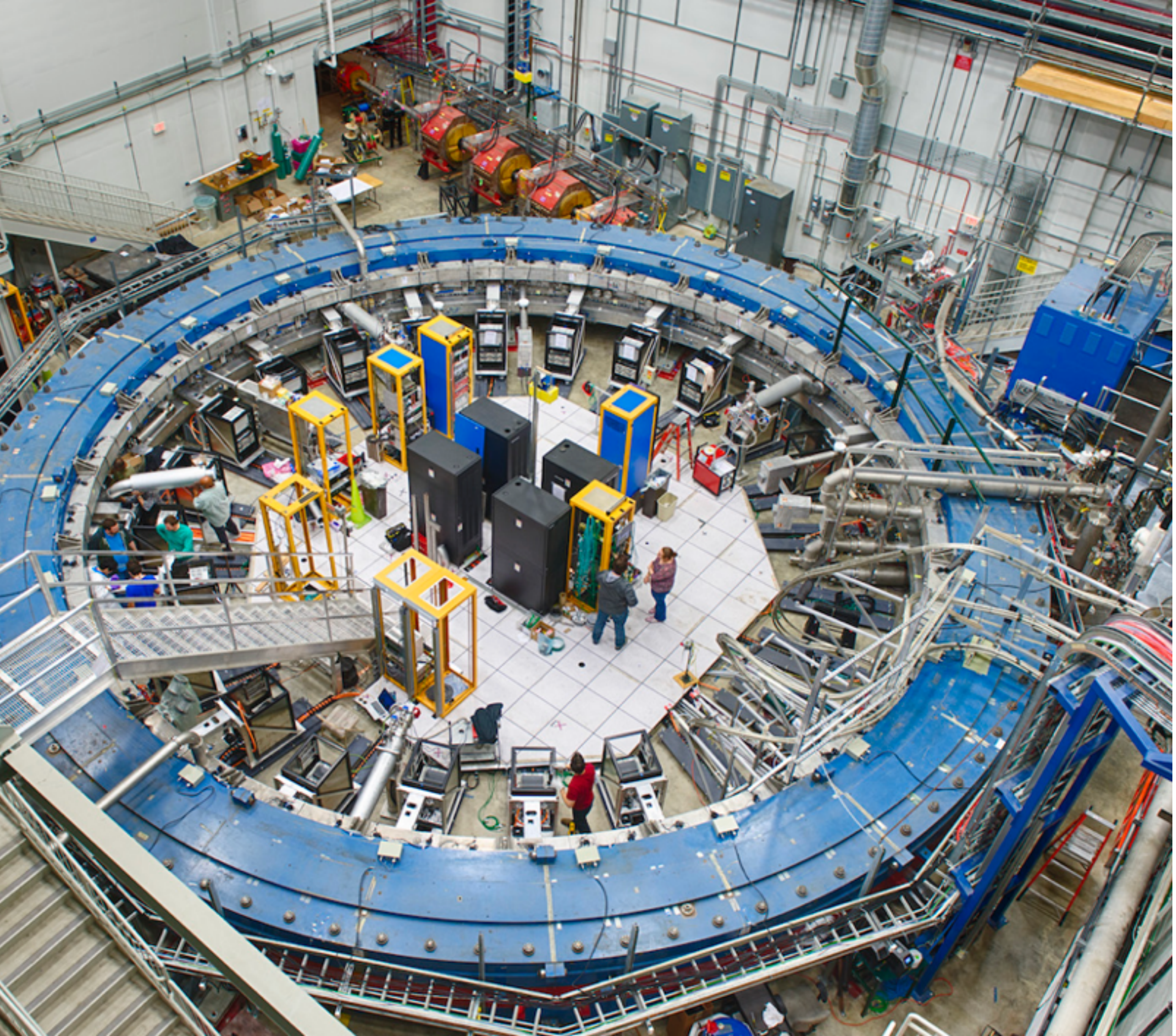


The first results of the Muon g-2 experiment at Fermilab

Prof. Dr. Martin Fertl

PANIC 2021

September 7th, 2021

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Outline

Muon g-2: Status of theory vs. experiment before April 7th, 2021

The Muon g-2 experiment at FNAL

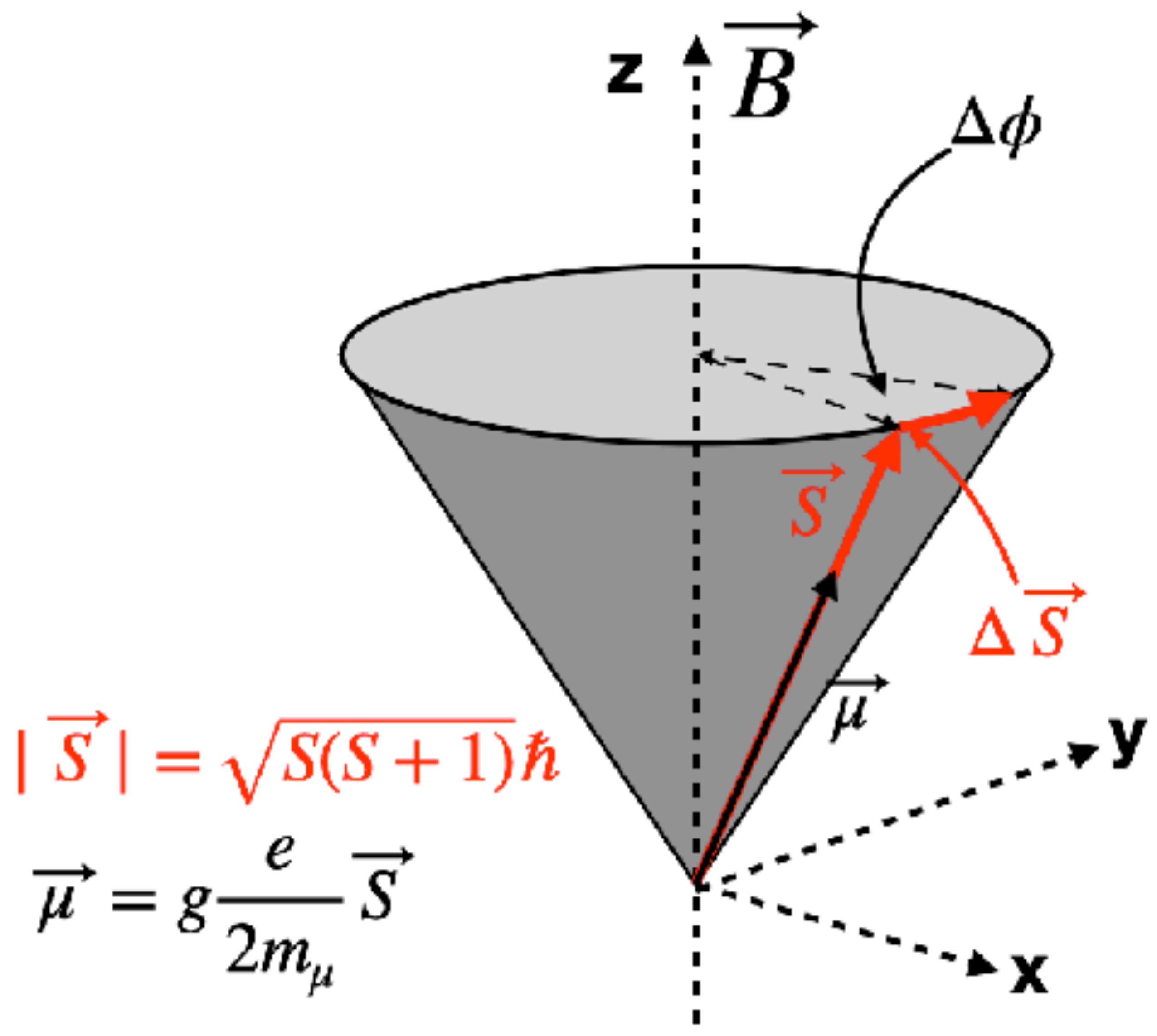
- The measurement principle
- The muon source
- The muon storage ring and its instrumentation

Selected aspects of the data analysis chain

- The anomalous spin precession frequency and its corrections
- The precision magnetic field and its corrections

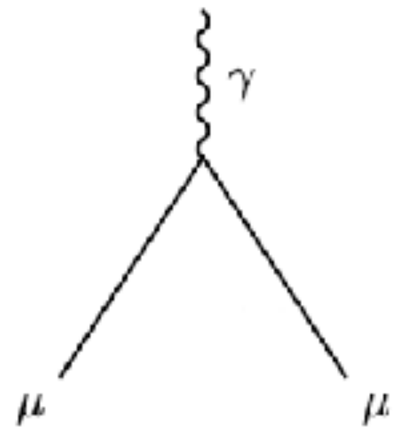
The experimental result

The magnetic moment of a charged lepton

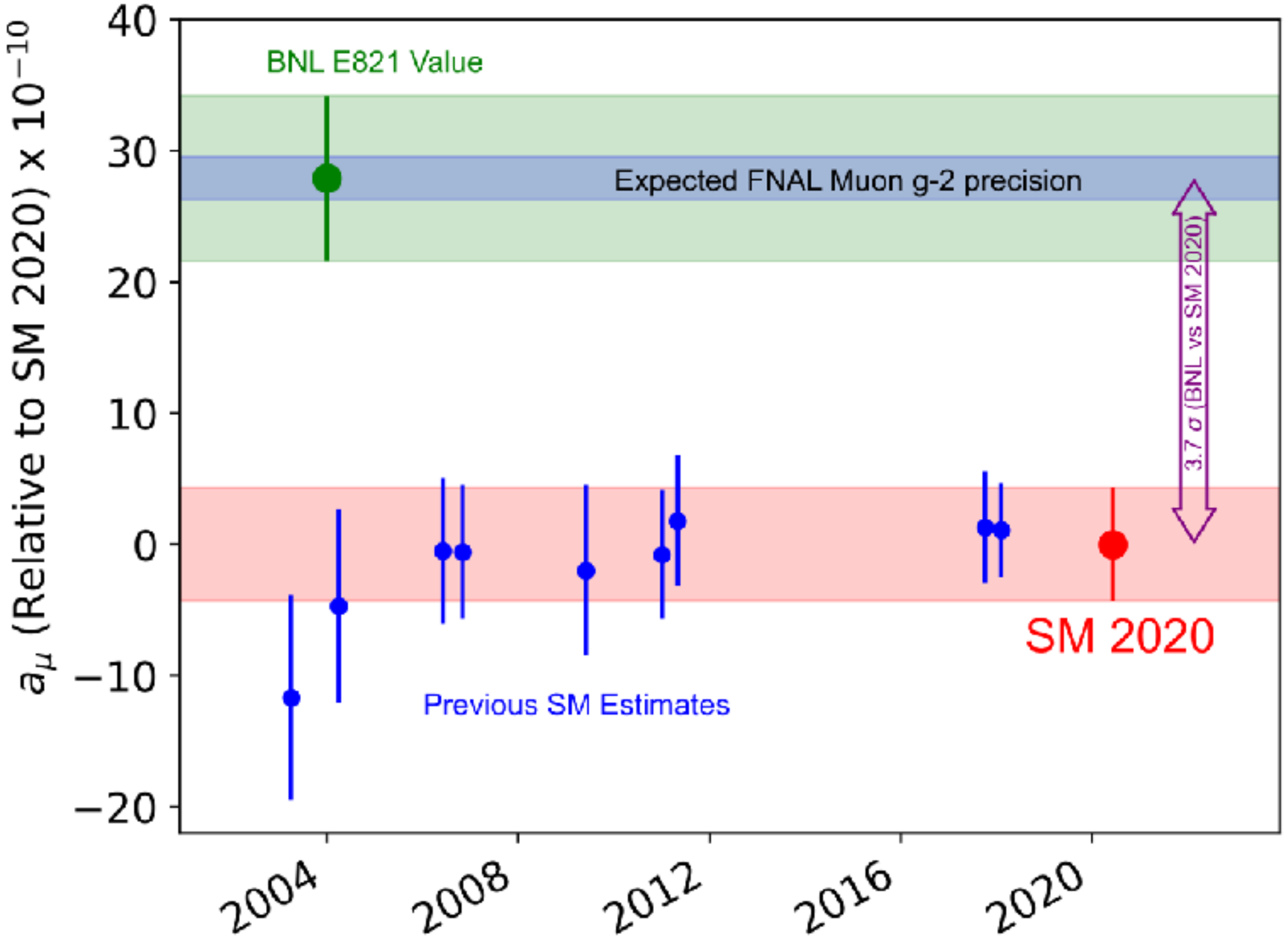


Charged particle with magnetic dipole moment and spin

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



SM prediction meets the experiment (before April 7, 2021)



Experiment (BNL E821): $a_\mu^{\mathrm{BNL}} = 116592089 \pm 63$ (540 ppb)

Total SM prediction: $a_\mu^{\mathrm{SM}} = 116591810 \pm 43$ (368 ppb)

Discrepancy: $\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (279 \pm 76) \times 10^{-11}$

Evolved to 3.7 σ deviation between SM and BNL experiment!

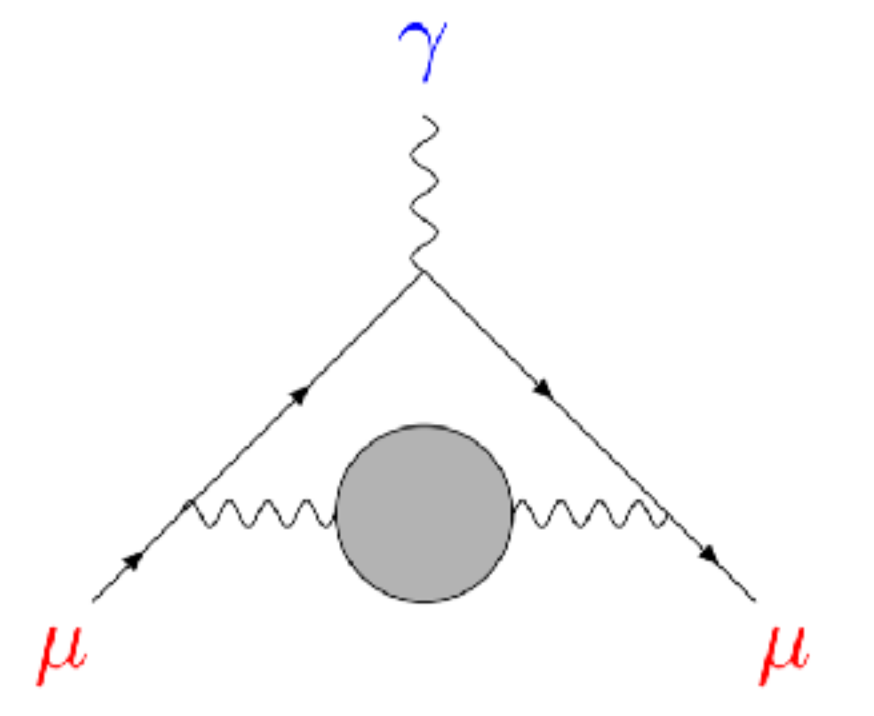
Goal of the Muon g-2 experiment at Fermi National Laboratory

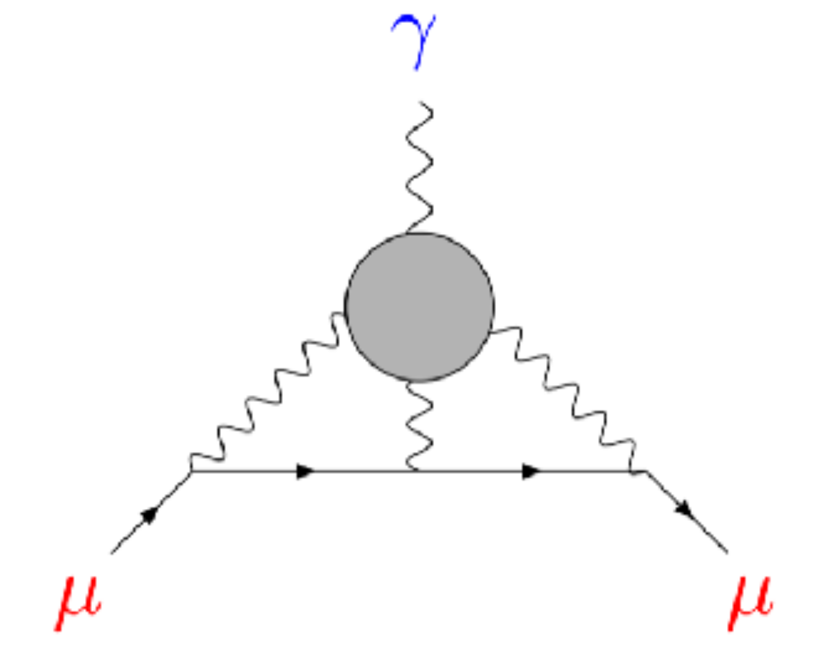
Reduction of experimental uncertainty by a factor 4!

Recent evaluations of the SM prediction of a_μ

Units: xxx 10^{-11}

QED ($\mathcal{O}(\alpha^5)$, > 12000 digrams):	116584718.931 ± 0.104
Electroweak:	153.6 ± 1.0
LO hadronic vacuum polarization:	6931 ± 40
NLO HVP:	-98.3 ± 0.7
NNLO HVP:	12.4 ± 0.1
LO hadronic light-by-light scattering:	92 ± 19
NLO hLbL scattering:	2 ± 1





Uncertainty dominated by hadronic physics contributions!

Total SM prediction: $a_\mu^{\mathrm{SM}} = 116591810 \pm 43$ (368 ppb)

Theory update on Hlbl:
Johan Bijnens (5 Sep 2021, 16:15)

Numbers taken from "Muon g-2 Theory Initiative White Paper": Phys. Rept. 887 (2020) 1-166

The two clocks of a charged lepton

A *relativistic* charged lepton circulating a homogenous magnetic field experiences two effects:

<u>Cyclotron motion</u>

Equilibrium between centrifugal and Lorentz force

<u>Cyclotron frequency</u>

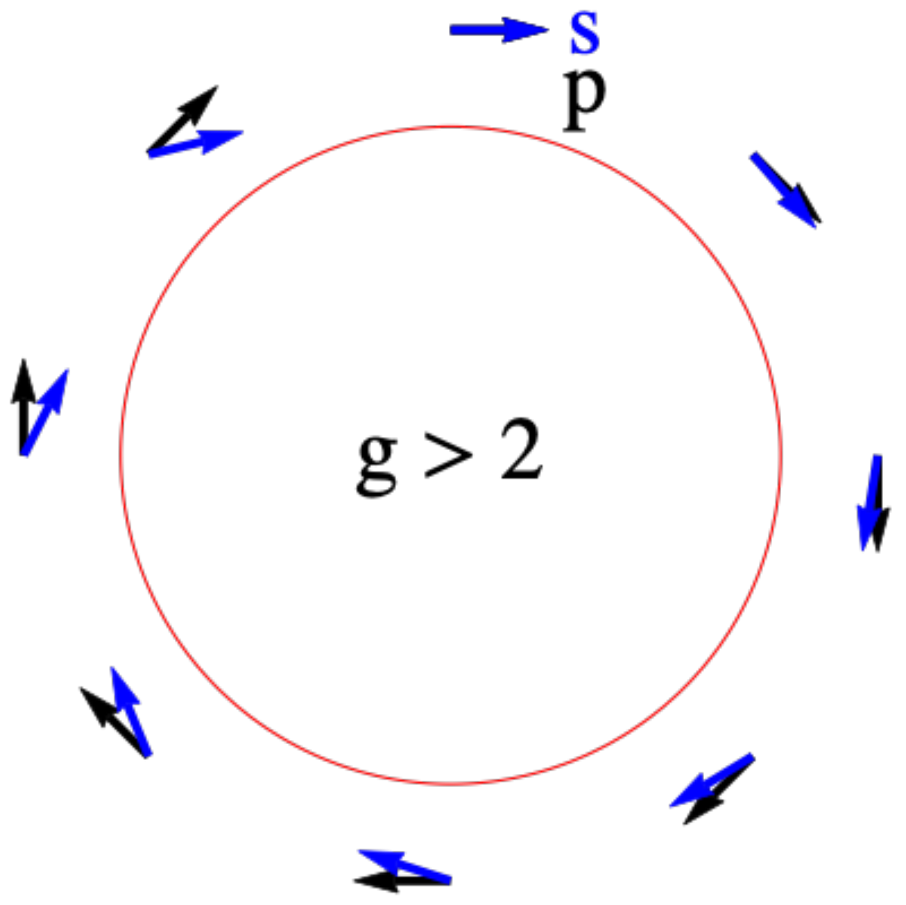
$$\vec{\omega}_{\mathrm{c}} = -\frac{Qe}{m\gamma}\vec{B}$$

<u>Spin precession</u>

Coupling of magnetic moment and field

<u>Larmor frequency</u>

$$\vec{\omega}_{\mathrm{s}} = -g\frac{Qe}{2m}\vec{B} - (1-\gamma)\frac{Qe}{\gamma m}\vec{B}$$

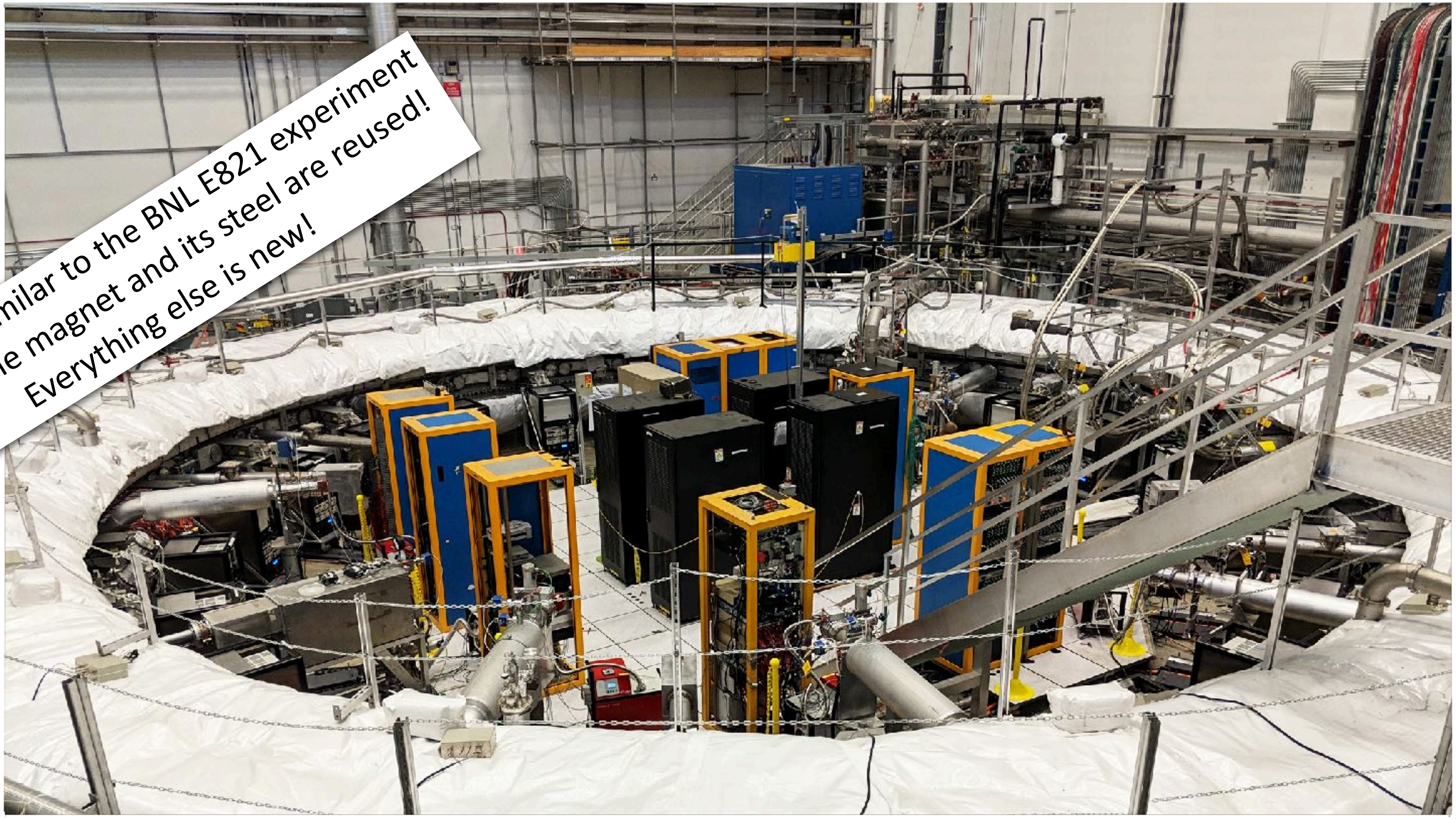


<u>Anomalous spin precession frequency:</u>

$$\vec{\omega}_{\mathrm{a}} = \vec{\omega}_{\mathrm{s}} - \vec{\omega}_{\mathrm{c}} = -\left(\frac{g-2}{2}\right)\vec{B} = -a\frac{Qe}{m}\vec{B}$$

Independent of particle momentum!

The muon g-2 experiment at Fermilab



Looks very similar to the BNL E821 experiment
But only the magnet and its steel are reused!
Everything else is new!

