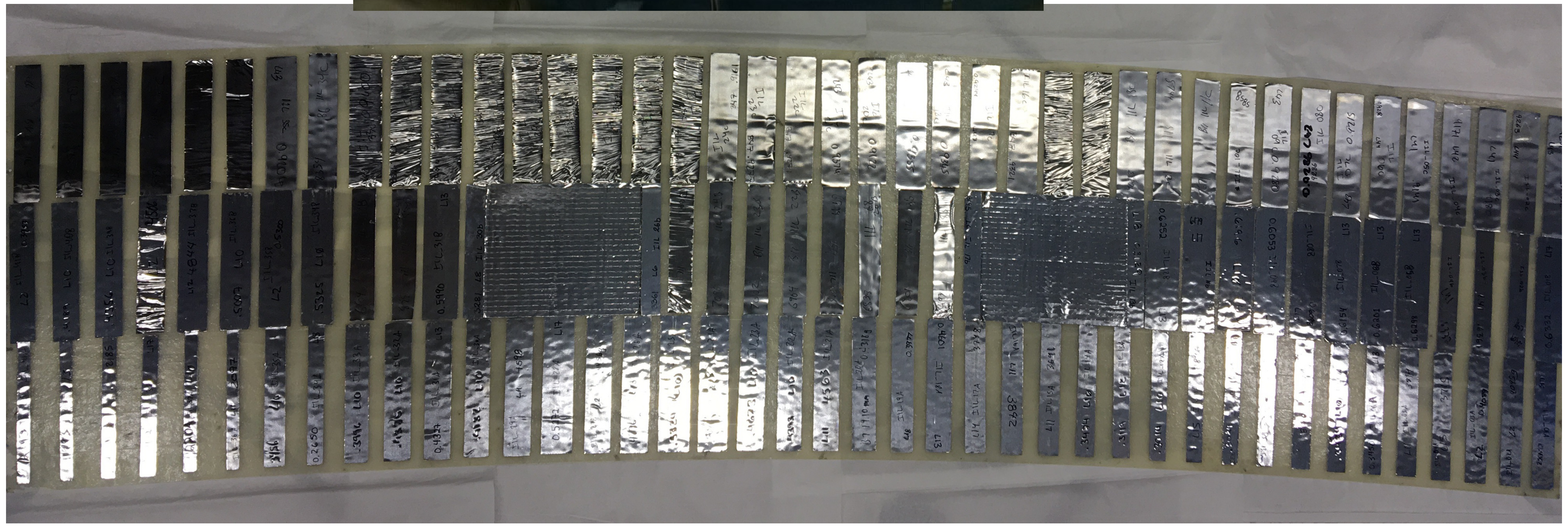
Coarse tuning: top hat & wedge adjustments (**dipole, quadrupole**)

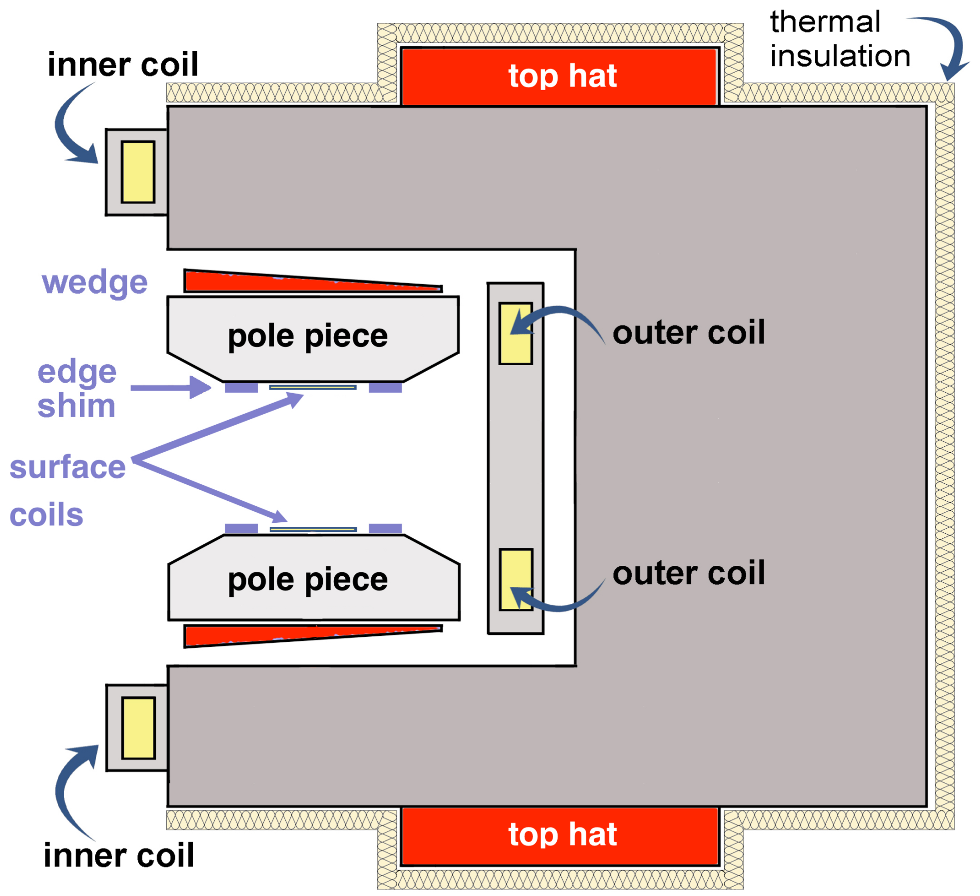
- Least-squares fit to field maps predicts top hat and wedge positions

Fine tuning: iron foils (**quadrupole, sextupole,…**)

