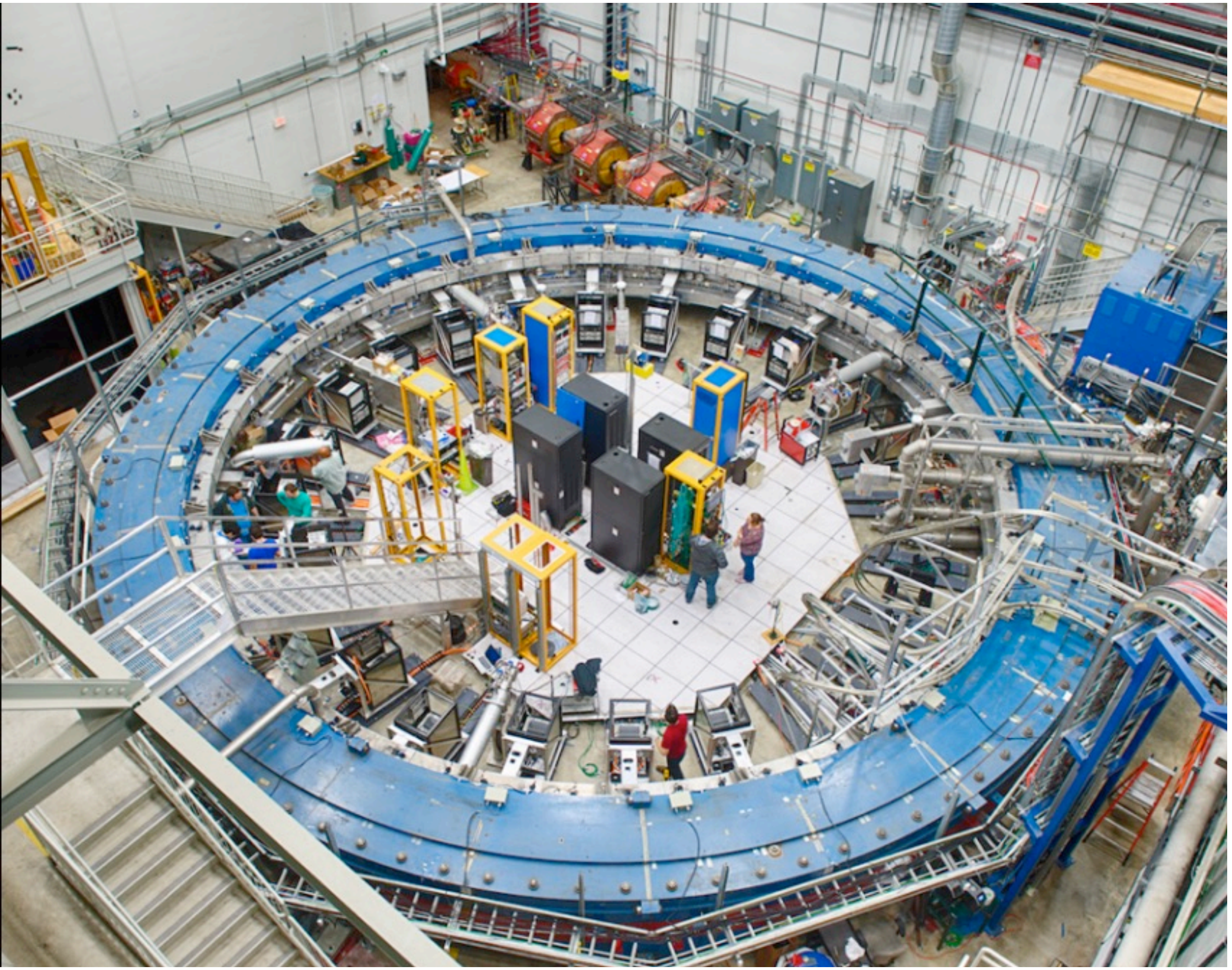


Tracking the magnetic field in the Fermilab Muon g-2 experiment

René Reimann
for the Muon g-2 collaboration

ICHEP 2022, Bologna

Jun 7th , 2022

PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

μ g-2

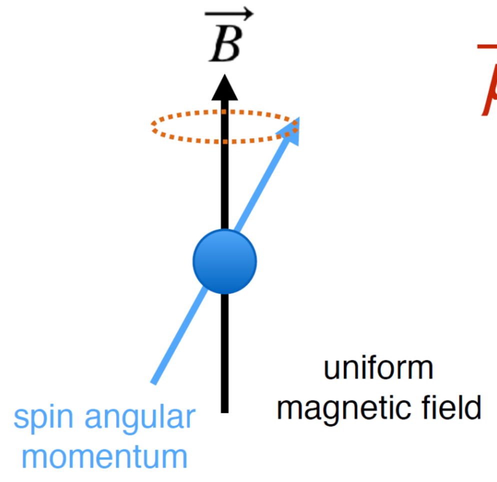
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

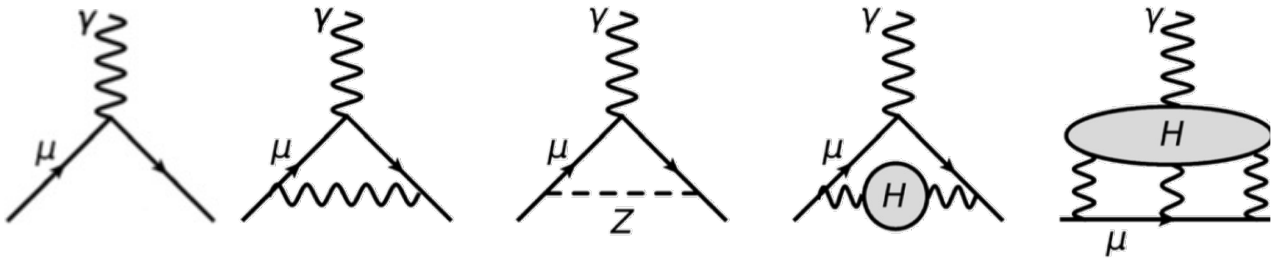
Muon g-2

$$\vec{\mu}_\mu = -g_\mu \frac{e}{2m_\mu}\vec{S}$$

magnetic moment   proportionality constant   spin

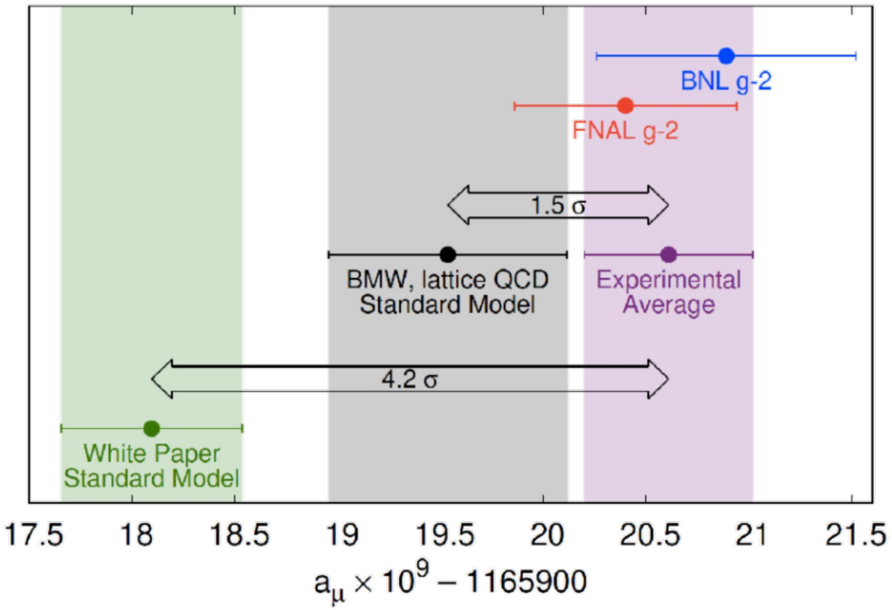


$\vec{\mu} \times \vec{B}$



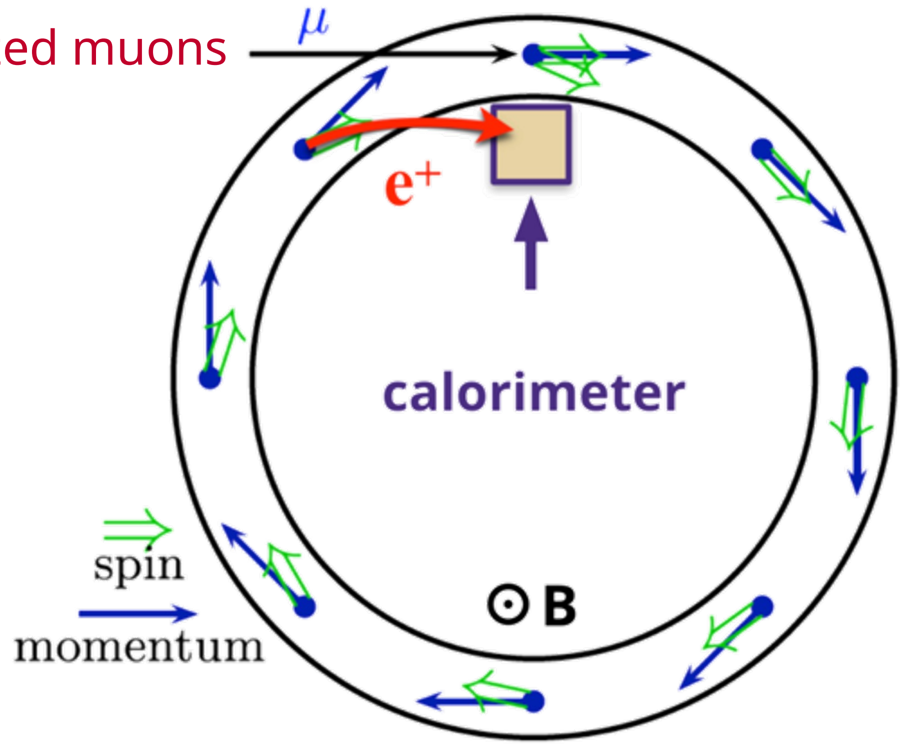
$$g = 2\left(\; 1 \;+\; a_\mu^{QED} \;+\; a_\mu^{EW} \;+\; a_\mu^{had} \;\right)$$

Figure: Zoltan Fodor



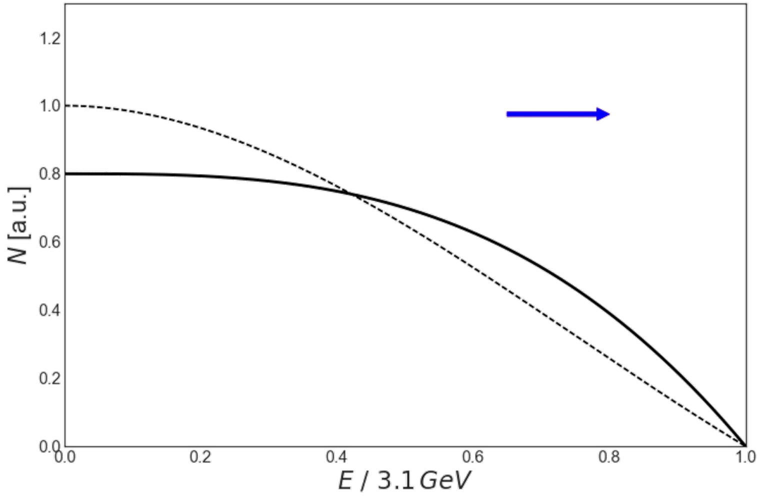
- Hadronic vacuum polarization dominates theoretical uncertainty.
- Dispersive and lattice QCD approach deviate
- Run 1 result consistent with BNL measurement

Measurement principle



Magnetic storage ring

- spin precession ω_S
- cyclotron motion ω_C



Measure energy of decay e^+

event rate varies with ω_a

$$\underbrace{\omega_S - \omega_C}_{\omega_a} = \underbrace{\frac{g_\mu - 2}{2}}_{a_\mu} \frac{e}{m_\mu} B$$

measured using nuclear magnetic resonance (NMR)