Clock frequency shifts for muons in motion

Evolution of muon's longitudinal polarization in a superposition of electric and magnetic fields

$$\frac{d}{dt}P_\mathrm{L} = \frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\overrightarrow{s_\perp}\cdot\left[a_\mu\hat{\beta}\times\overrightarrow{B} + \left(a_\mu - \frac{1}{\gamma^2-1}\right)\beta\overrightarrow{E}\right]$$

Spin component perpendicular to velocity

Non-relativistic and circular motion limit

Relativistically generated magnetic fields
"electric field correction"
"pitch correction"

Magnetic field maps and temporal interpolation

Reconstruction of complex beam dynamics

FNAL E989: $E \neq 0$ suppressed at $\gamma = 29.3$ "magic momentum"

Extracting a_μ - the external ingredients

Anchor B, e and m_μ to other high-precision measurements and calculations

$$\frac{\mu'_p(T_r)}{\mu_e(H)}$$

10.5 ppb uncertainty
at T_r = 34.7°C

Metrologia 13, 179 (1977)

$$\frac{\mu_e(H)}{\mu_e}$$

Bound state QED calculation
exact

Rev. Mod. Phys. 88, 035009 (2016)

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

Total uncertainty
from external quantities:
24 ppb

$$\frac{m_\mu}{m_e}$$

Muonium hyperfine splitting
22 ppb uncertainty

Phys. Rev. Lett. 82, 11 (1999)

$$\frac{g_e}{2}$$

Measurement with
0.28 ppt uncertainty

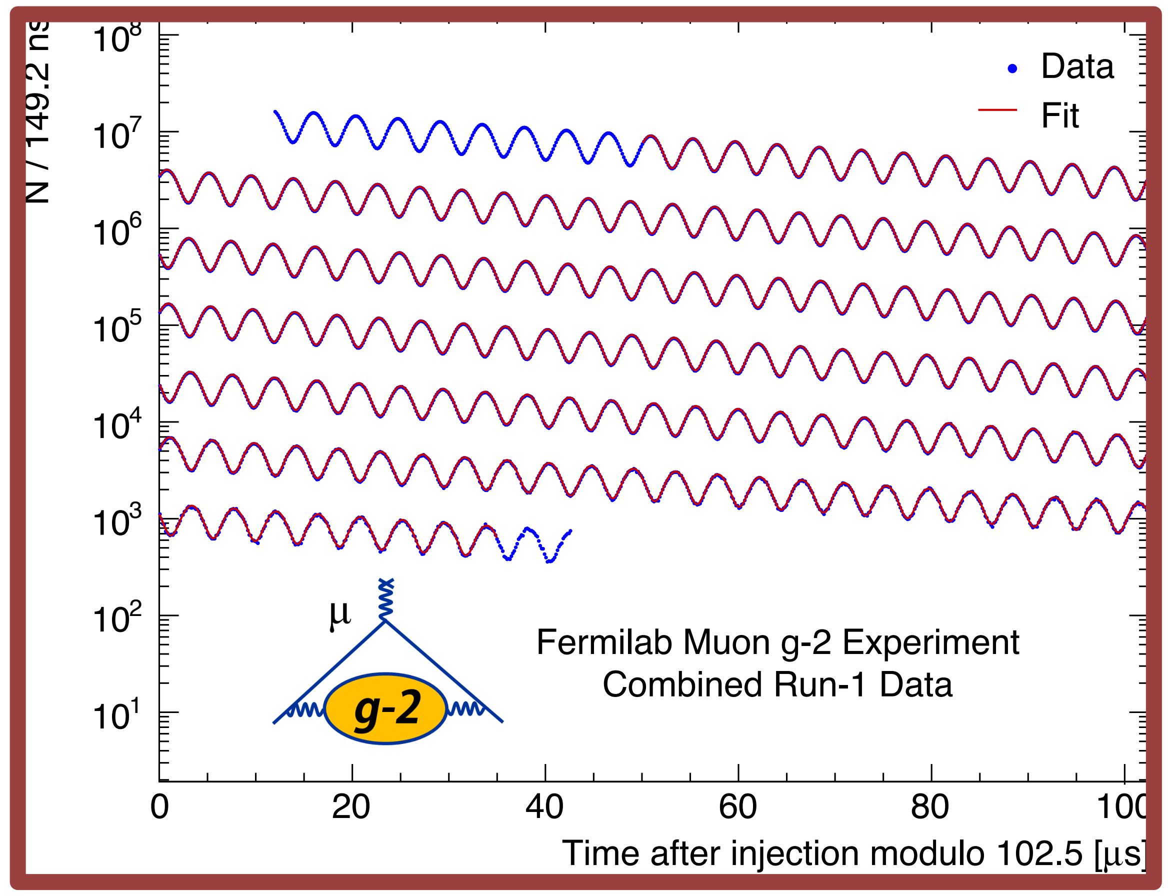
Phys. Rev. A 83, 052122 (2011)

Extracting a_μ - our challenge

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

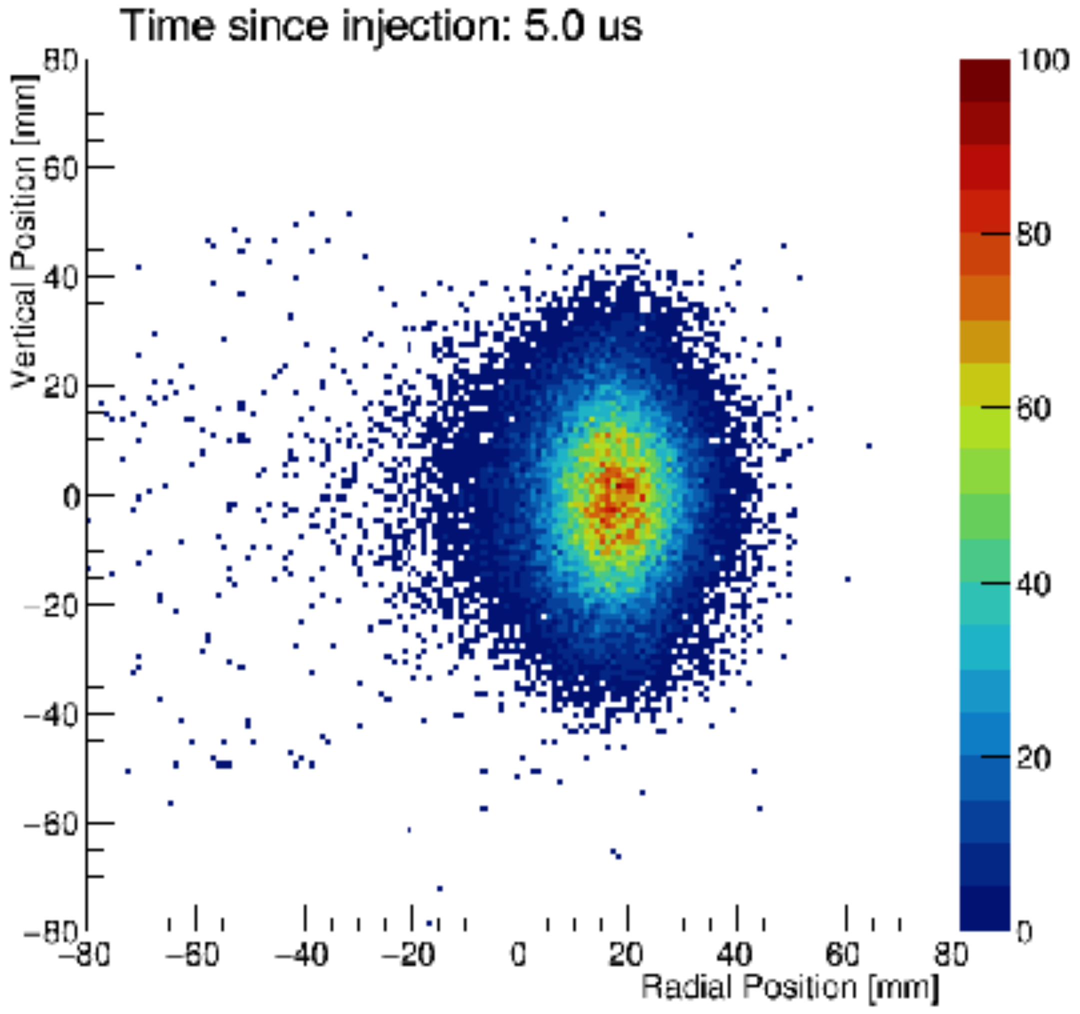
$$a_\mu = \frac{\omega_a}{B'} \frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Extracting a_μ - our tools



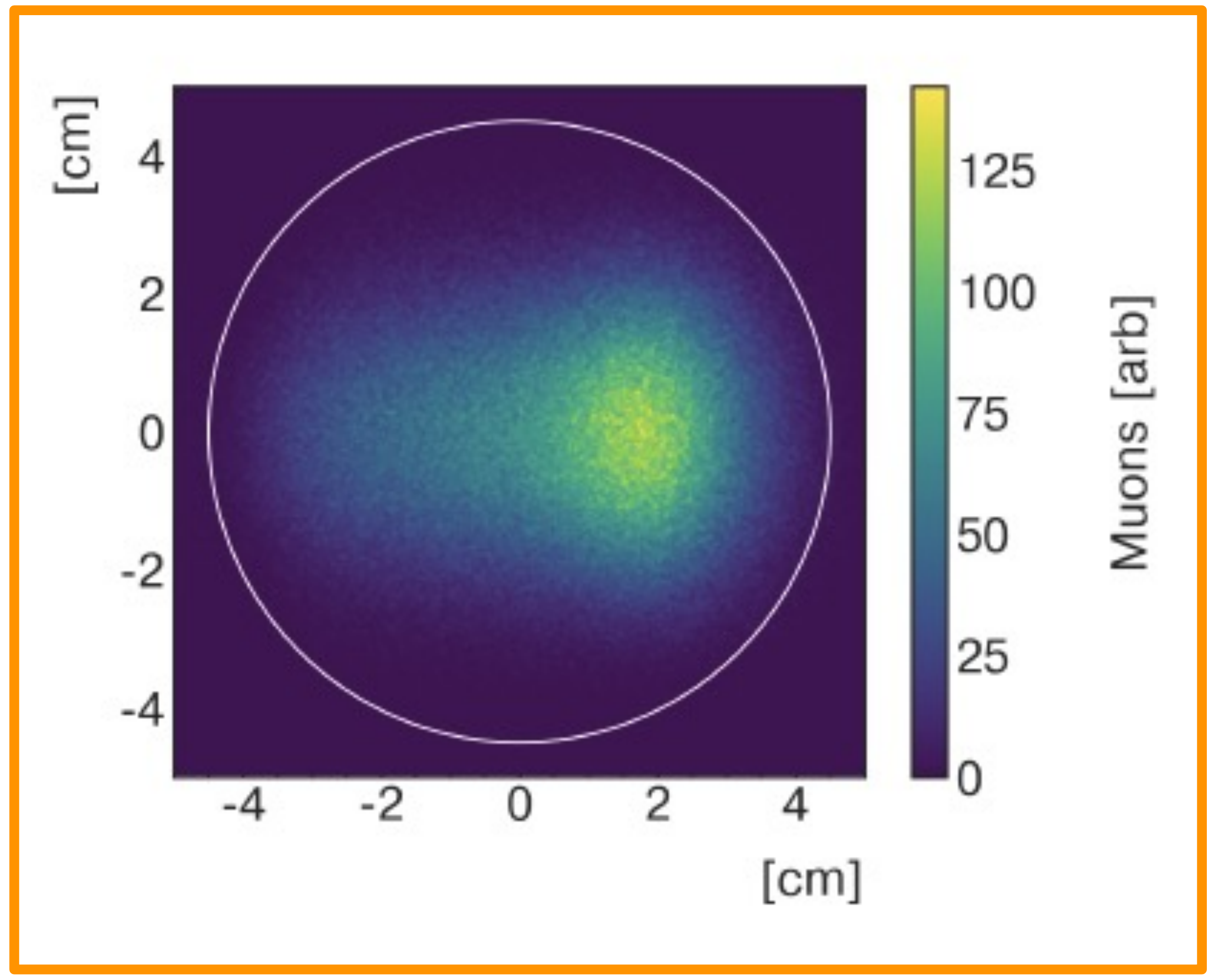
Anomalous spin precession frequency

Muon beam dynamics corrections



Clock blinding

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

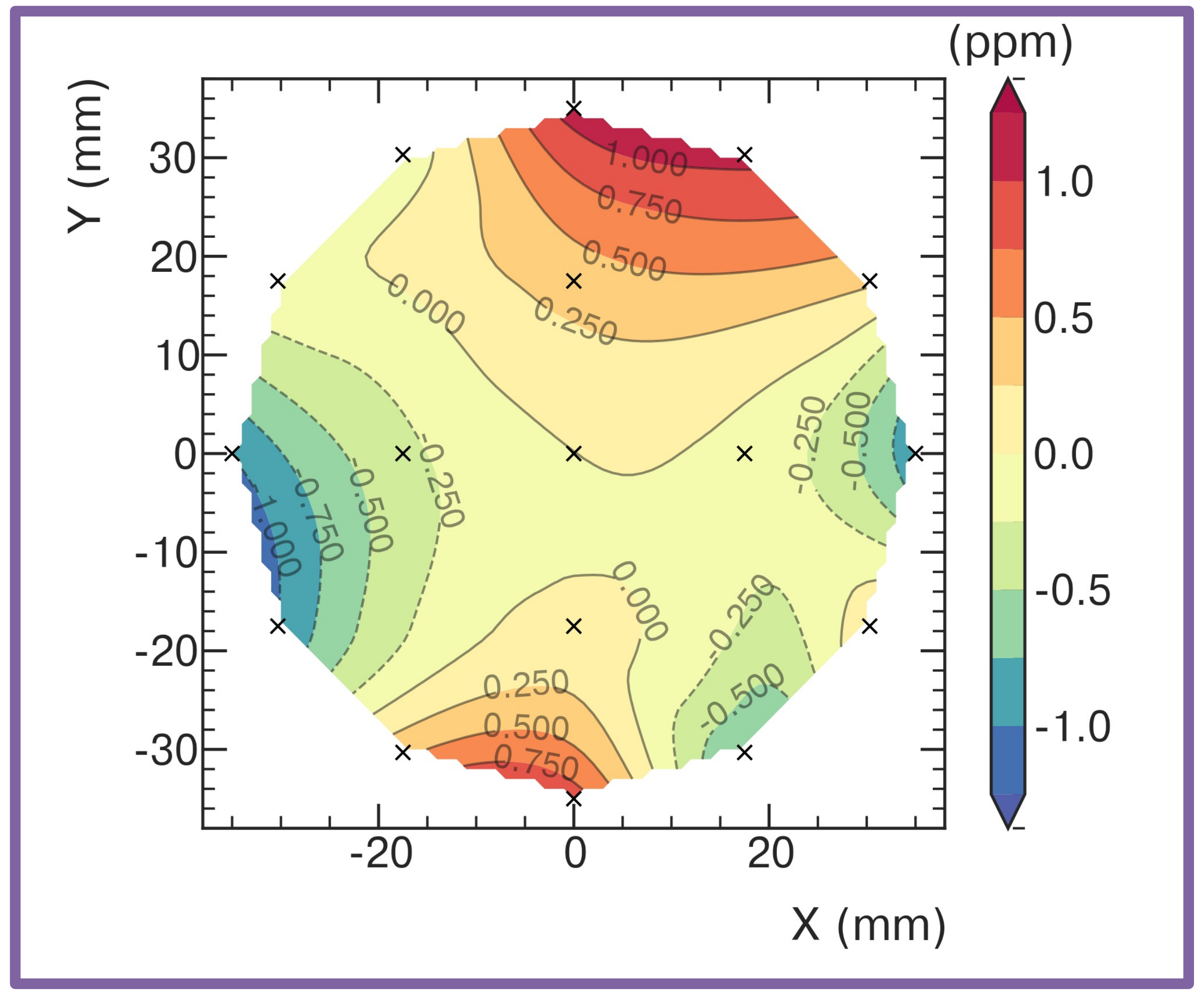


Spatial muon distribution

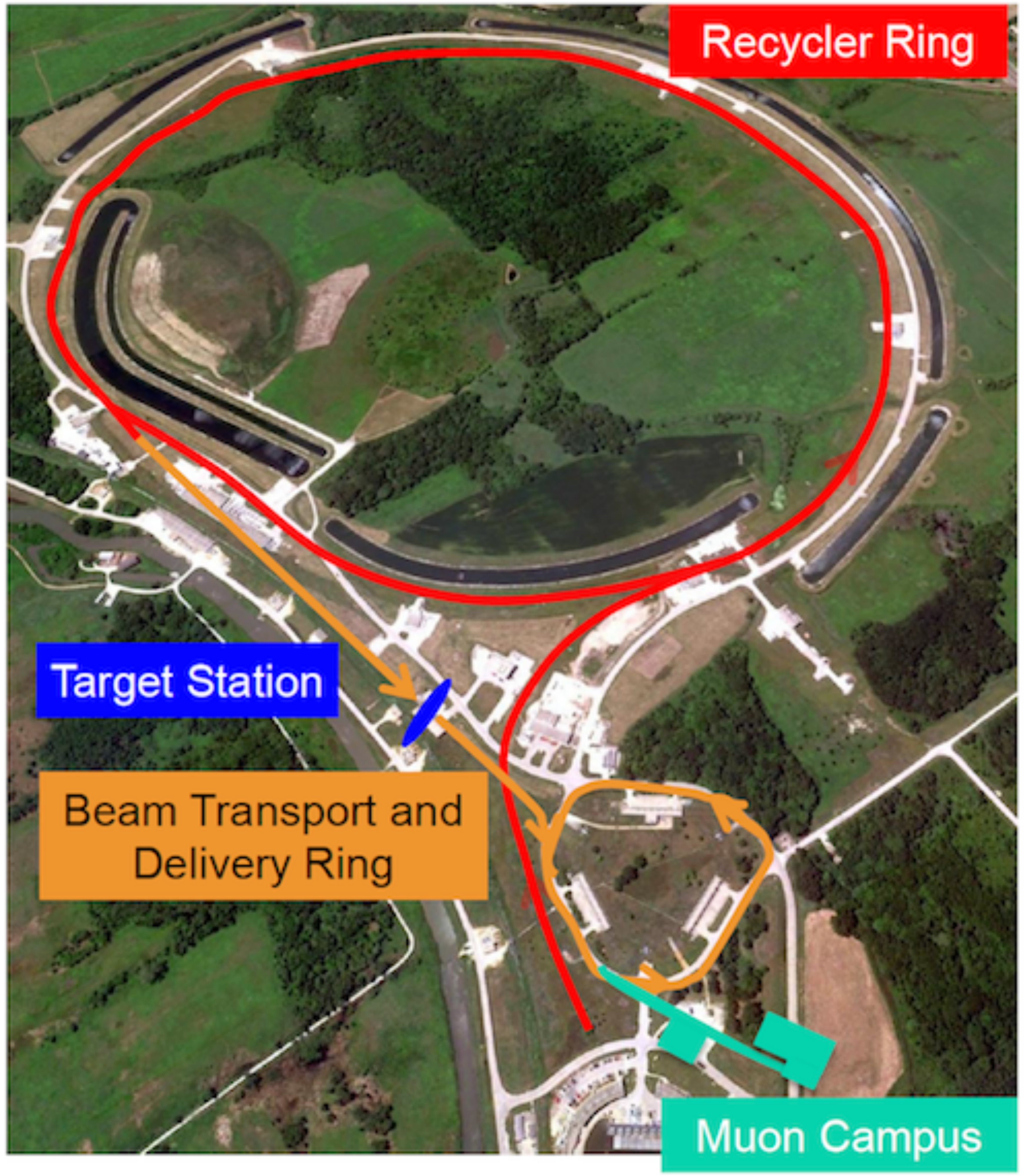
Spatial distribution of magnetic field

Transient magnetic fields

Calibration

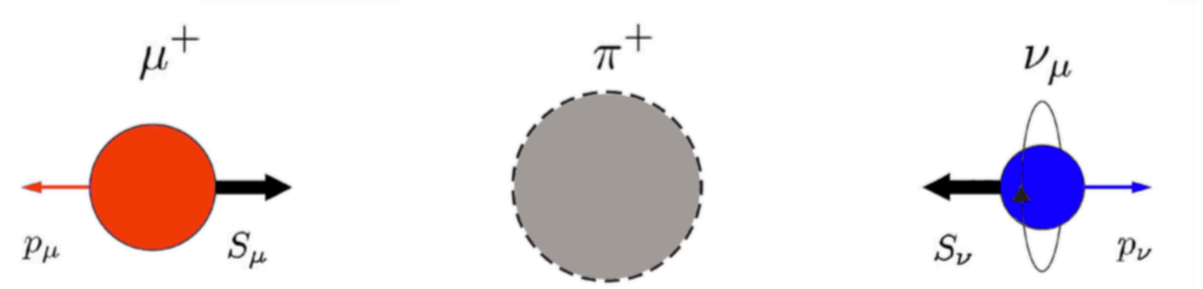


Polarized muons at Fermilab muon campus

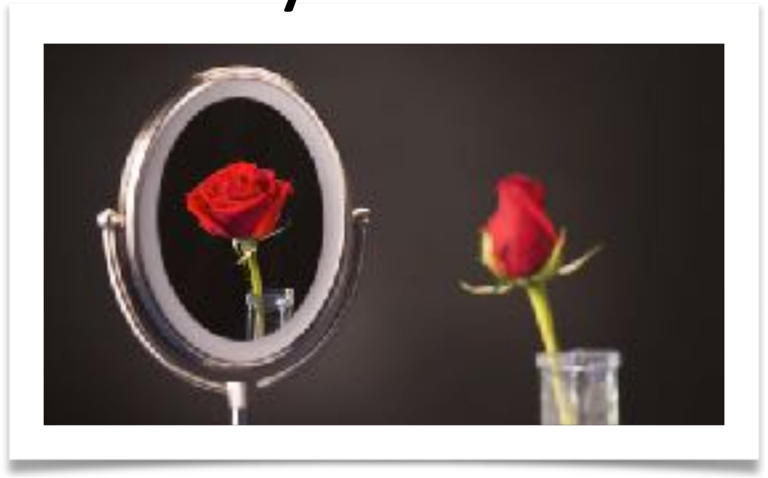


8 GeV p+ strike target, 120 ns bunch length
8 bunches spaced by 10 ms, second bunch train 200 ms later

$$p^+ + p^+ \to p^+ + n + \pi^+$$



Parity violation!



Focus the "debris" into a momentum selective beam line

$$p = 3.094\,\mathrm{GeV/c} \pm 2\,\%$$

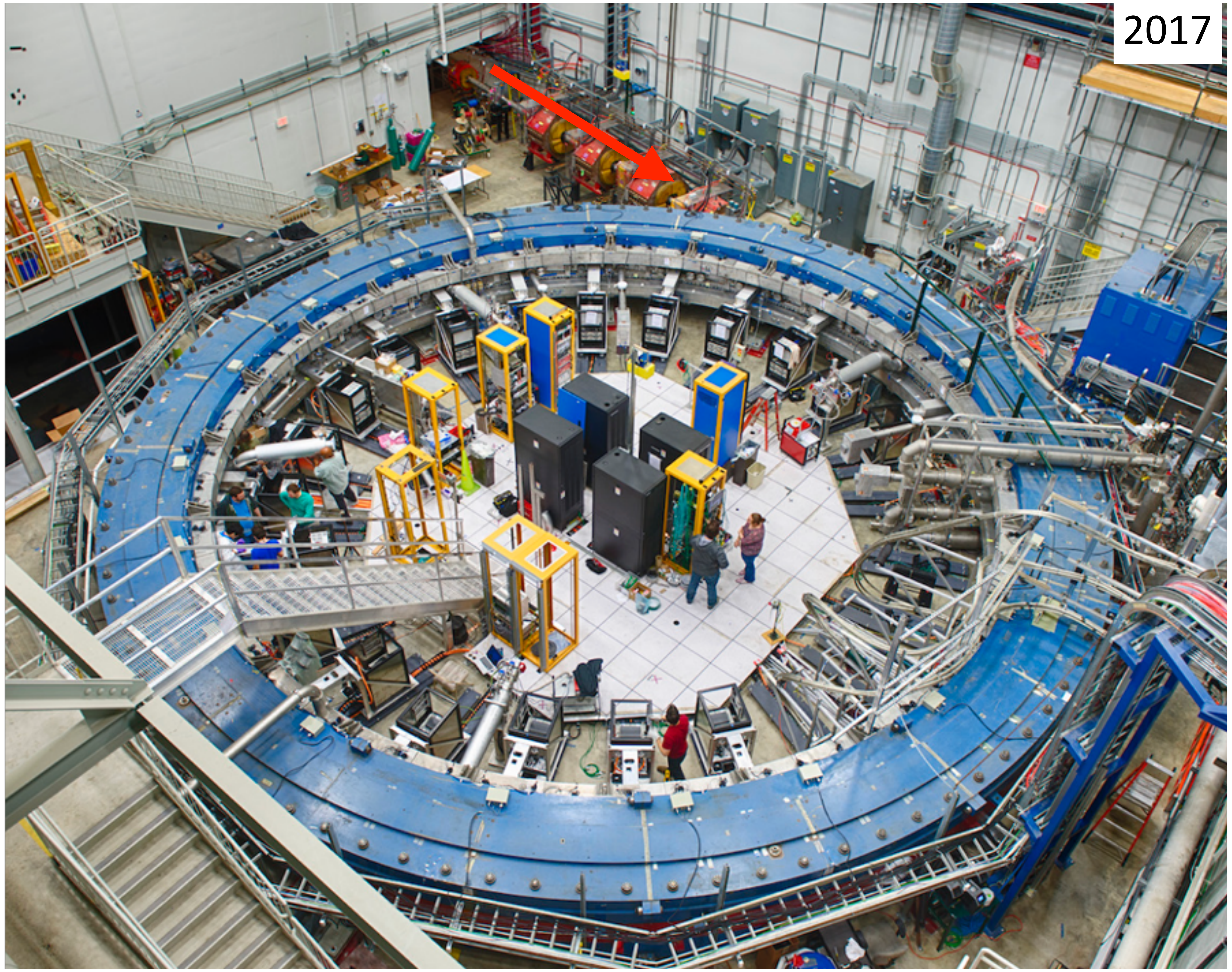
Energy (!) disperse delivery ring: μ^+ outrun p^+, π^+ decay away

Pure lepton beam: 60 - 70% μ^+, 30 - 40% e^+

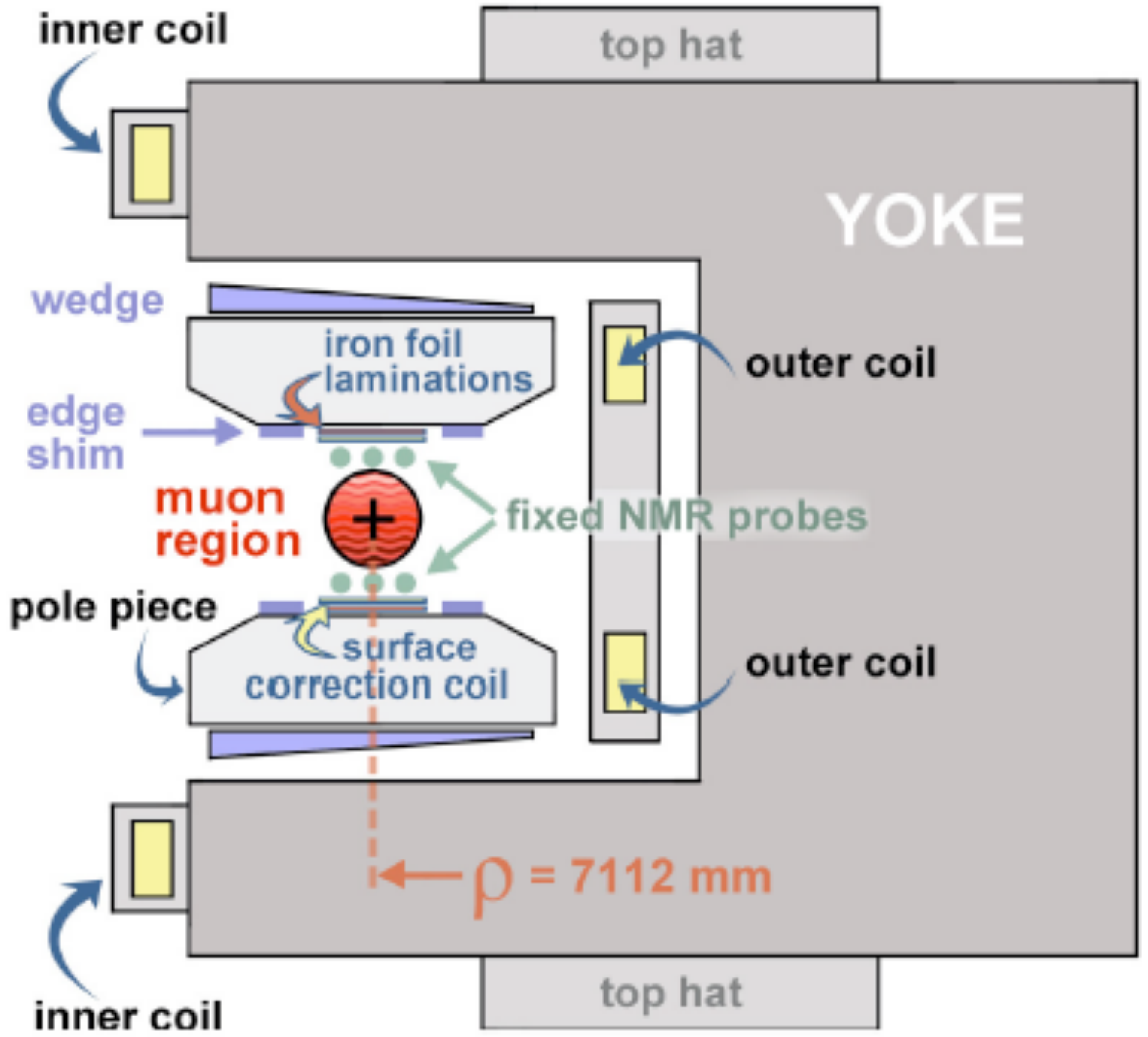
Decay figure: K.S. Khaw, PhD thesis, ETH Zürich, 2015; Muon Campus: M. Convery;
Rose in mirror: R. Hahn, Fermilab in the context of "Charge-parity violation" https://www.symmetrymagazine.org/article/charge-parity-violation

