Measuring the Anomalous Magnetic Moment of the Muon

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On Behalf of the Muon g-2 Collaboration

PASCOS, Manchester UK

July 3rd, 2019

Outline

- Introducing the anomaly
- Standard Model contributions
- Theoretical status and prospects
- Fermilab Muon g-2 experiment
  - Measurement principle
  - Analysis methods
  - Current status and prospects
- Conclusions

Muon Magnetic Moment

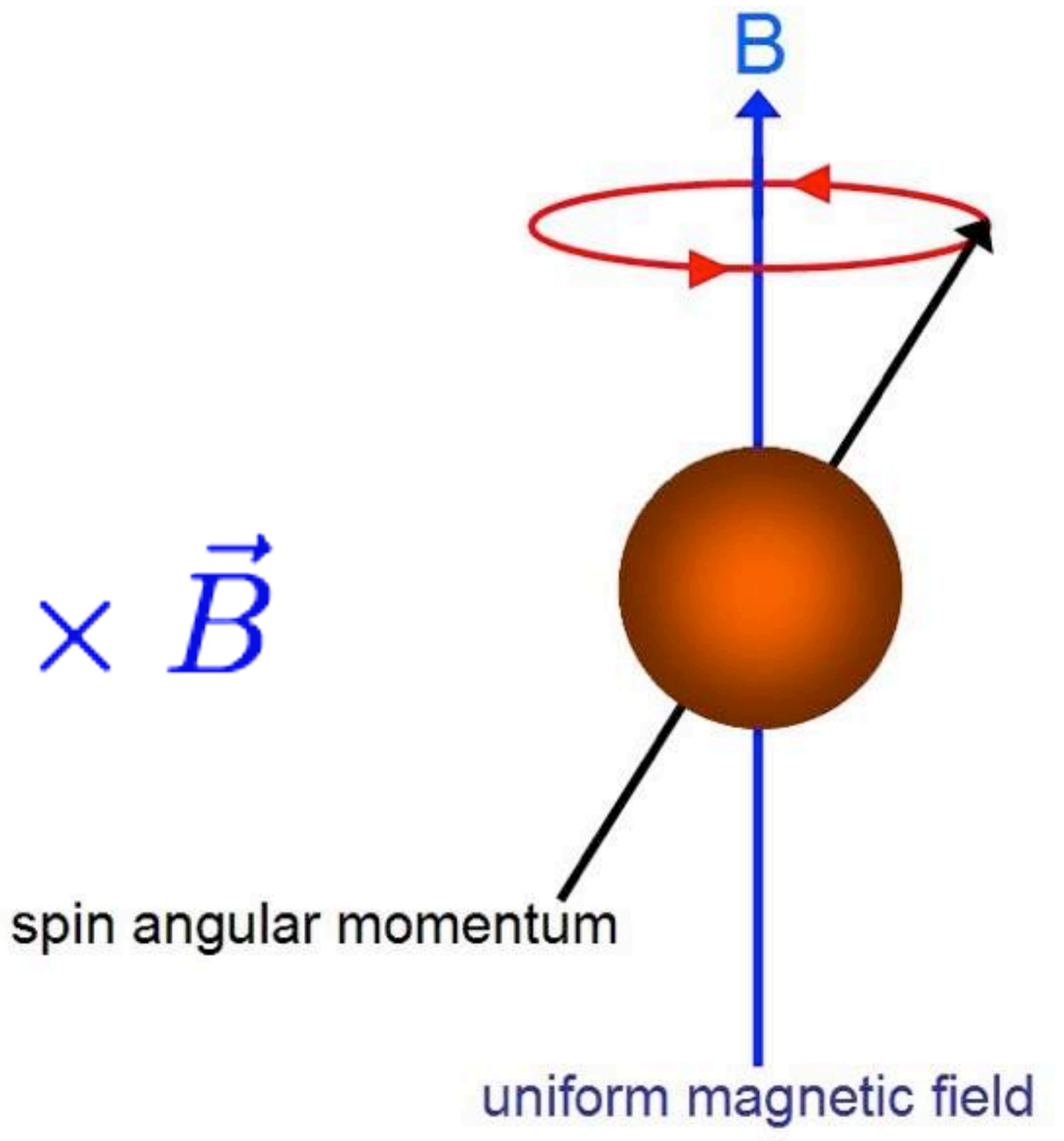
- The muon has an intrinsic magnetic moment that is coupled to its spin via the gyromagnetic ratio *g*:

$$\vec{\mu} = g \frac{e}{2m_\mu} \vec{S}$$

- Magnetic moment (spin) interacts with external B-fields

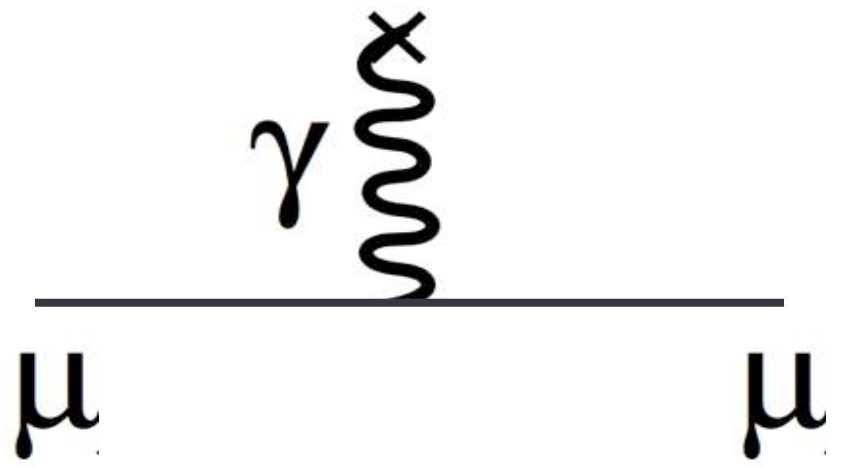
$$\vec{\mu} \times \vec{B}$$

- Makes spin precess at frequency determined by *g*

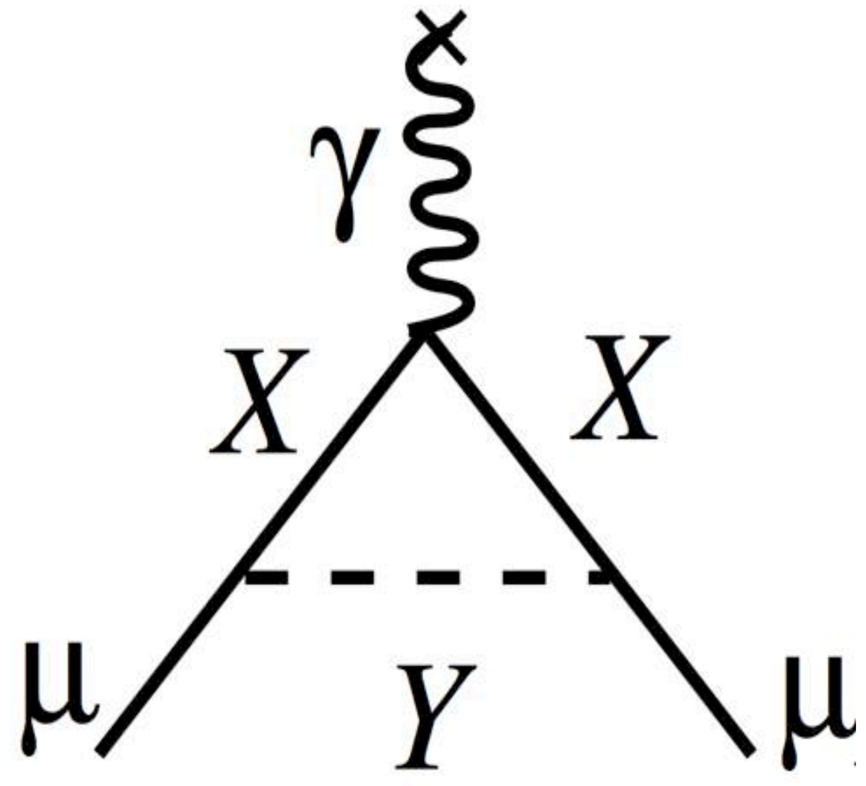


Magnetic Moment & Virtual Loops

- For a pure Dirac spin-½ charged fermion, g is exactly 2

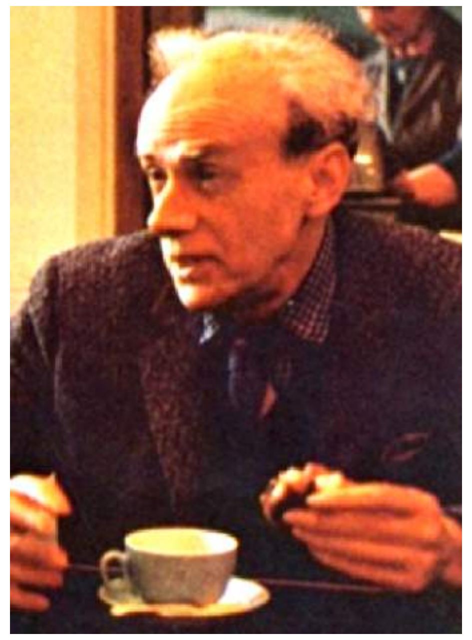


- Interactions between the muon and virtual loops change the value - X & Y particles could be SM or new physics:

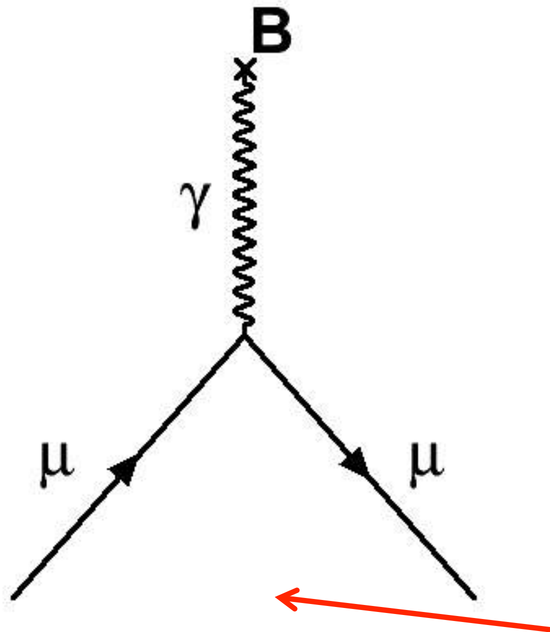


Standard Model Components of g-2

Dirac



Charged,
spin ½ particle



$$g_\mu = 2$$

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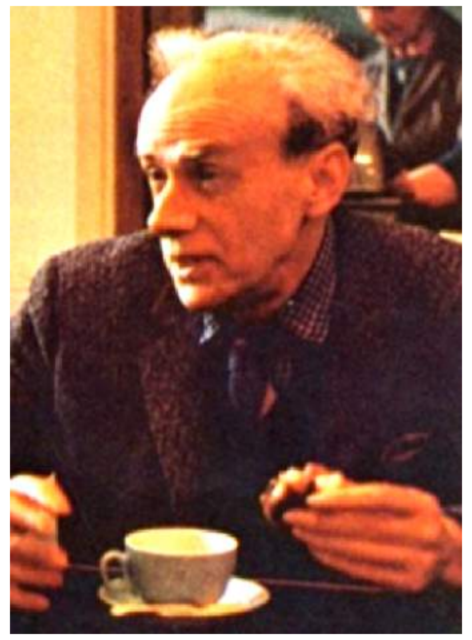

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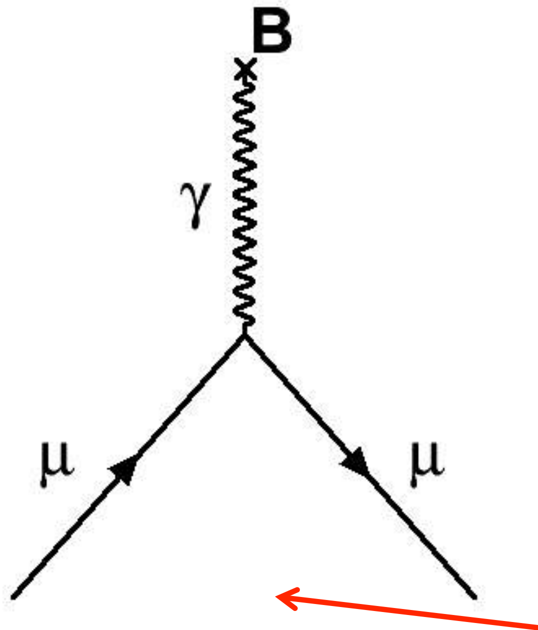

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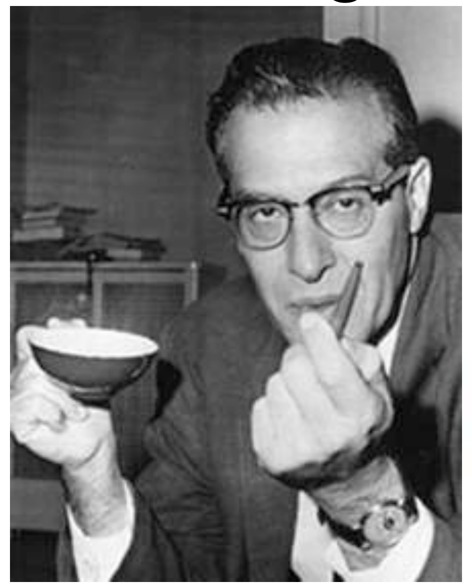
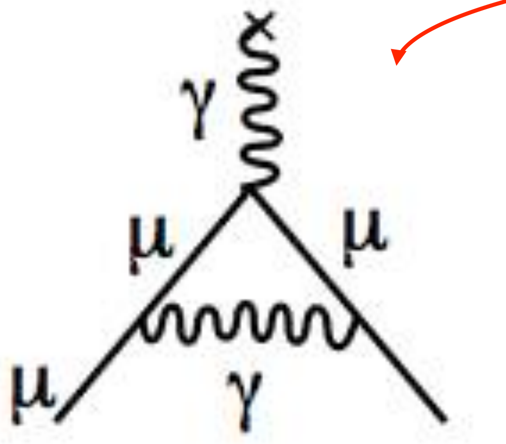
Schwinger





$$\frac{\alpha}{2\pi} = 0.00232$$

1st Order QED

Standard Model Components of g-2

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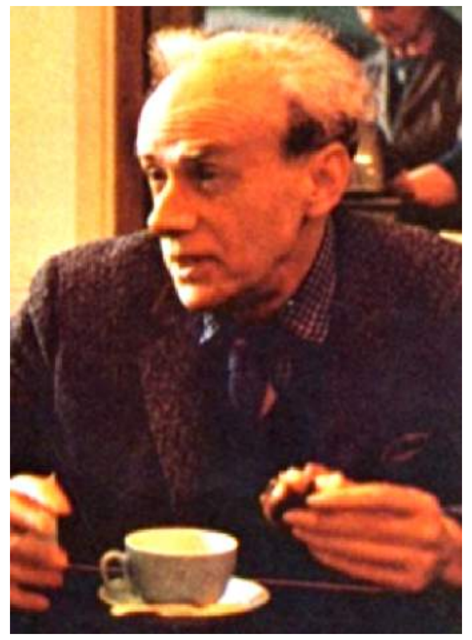

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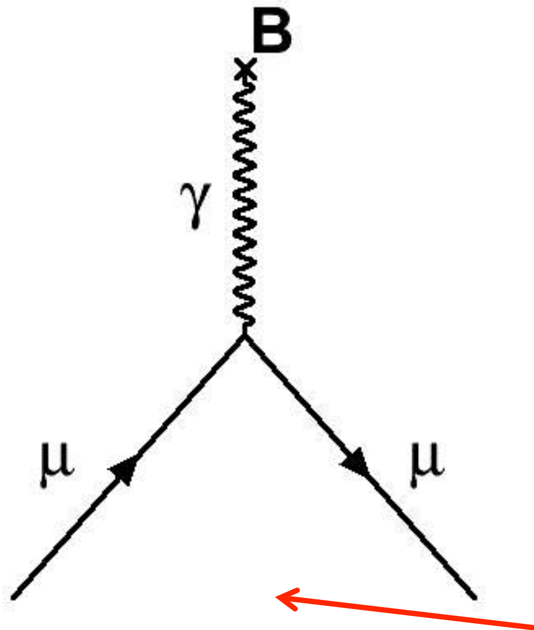
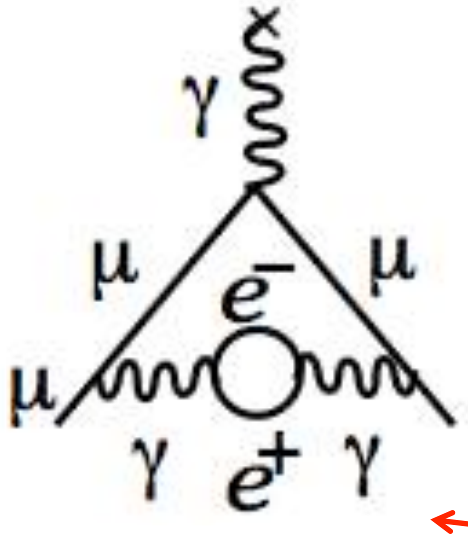


Kinoshita

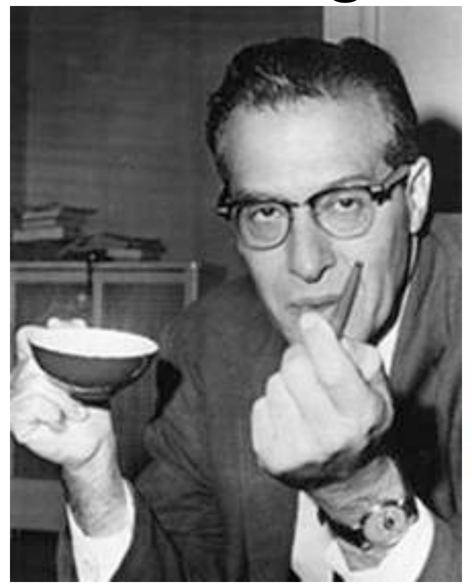
Up to 10th
Order QED

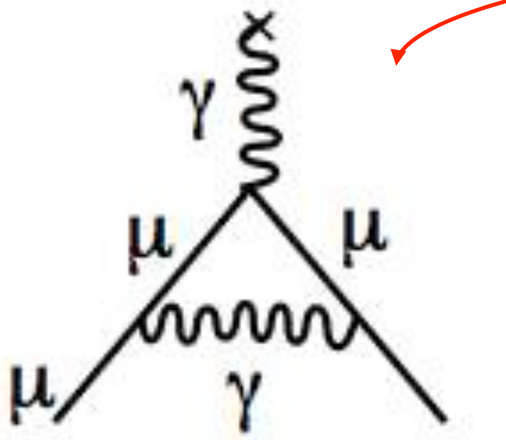


+12671
diagrams

$$g_\mu = 2.0$$

Schwinger





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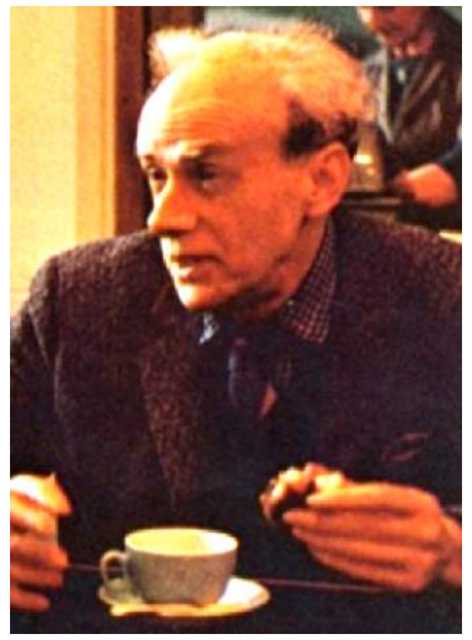

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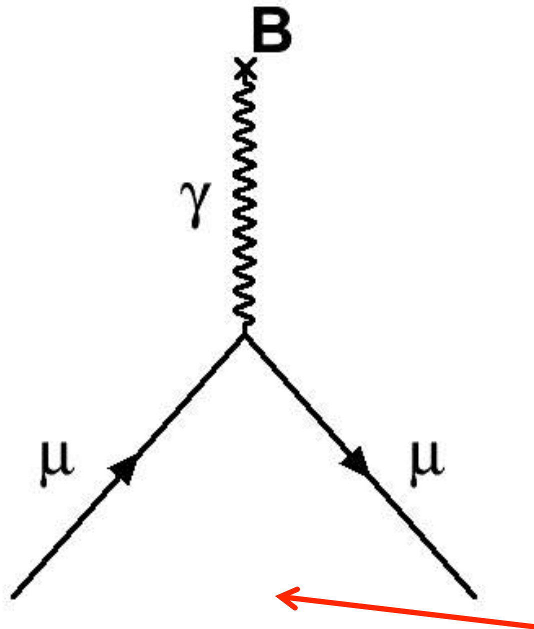

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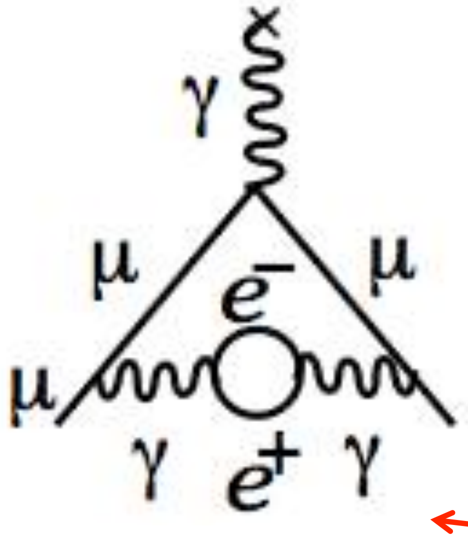

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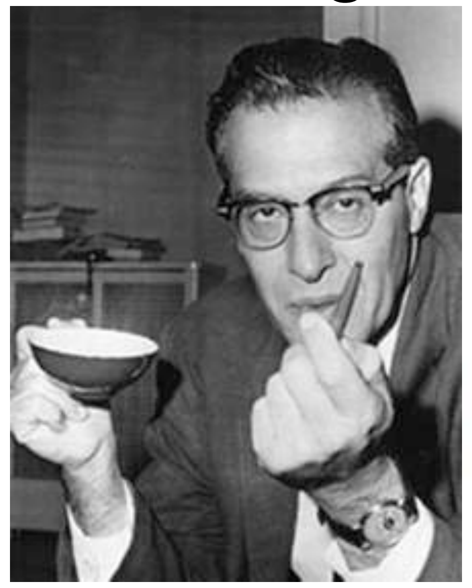

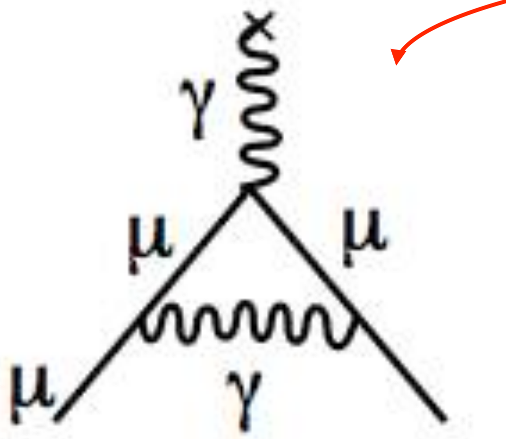

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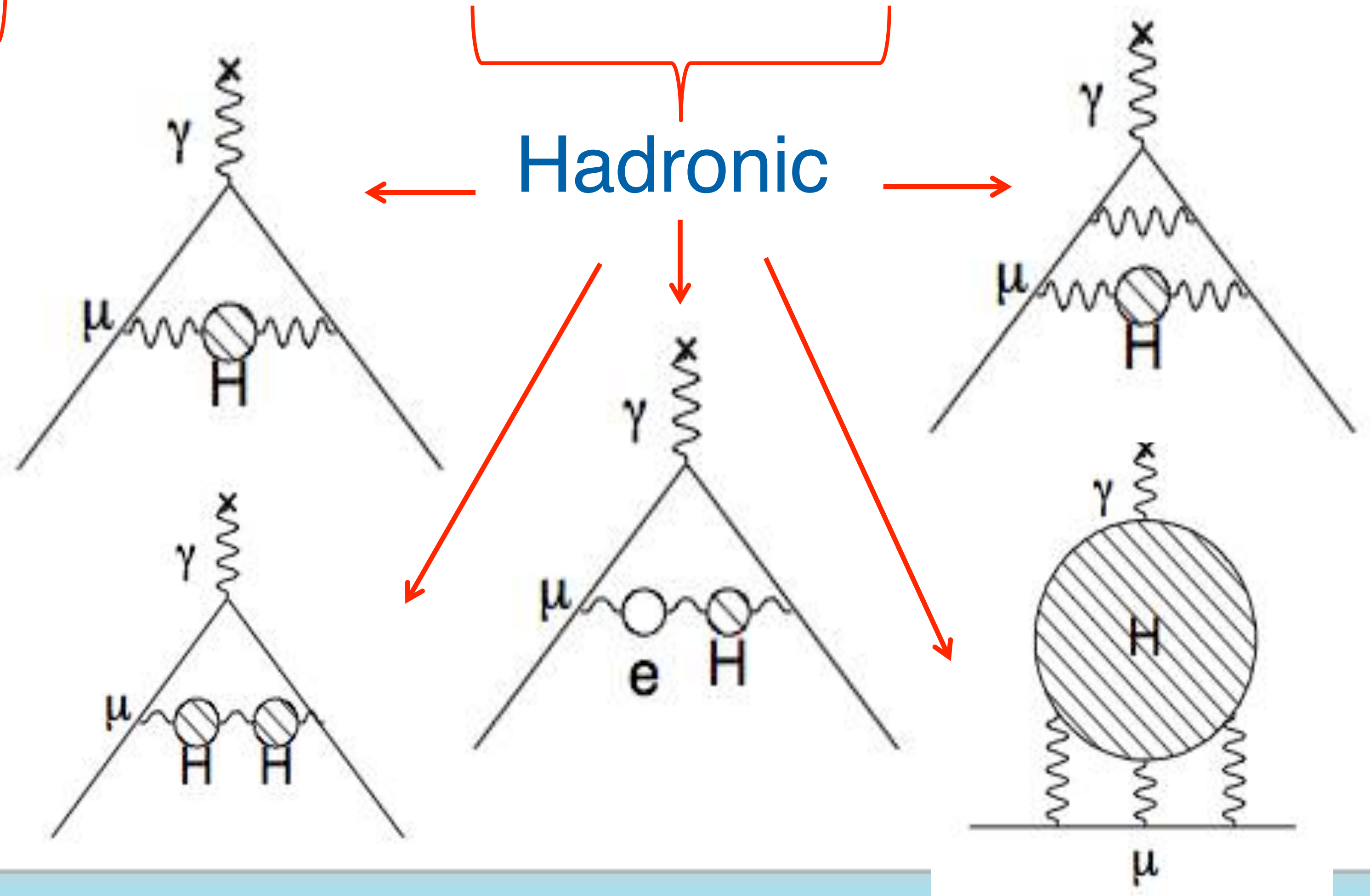

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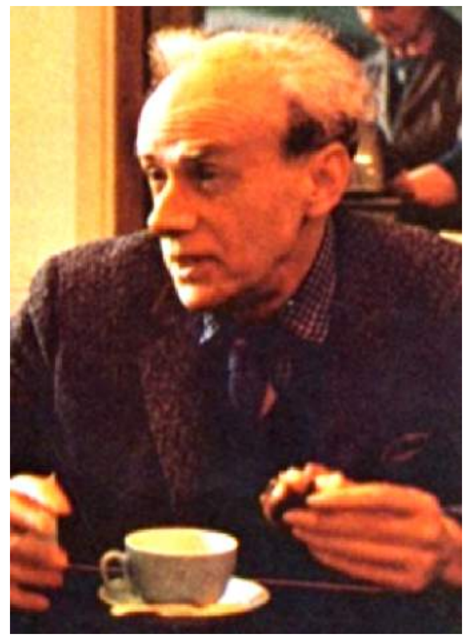

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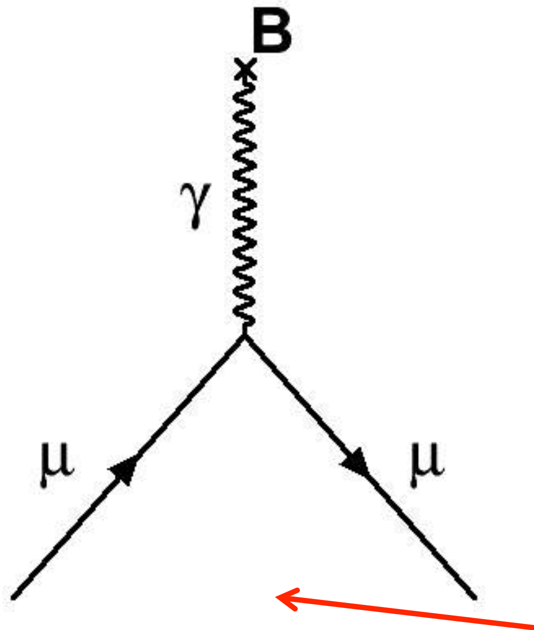

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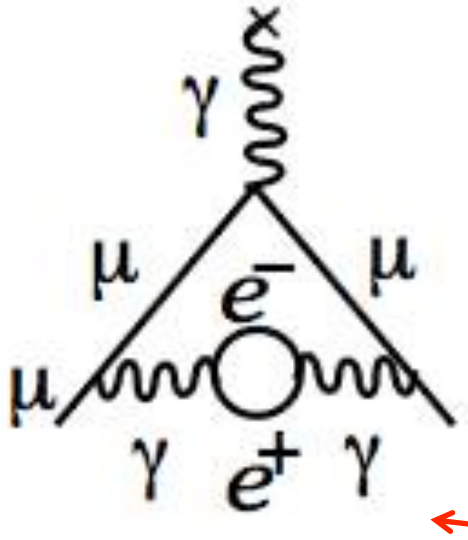

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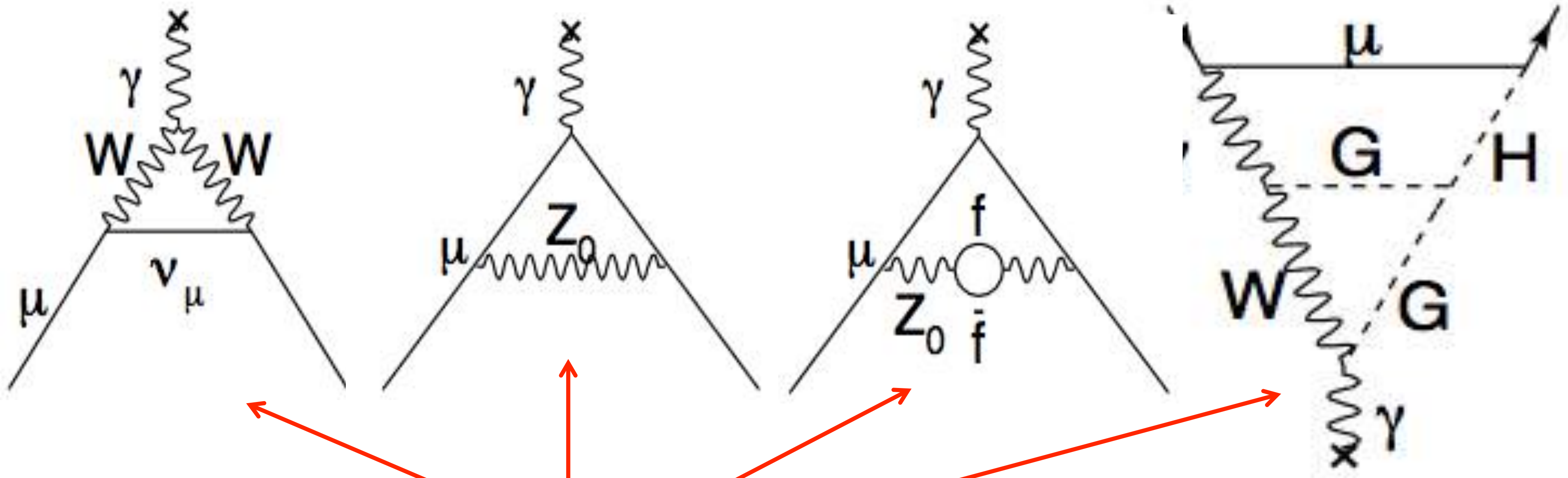
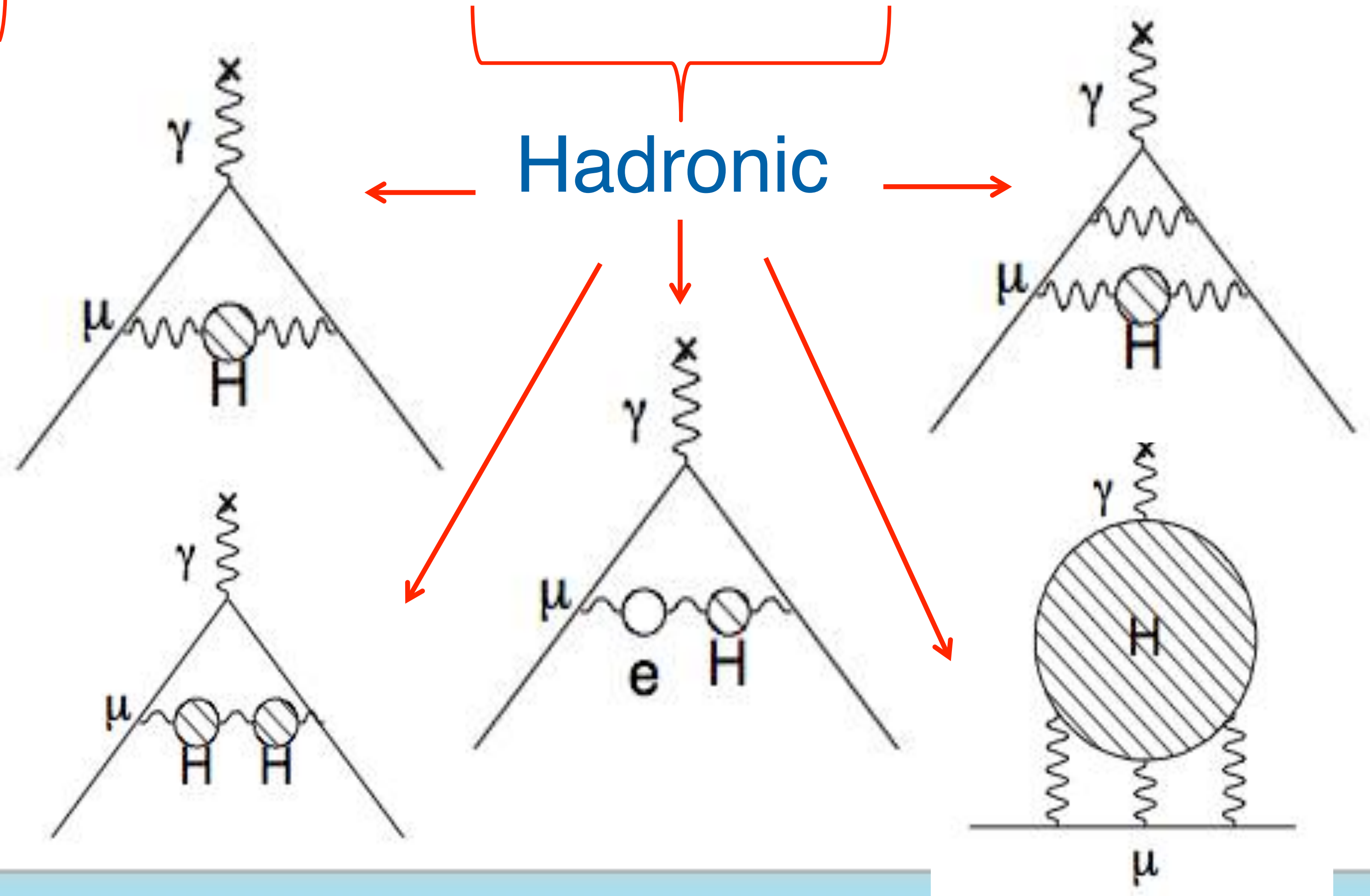


Electroweak

$$g_\mu = 2.002\,331\,841\,7$$

Hadronic



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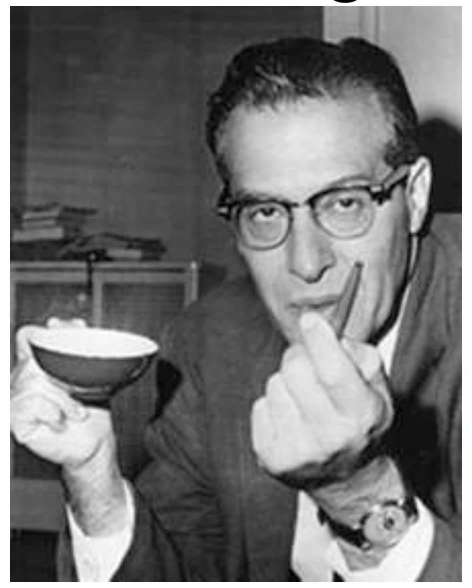

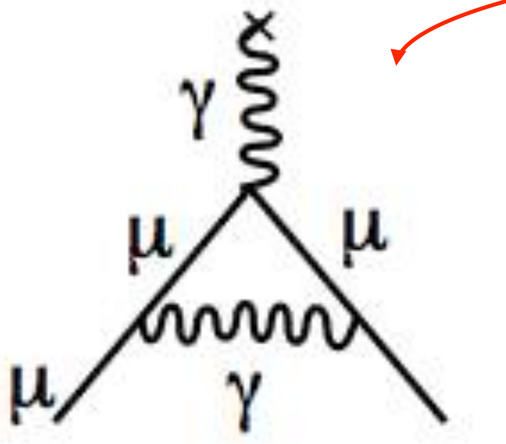

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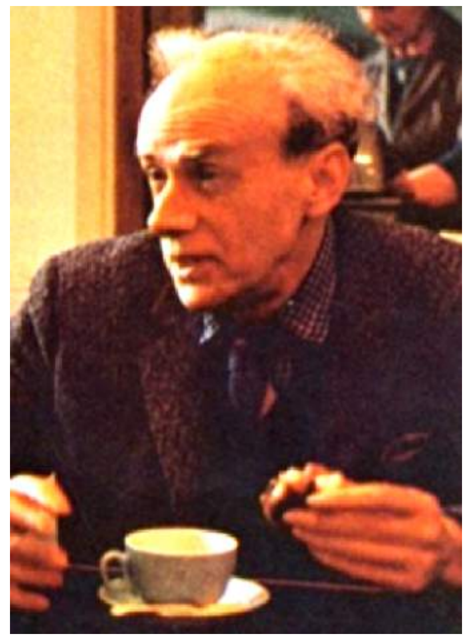
Fermilab

Standard Model Components of g-2

Dirac



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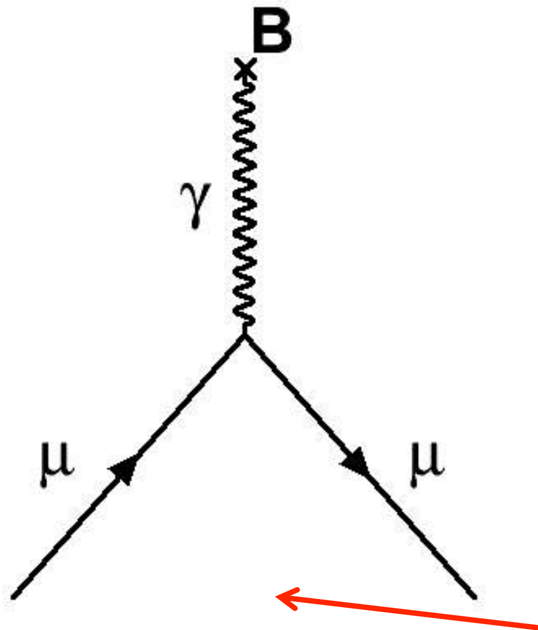

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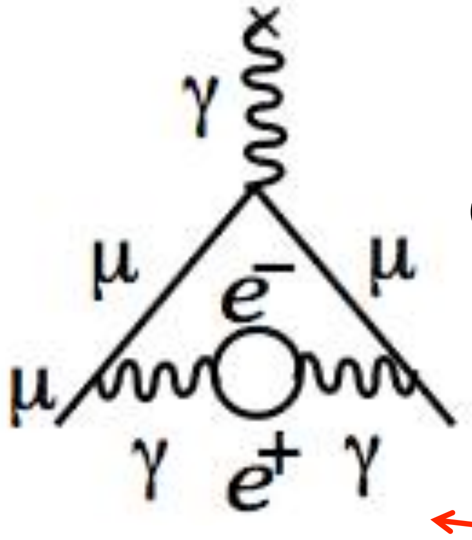

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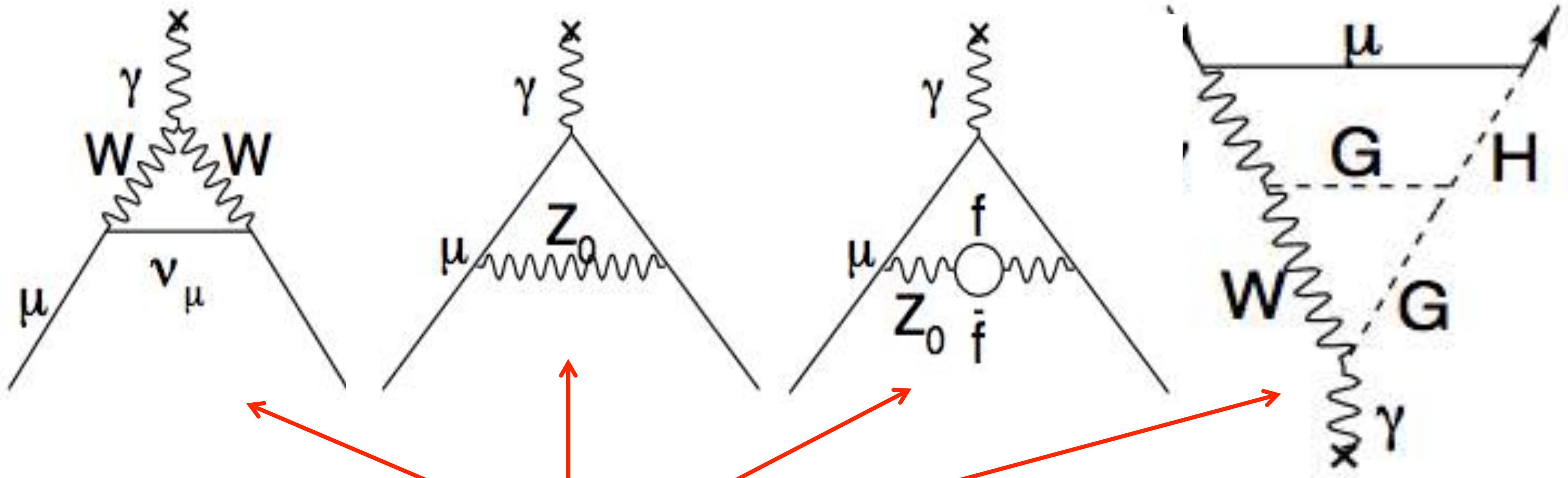

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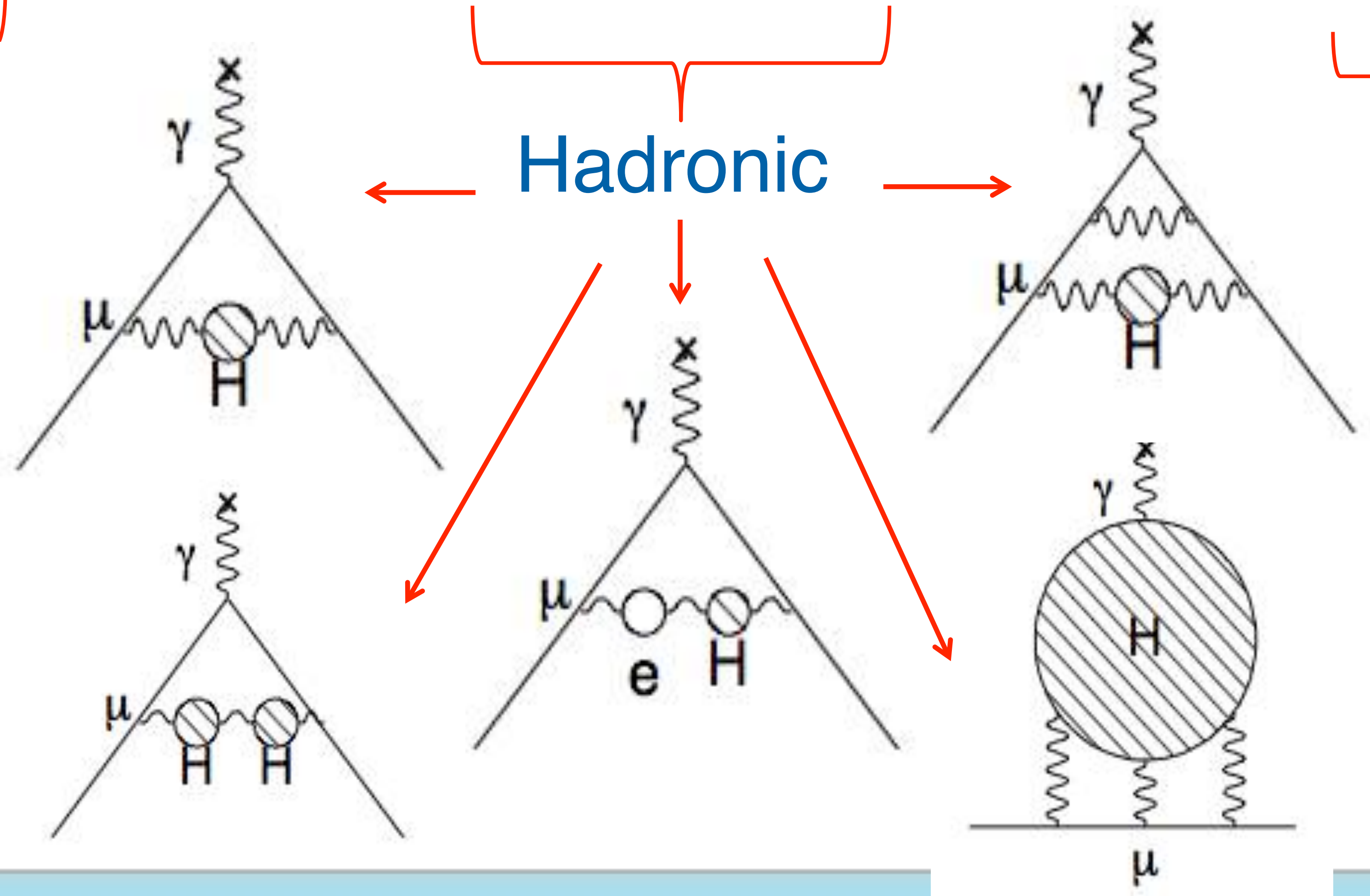
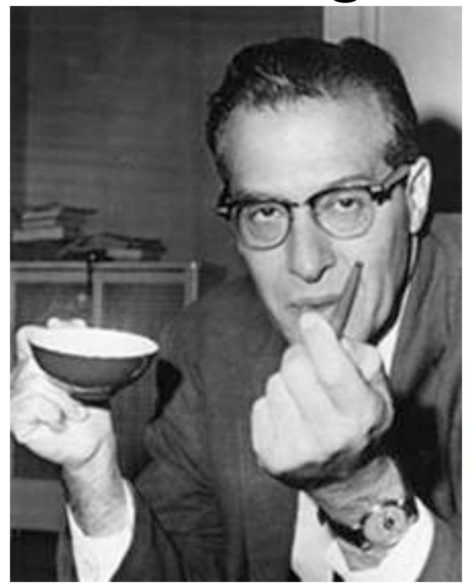
$$g_\mu = 2.002\,331\,841\,78(126)$$

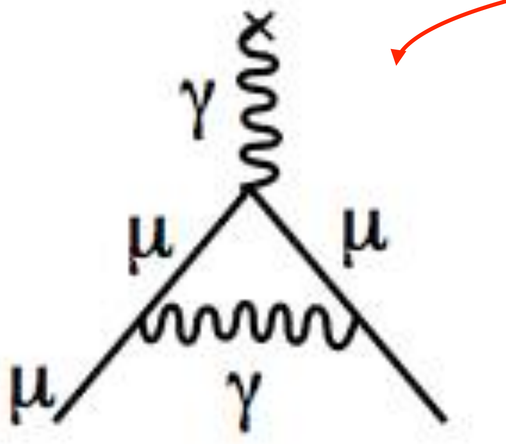
Hadronic



BSM?

