A Measurement of Positive Muon Anomalous Magnetic Moment to 0.46 ppm

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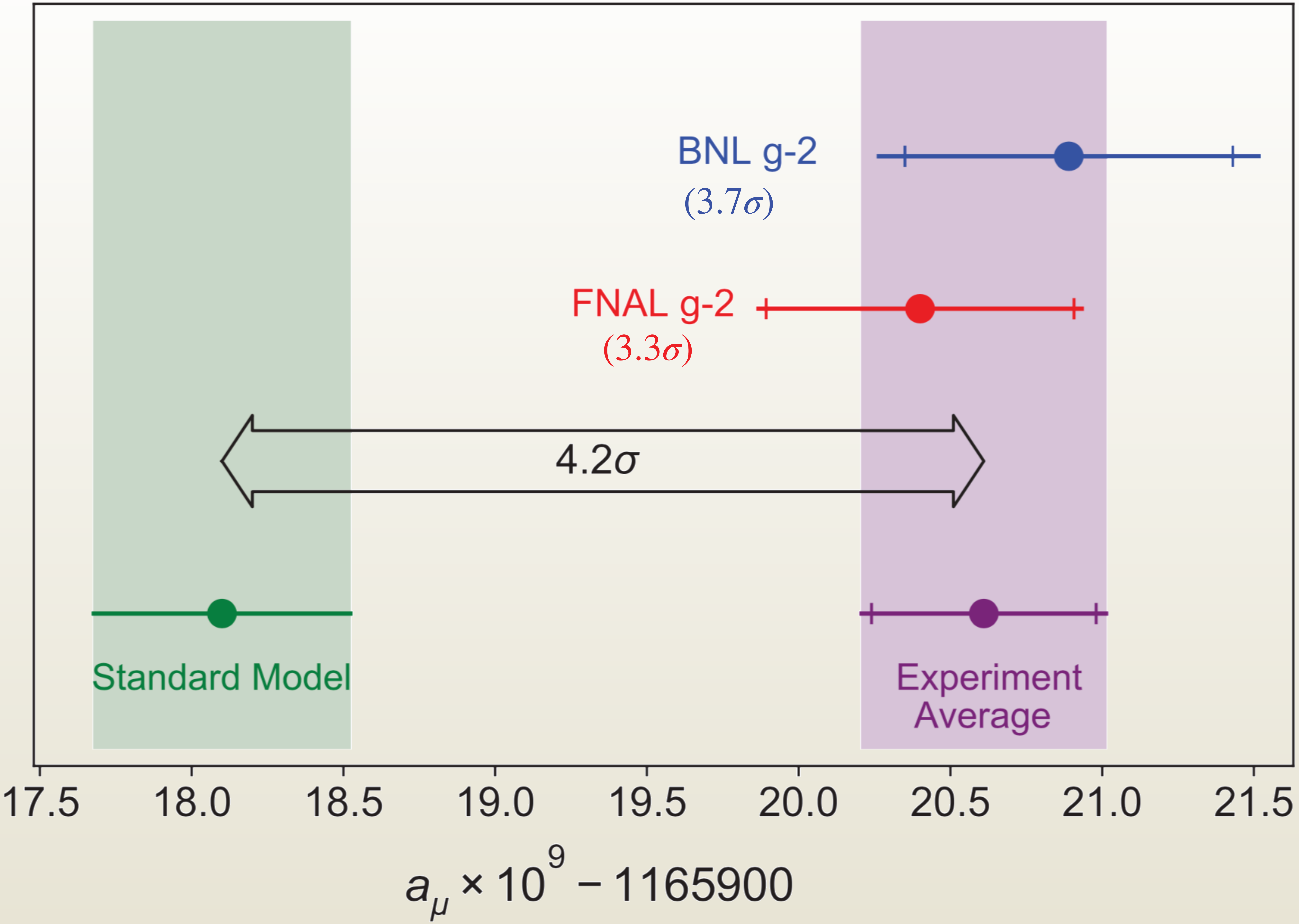
for the Muon g–2 Collaboration

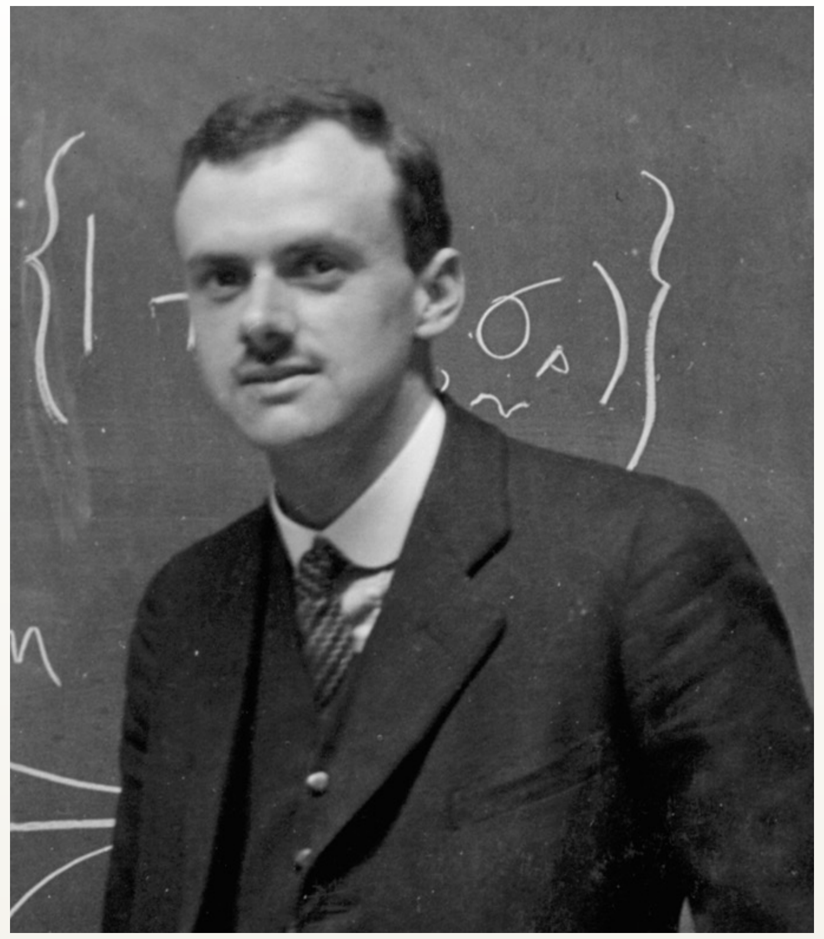

BNL g-2
(3.7σ)
FNAL g-2
(3.3σ)
4.2σ
Standard Model
Experiment Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

Outline

- Introduction
- Experimental methods
- Analysis
- Result

Introduction

Magnetic moment and the anomaly



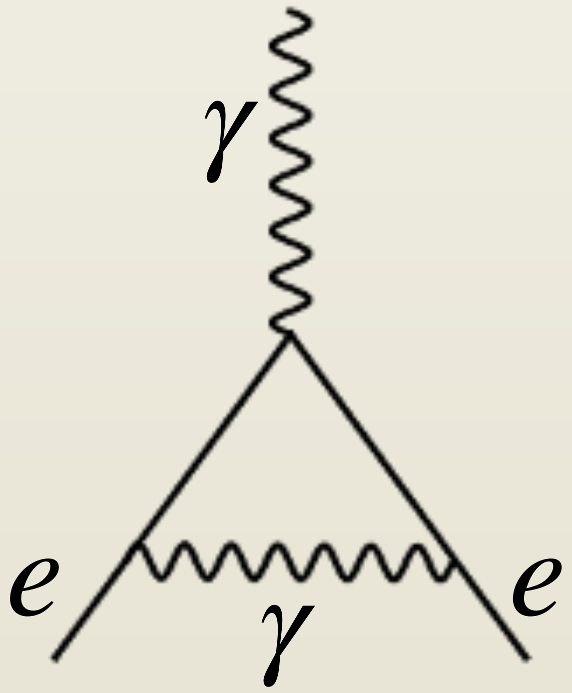
- Intrinsic magnetic moment of a particle with spin $\overrightarrow{S}$: $\vec{\mu} = g\frac{q}{2m}\vec{S}$
- Dirac theory predicted the gyromagnetic factor g = 2 for spin $1/2$ & point-like particles
- Precision measurement of electron showed g_e = 2.00238(6)

Anomalous magnetic moment (or the anomaly): $a \equiv \frac{g-2}{2}$

$a_e^{meas} = 0.00119(3)$

- J. Schwinger was the first who calculated the 1-loop QED correction for electron

$$a_e = \frac{\alpha}{2\pi} \simeq 0.00116$$



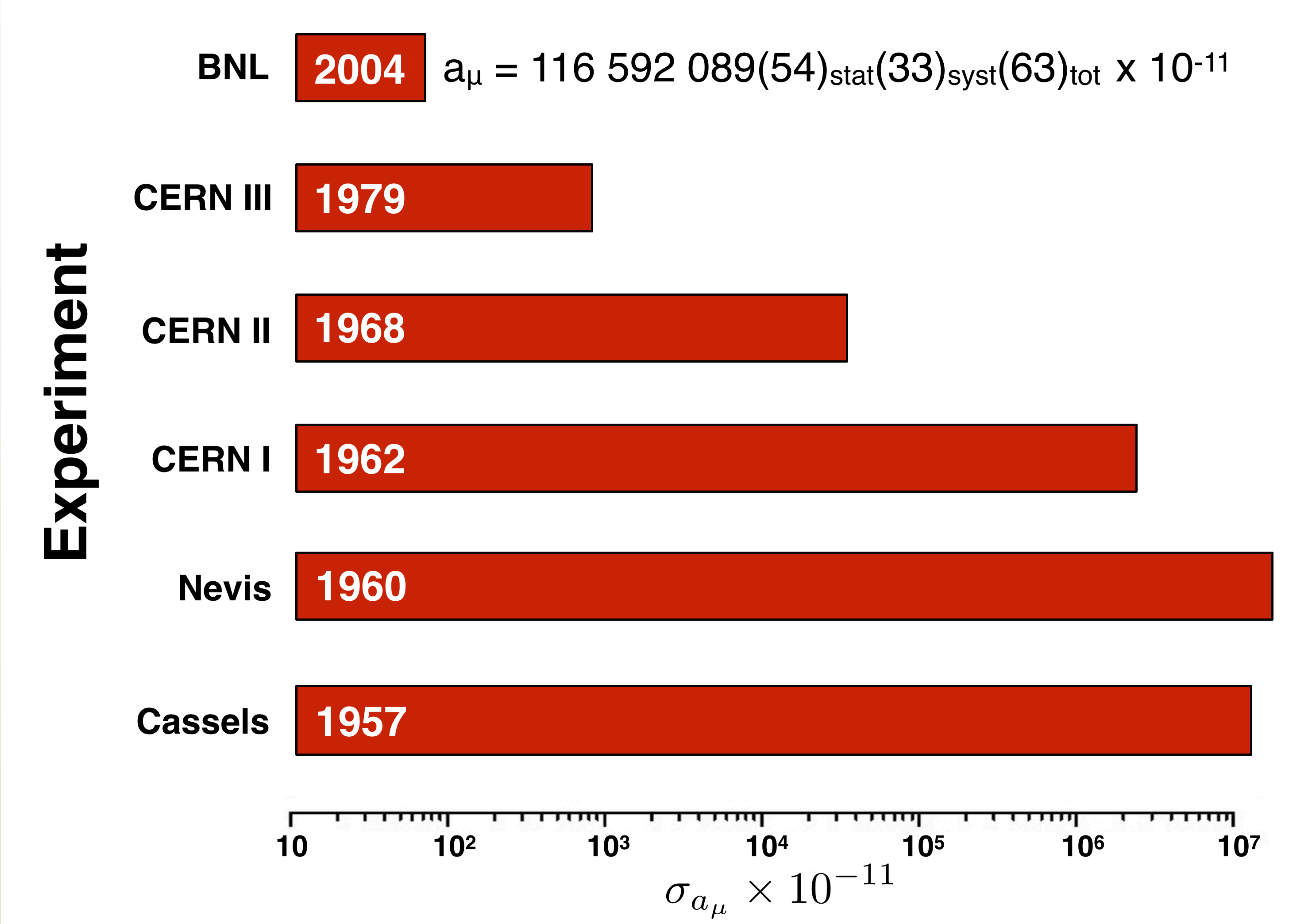
- a_e is the most precise test of QED!

Why muons?

- Both electron and muon magnetic moments can be measured and calculated to extraordinary precision
  - Actually, electrons are measured >2000 times more precisely than muons:
    - Electrons: $\delta a_e = 2.8 \times 10^{-13}$, (0.24 ppb)
    - Muons: $\delta a_\mu = 6.3 \times 10^{-10}$, (540 ppb)
- But, sensitivity to New Physics scales as $(m_l / m_X)^2$
  - The muon is $(m_\mu / m_e)^2 \simeq 43000$ times more sensitive than the electron to heavy particles
- And muons have intrinsic properties enabling a spin precision measurement:
  - Born polarized from pion decay
  - Parity violating decay is self-analyzing with respect to spin direction

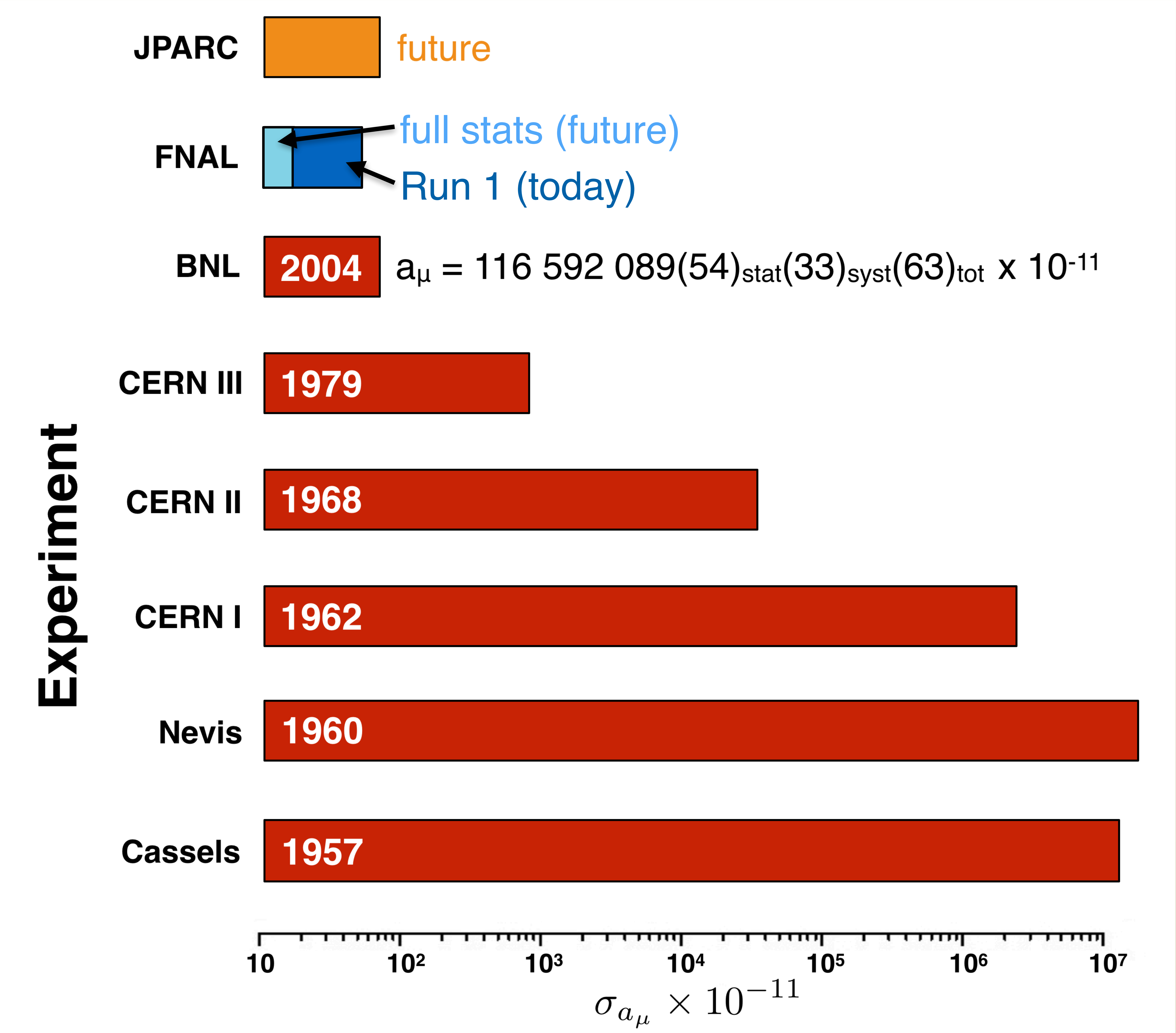
A history of muon anomaly measurements

- Storage ring experiments
  - Dilated lifetime, much better statistics
  - Sensitive to a_μ, much better precision
- Stopped muons experiments
  - Muons were stopped in targets inside a magnetic field
  - Measuring g directly, a few percent precision



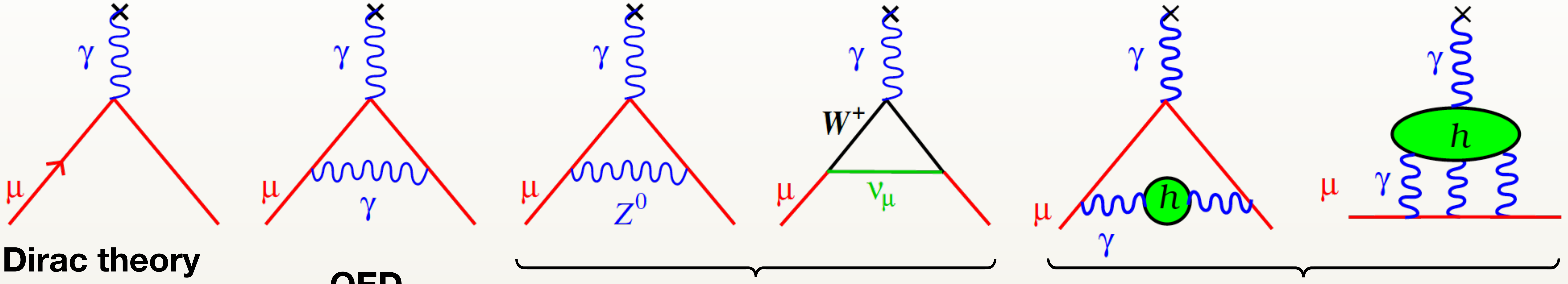
A history of muon anomaly measurements

- More than 5 orders of magnitude gain in precision!
- The Fermilab experiment aims for 4x improvement in precision
  - Run 1 result is comparable to the Brookhaven experiment



$a_\mu = 116\,592\,089(54)_{stat}(33)_{syst}(63)_{tot} \times 10^{-11}$

The muon anomaly a_μ in the Standard Model



Dirac theory

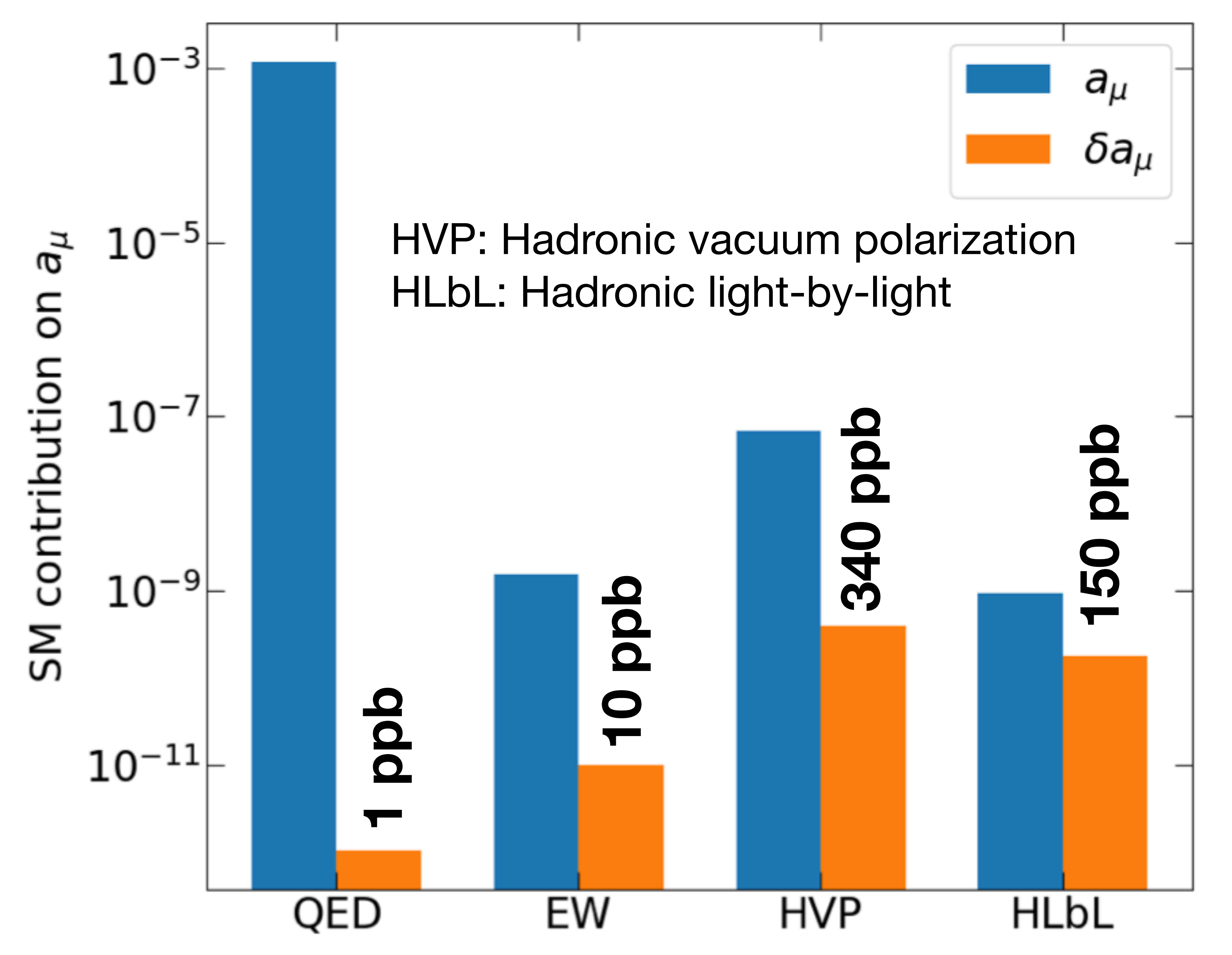
$a_\mu = 0$

QED

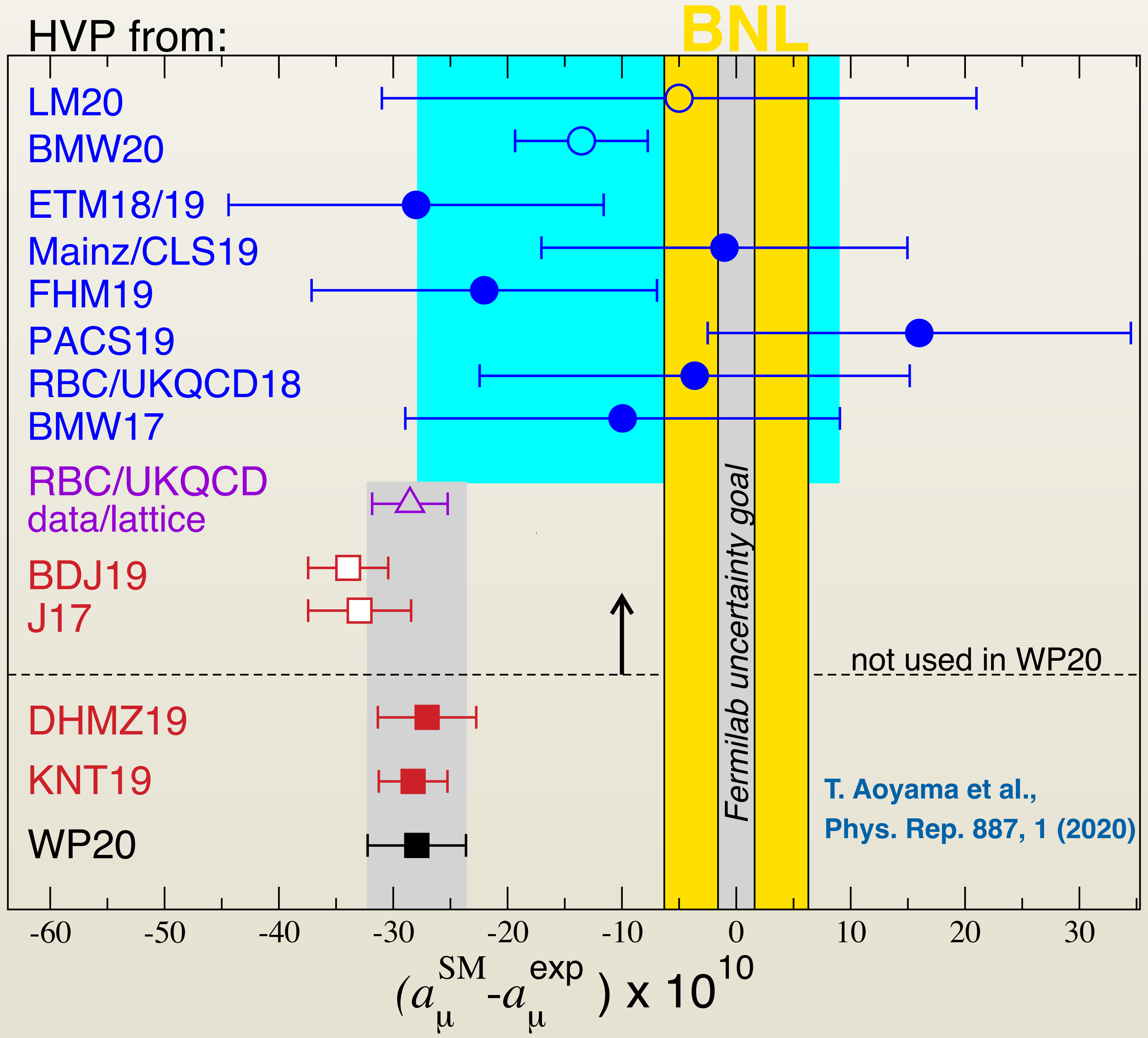
Electro-Weak

Hadronic

$$\boxed{a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm Weak} + a_\mu^{\rm HVP} + a_\mu^{\rm HLbL} = 116591810\,(43) \times 10^{-11}}$$



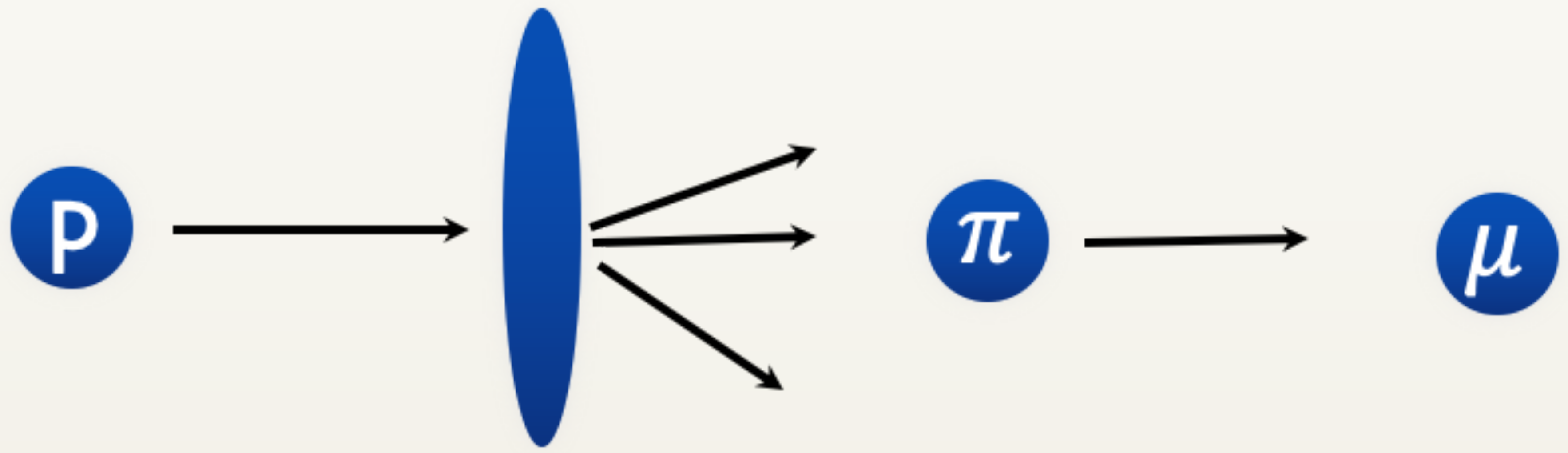
Muon g-2
Theory Initiative

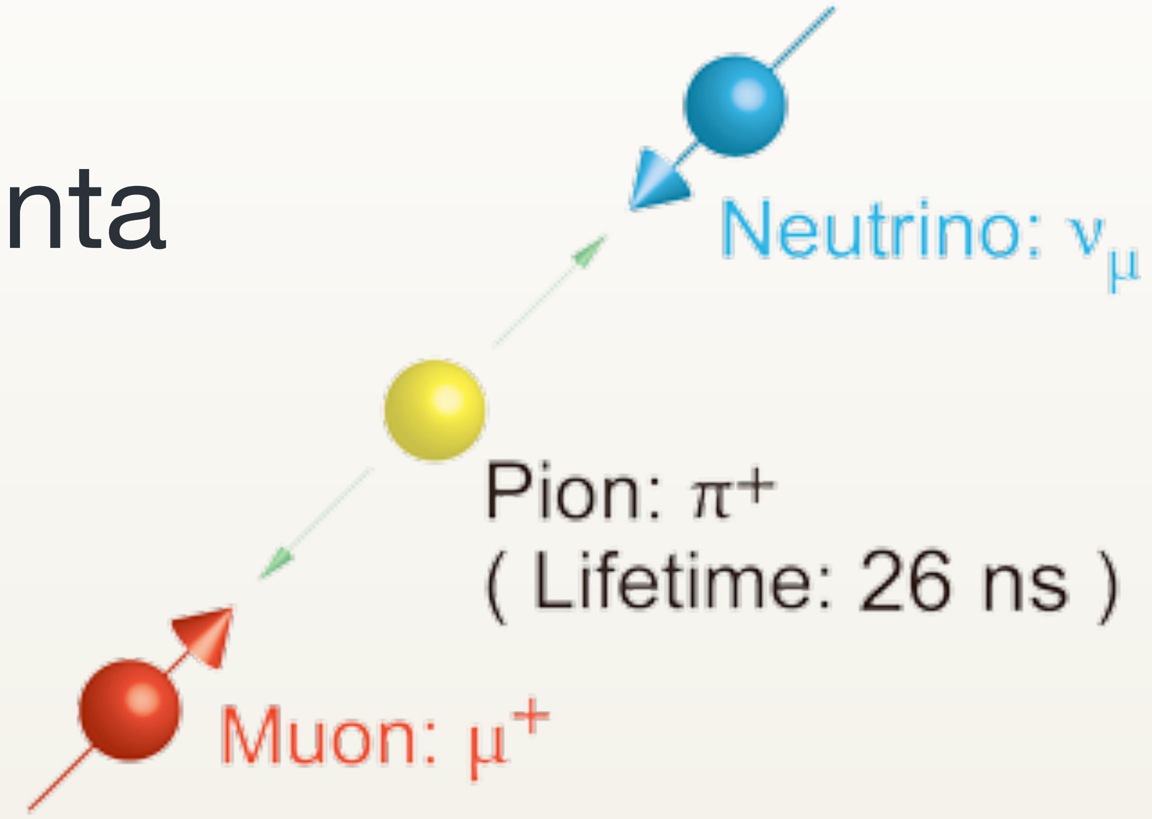


Experimental methods

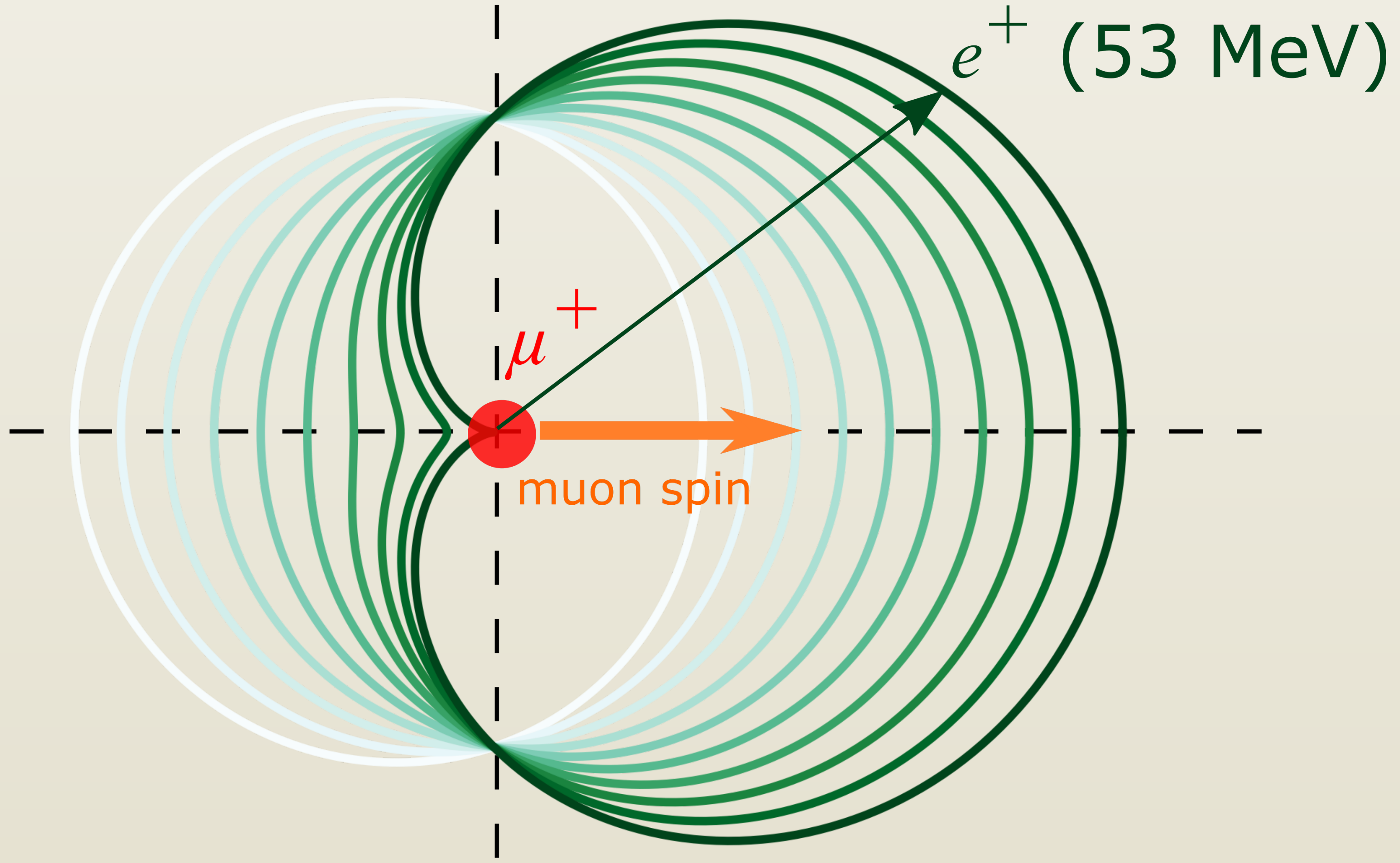
Muon production and decay

- Production: muons from $\pi^+ \rightarrow \mu^+\nu_\mu$ are polarized
  - In lab frame, forward decay muons have highest momenta