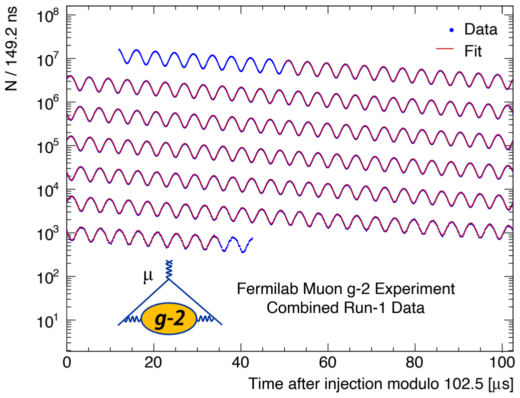
spin precession of protons

$$B = \frac{\hbar \tilde{\omega}'_p(T)}{2\mu'_p(T)}$$

Extracting a_μ

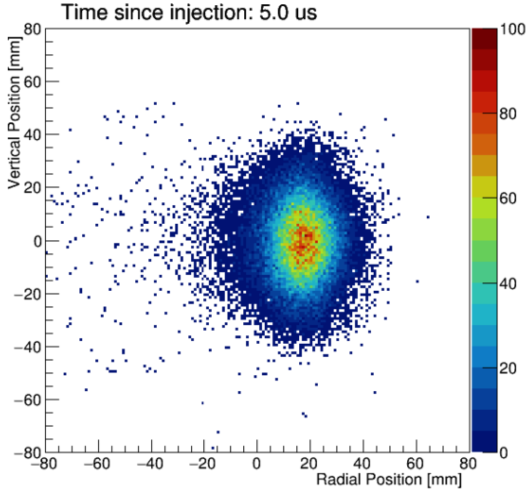
external measurements known to 25ppb

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



Talk by L. Cotrozzi
Quarks & Lepton Flavor Physics
Jul 8, 11:32

Talk by A. Driutti
Accelerators, Jul 7, 9:30AM

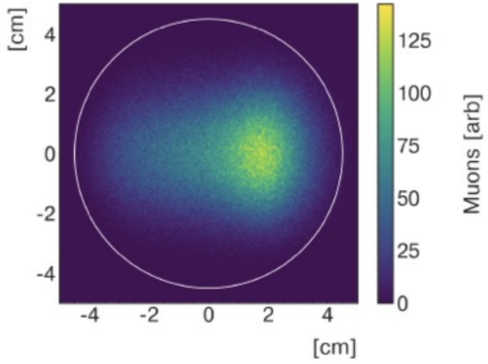


Anomalous spin precession frequency

Clock blinding

Muon beam dynamics corrections

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\,\omega_a^{\text{meas}}(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\,\langle M(x,y,\phi) \times \omega'_p(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

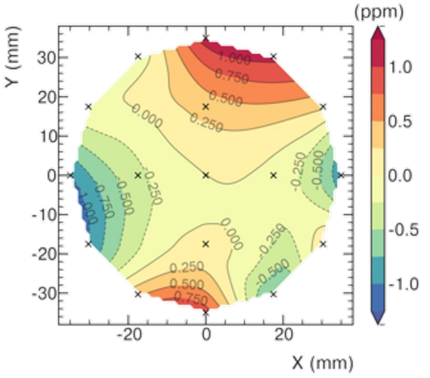


Spatial muon distribution

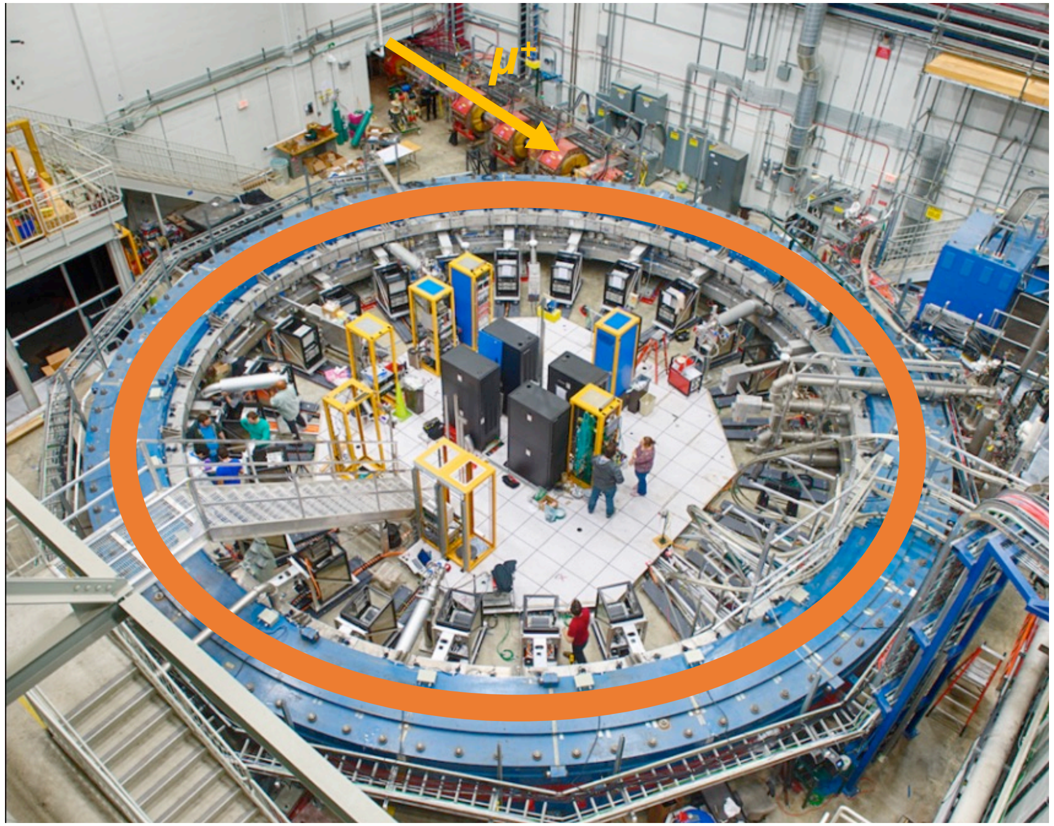
Spatial distribution of magnetic field

Transient magnetic fields

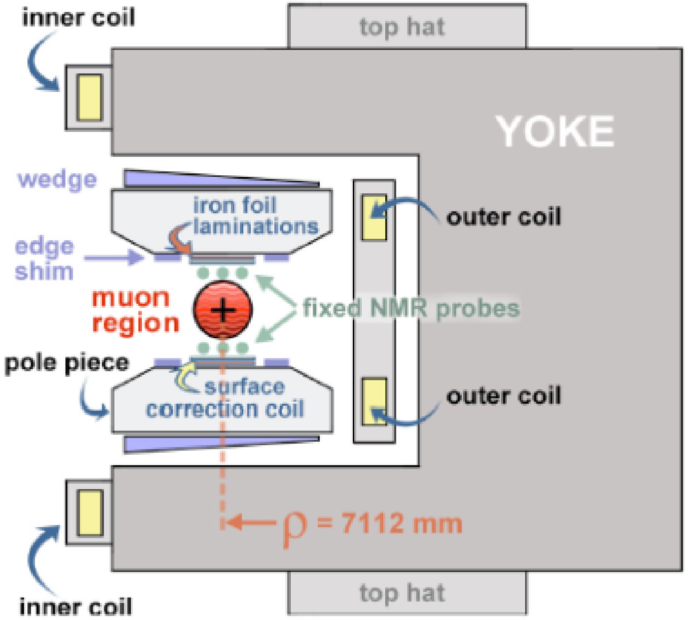
Calibration



Superconducting storage ring magnet

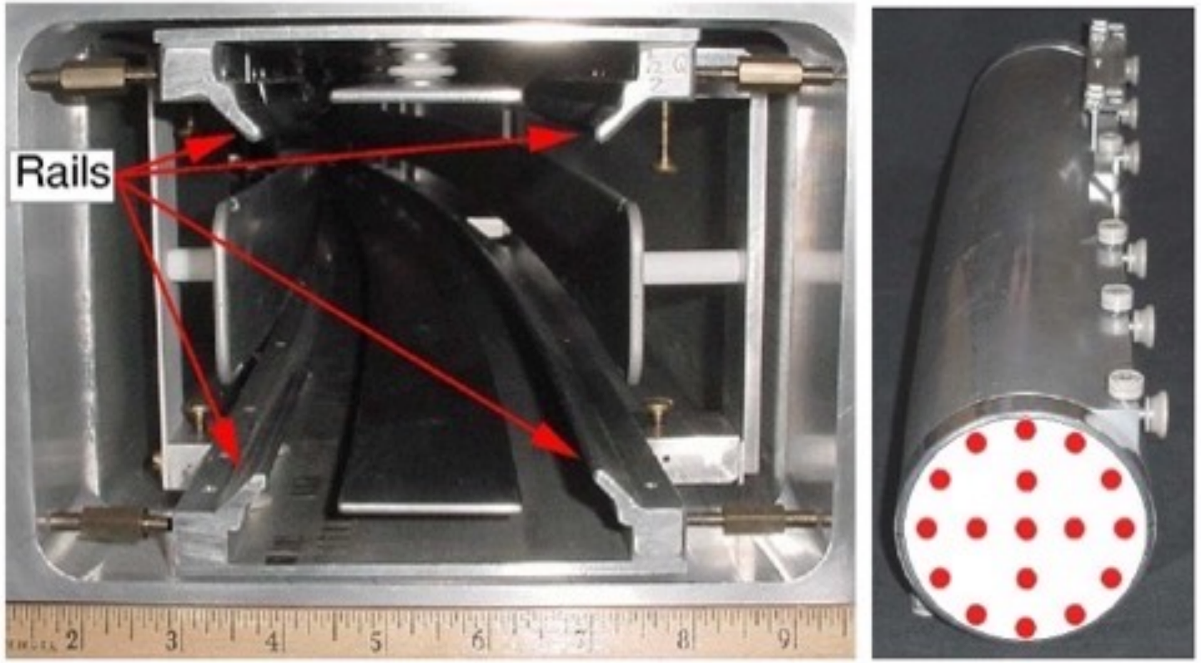


- $p_\mu^{magic} = 3.094 \frac{GeV}{c} \pm 0.5\%$
- 3 cryostats with 4 superconducting coils (5300 A)
- 1.45 T vertical magnetic field
- 90 mm muon storage region
- 180 mm gap for vacuum chambers



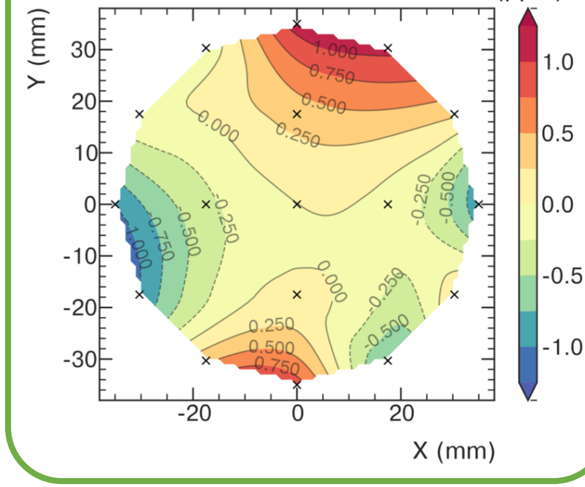
Trolley System

- 17 NMR probes
- Measures spatial field distribution in storage region
- Pulled through ring every ~3 days

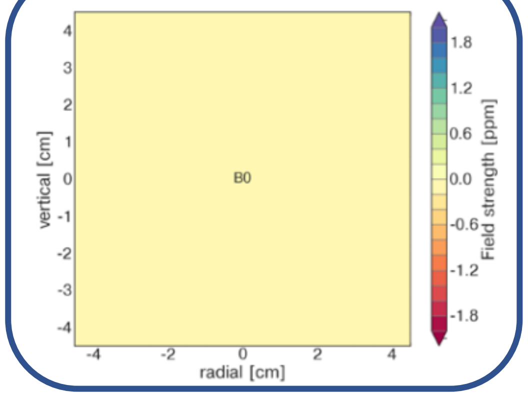


Spatial distribution of field

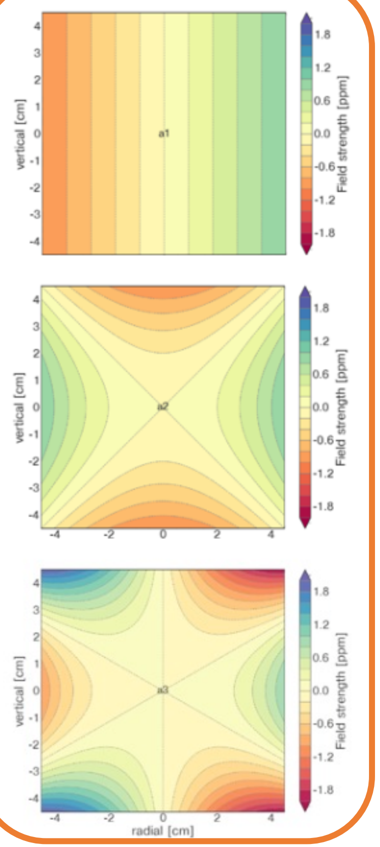
$$B(r,\theta) = B_0 + \sum_{n=1}^{4} \left(\frac{r}{r_0}\right)^n [a_n \cos(n\theta) + b_n \sin(n\theta)]$$

