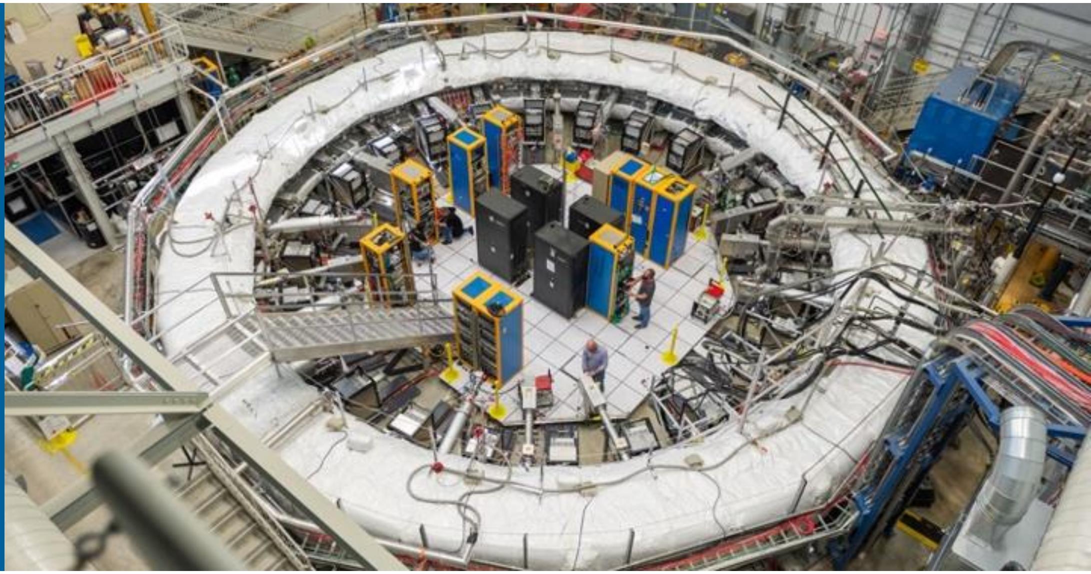
PRECISION MEASUREMENT OF THE MUON MAGNETIC MOMENT ANOMALY AT THE FERMILAB MUON $g-2$ EXPERIMENT



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On behalf of the Fermilab Muon g-2 Collaboration

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CONTENTS

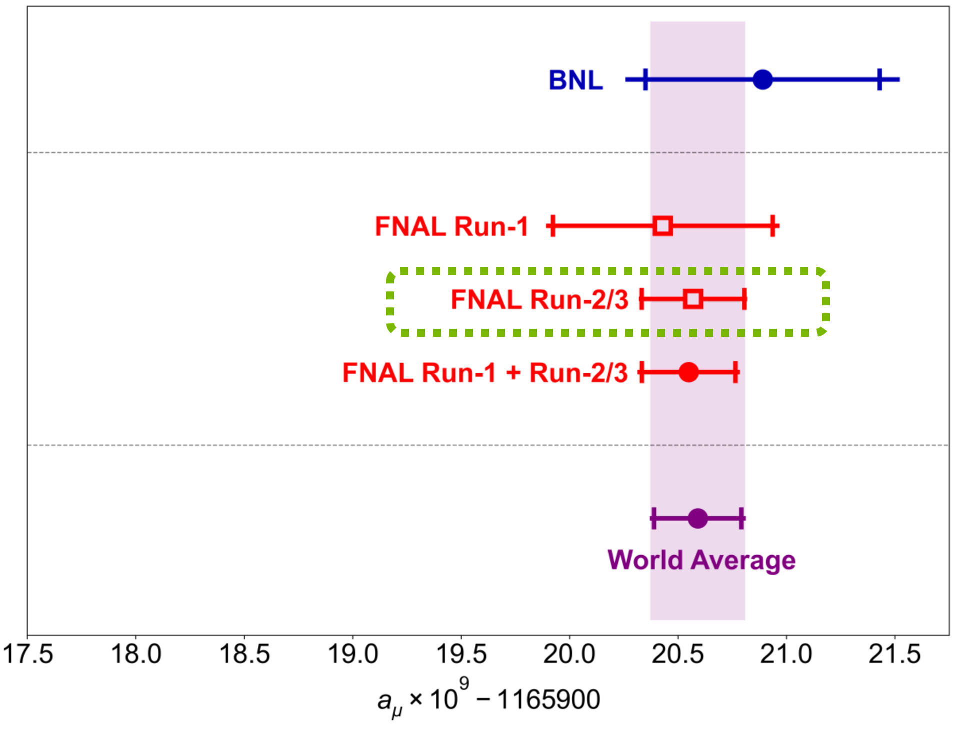
The Fermilab Muon g-2 Experiment released its Run-2/3 results in August 2023:

$$a_\mu(\mathrm{FNAL, Run\ 2/3}) = 0.00116592057(25)\ [0.21\ ppm]$$

New PRD paper at ArXiv:2402.15410

This talk includes:

- Introduction to muon g-2 and the Fermilab Muon g-2 Experiment
- Experiment setup, measurements, and corrections
- Result and Improvements in Run 2/3
- Updates and outlook



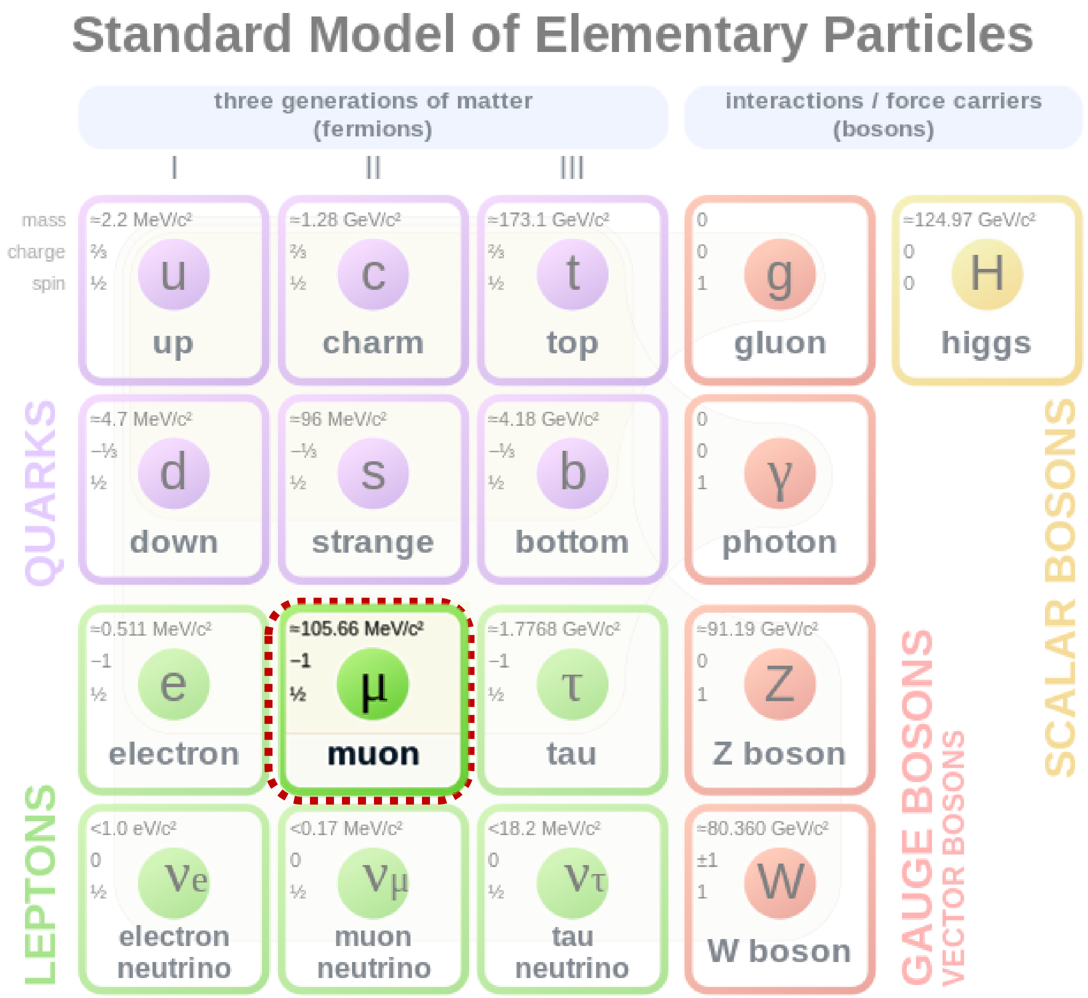
MUON AND MUON $g-2$

- Muon: 2nd generation charged lepton
- ~200x more massive than electron
  - More sensitive to virtual particles (loops)
  - Not heavy enough for hadronic decays
- 2.2 μs lifetime (at rest), easier to manipulate at accelerators
  - Decays to $e^-, \bar{\nu_e}, \nu_\mu$ in a self-analyzing parity violating manner (i.e., electrons tend to be emitted along the muon's spin direction)
- "g" is a dimensionless factor linking magnetic moment $\vec{\mu}$ of a particle with its spin $\vec{s}$:

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

- Dirac theory of elementary spin-½ particle says g=2, on the tree level. Standard Model tells us there are other contributions. We define the anomalous magnetic moment a as:

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

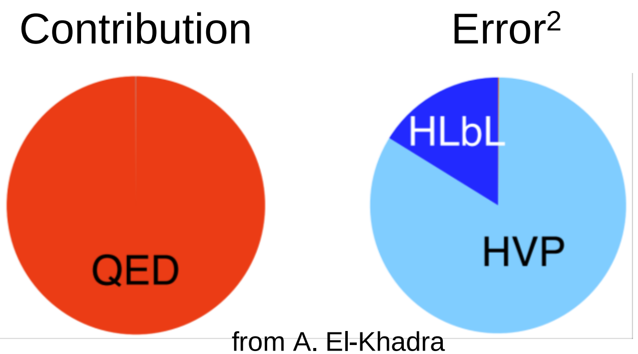


From wikipedia.org

STANDARD MODEL PREDICTIONS OF a_μ

- Last comprehensive update from Muon g-2 Theory Initiative: 2020 White Paper, Phys. Rep. 887 (2020)
- Most recent update in the previous talk by Shaun Lahert
- The SM contributions to a_μ was

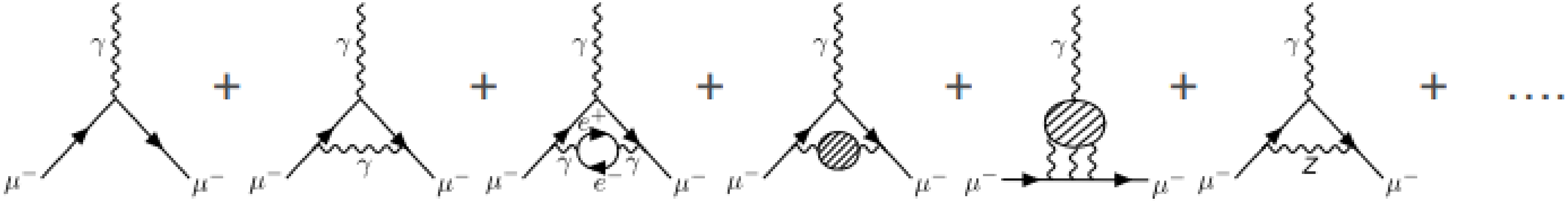
$$a_\mu^{SM} = 116591810(43) \times 10^{-11}$$



from A. El-Khadra

Dominant contribution from QED, but ***dominant uncertainty*** from QCD

- HVP from two approaches
  - Dispersive approach using e^-e^+ data
  - Lattice QCD (not used in 2020 WP)
- A lot of progresses over the last years!



Dirac
2

Schwinger
1st order QED
$\alpha/2\pi$

Vacuum
polarization
higher order QED

Hadronic Virtual
Particle (HVP)
$6845(40) \times 10^{-11}$

Hadronic Light-by-Light
$92(18) \times 10^{-11}$

Electroweak
$153.6(1.0) \times 10^{-11}$

Uncertainty: 0.1×10^{-11}

Dominant uncertainty

WHAT CAN WE LEARN FROM MUON $g-2$?

- Precision test of the Standard Model:
  - BNL muon g-2 saw a ~3.5σ discrepancy
  - Theory calculations were to ~0.4 parts-per-million (ppm)
  - Experiment goal for entire Fermilab Muon g-2 Experiment: 0.14 ppm (total, 0.10 ppm each for stat. and syst. uncertainties)
- Indicator of new physics:
  certain BSM physics models can accommodate large deviations (see https://arxiv.org/pdf/2104.03691.pdf)
  - Certain flavors of SUSY
  - Some Two-Higgs doublet models
  - Lepto-quarks, vector-like leptons
  - Some axion-like particles, etc.
- Like other experiments on the intensity/precision frontier, confirmed deviation can be indicators for new physics, and consistency with SM predictions can largely constrain parameter spaces for new models

Past and future experiments

- CERN II (1974):
  270ppm precision
- CERN III (1978):
  7ppm precision
- BNL E821 (2006):
  0.54ppm precision
  (~3.5σ deviation from theory)

- Fermilab E989 (us)

- E34 at JPARC (~JFY2028)
  Different technical details

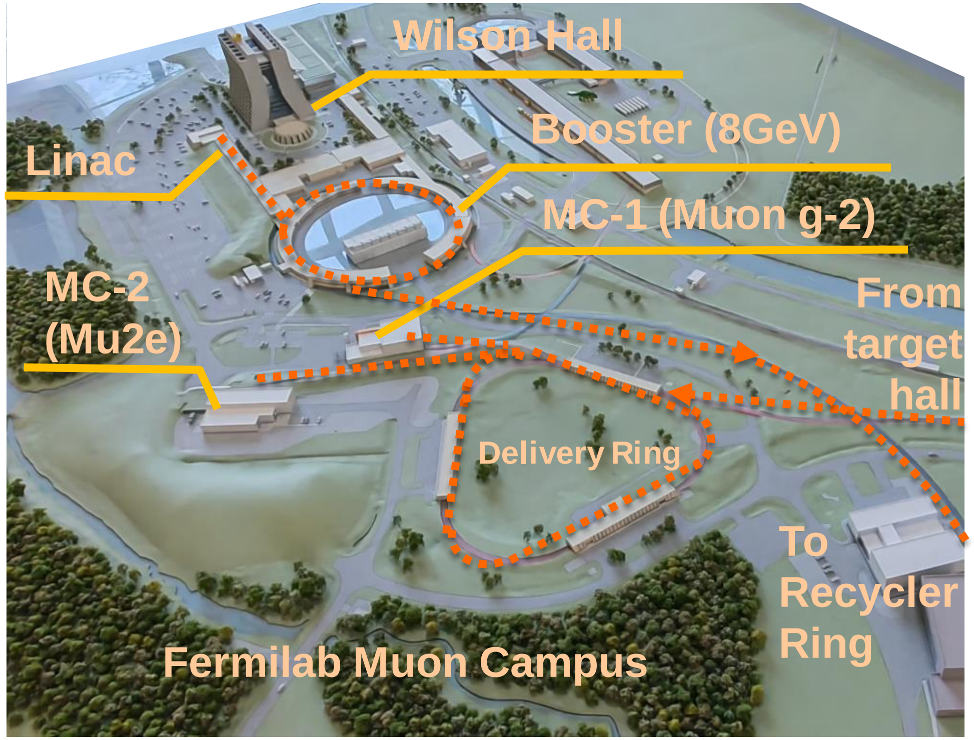
THE MUON $g - 2$ EXPERIMENT AT FERMILAB

- Critical timeline milestones:
  - CD0 in 2012
  - Magnet move from BNL in 2013
  - First muon beam in 2017
    - 6 physics runs over 6 years
  - End of data taking in 2023