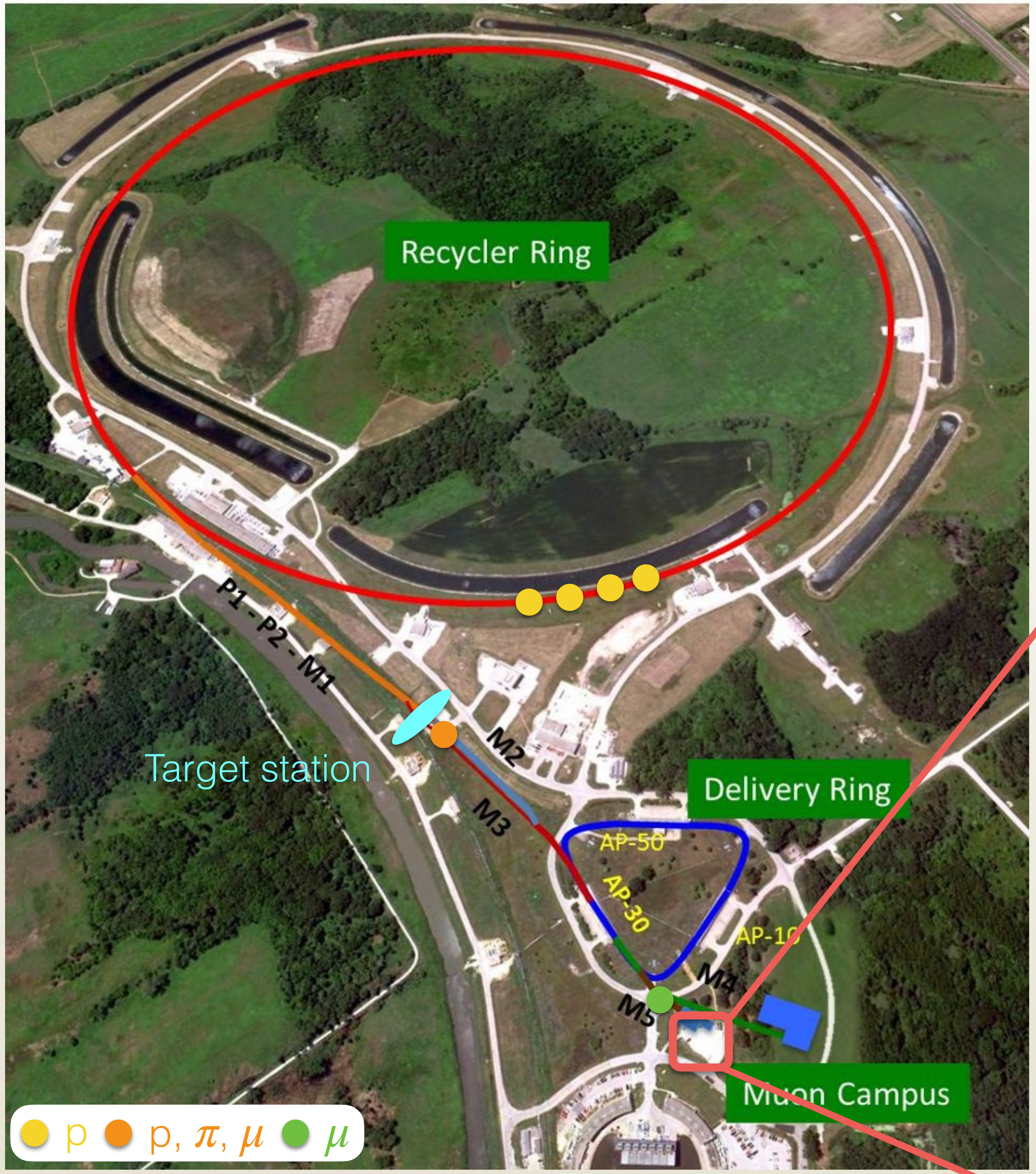


- “Self-analyzing” decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$: positron carries information about muon spin at the time of decay

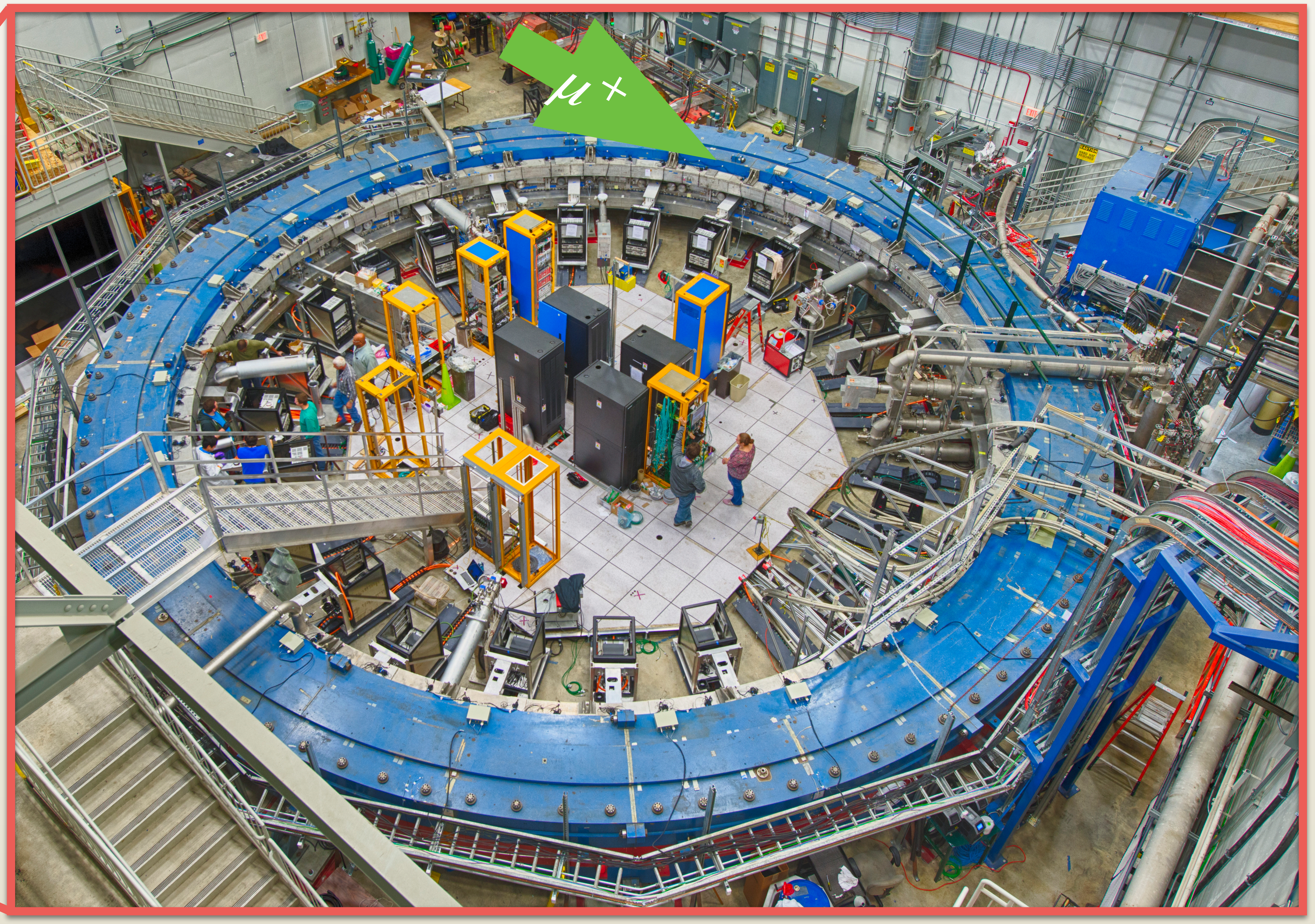


Positrons with highest energies tend to emit along muon spin direction

Muon campus at Fermilab



- 8 GeV proton beam
- Select 3.09 GeV secondaries (mixture of protons, pions and muons) in the Delivery Ring. After 4 turns, all pions decay, protons are separated by time-of-flight
- Select forward decay muons (highest momentum) → clean source of intense, polarized muons at 3.09 GeV



Spin precession in magnetic field

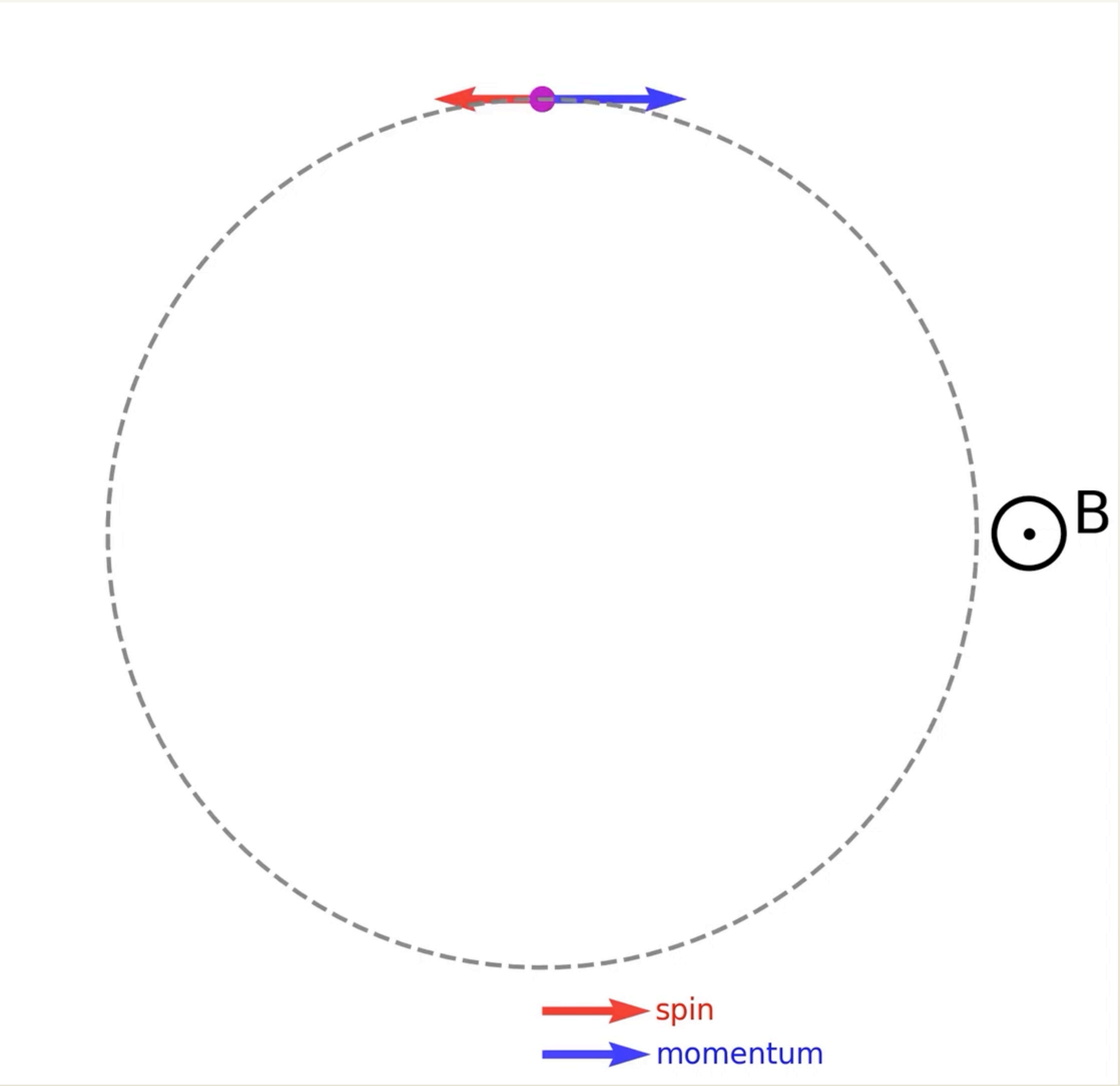
- Longitudinally polarized muons in a uniform dipole magnetic field B → spin precesses because of the torque $\vec{\mu} \times \vec{B}$
- Consider difference between spin precession and cyclotron frequencies:
  - Cyclotron frequency: $\vec{\omega}_c = -\frac{e}{\gamma m}\vec{B}$
  - Spin frequency: $\vec{\omega}_s = -\frac{e}{\gamma m}\vec{B}(1+\gamma a_\mu)$

$$\begin{aligned}\vec{\omega}_a &= \vec{\omega}_s - \vec{\omega}_c \\ &= -a_\mu \frac{e}{m}\vec{B}\end{aligned}$$

What we want to measure

Observables

Exaggerated, muon spin makes about 12° per revolution



Measuring the muon anomaly a_μ

- Magnetic field is measured by NMR techniques → express B in terms of proton Larmor precession frequency $\hbar\omega'_p = 2\mu_p B$
- And after a little manipulation

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

Precession frequency of a shielded proton (in a spherical sample of water at 34.7 °C) in the same magnetic field B

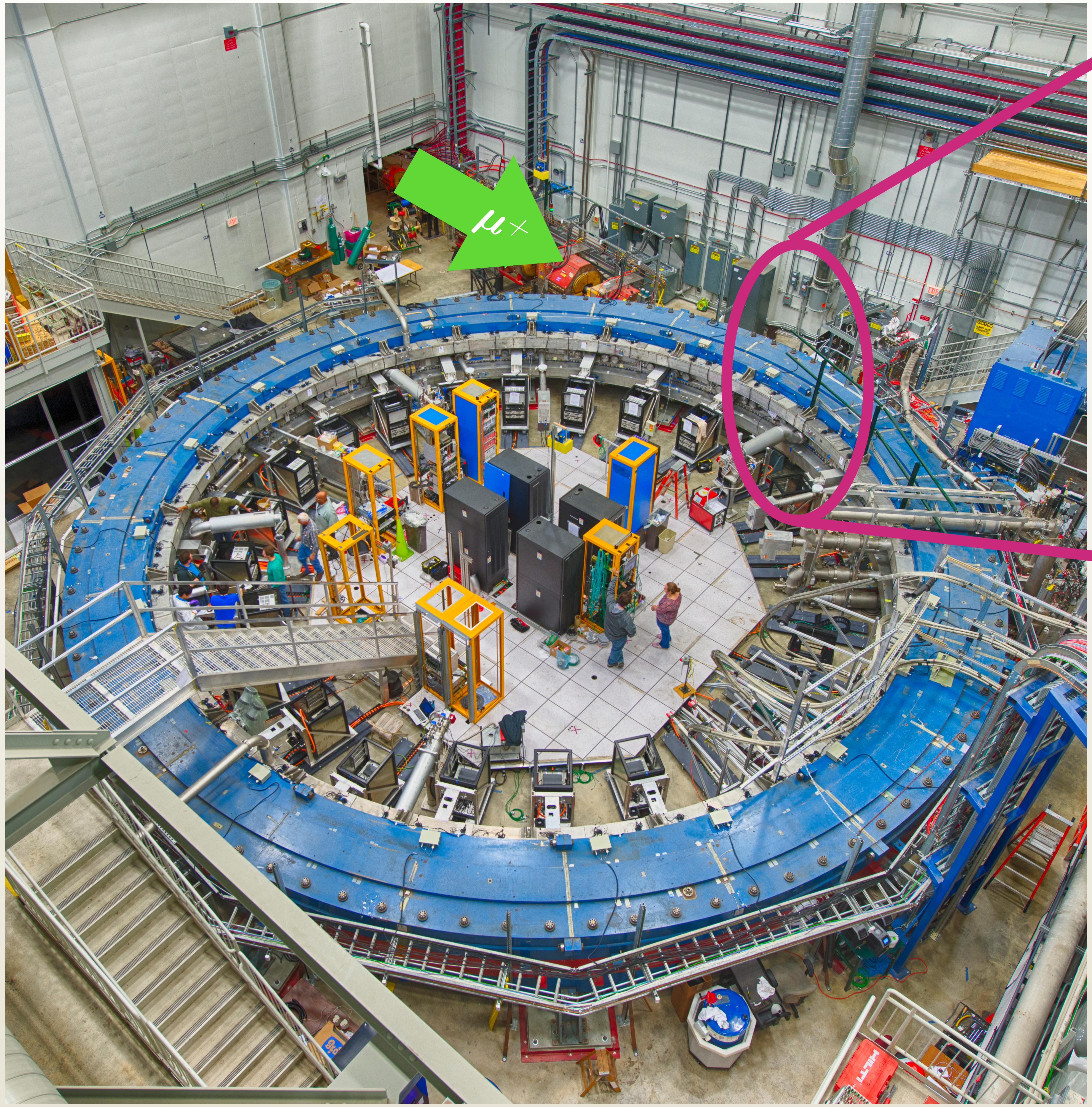
R_μ: what we measure in the experiment

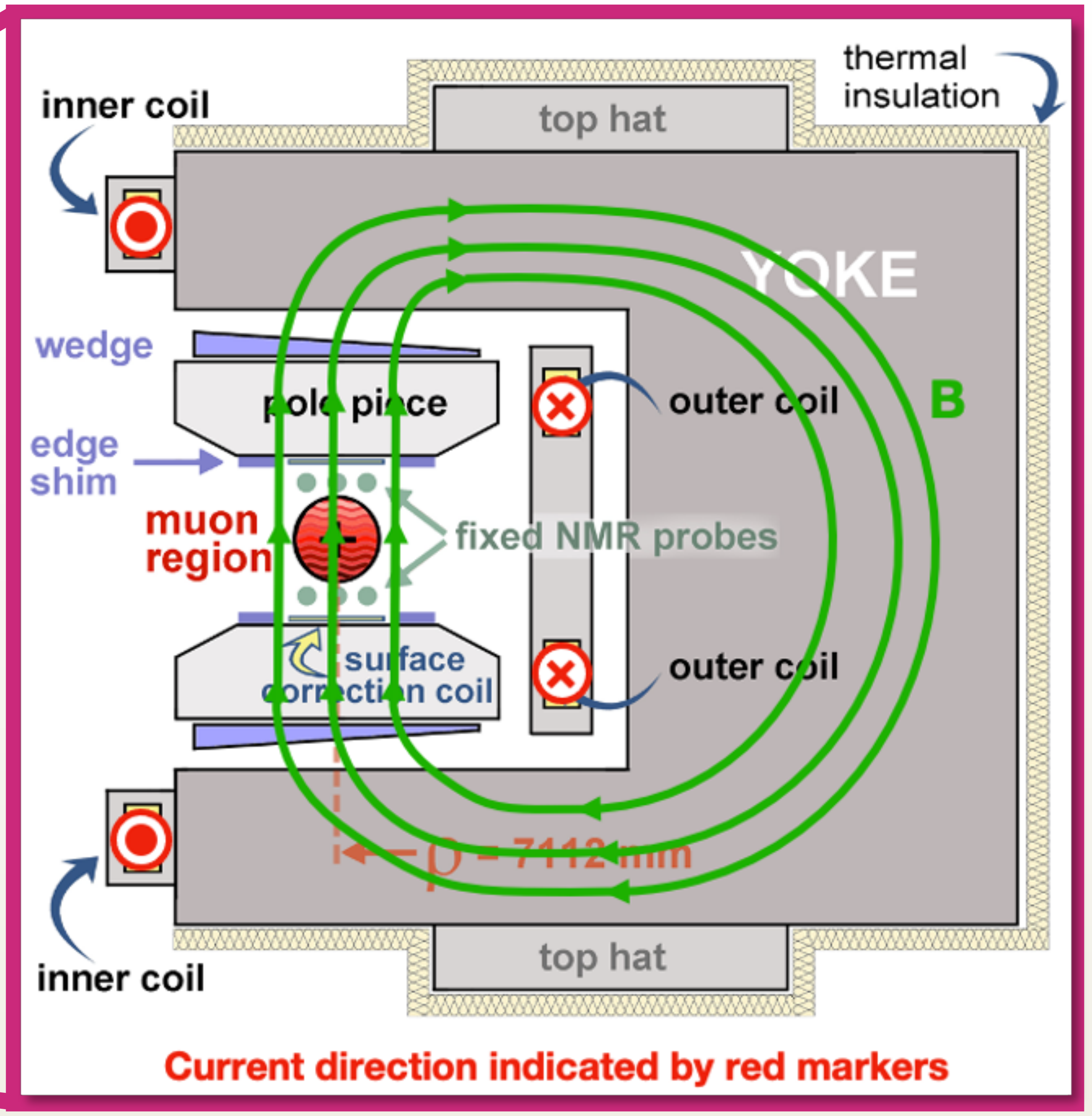
$\frac{\mu'_p(T_r)}{\mu_e(H)}$	10.5 ppb uncertainty at T$_r$ = 34.7°C Metrologia 13, 179 (1977)
$\frac{\mu_e(H)}{\mu_e}$	Bound state QED calculation, exact Rev. Mod. Phys. 88, 035009 (2016)
$\frac{m_\mu}{m_e}$	Muonium hyperfine splitting 22 ppb uncertainty Phys. Rev. Lett. 82, 11 (1999)
$\frac{g_e}{2}$	0.28 ppt uncertainty Phys. Rev. A 83, 052122 (2011)

- In practice it is a little more complicated:

$$R_\mu = \frac{\overbrace{f_{\text{clock}}}^{\text{Hardware blinded clock}}\,\omega_a^m(1+\overbrace{C_e+C_p+C_{ml}+C_{pa}}^{\text{Beam dynamics corrections}})}{\underbrace{f_{\text{calib}}}_{\text{Absolute calibration}}\,\underbrace{\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle}_{\text{Spacial convolution with muon beam distribution}}(1+\underbrace{B_k+B_q}_{\text{Magnetic transient corrections}})}$$

The storage ring





Current direction indicated by red markers

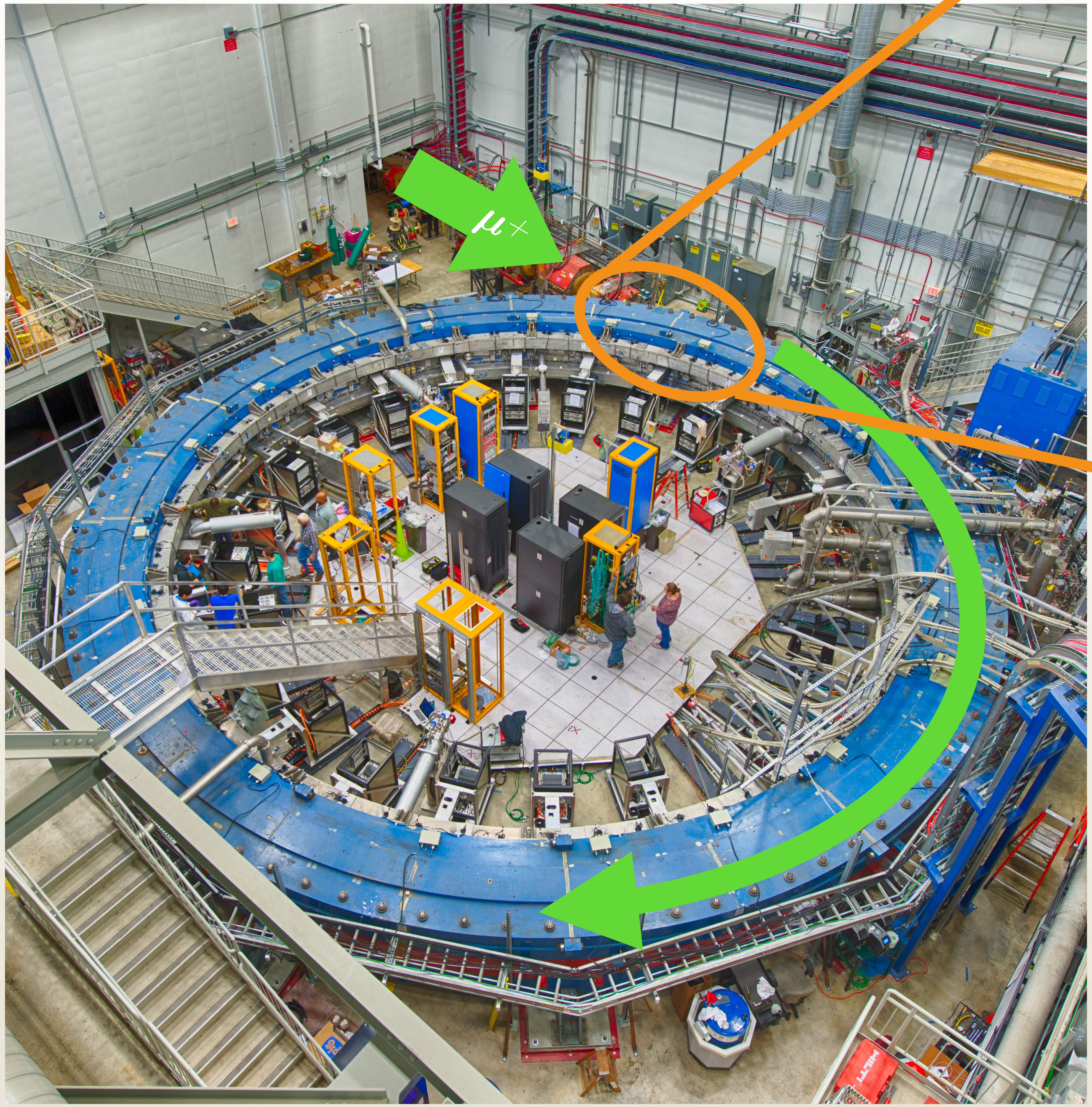
- B = 1.45 T (~5200 A)
- 12 C-shaped yokes
- Field shape: determined by positioning of pole pieces, wedge-shaped pieces of steel, programmable surface coils
  - ~10,000 knobs to fine tune the field

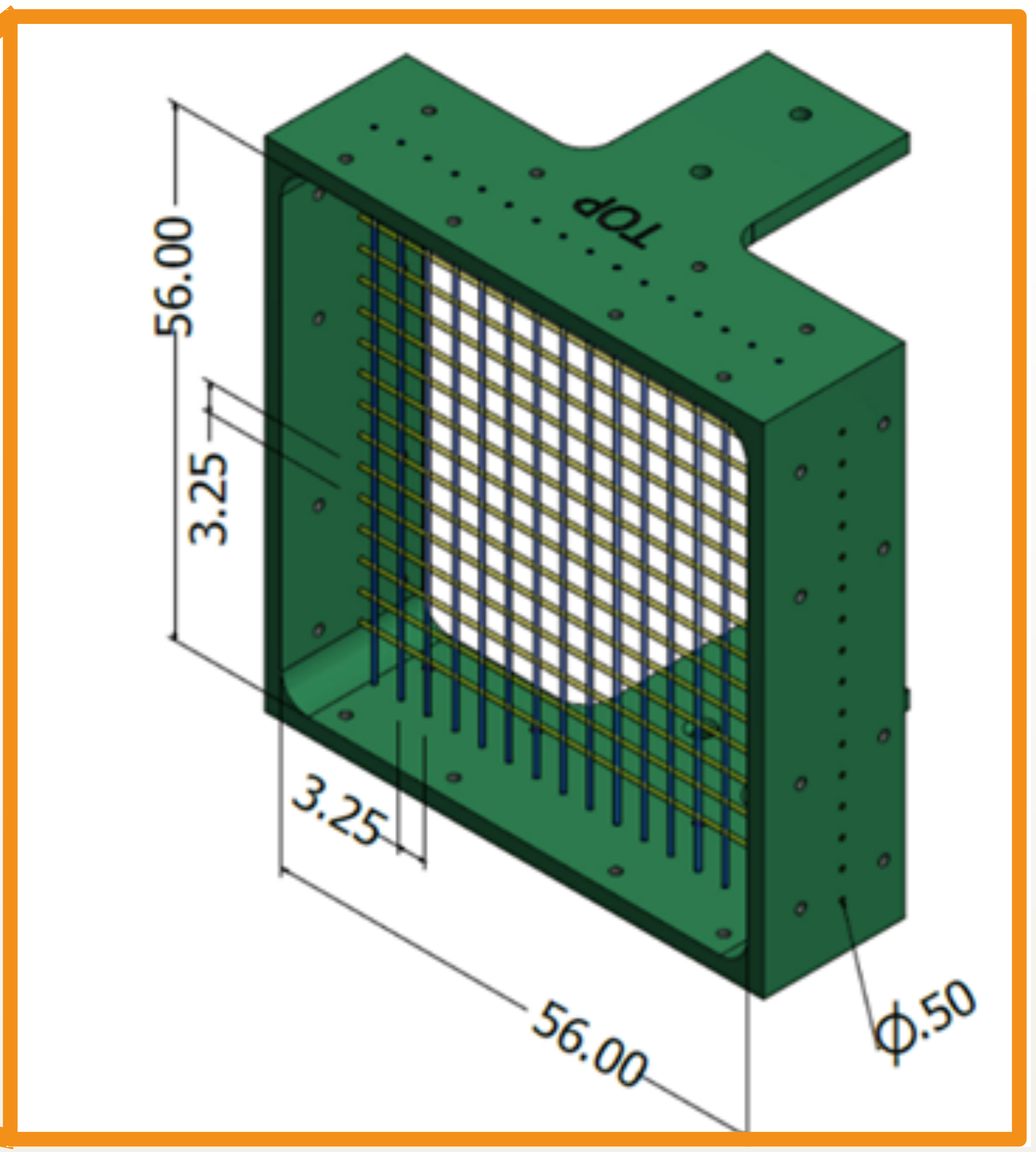
The magnetic field

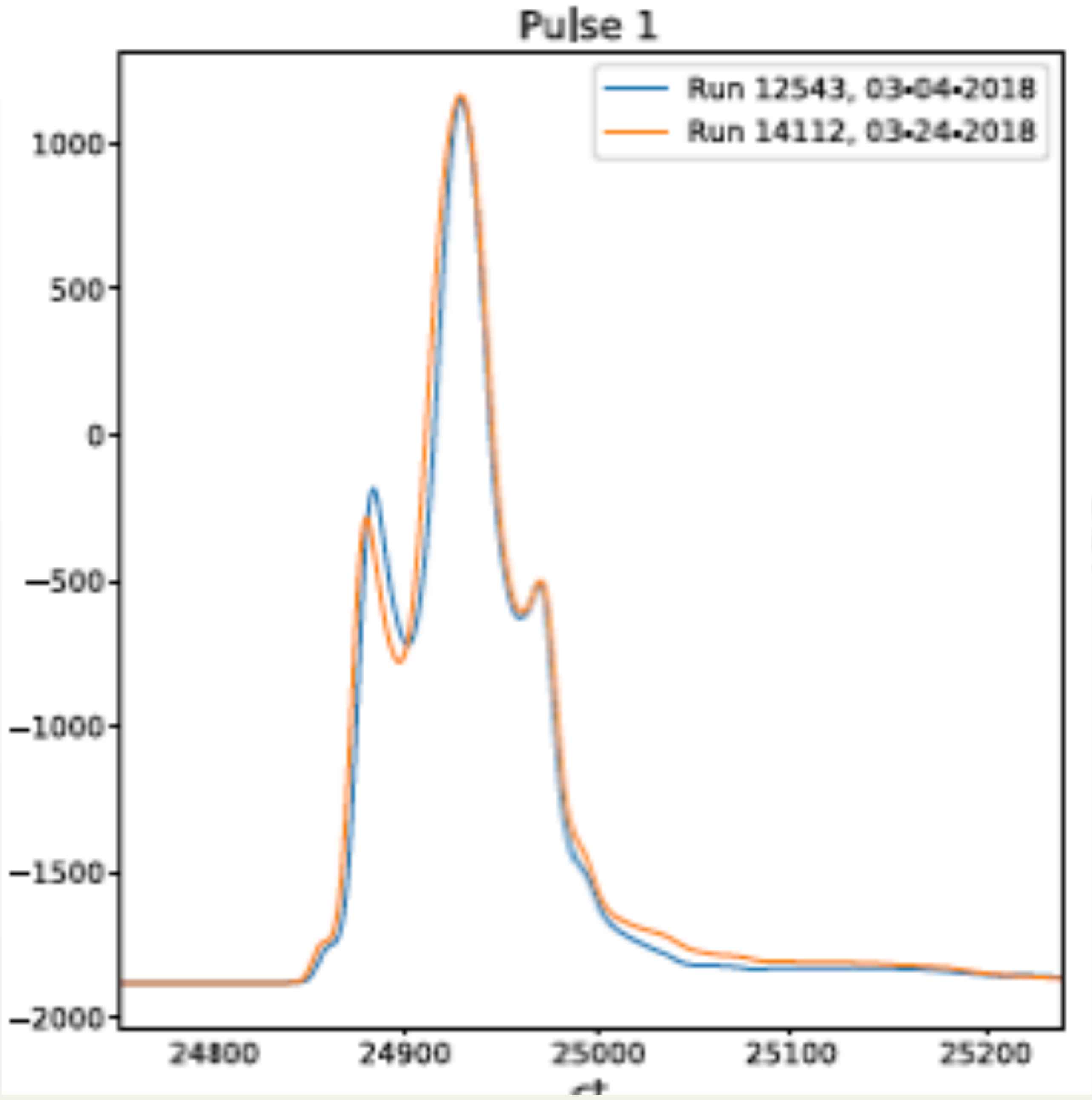
- Field uniformity 14 ppm RMS, ~3x better than BNL

