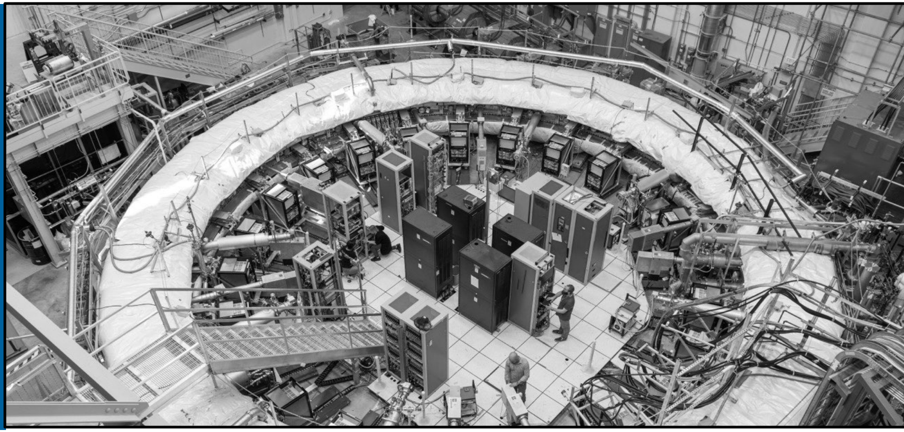
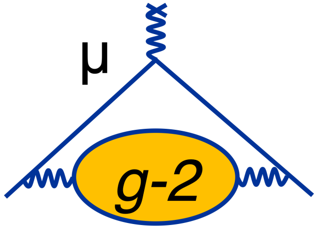
STATUS OF FERMILAB G—2 ANALYSIS TOWARDS FINAL RESULT



SIMON CORRODI
Argonne National Laboratory

on behalf of the Muon g-2 collaboration
III Workshop on Muon Precision Physics (MPP2024)
November 13th 2024

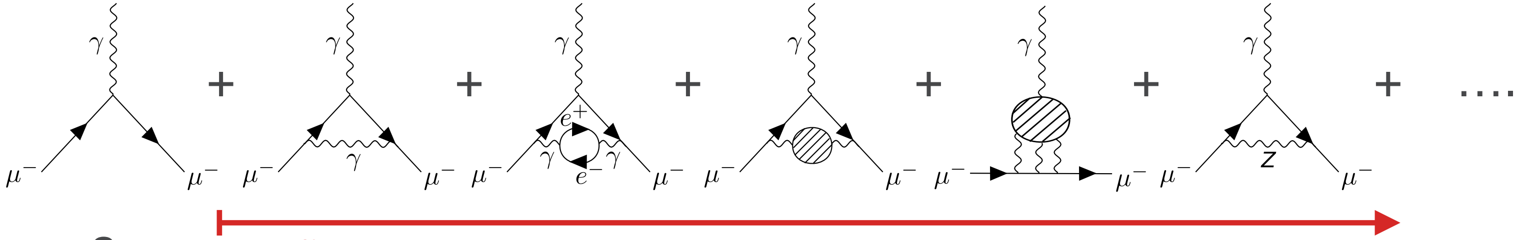


INTRINSIC MAGNETIC MOMENT

Magnetic moment $\vec{\mu}$ is connected to spin $\vec{s}$ via dimensionless factor g

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

"gyromagnetic ratio"



2

a_μ

muon magnetic anomaly: $a_\mu \equiv \frac{g_\mu - 2}{2}$

THE MAGNETIC MOMENT OF THE MUON: HISTORY

Storage Ring

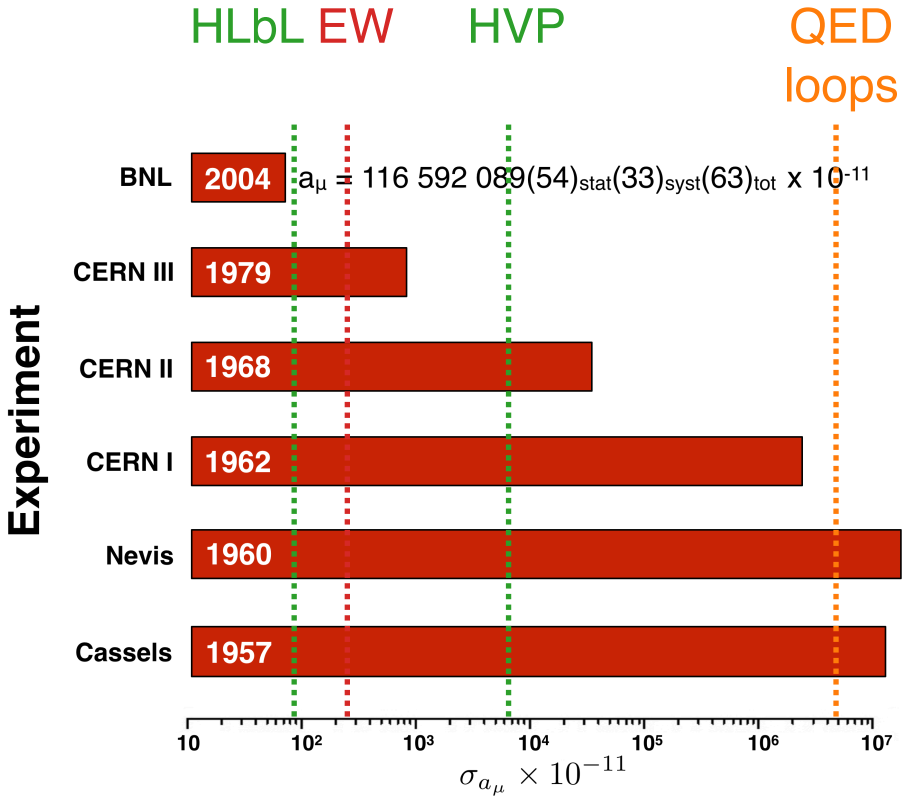
Dilated lifetime

measurement of a_μ, more precise

Stopped Muons

Stop muons in a magnetic field

measurement of g_μ directly



THE MAGNETIC MOMENT OF THE MUON: HISTORY

~3.5σ sigma between a_μ^{exp} and a_μ^{SM}

Storage Ring

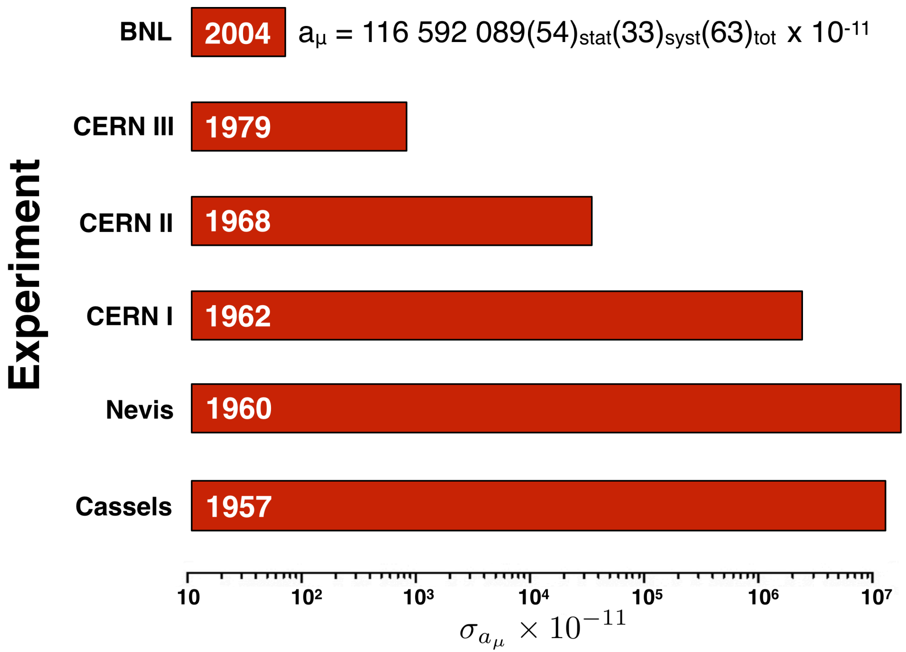
Dilated lifetime

measurement of a_μ, more precise

Stopped Muons

Stop muons in a magnetic field

measurement of g_μ directly



THE MAGNETIC MOMENT OF THE MUON: HISTORY

FNAL **goal**: 4 x improvement

Storage Ring

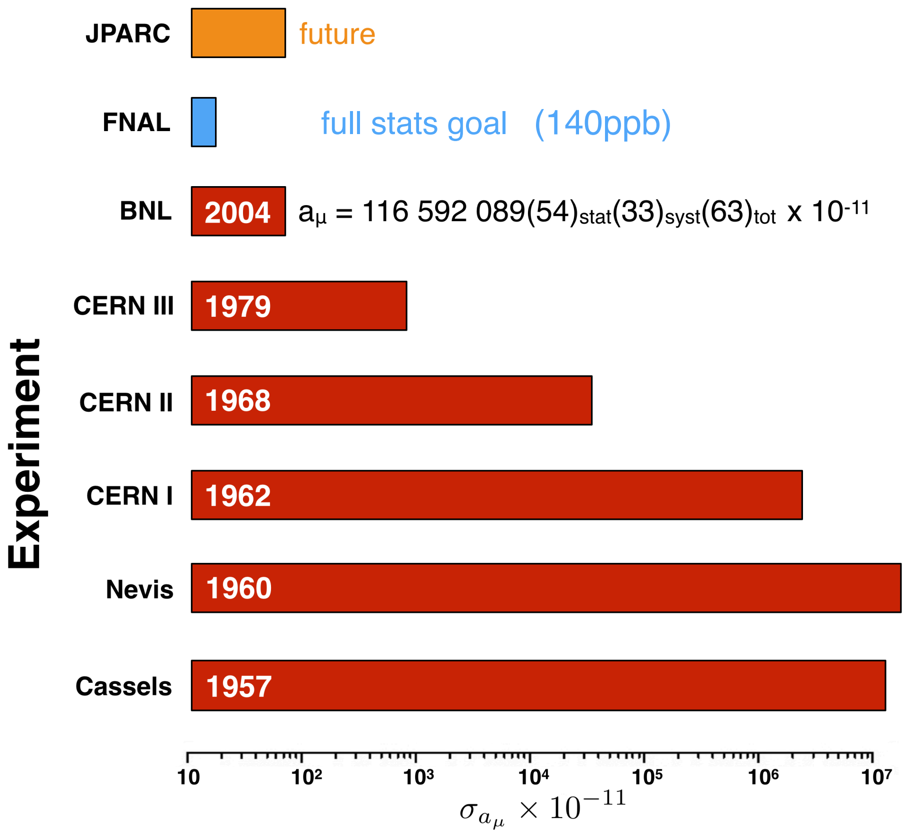
Dilated lifetime

measurement of a_μ, more precise

Stopped Muons

Stop muons in a magnetic field

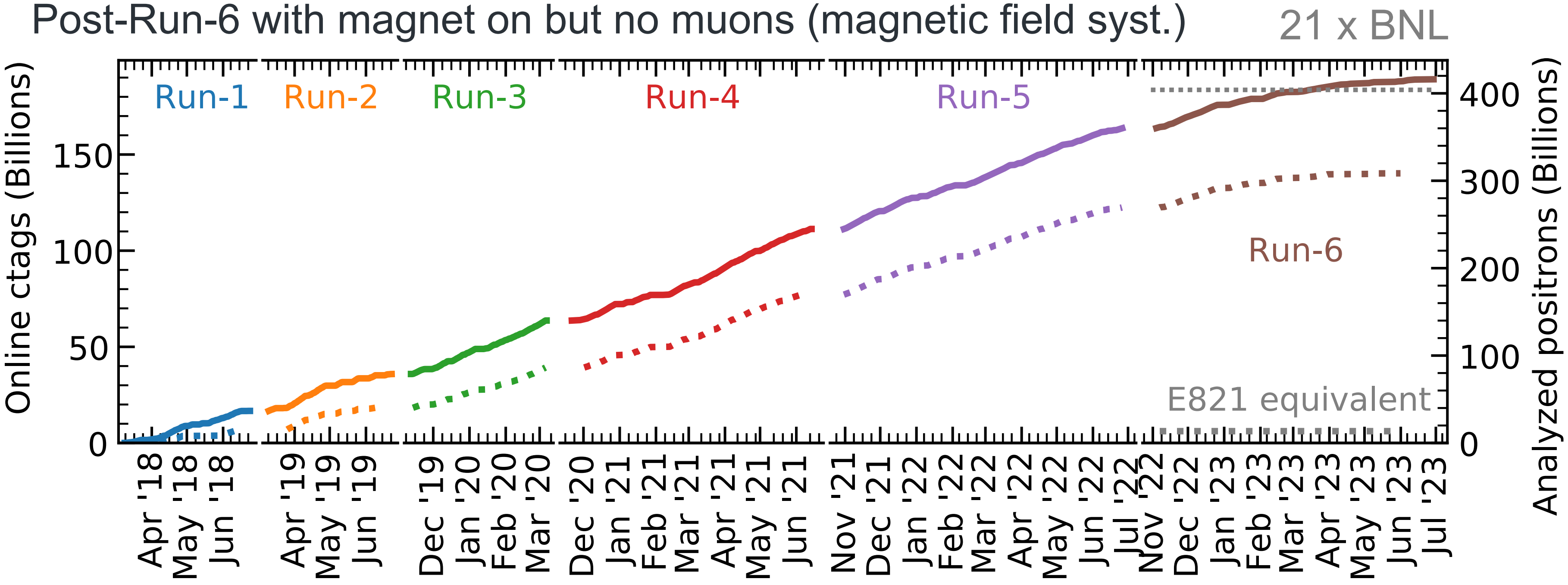
measurement of g_μ directly



FERMILAB MUON G-2 DATA TAKING

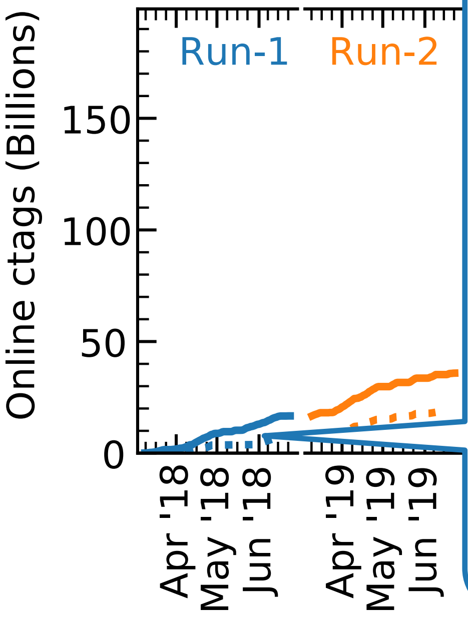
6 years of data taking, passed the TDR goal 21 x BNL statistics

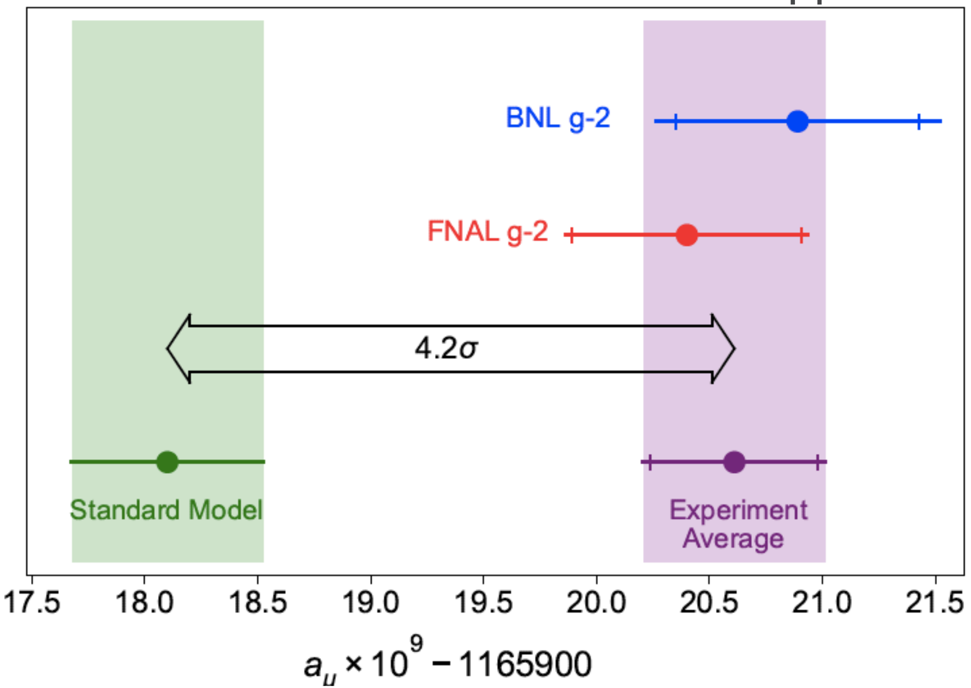
Post-Run-6 with magnet on but no muons (magnetic field syst.)



FERMILAB MUON G

6 years of data takin

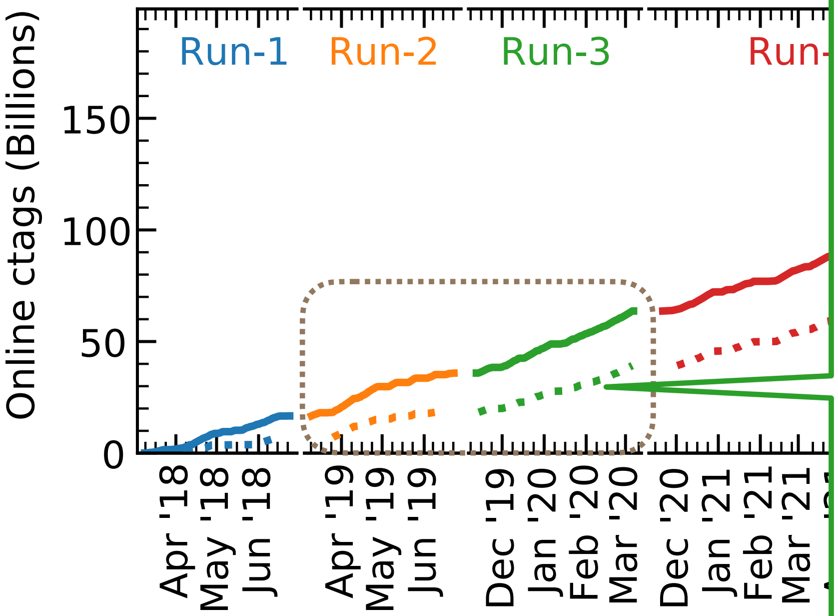




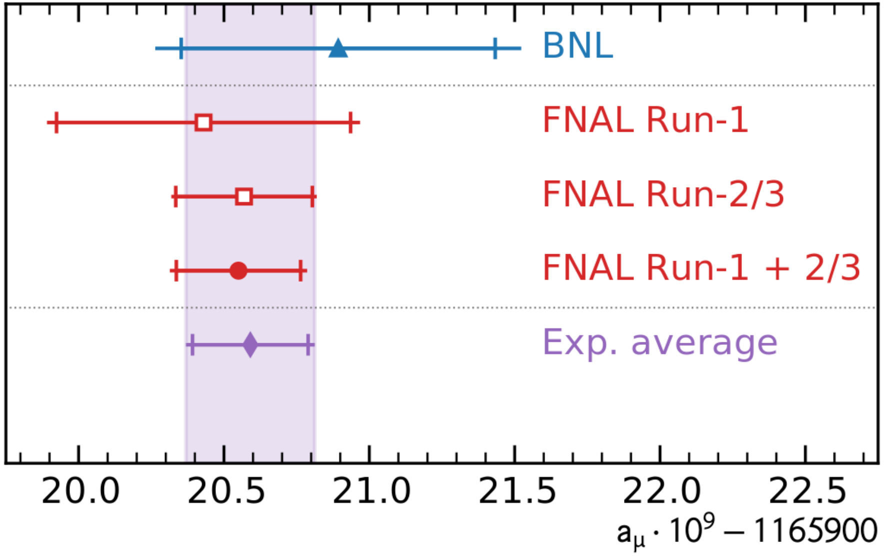
$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

