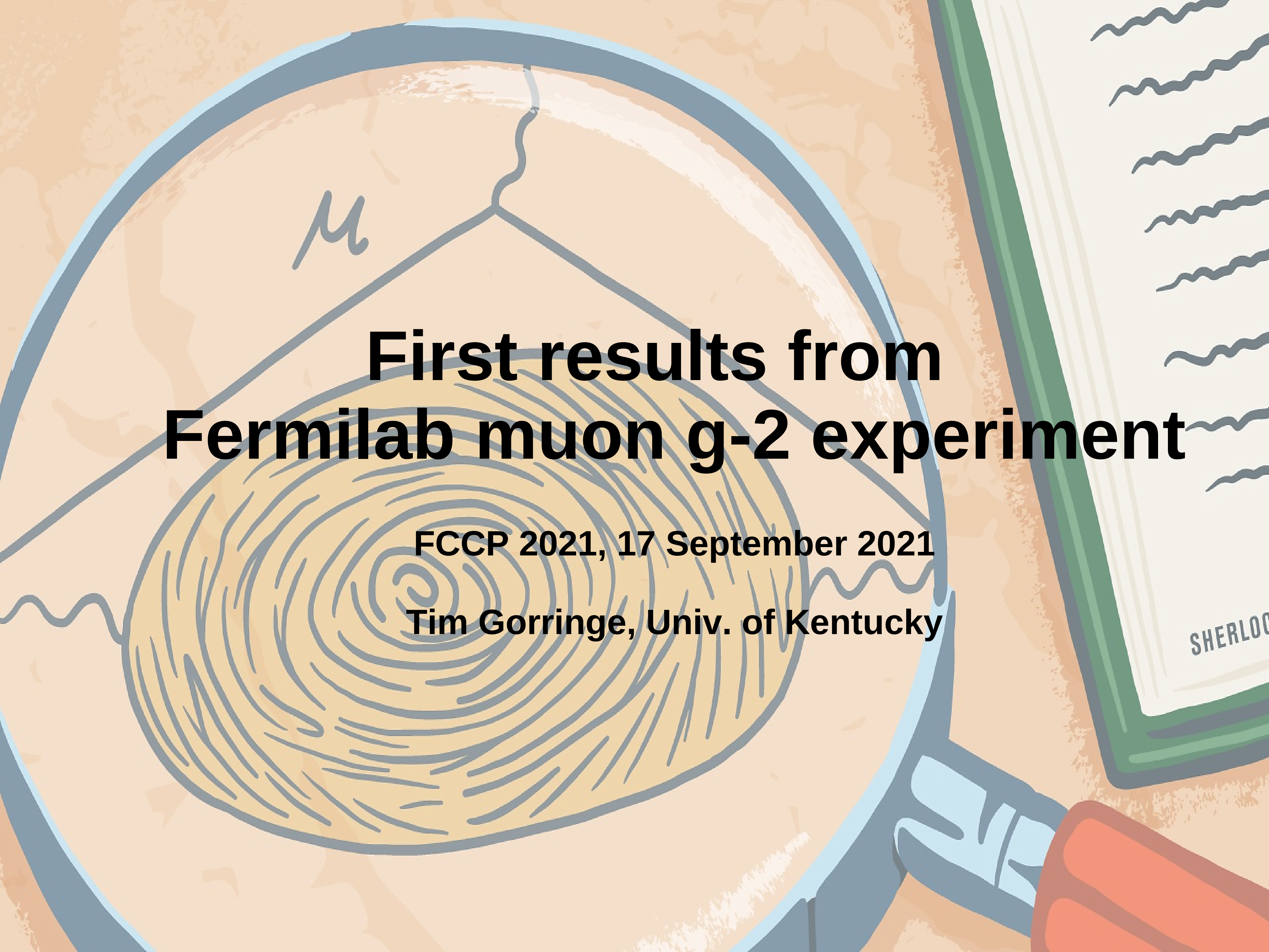


First results from Fermilab muon g-2 experiment

FCCP 2021, 17 September 2021

Tim Gorringe, Univ. of Kentucky

Muon g-2 collaboration

