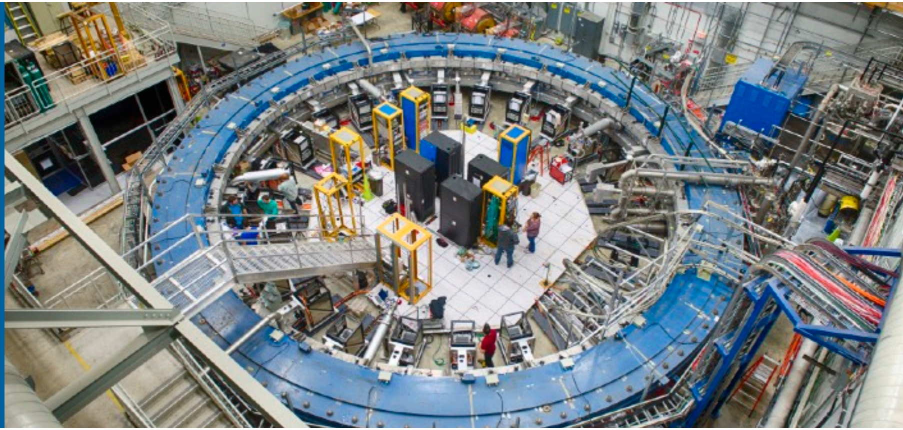
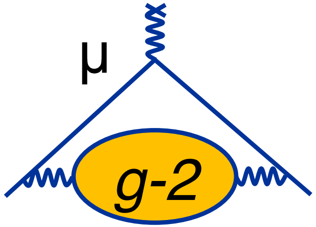
Argonne NATIONAL LABORATORY

RESULTS FROM THE MUON G-2 EXPERIMENT AT FERMILAB

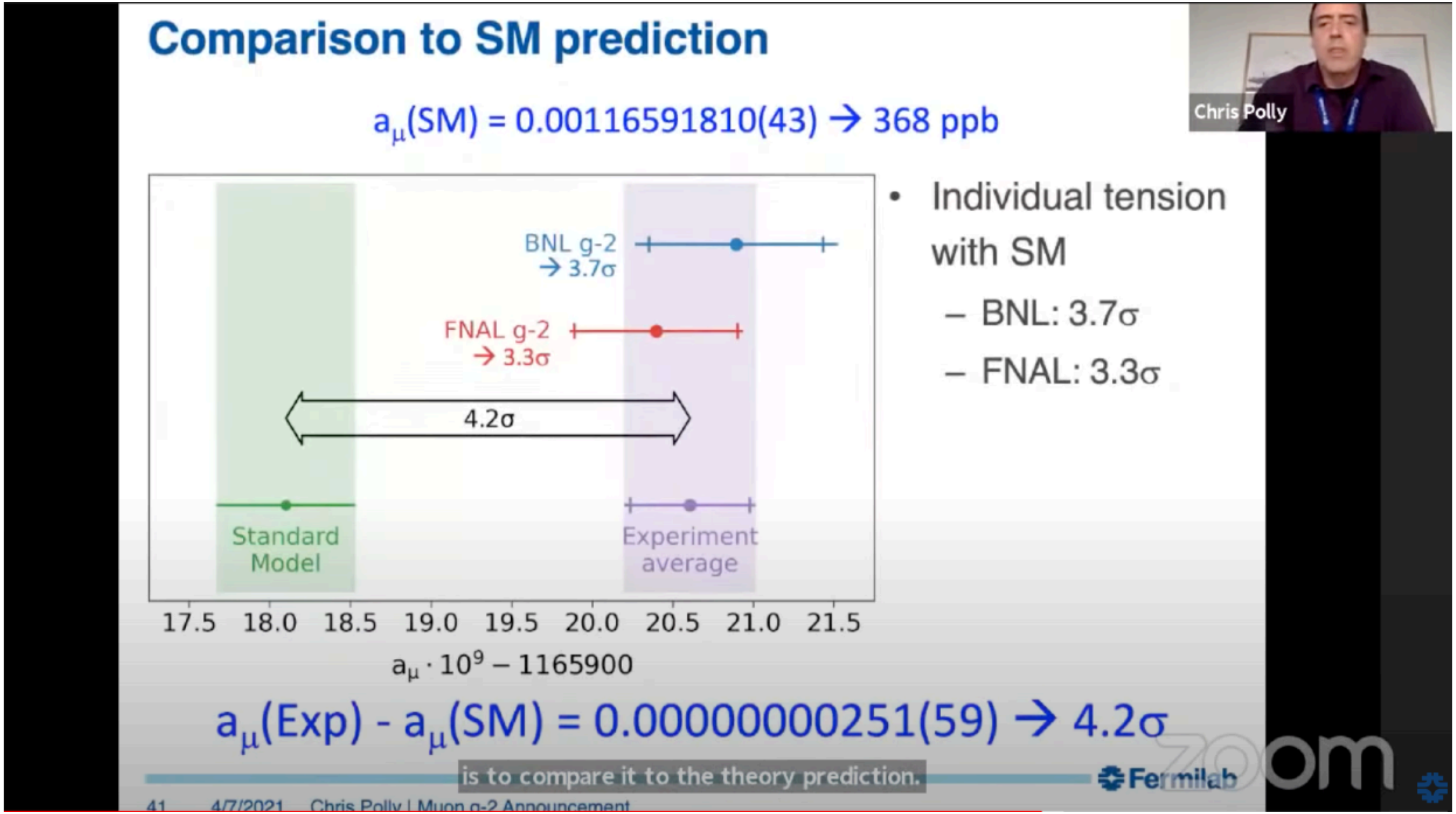


SIMON CORRODI
Argonne National Laboratory

on behalf of the Muon g-2 collaboration
NuFact 2021
Sep 6 - 11, 2021



APRIL 7TH: FERMILAB MUON G-2 EXPERIMENT ANNOUNCED THE FIRST RESULT



APRIL 7TH: FERMILAB MUON G-2 EXPERIMENT ANNOUNCED THE FIRST RESULT

PRAB

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

T. Albahri,[30] A. Anastasi,[10] K. Badgley,[7] S. Baeßler,[36,a] I. Bailey,[17,b] V. A. Baranov,[15] E. Barlas-Yucel,[28]

PRA

Magnetic Field Measurement and Analysis for the Muon $g-2$ Experiment at Fermilab

T. Albahri,[39] A. Anastasi,[11,a] K. Badgley,[7] S. Baeßler,[47,b] I. Bailey,[19,c] V. A. Baranov,[17] E. Barlas-Yucel,[37]

PRD

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g-2$ experiment

T. Albahri,[39] A. Anastasi,[11,a] A. Anisenkov,[4,b] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17]

PRL

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi,[44] T. Albahri,[39] S. Al-Kilani,[36] D. Allspach,[7] L. P. Alonzi,[48] A. Anastasi,[11,a] A. Anisenkov,[4,b] F. Azfar,[44] K. Badgley,[7] S. Baeßler,[47,c] I. Bailey,[19,d] V. A. Baranov,[17] E. Barlas-Yucel,[37] T. Barrett,[6] E. Barzi,[7] A. Basti,[11,32] F. Bedeschi,[11] A. Behnke,[22] M. Berz,[20] M. Bhattacharya,[43] H. P. Binney,[48] R. Bjorkquist,[6] P. Bloom,[21] J. Bono,[7] E. Bottalico,[11,32] T. Bowcock,[39] D. Boyden,[22] G. Cantatore,[13,34] R. M. Carey,[2] J. Carroll,[39] B. C. K. Casey,[7] D. Cauz,[35,8] S. Ceravolo,[9] R. Chakraborty,[38] S. P. Chang,[18,5] A. Chapelain,[6] S. Chappa,[7] S. Charity,[7] R. Chislett,[36] J. Choi,[5] Z. Chu,[26,e] T. E. Chupp,[42] M. E. Convery,[7] A. Conway,[41] G. Corradi,[9] S. Corrodi,[1] L. Cotrozzi,[11,32] J. D. Crnkovic,[3,37,43] S. Dabagov,[9,f] P. M. De Lurgio,[1] P. T. Debevec,[37] S. Di Falco,[11] P. Di Meo,[10] G. Di Sciascio,[12] R. Di Stefano,[10,30] B. Drendel,[7] A. Driutti,[35,13,38] V. N. Duginov,[17] M. Eads,[22] N. Eggert,[6] A. Epps,[22] J. Esquivel,[7] M. Farooq,[42] R. Fatemi,[38] C. Ferrari,[11,14] M. Fertl,[48,16] A. Fiedler,[22] A. T. Fienberg,[48] A. Fioretti,[11,14] D. Flay,[41] S. B. Foster,[2] H. Friedsam,[7] E. Frlež,[47] N. S. Froemming,[48,22] J. Fry,[47] C. Fu,[26,e] C. Gabbanini,[11,14] M. D. Galati,[11,32] S. Ganguly,[37,7] A. Garcia,[48] D. E. Gastler,[2] J. George,[41] L. K. Gibbons,[6] A. Gioiosa,[29,11] K. L. Giovanetti,[15] P. Girotti,[11,32] W. Gohn,[38] T. Gorringe,[38] J. Grange,[1,42] S. Grant,[36] F. Gray,[24] S. Haciomeroglu,[5] D. Hahn,[7] T. Halewood-Leagas,[39] D. Hampai,[9] F. Han,[38] E. Hazen,[2] J. Hempstead,[48] S. Henry,[44] A. T. Herrod,[39,d] D. W. Hertzog,[48] G. Hesketh,[36] A. Hibbert,[39] Z. Hodge,[48] J. L. Holzbauer,[43] K. W. Hong,[47] R. Hong,[1,38] M. Iacovacci,[10,31] M. Incagli,[11] C. Johnstone,[7] J. A. Johnstone,[7] P. Kammel,[48] M. Kargiantoulakis,[7] M. Karuza,[13,45] J. Kaspar,[48] D. Kawall,[41] L. Kelton,[38] A. Keshavarzi,[40] D. Kessler,[41] K. S. Khaw,[27,26,48,e] Z. Khechadoorian,[6] N. V. Khomutov,[17] B. Kiburg,[7] M. Kiburg,[7,21] O. Kim,[18,5] S. C. Kim,[6] Y. I. Kim,[5] B. King,[39,a] N. Kinnaird,[2] M. Korostelev,[19,d] I. Kourbanis,[7] E. Kraegeloh,[42] V. A. Krylov,[17] A. Kuchibhotla,[37] N. A. Kuchinskiy,[17] K. R. Labe,[6] J. LaBounty,[48] M. Lancaster,[40] M. J. Lee,[5] S. Lee,[5] S. Leo,[37] B. Li,[26,1,e] D. Li,[26,g] L. Li,[26,e] I. Logashenko,[4,b] A. Lorente Campos,[38] A. Lucà,[7] G. Lukicov,[36] G. Luo,[22] A. Lusiani,[11,25] A. L. Lyon,[7] B. MacCoy,[48] R. Madrak,[7] K. Makino,[20] F. Marignetti,[10,30] S. Mastroianni,[10] S. Maxfield,[39] M. McEvoy,[22] W. Merritt,[7] A. A. Mikhailichenko,[6,a] J. P. Miller,[2] S. Miozzi,[12] J. P. Morgan,[7] W. M. Morse,[3] J. Mott,[2,7] E. Motuk,[36] A. Nath,[10,31] D. Newton,[39,h] H. Nguyen,[7] M. Oberling,[1] R. Osofsky,[48] J.-F. Ostiguy,[7] S. Park,[5] G. Pauletta,[35,8] G. M. Piacentino,[29,12] R. N. Pilato,[11,32] K. T. Pitts,[37] B. Plaster,[38] D. Počanić,[47] N. Pohlman,[22] C. C. Polly,[7] M. Popovic,[7] J. Price,[39] B. Quinn,[43] N. Raha,[11] S. Ramachandran,[1] E. Ramberg,[7] N. T. Rider,[6] J. L. Ritchie,[46] B. L. Roberts,[2] D. L. Rubin,[6] L. Santi,[35,8] D. Sathyan,[2] H. Schellman,[23,i] C. Schlesier,[37] A. Schreckenberger,[46,2,37] Y. K. Semertzidis,[5,18] Y. M. Shatunov,[4] D. Shemyakin,[4,b] M. Shenk,[22] D. Sim,[39] M. W. Smith,[48,11] A. Smith,[39] A. K. Soha,[7] M. Sorbara,[12,33] D. Stöckinger,[28] J. Stapleton,[7] D. Still,[7] C. Stoughton,[7] D. Stratakis,[7] C. Strohman,[6] T. Stuttard,[36] H. E. Swanson,[48] G. Sweetmore,[40] D. A. Sweigart,[6] M. J. Syphers,[22,7] D. A. Tarazona,[20] T. Teubner,[39] A. E. Tewsley-Booth,[42] K. Thomson,[39] V. Tishchenko,[3] N. H. Tran,[2] W. Turner,[39] E. Valetov,[20,19,27,d] D. Vasilkova,[36] G. Venanzoni,[11] V. P. Volnykh,[17] T. Walton,[7] M. Warren,[36] A. Weisskopf,[20] L. Welty-Rieger,[7] M. Whitley,[39] P. Winter,[1] A. Wolski,[39,d] M. Wormald,[39] W. Wu,[43] and C. Yoshikawa[7]
(The Muon $g-2$ Collaboration)