FERMILAB MUON G-2 DATA TAKIN

6 years of data taking, passed the TD



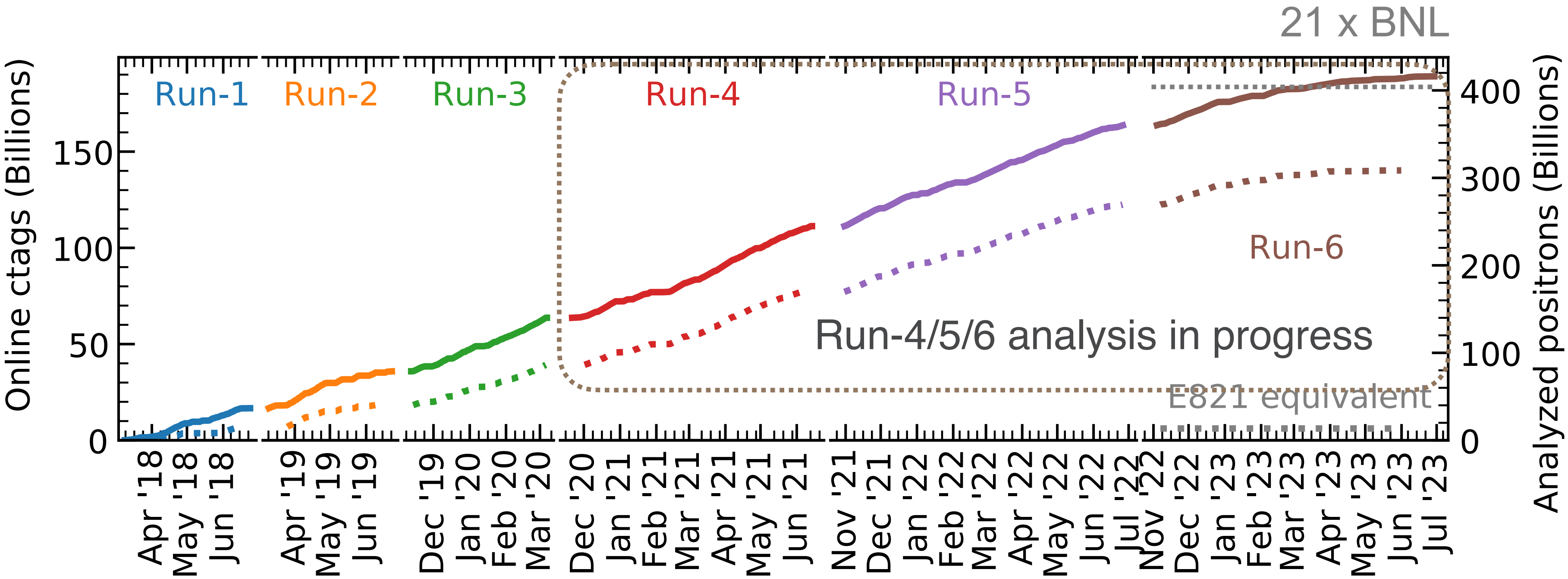
Run-2/3 Result: 2023 :: 0.2 ppm

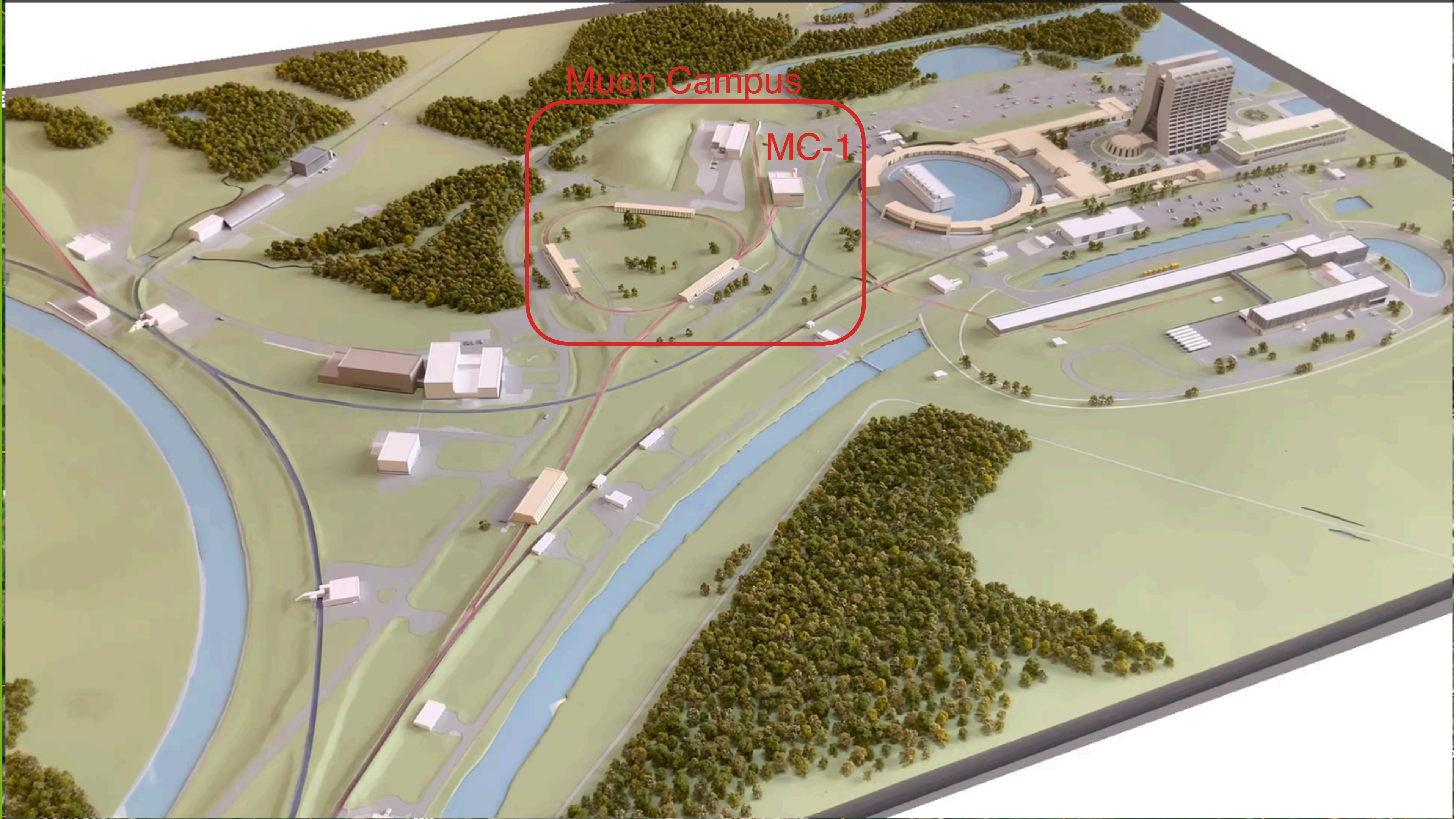


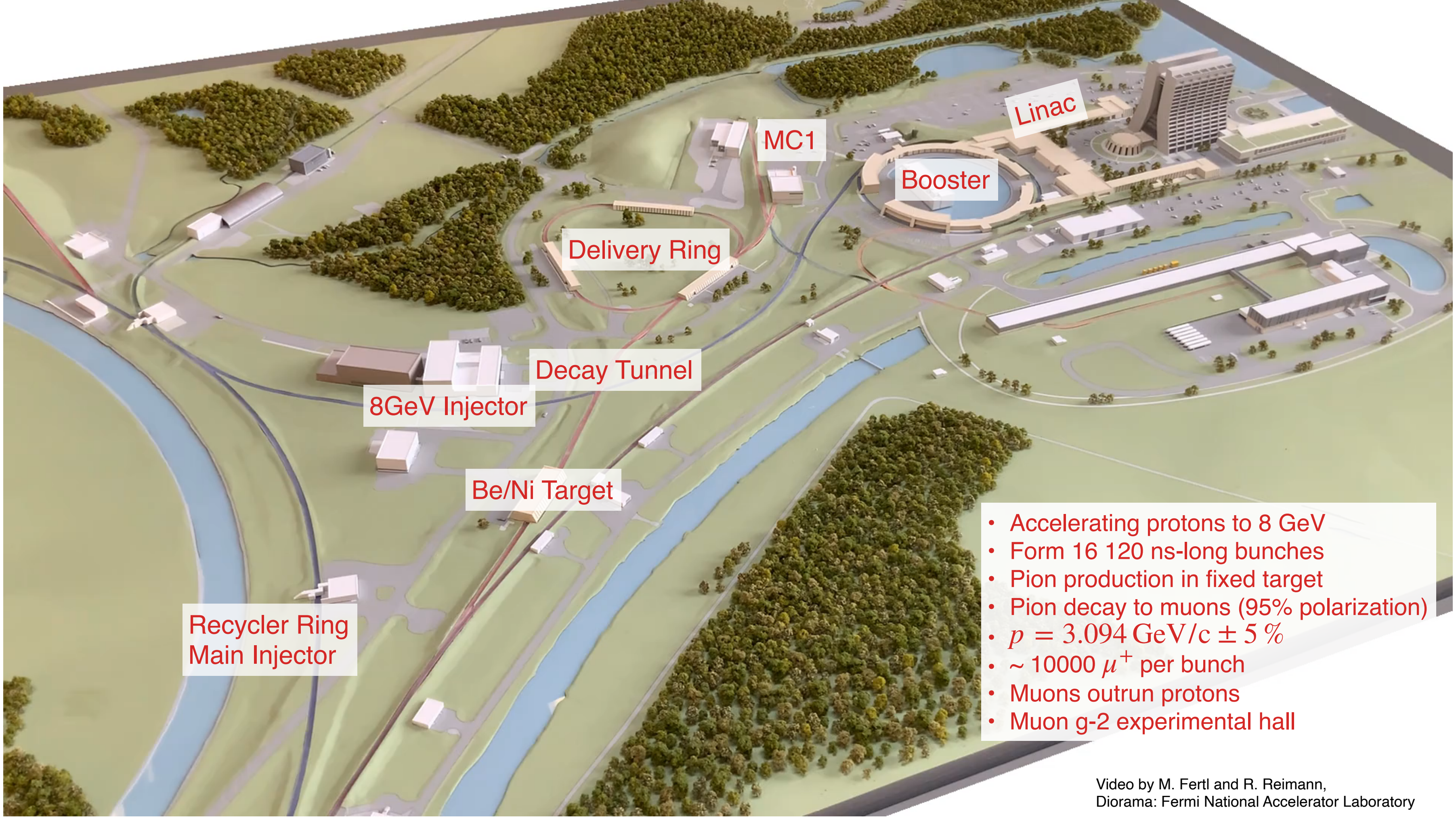
a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

FERMILAB MUON G-2 DATA TAKING

6 years of data taking, passed the TDR goal 21 x BNL statistics



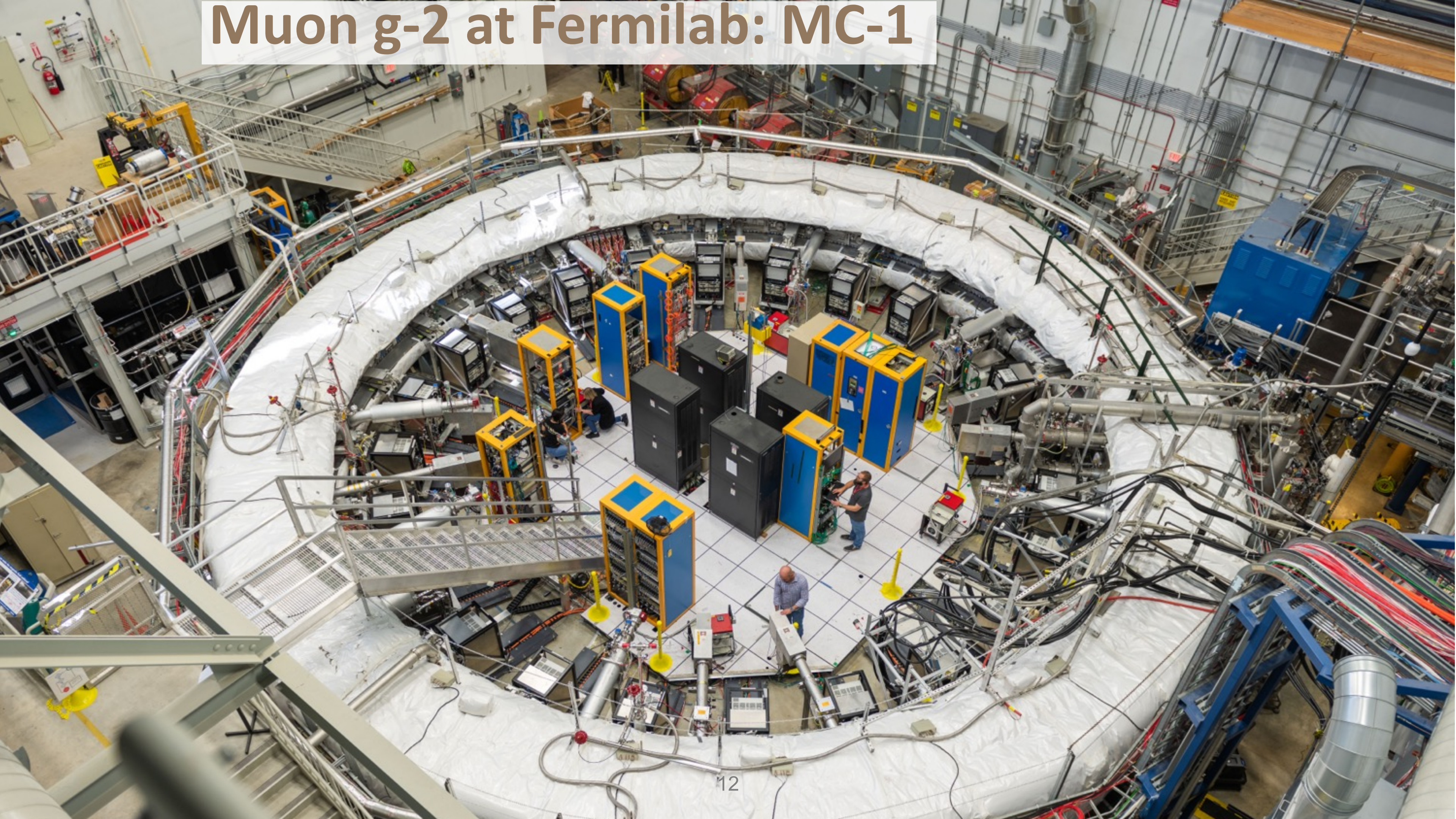

Muon Campus
MC-1

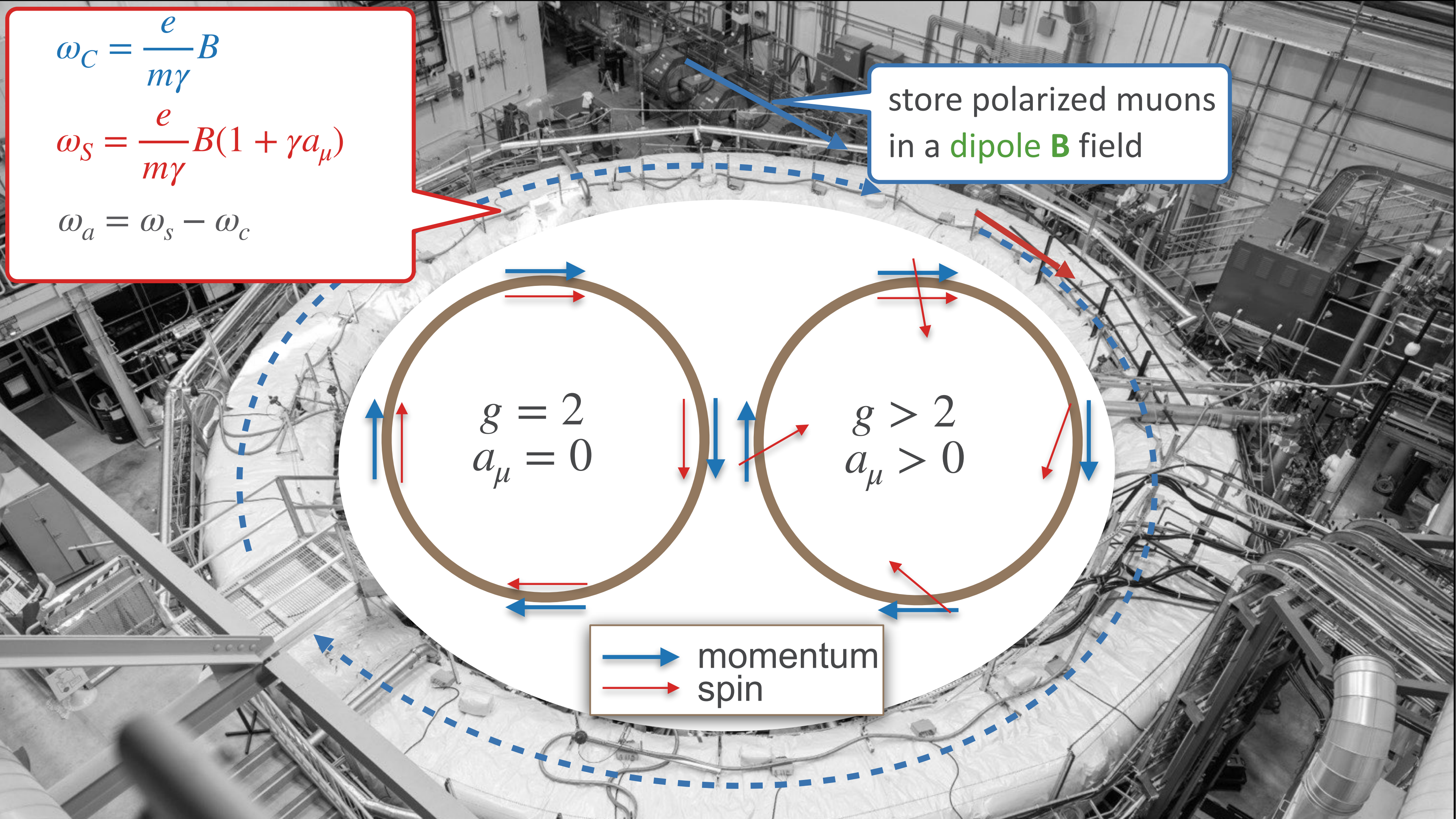


- Accelerating protons to 8 GeV
- Form 16 120 ns-long bunches
- Pion production in fixed target
- Pion decay to muons (95% polarization)
- $p = 3.094\,\mathrm{GeV/c} \pm 5\,\%$
- ~ 10000 μ^+ per bunch
- Muons outrun protons
- Muon g-2 experimental hall

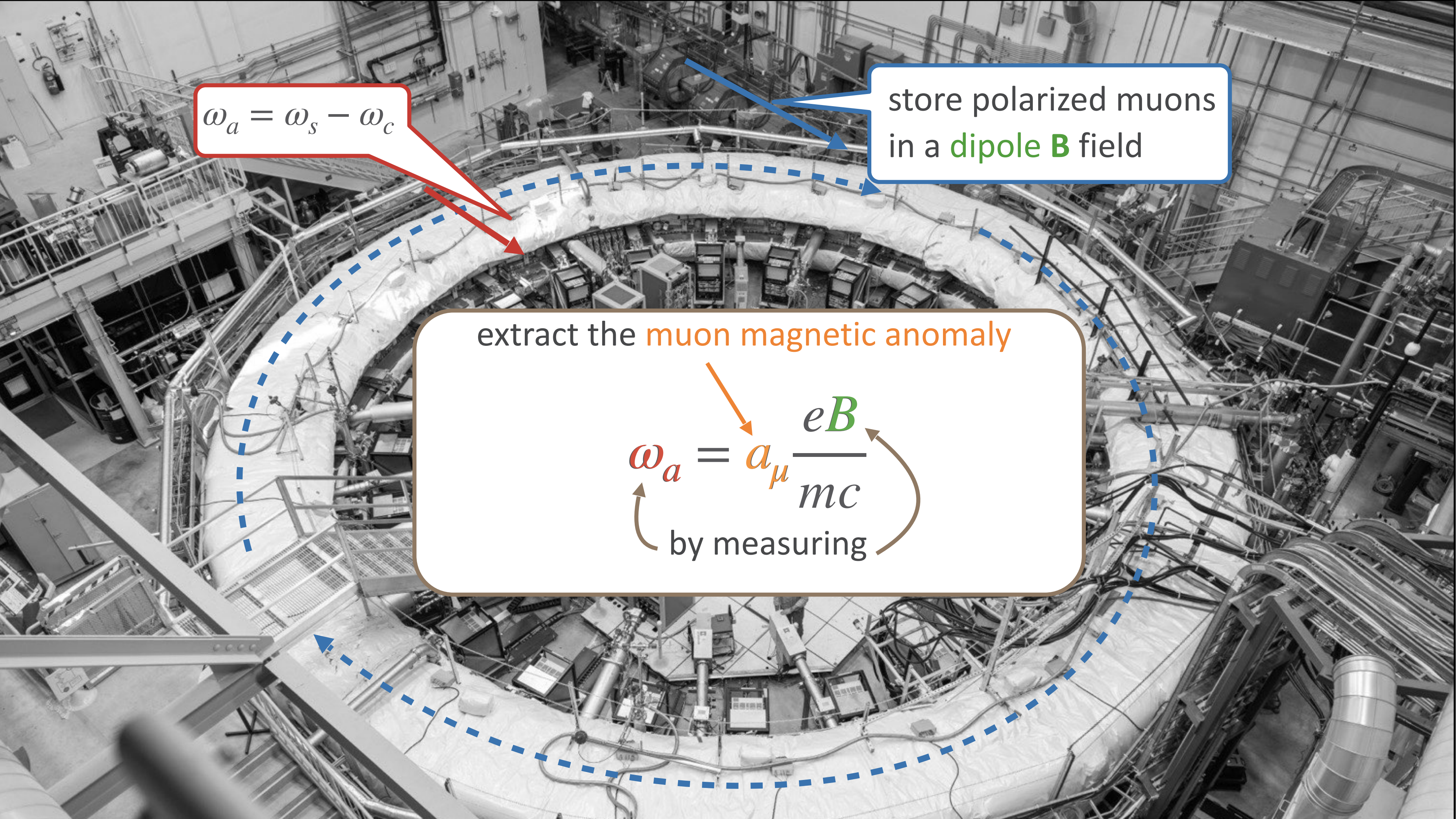
Video by M. Fertl and R. Reimann,
Diorama: Fermi National Accelerator Laboratory

Muon g-2 at Fermilab: MC-1





$\omega_C = \frac{e}{m\gamma}B$
$\omega_S = \frac{e}{m\gamma}B(1+\gamma a_\mu)$
$\omega_a = \omega_s - \omega_c$
store polarized muons
in a dipole **B** field
$g = 2$
$a_\mu = 0$
$g > 2$
$a_\mu > 0$
momentum
spin


$\omega_a = \omega_s - \omega_c$
store polarized muons in a dipole **B** field
extract the muon magnetic anomaly
$\omega_a = a_\mu \frac{eB}{mc}$
by measuring

WHAT IS THE MAGIC MOMENTUM?

