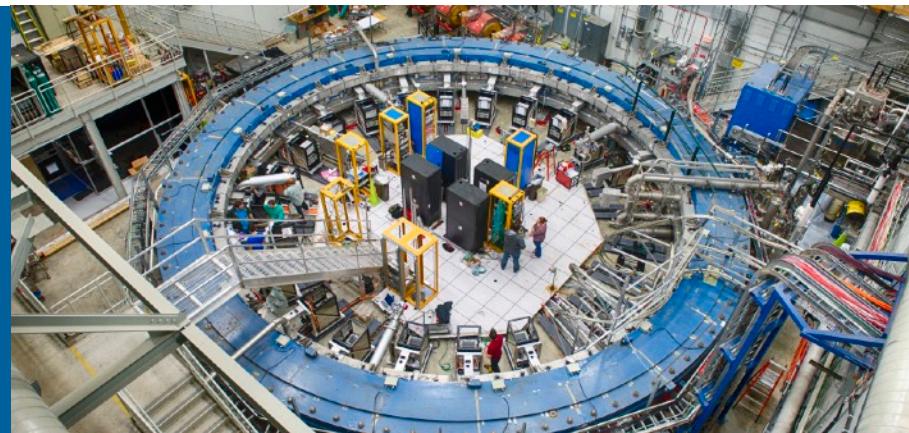
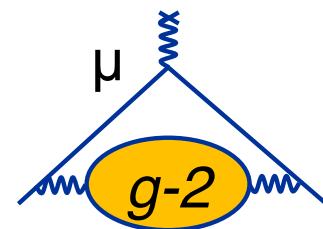


THE FERMILAB MUON G-2 EXPERIMENT STATUS AND OUTLOOK



SIMON CORRODI
Argonne National Laboratory

on behalf of the Muon g-2 collaboration
PSI 2022
October 16 - 21, 2022



THE MAGNETIC MOMENT OF THE MUON

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

Magnetic moment connected to spin via dimensionless factor **g**: gyromagnetic ratio

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

the anomalous magnetic moment

THE MAGNETIC MOMENT OF THE MUON: HISTORY

Stopped Muons

Stop muons in a magnetic field
measurement of g_μ directly



Experiment

BNL **2004** $a_\mu = 116\ 592\ 089(54)\text{stat}(33)\text{syst}(63)\text{tot} \times 10^{-11}$

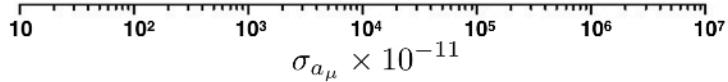
CERN III **1979**

CERN II **1968**

CERN I **1962**

Nevis **1960**

Cassels **1957**



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



Experiment

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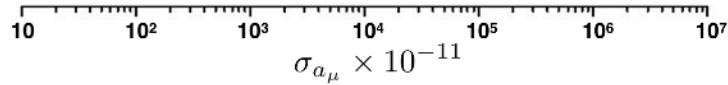
CERN III **1979**

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Nevis **1960**

Cassels **1957**



THE MAGNETIC MOMENT OF THE MUON: HISTORY

FNAL goal: 4 x improvement

Storage Ring

Dilated lifetime

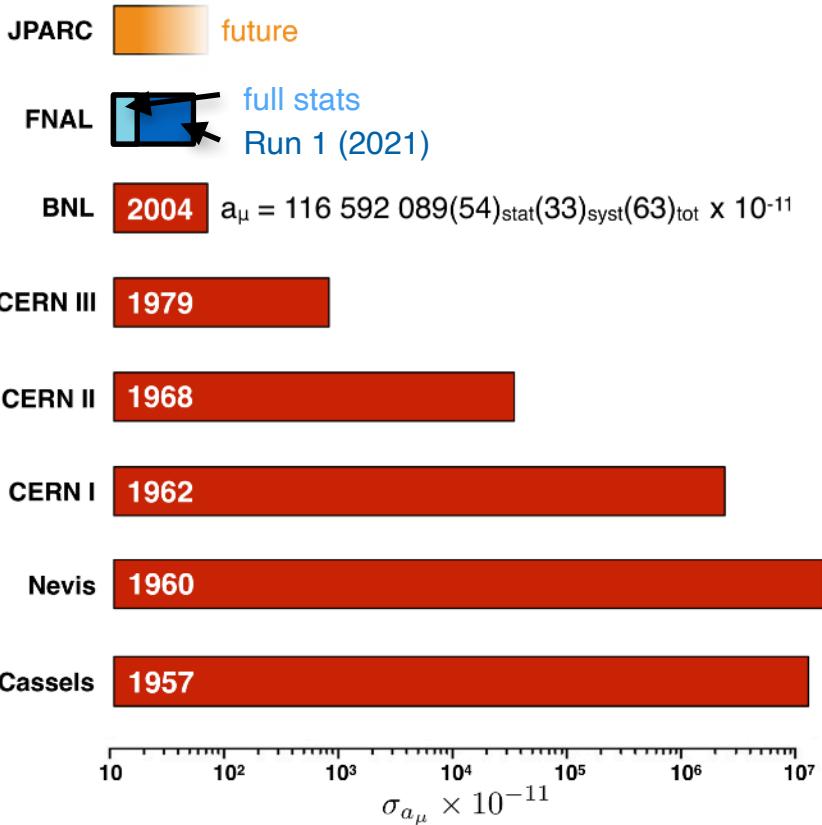
measurement of a_μ , more precise

Stopped Muons

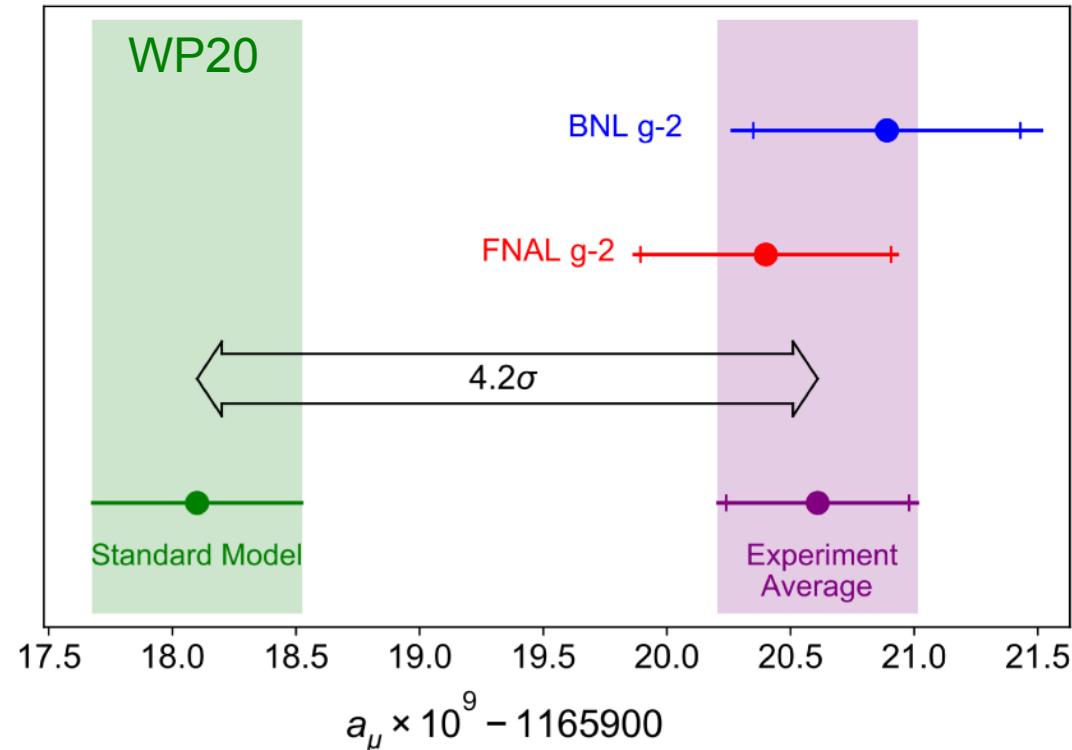
Stop muons in a magnetic field
measurement of g_μ directly



Experiment



THE BOTTOM LINE UP FRONT... OUR RUN-1 RESULT

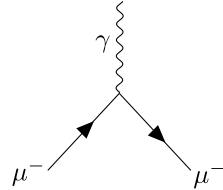


$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46 \text{ ppm})$$

$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35 \text{ ppm})$$

THE MAGNETIC MOMENT OF THE MUON: FROM THEORY

Dirac g=2 (1928)
for $s=1/2$ particles



Muon g-2 Theory Initiative

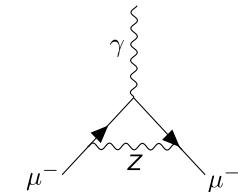
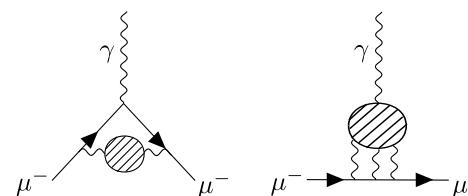
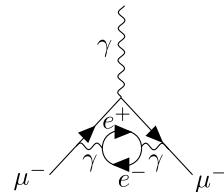
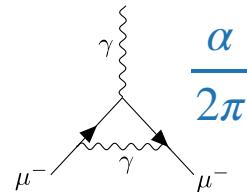
$$a_\mu(\text{SM}) = 116591810(43) \times 10^{-11}$$

Schwinger (1948)
1st order QED
uncertainty: 0.1×10^{-11}

Vacuum polarizations
Higher order QED
uncertainty: 0.1×10^{-11}

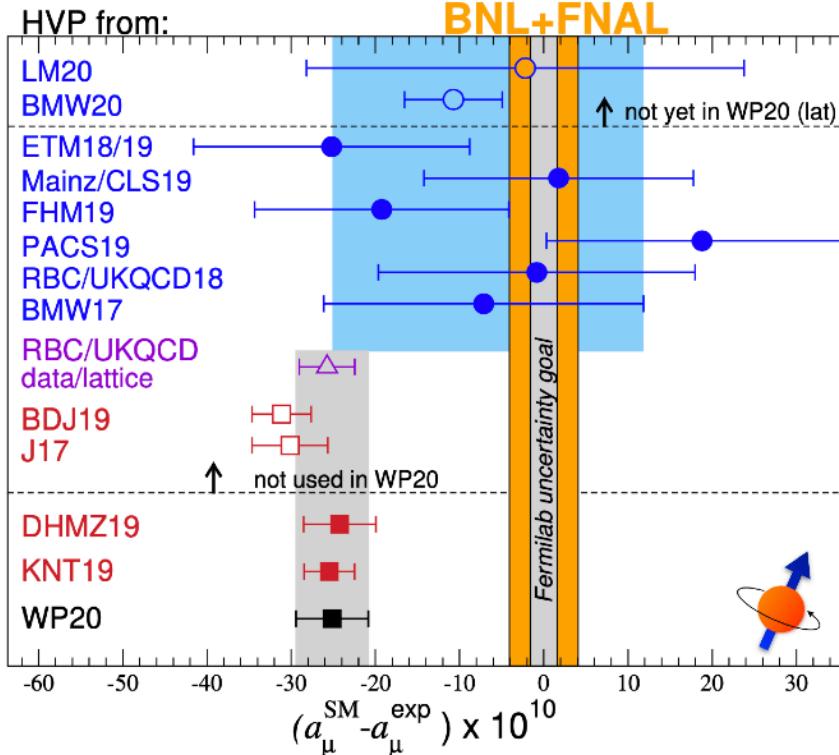
Hadronic
HVP: $6845(40) \times 10^{-11}$
HLbL: $92(18) \times 10^{-11}$

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



THE MAGNETIC MOMENT OF THE MUON: FROM THEORY

Very active theory community

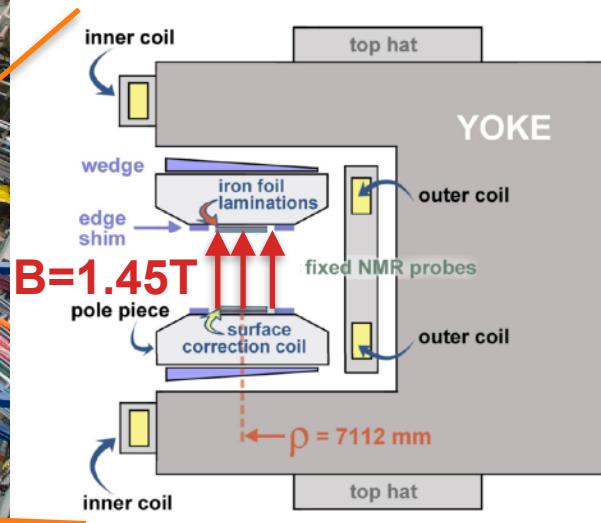
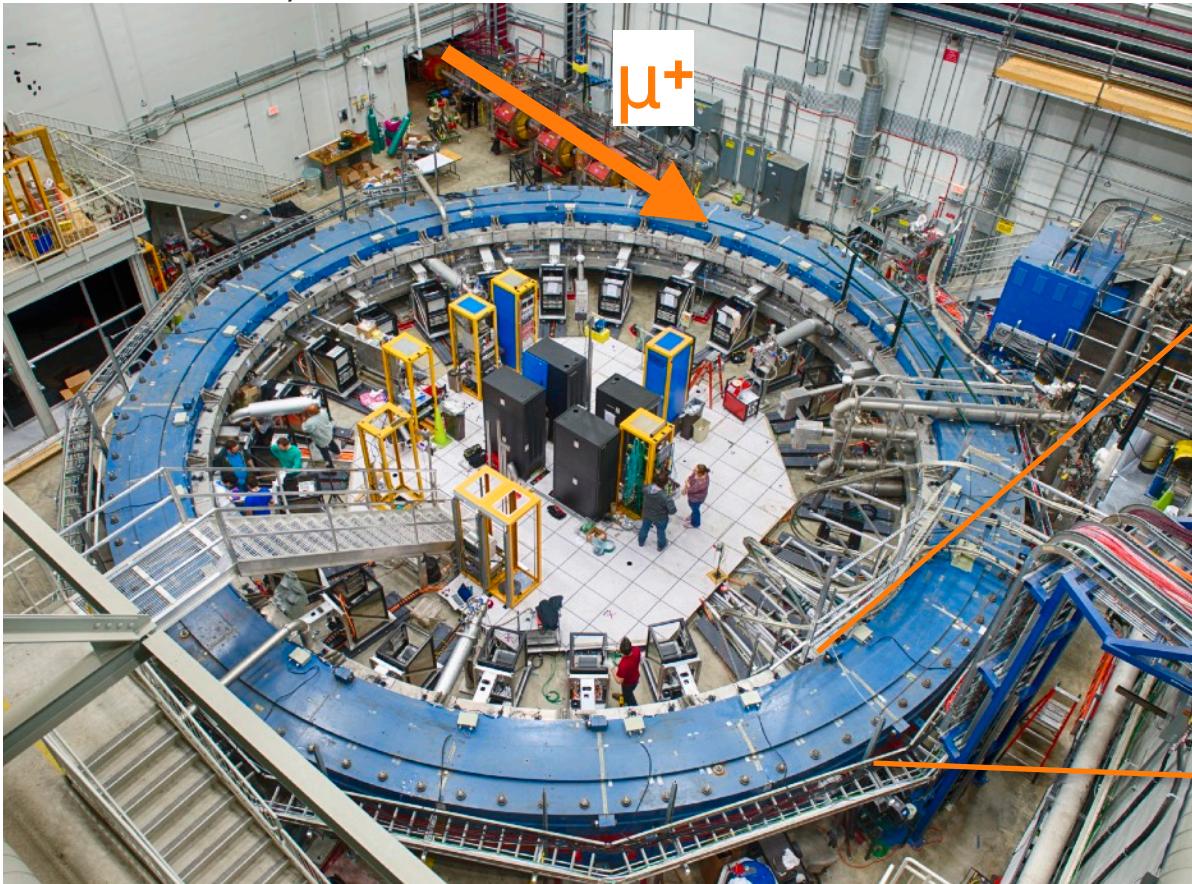