THE MAGNETIC MOMENT OF THE MUON

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

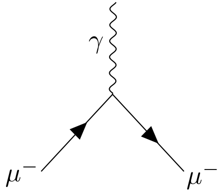
Magnetic moment connected to spin via dimensionless factor g: gyromagnetic ratio

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

the anomalous magnetic moment

THE MAGNETIC MOMENT OF THE MUON: FROM THEORY

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



Muon g-2 Theory Initiative

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

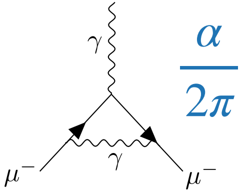
Schwinger (1948)
1st order QED

Vacuum polarizations
Higher order QED

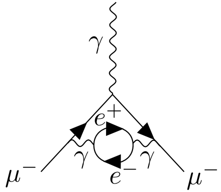
uncertainty: 0.1×10^{-11}

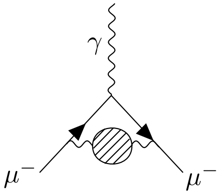
Hadronic
HVP: $6845(40) \times 10^{-11}$
HLbL: $92(18) \times 10^{-11}$

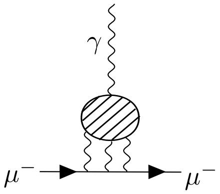
Electroweak
$153.6(1.0) \times 10^{-11}$

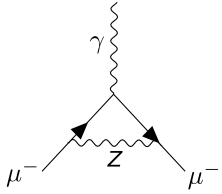


$$\frac{\alpha}{2\pi}$$

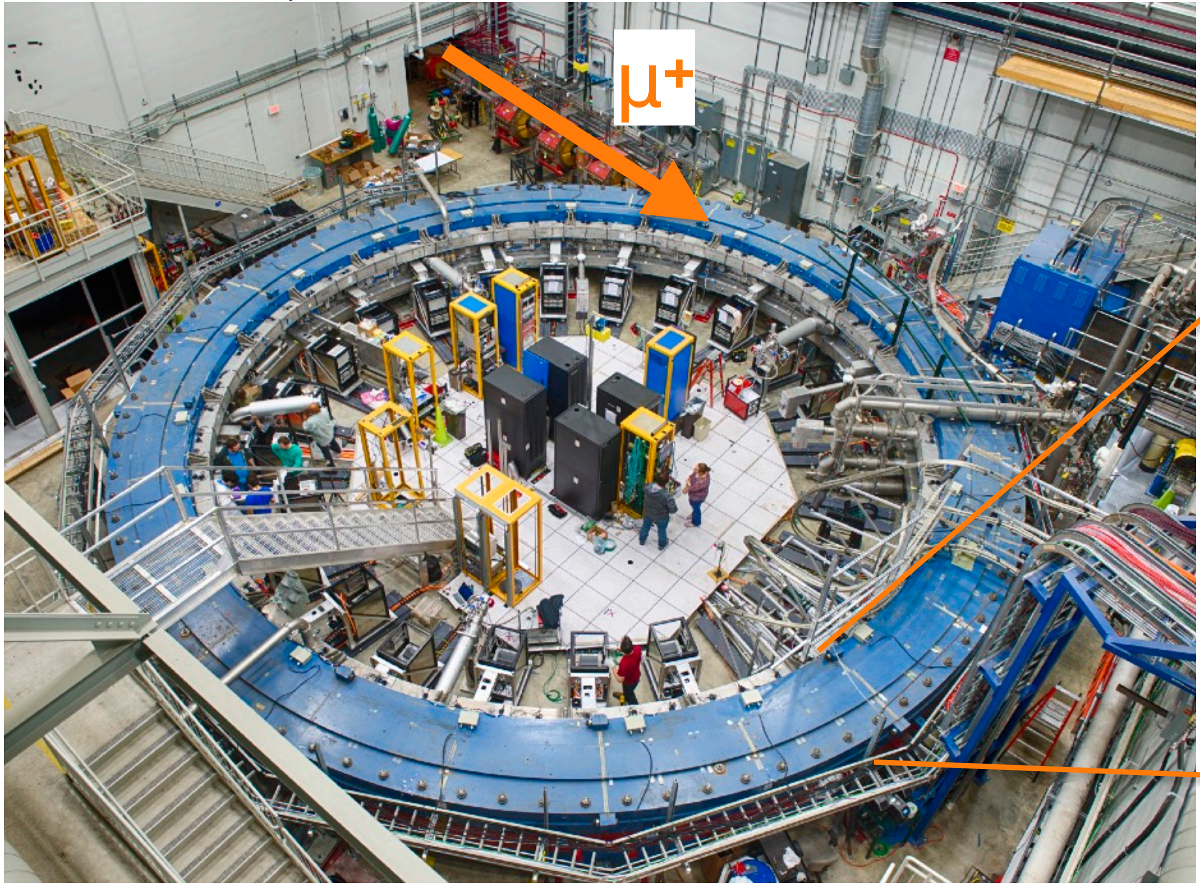


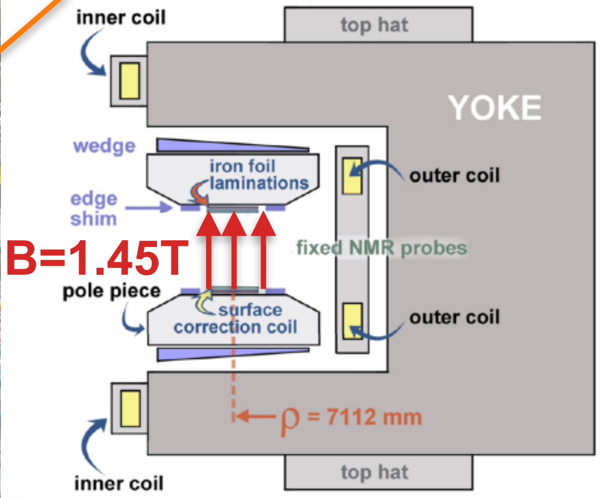






MEASURE a_μ IN A STORAGE RING





MEASURE a_μ IN A STORAGE RING

Cyclotron frequency

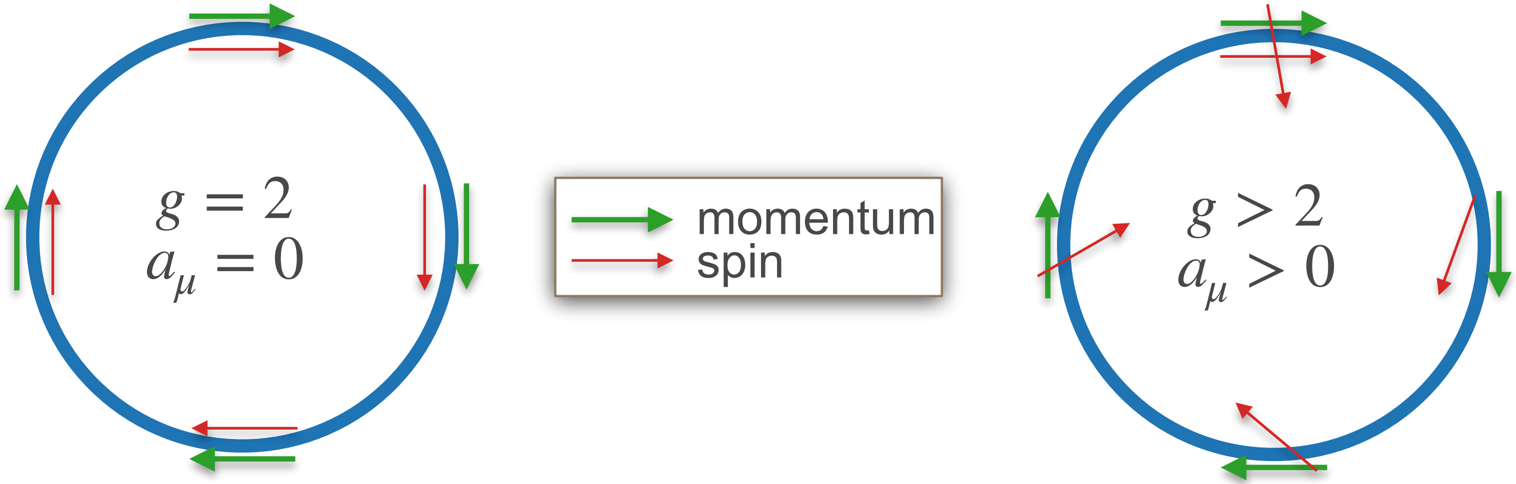
$$\omega_C = \frac{e}{m\gamma}B$$

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



STORAGE RING: HOW WE STORE THE MUONS

pitch corrections: C_p E-field corrections: C_e

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

~0 ~0

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

MEASURE a_μ IN A STORAGE RING

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

bound state QED calc., exact

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

0.28 ppb uncertainty
Phys. Rev. A **83**, 052122 (2011)

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

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

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

MEASURE a_μ IN A STORAGE RING

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

unblinding factor precession beam dynamics corrections

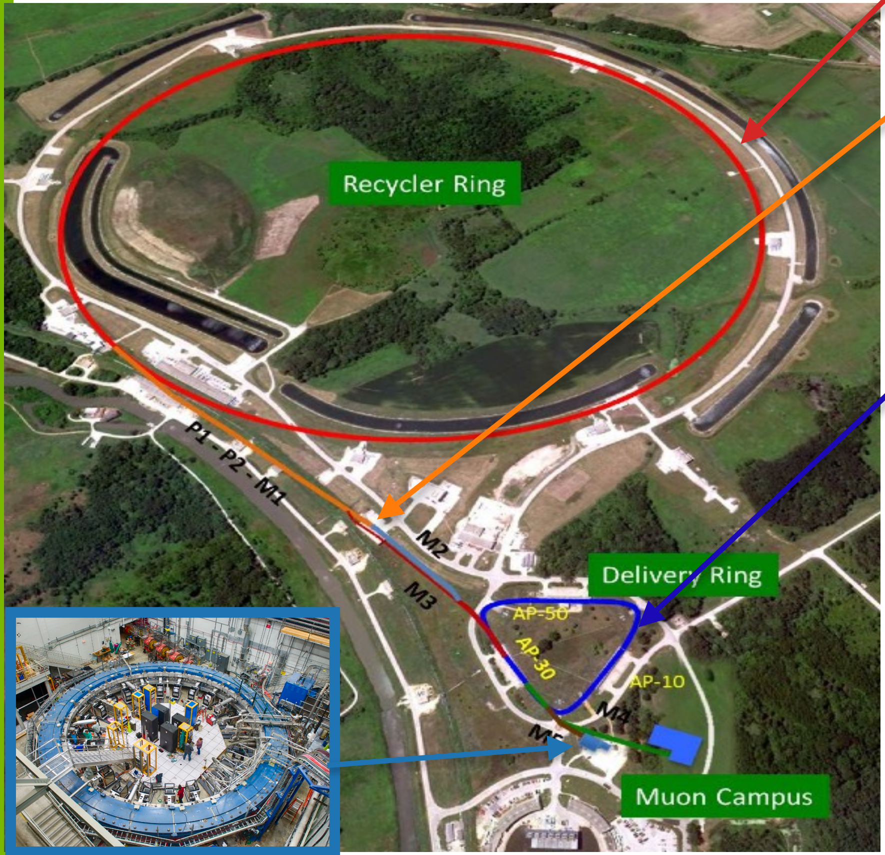
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \right\rangle \left(1 + B_K + B_Q\right)}$$