The superconducting magnet in MC1

Particles from delivery ring

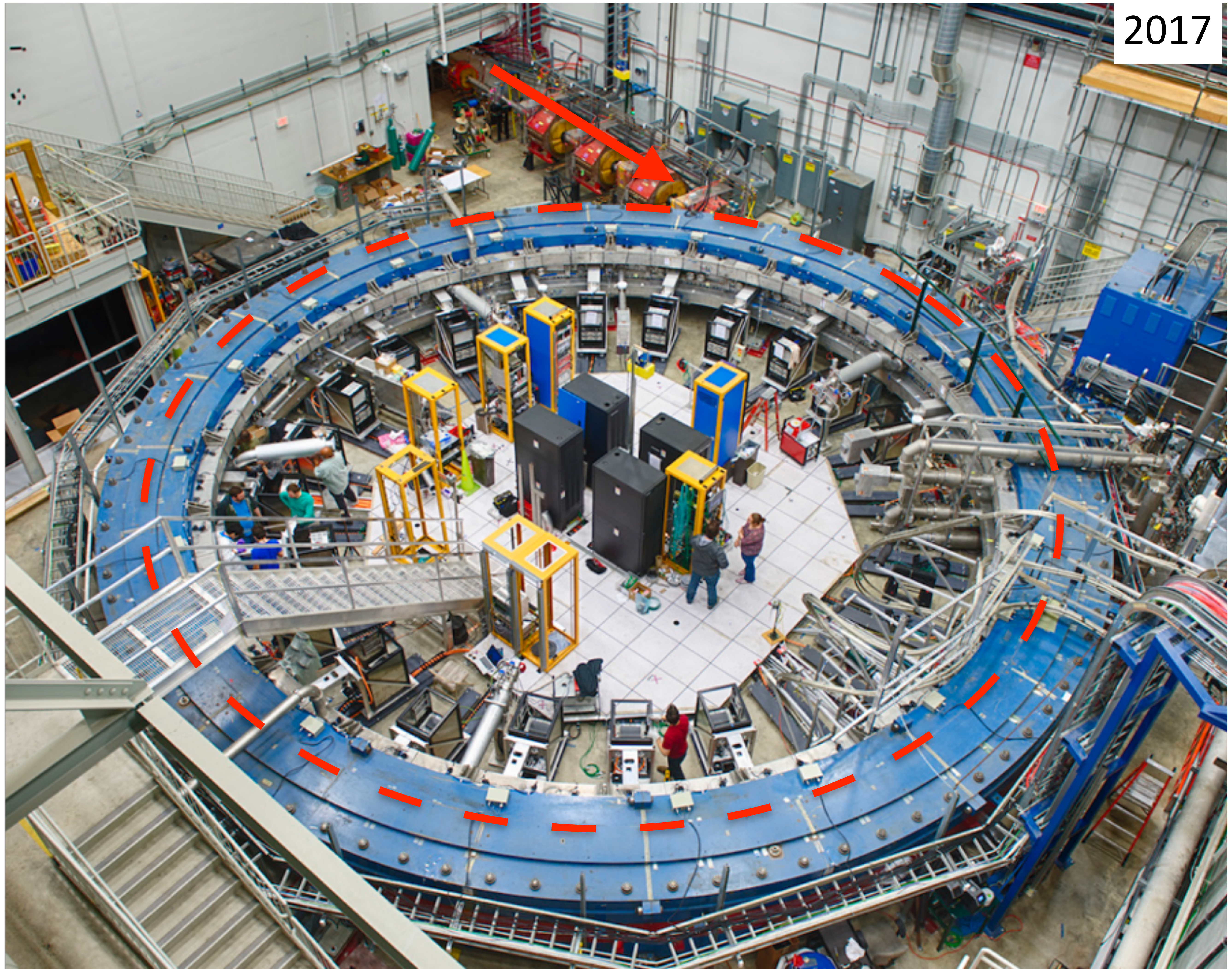


Magic momentum: $p_\mu^{\text{magic}} = 3.094\,\text{GeV/c} \pm 0.5\,\%$

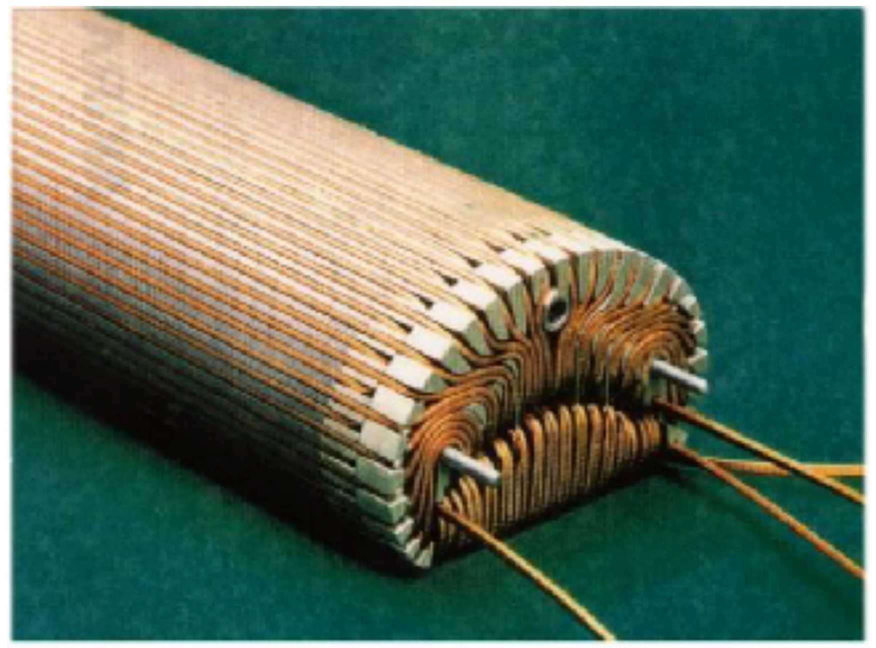


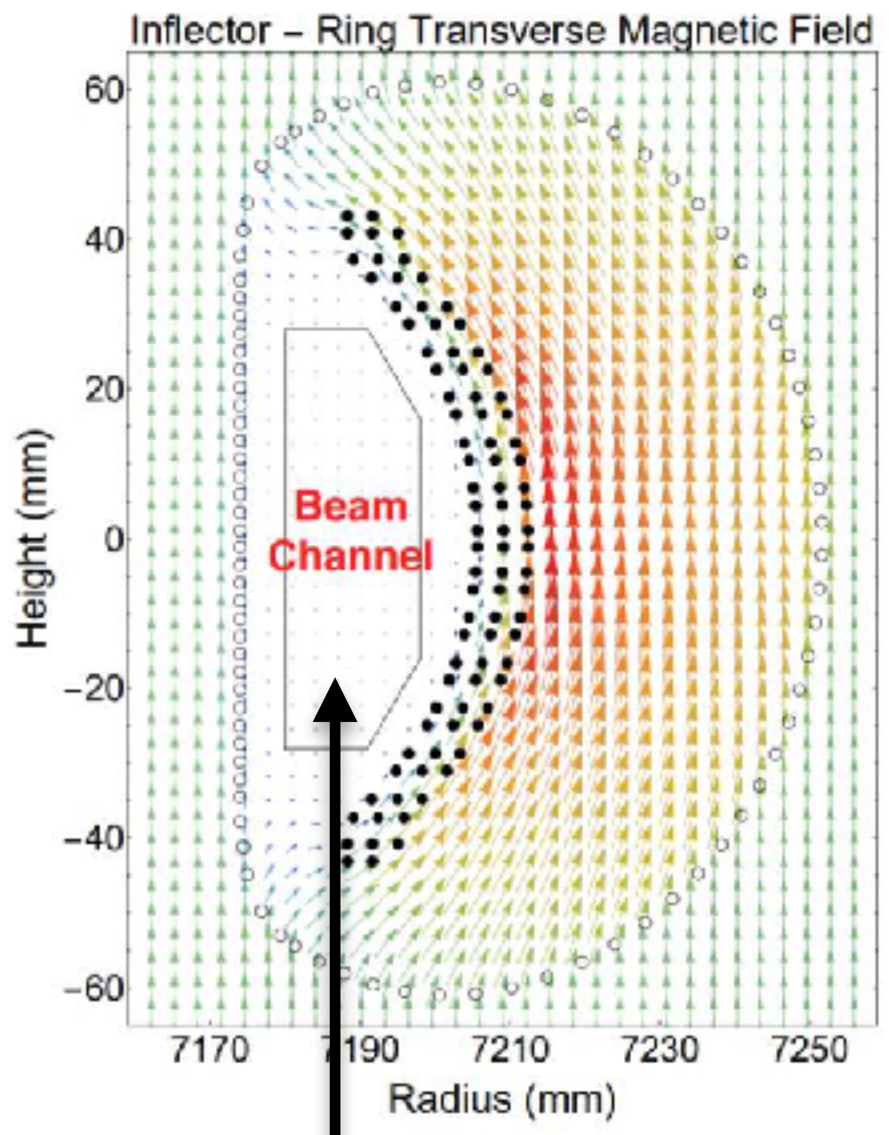
The muon inflector magnet

Particles from delivery ring



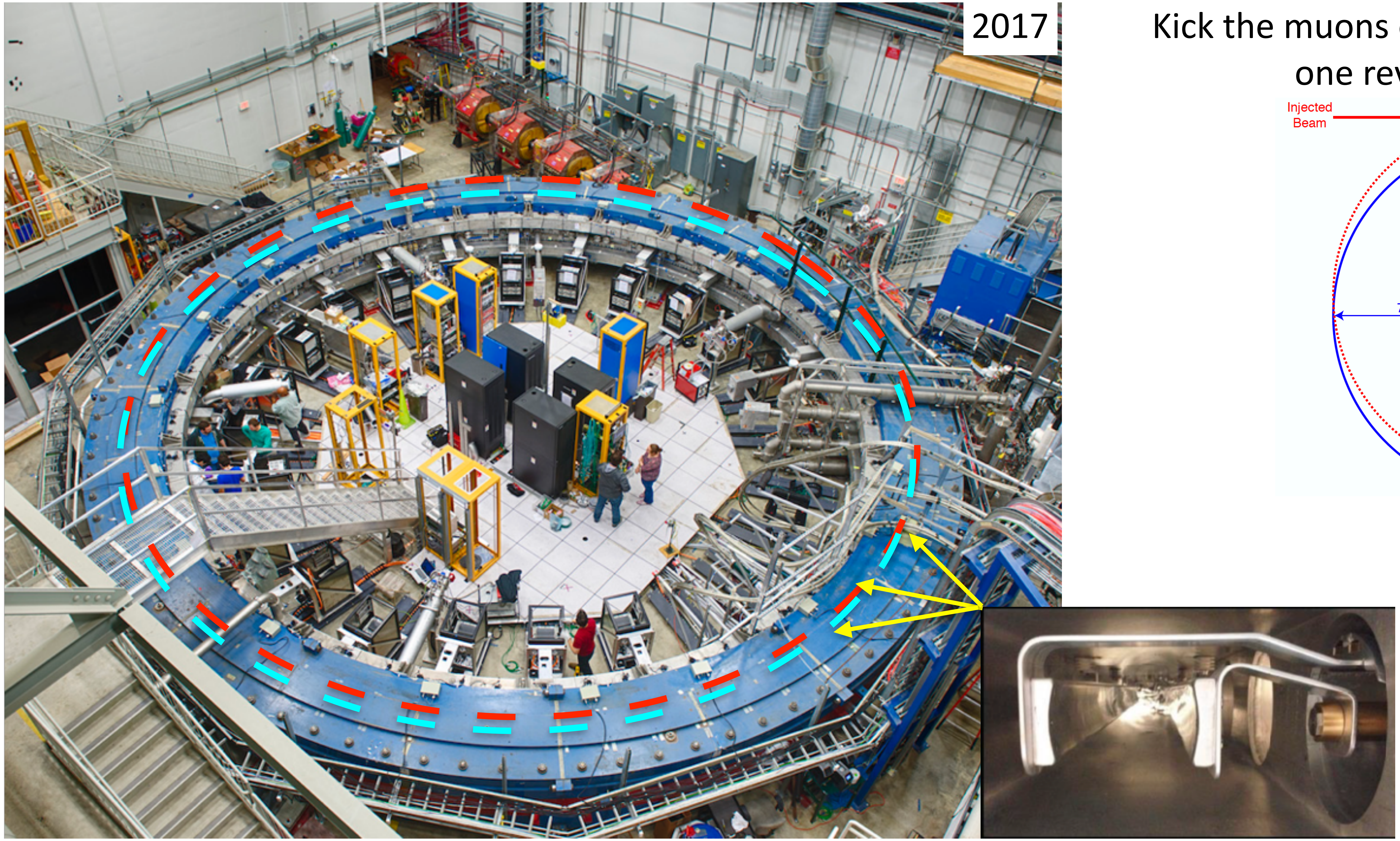
Superconducting inflector magnet cancels return B field in iron yoke to make muon travel straight!



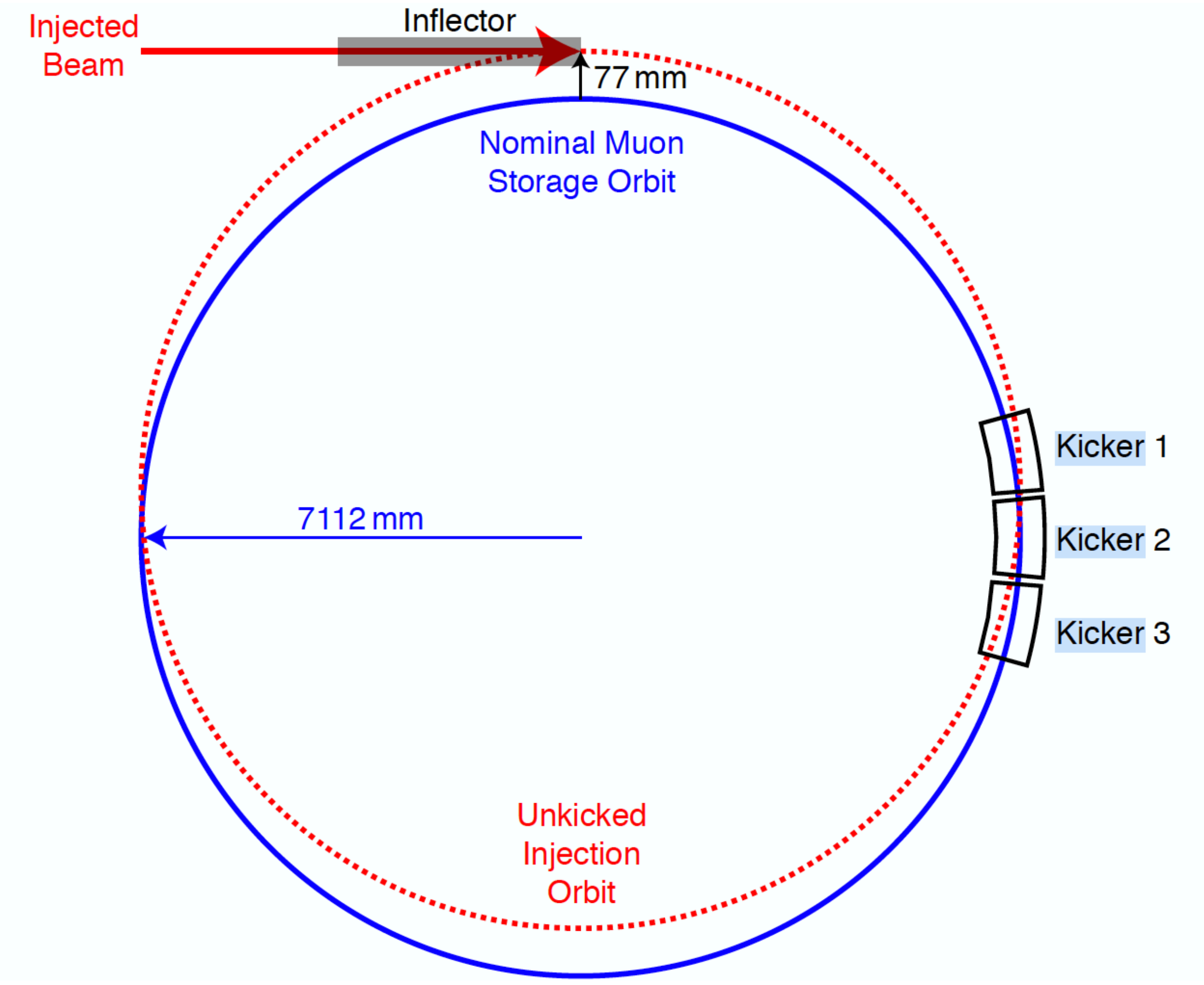


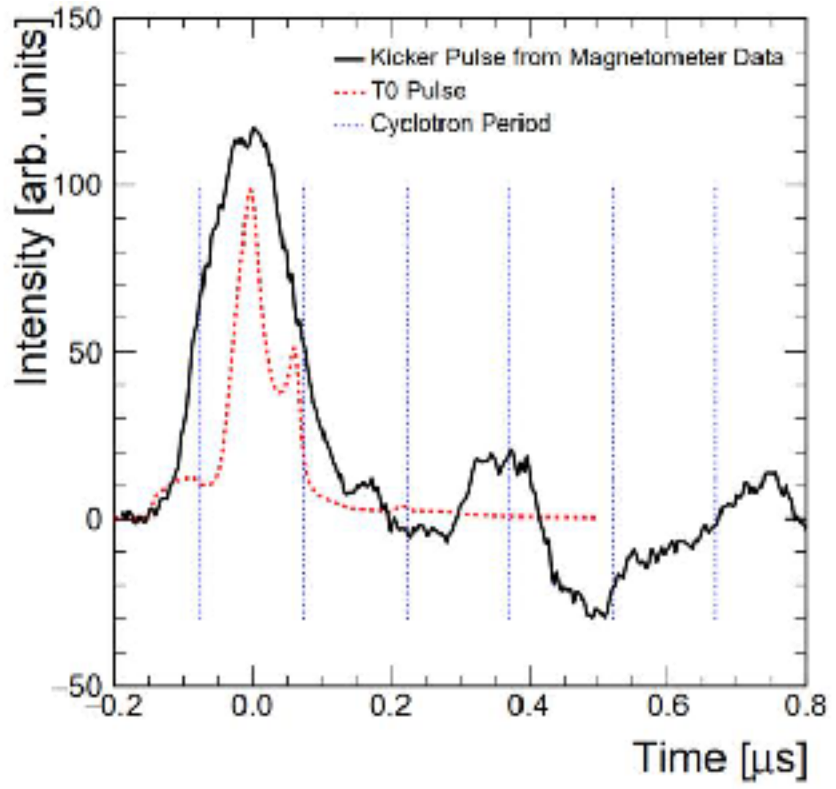
Field free region

The fast kicker

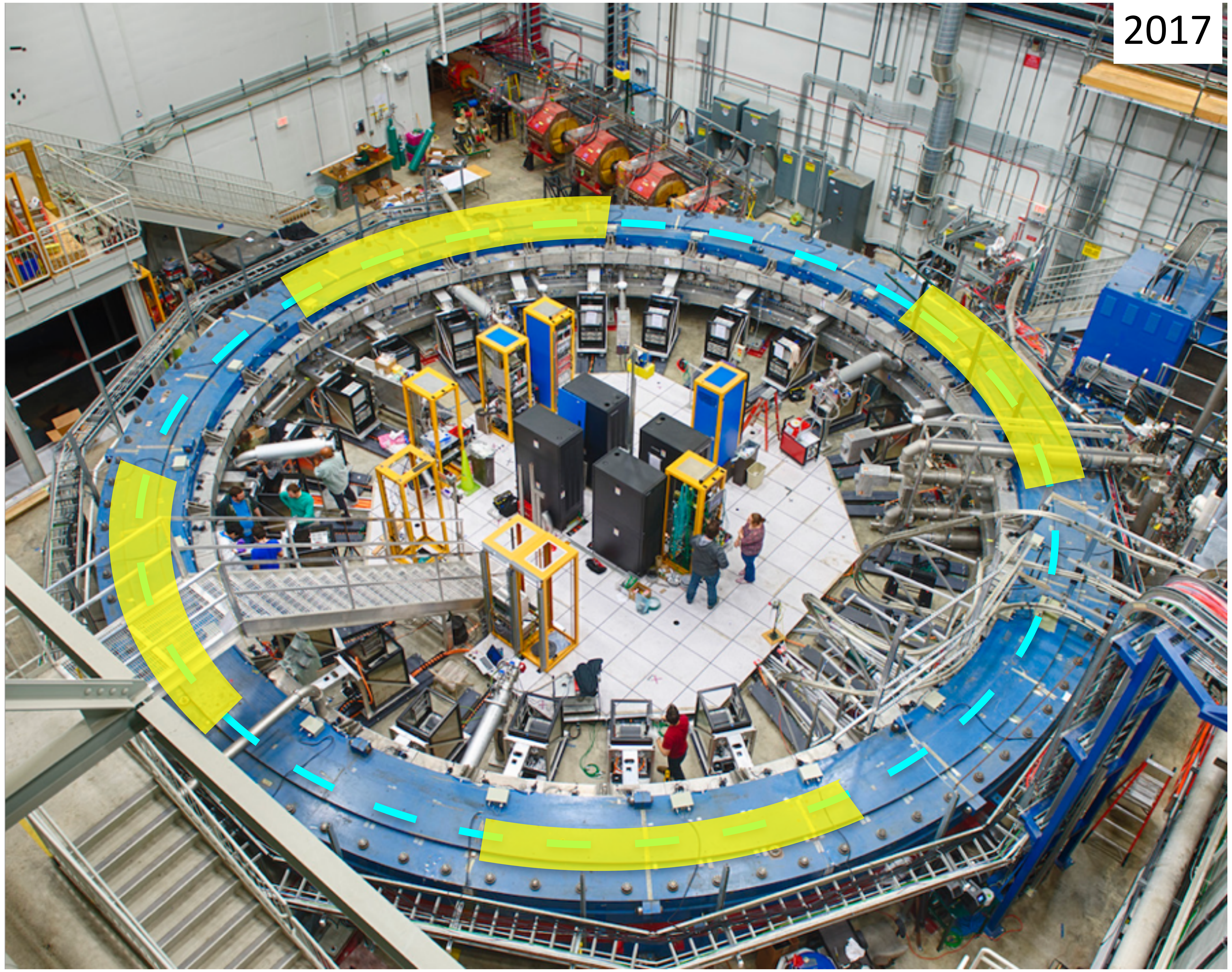


Kick the muons on their storage orbit within one revolution (≈ 149 ns)





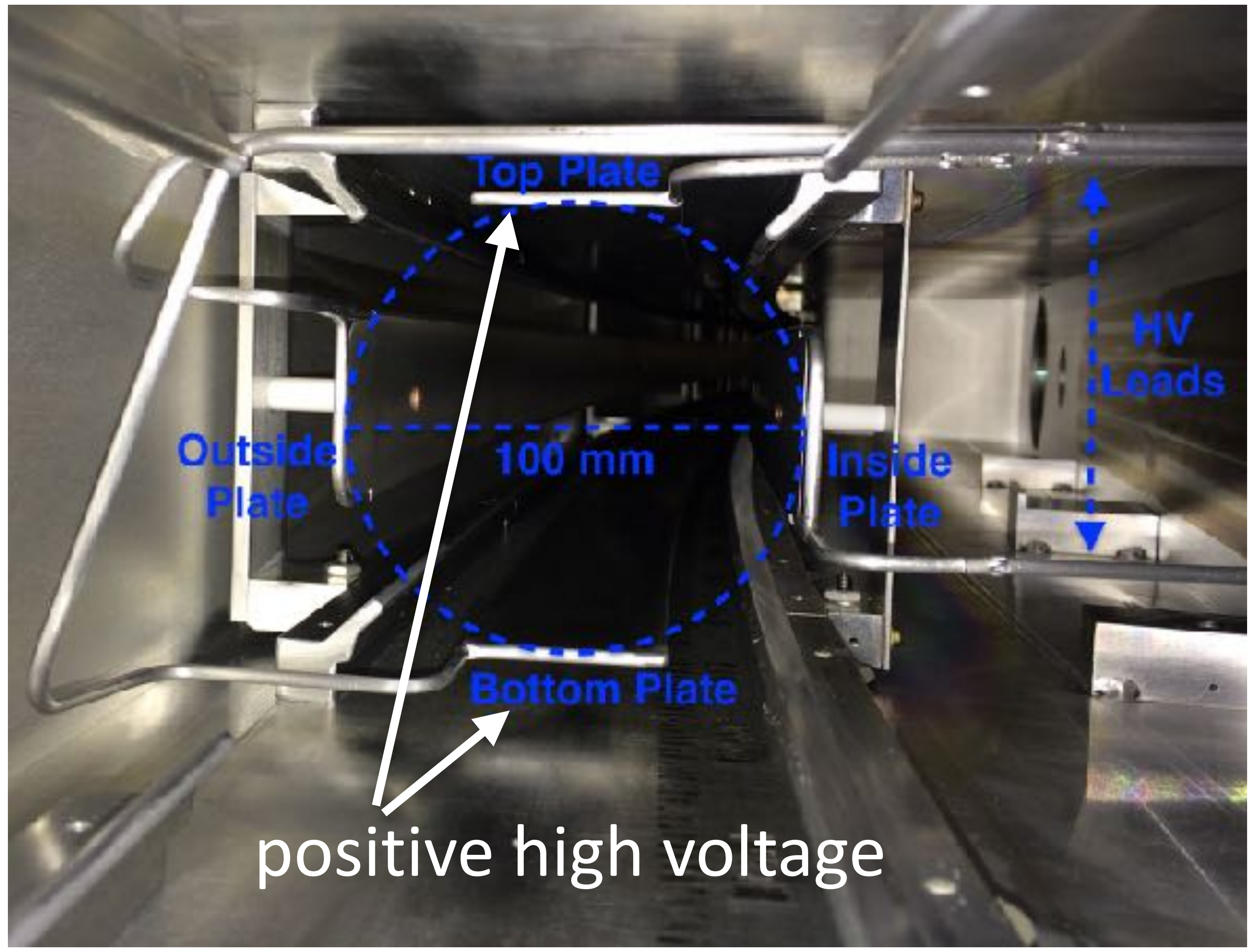
The electrostatic quadrupoles



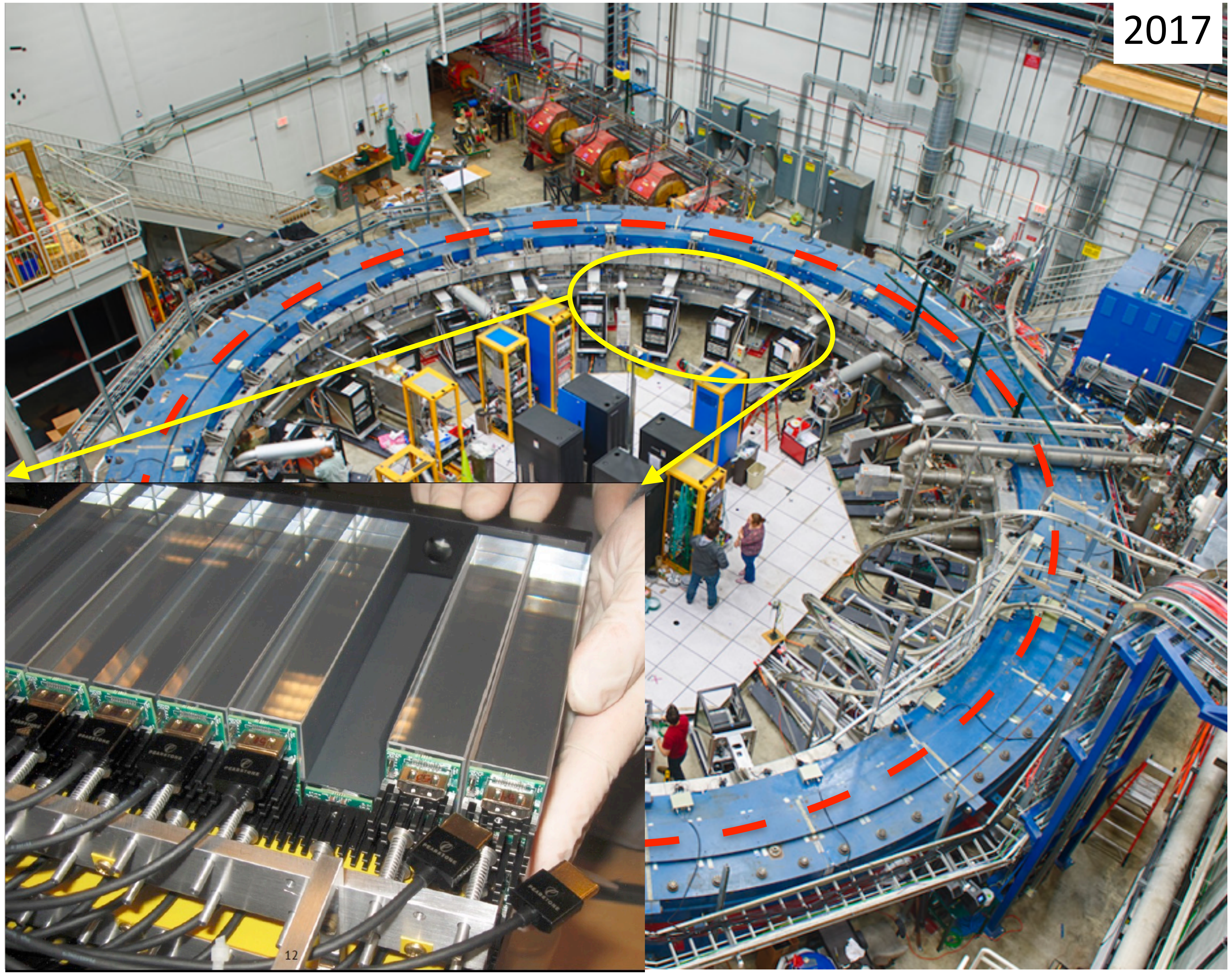
Pulsed “electrostatic” quadrupoles

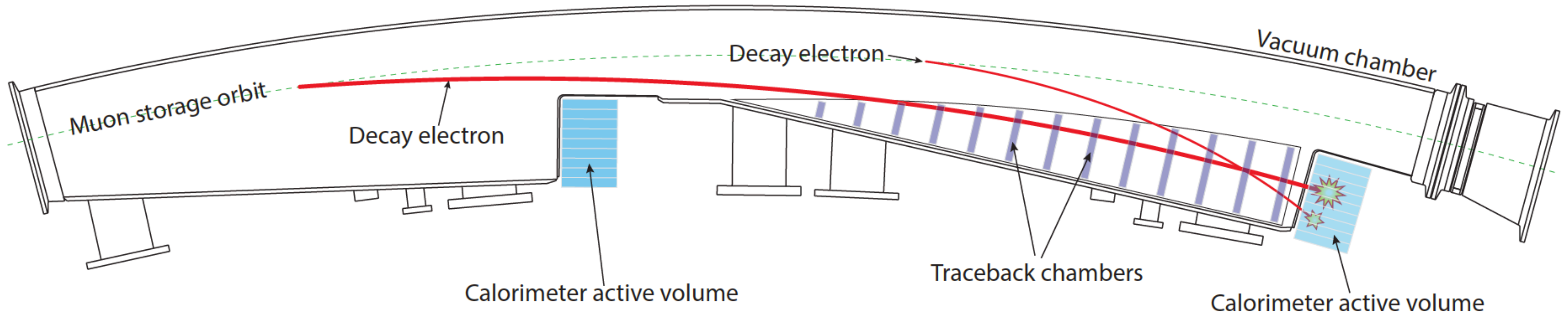
Vertical focusing and confinement of muon beam

