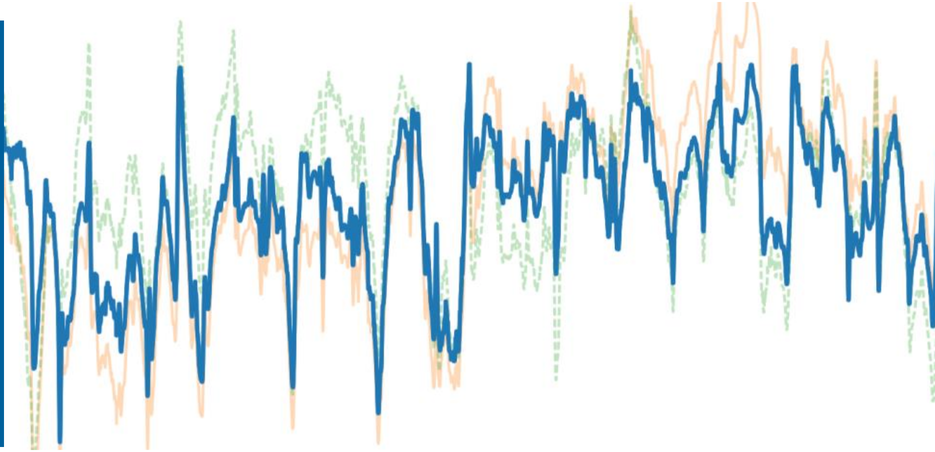
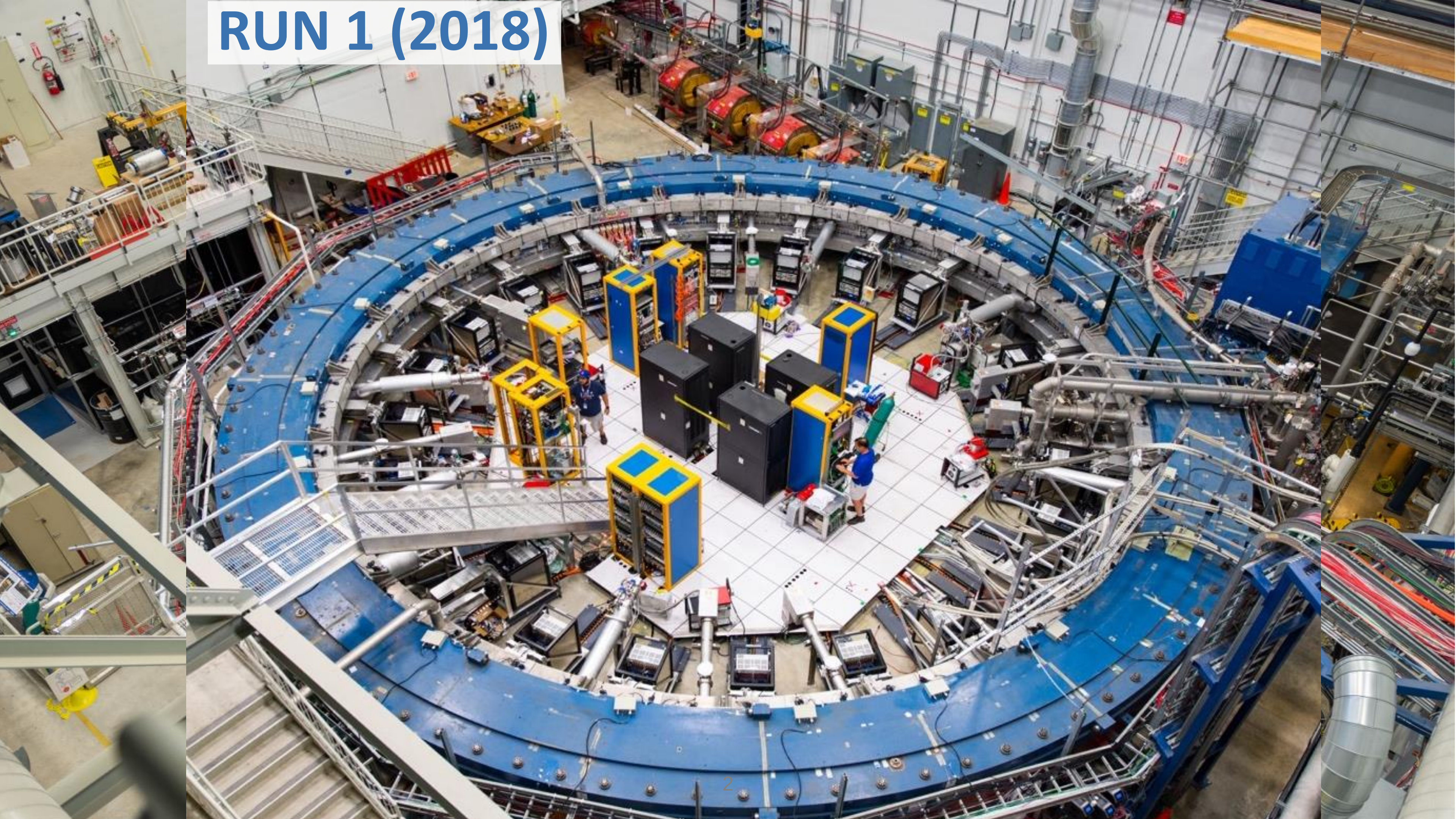
MEASUREMENT OF THE MAGNETIC FIELD IN THE FERMILAB MUON G-2 EXPERIMENT



SIMON CORRODI
Argonne National Laboratory

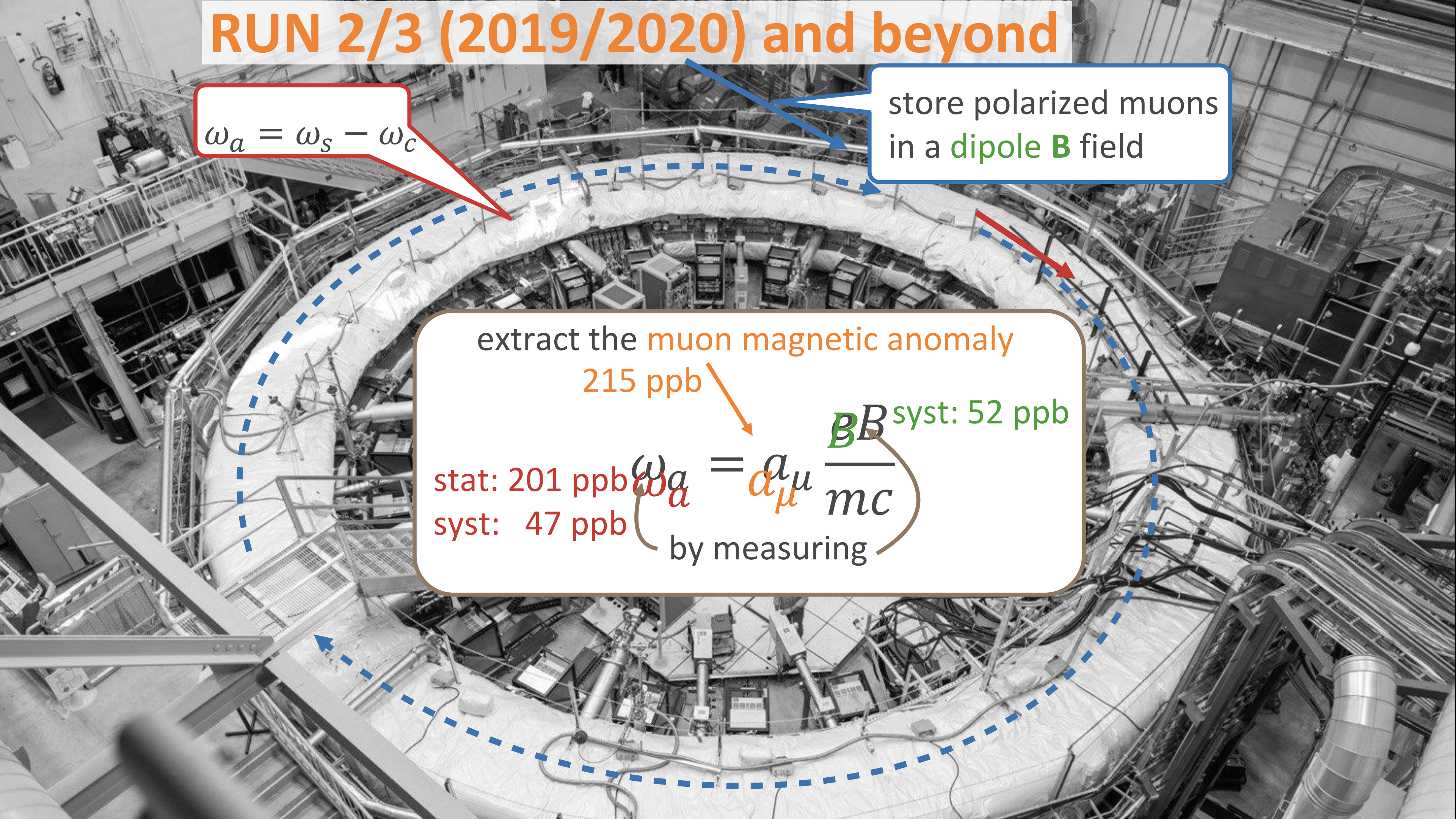
on behalf of the Muon g-2 collaboration
NuFact 2023, Seoul
August 25, 2023