absolute field calibration

magnetic field sampled by the muon distribution

Magnetic transients corrections

THE MUONS



8 GeV protons in recycler

Target

2 x 8 shots

p/π/μ beam, p kicked away, π decay

$\pi^+ \rightarrow \mu^+ \nu_\mu$ 95% polarized muons

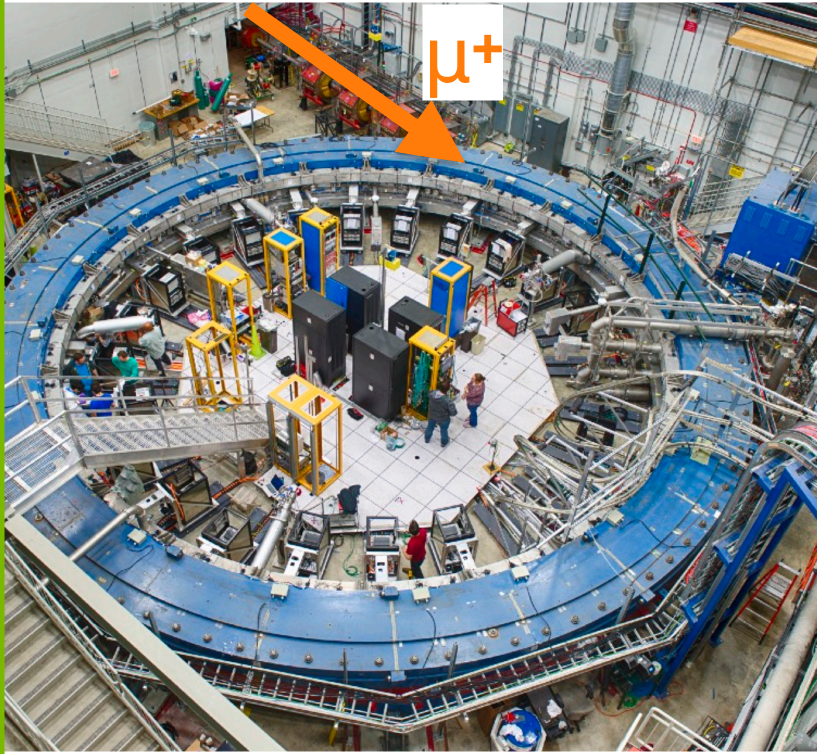
$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \, x \, \vec{E}}{c}\right)$$

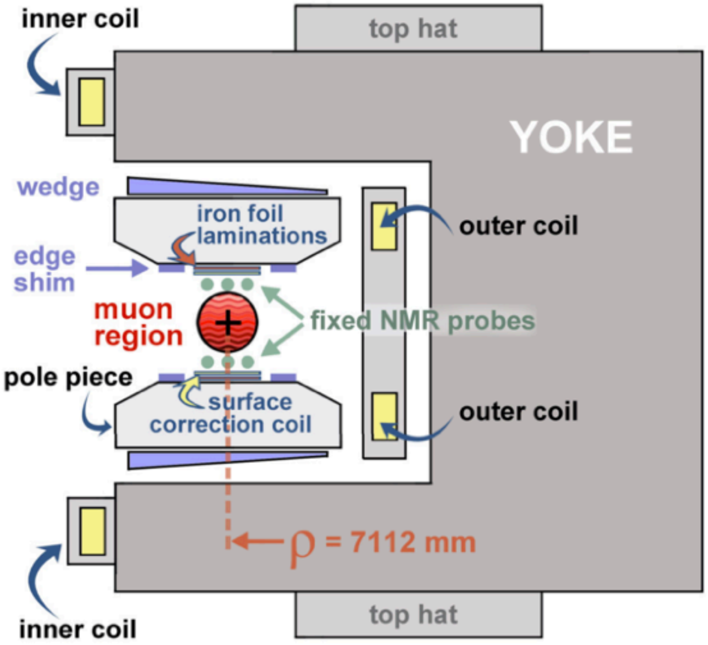
fo $p = p_{\text{magic}} = \frac{mc}{\sqrt{a_\mu}} = 3.094 \text{ GeV/c}$

Store muons for ~700us (~10 lifetimes)

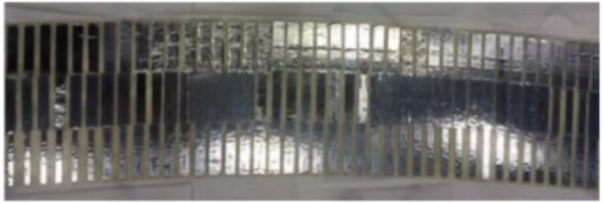

EMMERT
INTERNATIONAL
EMMERT
Driving Discovery in Particle Physics
EMMERT

HOW TO STORE MUONS: MAGNETIC FIELD

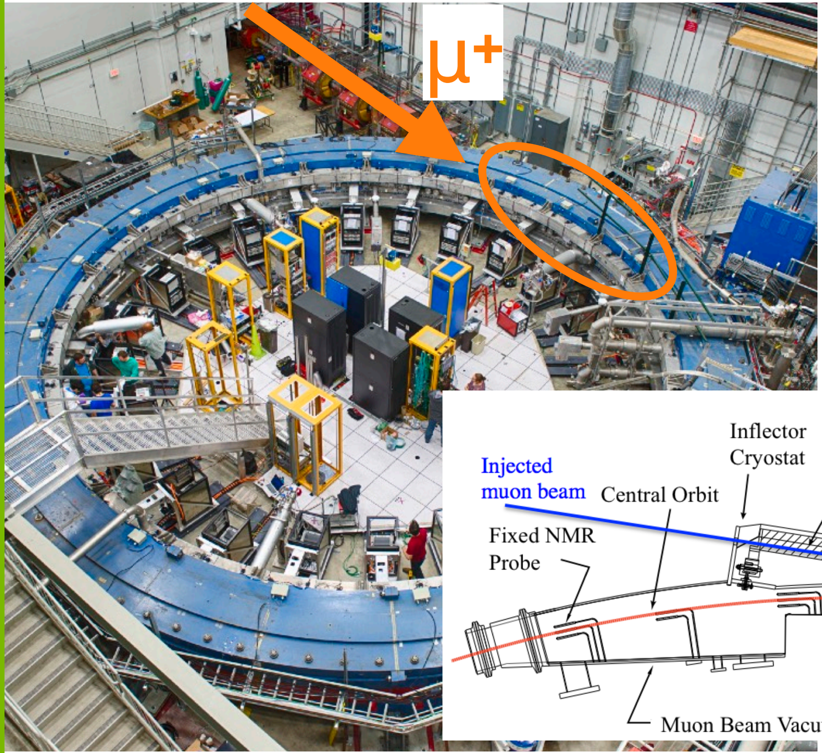


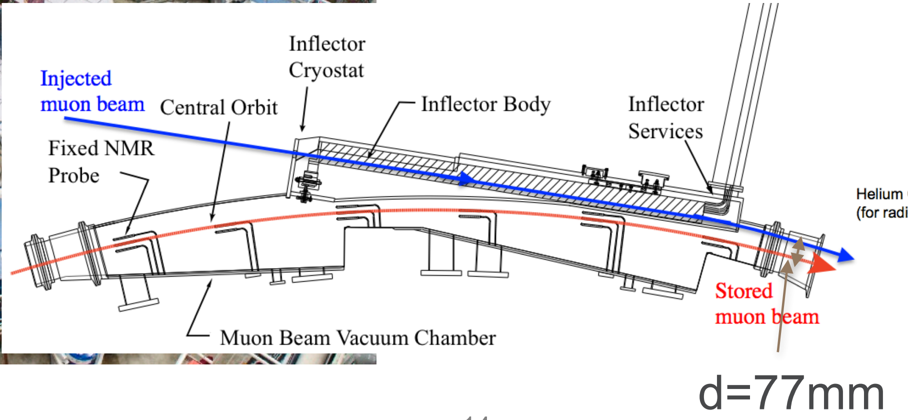


Fully-assembled lamination (10 degrees wide)

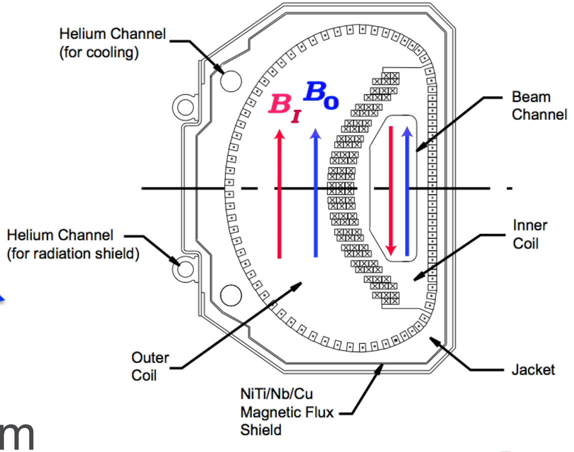


HOW TO STORE MUONS: THE INFLECTOR

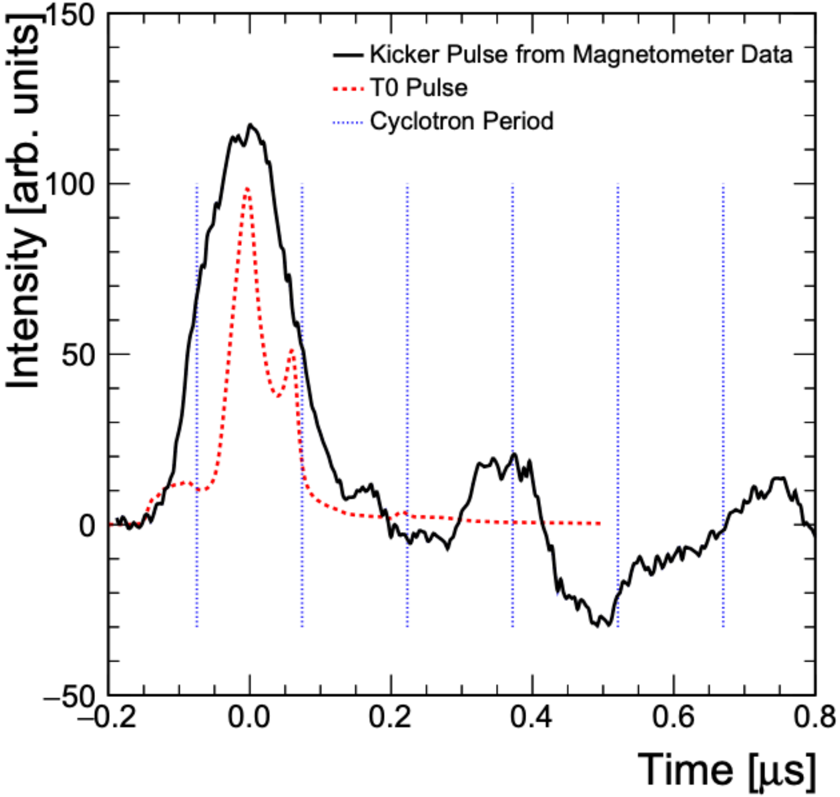




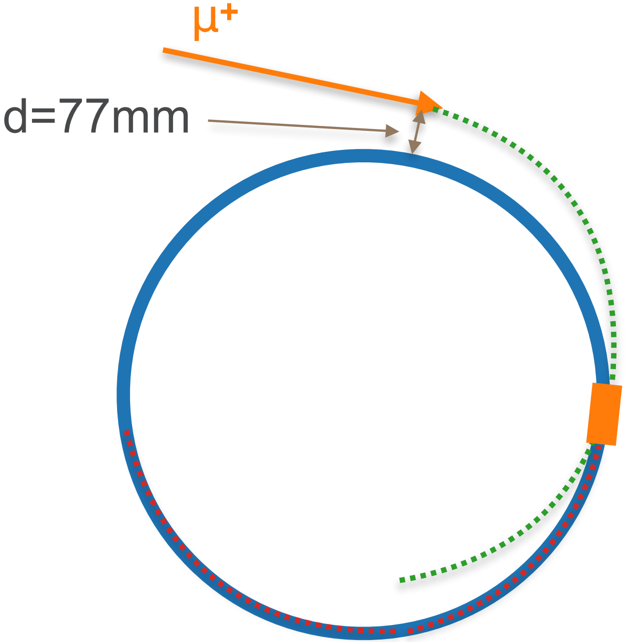
- Need to cancel field in beam channel
- prevents strong deflection of the beam