- Modeled as saturated dipoles in 1.45 T field
- Computer code predicts foil width (mass) distribution to fill in the valleys of the field map

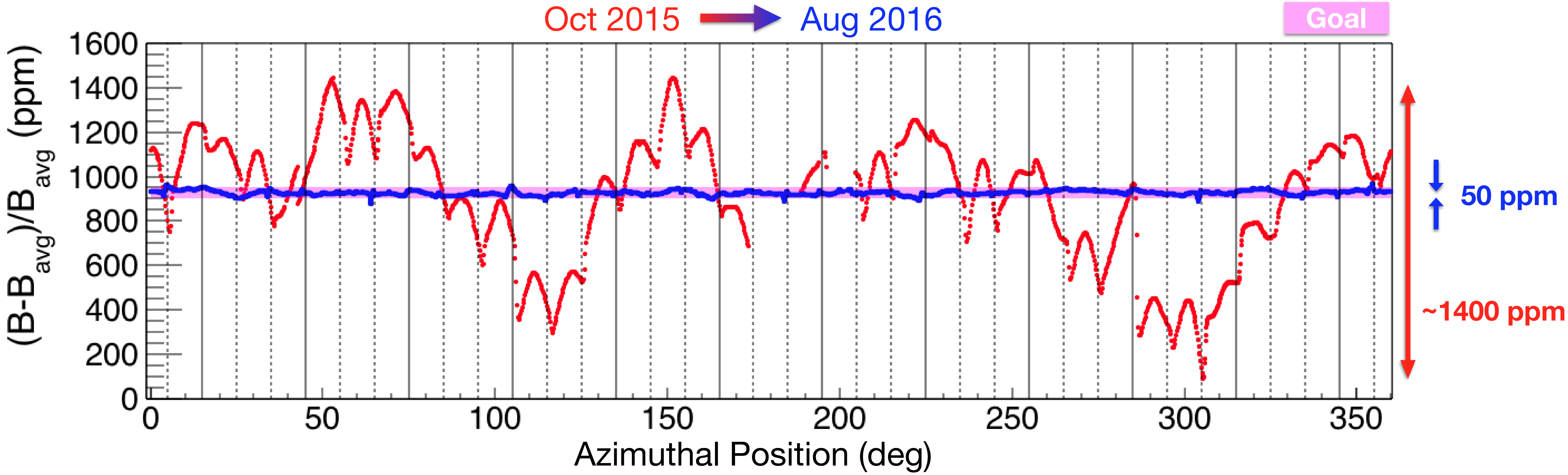




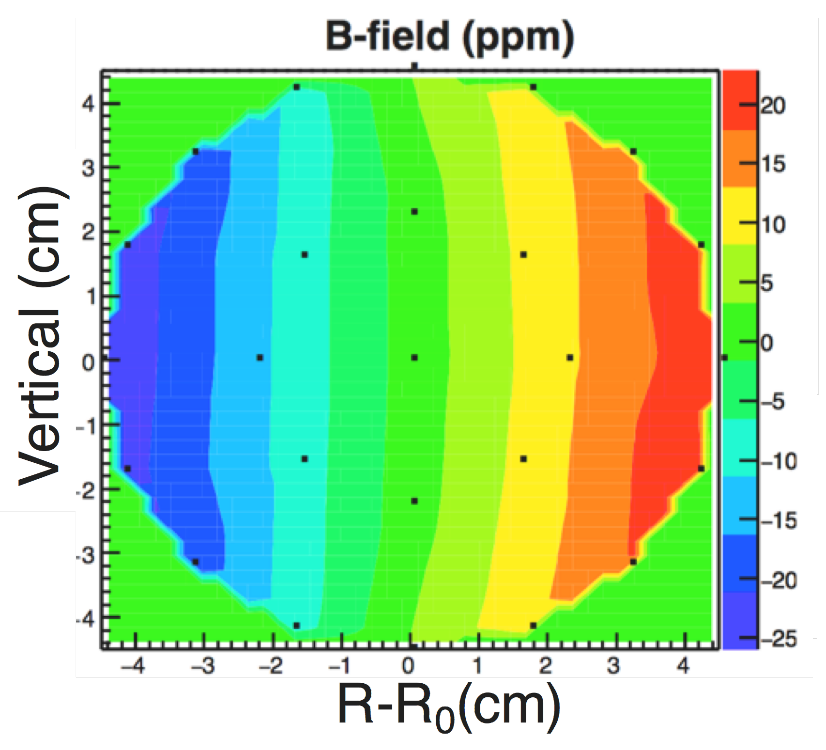


Magnetic Field Uniformity: Rough Shimming