Lattice results:

lots of current work ongoing to understand possible discrepancy

comparison of intermediate windows

MEASURE a_μ IN A STORAGE RING



MEASURE a_μ IN A STORAGE RING

Cyclotron frequency

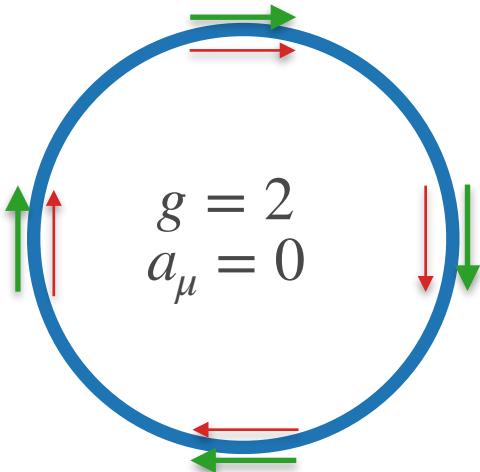
$$\omega_C = \frac{e}{m\gamma} B$$

Spin precession

$$\omega_S = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

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

NMR: $\hbar\omega_p' = 2\mu_p |B|$



→ momentum
→ spin

MEASURE a_μ IN A STORAGE RING

Cyclotron frequency

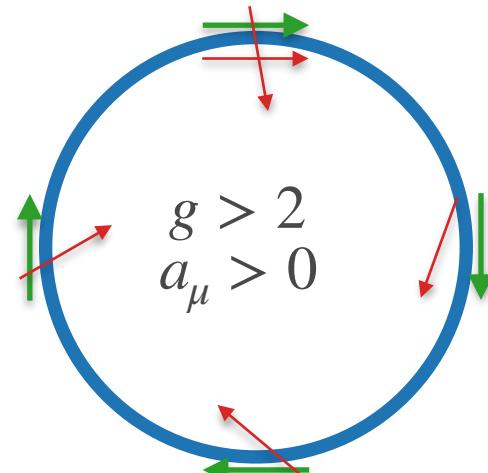
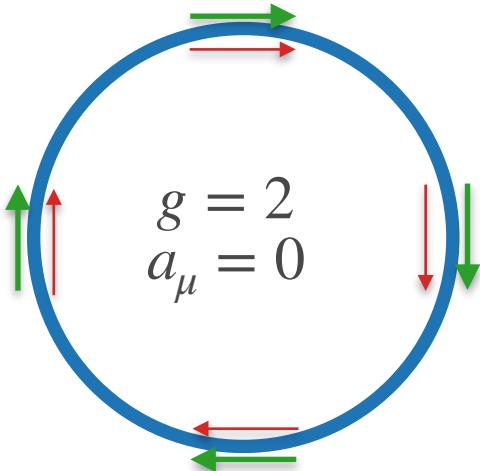
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STORAGE RING: HOW WE STORE THE MUONS

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

~ 0 ~ 0

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

STORAGE RING: HOW WE STORE THE MUONS

pitch corrections: C_p E-field corrections: C_e

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MEASURE a_μ IN A STORAGE RING

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

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

bound state QED calc., exact

0.28 ppt uncertainty
Phys. Rev. A **83**, 052122 (2011)
2022: 0.13ppt, arXiv 2209.13084

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

MEASURE a_μ IN A STORAGE RING

TDR goal:
140 ppb
(4 fold improvement
over the BNL result)

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MEASURE a_μ IN A STORAGE RING

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blinding factor precession beam dynamics corrections

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

absolute field
calibration

magnetic field sampled
by the muon distribution

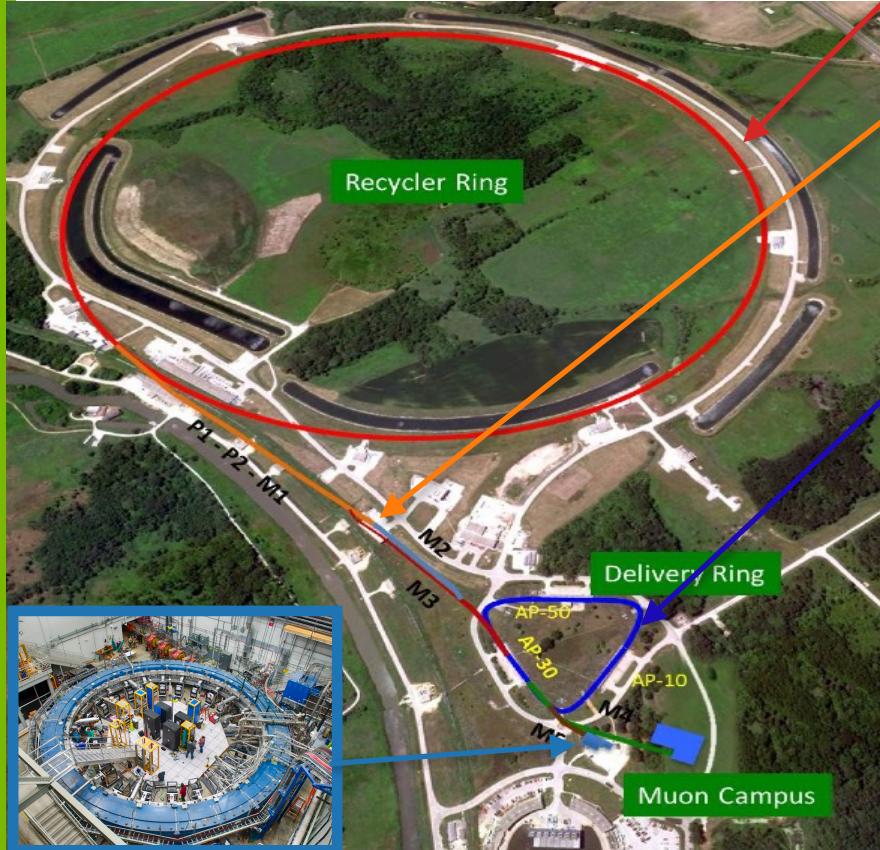
Magnetic transients
corrections

THE MAGNET: THE BIG MOVE





THE MUONS



8 GeV protons in recycler

Target

p/π/μ beam, p kicked away, π decay

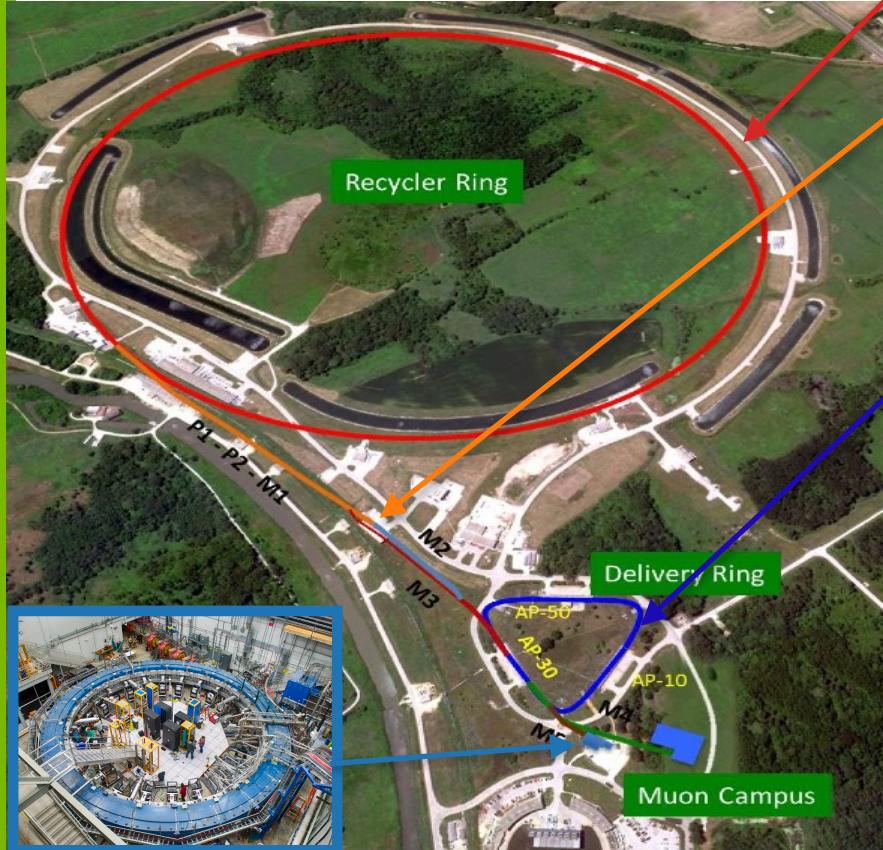
$$\pi^+ \rightarrow \mu^+ \nu_\mu \quad 95\% \text{ polarized muons}$$

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

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

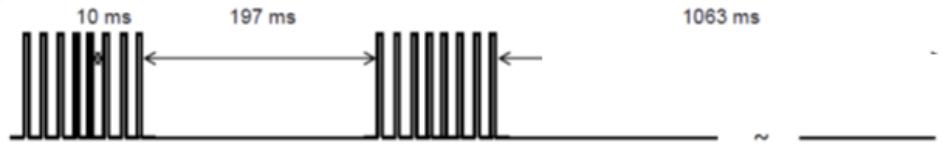
Store muons for ~700us (~10 lifetimes)

THE MUONS



8 GeV protons in recycler

Target



2 x 8 shots

p/π/μ beam, p kicked away, π decay

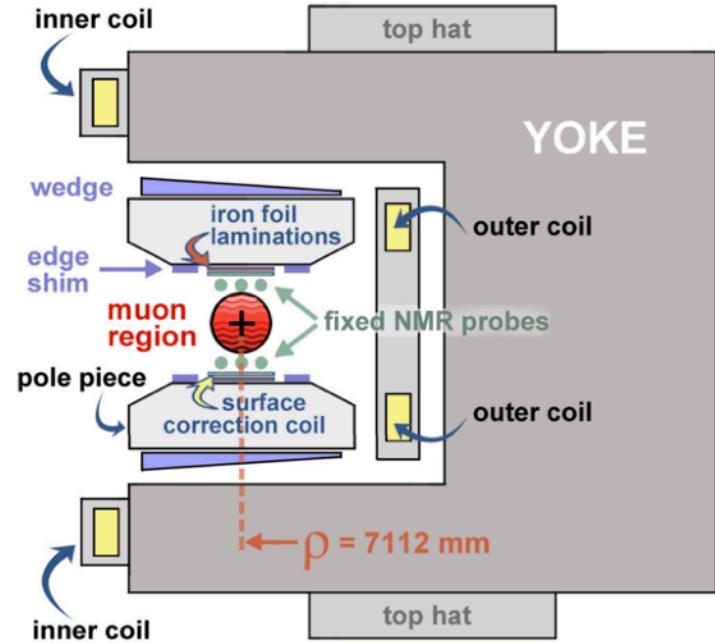
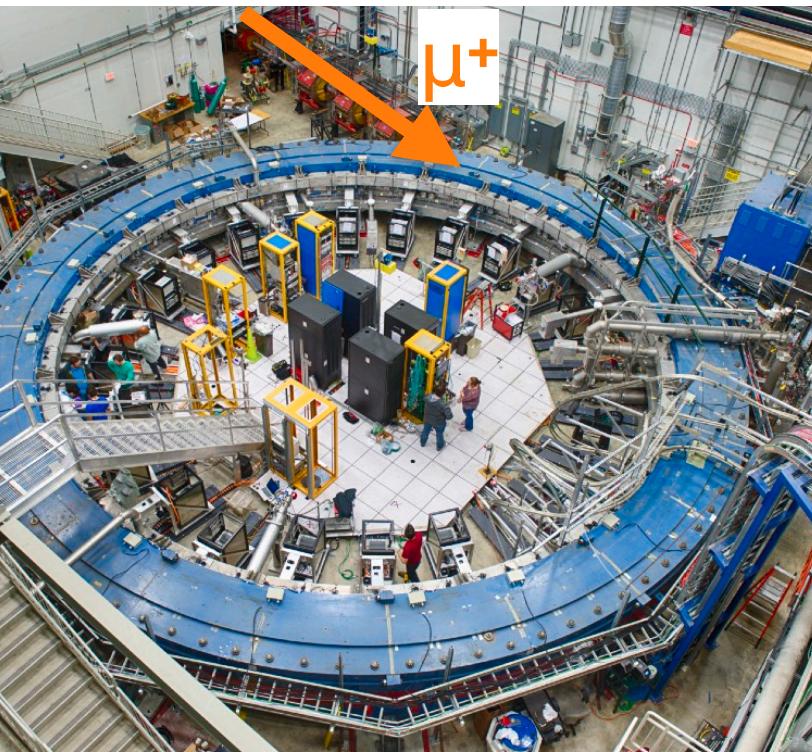
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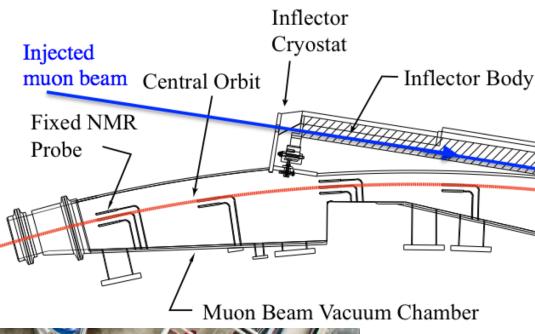
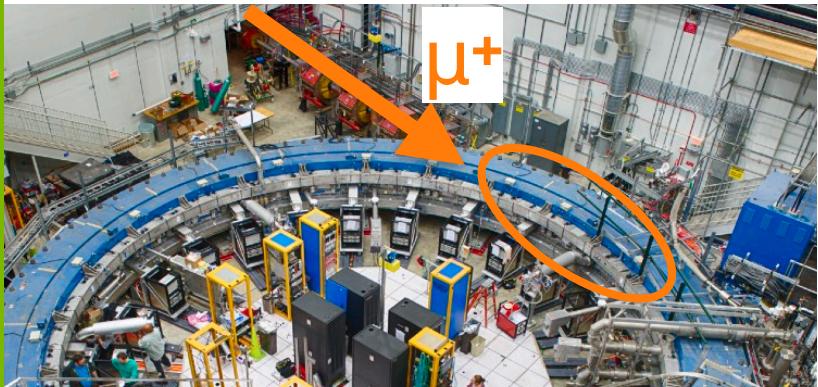
HOW TO STORE MUONS: MAGNETIC FIELD



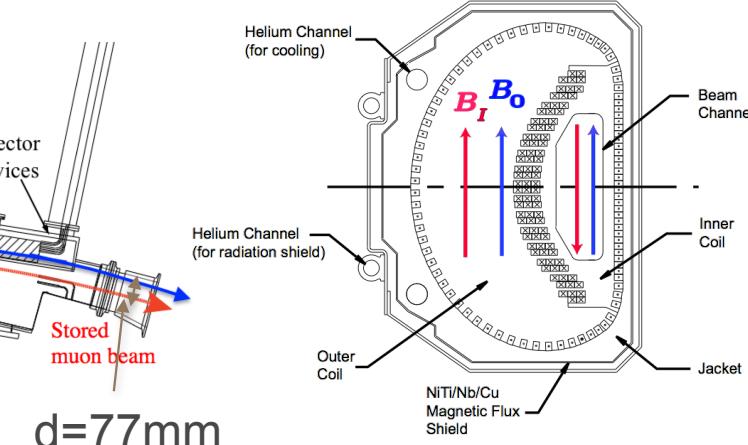
Fully-assembled lamination (10 degrees wide)