Schwinger





1st Order QED

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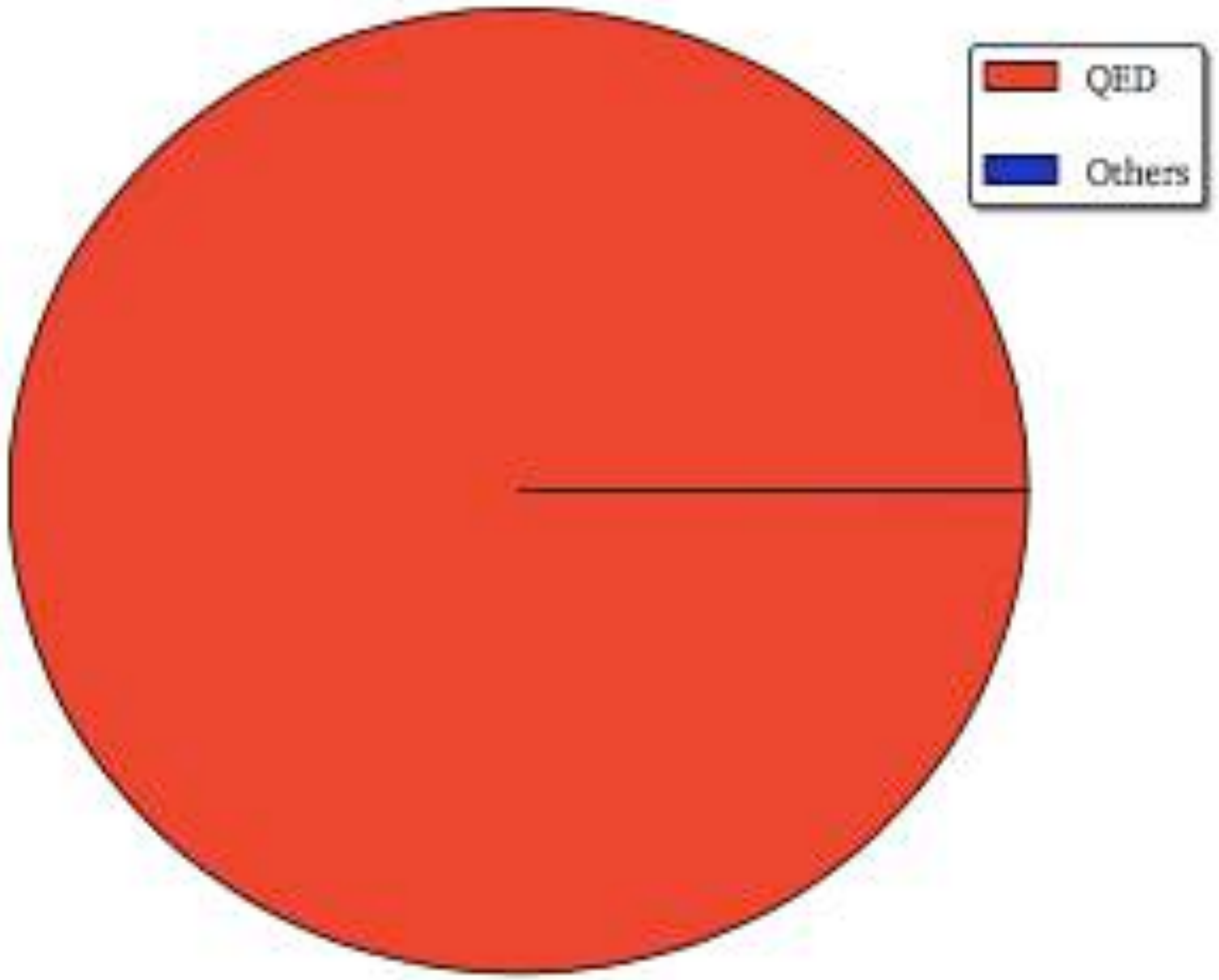
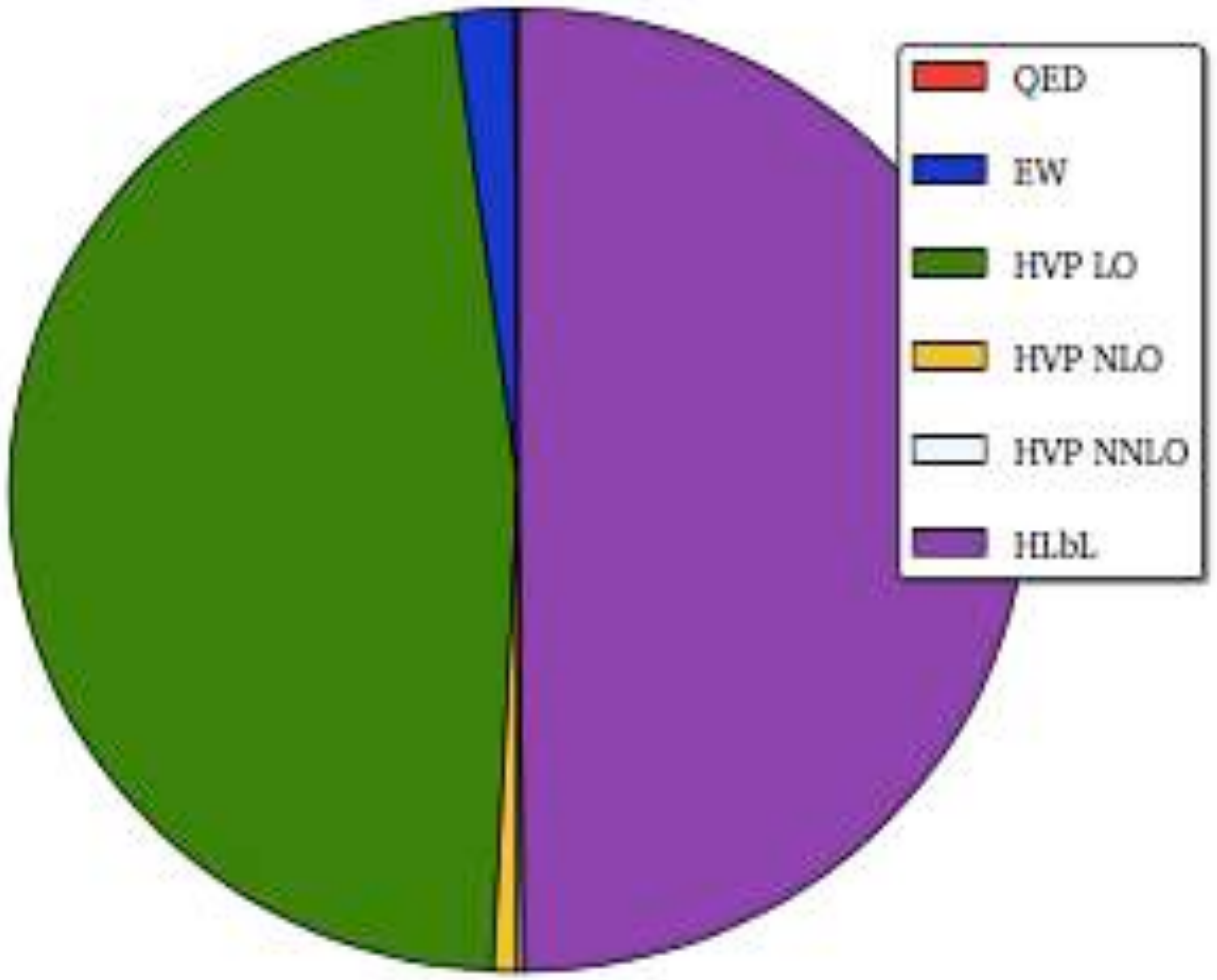
Standard Model Uncertainties

$$a_\mu = \frac{g_\mu - 2}{2}$$

a_μ^{SM}



δa_μ^{SM}



- The SM value of a_μ is dominated by QED
- But its uncertainty is dominated by Hadronic contributions
- Split into Hadronic Vacuum Polarisation (HVP) & Hadronic Light by Light (HLbL)

a_μ Theoretical Status

Contribution	Value (x 10^{-11})	Reference
QED	116 584 718.95 ± 0.08	PRL **109** 111808 (2012)
EW	153.6 ± 1.0	PRD **88** 053005 (2013)

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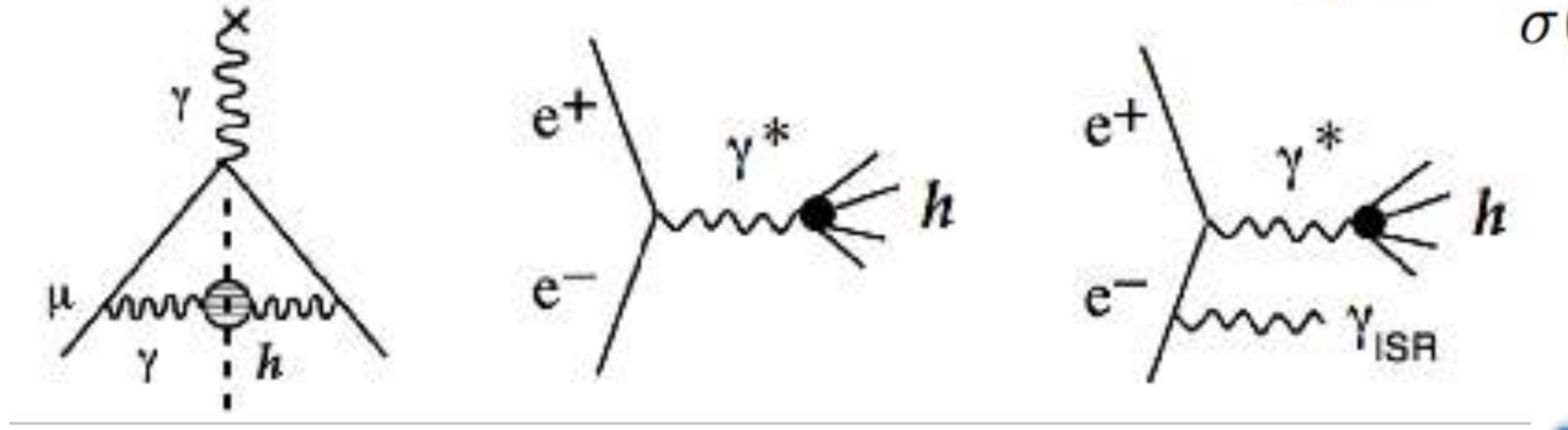
HVP (LO)	6931 ± 34	EPJ C **77** 827 (2017)
HVP (LO)	6933 ± 25	PRD **97** 114025 (2018)

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)

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

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



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HVP (NLO)	**-98.2 ± 0.4**	PRD **97** 114025 (2018)
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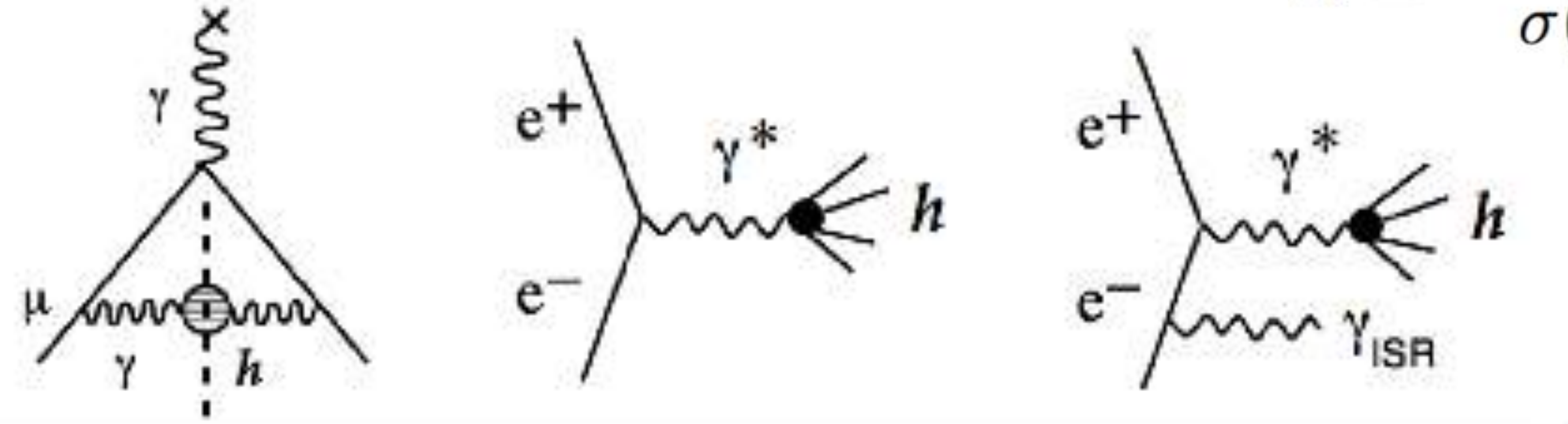

Fermilab

a_μ Theoretical Status

New *ab initio* approaches [PRD **98** 094503 (2018)] finding consistent result of (-93 ± 13) x 10^{-11} — **lattice making big strides**

		12)
		13)
		7)
H... O)	**6933 ± 25**	PRD **97** 114025 (2018)
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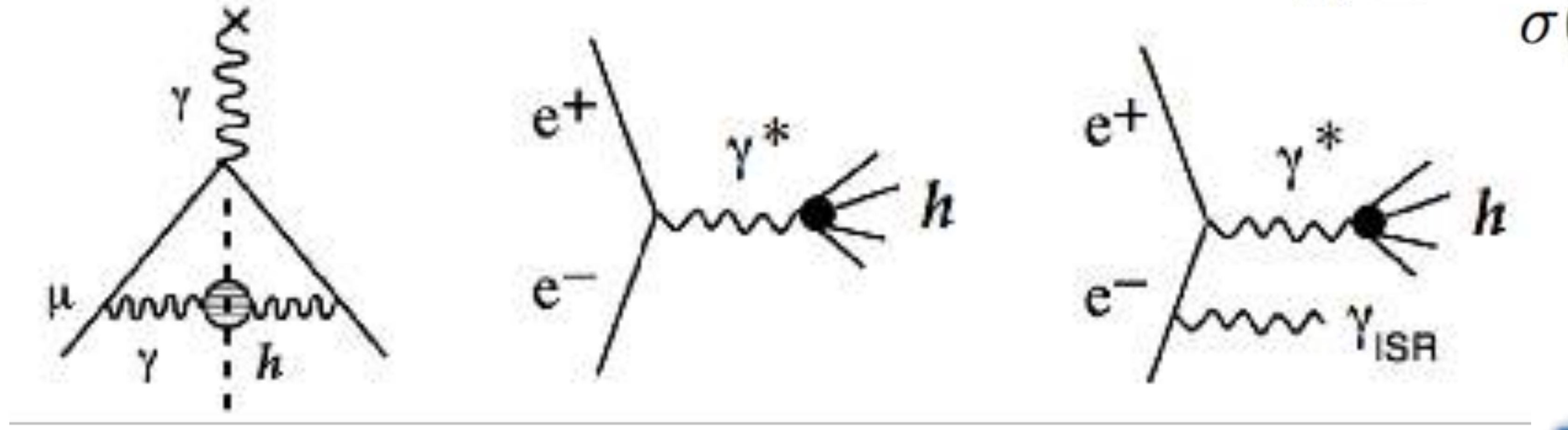

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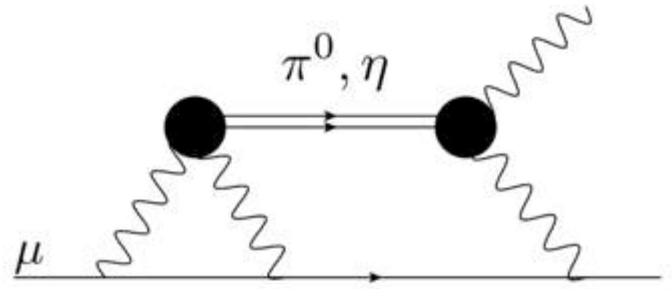
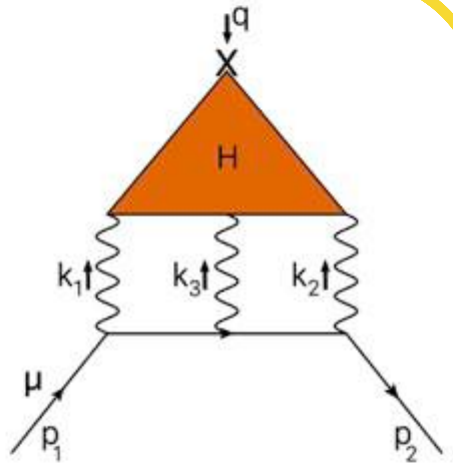
HLbL (LO + NLO)	101 ± 26	PLB 735 90 (2014), EPJ Web Conf 118 01016 (2016)
Total SM	**116 591 818 ± 43 (368 ppb)**	
	116 591 821 ± 36 (309 ppb)	

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
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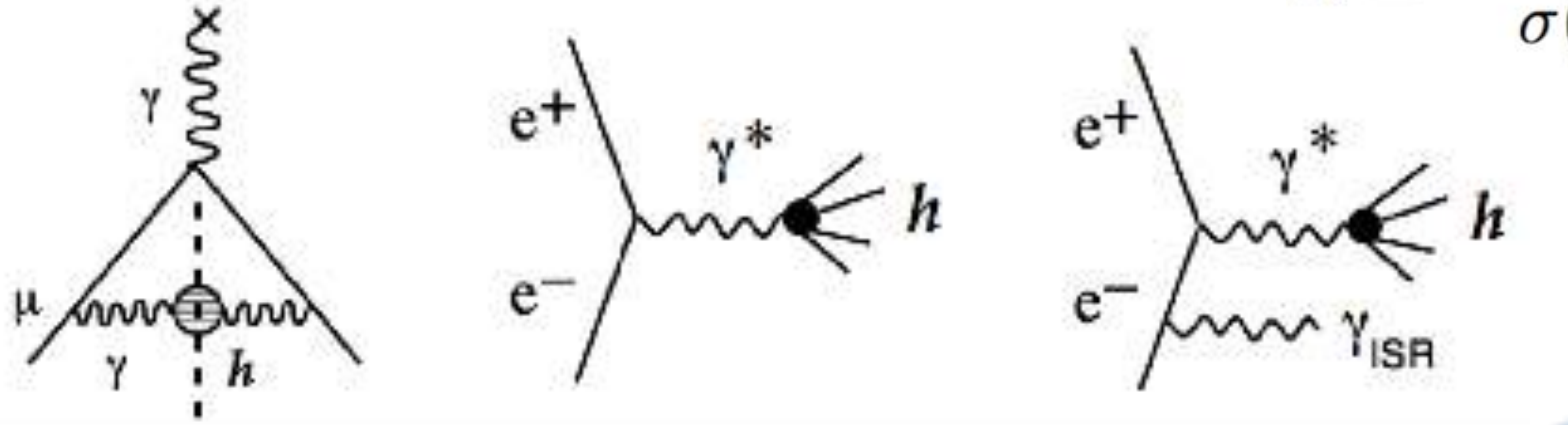

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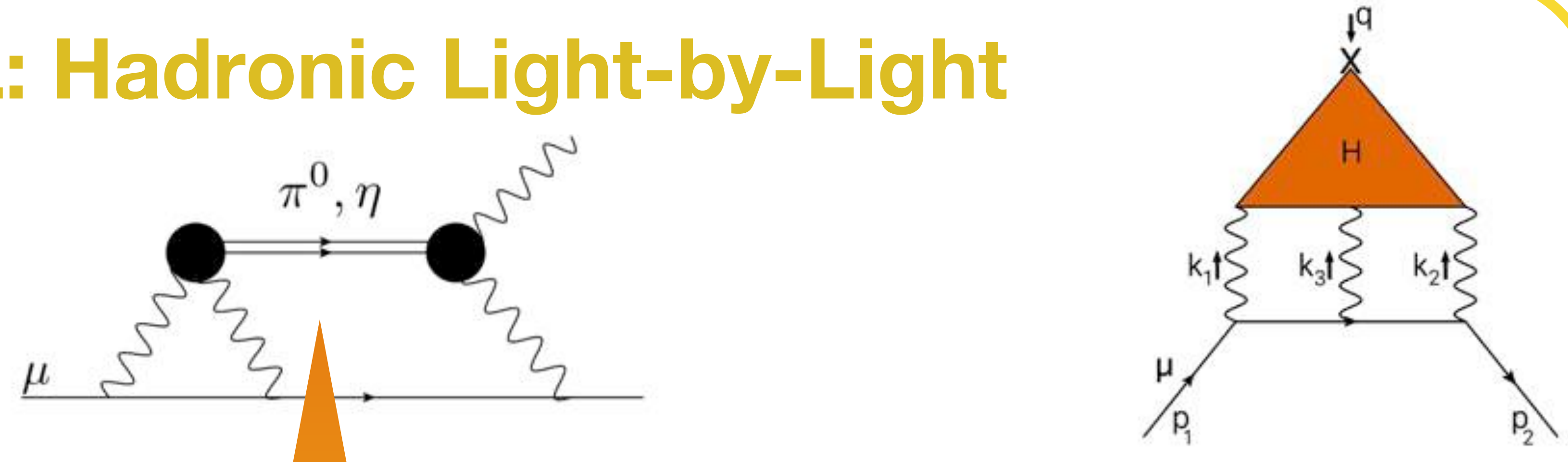
[illegible]	**[illegible]91 818 ± 43**	[illegible]
[illegible]	**[illegible]91 821 ± 36**	[illegible]

Builds confidence in HLbL term

HLbL: Hadronic Light-by-Light



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- **Theory Pro[illegible]** [illegible]ew dispersive calculation approach; extend the l[illegible]ite volume, disconnected diagrams); [illegible]gress

Recent data-driven calculation [PRL **121** 112002 (2018)] for $a_\mu^{\pi^0-\text{pole}}$ is consistent with earlier vector-, lowest-meson dominance calcs [PRD **65** 073034 (2002), PRD **94** 053006 (2016), EJC **75** 586 (2015)]

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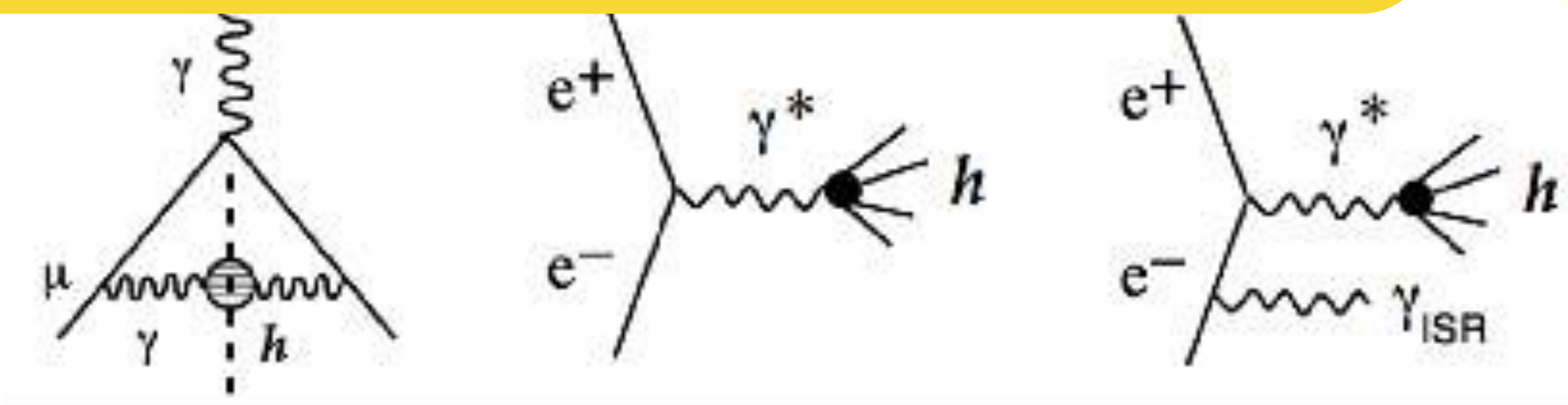
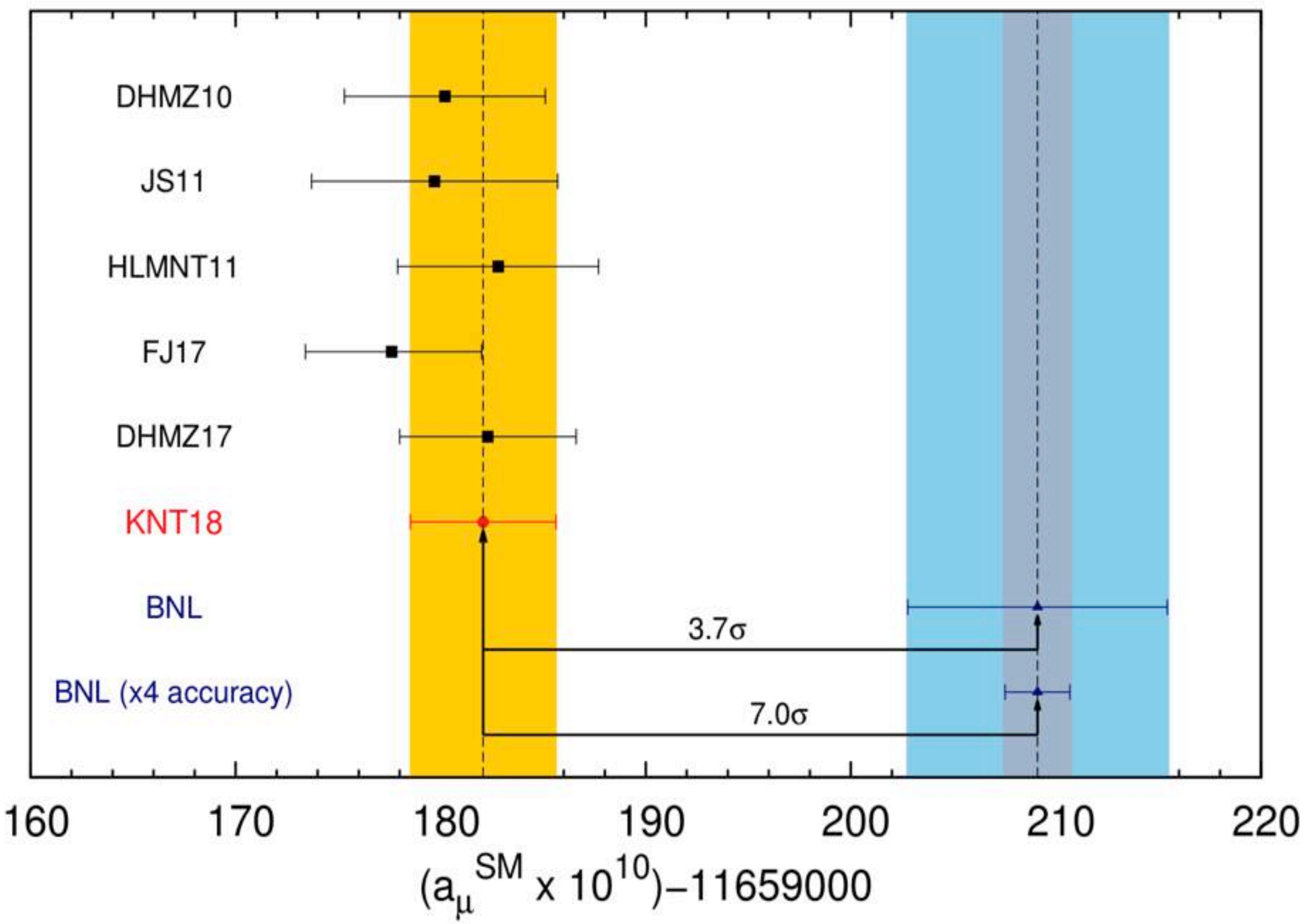


Current status

- New combination (KNT18) has not moved central value significantly, reduced uncertainties
- > 3.5σ discrepancy persists
- Theory groups are making progress to achieve competitive uncertainties on same time scale as new FNAL experiment…

PRD **97** 114025 (2018)



The Fermilab Muon g-2 Experiment

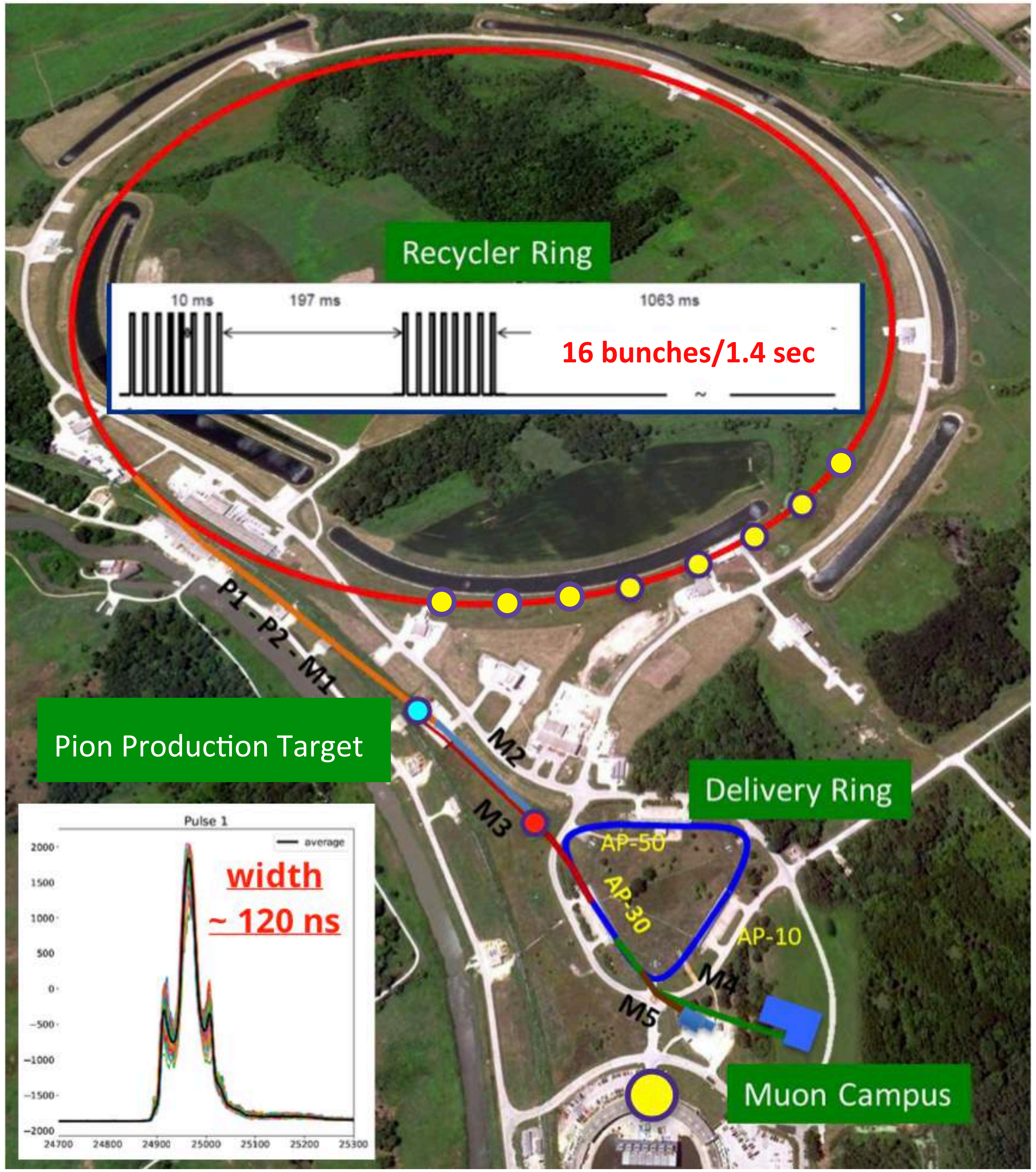
Muon g-2: 33 Institutions, 7 countries, 203 Members

Why Fermilab?

- BNL limited by statistics
  (540 ppb on 9 x 10^9 detected e^+)
- E989 goal: Factor of 21 more statistics
  (2 x 10^{11} detected e^+)

Fermilab advantages

- Long beam line to collect $\pi^+ \rightarrow \mu^+$
- Much reduced amount of p, π in ring
- 4x higher fill frequency than BNL



Measurement Principle

- Inject polarized muon beam into magnetic storage ring
- Measure **difference** between spin precession and cyclotron frequencies
- If g = 2, $\omega_a = 0$
- $g \neq 2$, $\omega_a \cong (e/m_\mu)a_\mu B$

Spin precession freq.

$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

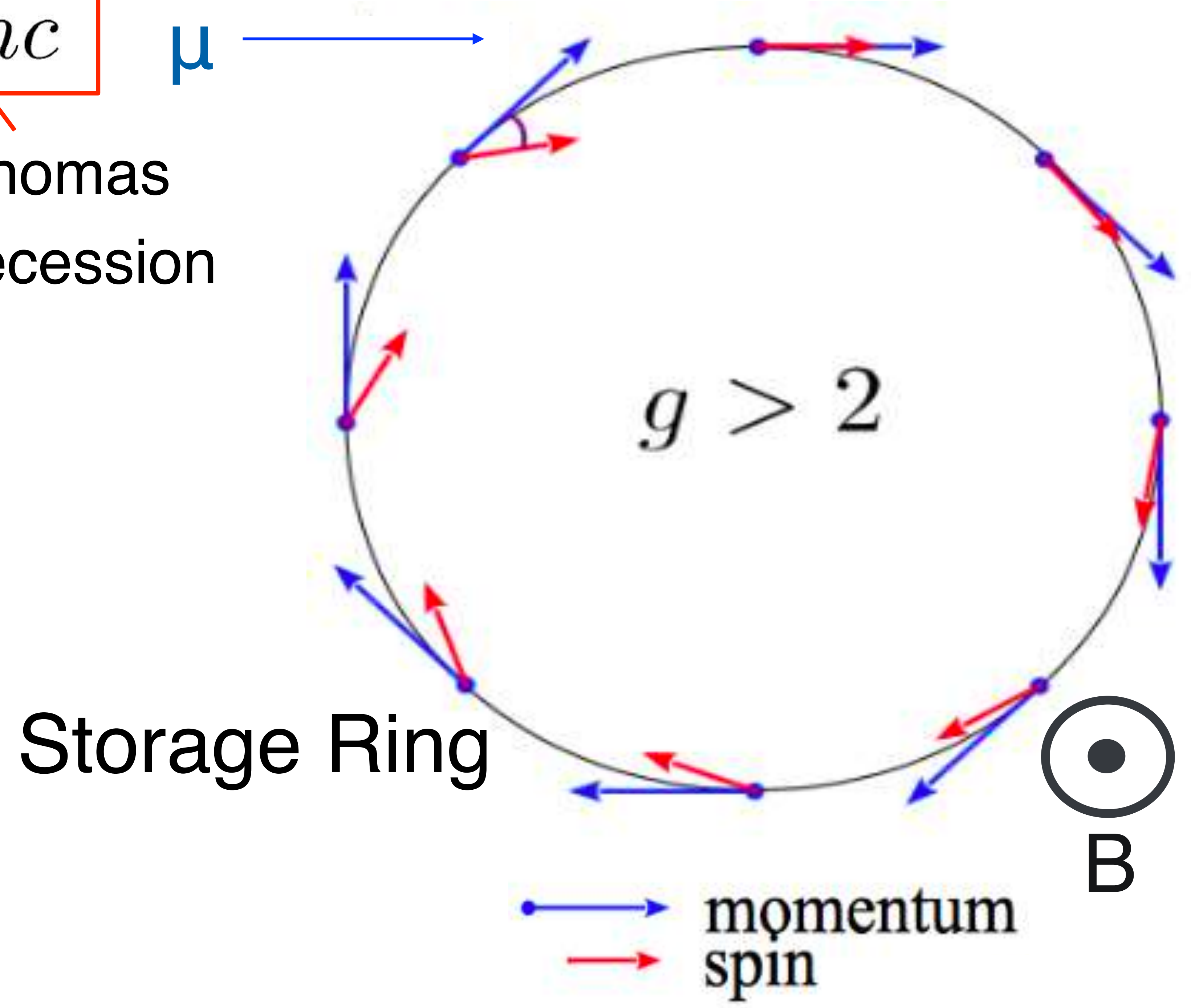
Larmor precession

Thomas precession

Cyclotron freq.

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

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$



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

3 ppb 22 ppb 0.3 ppt

Rev. Mod. Phys. **88**, 035009 (2016)

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

Real World Considerations

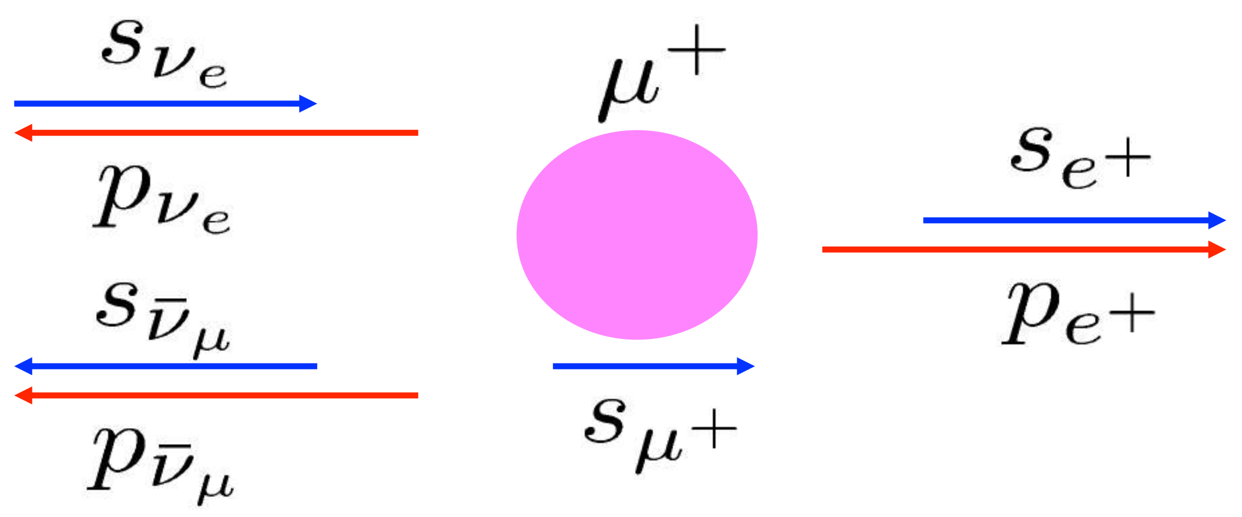
- Muon beam has a small vertical component
- We need to use Electric fields to focus the beam so we can store the muons

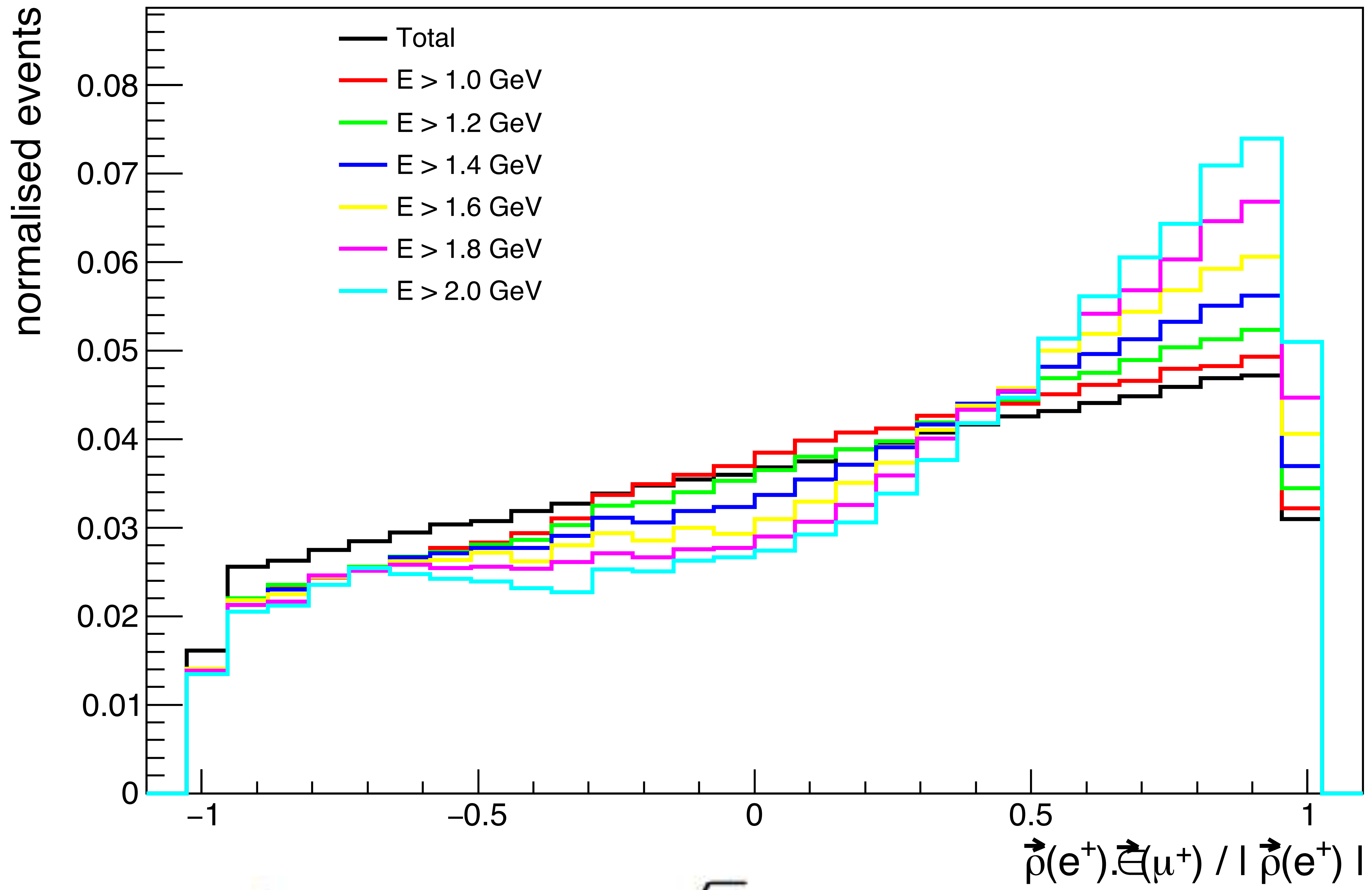
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}\right]$$

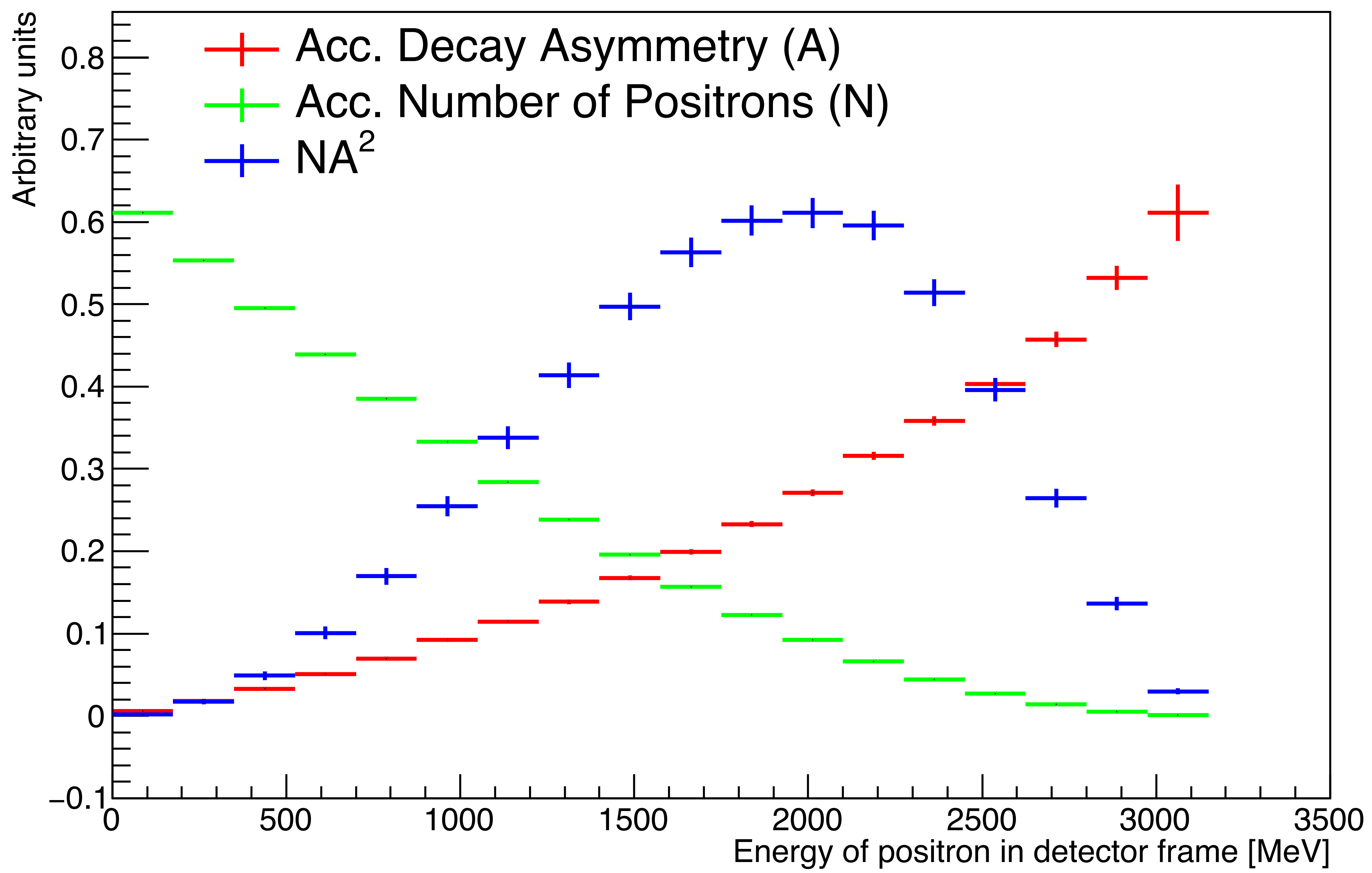
- This introduces an unwanted $\beta \times E$ term…
- …unless γ = 29.3, then E-field term vanishes: we call this the “magic” momentum (3.094 GeV)
- Leaves 2 effects that we can’t ignore:
  - Not all muons are exactly at magic momentum
  - Some small degree of vertical motion of muons (reduces effective B-field)
- We use tracker and beam dynamics models to calculate the small corrections for these (< 1 ppm)

Measuring the muon spin…

- e⁺ preferentially emitted in direction of muon spin





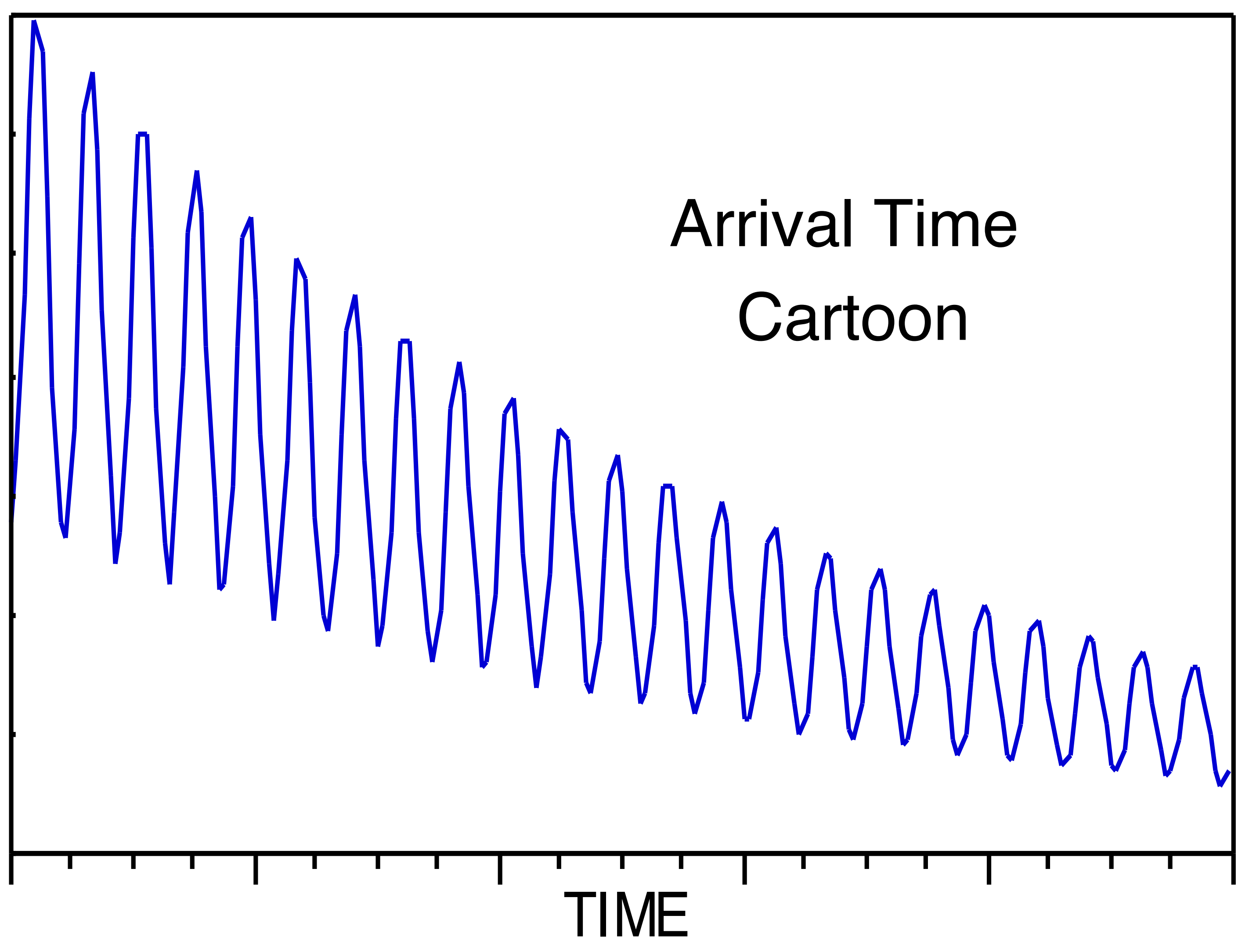


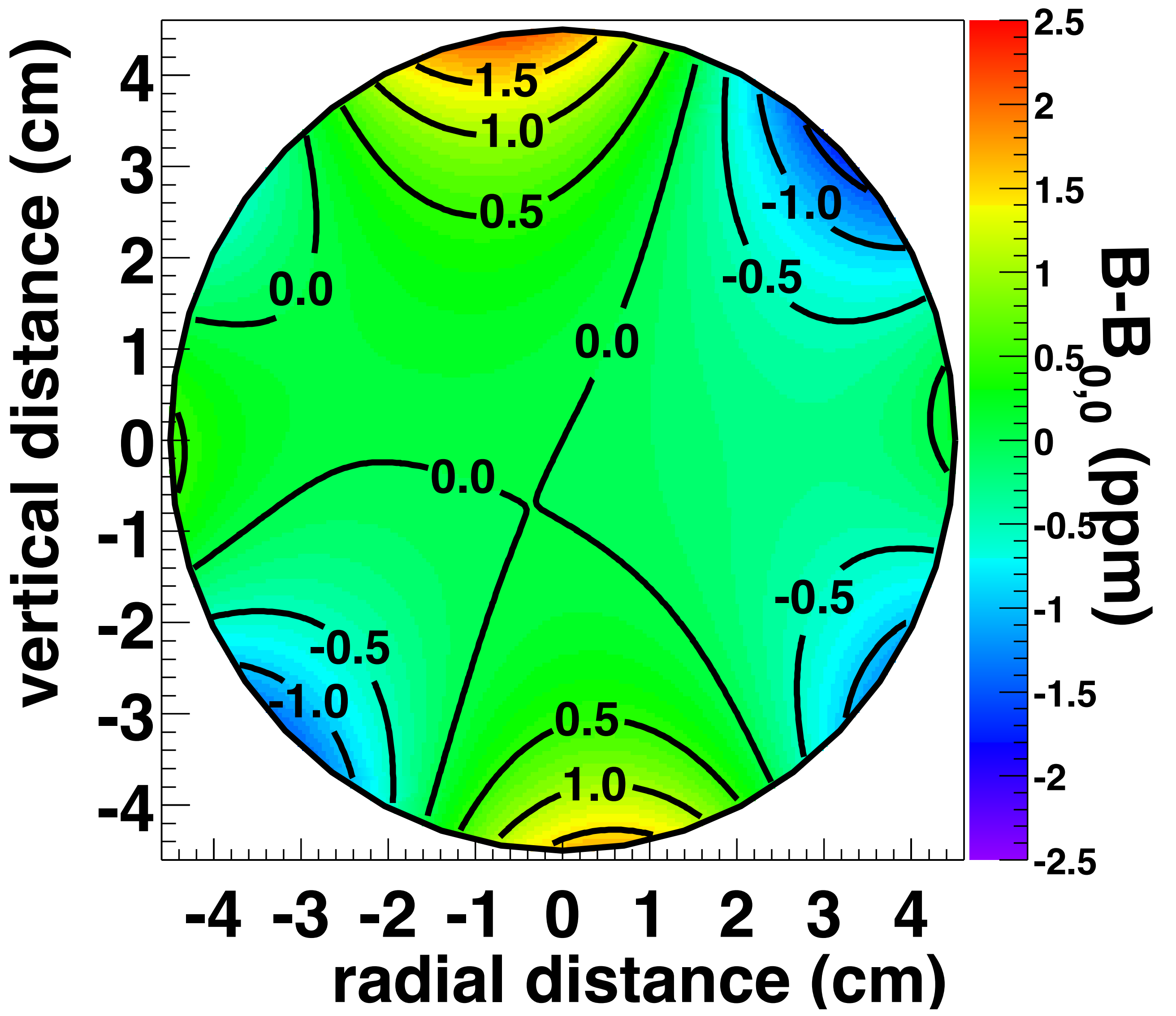
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{NA^2}}$$

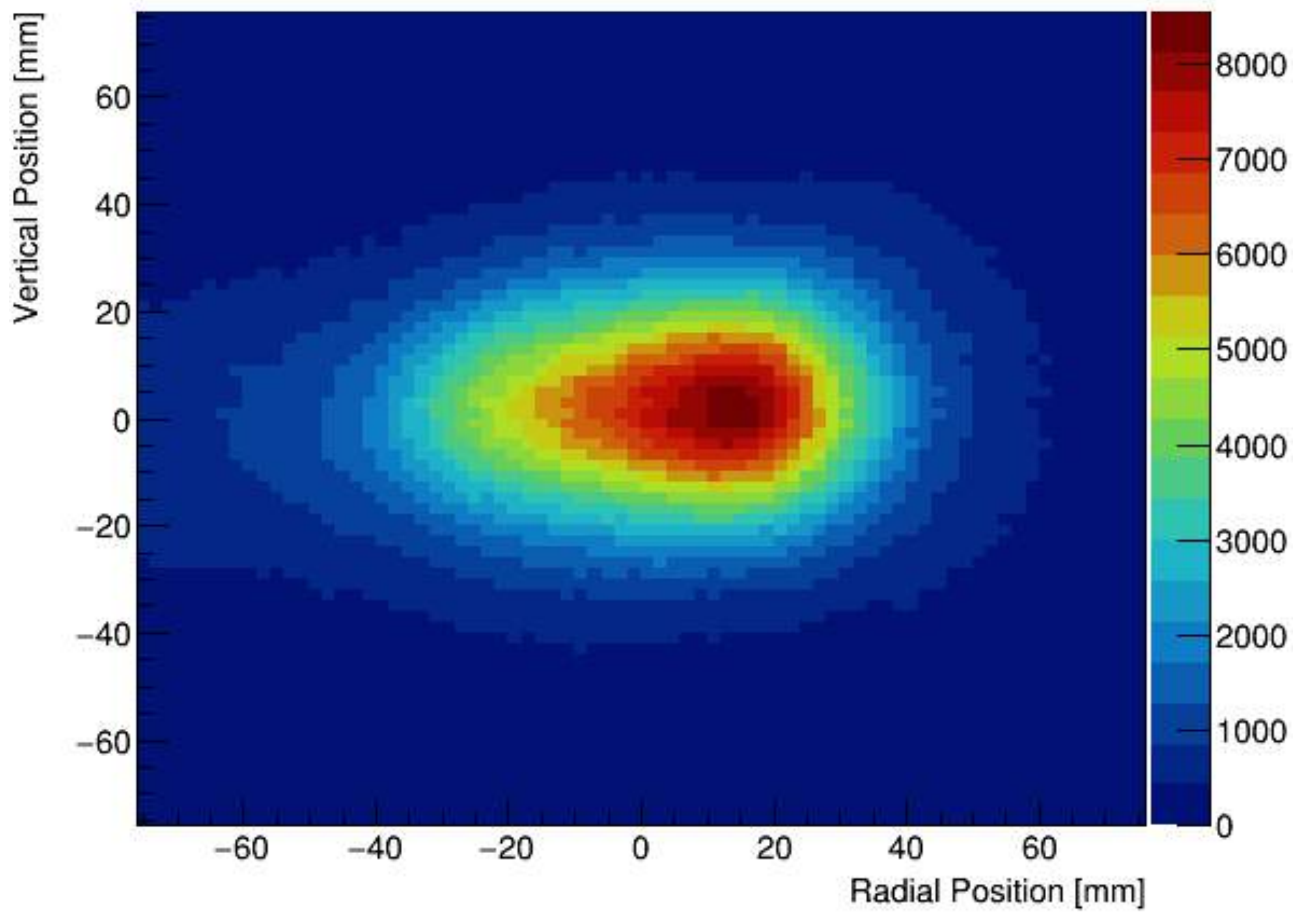
- Asymmetry is larger for high momentum e+
- Optimal cut at E~1.8 GeV

Measurement Principle

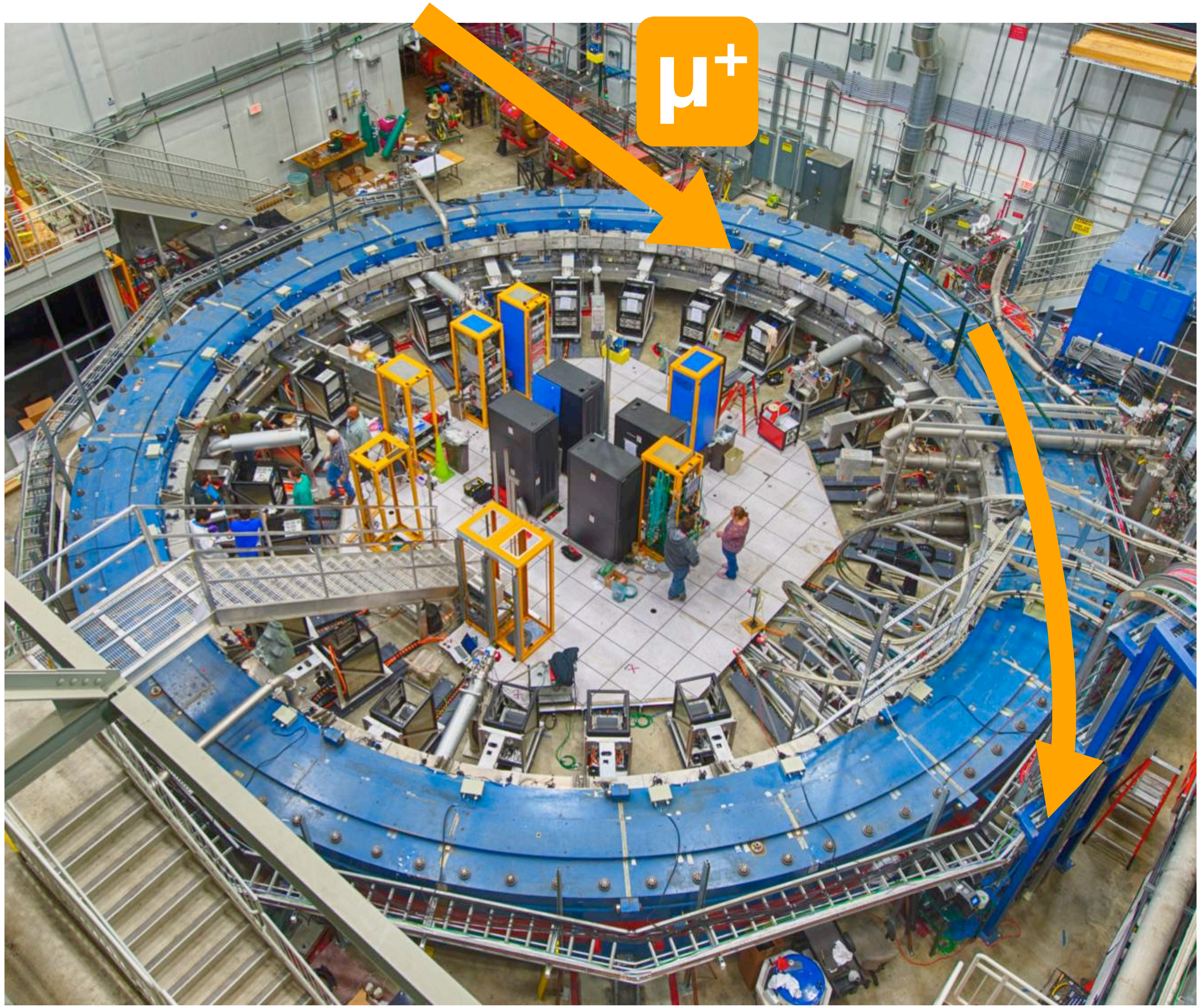
- Three ingredients to measure $a_\mu \sim (\omega_a / \tilde{\omega}_p)$
  - ω_a: Arrival time spectrum of high energy positrons
  - ω_p: Magnetic field in storage region measured by proton NMR
  - $\tilde{\omega}_p$: Muon distribution to get weighted magnetic field frequency