Extensive program of adjusting shimming knobs to achieve ± 25 ppm uniformity

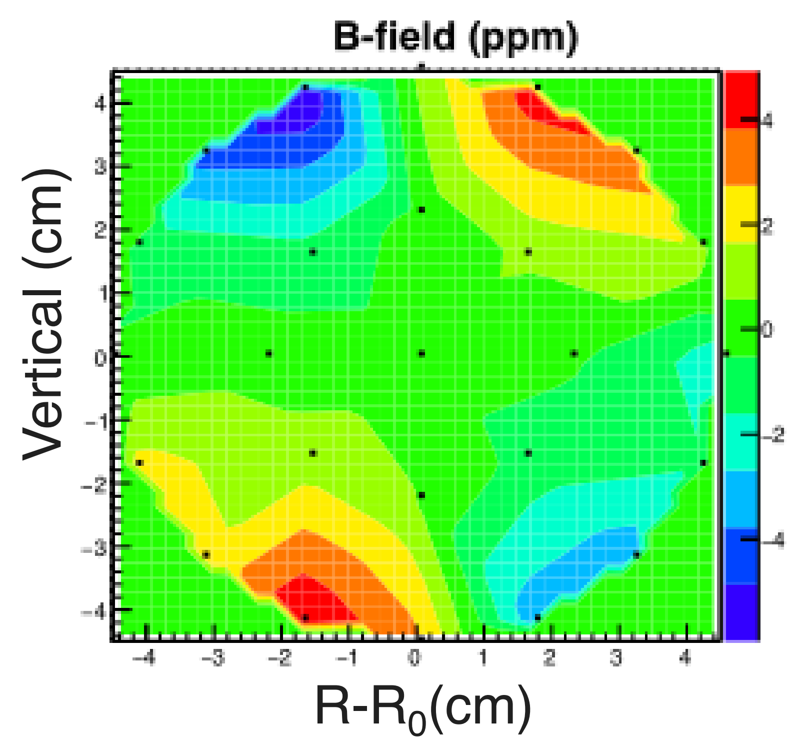


Azimuthally-Averaged Maps



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

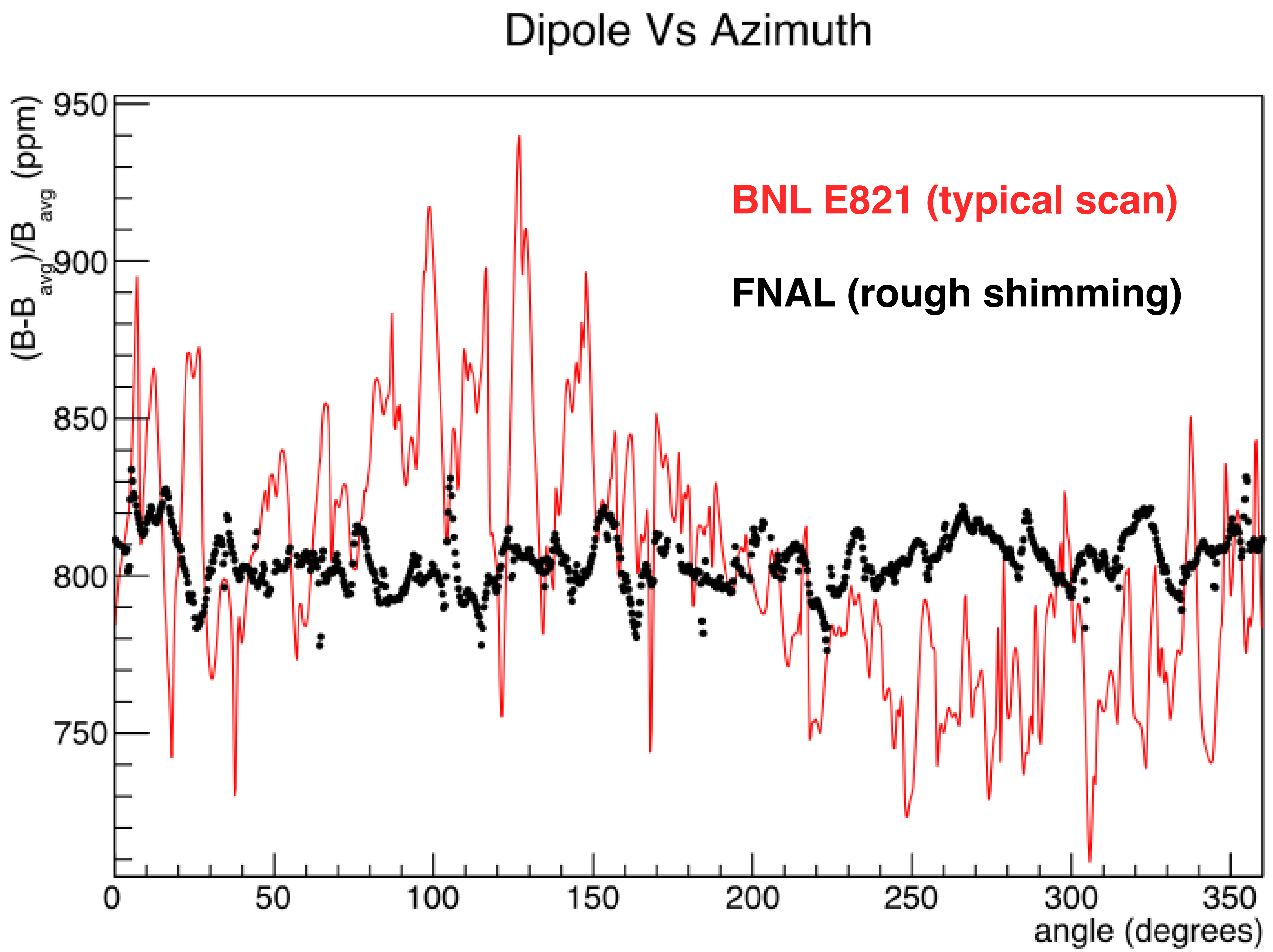
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