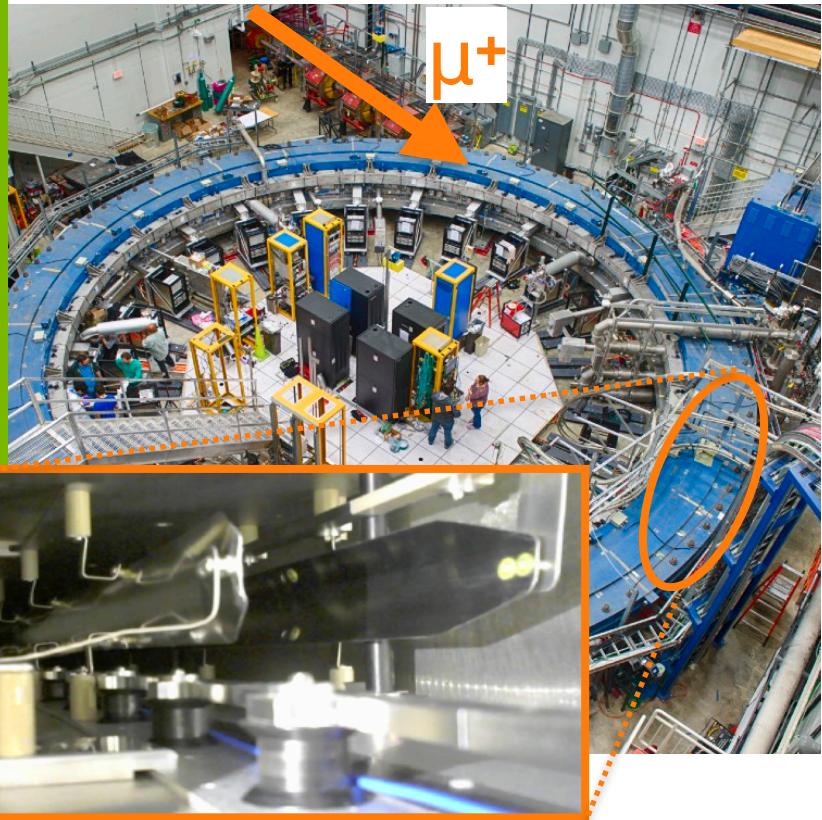
HOW TO STORE MUONS: THE INFLECTOR



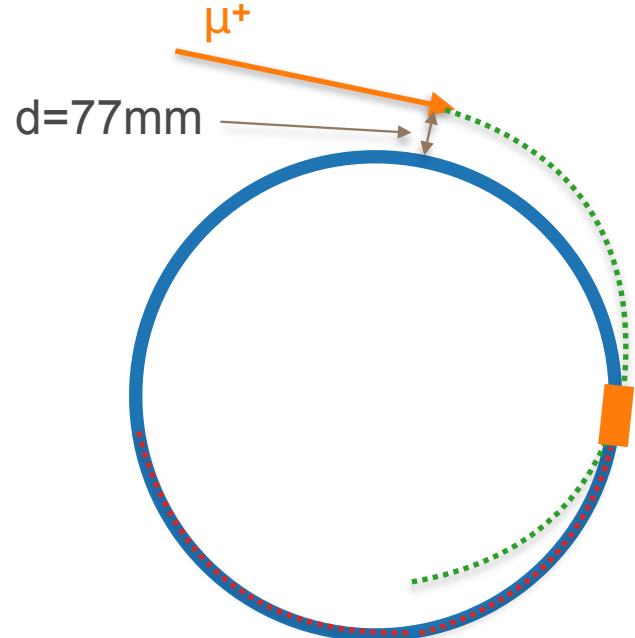
- Need to cancel field in beam channel
- prevents strong deflection of the beam



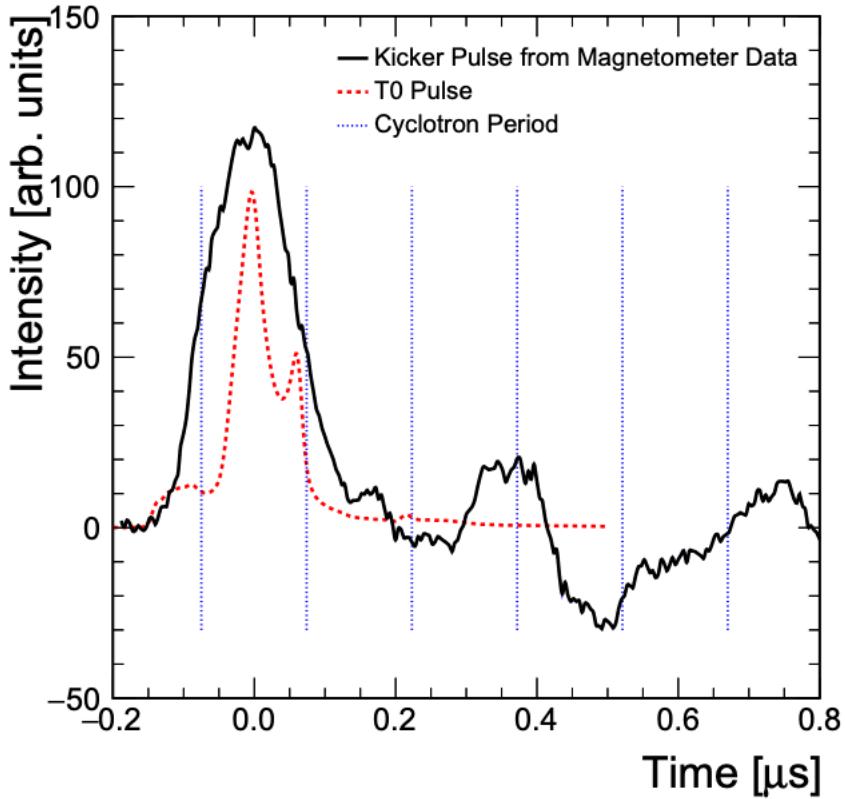
HOW TO STORE MUONS: THE KICKER



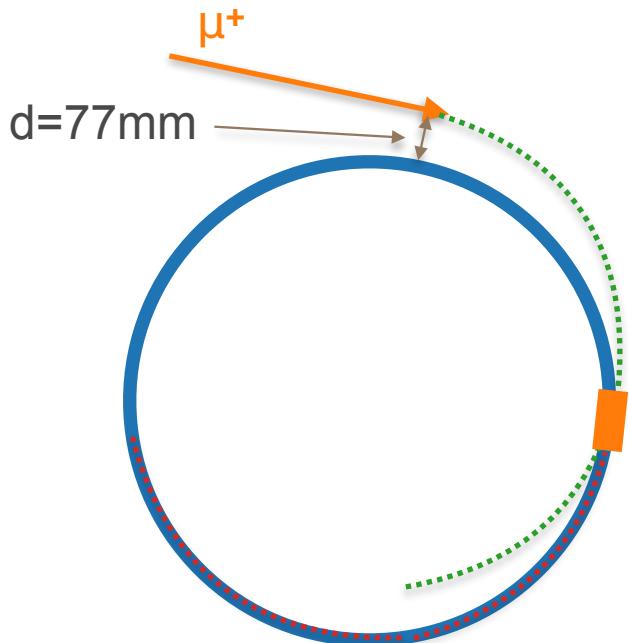
- Incident beam center 77 mm off from center of storage region
- tears muon onto store orbit



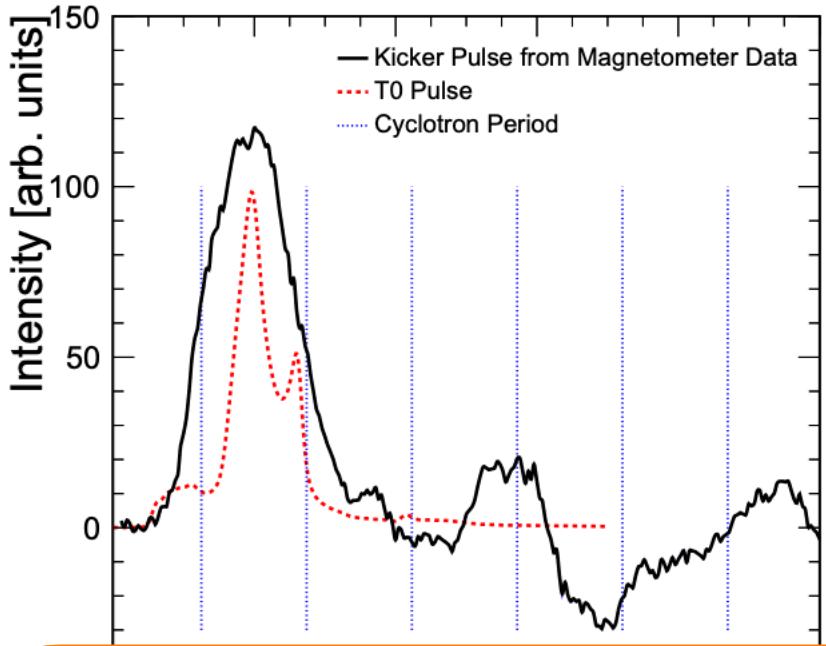
HOW TO STORE MUONS: THE KICKER



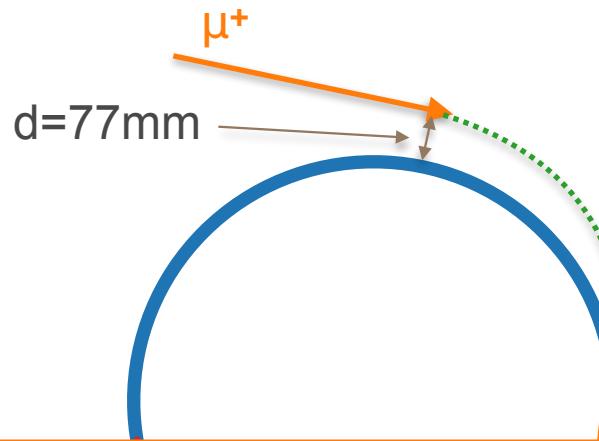
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HOW TO STORE MUONS: THE KICKER



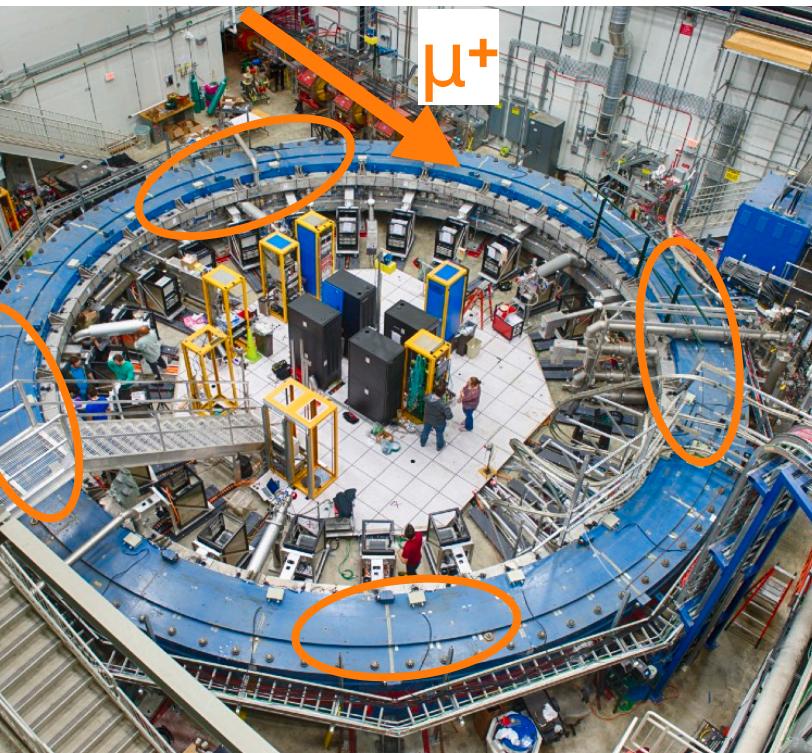
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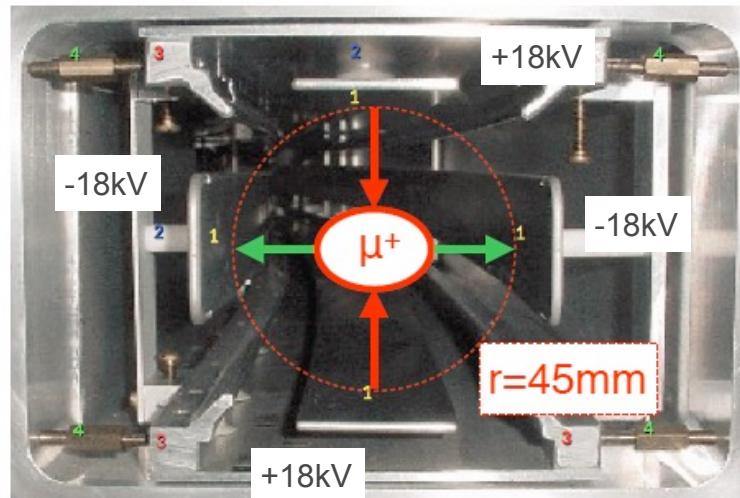
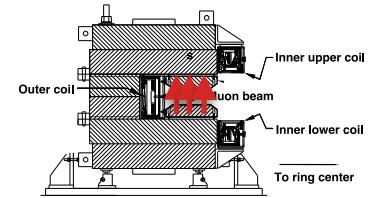
Upgrade since run 1:

New kicker cable allow for proper kicker, reducing the equilibrium radius.

HOW TO STORE MUONS: FOCUSING

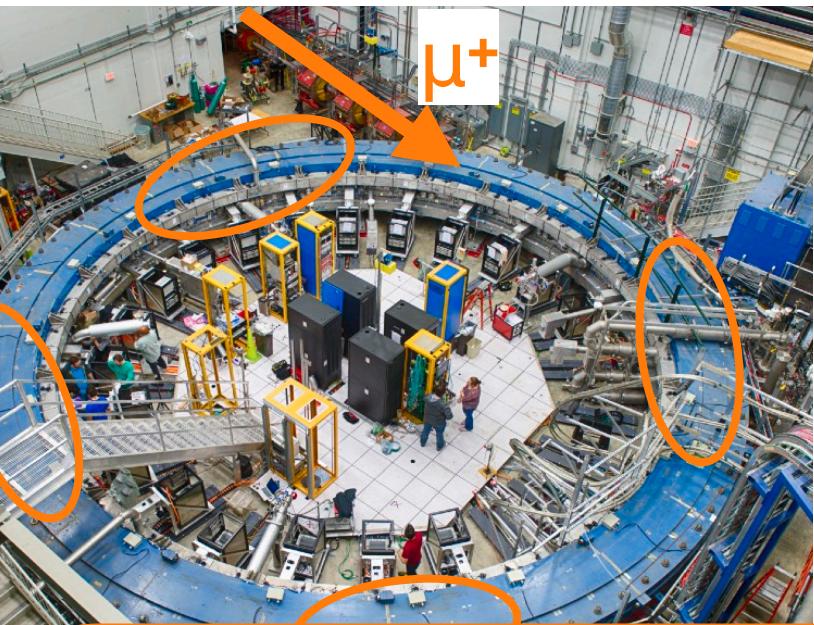


- Radial focus:
1.45T vertical B field
- Vertical focus:
electrostatic quadrupoles (43% of the ring)



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

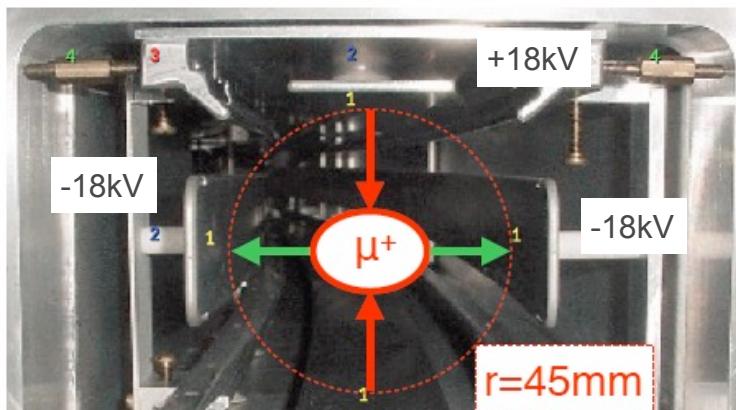
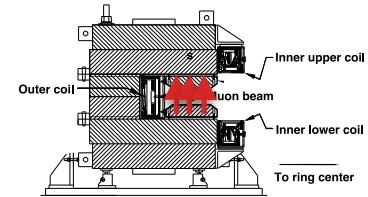
HOW TO STORE MUONS: FOCUSING



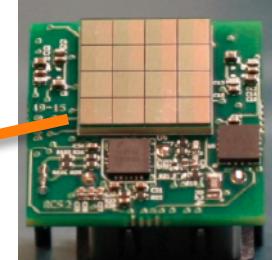
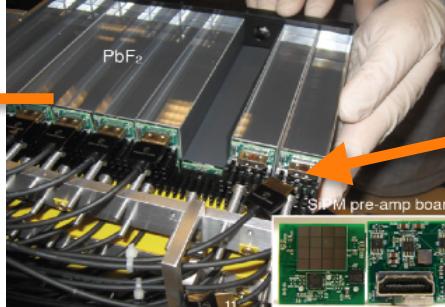
Upgrade since run 1:

Broken high voltage resistors in run 1 led to an additional early-to-late effects.