RUN 1 (2018)



RUN 2/3 (2019/2020) and beyond

RUN 2/3 (2019/2020) and beyond



$\omega_a = \omega_s - \omega_c$

store polarized muons in a dipole **B** field

extract the muon magnetic anomaly

215 ppb

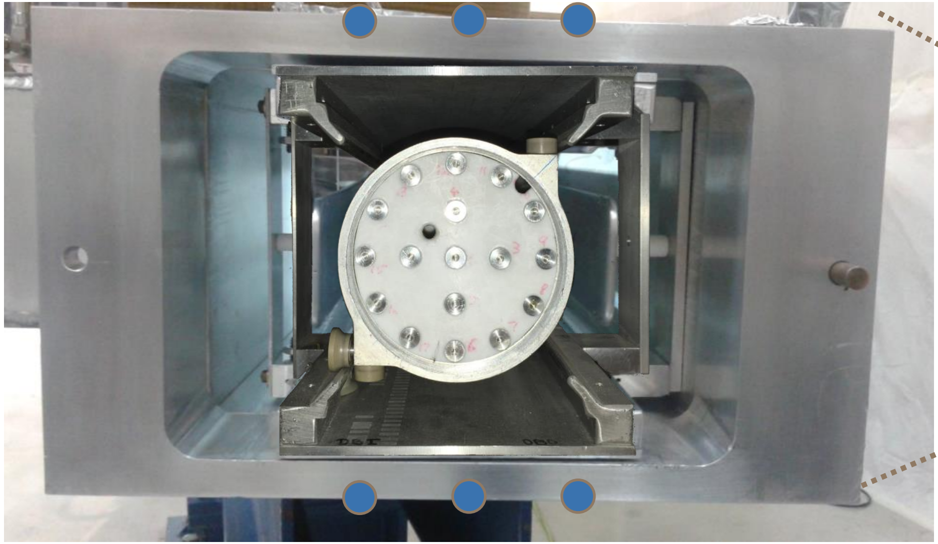
$$\omega_a = a_\mu \frac{eB}{mc}$$

stat: 201 ppb
syst: 47 ppb

syst: 52 ppb

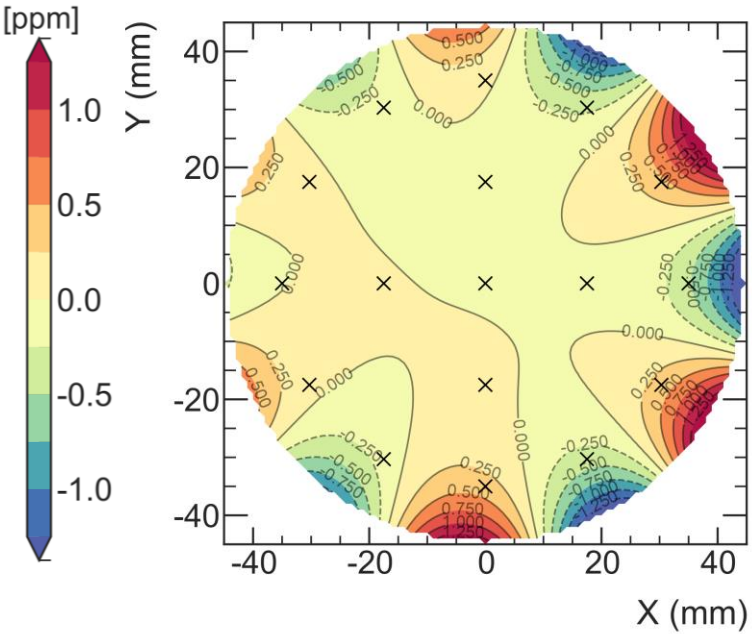
by measuring

Filed Monitor: Fixed NMR Probes



Trolley: Field Mapper

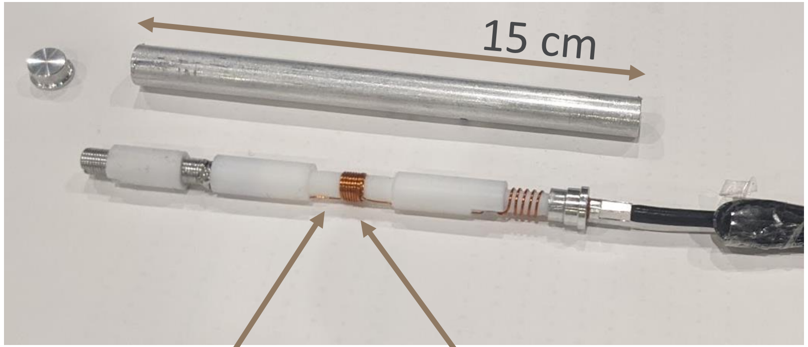
Designed for homogeneity (and stability)



azimuthally averaged B field

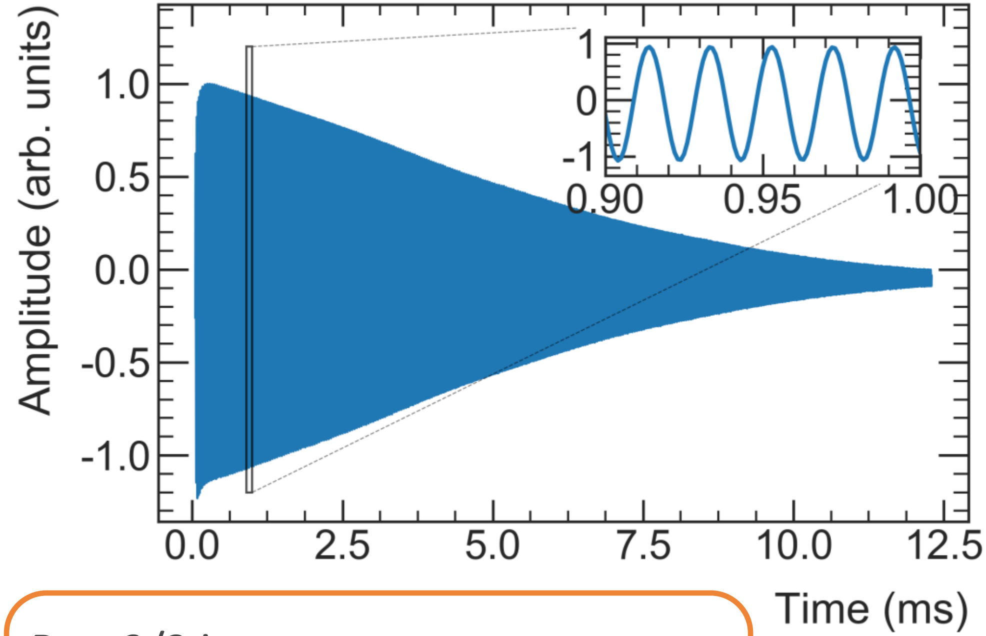
NUCLEAR MAGNETIC RESONANCE: "COMAGNETOMETER"