- FNAL shim
- BNL shim

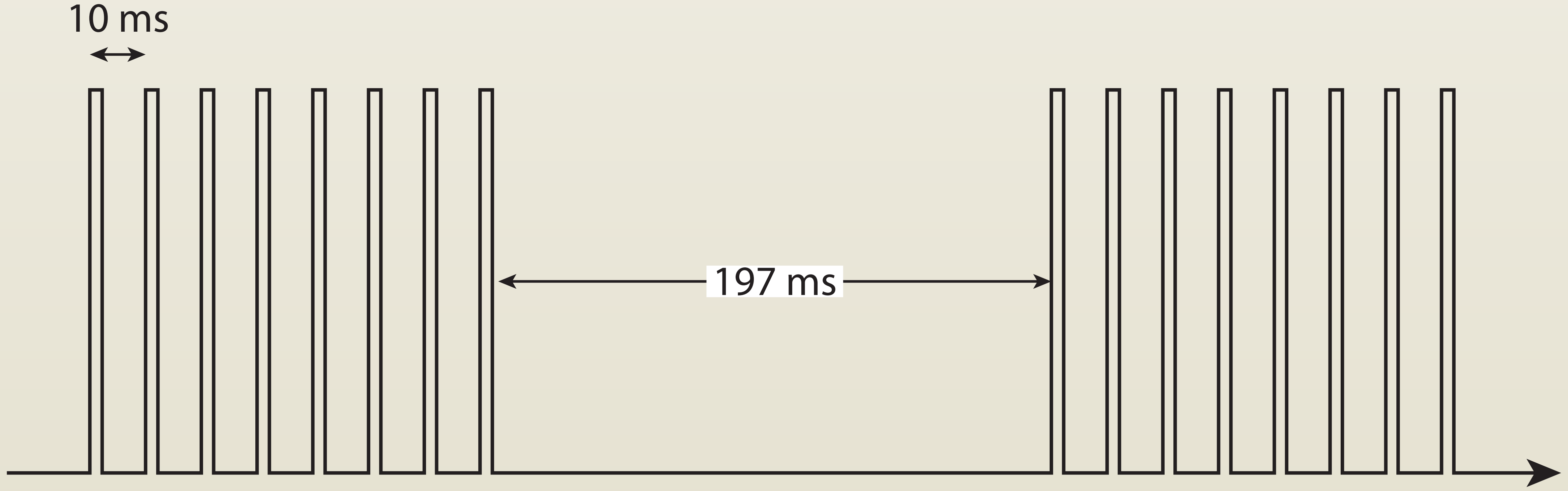
Muon beam injection



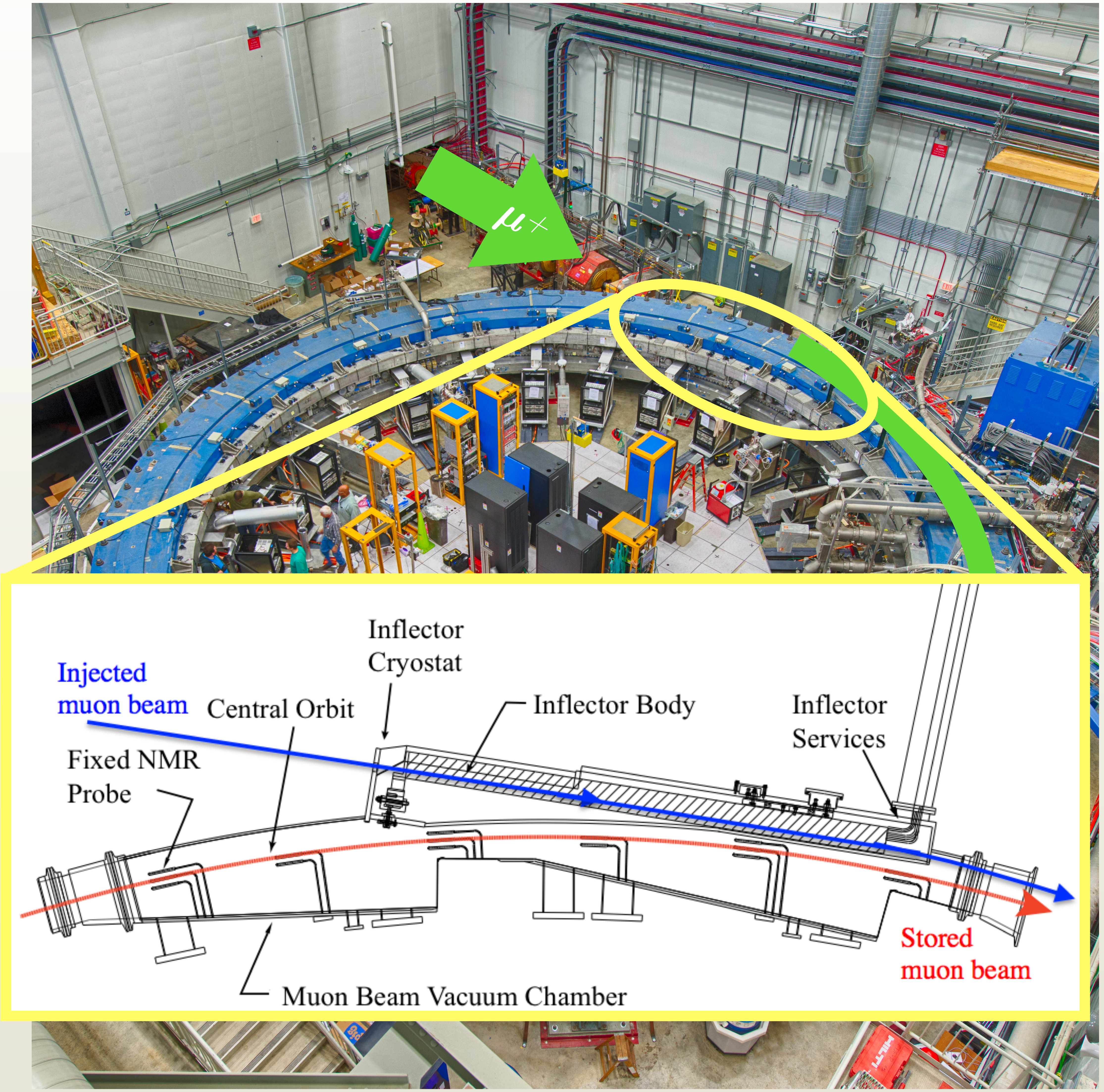




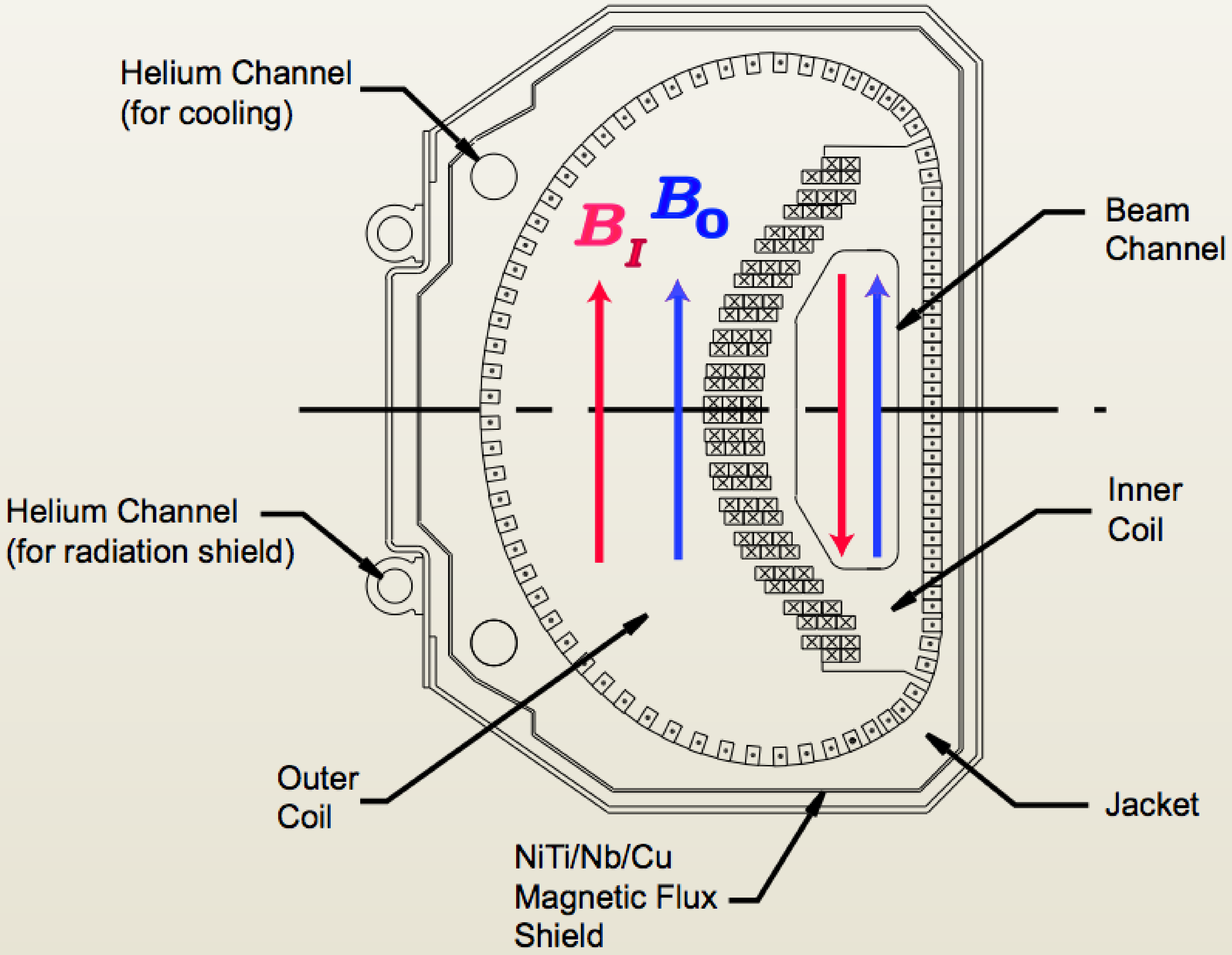
- Incoming muon beam is monitored by 1 plastic scintillator & 2 in-beam scintillating fiber detectors
- Pulsed muon beam, 100 ns width



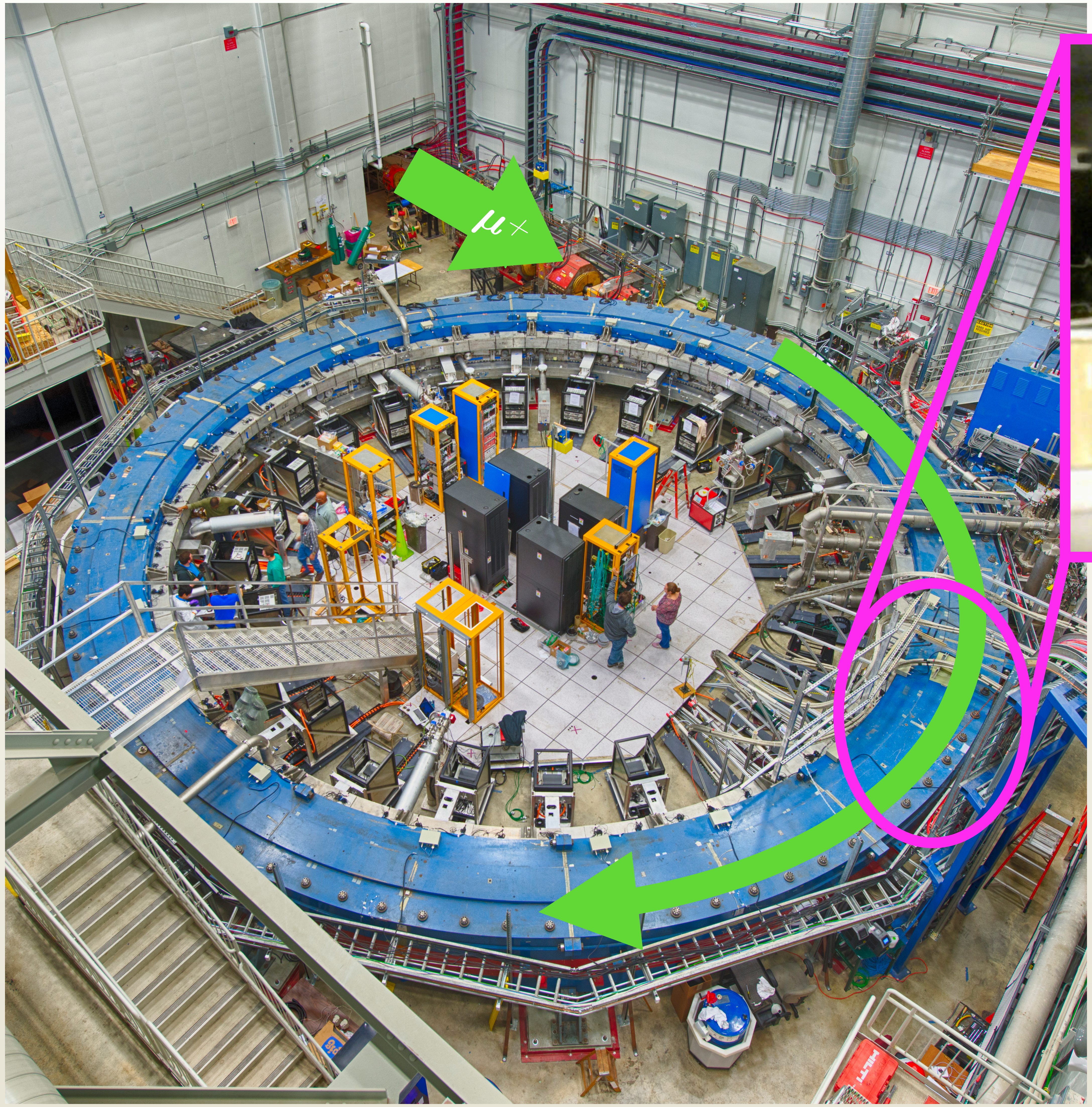
Muon beam injection

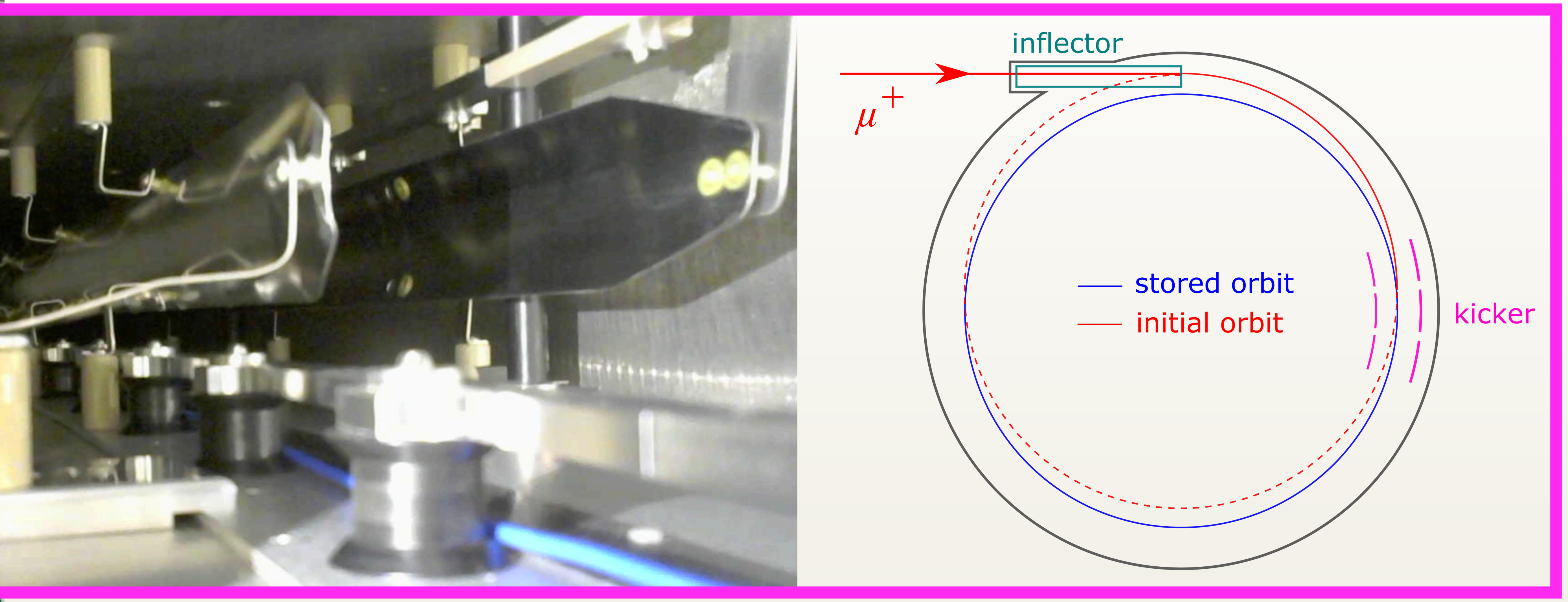


- “Inflector magnet” creates a zero-field region where the beam can be injected into the ring
  - And minimal disturbance to the main magnet field



Kicking muons into stored orbit



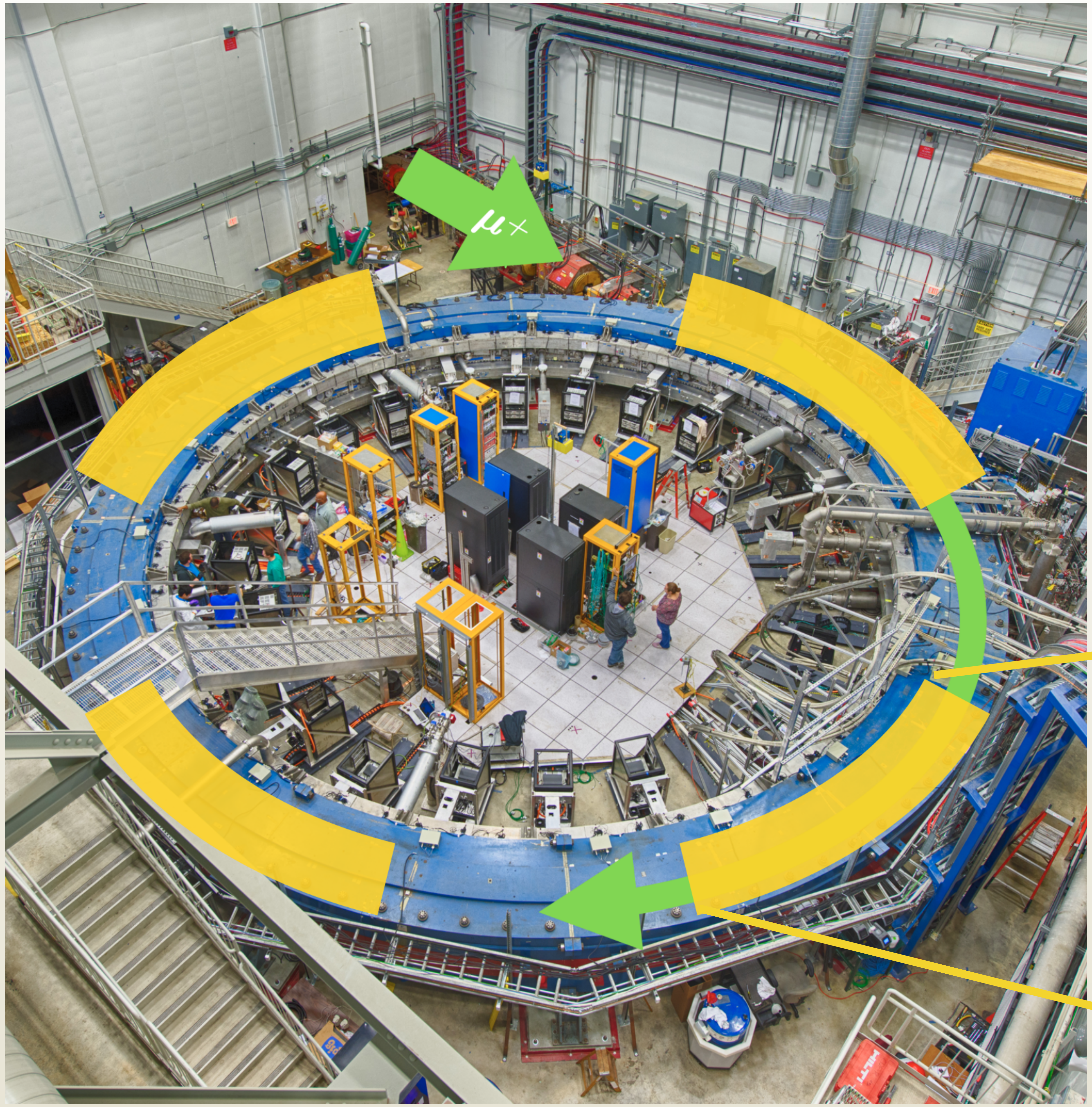


- 3 fast kicker magnets
  - After inflector, muons enter storage region at r = 77 mm outside central closed orbit

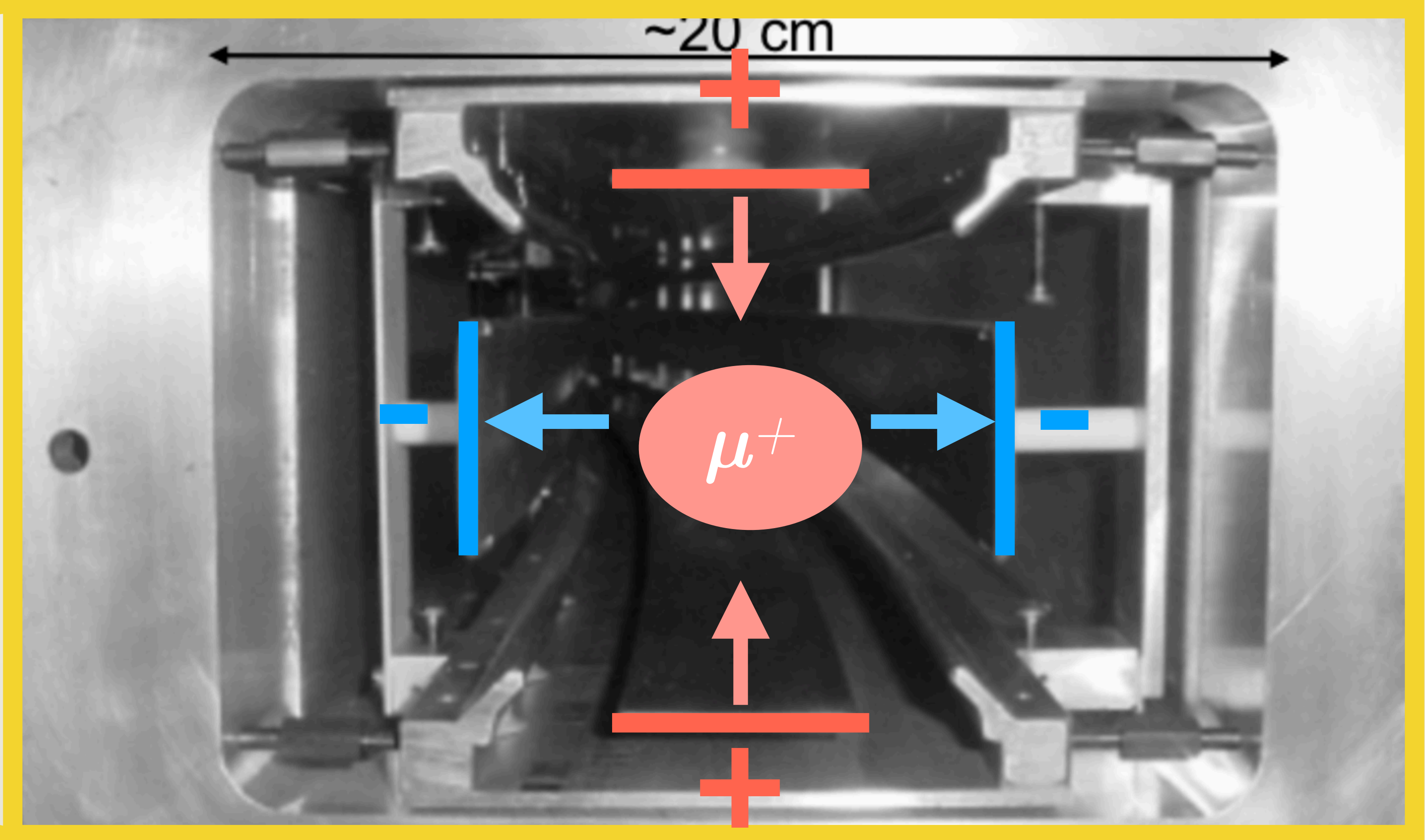
→ need fast kicker pulse to steer muons onto stored orbit

- Strength was less than ideal in Run 1

Muon focusing with quadruple electric field



- Electrostatic Quadrupoles (ESQ)
  - Drives the muons towards the central part of storage region vertically
  - Aluminum electrodes cover ~43% of total circumference
  - The quadrupoles are charged ~30 μs before muon injection, then keep the voltage for about 700 μs



Complications of the focusing electric field

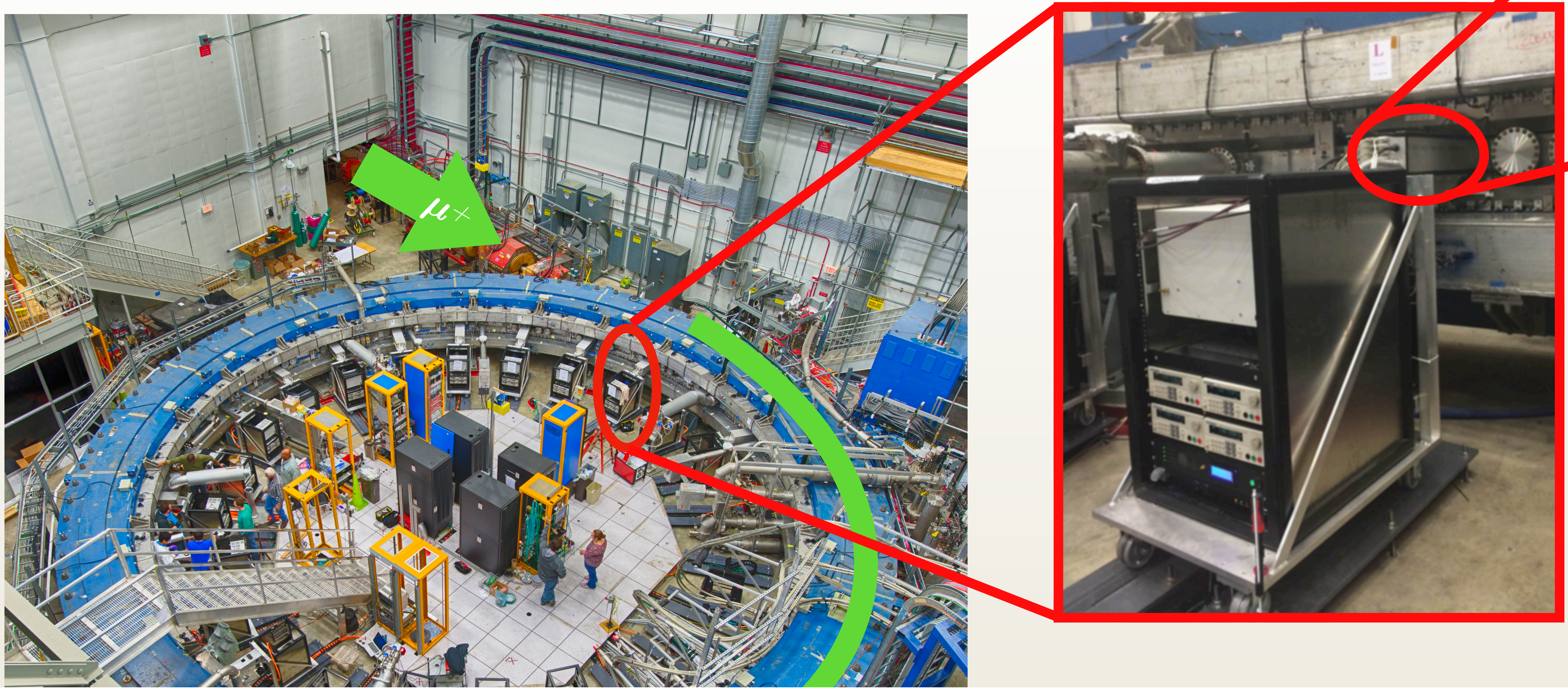
- Introduces 2 more terms that reduce the precession frequency:

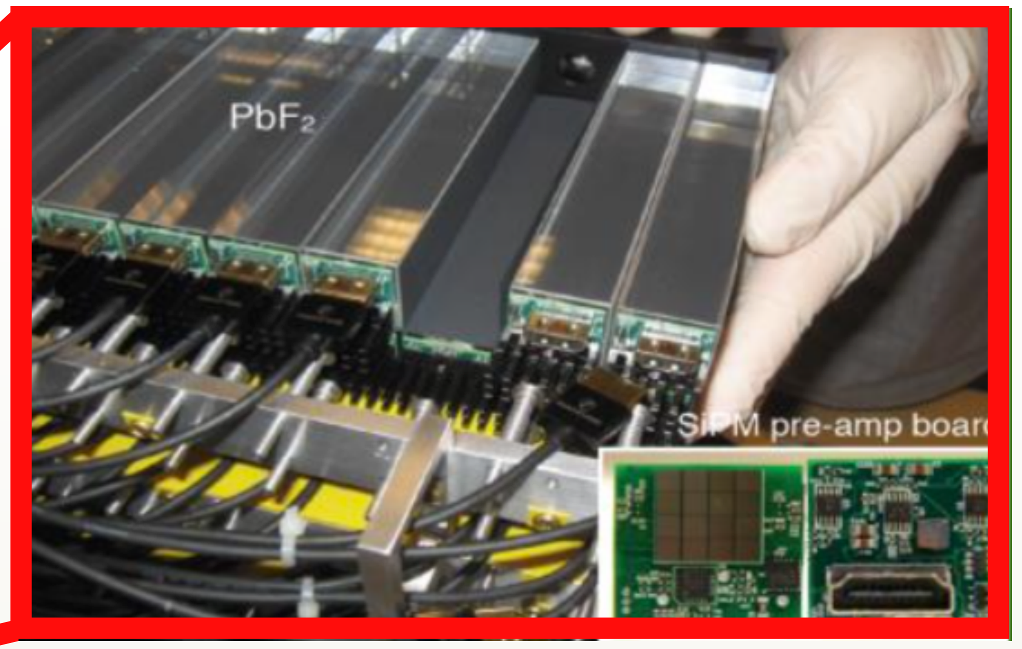
$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu \frac{\gamma}{\gamma + 1}(\vec{\beta}.\vec{B})\vec{\beta}\right]$$

- The first term can be minimized by choosing $\gamma = 29.3$ ($p_\mu = 3.09$ GeV/c a.k.a. magic momentum)
    - Muon beam momentum has a spread of 0.1% → need a correction (so-called electric field correction)
- The second one relates to vertical motion (aligned with B field), can be corrected for if the beam profile is known → pitch correction

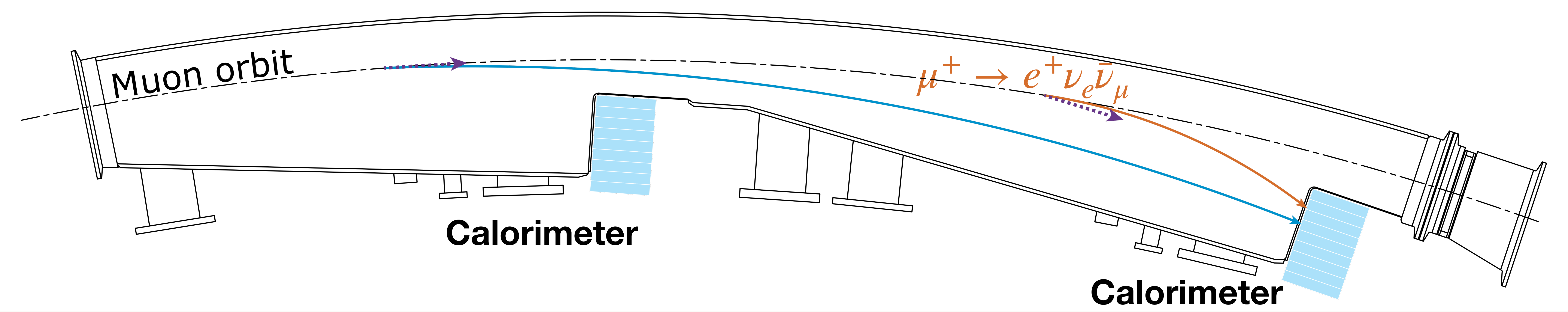
$$R_\mu = \frac{f_{\text{clock}}\,\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