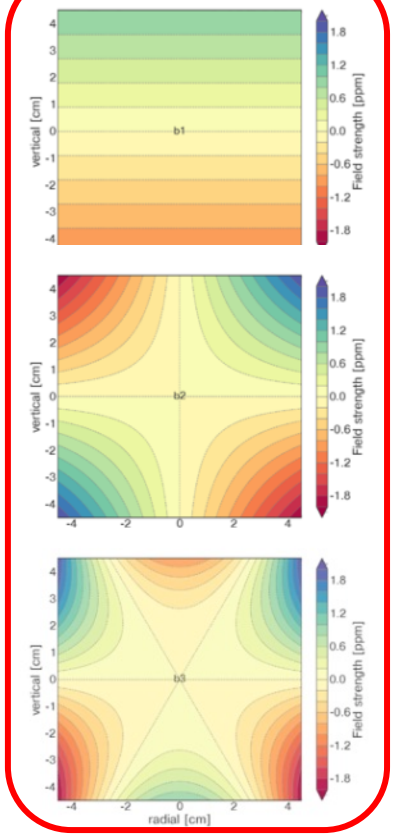


azimuthal slice



dipole



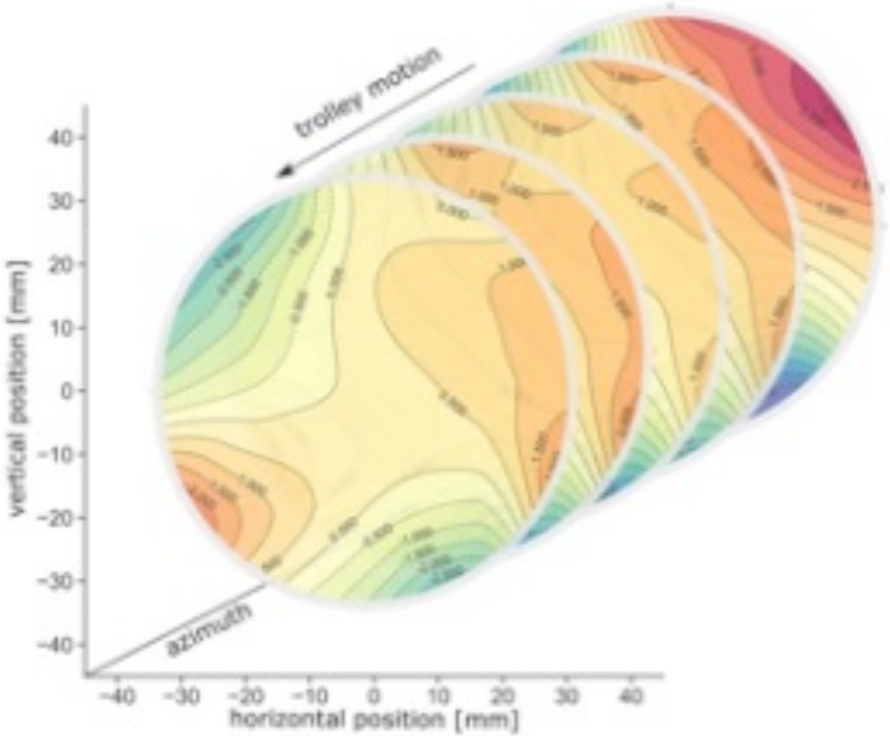


quadrupole

sextupole

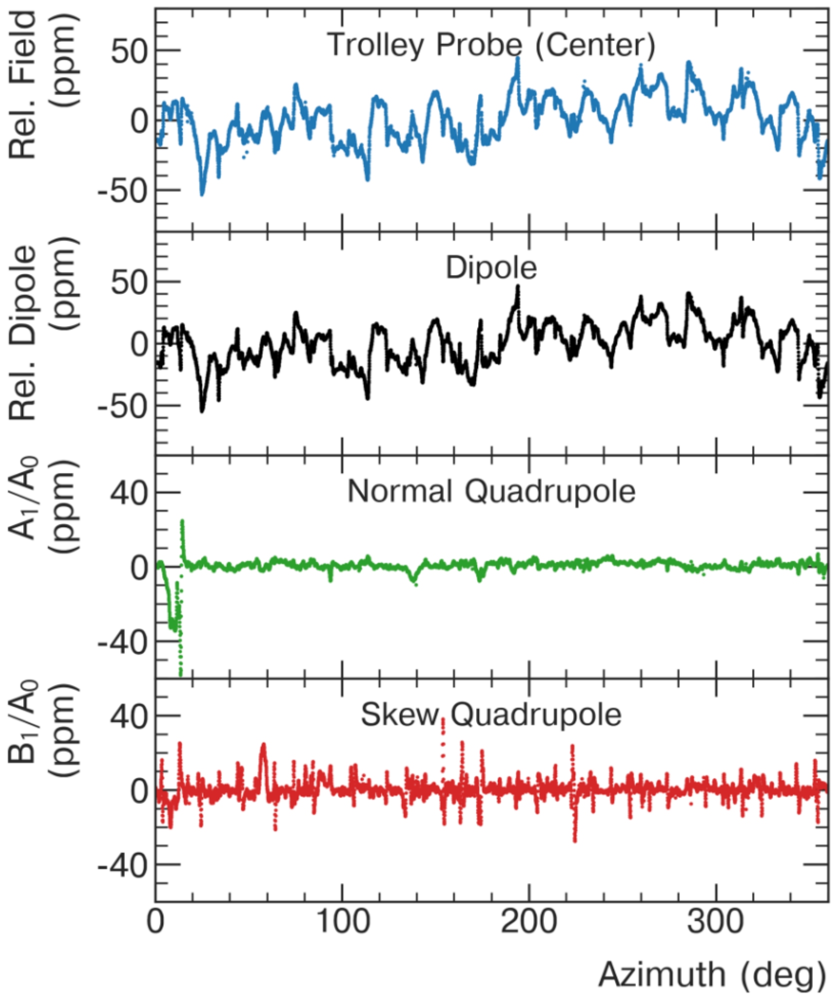
octupole

Trolley measurements



>8000 azimuthal locations

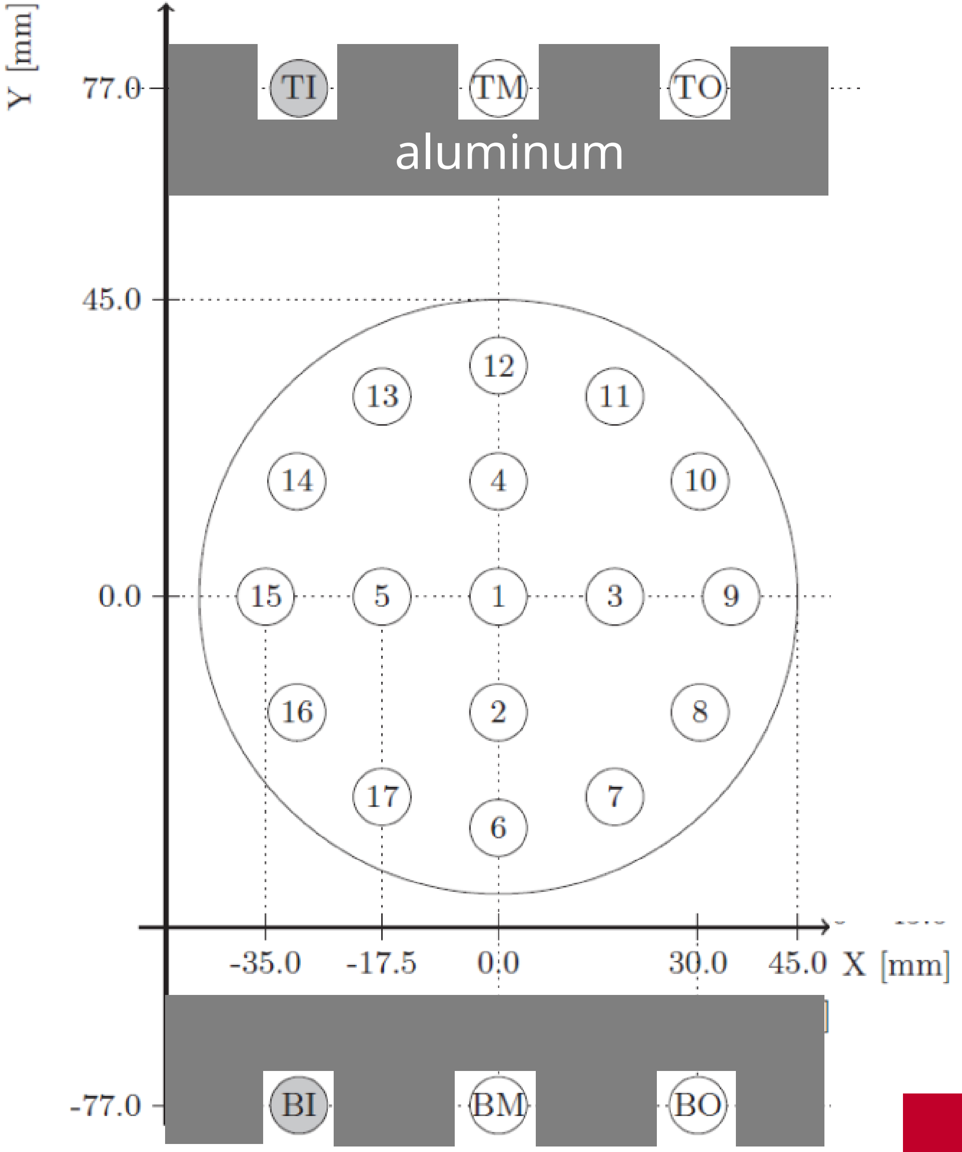
Phys. Rev. A **103**, 042208 (2021)



Trolley measures spatial distribution, but can not measure while muon beam

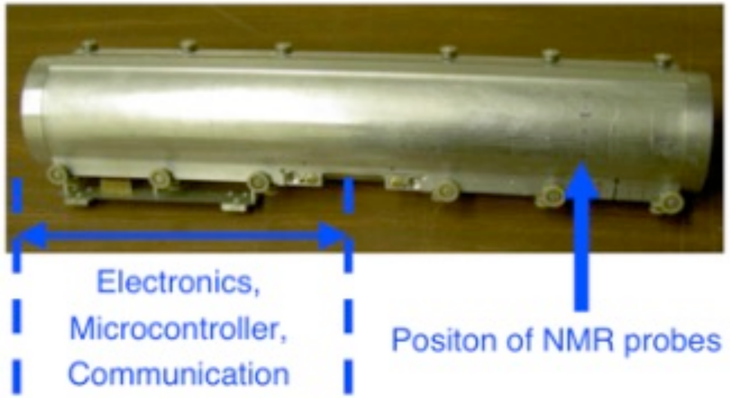
Fixed Probe System

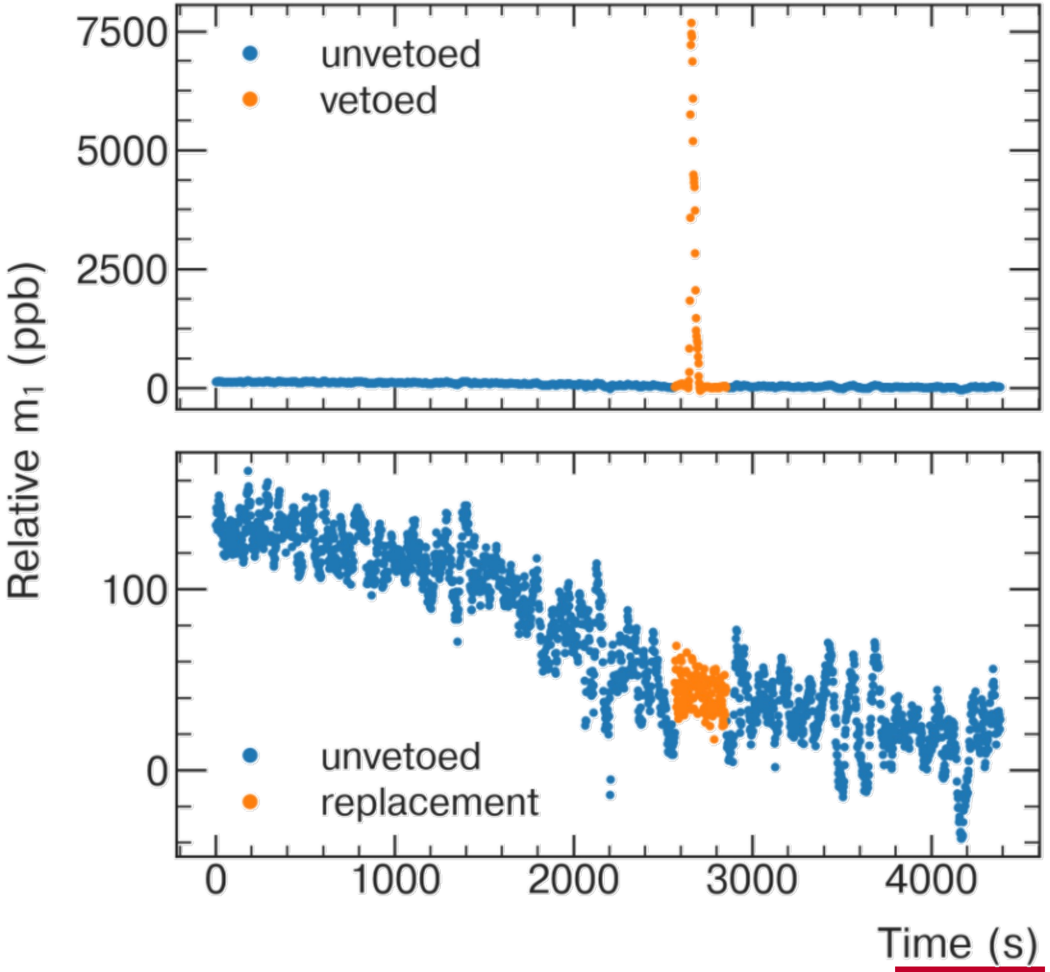
- 72 azimuthal location (stations)
- allows to extract 4 to 5 multipole moments
- tracks field drift 24/7
- measures field differences