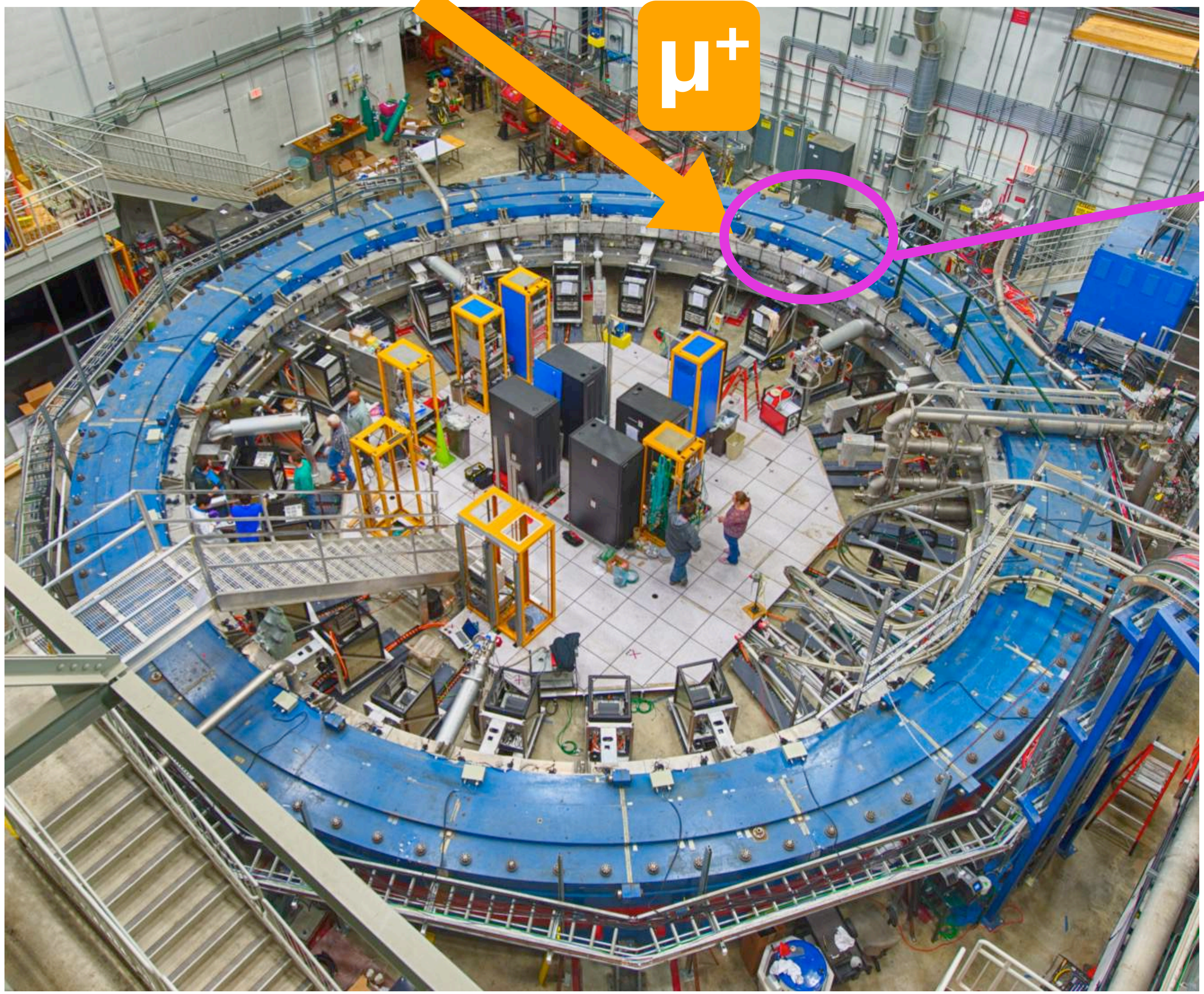




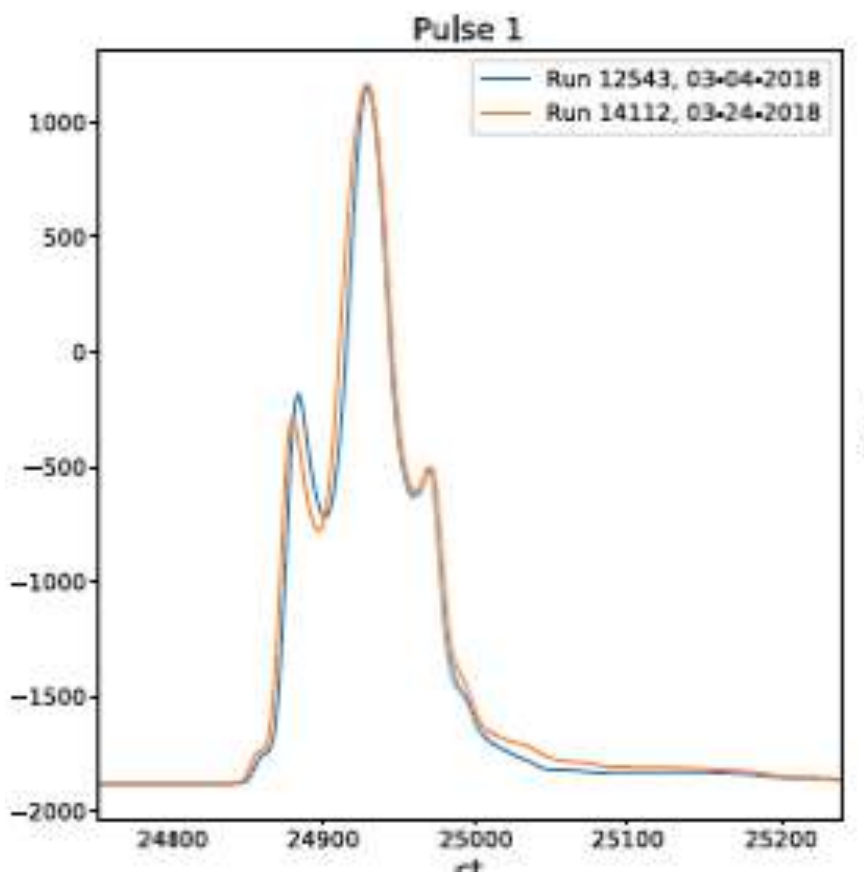
Muon Beam Injection



Muon Beam Injection

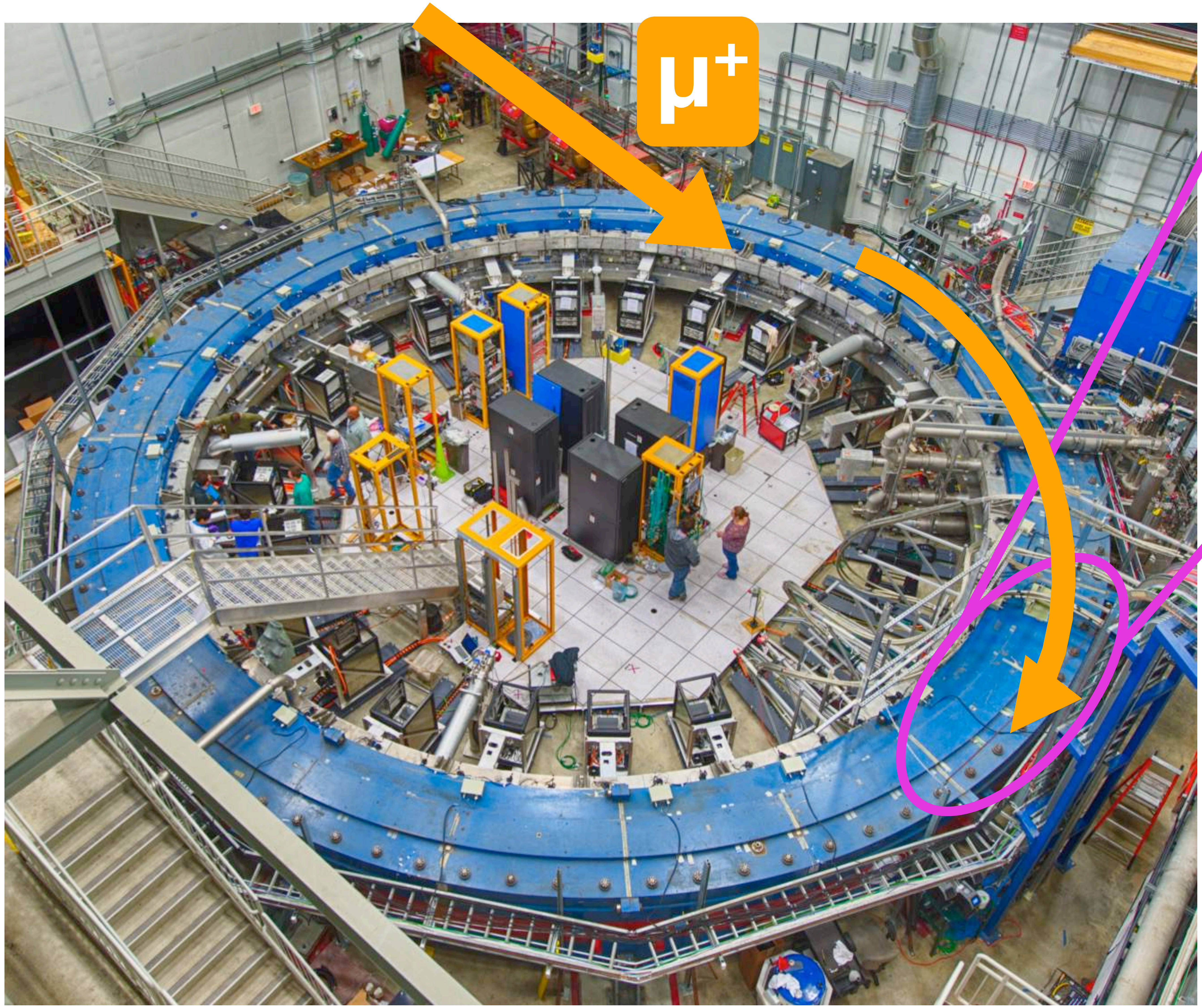


- Monitor beam profile before entrance with scintillating X and Y fibres
- Get time profile of beam using scintillating pad
- ~125ns wide

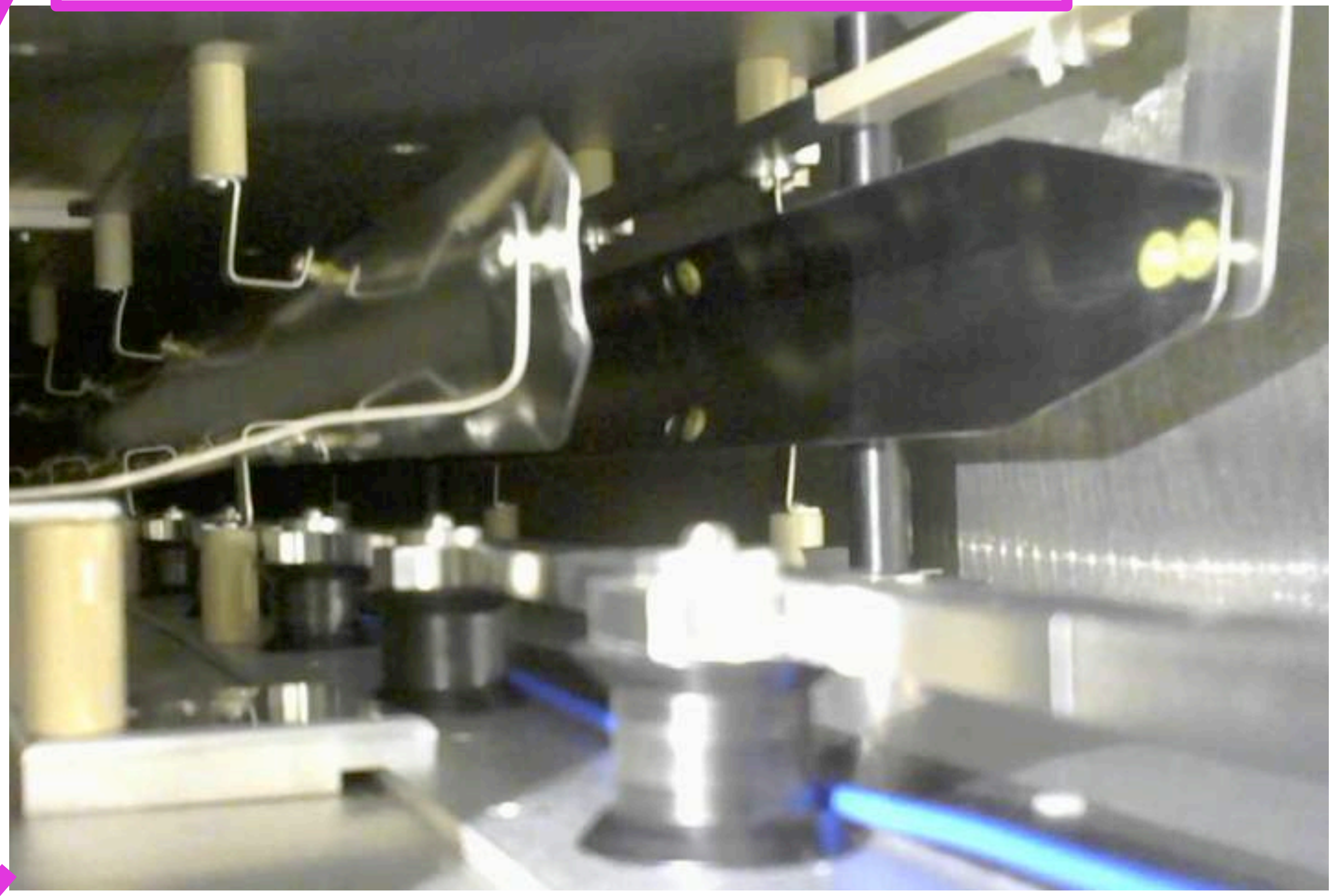


- Cancel B-field during injection using Inflector, so muons can get into the ring

Muon Beam Injection

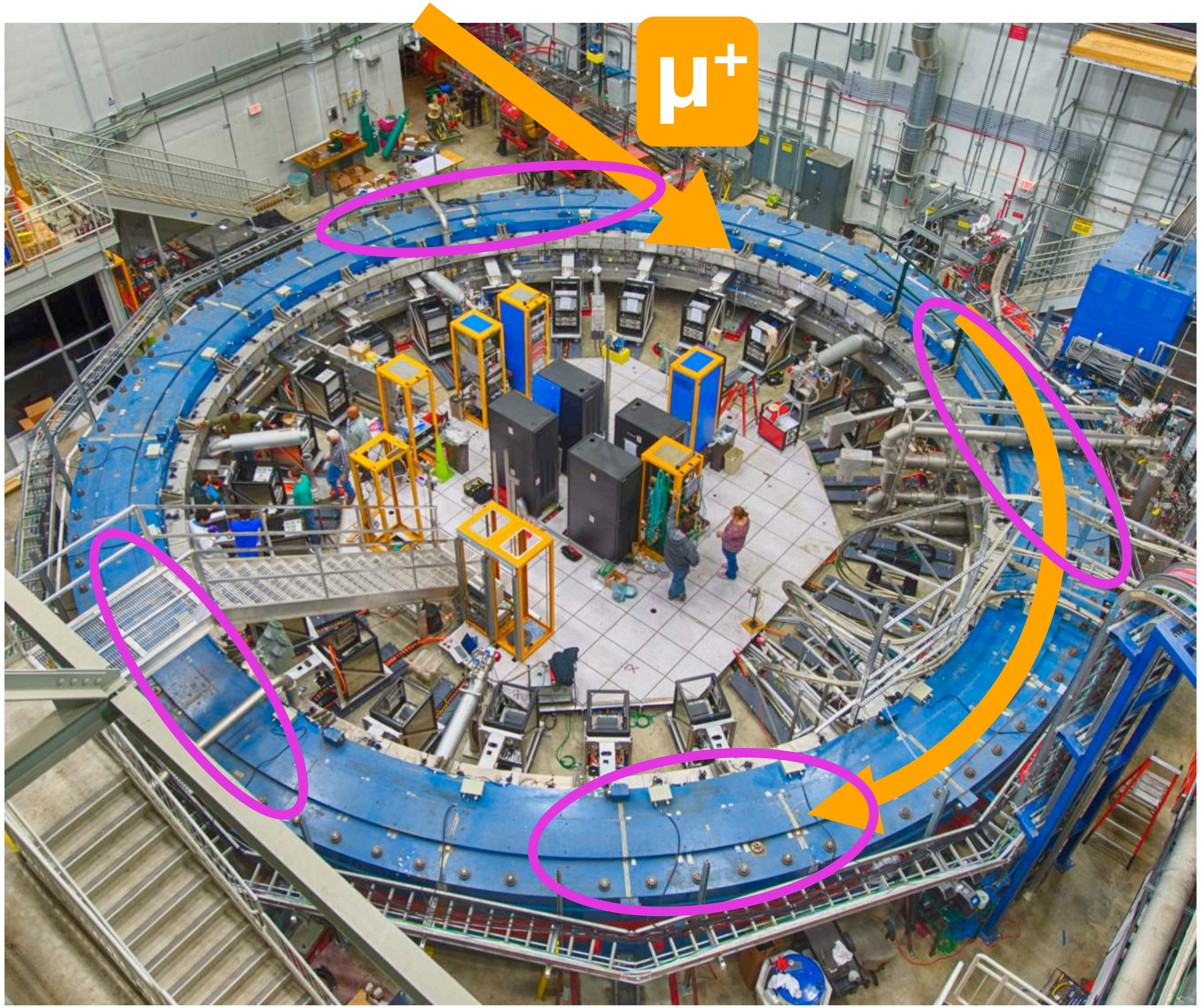


Kicker magnets



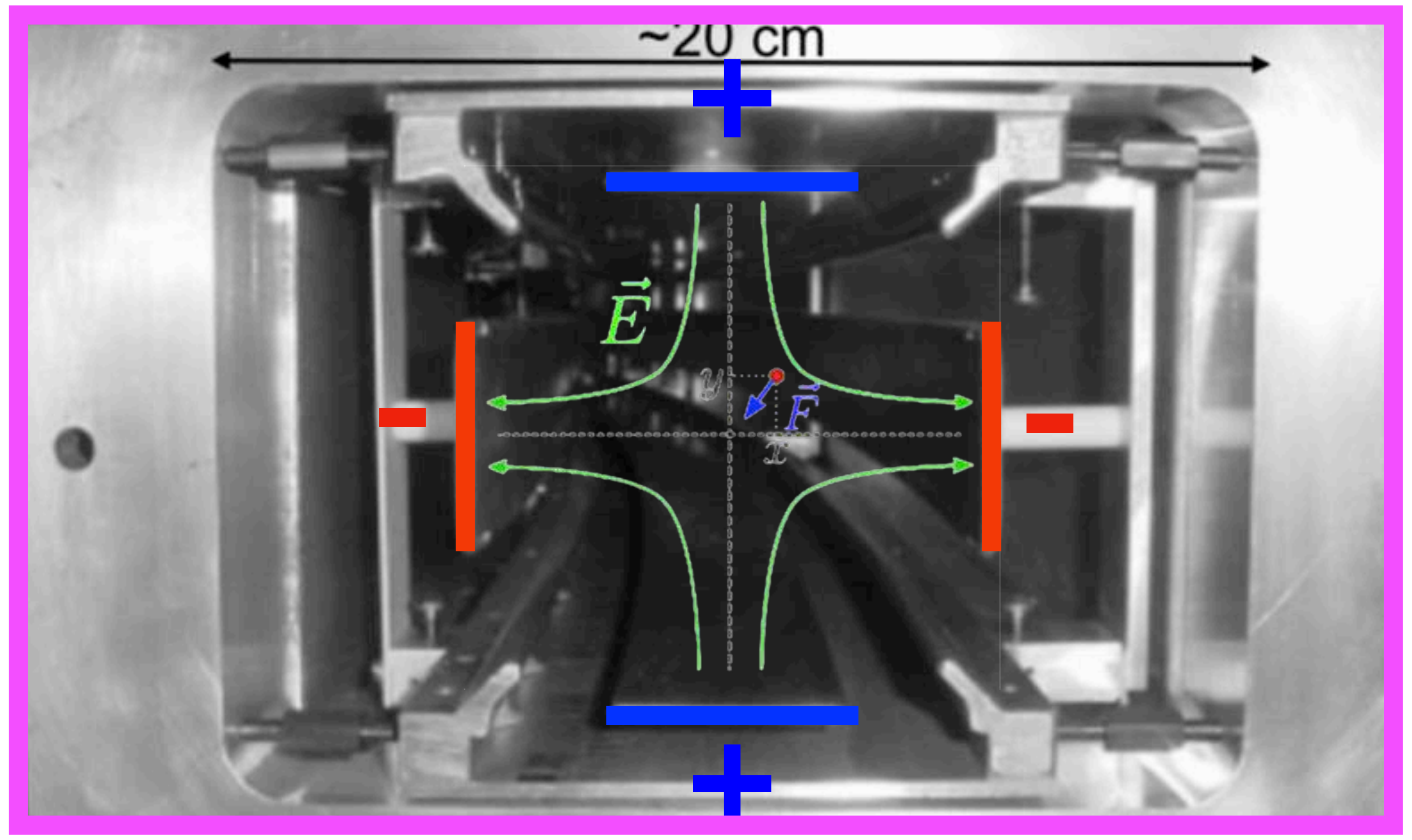
- After inflector, muons enter storage region at r = 77 mm outside central closed orbit
- Deliver pulse in < 149 ns to muon beam
- Steer muons onto stored orbit

Muon Beam Injection

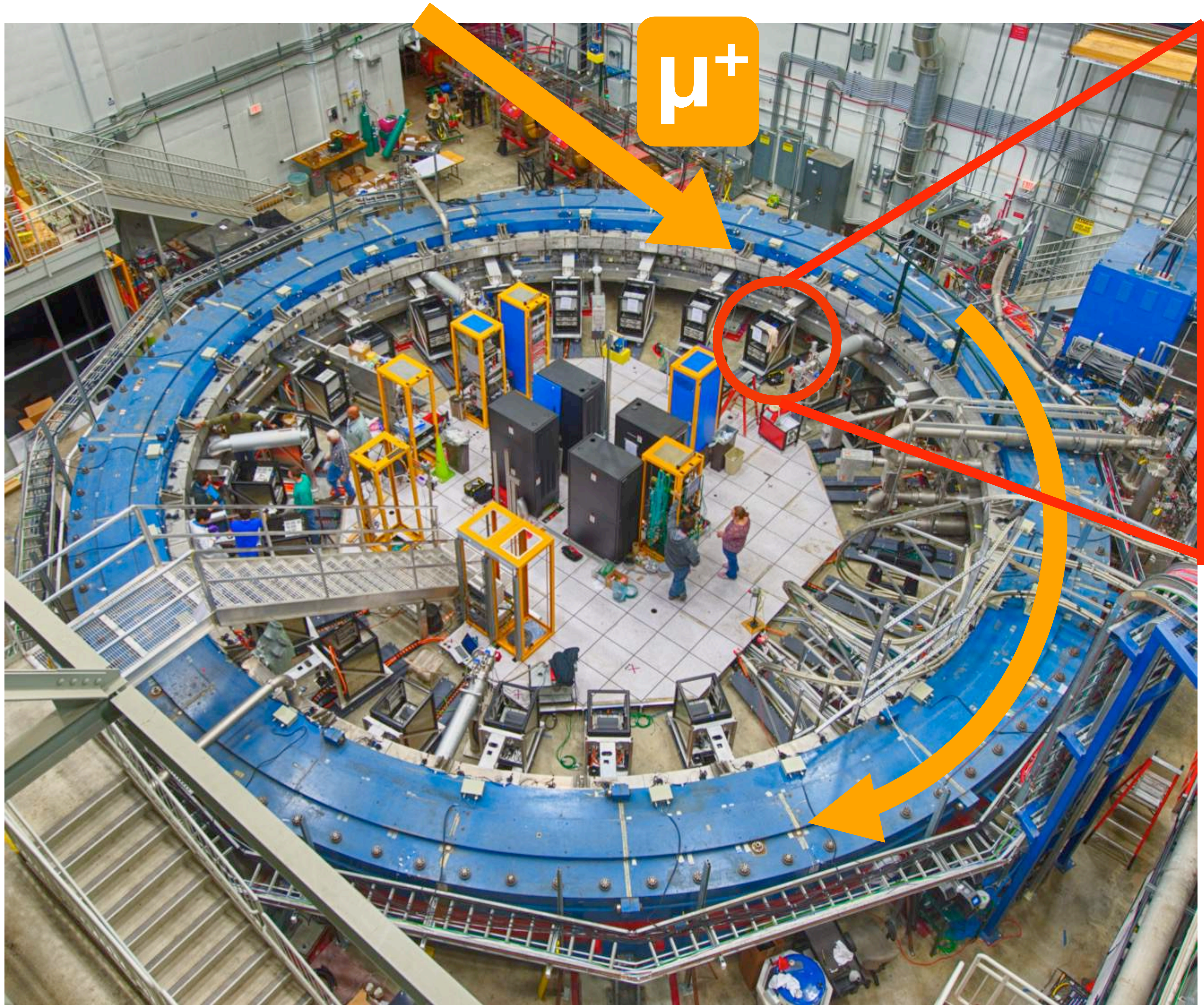


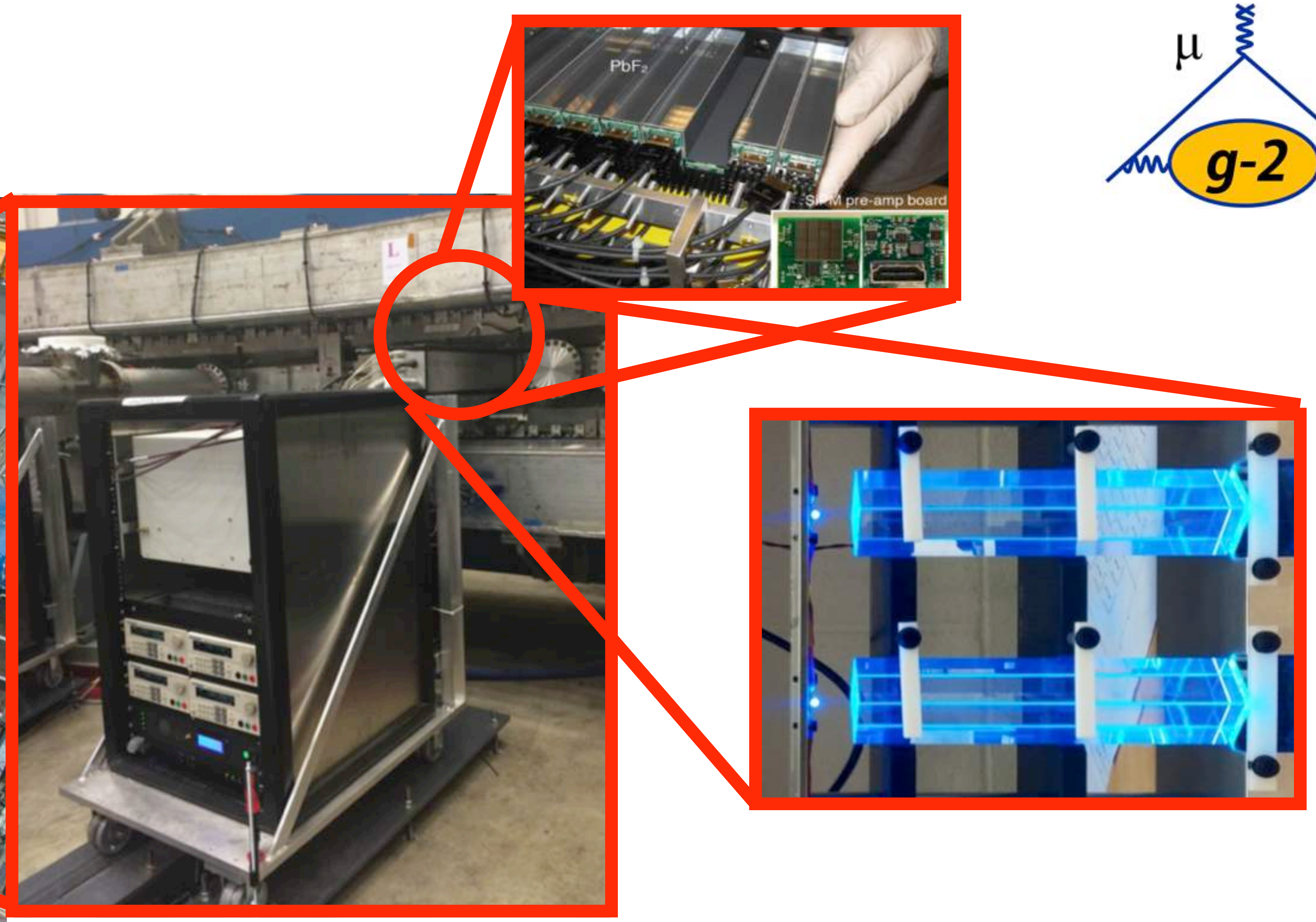
Electrostatic quadrupoles

- Drive the muons towards the central part of storage region vertically
- Minimizes beam "breathing", improves muon orbit stability
- Aluminum electrodes cover ~43% of total circumference



Muon Beam Injection

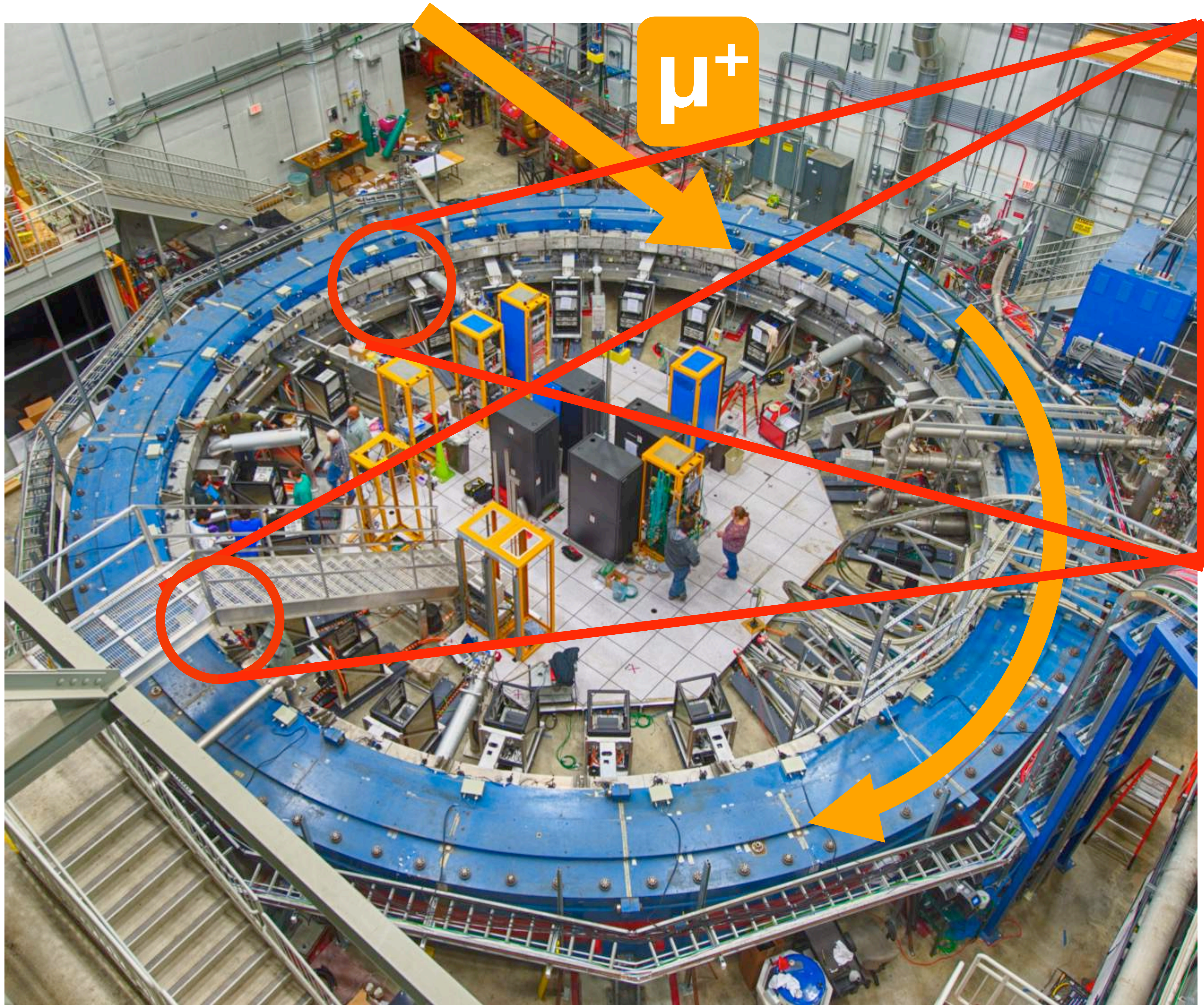




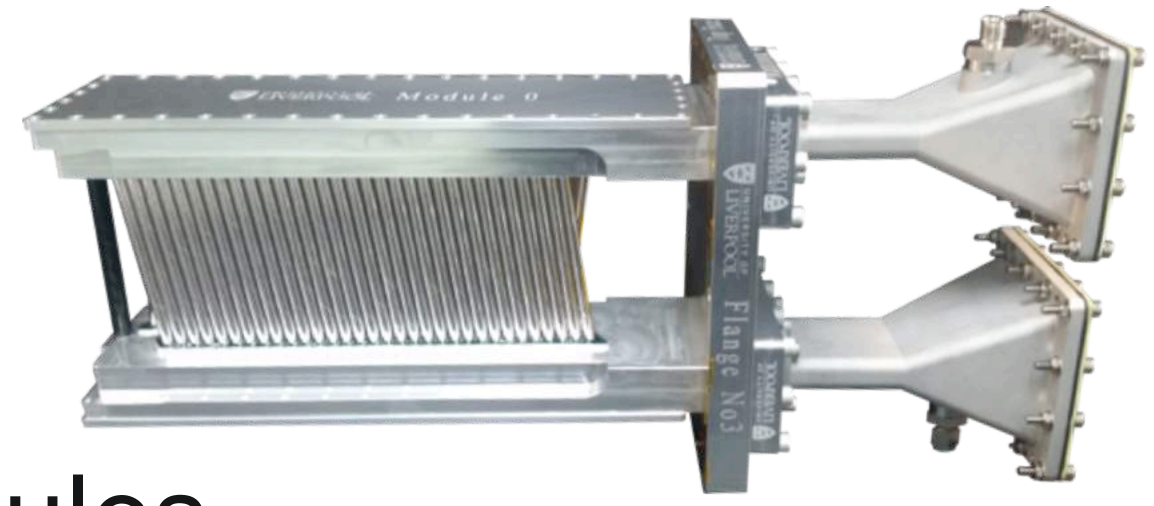
24 segmented PbF_2 crystal calorimeters

- Each crystal array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels in total)

Muon Beam Injection



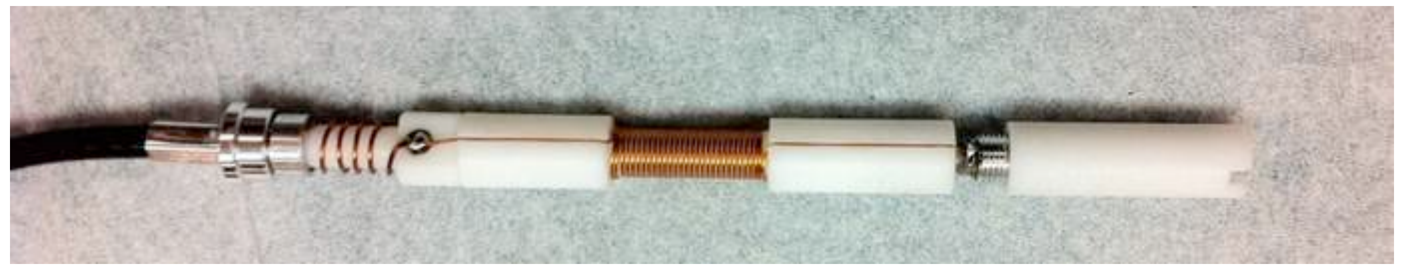
2 Tracking stations



- Each contain 8 modules
- 128 gas filled straws in each module
- Traceback postrons to their decay point

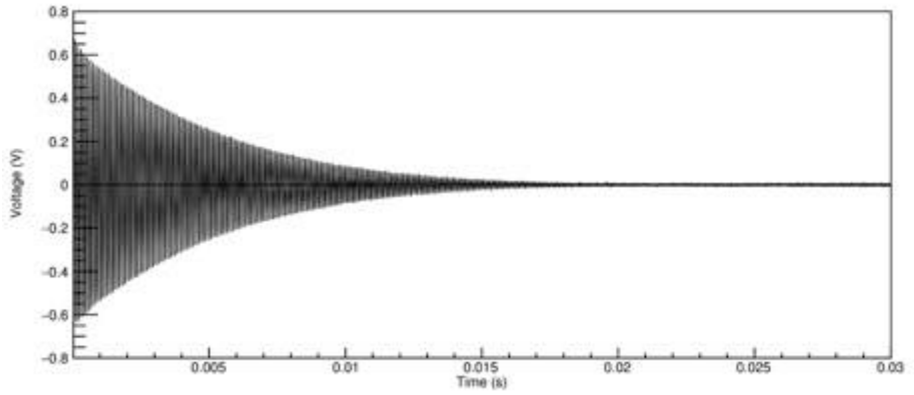
Monitoring and Mapping the Magnetic Field

Pulsed NMR

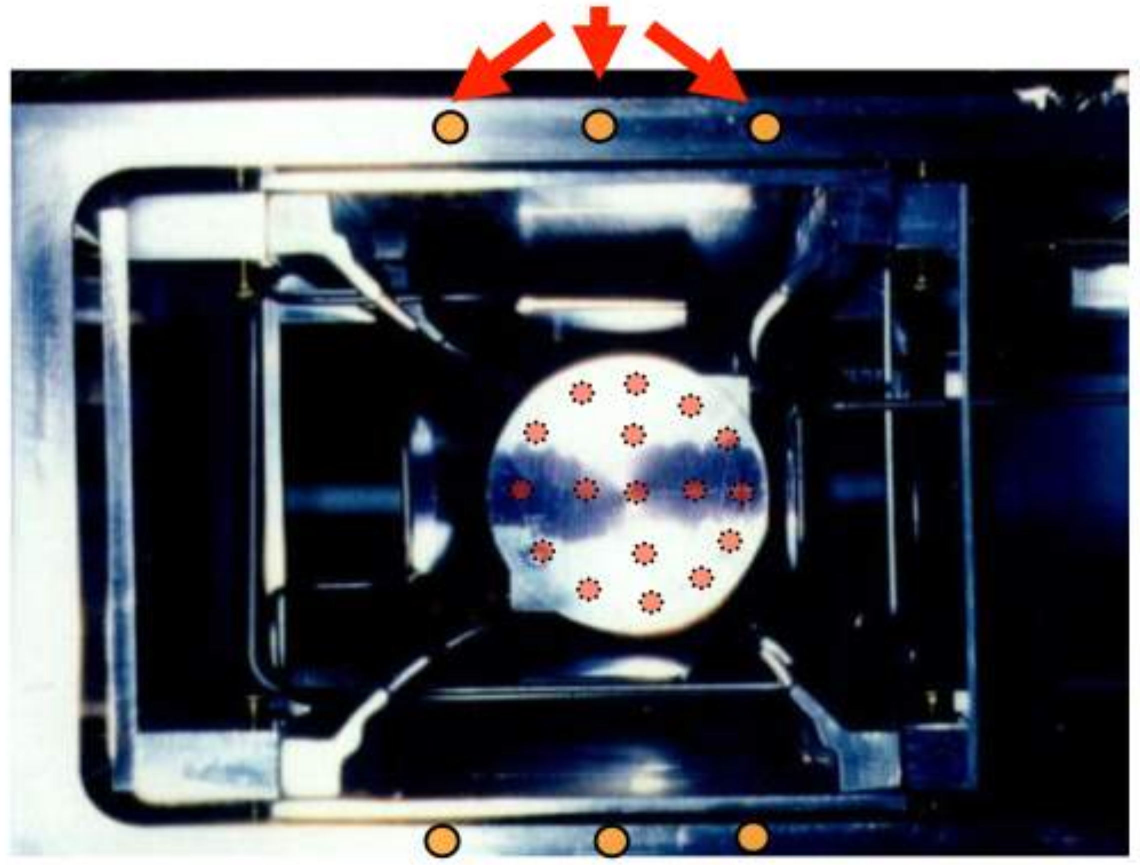


- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)

- Extracted frequency precision: 10 ppb/FID

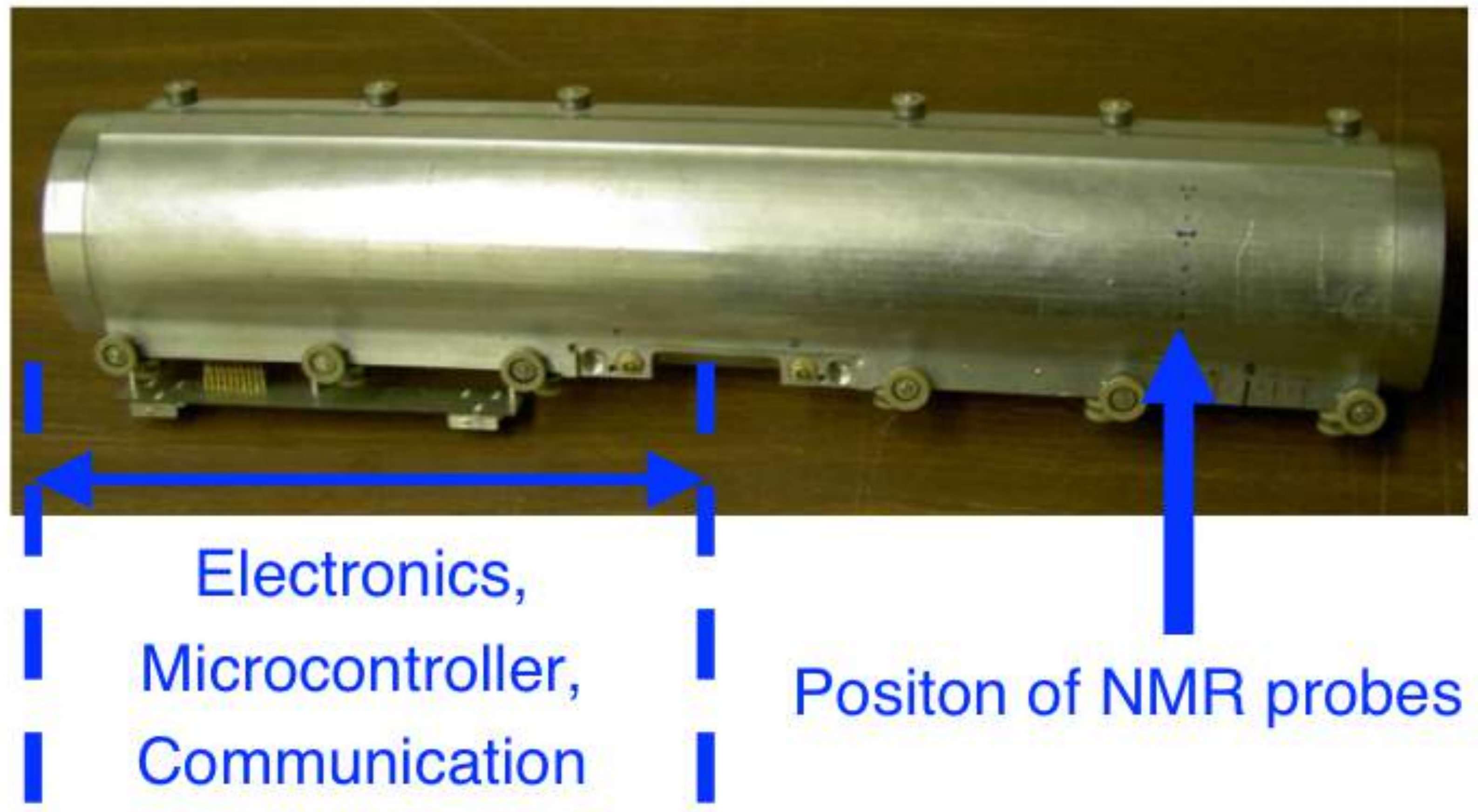


Fixed probes on vacuum chambers



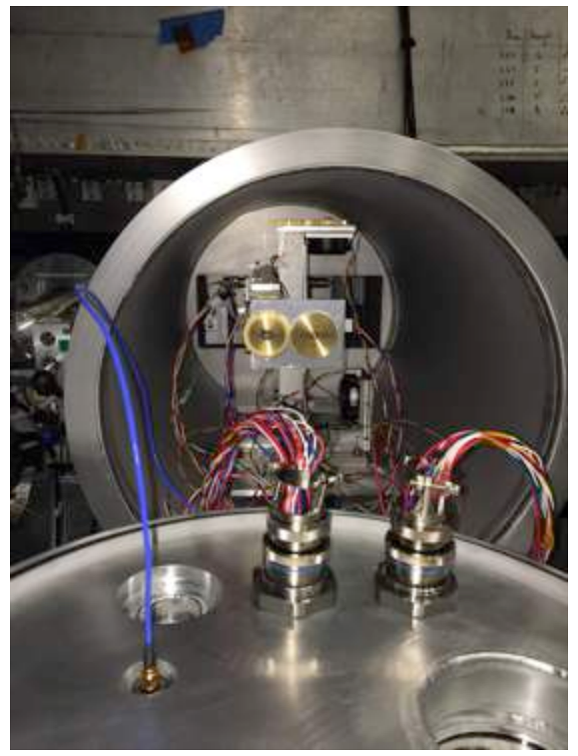
- Measure field while muons are in ring – 378 probes **outside** storage region

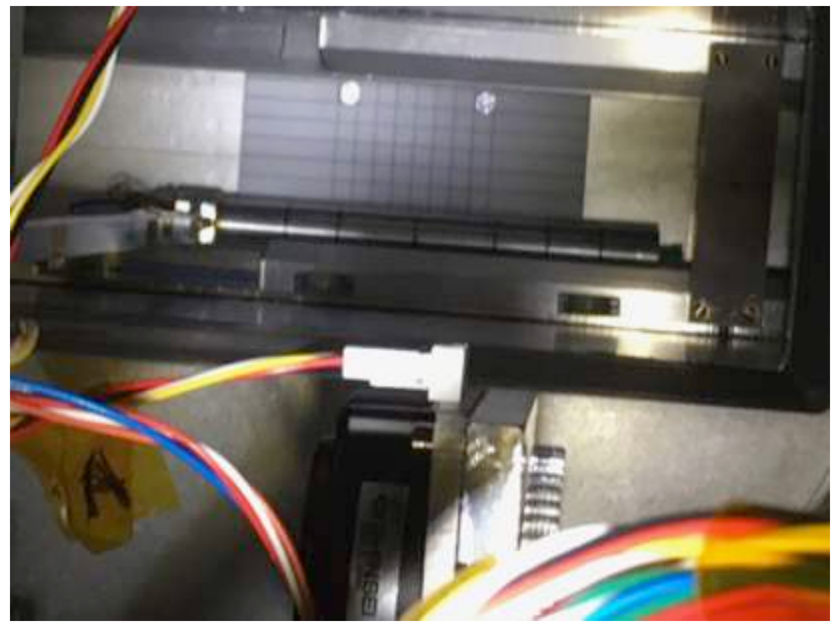
Trolley matrix of 17 NMR probes



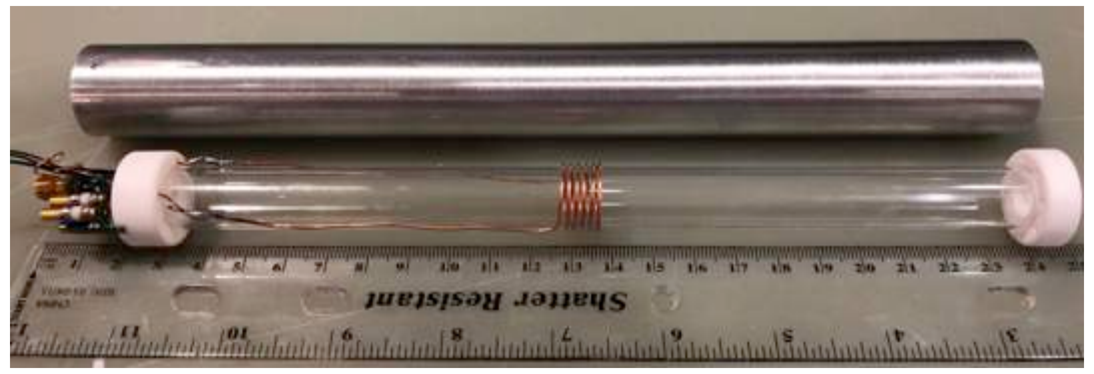
- Measure field in storage region during **specialized runs** when **muons are not being stored**

- **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





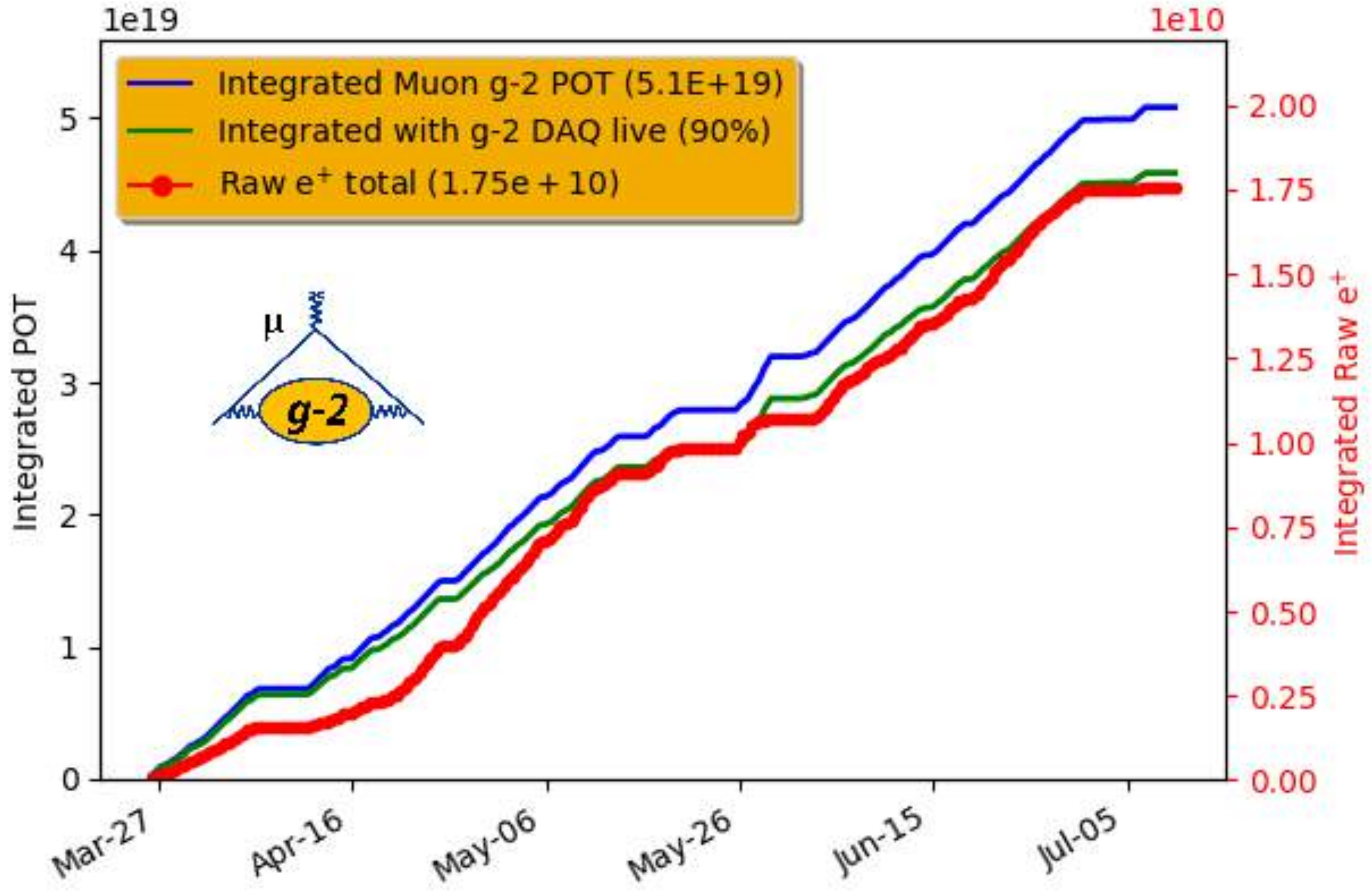
Plunging Probe



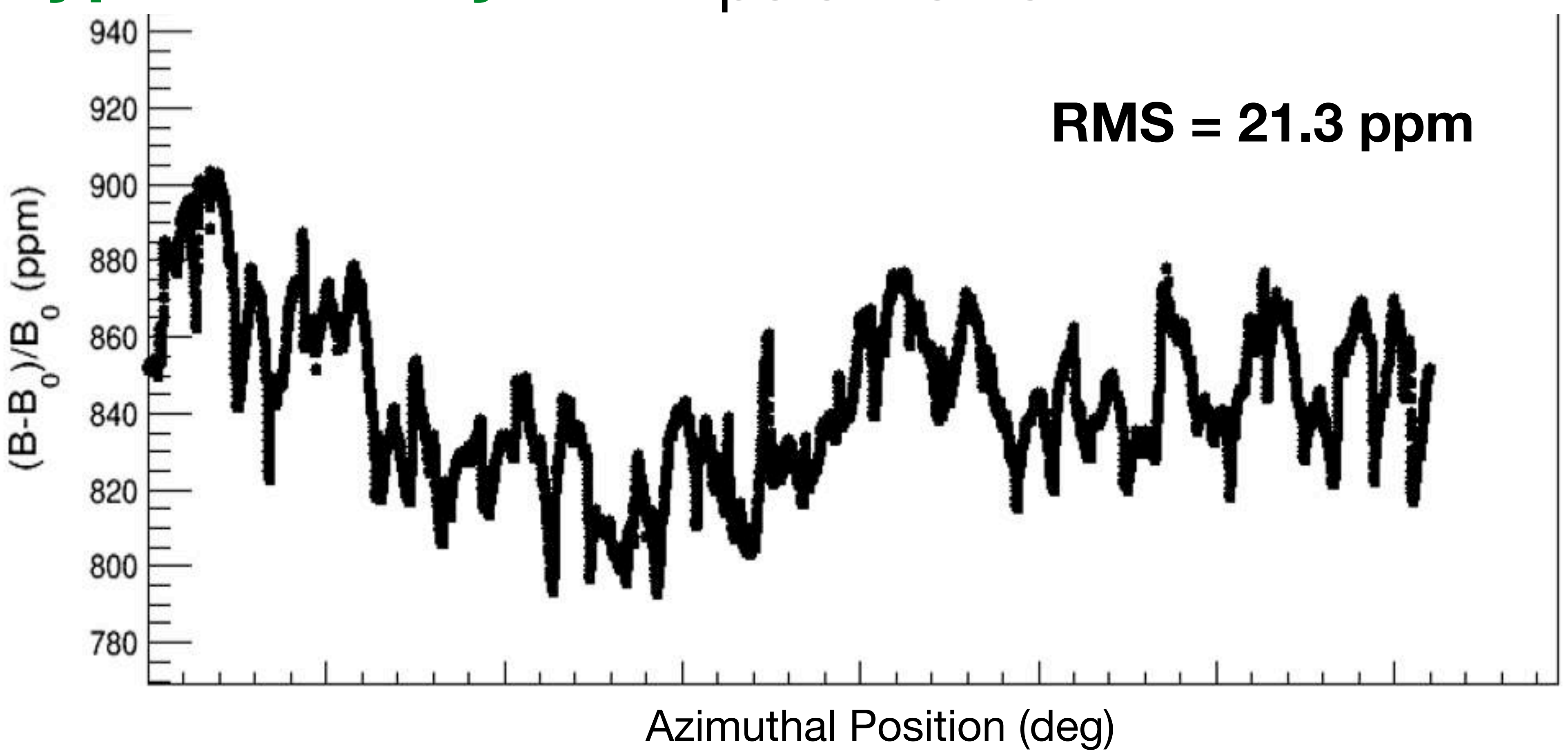
Run 1 Overview

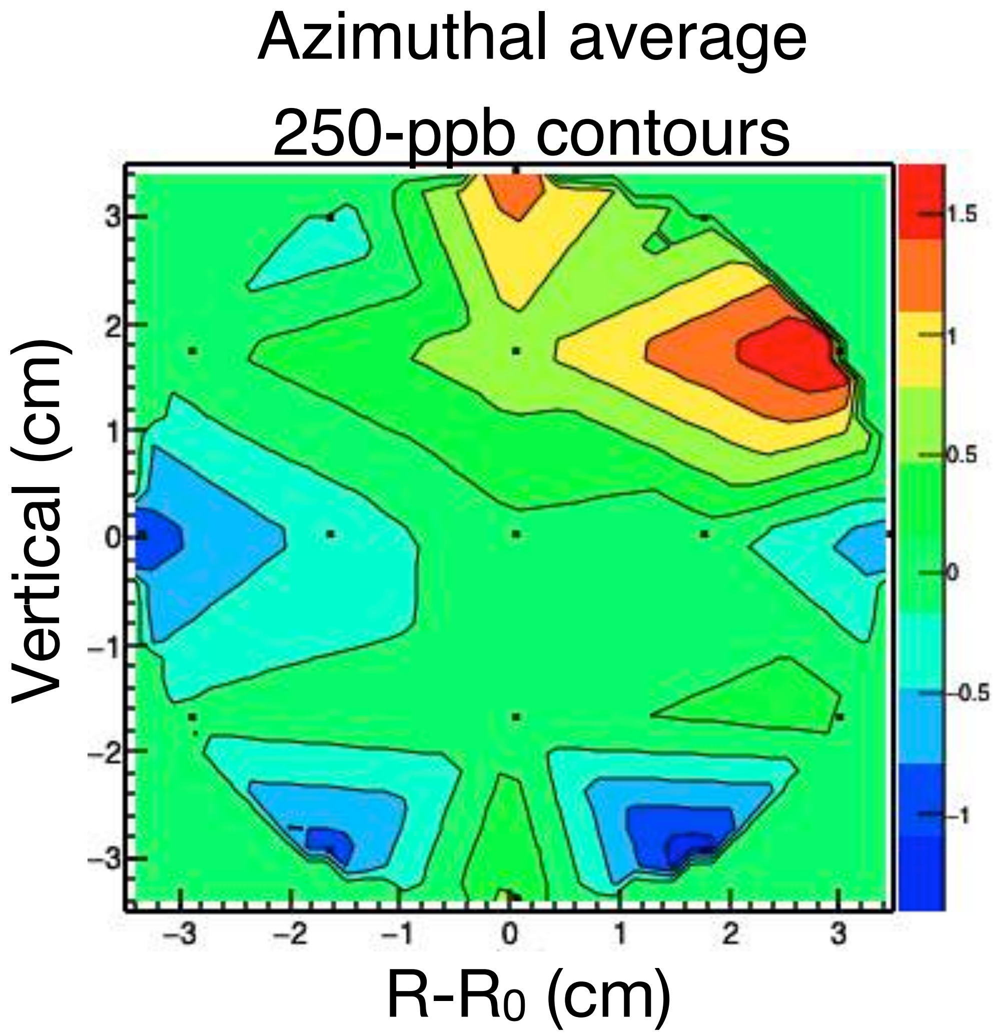
- Data taking period: April—July 2018
- Accumulated ~ 1.4 x BNL statistics (after data quality cuts) — **$\delta\omega_a$(stat) ~ 350 ppb**
- Field uniformity ~ 2x better than BNL