$$B = \gamma_p \omega_p$$



proton rich sample

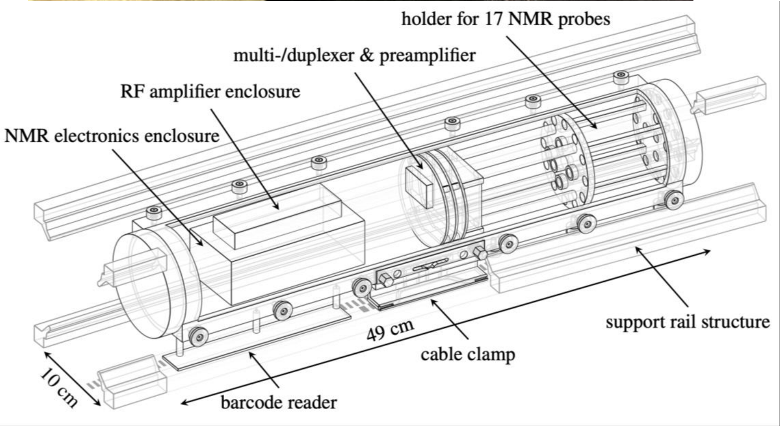
coil:
spin-flip & pick-up

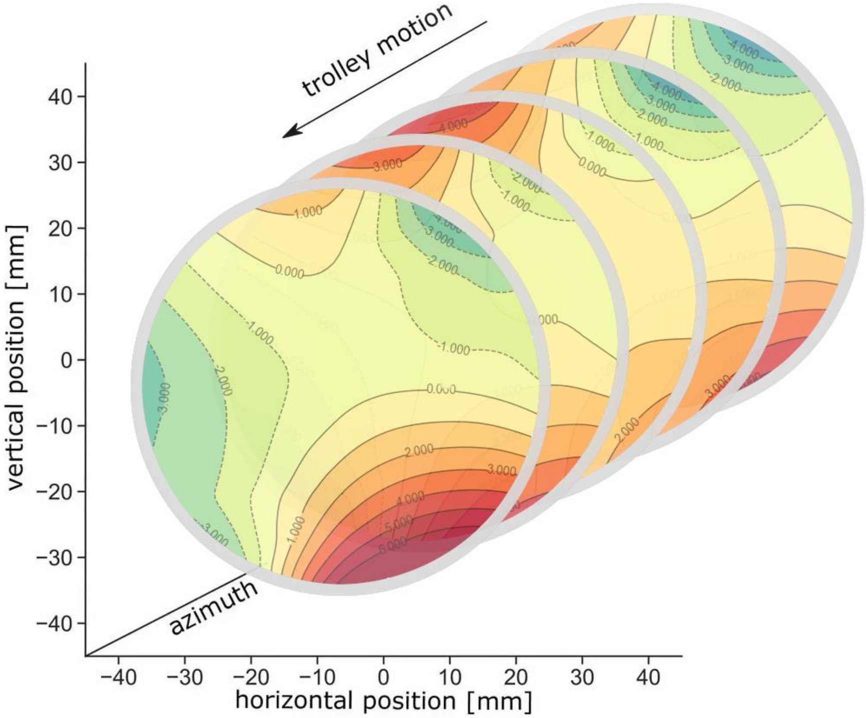


Run-2/3 improvement:
Evaluation of unc. in ω_p extraction
uncertainty: 16 - 19 ppb

MAPPING THE FIELD: THE TROLLEY

17 probes, moves around the ring (70min)



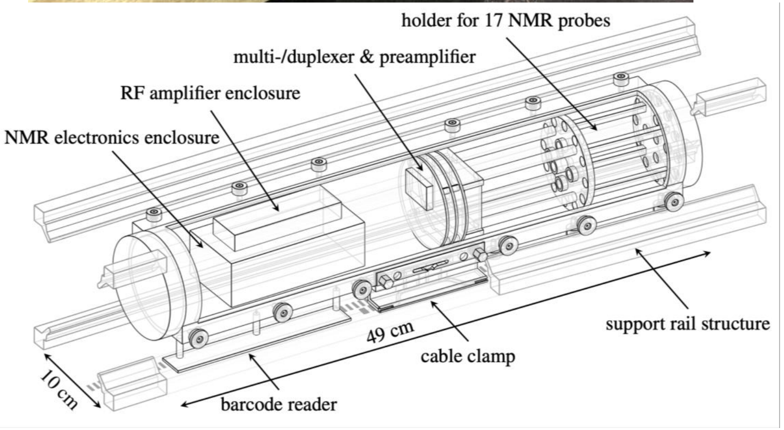


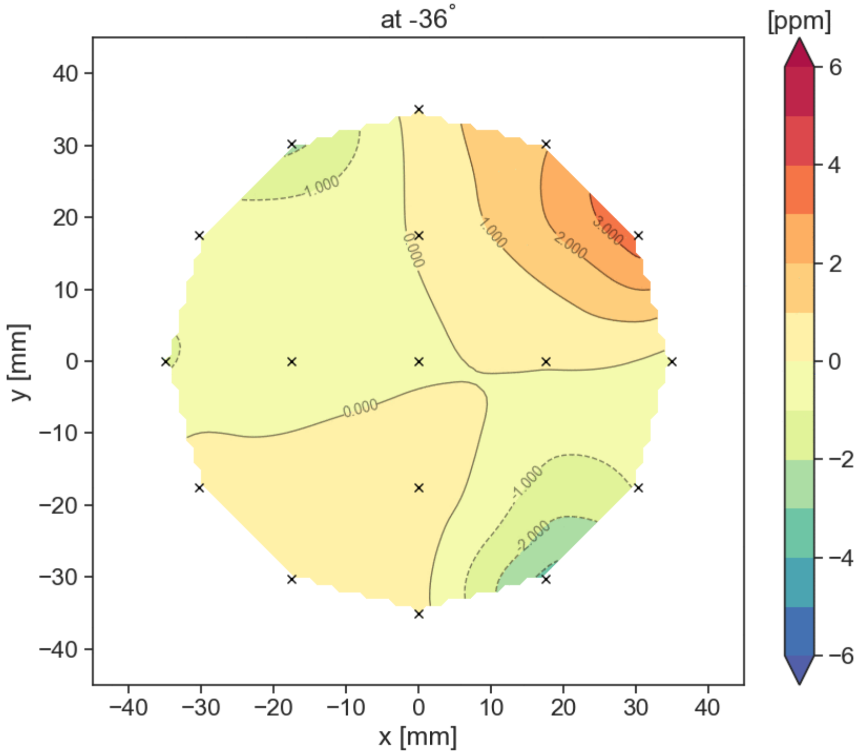
~9000 2D field maps around the ring

Argonne NATIONAL LABORATORY

MAPPING THE FIELD: THE TROLLEY

17 probes, moves around the ring (70min)



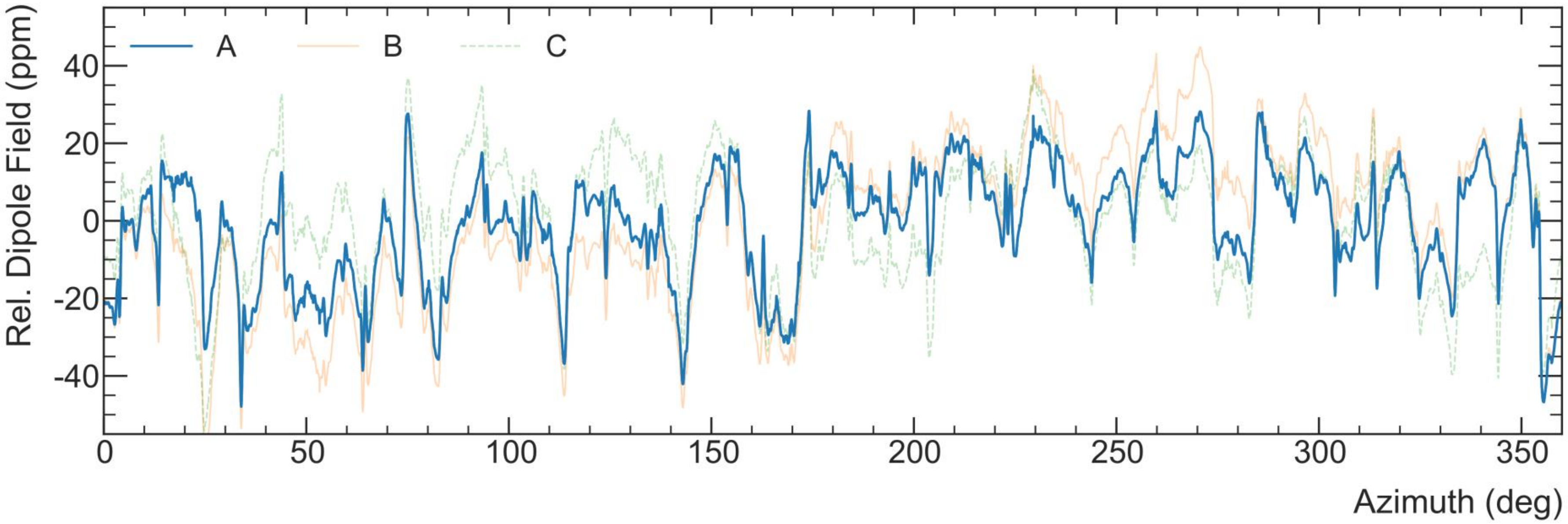


Argonne NATIONAL LABORATORY

FIELD MAPS

12 parameter multipole expansion to describe the field in 2D slices
RMS around the ring <20 ppm