Trolley Footprint Removal

Phys. Rev. A **103**, 042208 (2021)

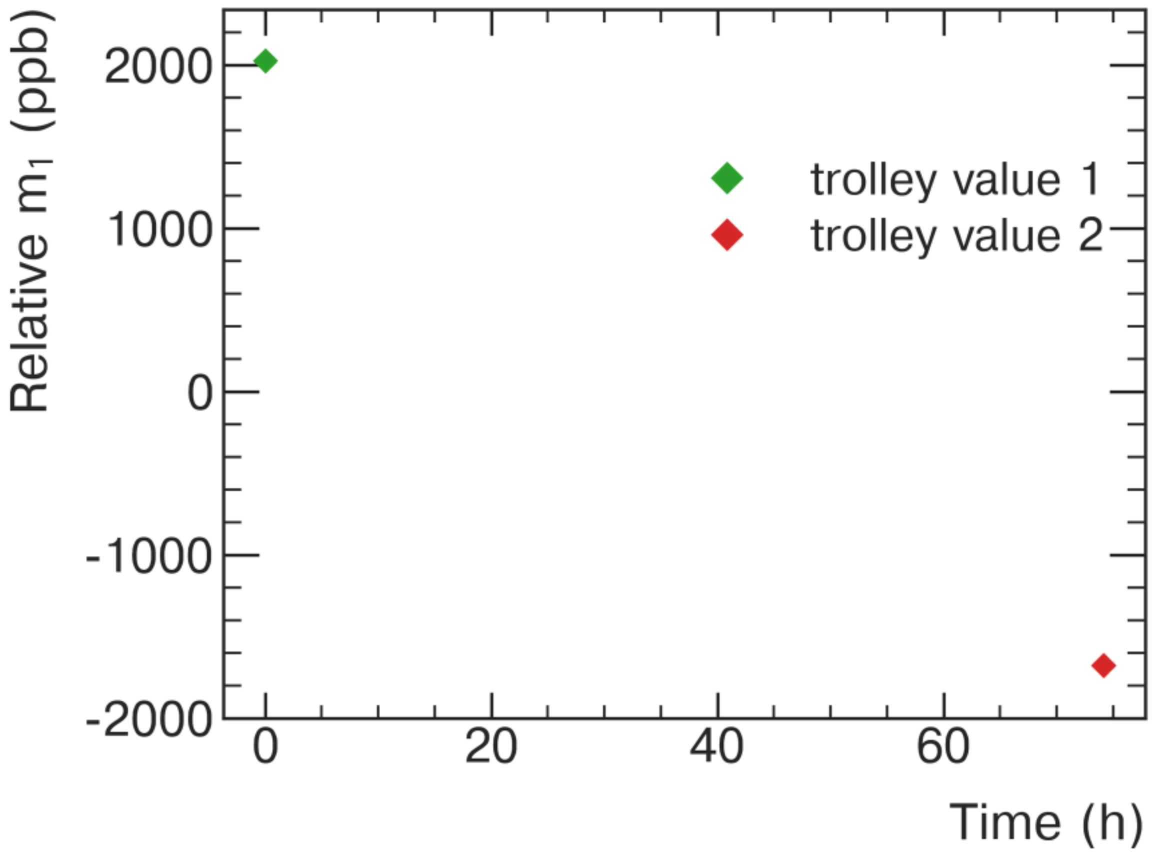




- trolley electronics disturbs field (footprint)
- veto measurements
- interpolate from neighboring probes

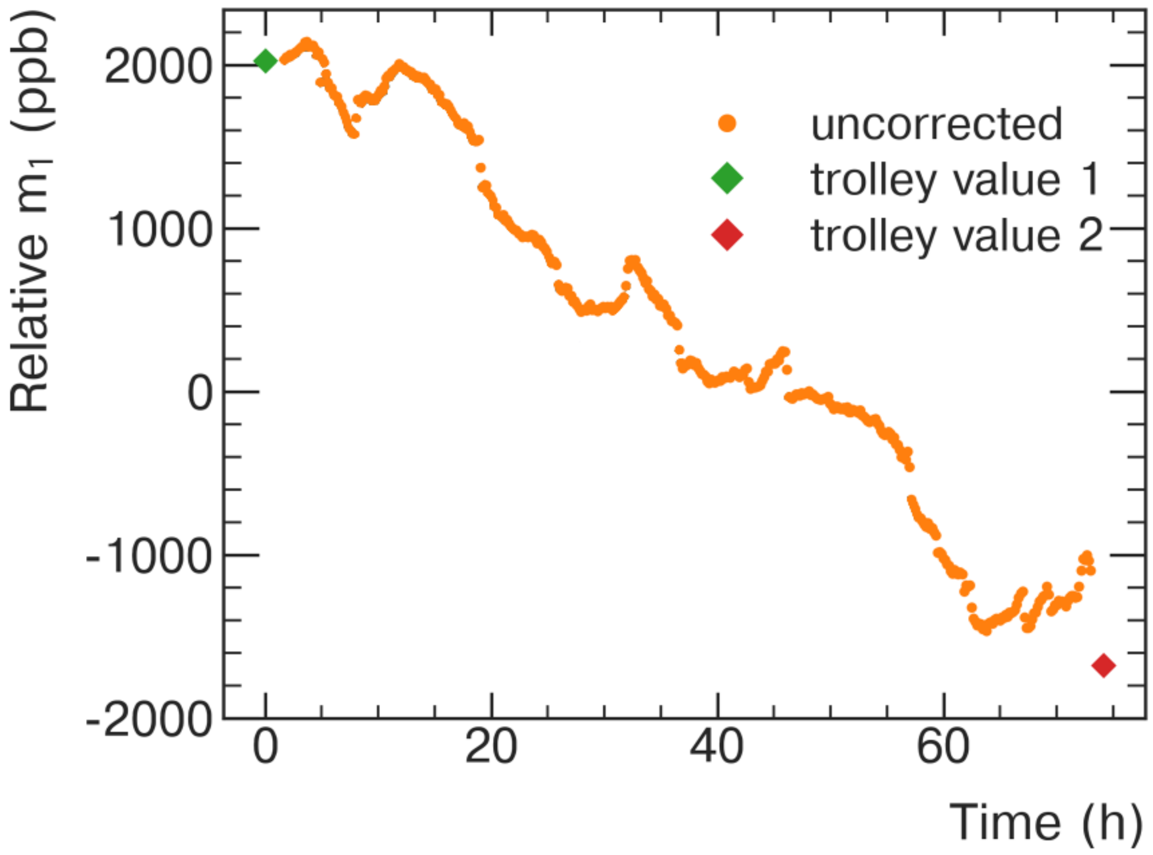
Time tracking

Phys. Rev. A **103**, 042208 (2021)



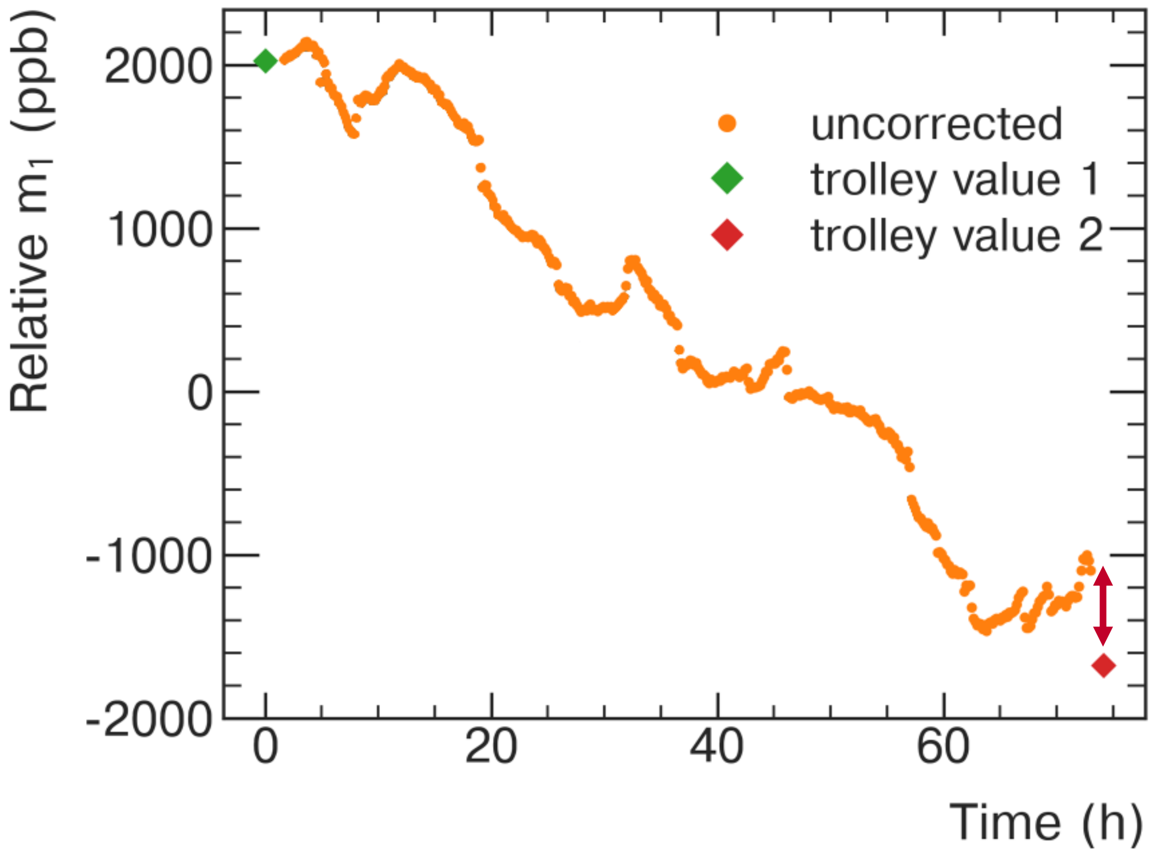
Time tracking

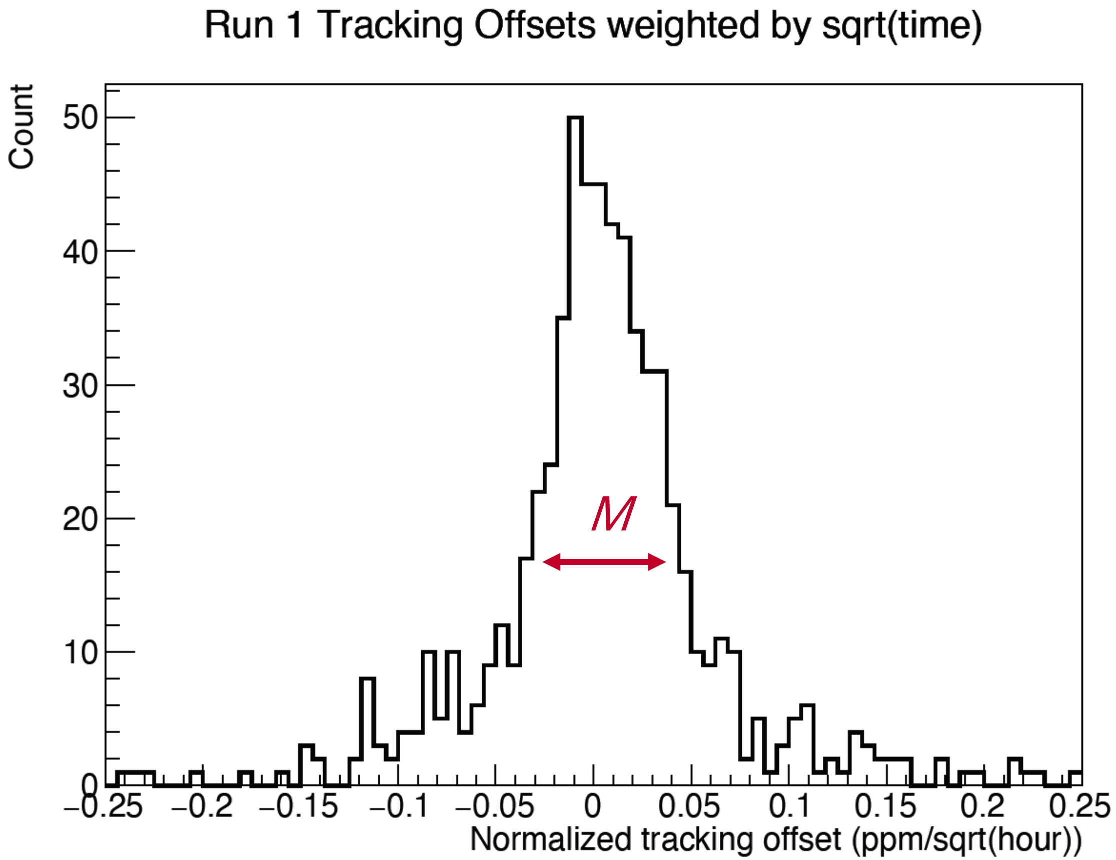
Phys. Rev. A **103**, 042208 (2021)