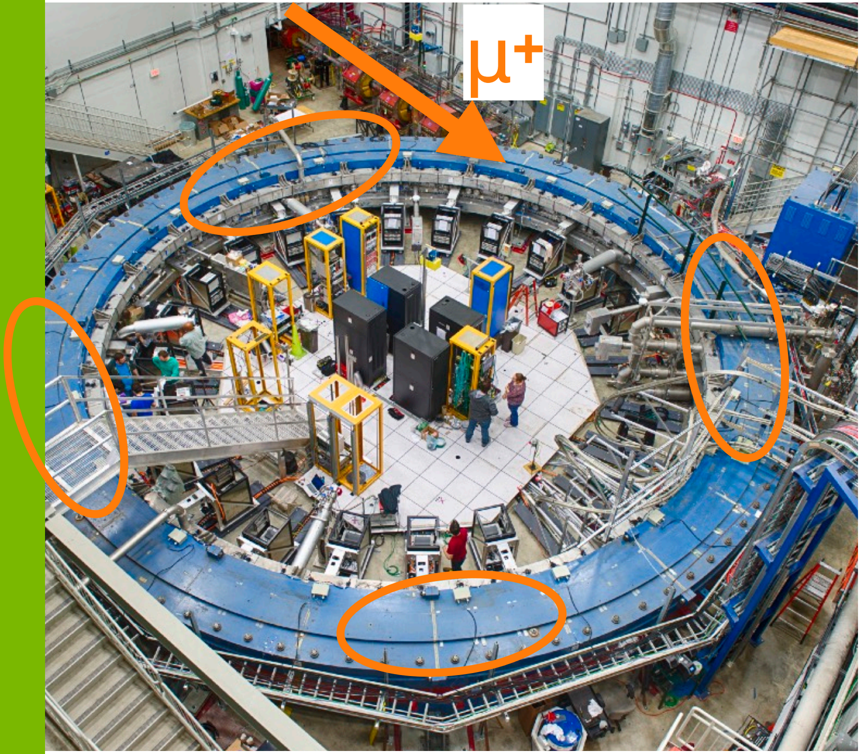
HOW TO STORE MUONS: THE KICKER



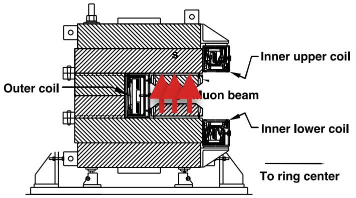
Incident beam center 77 mm off from center of storage region
tears muon onto store orbit



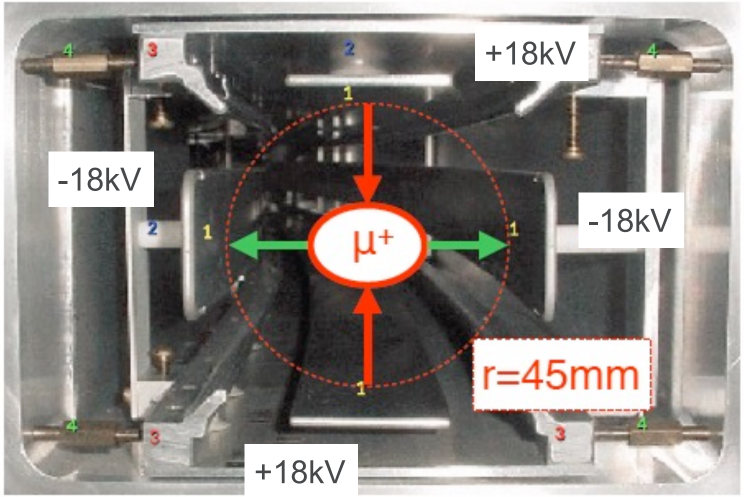
HOW TO STORE MUONS: FOCUSING



- Radial focus:
  1.45T vertical B field

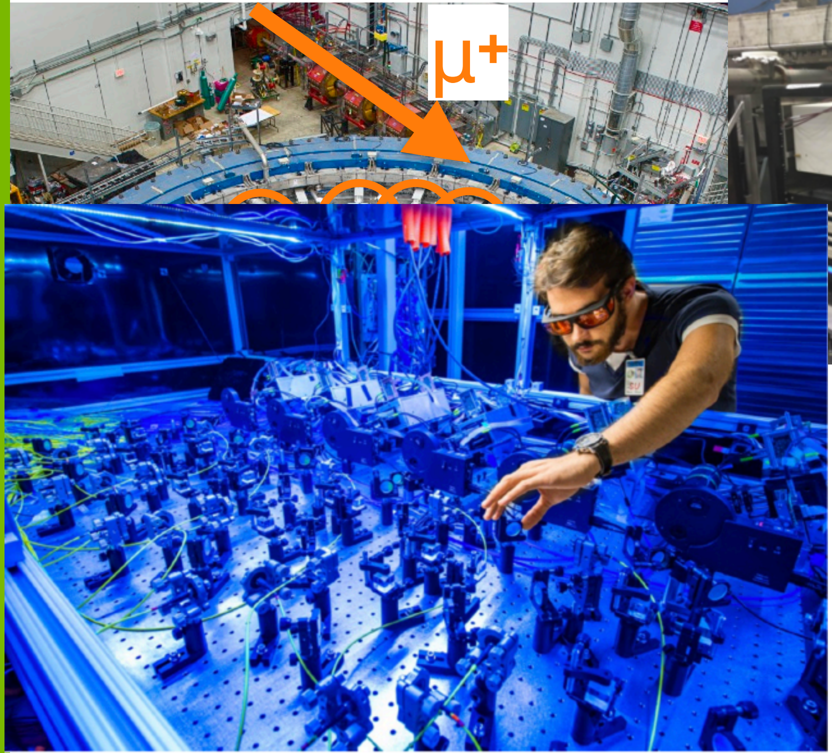


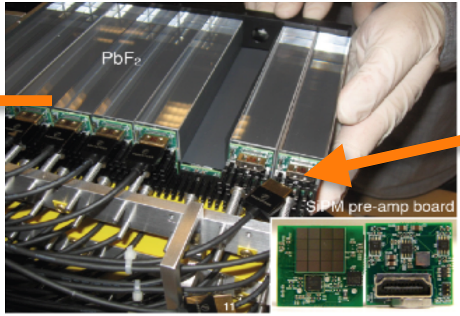
- Vertical focus:
  electrostatic quadrupoles (43% of the ring)

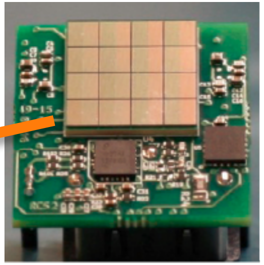


$$\vec{\omega}_a = -\frac{q}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} x \vec{E}}{c}\right)$$

THE MEASUREMENT: CALORIMETERS (ω_a^{meas})







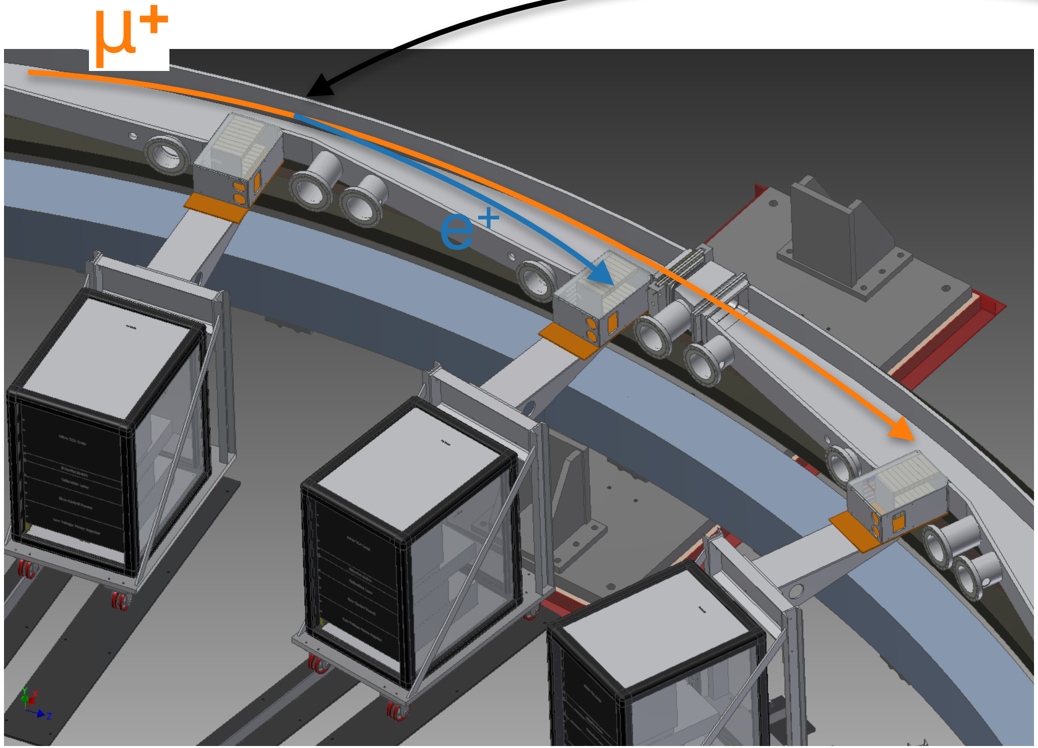
24 Calorimeters with 54 (9x6) Cherenkov PbF_2 crystals read out by SiPMs

- arrival time (~100ps) & energy of e^+ (~5% at 2GeV)

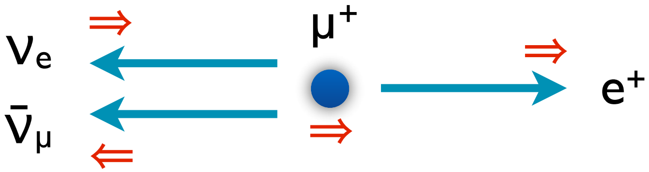
- Laser system for gain response calibration throughout data taking

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

THE MEASUREMENTS: CALORIMETERS (ω_a^{meas}) ω_a

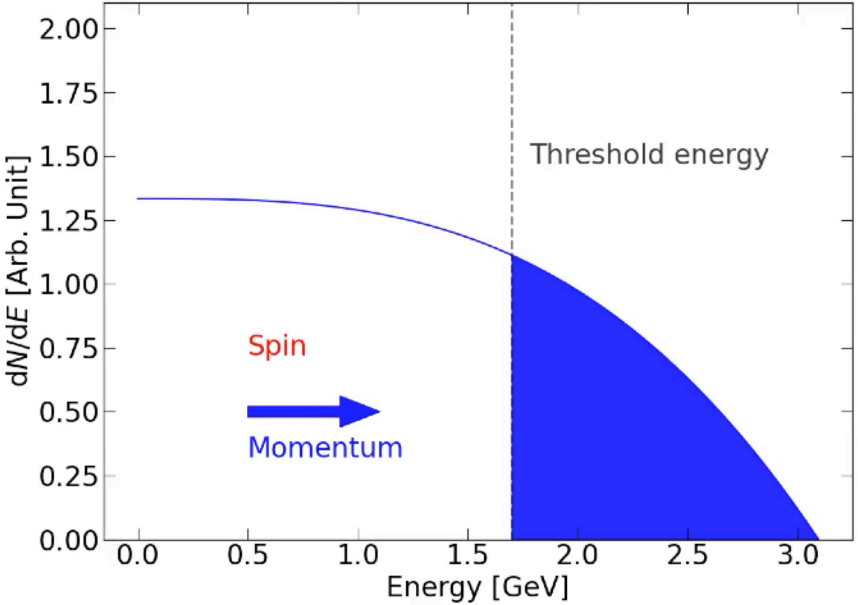


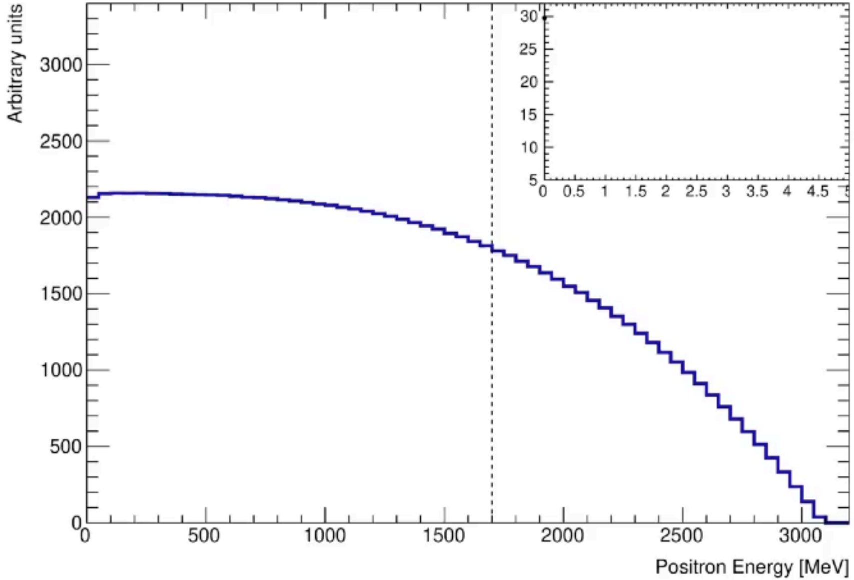
- Parity violating decay (Michel)
- Highest-energy e⁺ emitted preferentially along muon spin