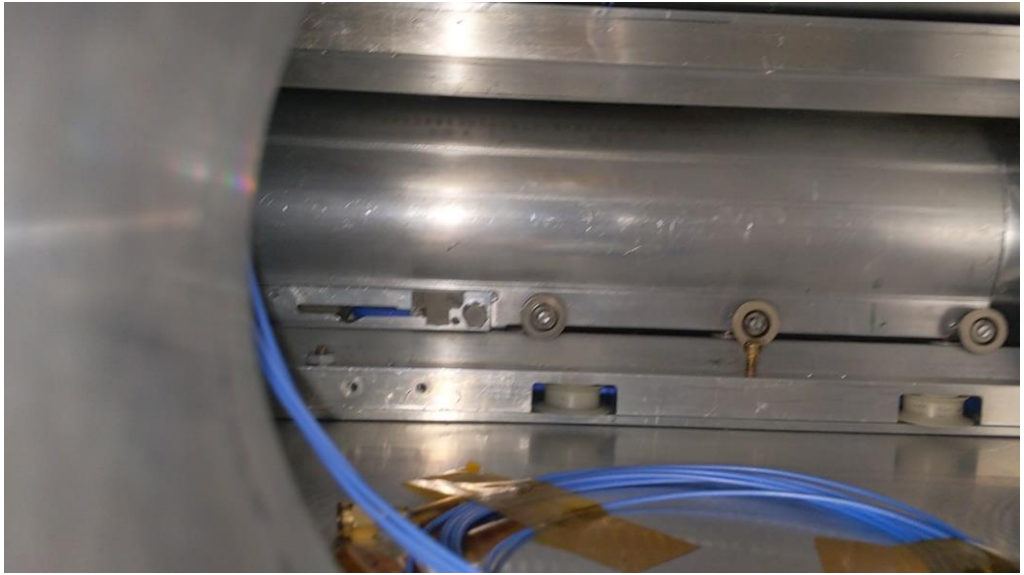
take field maps every 3-5 days



uncertainty from parametrization: 3 - 8 ppb

FIELD MAPS: CHALLENGES

Challenges/sources of uncertainties



(Non-uniform) motion
-> small eddy currents
uncertainty: 18 ppb

non perfect rail alignment
uncertainty: ~10 ppb

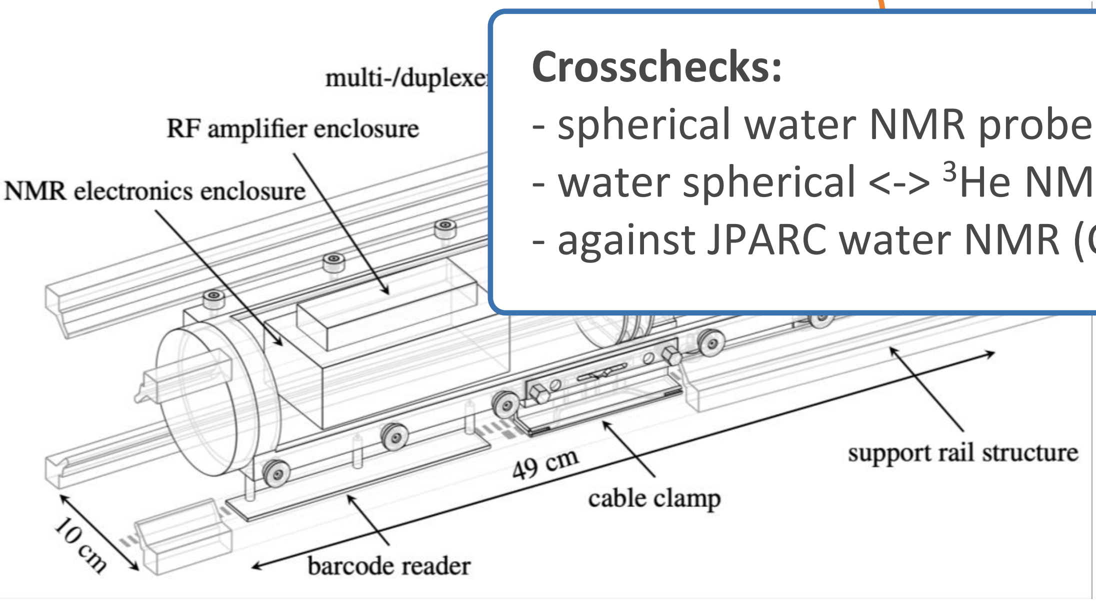
position determination
uncertainty: 4 ppb

Run-2/3 improvement:
NMR probe temperature dependence
uncertainty: 9-15 ppb

CALIBRATION

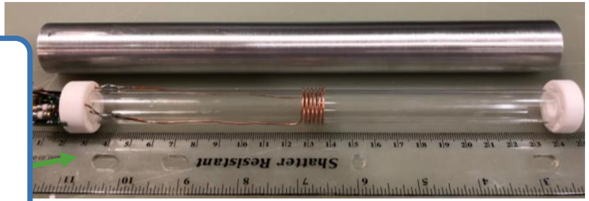
Calibrate to the Lamor frequency of shielded protons in a spherical sample: ω'_p

NMR probes are in the "trolley's magnetic environment"



Crosschecks:
- spherical water NMR probe (BNL)
- water spherical <-> ^{3}He NMR
- against JPARC water NMR (CW)

water based calibration probe



ce in situ *uncertainty: 17 ppb*

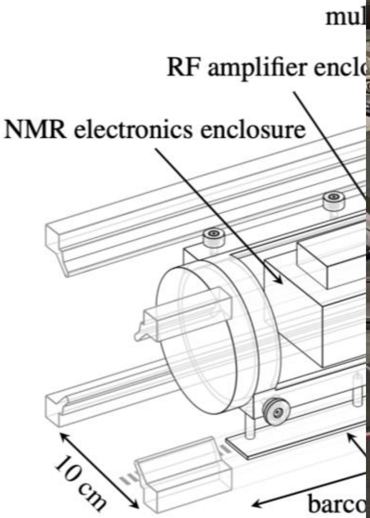
2) correct for material effects
3) correct from cylinder -> sphere