Time tracking

Phys. Rev. A **103**, 042208 (2021)

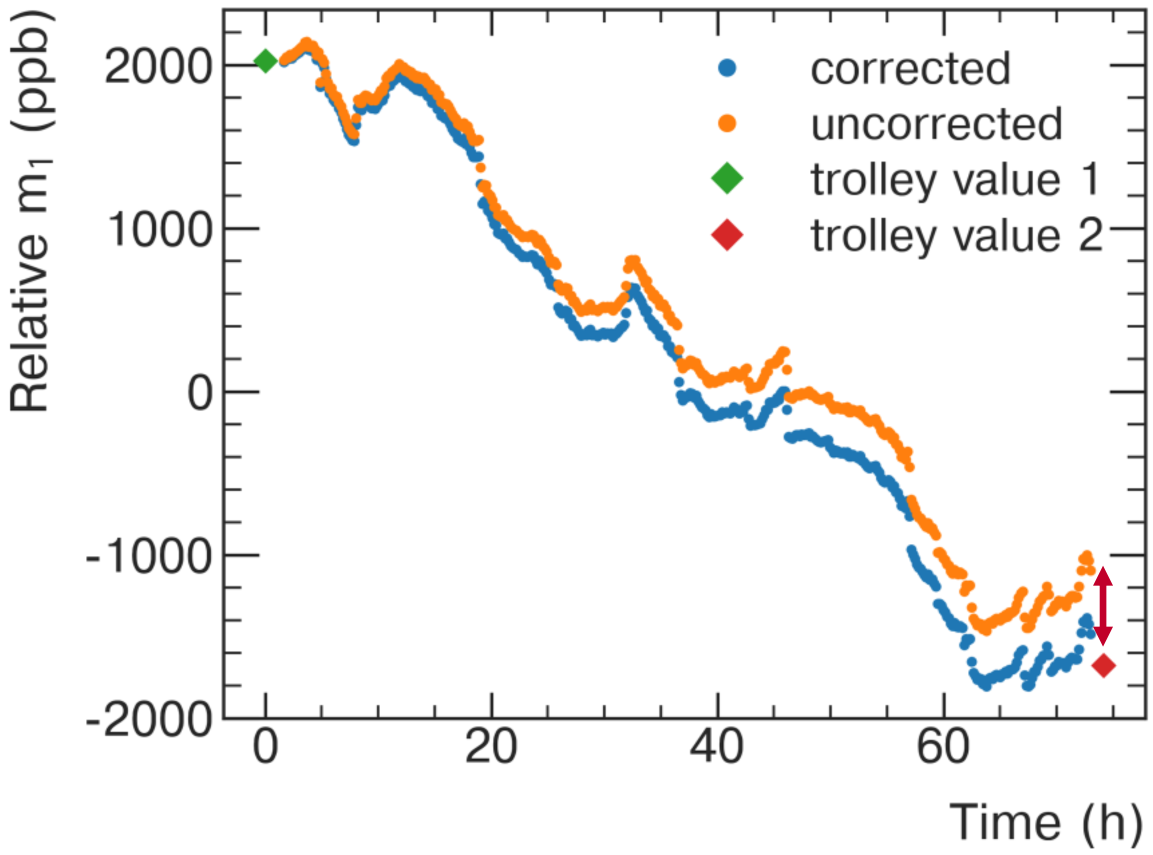


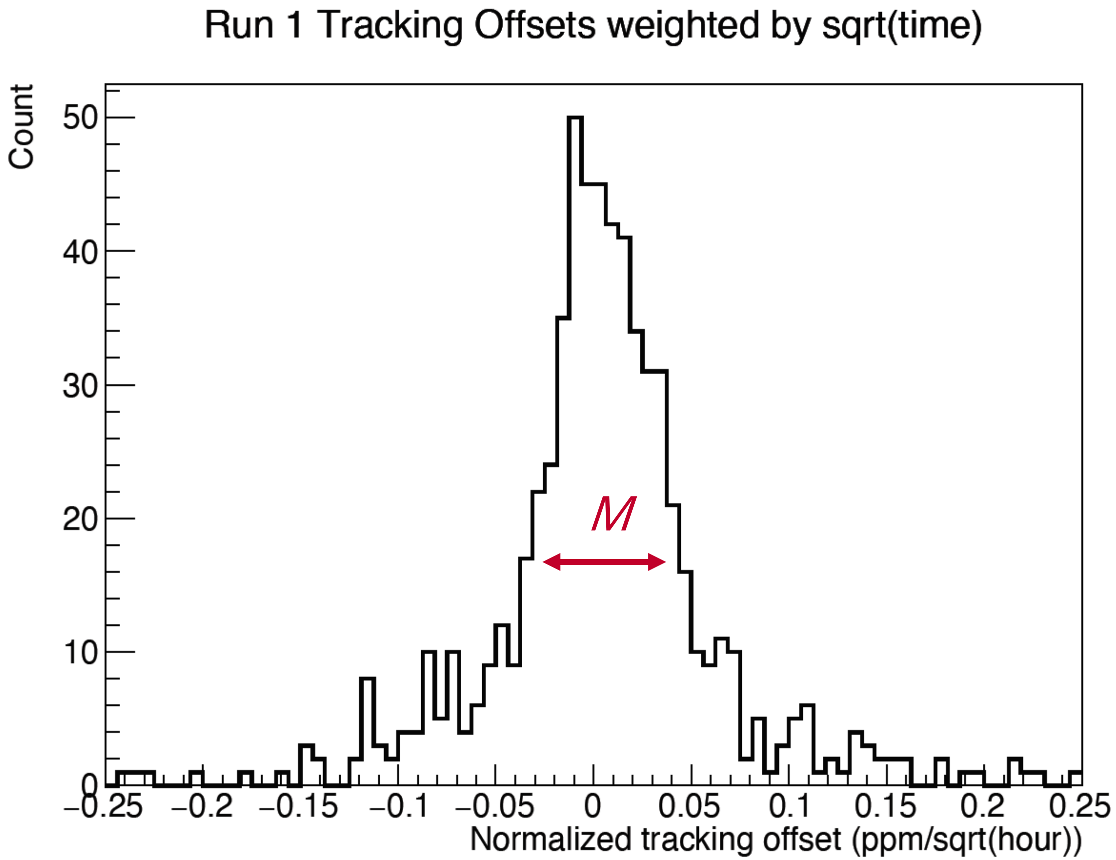


drifts in higher order moments lead to **tracking offset**

Time tracking

Phys. Rev. A **103**, 042208 (2021)



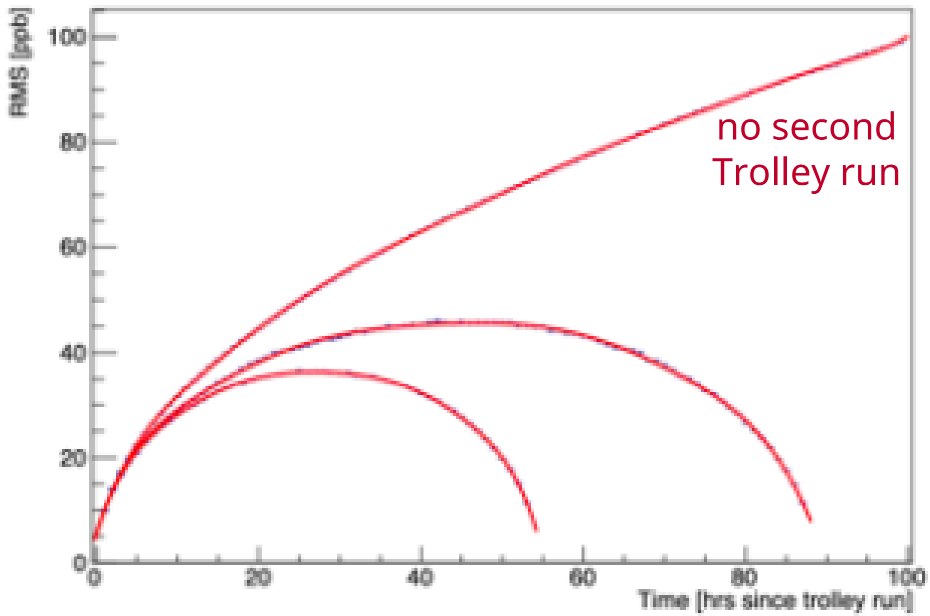


drifts in higher order moments lead to **tracking offset**

Tracking Uncertainty

- Fixed Probe drift: Random walk
- End point known: Brownian bridge model

$$\sigma(t_1, t_2) = M\frac{(T - t_2)t_1}{T}$$



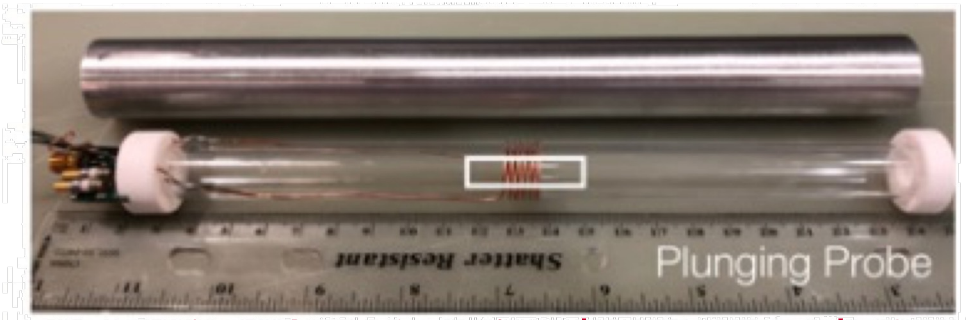
Uncertainty vs time

Improvements

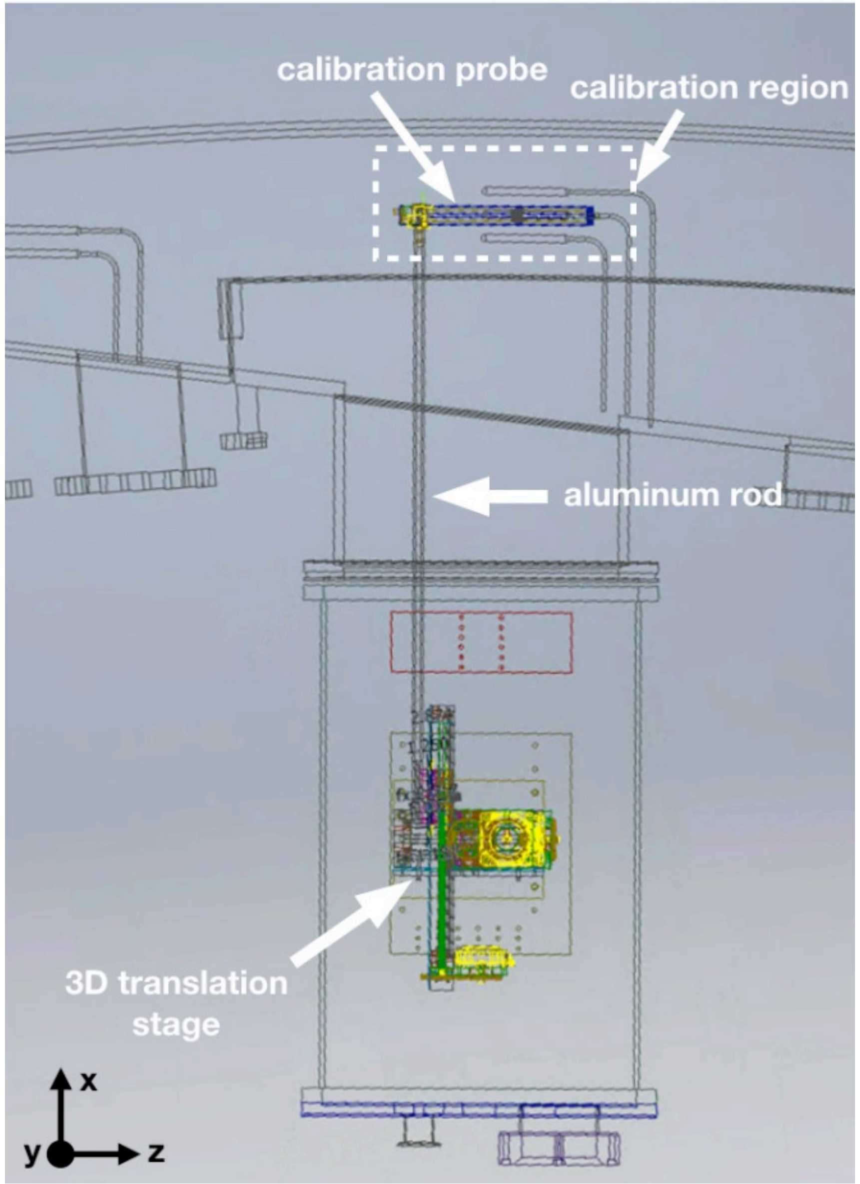
- improved position determination
- continues azimuthal treatment (virtual trolley, Fourier method)
- improved trolley footprint removal
- more trolley runs
- improved field stability by temperature regulation