Accumulated statistics



Typical trolley run





Systematic Uncertainty Comparison: E821 and E989

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

- New hardware (calorimeters, trackers, NMR)
- Improved analysis techniques
- Reduce uncertainties by at least a factor of 2.5

ω_a Goal: Factor of 3 Improvement		
Category	**E821 (ppb)**	**E989 Goal (ppb)**
Gain Changes	120	20
Lost Muons	90	20
Pileup	80	40
Horizontal CBO	70	< 30
E-field/pitch	110	30
Quadrature Sum	**214**	**70**

ω_p Goal: Factor of 2.5 Improvement		
Category	**E821 (ppb)**	**E989 Goal (ppb)**
Field Calibration	50	35
Trolley Measurements	50	30
Fixed Probe Interpolation	70	30
Muon Convolution	30	10
Time-Dependent Fields	–	5
Others	100	50
Quadrature Sum	**170**	**70**

Run-1 Analysis Status — ω_a

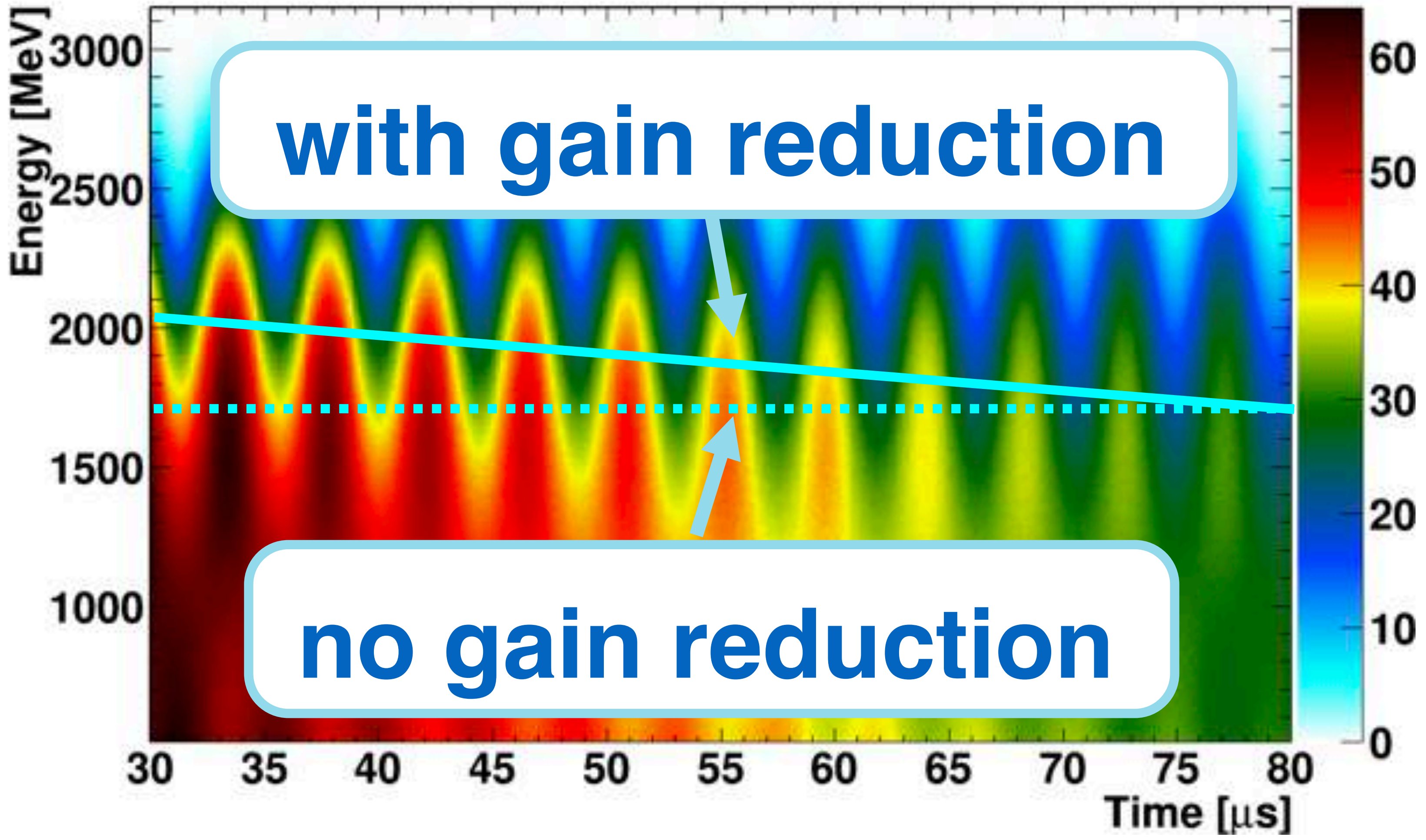
Run 1 Analysis Status: ω_a

- Account for a number of effects that can affect the extraction of ω_a

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

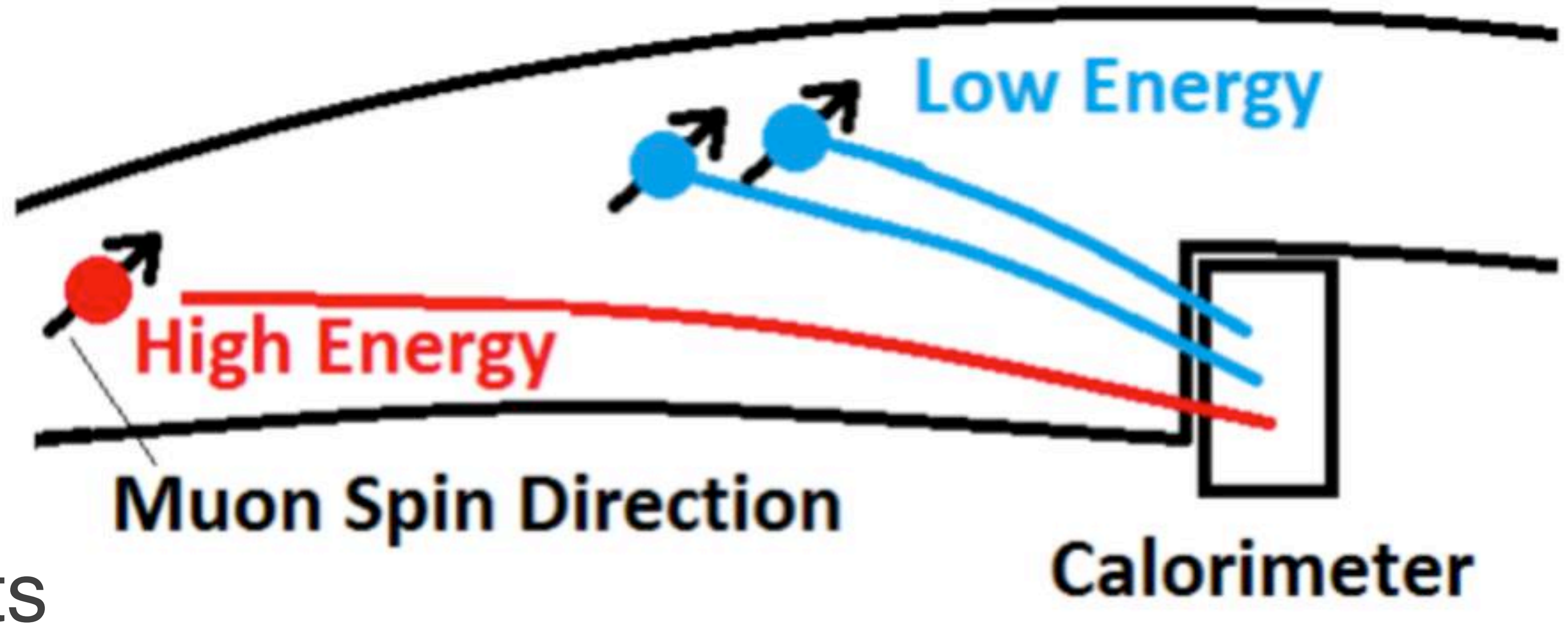
Detector effects

Gain instability



- Gain changes over time in calorimeters affects phase of signal: $N \rightarrow N(t)$, $A \rightarrow A(t)$, $\phi \rightarrow \phi(t)$
- Laser system provides corrections

Event pileup



- Low-energy events can mimic high-energy events in calorimeter
- Spin precession phase varies with energy — apparent high-energy decay carries phase of low-energy decays

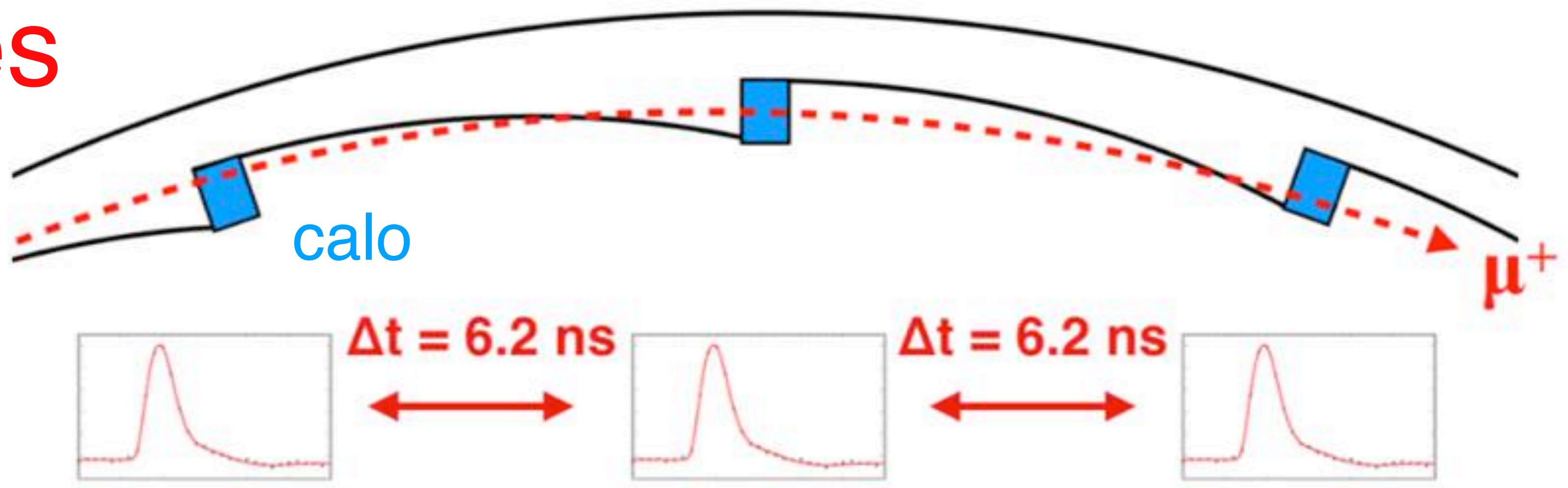
Run 1 Analysis Status: ω_a

- Account for a number of effects that can affect the extraction of ω_a

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

Beam dynamics

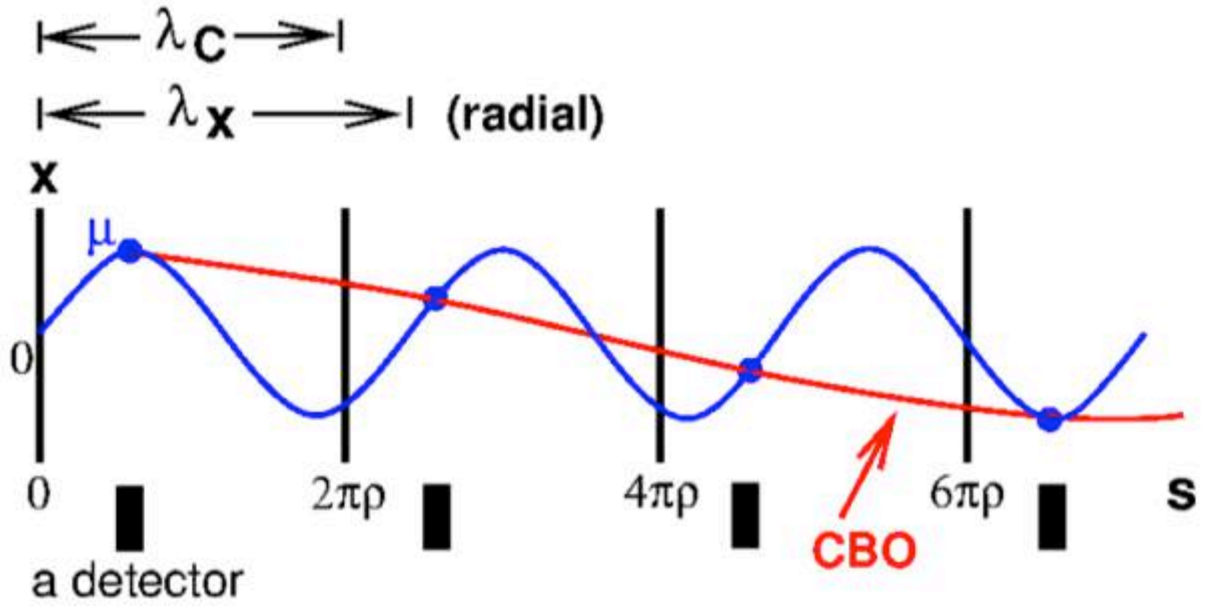
Muon losses

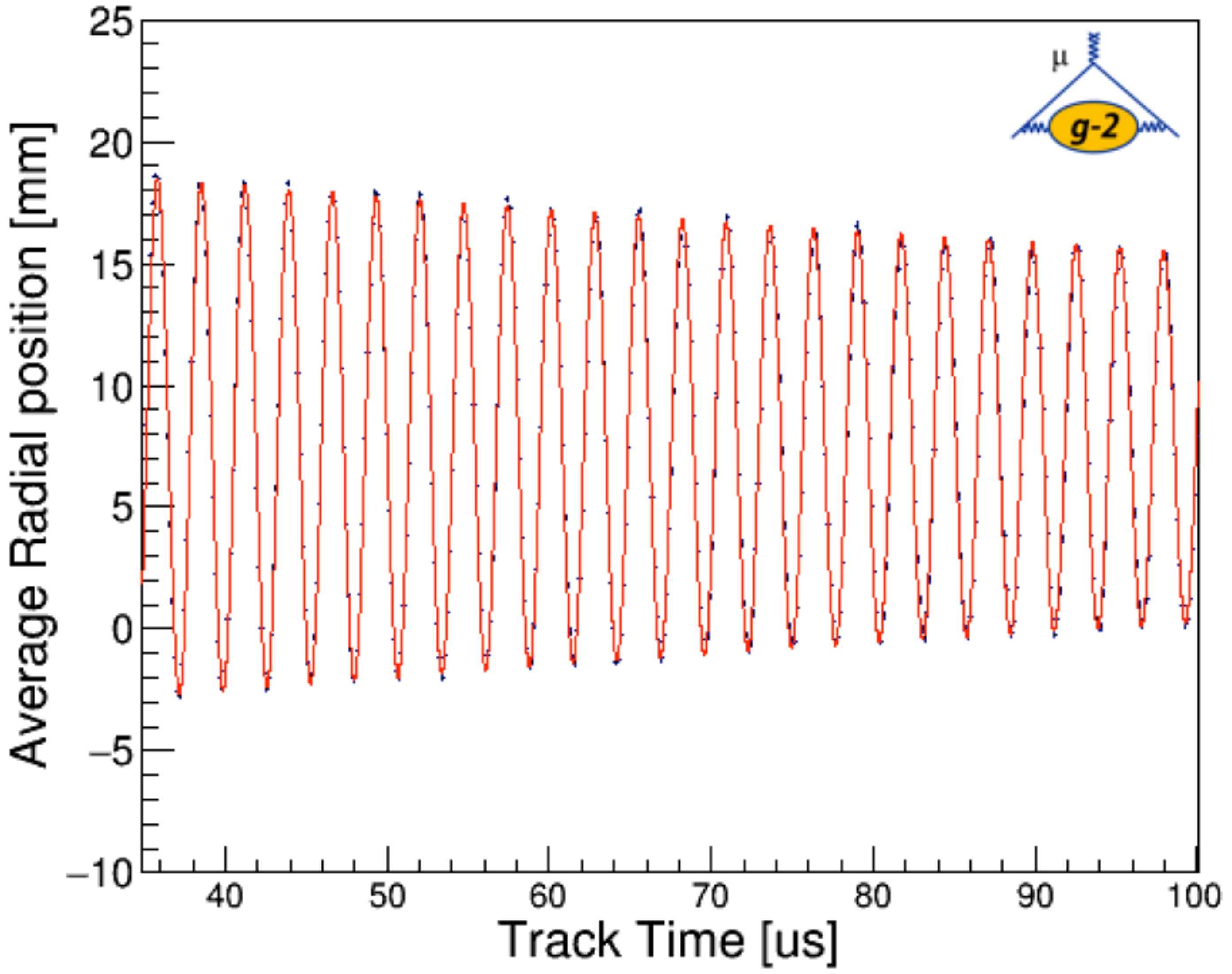


- Muons can leave storage ring by decaying or escaping
- Exhibit specific signature in multiple calorimeters
- Amplitude N_0 scaled by:

$$\Lambda(t) = 1 - K_{\mathrm{loss}} \int_0^t e^{t'/\tau} L(t')dt'$$

Coherent betatron oscillations (CBO)

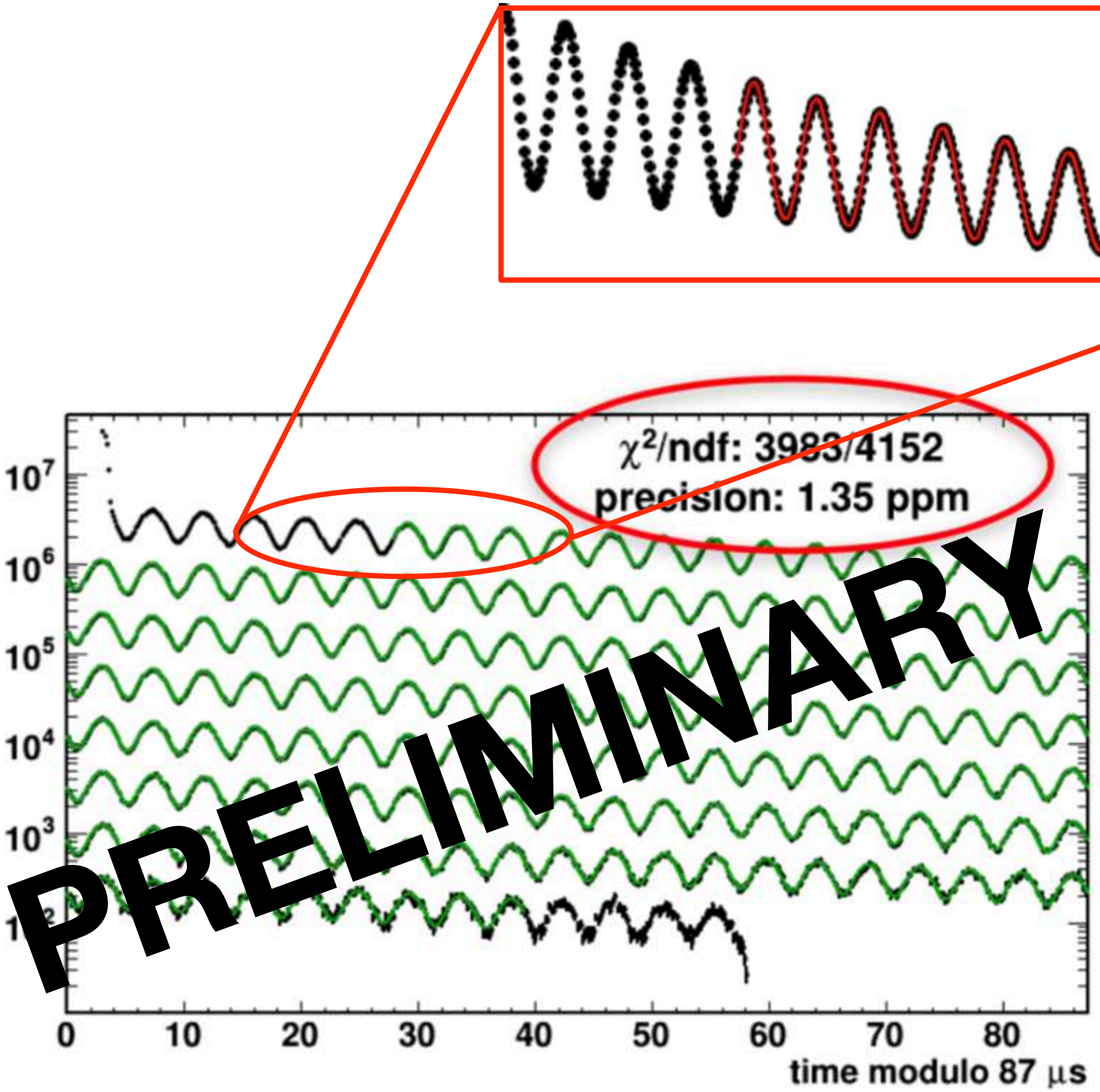




- Acceptance of calorimeters affected by coherent radial beam motion
- Amplitude N_0 scaled by:

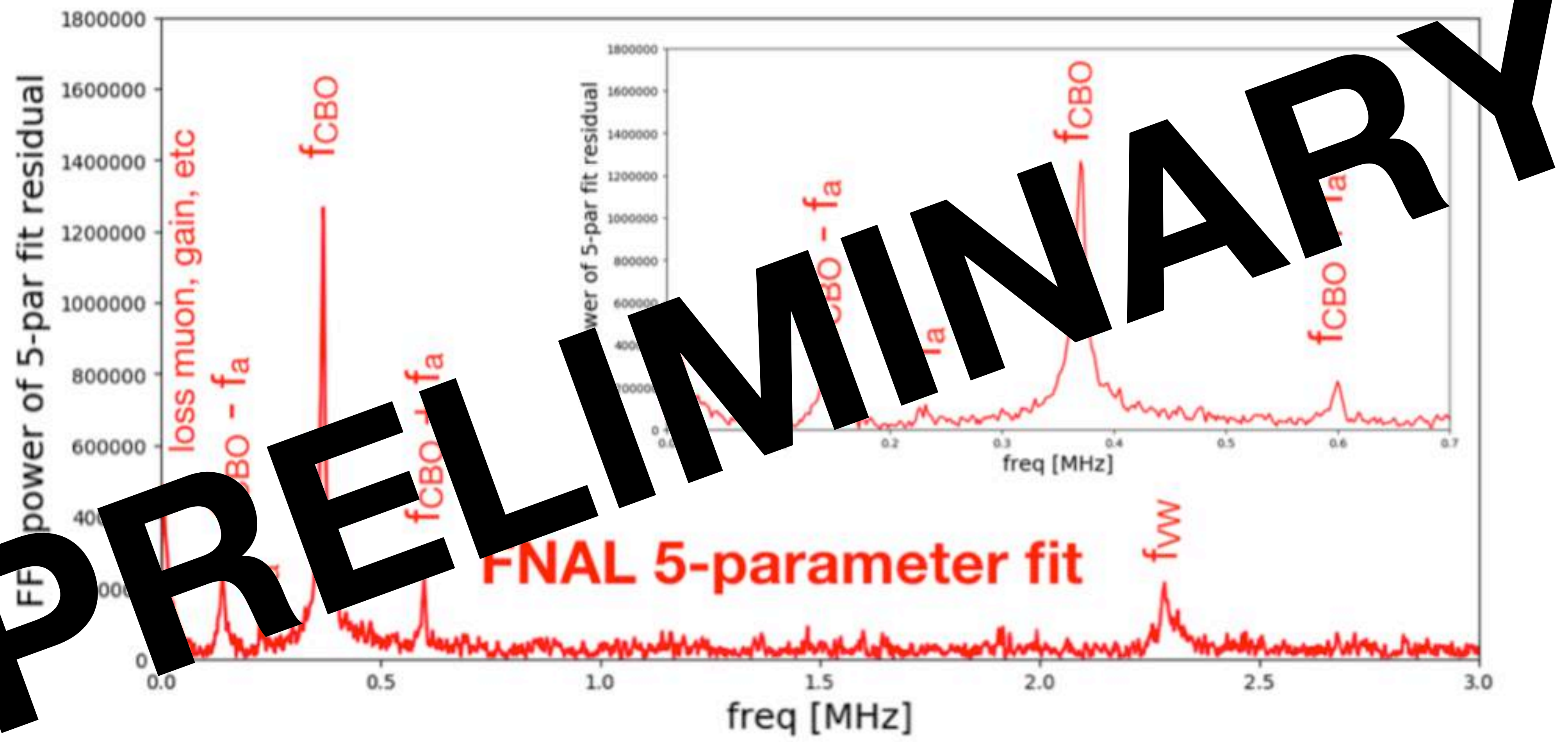
$$C(t) = 1 - e^{-t/\tau_{\mathrm{CBO}}} A_1 \cos\left(\omega_{\mathrm{CBO}} t + \phi_1\right)$$

Run 1 Analysis Status: ω_a

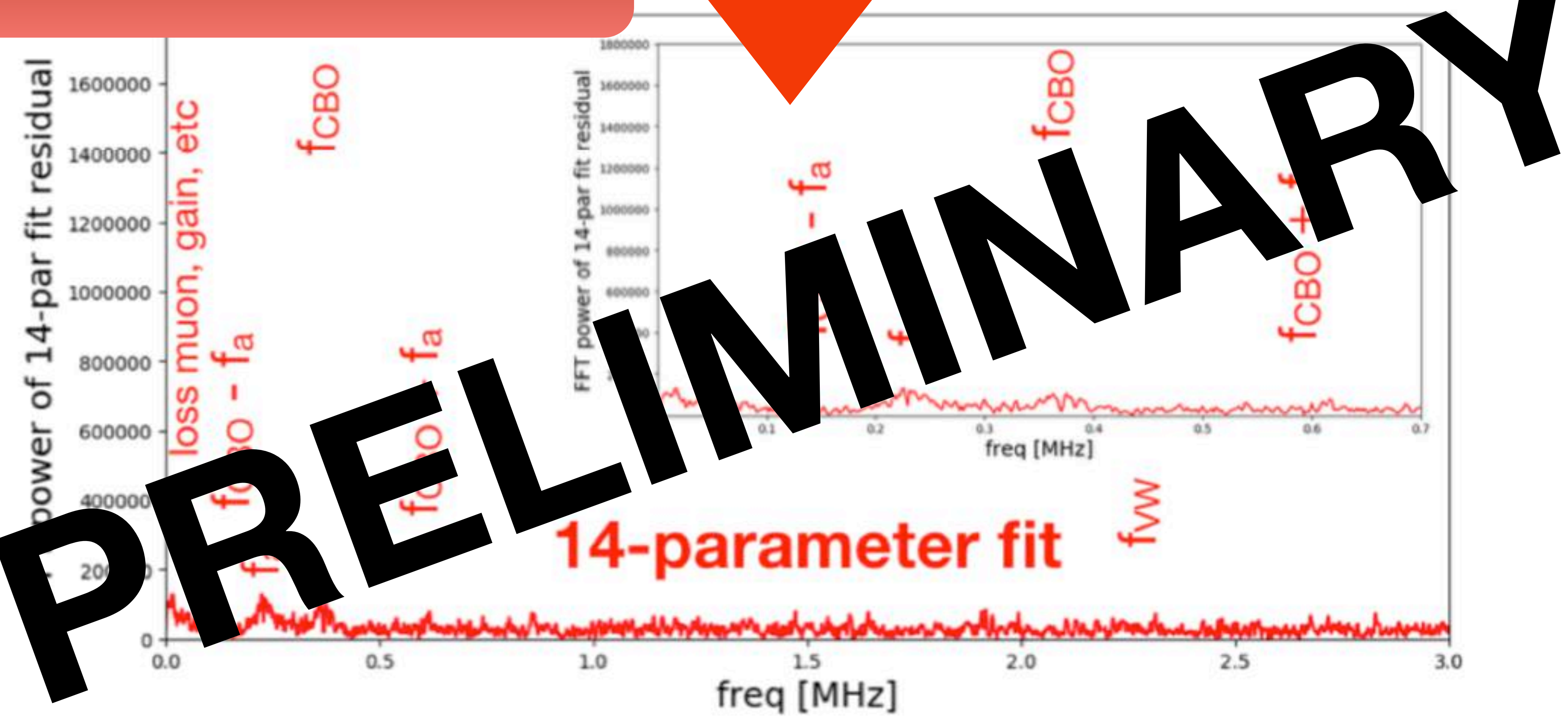


Simple five-parameter fit

FFT of fit residuals



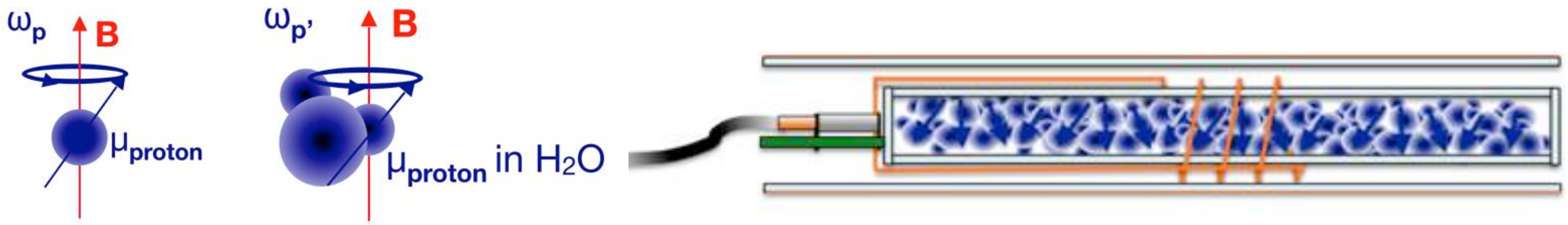
Big improvements when accounting for CBO, lost muons,…



Run-1 Analysis Status — ω_p

Run 1 Analysis Status: ω_p — Field Calibration

- 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



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

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

- **Known to 2.5 ppb**

Magnetic susceptibility of water gives shape-dependent perturbation

- ε = 4π/3 (sphere), 2π (cylinder) when probe is perpendicular to B
- **Known to 5 ppb**

Magnetization of probe materials perturbs the field at site of protons

- **Measured to 6.5 ppb**

Goal: Determine total correction to ≤ 35 ppb accuracy

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

Run 1 Analysis Status: ω_p — Field Calibration

Plunging Probe

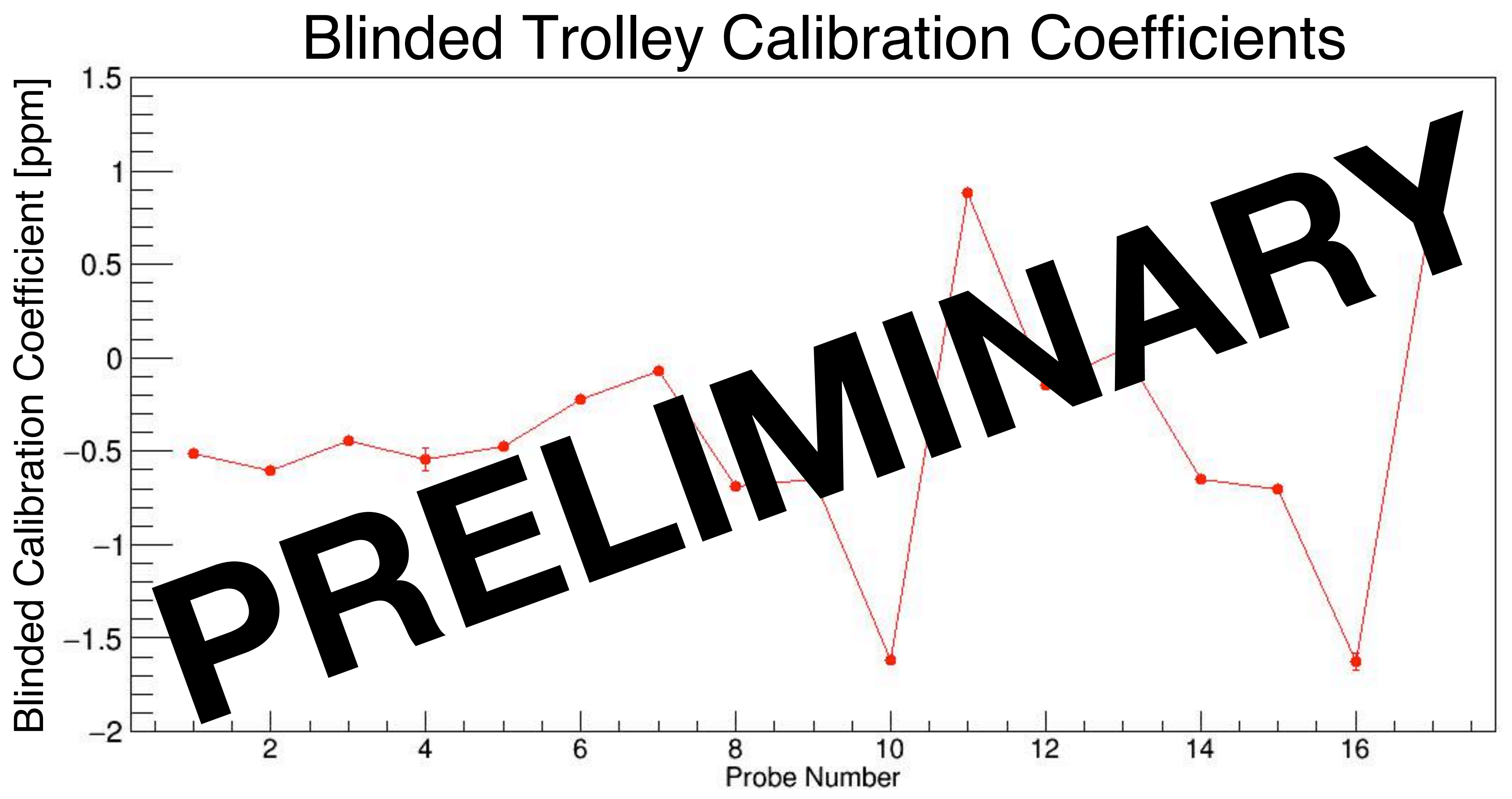
- Achieved **small perturbation of plunging probe** ~ (-5.0 ± 6.5) ppb
- Quantified uncertainties on plunging probe material, dynamic effects — **under budget of 35 ppb**

Plunging Probe Uncertainties	
Effect	**Uncertainty (ppb)**
Probe Perturbation to Field (includes images)	6.5
Radiation Damping	20
Proton Dipolar Field	2
Oxygen Contamination of Water Sample	< 1
TOTAL	**21**

PRELIMINARY

Trolley Calibration

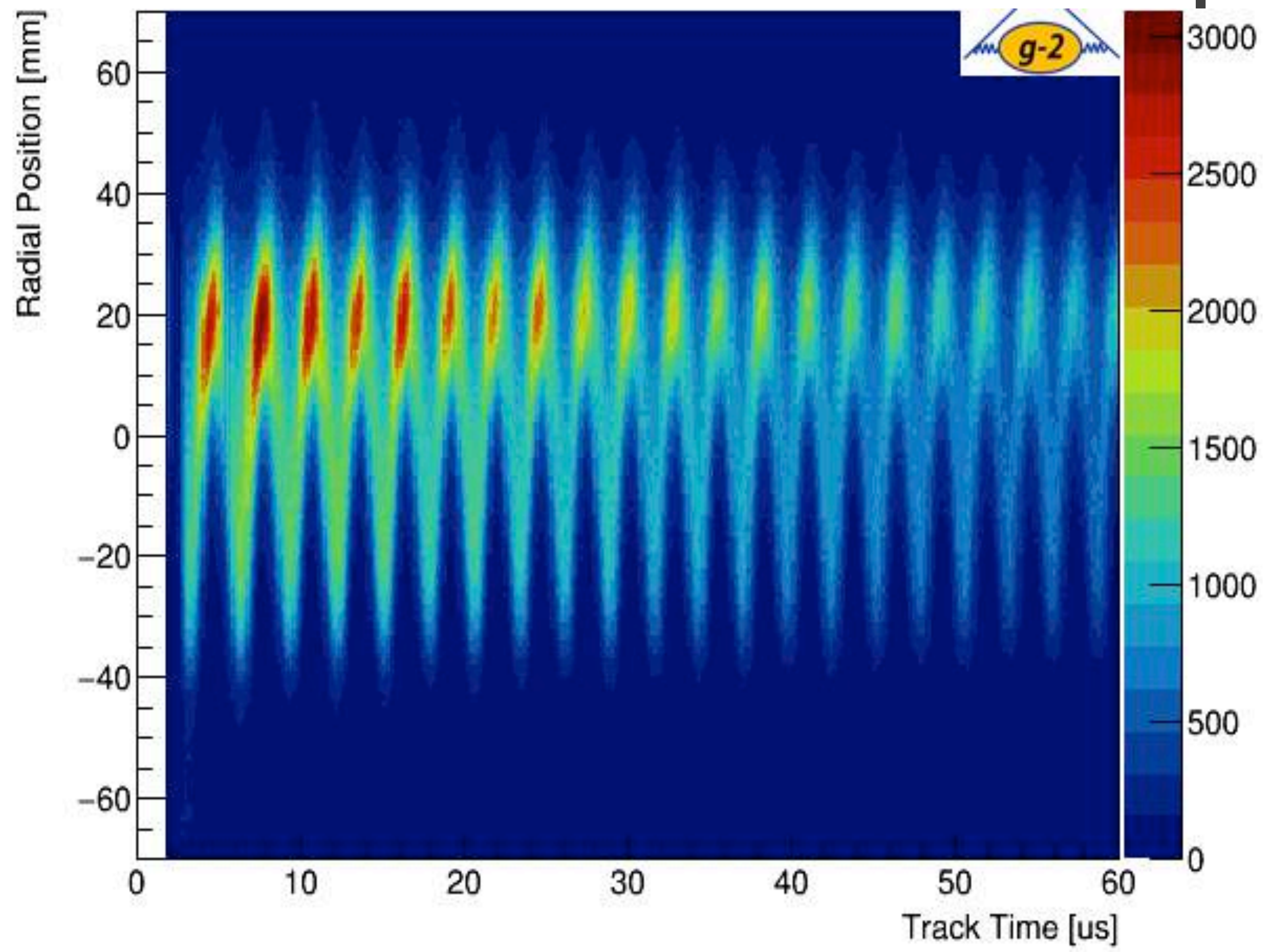
- **Calibration of trolley probes under control**
- Factor of ≥ 2 improvement on uncertainties for nearly all probes compared to E821
- Uncertainty is ~ 26 ppb on average per probe — **under budget of 30 ppb**

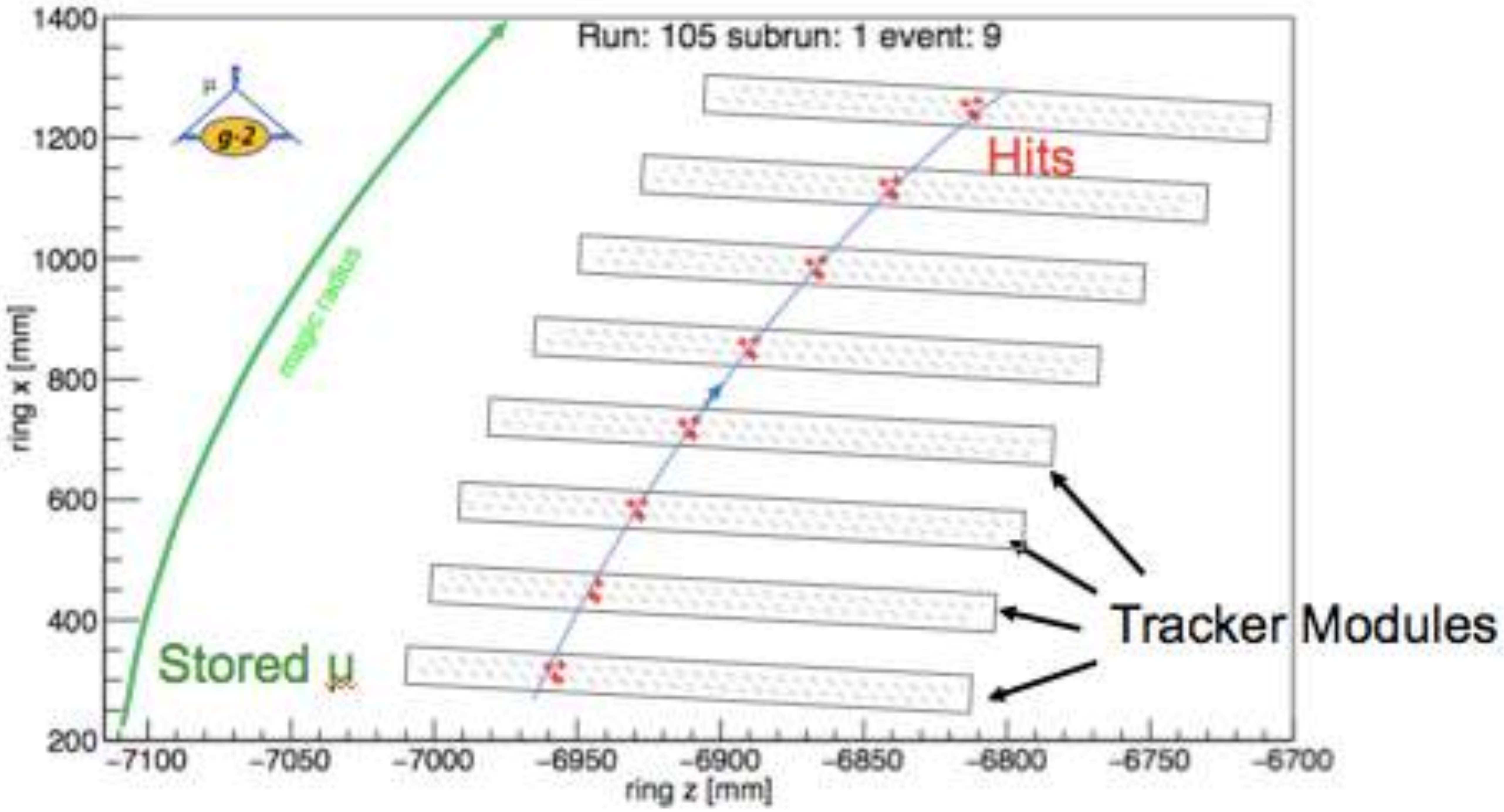


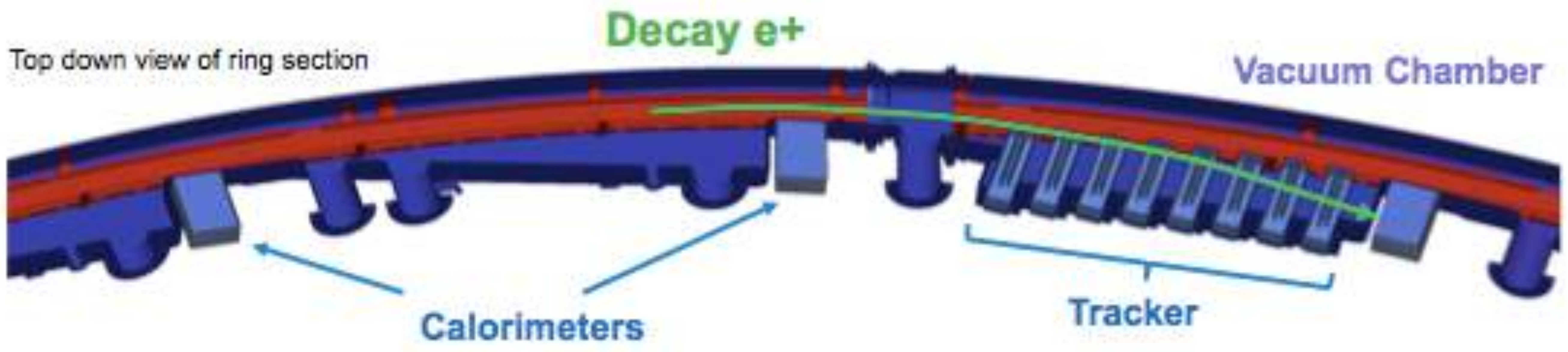
Run-1 Analysis Status — $\tilde{\omega}_p$

Position of the beam

- Use Trackers to measure the beam
- Extrapolate tracks back through B-field to point of radial Tangency
- Observe beam moving in time
- Use Trolley-Fixed probe interpolation to tell us the field at these positions

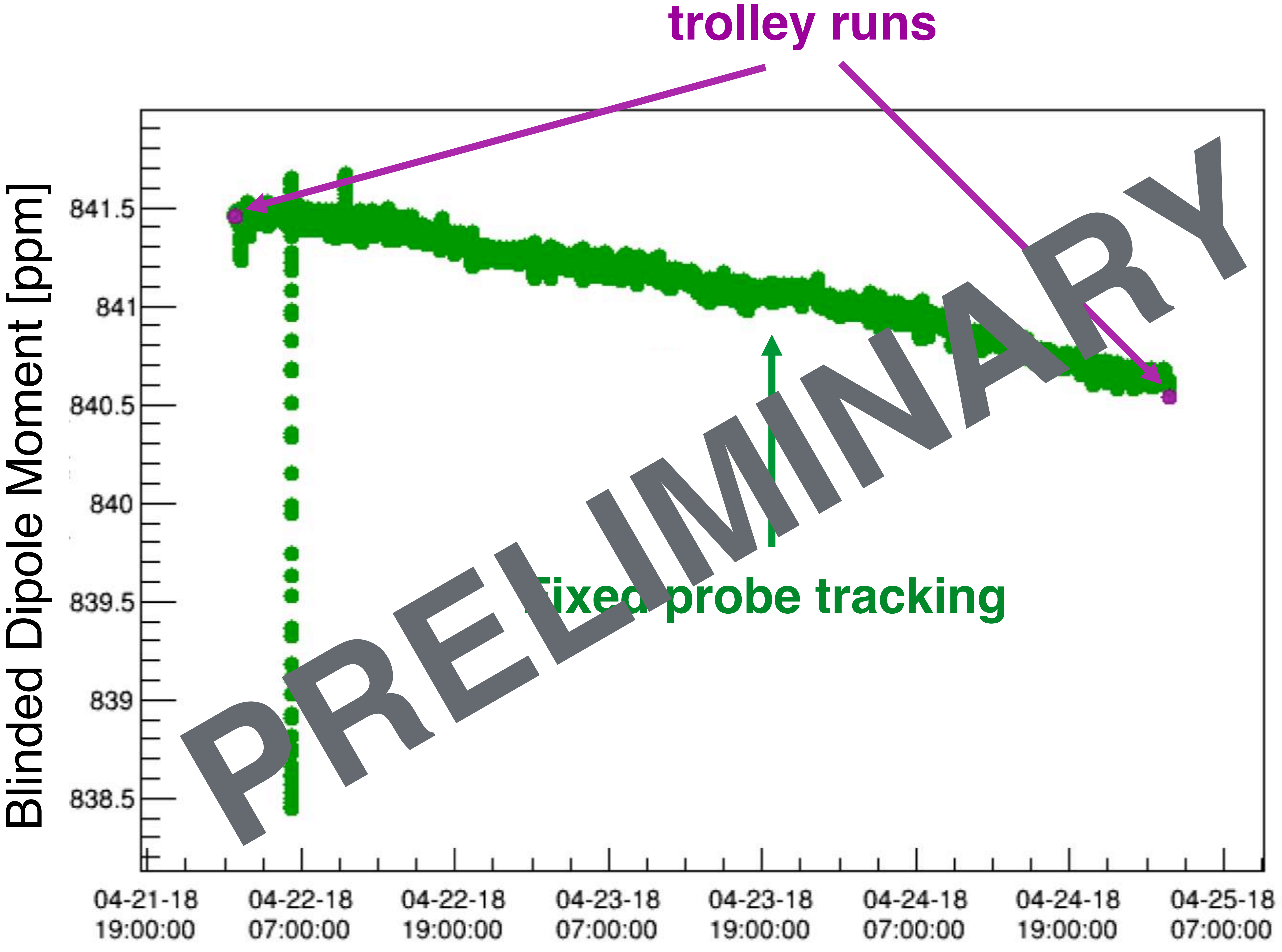






Run 1 Analysis Status: $\tilde{\omega}_p$ — Field Interpolation

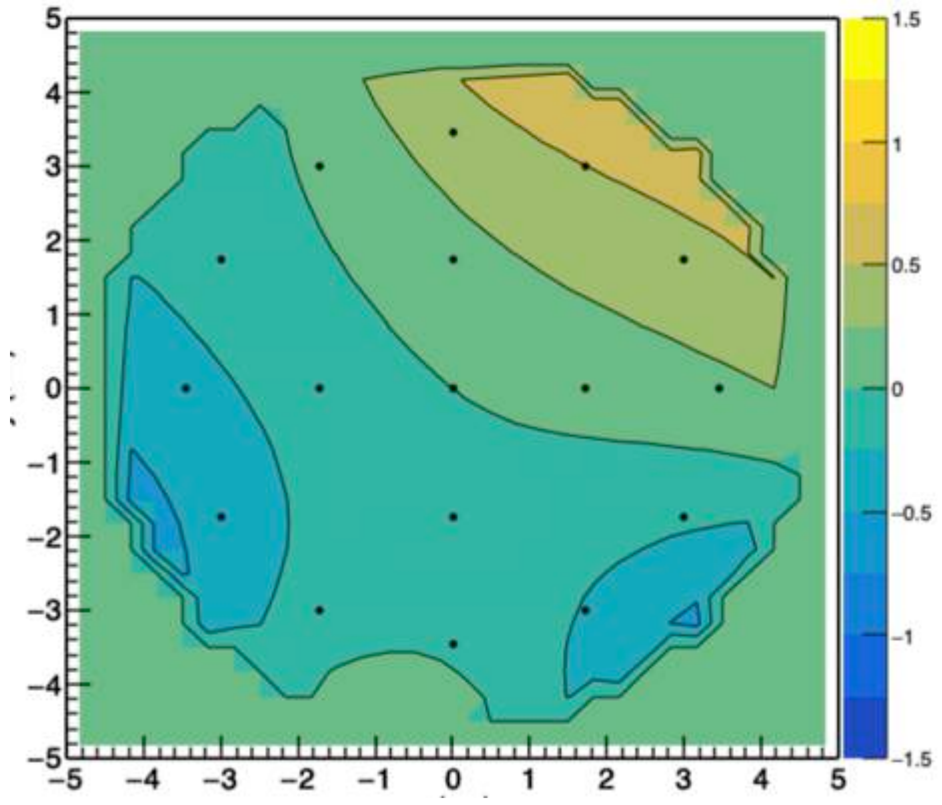
- Need to determine ω_p at all times while storing muons
- Interpolate between trolley maps using fixed probe data
- Tracking algorithms showing good agreement with trolley runs
- Also tracking higher-order multipole moments — important for extracting $\tilde{\omega}_p$



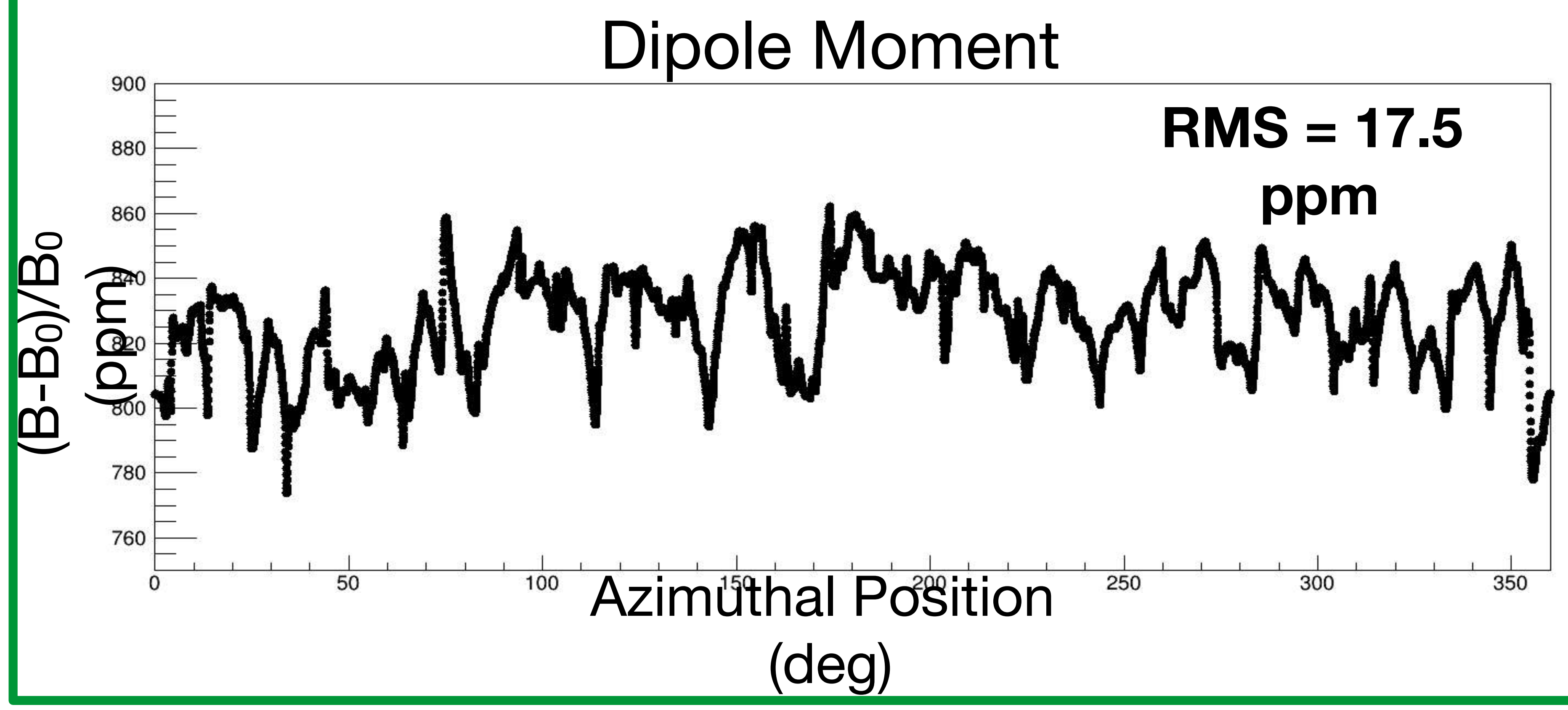
Run 2 Overview

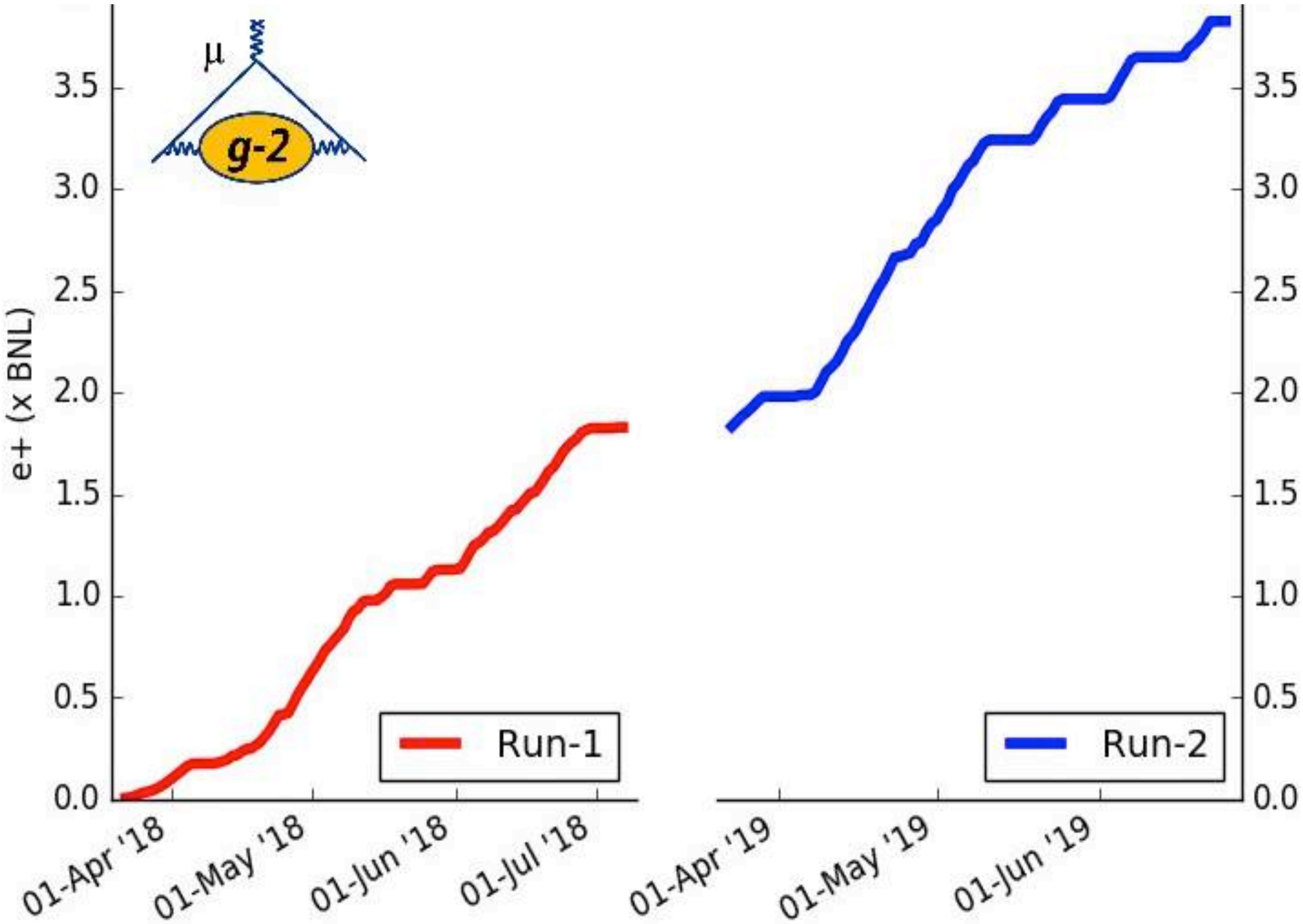
- More data taken during 2019
- Field uniformity expected to be similar to run 1

Azimuthal average
250-ppb contours



Recent trolley run





Can take 5% of a BNL per day!