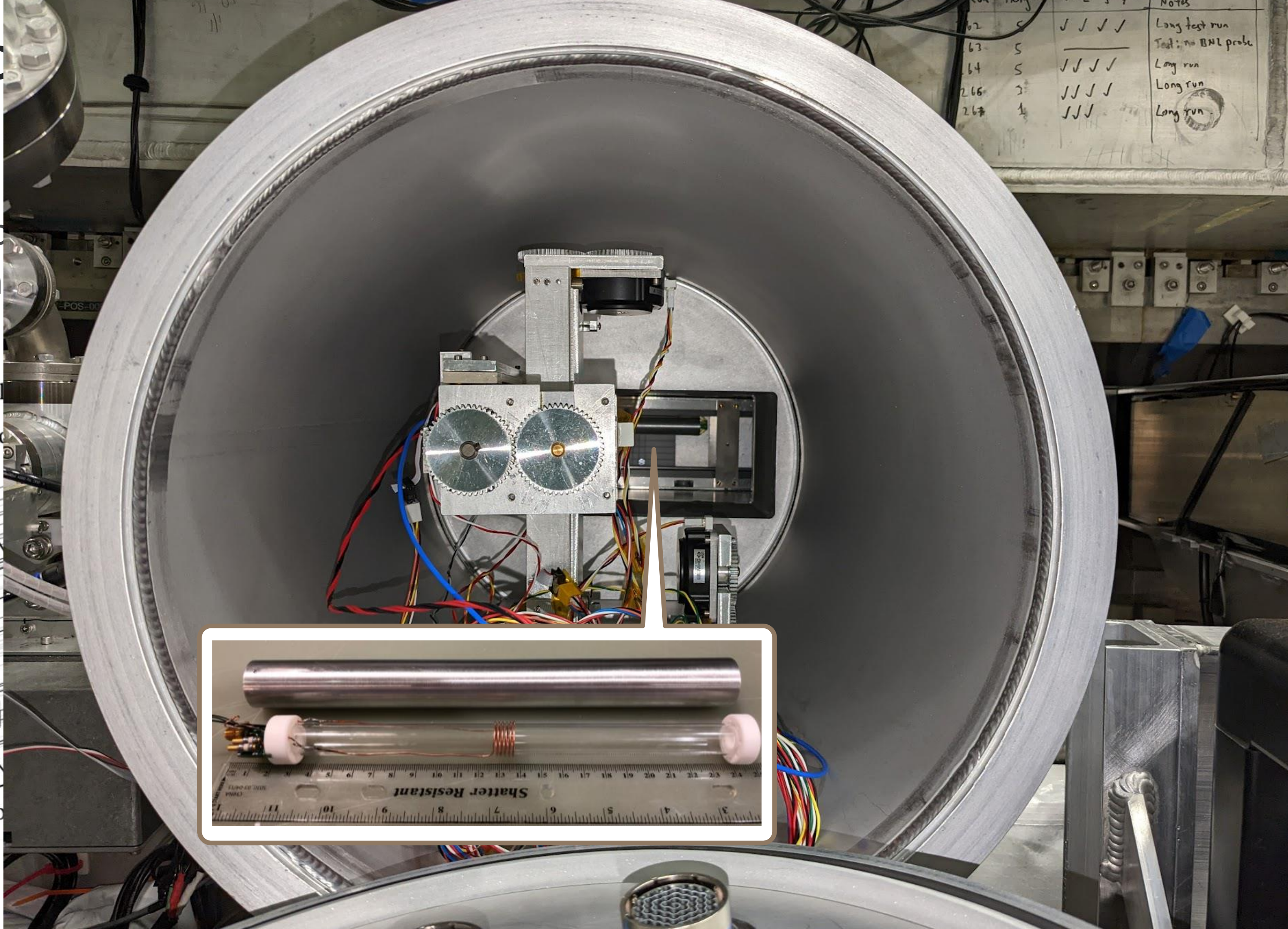
uncertainty: 9 ppb

CALIBRATIC

Calibrate to the

NMR p
“trolley’s m





CALIBRATION

Calibrate to the Lamor frequency of shielded protons in a spherical sample: ω_p'

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

10.5 ppb uncertainty (hydrogen maser)
Metrologia **13**, 179 (1977)

bound state QED calc., exact

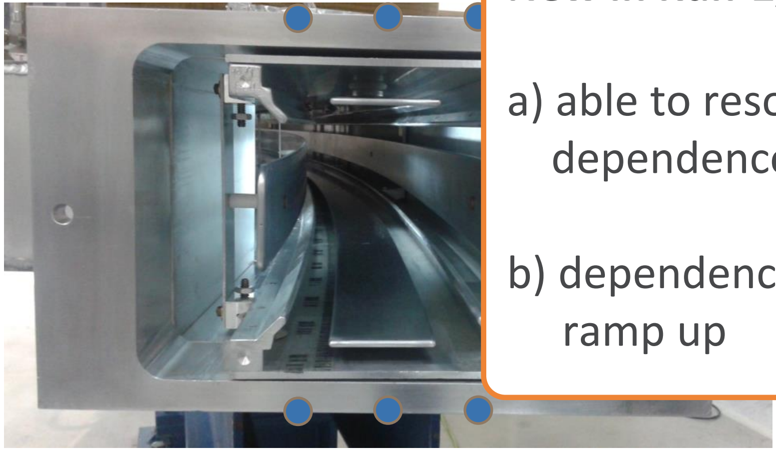
0.13 ppt uncertainty
PDG, dominated by
Phys. Rev. Lett. **130**, 071801 (2023)

22 ppb uncertainty
(Muonium hyper fine split.)
Phys. Rev. Lett. **82**, 711 (1999)

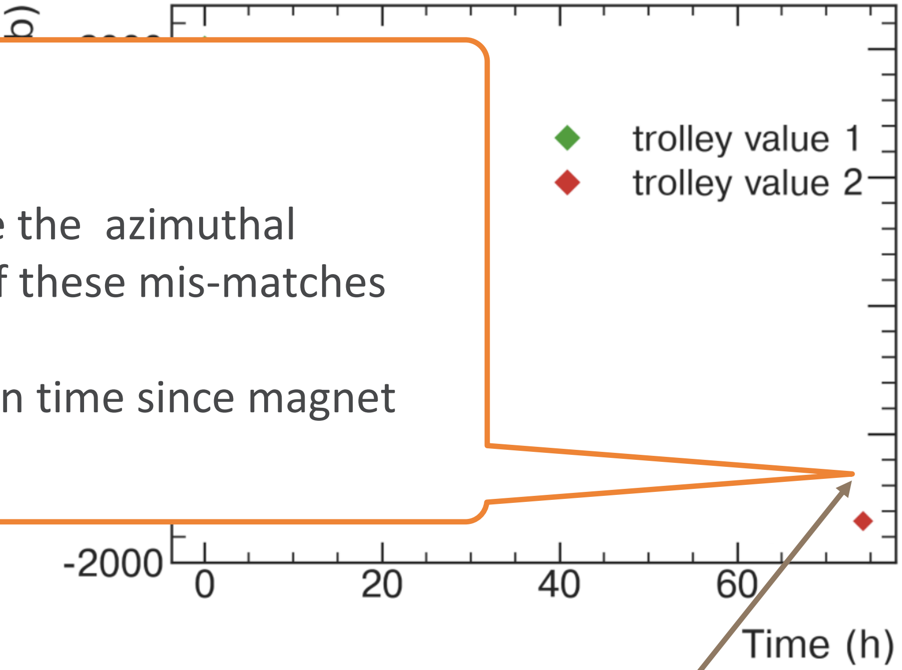
magnetic field
seen by the muons

TRACKING THE FIELD OVER TIME

378 Fixed Probes
- Outside of the storage region
- 72 position, ~5deg a



the filed at one azimuth



New in Run-2/3

a) able to resolve the azimuthal dependence of these mis-matches

b) dependence on time since magnet ramp up

tracking uncertainty from these mis-matches

uncertainty: ~17 ppb

WEIGHTING THE FIELD BY THE MUON DISTRIBUTION

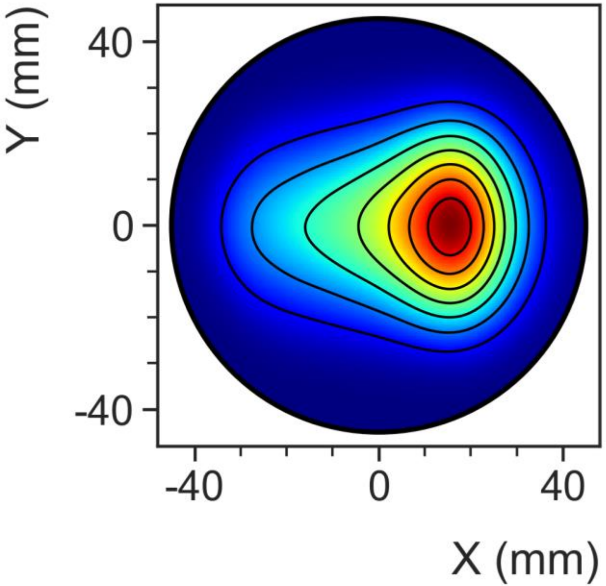
field maps $\omega_p'(x, y, \phi; t)$
tracked by the fixed probes

muon distribution $M(x, y, \phi; t)$
from trackers + simulation

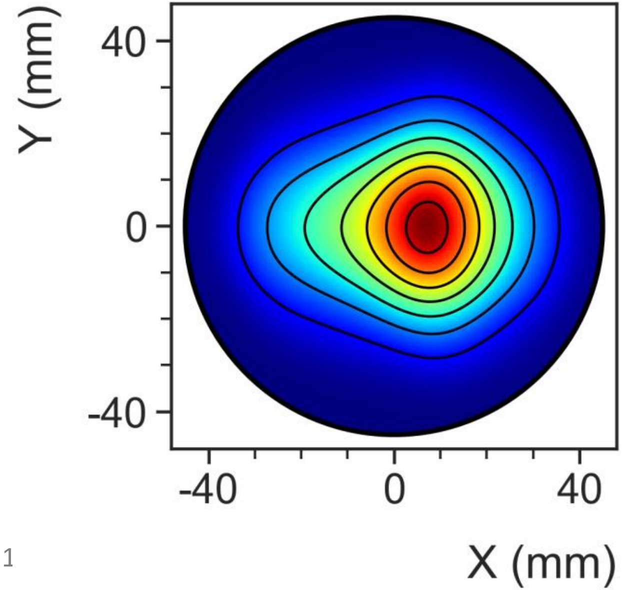
uncertainty: 7 - 13 ppb

$$\tilde{\omega}_p'(t) = \frac{\int \omega_p'(x, y, \phi; t) M(x, y, \phi; t) dV}{\int M(x, y, \phi; t) dV}$$