Trolley Probe Calibration

- Absolute calibrated water probe
- Cross-calibrated at Argonne National Lab test magnet



- Probe can be placed in ring by 3D translation stage
- Swap trolley and calibration probe to get calibration constant
- Derive calibration constants for each trolley probe



Improvements

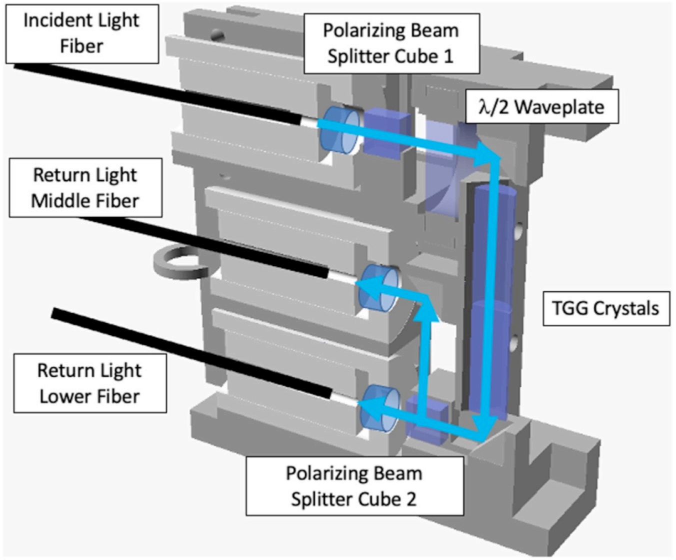
- Study of temperature effects
- Calibration twice a year with automated procedure
- Consistent results

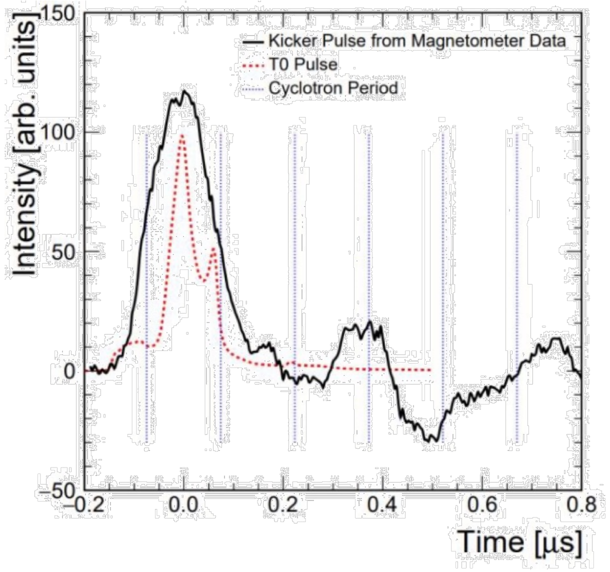
Kicker transient magnetic field

Kicker used to place beam on storage orbit

Kicker pulse induces 22mT field in radial direction

Measurement based on optical faraday rotation



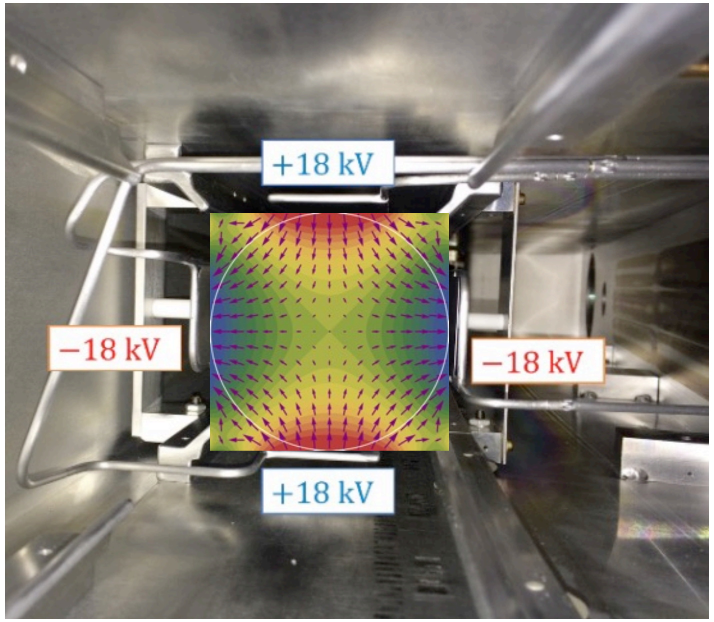


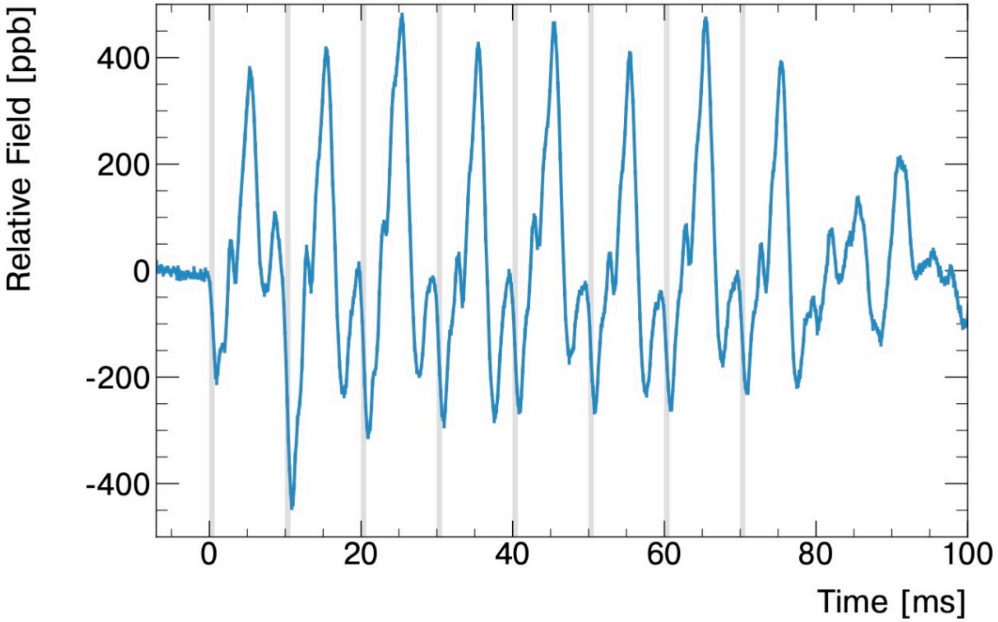
Improvements

- Reduced uncertainties due to vibration mitigation
- Second independent magnetometer ready to go

Beam related magnetic field transients

Pulsing electrostatic quadrupoles for beam confinement leads to magnetic field transient.



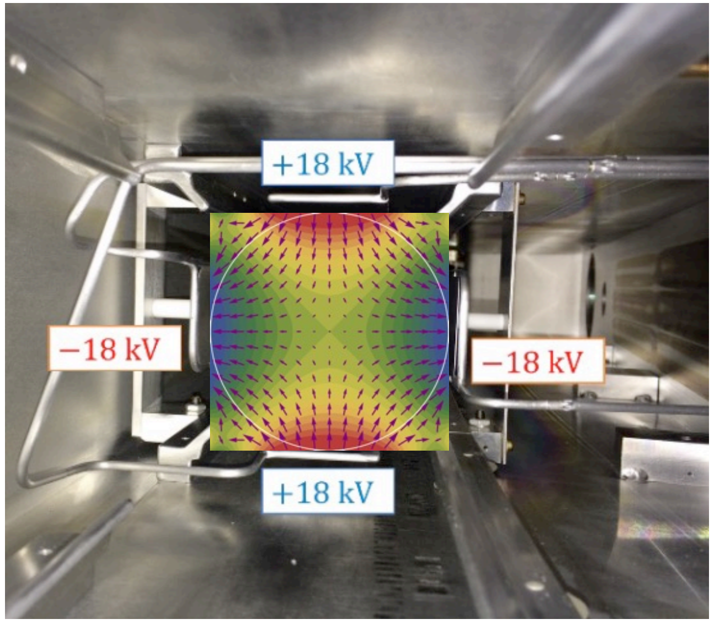


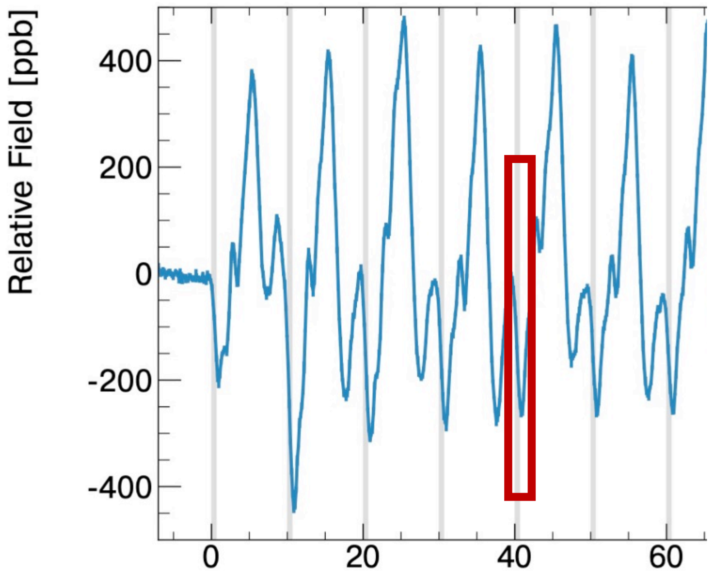
Only measured after run 2 → conservative estimates

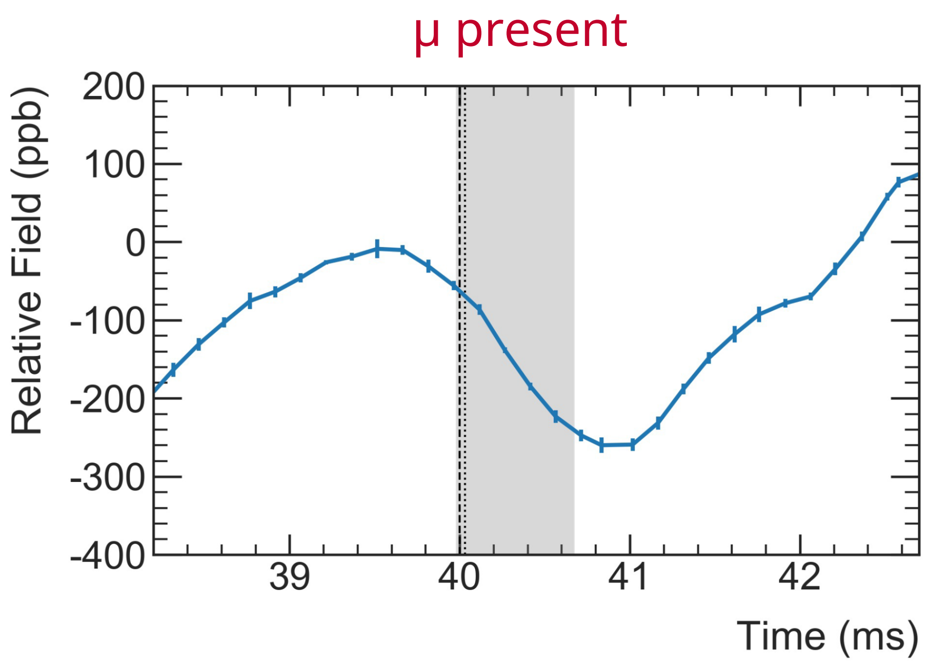
Full mapping of ring between run 4 and run 5

Beam related magnetic field transients

Pulsing electrostatic quadrupoles for beam confinement leads to magnetic field transient.