Magnetic Field Comparison: BNL E821 and FNAL E989



- Laminations very successful in reducing field variations

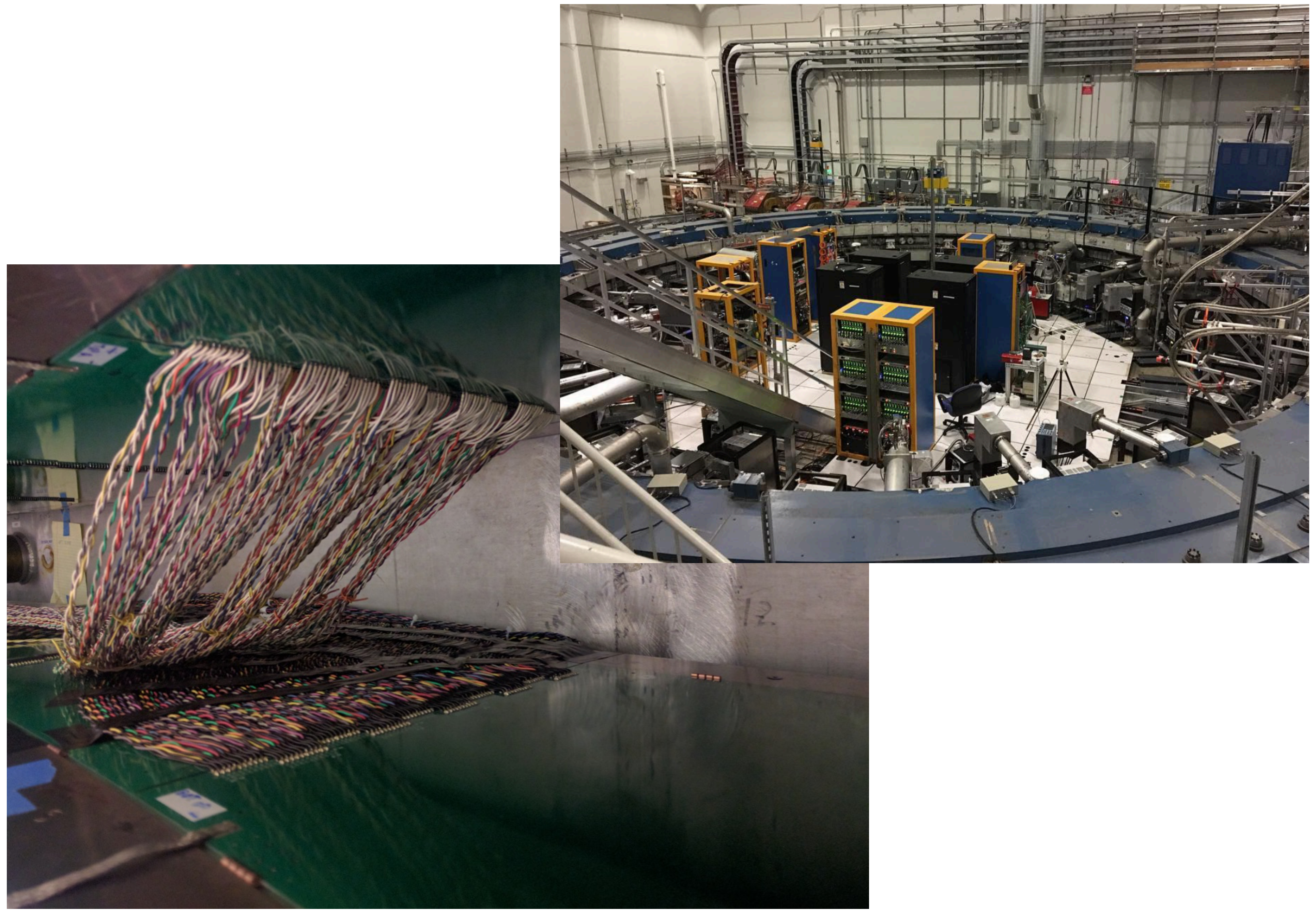
- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

Active Shimming: Surface Correction Coils

- Continuous PCB traces going around the ring on pole surfaces
- 100 concentric traces on upper poles, 100 on lower poles
- Current range: ± 2.5 A
- Used to cancel higher-order multipole moments in the magnetic field (on average)
- Trolley scans serve as input

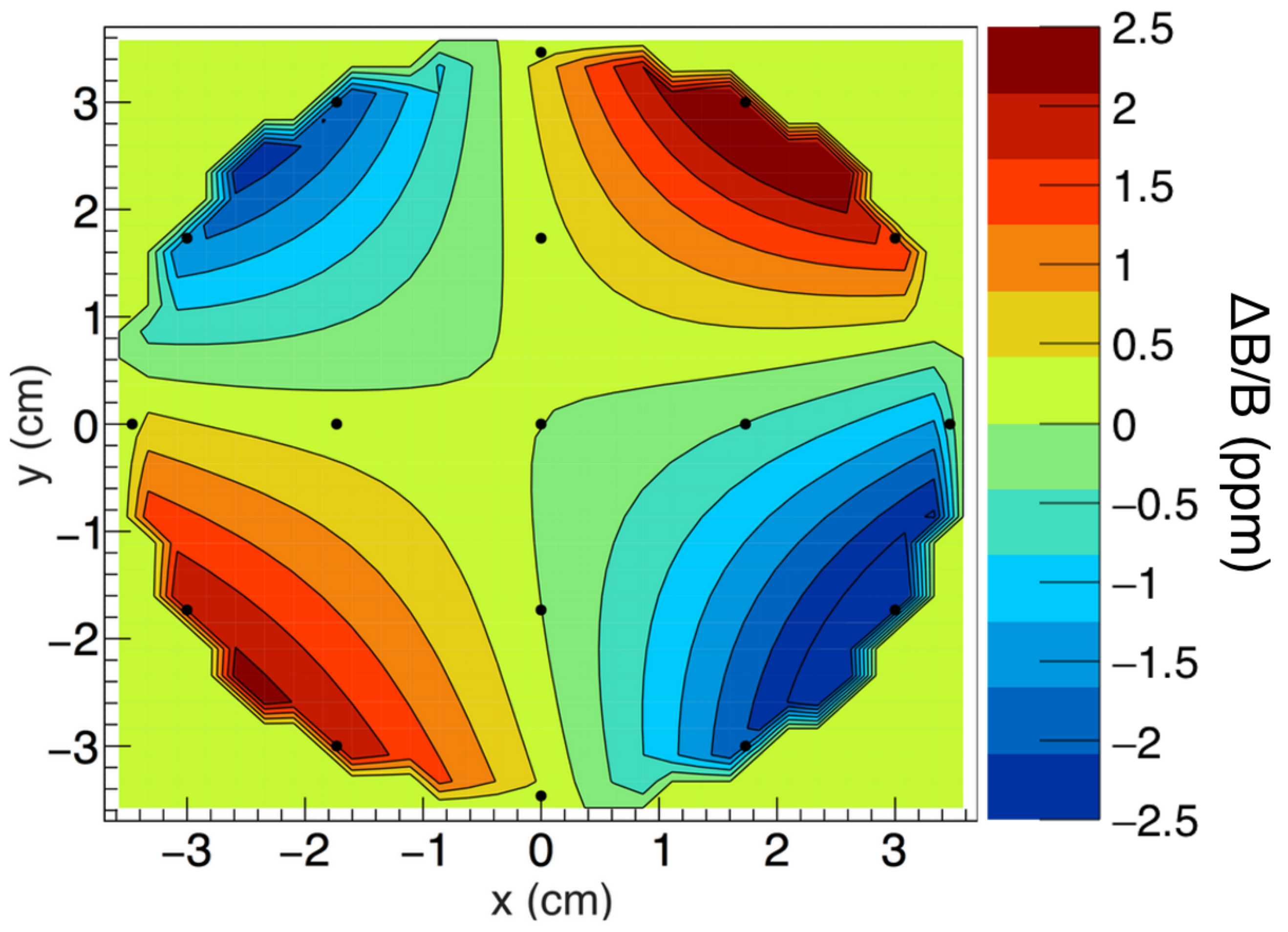
Radial dependence of coil currents for a given multipole