Run-2 and Run-3a

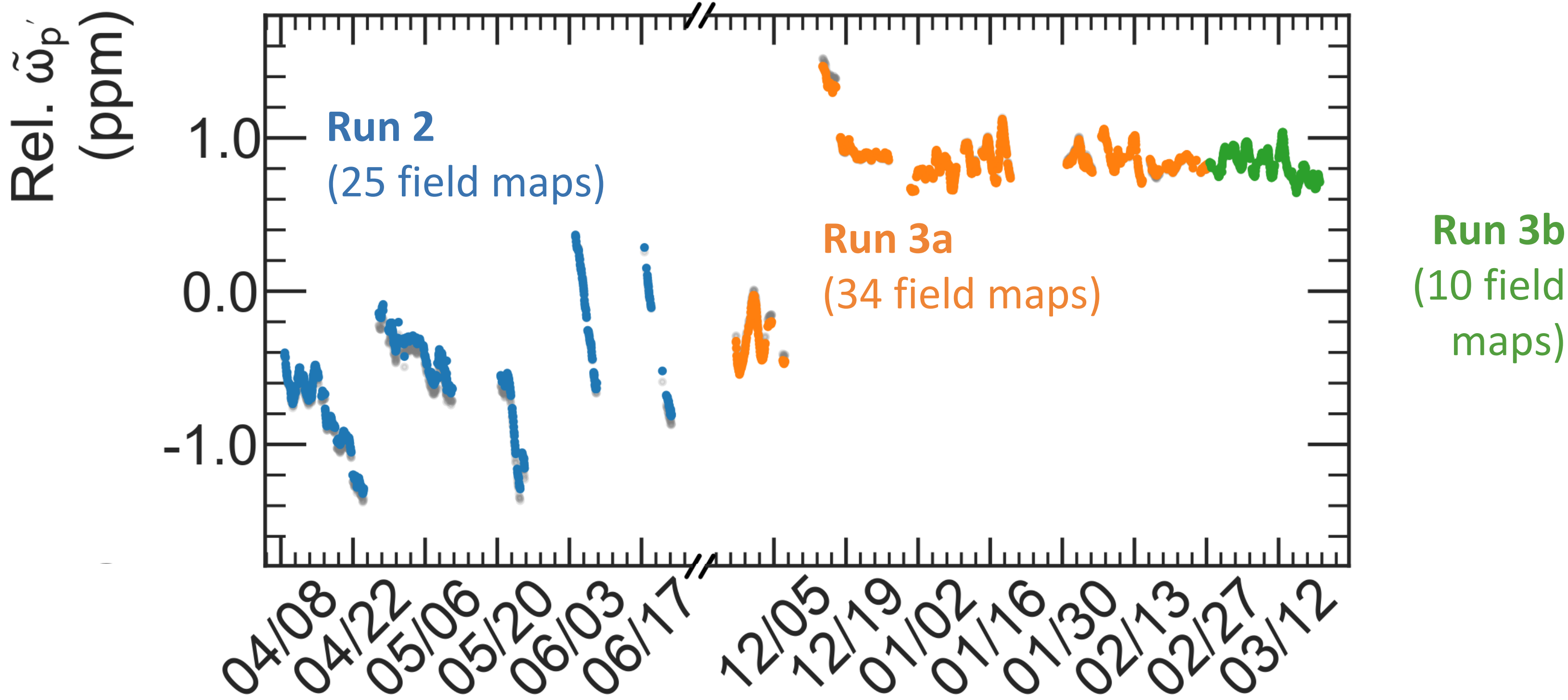


Run-3b: upgraded kickers

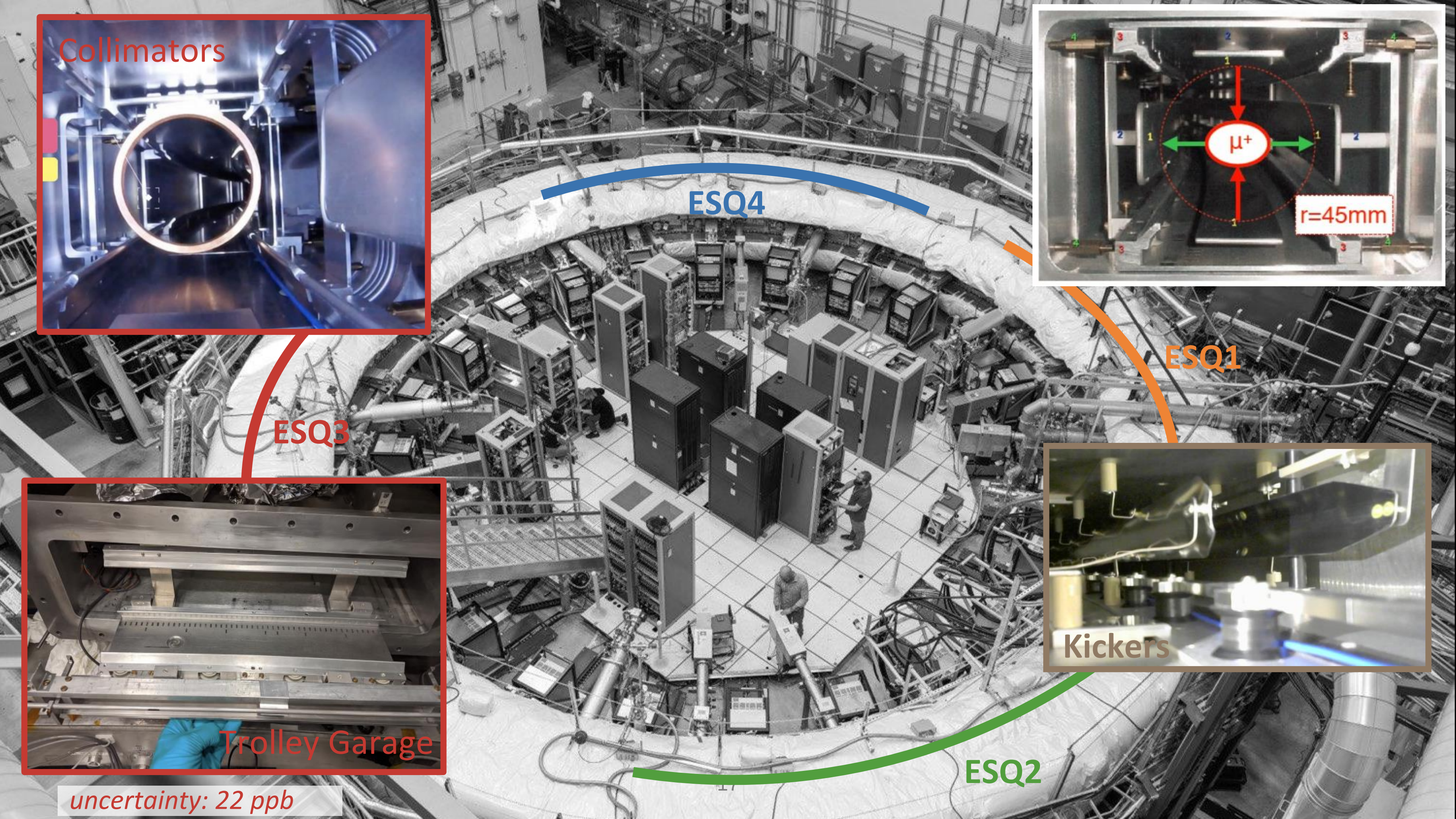


THE MAGNETIC FIELD OF RUN 2/3

two independent analysis chains



Total field maps Run-2/3: 69 (Run-1: 14)