Measuring spin precession frequency



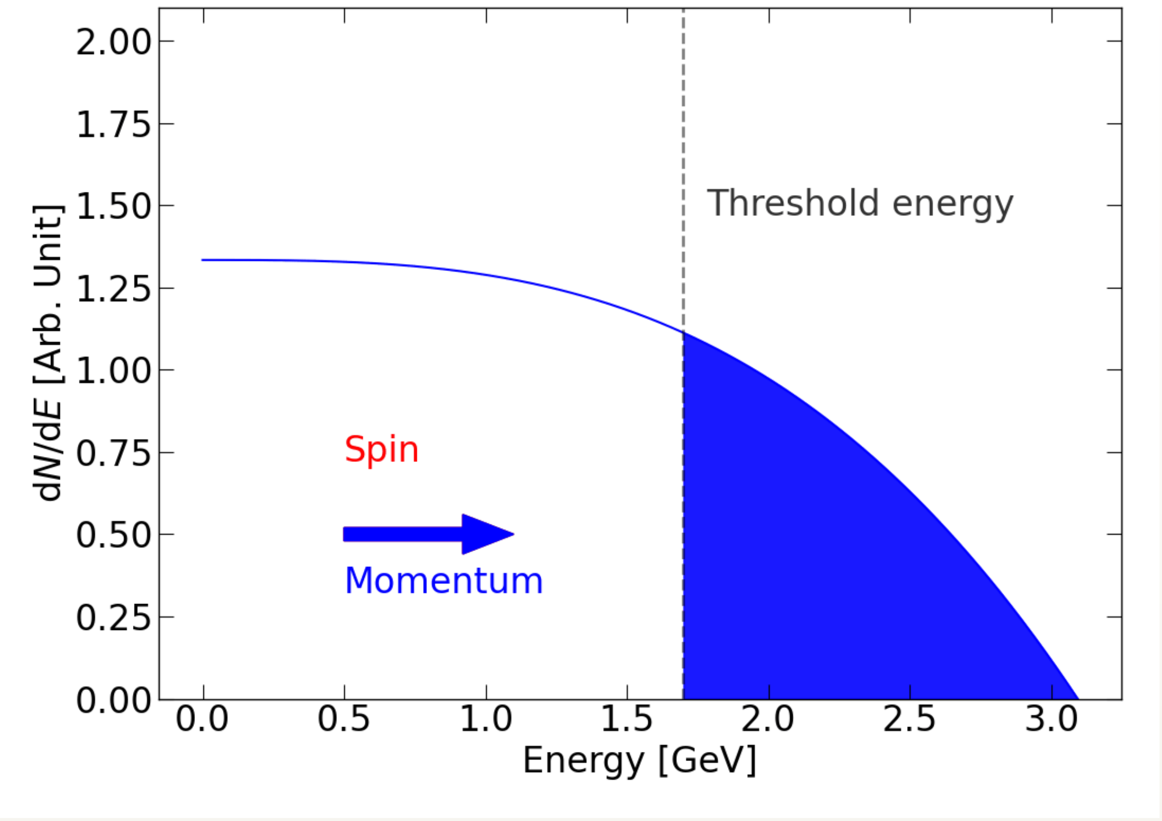


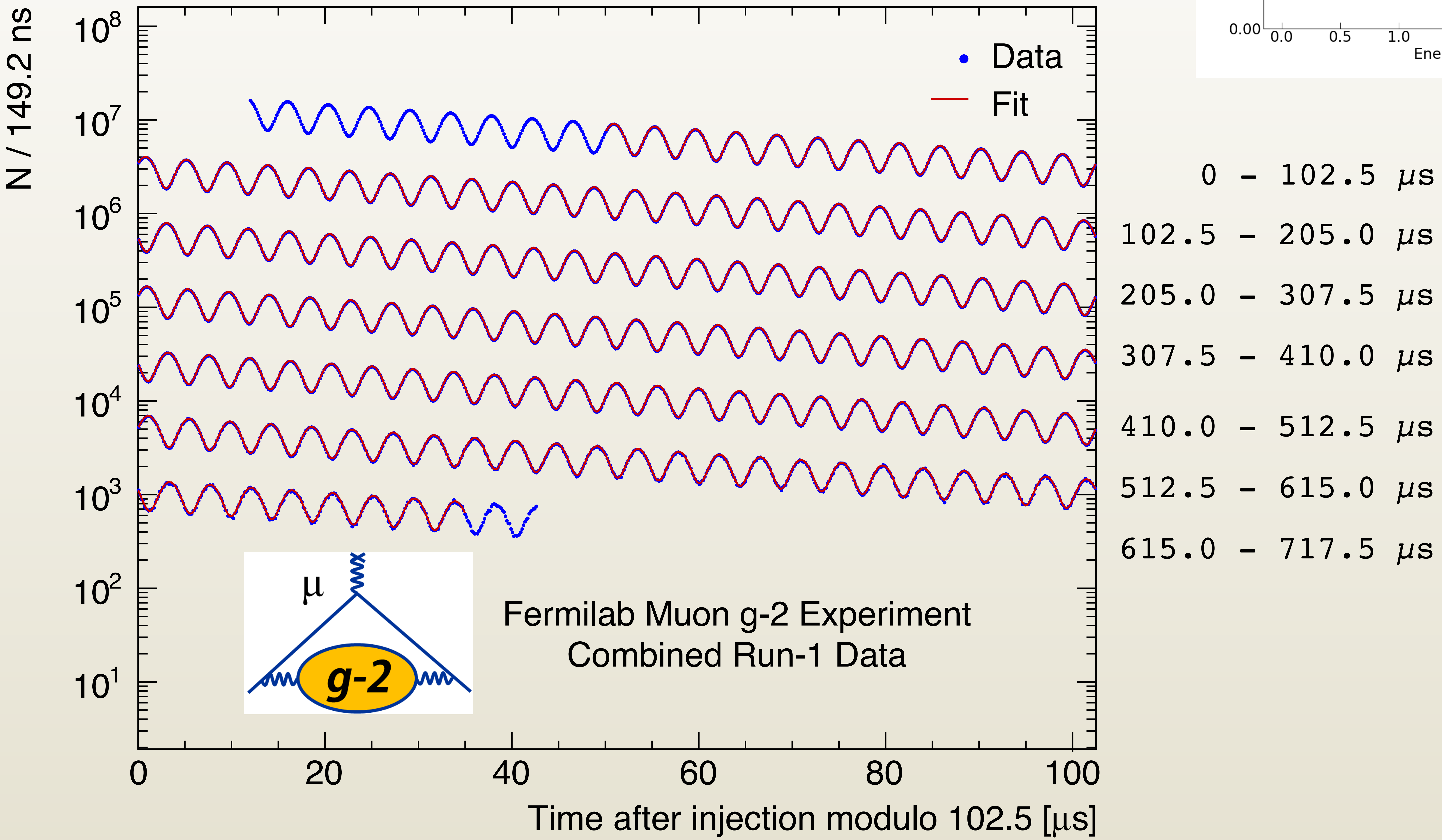
- 24 segmented PbF_2 calorimeters
  - Observing positrons from μ^+ decays
  - Energy of positron is correlated to muon spin direction at the time of decay



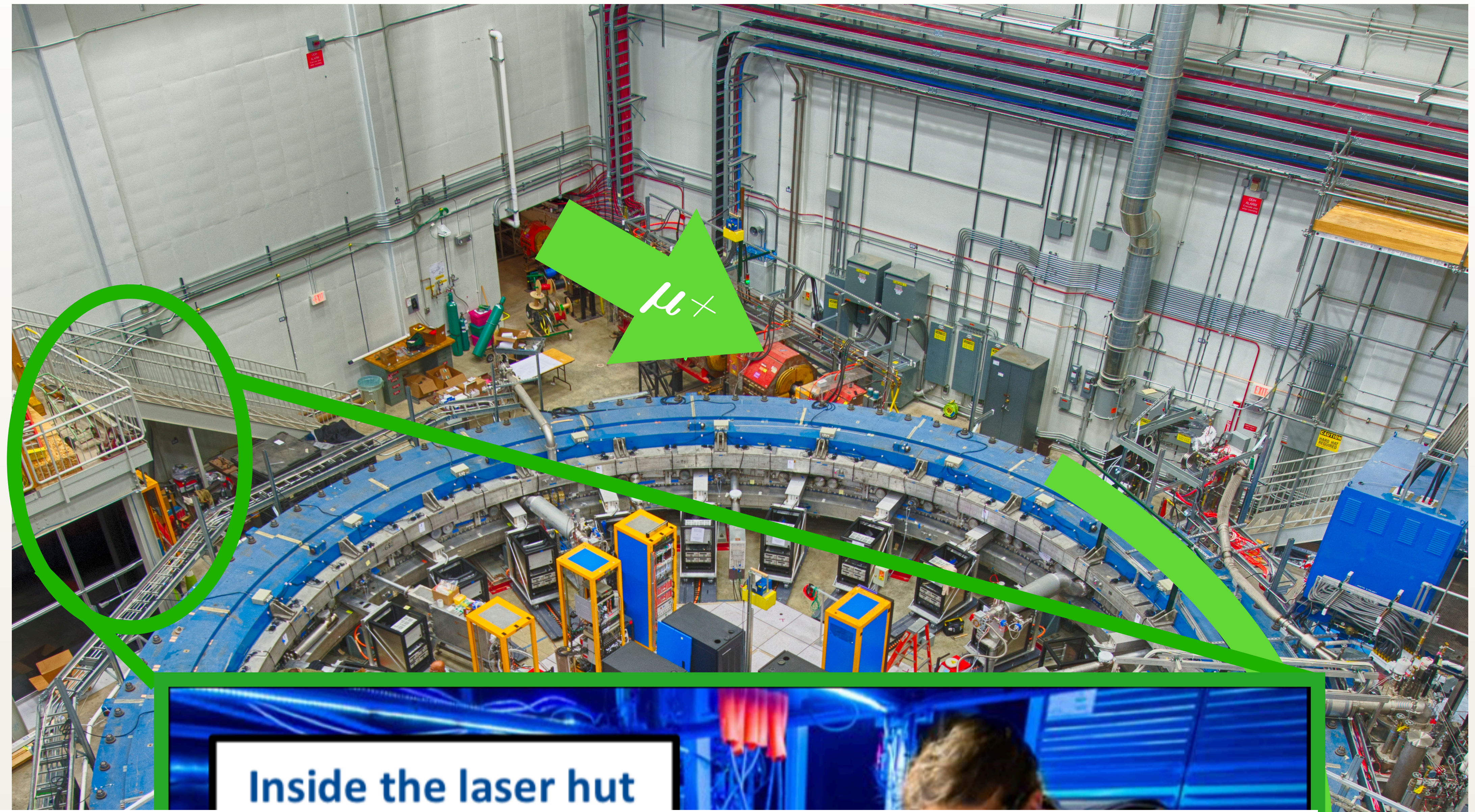
The wiggle plot

- As muon spin precessing, the number of observed decay positrons is modulated by the precession frequency

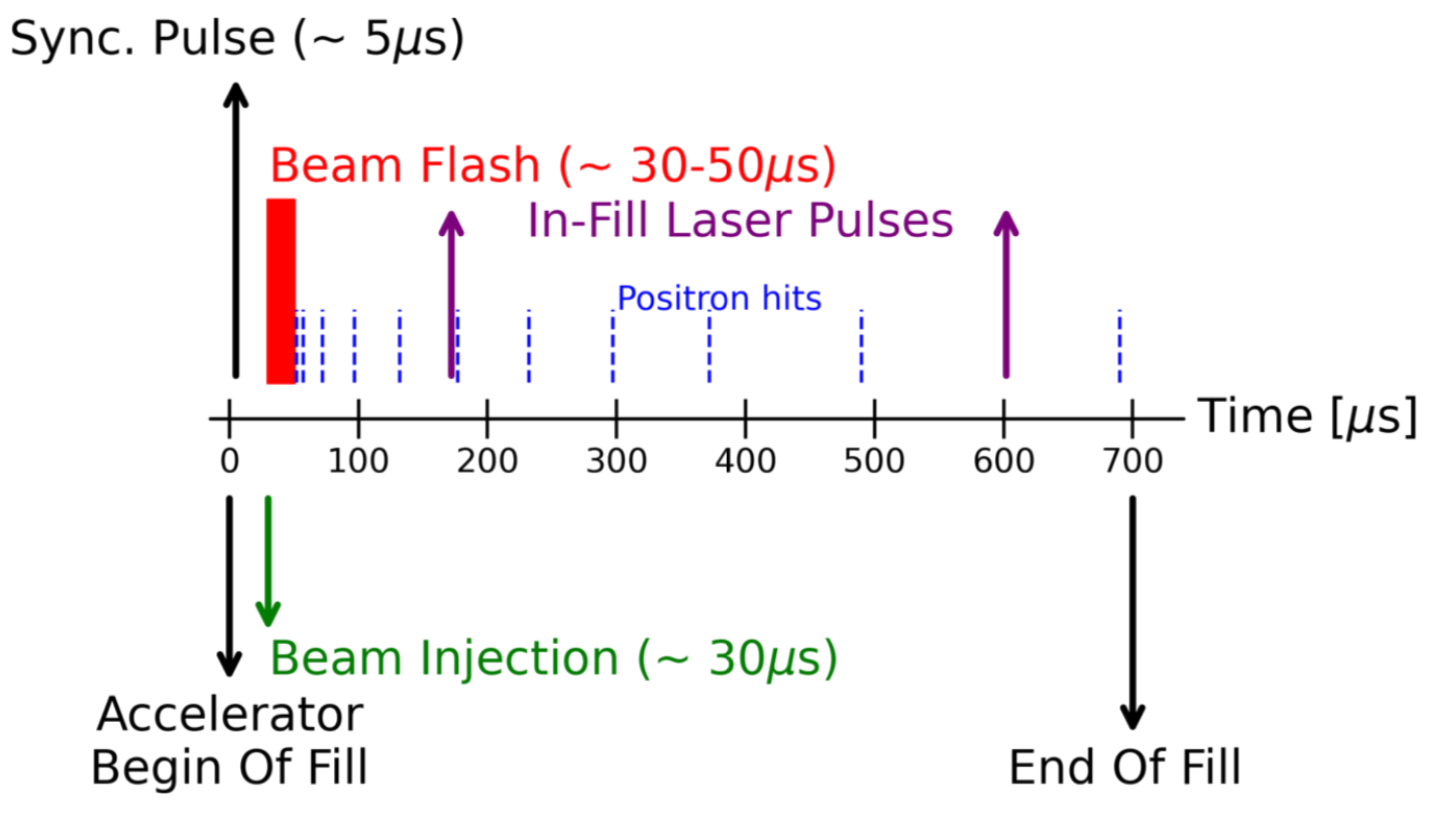


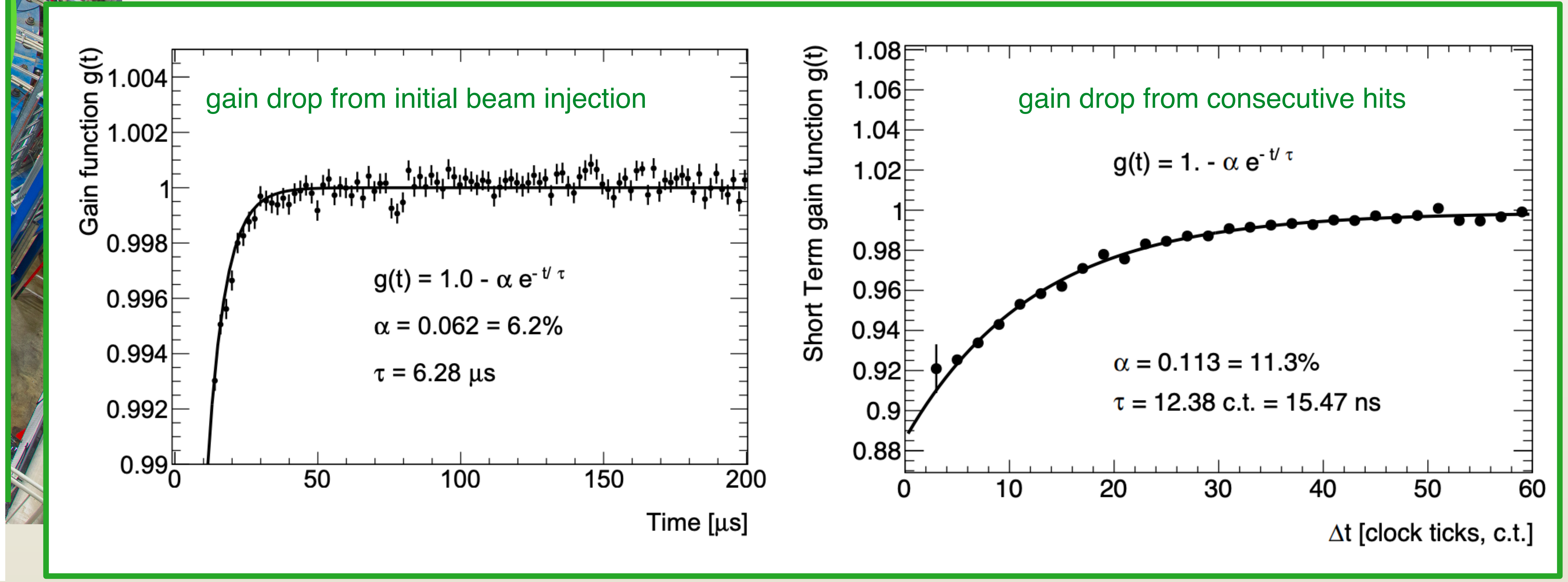


Monitoring the calorimeter gain stability

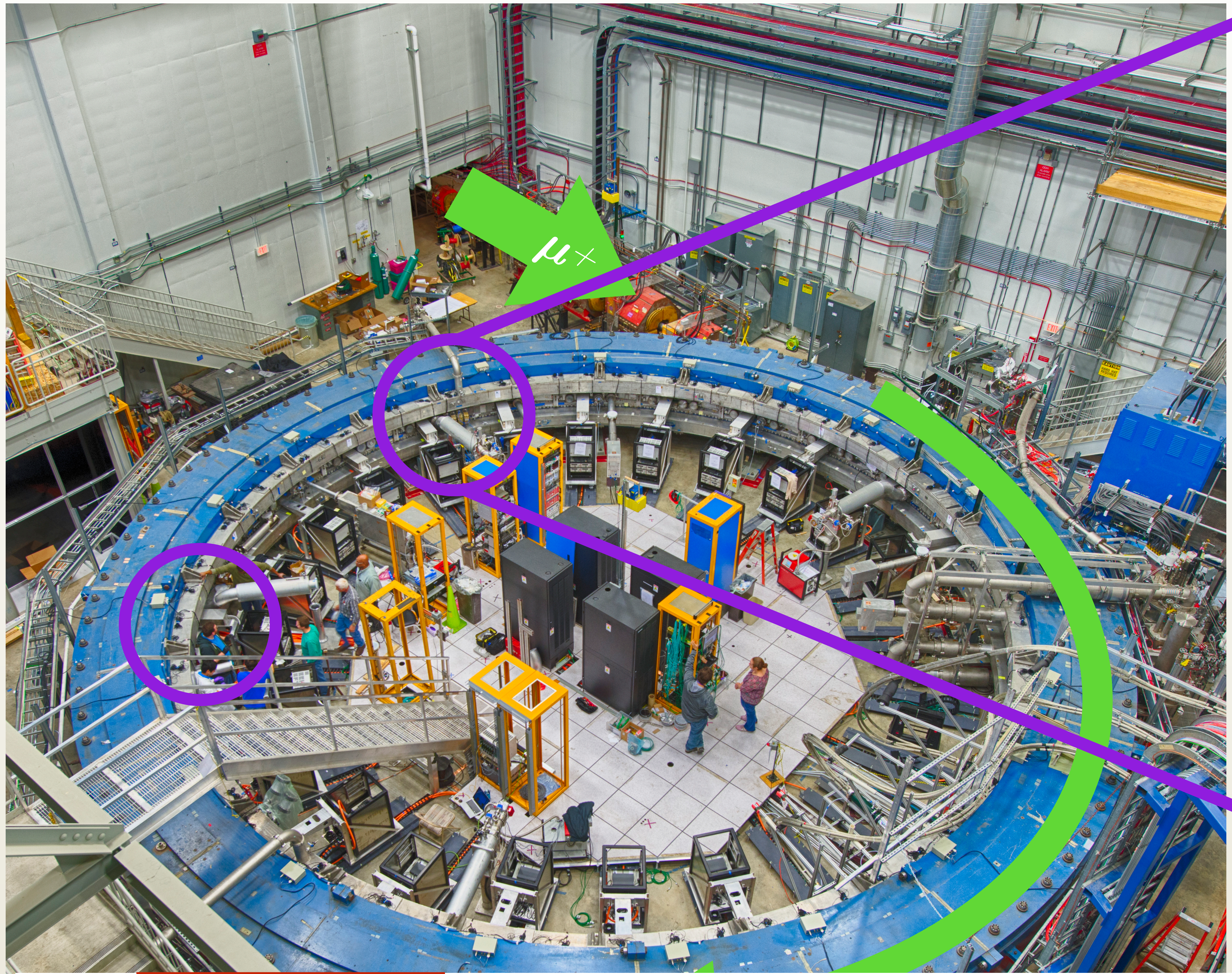


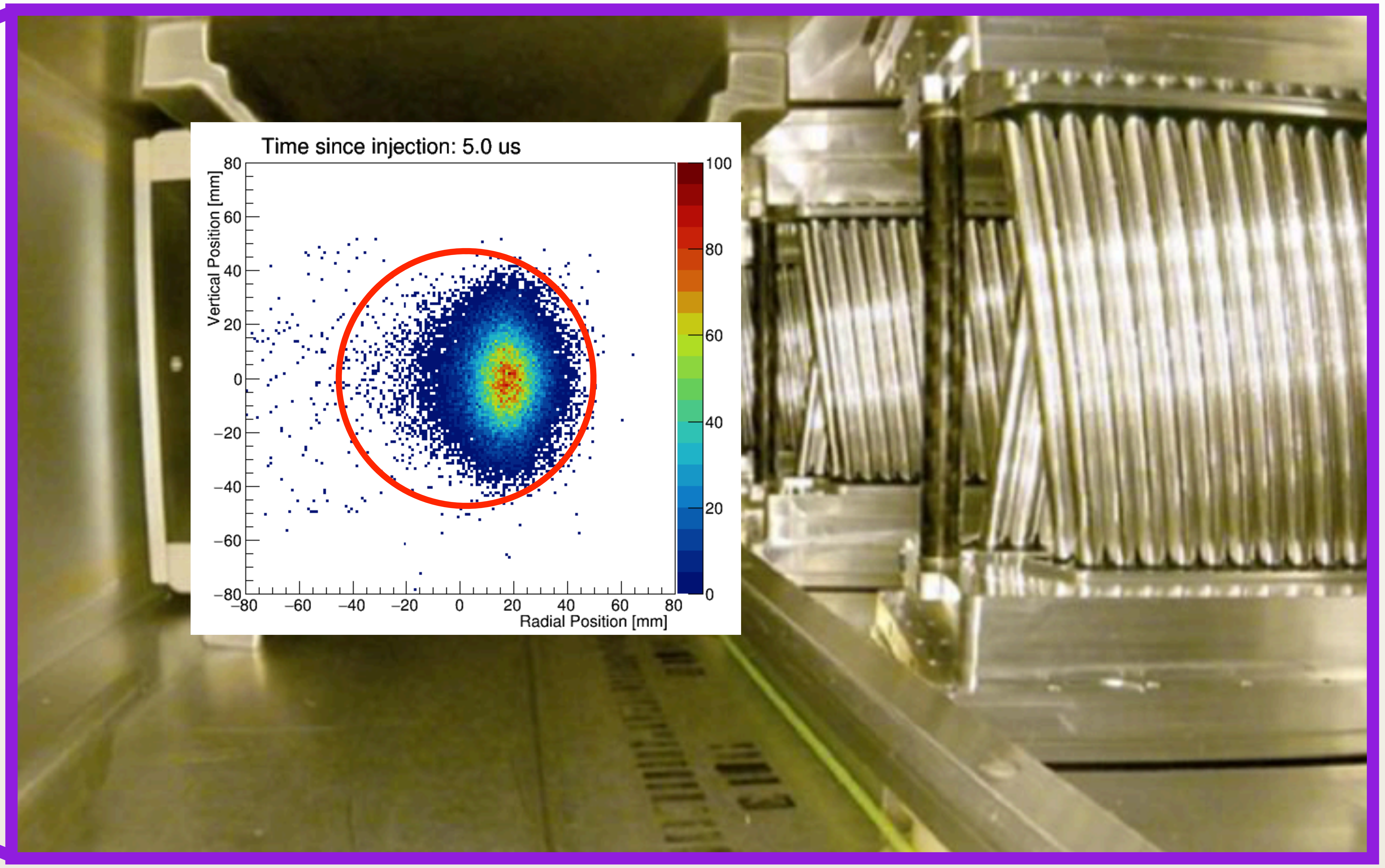
- Laser system
  - Fire laser pulses with fixed intensity into calorimeters after each muon fill
  - Calibrate calorimeter gain response throughout data taking

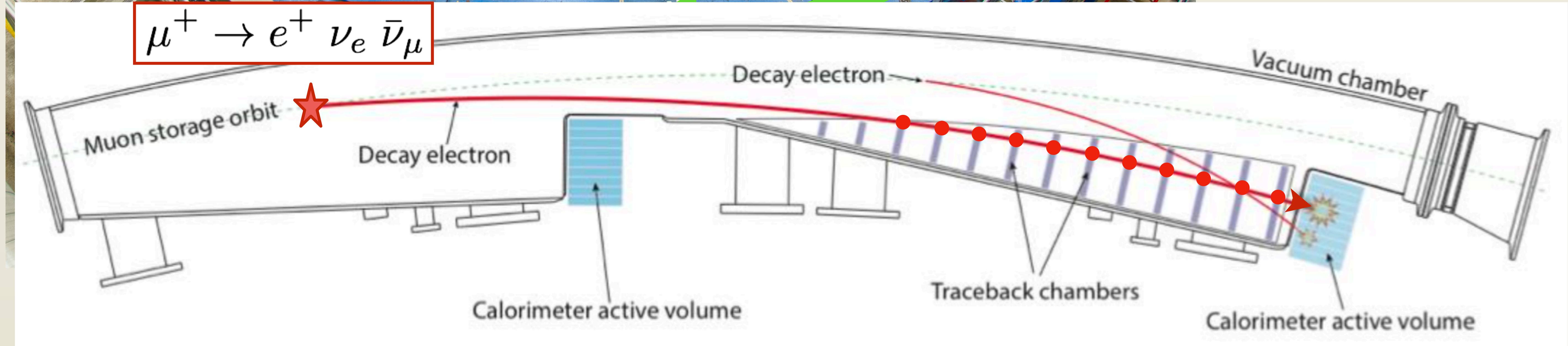




Measuring beam dynamics

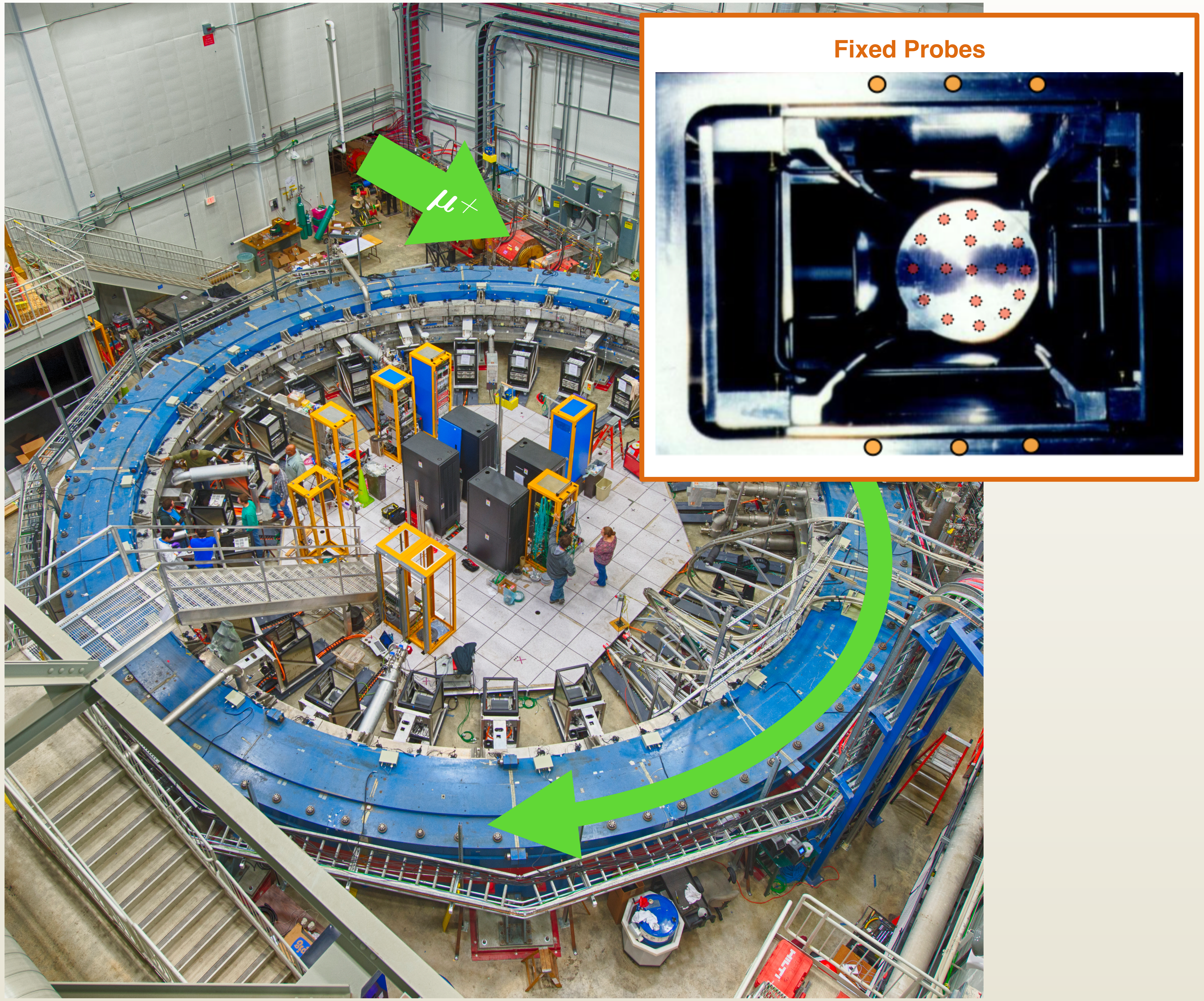






- 2 straw-tube tracker stations
  - Measure decay positron trajectories
  - Allow reconstruction of muon beam profile

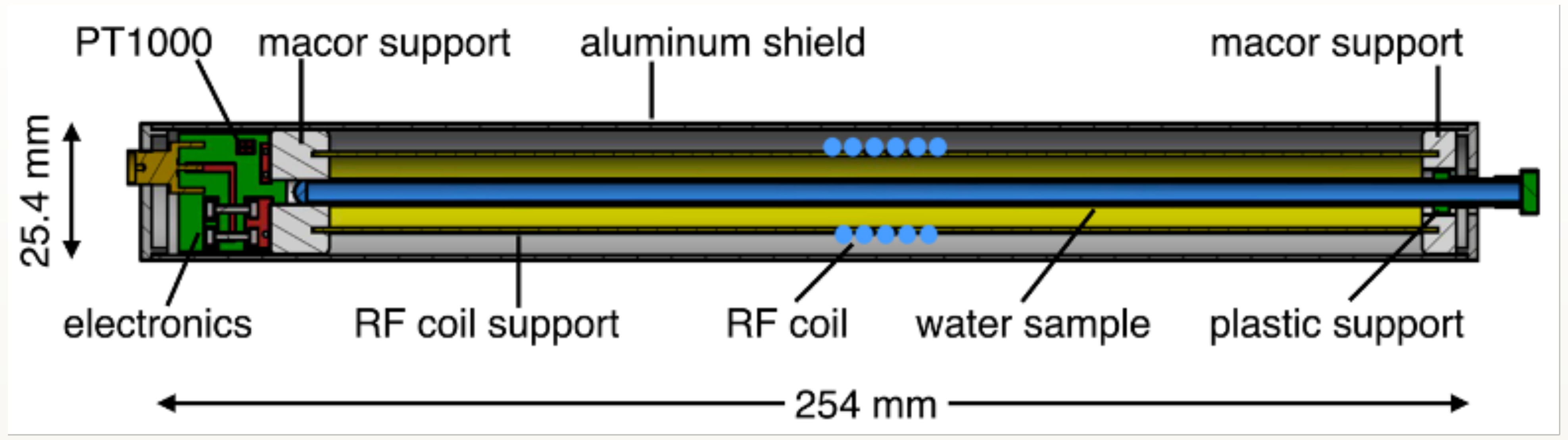
Measuring the magnetic field

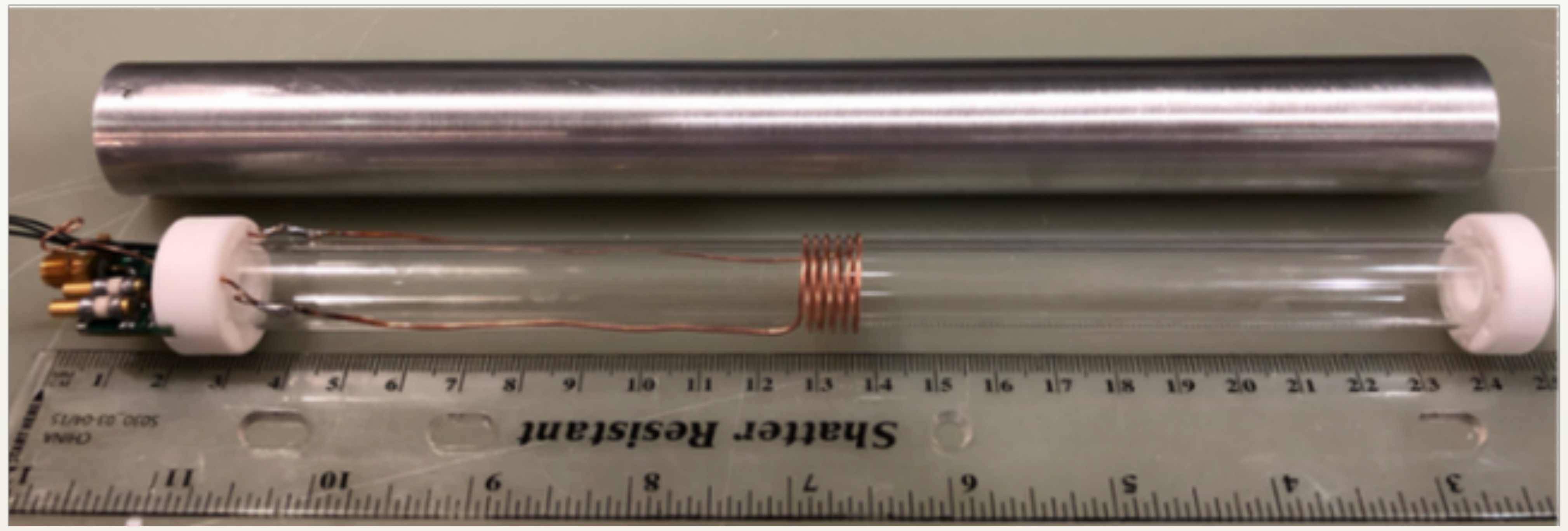


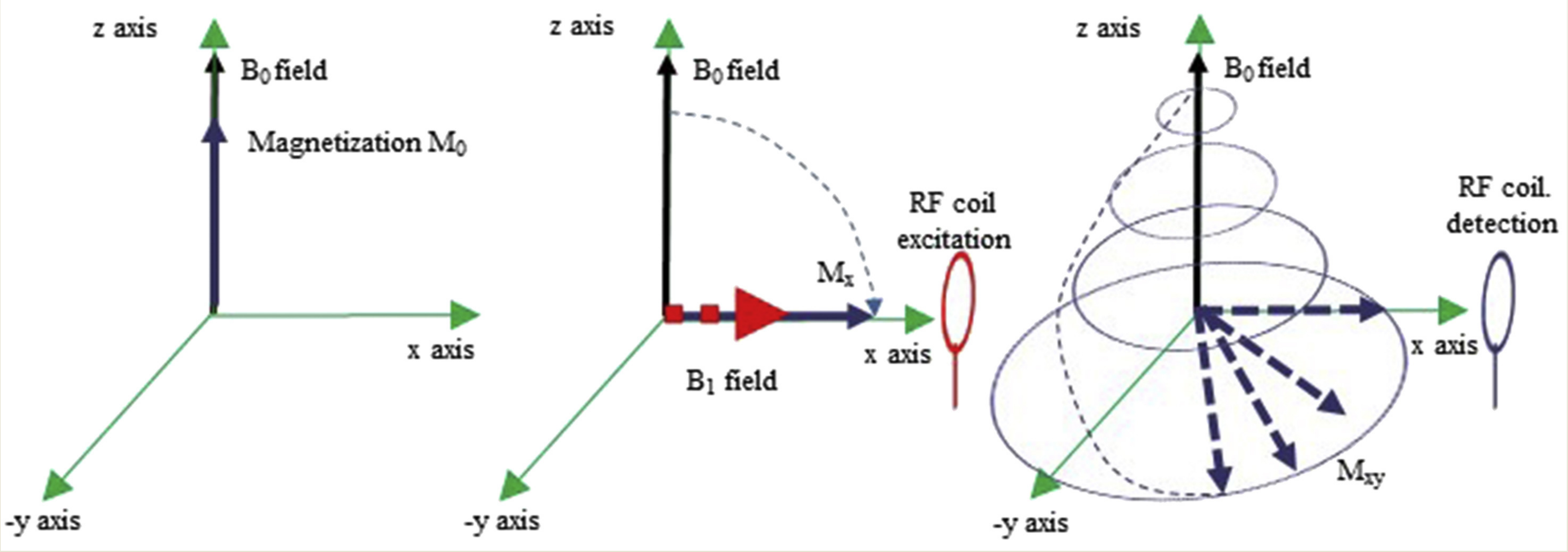
- 378 NMR probes in 72 stations around the ring, monitoring 24/7
- One motorized cart (trolley) with 17 NMR probes to map the magnetic field in the muon storage region every 2-3 days