extract the muon magnetic anomaly

pitch corrections: C_p

E-field corrections: C_e

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

by measuring

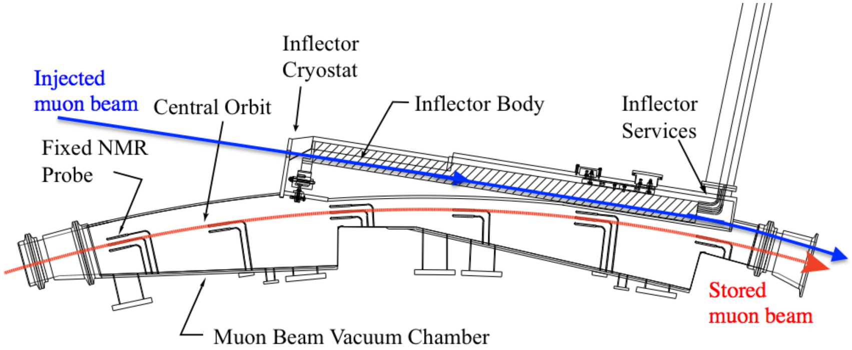
~0

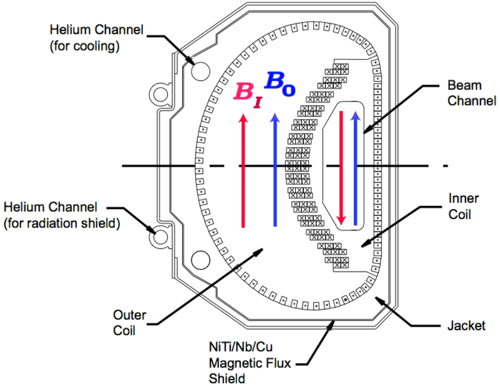
~0

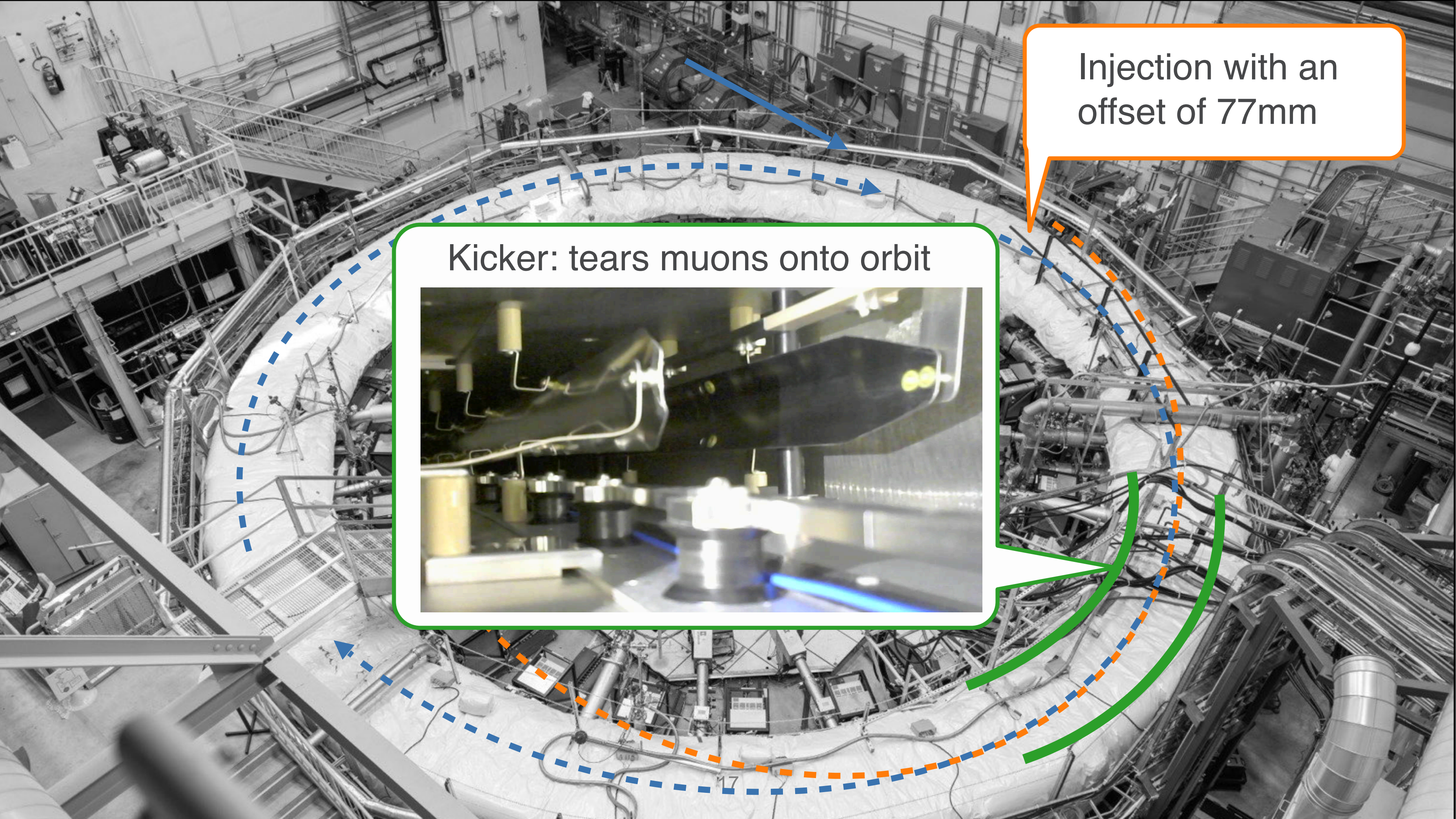
$$p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094\,\text{GeV/c}$$

Injection with an offset of 77mm

"Inflector" magnet: provides field free injection path

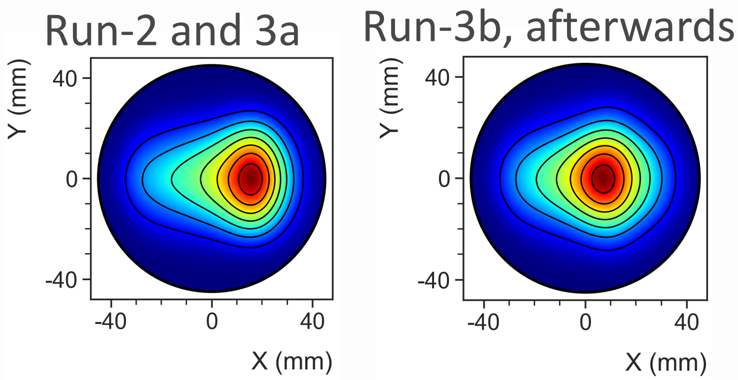




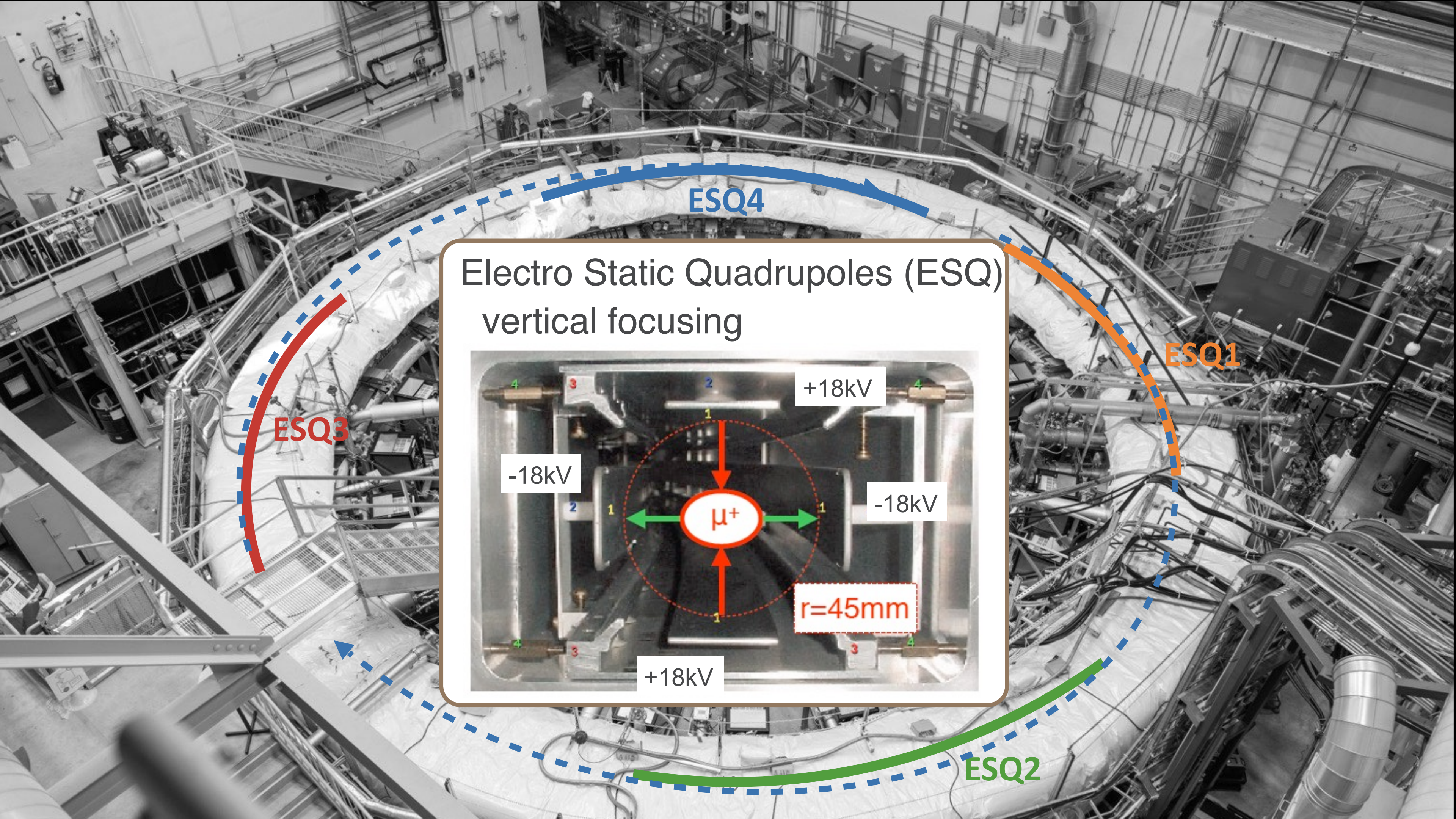

Injection with an offset of 77mm
Kicker: tears muons onto orbit

Run-1: lot of “issues” (sparks), different settings -> datasets

Run-3a/3b: upgraded kicker cables, allowing for larger kick



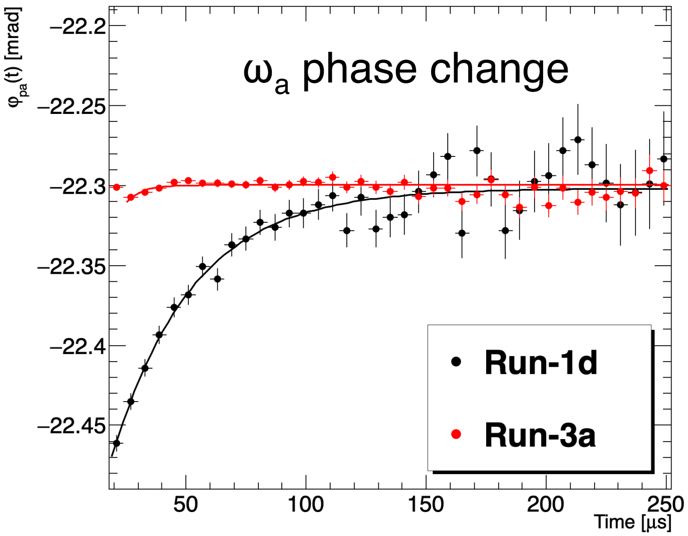
Run-4/5/6: consistent with Run-3b



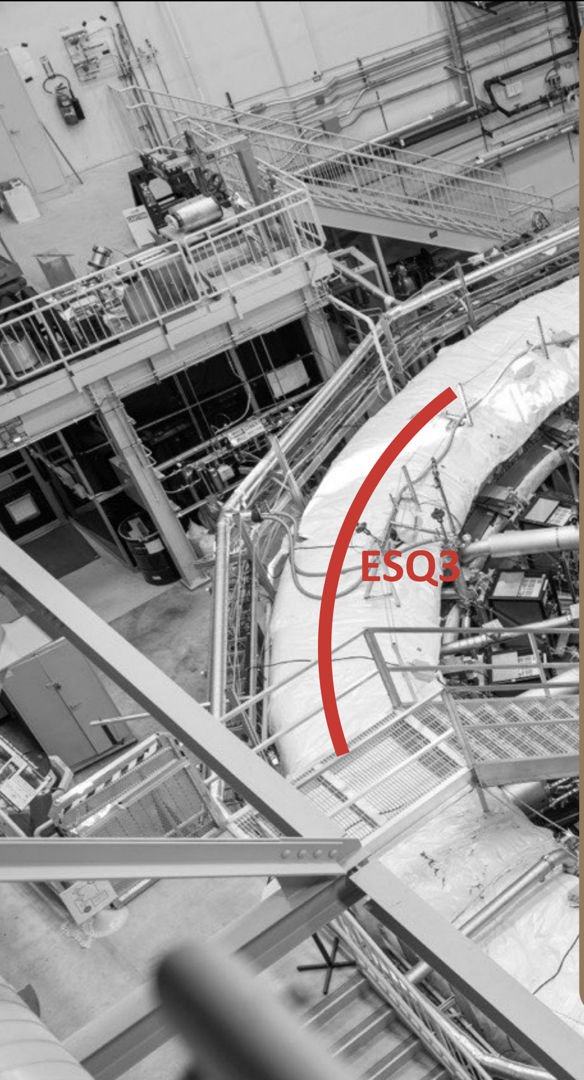
Electro Static Quadrupoles (ESQ)
vertical focusing
ESQ4
ESQ1
ESQ3
ESQ2
+18kV
-18kV
-18kV
+18kV
μ+
r=45mm

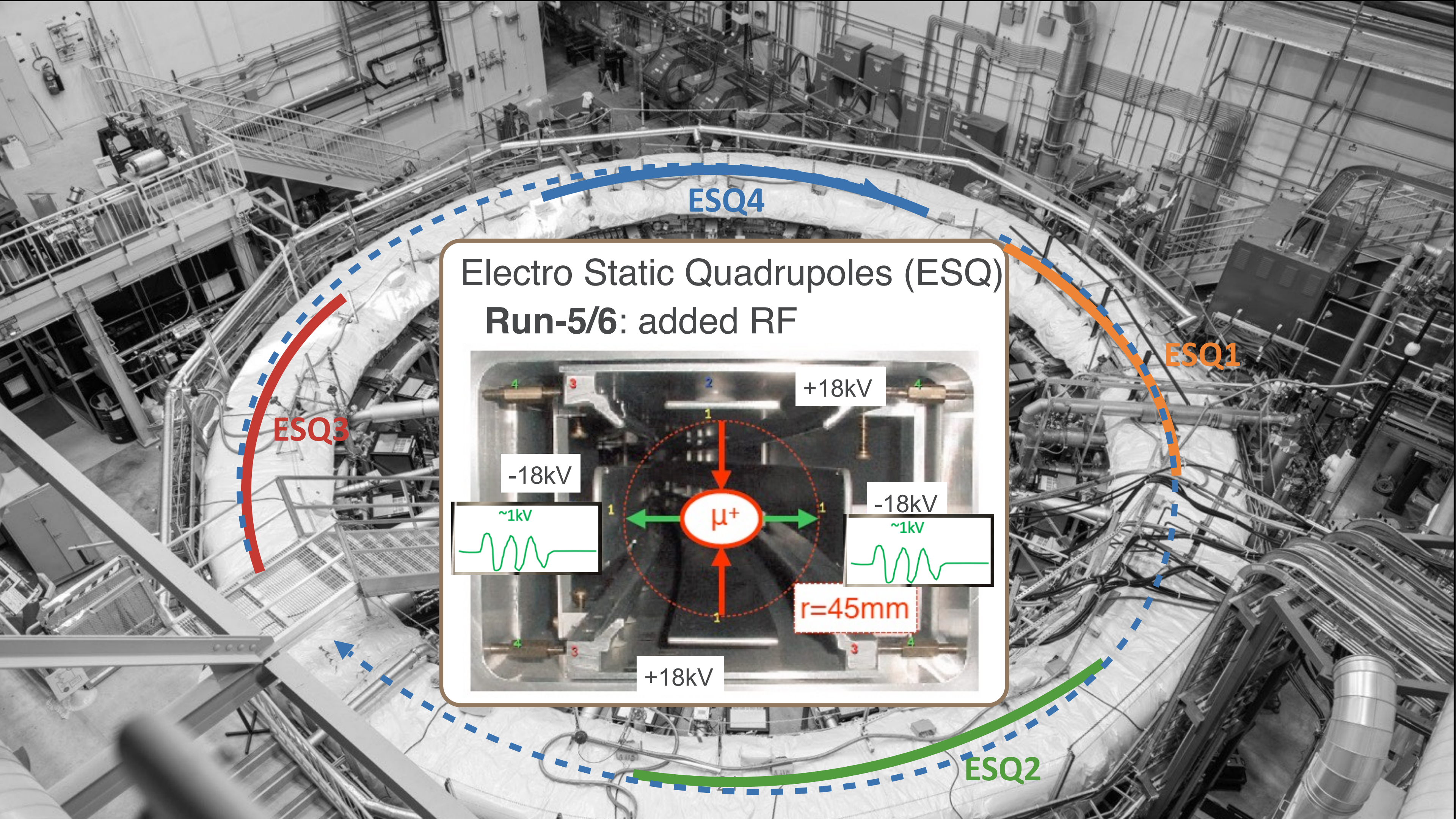
Electro Static Quadrupoles (ESQ)

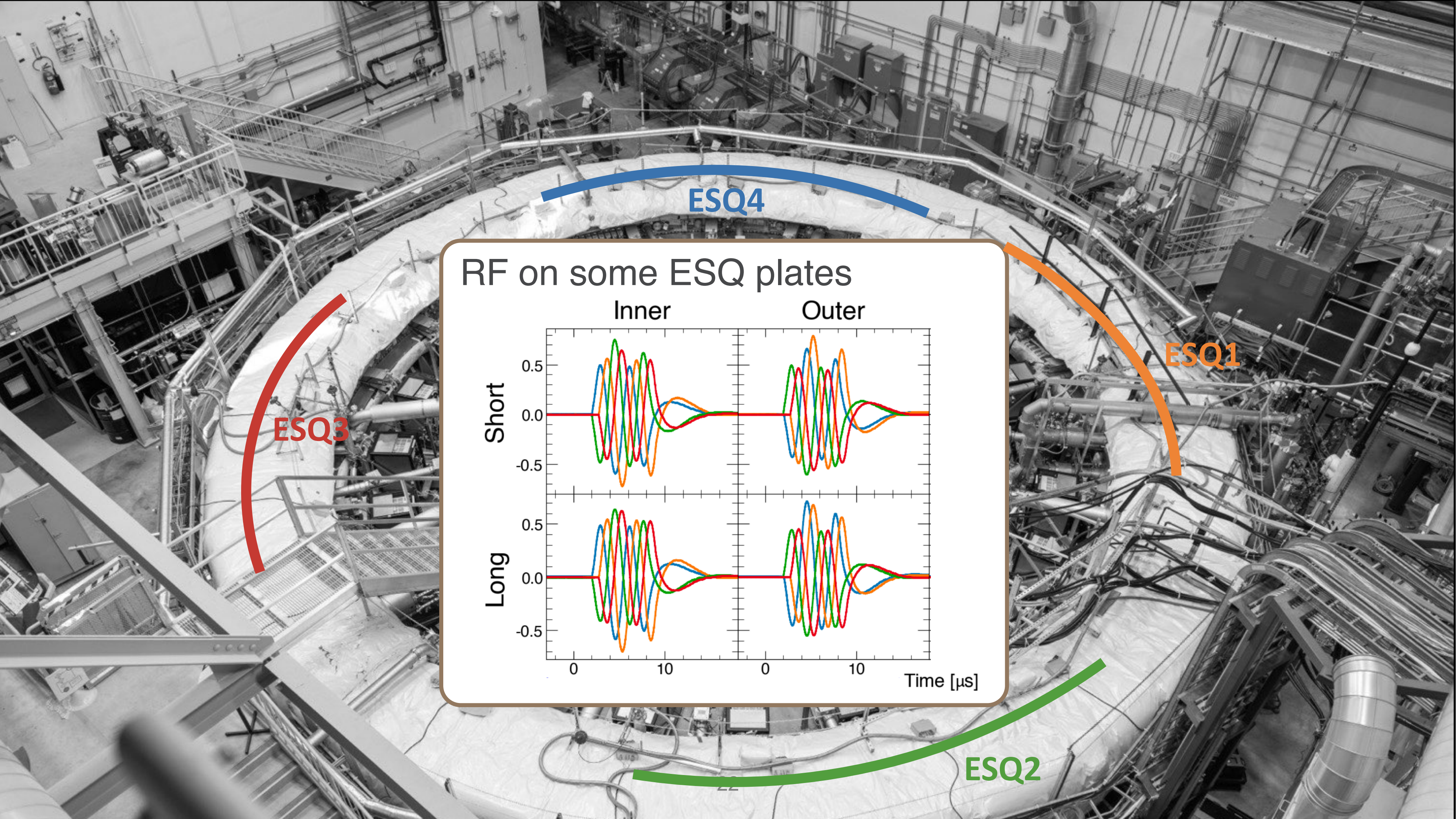
Run-1: - broken HV resistors
- slower charge up
- “unstable” beam