  - First result in 2021
  - Run 2/3 result released in August 2023

- Experiment located on Fermilab Muon Campus
  - 8 GeV proton beam from Booster
  - Hit proton target in the target hall to produce pions among other particles
  - Pions decay to muons in the delivery ring, muons with “magic momentum” are selected and transferred to MC-1

Photo credit: Reidar Hahn, Fermilab

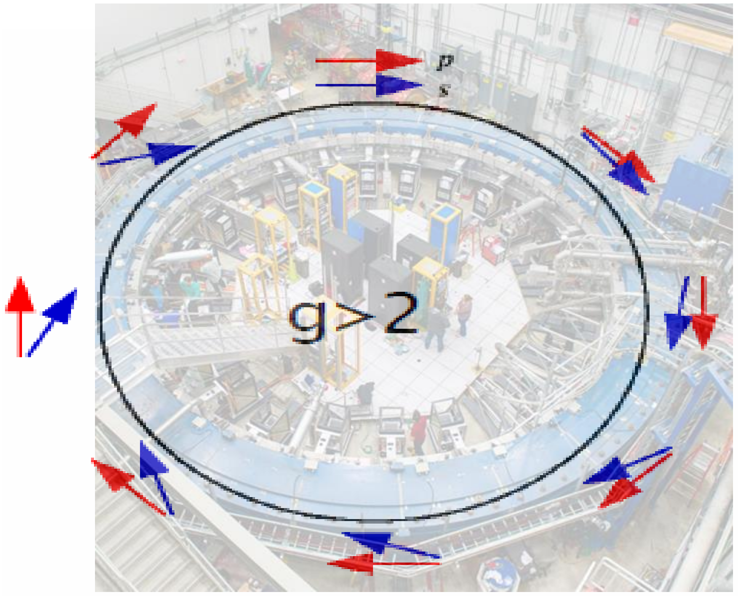


HOW TO MEASURE MUON $g-2$: MUONS IN A STORAGE RING

- **Polarized** muons are stored in a ring of **dipole** magnetic field
- For g>2, **muon spin** rotates **ahead** of **muon momentum** as muon goes around the ring
- The frequency difference ω_a is the difference of spin precession frequency and cyclotron frequency:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{q}{m}\vec{B} + \frac{q}{m}\left[\boxed{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}} + \boxed{a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta}}\right]$$

  - For horizontally circulating muons in a vertical $\vec{B}$ field, $\vec{\beta}\cdot\vec{B}=0$, third term goes to 0
  - For a special Lorentz factor $\gamma_\mu = \sqrt{1+1/a_\mu} \approx 29.3$ $(\mathrm{p} = 3.094\ \mathrm{GeV/c})$, second term also cancels to the first order ⇒ “Magic momentum”



- Then only the first term left. Things to measure are:
  - Spin precession frequency $\vec{\omega}_a$
  - Magnetic field $\vec{B}$

THE STORAGE RING MAGNET

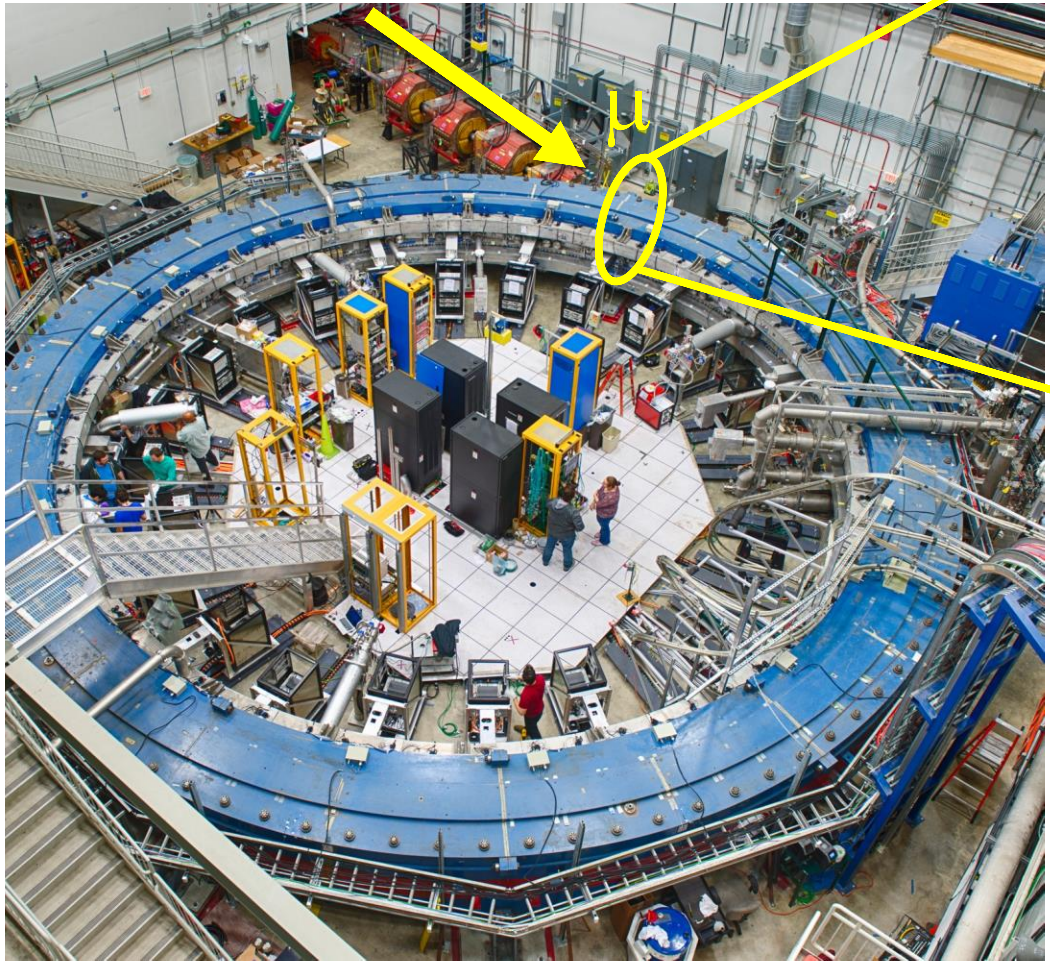
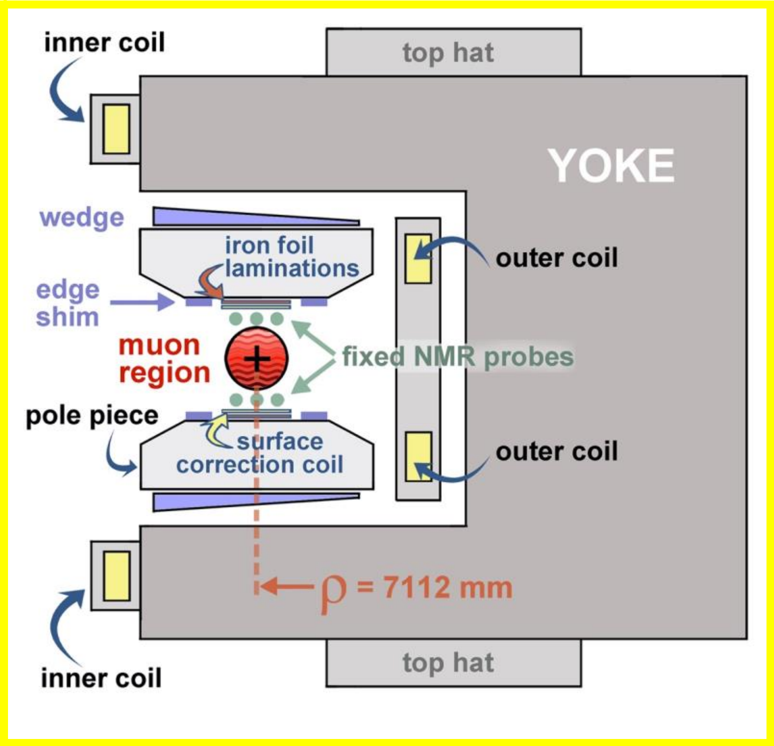


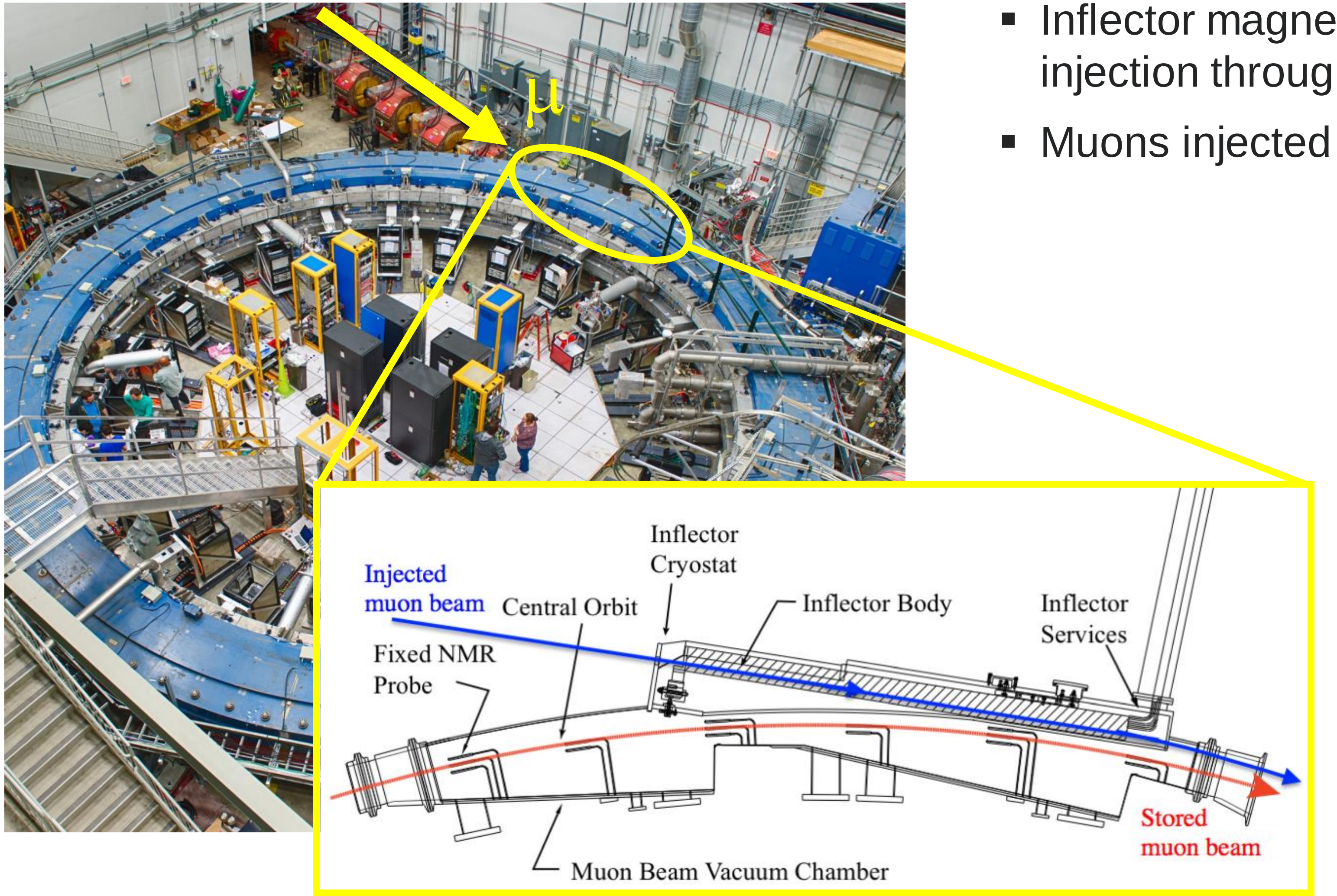
Photo credit: Reidar Hahn, Fermilab



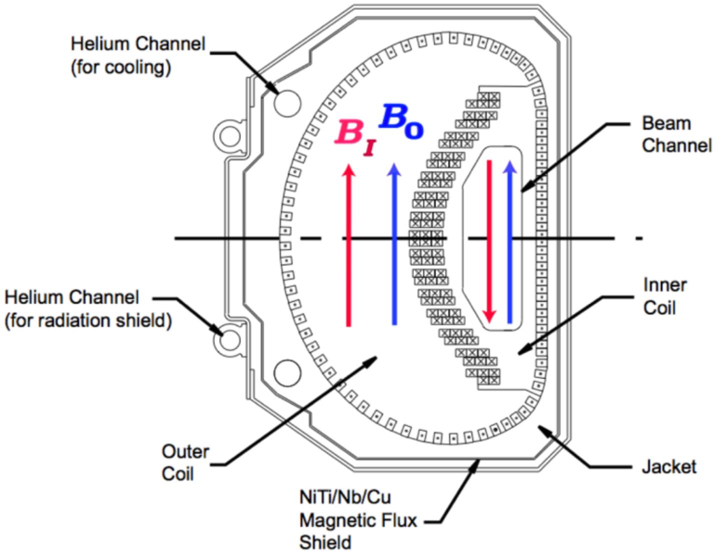
- Superconducting coils with C-shaped yokes
- 1.45 T field strength
- Size determined by the “magic momentum” and the magnetic field strength
- Hats and wedges shims tune the dipole, iron foils fine tune the field, and surface correction coils tune higher multipoles
- Typical field RMS around the ring < 20 ppm

MUON INJECTION & STORAGE: INFLECTOR MAGNET

- Inflector magnet cancels main field for muon injection through yoke
- Muons injected with 77mm offset from ideal orbit