Collimators
ESQ4
μ+
r=45mm
ESQ1
ESQ3
Kickers
Trolley Garage
ESQ2
uncertainty: 22 ppb

TF

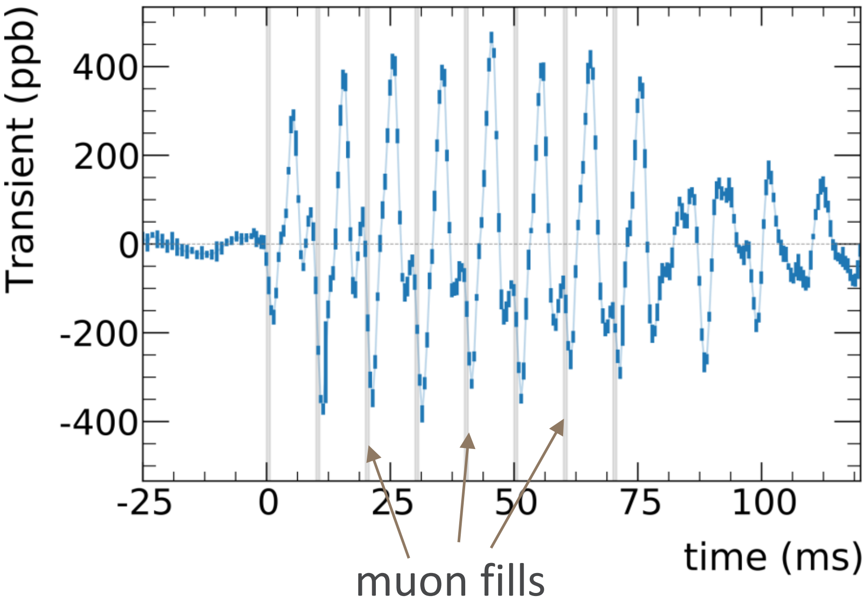
Ed

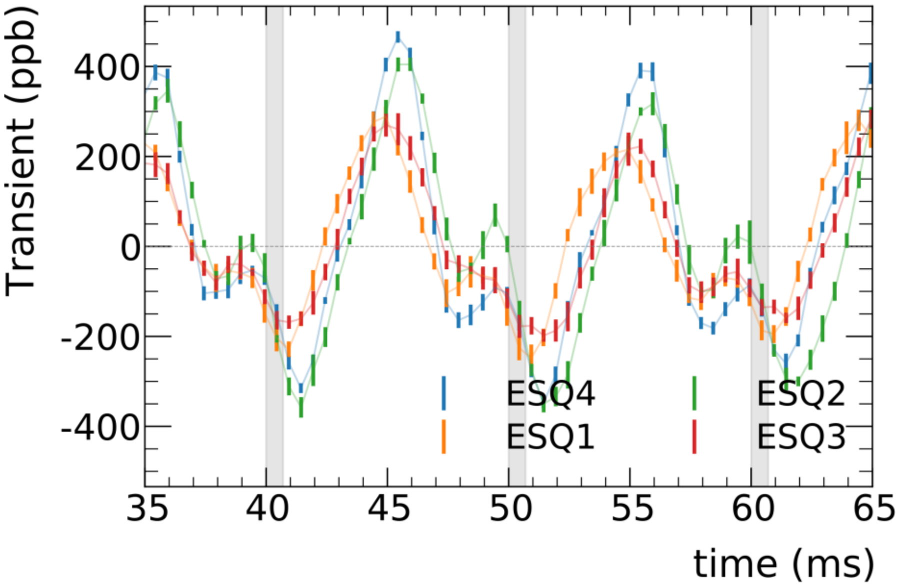
Fi

TRANSIENT FIELDS FROM ESQ VIBRATIONS

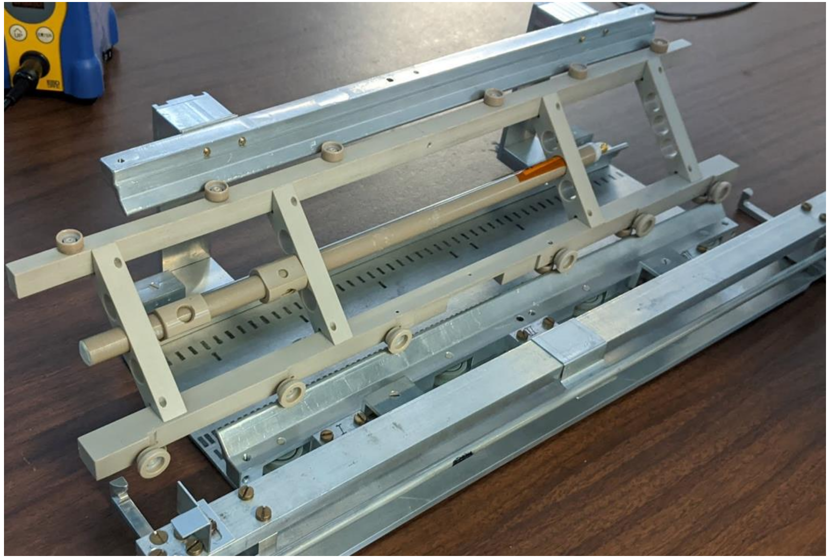
Mechanical vibrations of ESQ plates cause magnetic field changes.

at one location (in ESQ 4)