Quasi-penning trap cover 43% of the ring



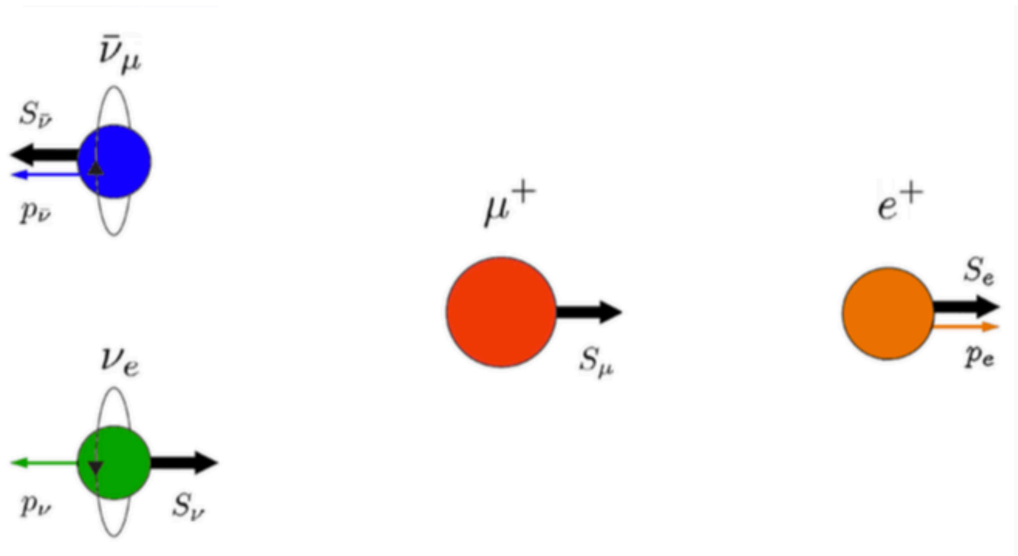
The positron calorimeter system

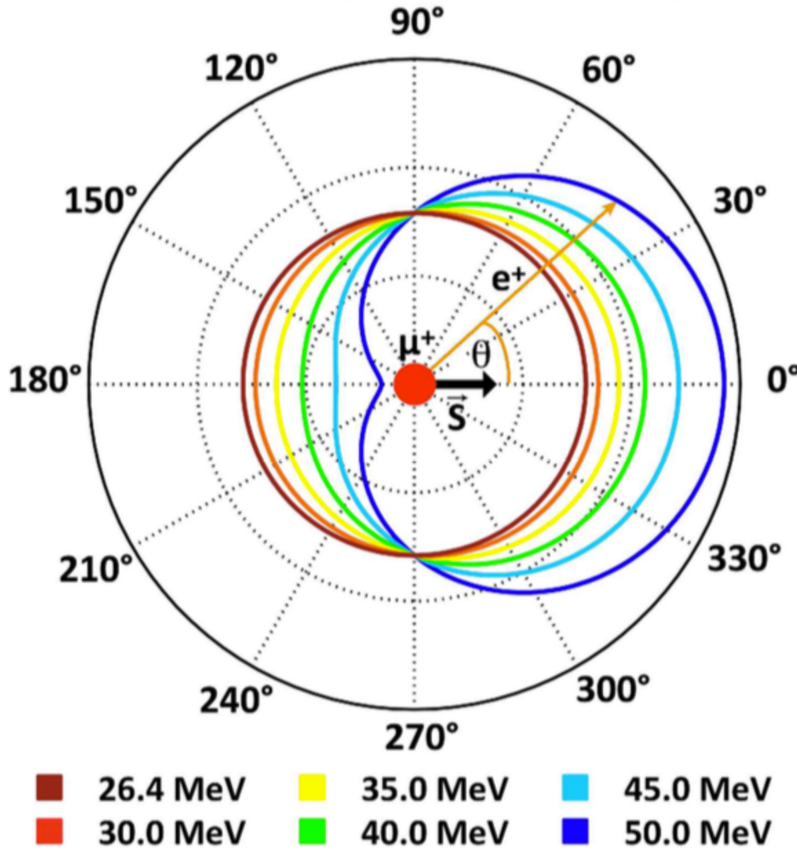




Parity violation, again!

In the muon rest frame





24 calorimeter stations to detect the decay positrons
9 x 6 arrays of PbF_2 crystals (Cherenkov detectors!)

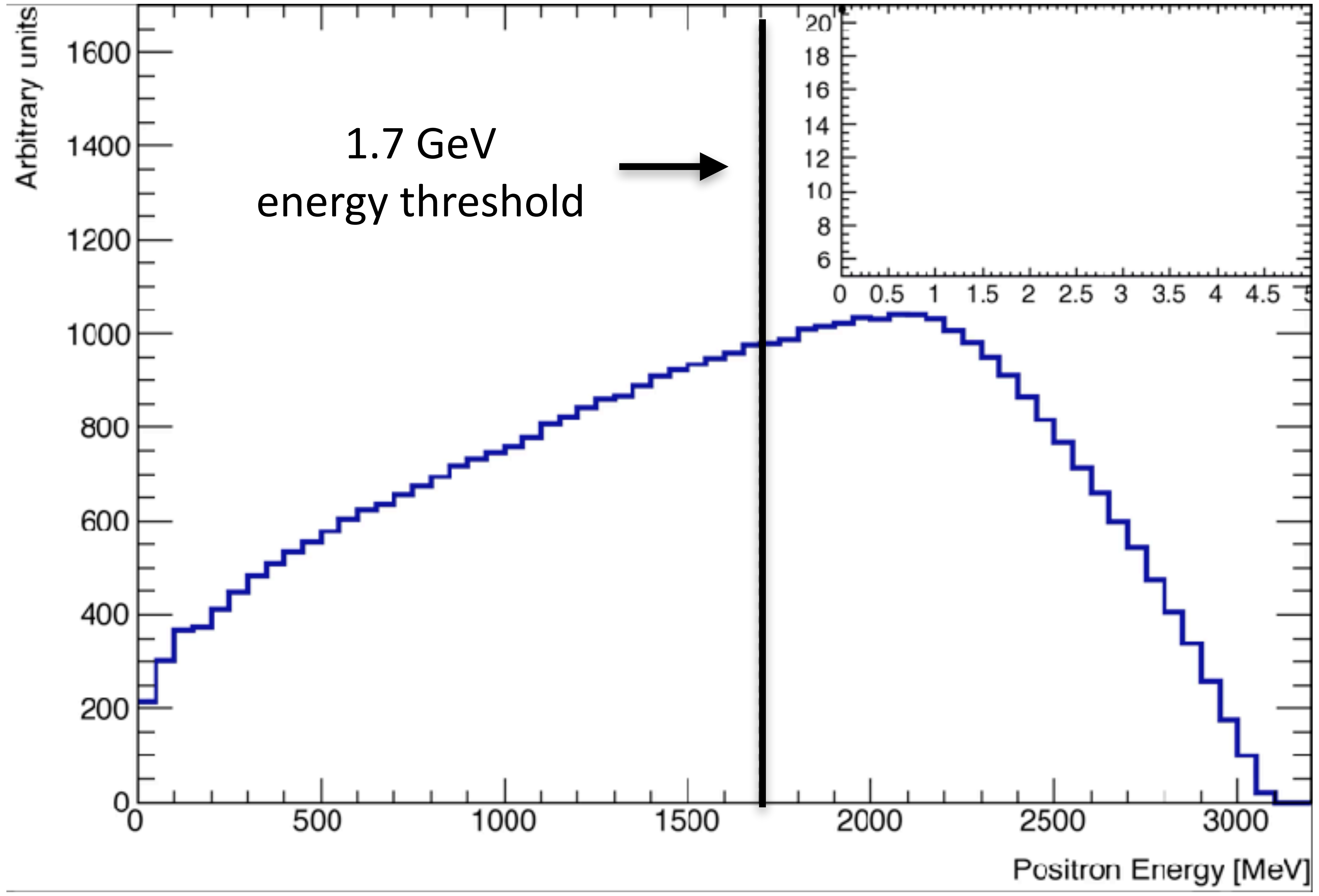
JG|U

Wiggle plot basics and laser calibration system

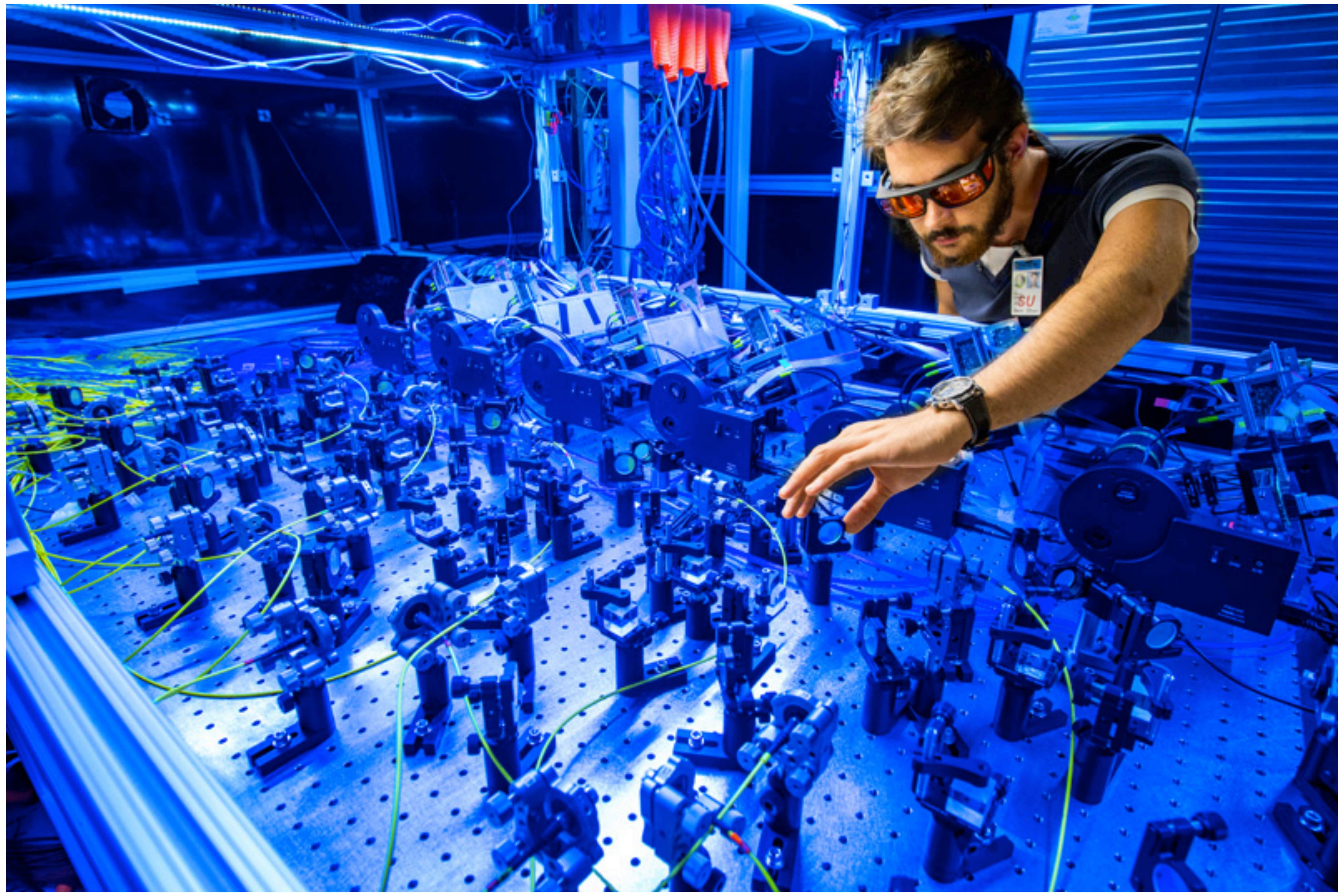
Spin precession in muon rest frame

transforms to

above-energy-threshold count rate modulation in laboratory frame



Dedicated laser calibration system to ensure energy calibration of calorimeter system

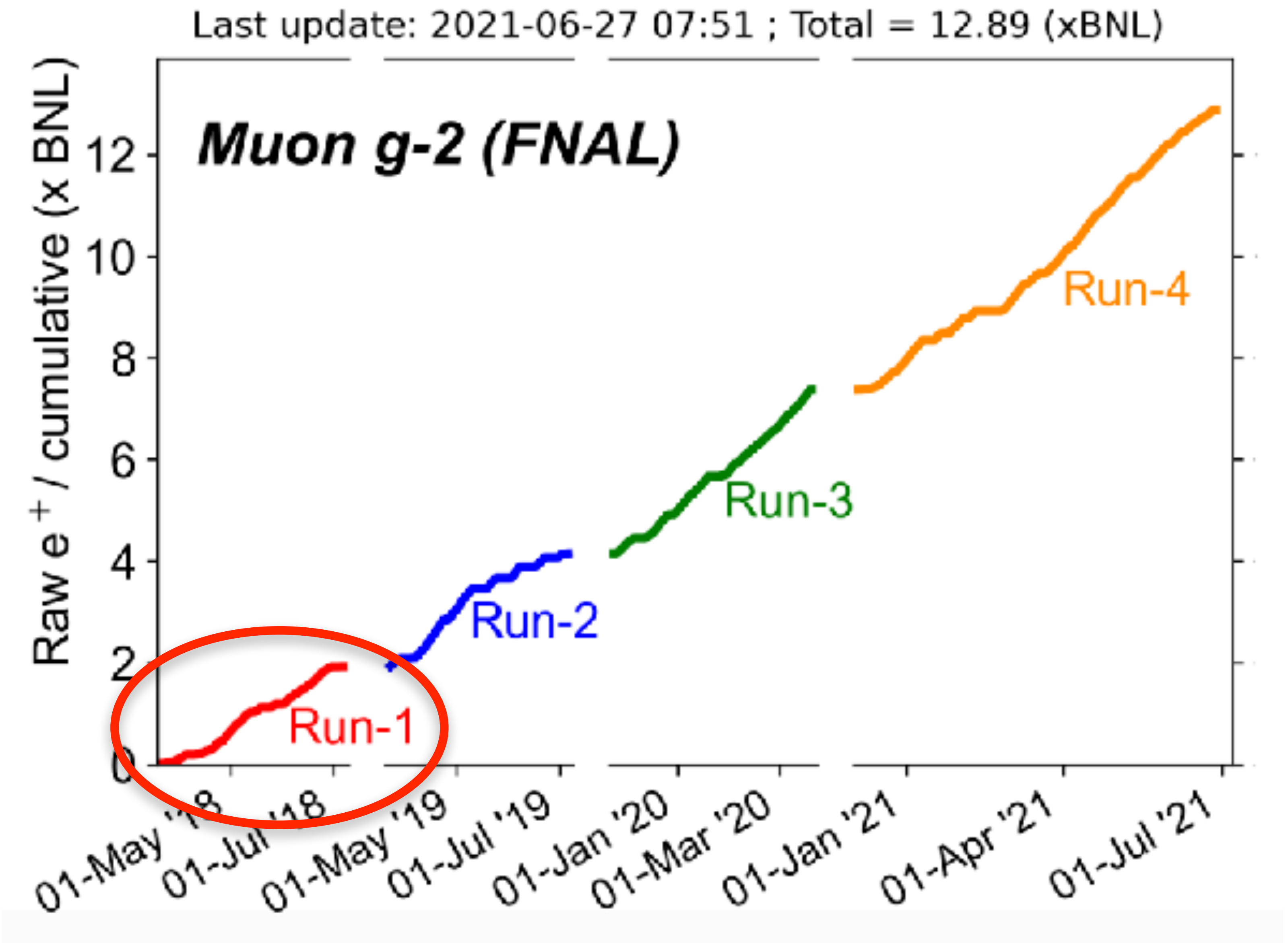


The blinding of the master clock …

- … by Greg Bock and Joe Lykken in 2018 (hardware blinding) …

- … and additional software blind for each ω_a analysis team

The statistics and the uncertainty table for Run 1



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

Uncertainty dominated by statistics!

Already surpassed the anticipated goal (70 ppb)!

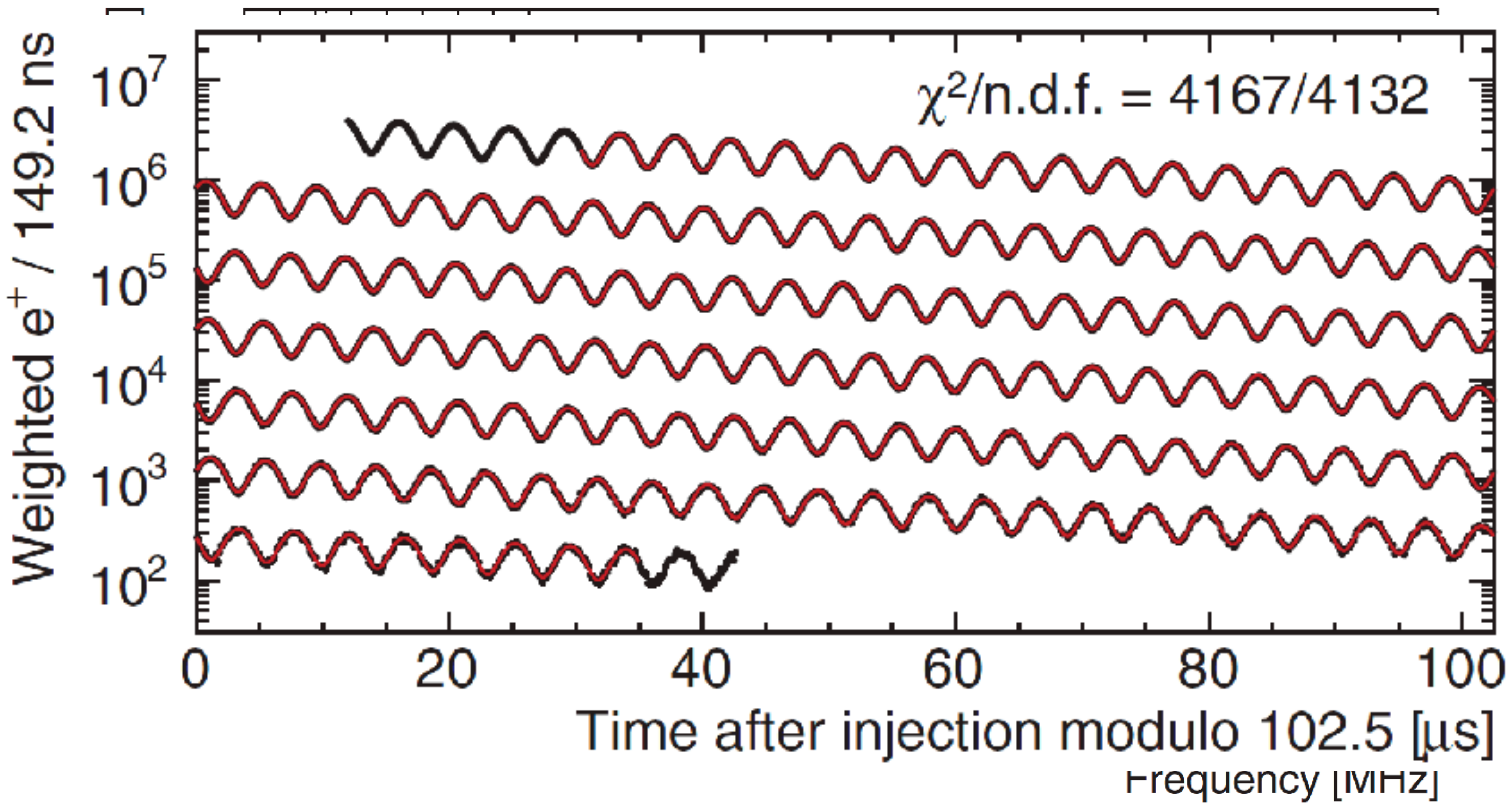
Work in progress for runs 2-5!

Total uncertainty dominated by statistics!

Dataset	Date	Field index n ESQ HV [kV]	Kicker HV [kV]	Number of positrons
1a	Apr 22, 2018 - Apr 25, 2018	0.108 18.3	130	0.9×10^9
1b	Apr 26, 2018 - May 02, 2018	0.120 20.4	137	1.3×10^9
1c	May 04, 2018 - May 12, 2018	0.120 20.4	132	2.0×10^9
1d	Jun 06, 2018- Jun 29, 2018	0.108 18.3	125	4.0×10^9

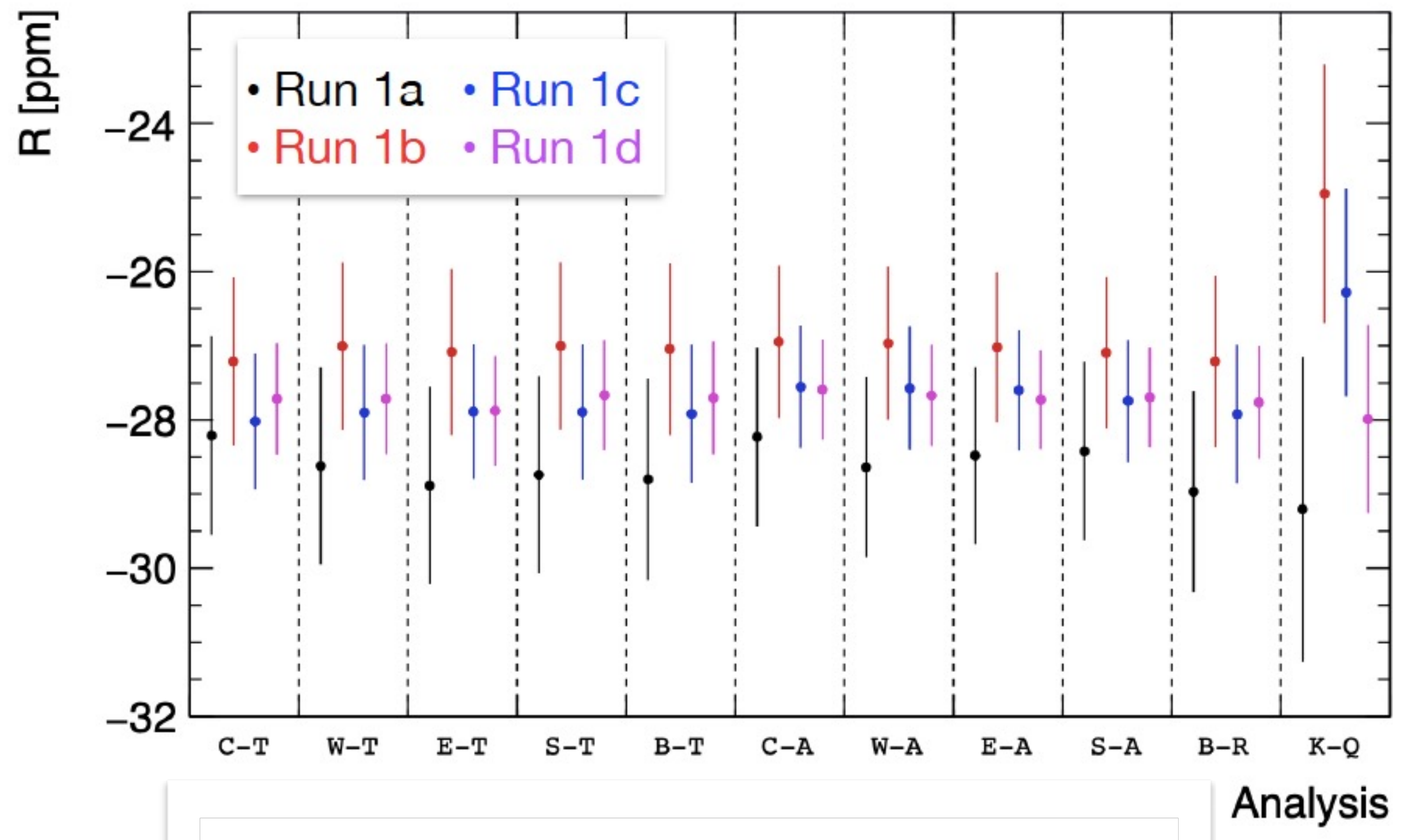
Extract ω_a^{meas} from the wiggle plot

Histogram of decay e^+ arrival times (wiggle plot)



Separate analyses for Runs 1a-1d:
3 independent event reconstruction schemes
11 different and independent analyses
6 independent groups

Extensive systematic checks passed:
→ "Software" unblinding to check consistency, hardware blinding still in place

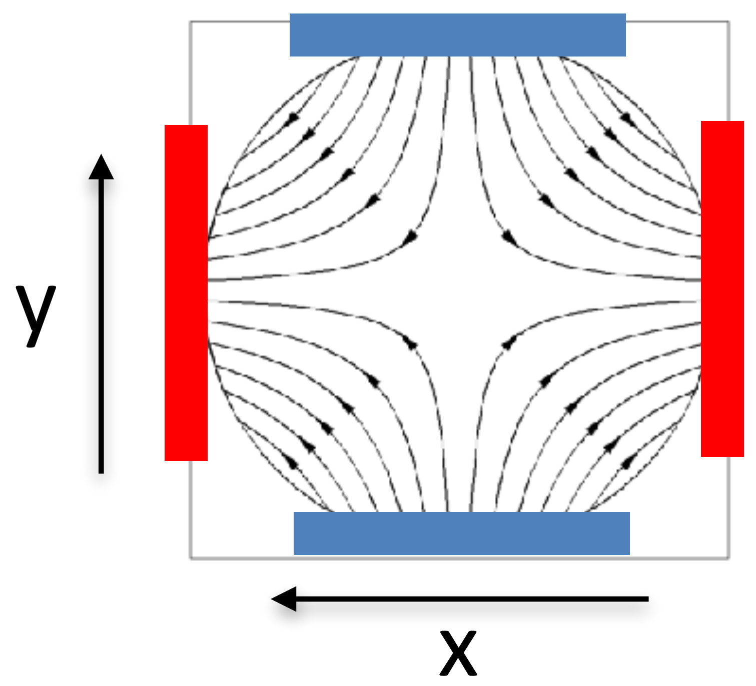


- **434 ppb** statistical uncertainty
- **56 ppb** systematic uncertainty

The long-known corrections: E-field and pitch correction

$$\frac{d}{dt}P_{\mathrm{L}} = \frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s}_{\perp}\cdot\left[a_{\mu}\hat{\beta}\times\vec{B} + \left(a_{\mu} - \frac{1}{\gamma^2-1}\right)\beta\vec{E}\right]$$

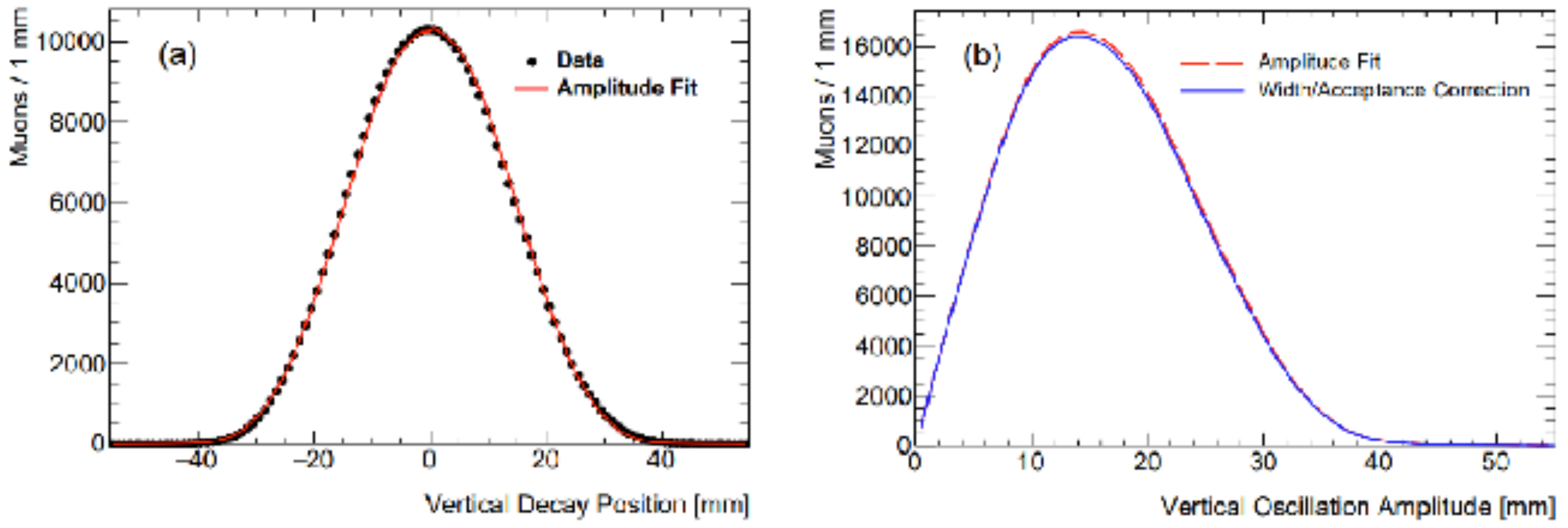
Pitch correction



Electrostatic focusing → spin precession due to E_x and vertical harmonic motion in quadratic E field!