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

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

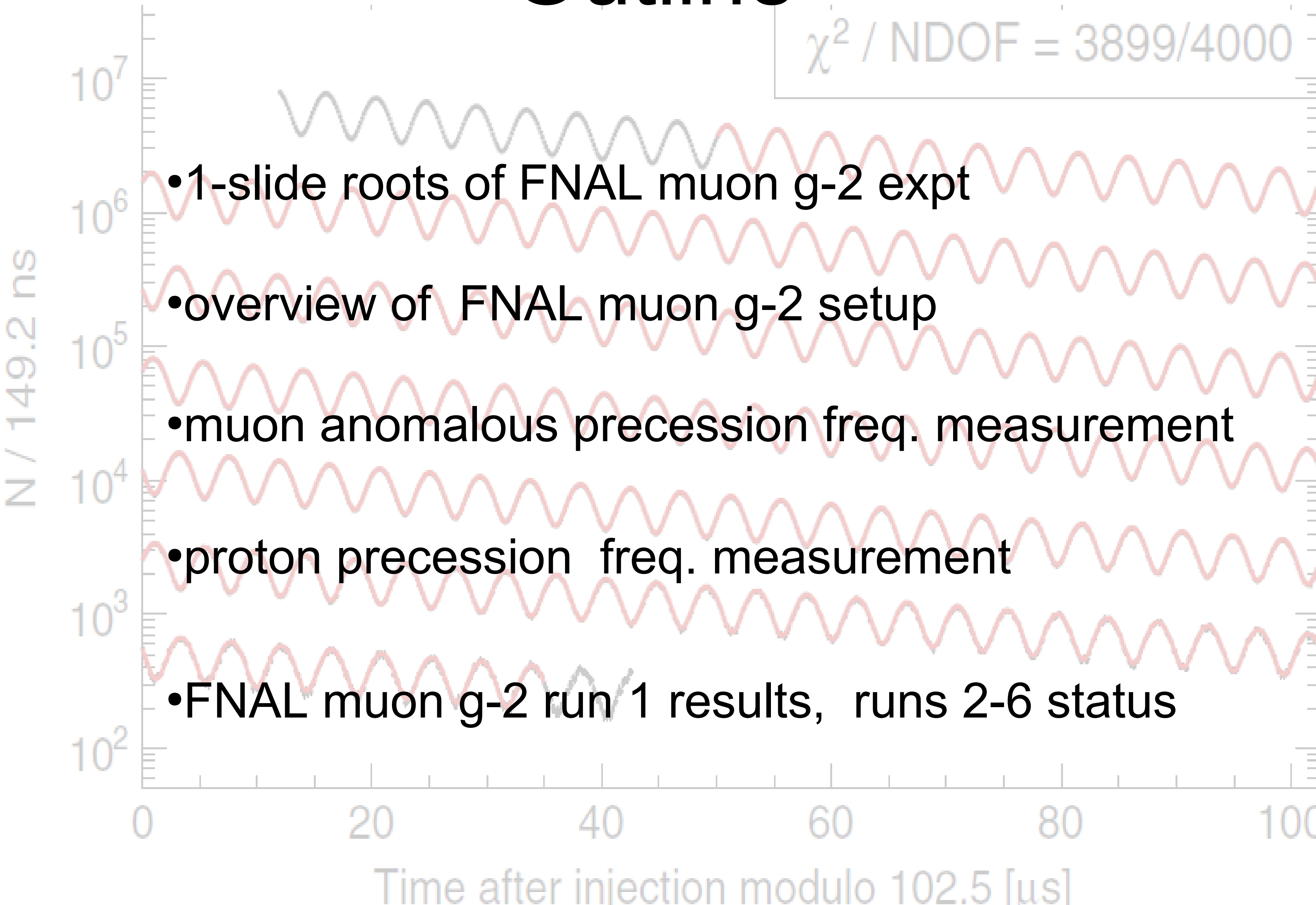
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