- Radial focus:
1.45T vertical B field
- Vertical focus:
electrostatic quadrupoles (43% of the ring)



THE MEASUREMENTS: CALORIMETERS (ω_a^{meas})



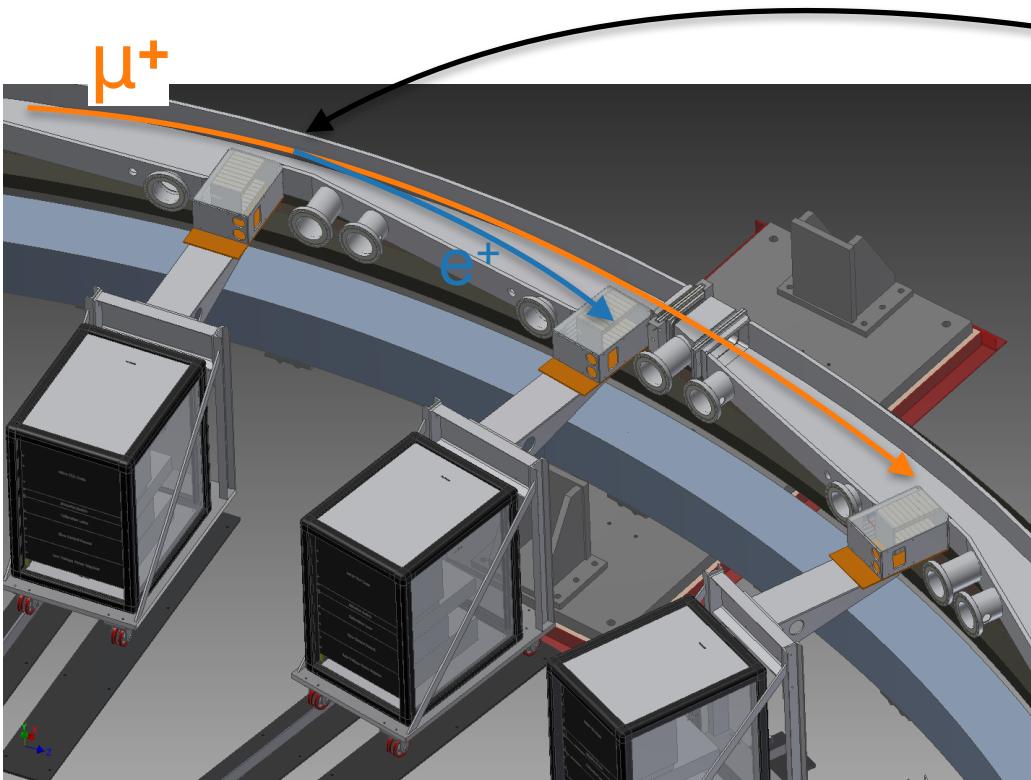
24 Calorimeters with 54 (9x6) Cherenkov
PbF₂ crystals read out by SiPMs
- arrival time (~100ps) & energy of e⁺ (~5% at 2GeV)

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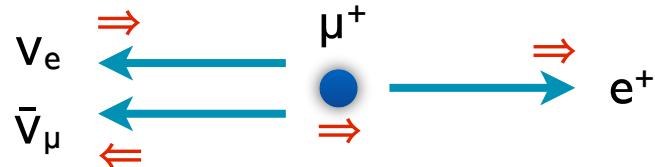


- 24 Calorimeters with 54 (9x6) Cherenkov PbF₂ crystals read out by SiPMs
 - arrival time (~100ps) & energy of e⁺ (~5% at 2GeV)
 - Laser system for gain response calibration throughout data taking
(stability 10⁻³, rate difference 10⁴)

THE MEASUREMENTS: CALORIMETERS (ω_a^{meas})

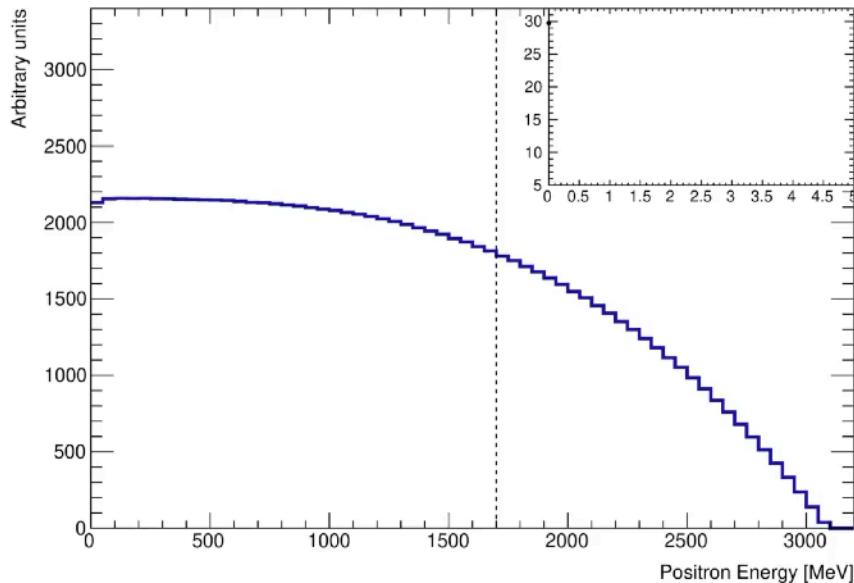
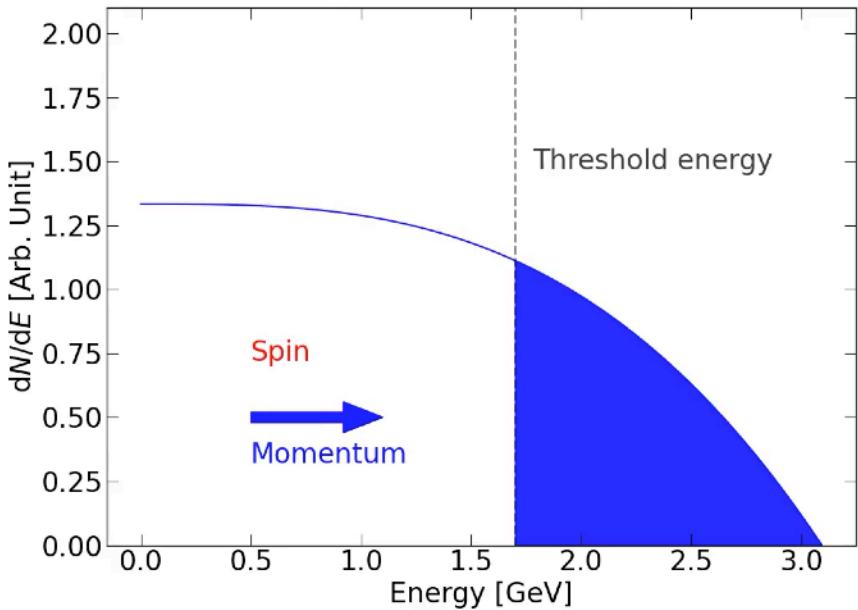


- Parity violating decay (Michel)
- Highest-energy e^+ emitted preferentially along muon spin



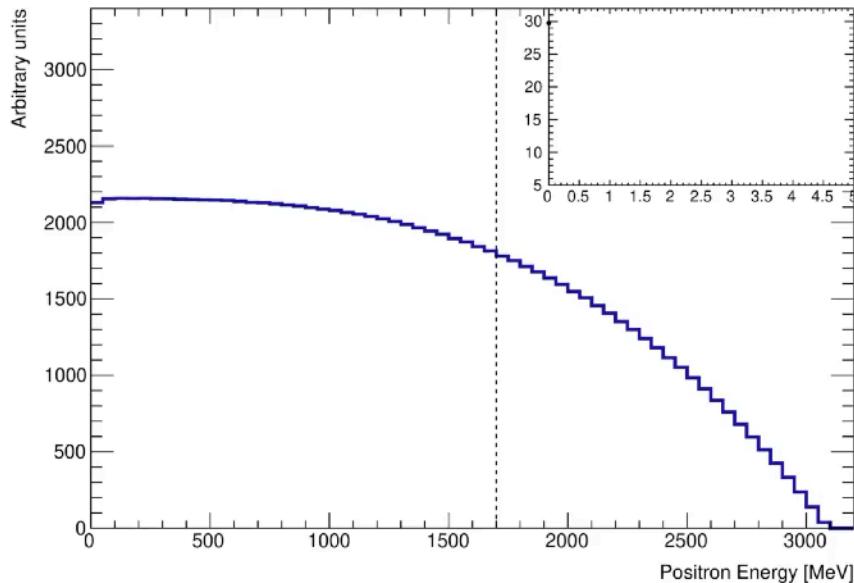
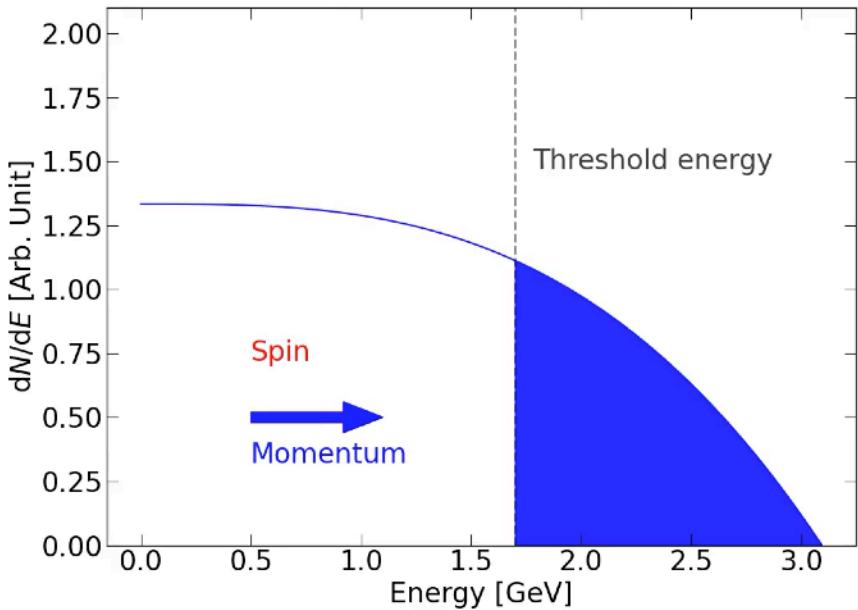
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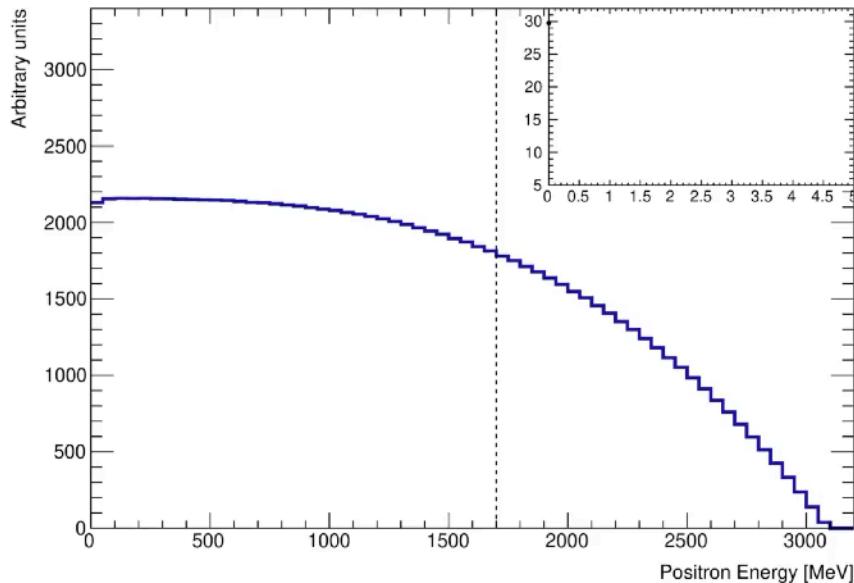
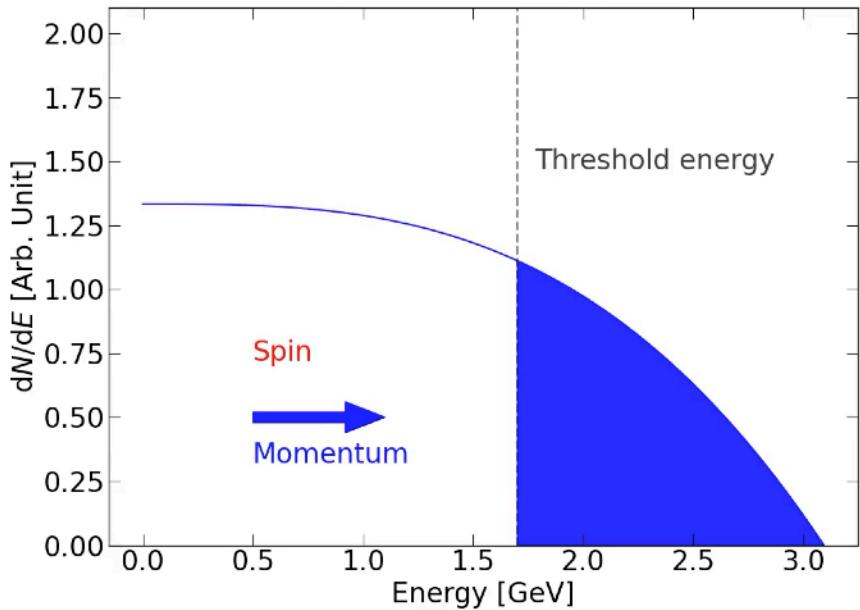
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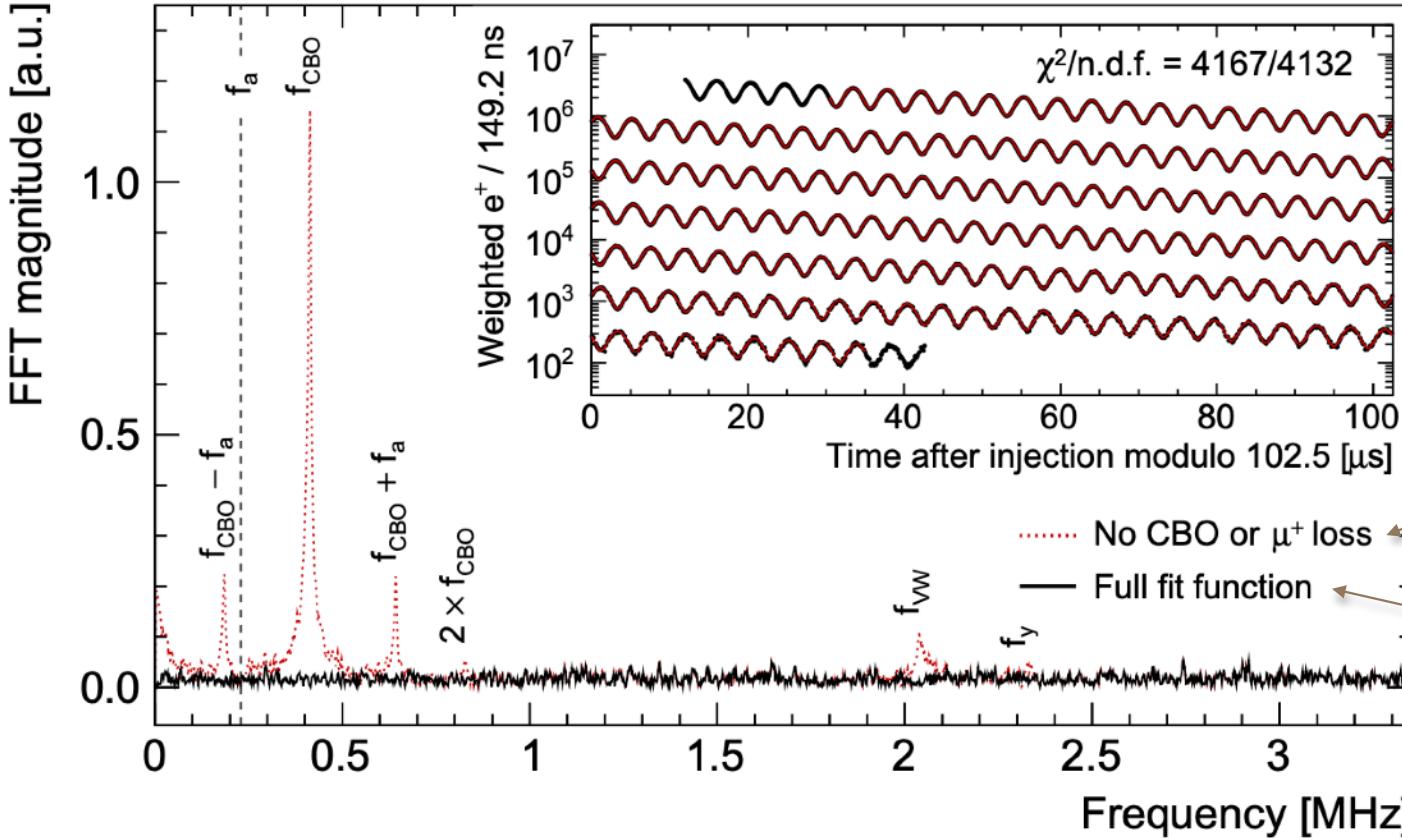
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MEASUREMENTS: ω_a^{meas}