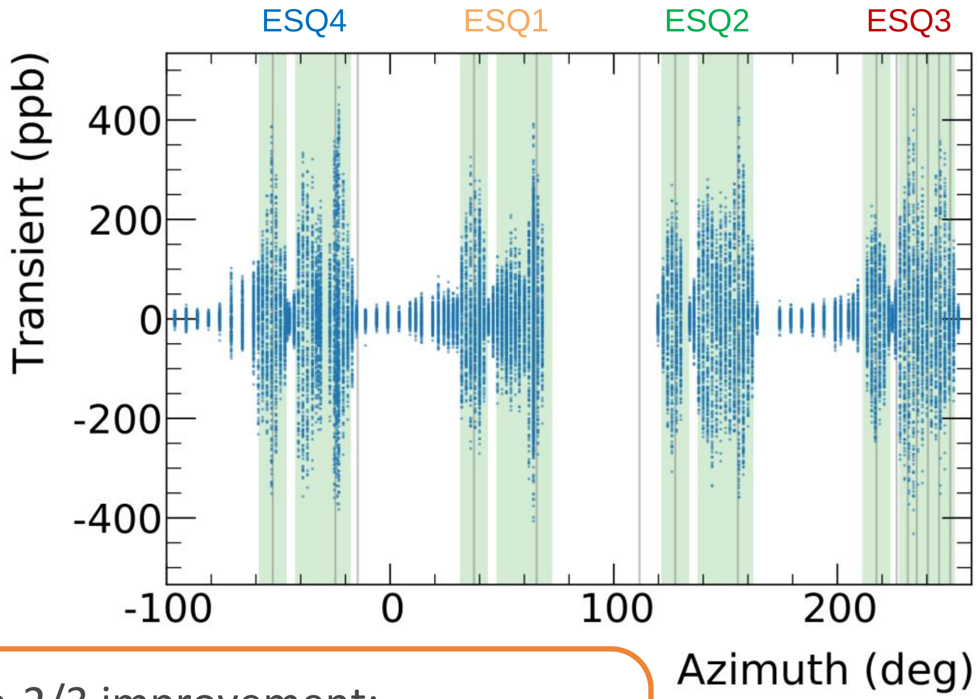




TRANSIENT FIELDS FROM ESQ VIBRATIONS



vacuum sealed NMR probe

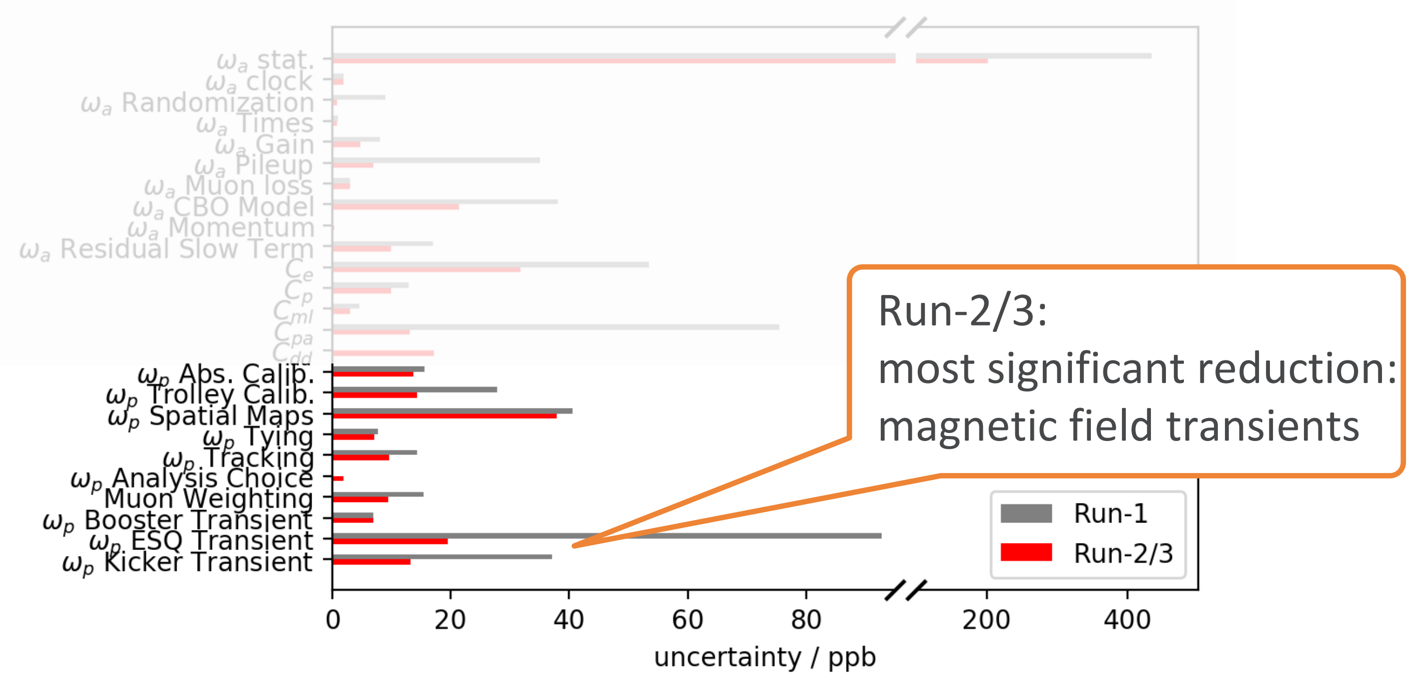


Run-2/3 improvement:
mapping of azimuthal dependence
uncertainty: 92 ppb -> 20 ppb

THE MAGNETIC FIELD OF RUN-2/3: SUMMARY

Total field syst. in Run-2/3: **52 ppb** (TDR goal: 70 ppb)

Outlook: syst. unc. expectation for Run-4/5/6 < 70 ppb



The Muon g – 2 Experiment was performed at the 326 Fermi National Accelerator Laboratory, a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, 329 LLC (FRA), acting under Contract No. DE-AC02- 330 07CH11359. Additional support for the experiment was provided by the Department of Energy offices of HEP and NP (USA), the National Science Foundation (USA), the Istituto Nazionale di Fisica Nucleare (Italy), the Science and Technology Facilities Council (UK), the Royal Society (UK), the National Natural Science Foundation of China (Grant No. 11975153, 12075151), MSIP, NRF and IBS-R017-D1 (Republic of Korea), the German Research Foundation (DFG) through the Cluster of Excellence PRISMA+ (EXC 2118/1, Project ID 39083149), 340 the European Union Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreements No. 101006726, No. 734303, European Union STRONG 2020 project under grant agreement No. 824093 and the Leverhulme Trust, LIP-2021-01.

TRANSIENT FIELDS FROM THE KICKERS

Description	Uncertainty [ppb]			
	2021	2022	Run-3b	Run-2/3a
vibration ambiguity	8.3	12.8	10.5	9.9
transient variance			4.2	3.9
azimuthal	3.1	4.7	3.9	3.7
transverse	4.4	6.8	5.6	5.3
calibration	0.3	0.2	0.3	0.3
baseline	2.5	0.2	1.3	1.2
scaling				1.7
pulse shape diff.				4.2
Sub total			13.3	13.3

TRANSIENT FIELDS FROM ESQ VIBRATIONS

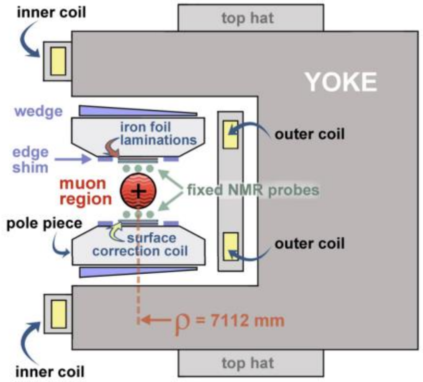
Description	Correction [ppb]	Uncertainty [ppb]
frequency extraction		5
skin depth		2
stability over time		8
azimuthal averaging		11
transverse dependence		5.3
measurement apparatus		10.5
fill-by-fill variations		2
second bunch train		5
Sub total	-21.0	19.5

THE MAGNETIC FIELD OF RUN-2/3: SUMMARY

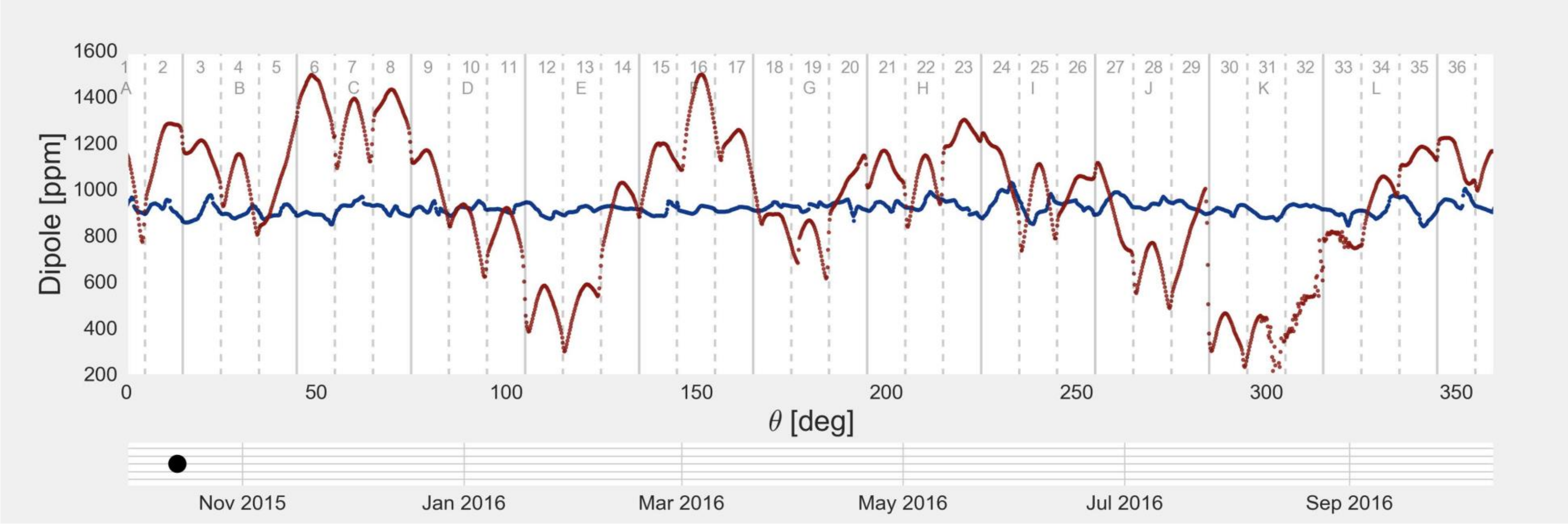
Description	Uncertainty [ppb] Run-2	Run-3a	Run-3b
Calibration probe		8.9	
Trolley calibration		17.0	
Spacial Field Maps	37.2	38.5	38.1
Tracking	17.3	16.5	17.8
Muon Weighting	13.4	7.9	6.9
Transient Booster		7	
Transient Kicker		13.3	
Transient ESQ		19.5	
Sub total correlated			
Sub total uncorrelated			

Total field syst. in Run-2/3: 52 ppb (TDR goal: 70 ppb)

HOW TO STORE MUONS: MAGNETIC FIELD



Fermilab: ~15 ppm RMS (~75 ppm peak-to-peak)
BNL E821: ~35 ppm RMS (~200 ppm peak-to-peak)



MAGNET TEMPERATURE