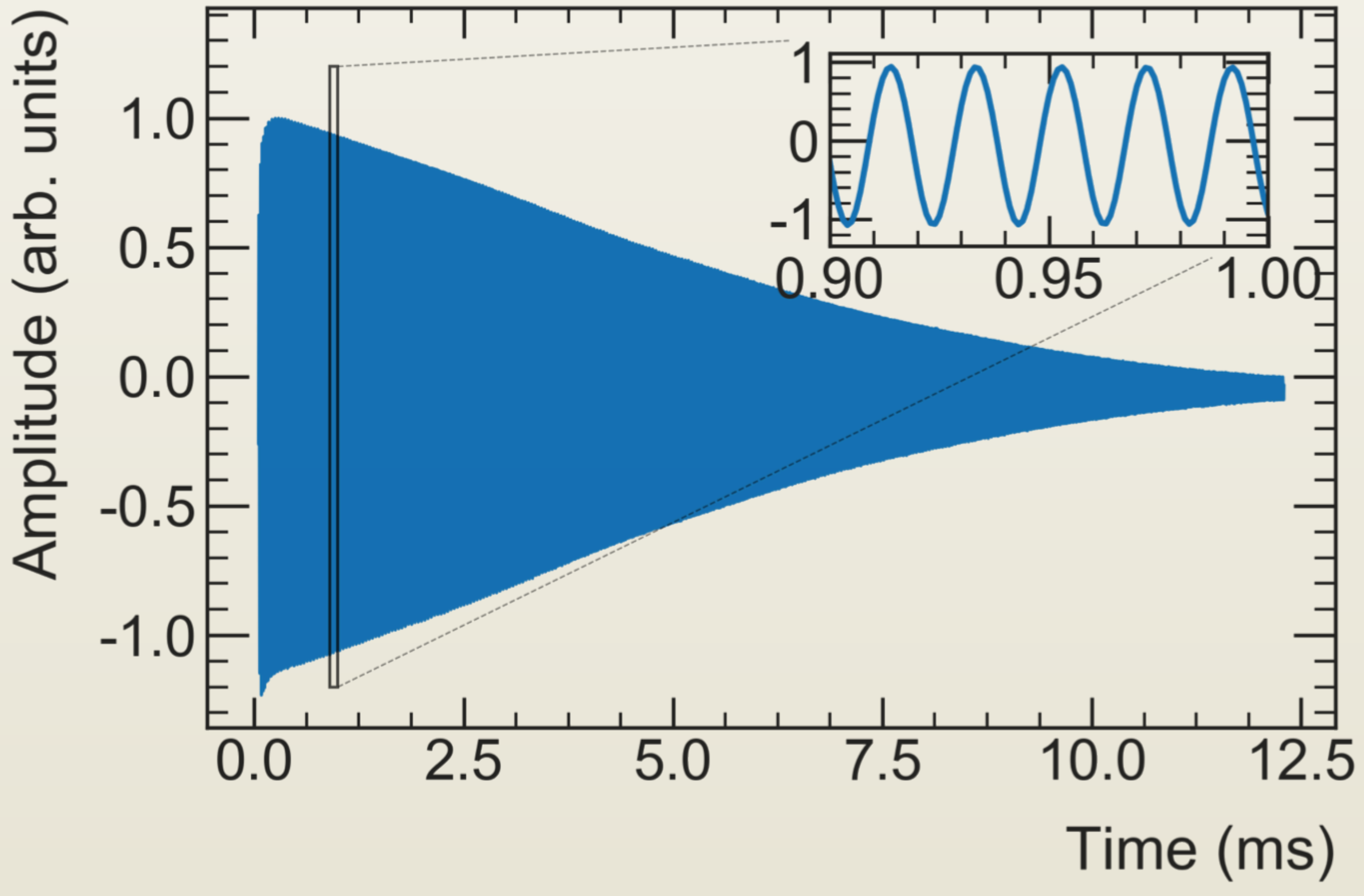
NMR technique

- Return B field strength in terms of precession frequency of a proton
- E.g: pulsed NMR
  - π/2 RF pulse is used to rotate a proton spin
  - detect the free induction decay using a pick up coil around the sample





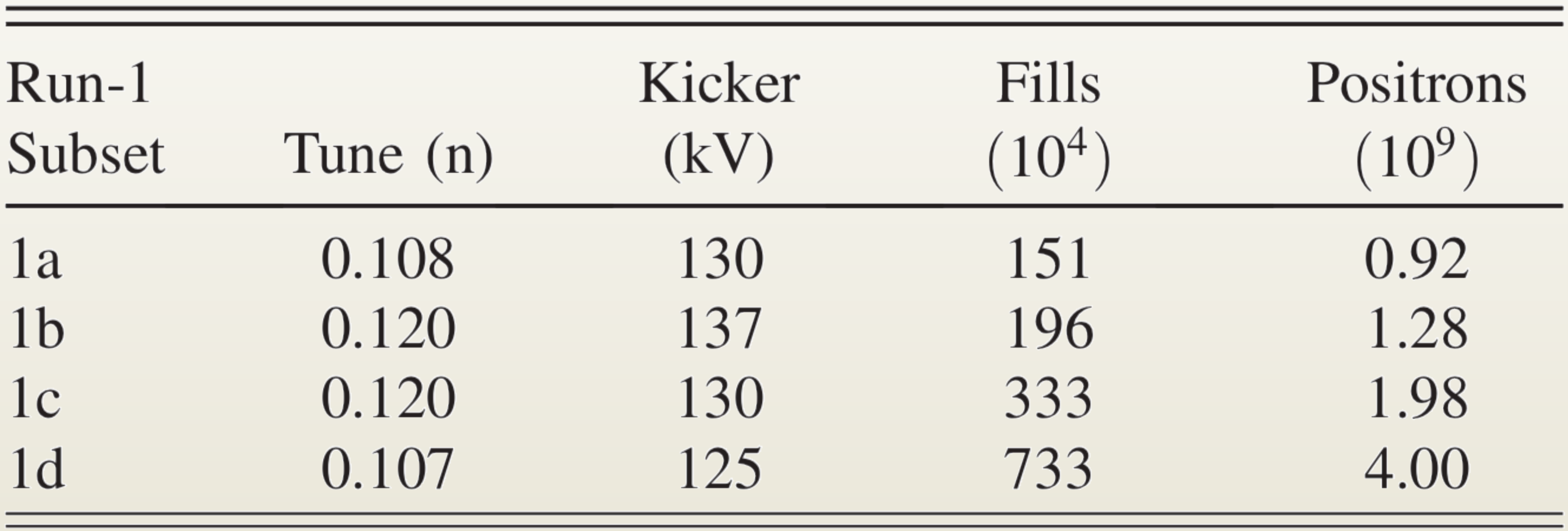




Analysis

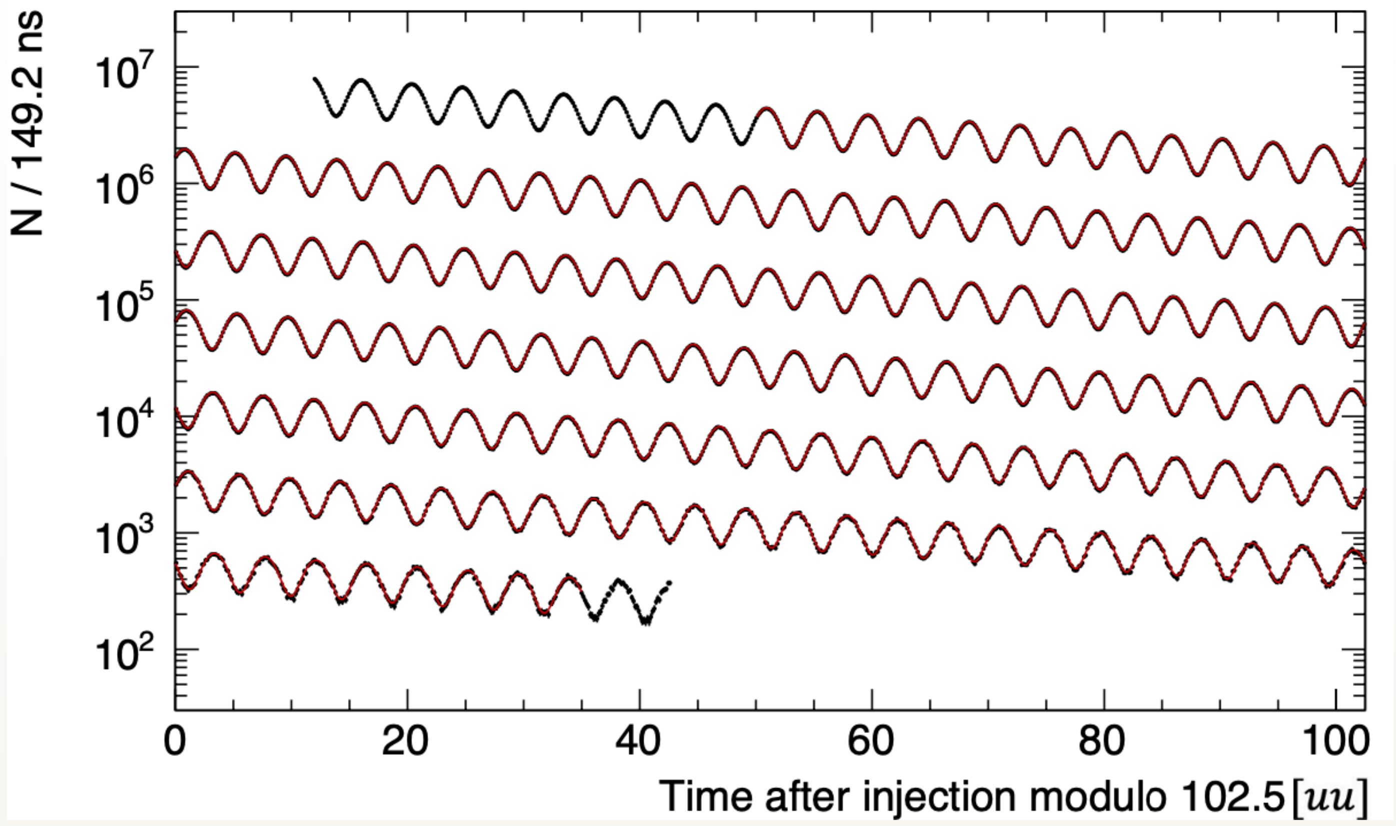
Run 1 datasets

- 4 datasets, based on kicker and focusing quadrupole settings
- Each dataset is analyzed separately



Run-1 Subset	Tune (n)	Kicker (kV)	Fills (10^4)	Positrons (10^9)
1a	0.108	130	151	0.92
1b	0.120	137	196	1.28
1c	0.120	130	333	1.98
1d	0.107	125	733	4.00

Precession frequency ω_a



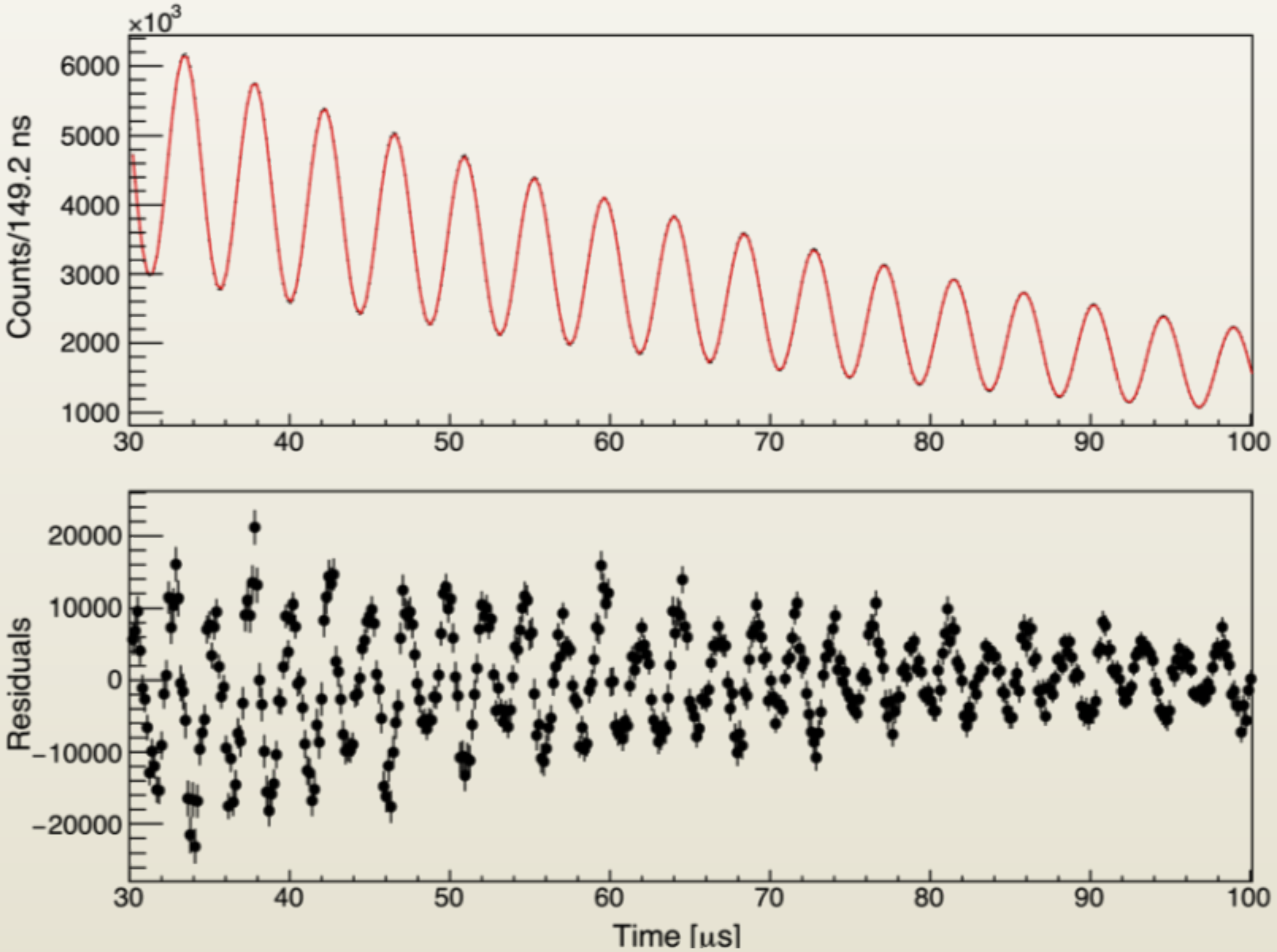
- Naive fit function

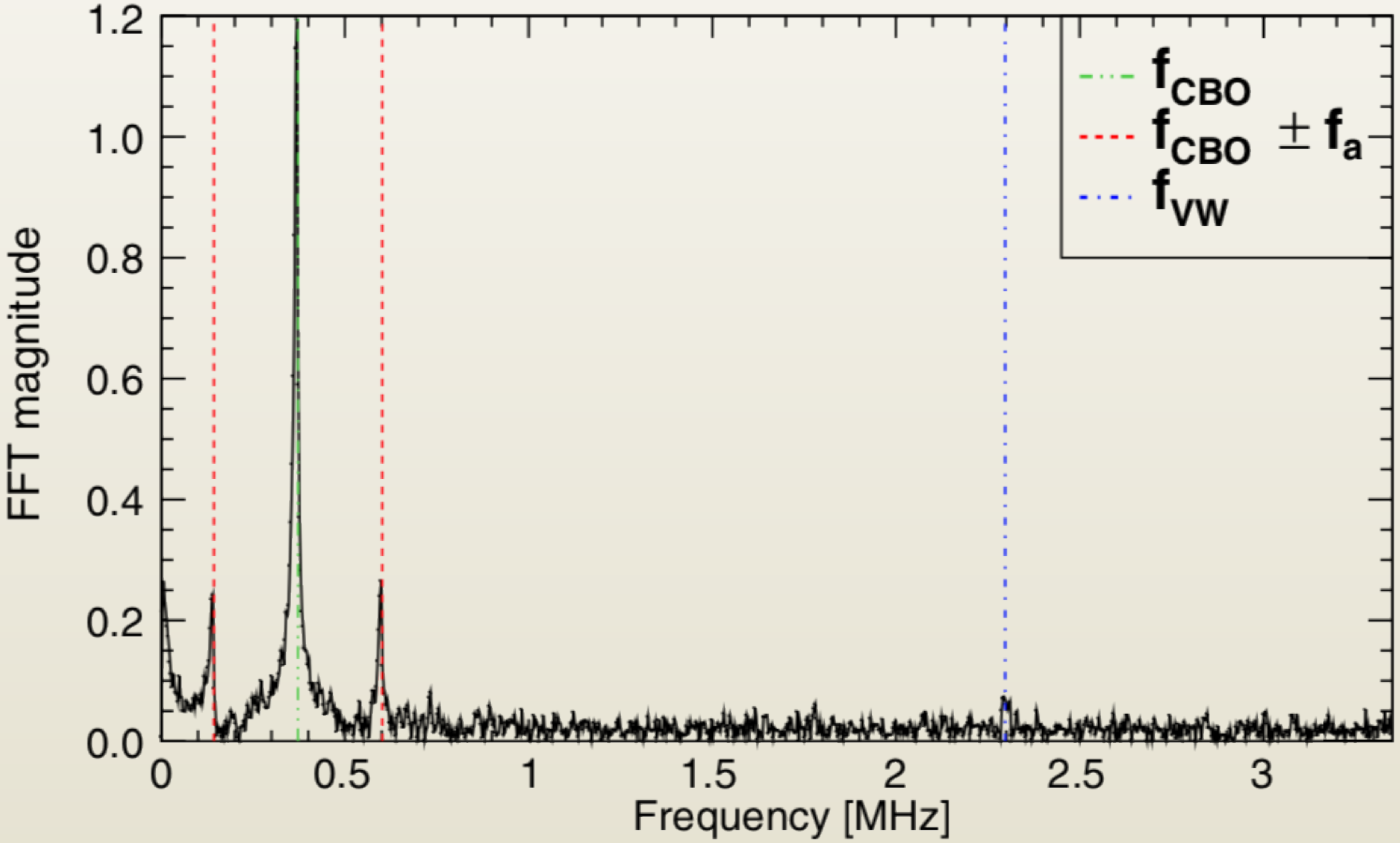
$$F(t) = N_0 e^{-t/\gamma\tau_\mu}\left[1 + A_0 \cos(\omega_a^m t + \phi)\right]$$

(Muon decay)

(Oscillation due to precession)

does not capture beam dynamics and results in significant residuals





Precession frequency ω_a - Full fit function

- Full fit function incorporates effects from beam dynamics, detector acceptance

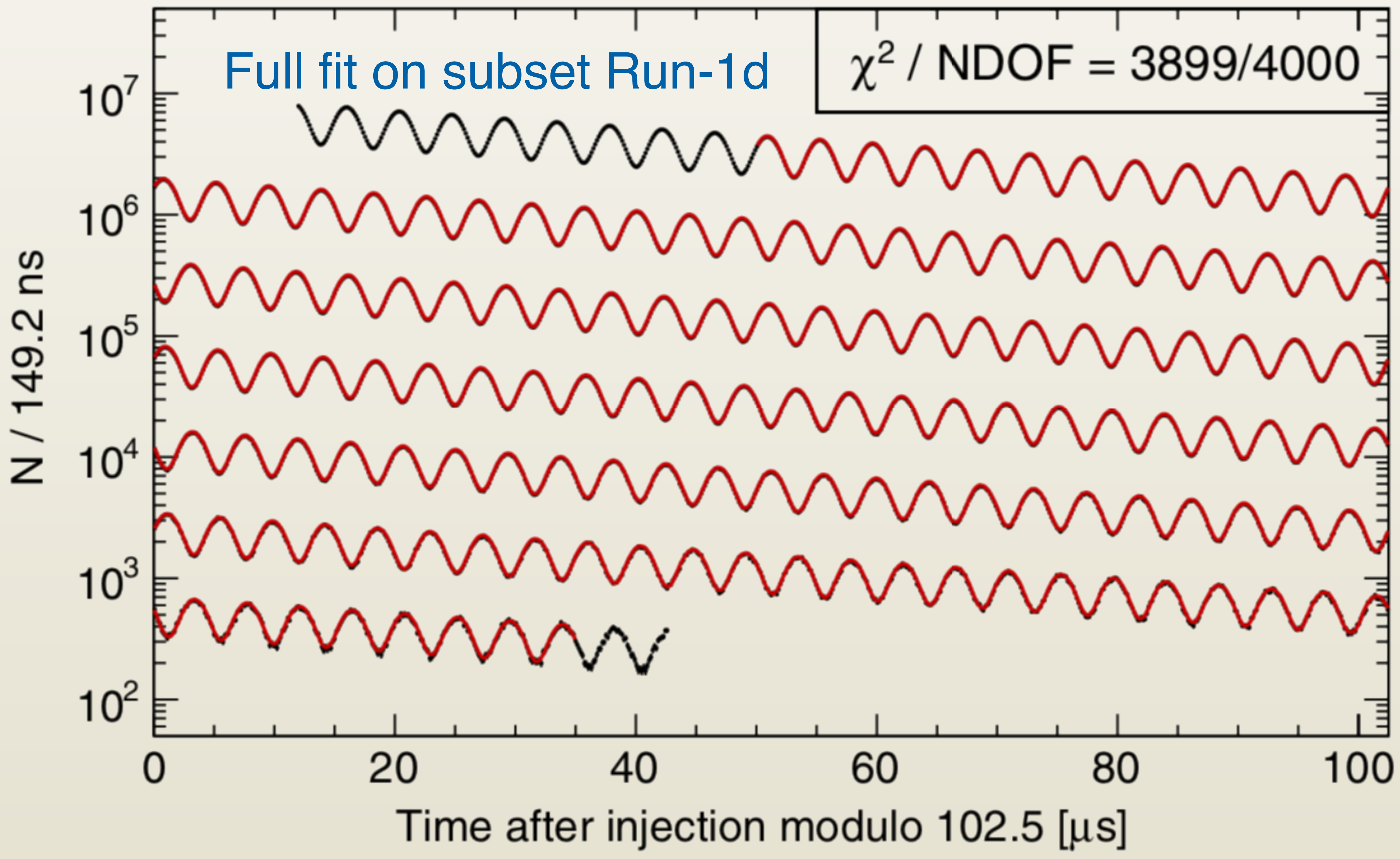
$$F(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \cdot \left[1 + A_0 \cdot A_x(t) \cdot \cos\left(\omega_a^m t + \phi_0 \cdot \phi_x(t)\right)\right]$$

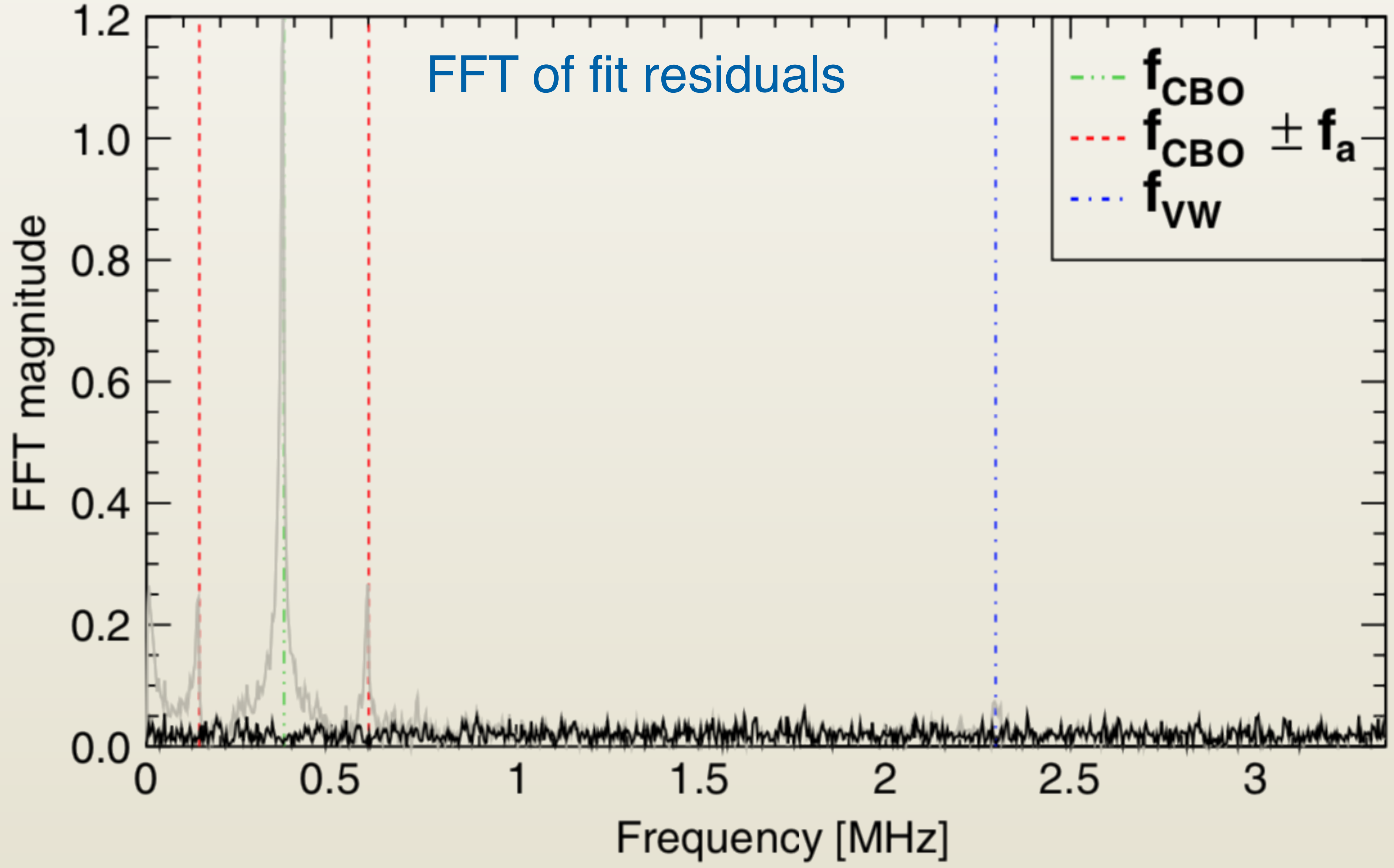
$$\begin{aligned} N_x(t) &= 1 + e^{-1t/\tau_{\text{CBO}}} A_{N,x,1,1} \cos(1\omega_{\text{CBO}} t + \phi_{N,x,1,1}) \\ &\quad + e^{-2t/\tau_{\text{CBO}}} A_{N,x,2,2} \cos(2\omega_{\text{CBO}} t + \phi_{N,x,2,2}), \end{aligned}$$

$$\begin{aligned} N_y(t) &= 1 + e^{-1t/\tau_y} A_{N,y,1,1} \cos(1\omega_y t + \phi_{N,y,1,1}) \\ &\quad + e^{-2t/\tau_y} A_{N,y,2,2} \cos(1\omega_{\text{VW}} t + \phi_{N,y,2,2}), \end{aligned}$$

$$A_x(t) = 1 + e^{-1t/\tau_{\text{CBO}}} A_{A,x,1,1} \cos(1\omega_{\text{CBO}} t + \phi_{A,x,1,1}),$$

$$\phi_x(t) = 1 + e^{-1t/\tau_{\text{CBO}}} A_{\phi,x,1,1} \cos(1\omega_{\text{CBO}} t + \phi_{\phi,x,1,1}).$$



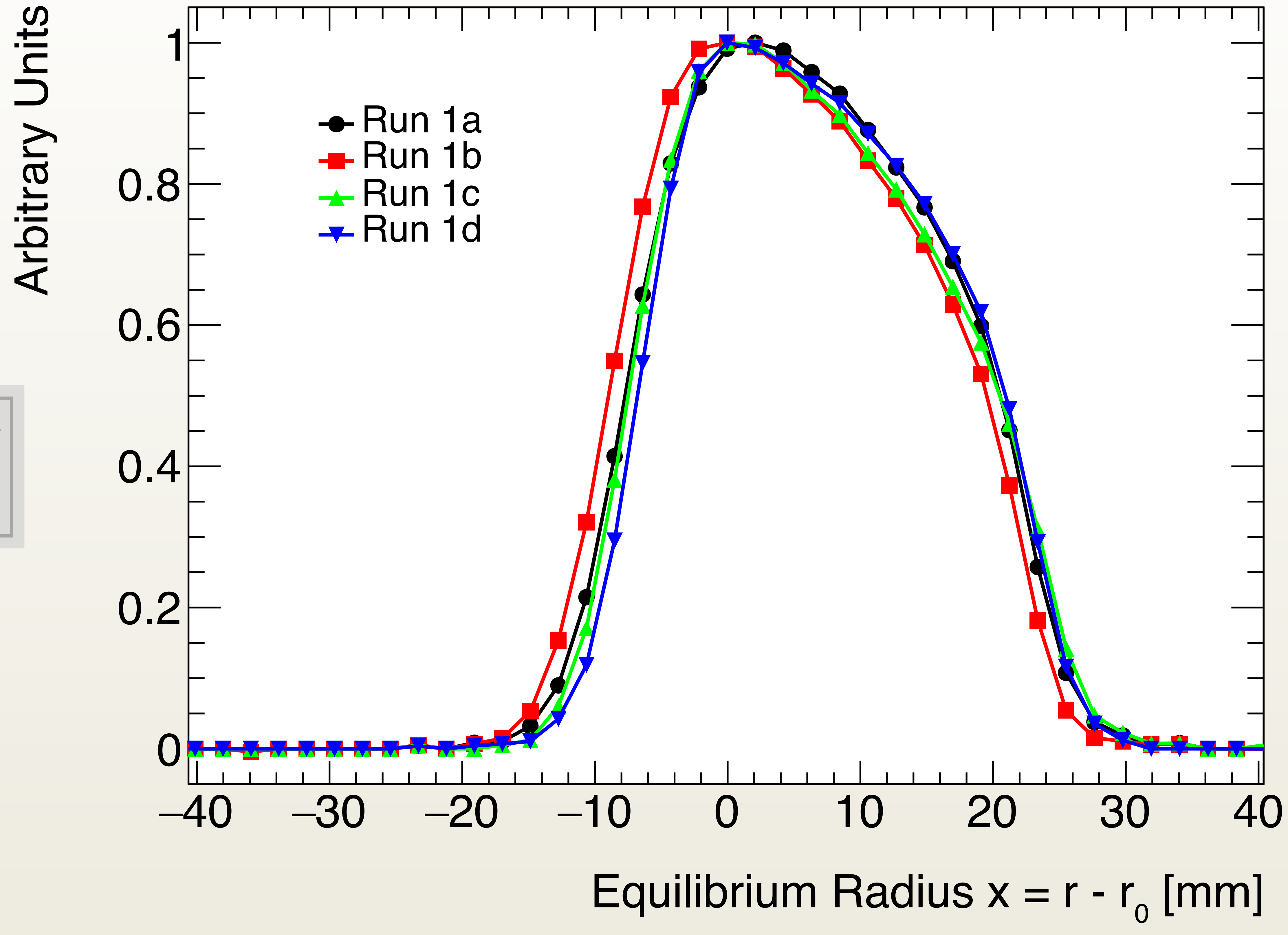


Electric field correction

- The largest correction to ω_a
- Comes from the fact that not all muons are at magic momentum