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

200 collaborators
35 Institutions
7 countries

Outline

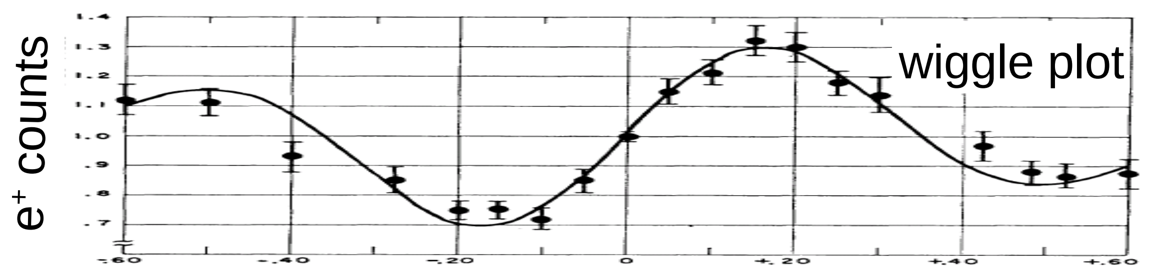


- 1-slide roots of FNAL muon g-2 expt
- overview of FNAL muon g-2 setup
- muon anomalous precession freq. measurement
- proton precession freq. measurement
- FNAL muon g-2 run 1 results, runs 2-6 status

Roots of muon g-2 experiments.

1947 – discovery of pion and identification of $\pi \rightarrow \mu \rightarrow e$ decay chain

1957 – discovery of muon polarization in $\pi \rightarrow \mu\nu$ via electron asymmetry in $\mu \rightarrow e\nu\nu$ decay

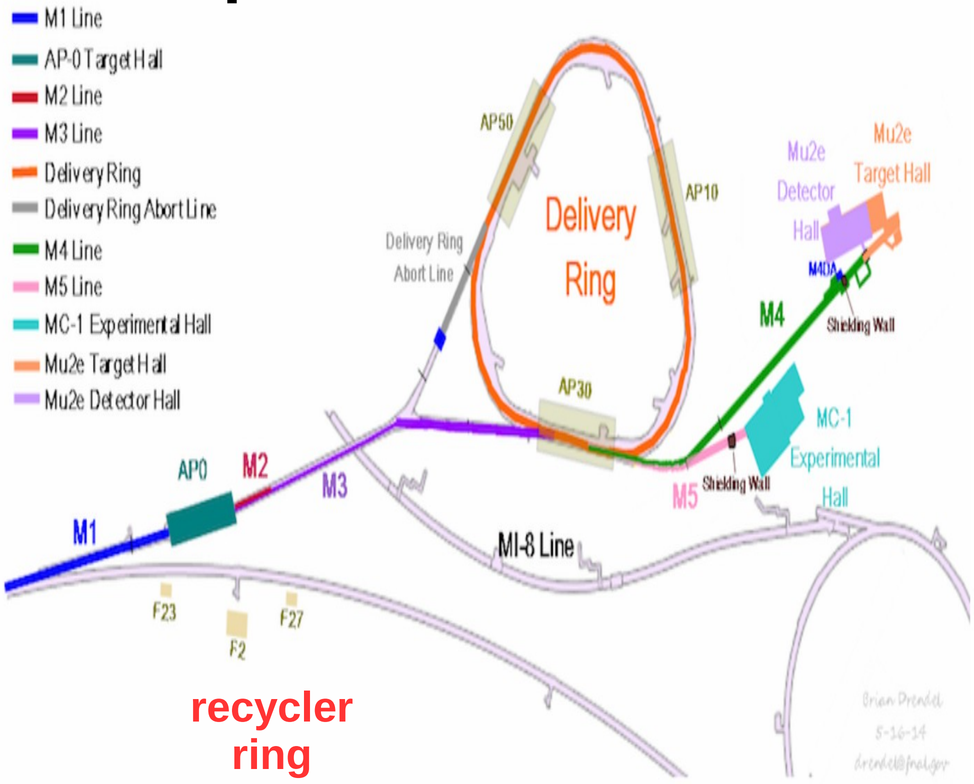


1960 – measurement of muon anomaly $a_\mu = (1.22 \pm 0.08) \times 10^{-3}$ in accord with $\alpha/2\pi$ self-interaction term and a_e

$\pi \rightarrow \mu \rightarrow e$ is `gift of nature', a portal to second generation that offers tools (polarized μ's, analyzing e's) for a_μ precision measurements