MEASUREMENTS: ω_a^{meas}

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

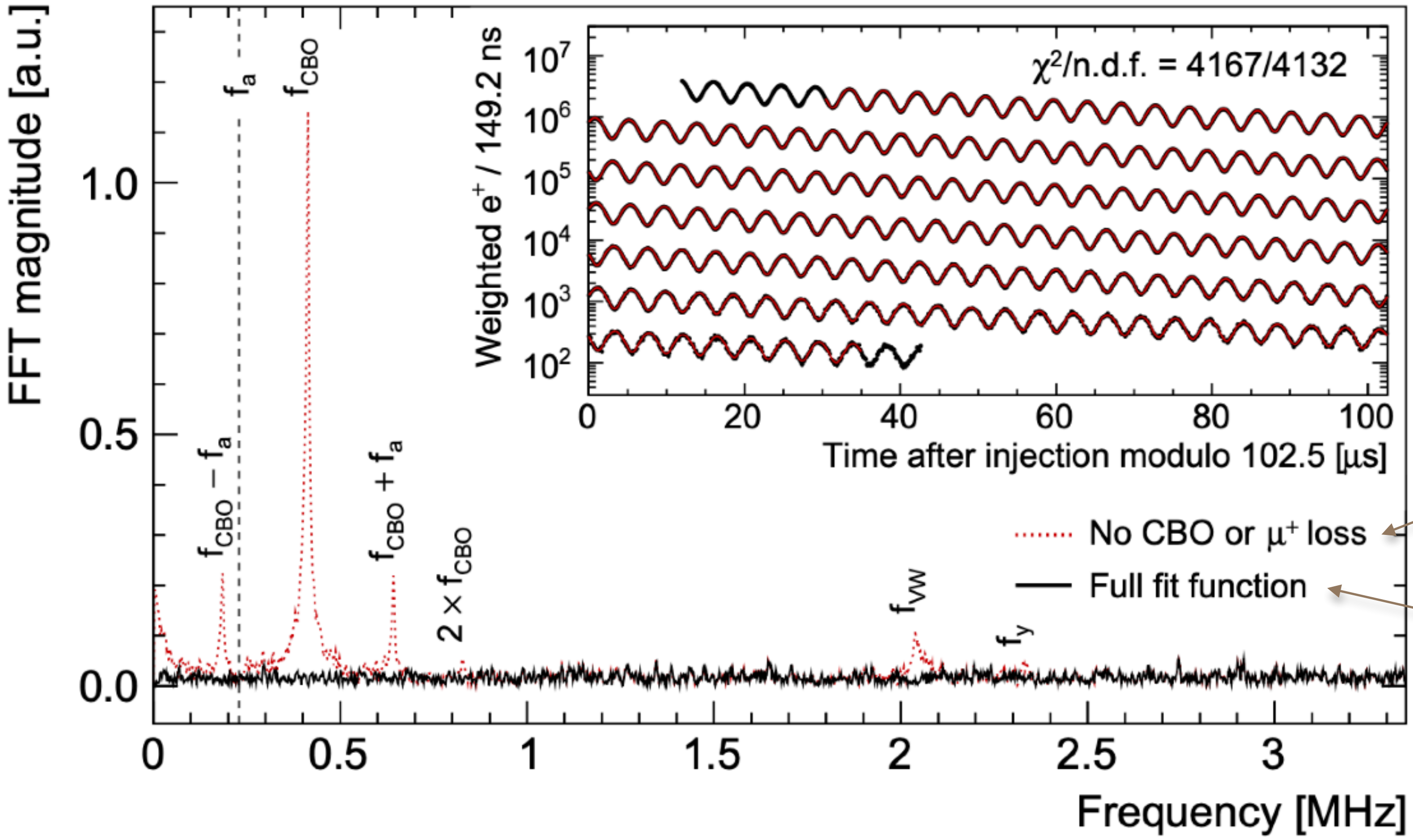




MEASUREMENTS: ω_a^{meas}

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

Example from dataset 1d



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

22 parameter fit

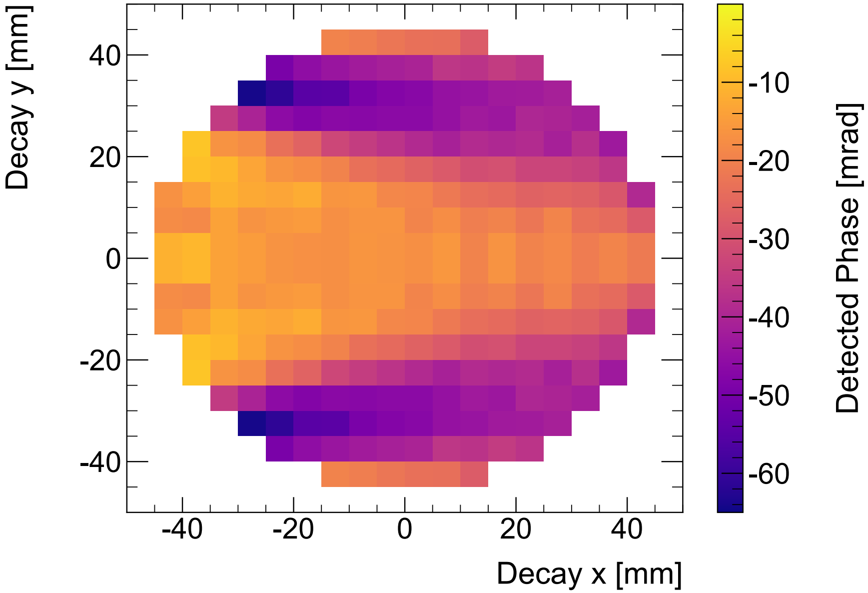
**CBO: Coherent Betatron Oscillation*

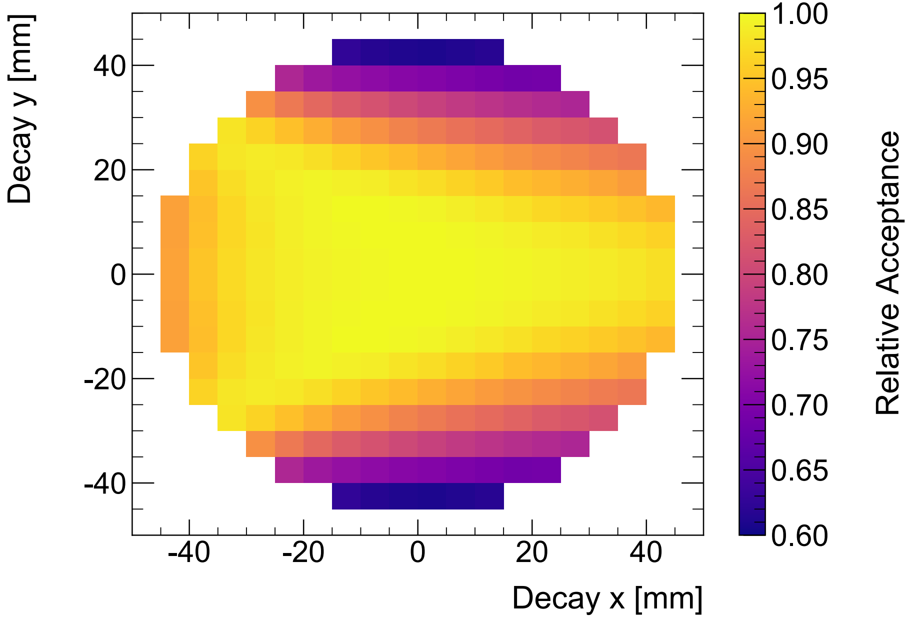
MEASUREMENTS: ω_a^{meas}

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

$$N(t) = N_0 e^{-t/\gamma\tau_\mu}[1 + A\cos(\omega_a t + \phi_0)]$$

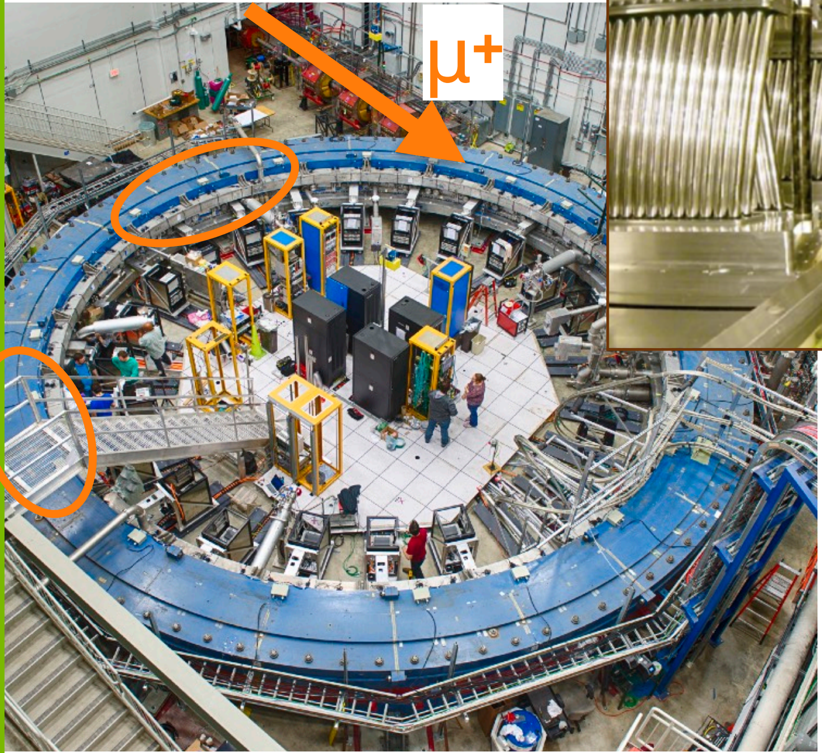
Early-to-late effects $\phi \rightarrow \phi(t)$ -> corrections needed