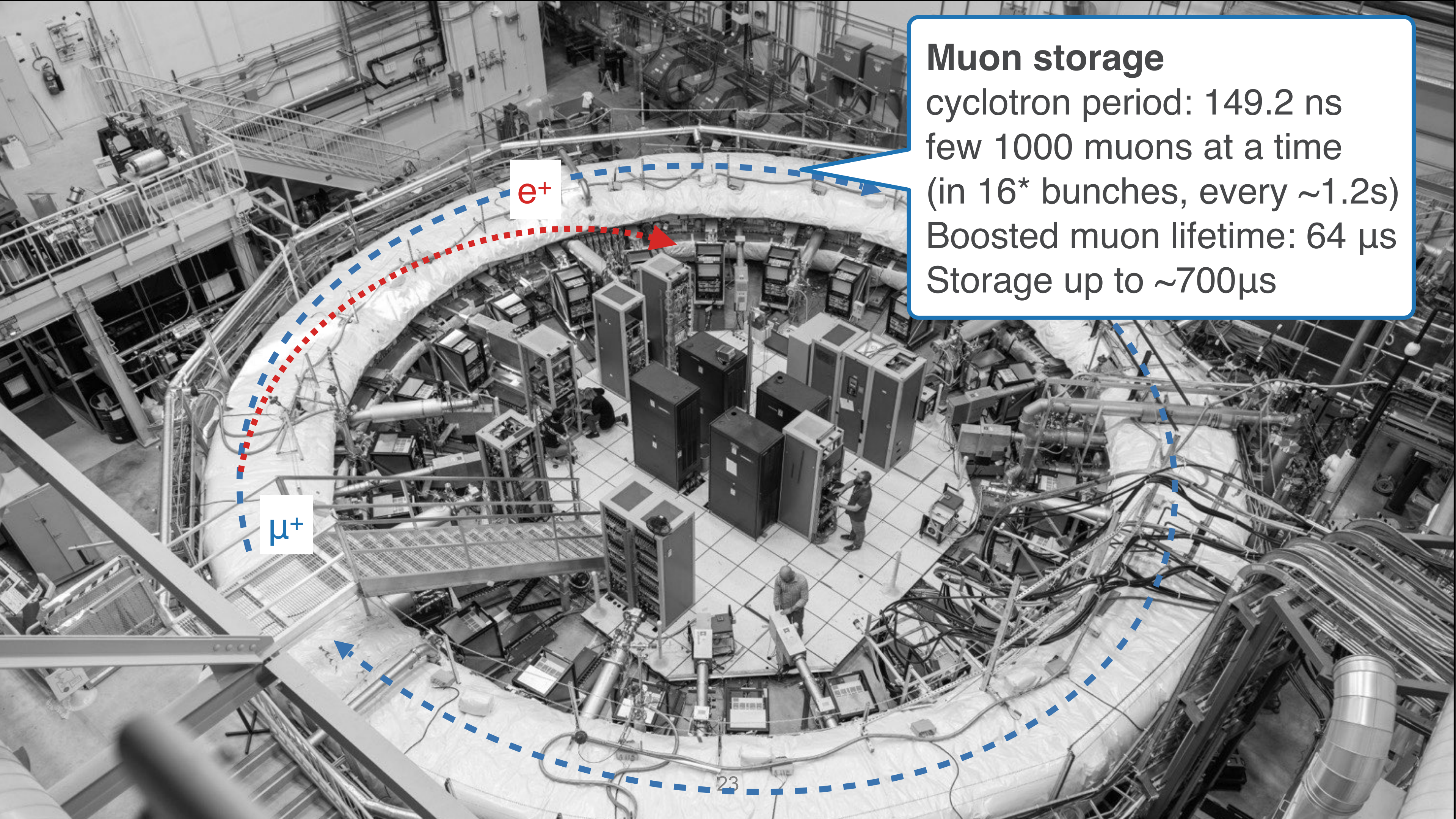


Run-2/3, 4/5/6: fixed
(and monitored)



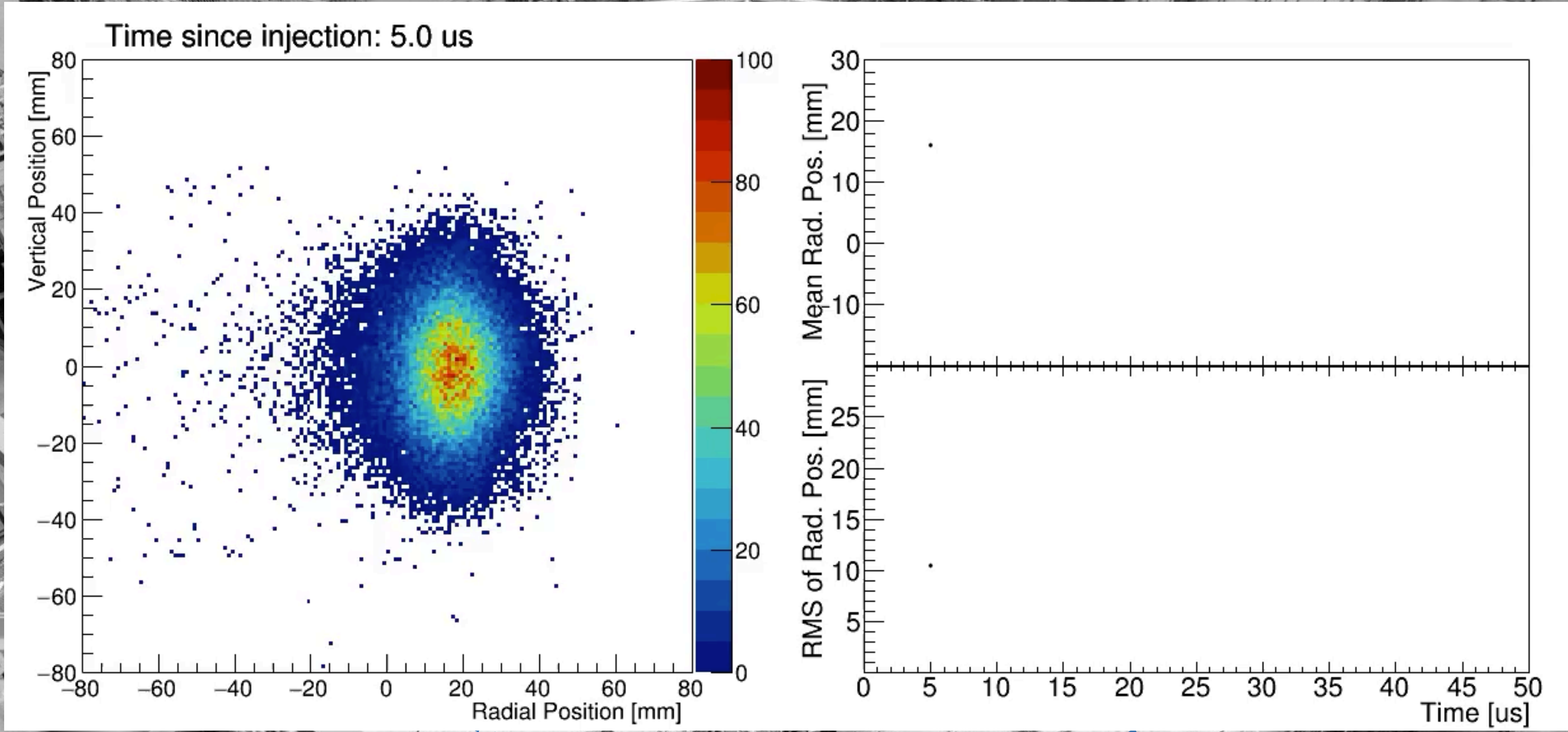

ESQ4
Electro Static Quadrupoles (ESQ)
Run-5/6: added RF
+18kV
-18kV
~1kV
μ+
-18kV
~1kV
r=45mm
+18kV
ESQ1
ESQ3
ESQ2


RF on some ESQ plates
ESQ4
ESQ1
ESQ3
ESQ2
Inner
Outer
Short
Long
0.5
0.0
-0.5
0
10
Time [μs]



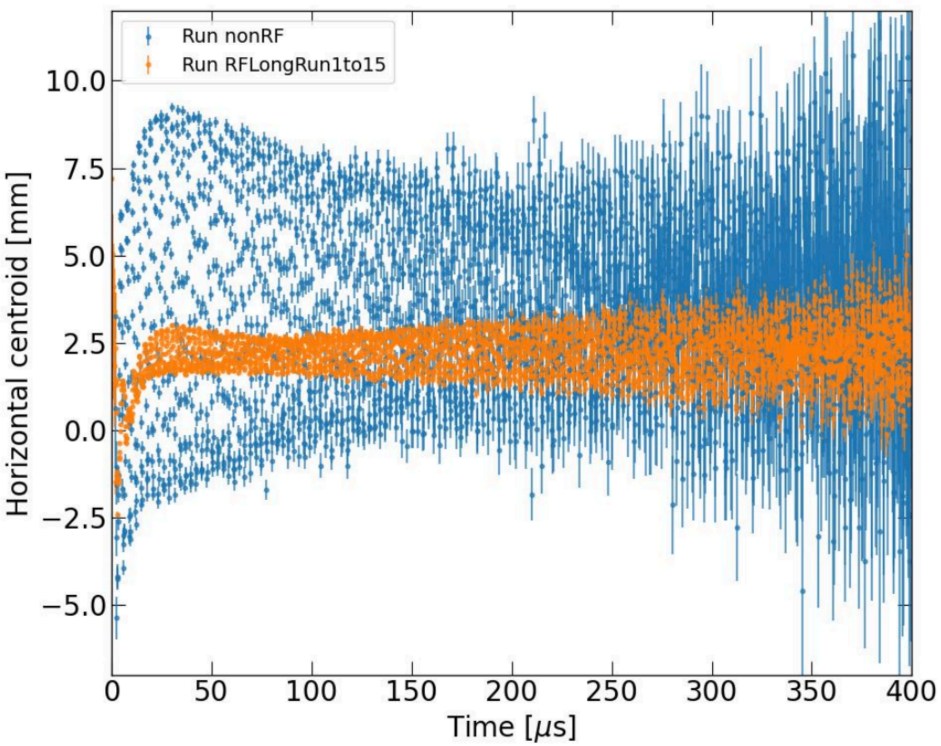
Muon storage

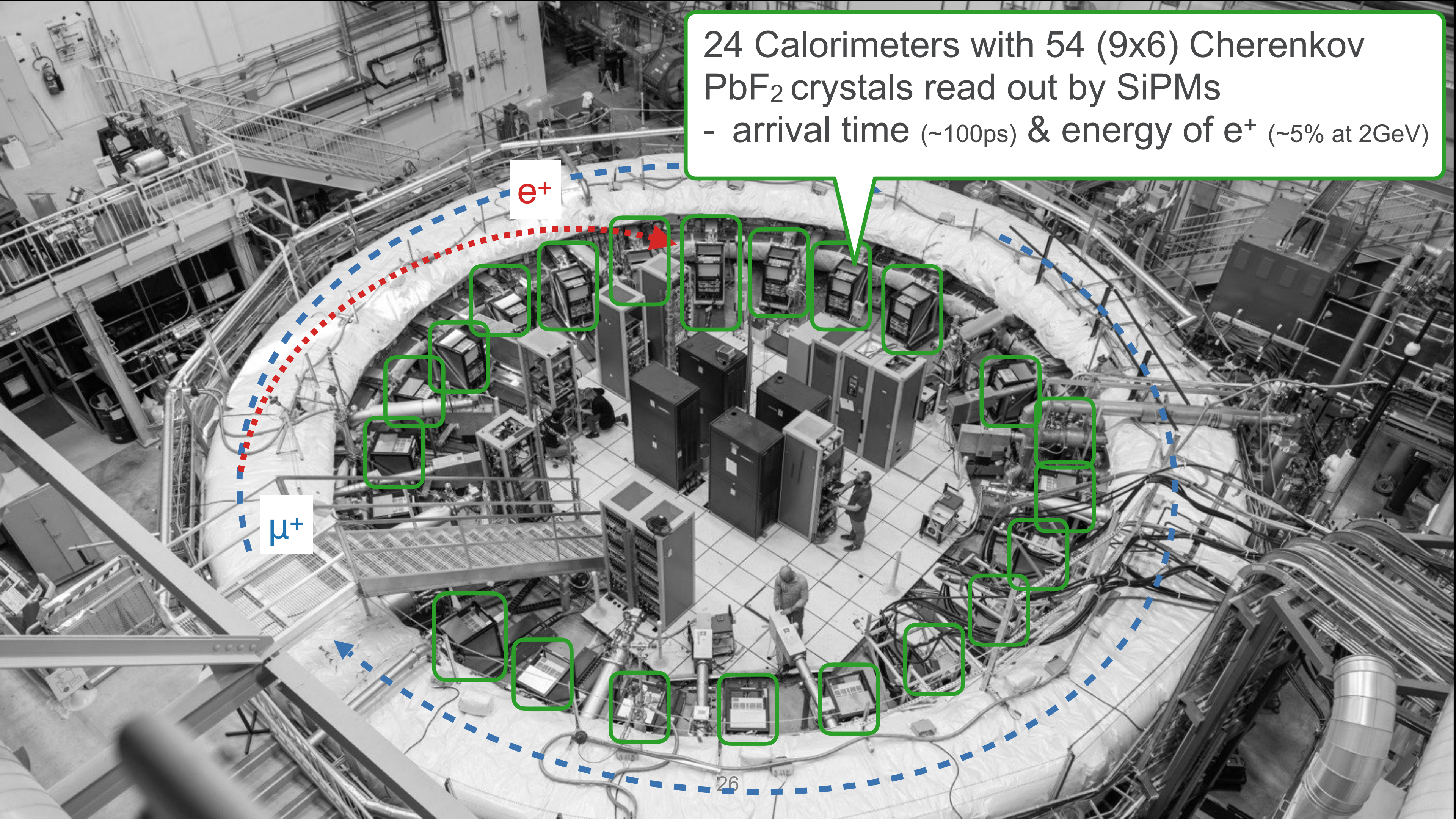
cyclotron period: 149.2 ns
few 1000 muons at a time
(in 16* bunches, every ~1.2s)
Boosted muon lifetime: 64 μs
Storage up to ~700μs

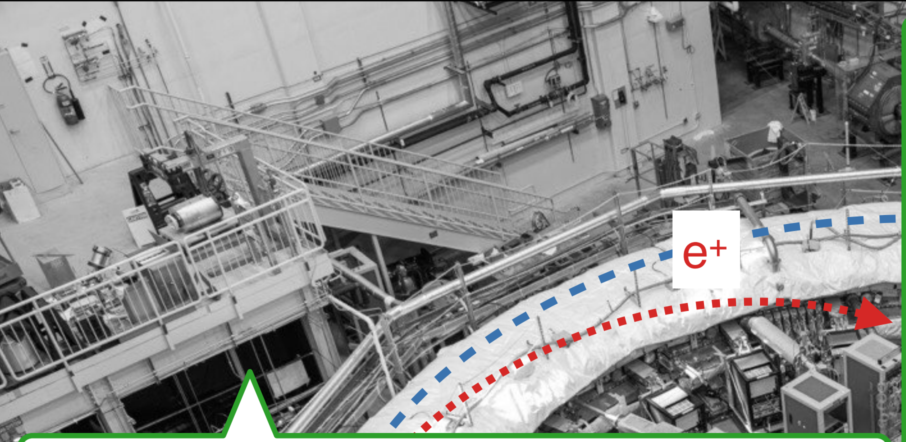


Time since injection: 5.0 us
Vertical Position [mm]
Radial Position [mm]
Mean Rad. Pos. [mm]
RMS of Rad. Pos. [mm]
Time [us]

Coherent Betatron Oscillation (CBO) with ESQ RF (Run-5/6)

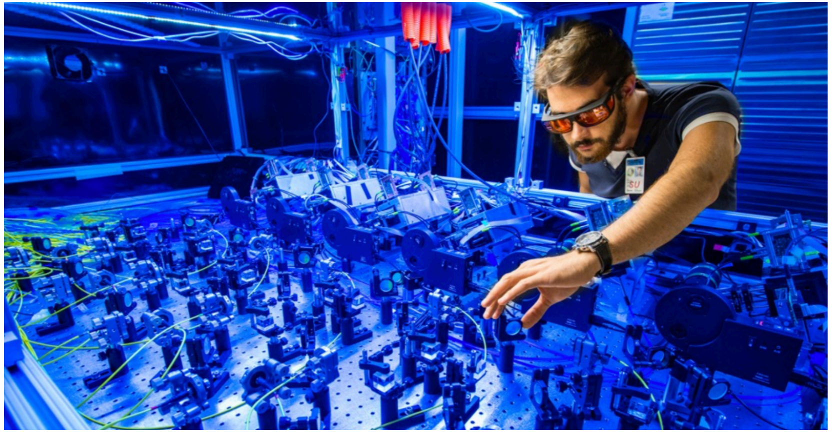



24 Calorimeters with 54 (9x6) Cherenkov
PbF_2 crystals read out by SiPMs
- arrival time (~100ps) & energy of e^+ (~5% at 2GeV)
e^+
μ^+



Laser system for gain response calibration throughout data taking

stability 10^{-3}, rate difference 10^{4}



24 Calorimeters with 54 (9x6) Cherenkov PbF_2 crystals read out by SiPMs

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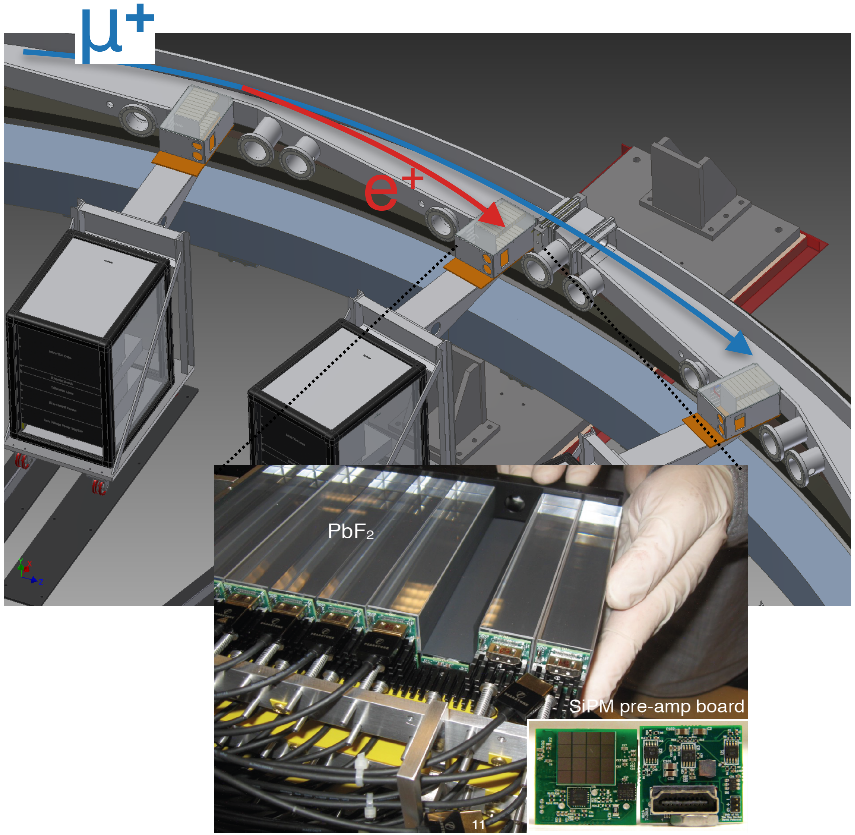
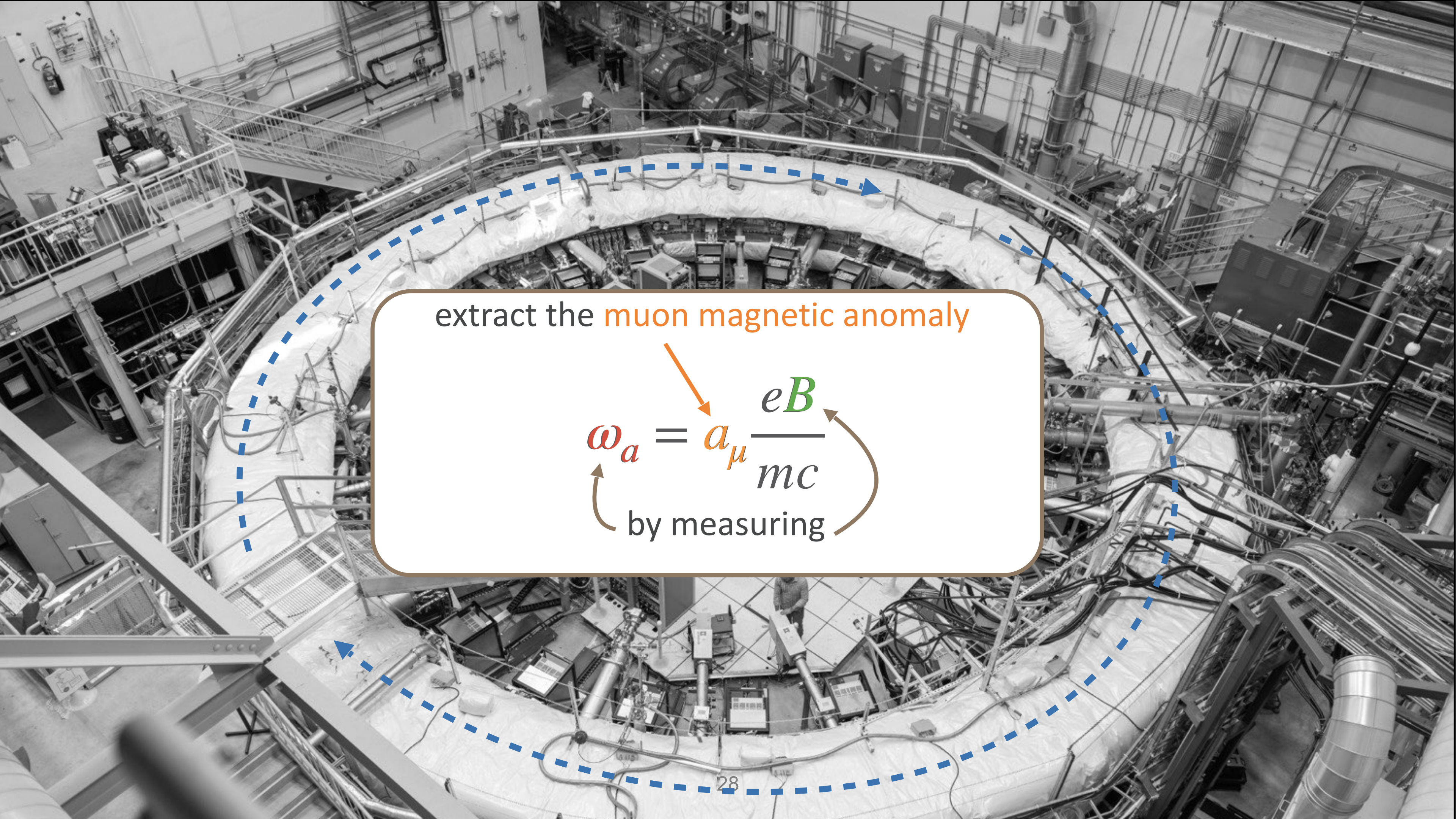