Summary

Theoretical calculations

- Highly sensitive test of the SM with discrepancy between theory and experiment at the 3.7σ level
- Improvements in Lattice techniques becoming competitive for HVP uncertainty
- New data for HVP improving uncertainty, and not moving central value
- Data driven methods for HLbL agree with theory, too soon for competitive uncertainties
- On course for improvement on same time scale as Fermilab result

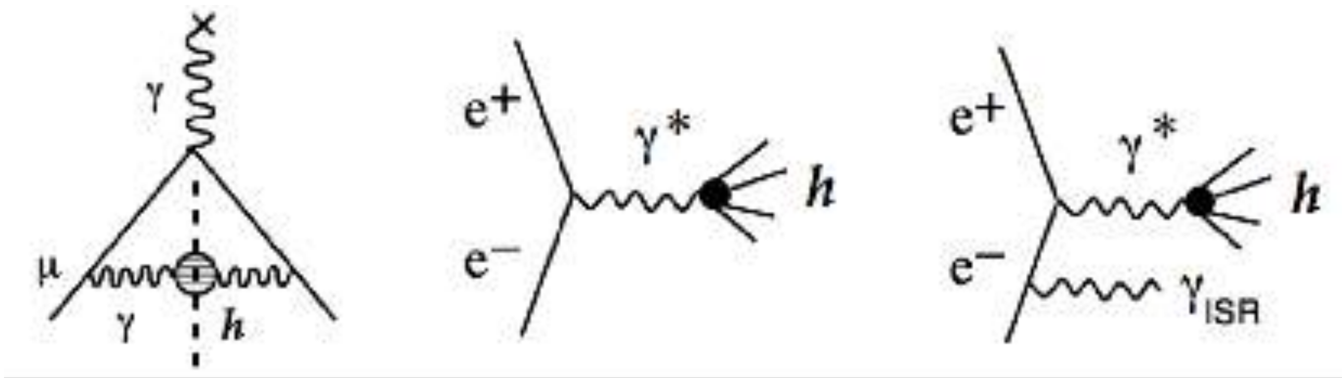
The Fermilab Muon g-2 Experiment

- Completed Run 1 in July 2018: result planned for late 2019. Statistic ~1.5 x BNL
- Run 2 nearly complete (this Saturday!) — another 2 x BNL this year
- Taking 5% of a BNL a day, on course for 21 BNLs over next 2 years
- No new systematic uncertainties unearthed, all at or below target level for run 1
- Aiming for $>5\sigma$ result (if central value remains the same as BNL) at end of year

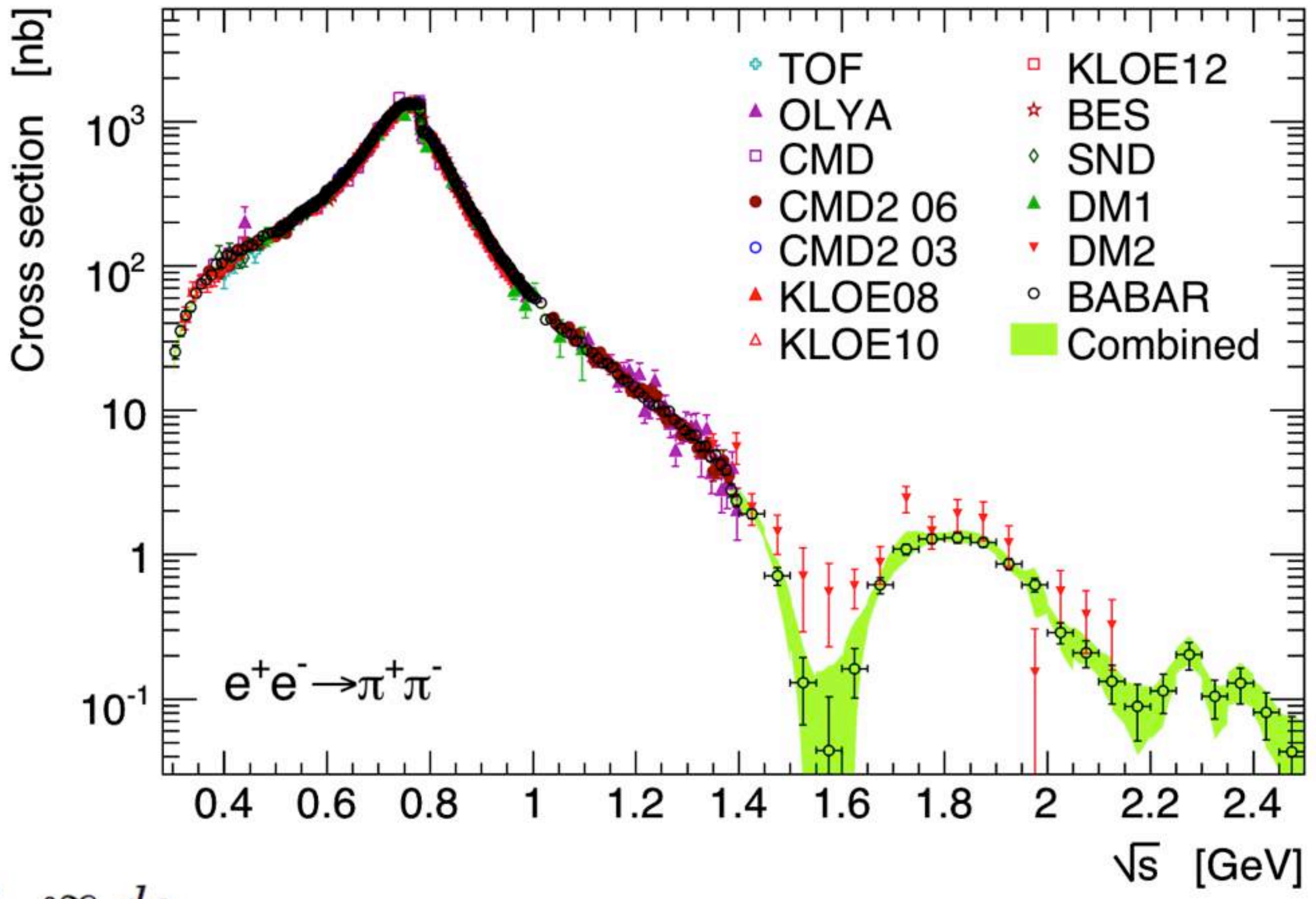
Thank you!

Backup

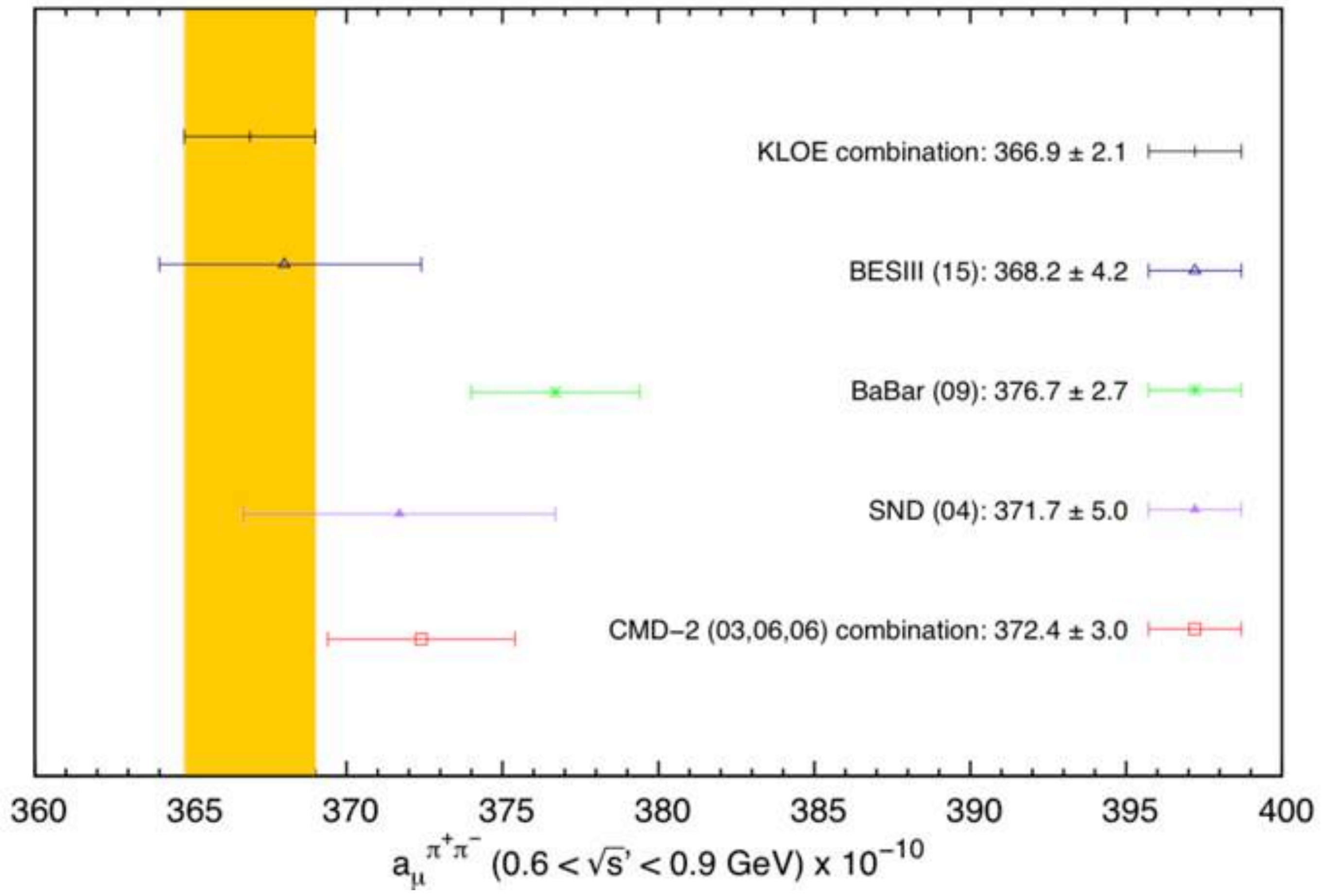
Hadronic Vacuum Polarization



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



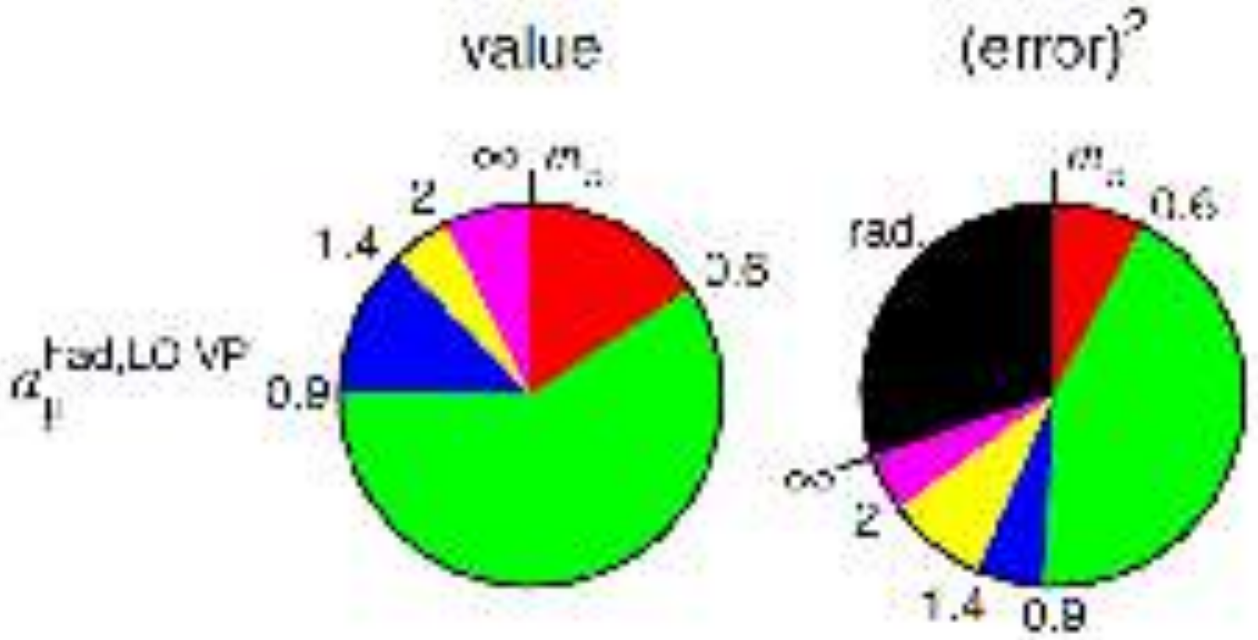
- **Critical input to HVP** from e^+e^- colliders (SND, CMD3, BaBar, KLOE, Belle, BESIII)
- **BESIII:** 3x more data available, luminosity measurement improvements
- **VEPP-2000:** Aiming for 0.3% (fractional) uncertainty; radiative return + energy scan
- **CMD3:** Will measure up to 2 GeV (energy scan,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



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

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

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

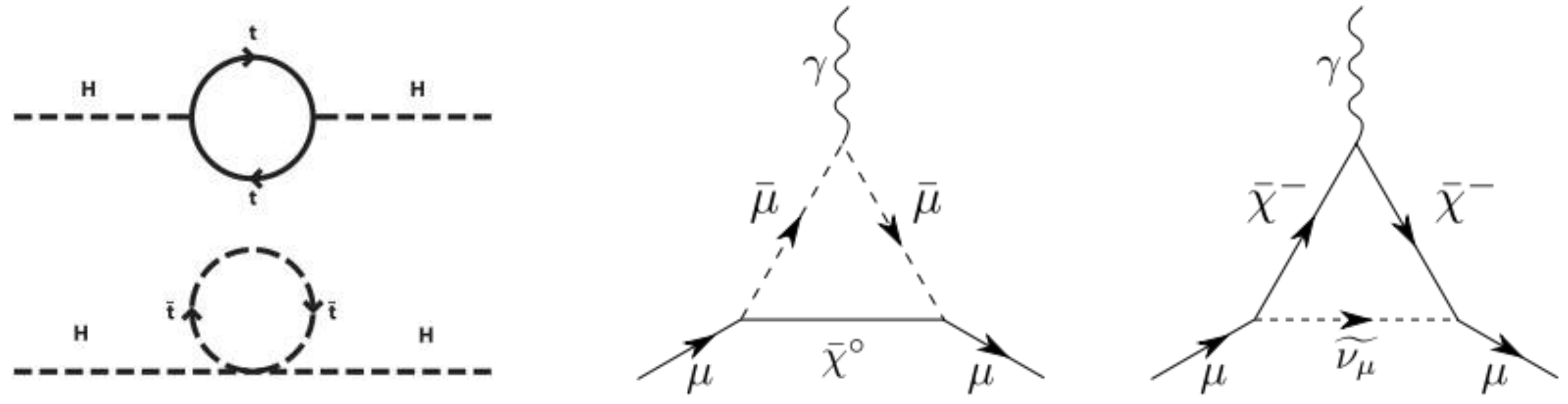


- **Lattice calculations** of a_μ^{HVP} to 1% possible, 30% for HLbL in 3—5 years

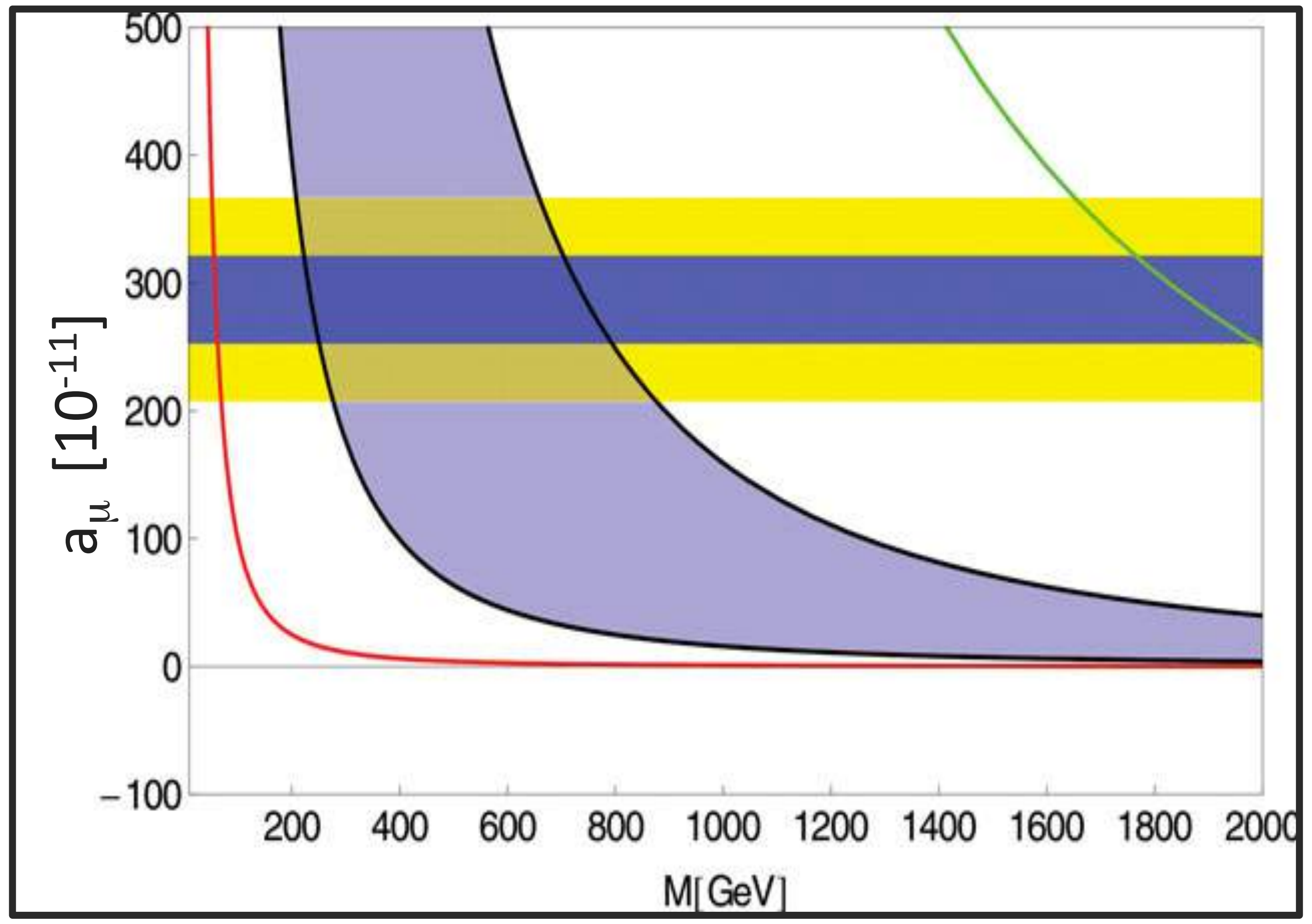
Physics Beyond the Standard Model?

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**



- **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

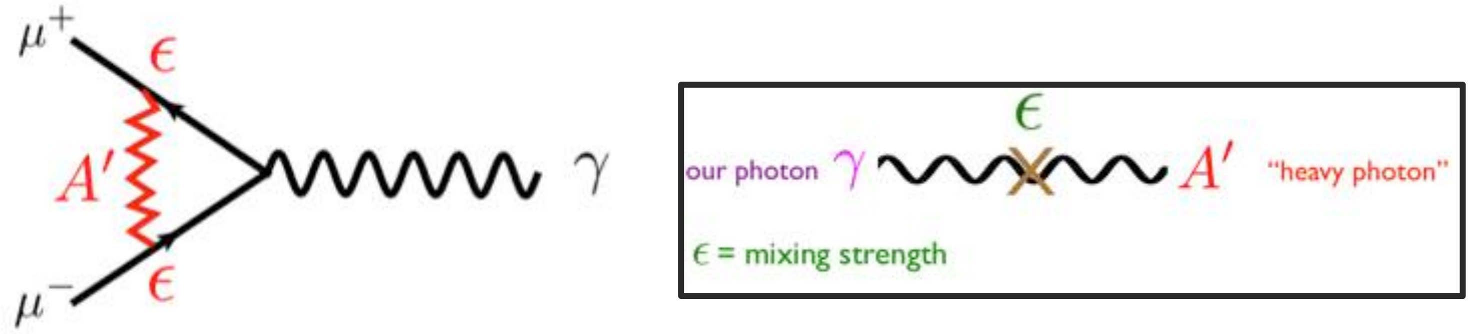


D. Hertzog, Ann. Phys. (Berlin), 2015, courtesy D. Stockinger

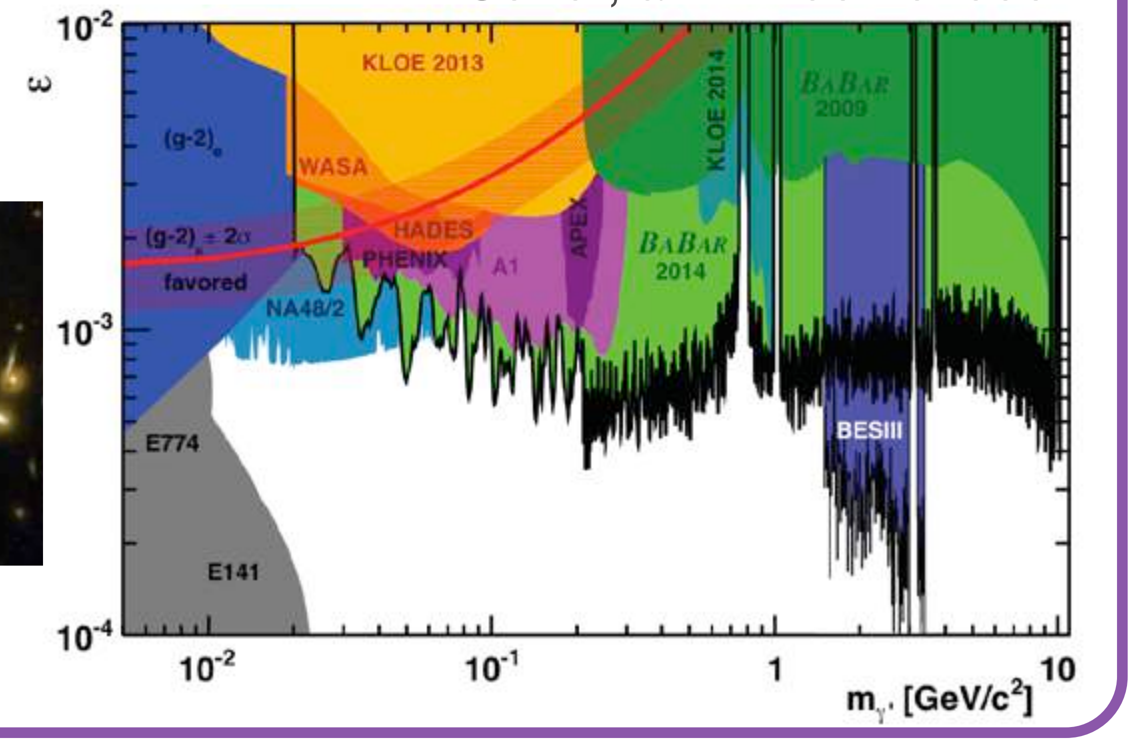
- Z', W', UED, Littlest Higgs
  - Assumes typical weak coupling
- Radiative muon mass generation
- Unparticles, Extra Dimension Models, SUSY (tan β = 5 to 50)

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



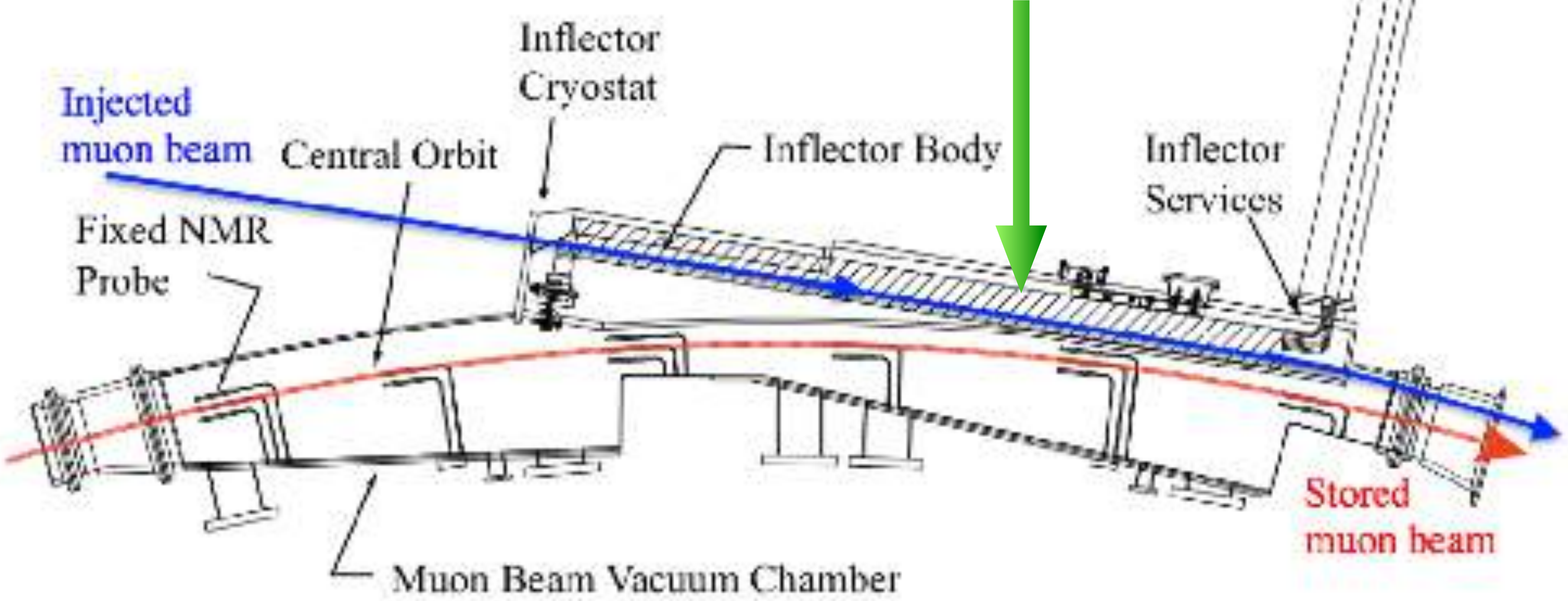
The Big Move: Transporting the Ring from BNL to FNAL

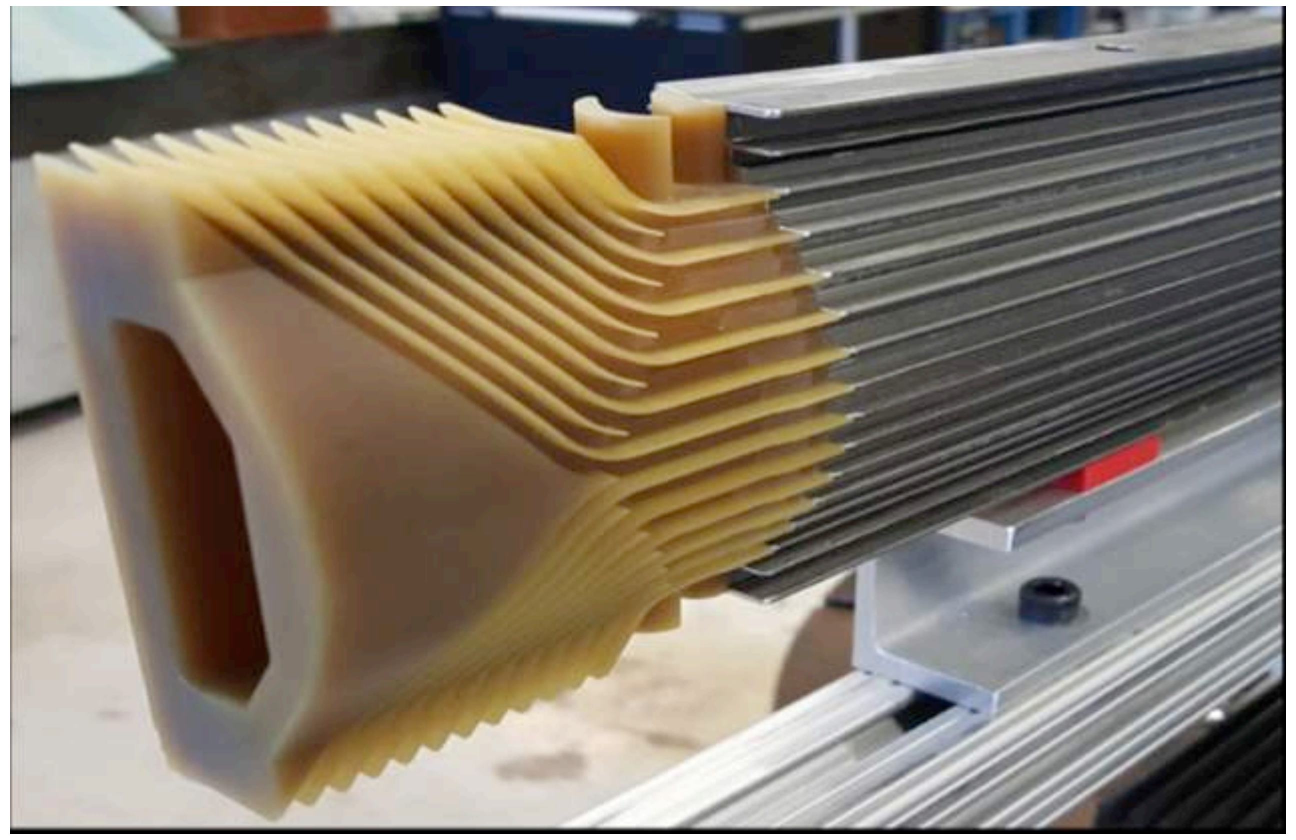
- June 2013—June 2015
- Ring deconstructed at BNL, transported by barge/flatbed trailer
- Reassembled at FNAL
- Ring successfully cooled and powered to 1.45 T in September 2015 — remarkable achievement!

Getting Muons Into the Ring: Inflector Magnet

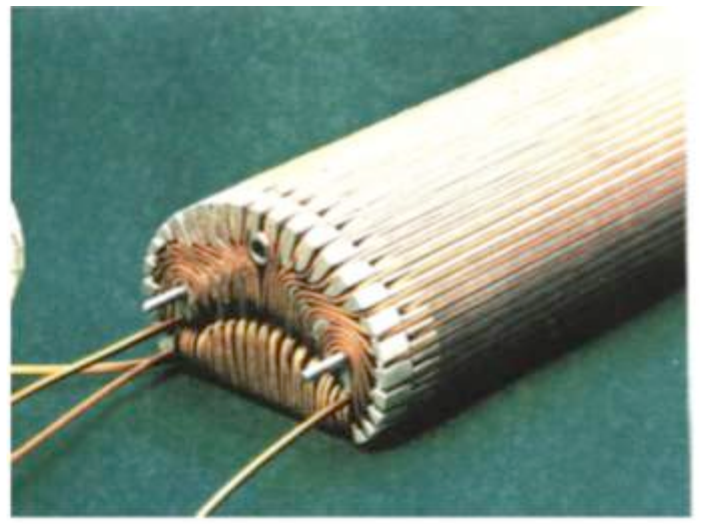
- Outside ring: B = 0 T, inside: B = 1.45 T
- Need to cancel field in order to get muons in (strong deflection otherwise)
- No perturbation to field outside shield
- New inflector design with higher transmission under development
- **Improve injection by 40%**

Energizing coils cancels the field in the beam channel

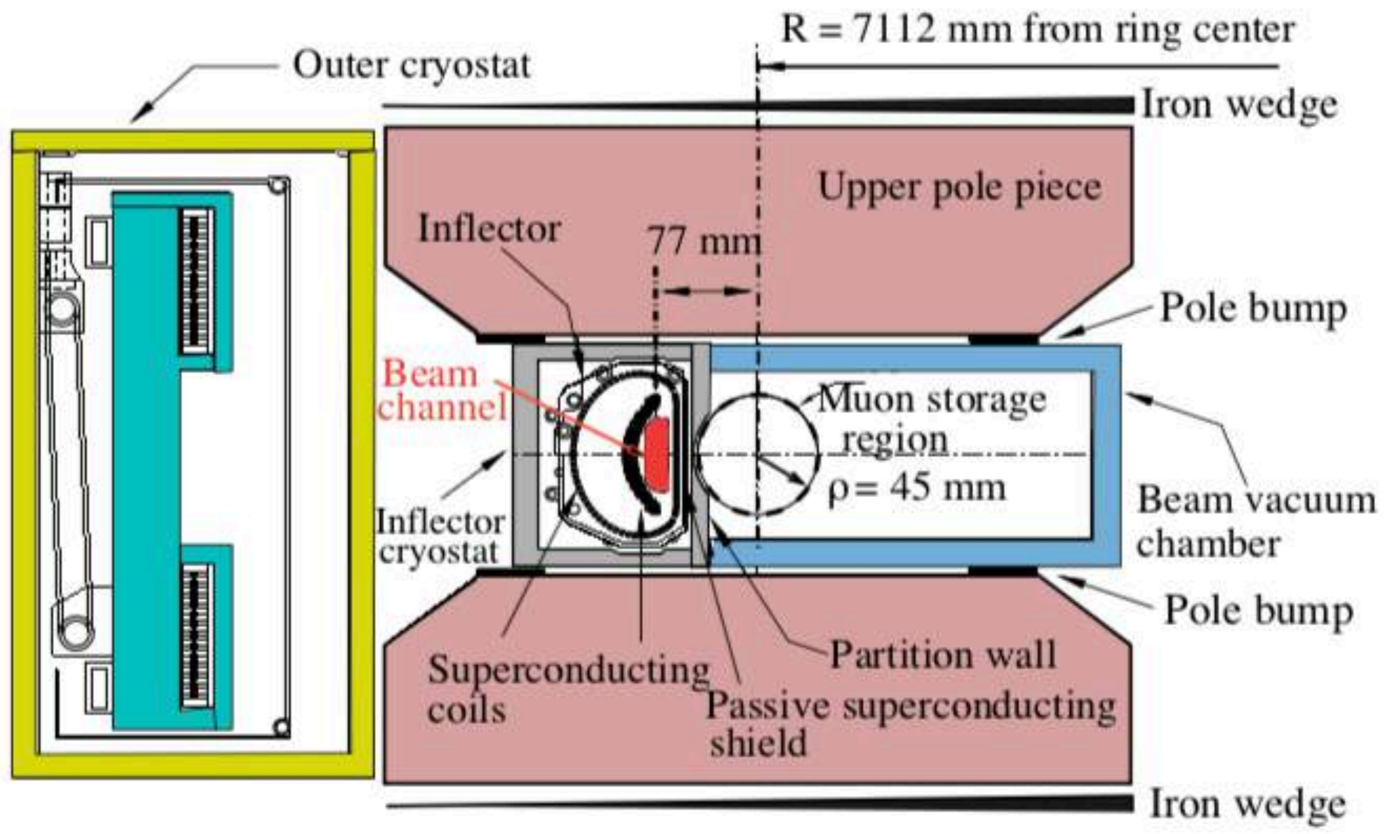


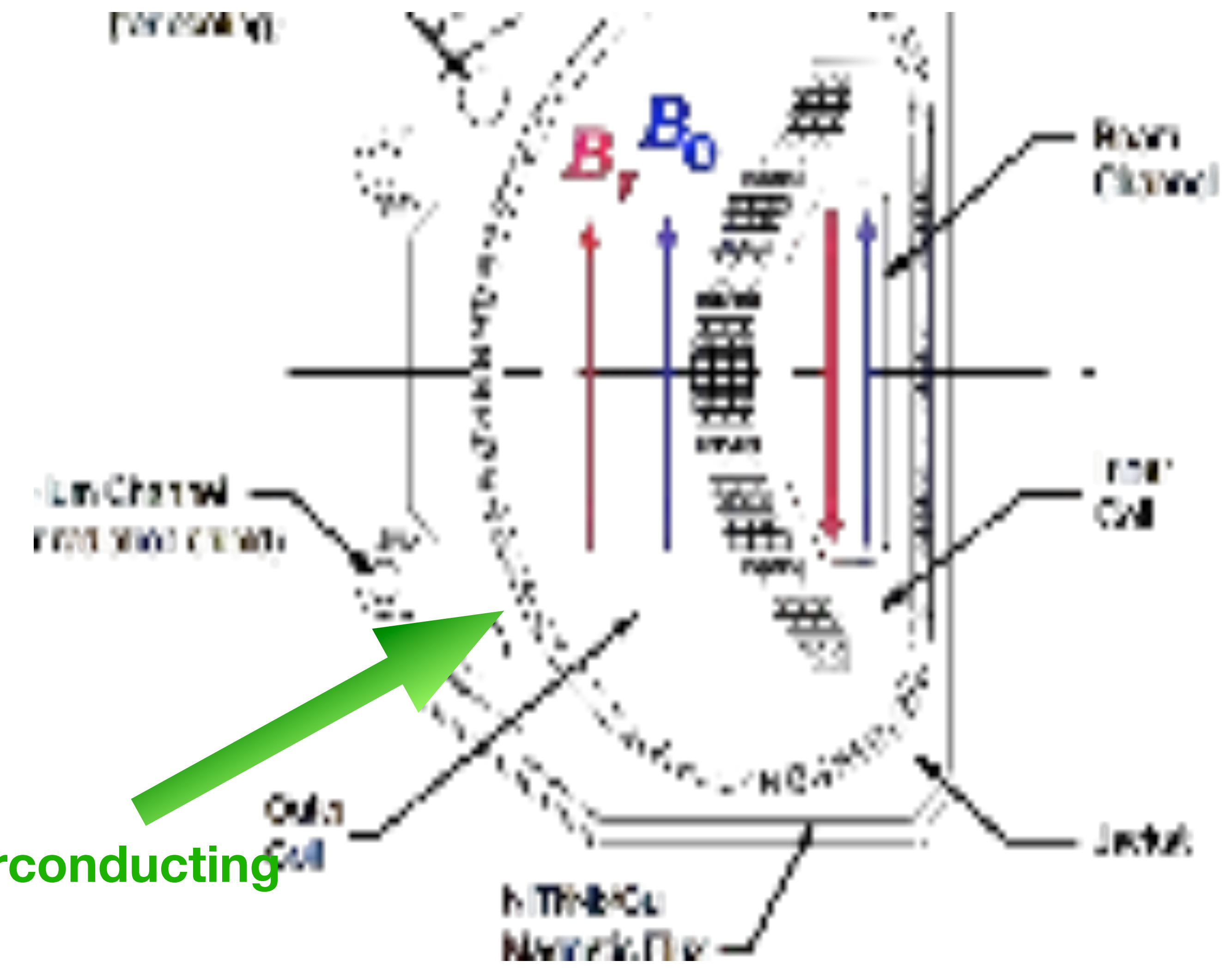


New inflector coil winding mount



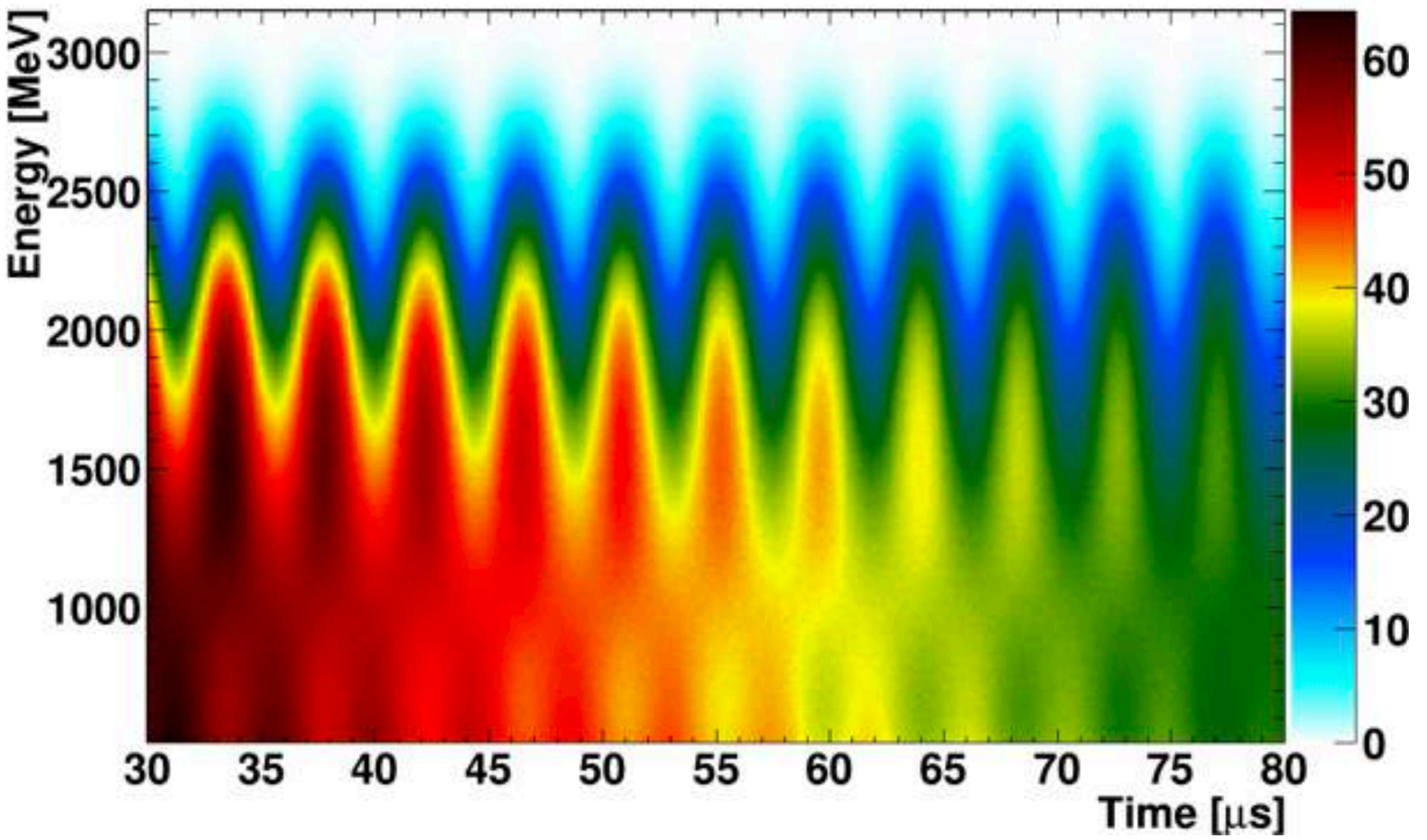
Present inflector



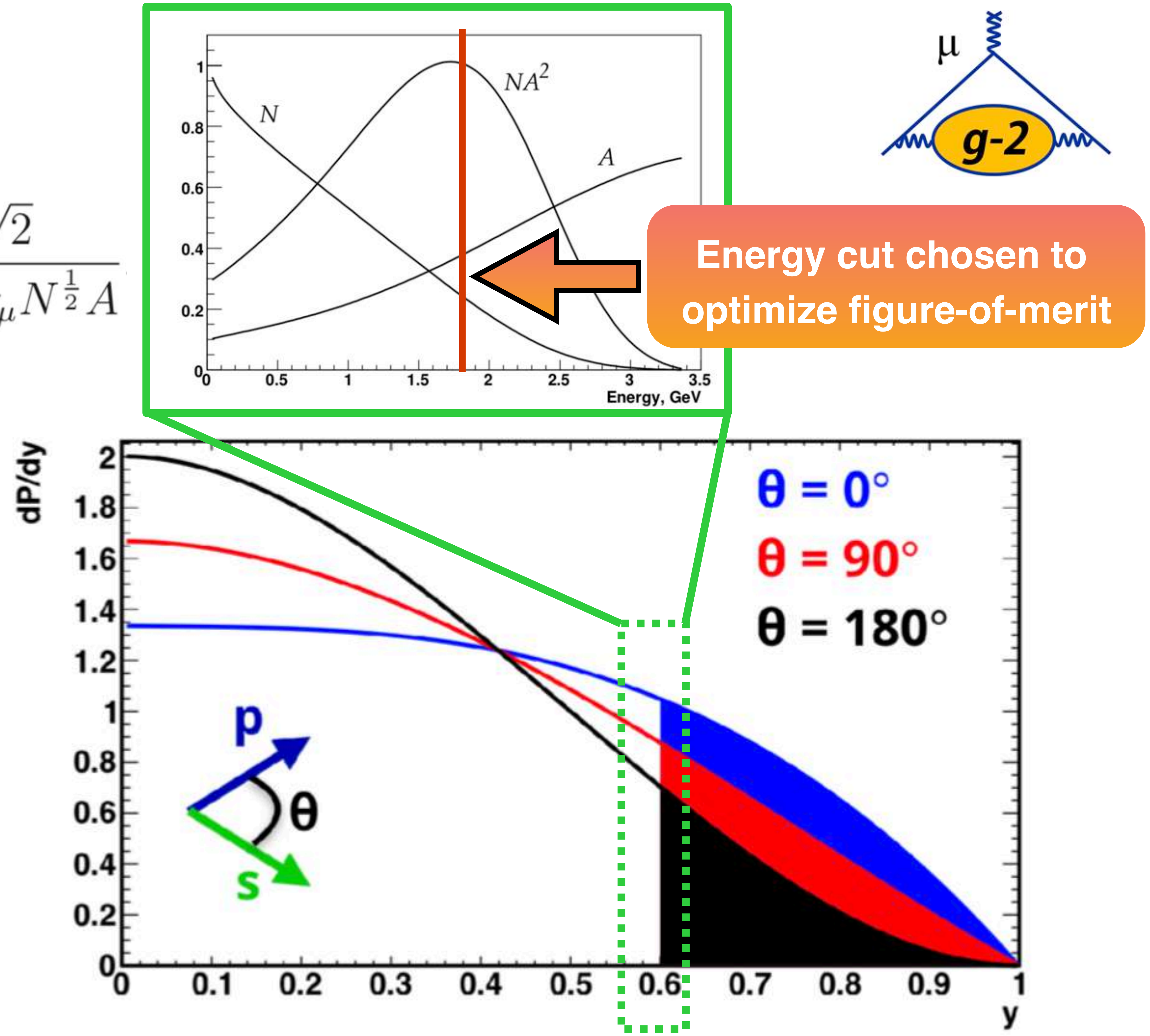


Super currents in passive superconducting shield prevents flux leakage

Run 1 Analysis Status: ω_a



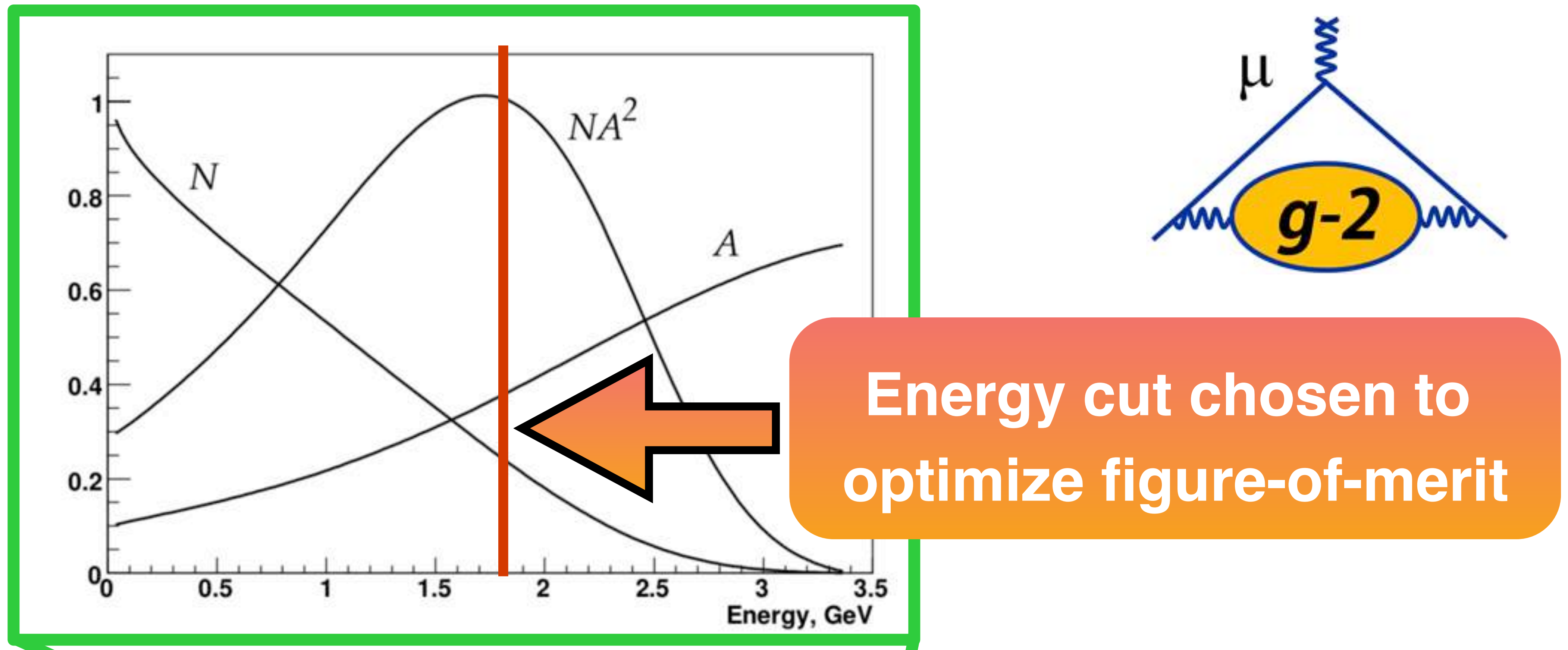
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$