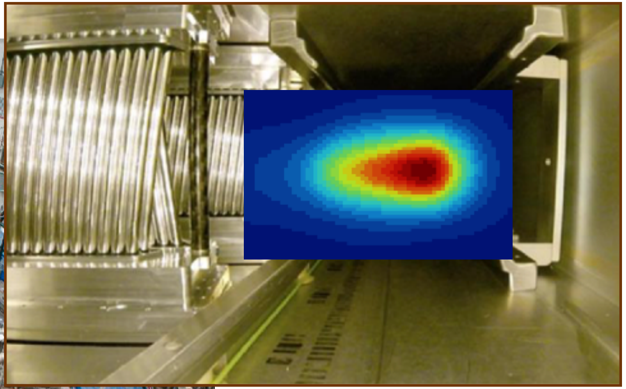


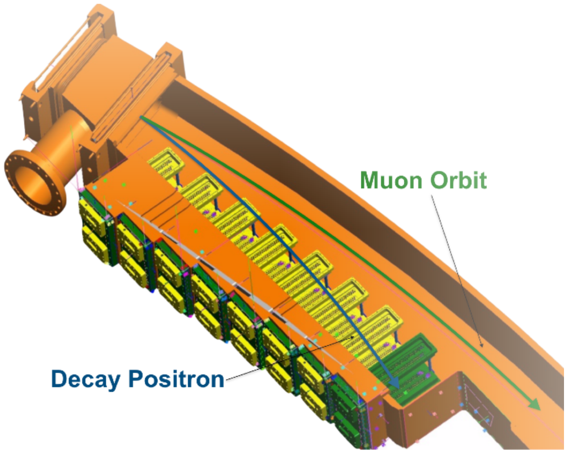


TRACKERS: BEAM DYNAMICS

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







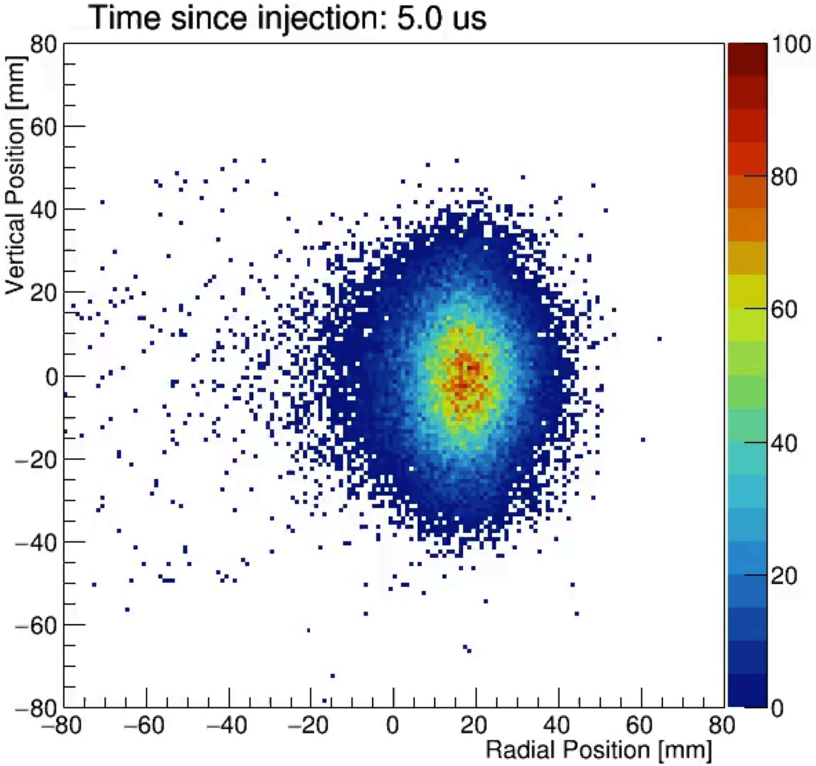
2 straw-tracker stations

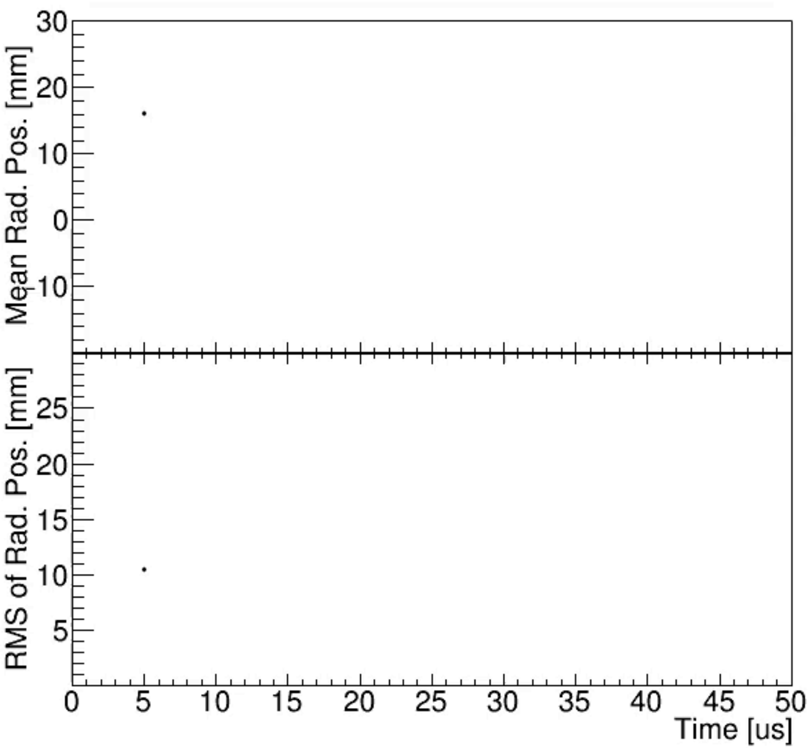
(each 8 modules, 4 layers of 32 straws, 50:50 Ar:Ethane, res ~100um)

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

TRACKERS: BEAM DYNAMICS

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



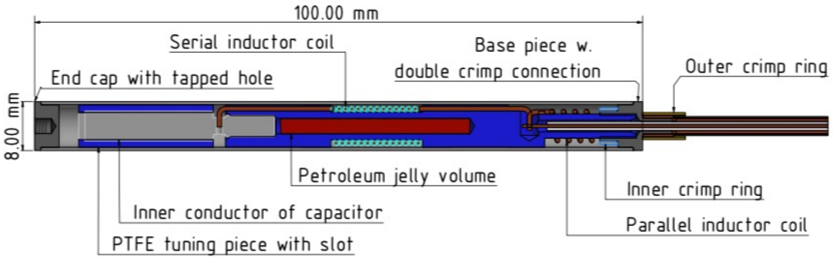


*CBO: Coherent Betatron Oscillation

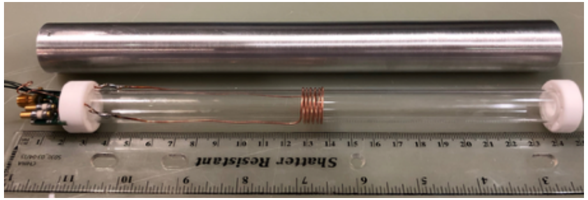
NUCLEAR MAGNETIC RESONANCE (NMR)

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

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

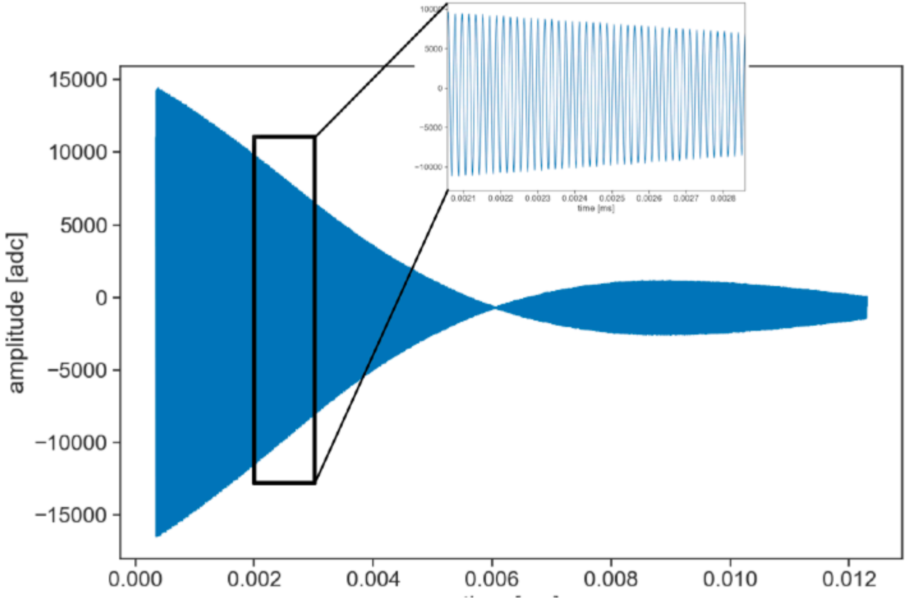


Petroleum Jelly probes



H_20 calibration probe (f_{calib})

Free Induced Decay (FID)



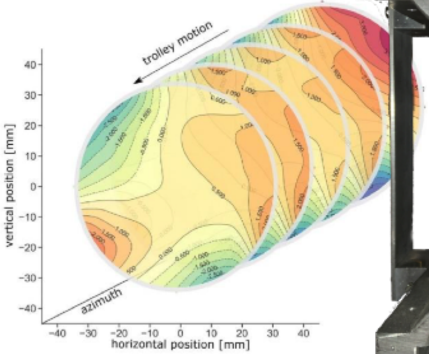
time [s]

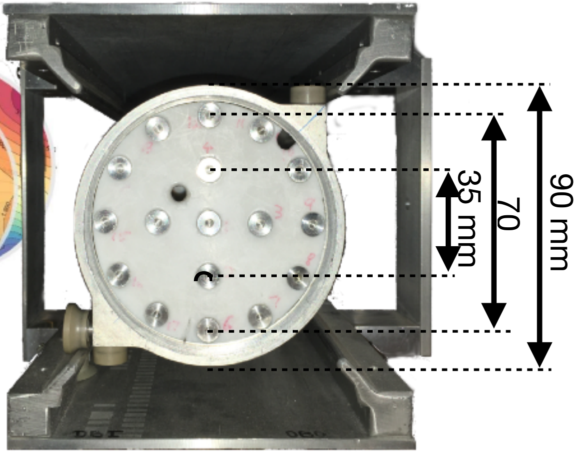
THE FIELD MEASUREMENT

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

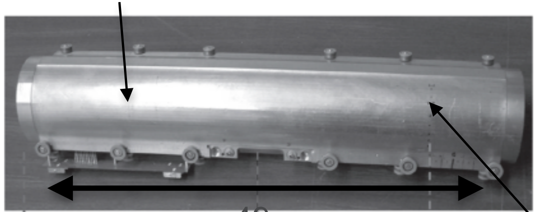
Trolley

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





Electronics

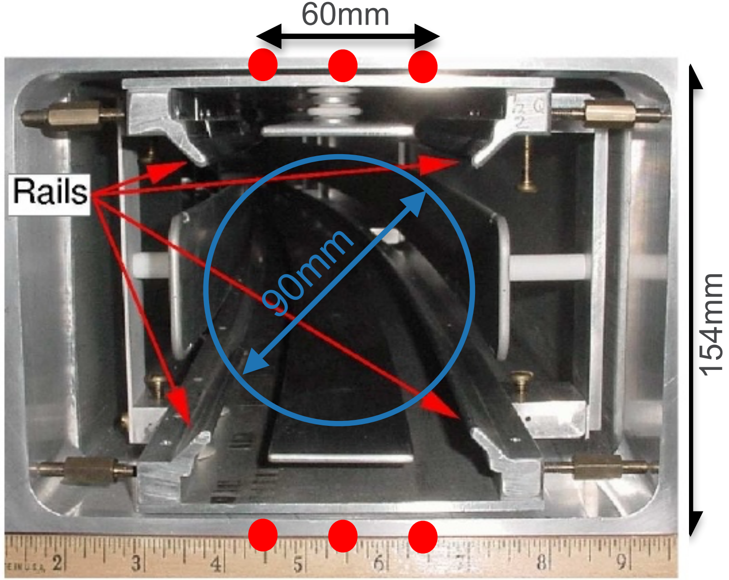


~49cm

NMR probes

378 Fixed Probes

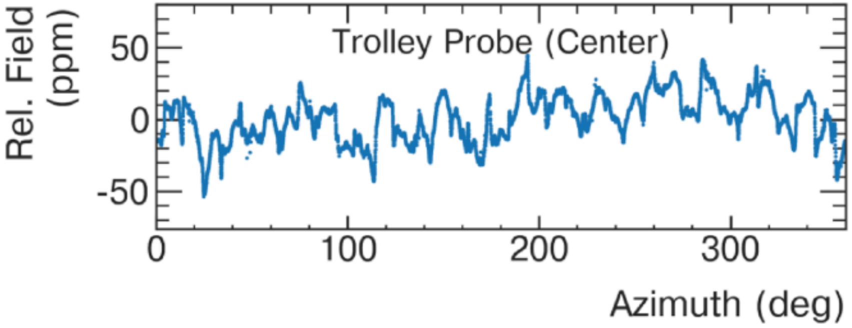
- Outside of the storage region
- 72 position, ~5deg apart