Example from dataset 1d

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



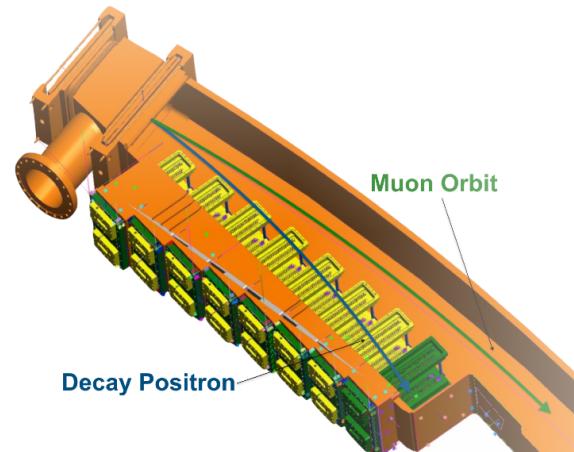
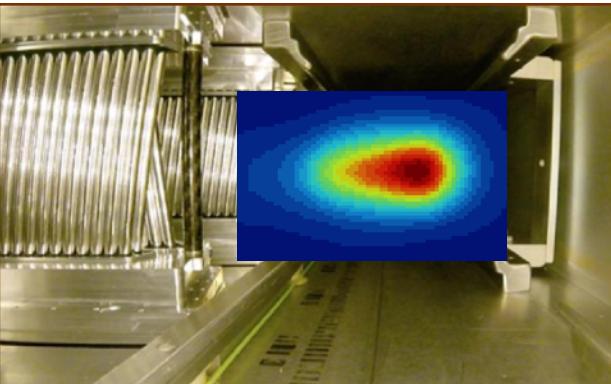
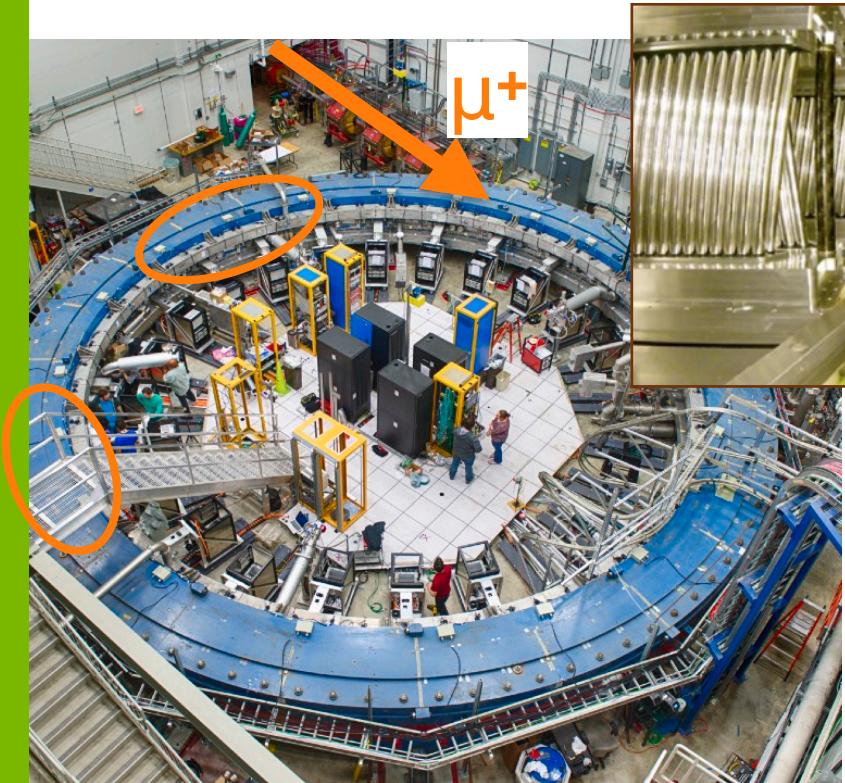
$N_0 e^{-t/\tau} [1 - A \cos(\omega_a t + \phi)]$

22 parameter fit

*CBO:
Coherent Betatron
Oscillation

TRACKERS: BEAM DYNAMICS

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



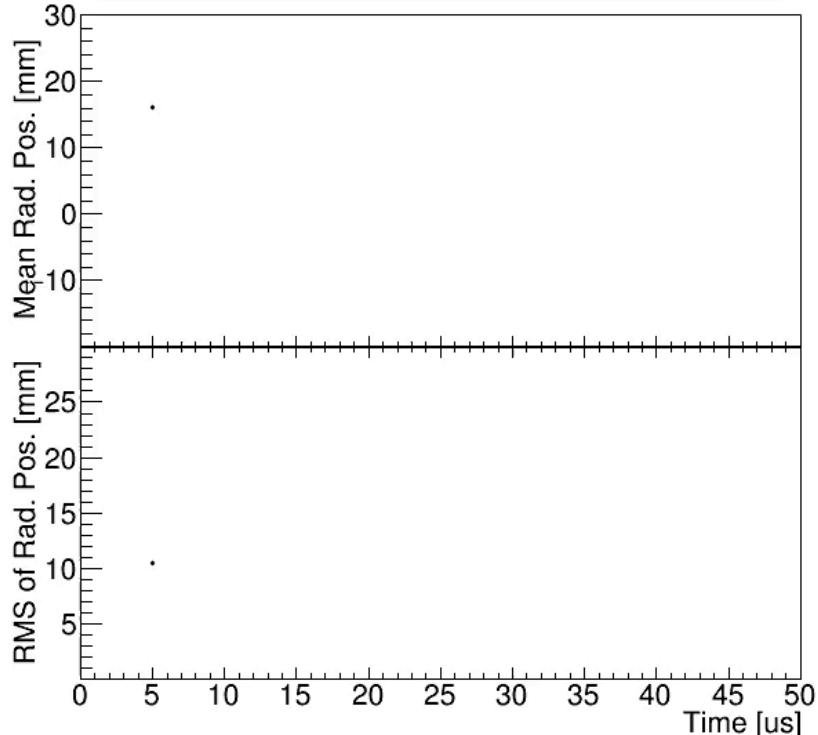
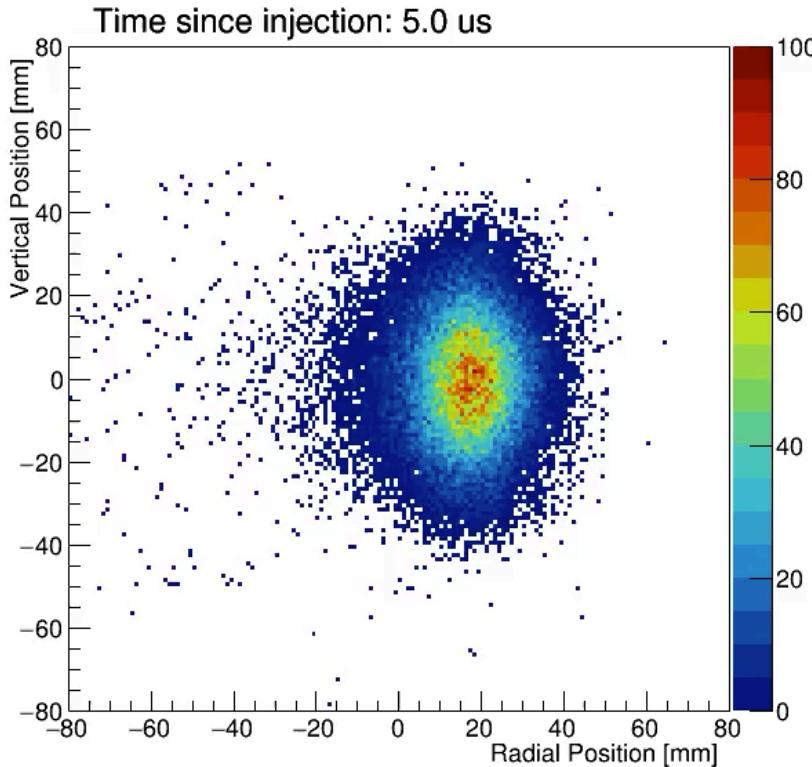
2 straw-tracker stations

(each 8 modules, 4 layers of 32 straws, 50:50 Ar:Ethane, res ~100um)

Muon distribution + field maps: $\tilde{\omega}'_p$
Handle on beam dynamics

TRACKERS: BEAM DYNAMICS

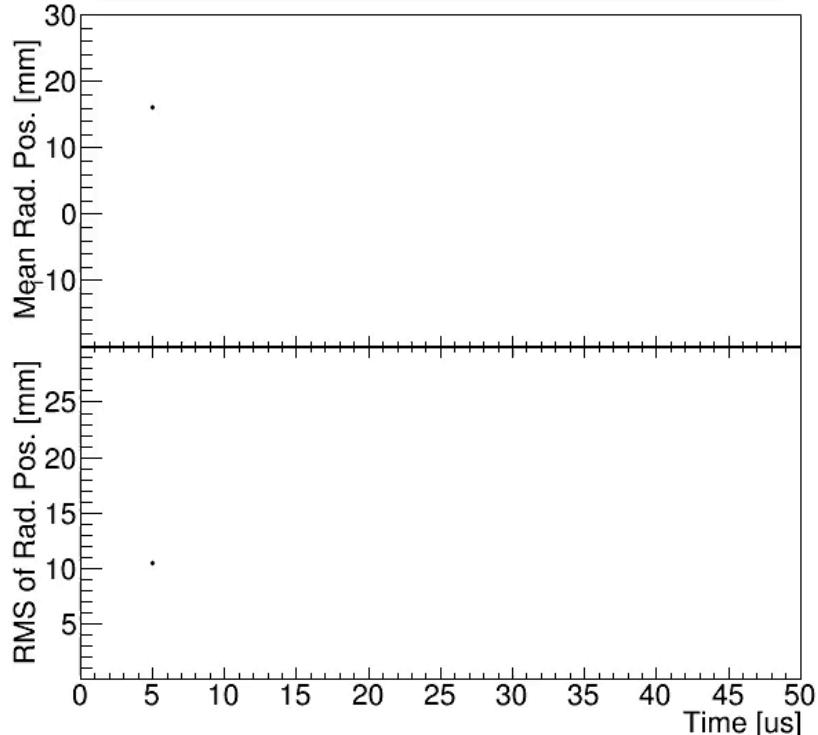
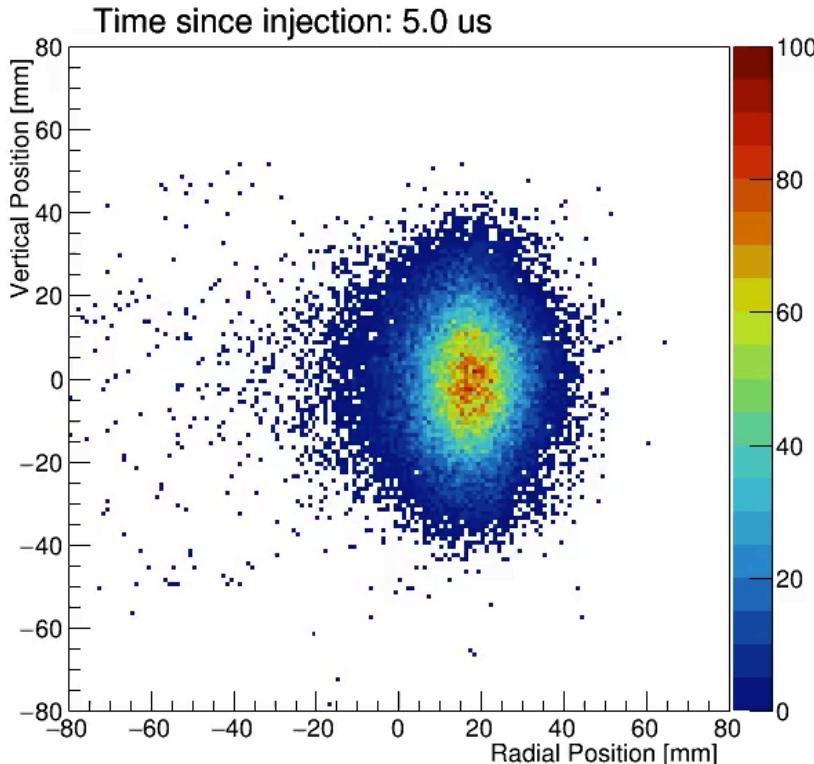
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}} \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa} \right)}{f_{\text{calib}} \left\langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \right\rangle (1 + B_K + B_Q)}$$