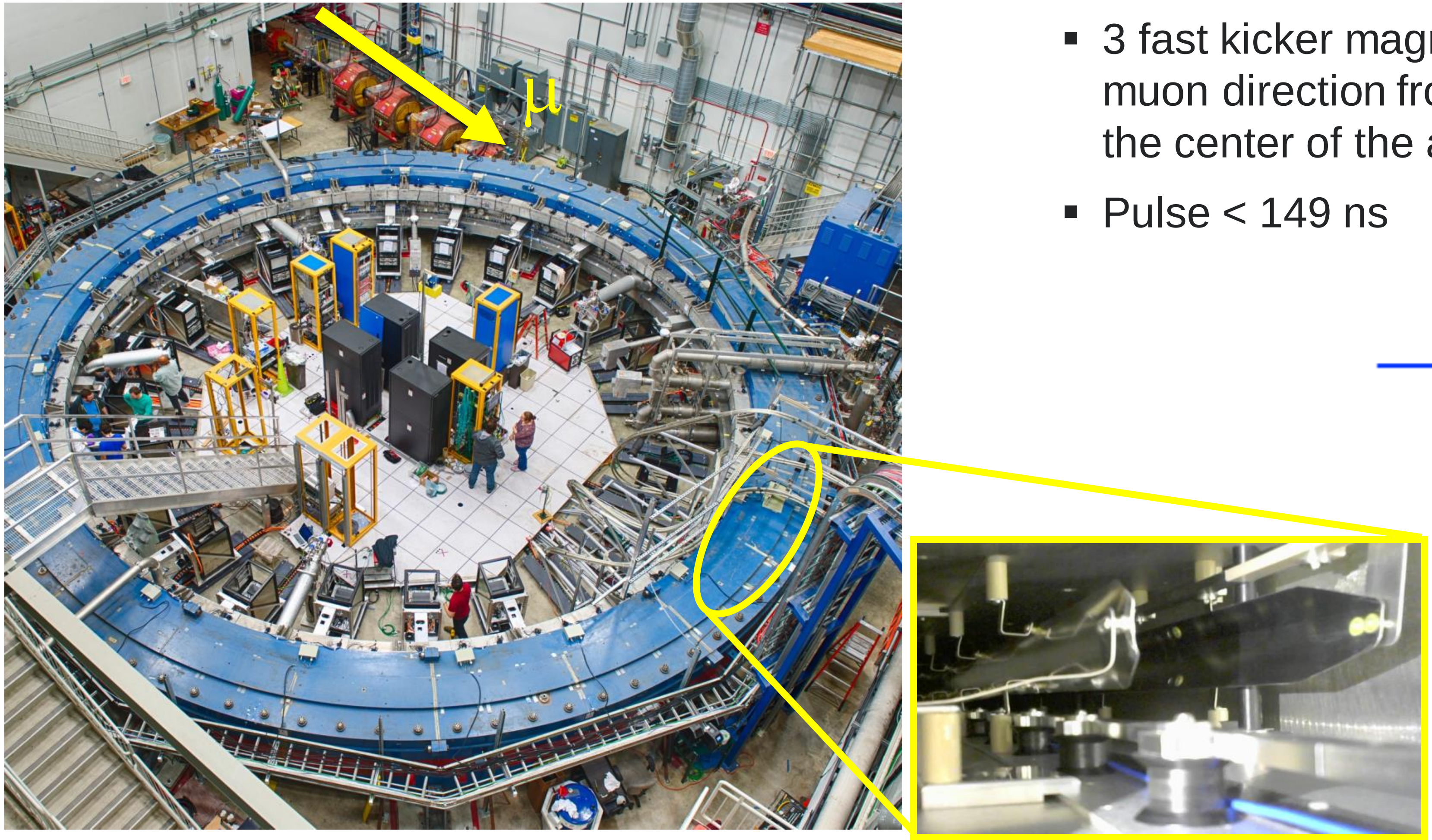
Inflector top view



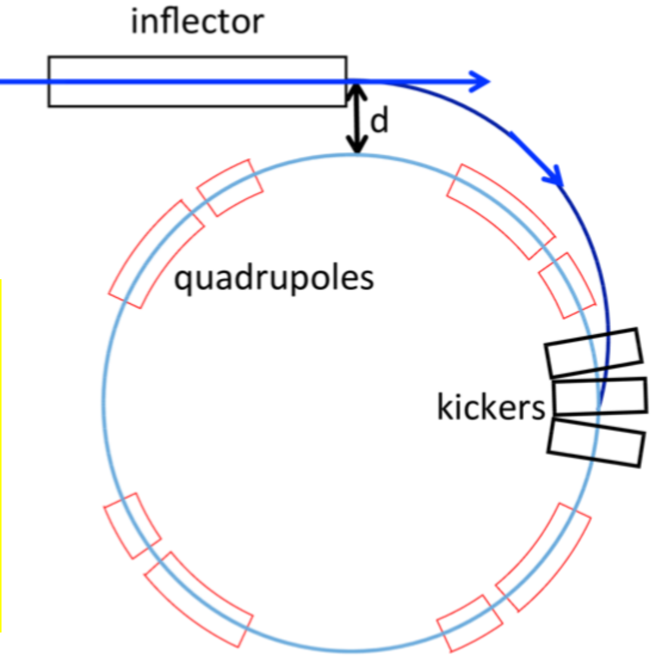
Inflector cross section

MUON INJECTION & STORAGE: KICKER MAGNET

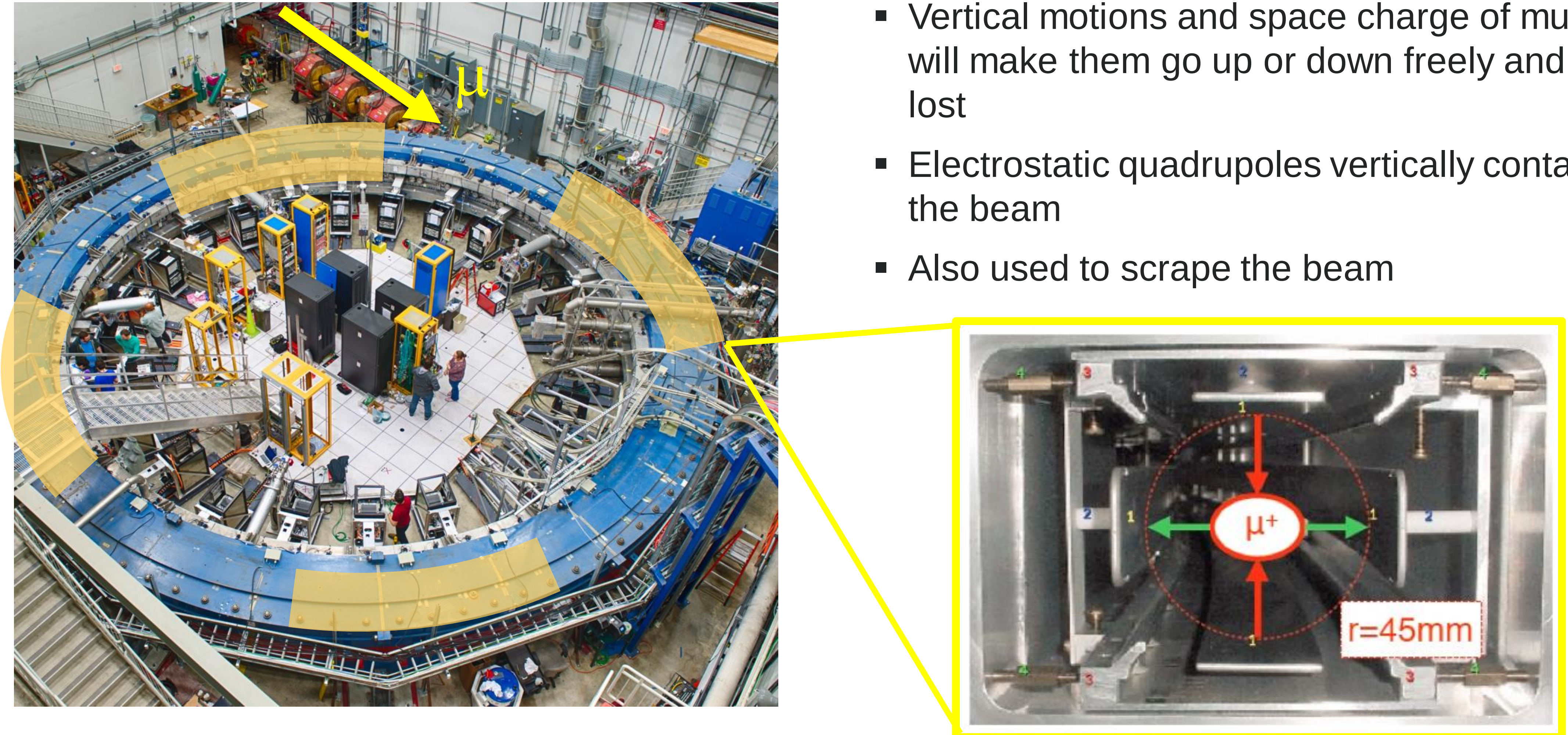
- 3 fast kicker magnets (Kickers) tweak the muon direction from injection trajectory to the center of the aperture
- Pulse < 149 ns



Kicker plates



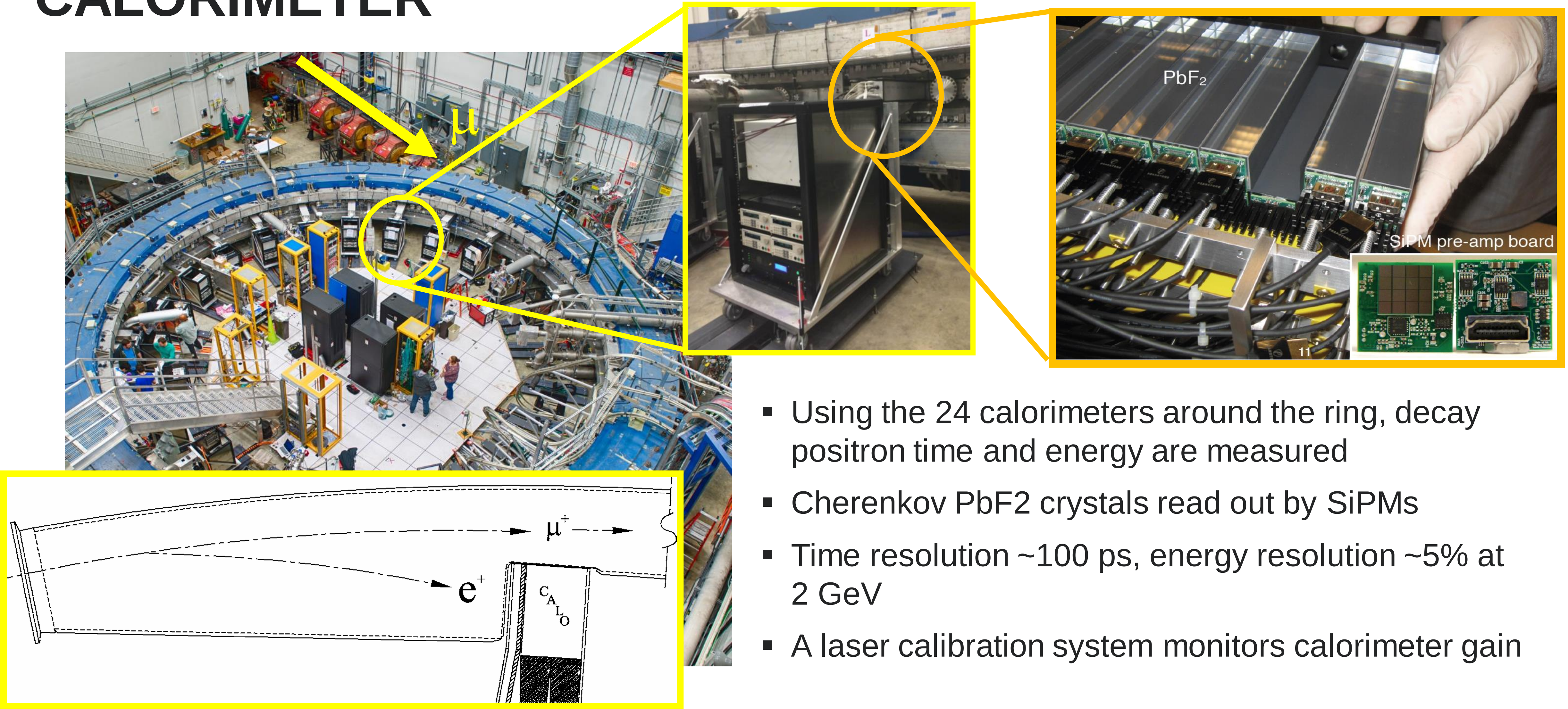
MUON INJECTION & STORAGE: ELECTROSTATIC QUADRUPOLES



- Vertical motions and space charge of muons will make them go up or down freely and get lost
- Electrostatic quadrupoles vertically contain the beam
- Also used to scrape the beam

Quadrupole plates

MEASURING MUON SPIN PRECESSION FREQUENCY: CALORIMETER



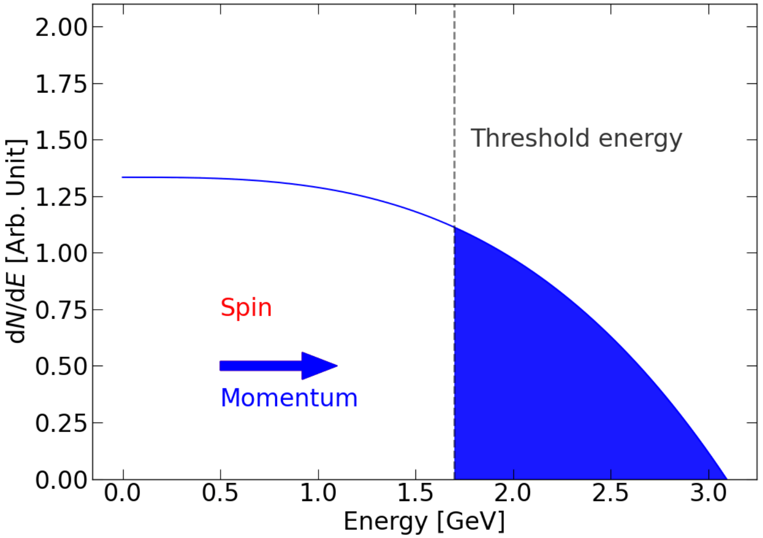
- Using the 24 calorimeters around the ring, decay positron time and energy are measured
- Cherenkov PbF2 crystals read out by SiPMs
- Time resolution ~100 ps, energy resolution ~5% at 2 GeV
- A laser calibration system monitors calorimeter gain

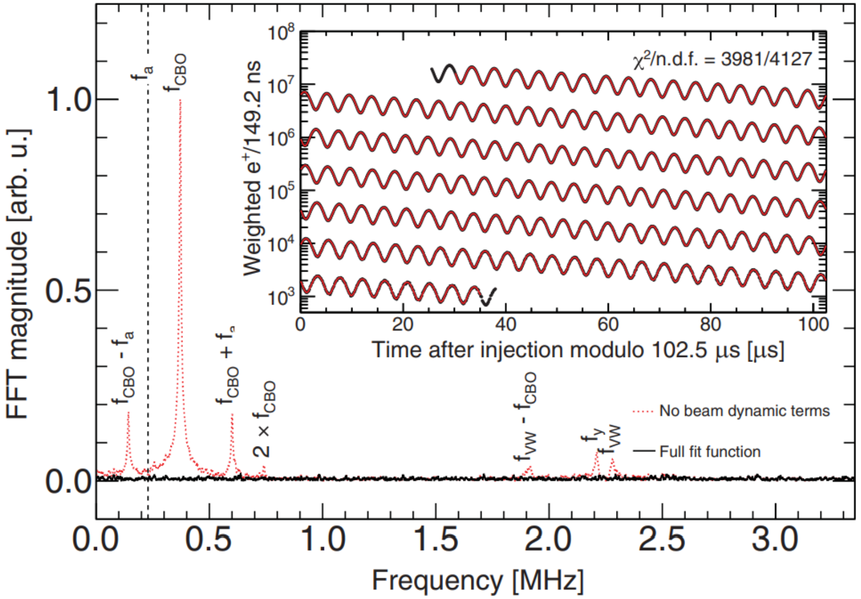
MEASURING MUON SPIN PRECESSION FREQUENCY