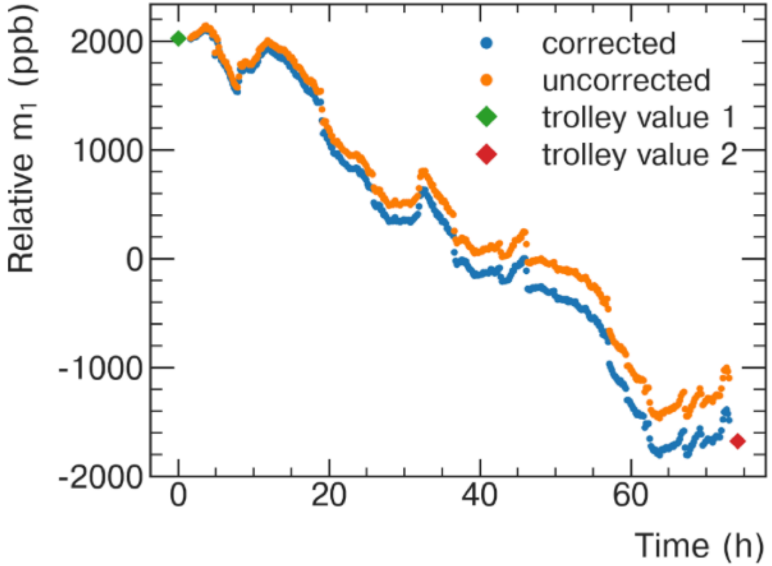
THE FIELD MEASUREMENT

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

Trolley (every ~3 days)
Field inside the muon storage volume



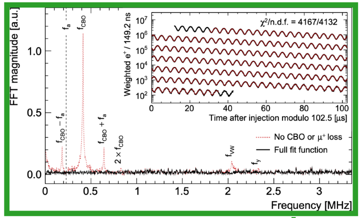
378 Fixed Probes (from the outside)
Track the field between field maps



Uncertainty: random walk model (Brownian bridge)

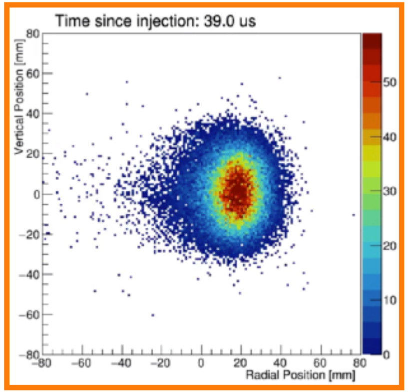
BACK TO THE MASTER FORMULA

Matteo Sorbara
(WG 4)



precession

Alessandra Luca
(WG 3)



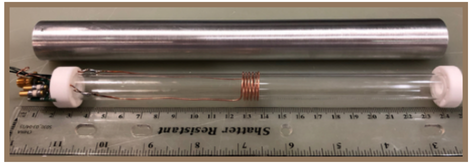
beam dynamics
corrections

unblinding factor

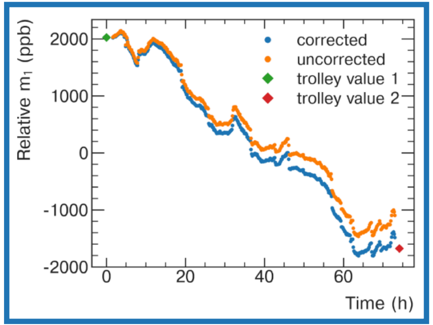
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\mathrm{clock}}\,\omega_a^{\mathrm{meas}}\left(1+C_e+C_p+C_{ml}+C_{pa}\right)}{f_{\mathrm{calib}}\,\left\langle \omega'_p(x,y,\phi)\times M(x,y,\phi)\right\rangle\left(1+B_K+B_Q\right)}$$

magnetic field sampled
by the muon distribution

absolute field
calibration

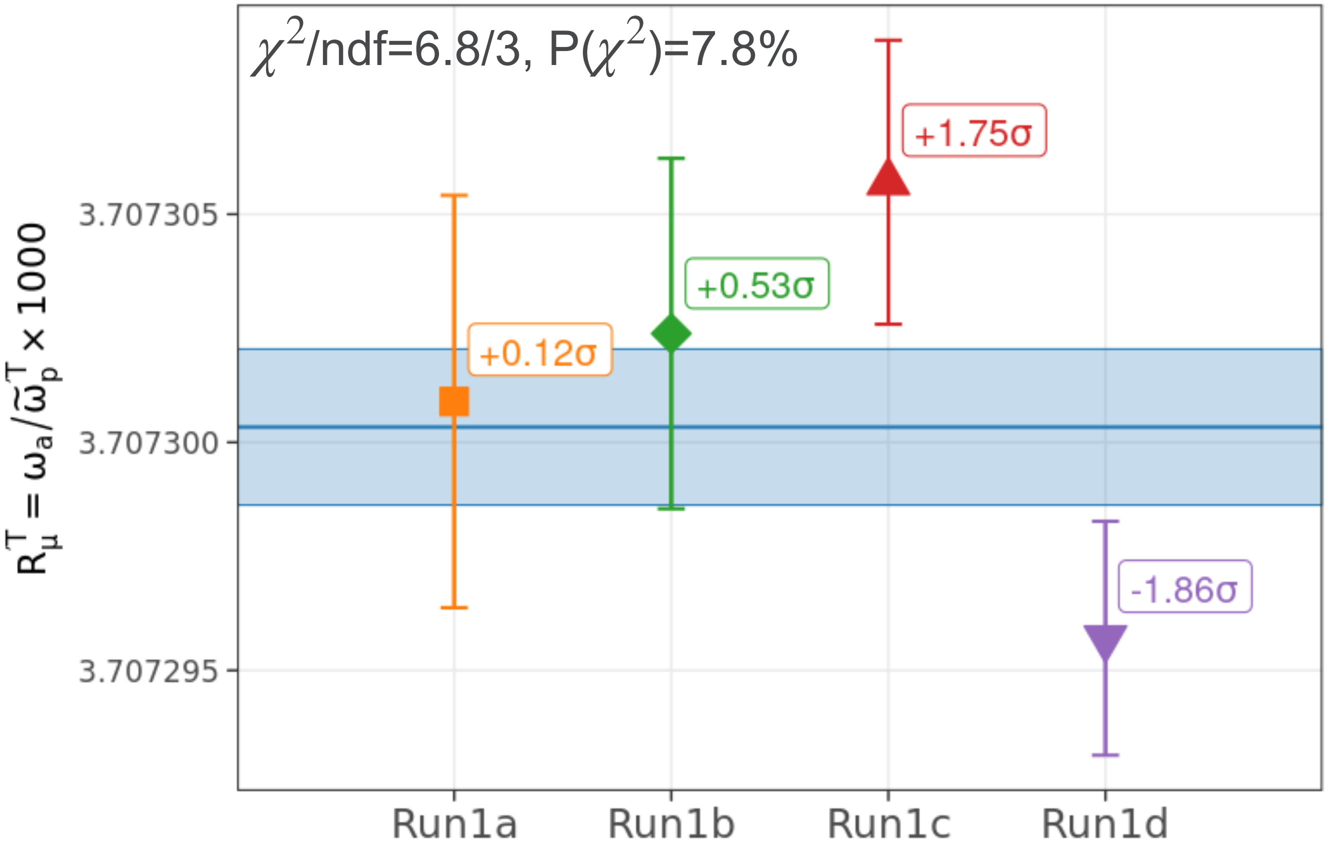


Magnetic transients
corrections



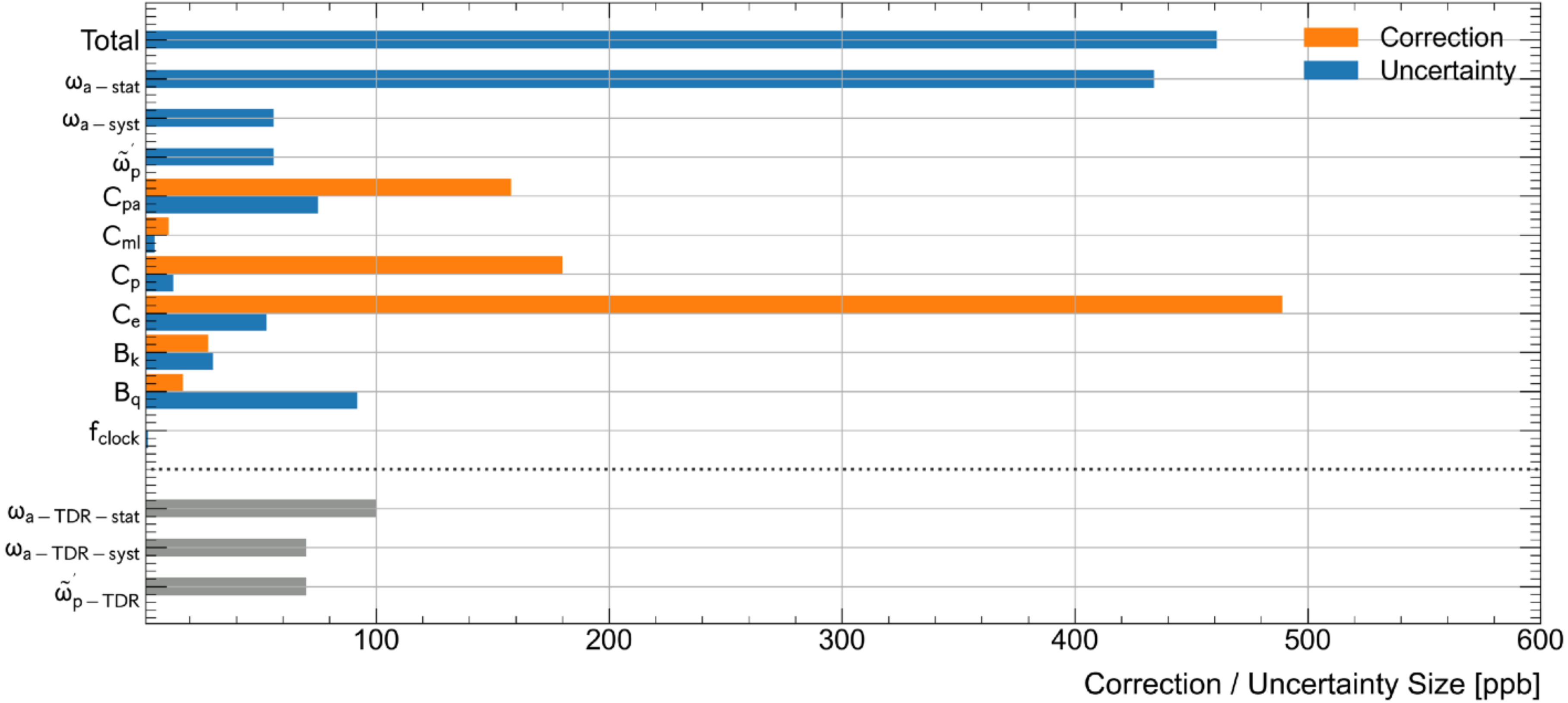
Alec Tewsley-Booth
(WG 4)