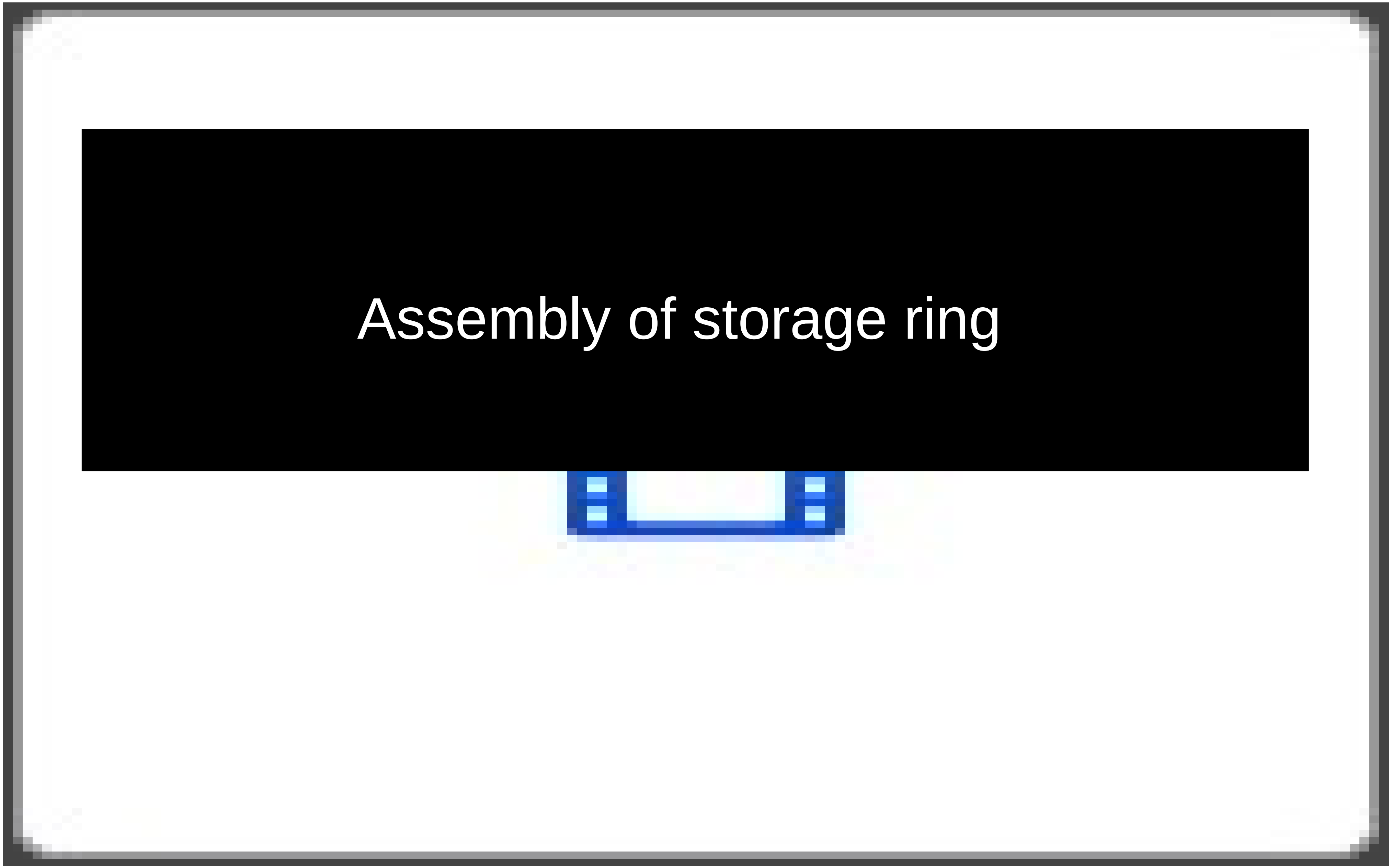
FNAL g-2 expt overview.