- Due to self-analyzing parity violating weak decay, high energy positrons are emitted more along the direction of the muon spin
- Decay positron distribution above an optimal energy threshold of E~1.7 GeV, over time, produces "wiggle" plot
- Main feature in the wiggle plot coming from the spin precession ω_a and muon lifetime τ

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

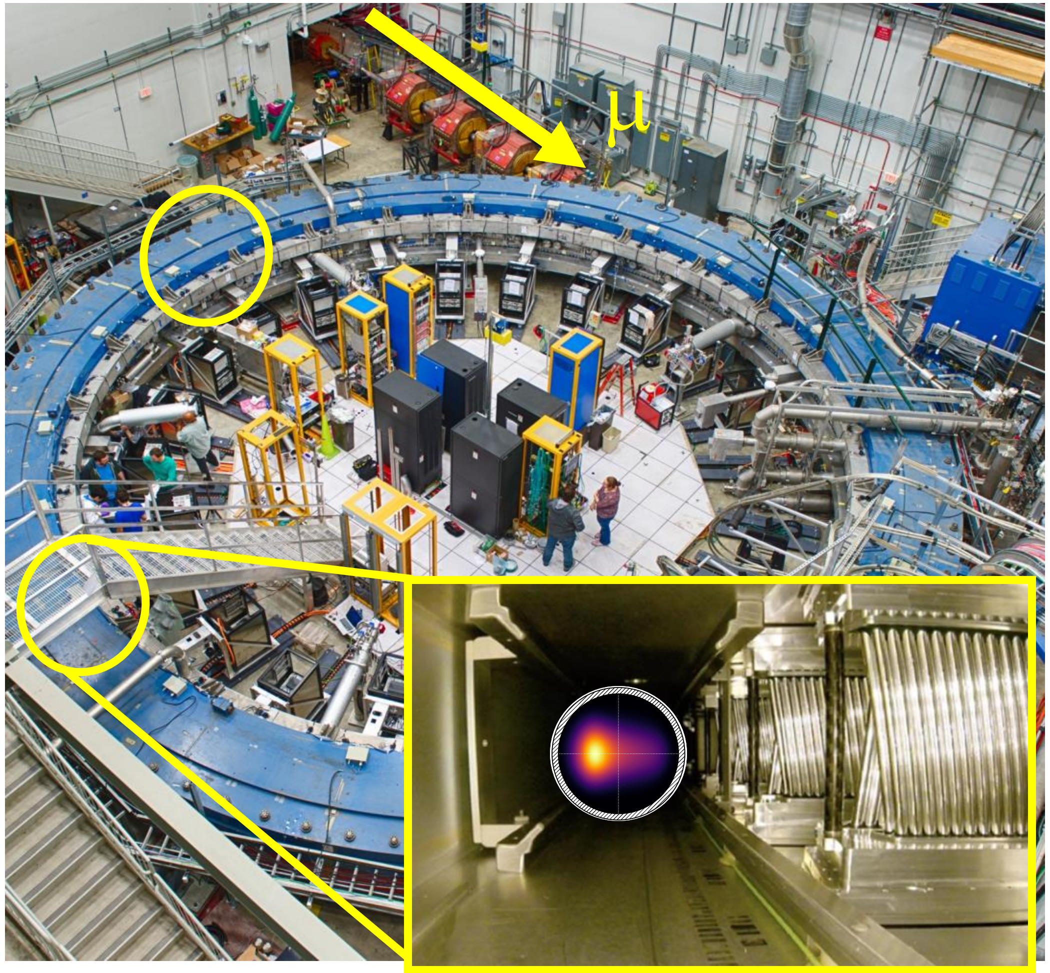
- Additional features of beam dynamics is captured through more complicated fit function

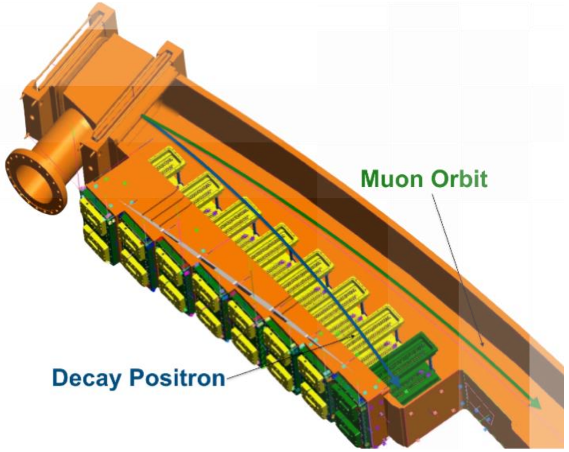


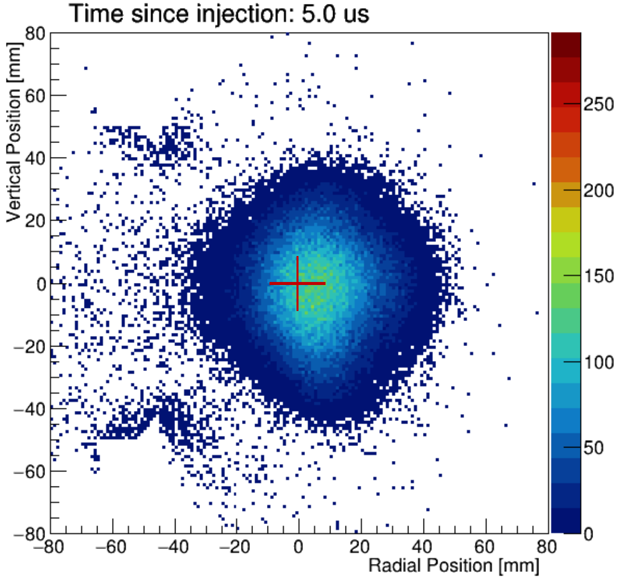


PHYSICAL REVIEW LETTERS 131, 161802 (2023)

MEASURING THE MUON DISTRIBUTION: STRAW TRACKERS







- 2 in-vacuum straw trackers
  - Sub-millimeter tracking uncertainty
  - Track reconstruction allows relating decayed positrons to the initial muon orbit
- Beam profile tells the muon distribution inside the storage region
- It provides a handle on beam dynamics

BEAM DYNAMICS CORRECTIONS

$$\omega_a = f_{clock} \cdot \omega_a^m \boxed{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}$$

Unblinding factor

Frequency from wiggle plot

Beam dynamics related corrections

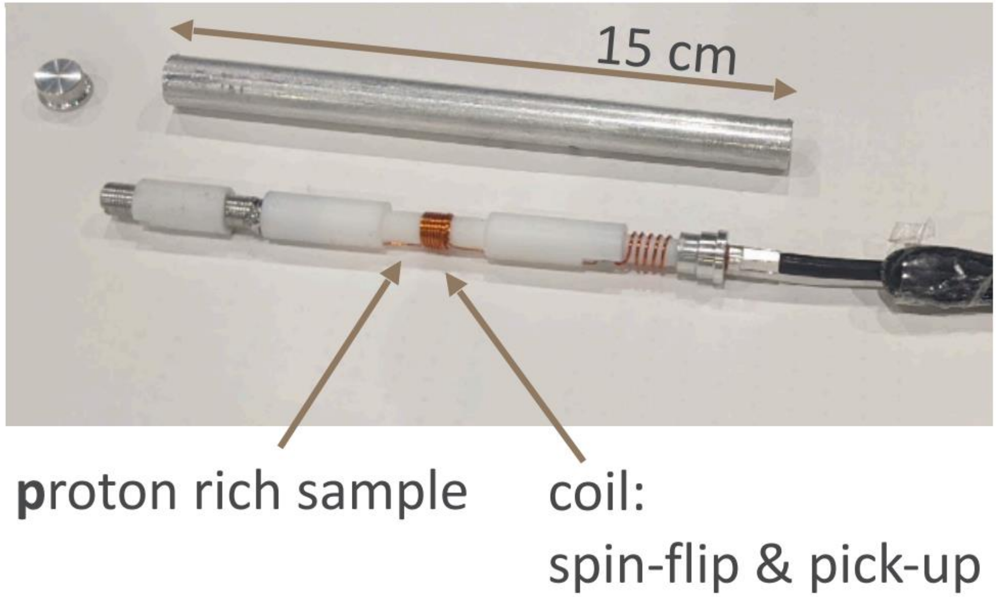
- Tracker measurements combining with simulations are used to understand the beam dynamics inside the storage ring
- Additional dynamics-related corrections in two categories are applied:
  - Spin dynamics: corrections since spin precession frequencies contain additional terms.
    - C_e: Electric field correction. Muons not exactly at magic momentum, $a_\mu - \frac{1}{\gamma^2 - 1} \neq 0$.
    - C_p: Vertical beam motion correction. $\vec{\beta} \cdot \vec{B} \neq 0$.
  - Varying phases:
    - C_{pa}: ω_a phase depends on the decay position inside the beam duct due to detector acceptance. With changing beam profile over time, bias rises and needs correction.
    - C_{dd}: Differential decay. Boosted muon lifetime is momentum dependent, whose magnitude changes over time. Needs correction.
    - C_{ml}: Muon loss is also momentum dependent.

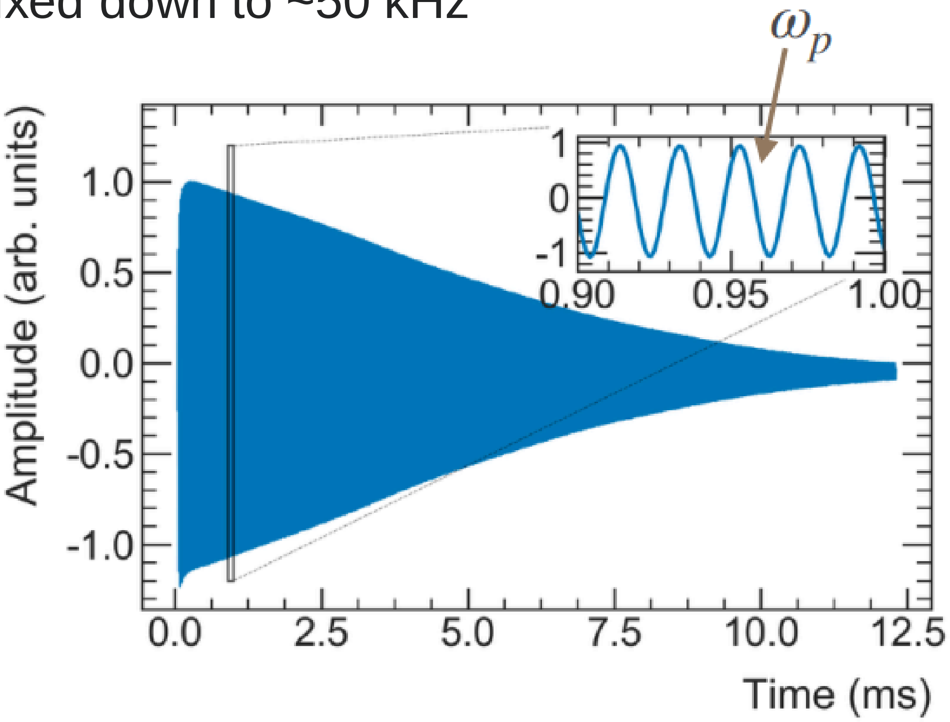
MEASURING MAGNETIC FIELD: PULSED NMR

- We measure the magnetic field through measuring Larmor frequency of shielded protons using pulsed Nuclear Magnetic Resonance (NMR)

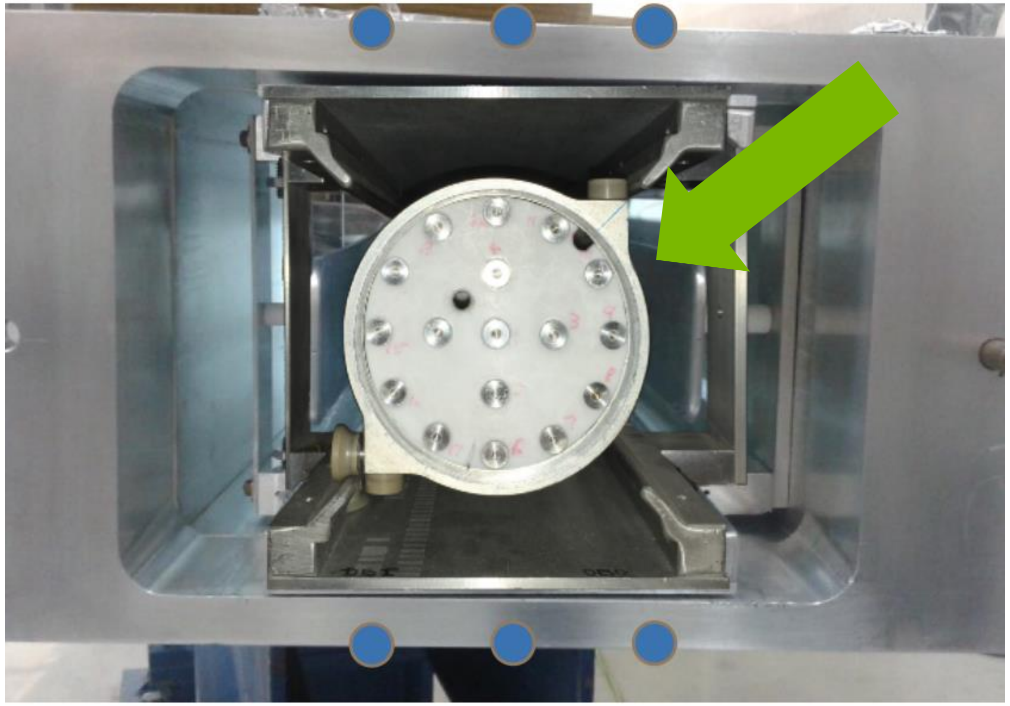
$$B = \frac{\hbar\omega_p(T)}{2\mu_p(T)}$$

- A cylindrical proton-rich sample (petroleum jelly)
- Coil provides an RF $\pi/2$ pulse to rotate the sample magnetization. The same coil picks up the signal during relaxation. Bottom right plot shows the signal mixed down to ~50 kHz