*CBO: Coherent Betatron Oscillation

TRACKERS: BEAM DYNAMICS

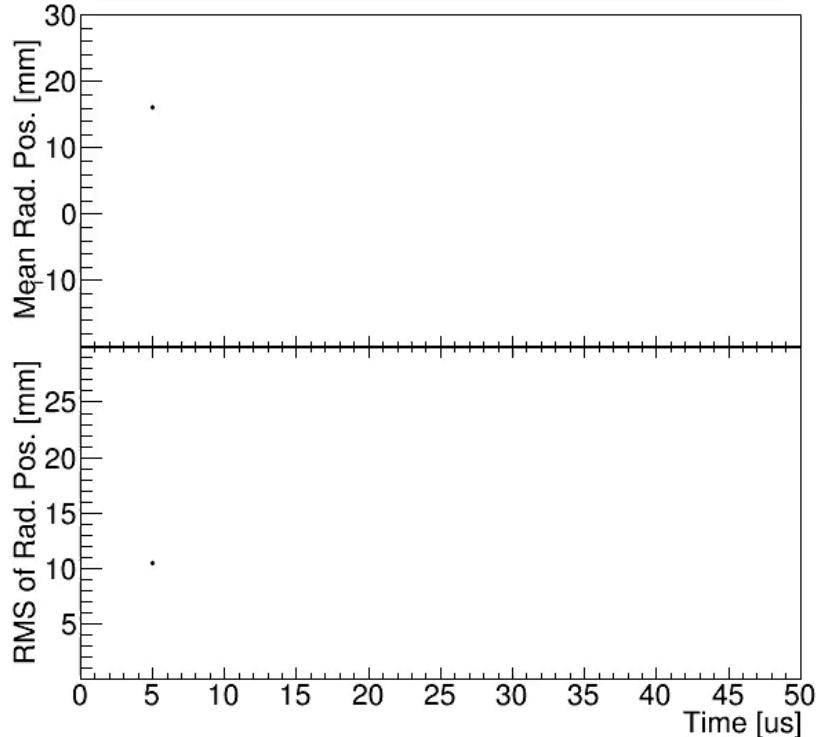
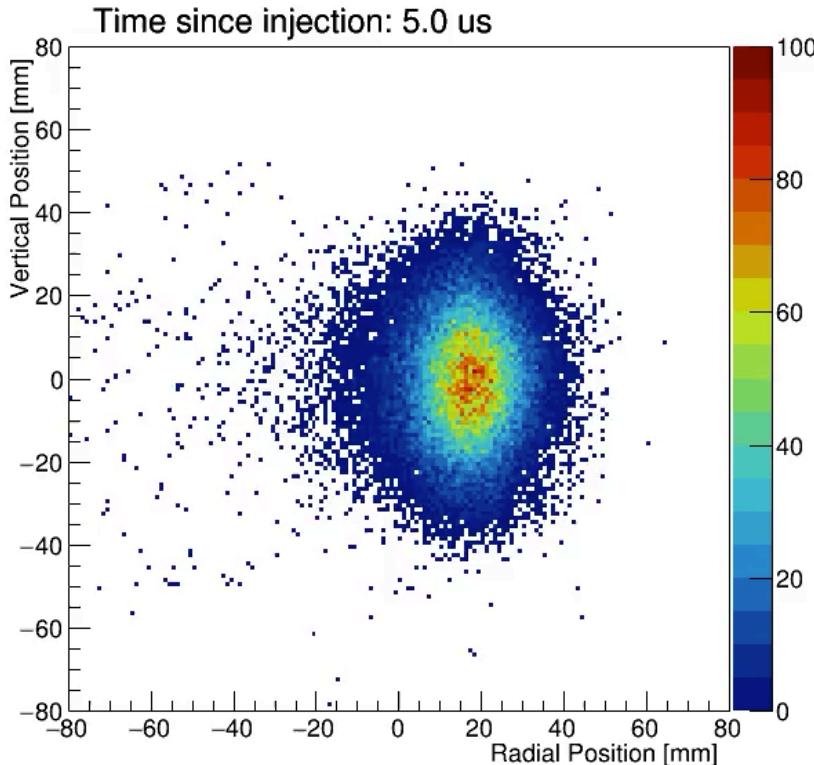
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}} \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa} \right)}{f_{\text{calib}} \left\langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \right\rangle (1 + B_K + B_Q)}$$



*CBO: Coherent Betatron Oscillation

TRACKERS: BEAM DYNAMICS

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

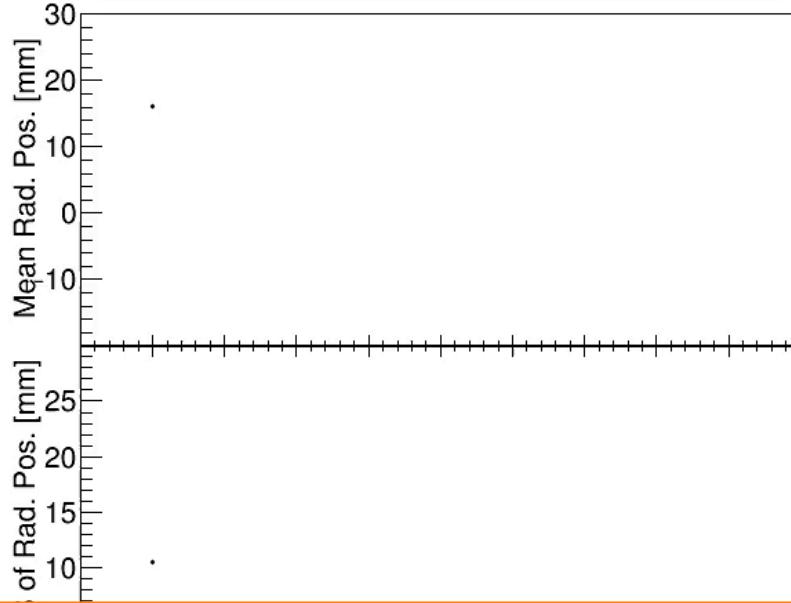
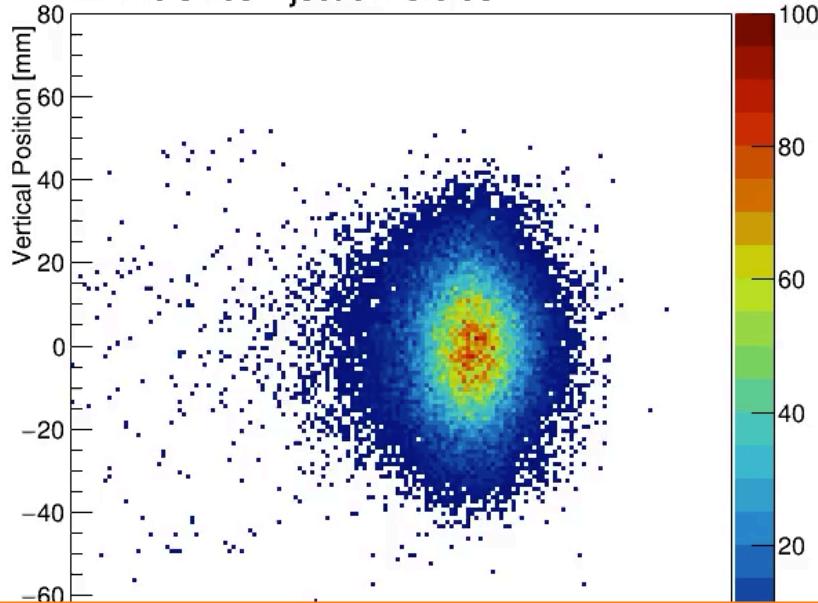


*CBO: Coherent Betatron Oscillation

TRACKERS: BEAM DYNAMICS

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

Time since injection: 5.0 us



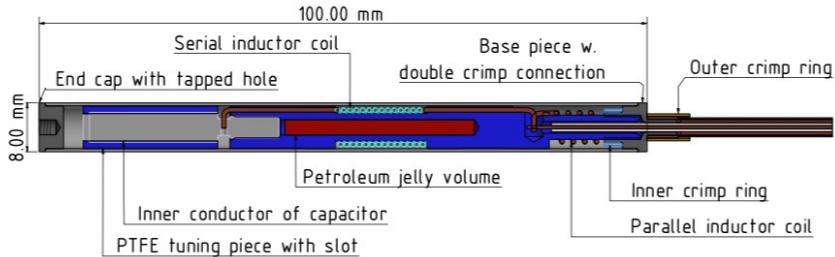
Upgrade since run 1:

Additional RF on the ESQ since the end of run 4 allows to reduce the CBO.

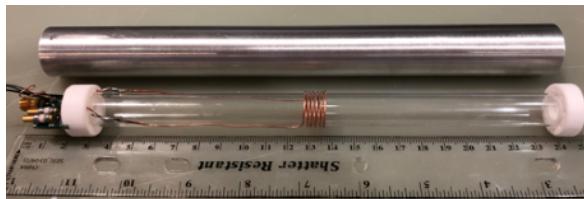
NUCLEAR MAGNETIC RESONANCE (NMR)

$$\hbar\omega'_p = 2\mu_p |B|$$

- Flip spins of a sample by delivering a $\pi/2$ -pulse
- measure Free Induced Decay (FID)



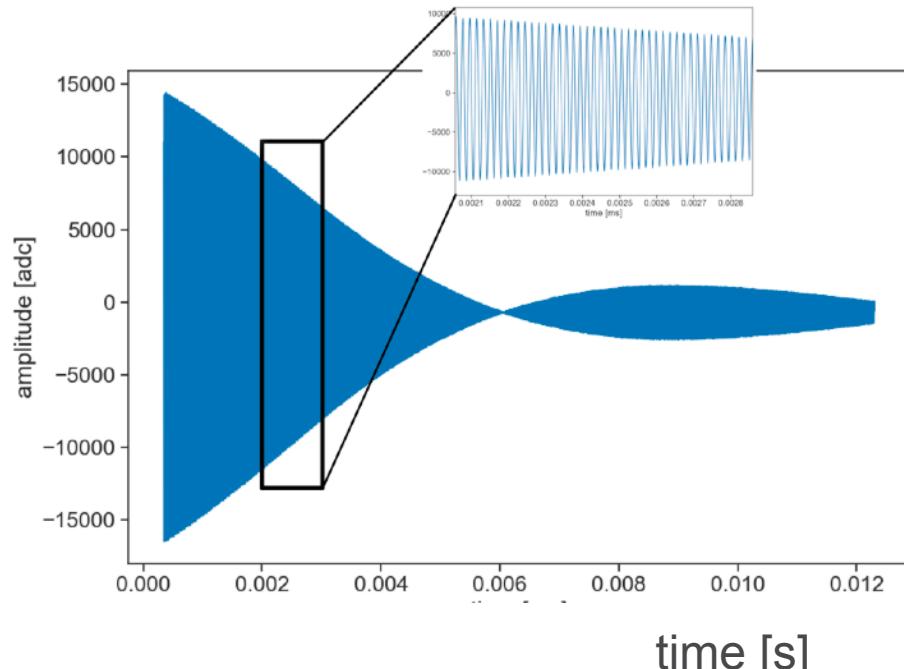
Petroleum Jelly probes



H₂O calibration probe (f_{calib})

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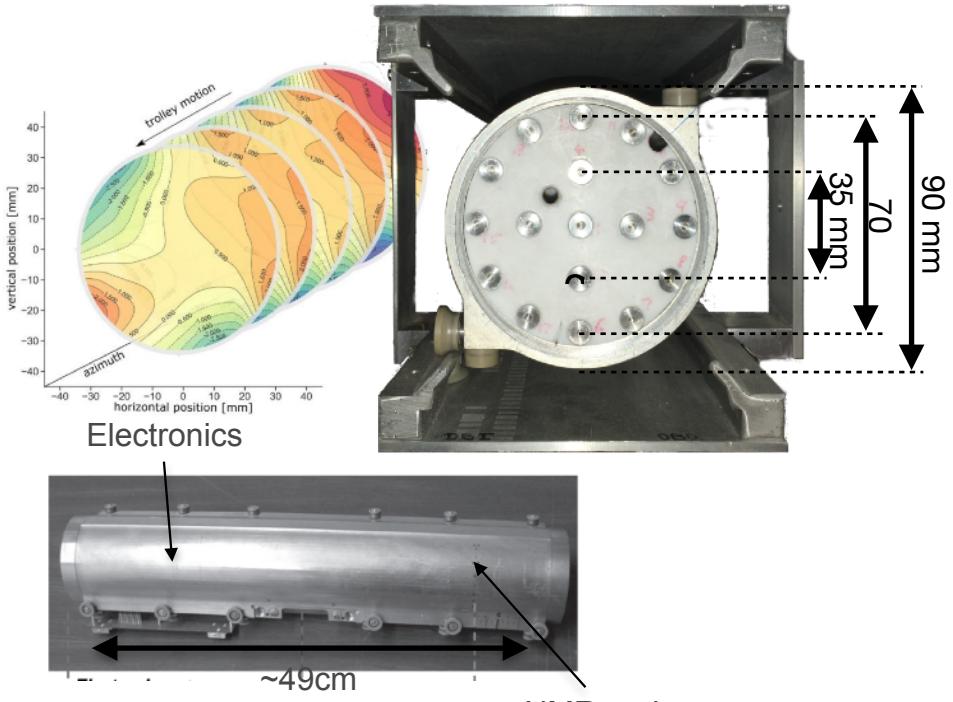
Free Induced Decay (FID)



THE FIELD MEASUREMENT

Trolley

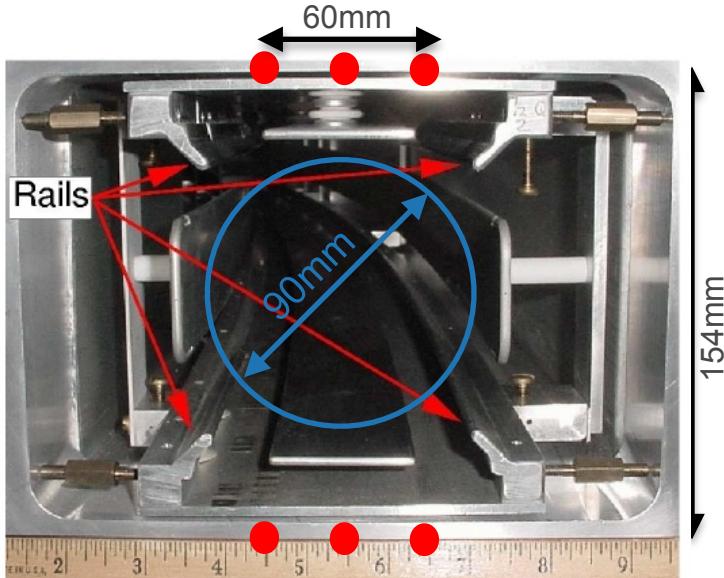
- inside the storage region, ~3 days
- 17 probes, moves around the ring



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

378 Fixed Probes

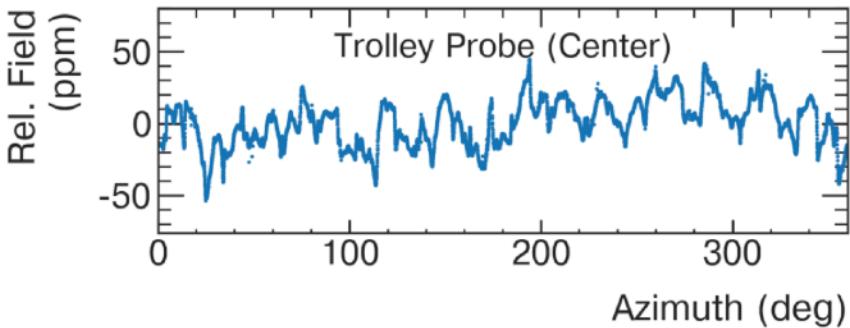
- Outside of the storage region
- 72 position, ~5deg apart



THE FIELD MEASUREMENT

Trolley (every ~3 to 5 days)

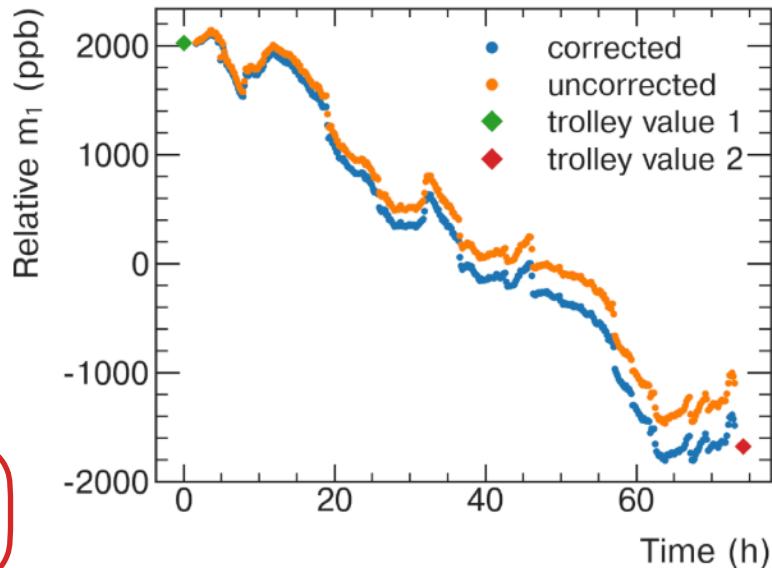
Field inside the muon storage volume



See poster: “The precision magnetic field in the Muon g-2 Experiment at Fermilab”