Multipole	Normal, Top	Normal, Bottom	Skew, Top	Skew, Bottom
Dipole	--	--	I	-I
Quadrupole	a	a	x	-x
Sextupole	ax	ax	x^2-a^2	-x^2+a^2
Octupole	3ax^2-a^3	3ax^2-a^3	x^3-3a^2x	-x^3+3a^2x
Decupole	ax^3-a^3x	ax^3-a^3x	x^4+a^4-6a^2x^2	-x^4-a^4+6a^2x^2

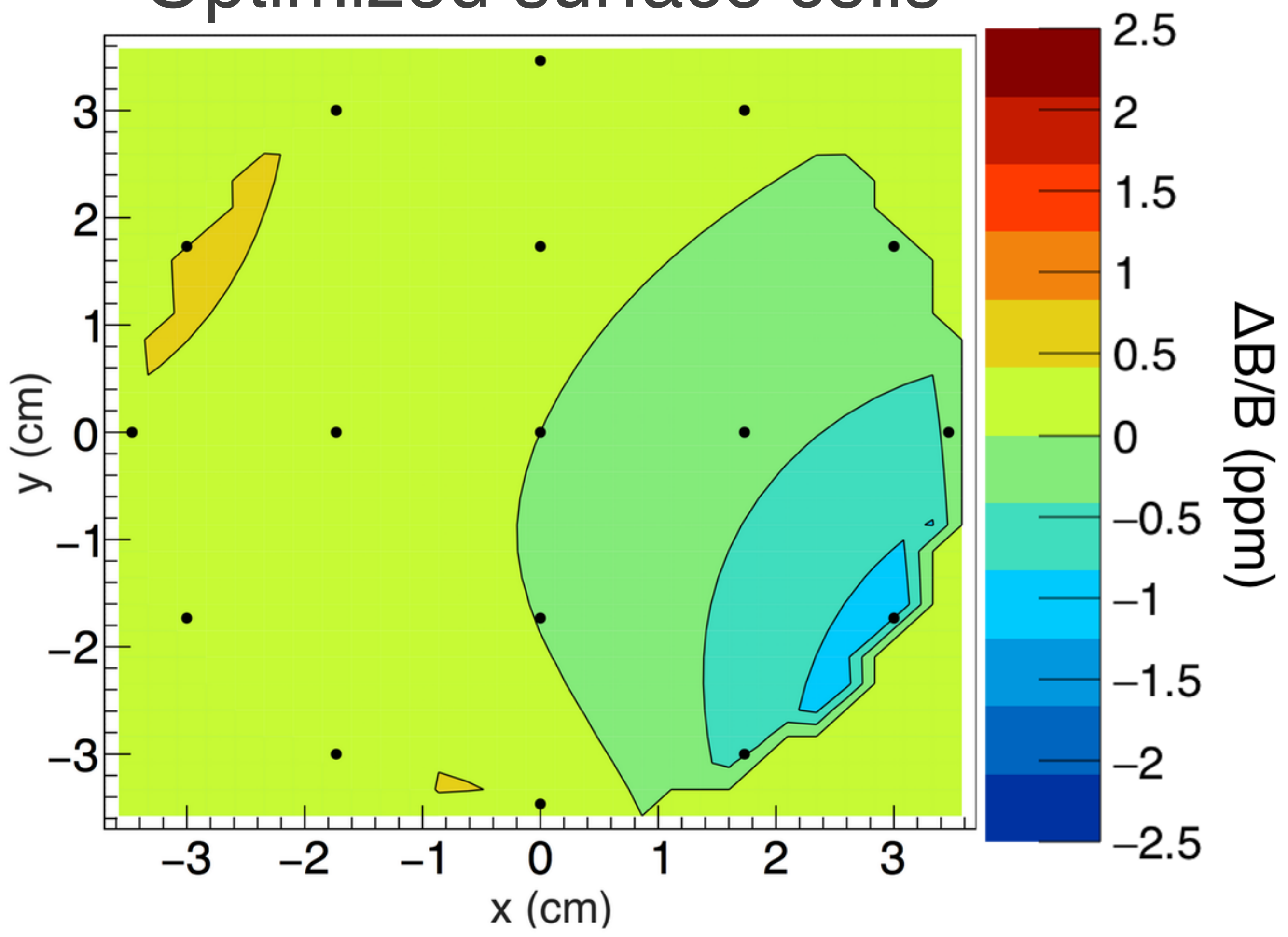


Azimuthally-averaged data

Non-optimized surface coils

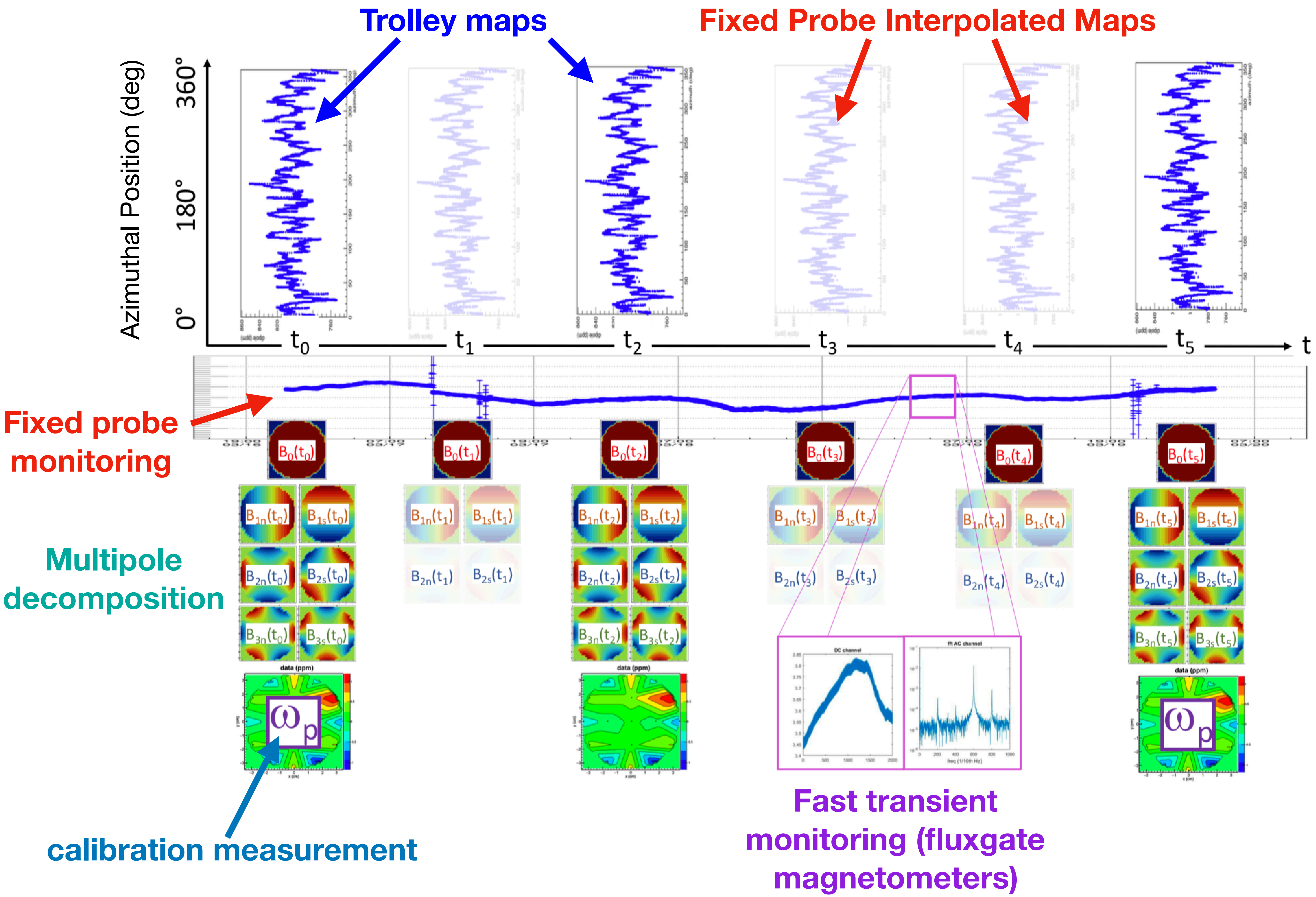


Optimized surface coils



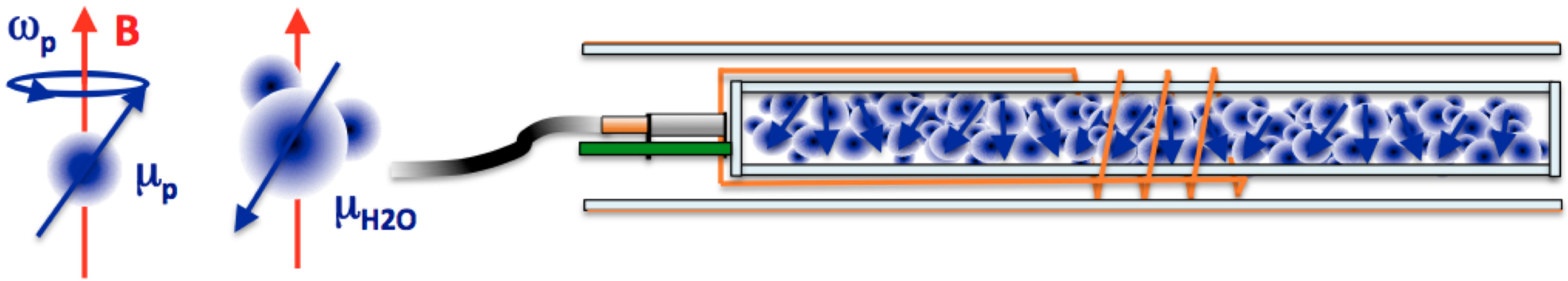
Monitoring and Mapping the Magnetic Field