FNAL muon campus



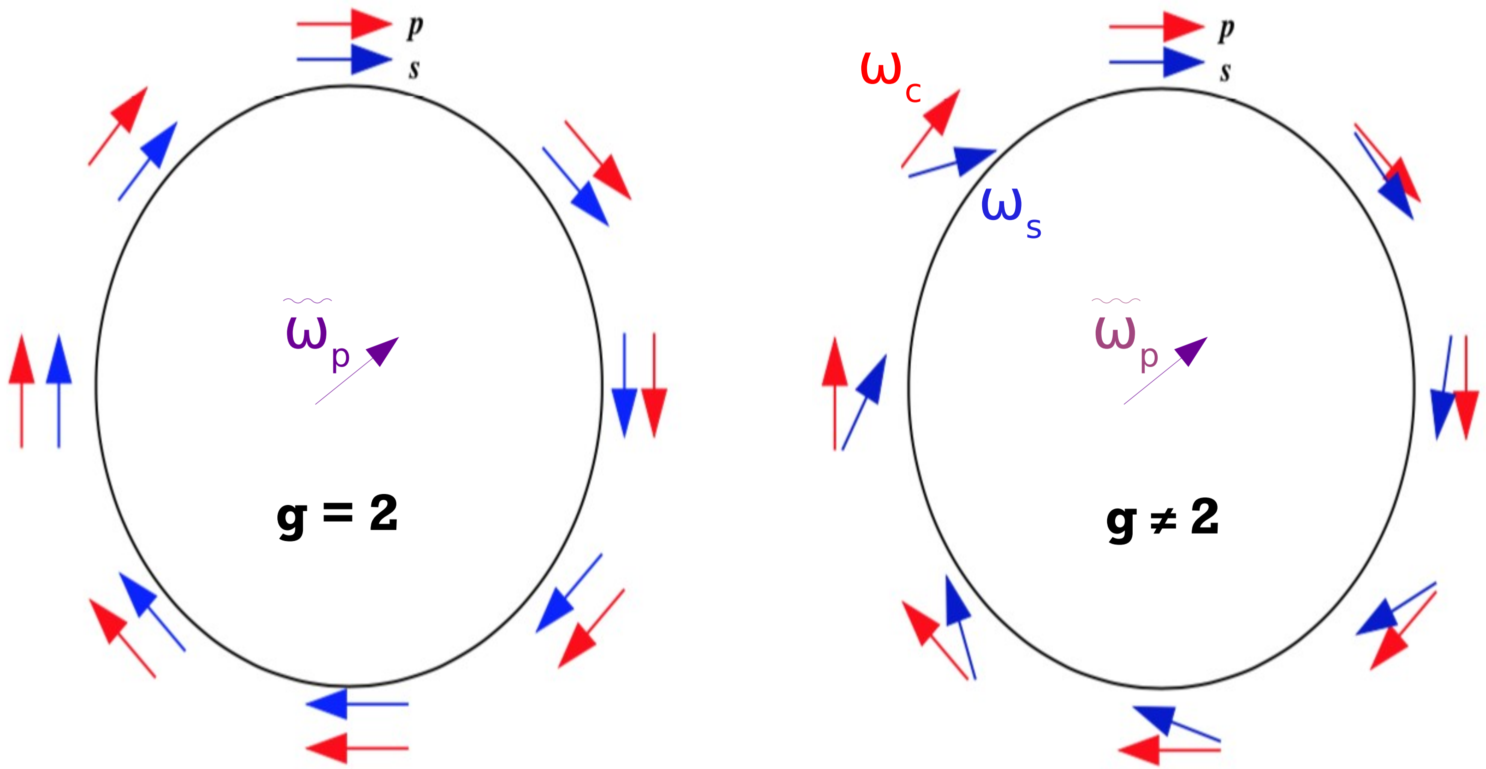
- 8 GeV protons to recycler ring for bunching
- extract bunches onto π-production target
- π's decay to polarized μ's in decay beamline
- injection to delivery ring for μ, π, p separation
- muons extracted to g-2 storage ring

Shoulders of BNL E821



ω_a , $\tilde{\omega}_p$ frequency concept

1. Store 3.094 GeV/c, polarized muons in uniform B-field
2. measure muon anomalous precession freq $\omega_a = \omega_s - \omega_c$ in $\bar{B}$ field
3. measure proton Lamor precession freq $\tilde{\omega}_p$ to determine $\bar{B}$



Cyclotron Period, T_C = 149 ns.