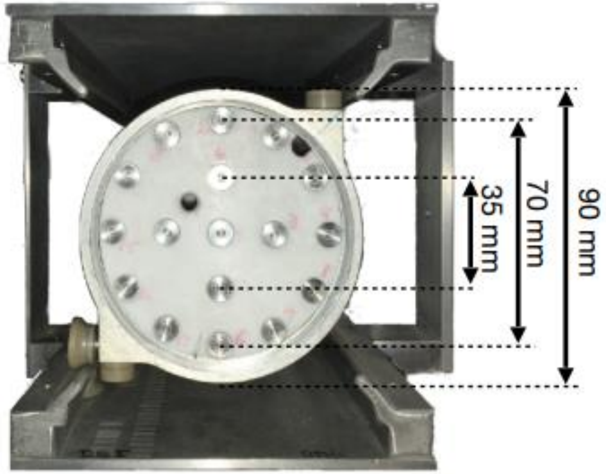
MEASURING MAGNETIC FIELD



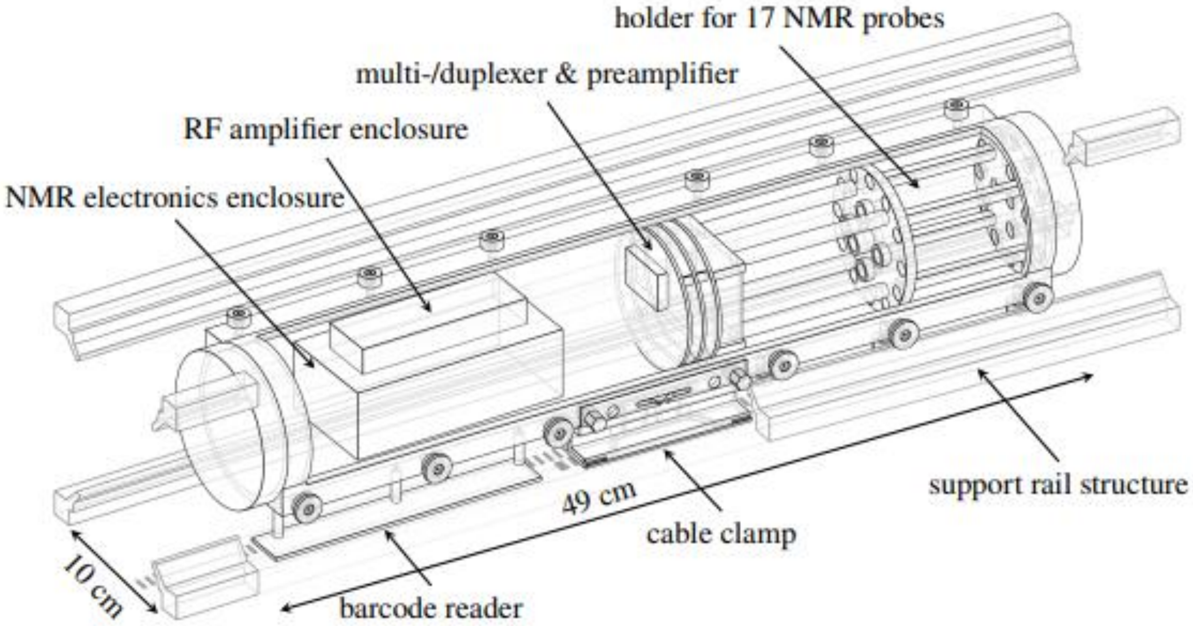
A cross-sectional view of the beam duct with trolley.
Fixed probes are above and below.

- 17 probes are mounted on a trolley
  - Measure in the muon storage region
  - Capable of tracking higher order multipoles, more sampling points around the ring
  - Only intermittent (every 3~5 days) as trolley blocks the storage ring

THE TROLLEY



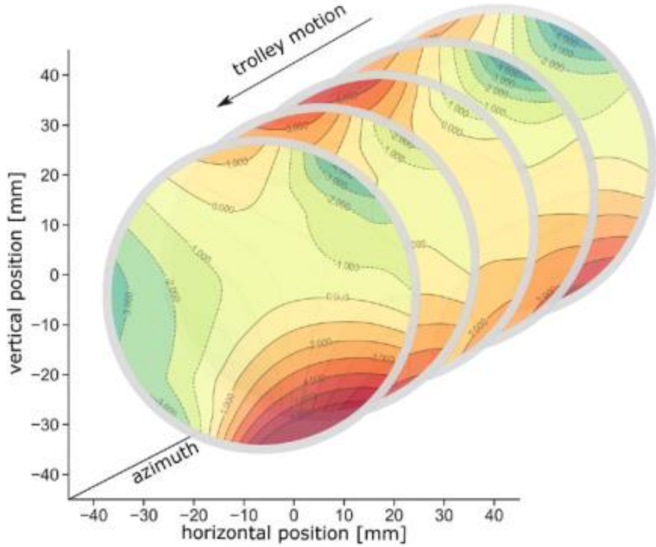
- The trolley can move around the ring and measure the magnetic field at different azimuthal slices: $B(x, y, \phi = \phi_k)$
- Barcode system around the ring tells the location of the trolley

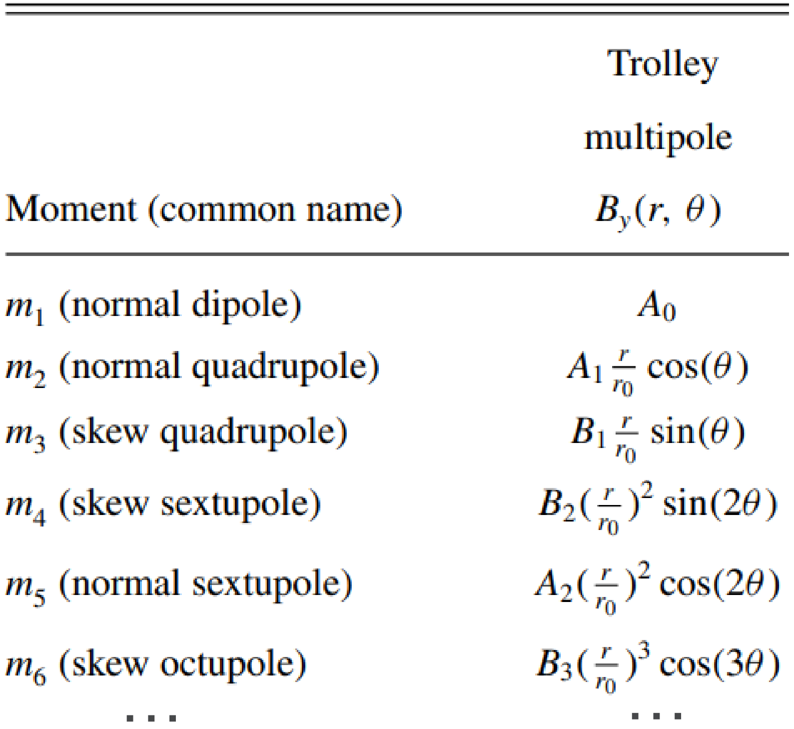


THE TROLLEY

- Moving around the ring at 1~1.5 cm/s, taking data at 2Hz: ~9000 2D field maps around the ring
- At each of these slices, the spatial dependence of the magnetic field can be expressed as multipole moments m_i, which comes from the general solution to the source-free Laplace equation in polar coordinates.

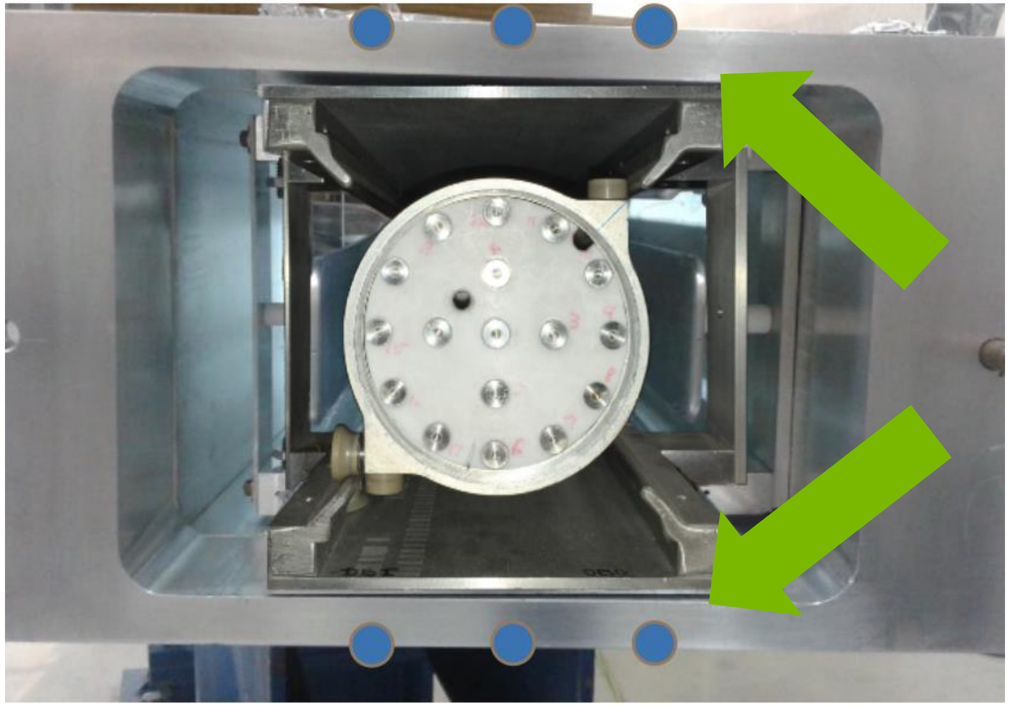
$$B \approx B_y = A_0 + \sum_{n=1} \left(\frac{r}{r_0}\right)^n [A_n \cos(n\theta) + B_n \sin(n\theta)]$$





Moment (common name)	Trolley multipole $B_y(r,\ \theta)$
m_1 (normal dipole)	A_0
m_2 (normal quadrupole)	$A_1 \frac{r}{r_0} \cos(\theta)$
m_3 (skew quadrupole)	$B_1 \frac{r}{r_0} \sin(\theta)$
m_4 (skew sextupole)	$B_2 (\frac{r}{r_0})^2 \sin(2\theta)$
m_5 (normal sextupole)	$A_2 (\frac{r}{r_0})^2 \cos(2\theta)$
m_6 (skew octupole)	$B_3 (\frac{r}{r_0})^3 \cos(3\theta)$
…	…

MEASURING MAGNETIC FIELD

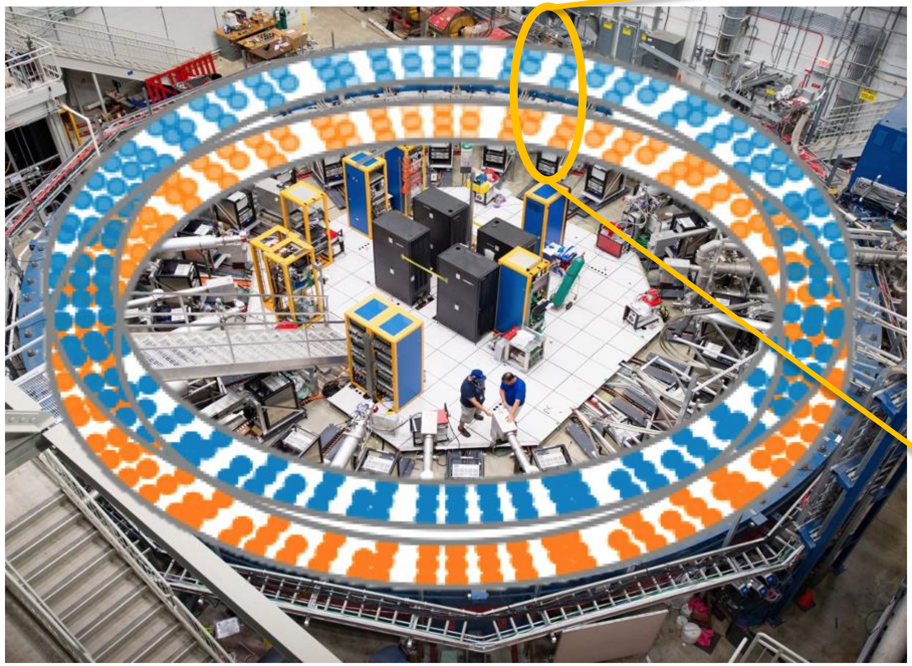


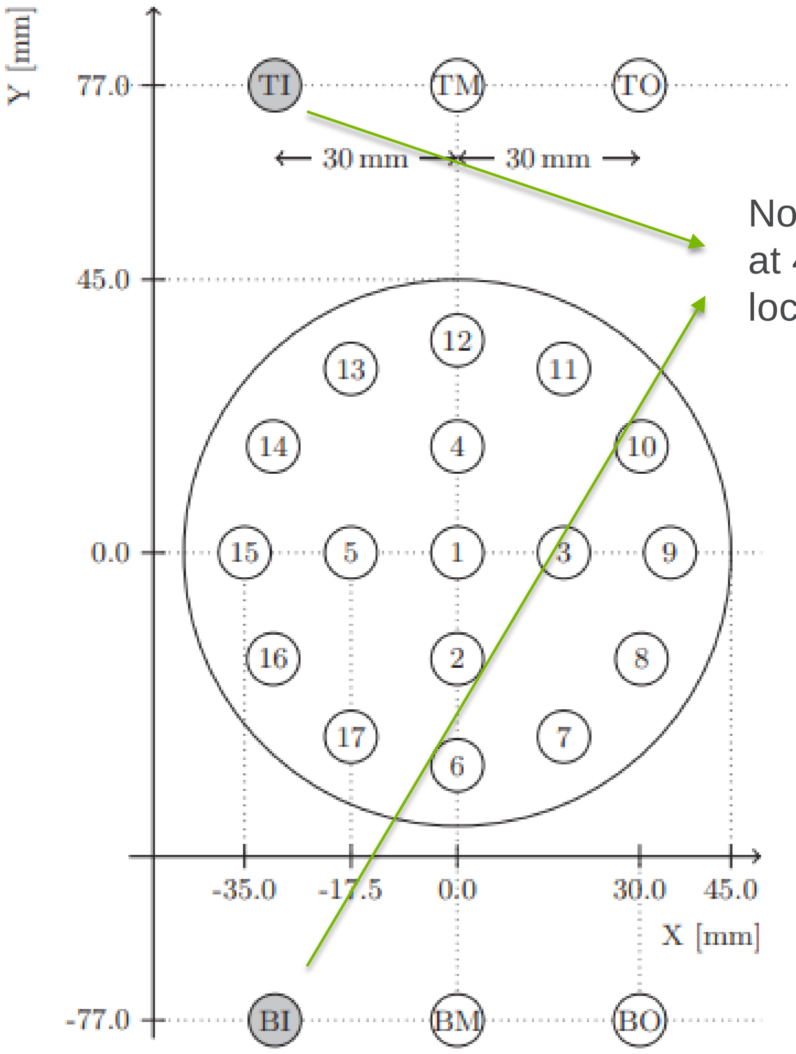
A cross-sectional view of the beam duct with trolley. Fixed probes are above and below.