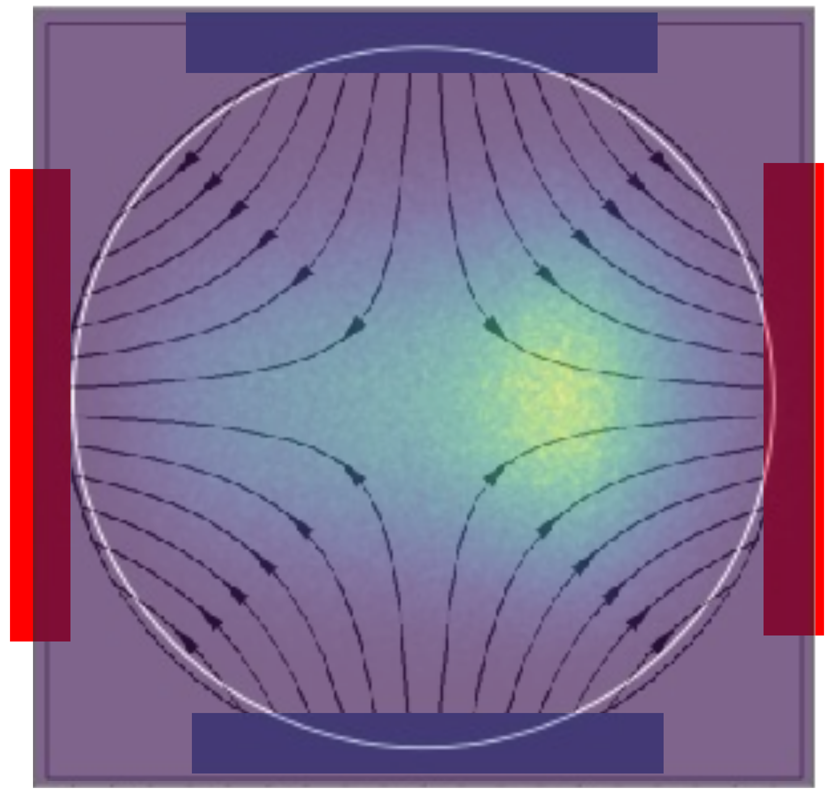
$$C_{\mathrm{p}} = \frac{n}{4R_0^2}\langle A^2\rangle$$

Trackers measure vertical oscillation amplitude

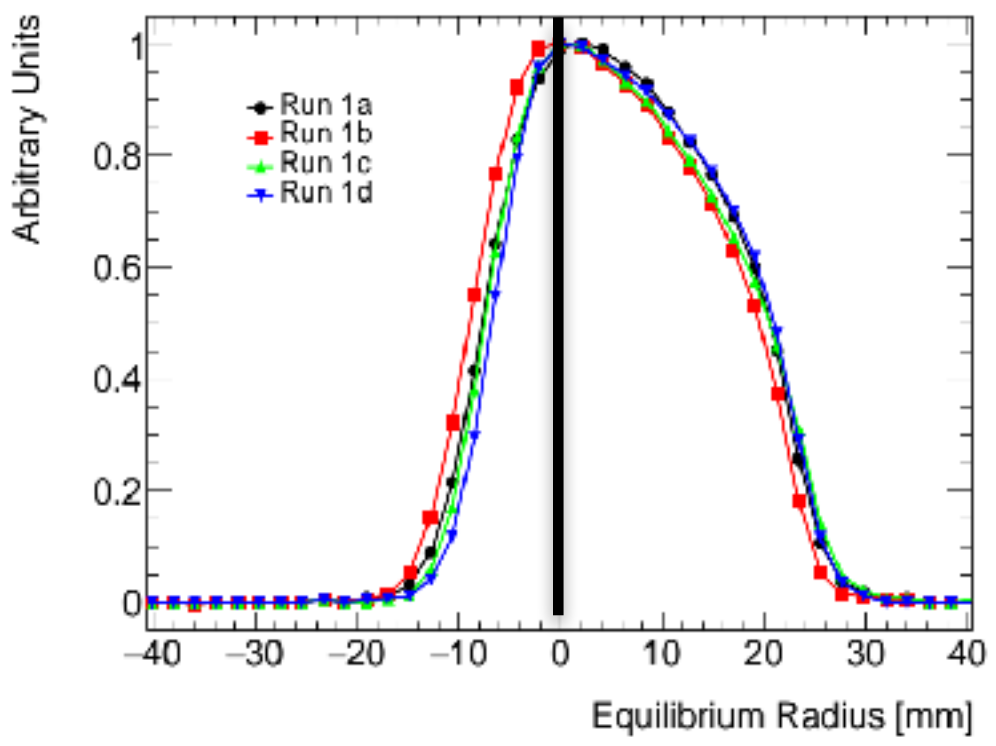


Correction: 180 ppb, Uncertainty: 13 ppb

Electric field correction



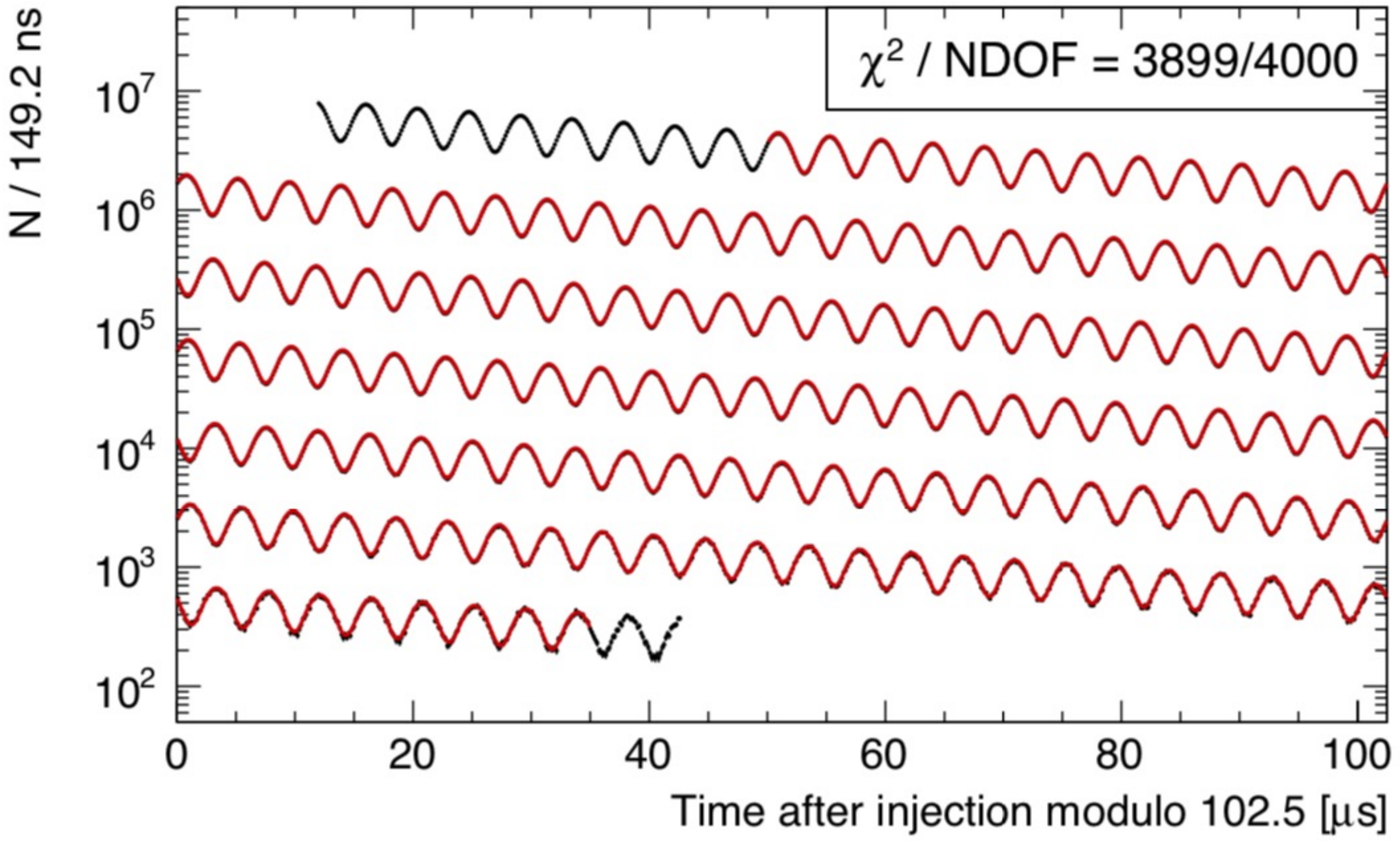
"Fast rotation analysis"



$$C_e = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

Correction: 489 ppb, Uncertainty: 53 ppb

Phase acceptance correction



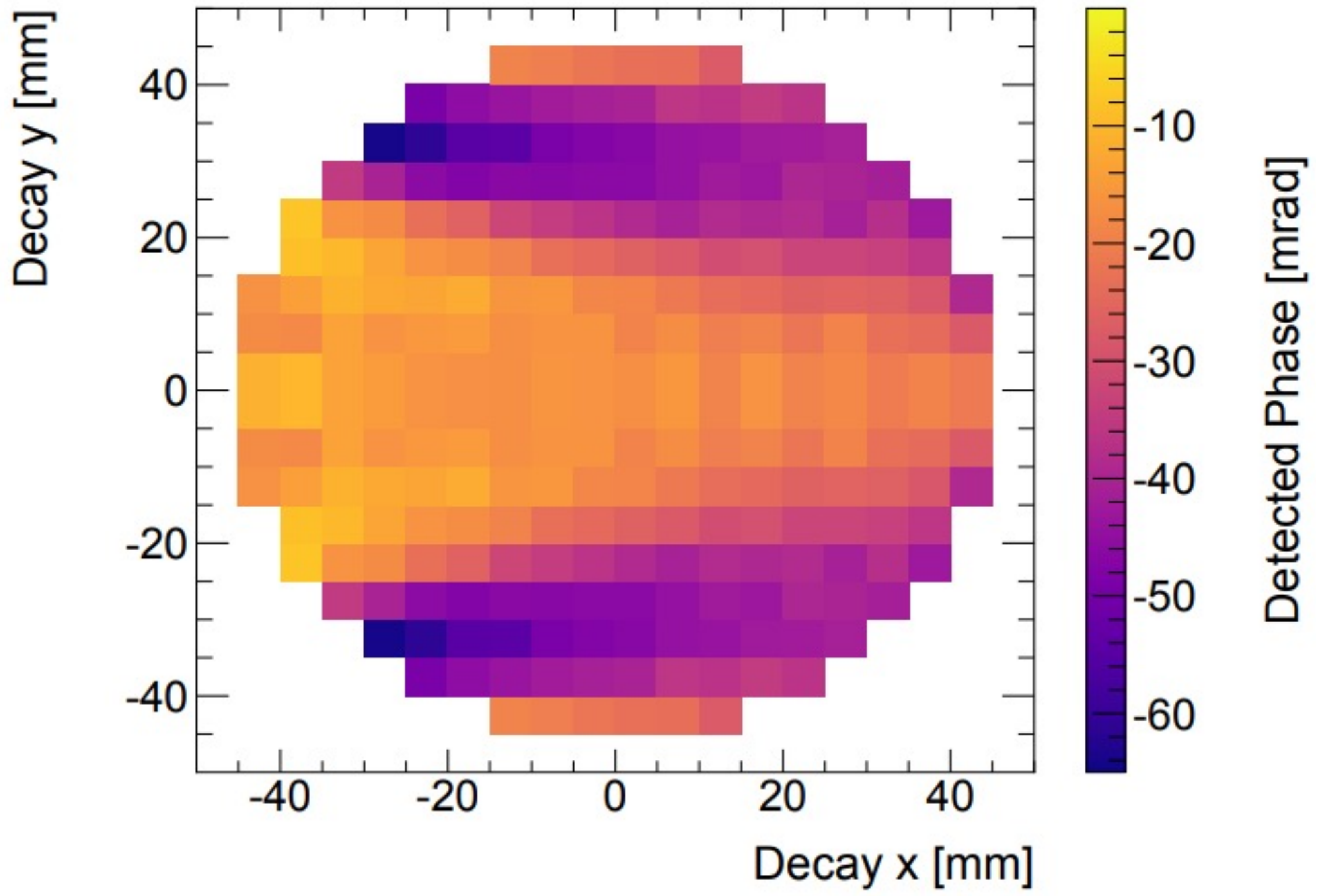
$$N(t) \approx N_0 e^{-\lambda t}\left[1 + A\cos\left(\omega_a t + \phi\right)\right]$$

If the phase of the muon ... is not stable, then:

$$\cos\left(\omega_a t + \phi_0 + \ldots\right) = \cos\left((\omega_a + \phi')t + \phi_0 + \ldots\right)$$

early-to-late effect

A possible frequency shift of ϕ'

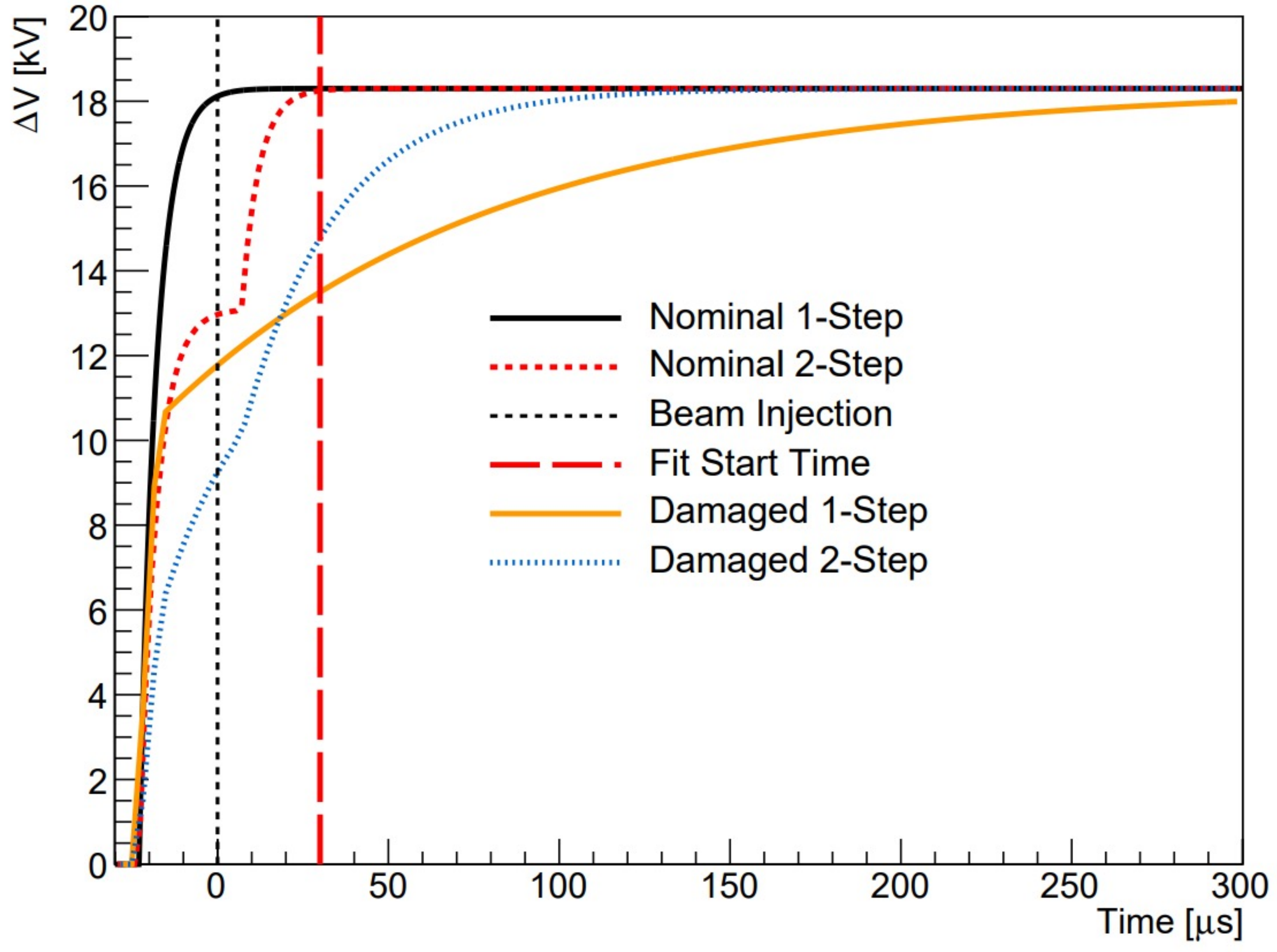


- The decay positrons carry a particular phase
- The phase depends on
  - Muon decay position
  - Decay positron energy

Extensive simulation campaign

- Not a problem if muon distribution is stable in time, but…

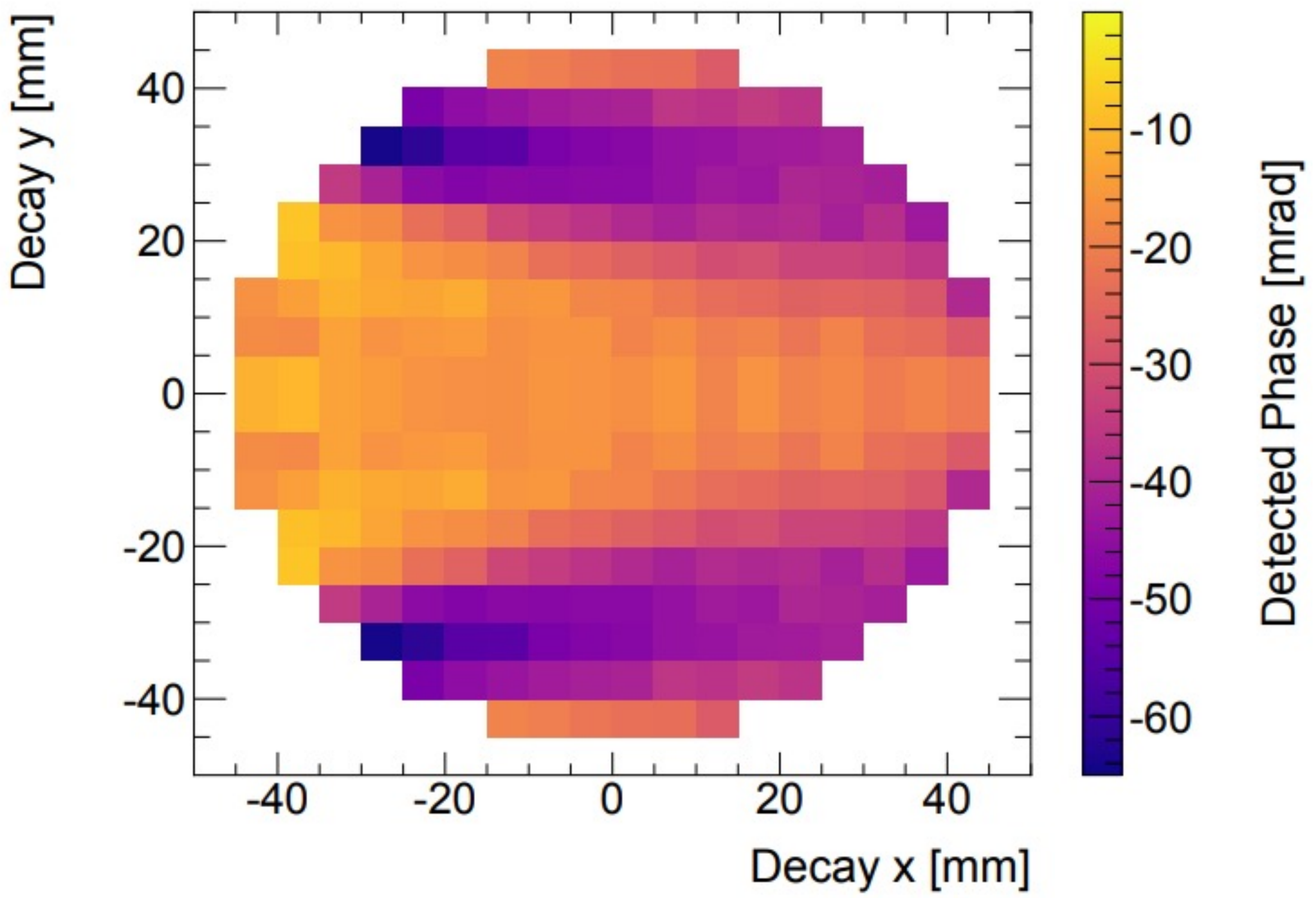
Phase acceptance correction: The voltage on the ESQs

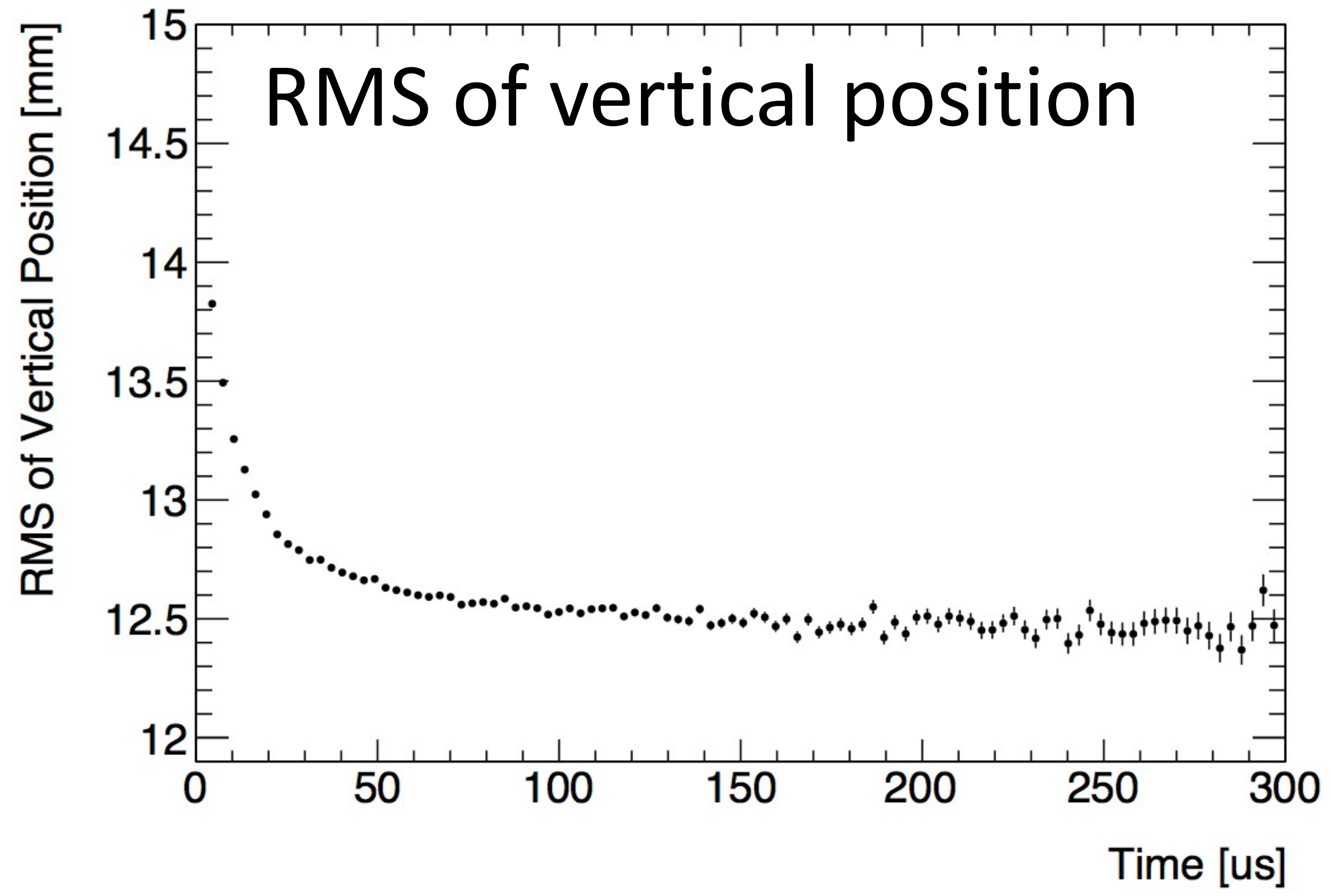


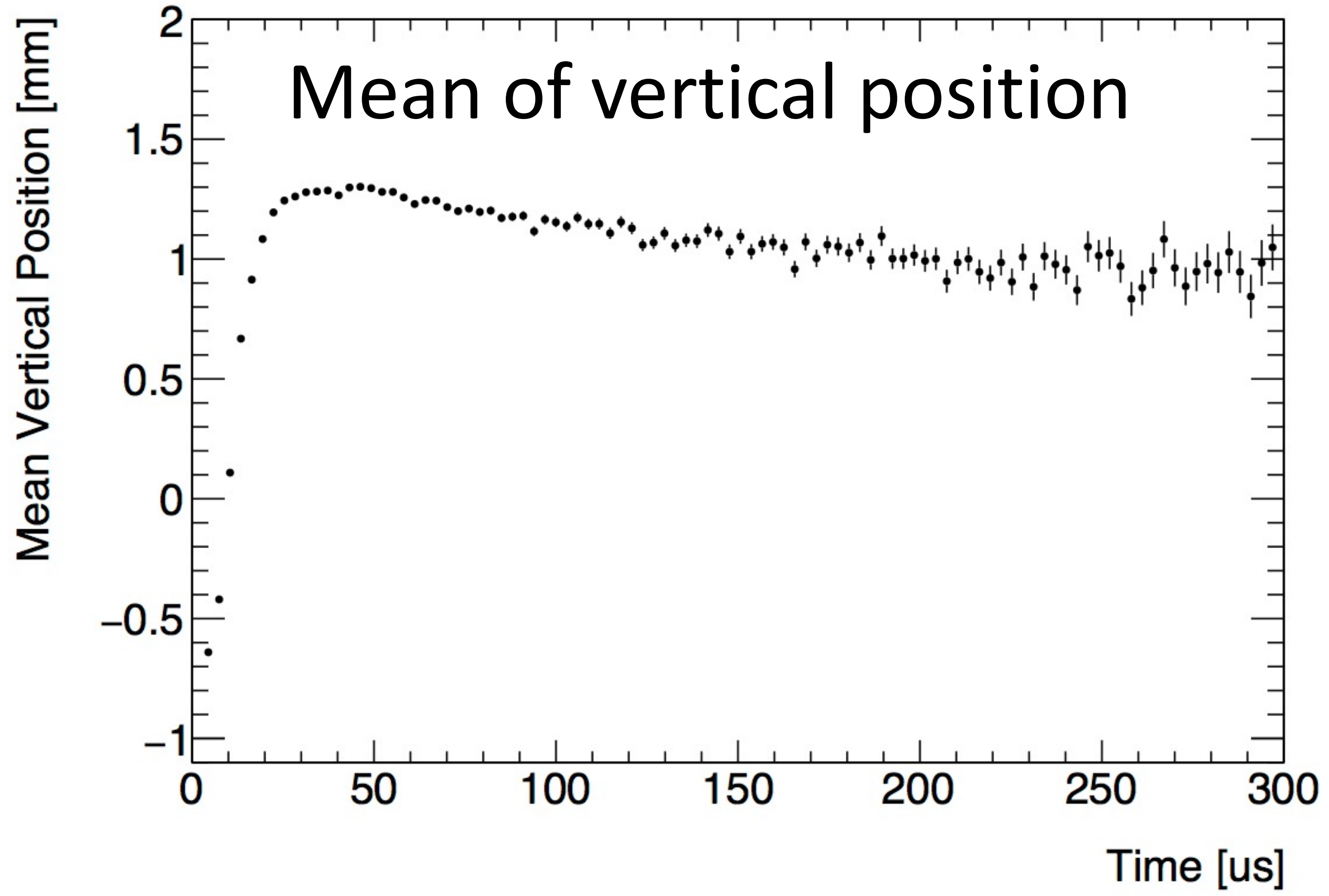
Systematic effect unique for Run 1 data (hardware fixed for run 2 and beyond):