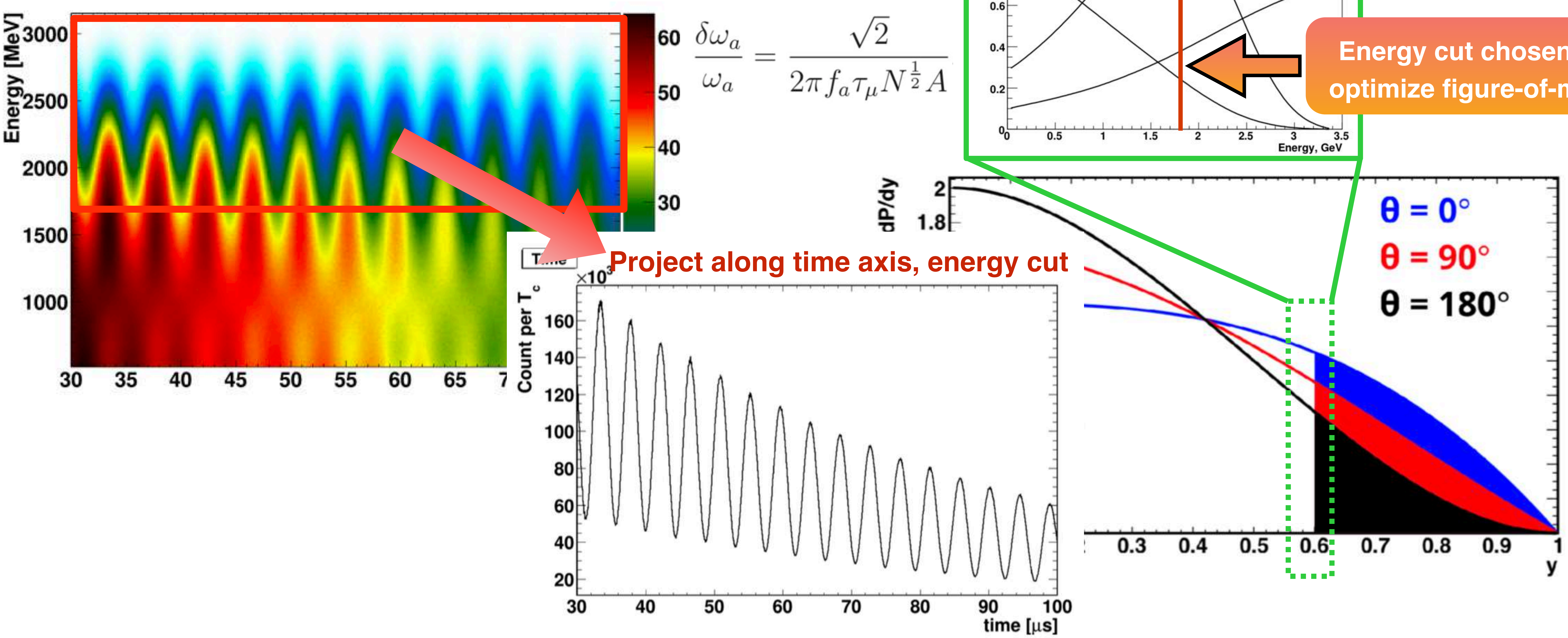


Fermilab

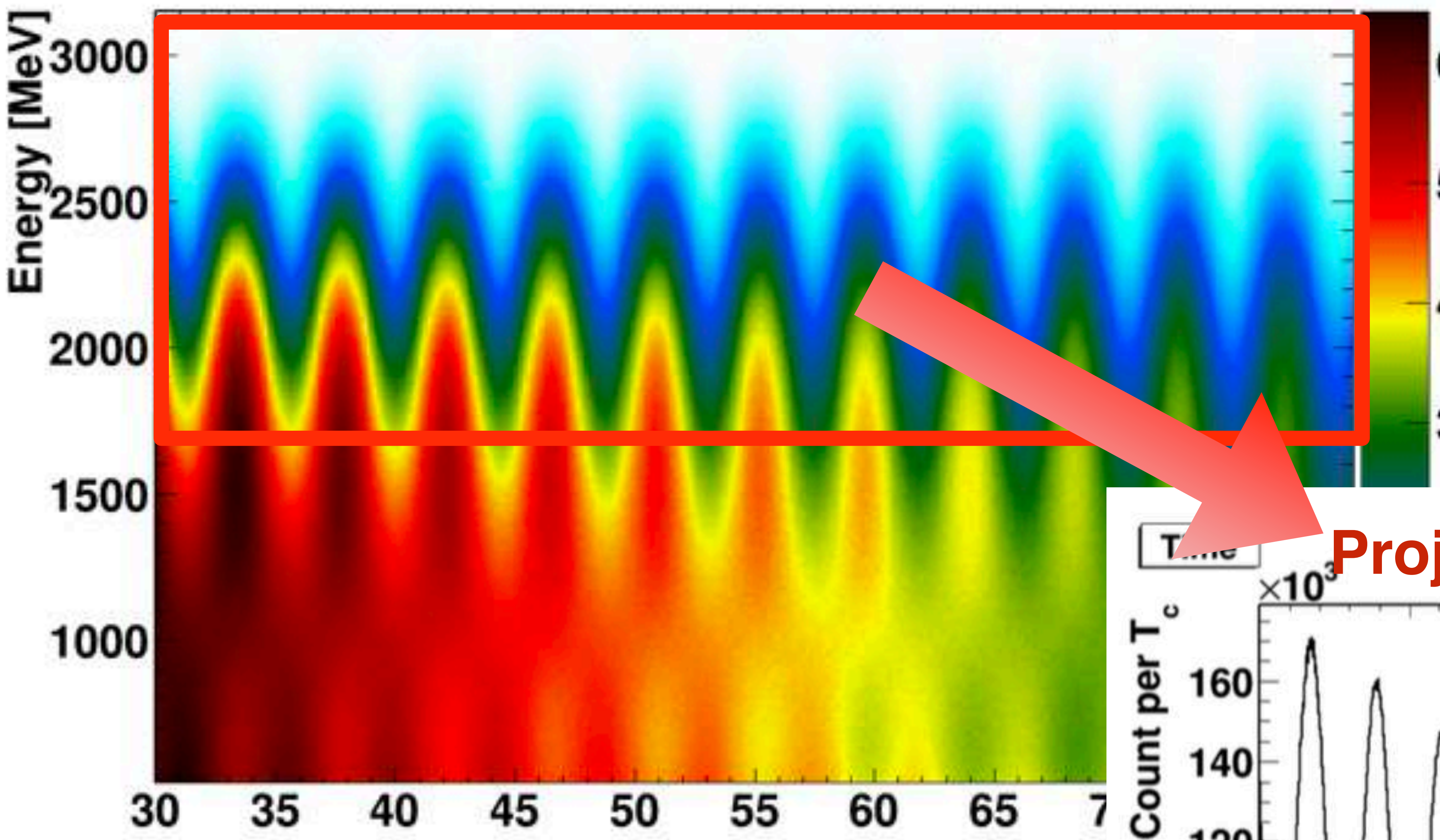
Run 1 Analysis Status: ω_a

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$

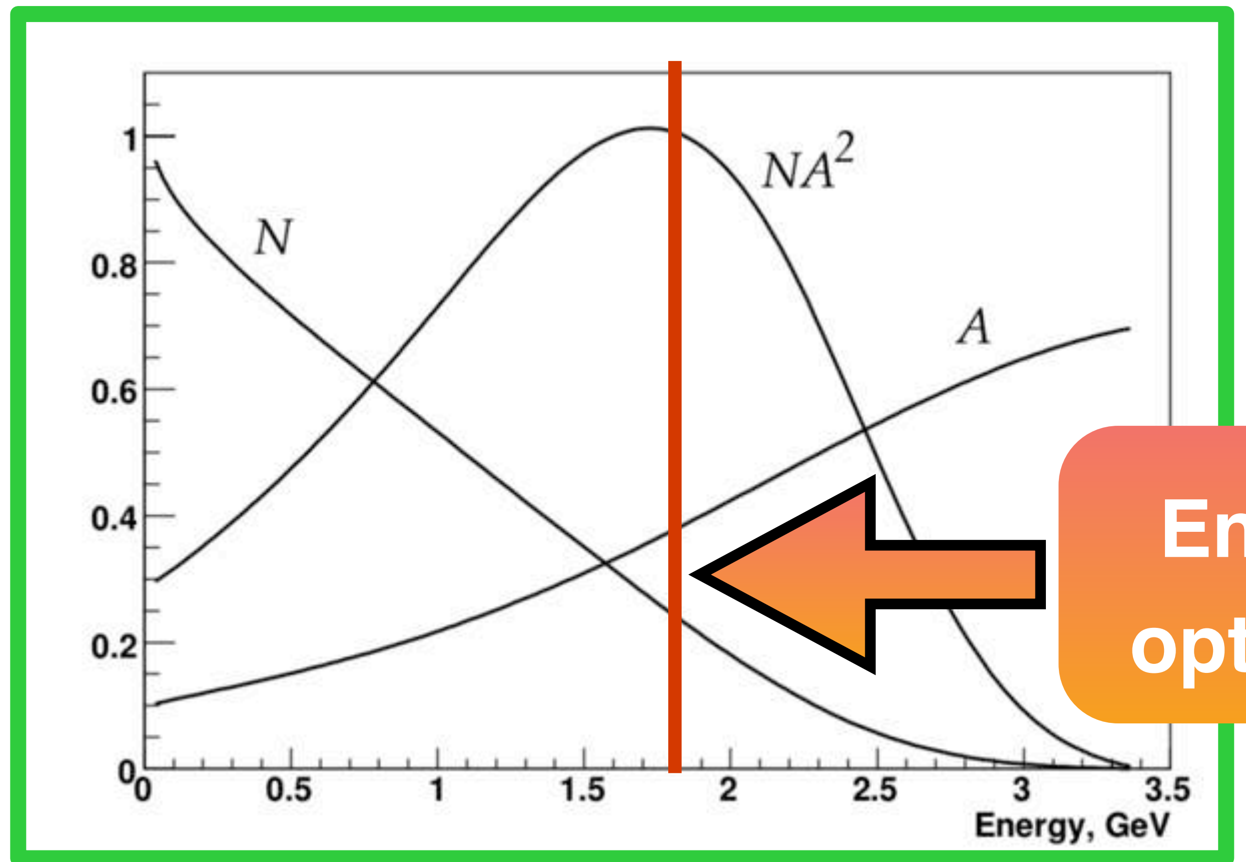




Run 1 Analysis Status: ω_a

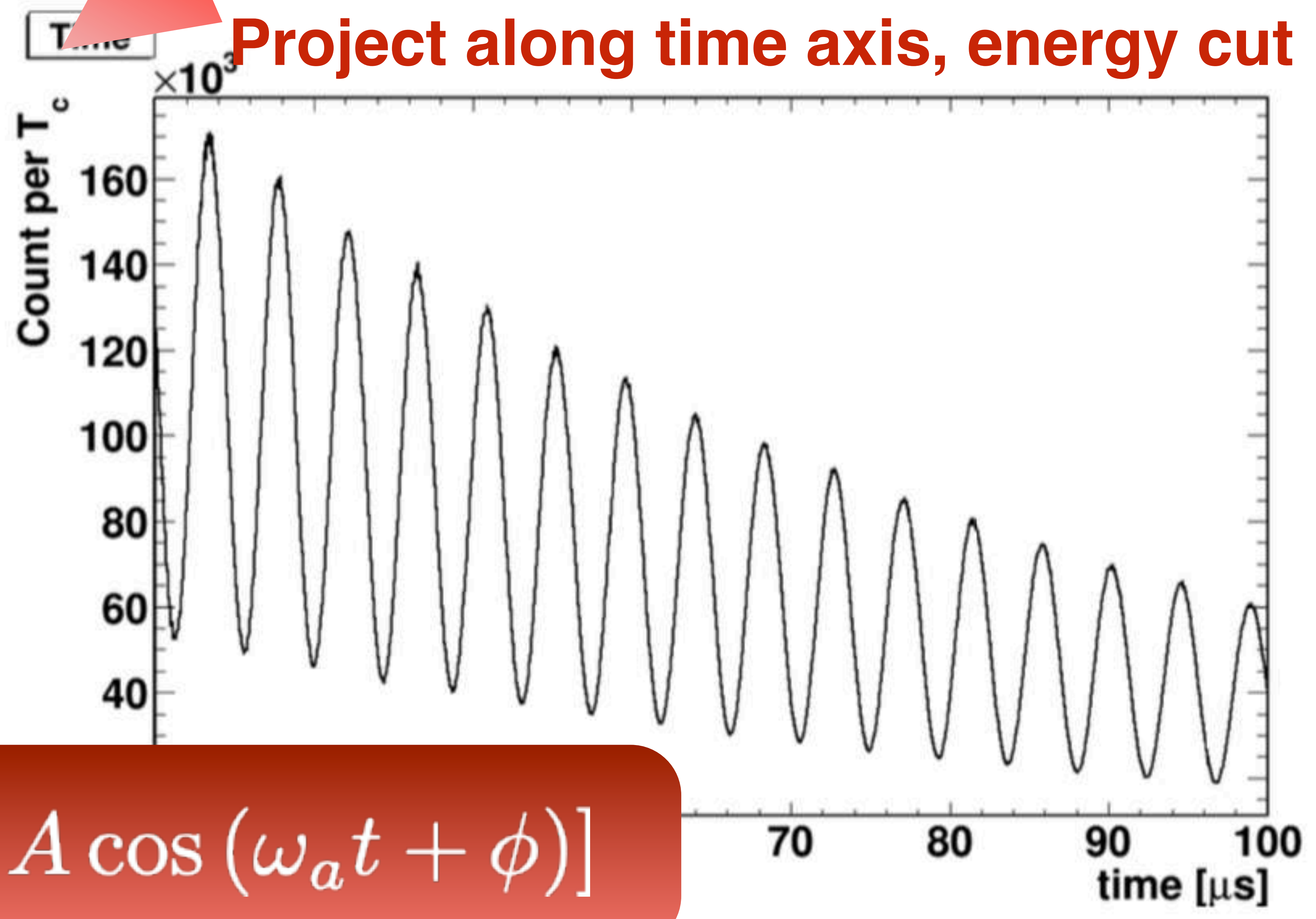


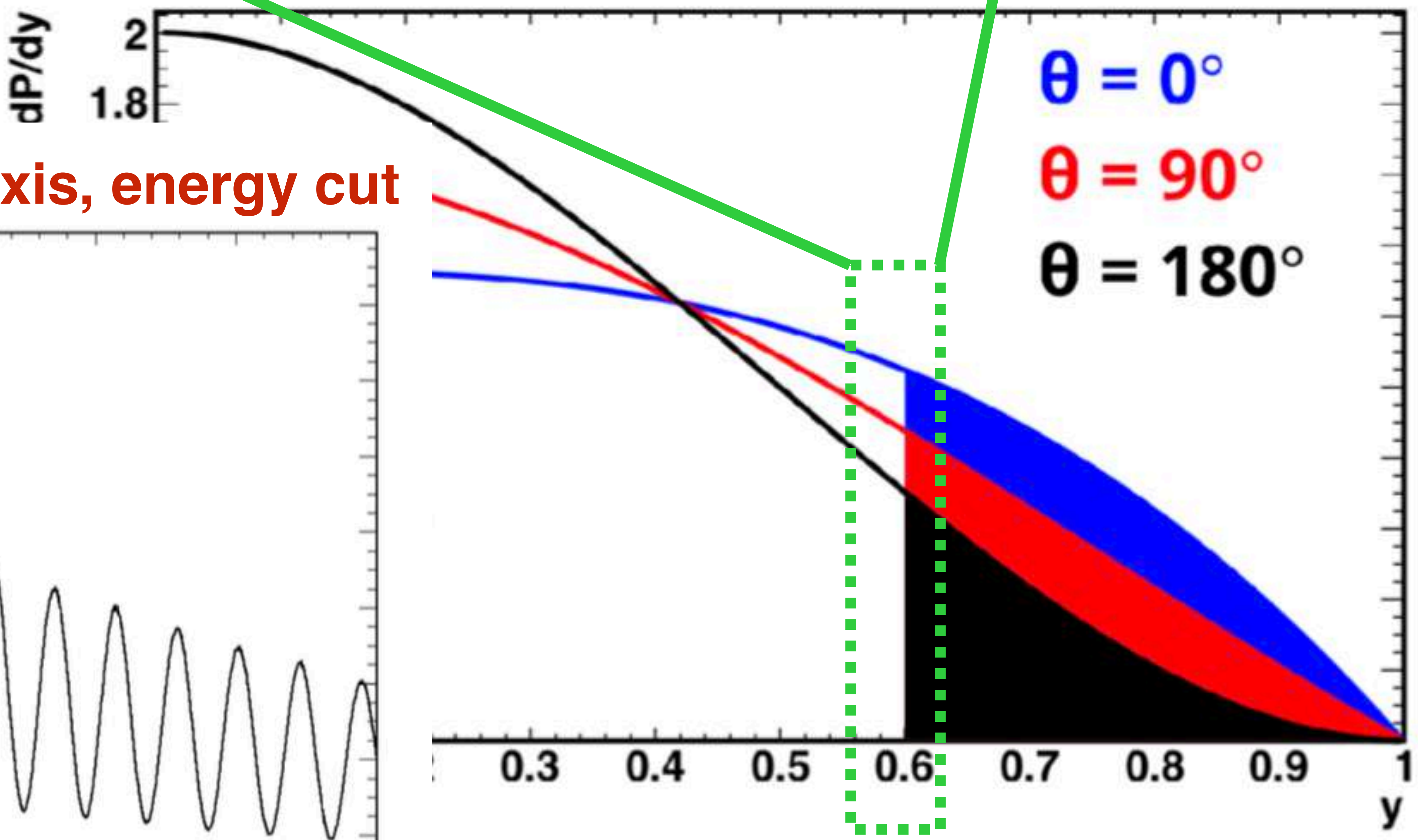
$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$



Energy cut chosen to optimize figure-of-merit

Project along time axis, energy cut



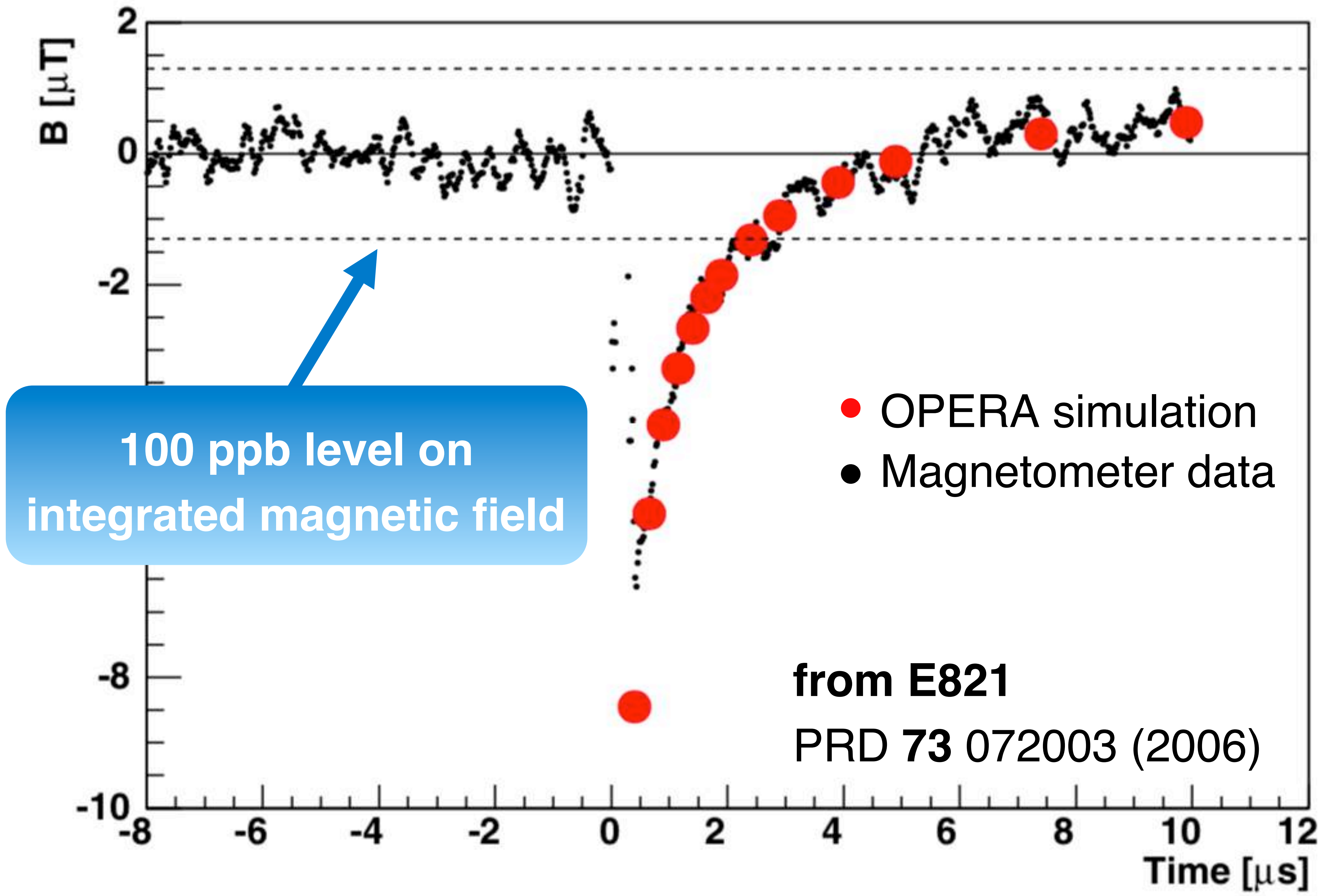


Fit to: $N(t) = N_0 e^{-t/\tau}\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$

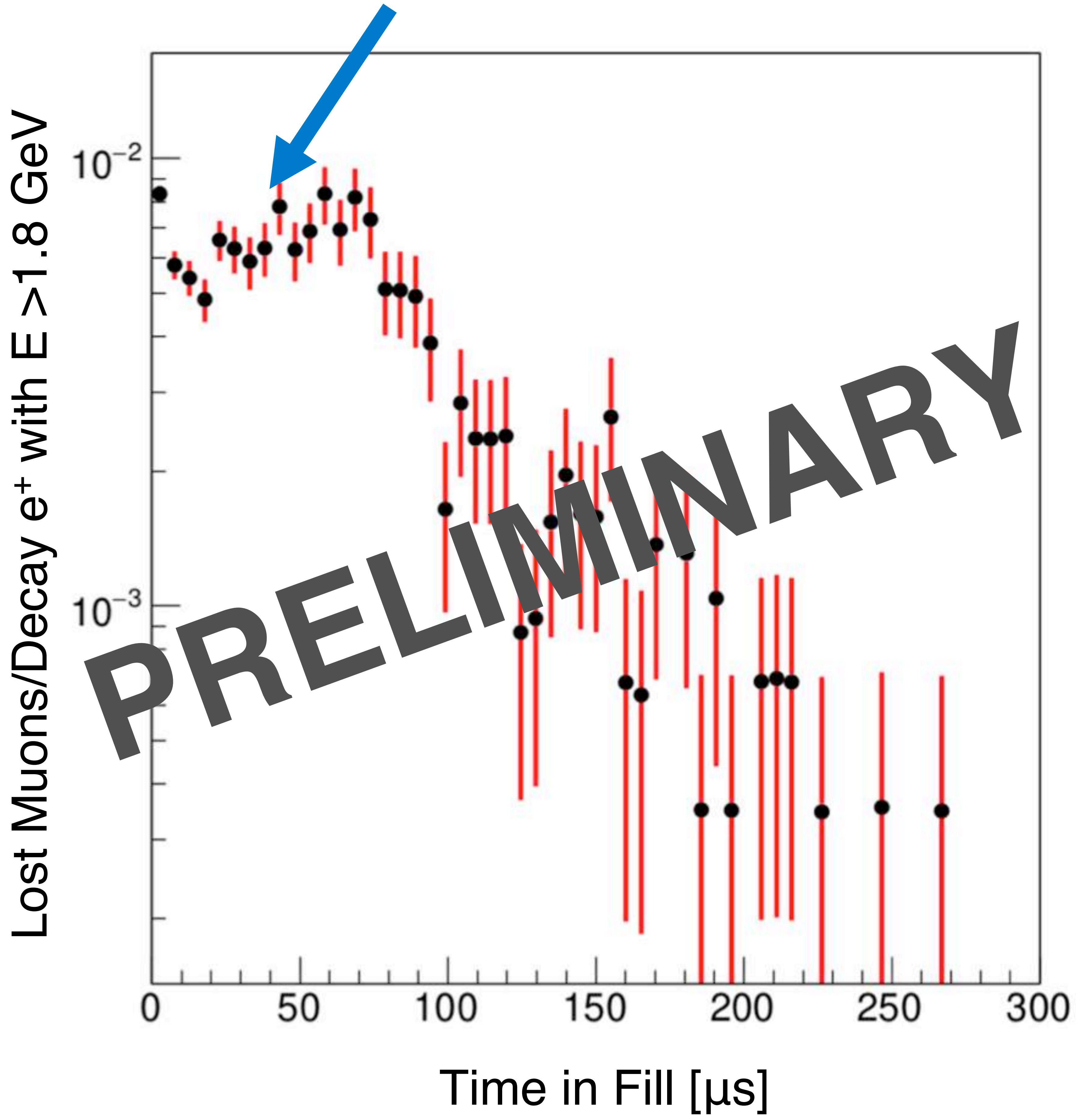
What Drives the ω_a Fit Start Time?

- Start fit window to extract ω_a at ~ 30 μs to avoid:

Kicker eddy currents affect the magnetic field



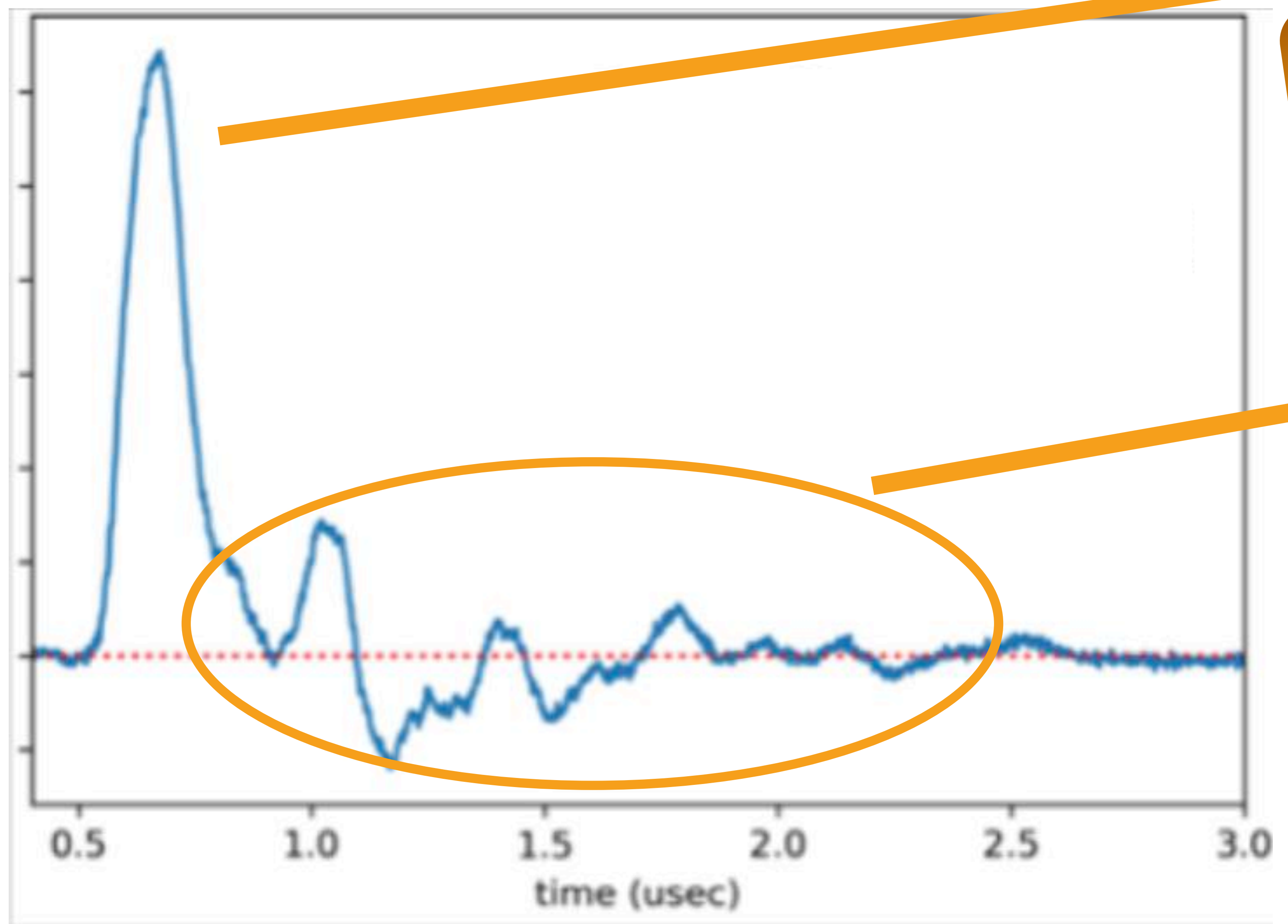
Quad scraping at early times to reduce losses



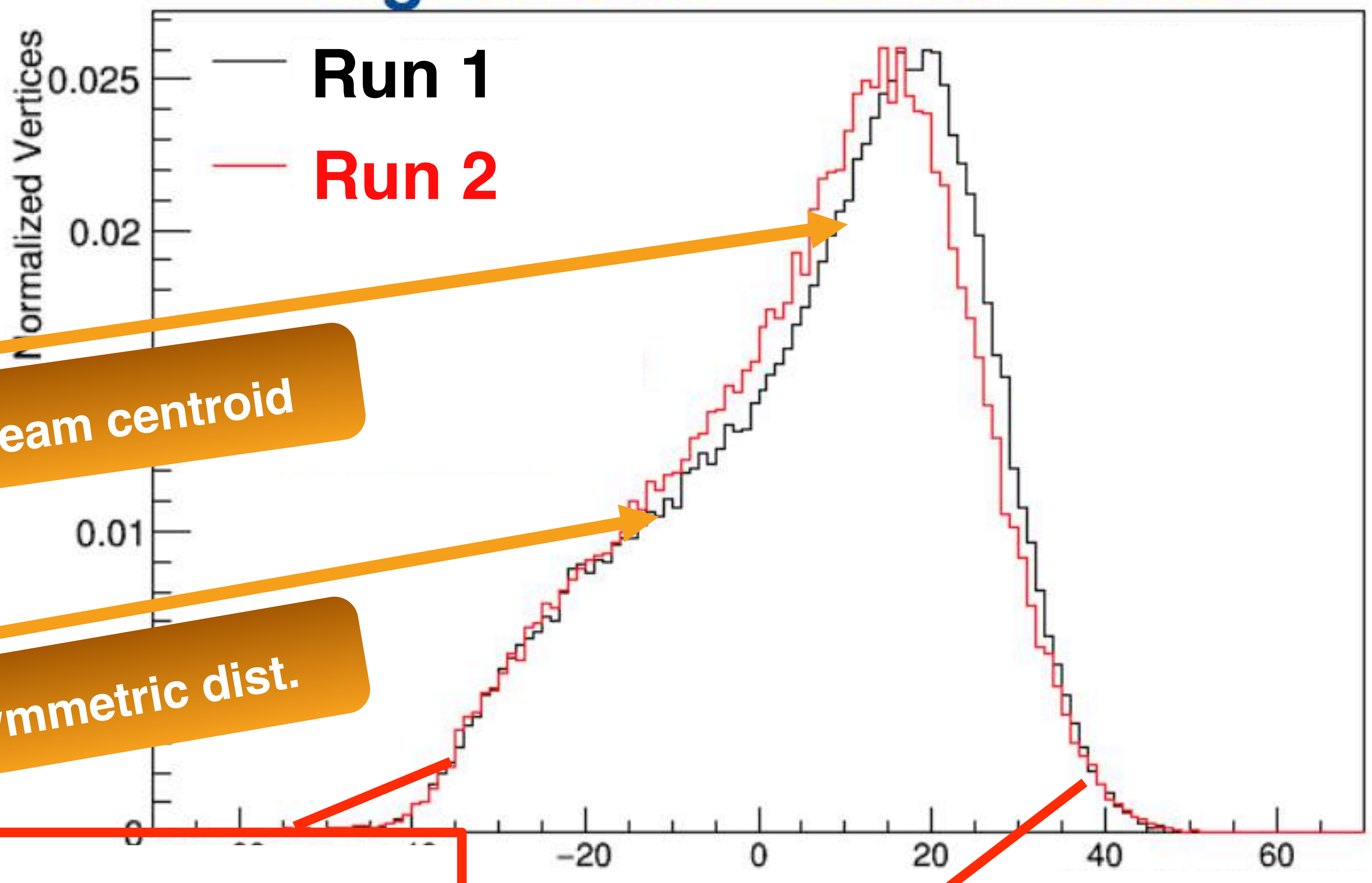
What Affects the Beam Shape?

- **Kicker pulse** strength, shape affects structure of beam
- **Beam width** affected by dynamics

Kicker Pulse



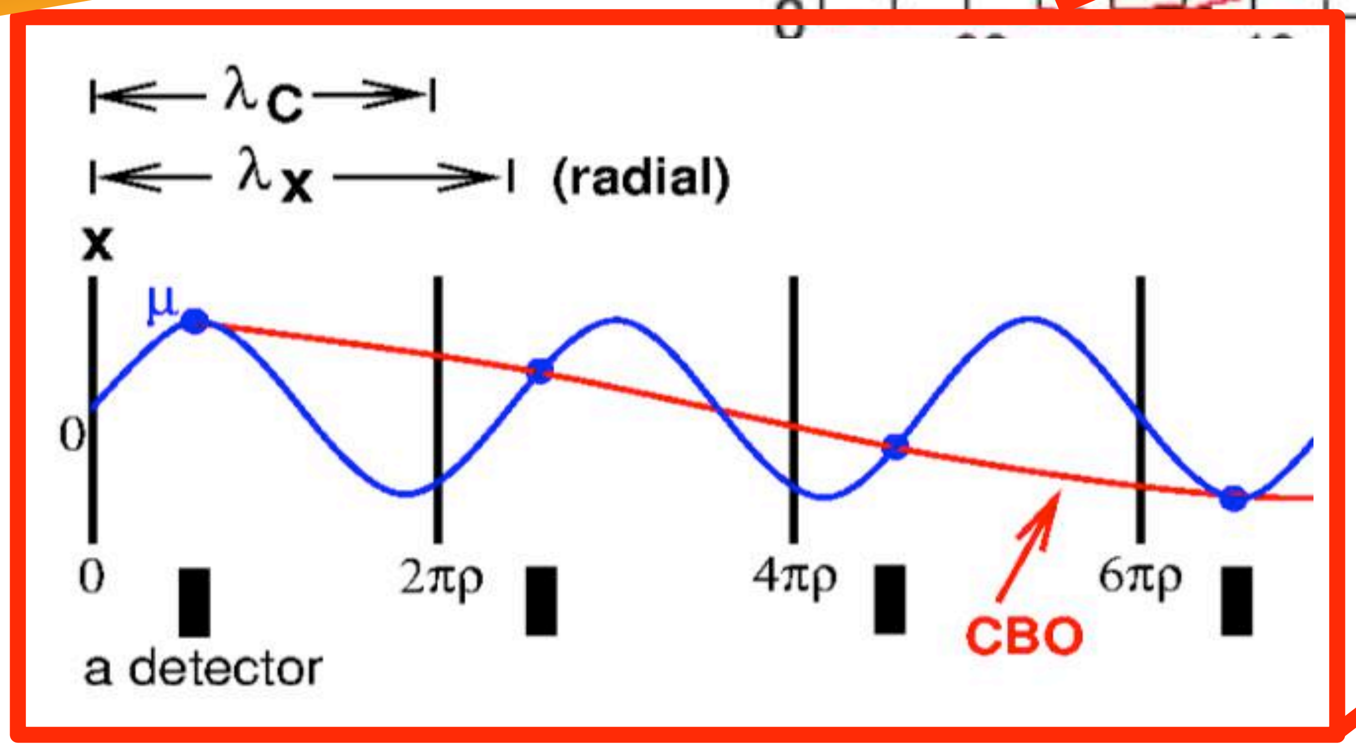
Higher kick → lower radius



Radial Beam Position [mm]

kick strength → beam centroid

ringing kick → asymmetric dist.



CBO → radial width

Beam Dynamics Corrections

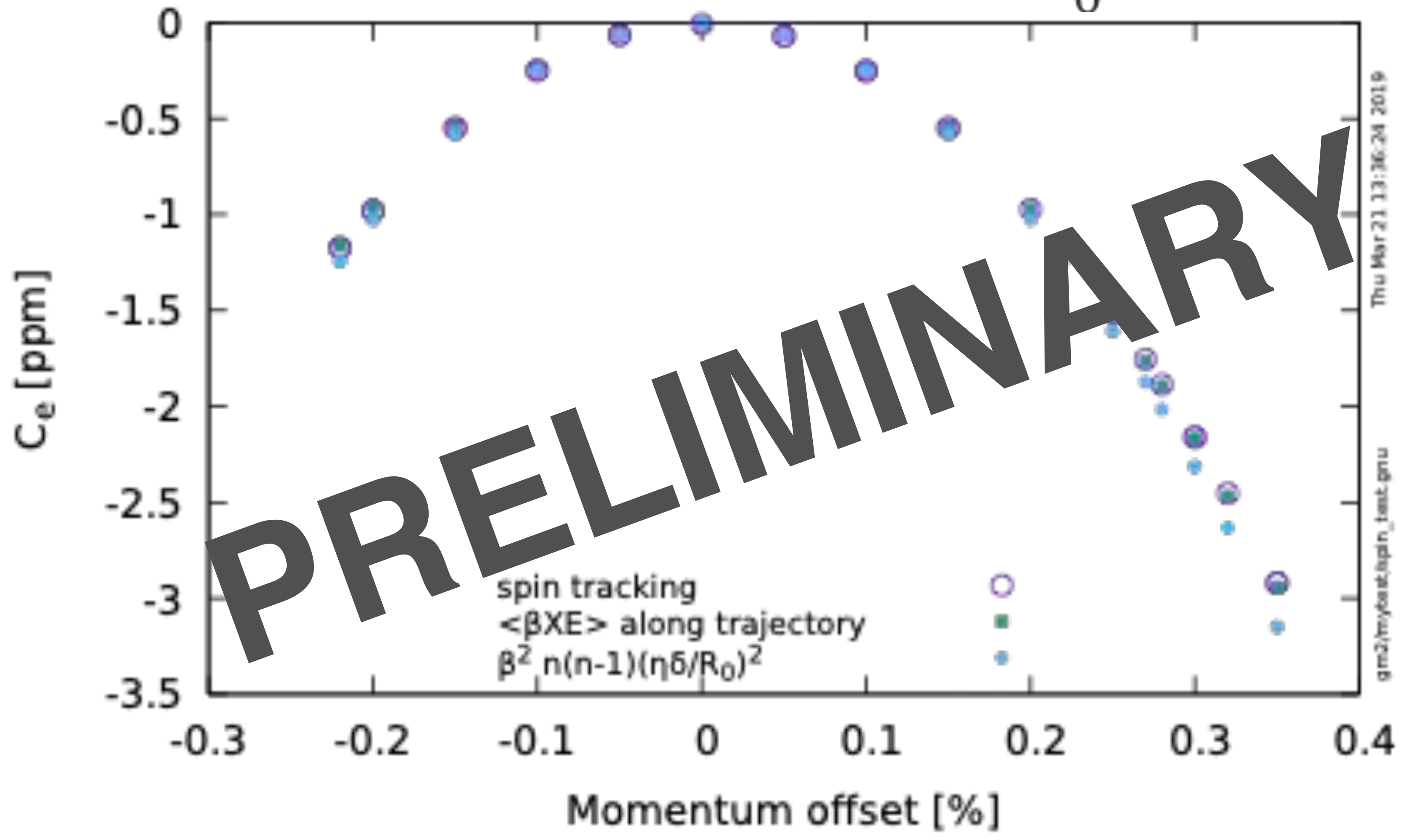
- Full expression for ω_a:

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

- Choose $\gamma = 29.3$ ($p_\mu = 3.094$ GeV/c)

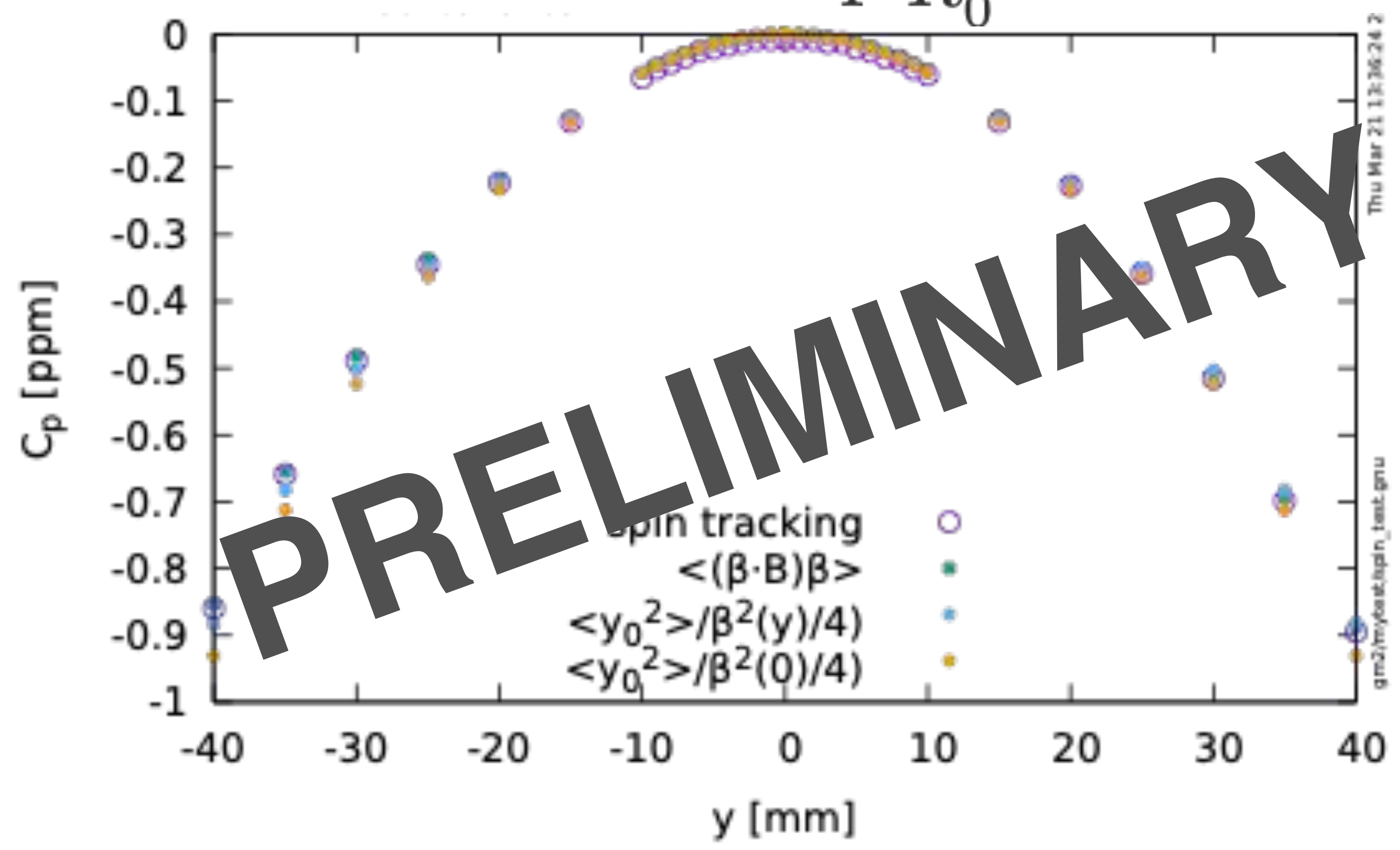
Not all μ^+ at this γ → **E-field correction**

$$C_E = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

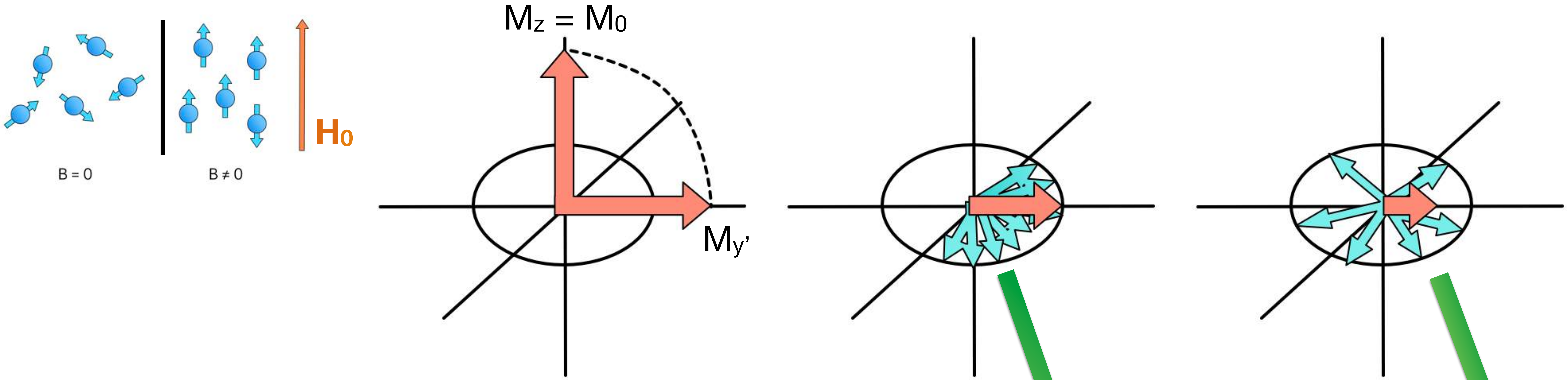


Vertical beam oscillations → **pitch correction**

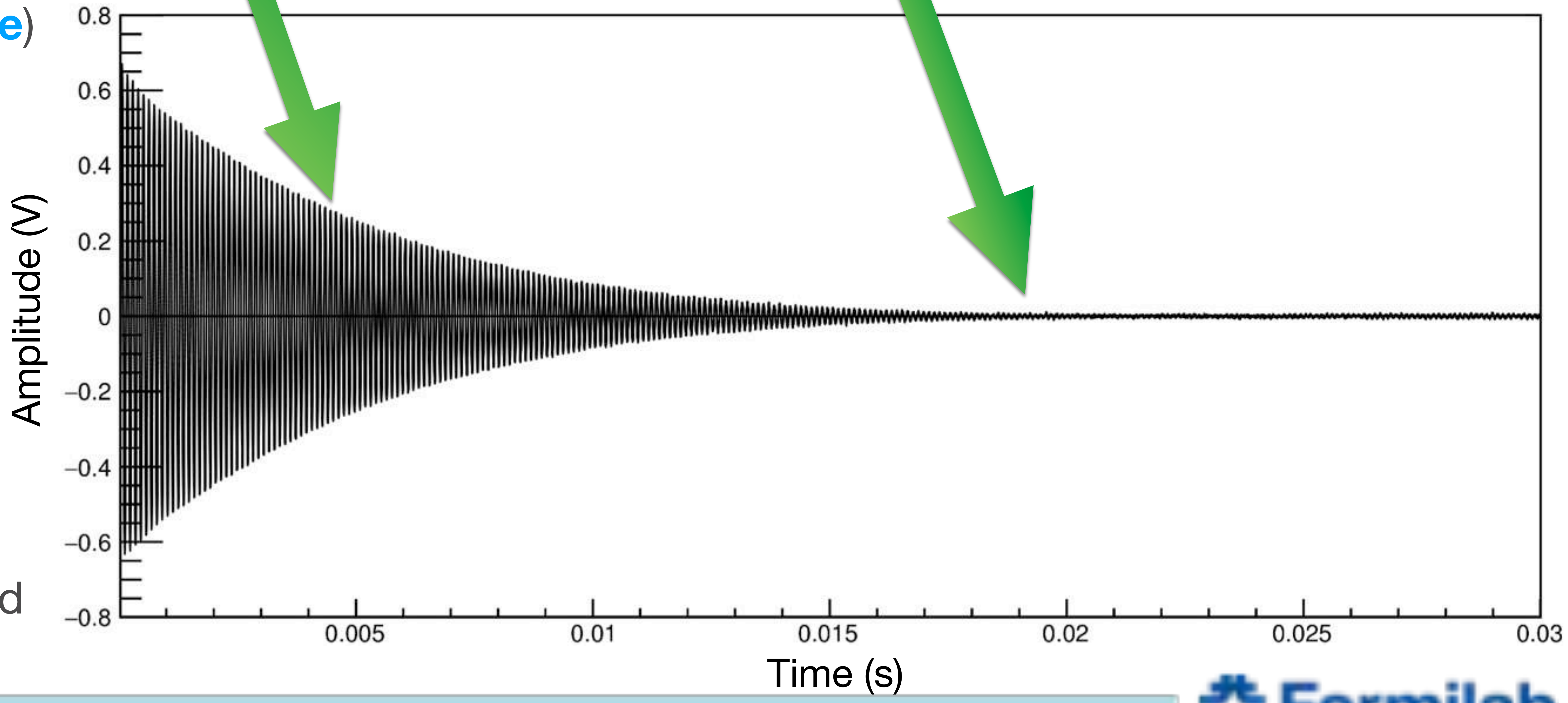
$$C_p = -\frac{n}{4}\frac{\langle y^2\rangle}{R_0^2}$$



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)



Magnetic Circuits

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

Can write a similar equation for magnets

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

Magnetomotive Force (mmf)

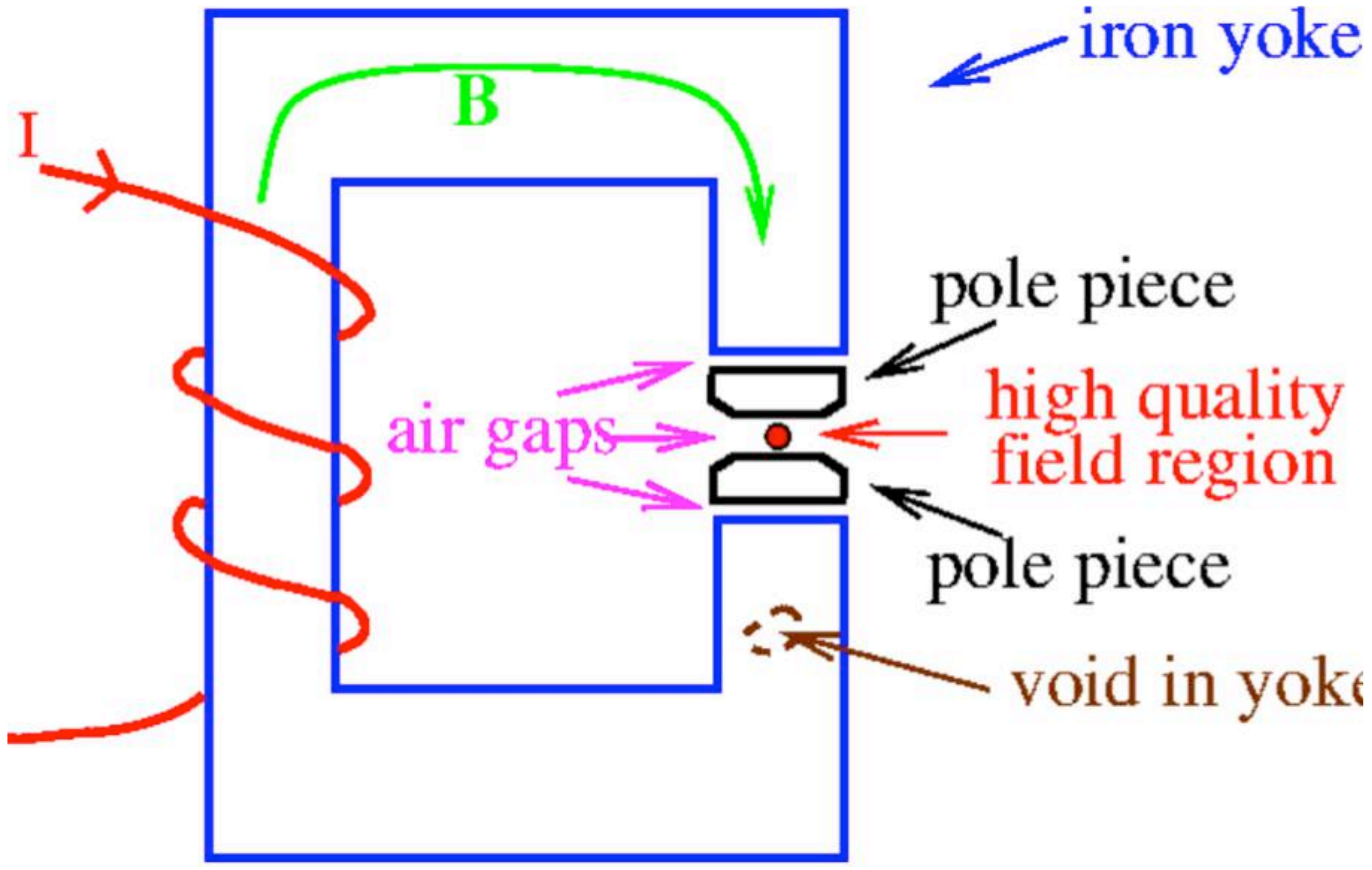
$$\vec{B} = \mu_0 (1 + \chi_m) \vec{H} = \mu \vec{H}$$

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

- Analogous to resistance in an electrical circuit $\boxed{V = IR \Leftrightarrow \mathcal{F} = \Phi \mathcal{R}}$
- 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)

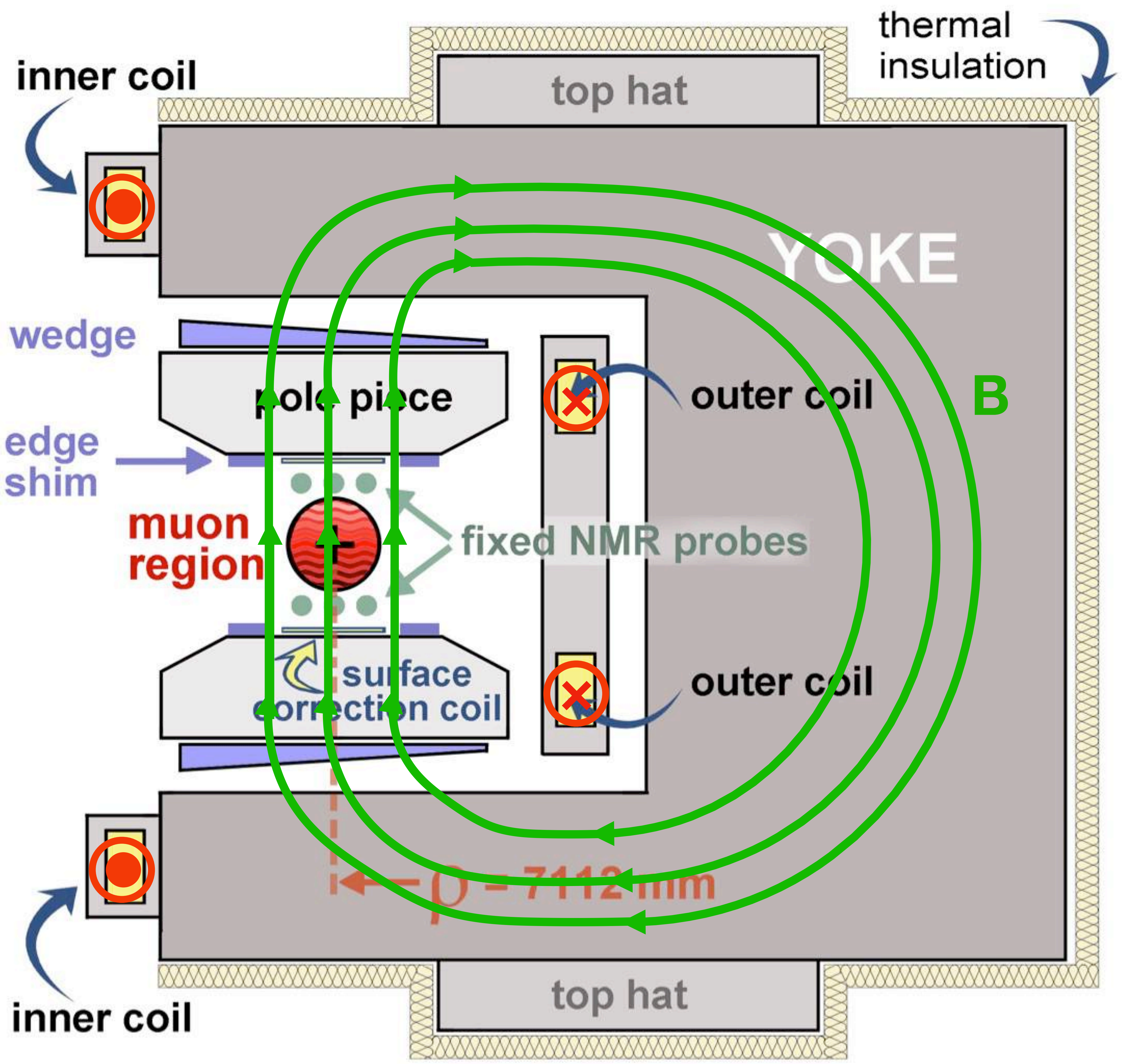
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