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}.\vec{B})\vec{\beta}\right]$$

$$C_e = 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0^2}$$

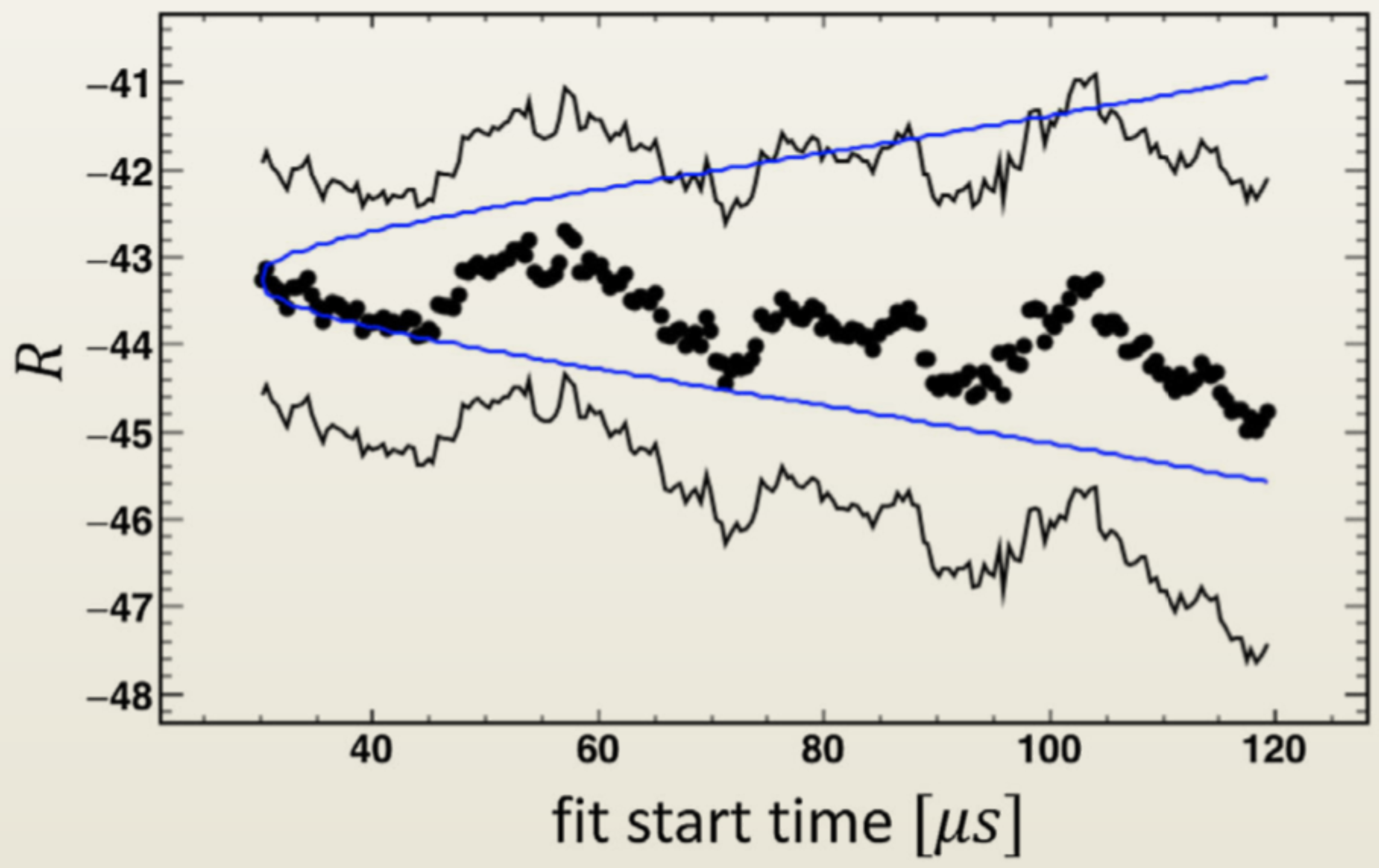


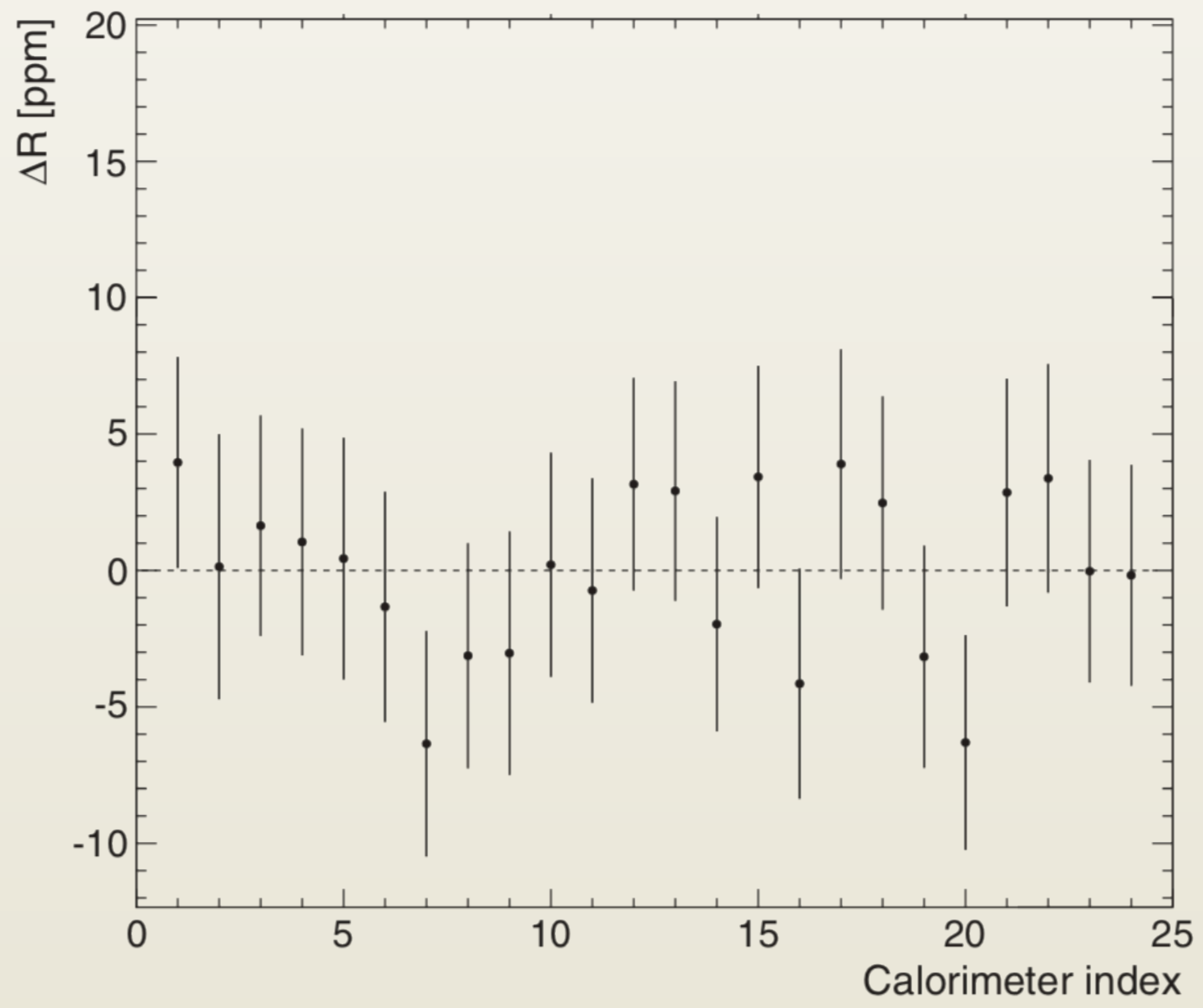
	1a	1b	1c	1d
Correction C_e [ppb]	471	464	534	475
Statistical	<1	<1	<1	<1
Total systematic	53	54	54	53
Fourier method	15	12	9	7
p-time correlation	52	52	52	52
Quad calibration	6	6	6	6
Field index	2	2	2	2

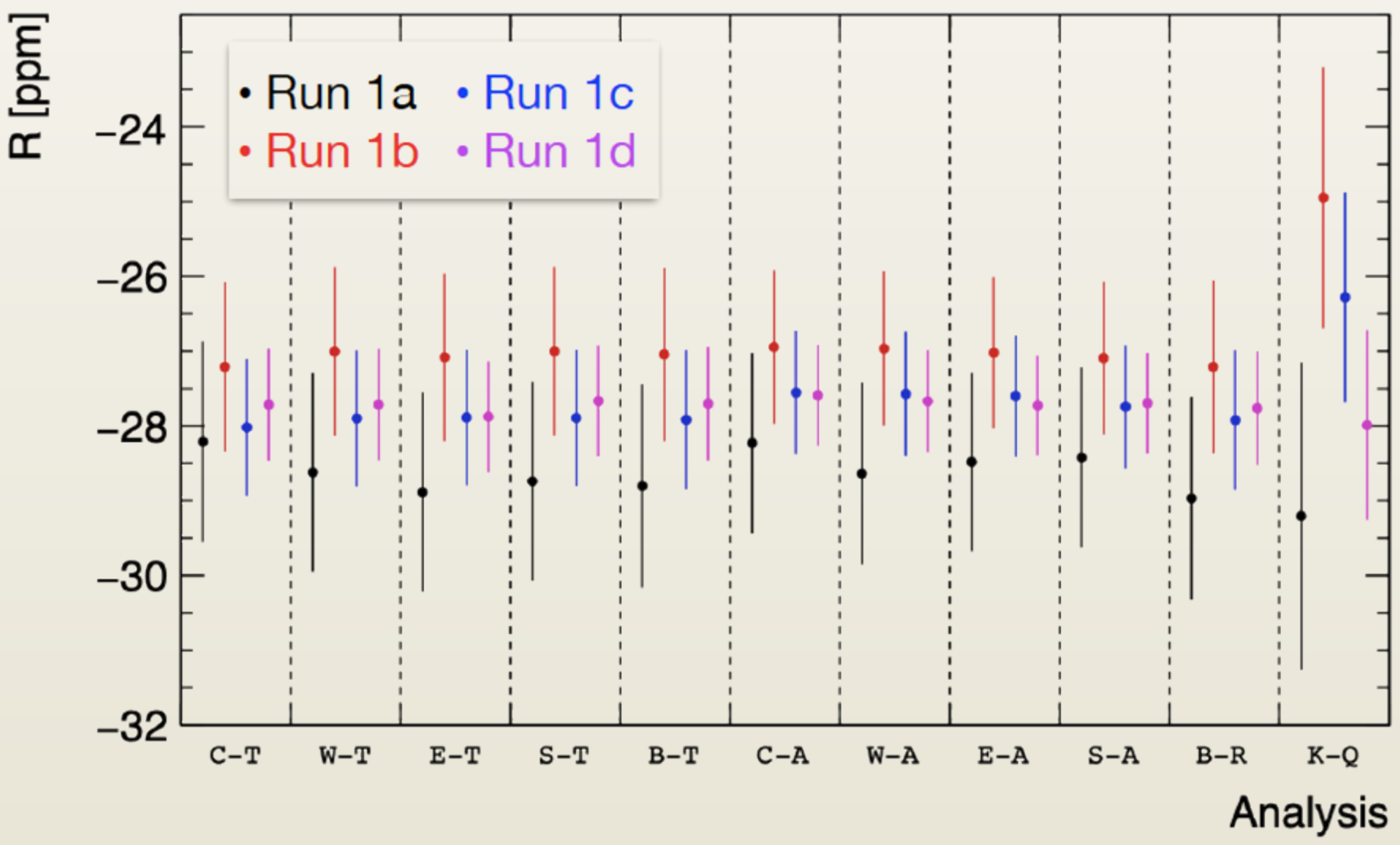
Precession frequency ω_a - Consistency checks

- 6 independent analysis groups
  - 2 different positron energy reconstruction algorithms,
  - 3 pile up correction algorithms,
  - 4 analysis methods

→ 11 different (highly correlated, though) analyses

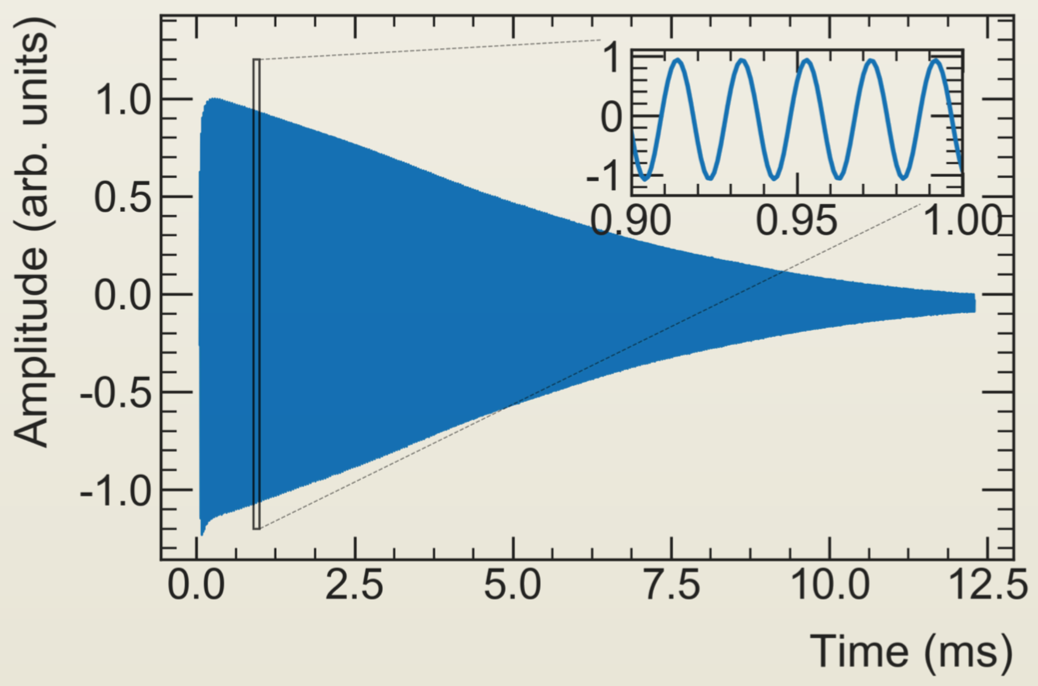


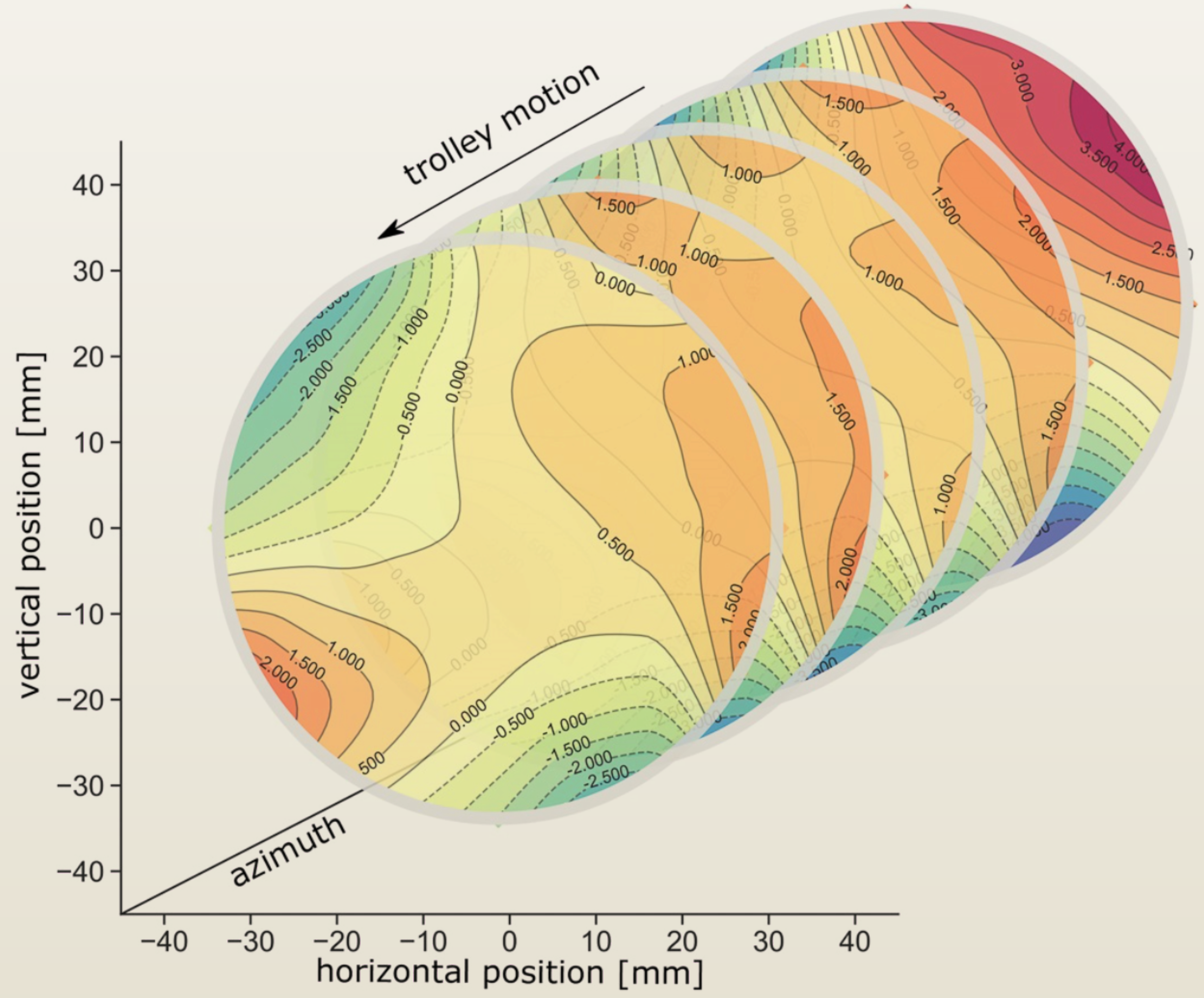


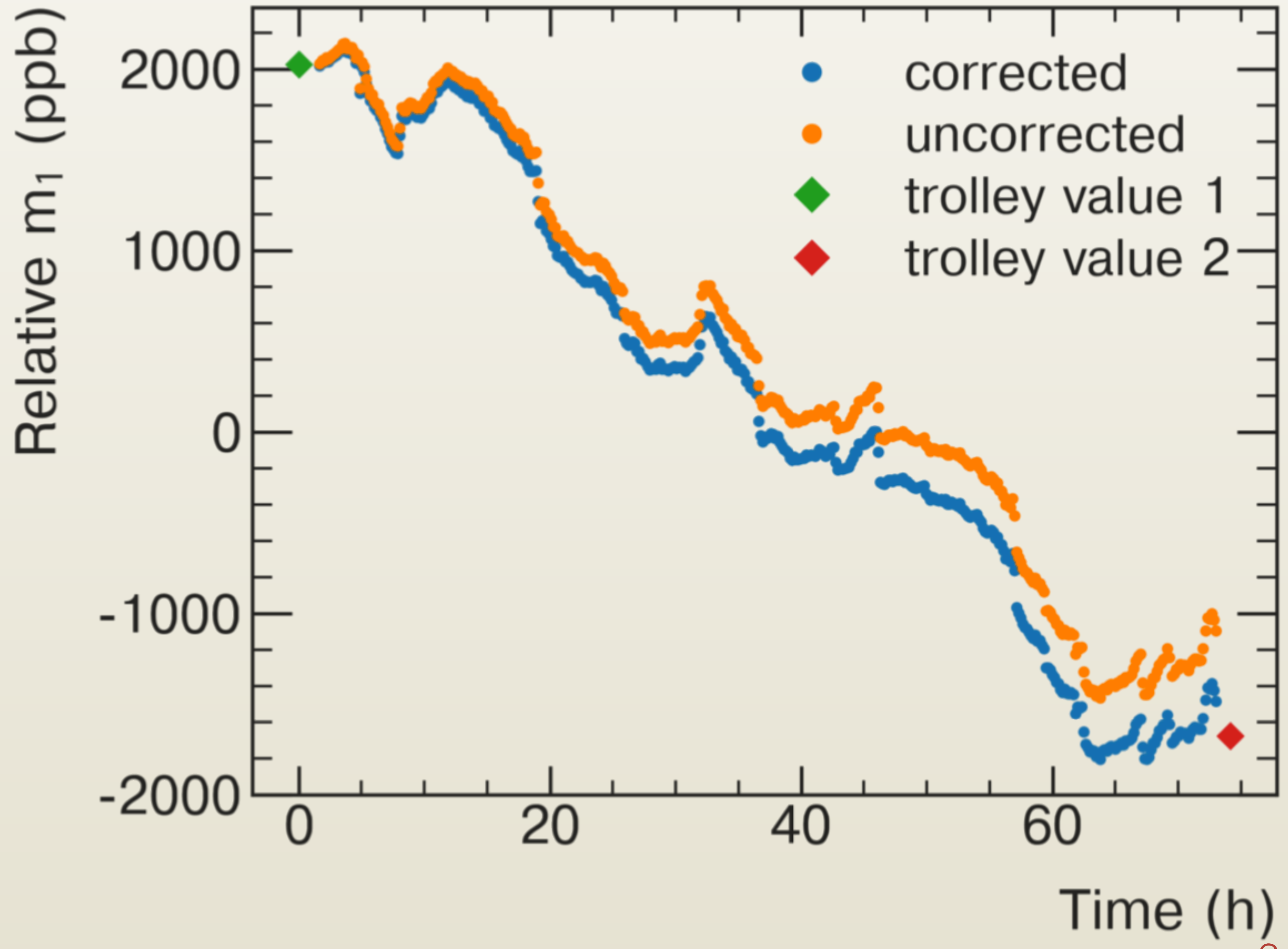


Magnetic field analysis - Field map by trolley

- Magnetic field is measured by extracting free induction decay (FID) signal from each NMR probe
  - 9000×17 data points per trolley run (every 2-3 days)
- Combine with data from fixed probes to account for field drift over time



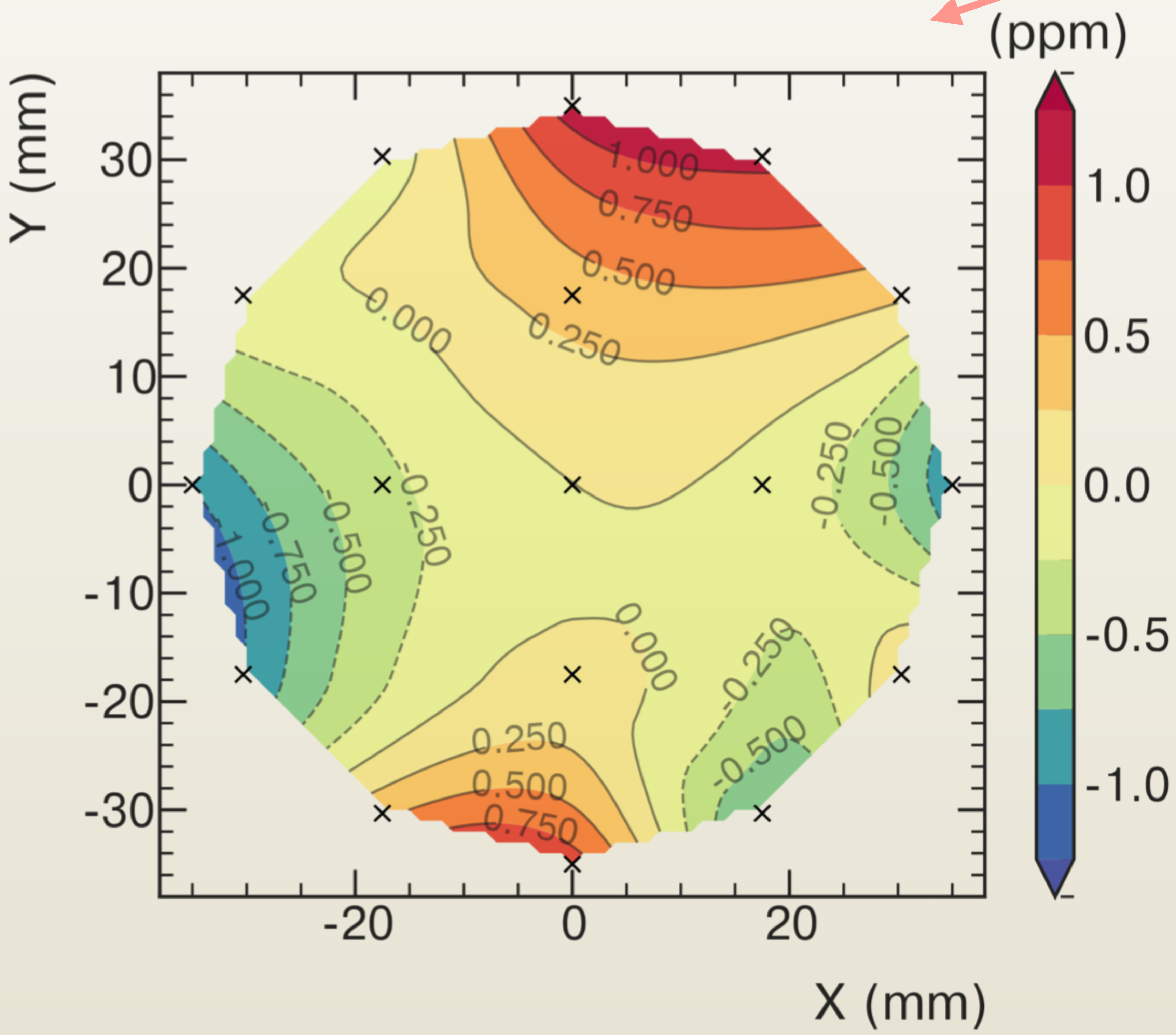


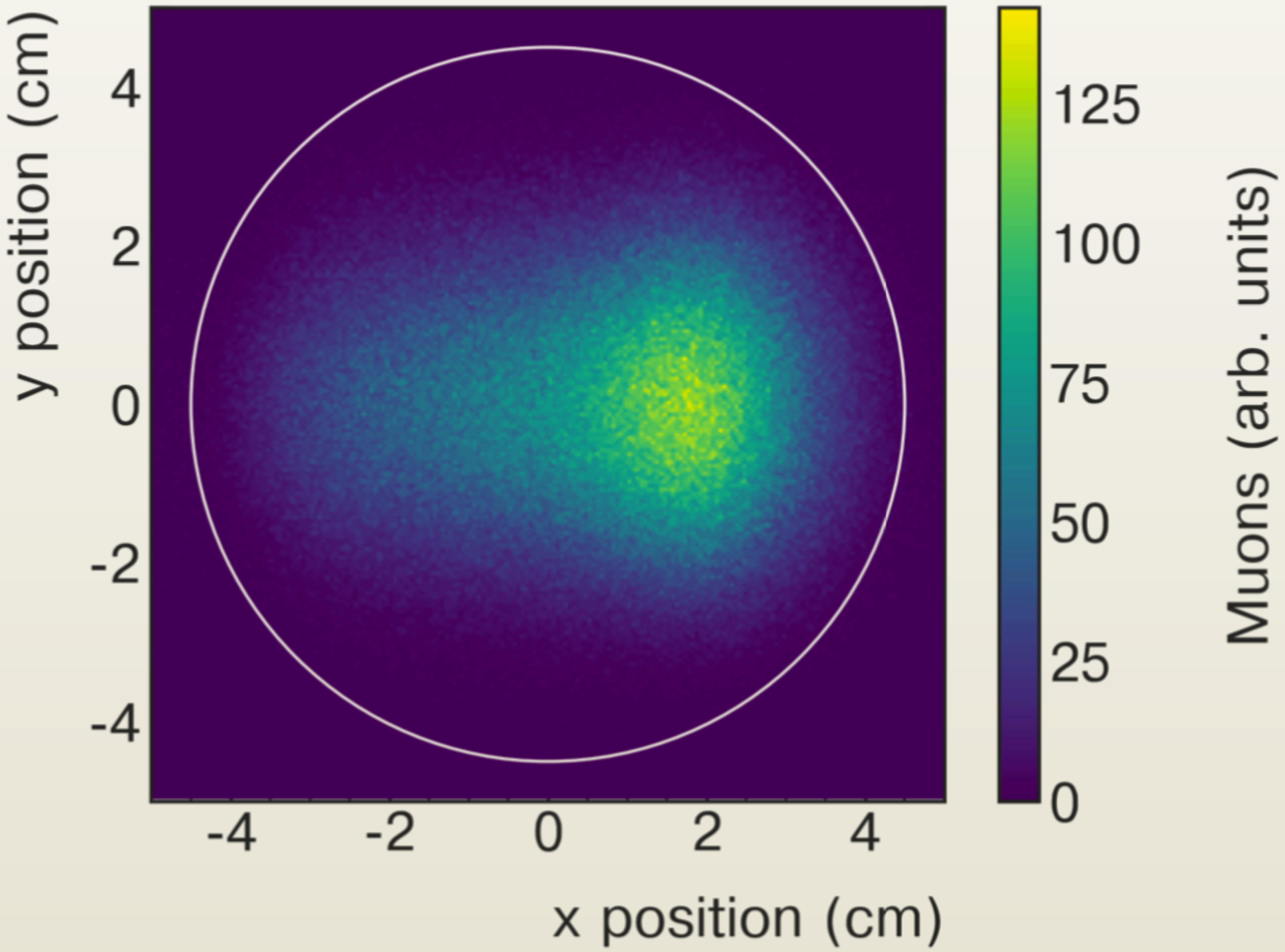


Magnetic field analysis - Muon distribution weighting

- We care about the magnetic field where muons occupy
  - The beam profile is obtained by the trackers

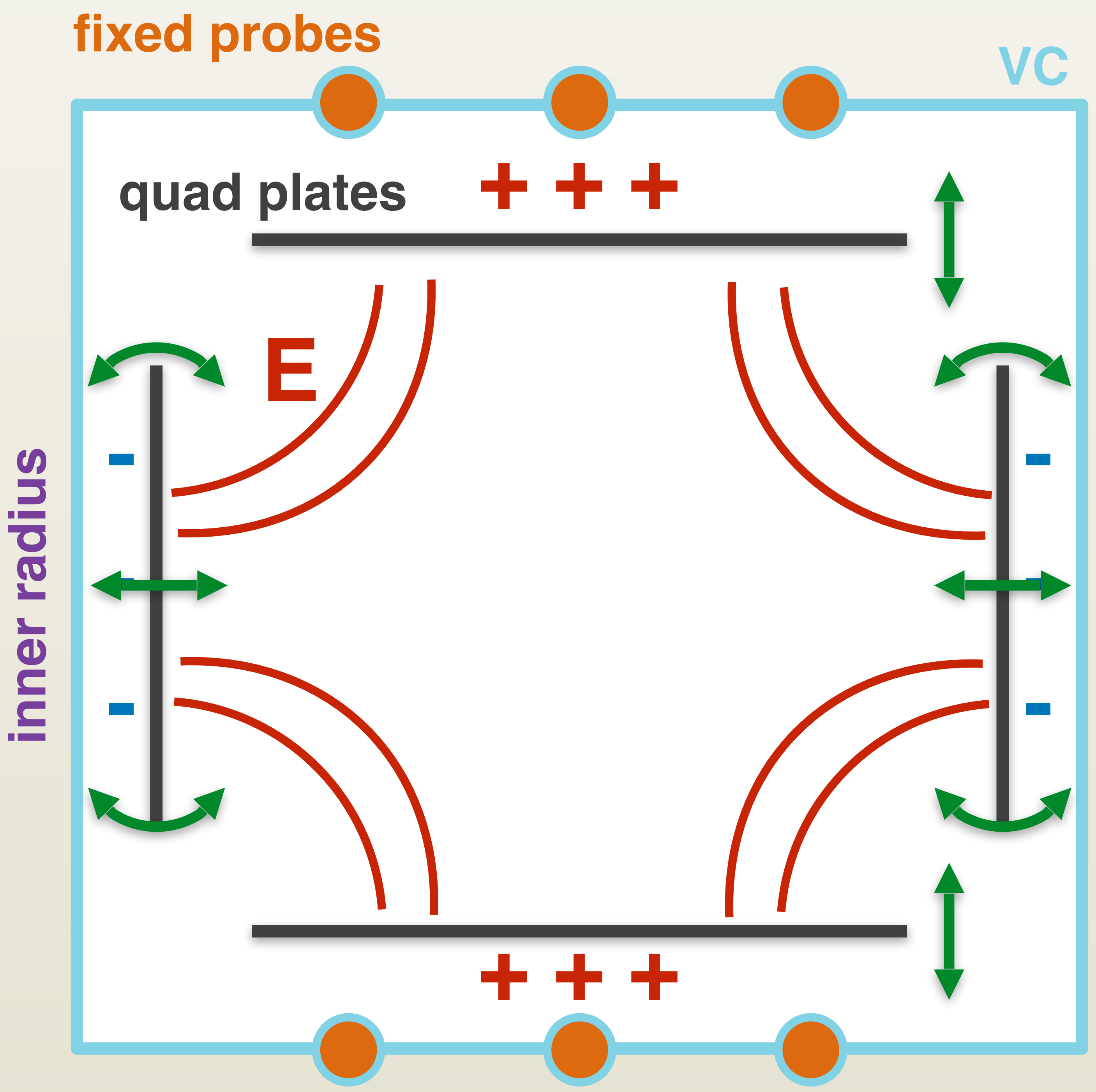
$$R_\mu = \frac{f_{\mathrm{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}}\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle (1 + B_k + B_q)}$$



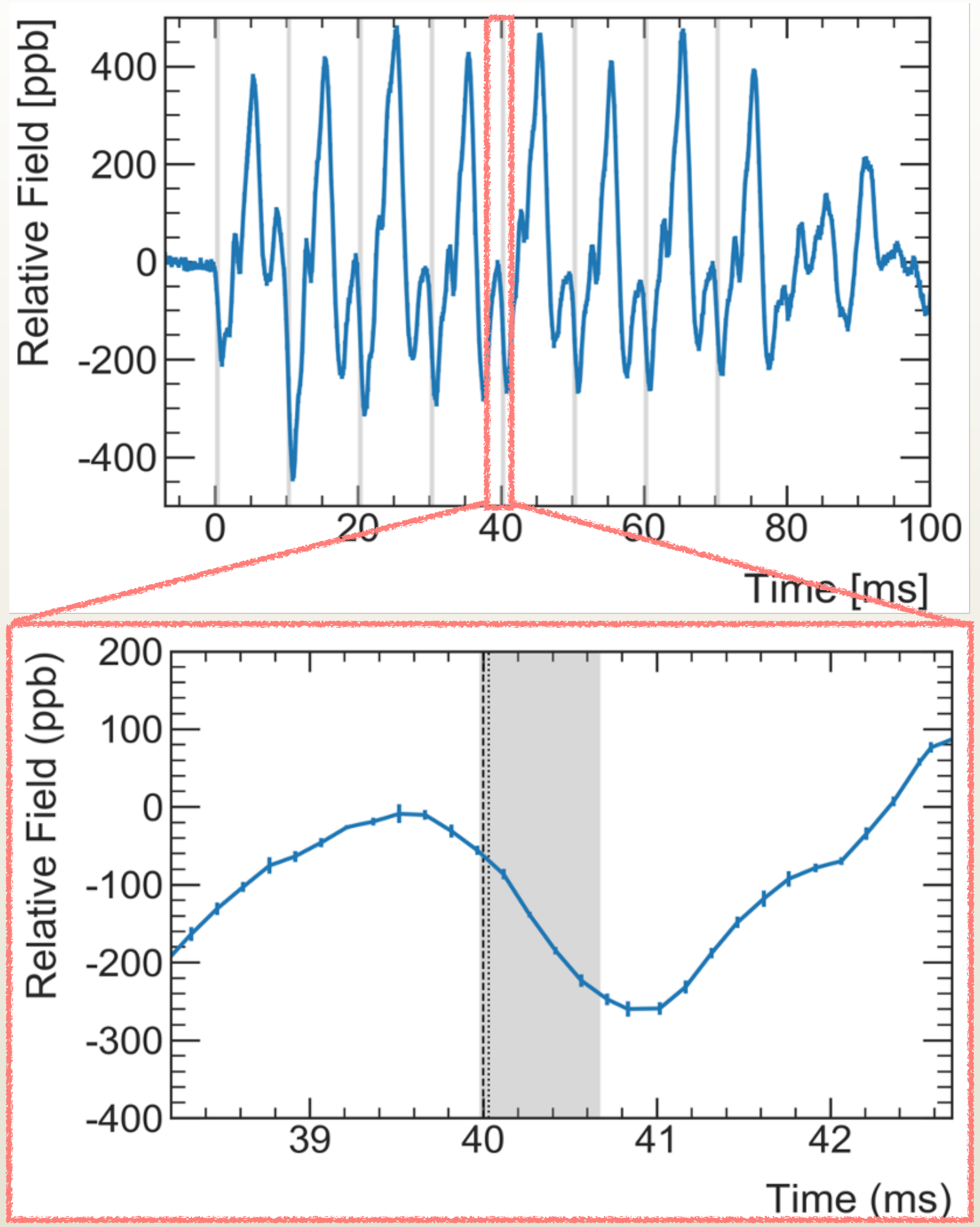


Quad transient correction

- Pulsing quadrupoles induces mechanical vibrations in conducting plates
  - Perturbs B-field
- Mapped effect with specially built NMR probes