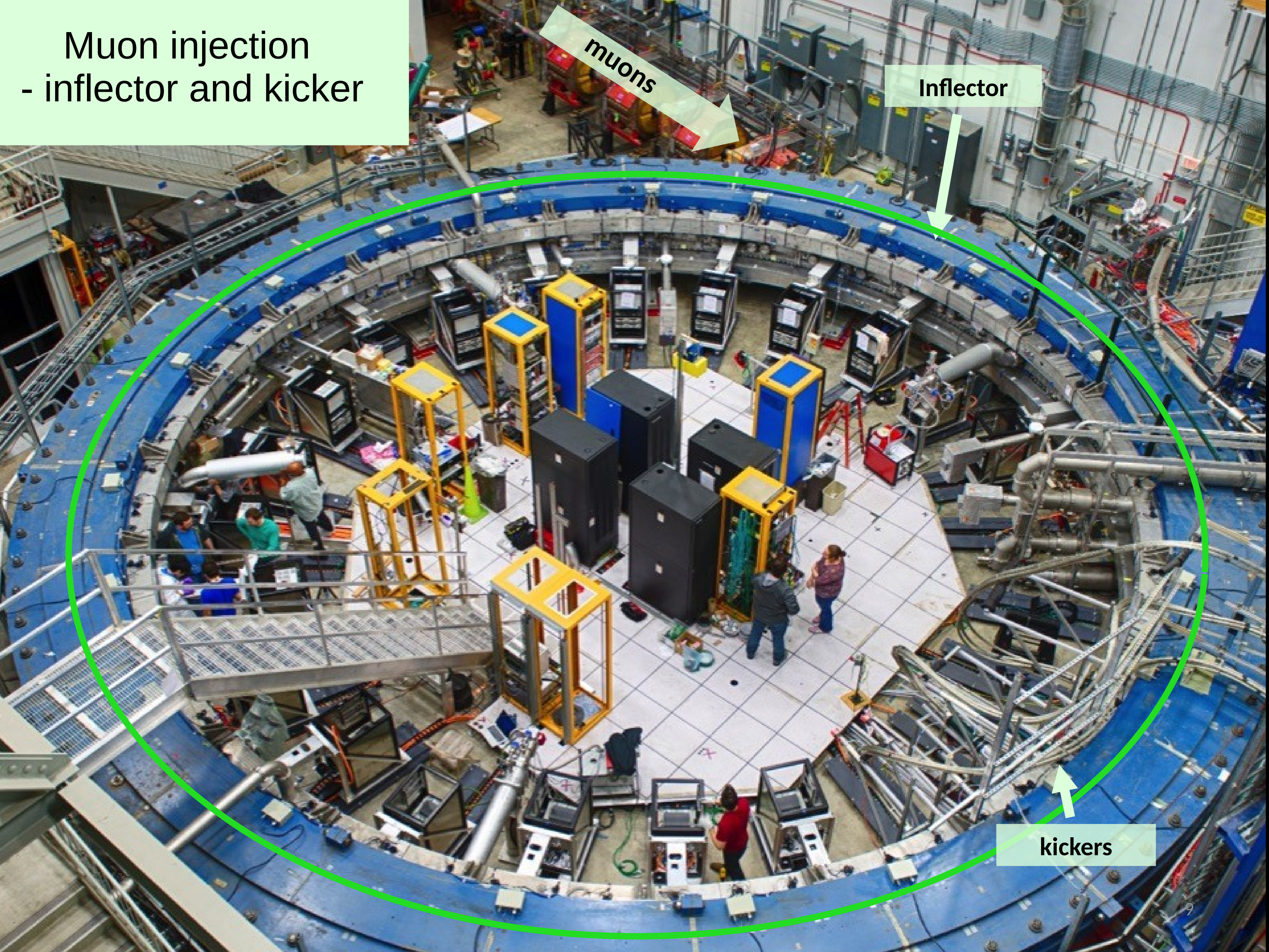
Anomalous Period, T_A = 4.37 μs.