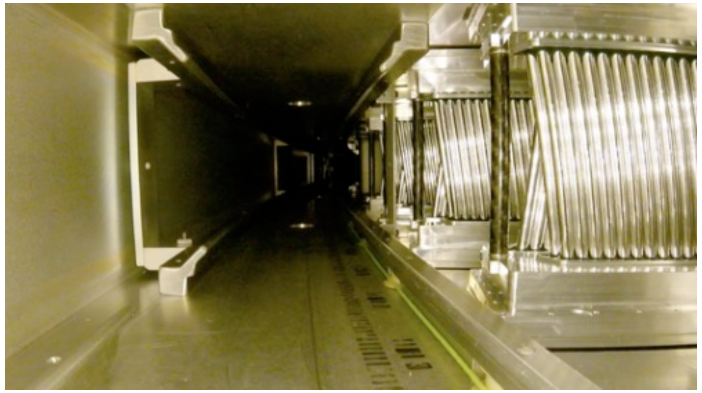
Only measured after run 2 → conservative estimates

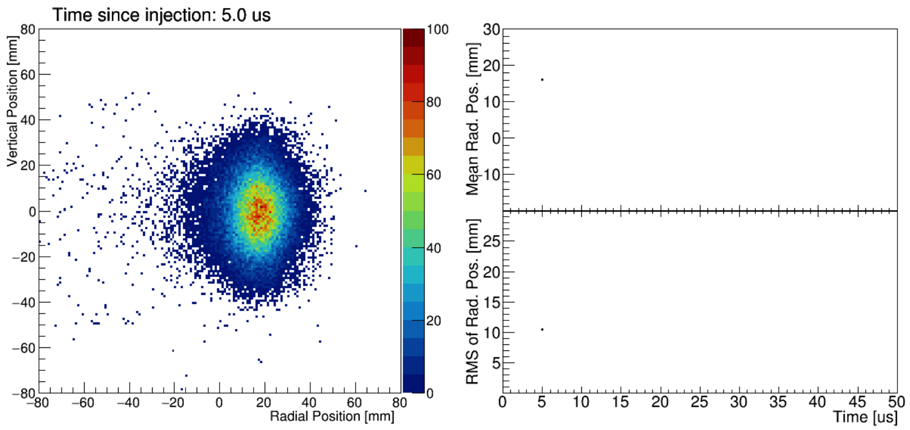
Full mapping of ring between run 4 and run 5

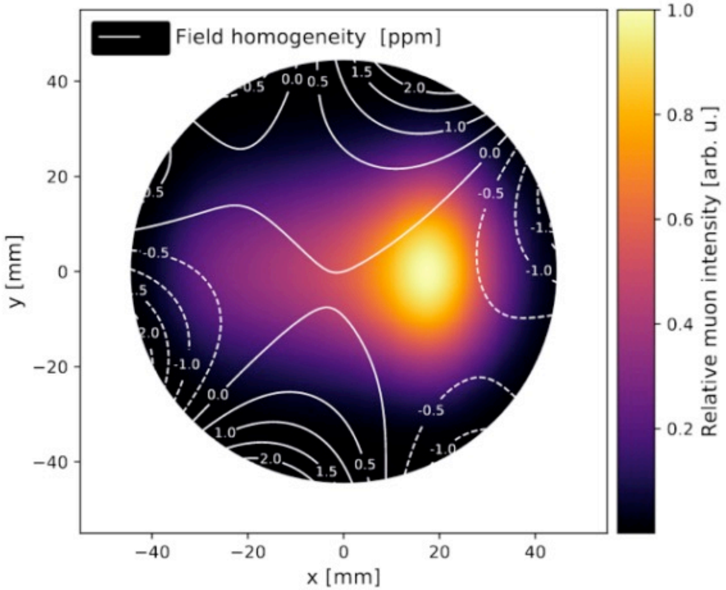
Improved understanding

Muon weighted average magnetic field

Using tracker profiles and beam dynamics simulation







Improvements

- Better placement of beam, due to replacing broken resistors
- Better placement of beam, due to stronger kick
- CBO reduction due to quad RF (run 5)

Summary

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

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\mathrm{clock}} \omega_a^{\mathrm{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}} \langle M(x,y,\phi) \omega'_p(x,y,\phi) \rangle (1 + B_k + B_q)}$$

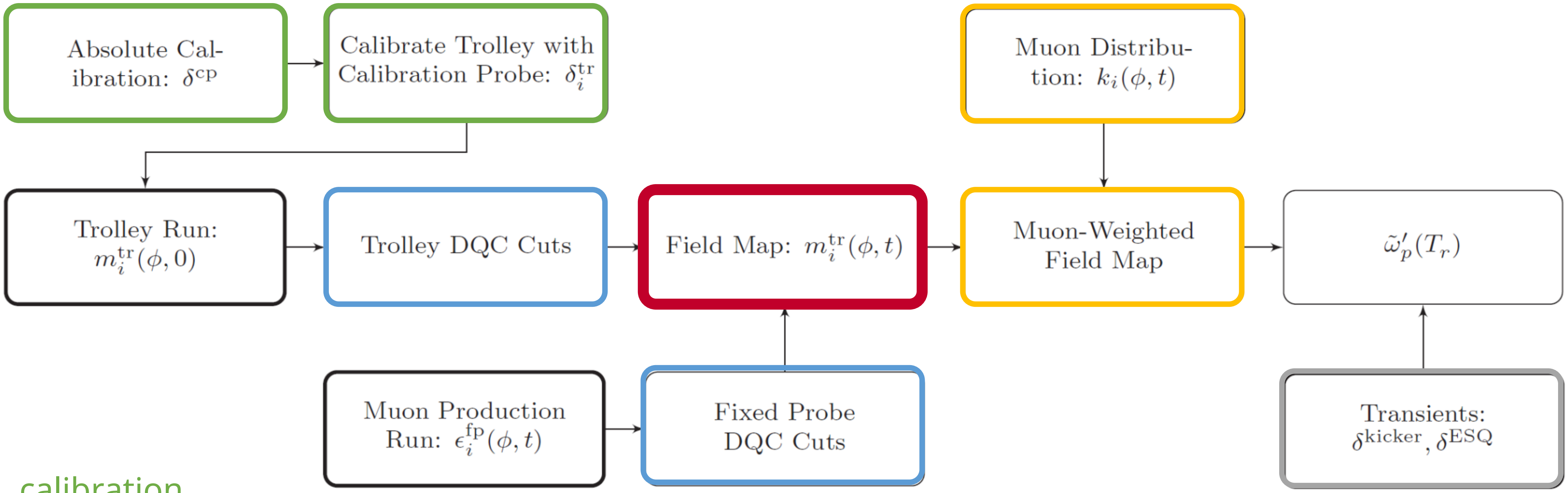
- First time a three-way comparison of a_μ is possible, very exciting
- Run 2 / 3 analysis on-going
- Magnetic field tracked by trolley system (spatial distribution) and fixed probe system (drift)
- Probes are calibrated with absolute calibrated water probe twice a year
- Detailed measurement campagnes to measure transient magnetic fields from kickers and quads
- Improvements in running conditions (temperature stability), data processing (position reconstruction) and analysis

Exciting times ahead!

Thank you

Backup

Magnetic Field Analysis Overview



calibration
quality cuts
field tracking
muon weighting
transients

Uncertainty budget

- Technical Design Report goal
  - Total uncertainty 140 ppb
  - Total systematic uncertainty 100 ppb
  - Magnetic field uncertainty 70 ppb

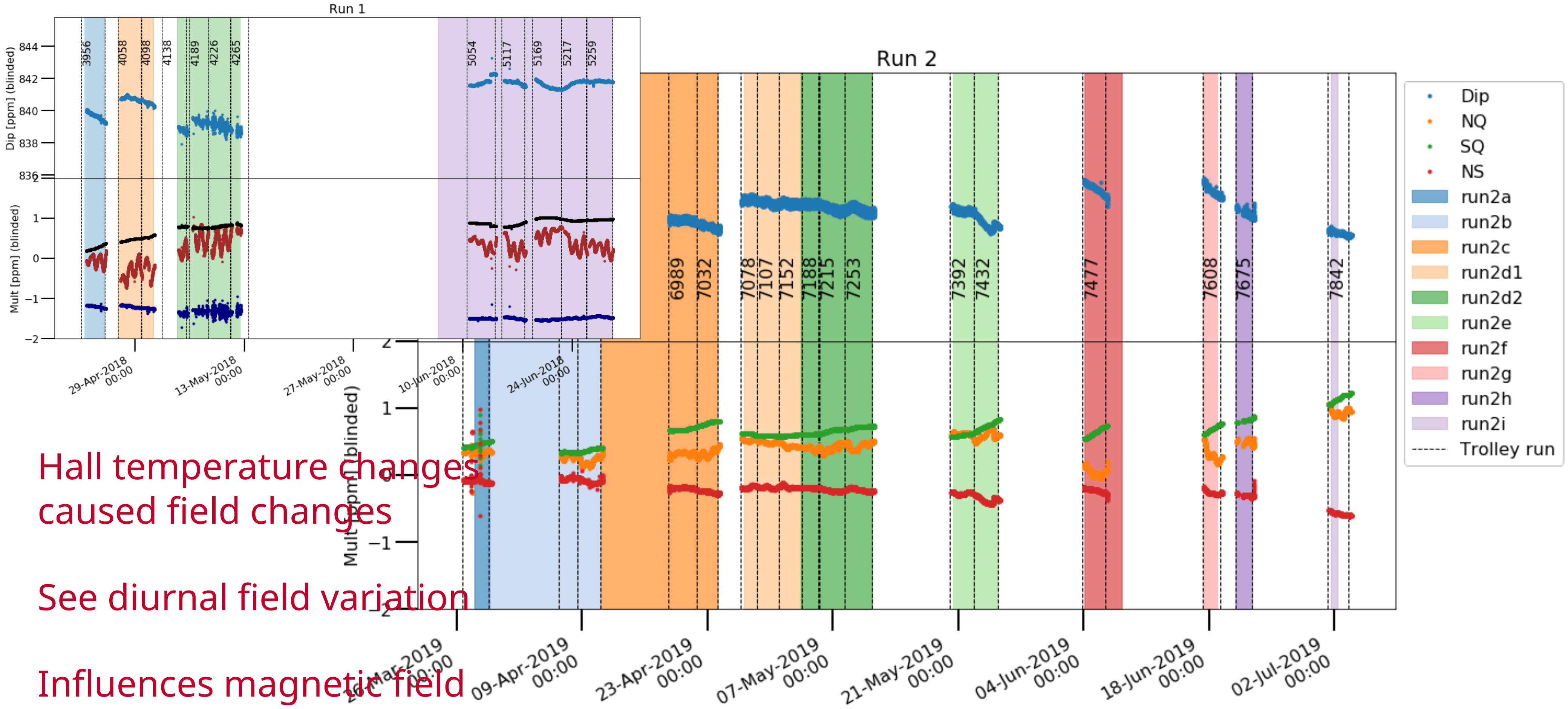
- Dominant magnetic field uncertainty due to transient fields from quadrupole and kicker operations
  - Conservative estimate for run 1
  - Detailed investigation ongoing

- Reduce tracking uncertainty to achieve overall goal

Run 1 uncertainties

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	434
ω_a^m (systematic)	...	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\mathrm{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	...	56
B_k	−27	37
B_q	−17	92
$\mu_p'(34.7°)/\mu_e$	...	10
m_μ/m_e	...	22
$g_e/2$	...	0
Total systematic	...	157
Total fundamental factors	...	25
Totals	544	462