- Fixed probes (FPs) permanently installed outside of the muon storage region track the magnetic field over time

FIXED PROBES: MAGNETIC FIELD OVER TIME

- 378 NMR probes around the ring out of the beam duct
  - 72 azimuthal location, in groups of 6 and 4 probes
  - Symmetric arrangement at each location
- Monitors the field change over time every ~1s
- Only six (four) moments can be calculated at a six-probe (four-probe) station. In practice we track up to m_5
- Help to interpolate the magnetic field over time





Not exist at 4-probe locations

MAGNETIC FIELD ANALYSIS

calibration → field maps → tracking → muon weighting → transients → $\tilde{\omega}'_p$

$$\tilde{\omega}'_p = f_{\text{calib}} \frac{\int \omega'_p(x,y,\phi;t)\cdot M(x,y,\phi;t)dV}{\int M(x,y,\phi;t)dV}\left(1+B_k+B_q\right)$$

- Trolley probes are calibrated against a plunging probe containing a cylindrical water sample and a known factor can be used to link the measurement to a value for spherical samples
- Trolley runs provides fine measurements of $\omega'_p(x,y,\phi)$ at limited time. Fixed probes have rich information on the field over time. Interpolation from the two provides magnetic field at all locations and all time
- Magnetic field weighted by muon distribution
- Transient field corrections are applied

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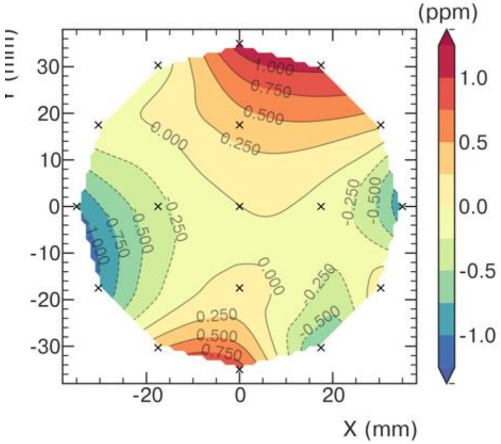

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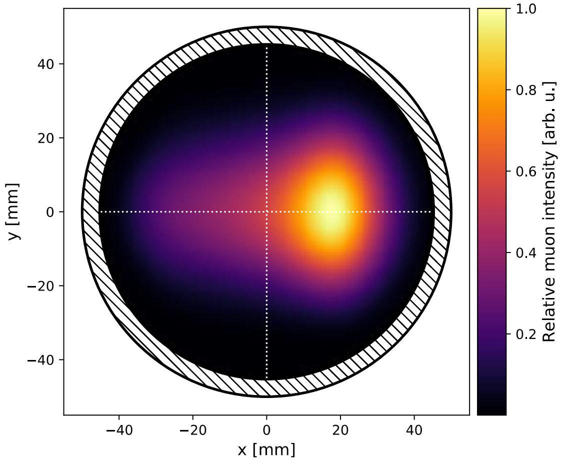

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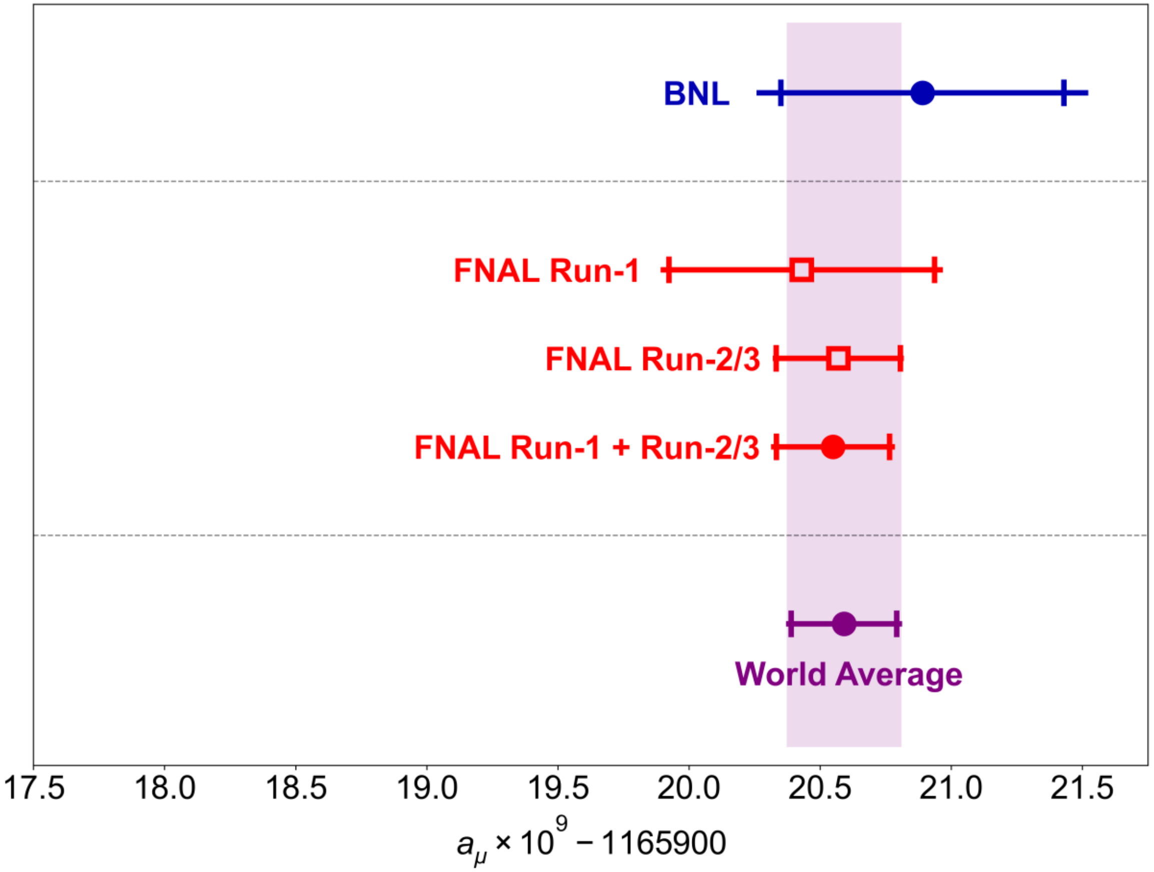
RUN 2/3 RESULT



- With spin precession frequency ω_a and Larmor frequency $\tilde{\omega}'_p$ of shielded protons in a spherical sample experiencing the same field as the stored muons from the NMR probes, the anomalous muon magnetic moment a_μ becomes:

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Known literature values

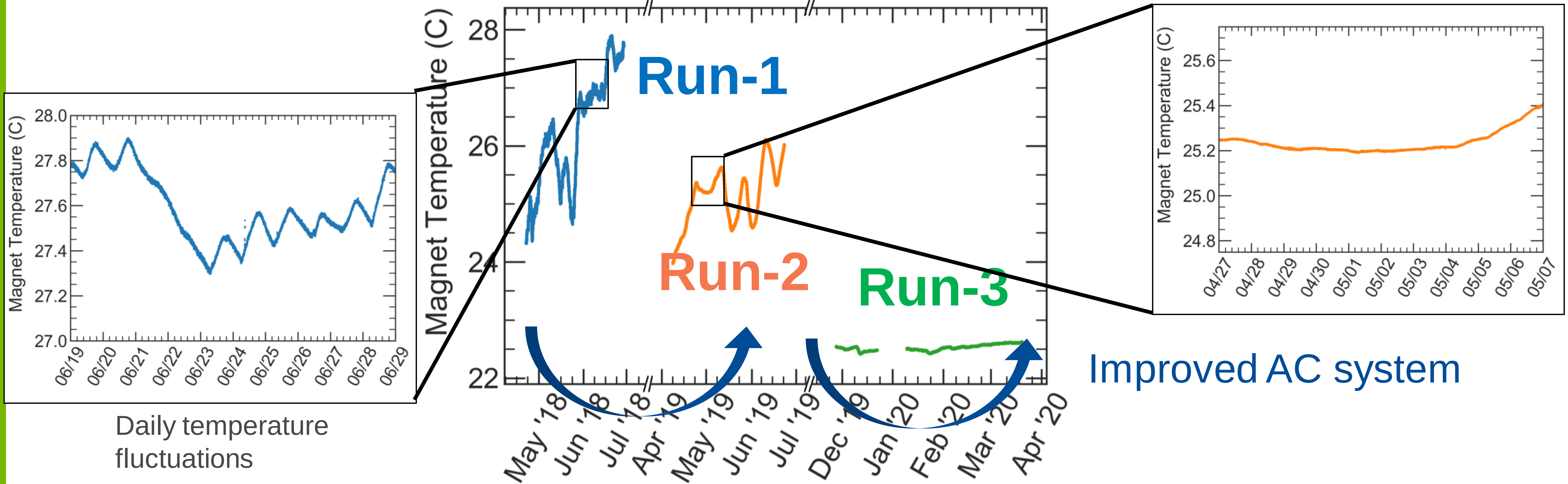
a_μ(FNAL; Run-2/3) = 0.00 116 592 057(25) [215 ppb]

[ppb]	Run-1	**Run-2/3**	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- Near-equal improvement; we are still statistically dominated
- The systematic uncertainty of 70 ppb surpasses our goal of 100 ppb!

SYSTEMATIC IMPROVEMENTS: FIELD STABILITY

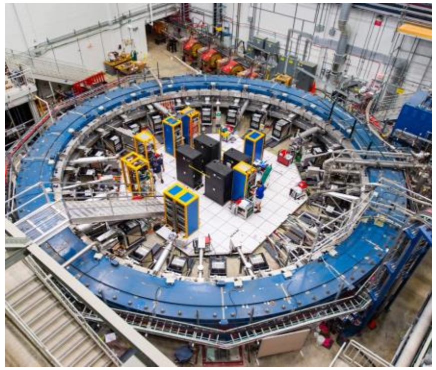
- From Run 1 to Run 2/3, improvement in temperature stability has made the magnetic field more stable

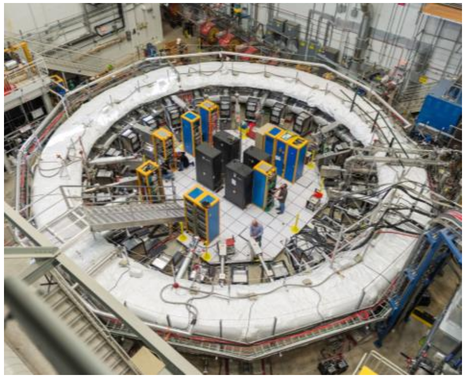


Daily temperature fluctuations

Improved AC system

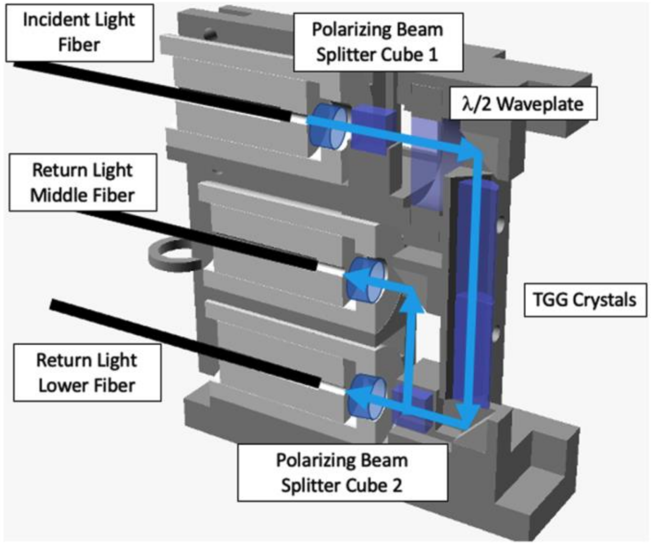
Added Insulation

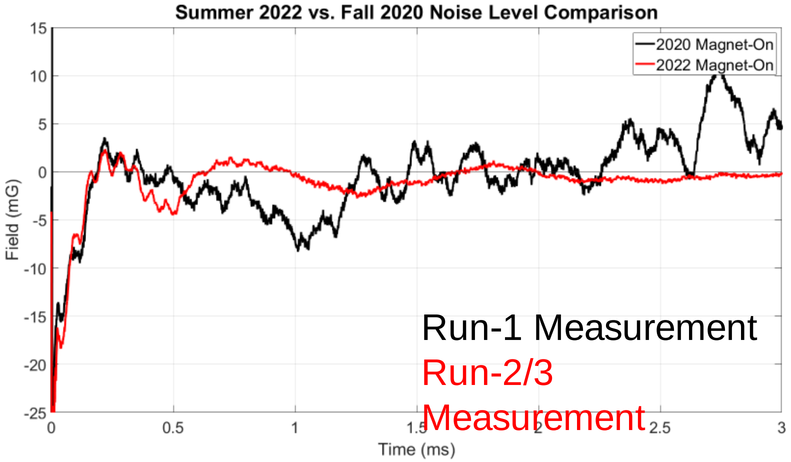




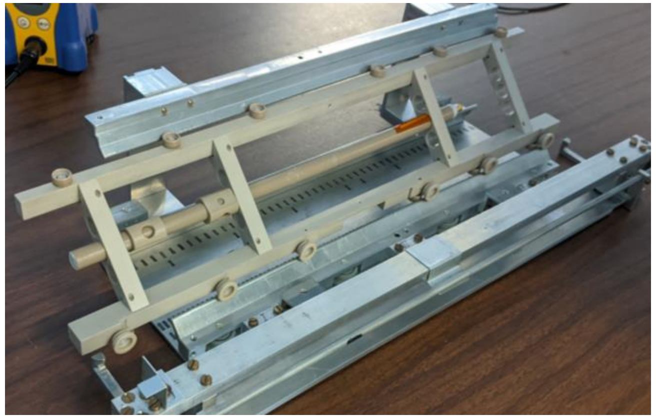
SYSTEMATIC IMPROVEMENTS: FIELD TRANSIENTS

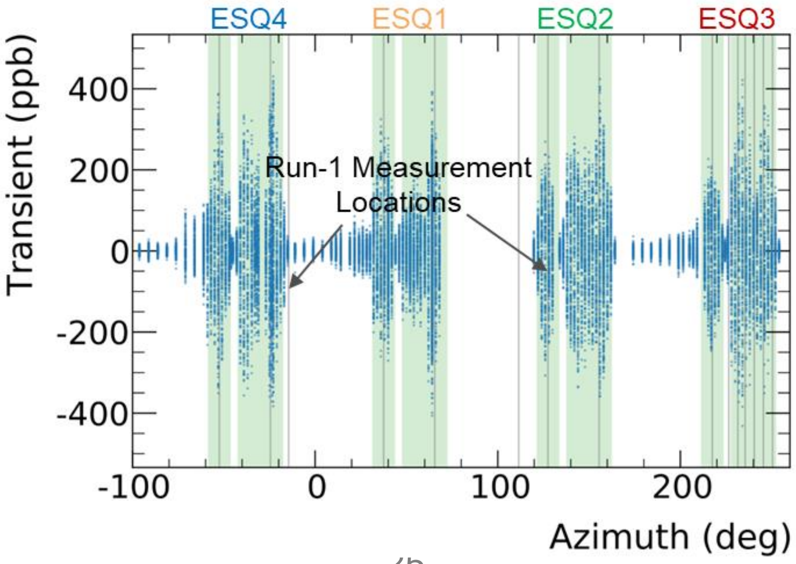
- Improvements systematic studies reduced the uncertainties in field kicker transient corrections and quadrupole transient corrections
  - Fast kicker magnets generate eddy currents, which give rise to transient magnetic field
  - During muon fills, the ESQs vibrate mechanically, and introduce oscillating magnetic fields