simplified relations

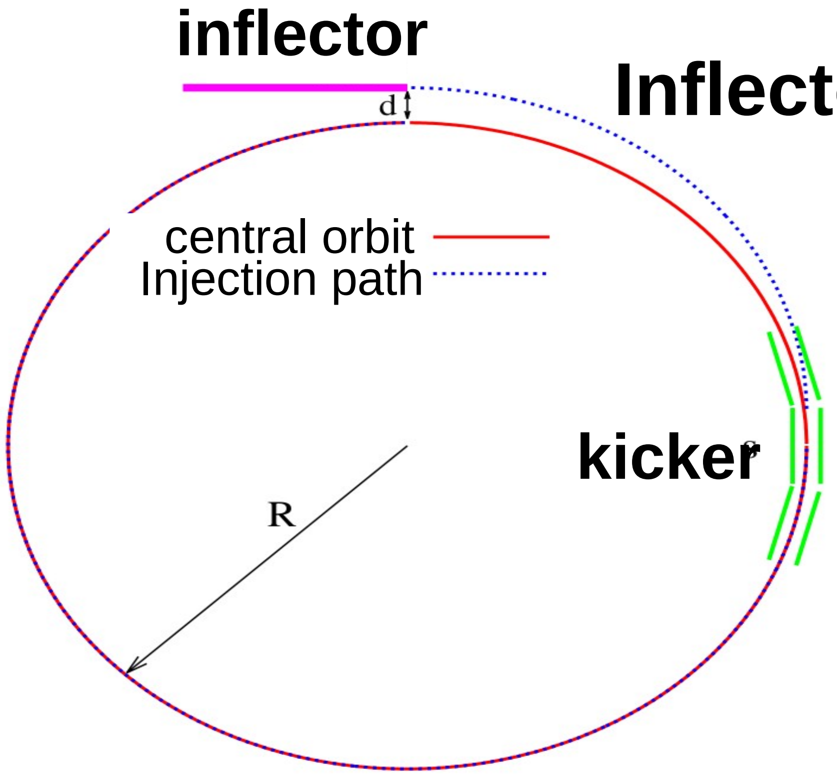
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \left(\frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \right)$$