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

378 Fixed Probes (from the outside)
Track the field between field maps

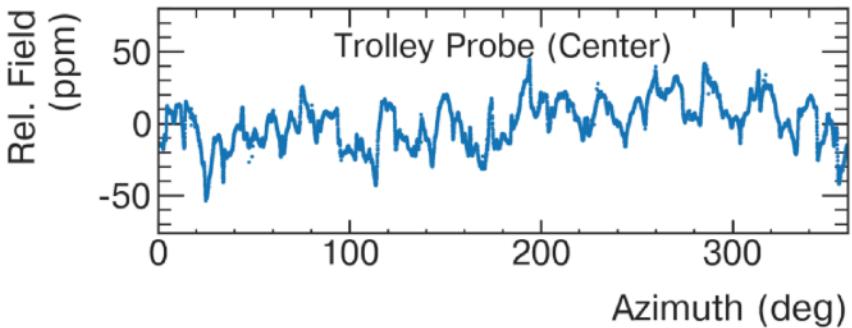


Uncertainty: random walk model
(Brownian bridge)

THE FIELD MEASUREMENT

Trolley (every ~3 to 5 days)

Field inside the muon storage volume



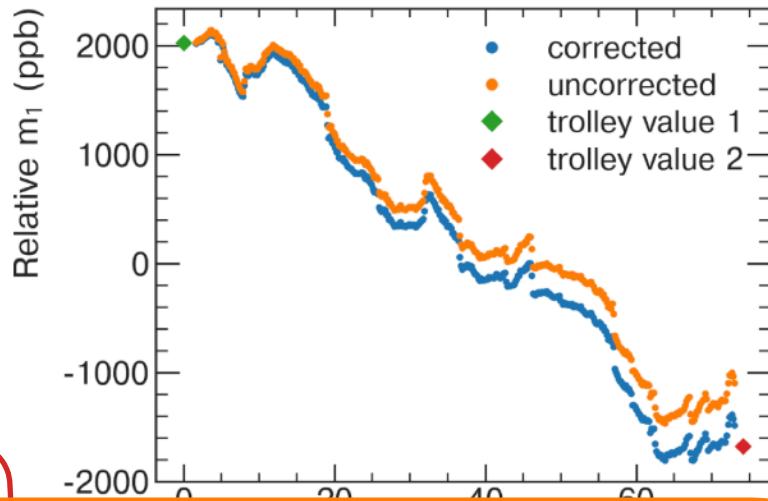
See poster: “The precision magnetic field

Upgrade since run 1:

Thermal insulation (run 2) and improved AC (run 3) increased the field stability.

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

378 Fixed Probes (from the outside)
Track the field between field maps

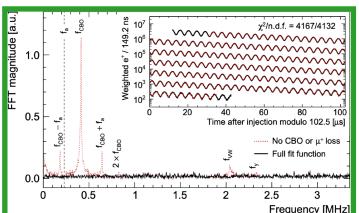






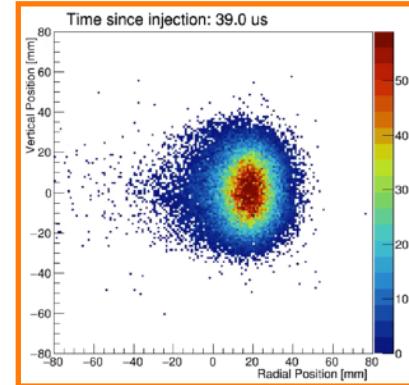
BACK TO THE MASTER FORMULA

unblinding factor

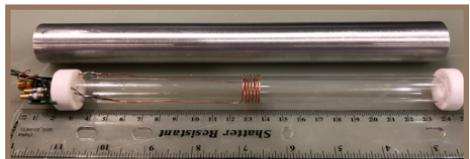


precession

beam dynamics
corrections



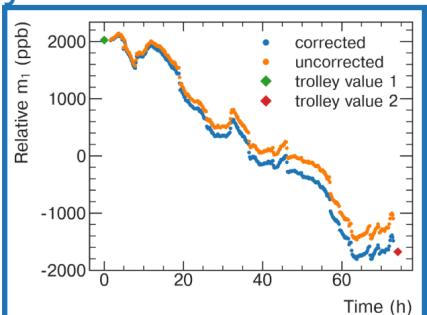
absolute field
calibration



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managed by UChicago Argonne, LLC.

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

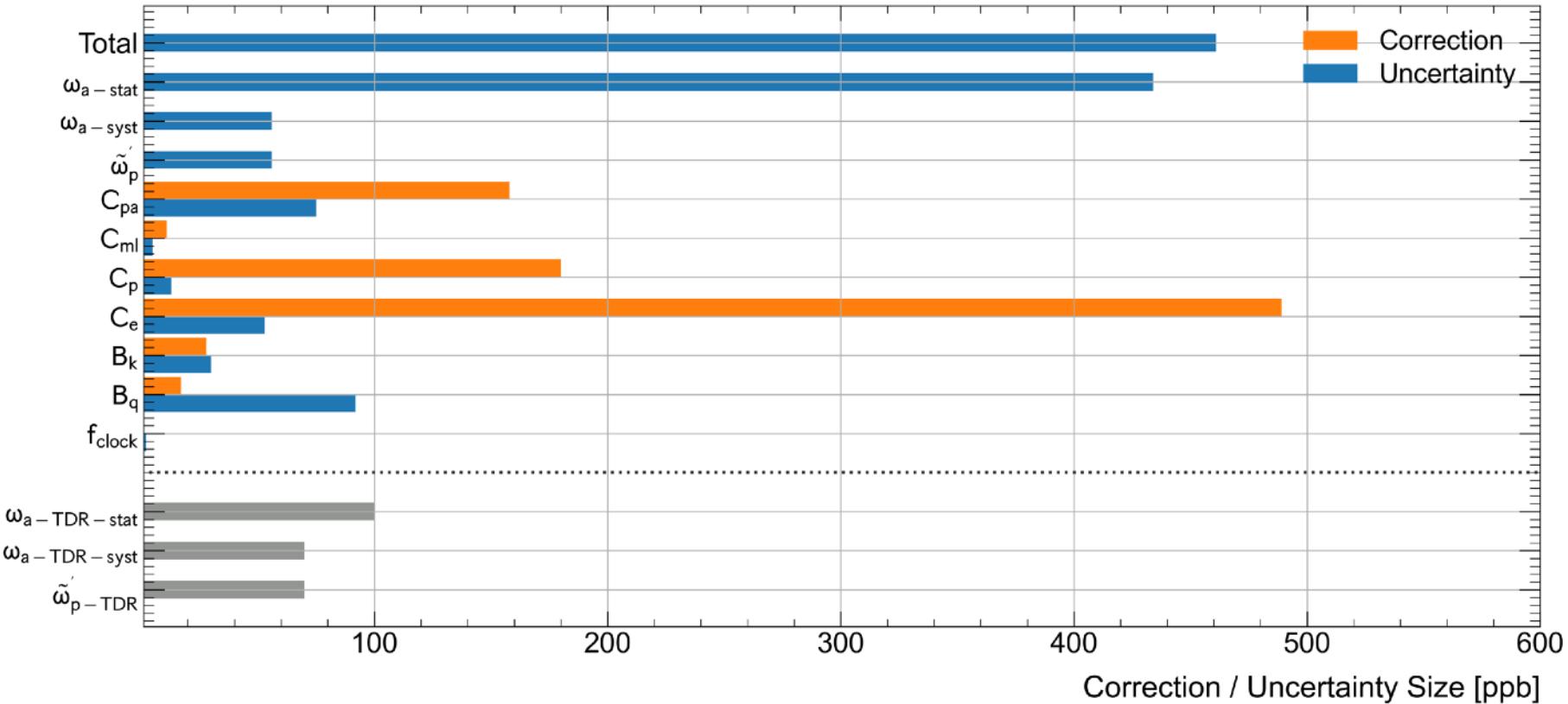
magnetic field sampled
by the muon distribution