- 2 high-voltage isolators for ESQ failed
- Time-dependent E-Field of on 2 ESQ plates
  → Change of vertical beam position and width

Correction: -158 ppb, Uncertainty: 75 ppb







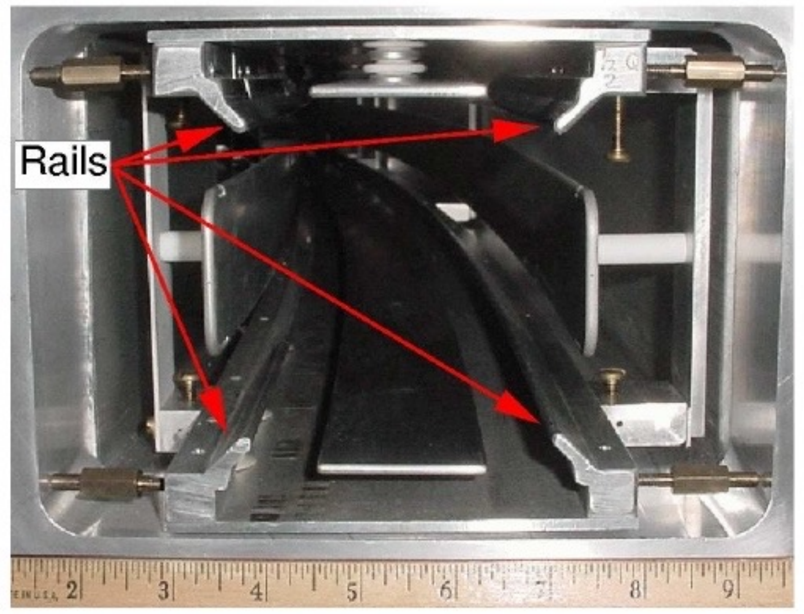
Extracting a_μ: the magnetic field distribution and calibration

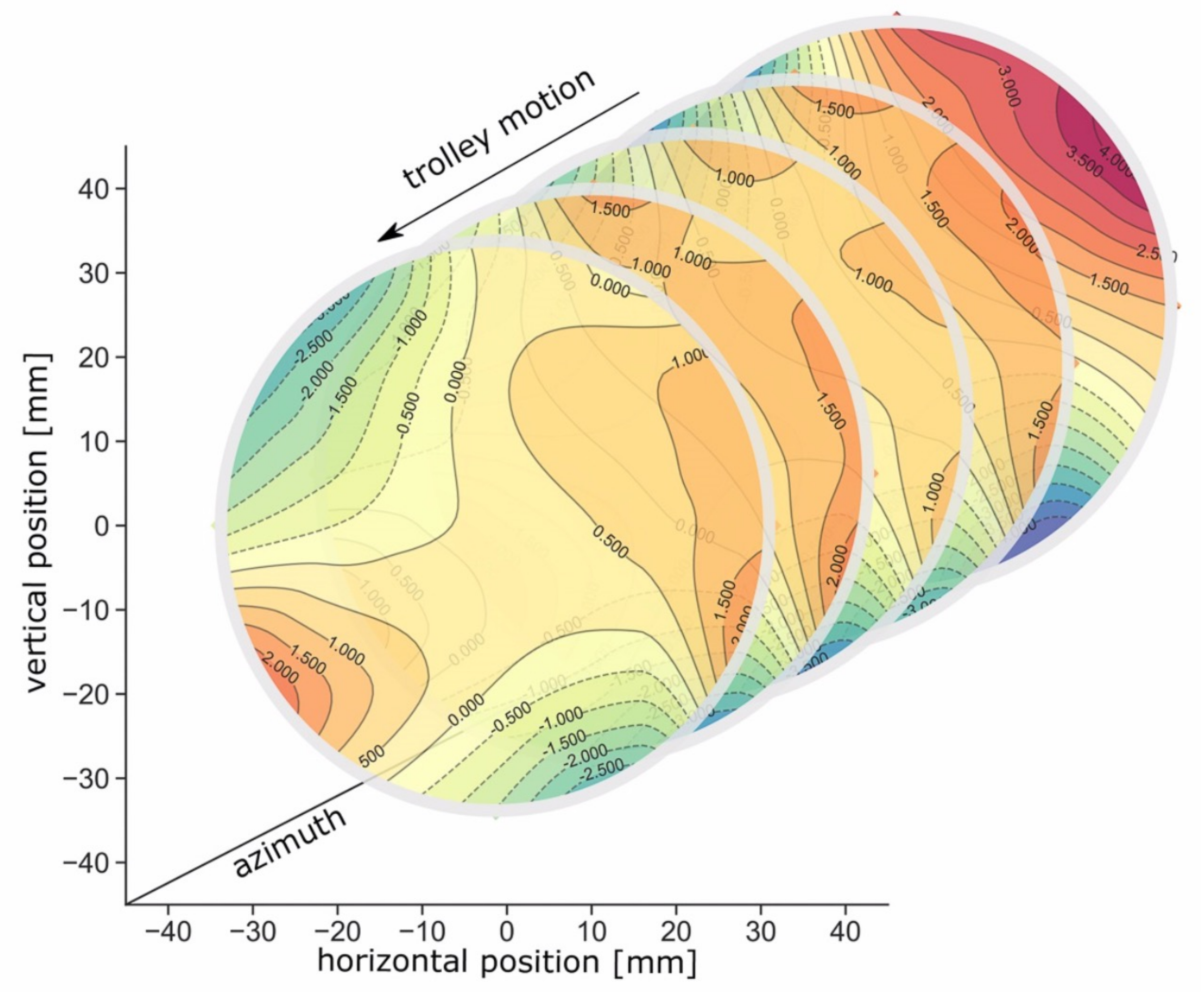
$$R' = \frac{\omega_a}{\omega'_p} = \frac{f_{\mathrm{clock}}\,\omega_a^{\mathrm{meas}}\left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{\boxed{f_{\mathrm{calib}}}\left\langle M\left(x, y, \phi\right)\boxed{\omega'_p\left(x, y, \phi\right)}\right\rangle\left(1 + B_k + B_q\right)}$$

The magnetic field calibration chain

"The trolley"

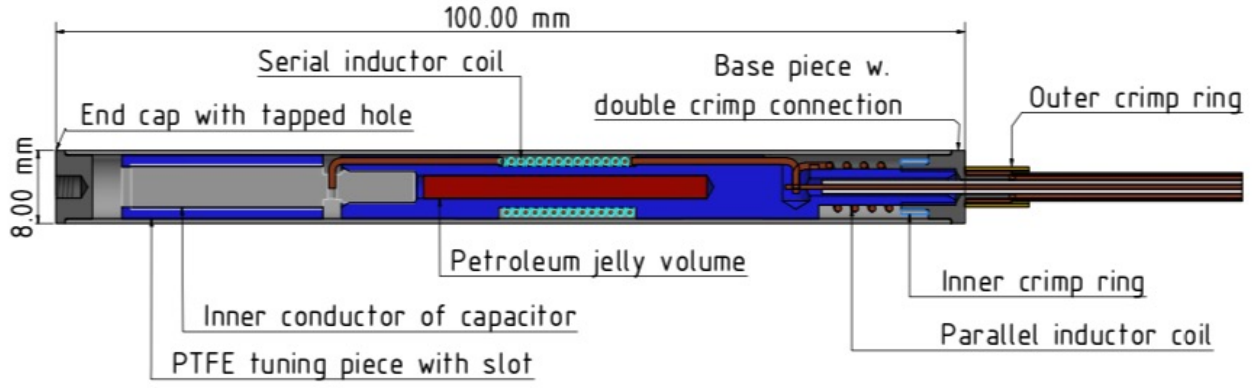
17 NMR probes, 3-day interval

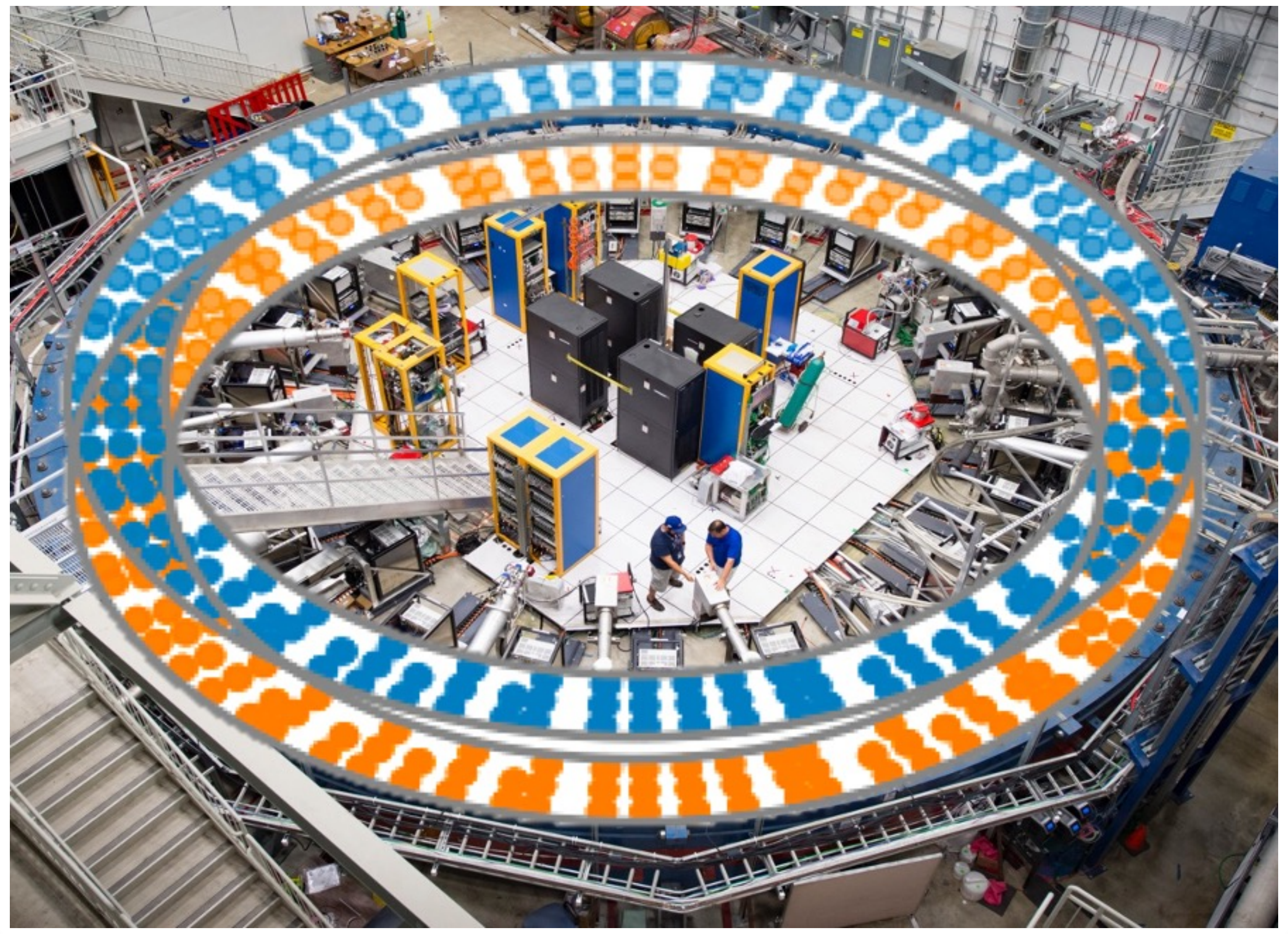




"The fixed probe array"

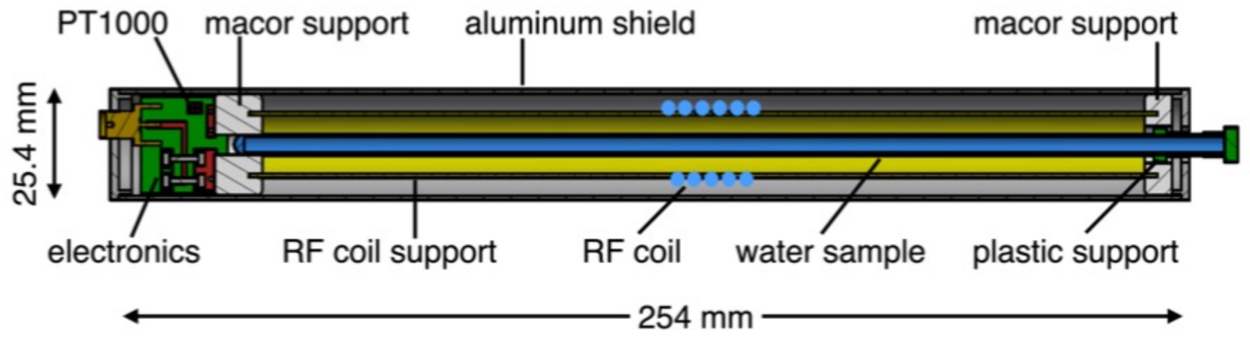
378 pulsed nuclear magnetic resonance probes measure 24/7 around μ beam

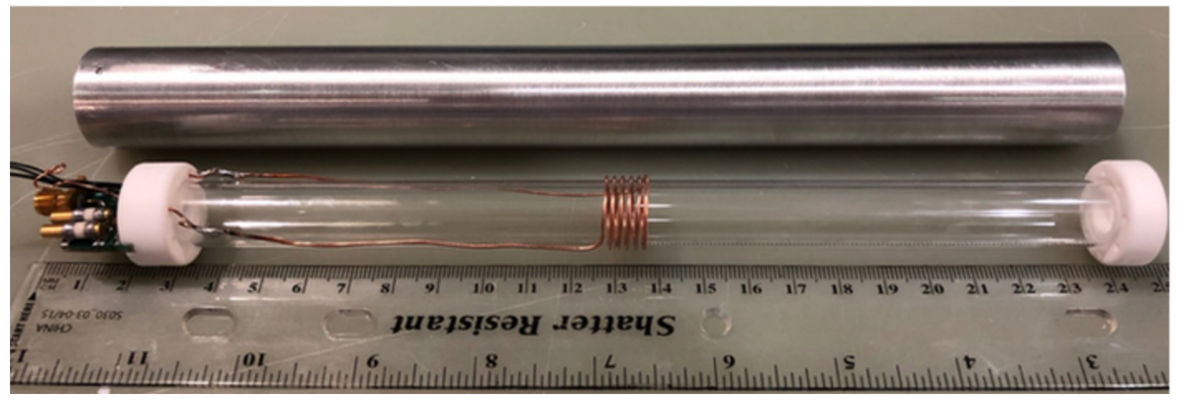




"The calibration"

"Plunging probe" to transfer absolute calibration to trolley probes

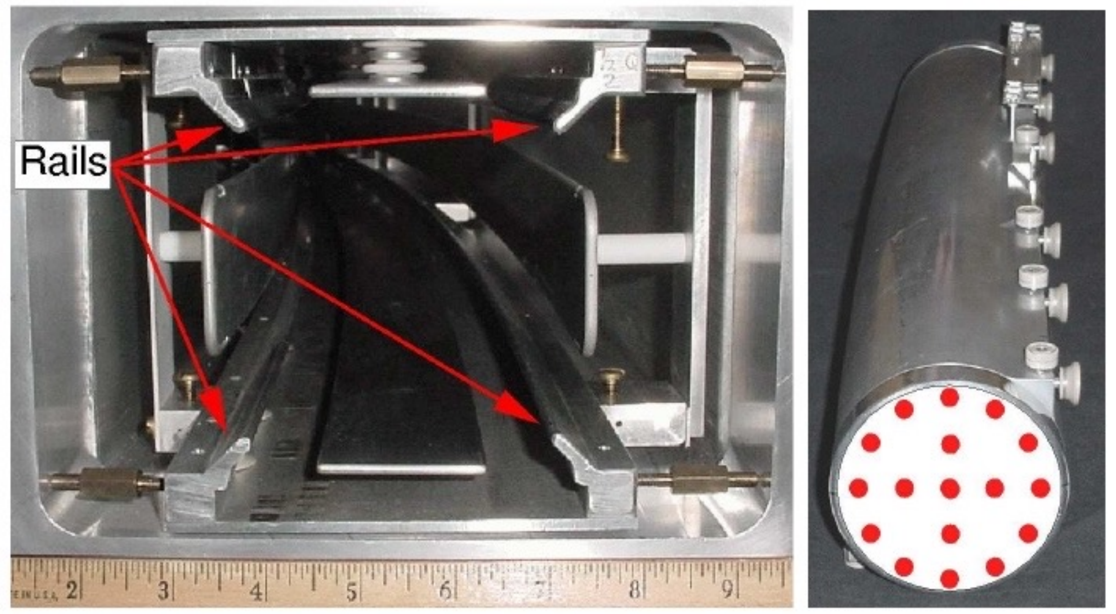


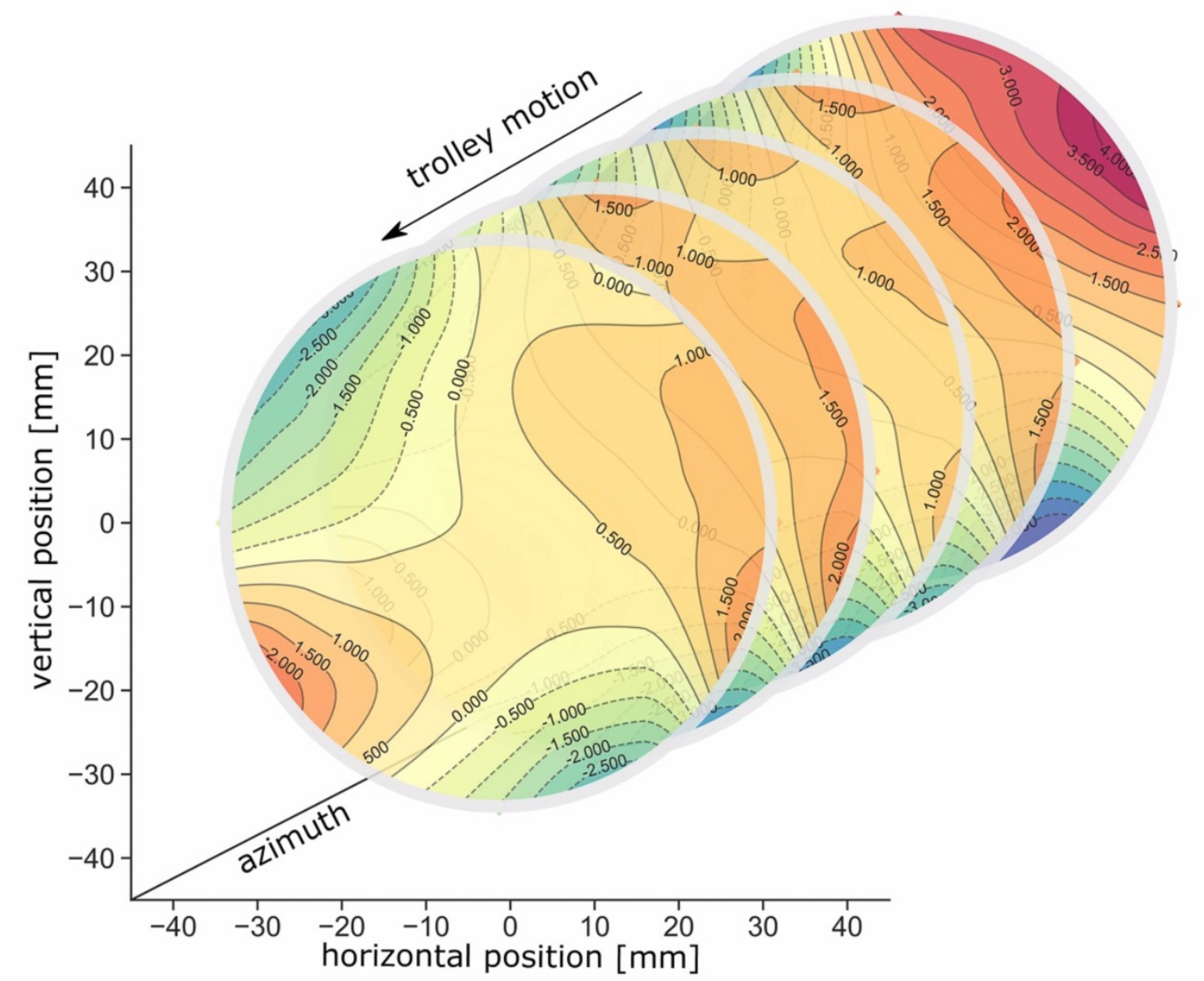


The precision magnetic field: spatial mapping

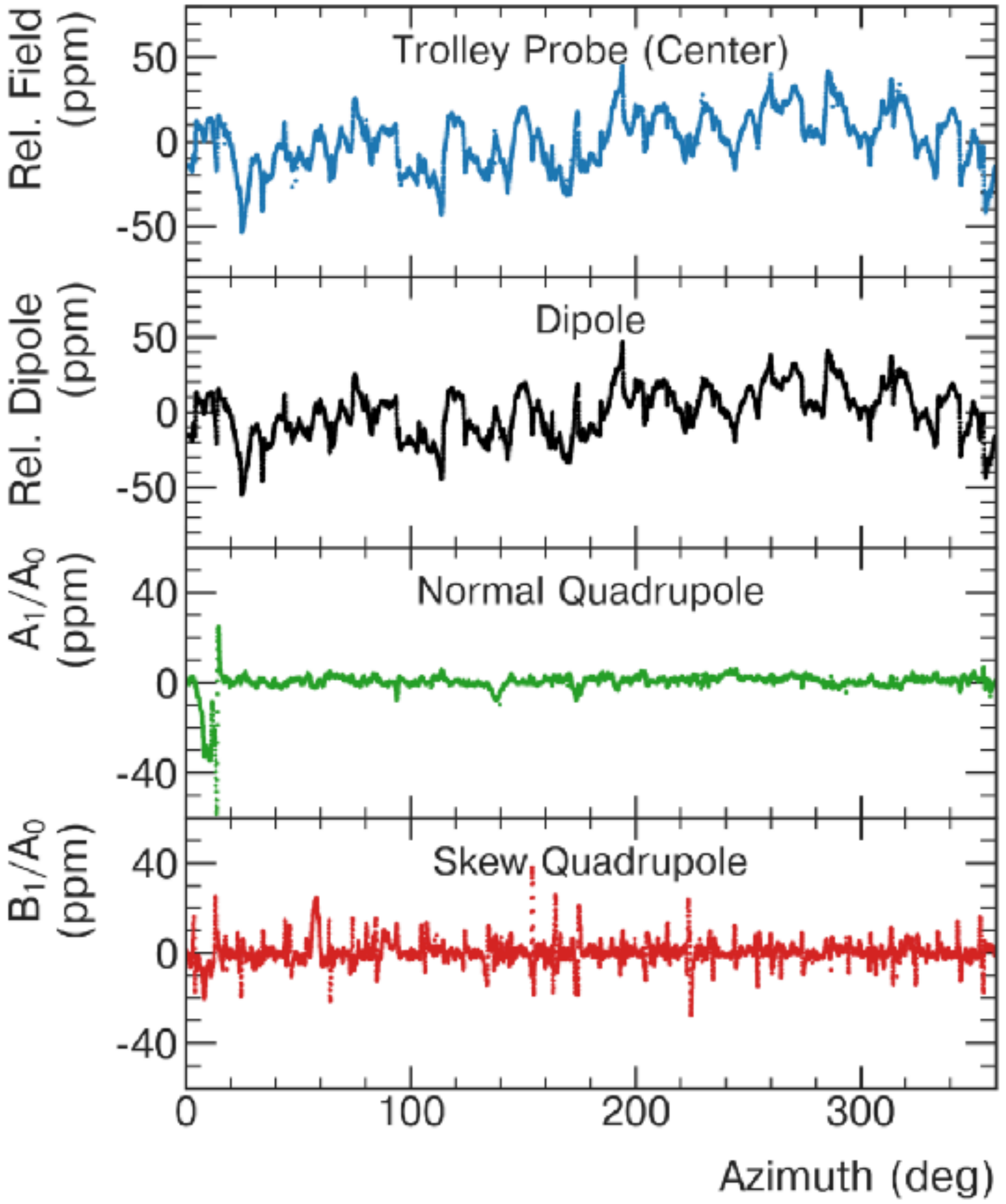
"The trolley"

17 NMR probes, 3-day interval

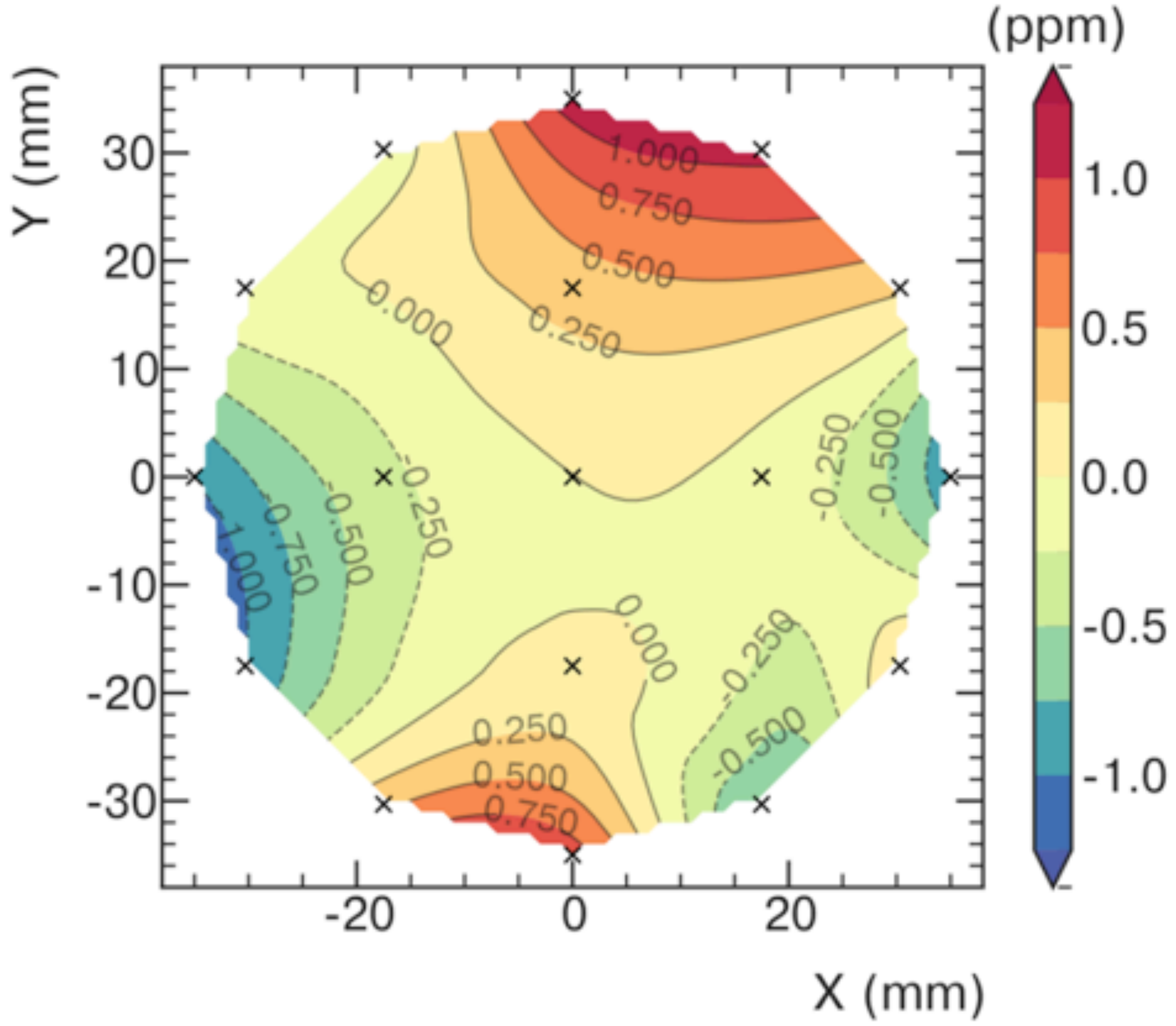




About 9000 azimuthal positions to make a field decomposition into 2D spatial multipoles