- **Trolley** runs every 3—4 days
- Monitor stability with **Fixed Probes**
- Build interpolated field maps using **Fixed Probes**
- Monitor fast transients with **Fluxgate Magnetometers**
- Field stabilized to ~ 30 ppb via **Programmable Current Source** (PID algorithm)
- Take dedicated data with **Plunging Probe** to calibrate the **Trolley** measurements



Calibration of the Magnetic Field

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



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

Corrections required for imperfect shapes

- Sphere: Asphericity of 1% => 25 ppb effect. Can be calculated if shape is known; measure by rotating sample about different axes
- Cylinder: can rotate about its long axis; try different length cylinders
- Want small rotational asymmetry => not dependent on probe angle

Two main tasks

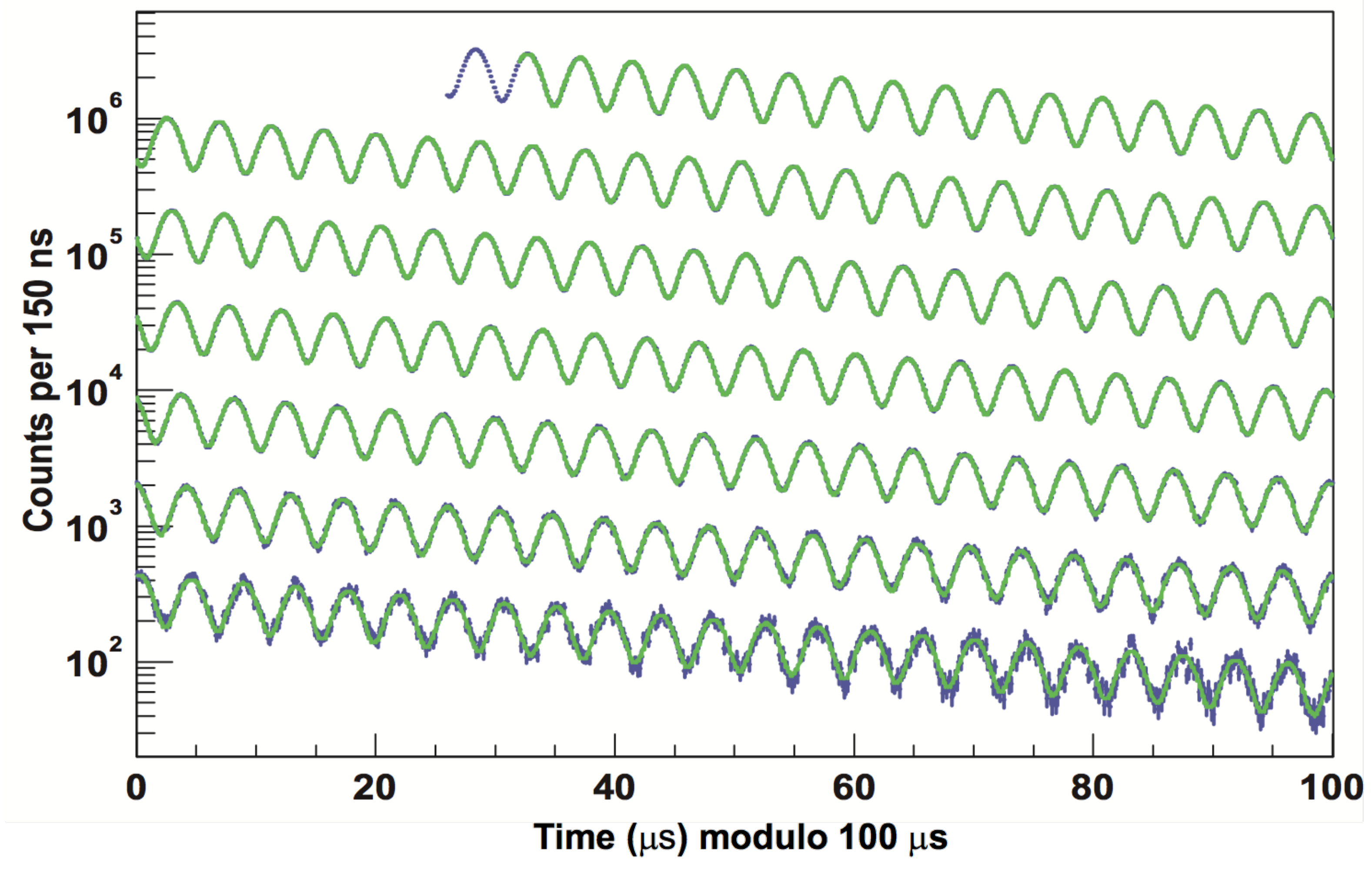
- Ensure material perturbations are small (~ 10 ppb)
- Measure the effects with high precision

These are **static** corrections; need to worry about **dynamic** ones too (radiation damping, RF coil inhomogeneity, time dependence of gradients, …)