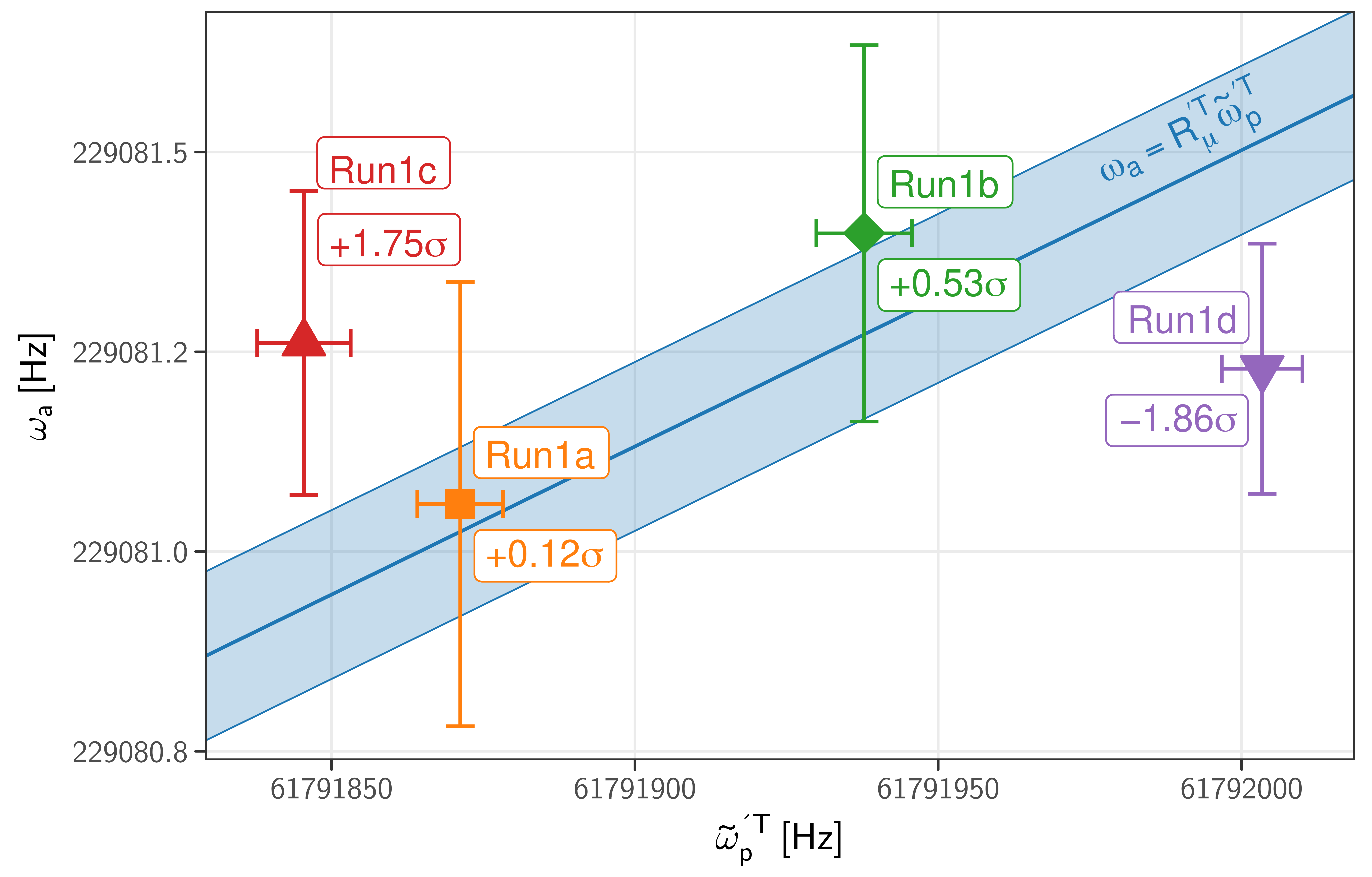


Dataset	Correction	Uncertainty
1a	-15	83
1b	-19	100
1c	-19	100
1d	-15	83



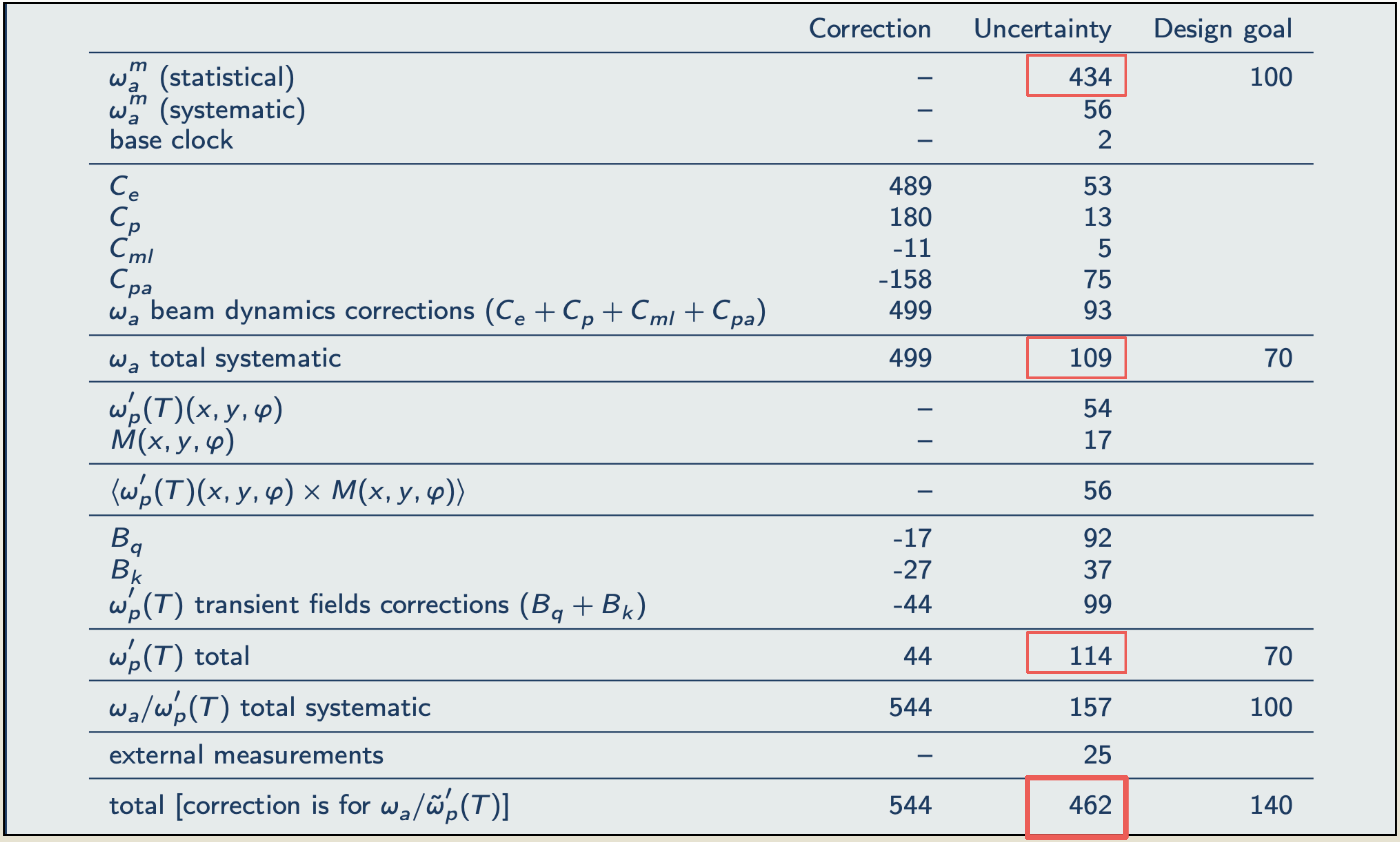
Result!

Combining ω_a and ω_p



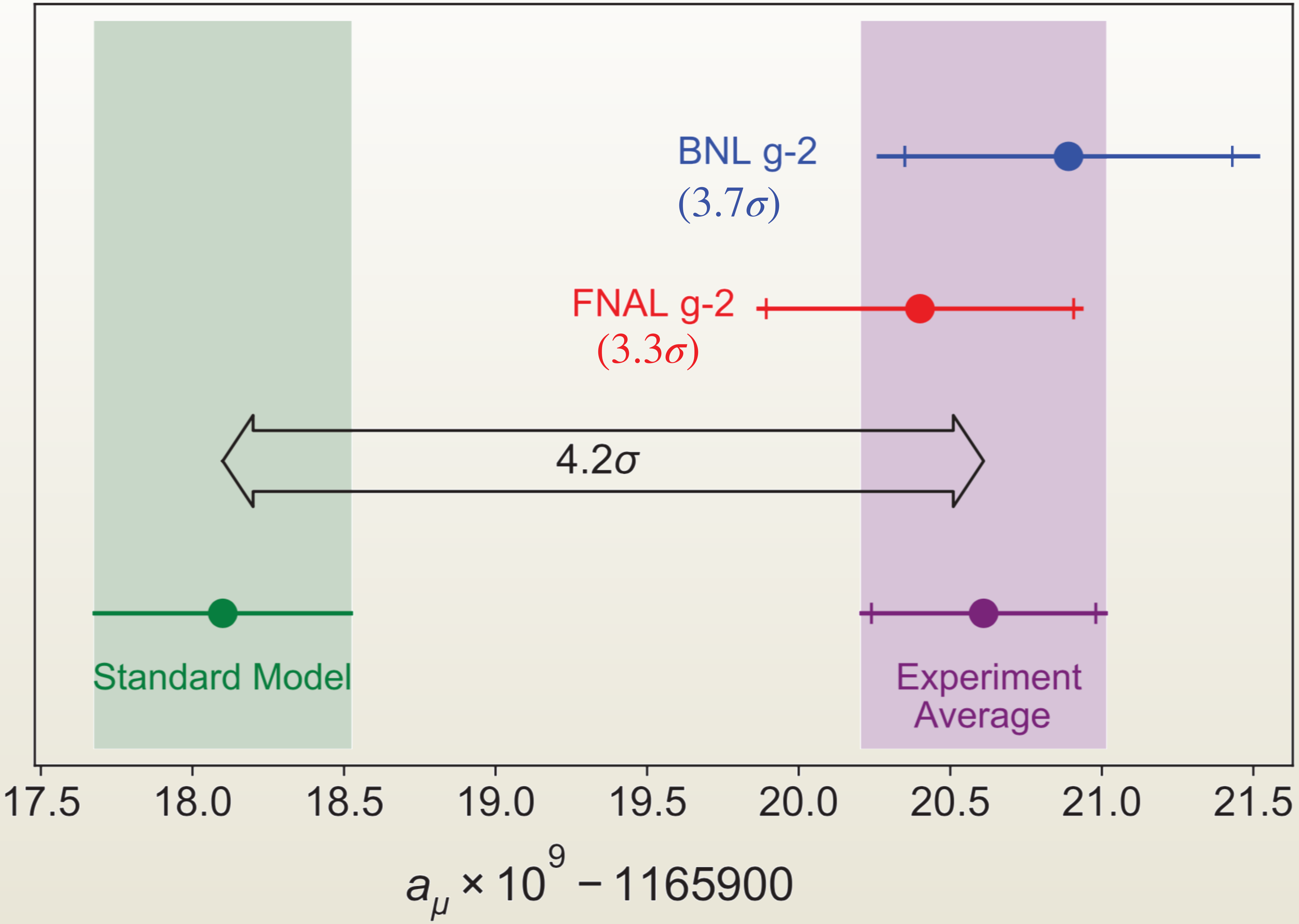
Run 1 uncertainties

$$R_\mu = \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$



	Correction	Uncertainty	Design goal
ω_a^m (statistical)	–	434	100
ω_a^m (systematic)	–	56	
base clock	–	2	
C_e	489	53	
C_p	180	13	
C_{ml}	-11	5	
C_{pa}	-158	75	
ω_a beam dynamics corrections ($C_e + C_p + C_{ml} + C_{pa}$)	499	93	
ω_a total systematic	499	109	70
$\omega'_p(T)(x, y, \varphi)$	–	54	
$M(x, y, \varphi)$	–	17	
$\langle \omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi) \rangle$	–	56	
B_q	-17	92	
B_k	-27	37	
$\omega'_p(T)$ transient fields corrections ($B_q + B_k$)	-44	99	
$\omega'_p(T)$ total	44	114	70
$\omega_a/\omega'_p(T)$ total systematic	544	157	100
external measurements	–	25	
total [correction is for $\omega_a/\tilde{\omega}'_p(T)$]	544	462	140

The anomaly a_μ



$$a_\mu(\mathrm{BNL}) = 116\,592\,089(63) \times 10^{-11} (540\,\mathrm{ppb})$$

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} (460\,\mathrm{ppb})$$

- Consistent with BNL measurement
- 15% improvement

$$a_\mu(\mathrm{Exp} - \mathrm{SM}) = 251(59) \times 10^{-11}$$

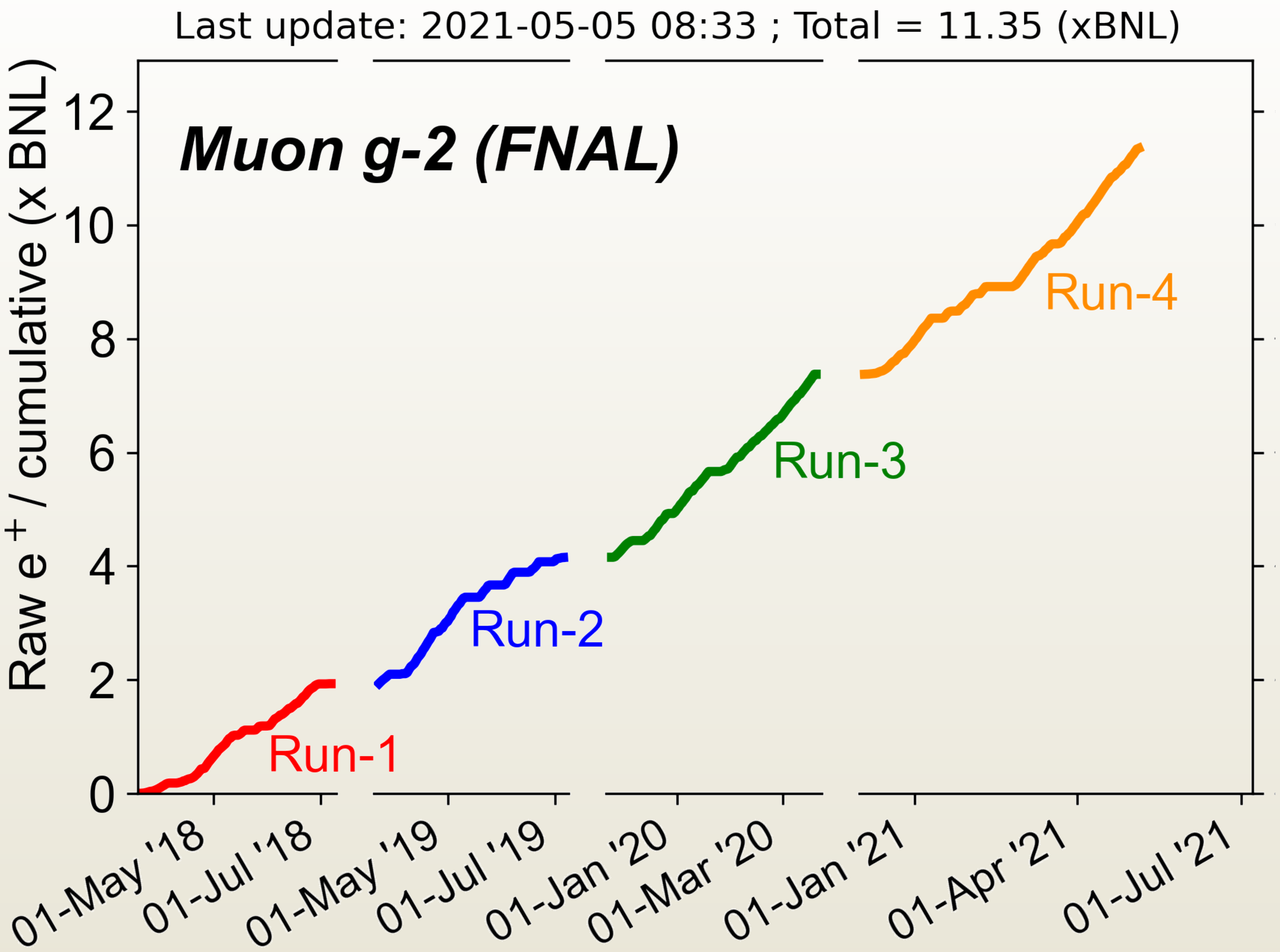
- Tension is at 4.2σ

$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} (350\,\mathrm{ppb})$$

- Uncertainty is comparable to prediction (370)

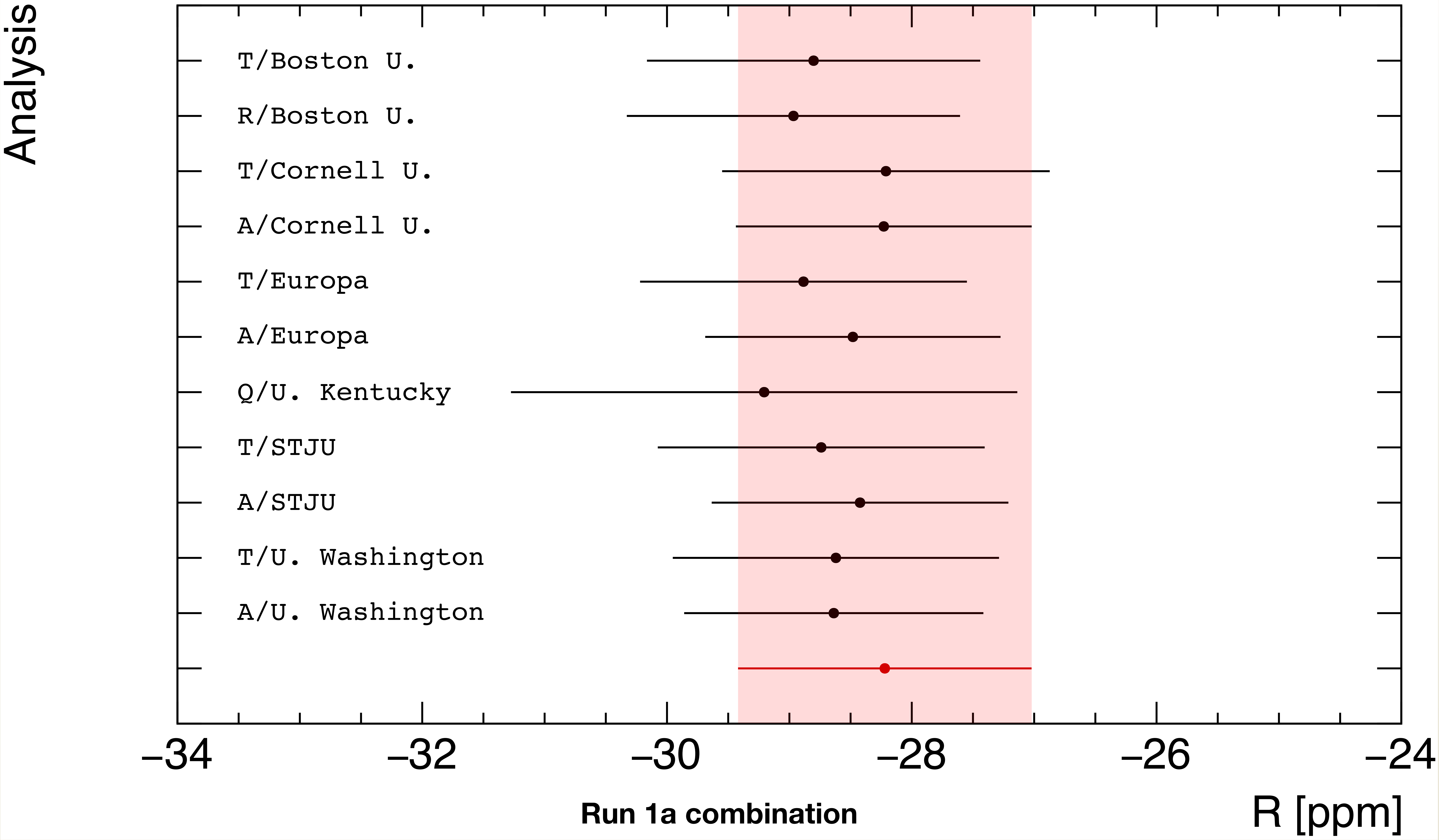
Outlook

- Run 1 is only 6% of the final data set
- Analysis for Run 2 and 3 are ongoing
    - Expect a factor of 2 improvement in precision
    - 18-month?
- Run 4 is in progress, expect to bring in 13x BNL statistics
- Run 5 next year would reach the design statistics of 20x BNL



Thanks for listening!

Combining result from different analyses



Combine 11 measurements into 1 (for each of the 4 Run1 run-groups)

least χ^2 fit procedure

- assuming Gaussian uncertainties $\Rightarrow$ least χ^2 fit returns optimal average

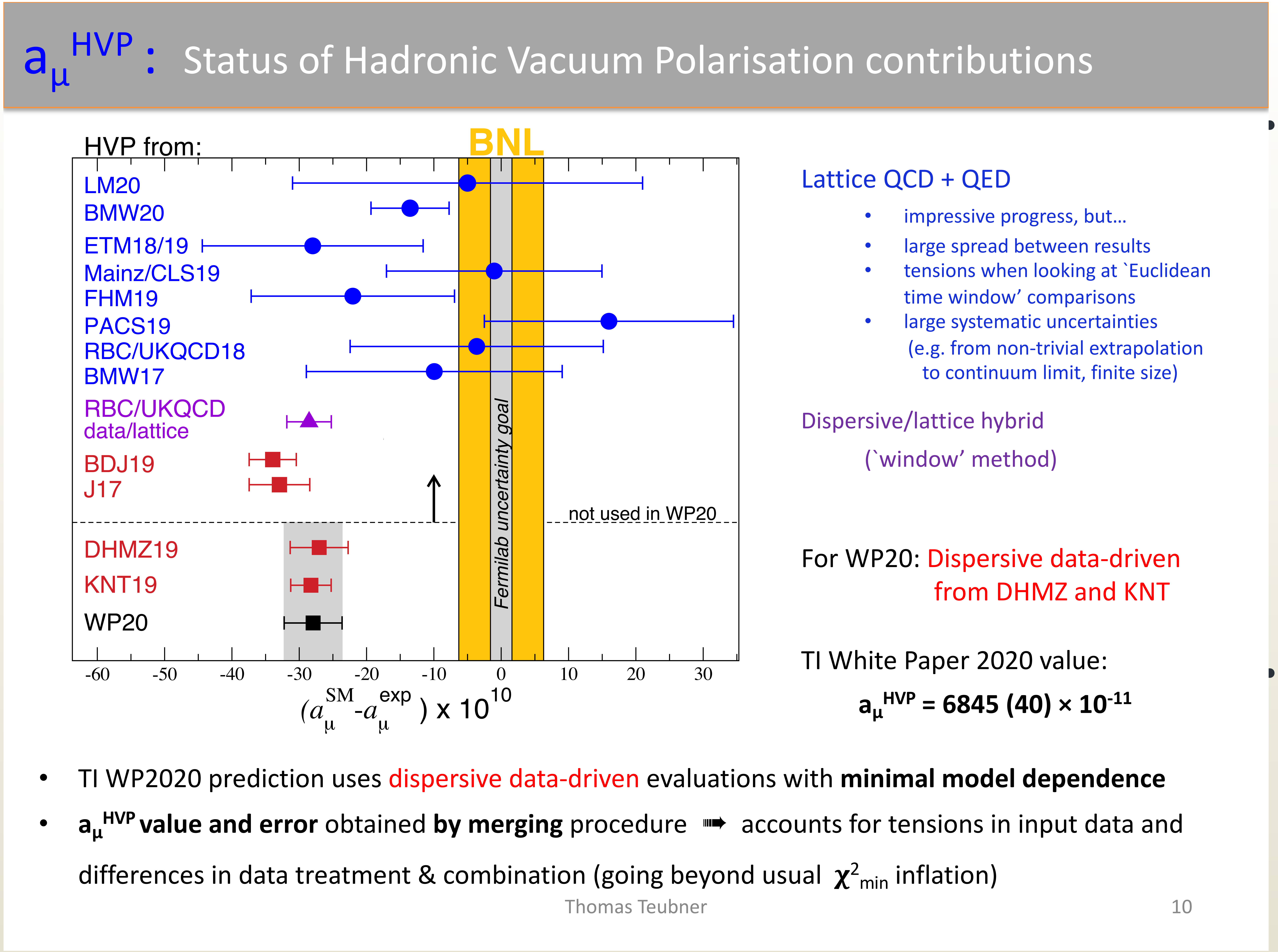
$$\chi^2(q_i) = (m_i - A_{ik} q_k)^t (E^m_{ij})^{-1} (m_j - A_{jl} q_l)$$

  - m_i = measurements of ω_a
  - q_1 = least χ^2 combination of m_i (ω_a for 1 run-group)
  - $A_{i1} = \{1, 1, \ldots\}$ model matrix, in general $m_j = \text{model}_{ji} q_i$, here all m_i modeled by just $1 \cdot q_1$
  - E^m_{ij} = covariance of m_i
- note: residuals of measurements vs. fit parameters have linear dependence on fit parameters q_i

solution: $$q_1 = \left[\left(A^t_{k1} (E^m_{kl})^{-1} A_{l1} \right)^{-1} A^t_{i1} (E^m_{ij})^{-1} \right] m_j = L^t_{j1} m_j$$ Best Linear Unbiased Estimator, BLUE

q_1 covariance: $$E^q_{11} = \left(A^t_{k1} (E^m_{kl})^{-1} A_{l1} \right)^{-1} = L^t_{k1} E^m_{kl} L_{l1}$$

- $\Rightarrow$ least χ^2 average value and covariance obtained same using linear combination coefficients L^t_{i1}
- note: covariance formula $\sigma^2_{q1} = E^q_{11} = L^t_{k1} E^m_{kl} L_{l1}$ holds for any linear combination $q_1 = L^t_{j1} m_j$
- note: this procedure is the exact solution if the covariance is known perfectly



a_μ^{HVP} : Status of Hadronic Vacuum Polarisation contributions

Lattice QCD + QED

- impressive progress, but…
- large spread between results
- tensions when looking at `Euclidean time window' comparisons
- large systematic uncertainties
  (e.g. from non-trivial extrapolation to continuum limit, finite size)

Dispersive/lattice hybrid

(`window' method)

For WP20: Dispersive data-driven from DHMZ and KNT

TI White Paper 2020 value:

a_μ^{HVP} = 6845 (40) × 10^{-11}

- TI WP2020 prediction uses dispersive data-driven evaluations with **minimal model dependence**
- **a_μ^{HVP} value and error** obtained **by merging** procedure ➠ accounts for tensions in input data and differences in data treatment & combination (going beyond usual χ^2_{min} inflation)

Thomas Teubner 10

- The BMW20 Result is the first Lattice QCD HVP result with sub % accuracy. The result is in tension with the traditional dispersive methods using data. On its own, BMW20 result implies much less room for new physics.
- Combining the BMW20 result is (currently) not straightforward. The g-2 Theory Initiative is working on it.

discrepancy $\approx 2 \times a_\mu^{\mathrm{SM,weak}}$

but: expect $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

a_μ is loop-induced, CP- and flavor-conserving and chirality-flipping

rather light, neutral (?) particles ⇝ Connection to dark matter?

Chirality flip enhancement ⇝ Window to muon mass generation? EWSB/generations?

Which models can still accommodate large deviation?

Many models involve enhancement mechanisms

but: experimental constraints!

General ideas still viable (SUSY, THDM, LQ, VLL, . . .)

but: restricted parameter space! Specific scenarios excluded!

Which models can still accommodate large deviation?

SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns

Two-Higgs doublet model

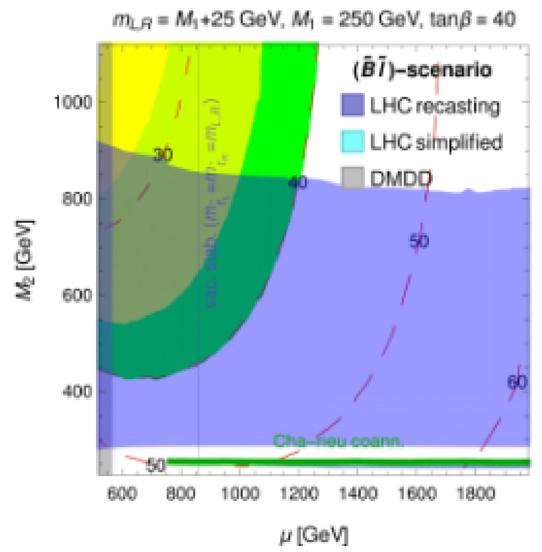
- Type I, II, Y, Type X(lepton-specific), flavour-aligned

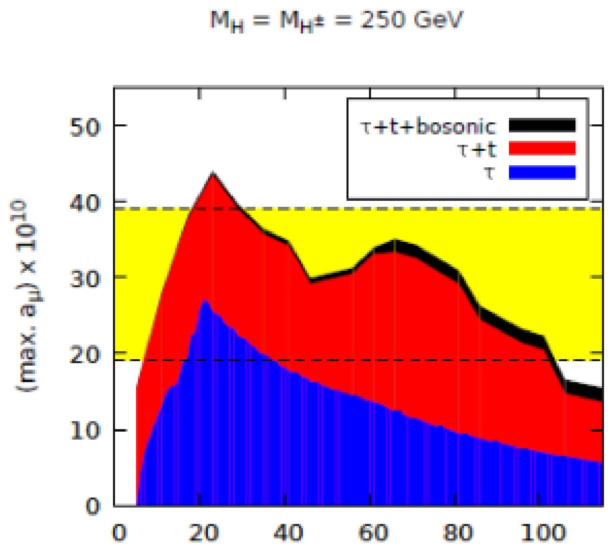
Lepto-quarks, vector-like leptons

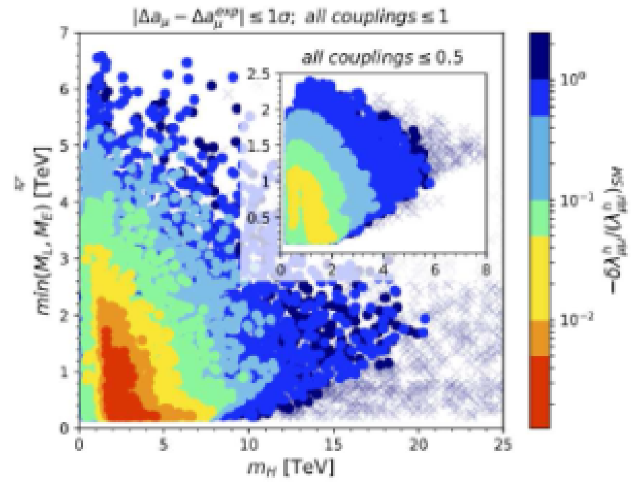
- scenarios with muon-specific couplings to μ_L and μ_R

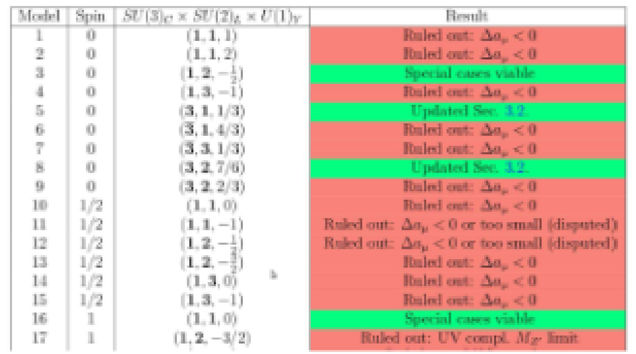
Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)









Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}},\mathbf{1},1/3)$	Updated Sec. 3.2.
6	0	$(\overline{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\overline{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.2.
9	0	$(\mathbf{3},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. $M_{Z'}$ limit

[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

The Measurement:

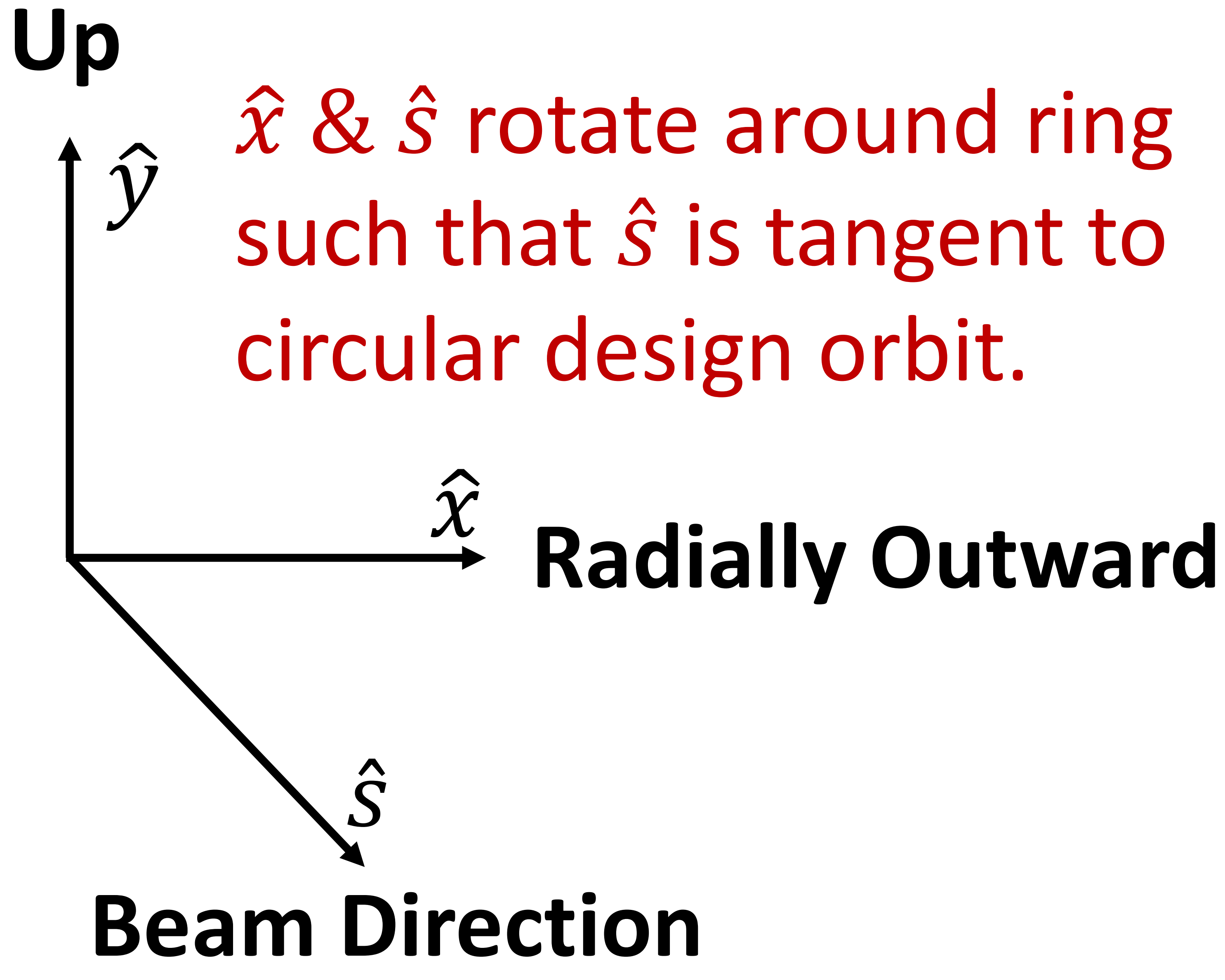
- Magnetic field provides radial confinement: $\vec{B} \sim B_0 \hat{y}$.
- Electric fields provide vertical focusing: $\vec{E} \sim E_1(x\hat{x} - y\hat{y})$.

$$x(s) \sim x_e + A_x \cos\left(\frac{\nu_x}{R_0} s + \phi_{x0}\right)$$

$$y(s) \sim A_y \cos\left(\frac{\nu_y}{R_0} s + \phi_{y0}\right)$$

Betatron Motion

$$\nu_x^2 + \nu_y^2 \sim 1$$



$\hat{x}$ & $\hat{s}$ rotate around ring such that $\hat{s}$ is tangent to circular design orbit.