Magnetic field stability

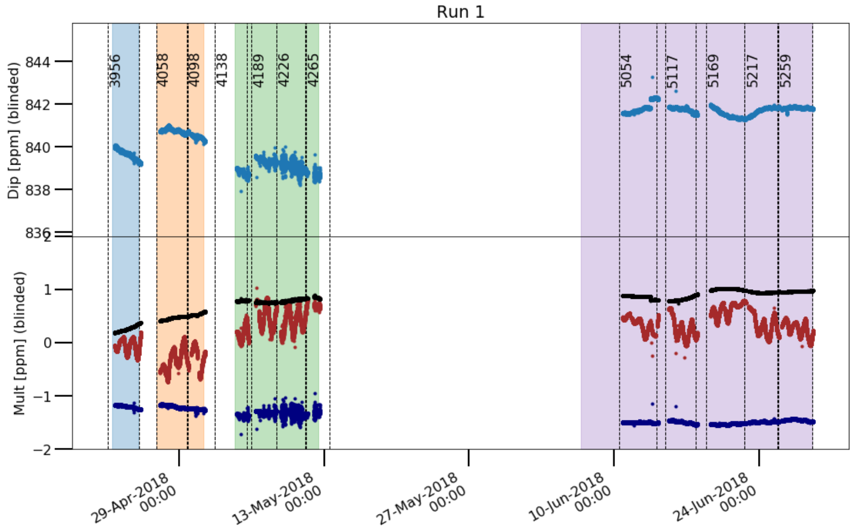


Hall temperature changes caused field changes

See diurnal field variation

Influences magnetic field systematic

Magnetic field stability



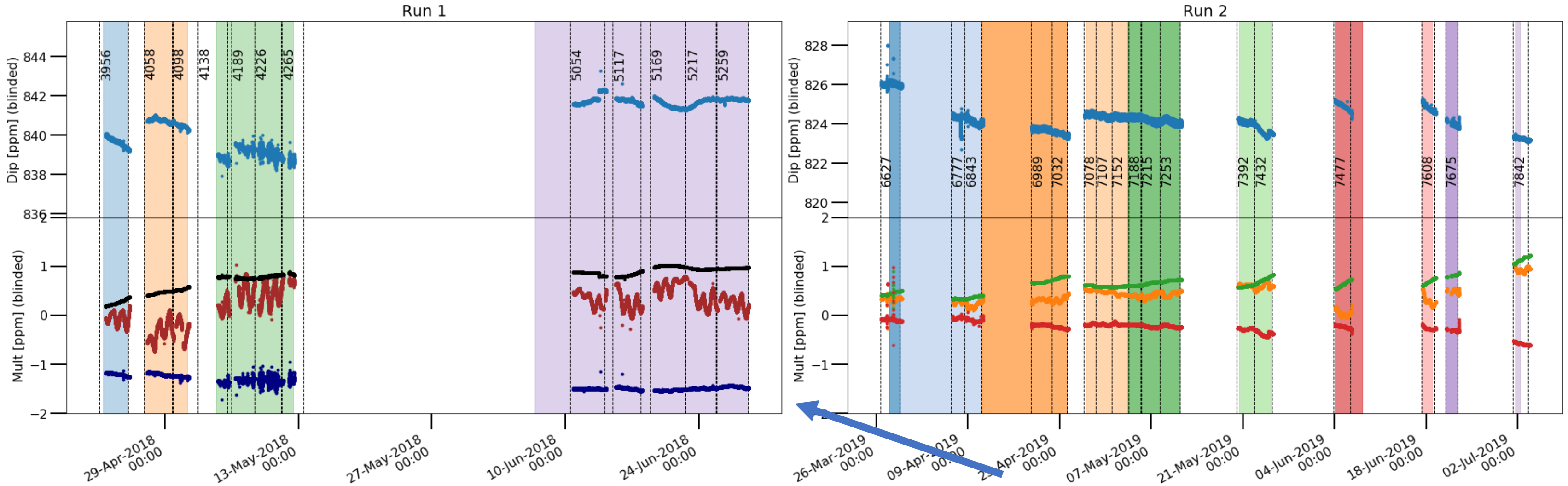
Magnet insulation

Hall temperature changes caused field changes

See diurnal field variation

Influences magnetic field systematic

Magnetic field stability



Magnet insulation

Hall temperature changes caused field changes

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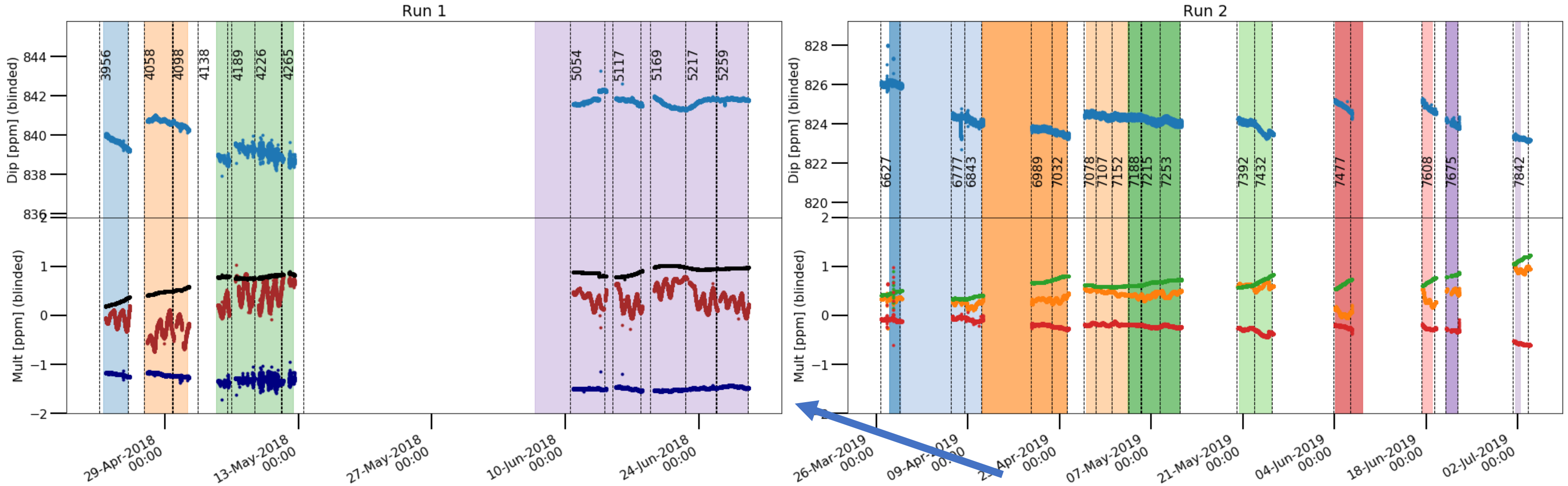
Influences magnetic field systematic

Magnetic field stability



Magnet insulation

Upgrade Air Conditioning System

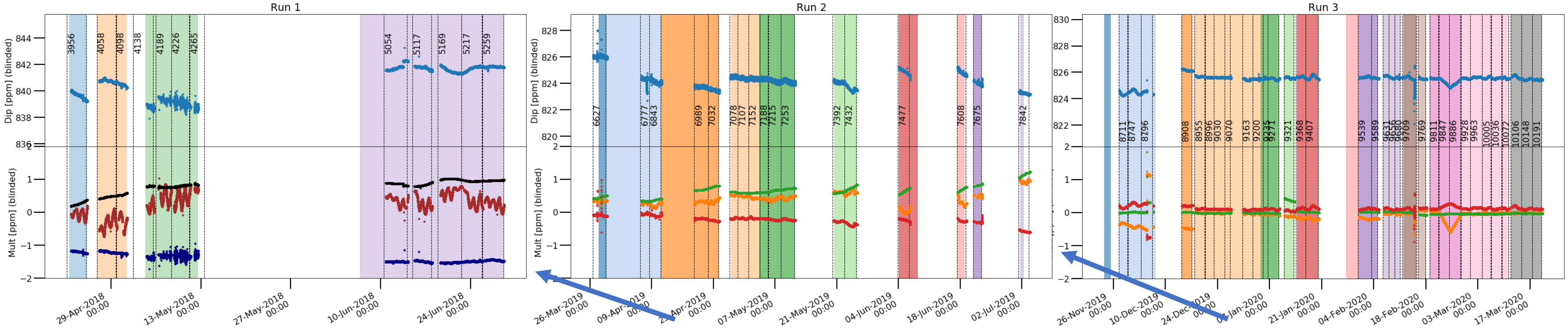
Hall temperature changes caused field changes

See diurnal field variation

Influences magnetic field systematic

Magnetic field stability

Improved
operating conditions



Magnet insulation

Upgrade Air Conditioning System

Hall temperature changes caused field changes

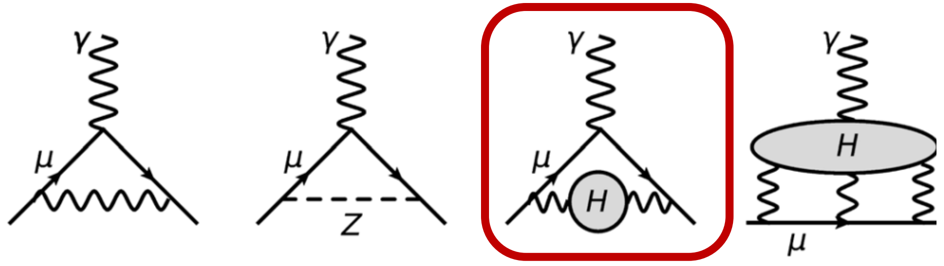
See diurnal field variation

Influences magnetic field systematic

Run 1 Result

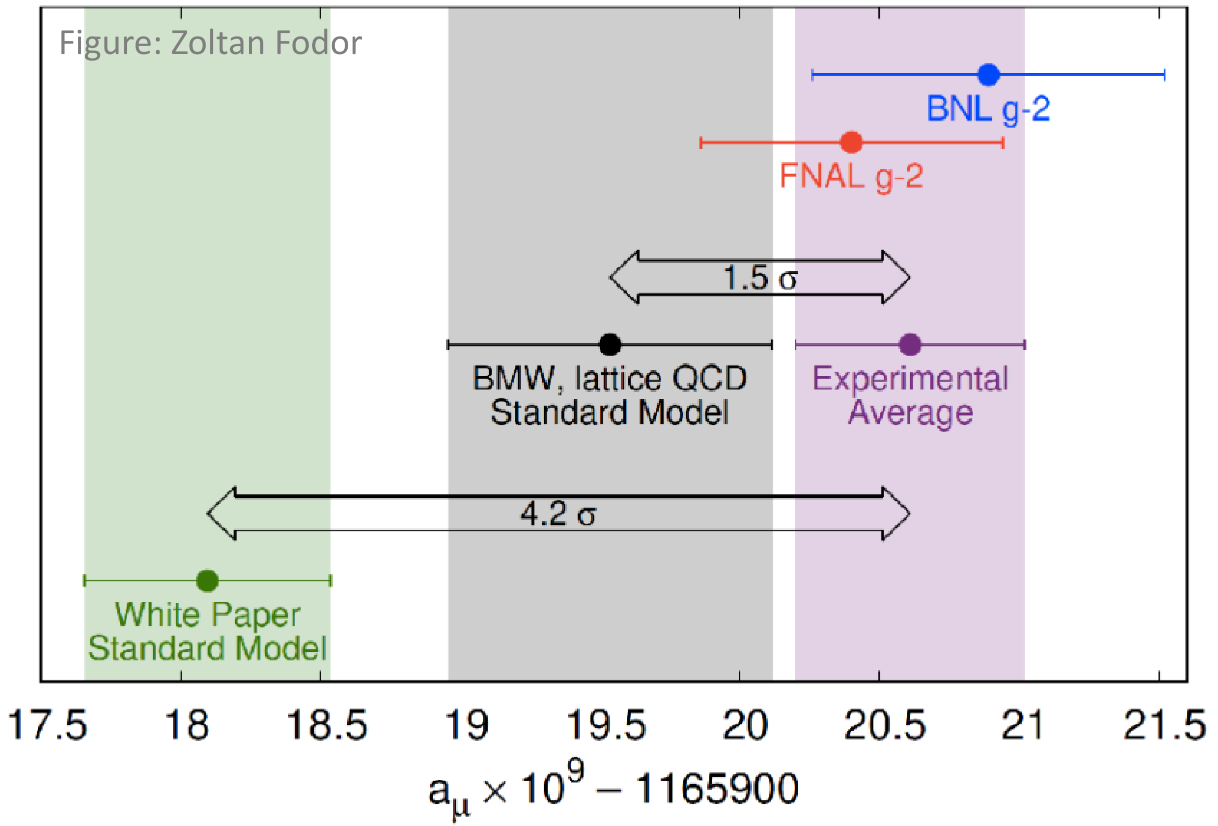
- Muon g-2 collaboration published Run 1 resul
  B. Abi *et al.* (Muon g−2 Collaboration) Phys. Rev. Lett. **126**, 141801, 20

- Uncertainty in theory calculation dominated b
  calculation of hadronic vacuum polarization



- Dispersive approach, 4.2σ tension
  T. Aoyama *et al.*, Phys. Rept. **887** (2020) 1-166

- Lattice QCD approach , 1.5σ tension
  Borsányi *et al.*, Nature **593**, 51–55, 2021 and arXiv:2002.12347



Magnetic Storage Ring

In order to measure to the required precision:

- Keep the field as **uniform** as possible
  - passive & active shimming
- Keep the field as **stable** as possible
  - power supply feedback & temperature stabilization
- Measure the field **experienced by the muons**

- Track **drifts** during the times when muons are present

- **Calibrate** the field measurements with a well-understood measurement standard