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

Shimming knobs

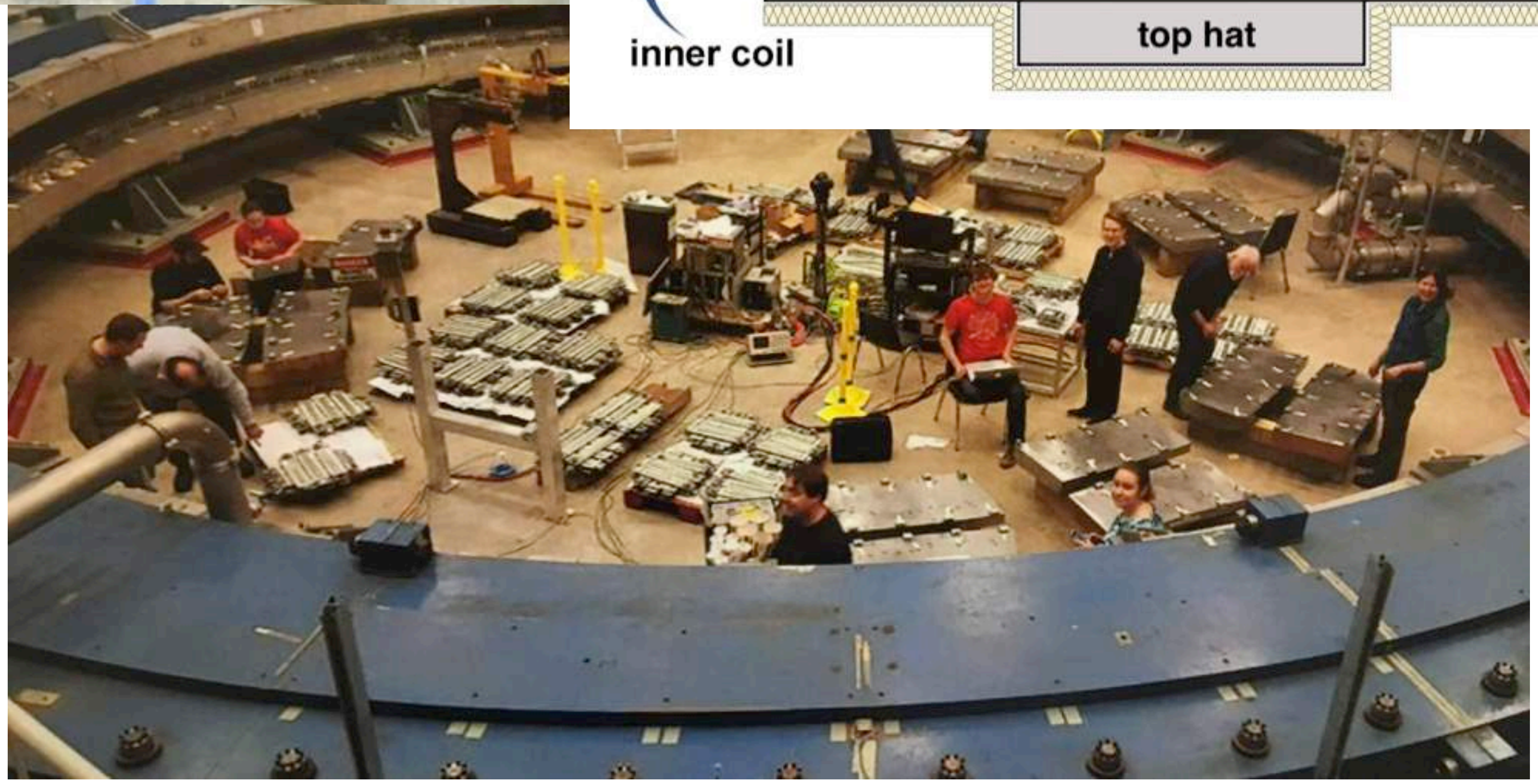
- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (30 deg effect, dipole)
- Wedges (10 deg effect, dipole, quadrupole)
- Edge shims (10 deg effect, dipole, quadrupole, sextupole)
- Laminations (1 deg effect, dipole, quadrupole, sextupole)
- Surface coils (360 deg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

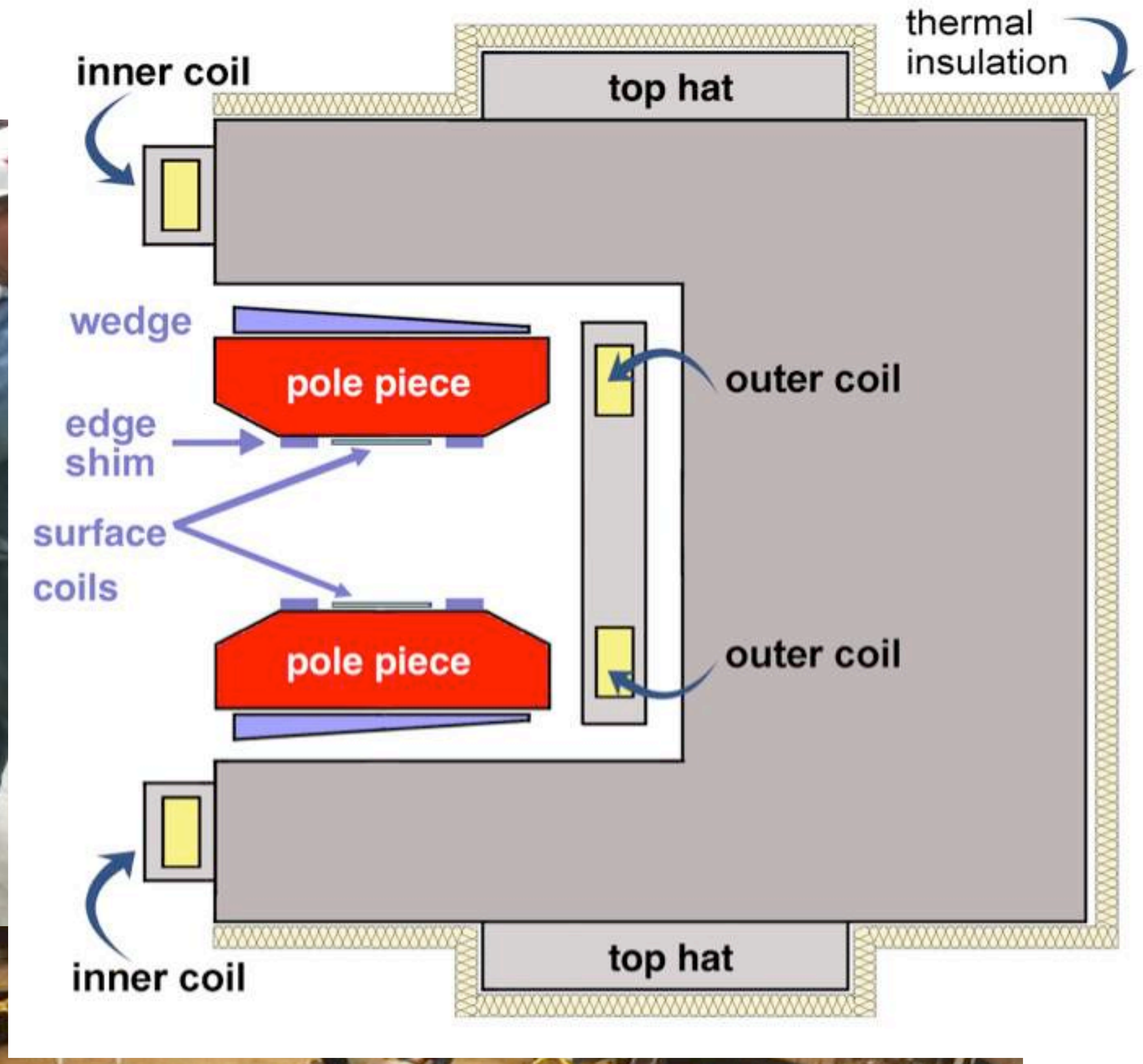


Current direction indicated by red markers

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

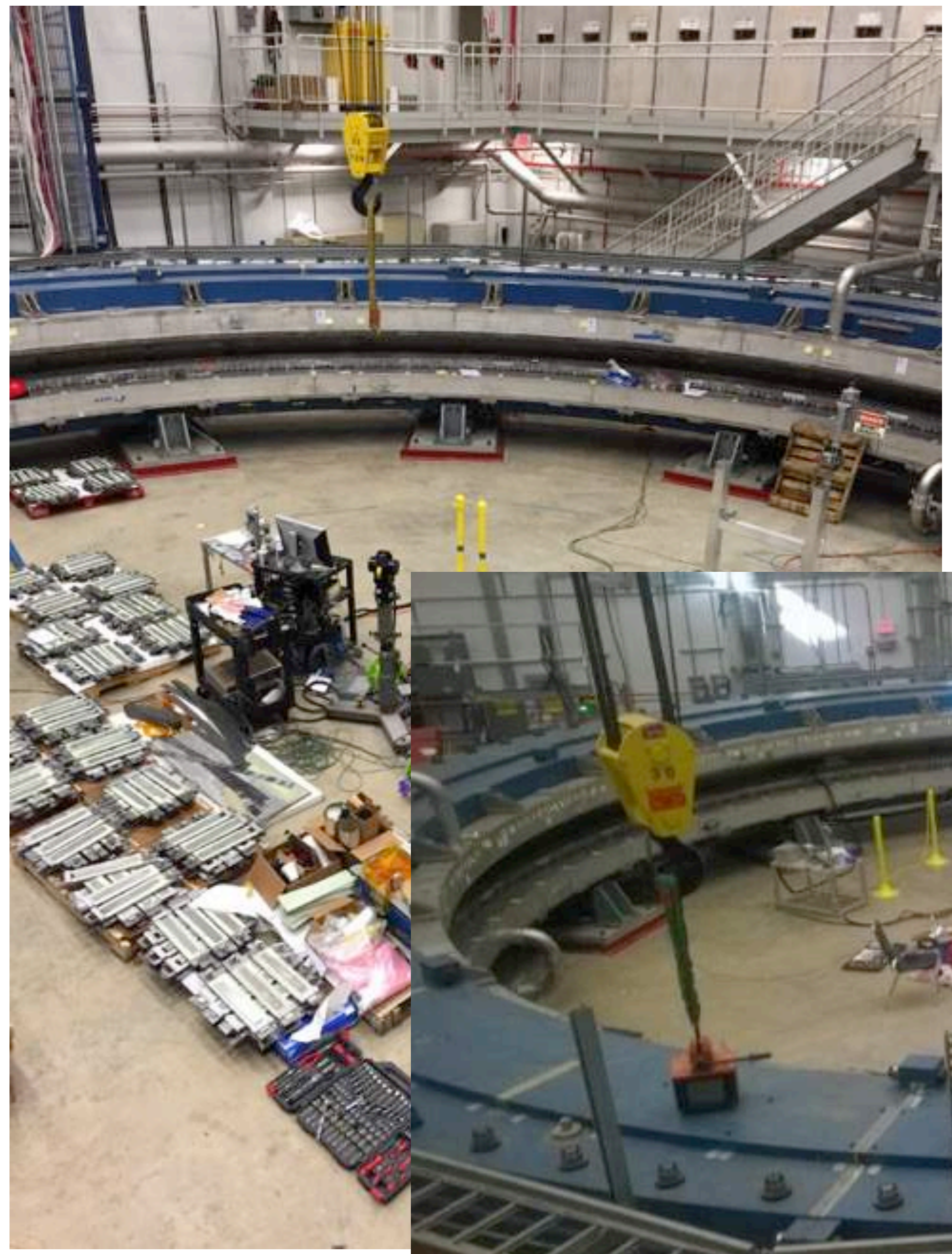
- 48 top hats
- 864 wedges
- ~8400 iron foils (on pole surfaces)

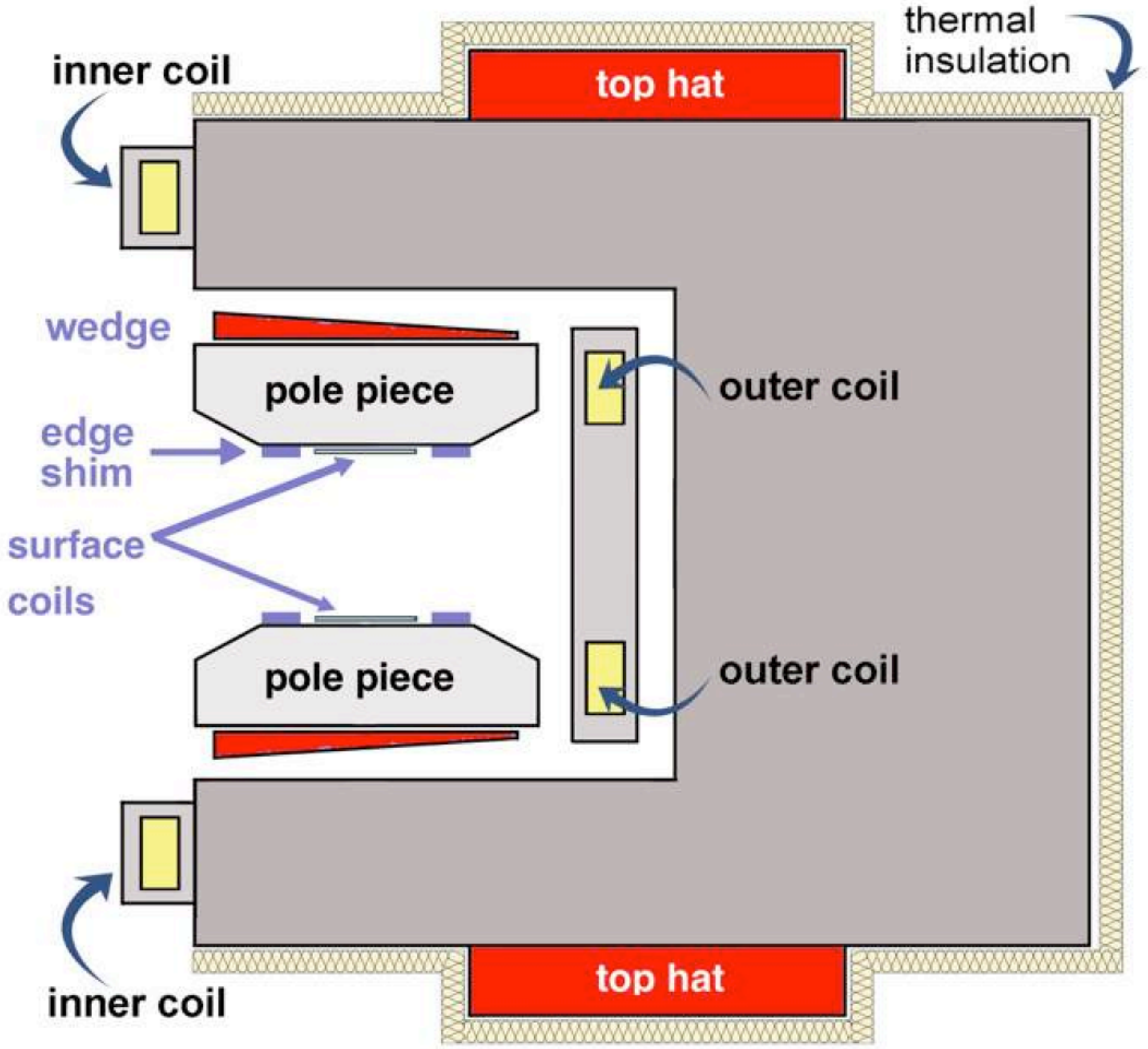
Coarse tuning: top hat & wedge adjustments (**dipole, quadrupole**)

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

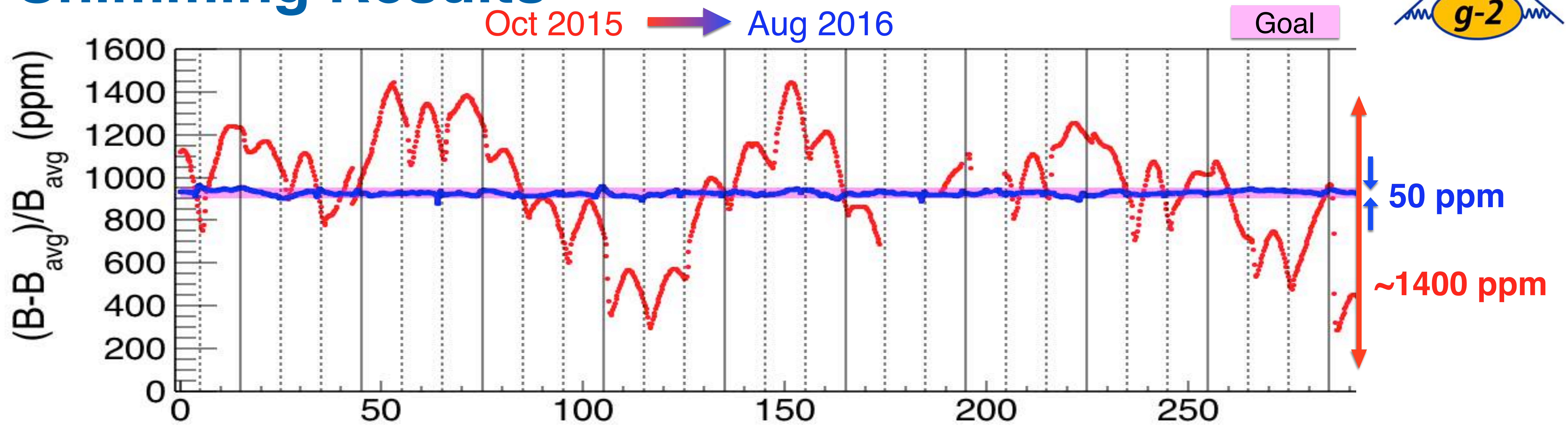
Fine tuning: iron foils (**quadrupole, sextupole,…**)

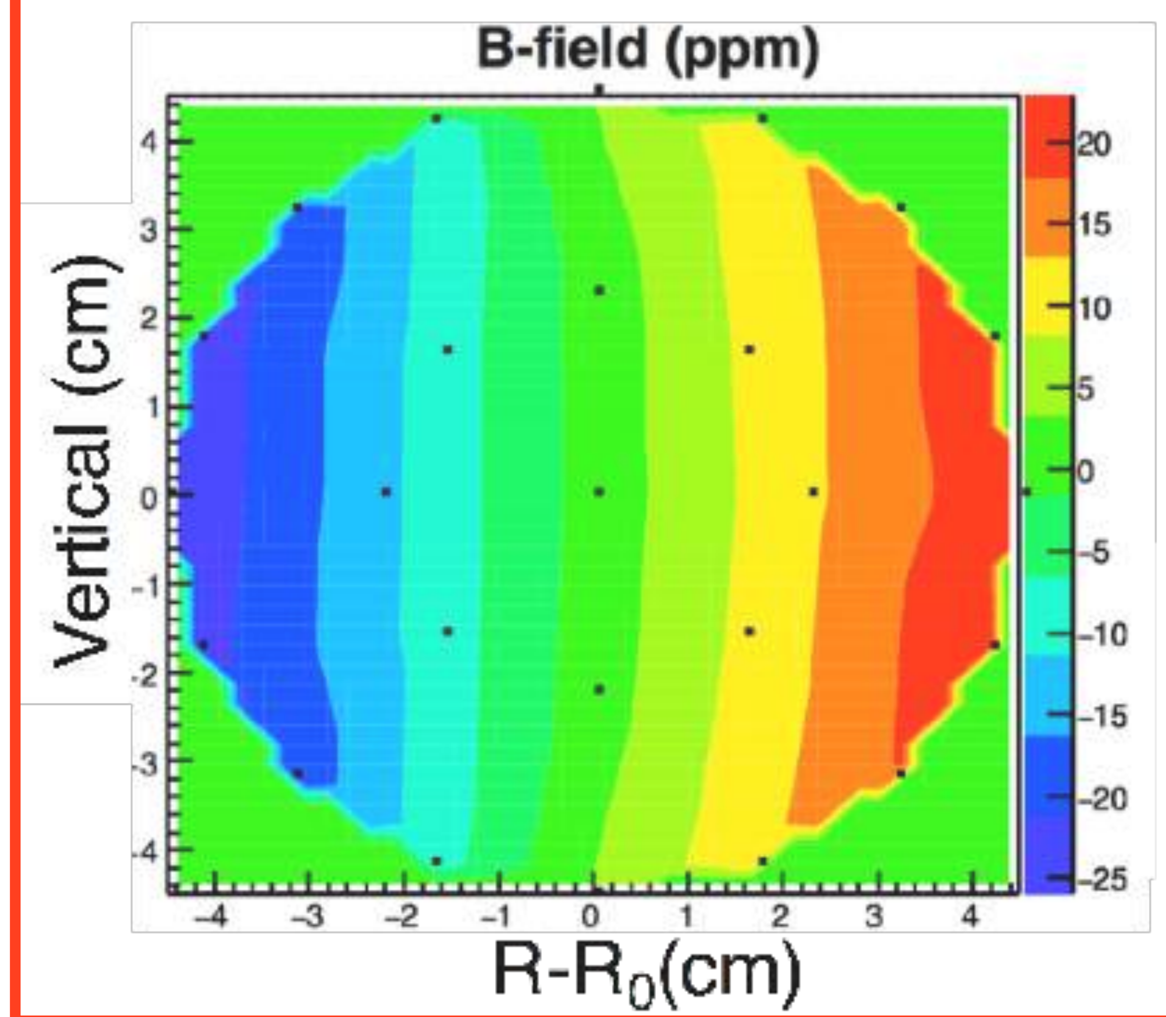
- Modeled as saturated dipoles in 1.45 T field
- Computer code predicts foil width (mass) distribution to fill in the valleys of the field map





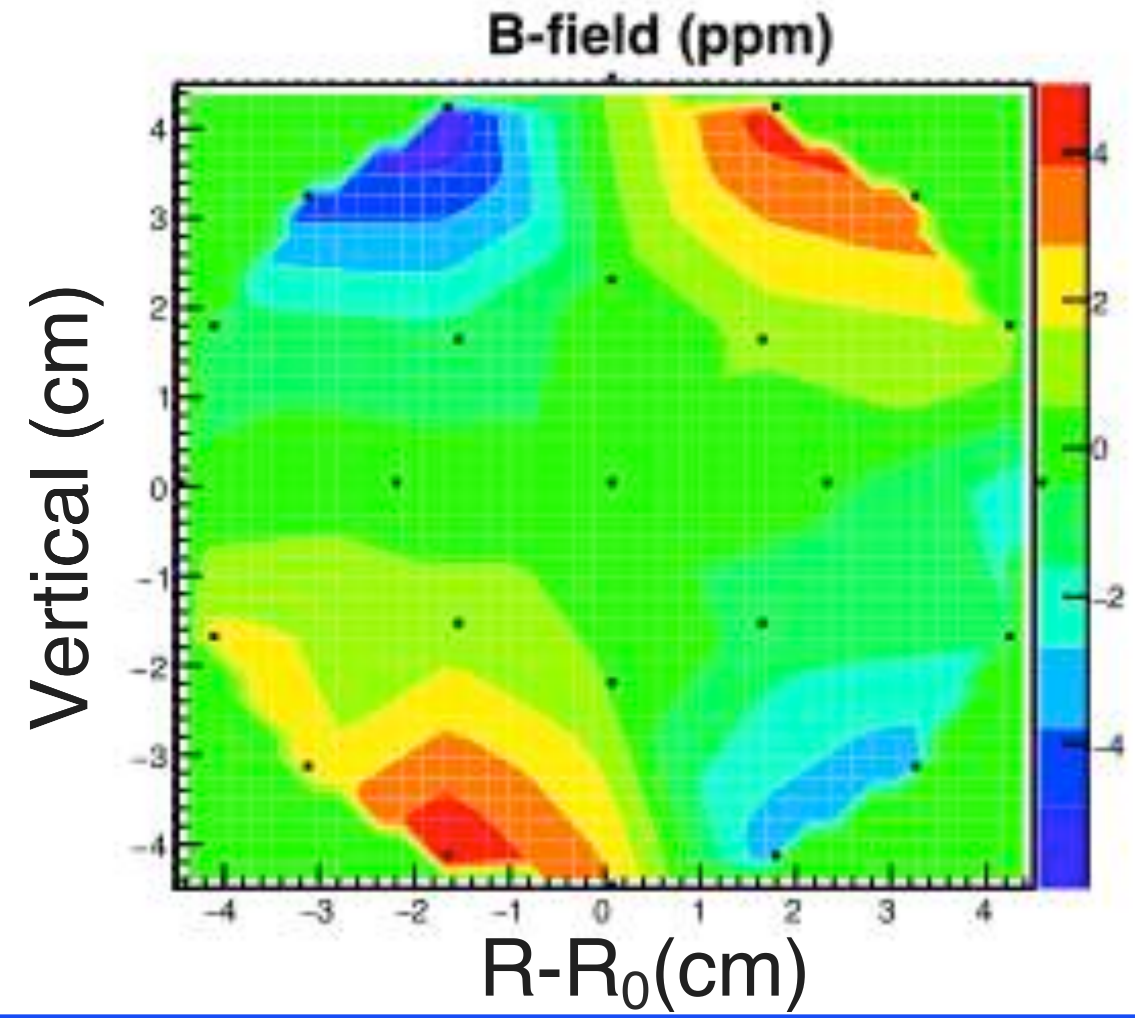
Rough Shimming Results





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

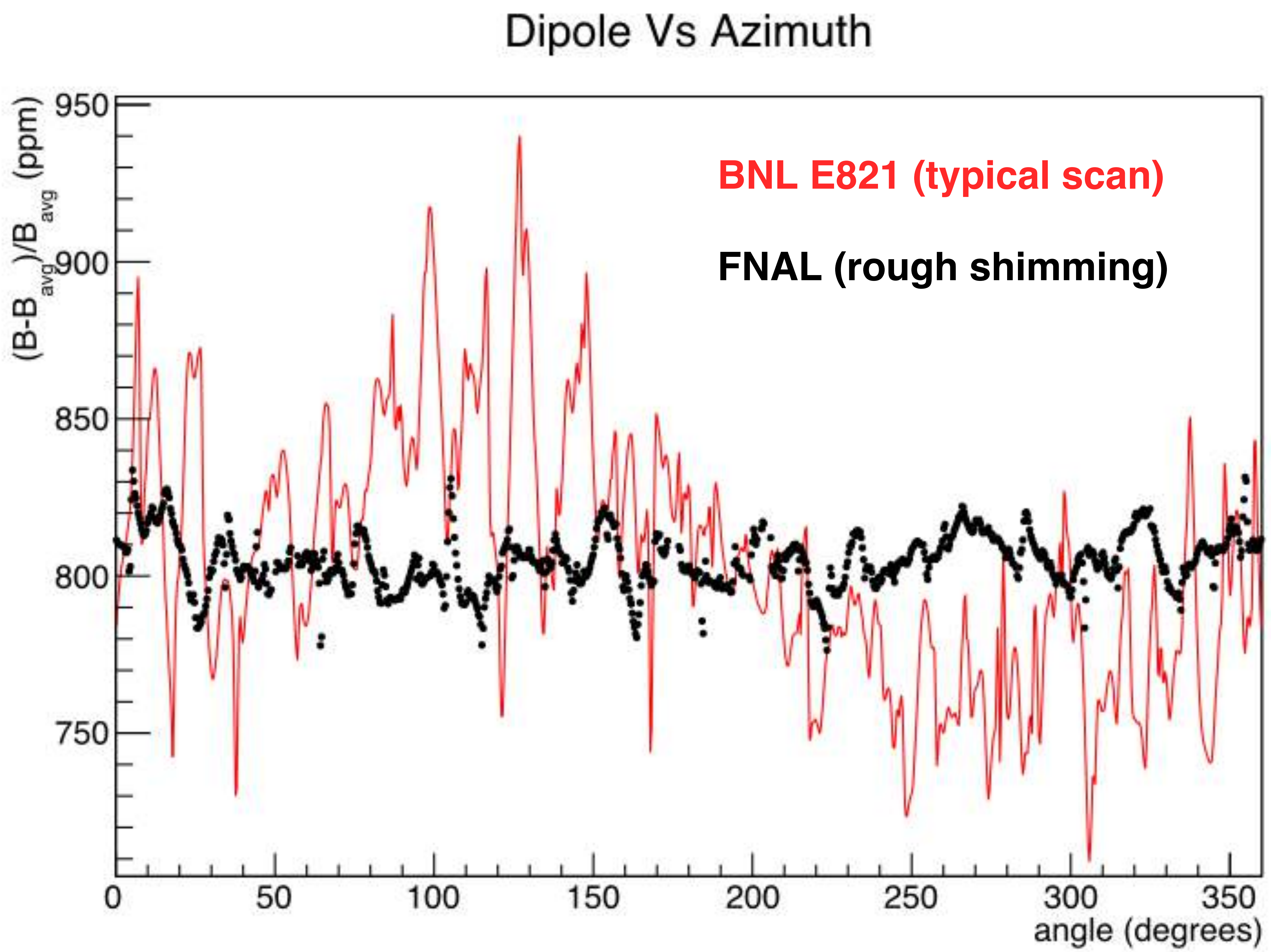
Oct 2015



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

Aug 2016

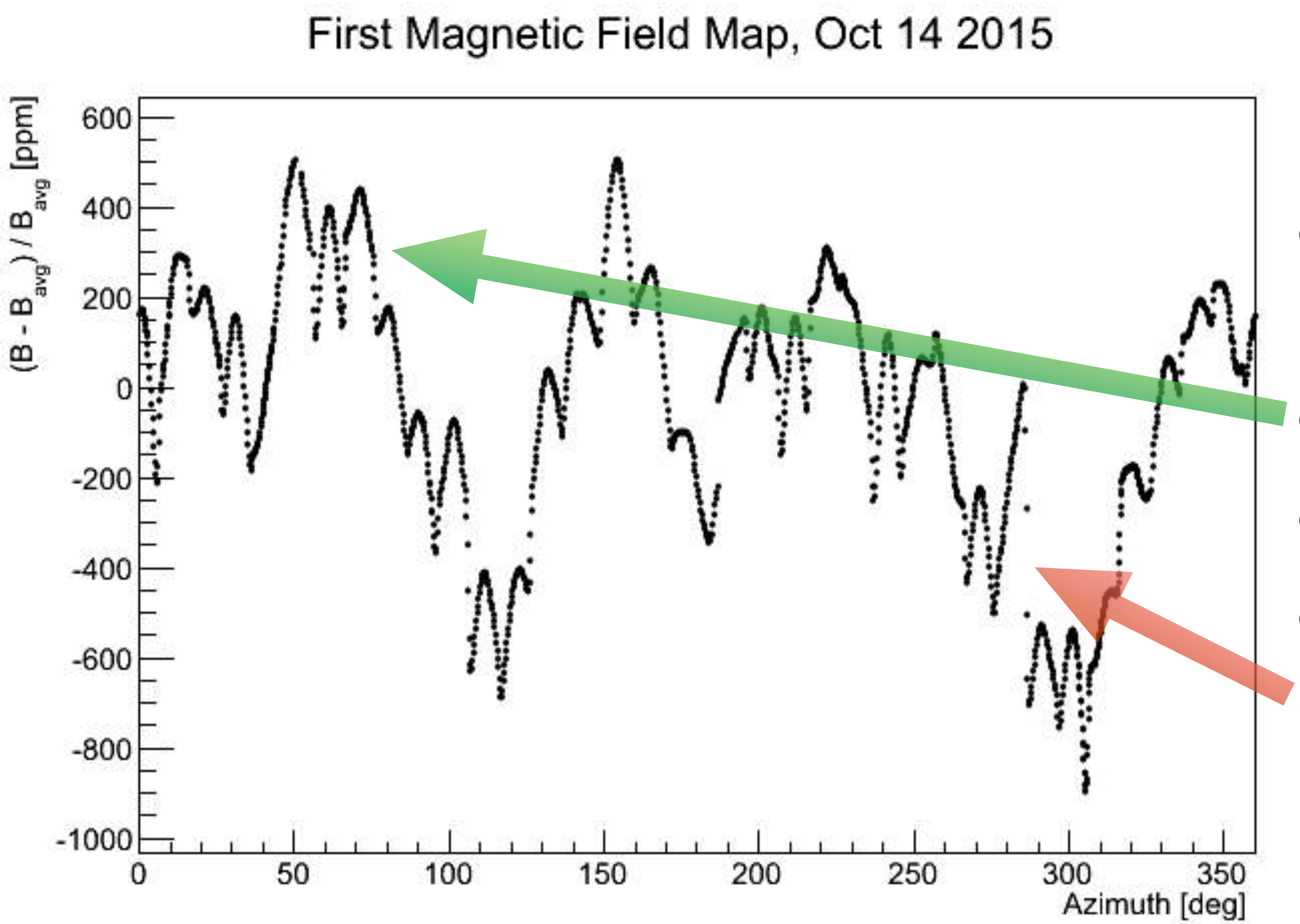
Magnetic Field Comparison: BNL 821 and FNAL E989



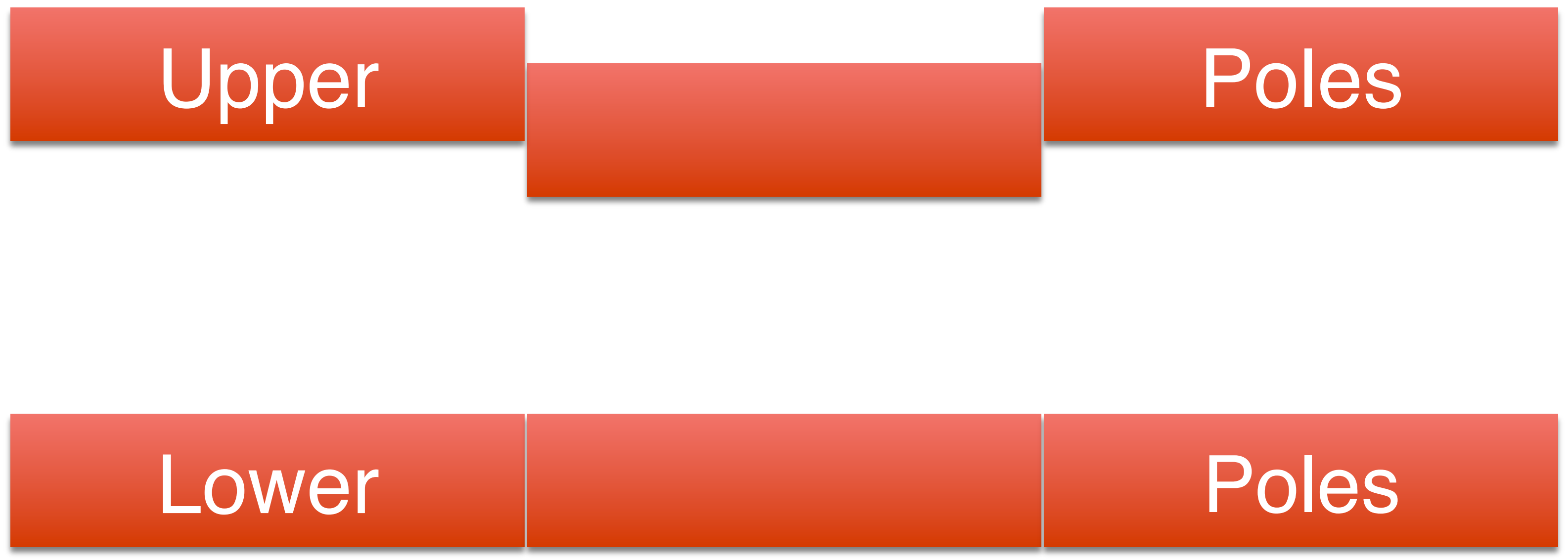
- Laminations very successful in reducing field variations

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

Magnetic Field Variations



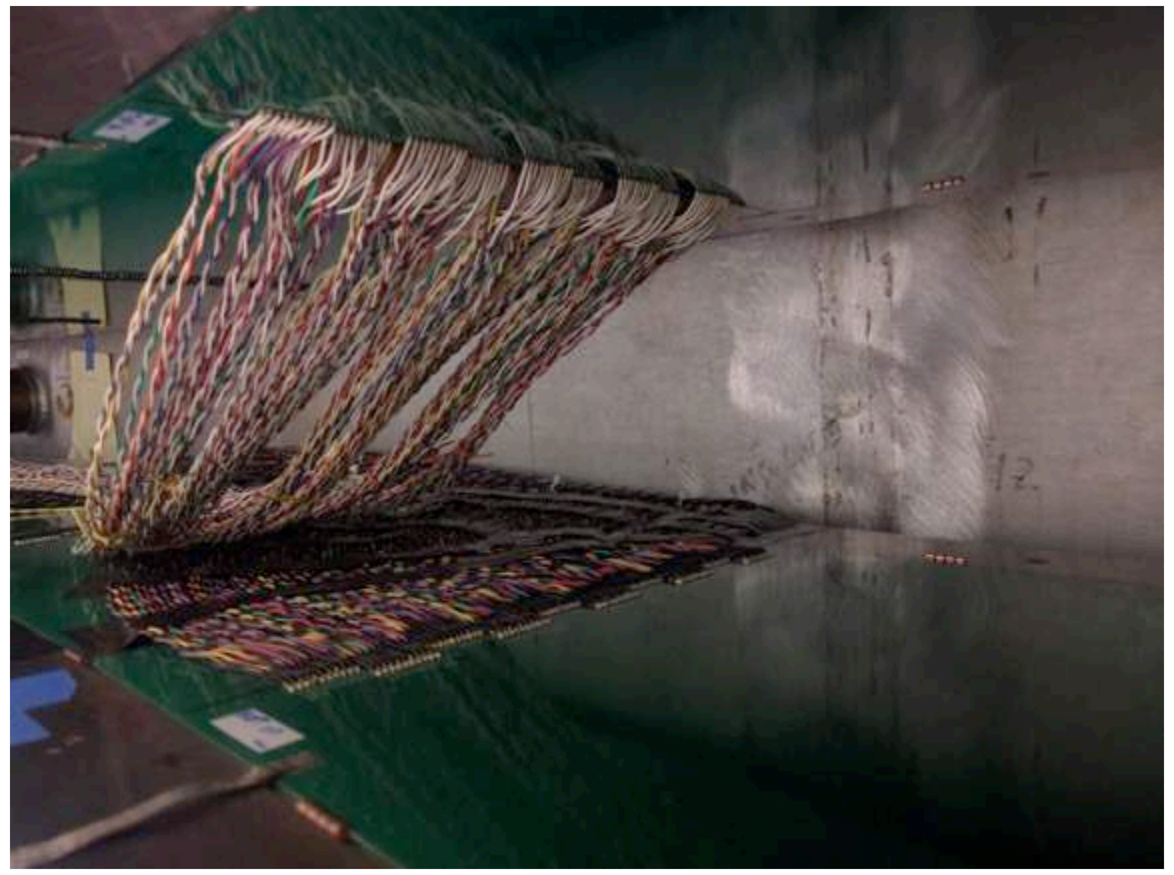
- Gradual drift from materials, pole gap changes
- 36 pairs of poles → 10-degree structure
- Pole shape: 
- Pole-to-pole discontinuities

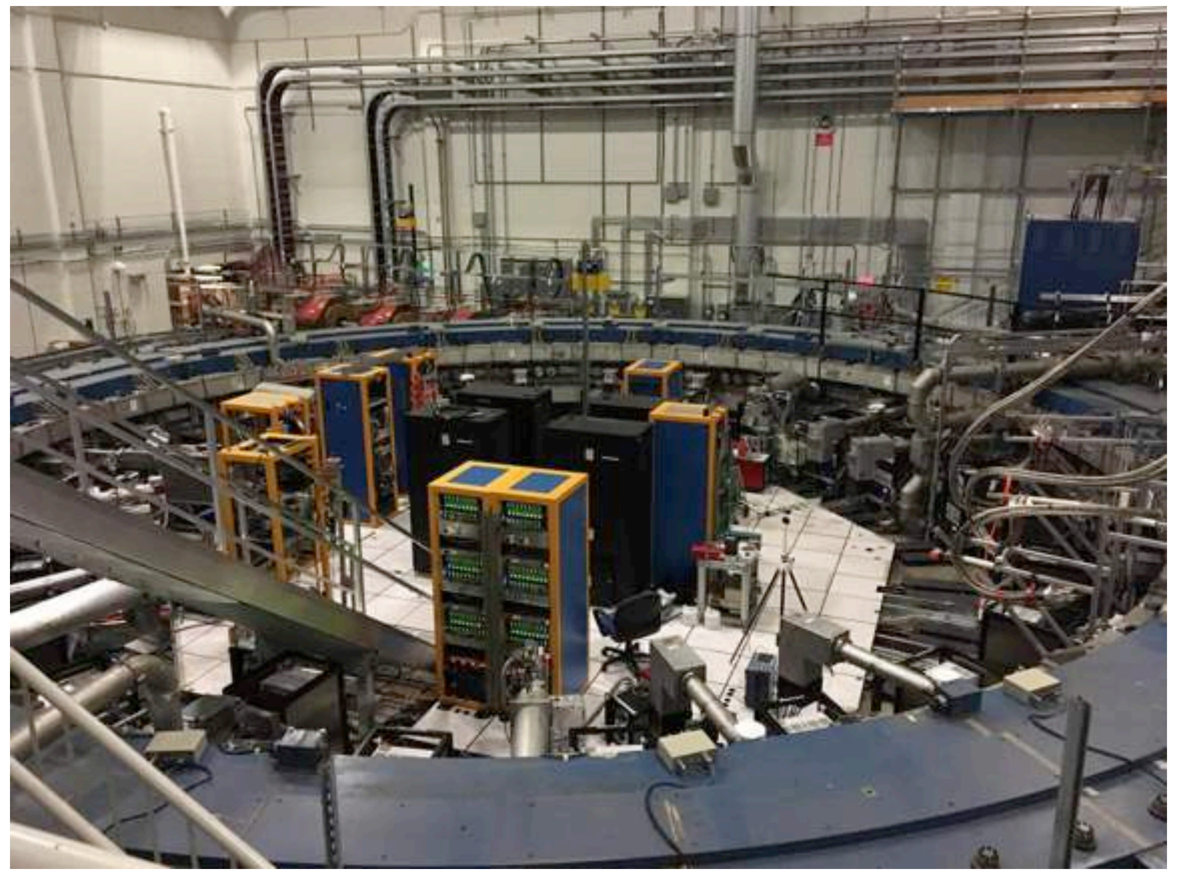


Auxiliary Field Systems

Surface Correction Coils

- Continuous PCB traces going around the ring on pole surfaces
- 100 concentric traces on upper poles, 100 on lower poles
- Programmable range: ± 20 ppm on the field
- Used to cancel higher-order multipole moments in the magnetic field (on average)



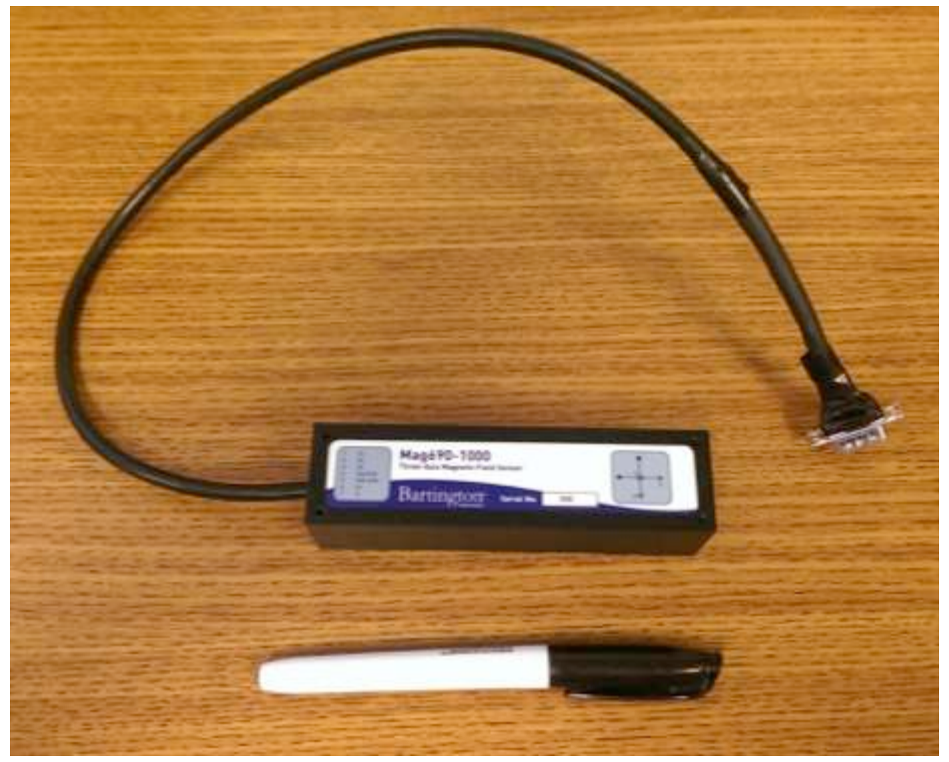


Power Supply Feedback

- Programmable current source with a range of ± 5 ppm on the field
- Uses data from **fixed probe** system to stabilize the field at a specified set point

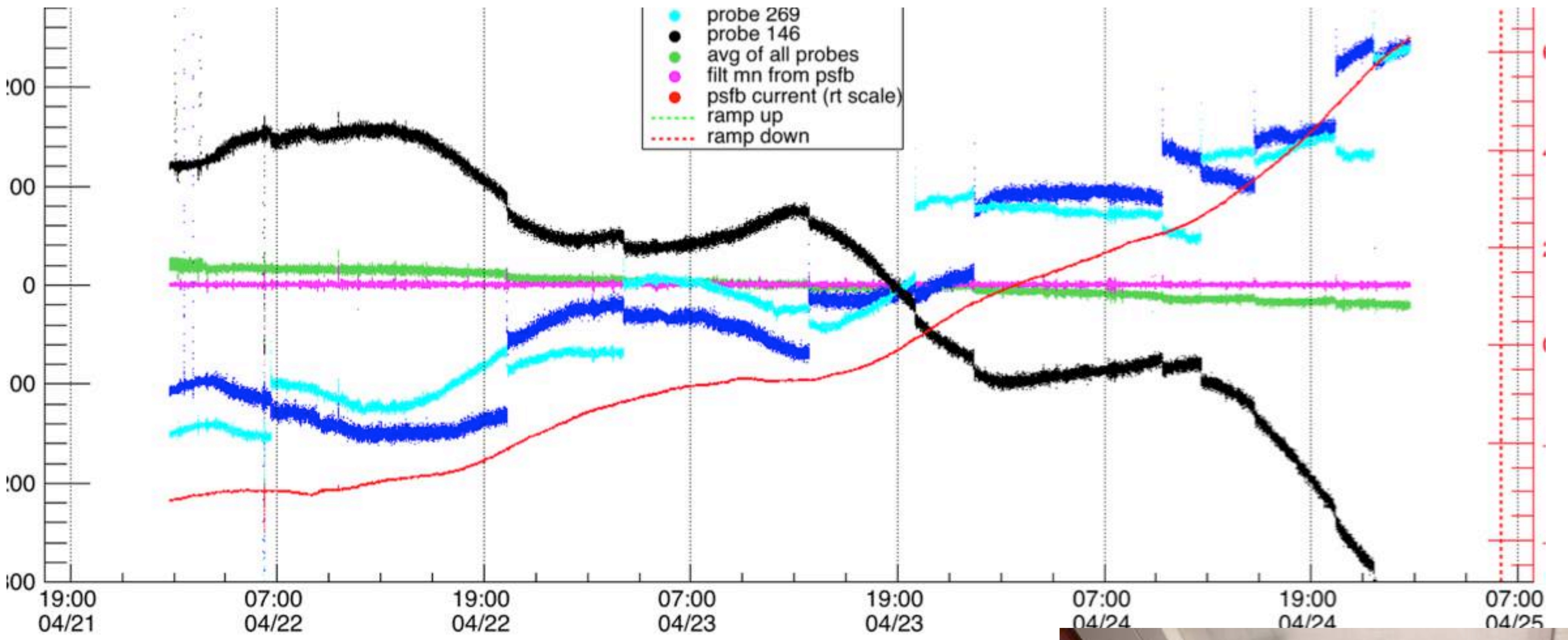
Fluxgates

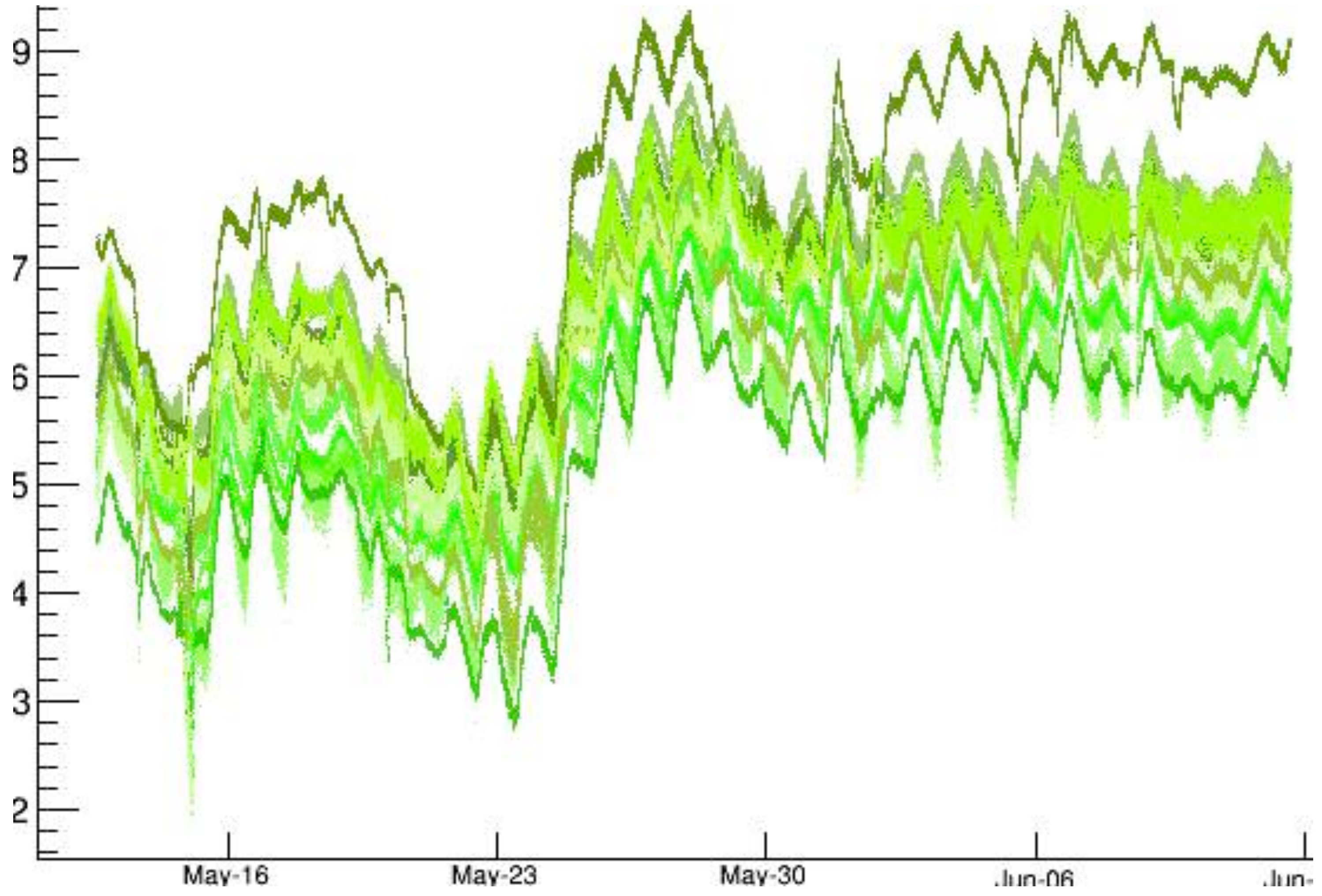
- Measure (x,y,z) components of transient fields in the hall
- Sensitive down to 10^{-9} T (DC or AC) fields
- Bandwidth up to 1 kHz



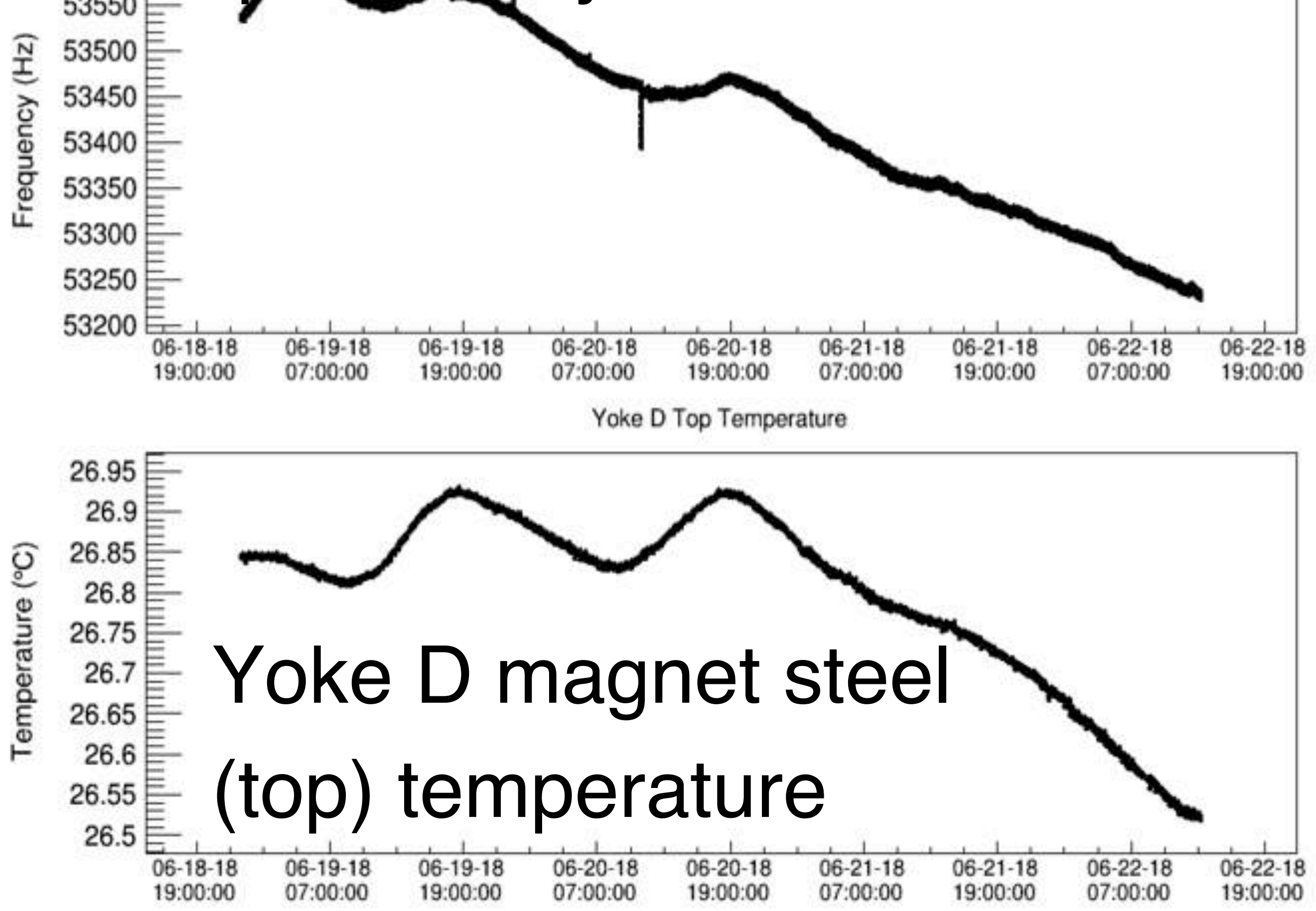
Magnet Insulation

- Temperature variations in the hall affect the quality of the magnetic field
  - Observed ~ 20 ppm/deg C effects on the dipole moment during the run
  - Also affects ability to track higher-order multipoles
- Two main issues
  - Large changes in average temperature over time (2–3°C)
  - Differential changes across the magnet (~3°C)
- Two-pronged solution:
  - Improved cooling system in the hall
  - Install fiberglass insulation blanket on magnet steel