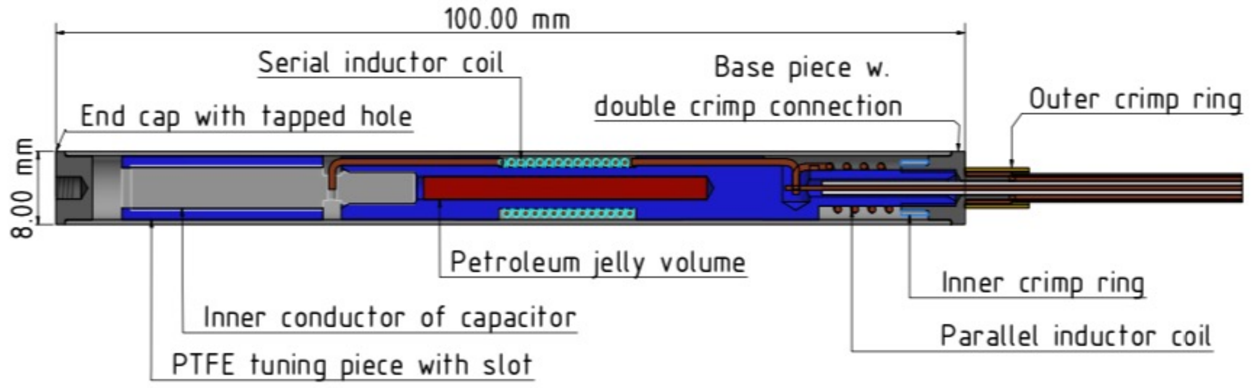
A typical azimuthally averaged magnetic field map

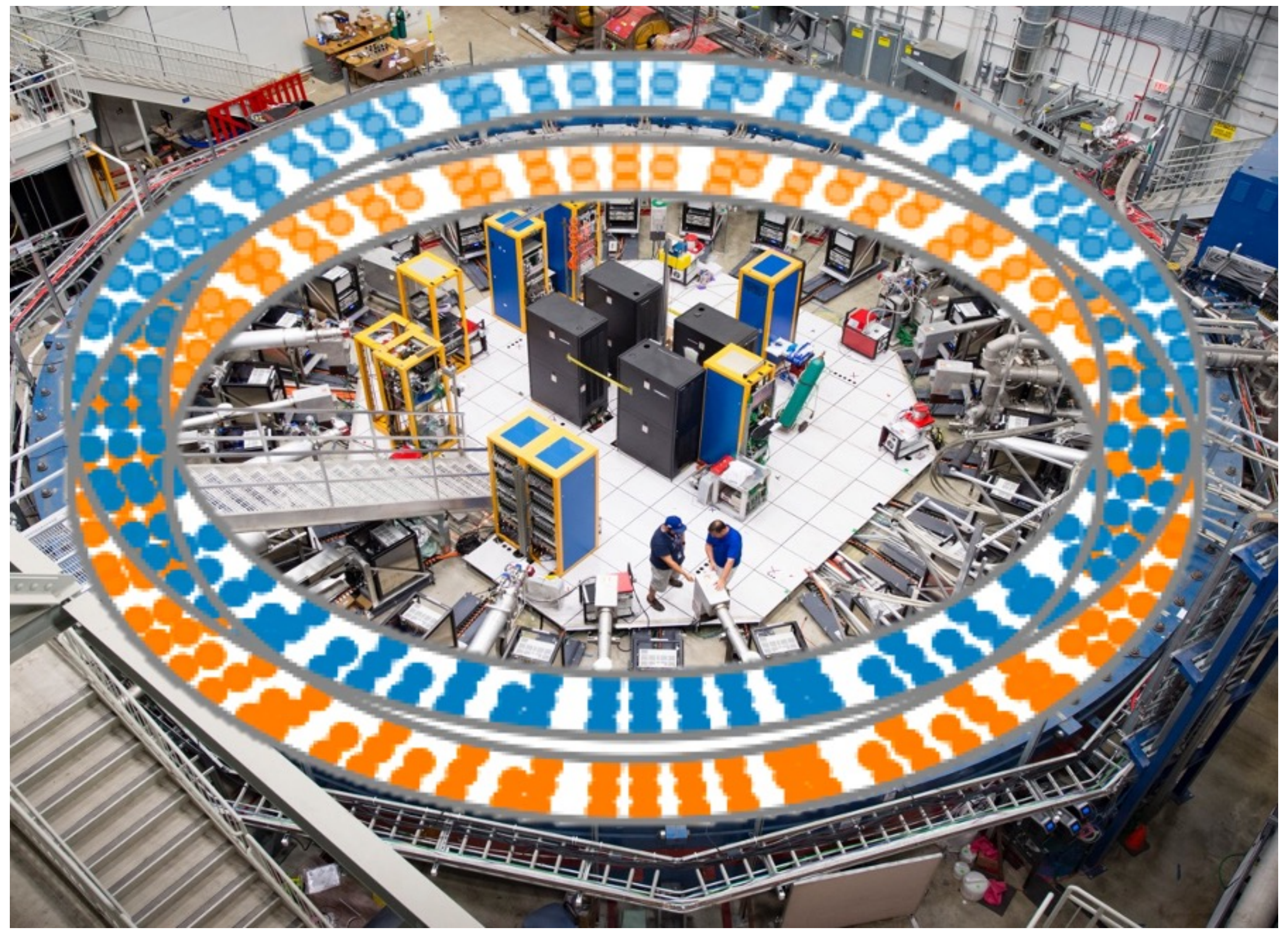


The precision magnetic field: tracking in time

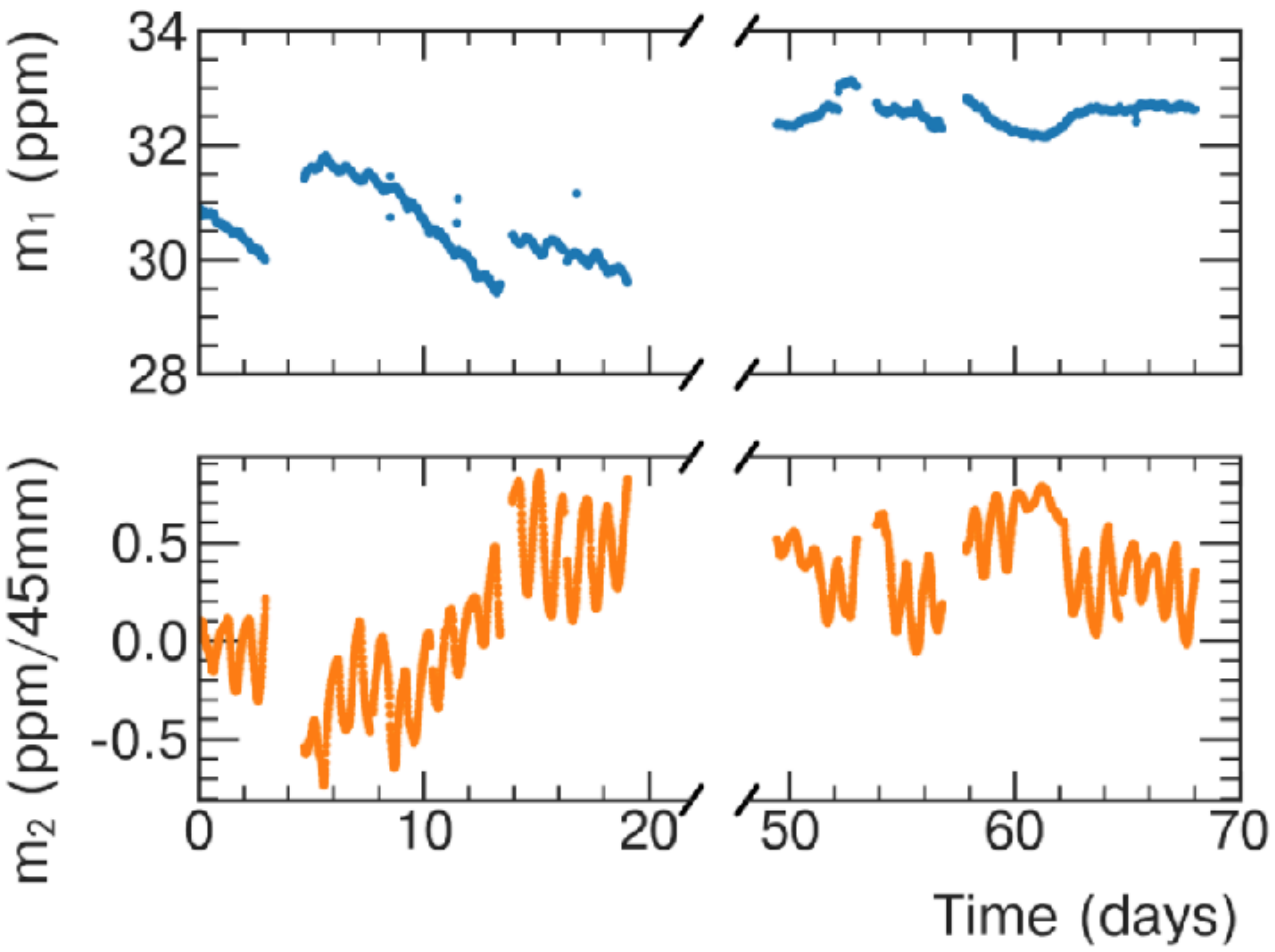
“The fixed probe array”

378 pulsed nuclear magnetic resonance probes measure 24/7 around μ beam





Tracking of the 2D multipole moments over the Run 1 datasets



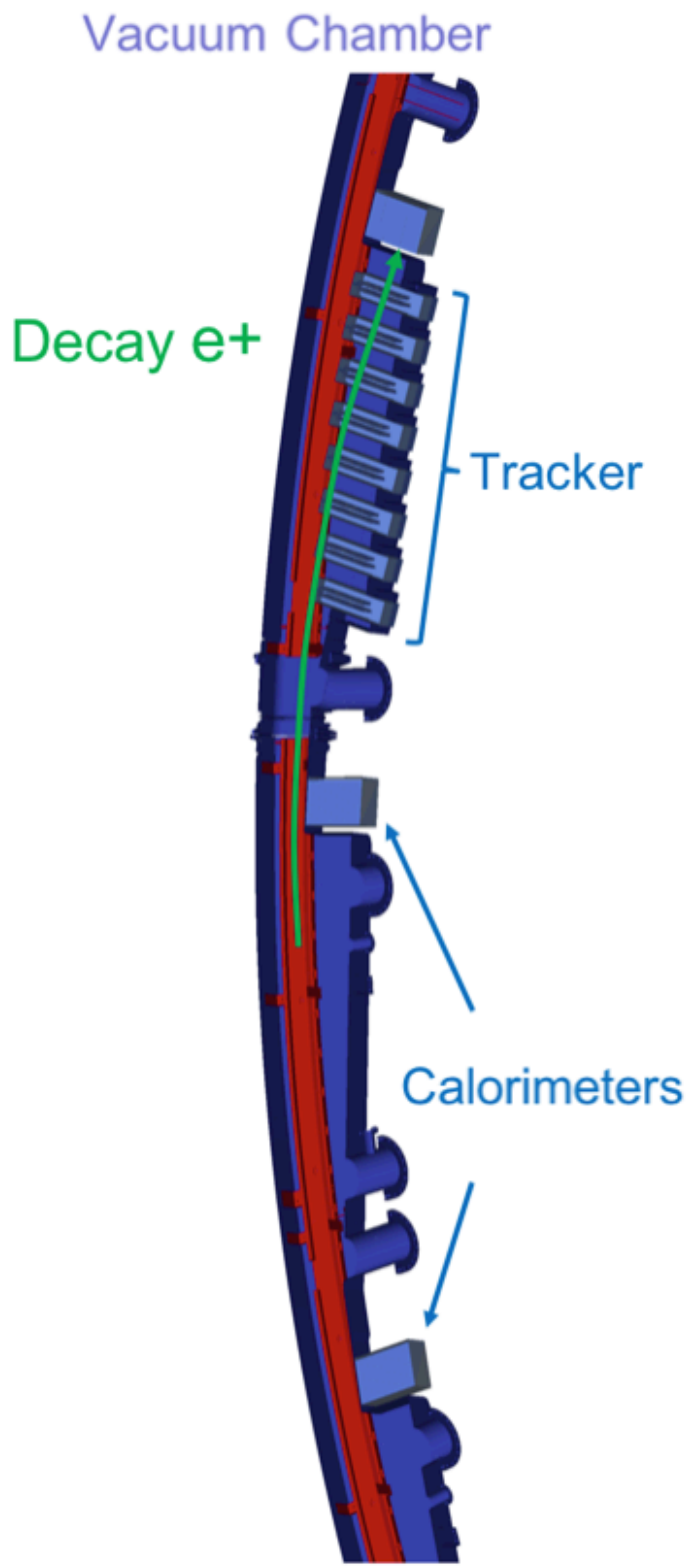
Dipole

Normal quadrupole

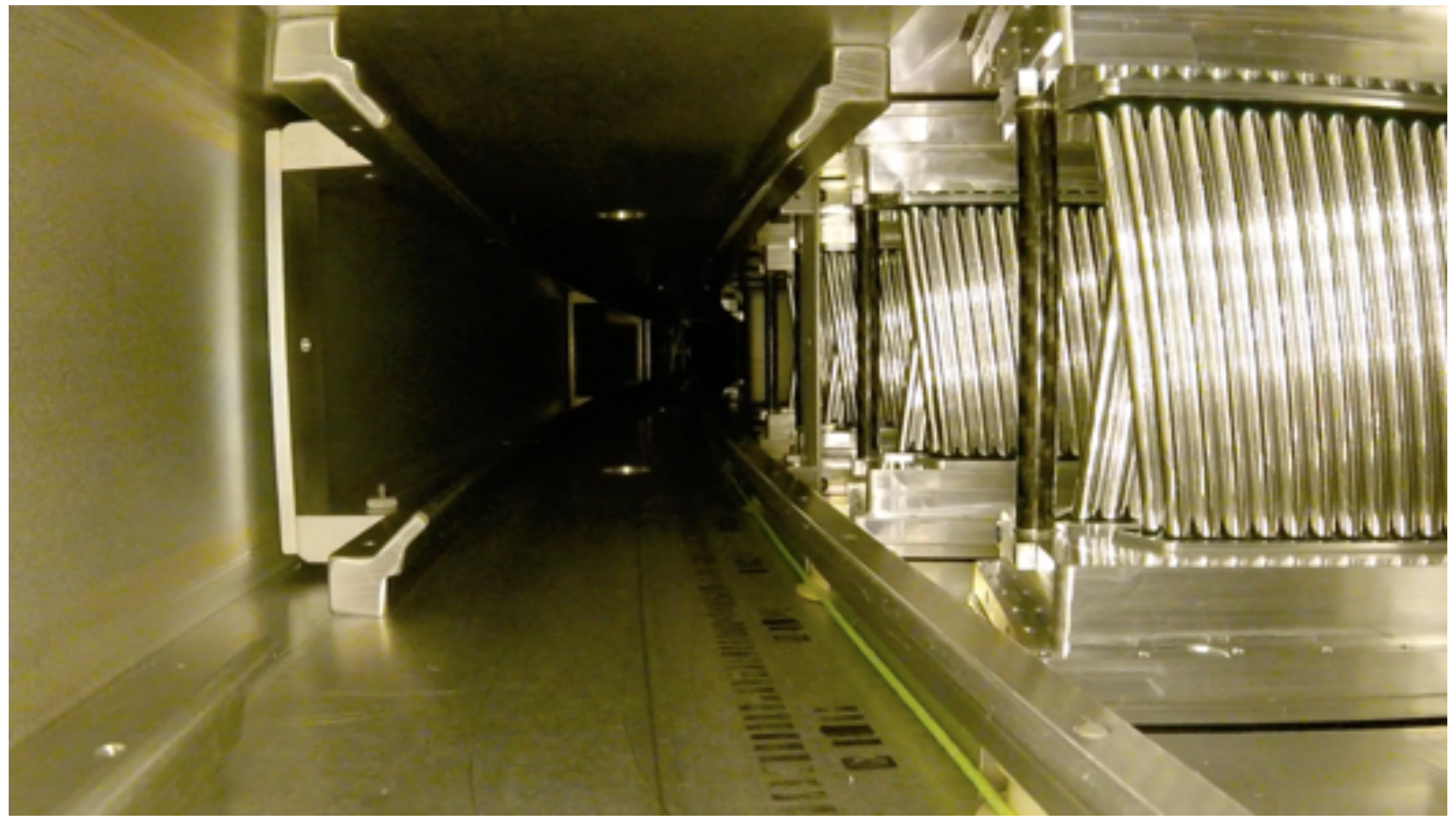
Extracting a_μ: the muon weighted average magnetic field

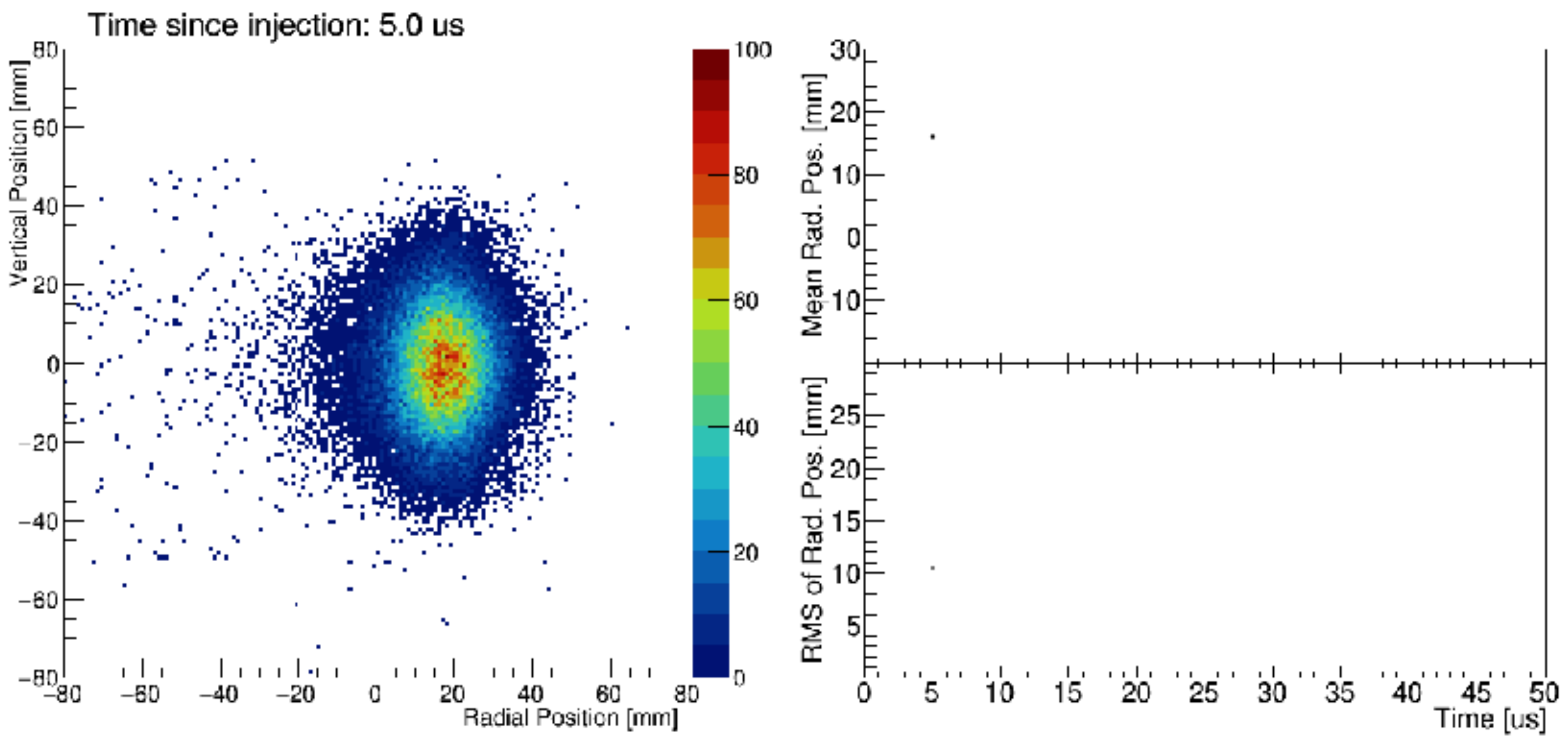
$$R' = \frac{\omega_a}{\omega_p'} = \frac{f_{\mathrm{clock}}\, \omega_a^{\mathrm{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\mathrm{calib}} \boxed{\left\langle M(x, y, \phi)\, \omega_p'(x, y, \phi) \right\rangle} \left(1 + B_k + B_q\right)}$$

The muon weighted average magnetic field

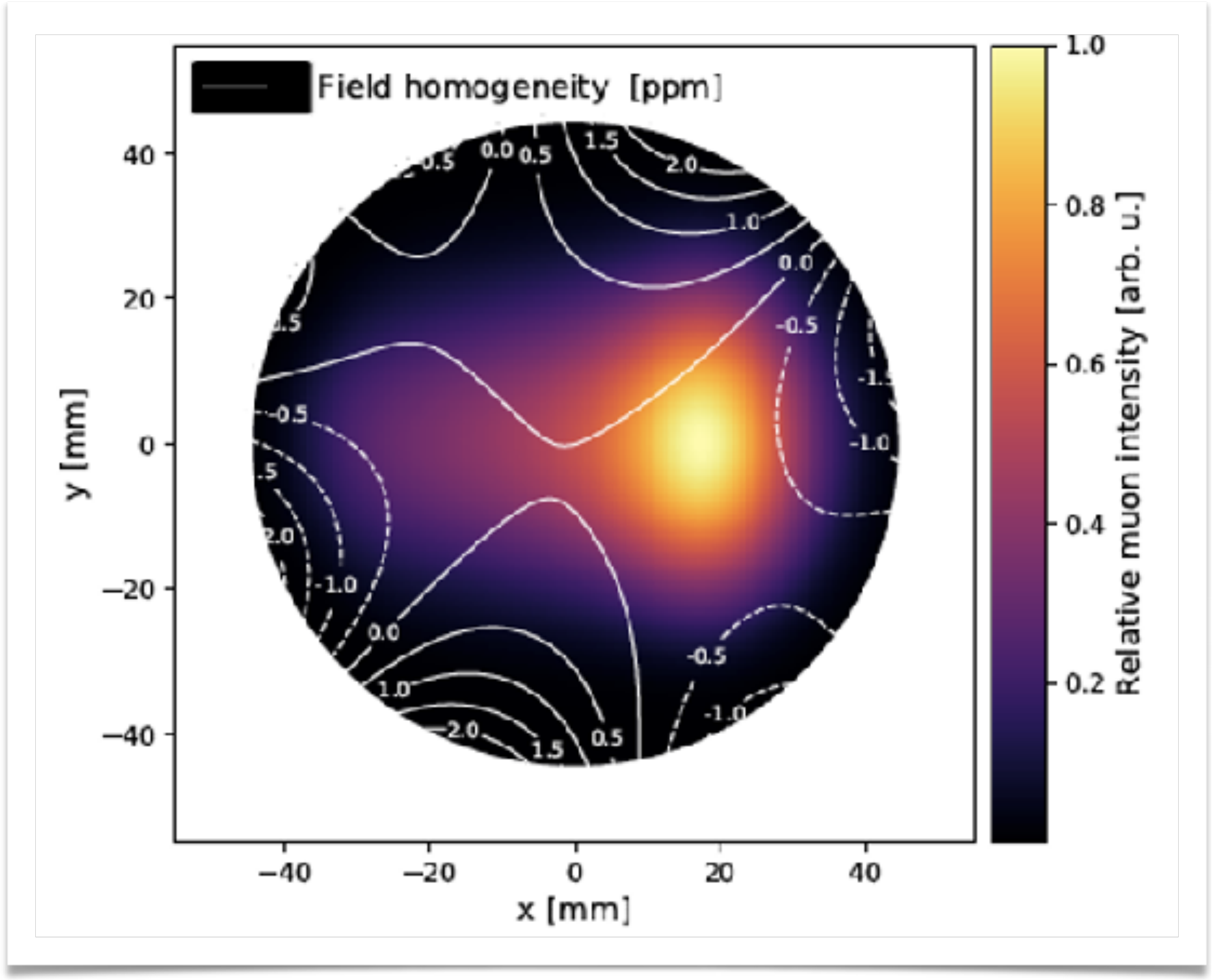


A muon's perspective of the tracker





Beam tracker stations combined with beam dynamics simulations



56 ppb uncertainty

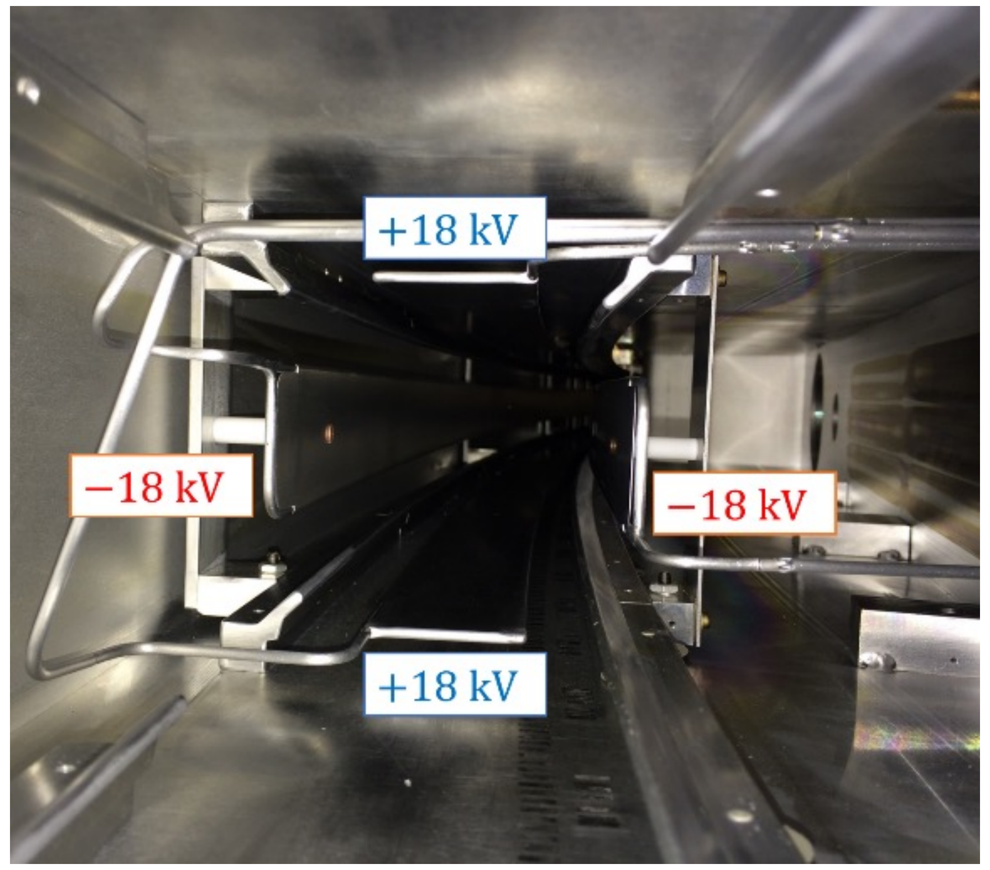
Incl. probe calibrations, field map, tracker alignment, beam dynamics model