Fiber-based Faraday magnetometer for measuring kicker transients (left); measured transient field after improving vibration damping (right)



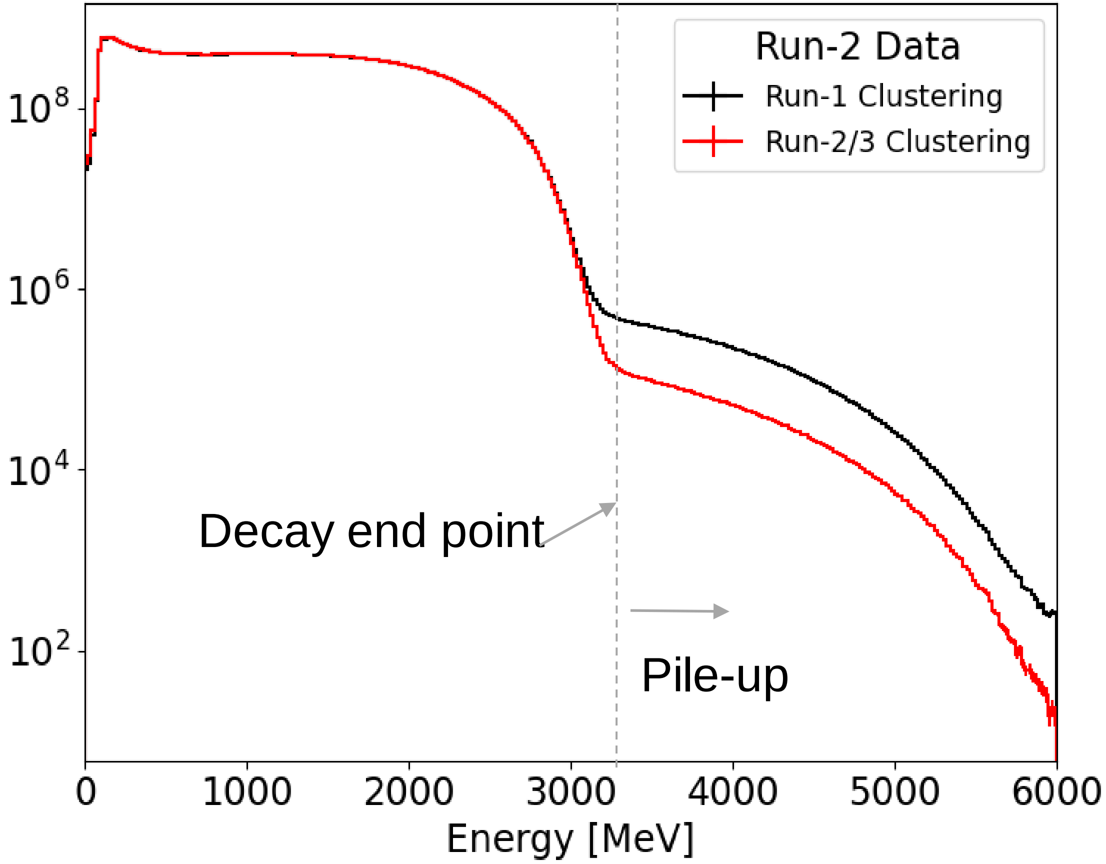


ESQ transients were measured at more locations for Run 2/3

SYSTEMATIC IMPROVEMENTS: ANALYSIS IMPROVEMENTS

For example:

- 2 positrons arriving at same time can be mistaken for 1 which can bias ω_a
- Reduce uncertainty with:
  - Better pileup reconstruction
  - Improved correction algorithm

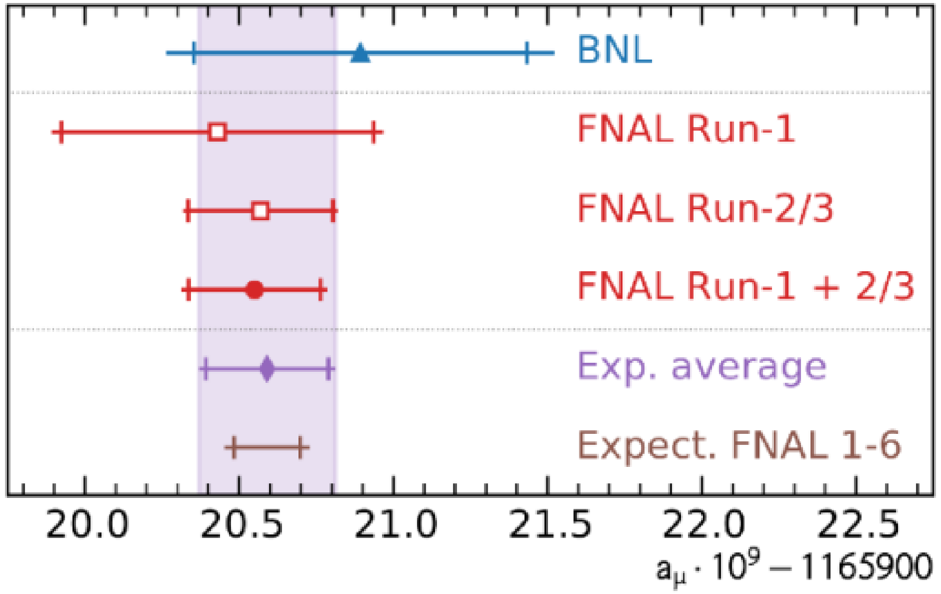


Decay end point

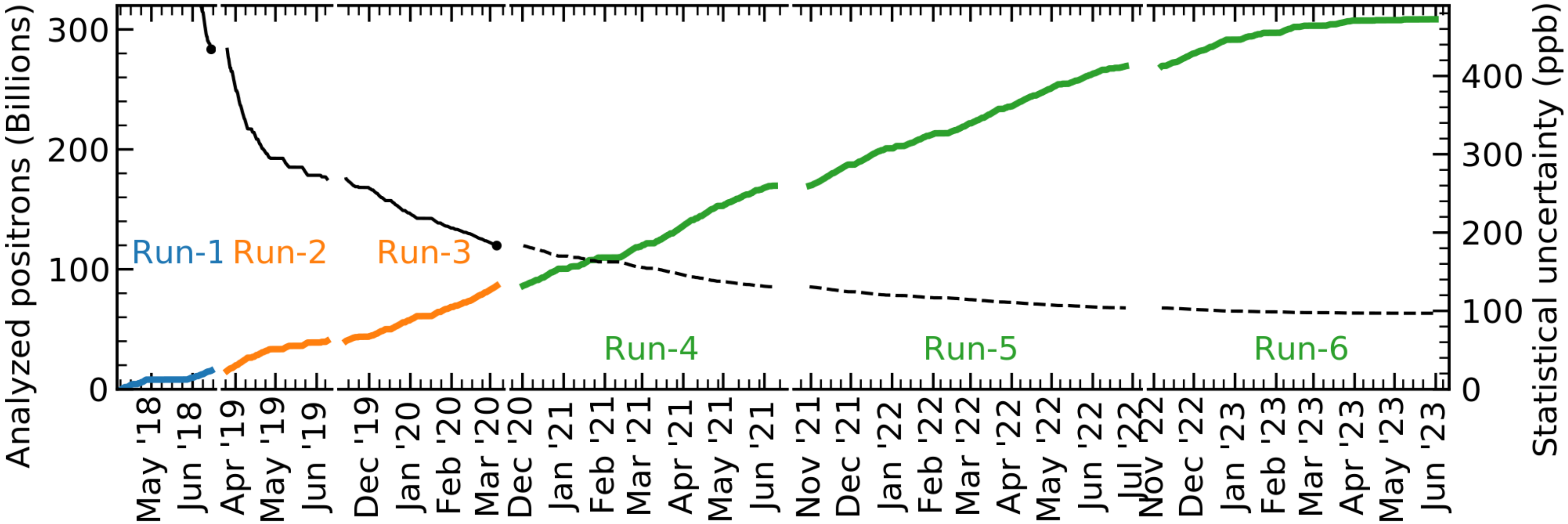
Pile-up

WHAT'S NEXT?

- By the end of Run 6, exceeded the 21 x BNL TDR goal
- Analysis for the dataset Run 4-6 ongoing. Expect to publish the full dataset in 2025
  - On track to reach and slightly surpass final precision goal of 140 ppb
  - Likely still statistics limited
- Other analyses include Muon EDM and BSM searches (CPT/LV & Dark Matter)



* Last bar ***only*** to show size of uncertainty. Mean value not shifted from the current experiment mean and is meaningless.



MUON g-2 COLLABORATION

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

USA National Labs
- Argonne
- Brookhaven
- Fermilab

182 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

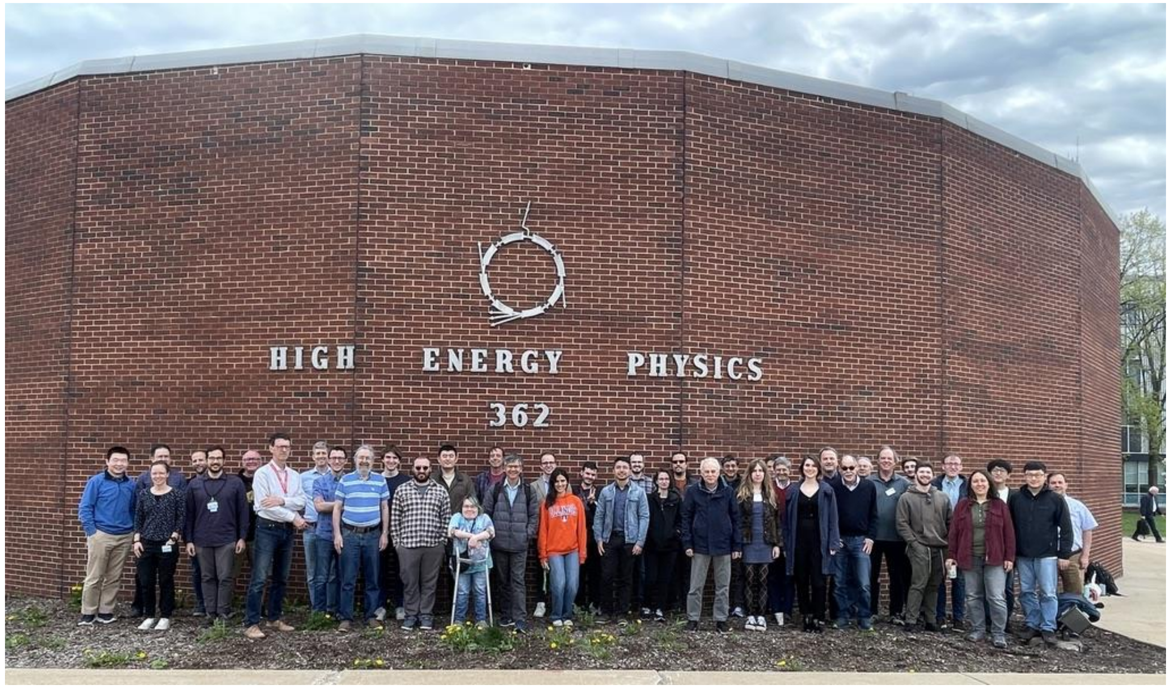
Germany
- Dresden
- Mainz

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

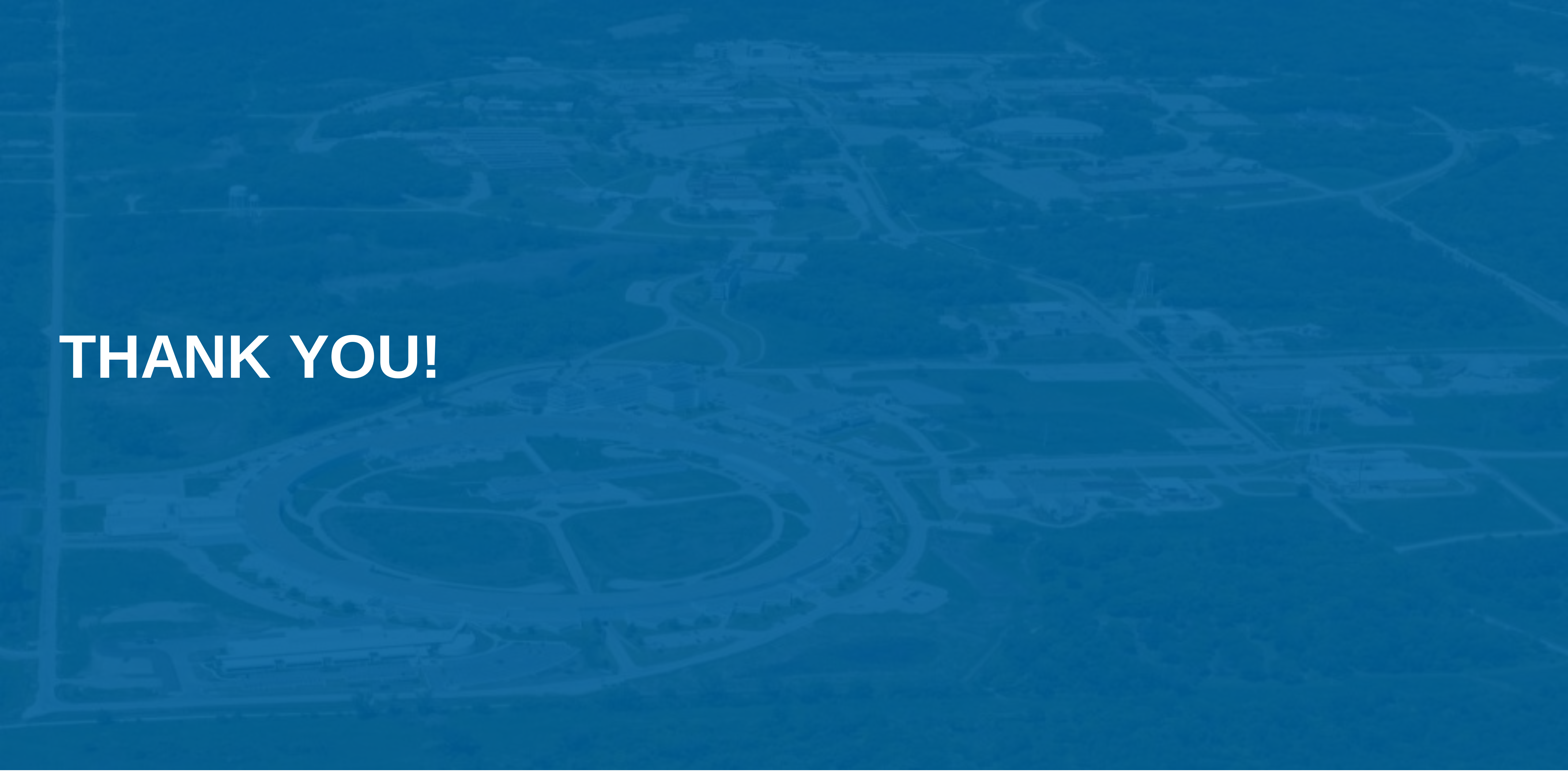
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

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



Collaboration meeting at Argonne National Laboratory, April 2024



THANK YOU!