Fixed probe on yoke D vacuum chamber (top)

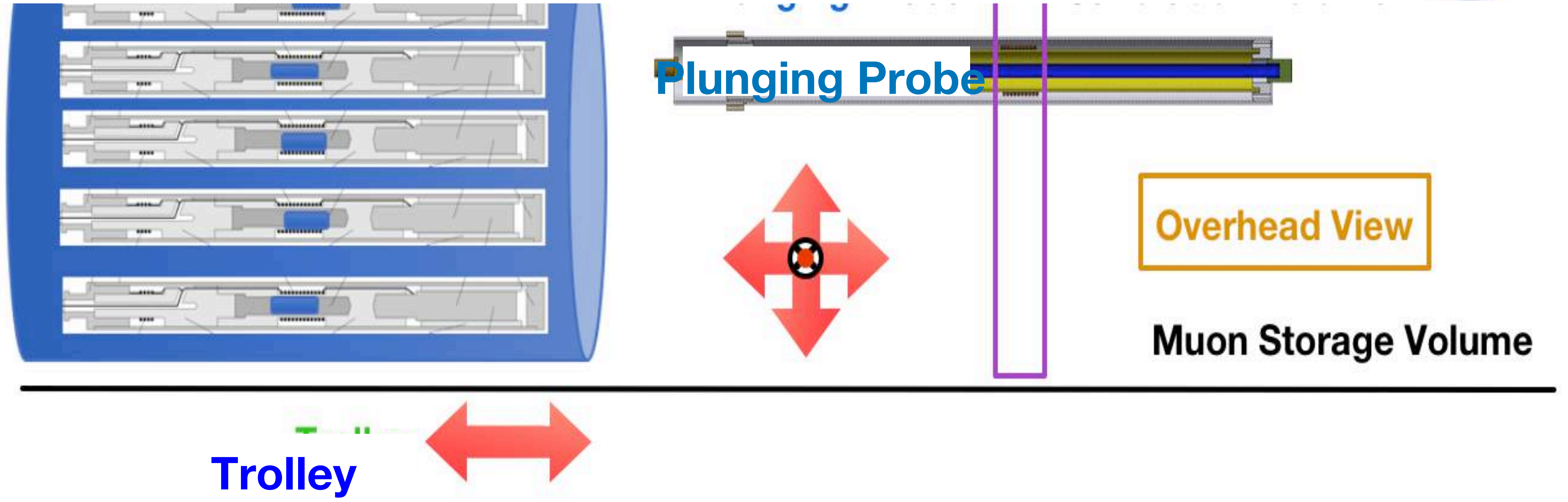


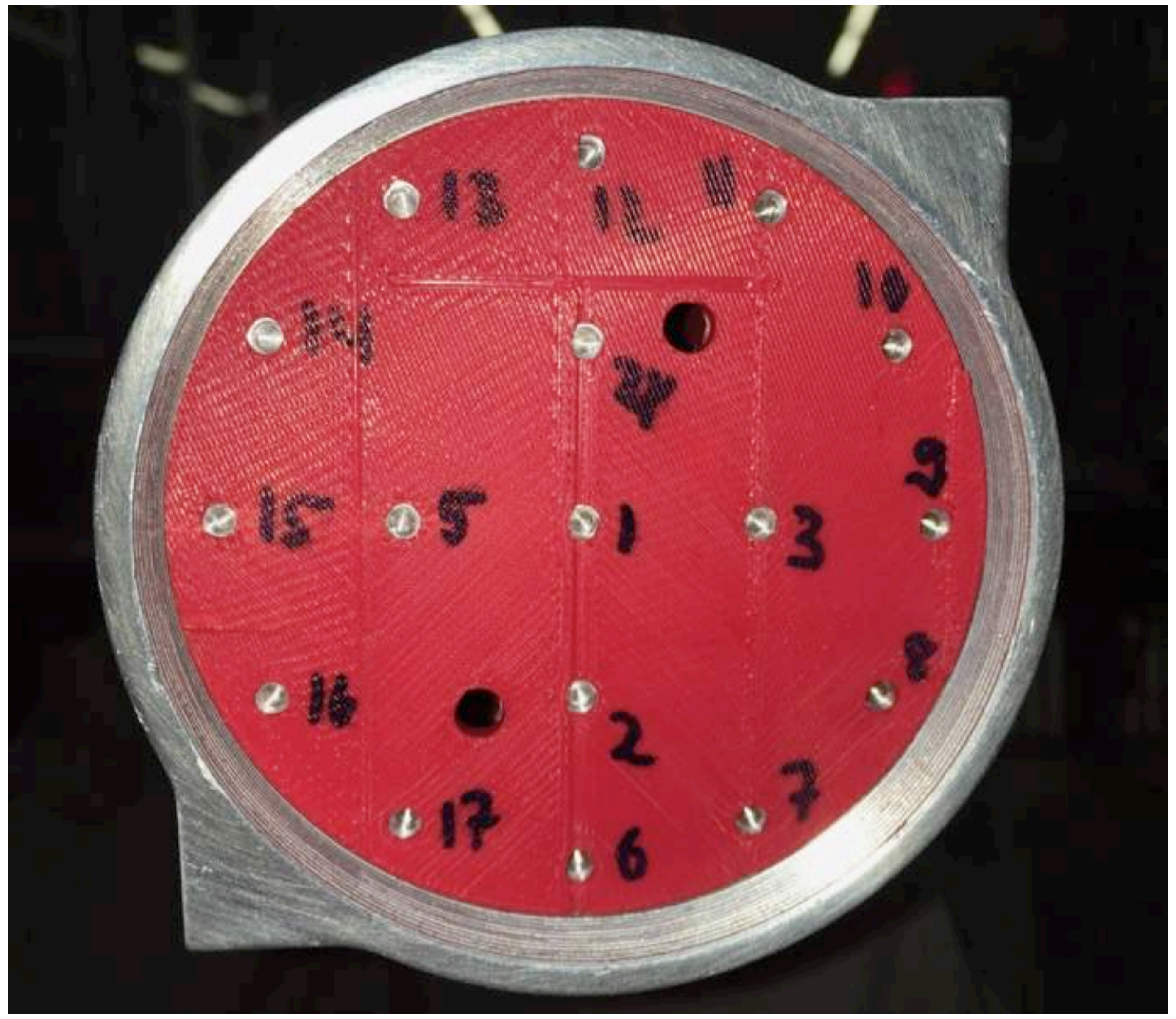
Installed blankets this past summer

Calibrating the Trolley

Procedure

- Select **trolley** probe to calibrate





Calibrating the Trolley

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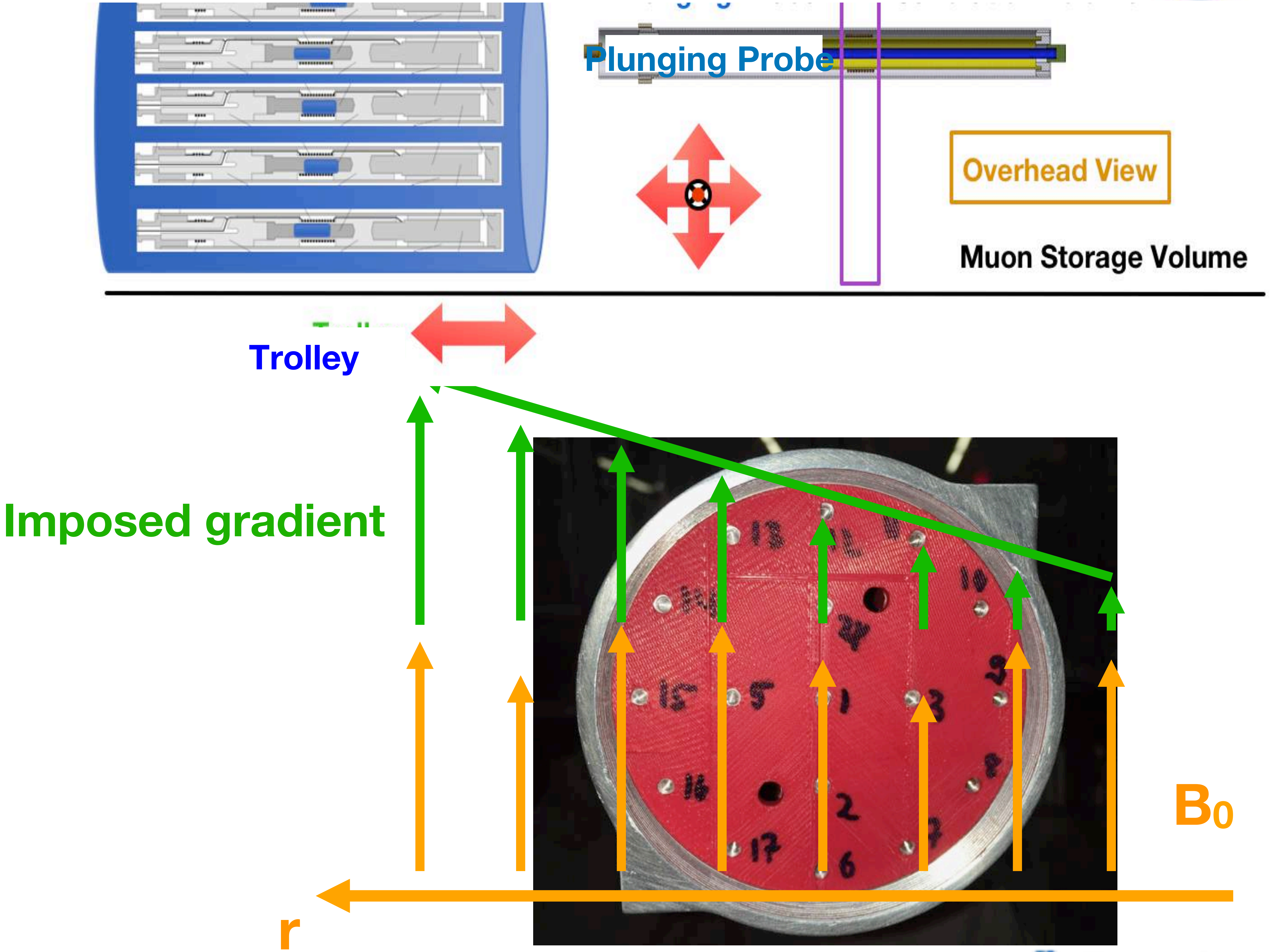
- Select **trolley** probe to calibrate
- Impose a **known gradient** across the trolley; compare to **bare field B_0**. **Define $\Delta B = B(I \neq 0) - B(I=0)$**



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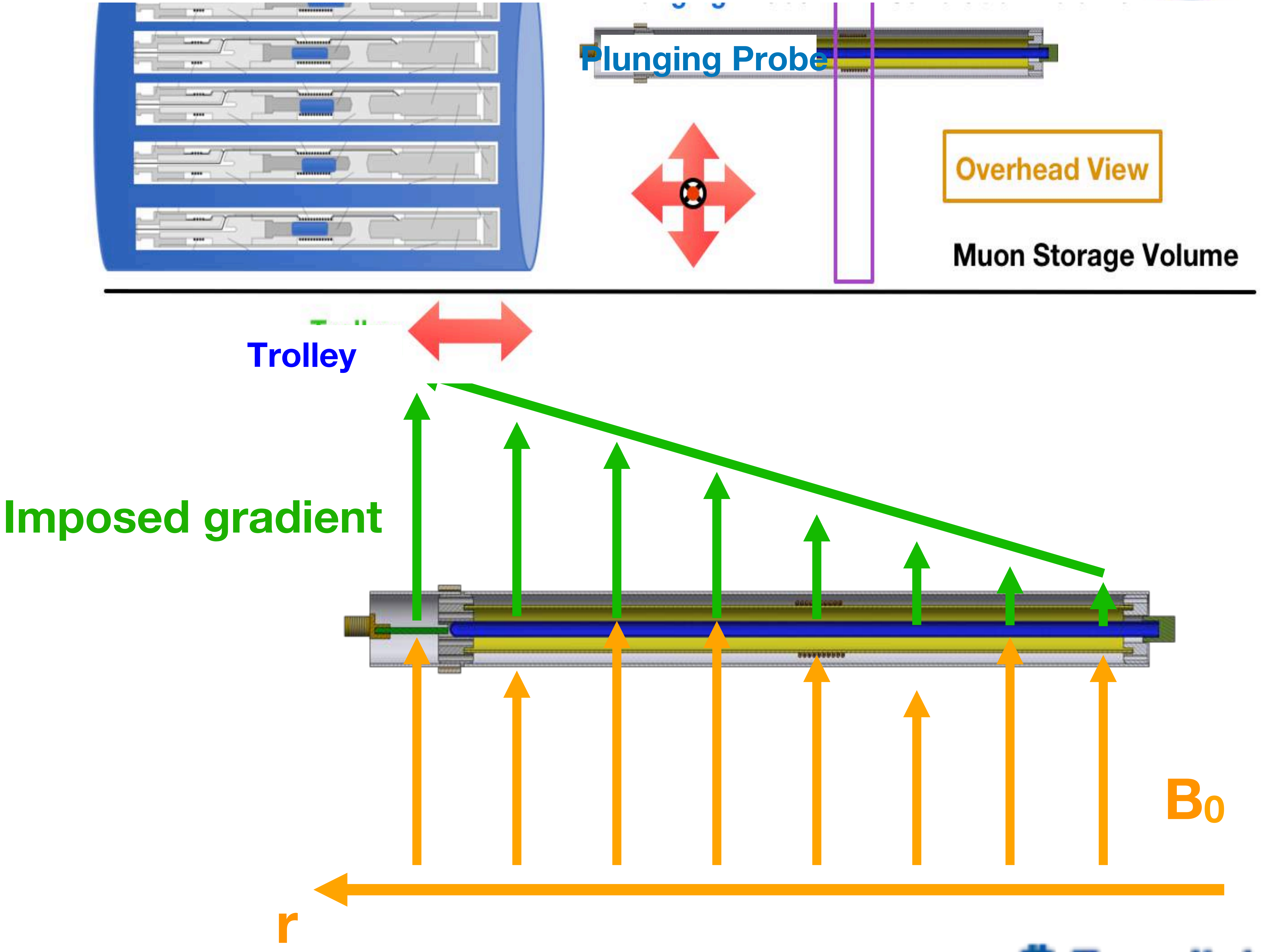

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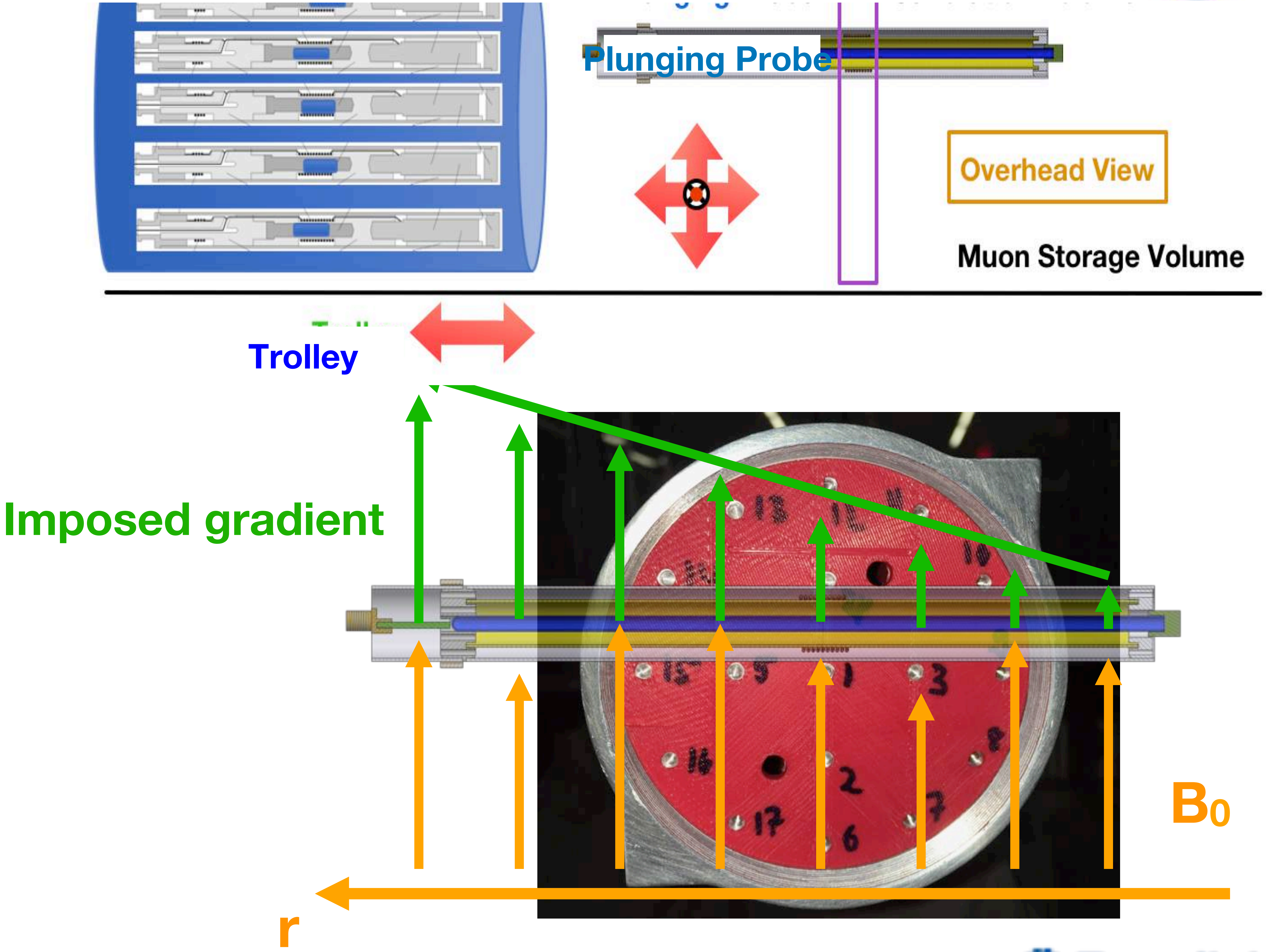
- Perform for radial, vertical, azimuthal coordinates



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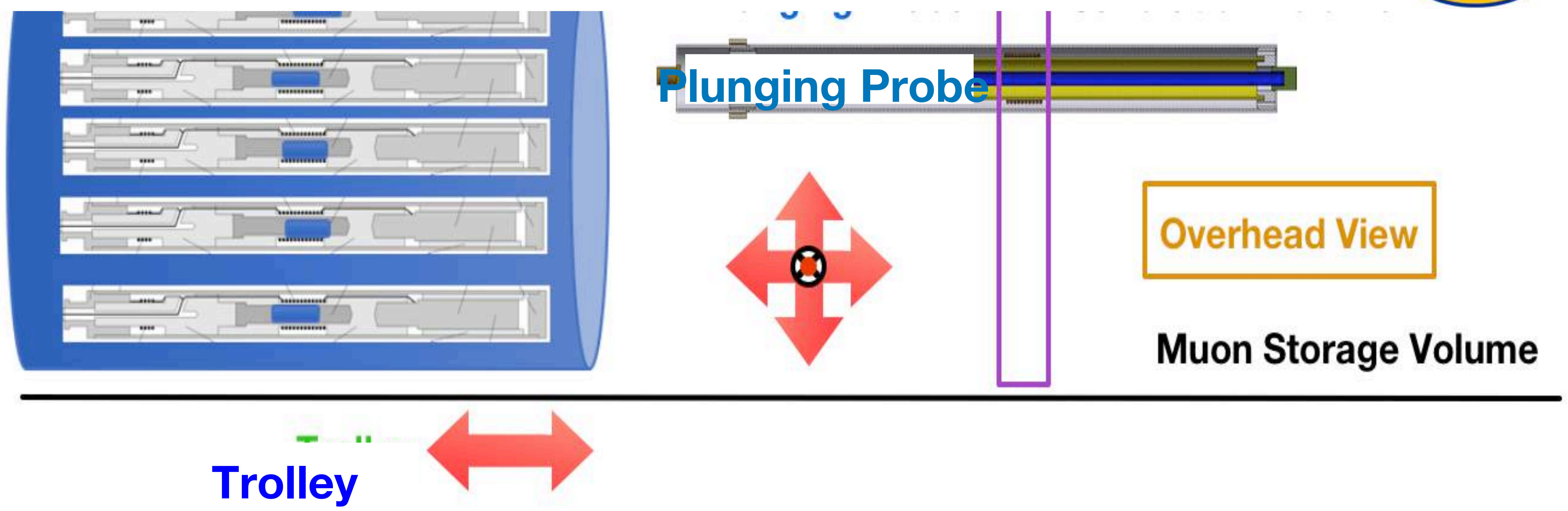
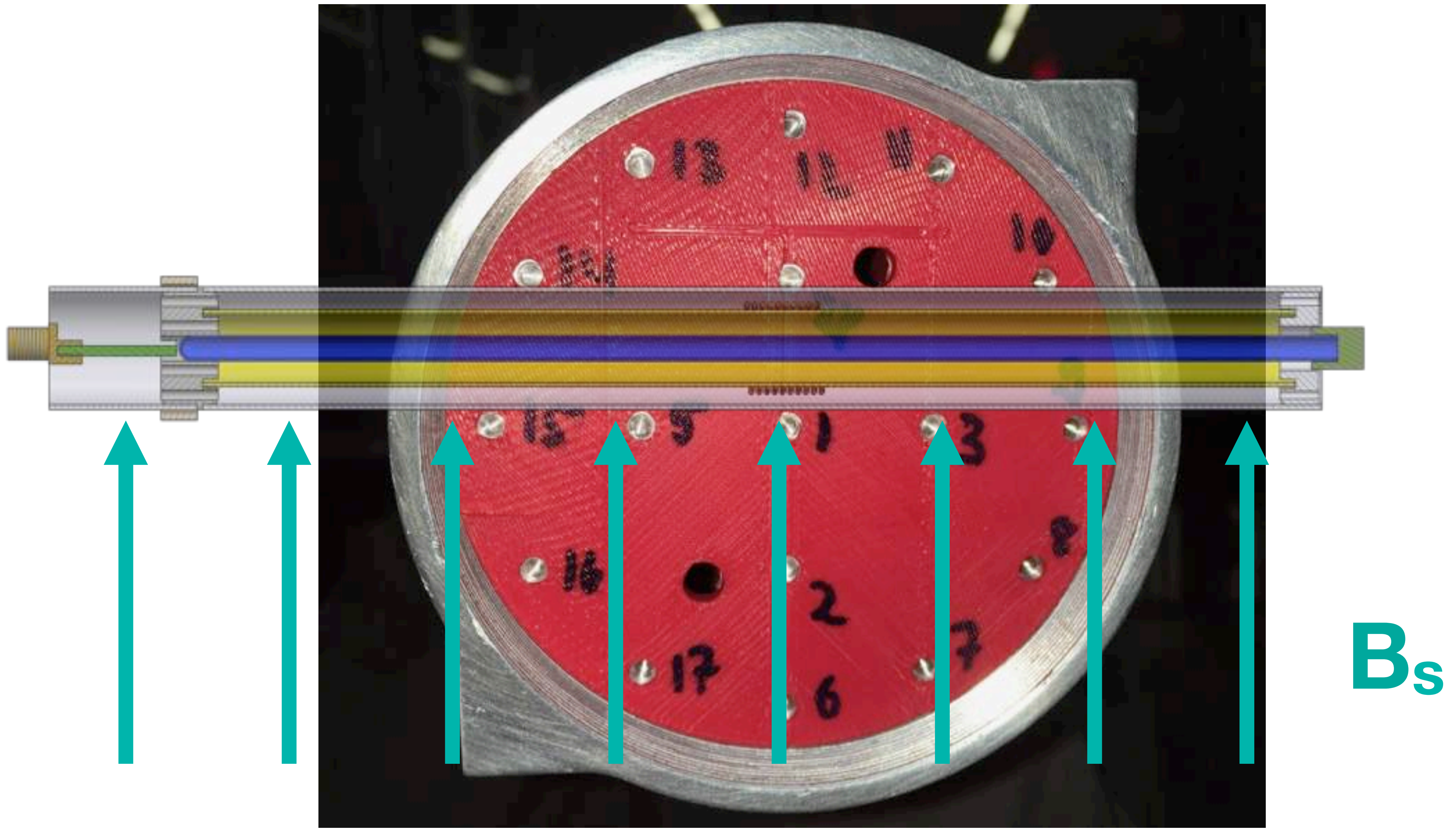
- Shim the field to be highly uniform, and measure using the **PP** and the **trolley** (rapid swapping)





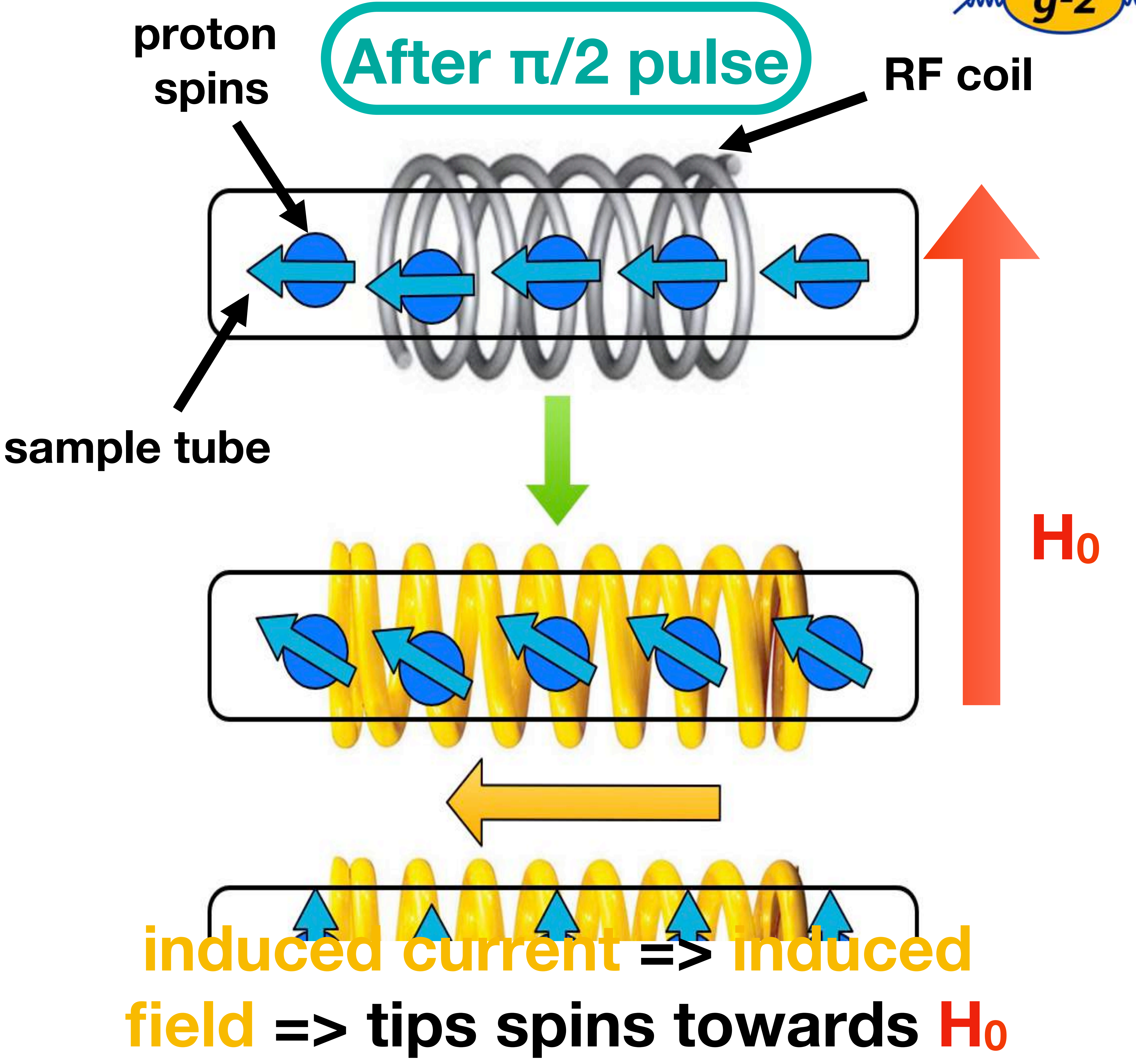
Radiation Damping

What is it?

- Precessing spins induce emf in pickup coil; this in turn generates an alternating magnetic field that **acts to rotate spins back towards the main field**
- **Size of effect: $\delta_{RD} \sim [(f_0-f_L)/f_0]\eta Q M_z(t)$**
  - f_0 = resonant frequency of circuit; f_L = Larmor frequency
  - η = filling factor; Q = quality factor of circuit
  - $M_z(t)$ = magnetization of sample

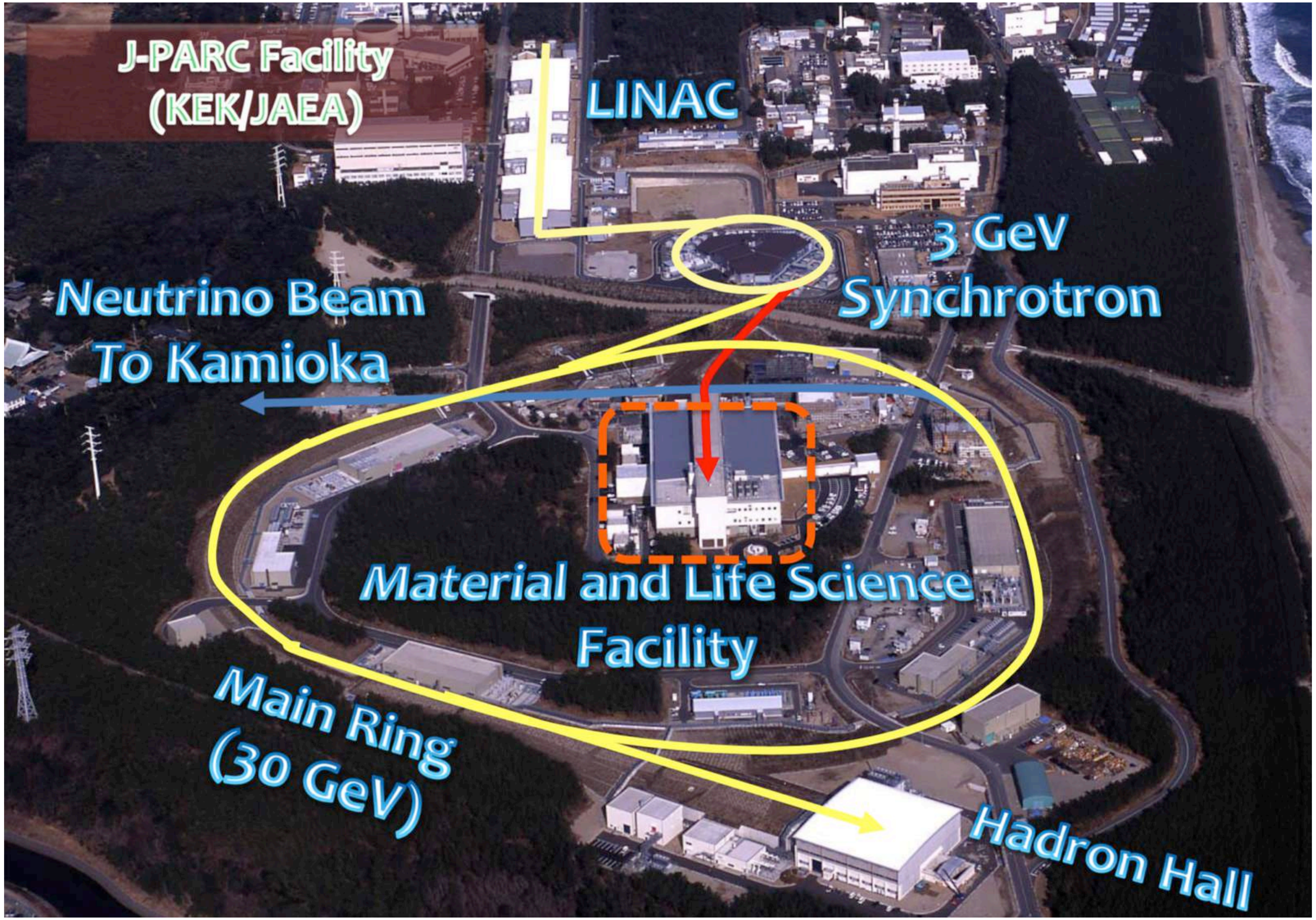
How to quantify?

- Use coils to produce a longitudinal field
  - Precise control over main field to mimic damping effect
- Vary π/2 pulse => vary $M_z(t)$ => changes δ_{RD}



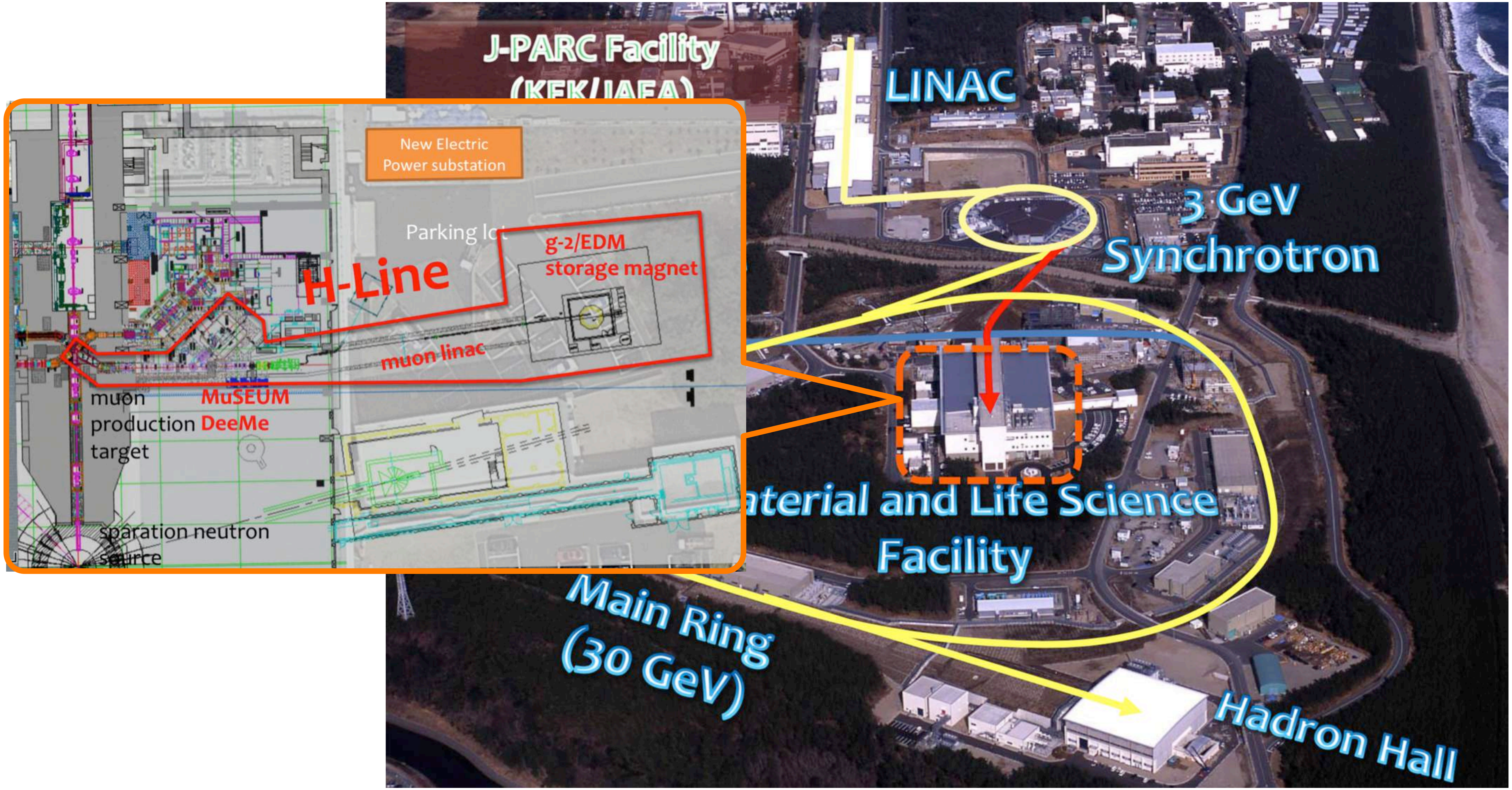
Muon g-2 at JPARC

JPARC Facilities



Images from Tsutomu Mibe

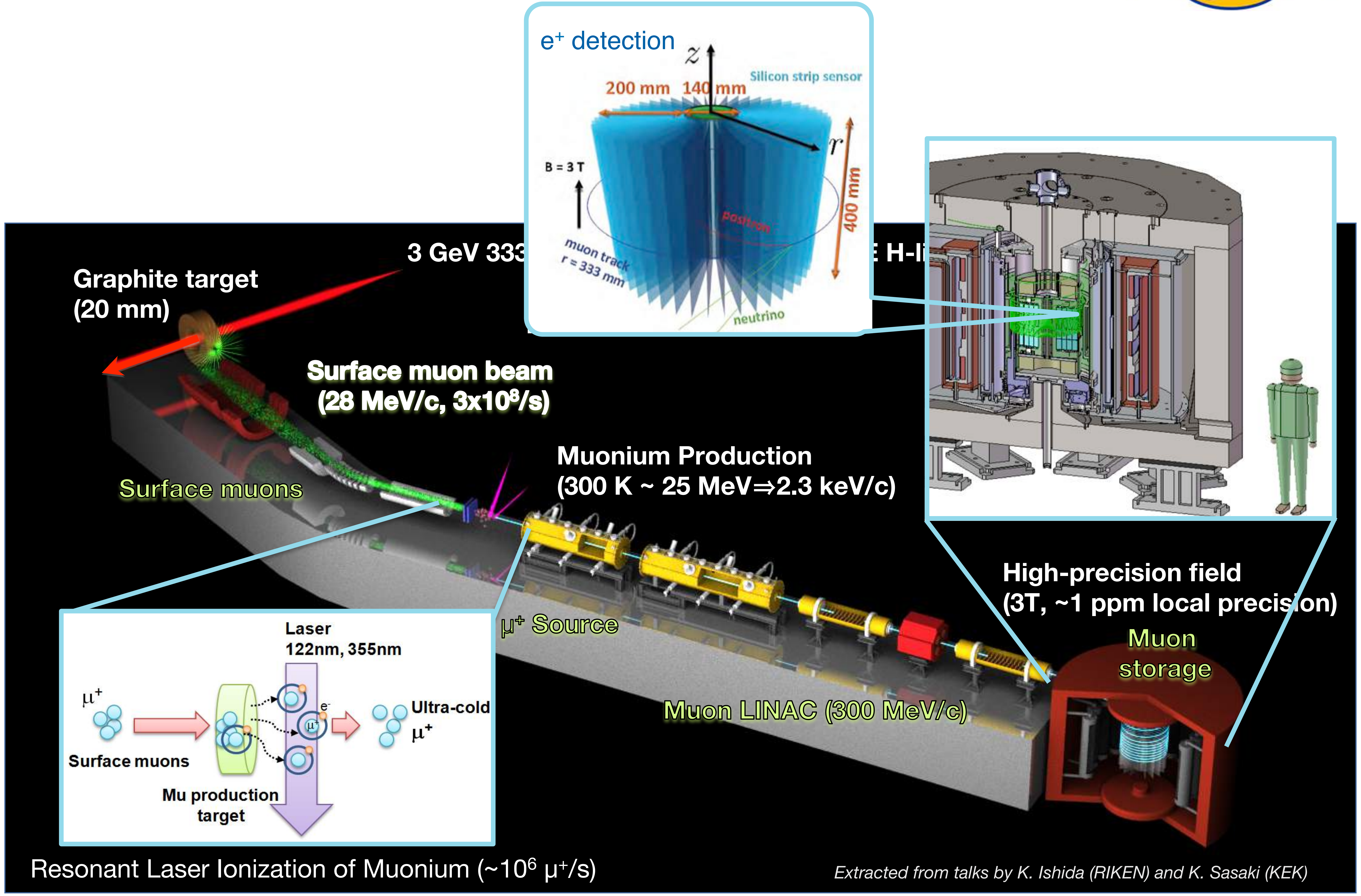
JPARC Facilities



Images from Tsutomu Mibe

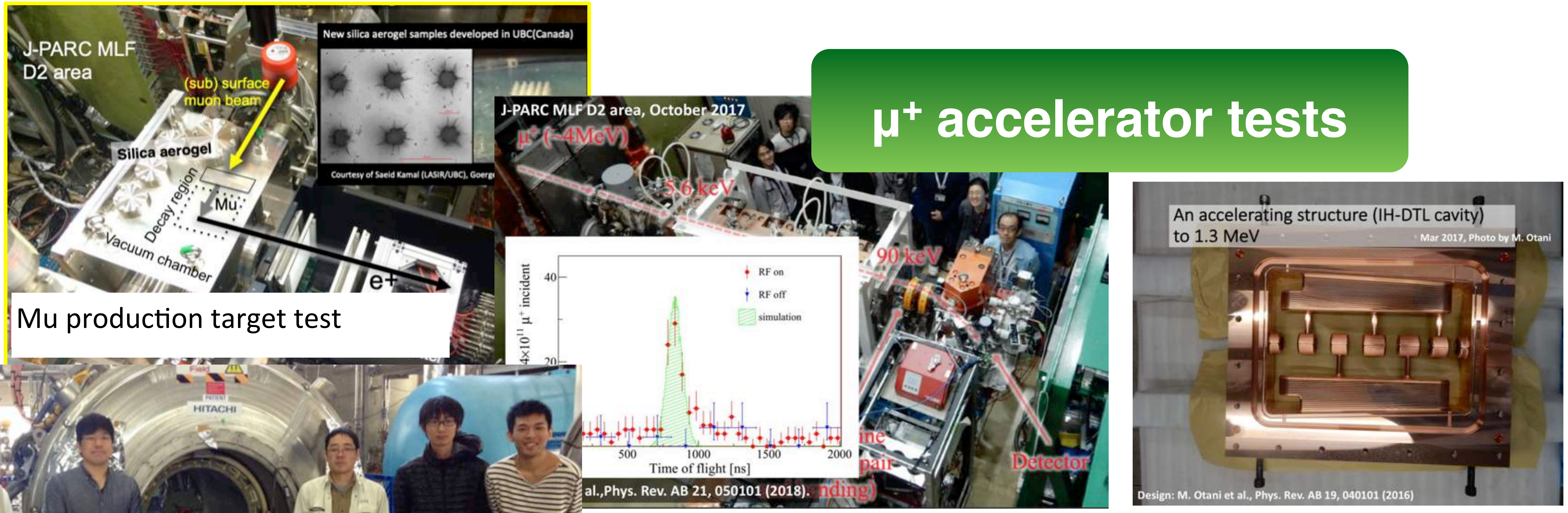
The Muon g-2 Experiment at JPARC

- New experiment being prepared in Japan
- Features
  - Low-emittance muon beam
  - 40 silicon high-resolution tracking vanes
  - High-uniformity storage field (~ 1 ppm)
- Different technique → different systematics
  - Excellent cross-check against E989 at FNAL



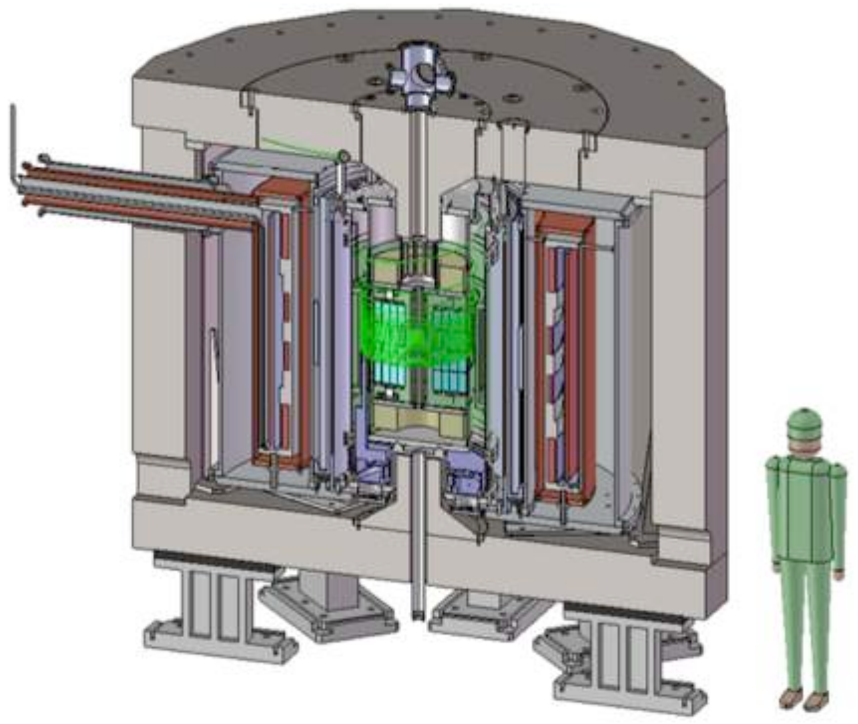
The Muon g-2 Experiment at JPARC: Current Status

- Various systems are progressing forward
  - Beamline
  - e^+ trackers
  - Magnetic field



Images from Tsutomu Mibe (KEK)

Muon g-2 Experiment Comparison



Parameter	E34 @ JPARC	E989 @ Fermilab
Beam	High-rate, ultra-cold muon beam (p = 300 MeV/c)	High-rate, magic-momentum muons (p = 3.094 GeV/c)
Polarization	P_{max} = 50-90% (spin reversal possible)	$P \approx$ 97% (no spin reversal)
Magnet	MRI-like solenoid ($r_{storage}$ = 33 cm)	Storage ring ($r_{storage}$ = 7 m)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Injection	Spiral + kicker (~90% efficiency)	Inflector + kicker (~5% efficiency)
Positron detector	Silicon vanes for tracking	Lead-fluoride calorimeter
B-field measurement	Continuous wave NMR	Pulsed NMR
Current sensitivity goal	450 ppb	140 ppb

Related Muon Physics

Ingredients to Extracting a_μ

- Recall the expression for a_μ:

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

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- m_μ/m_e value based on muonium hyperfine theory:

$$\Delta\nu_{\mathrm{Mu}}(\mathrm{Th}) = \frac{16}{3} c R_\infty \alpha^2 \frac{m_e}{m_\mu} \left(1 + \frac{m_e}{m_\mu}\right)^{-3} + \text{higher order terms}$$

- Equate theory to experiment, treat m_μ/m_e as a free parameter, obtain m_μ/m_e to 22 ppb

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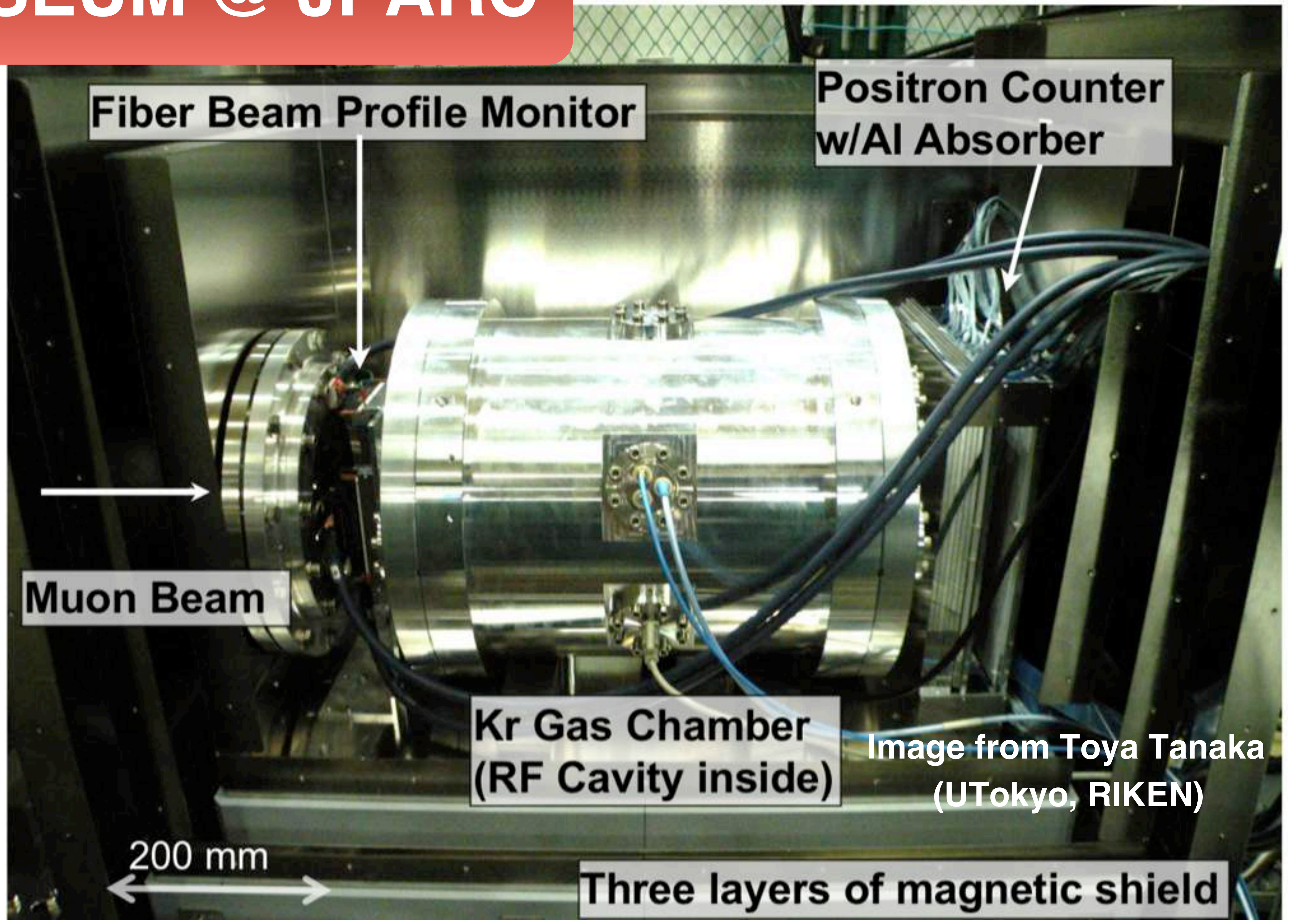
MuSEUM @ JPARC



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- Allows extraction of a_μ **independent of theory**:

$$a_\mu = \frac{\omega_a/\tilde{\omega}_p}{\mu_\mu/\mu_p - \omega_a/\tilde{\omega}_p}$$

MuSEUM @ JPARC

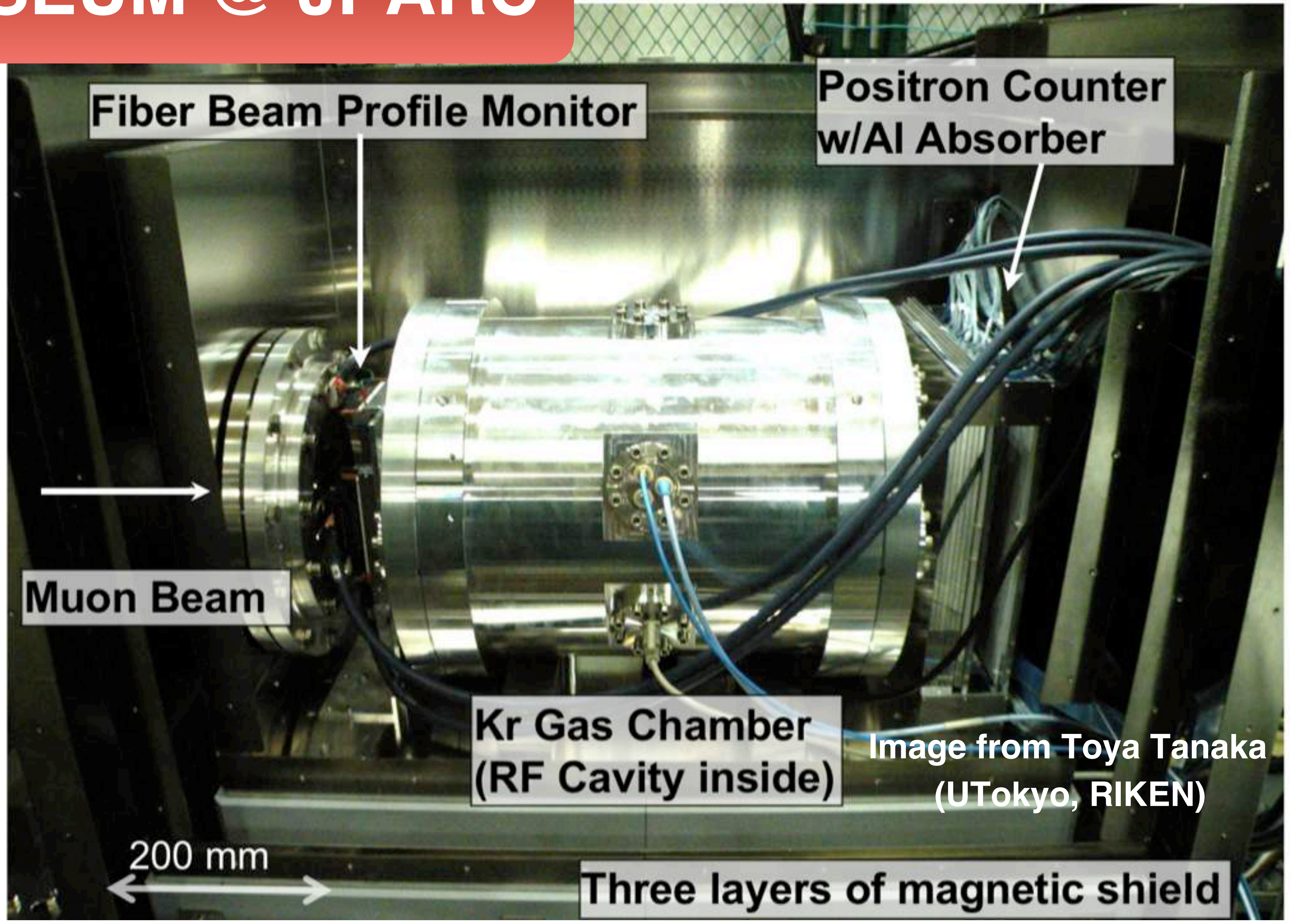

Image from Toya Tanaka (UTokyo, RIKEN)

EDM measurement at FNAL

- Precession plane tilts towards center of ring
- Causes an increase in muon precession frequency
- Oscillation is 90° out of phase with the a_μ oscillation
- 10 x improvement to current limit expected