THE RUN-1 RESULT

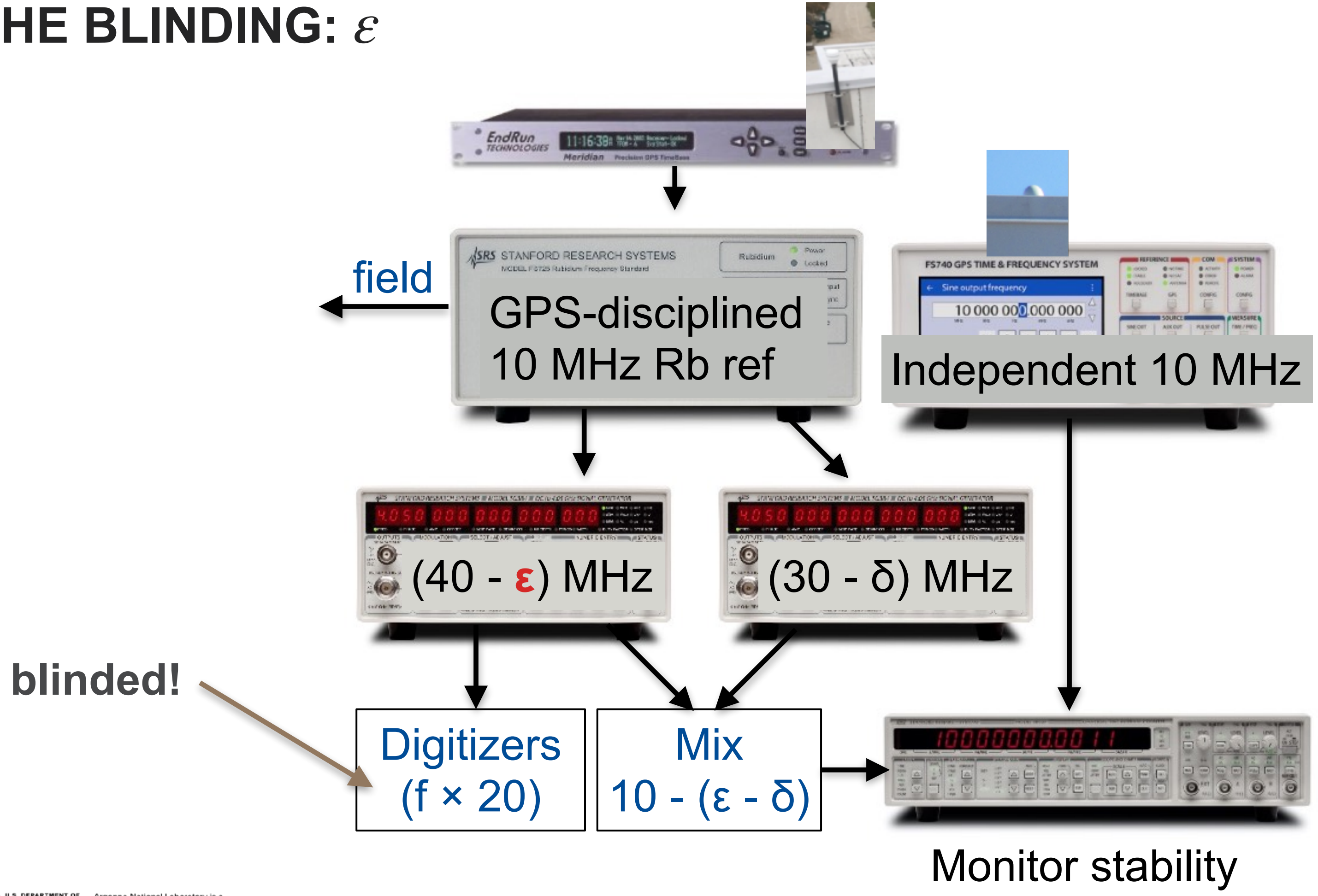


THE RUN-1 RESULT

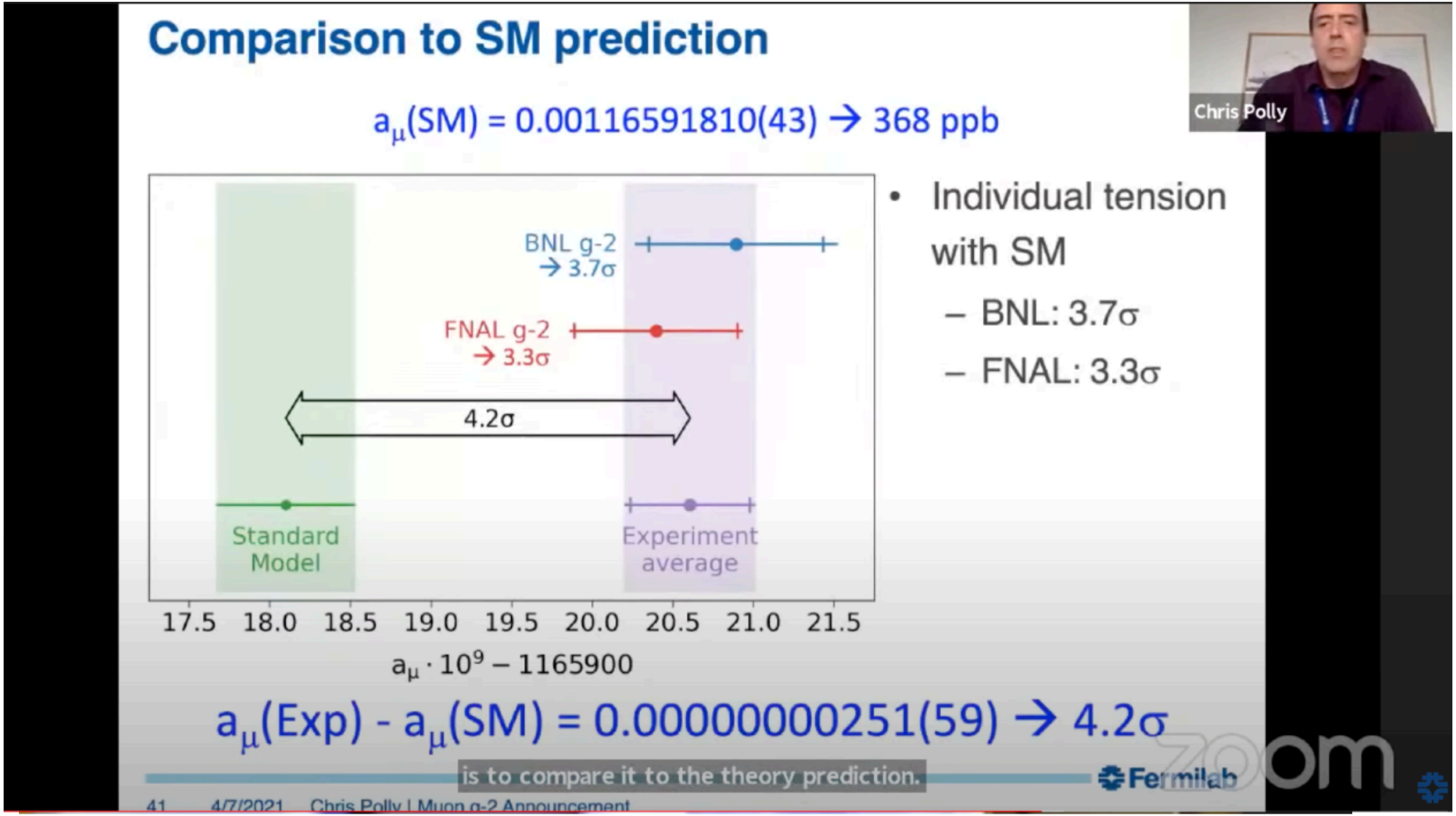
$$\frac{\omega_a}{\tilde{\omega}'_p} \approx \frac{f_{\text{clock}}\, \omega_a^{\text{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\text{calib}} \left\langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \right\rangle \left(1 + B_K + B_Q\right)}$$



THE BLINDING: ε

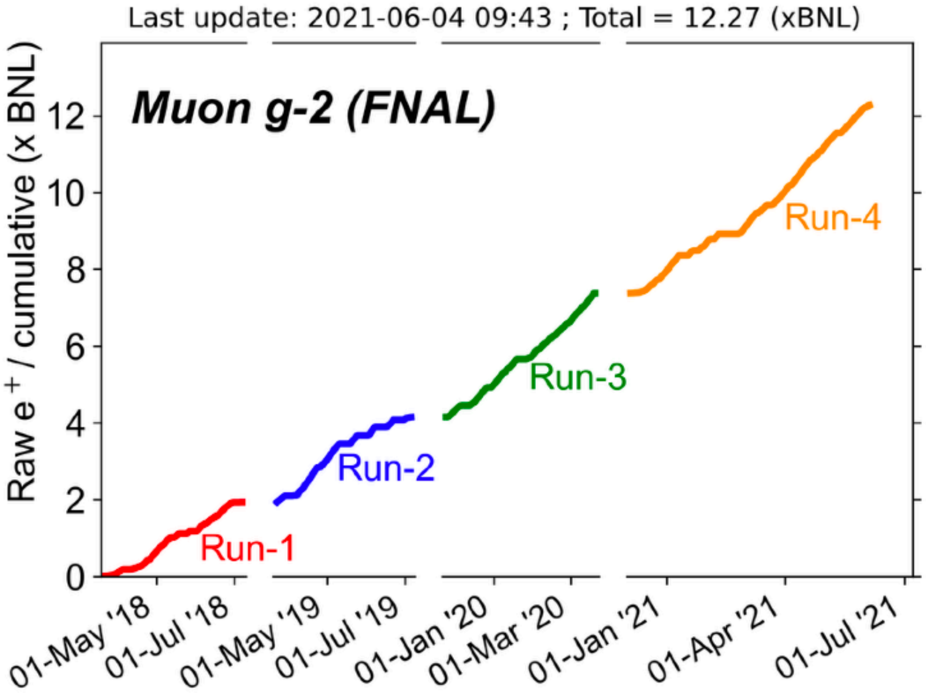


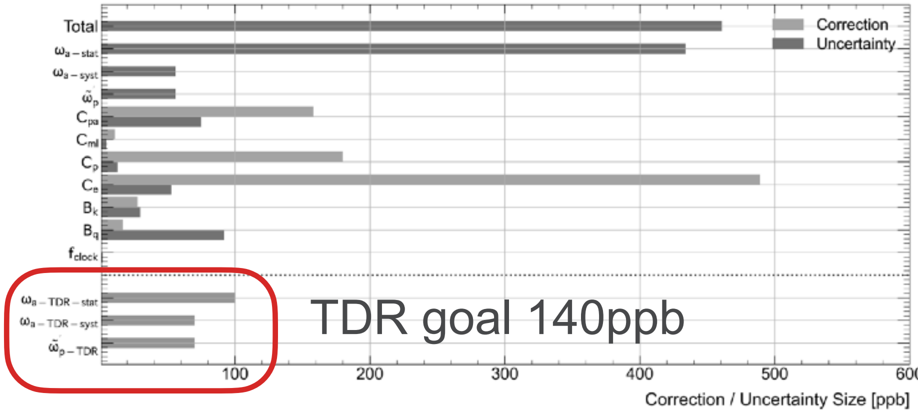
THE RUN-1 UNBLINDING



BEYOND RUN-1: WHATS NEXT

Run-1 publication: only ~6% of the full expected dataset





TDR goal 140ppb

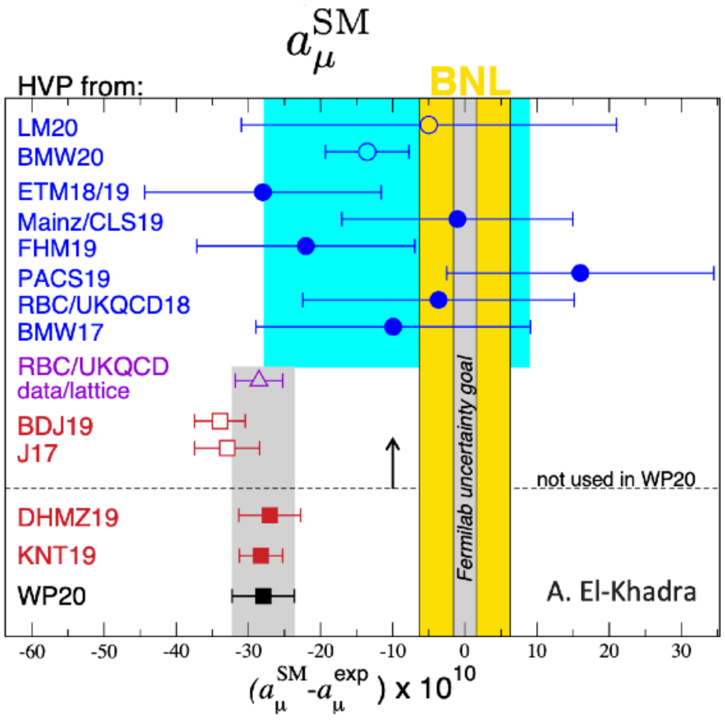
We expect at least two more runs
Run 5 & 6

BEYOND RUN-1: VERY EXITING TIMES

Much more data to come!

Also the theory side is very active!
New lattice results (and more expected) that will be scrutinized in the coming years.

Related: MUonE
Proposed experiment to measure a_μ^{HLO}



THE COLLABORATION

Run-1 unblinding ceremony

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

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Russia
- Budker/Novosibirsk
- JINR Dubna

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

Korea
- CAPP/IBS
- KAIST

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