Extracting a_μ: transients from ESQ

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

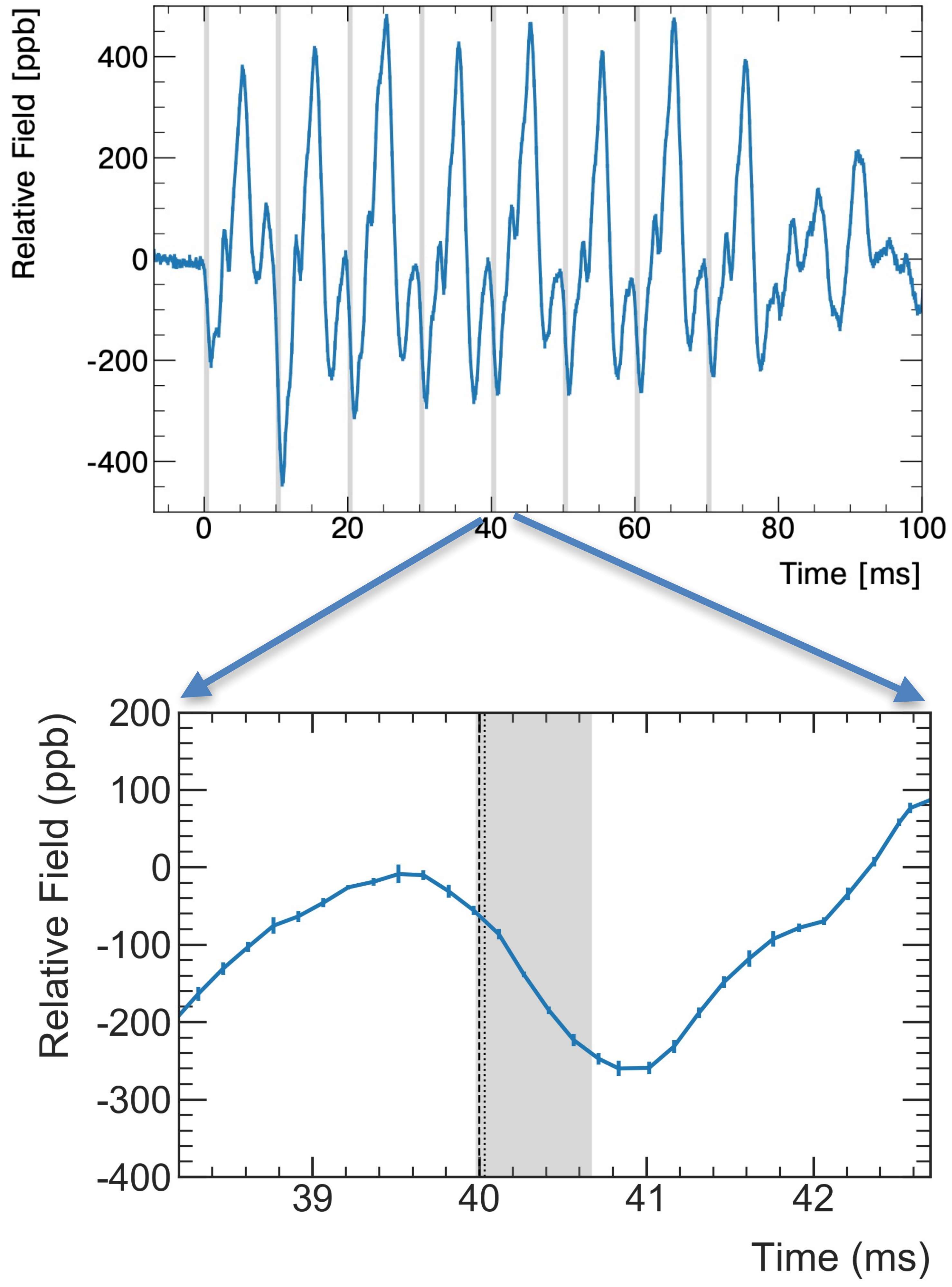
Transients from electrostatic quadrupoles (ESQ)

ESQ only static on the time scale of an muon beam bunch injection:

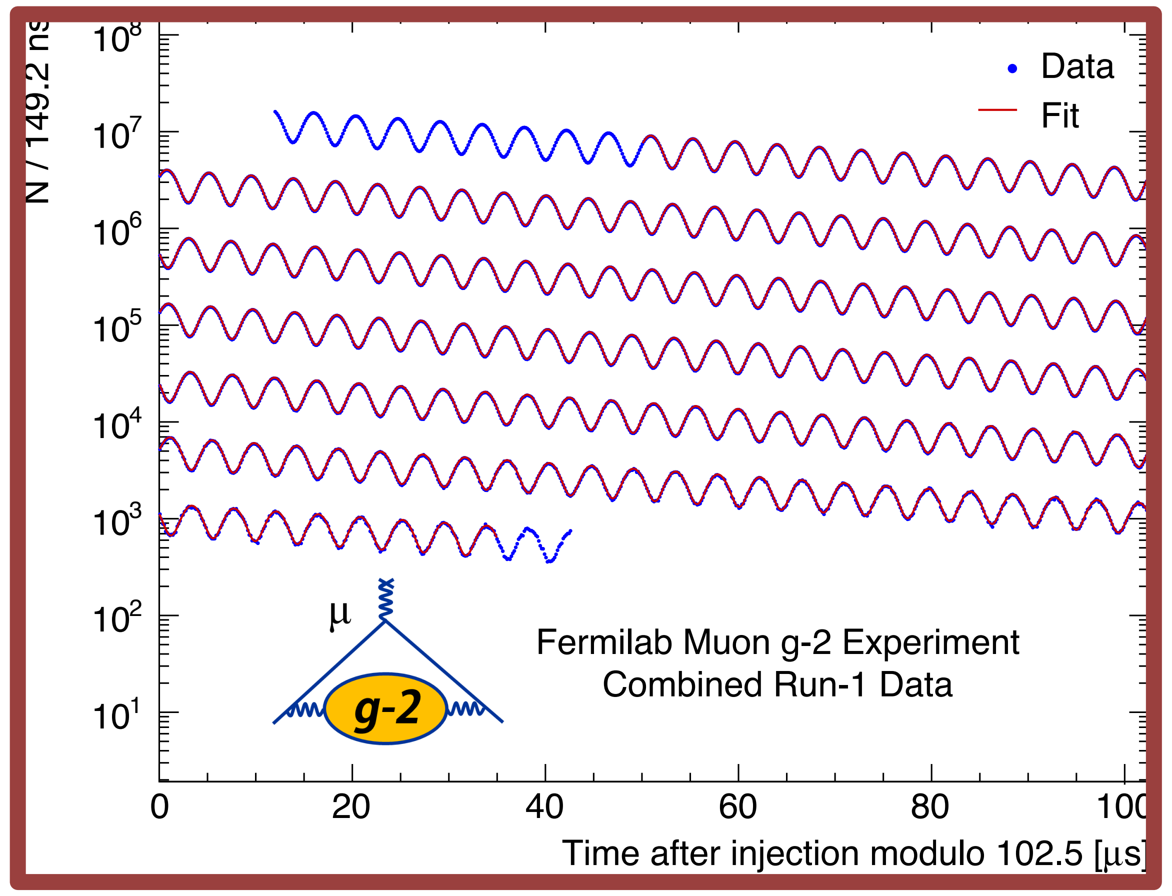


- Pulsing with high-voltage:
  - → mechanical vibrations of electric conductors
  - → perturbation of B field

Correction: 17 ppb
Uncertainty: 92 ppb

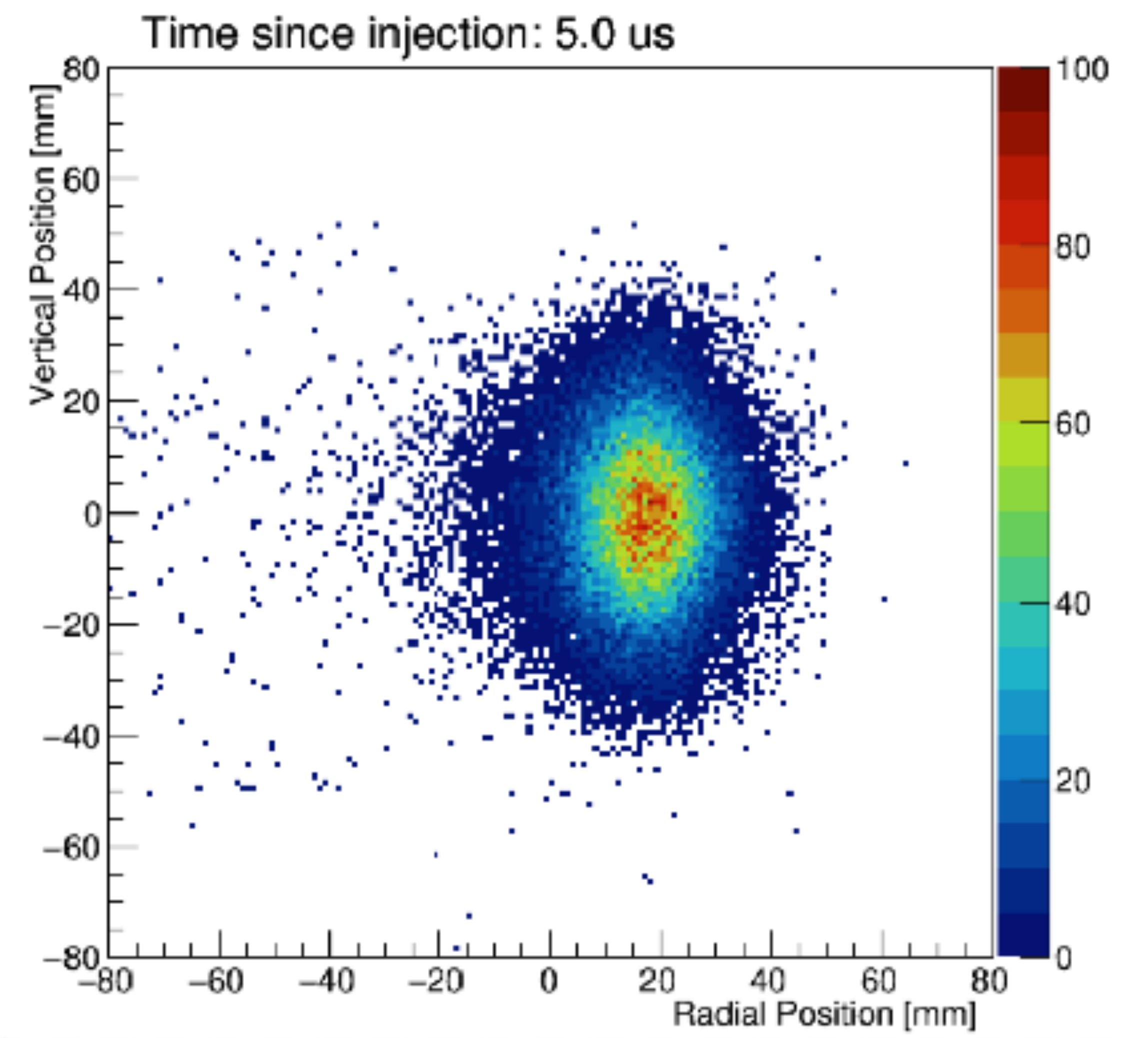


Extracting a_μ - our tools



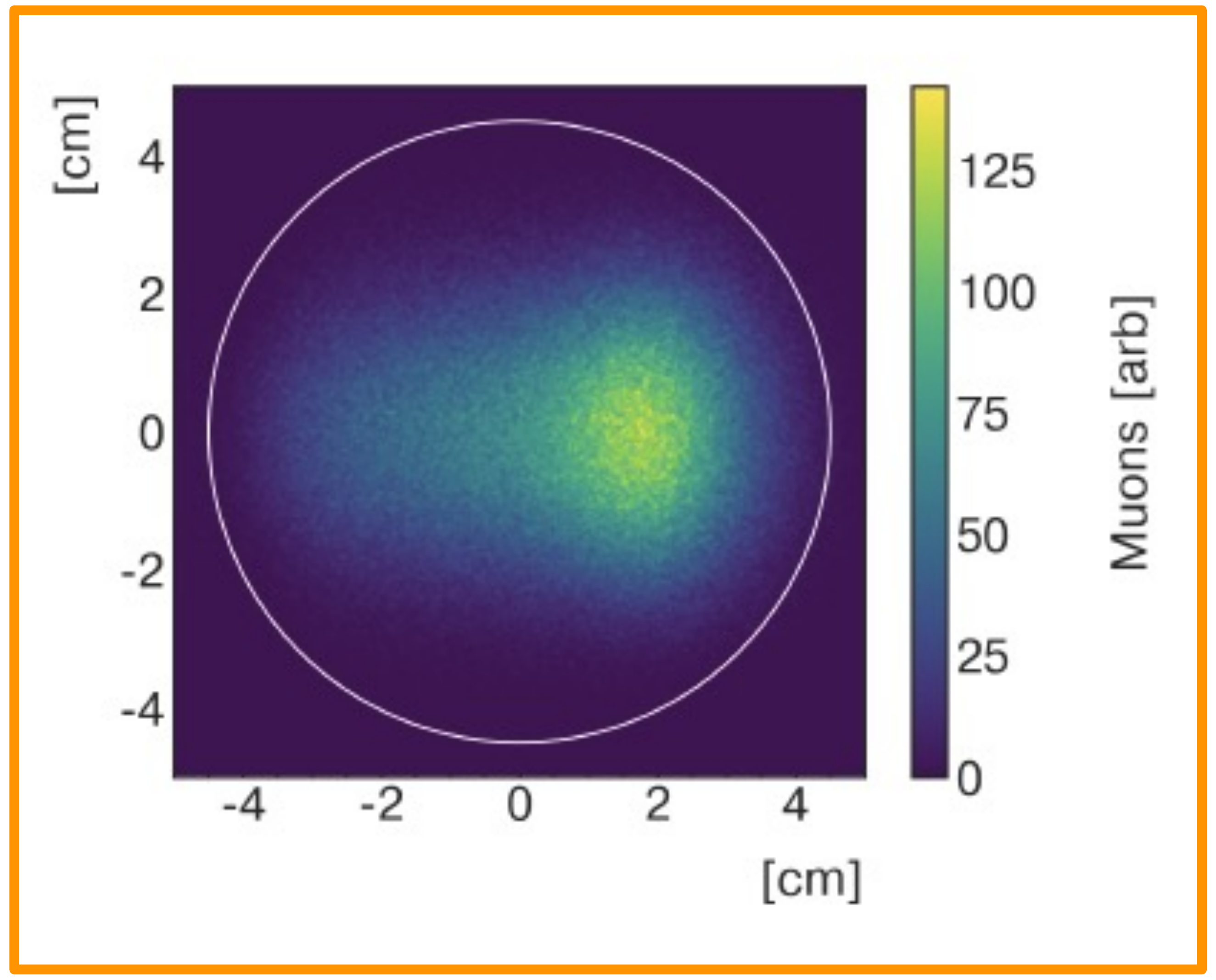
Anomalous spin precession frequency

Muon beam dynamics corrections



Clock blinding

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

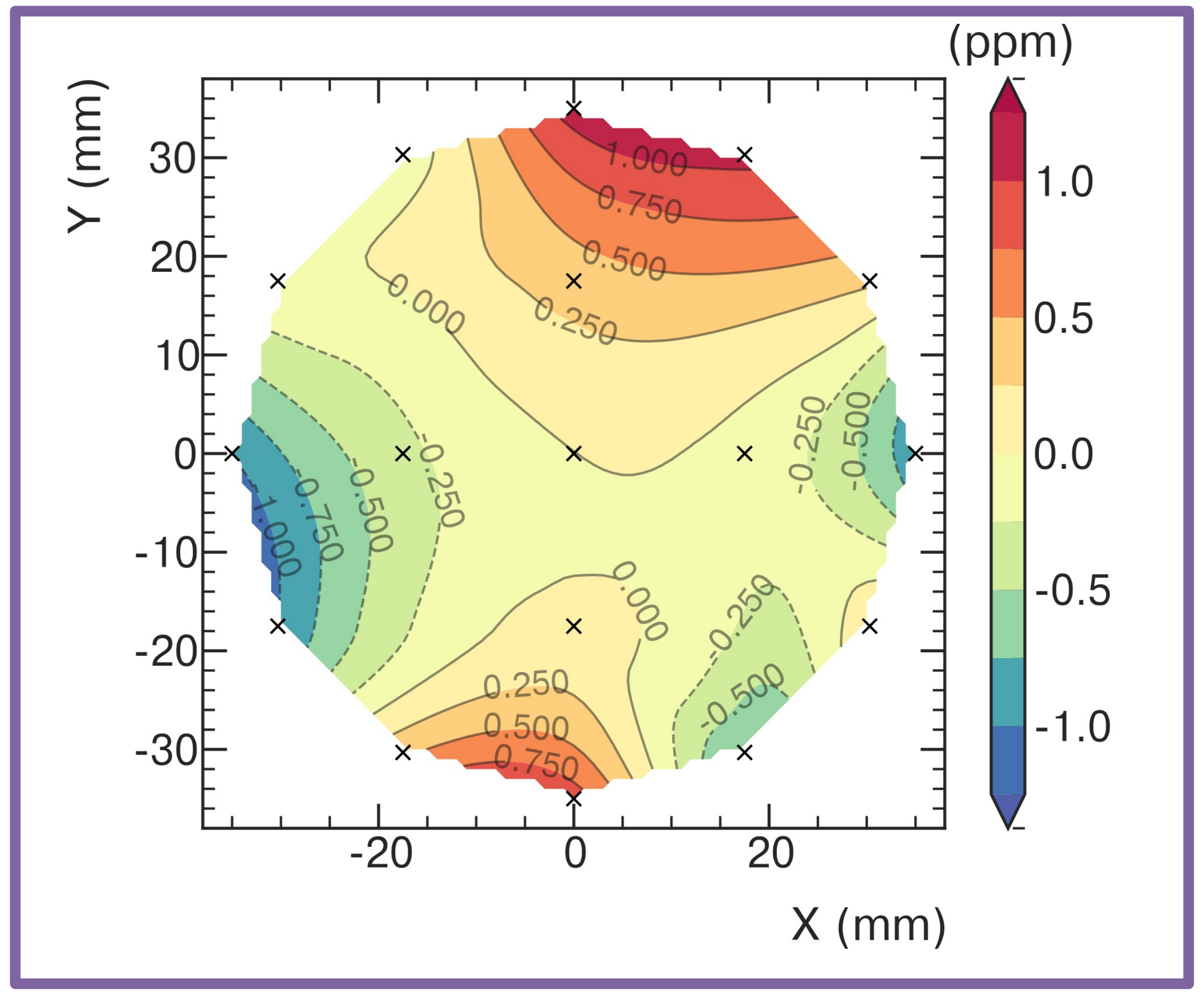


Spatial muon distribution

Spatial distribution of magnetic field

Transient magnetic fields

Calibration



All the analysis is available for you to look at in detail

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24,** 044002 (2021)

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

T. Albahri,[38] A. Anasta

PHYSICAL REVIEW D **103,** 072002 (2021)

Editors' Suggestion | Featured in Physics

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

T. Albahri,[38] A. Anastasi,[11,a]
T. Barrett,[6] A. Basti,[1]
E. Bottalico,[11,31] T. Bo
S. P. Chang,[18,5] A. Chapelai
J. D. Crnkovic,[3,36,42] S. D

PHYSICAL REVIEW A **103**, 042208 (2021)

Featured in Physics

Magnetic-field measurement and analysis for the Muon $g-2$ Experiment at Fermilab

T. Albahri,[39] A. Anastasi,
F. Bedeschi,[11] M. Berz,[2]
G. Cantatore,[13,34] R. M. Care
R. Chislett,[36] J. Choi,[5] Z
S. Dabagov,[9,||] P. T. De
V. N. Duginov,[17] M. Ea
A. Fioretti,[11,14] D. Flay,[41] N. S
L. K. Gibbons,[6] A. Gioios
F. Gray,[24] S. Haciomeroglu,[5] T
G. Hesketh,[36] A. Hibbert,
P. Kammel,[48] M. Kargiant

PHYSICAL REVIEW LETTERS **126,** 141801 (2021)

Editors' Suggestion | Featured in Physics

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]

The Muon g-2 collaboration ready to unblind …

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- UT Austin
- Virginia
- Washington

National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jao Tong University

United Kingdom
- Lancaster
- Liverpool
- University College London

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

Germany
- JGU Mainz
- TU Dresden

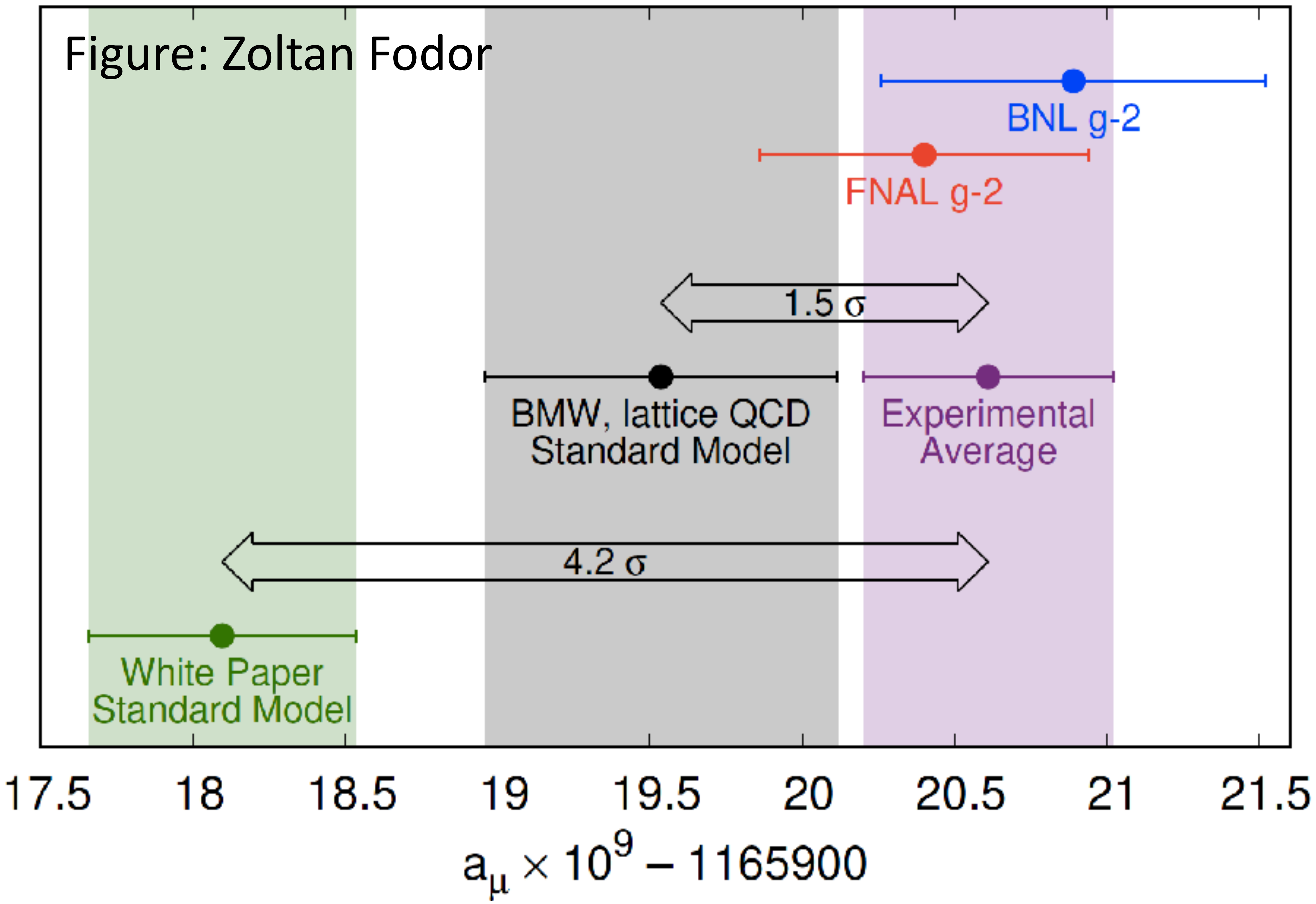
Russia
- JINR/Dubna
- Novosibirsk

South Korea
- CAPP/IBS
- KAIST

… on February 25th, 2021!

The 40 MHz clock was really set to:
39 997 784 MHz

Result from combined Run 1 datasets



a_μ(BNL) = 0.00116592089(63) → 540 ppb

a_μ(FNAL, R1) = 0.00116592040(54) → 463 ppb

Both experiments uncertainty dominated by statistics:

a_μ(Exp) = 0.00116592061(41) → 350 ppb

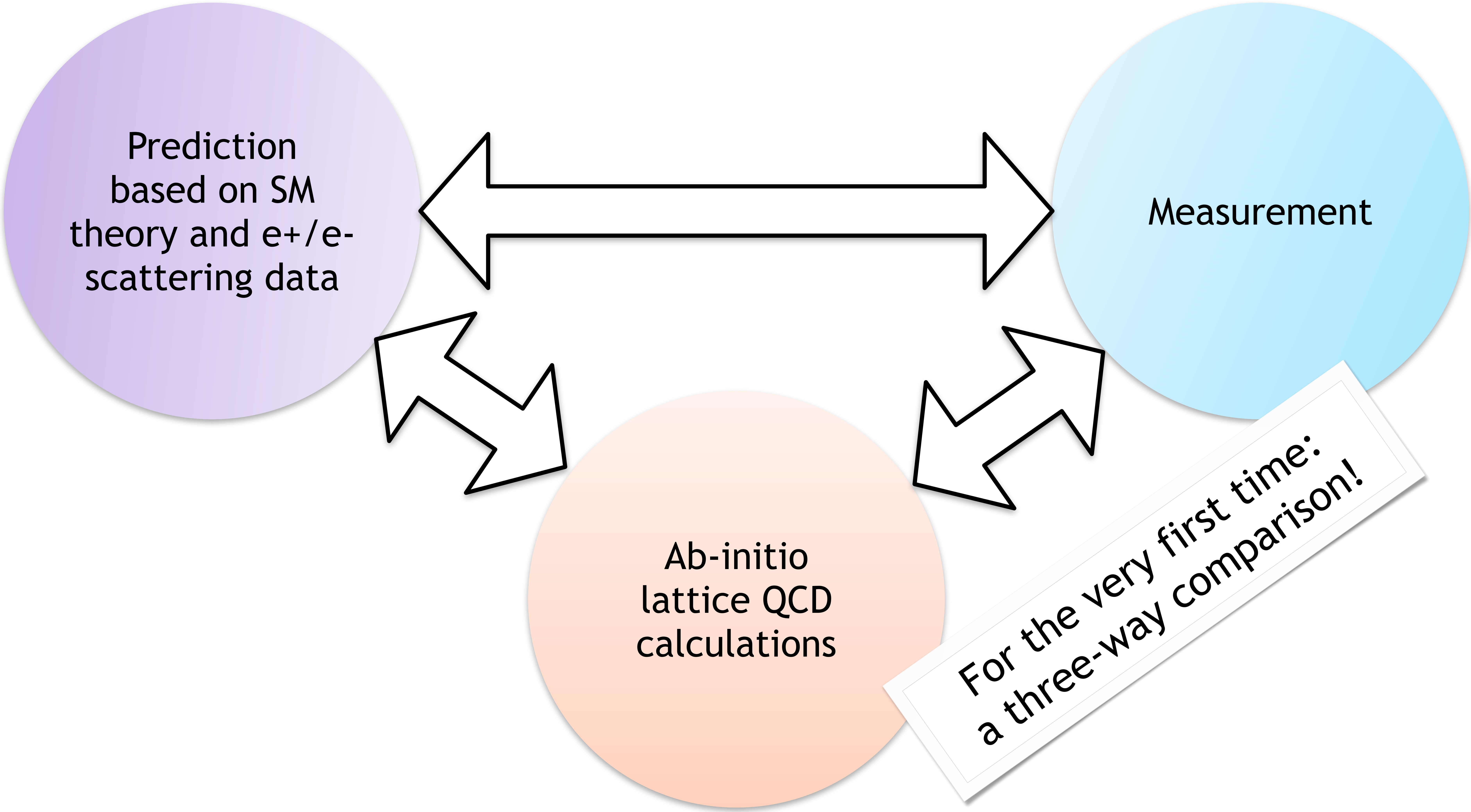
a_μ(SM) = 0.00116591810(43) → 350 ppb

4.2 σ discrepancy between experiment and community approved SM prediction

BUT: the very recent results from lQCD for HVP would reduce the tension to 1.5 σ!

*Borsányi et al., Nature **593**, 51–55, 2021*
and arXiv:2002.12347

A new era of a_μ comparisons



Predictions are hard to make if they concern the future…

New results from Fermilab Run 2 and 3 will feature

- More statistics
- Smaller systematics:
  - Better temperature stability
  - Beam on nominal orbit
  - Magnetic field transients measured

Independent measurement of muon g-2 at J-PARC

- Different experimental technique
- Different beam energy → Different magnetic field

Further theory developments

- Lattice QCD calculations of HVP awaiting independent results
- Proposed new data-driven HVP determination: MUonE at Cern
- Interpretation in a more context of LUV effects (see talk: Anders Thomsen, 5 Sep 2021, 14:30), PRL has > 250 citations to-date!