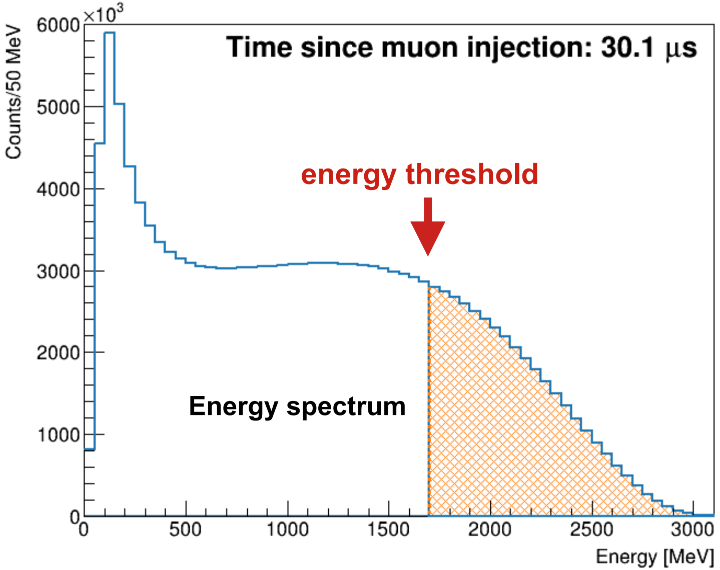
extract the muon magnetic anomaly

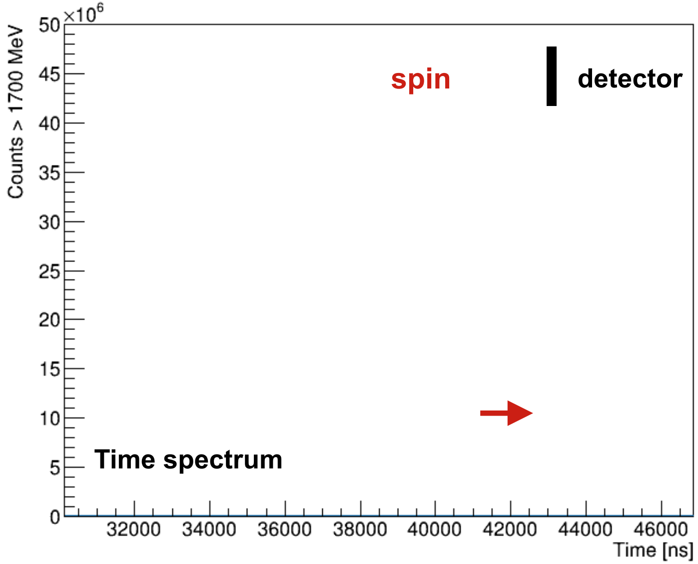
$$\omega_a = a_\mu \frac{eB}{mc}$$

by measuring

MEASURE: ω_a

Due to **parity violation** in muon decay, number of detected **high energy positrons** oscillates as muon **spin** points towards/away from detectors





Count positrons above an energy threshold

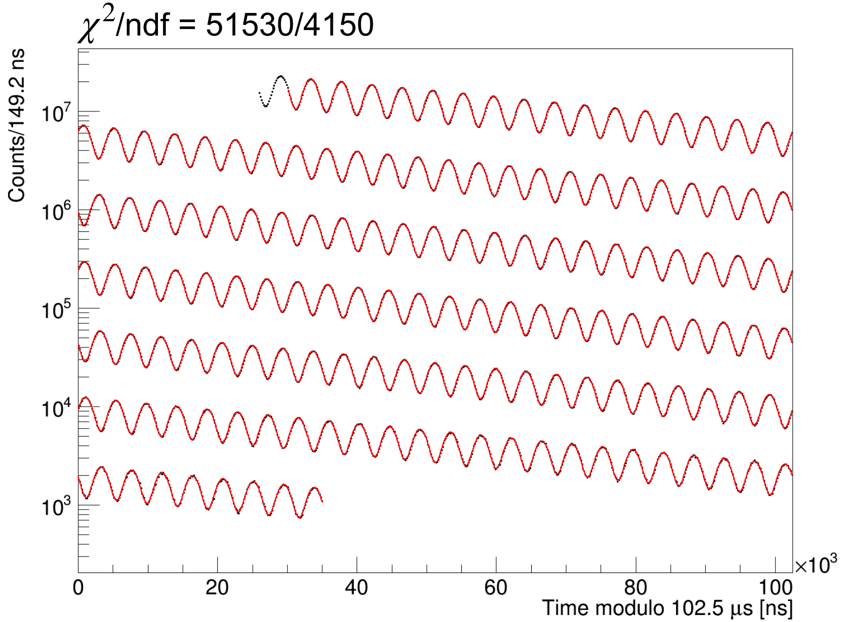
Counts **oscillate** at ω_a; extract frequency from time spectrum

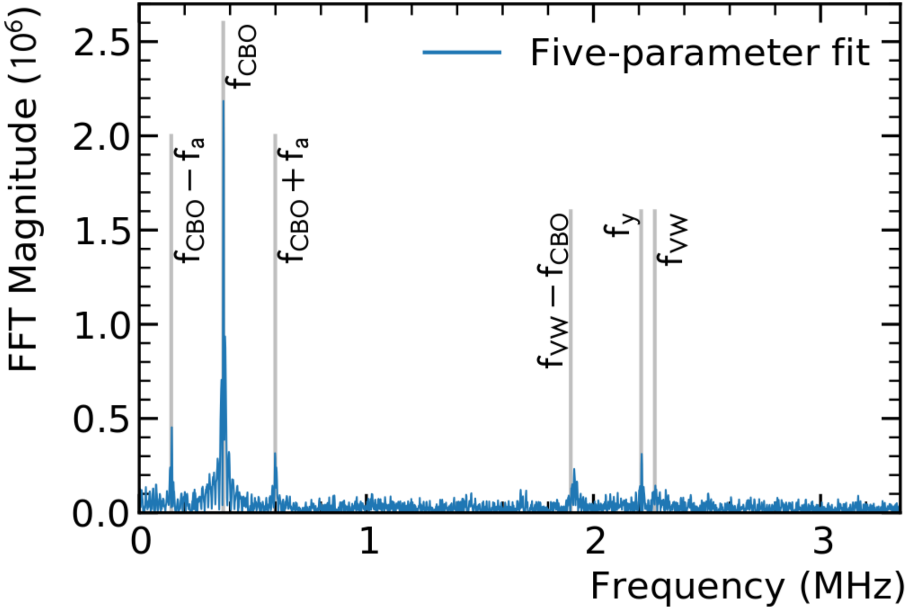
*for the final analysis we use an asymmetry weighted analysis

MEASURE: ω_a

Simplest model captures **exponential decay** & **g-2 oscillation**

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t - \phi)\right]$$ ("5 parameter fit")

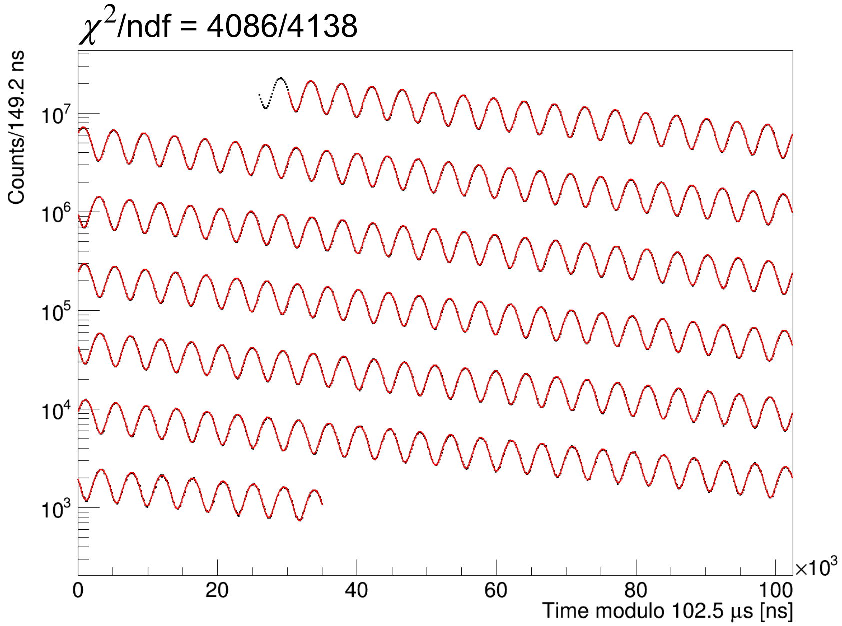


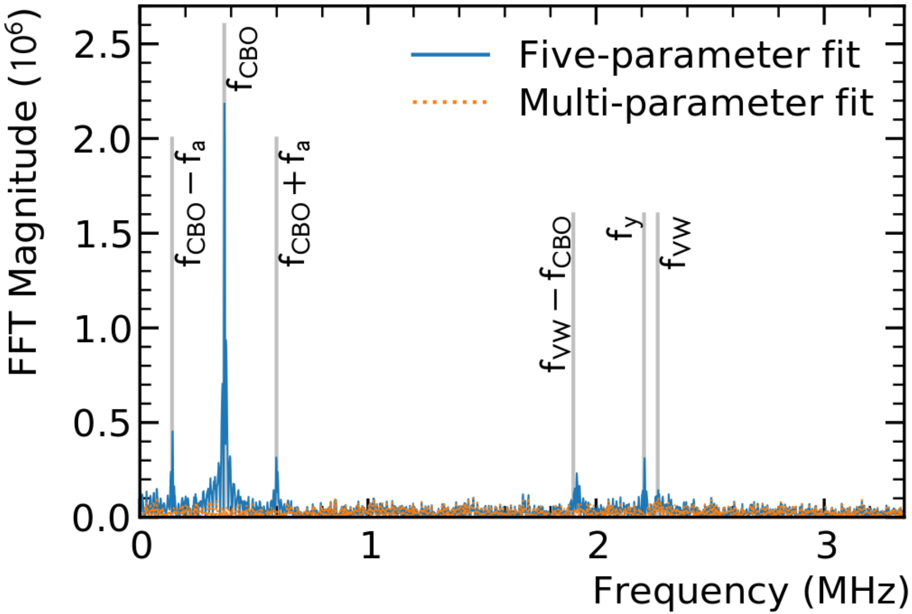


MEASURE: ω_a

Simplest model captures **exponential decay** & **g-2 oscillation**

must account for **beam oscillations**, **muons losses**, and **detector effects** (~1.6ppm shift in ω_a)





MEASURE: ω_a CORRECTIONS

$$\omega_a = \omega_a^m \left(1 + \underbrace{C_\mathrm{e} + C_\mathrm{p}} + \underbrace{C_\mathrm{pa} + C_\mathrm{dd} + C_\mathrm{ml}}\right)$$

E-field & Up/Down motion: Spin precesses slower than in basic equation

Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

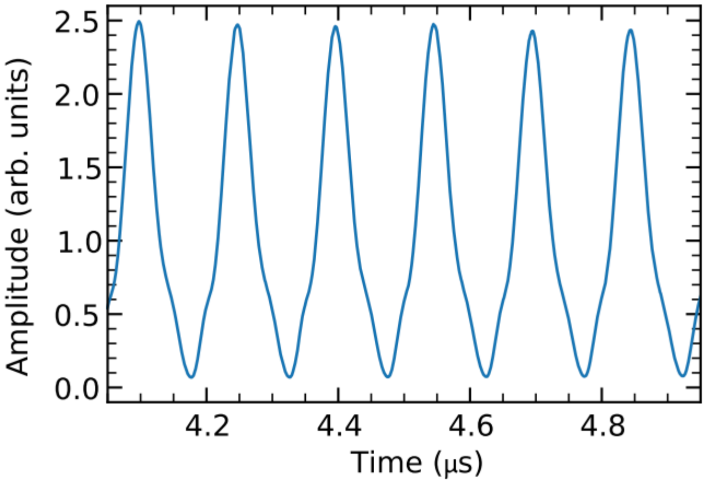
Total Run-2/3 correction was **622 ppb**, dominated by **E-field & Pitch**

C_e: E-FIELD CORRECTION

The largest beam dynamics correction, Run-2/3: 378-469 ppb ± 30-33ppb

Different methods:

- *"fast rotation":* extract the momentum(<x>)-distribution from the cyclotron frequency spread
  - Fourier method
    (needs correction from time-momentum correlations)
  - Binned Fit-method (CernExt)
    (needs additional constraints between many bins)



- *"Tracking"*: extract the momentum(<x>)-distribution from betatron oscillations

C_e: E-FIELD CORRECTION

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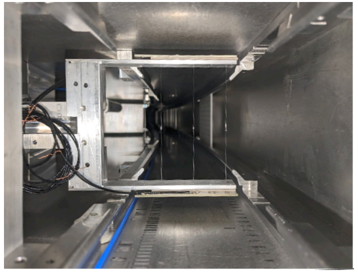
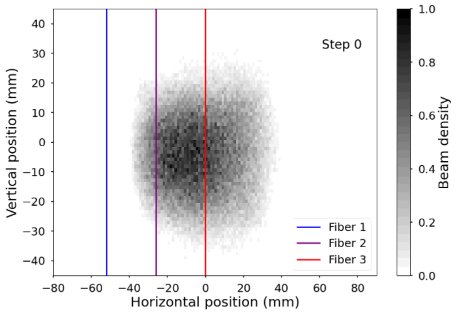
    (needs correction from time-momentum correlations)
  - Binned Fit-method (CernExt)
    (needs additional constraints between many bins)
- *"Tracking"*: extract the momentum(<x>)-distribution from betatron oscillations

Different "data"

- calorimeters
- Trackers
- miniSciFi (cross-checks)

new for Run-4/5/6





Minimally **In**trusive **Sci**ntillating **Fi**ber

C_p, C_{pa}, C_{ml} : PITCH, PHASE-ACCEPTANCE, AND MUON LOSS CORRECTIONS

Pitch:

Run-2/3: 170ppb±10ppb

- from the amplitude of the beam's vertical oscillation
- tracker data
- Corrected for the acceptance of the calorimeters

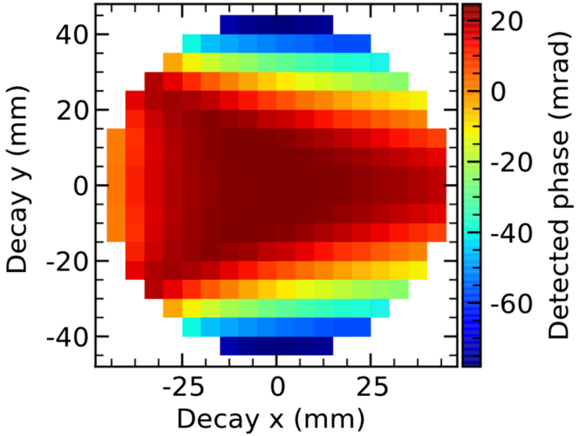
Run-4/5/6 closely follows the Run-2/3 analysis

Phase-Acceptance:

Run-1:

Run-2/3: -27ppb±13ppb

- calorimeter's phase-acceptance(x,y)



Run-4/5/6 closely follows the Run-2/3 analysis

Muon Loss:

Run-1:

Run-2/3: 0 ppb±3ppb

- Muon losses reduced by an order of magnitude in Run-2 and afterwards

Run-4/5/6 closely follows the Run-2/3 analysis

C_{dd}: DIFFERENTIAL-DECAY

g−2 phase (ϕ_0) dependence due to the spread of muon lifetime in the beam

$$C_{dd} = -\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a}\frac{d\phi_0}{dt} = \frac{1}{\omega_a}\frac{d\phi_0}{dp}\left(\frac{dp}{dt}\right)_{dd}$$

$(dp/dt)_{dd}$: (temporal) variation of beam averaged momentum

Run-2/3: -22 to -2ppb ± 18ppb

Contributions:

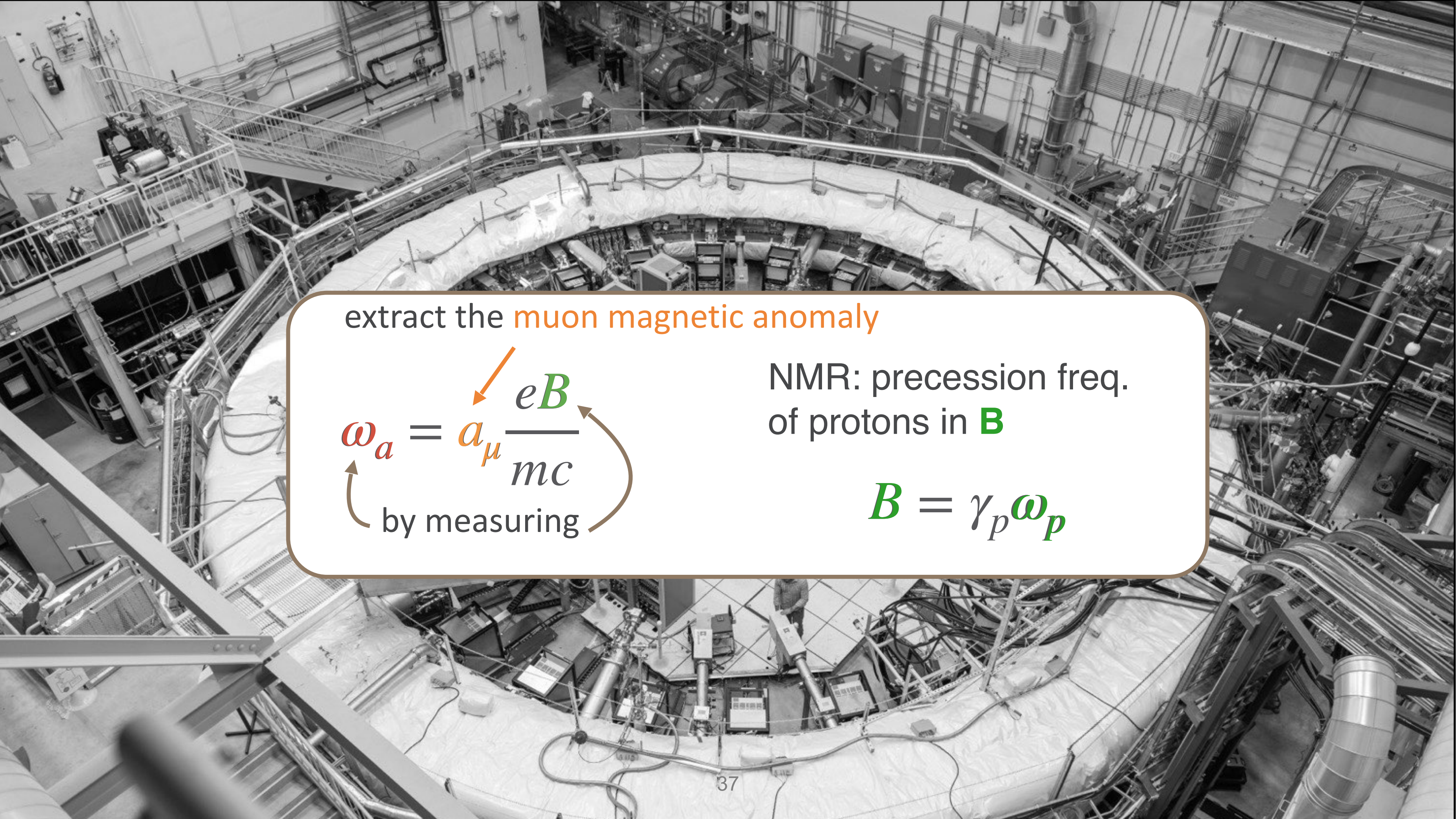
- Beam-line effects
- momentum-orbit (p-x) correlations (from beam injection)
- longitudinal phase variations (p-t) at injection

Run-2/3:

- Some direct measurements + beam dynamics simulations

Run-4/5/6:

- same tools as Run-2/3
- A promising (tracker) data based method is under development



extract the muon magnetic anomaly

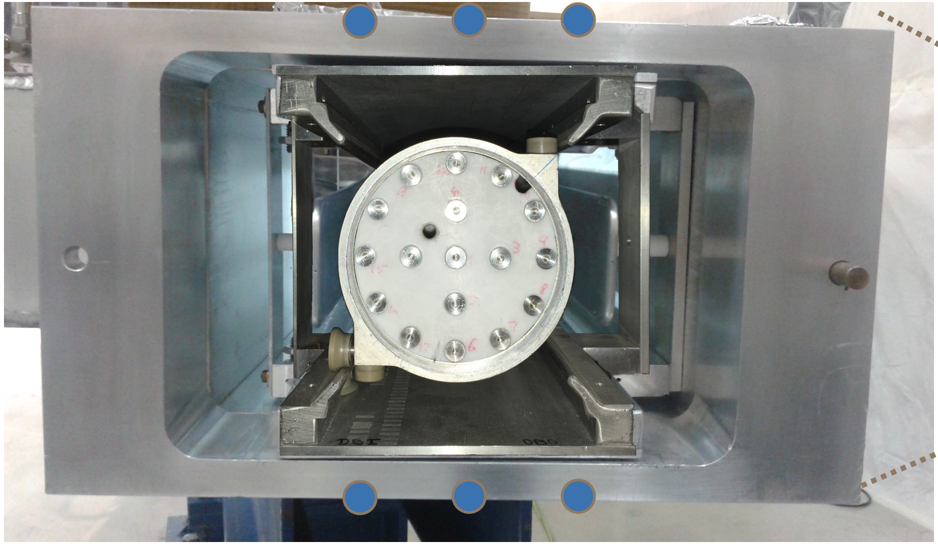
$$\omega_a = a_\mu \frac{eB}{mc}$$

by measuring

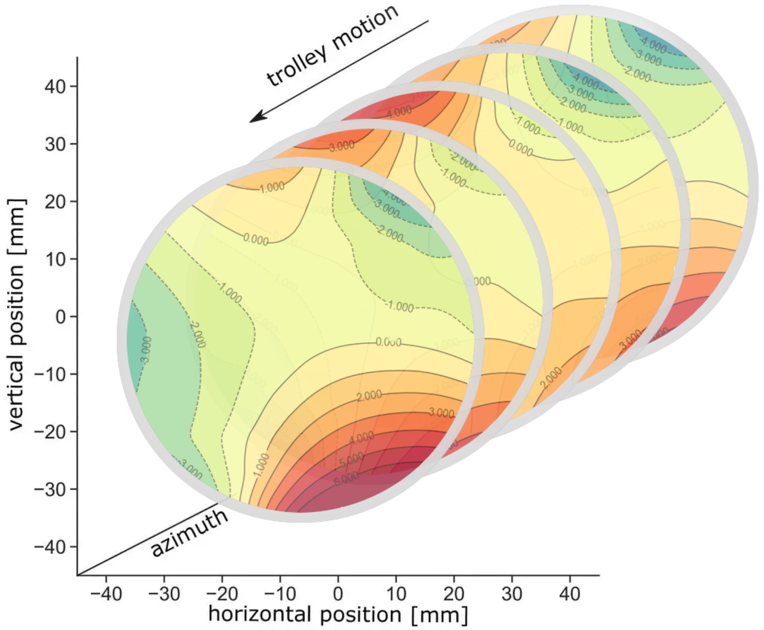
NMR: precession freq. of protons in **B**

$$B = \gamma_p \omega_p$$

Filed Monitor: Fixed NMR Probes



Trolley: Field Mapper

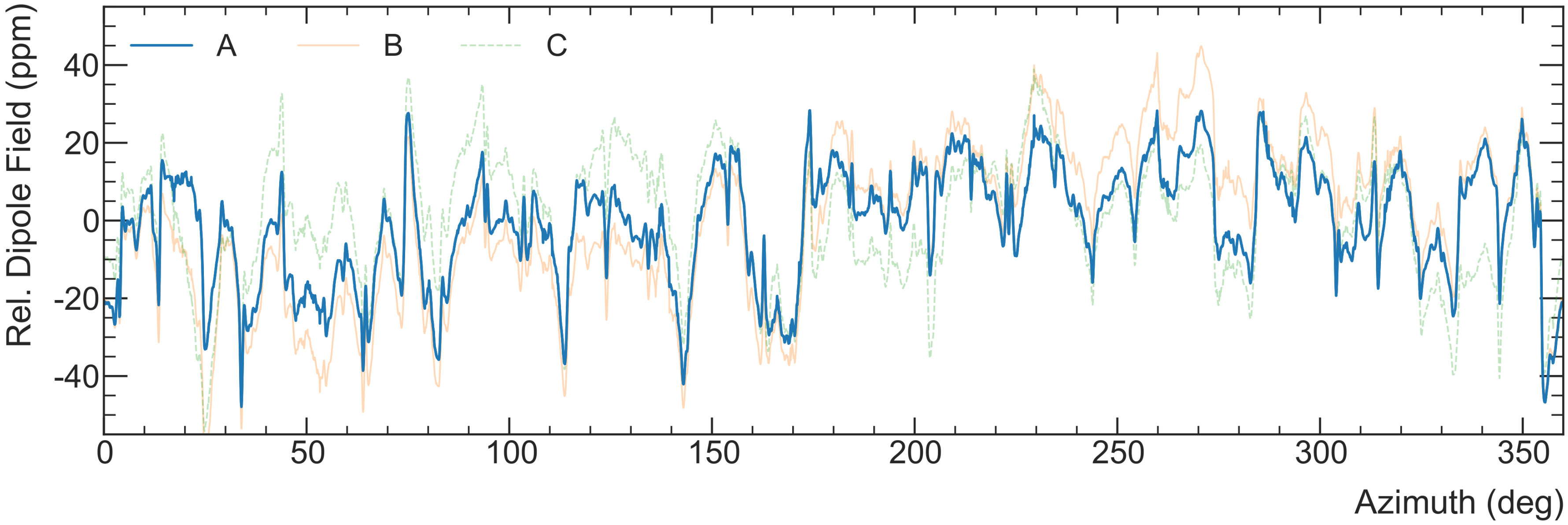


~9000 2D field maps around the ring

FIELD MAPS

RMS around the ring <20 ppm

take field maps every 3-5 days

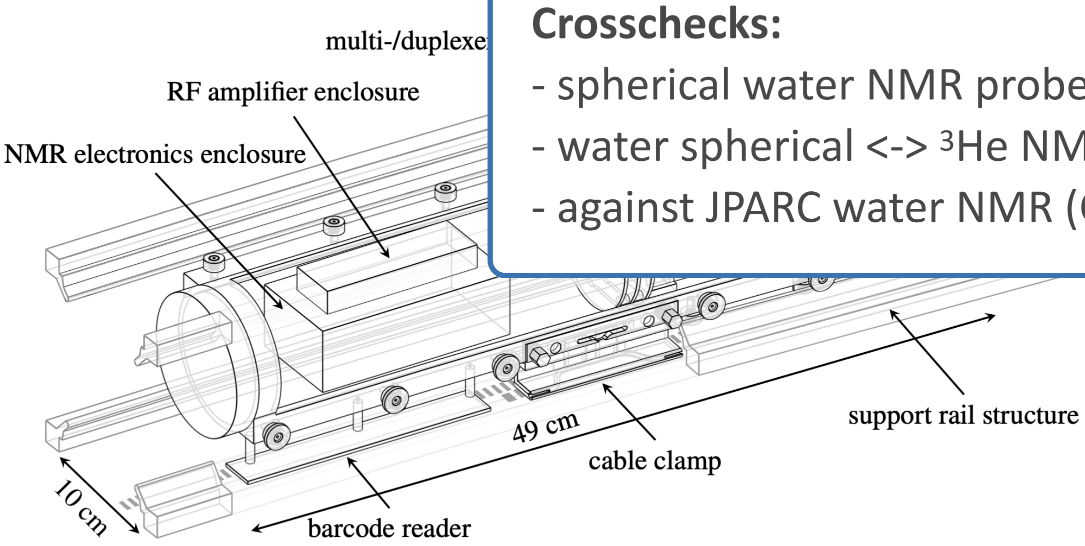


The field between field maps (trolley runs) is tracked by the fixed NMR probes.

CALIBRATION

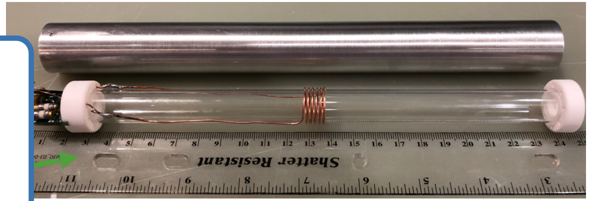
Calibrate to the Larmor frequency of shielded protons in a spherical sample: ω_p'

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

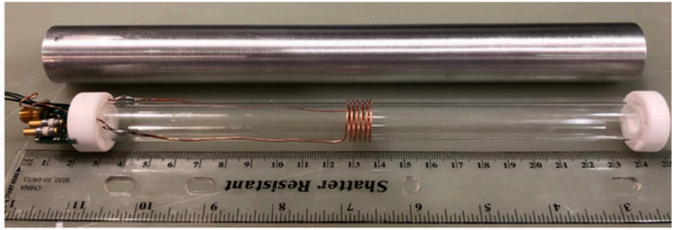


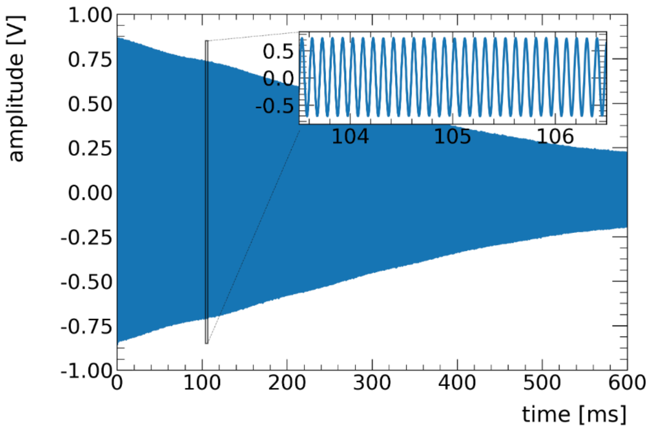
ce in situ *uncertainty: 17 ppb*

2) correct for material effects
3) correct from cylinder -> sphere
uncertainty: 9 ppb

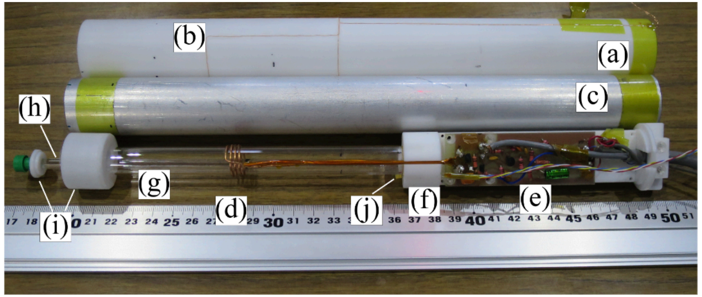
CROSS-CALIBRATIONS: EXAMPLE US/JP

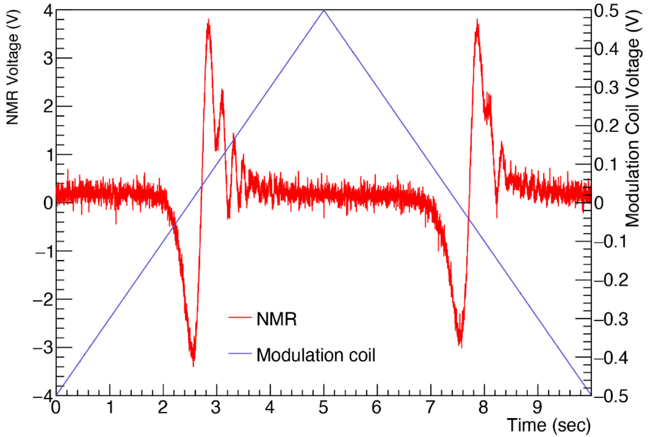
Fermilab: **pulsed** NMR





J-PARC: **continuous wave** (CW)



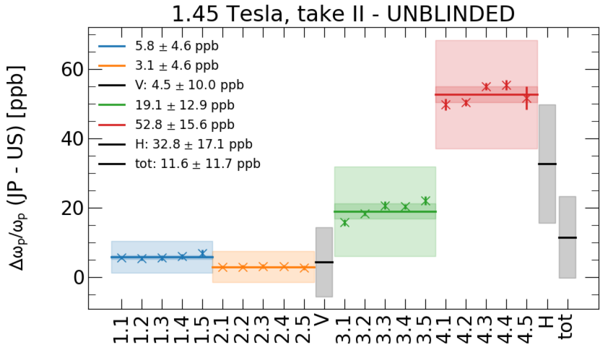


CROSS-CALIBRATIONS: EXAMPLE US/JP

Cross-calibrated 4 times:

- 1.45T - Fermilab field
- 1.7T - MuSEUM field
- 3.0T - J-PARC field
- 1.45T - Fermilab field

Some discrepancies in the first two, good agreement (better than ~15ppb) on the latest two iterations.



ABA group

CALIBRATION

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

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

bound state QED calc., exact

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

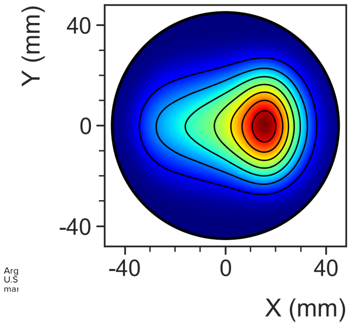
0.13 ppt uncertainty
PDG, dominated by
Phys. Rev. Lett. **130**, 071801 (2023)

magnetic field seen by the muons

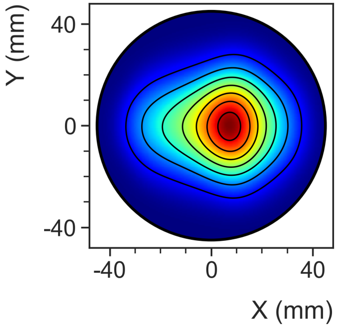
22 ppb uncertainty (Muonium hyper fine split.)

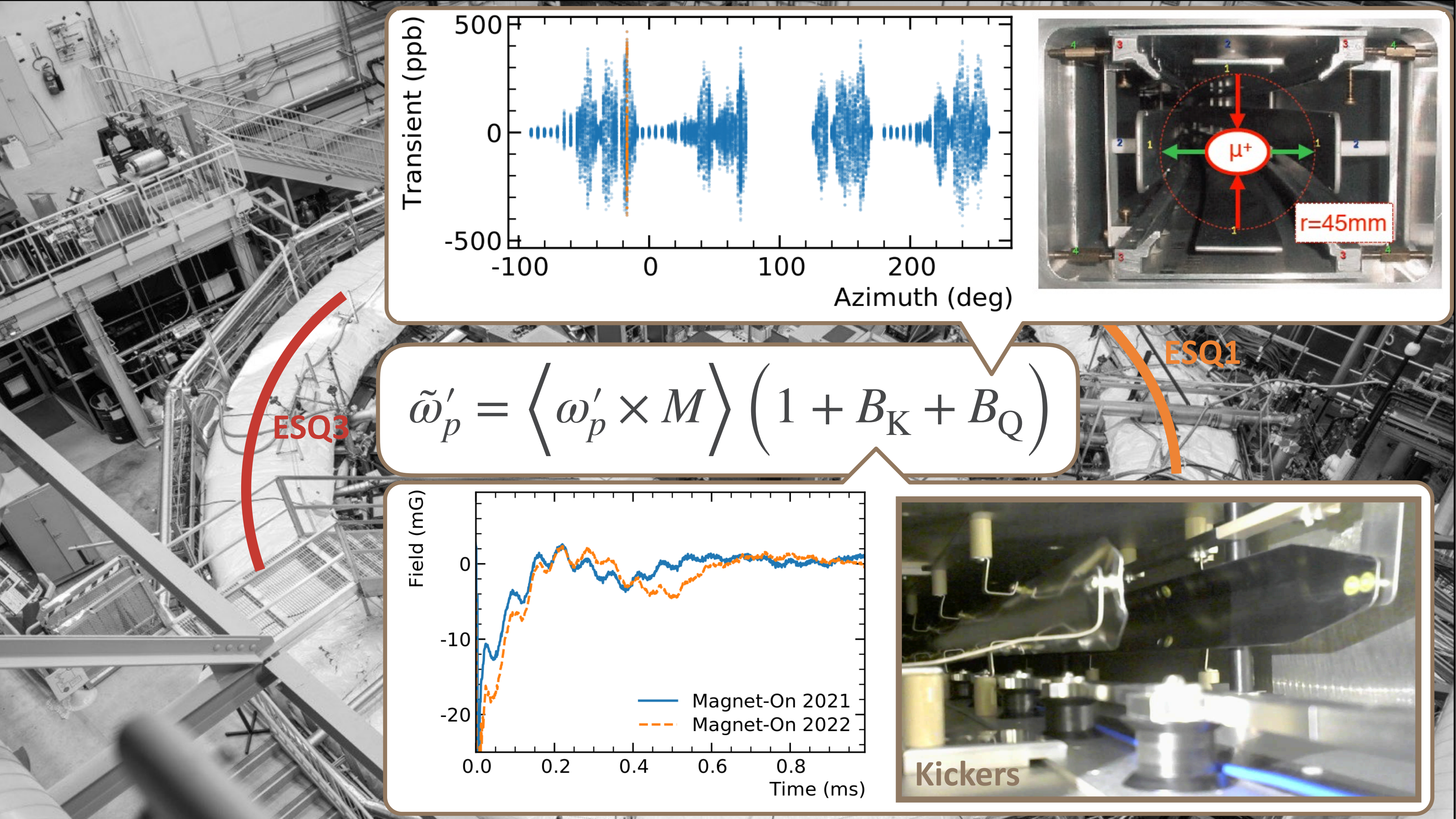
Phys. Rev. Lett. **82**, 711 (1999)

Run-2 and 3a



Run-3b: upgraded kickers



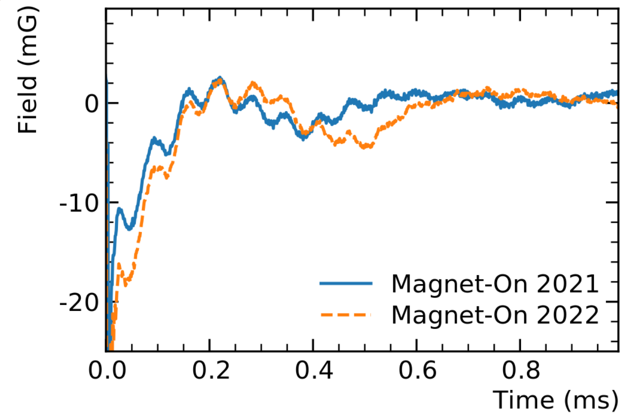

500
0
-500
Transient (ppb)
-100
0
100
200
Azimuth (deg)
μ+
r=45mm
ESQ1
ESQ3
$\tilde{\omega}'_p = \left\langle \omega'_p \times M \right\rangle \left(1 + B_K + B_Q\right)$
Field (mG)
0
-10
-20
0.0
0.2
0.4
0.6
0.8
Time (ms)
Magnet-On 2021
Magnet-On 2022
Kickers

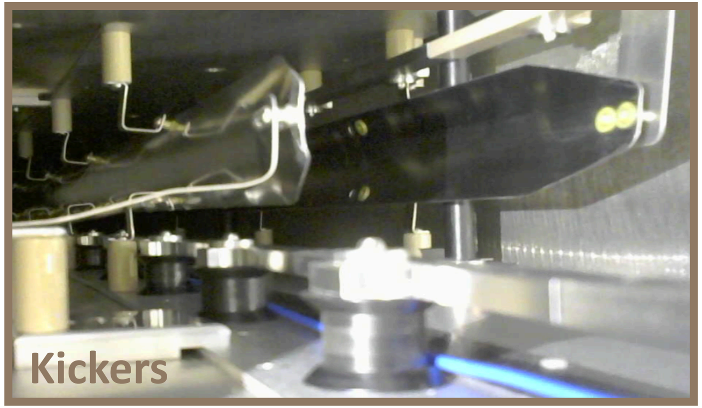
Run-4/5/6

- Measurements at much more positions, different kickers
- Two independent magnetometers/analysis teams
- New lab measurements for transverse model

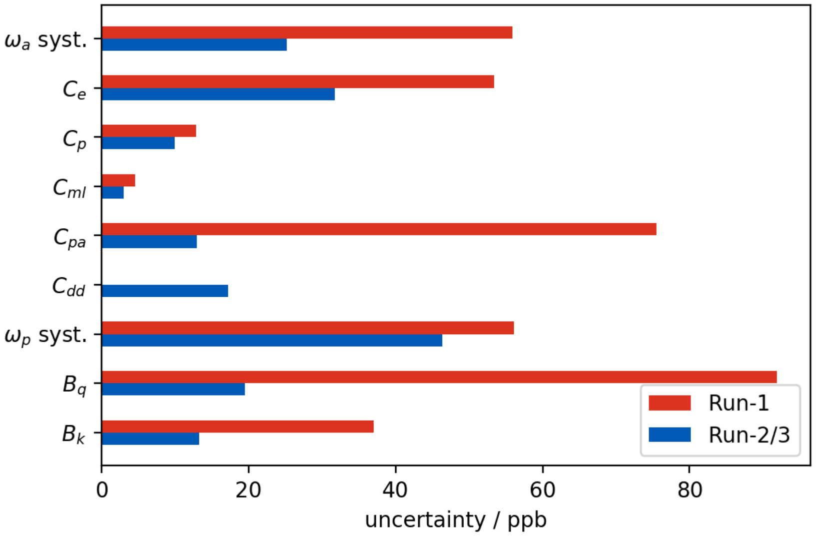
ESQ1

$$\tilde{\omega}'_p = \left\langle \omega'_p \times M \right\rangle \left(1 + B_{\mathrm{K}} + B_{\mathrm{Q}} \right)$$





SYSTEMATIC UNCERTAINTY - WHAT TO EXPECT

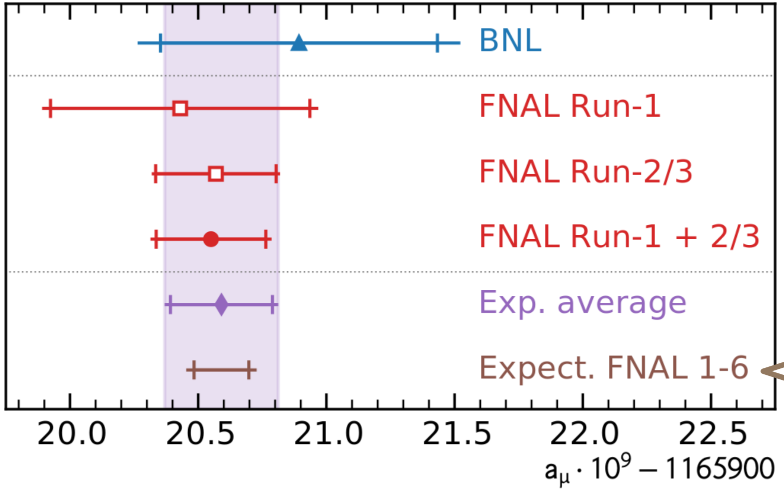


Total syst. Run-1: 157 ppb
Total syst. Run-2/3: 70 ppb
TDR goal: 100 ppb

Run-1: a few "large" systematics
B_q: new measurements
C_{pa}: fixed broken hardware
improved running conditions

Run-2/3: many individual systematics
on a very similar level
(~20 to 30 ppb)

Run-4/5/6: very similar conditions
added RF system to the ESQ
-> reducing beam oscillations