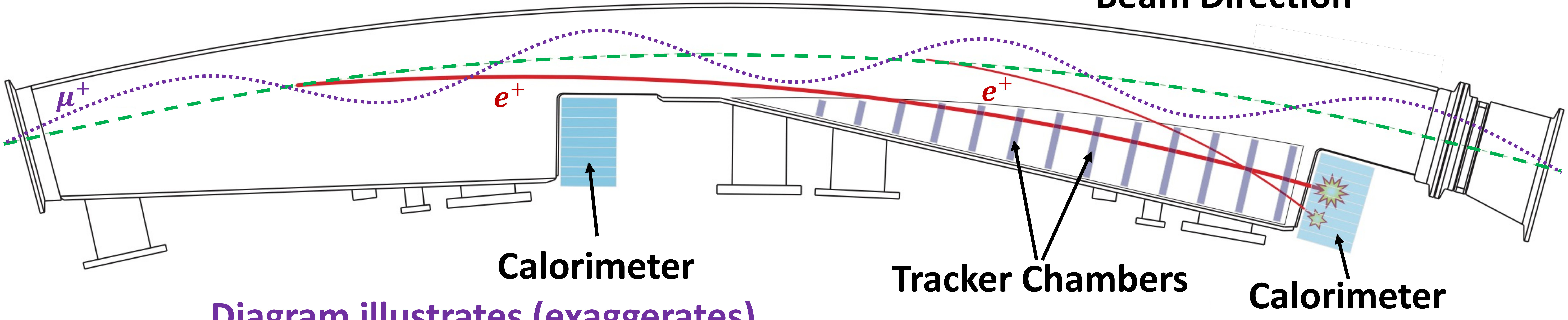


Diagram illustrates (exaggerates) betatron oscillations.

The Measurement:

Coherent oscillation effects must be included in fits to positron spectra!

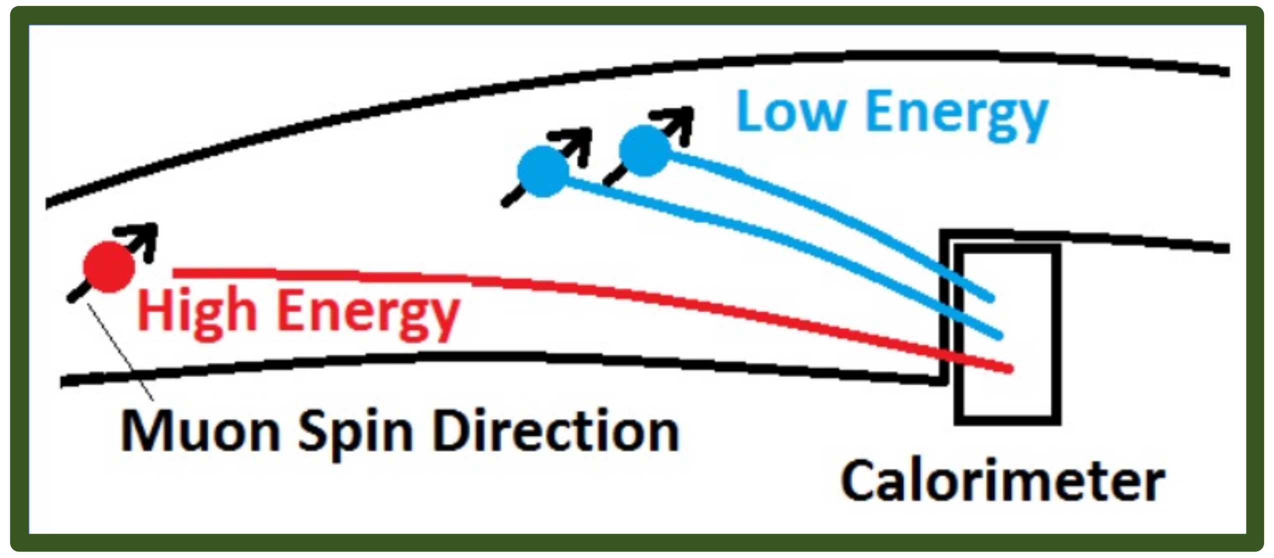
- Beam mean position oscillates.
- Beam width oscillates.
- Cyclotron motion creates an effective sample rate.
    - Detectors can measure alias frequencies.
- Oscillations decohere over time.

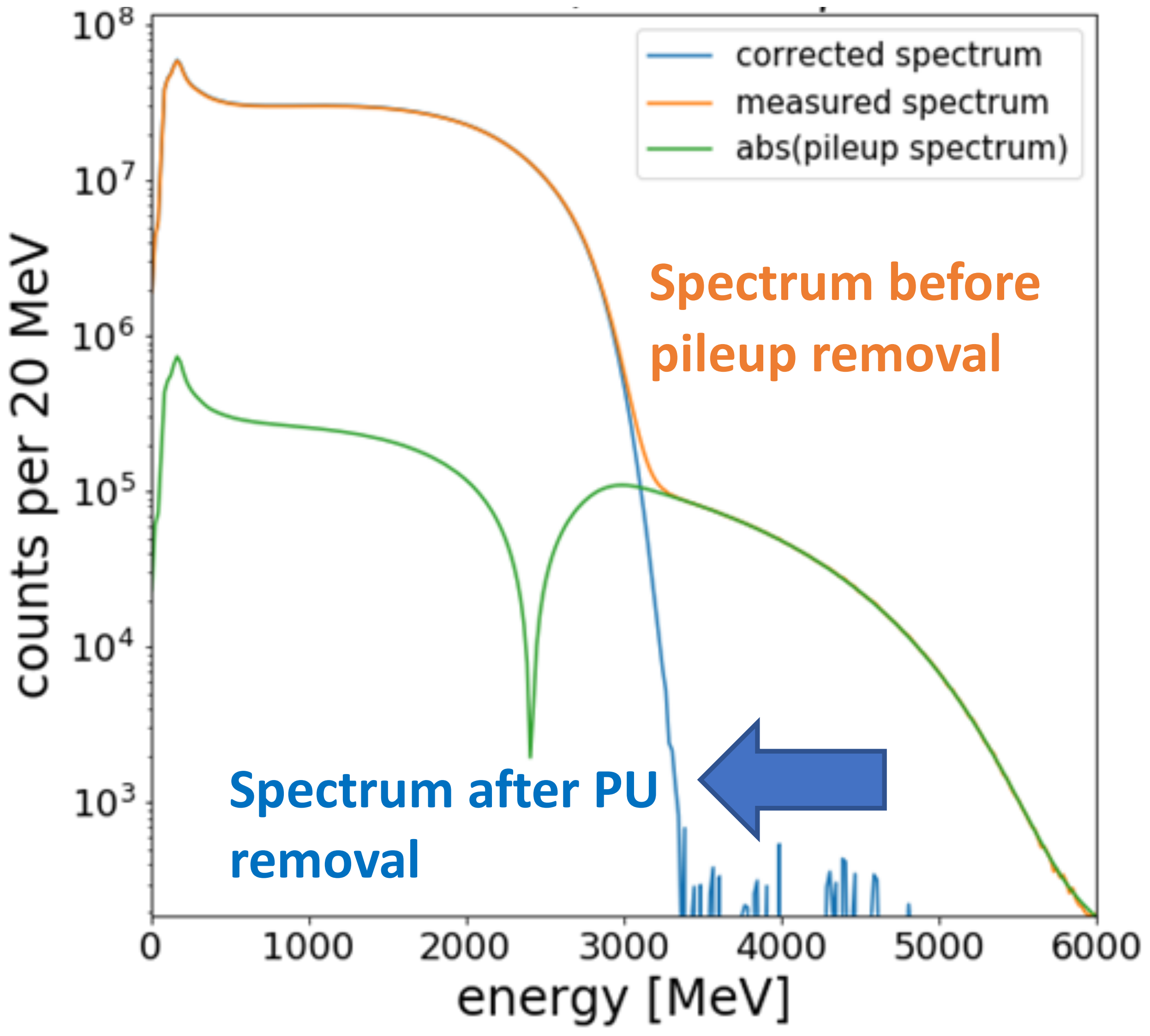
Diagram illustrates (exaggerates) betatron oscillations.

ω_a^m is determined by fitting decay e^+ spectra.

Pileup event correction:

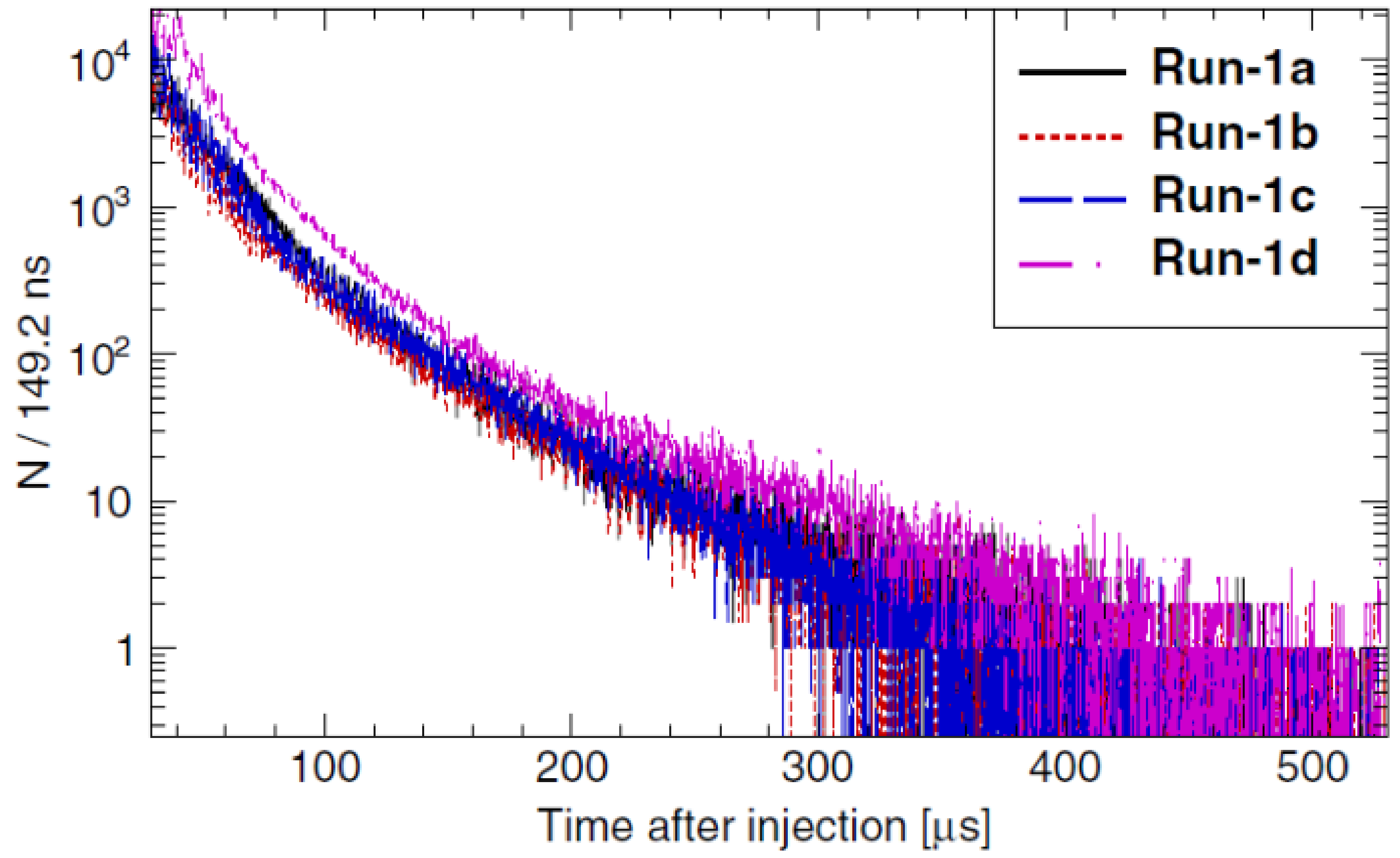
- 2 or more low energy e^+ hit calorimeter too close in space and time.
- Overlapping pulses treated as single high energy pulse .
- Distort time & energy spectra (carries a different phase).

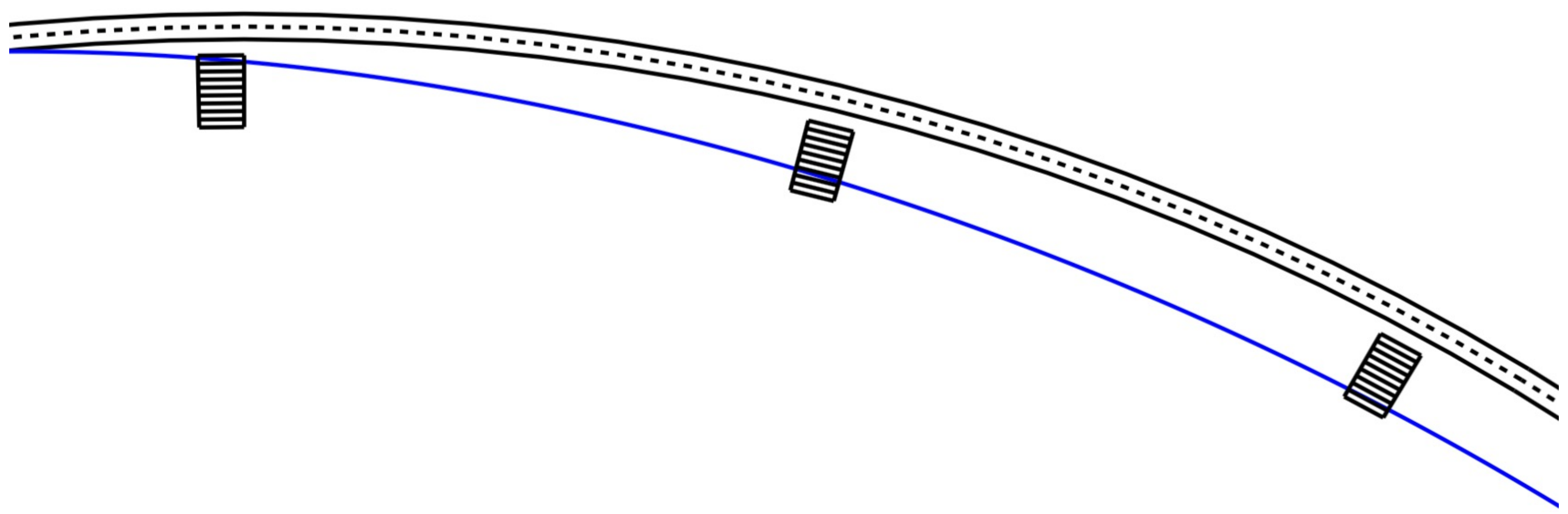




Data based μ^+ loss fit function model

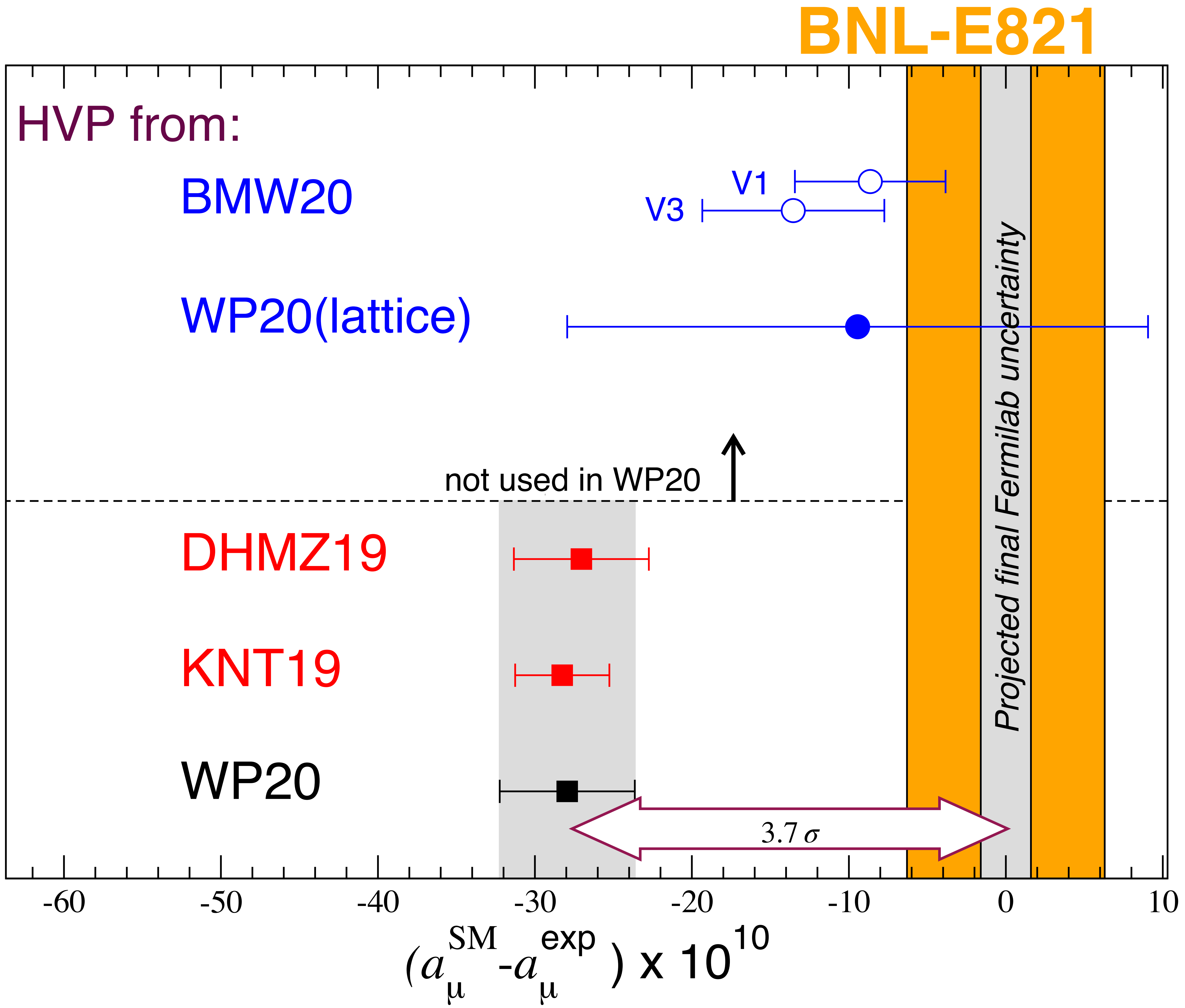
- Identify lost μ^+ with triple coincidence calorimeter MIPs.
- Modifies exponential decay (time dependent N_0).





Muon g-2: experiment vs theory

$$\boxed{a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}} = 116591810\,(43) \times 10^{-11}}$$

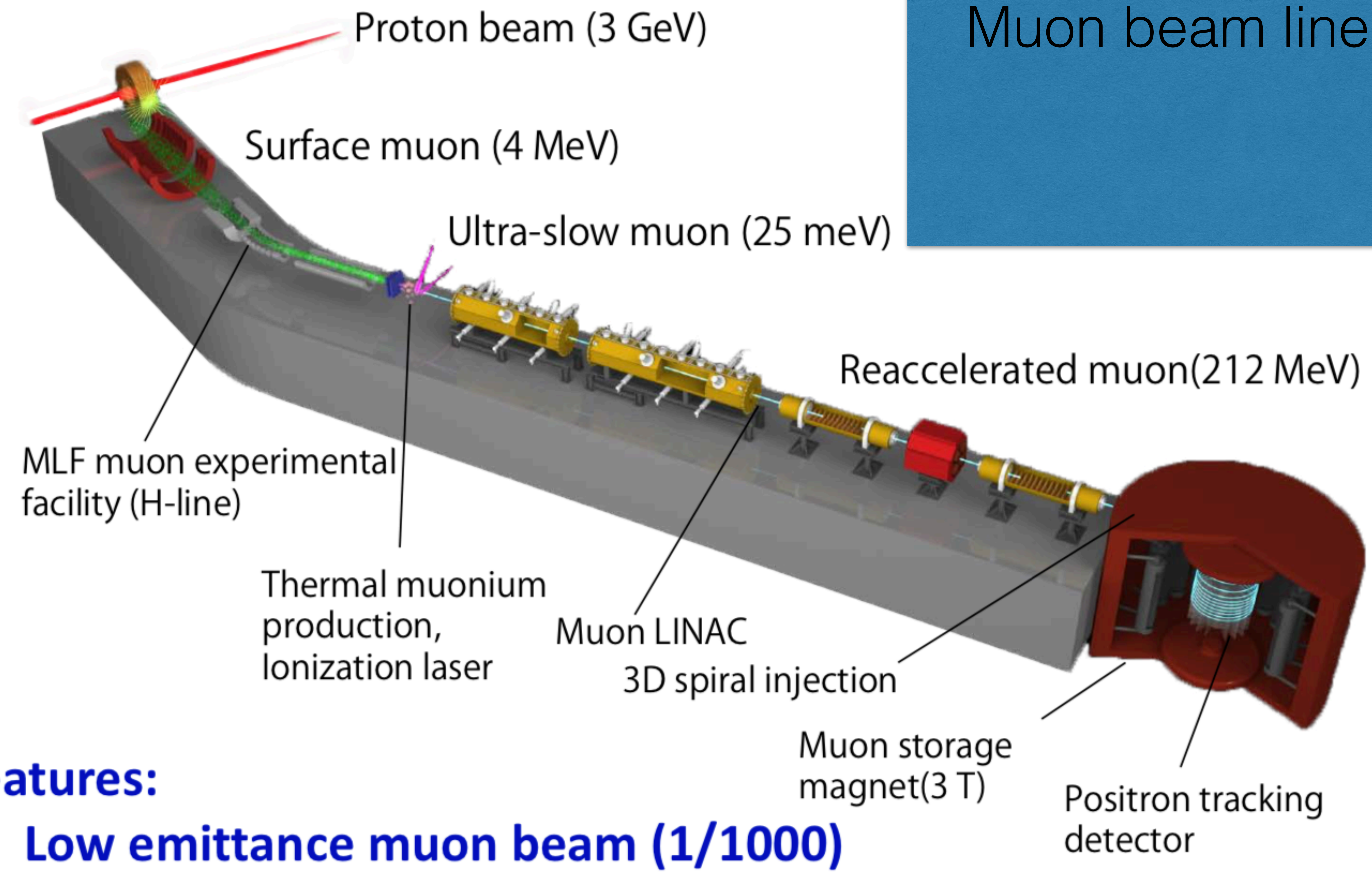


About the BMW20 calculation

- We experimentalists in E989 have adopted the policy of only comparing our result with the published value from the Theory Initiative. This work continues, and there will be a virtual meeting at KEK in June, which will be very interesting, given the recent lattice result. A new update will be forthcoming.

- “The BMW collaboration’s result is the first lattice calculation of HVP to reach sub-percent precision, and it is premature to draw firm conclusions from its comparison with the one obtained from data-driven evaluations”   Aida El-Khadra, co chair of the ITI steering committee.

Muon beam line

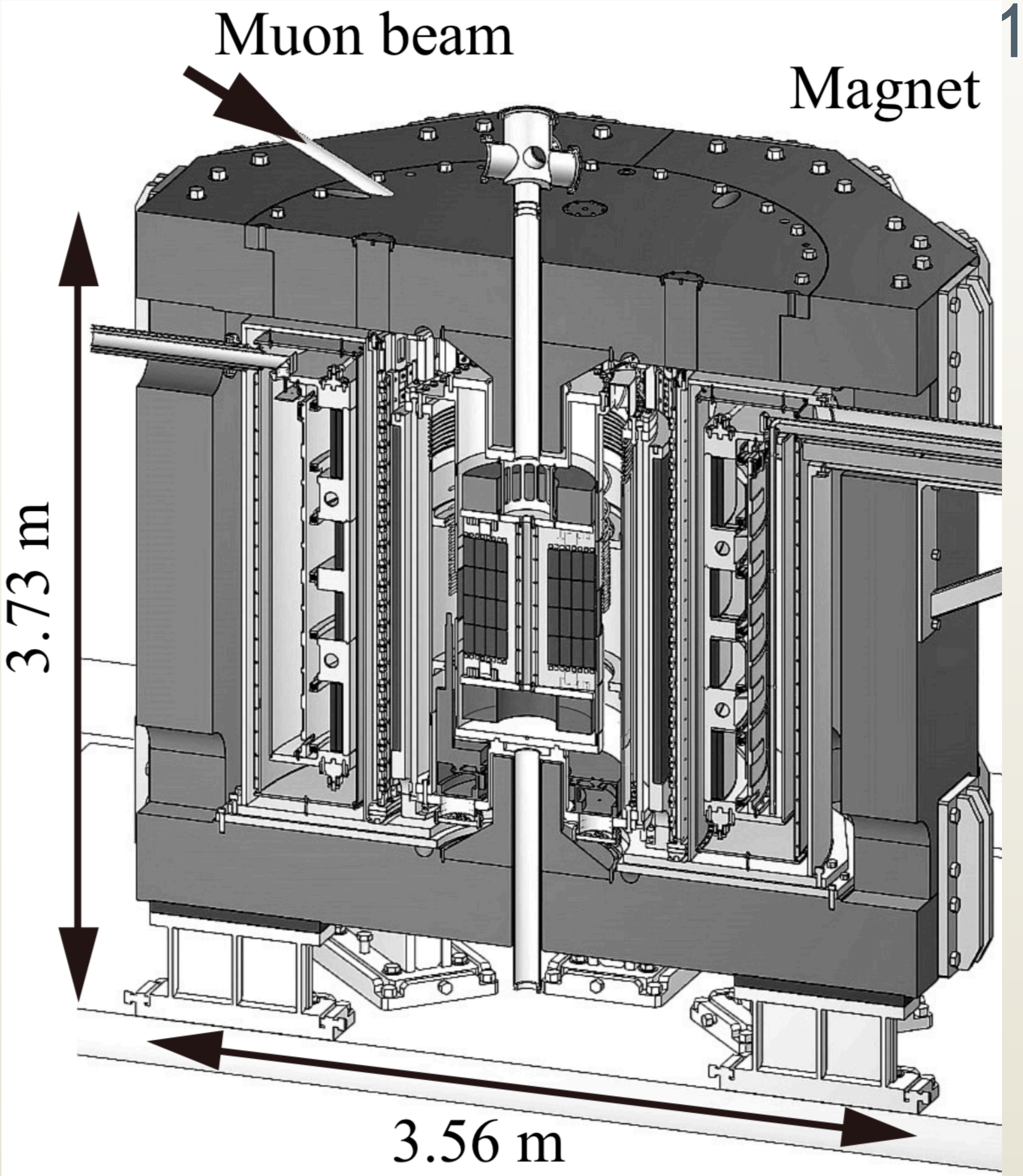


Features:

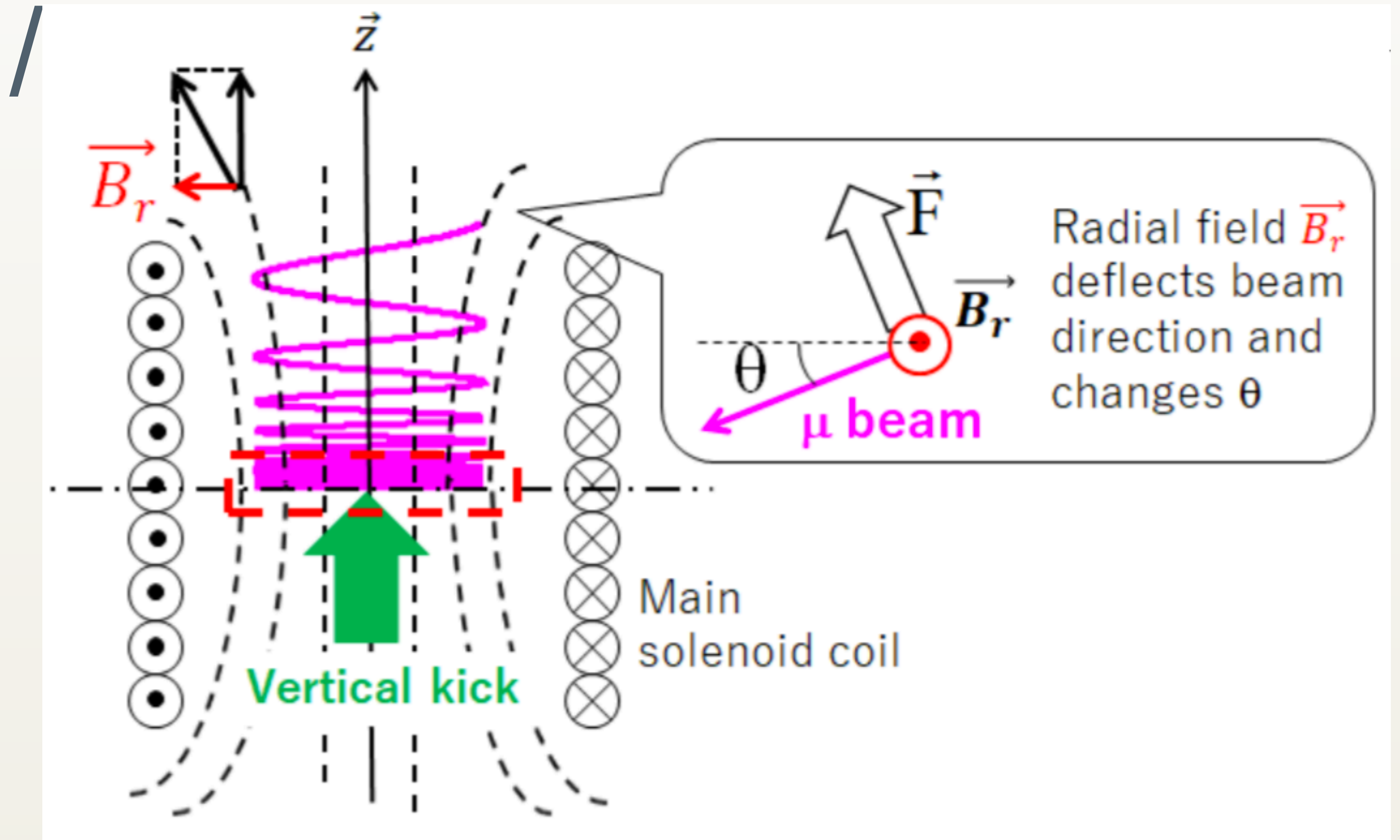
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**

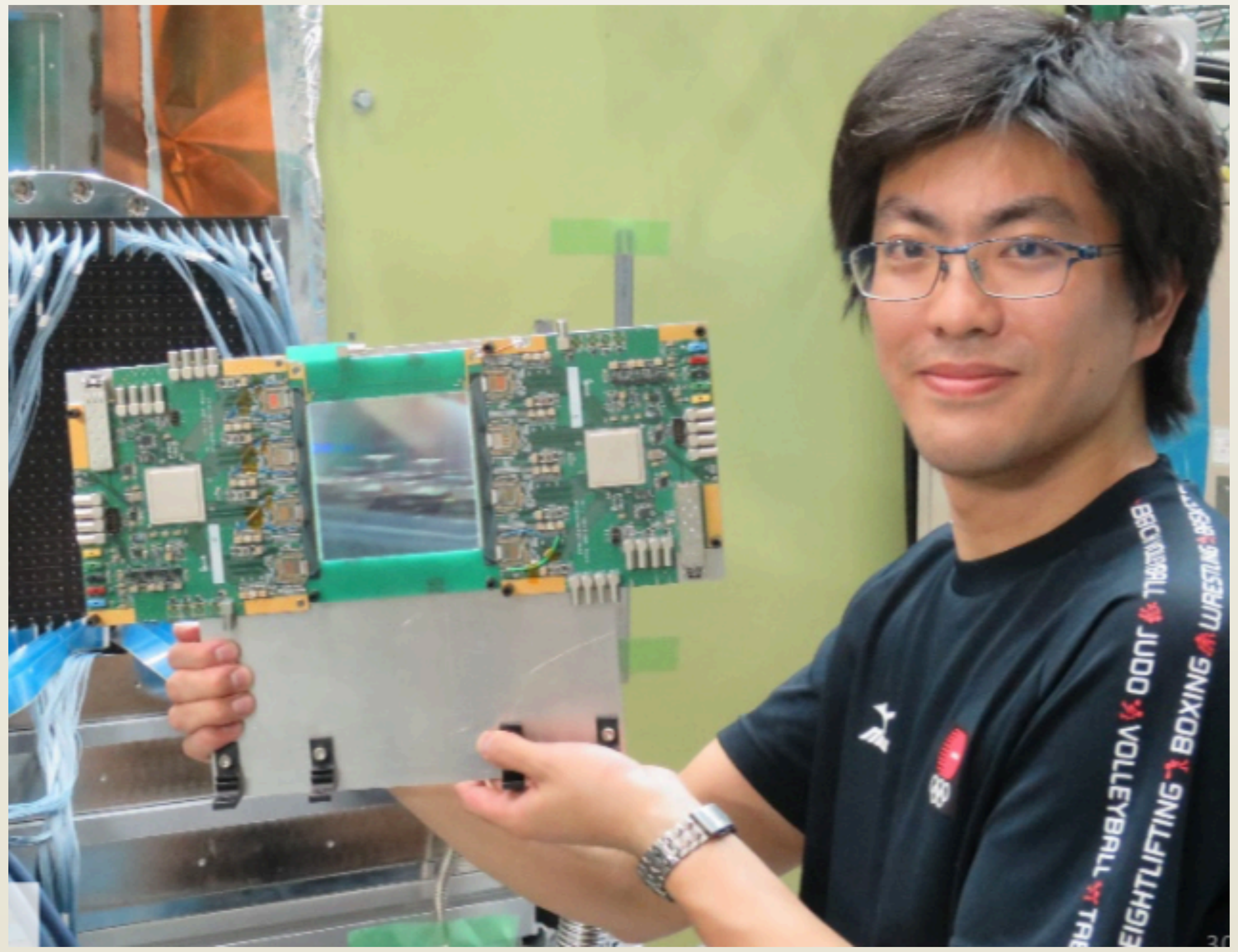
From T. Mibe-san

Muon storage region and positron detectors



1/





Comparisons

We essentially used the BNL magic momentum storage ring technique. But newer technology allowed us to scrutinize further and discovered new effects.

Jparc g-2 uses a low energy storage ring technique (no quads, no kickers, no inflector). But there are trade offs with rate and material and beam emittance.