Magnetic transients
corrections

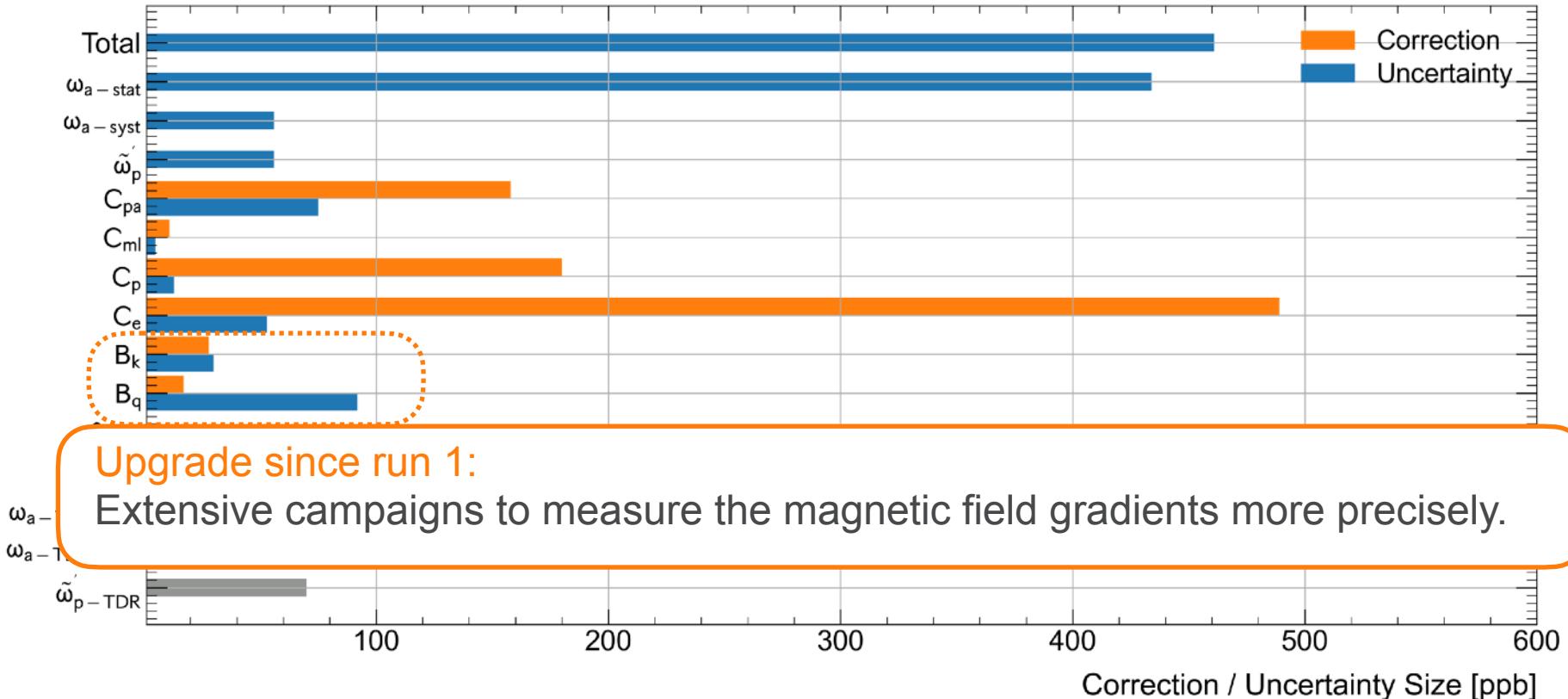
THE RUN-1 RESULT

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

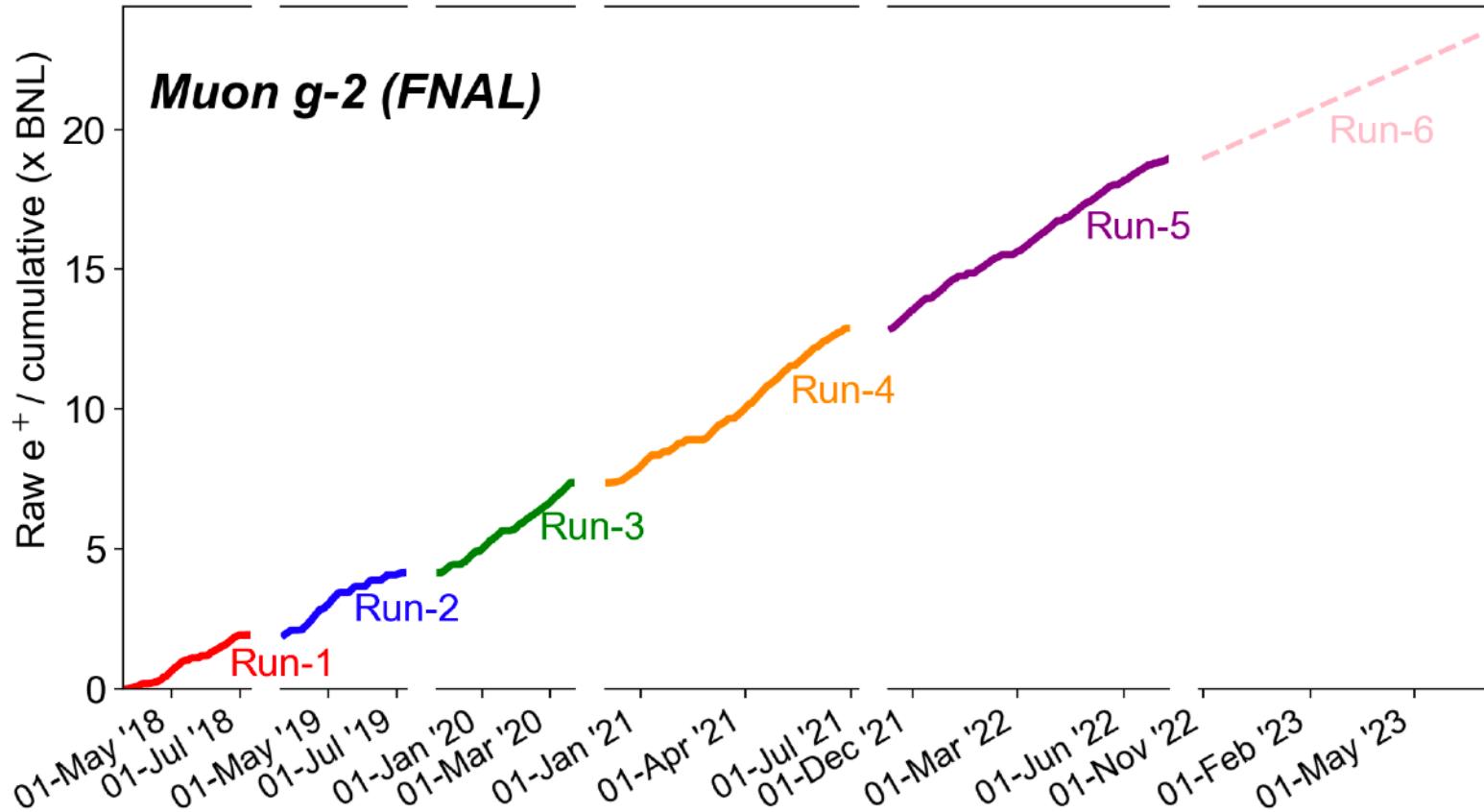


THE RUN-1 RESULT

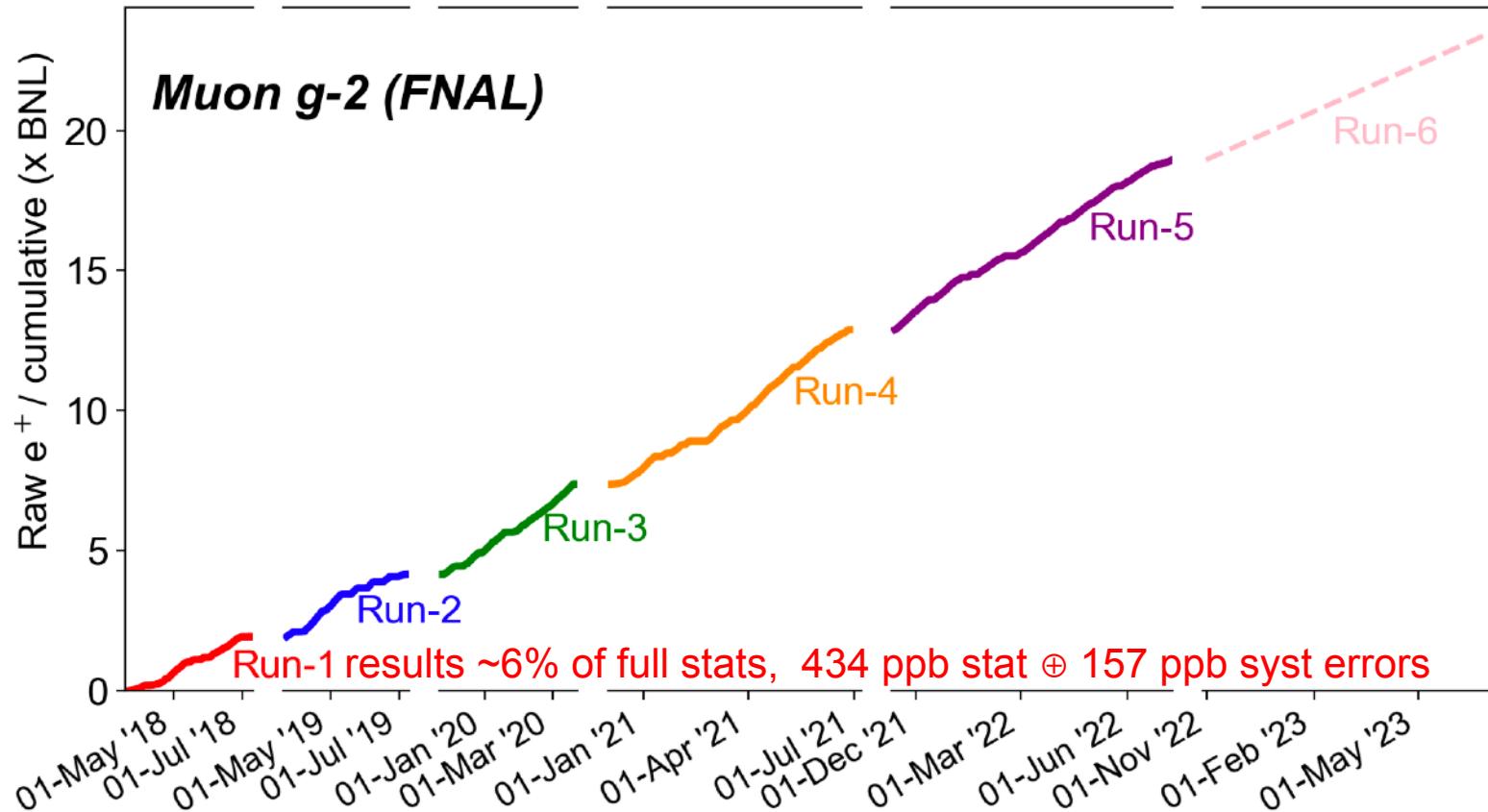
$$\frac{\omega_a}{\tilde{\omega}_p'} \approx \frac{f_{\text{clock}} \omega_a^{\text{meas}} (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p'(x, y, \phi) \times M(x, y, \phi) \rangle (1 + B_K + B_Q)}$$



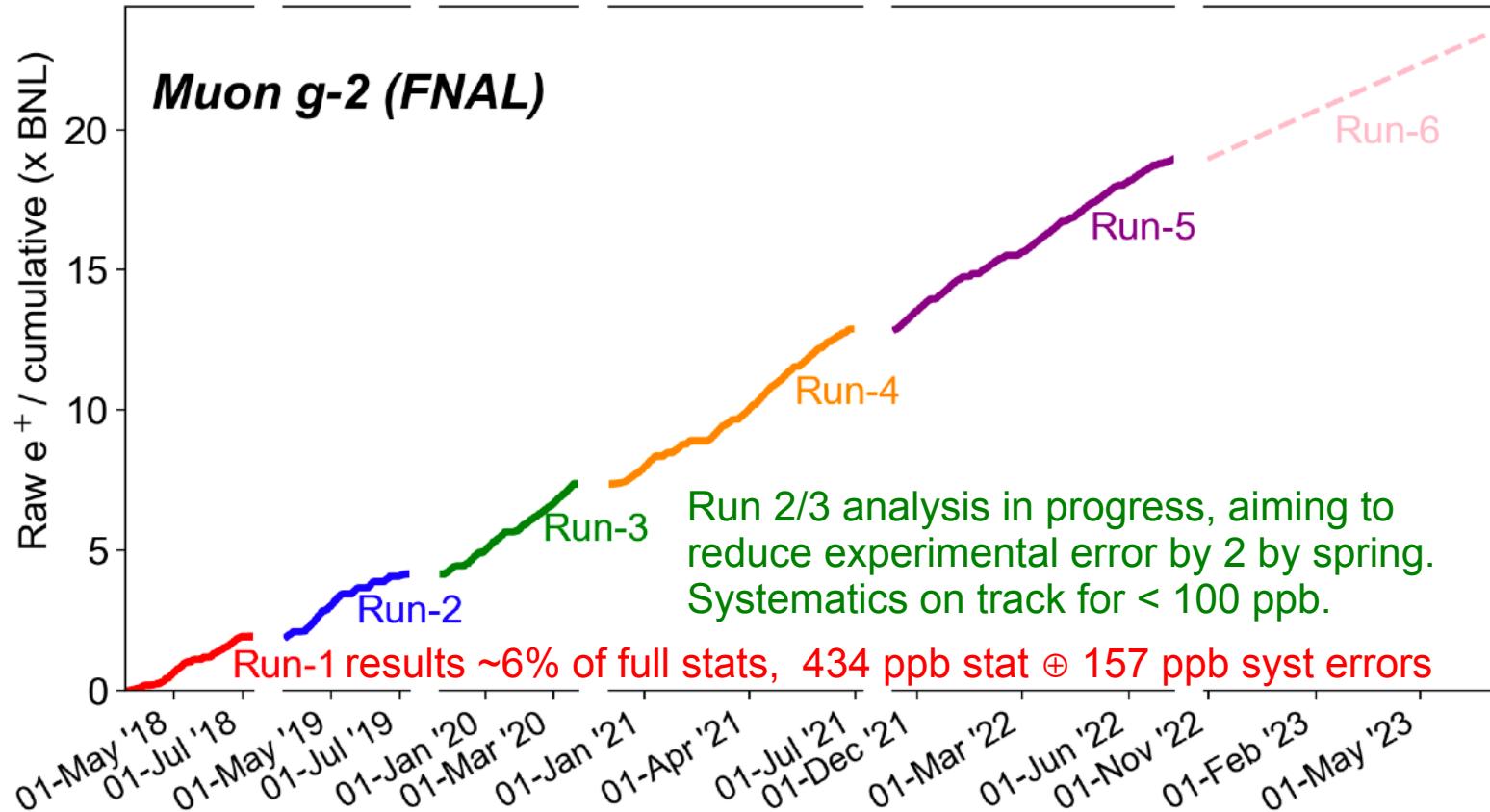
MORE TO COME: THE BEYOND RUN 1 ANALYSIS



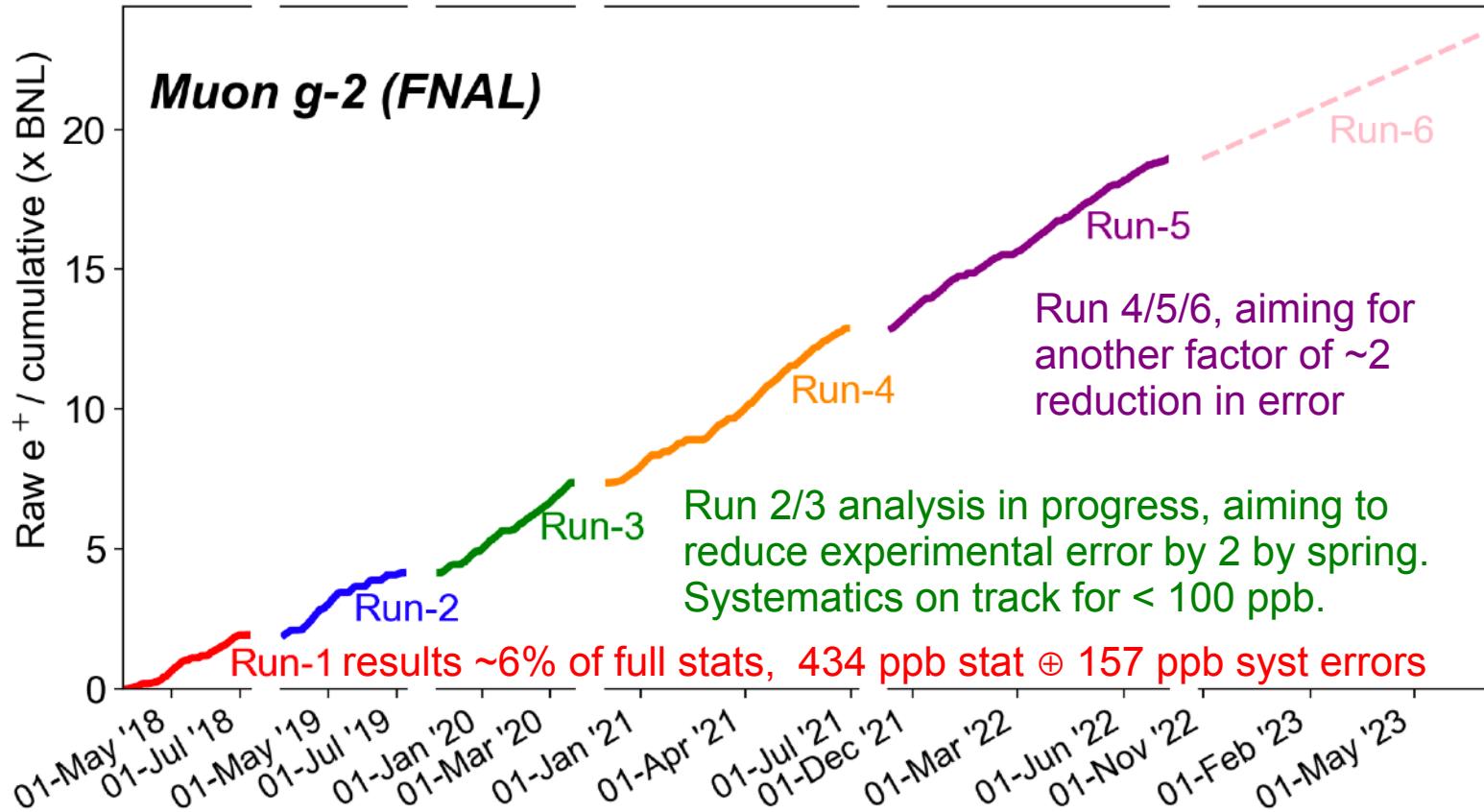
MORE TO COME: THE BEYOND RUN 1 ANALYSIS



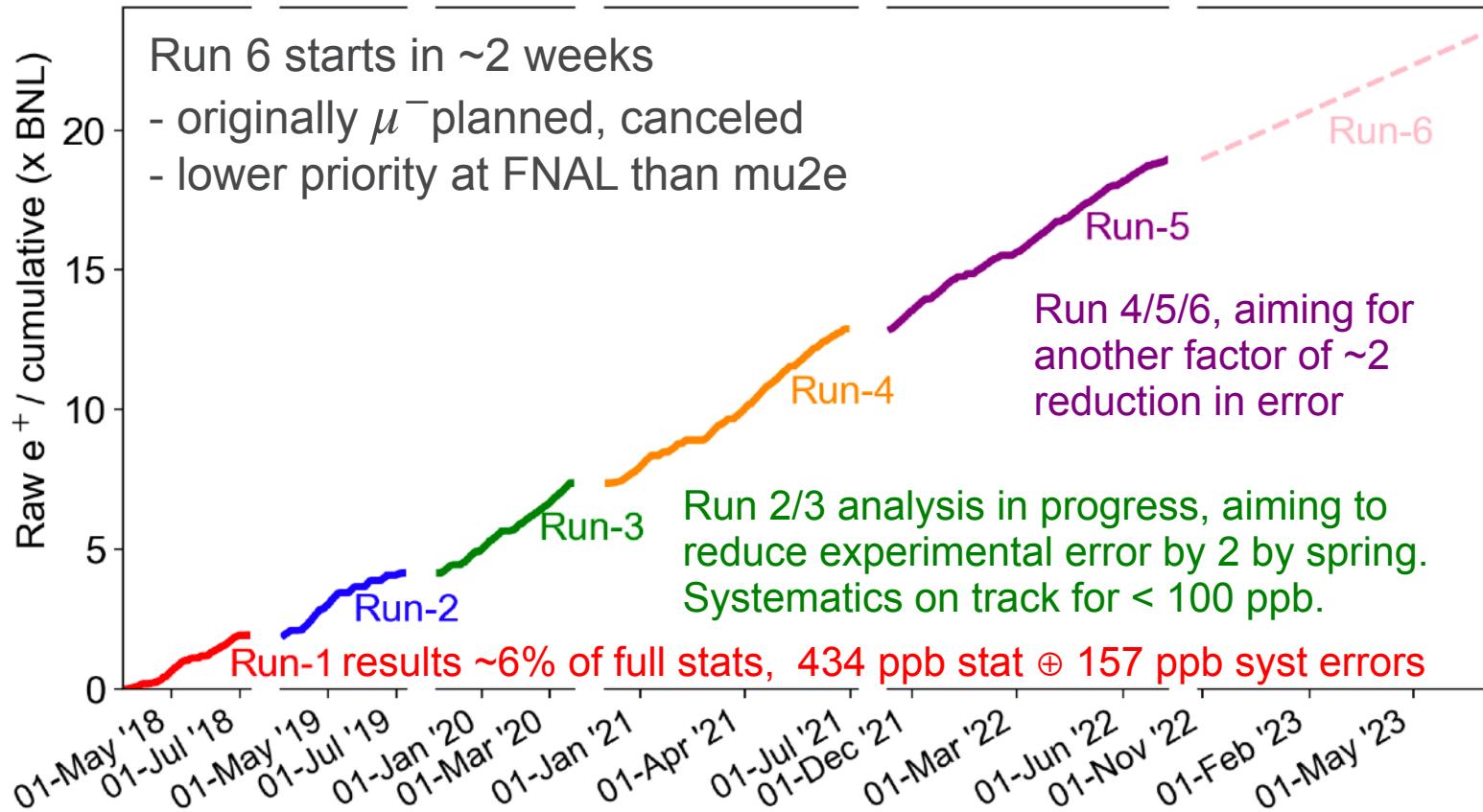
MORE TO COME: THE BEYOND RUN 1 ANALYSIS



MORE TO COME: THE BEYOND RUN 1 ANALYSIS



EVEN MORE TO COME: RUN 6



THE COLLABORATION

Run-1 unblinding ceremony



USA

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi

USA National Labs

- Argonne
- Brookhaven
- Fermilab

China

- North Central
- Northern Illinois
- Regis
- Virginia
- Washington



Germany

- Dresden
- Mainz



Russia

- Budker/Novosibirsk
- JINR Dubna



Italy



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



United Kingdom

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



Korea

- CAPP/IBS
- KAIST