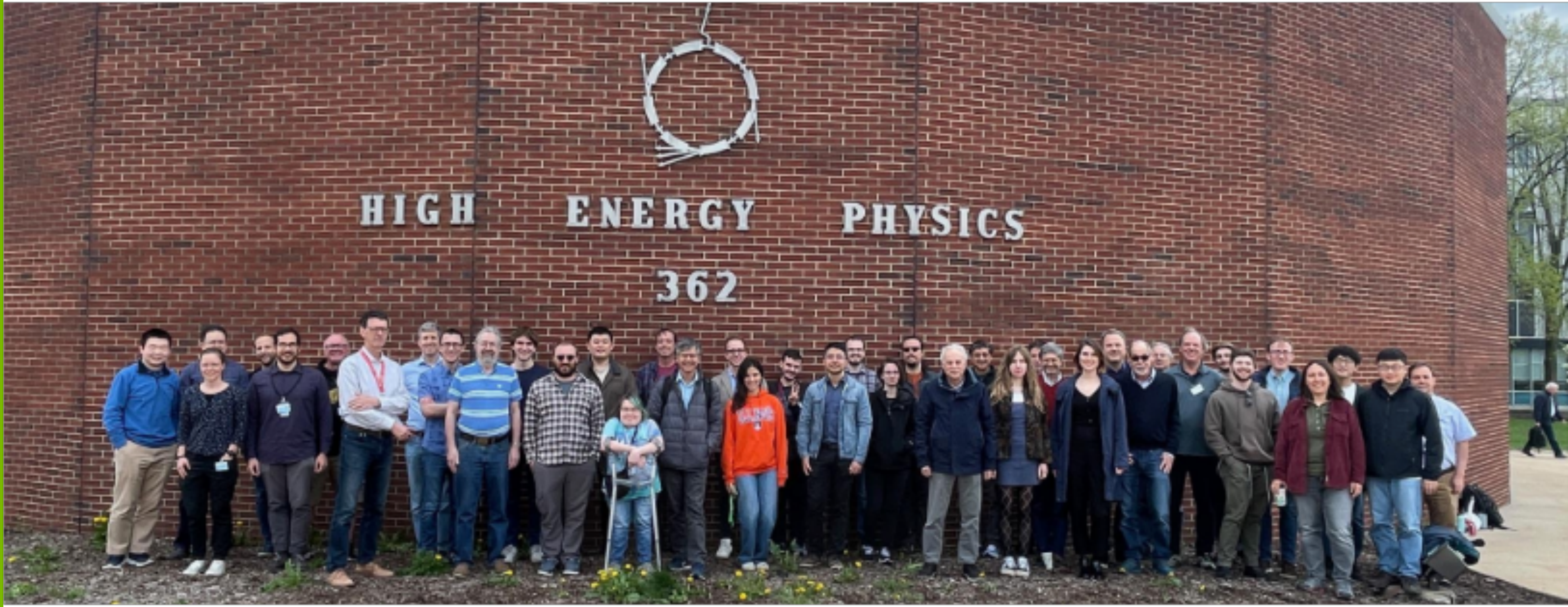
Expect to publish the full dataset 2025
~ 2x improved precision
likely still statistics limited

Other Analysis:
Muon EDM:
Current best limit from BNL Muon g-2:
$$|d_\mu| < 1.8 \times 10^{-19} e\,\mathrm{cm}\,(95\,\%\,\mathrm{CL})$$

we aim to improve to ~ $10^{-21} e\,\mathrm{cm}$
-> Mikio's talk on Thursday

BSM searches:
CPT/LV & Dark Matter

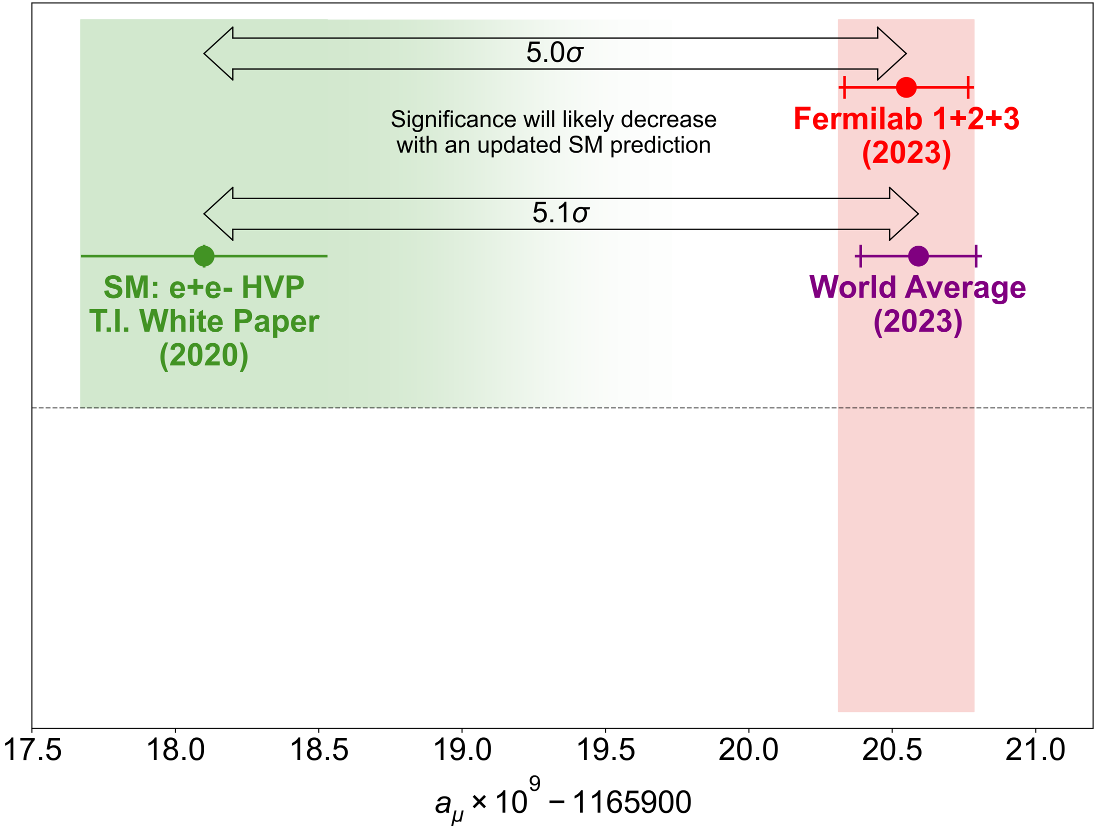
THE COLLABORATION



Collaboration meeting at Argonne in Spring 2024

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.

Theory prediction is less clear now then in 2021, but we can still compare

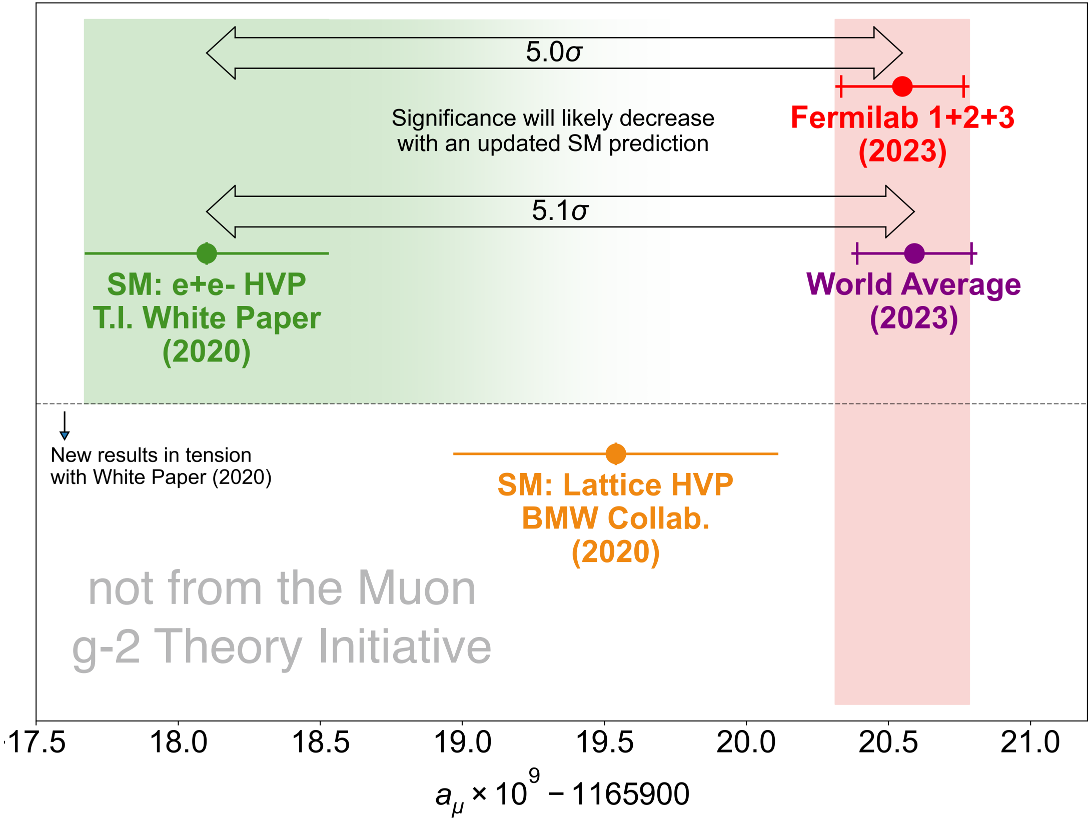


Large discrepancy between experiment and WP (2020)

Significance for **Fermilab alone** get to **5.0σ**

Updated prediction considering all available data will likely yield a smaller and less significant discrepancy

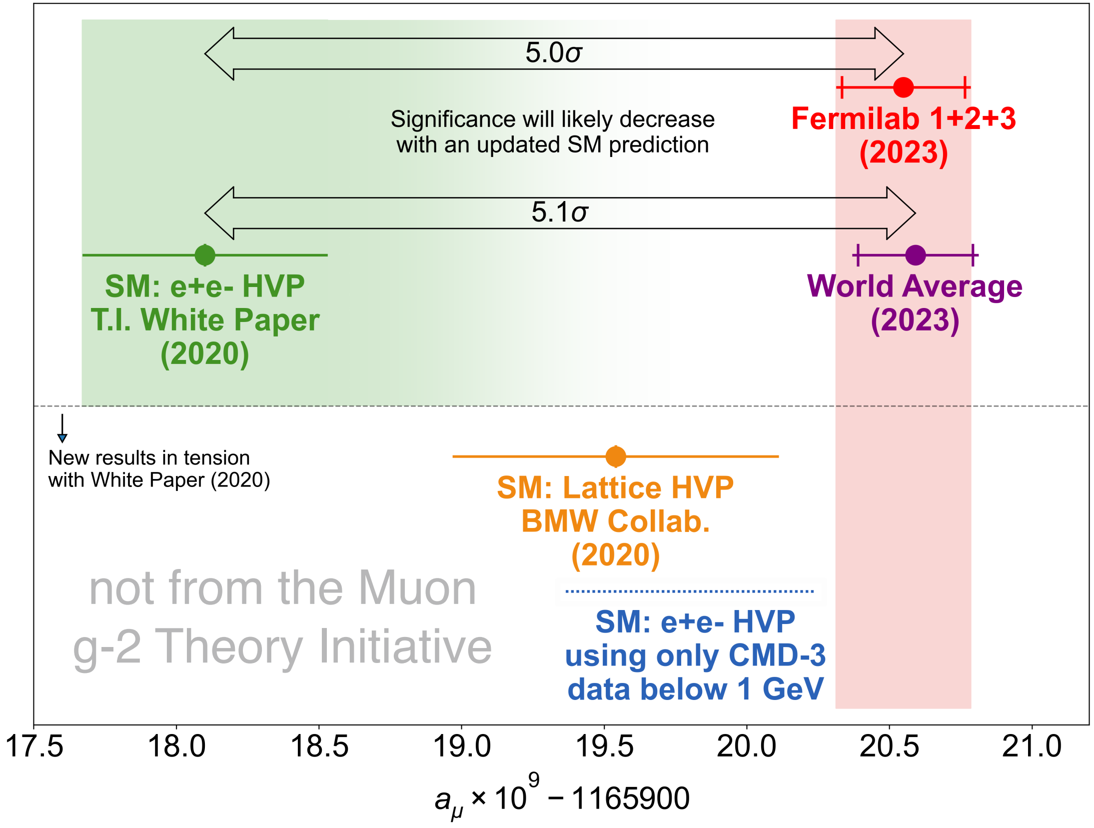
Theory prediction is less clear now then in 2021, but we can still compare



Include **BMW** result by swapping HVP from WP with their value

Note: BMW is currently the only full lattice calculation of HVP

Theory prediction is less clear now then in 2021, but we can still compare



Following A. Keshavarzi at Lattice 2023…

Substitute **CMD-3** data for HVP below 1 GeV

Cherry-picking one experiment but gives a bounding case

SND2k cannot be processed in this way, but would fall closer to WP (2020)

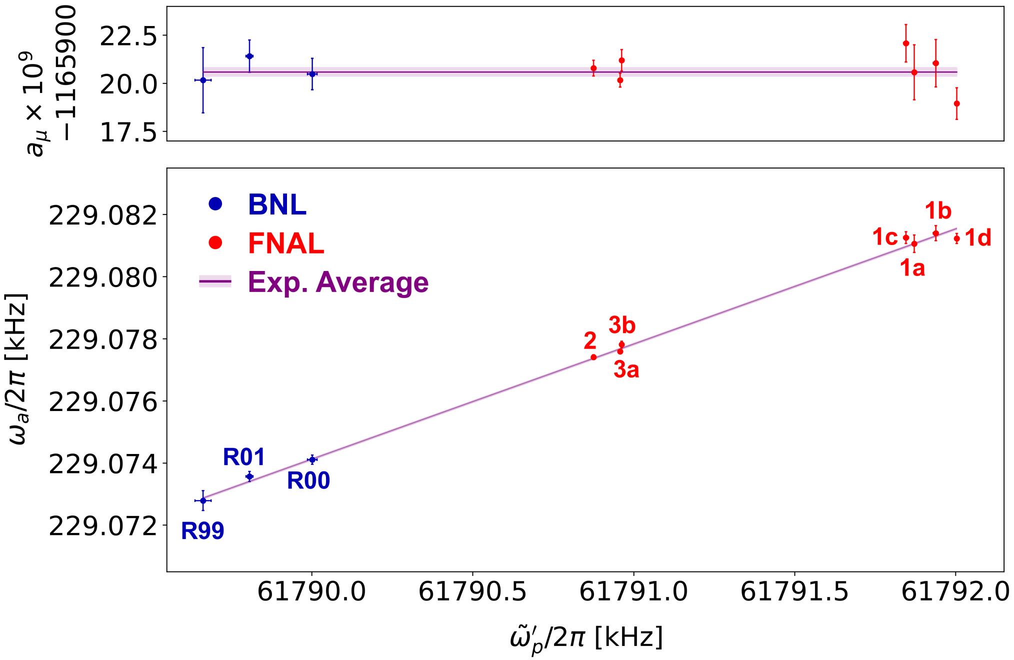
Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Argonne NATIONAL LABORATORY

COMPARING DATASETS: CROSSCHECKS

Datasets were taken at slightly different field settings



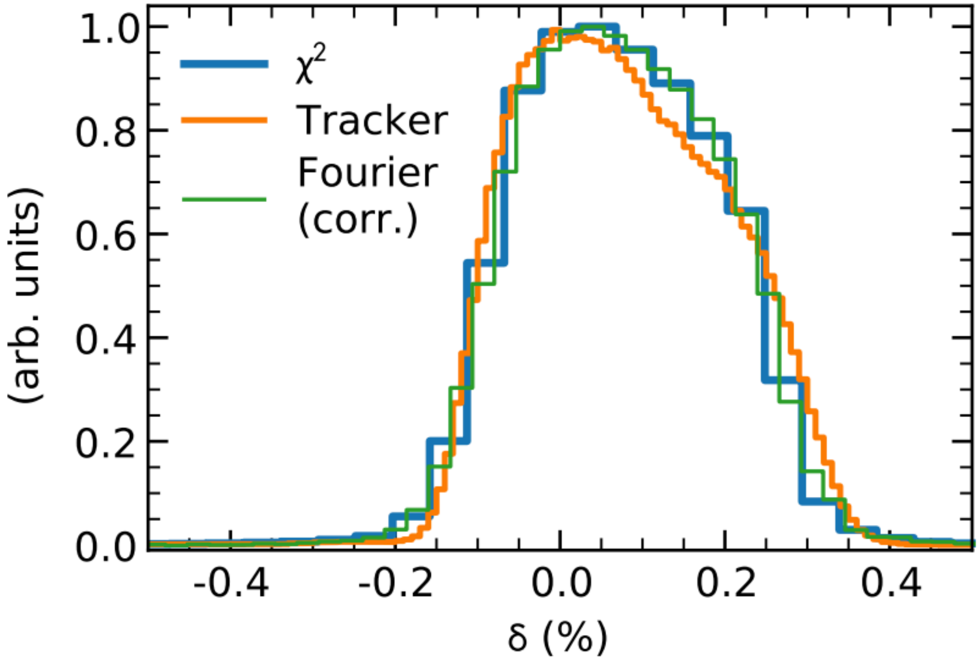
Example of one of the most basic “handles”:
other checks against day/night, temperature, …

C_e: E-FIELD CORRECTION

$$\frac{\Delta\omega_a}{\omega_a} = -2\frac{\beta_0}{cB_0}\delta E_x$$

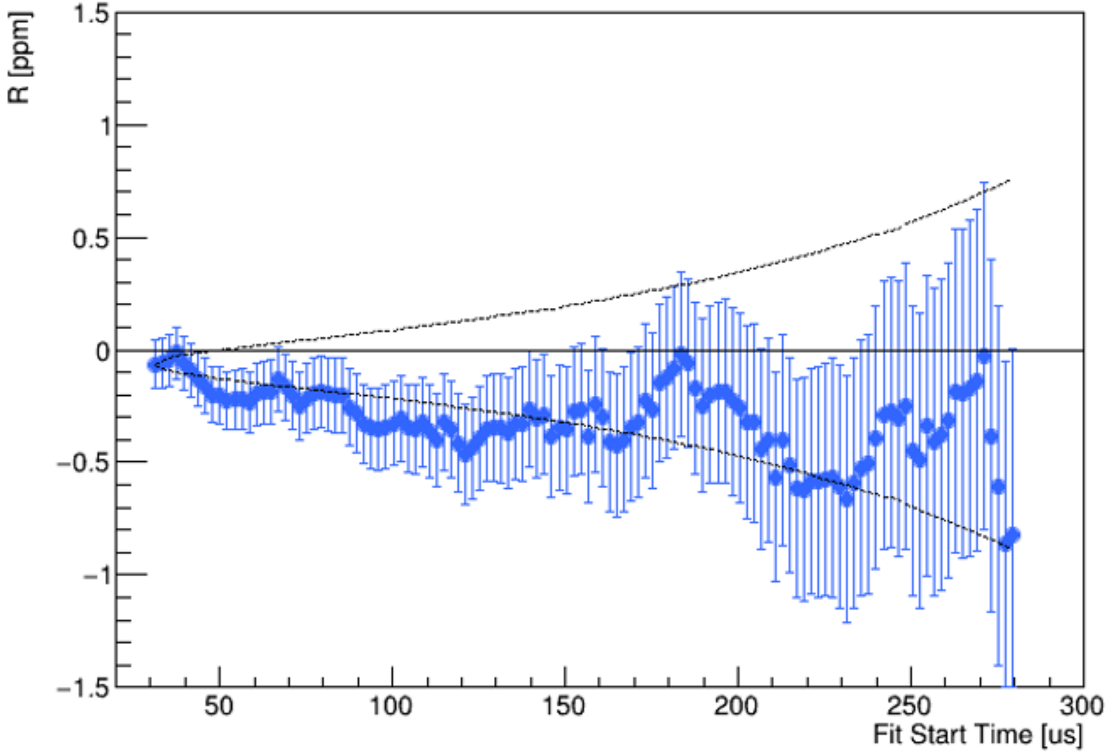
$$C_e = -\left\langle \frac{\Delta\omega_a}{\omega_a} \right\rangle \approx 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