BACKUP SLIDES

E34 AT J-PARC

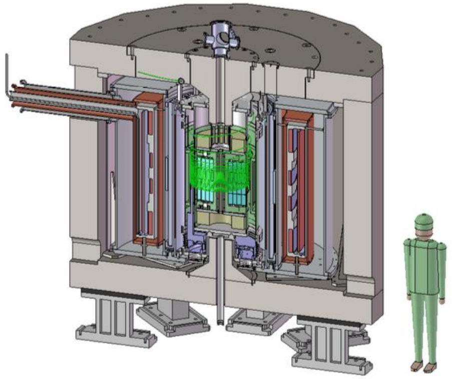


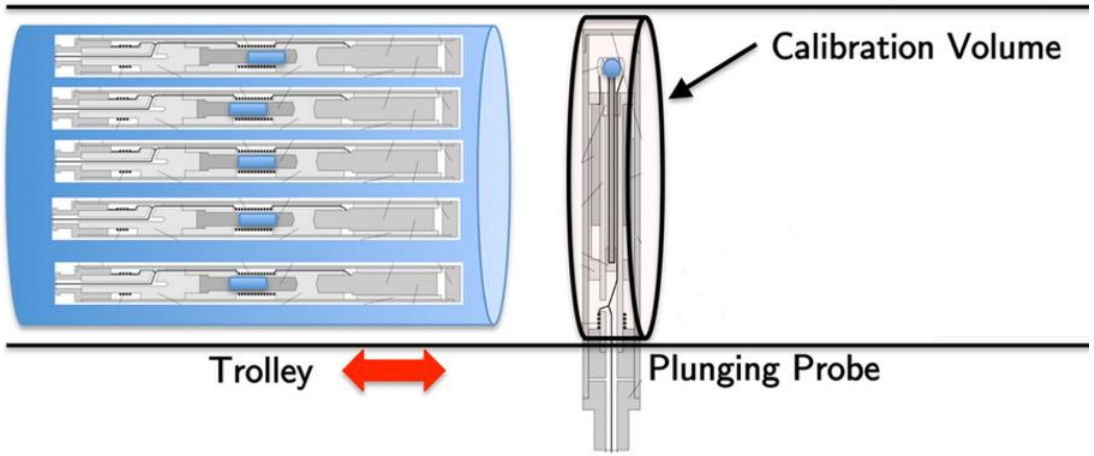
Photo credit: Reidar Hahn, Fermilab

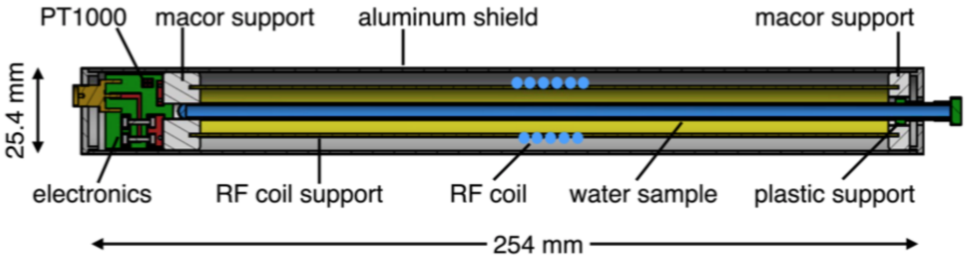
	E34 @ JPARC	E989 @ Fermilab
Beam	Ultra-cold muon beam ($p = 300$ MeV/c)	Magic-momentum ($p = 3.094$ GeV/C)
Polarization	$P_{max} = 50\%$	$P \approx 97\%$
Magnet	MRI-like solenoid ($r_{storage} = 33$cm)	Storage ring (7m radius)
B-field	3 Tesla	1.45 Tesla
B-field gradients	Small gradients for focusing	Try to eliminate
E-field	None	Electrostatic quadrupole
Current sensitivity goal	~400 ppb (possibly 100 ppb)	140 ppb

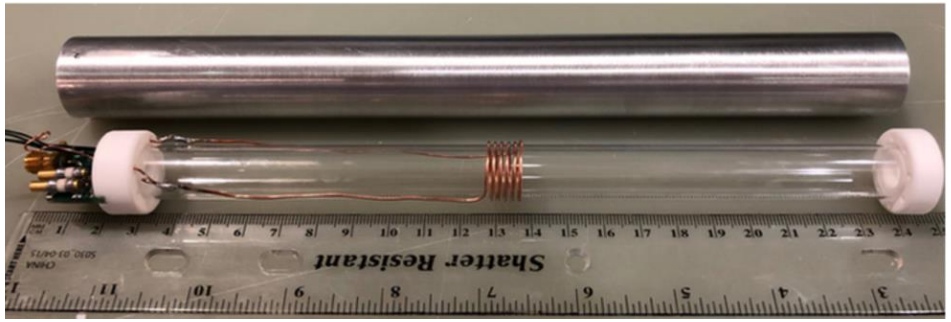
MAGNETIC FIELD ANALYSIS

calibration
field maps
tracking
muon weighting
transients
$\tilde{\omega}'_p$

$$\tilde{\omega}'_p = f_{\text{calib}} \frac{\int \omega'_p(x,y,\phi;t)\cdot M(x,y,\phi;t)\,dV}{\int M(x,y,\phi;t)\,dV}\left(1+B_k+B_q\right)$$







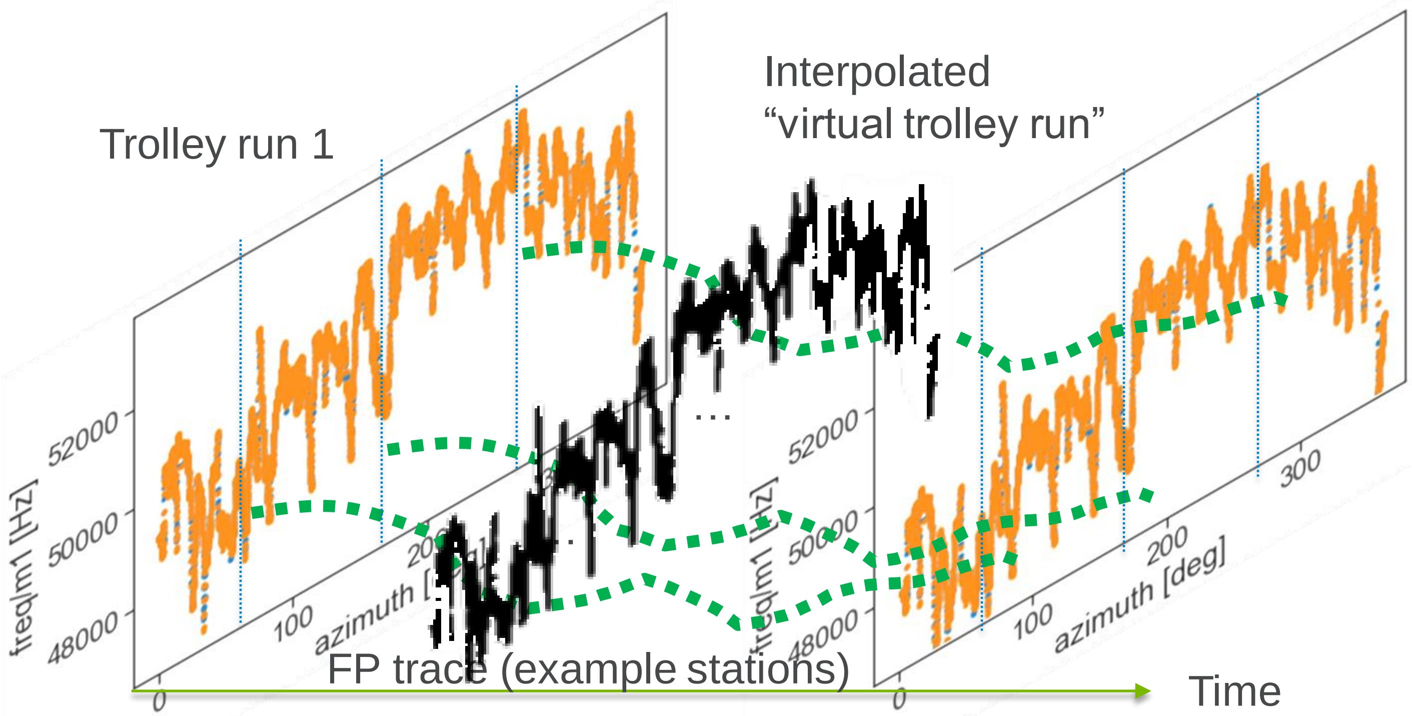
- Trolley probes are absolutely calibrated using a plunging probe with a cylindrical water sample
- Swapping the probes to measure the magnetic field in the same calibration volume

MAGNETIC FIELD ANALYSIS

calibration → field maps → tracking → muon weighting → transients → $\tilde{\omega}'_p$

$$\tilde{\omega}'_p = f_{\text{calib}} \frac{\int \omega'_p(x,y,\phi;t) \cdot M(x,y,\phi;t)dV}{\int M(x,y,\phi;t)dV}\left(1 + B_k + B_q\right)$$

- The magnetic moment multipoles are extracted from the trolley and fixed probe measurements
- $\omega'_p(x,y,\phi;t)$ around the storage ring at any given time is then interpolated, each multiple independently
- The magnetic field is then azimuthally averaged



Trolley run 2
(Some periods are bound by single side)

Interpolated
“virtual trolley run”

Trolley run 1

FP trace (example stations)

Time

MAGNETIC FIELD ANALYSIS

calibration
field maps
tracking
muon weighting
transients
$\tilde{\omega}'_p$

$$\tilde{\omega}'_p = f_{\text{calib}} \frac{\int \omega'_p(x,y,\phi;t)\cdot M(x,y,\phi;t)\,dV}{\int M(x,y,\phi;t)\,dV}\left(1+B_k+B_q\right)$$

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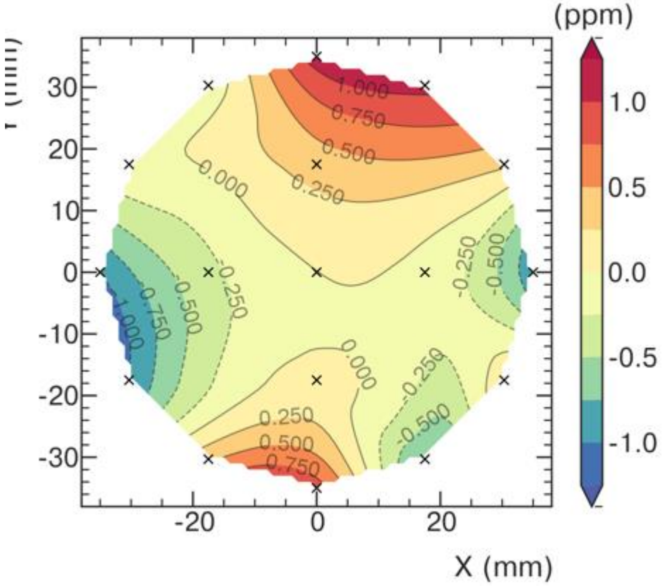
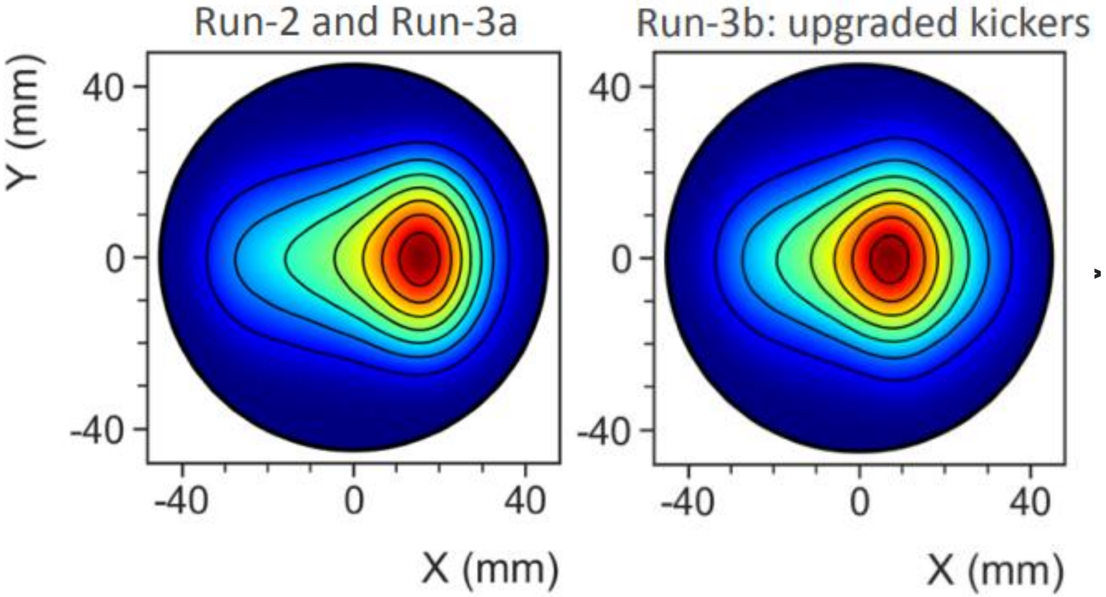


field maps $\omega'_p(x,y,\phi;t)$

×



muon distribution $M(x,y,\phi;t)$ from trackers + simulation to extrapolate from two stations to the whole ring

- Muon Weighting extracts the relevant magnet field for the muons

MAGNETIC FIELD ANALYSIS

calibration
field maps
tracking
muon weighting
transients
$\tilde{\omega}'_p$

$$\tilde{\omega}'_p = f_{\text{calib}} \frac{\int \omega'_p(x,y,\phi;t) \cdot M(x,y,\phi;t)\,dV}{\int M(x,y,\phi;t)\,dV} \left(1 + B_k + B_q\right)$$

- There are transient magnetic fields from kickers and electrostatic quadrupoles (components to keep the muons in the storage ring)
  - Very short-term behaviors on the order of sub-milliseconds to a few tens of milliseconds
  - Corrections and associated systematic uncertainties were obtained from dedicated studies
- Significantly reduced uncertainties in Run 2/3 (2019-2020)
  - Kicker transients: 37 ppb ⇒ 13 ppb
  - Quadrupole transients: 92 ppb ⇒ 20 ppb
  - Total field systematic uncertainty in Run 2/3 is 52 ppb (TDR goal 70 ppb)