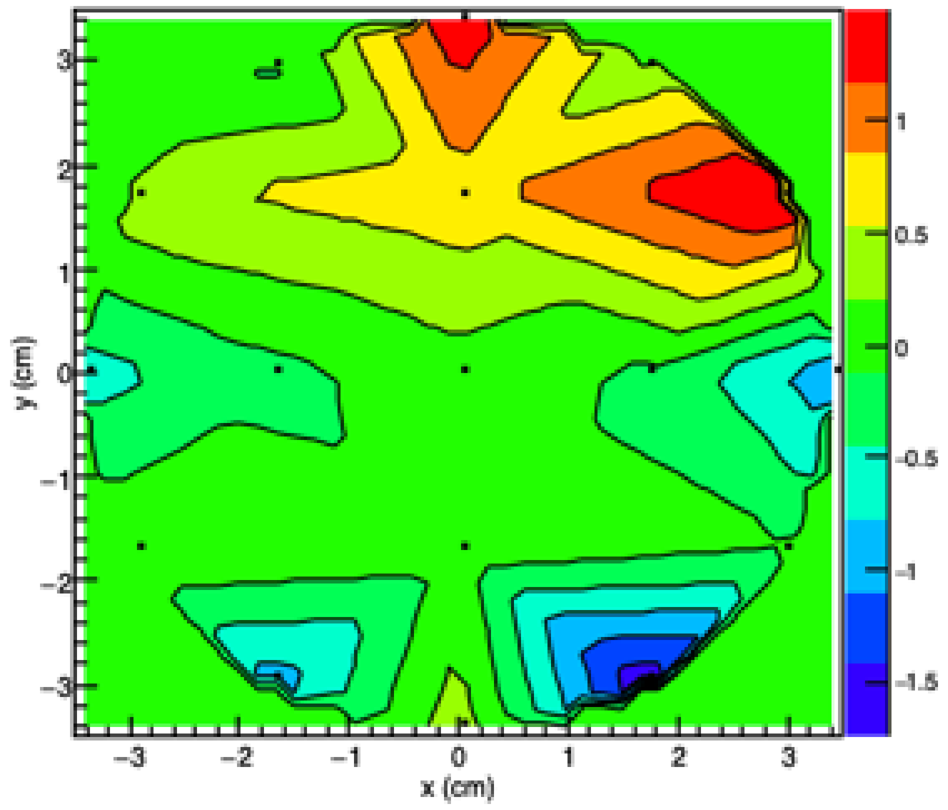
Extracting a_μ From Our Data

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

Measure muon decay to positrons

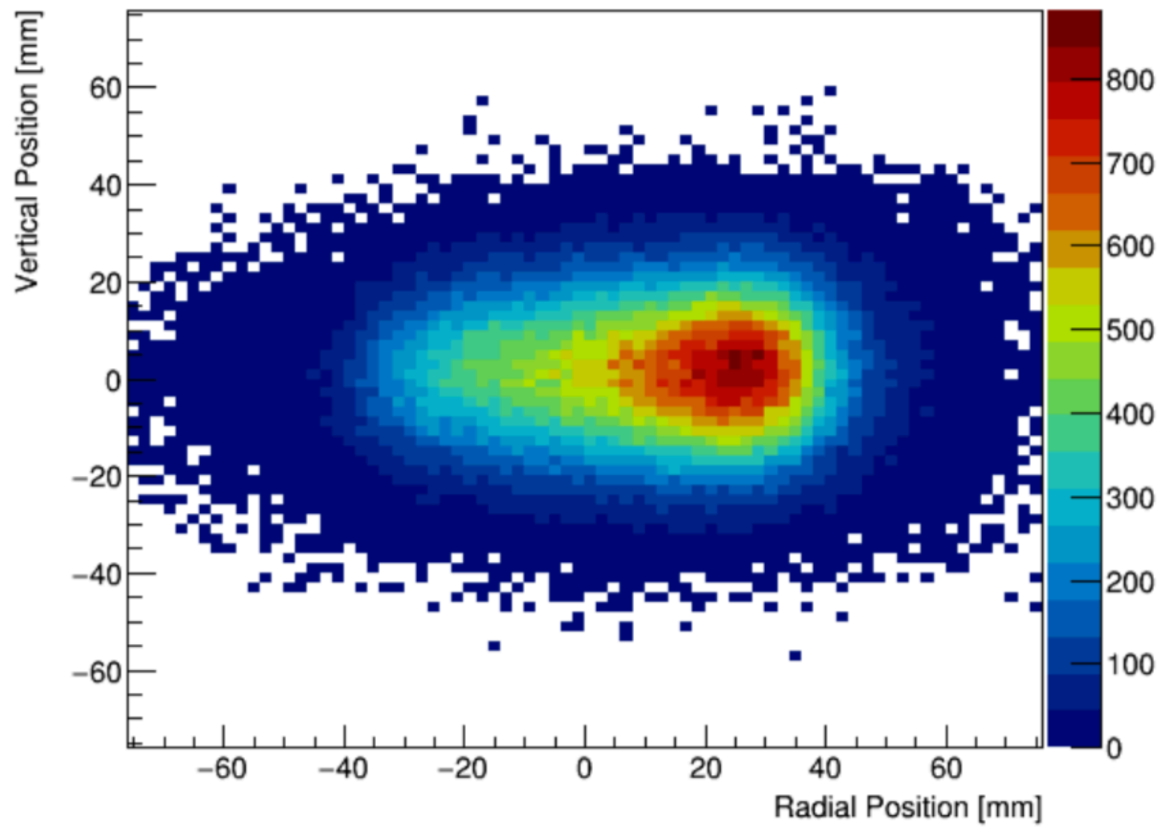


NMR map of field



x

Muon distribution



Know these from other experiments (to 25 ppb)

- μ_e/μ_p = -658.210 6866(20) [**3 ppb**]
- m_μ/m_e = 206.768 2826(46) [**22 ppb**]
- g_e = 1.001 159 652 180 91(26) [**0.3 ppt**]

P. J. Mohr et al, Rev. Mod. Phys. **88**, 035009 (2016)