Data subset 3E (Run-3)



$$\delta \approx (1-n)\frac{x_e}{R_0}$$

ω_a: STARTTIME SCANS



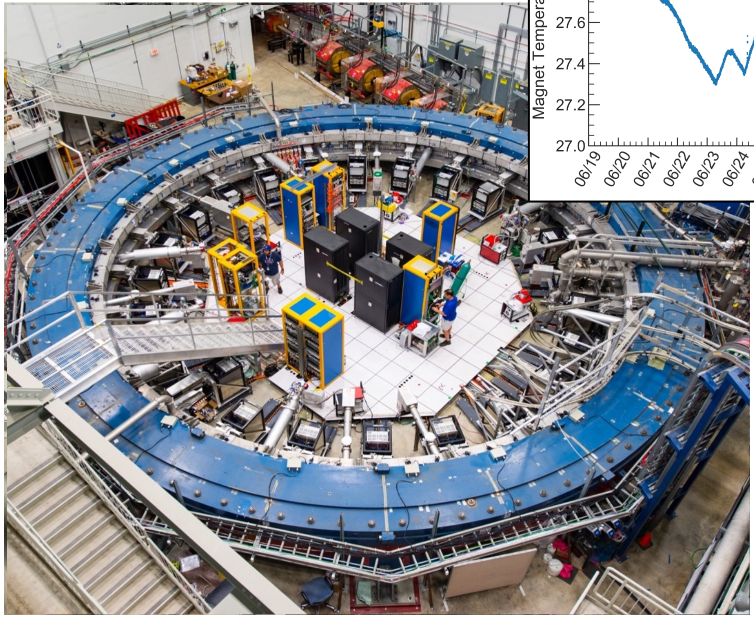
SYSTEMATIC UNCERTAINTY IMPROVEMENTS

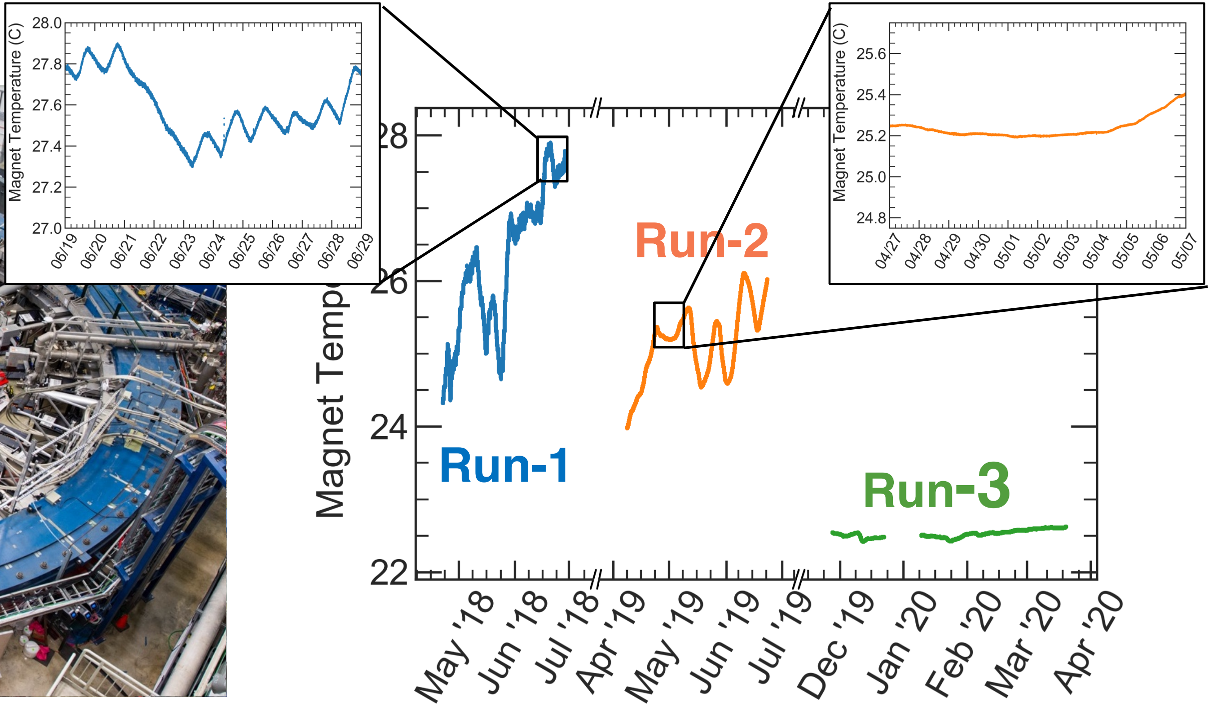
Running Conditions

Syst. Measuemrents

Analysis Improvements

Temperature Control

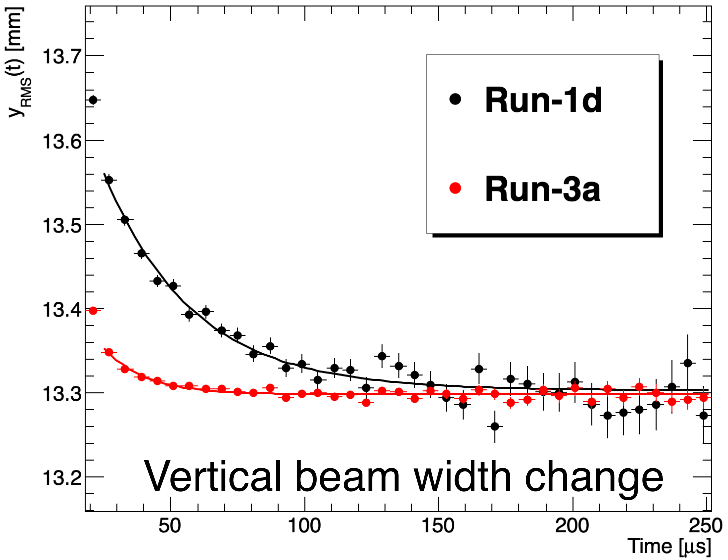


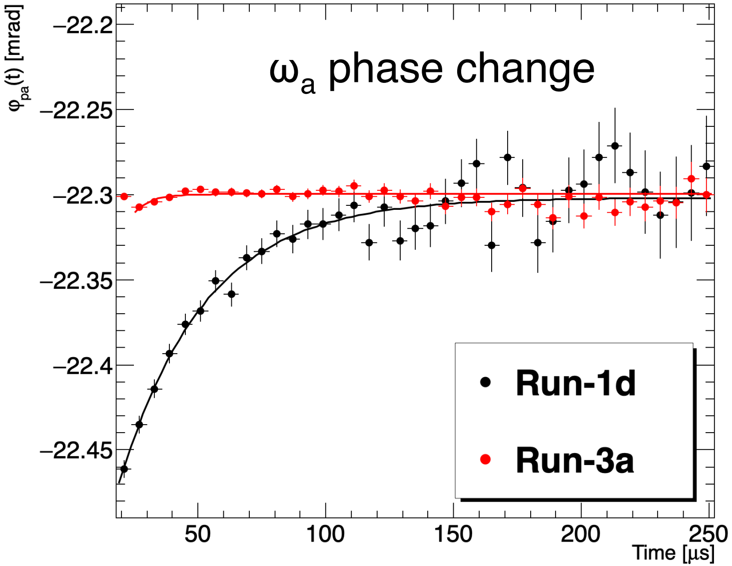


SYSTEMATIC UNCERTAINTY IMPROVEMENTS

Running Conditions | Syst. Measuemrents | Analysis Improvements

Run-1 had **damaged resistors** in 2/32 ESQ leading to **unstable beam storage**
Redesign and fixed before Run-2: C_{pa} uncertainty is reduced (75 ppb → 13 ppb)



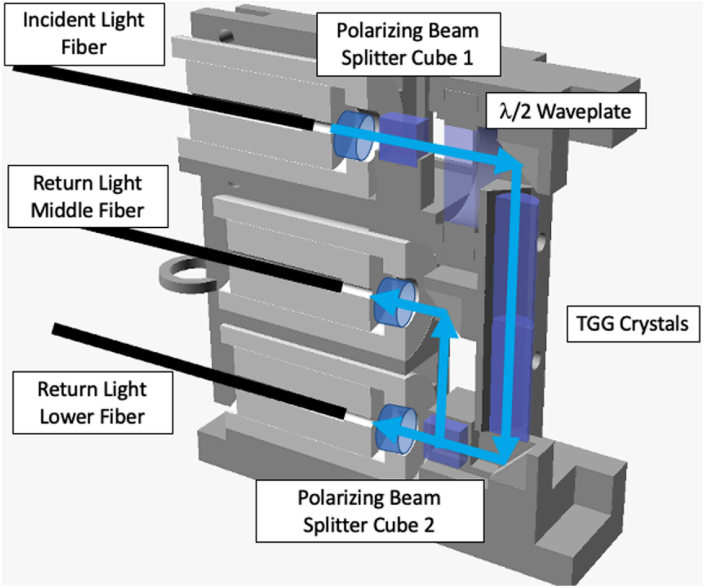


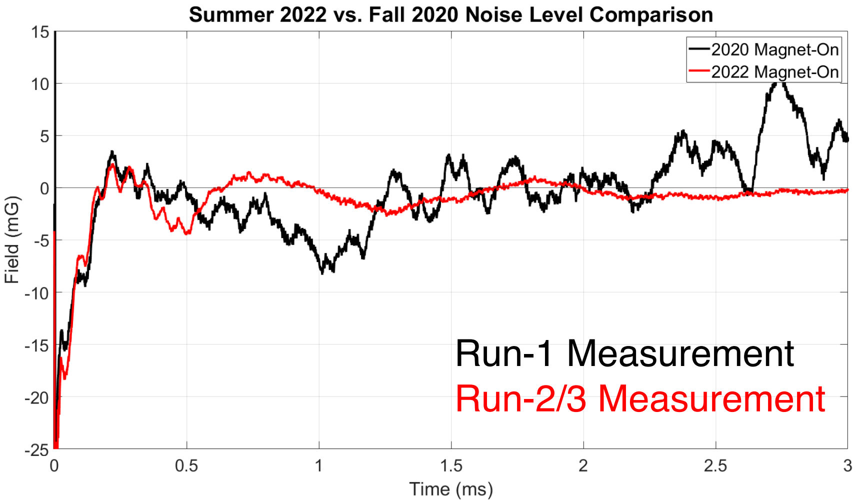
SYSTEMATIC UNCERTAINTY IMPROVEMENTS

Running Conditions | Syst. Measuemrents | Analysis Improvements

Eddy currents from the kickers cause transient magnetic fields

Fiber based Faraday magnetometer





SYSTEMATIC UNCERTAINTY IMPROVEMENTS

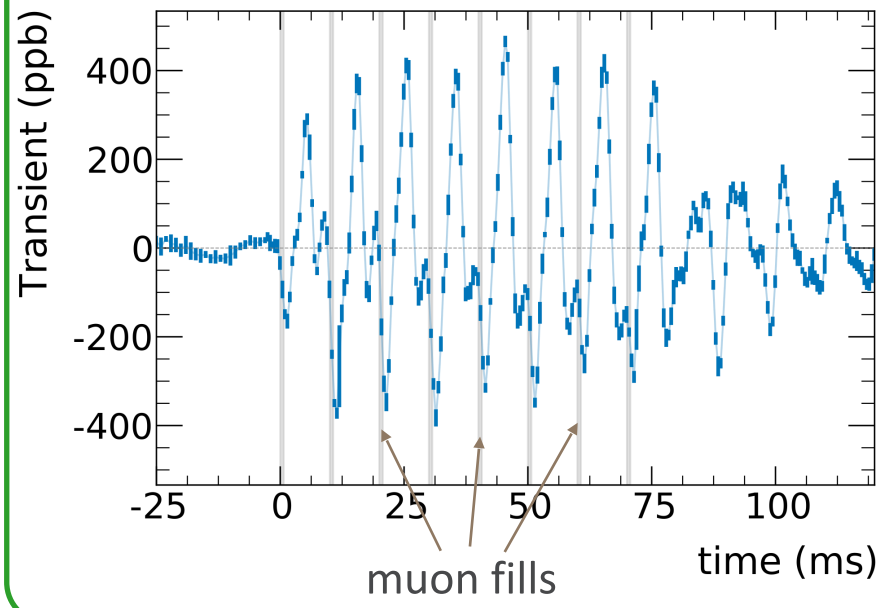
Running Conditions

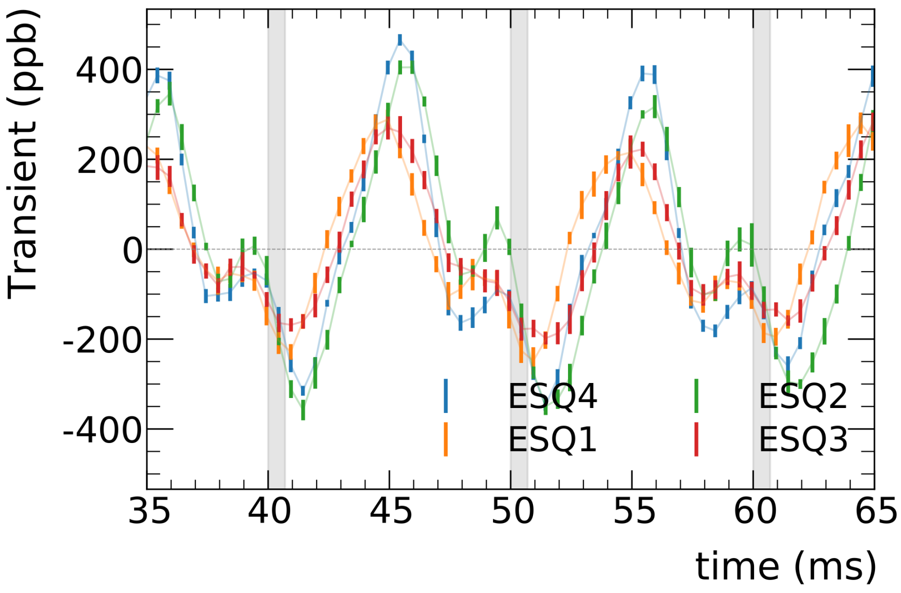
Syst. Measuemrents

Analysis Improvements

Mechanical vibrations of ESQ plates cause magnetic field changes.

at one location (in ESQ 4)

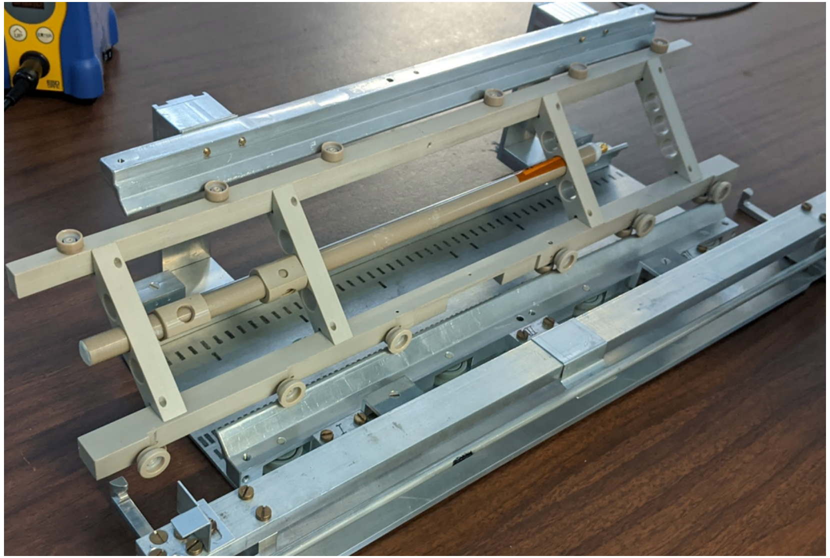




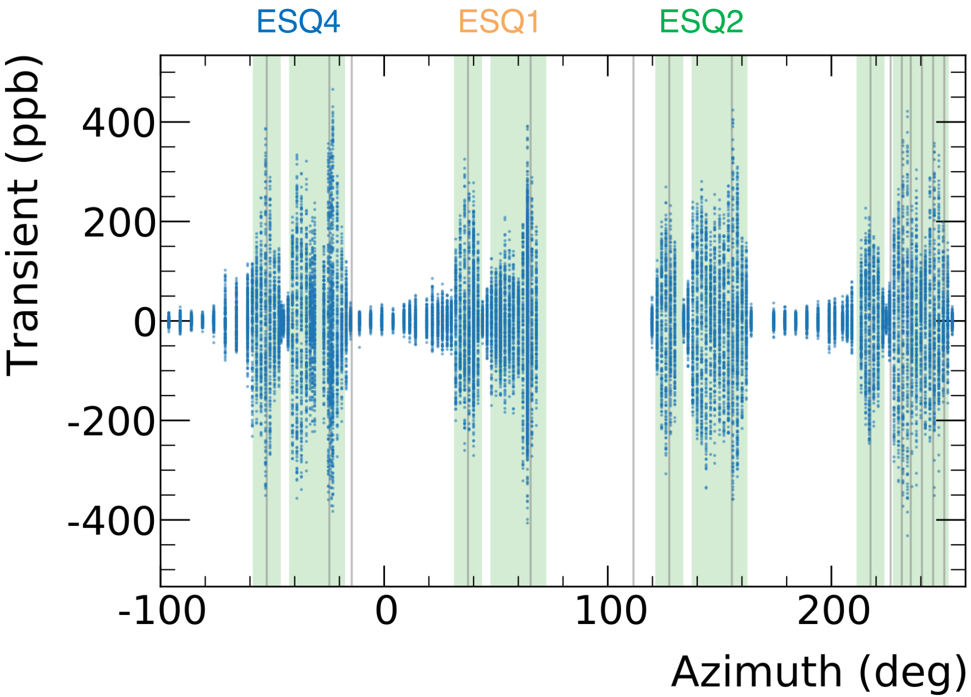
SYSTEMATIC UNCERTAINTY IMPROVEMENTS

Running Conditions | Syst. Measuemrents | Analysis Improvements

B_Q uncertainty: 92 ppb -> 20 ppb



vacuum sealed NMR probe



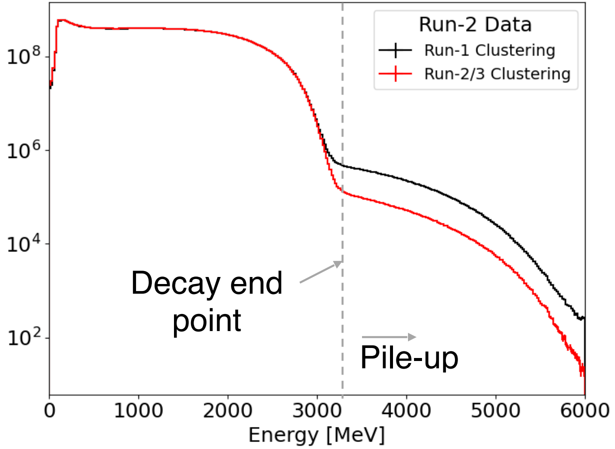
SYSTEMATIC UNCERTAINTY IMPROVEMENTS

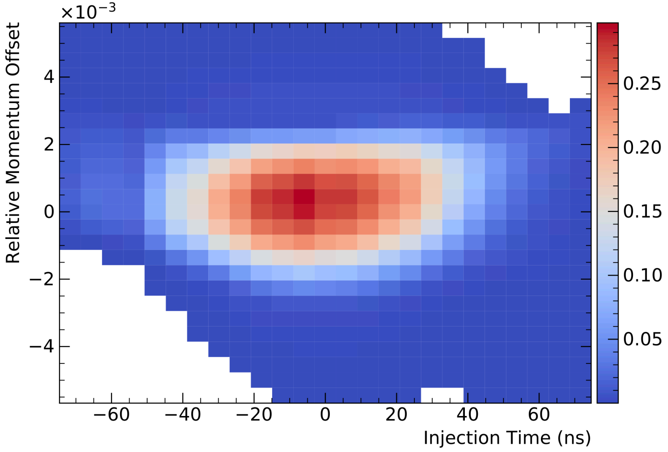
Running Conditions | Syst. Measuemrents | Analysis Improvements

2 e+ **arriving at same time** can be mistaken for 1: can **bias ω_a**

Reduce uncertainty by:

- Improved reconstruction, correction algorithm

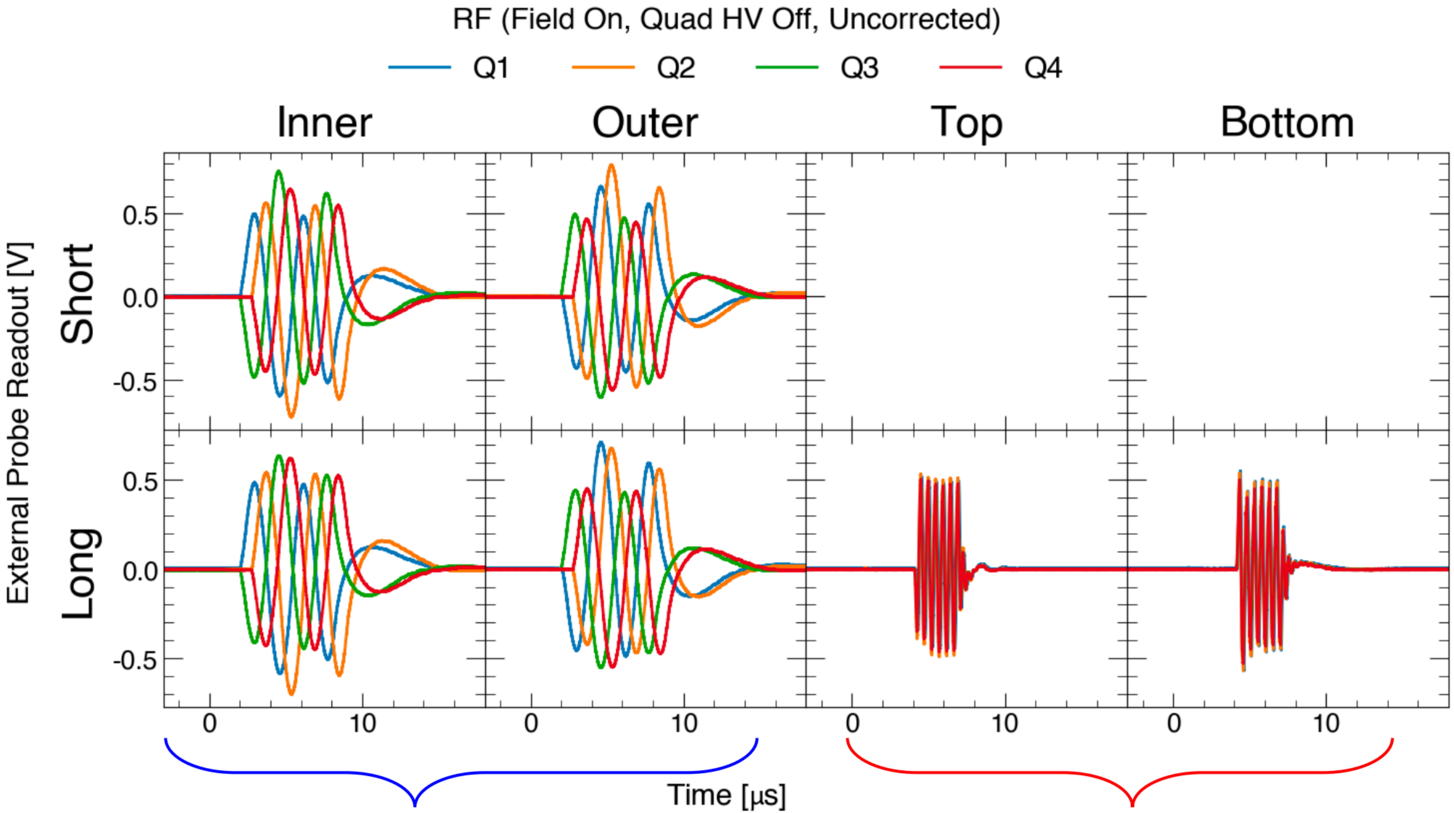




E-field correction depends on muon momentum distribution

Now **include correlations** between **momentum & time** of injection.

SYSTEMATIC UNCERTAINTY IMPROVEMENTS



Horizontal CBO reduction

Vertical CBO reduction