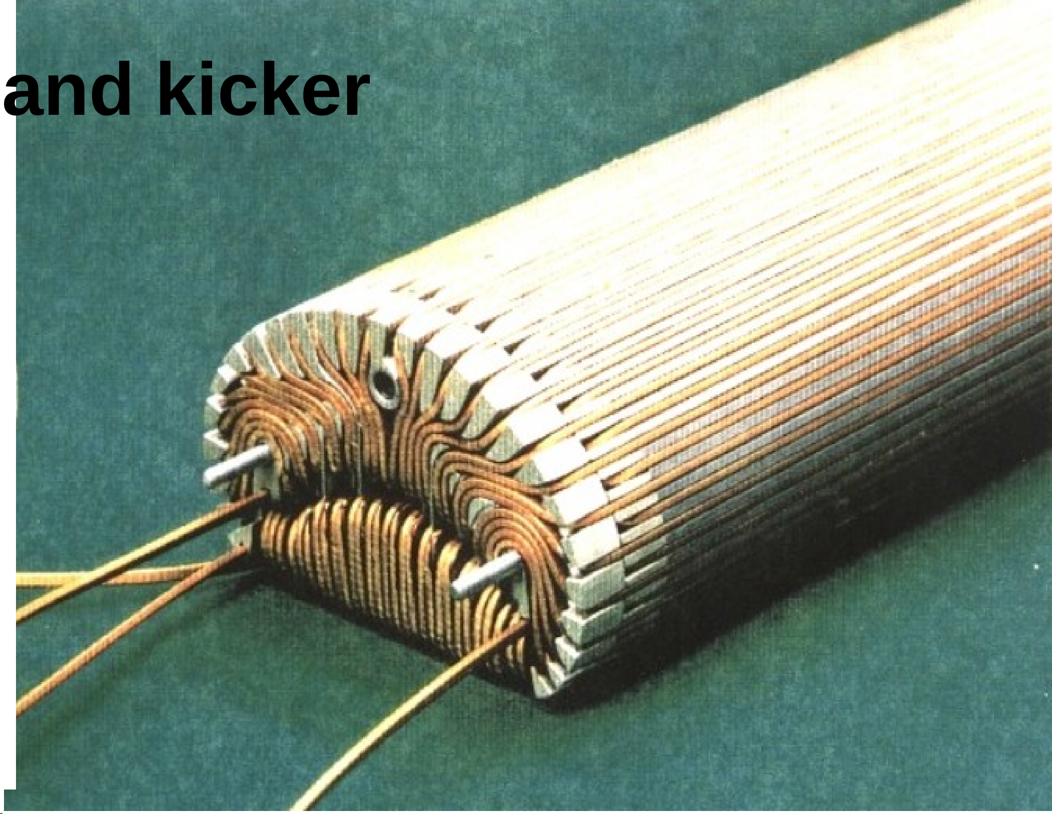
@ magic momentum

Muon injection
- inflector and kicker



Inflector and kicker

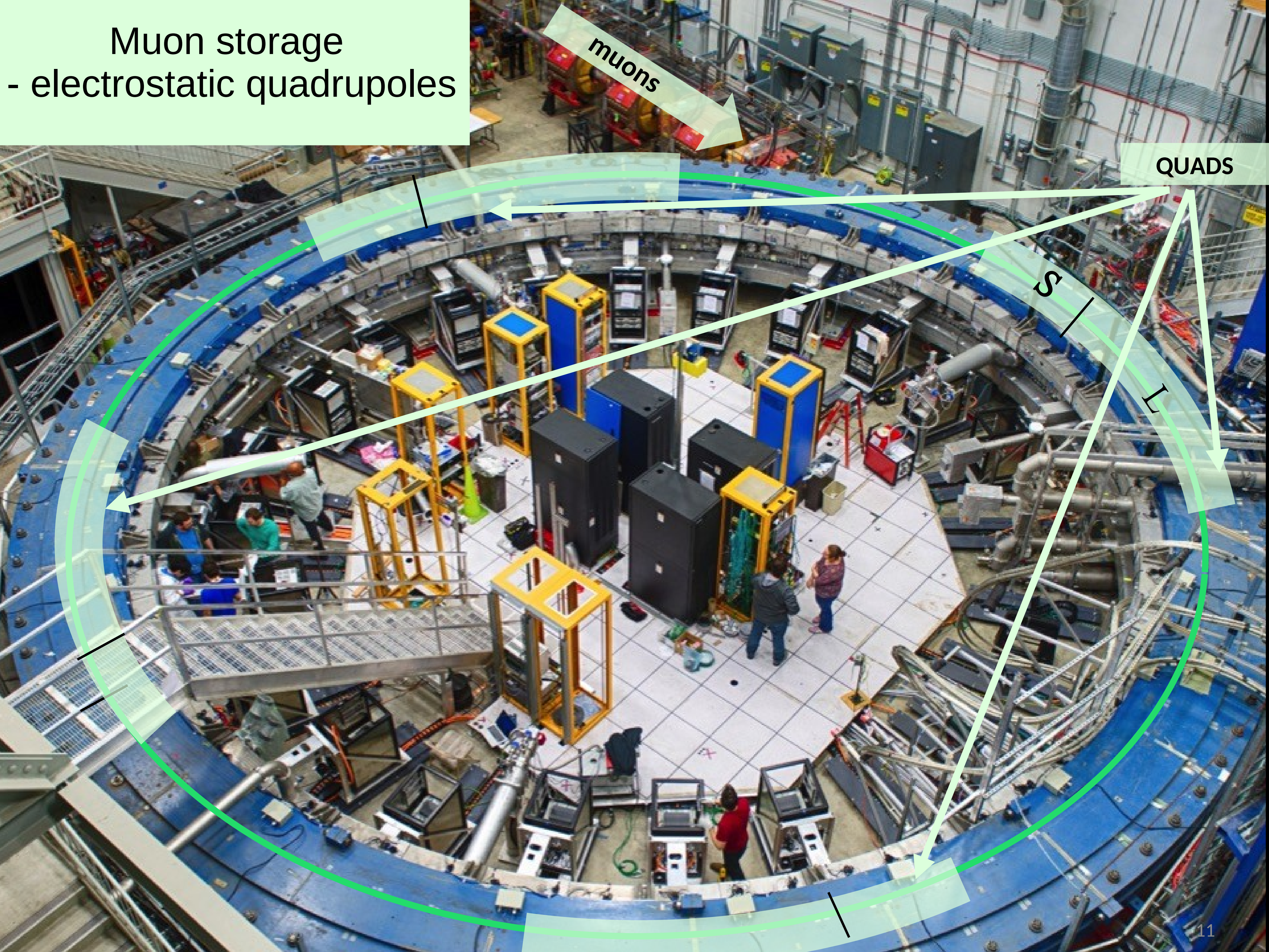




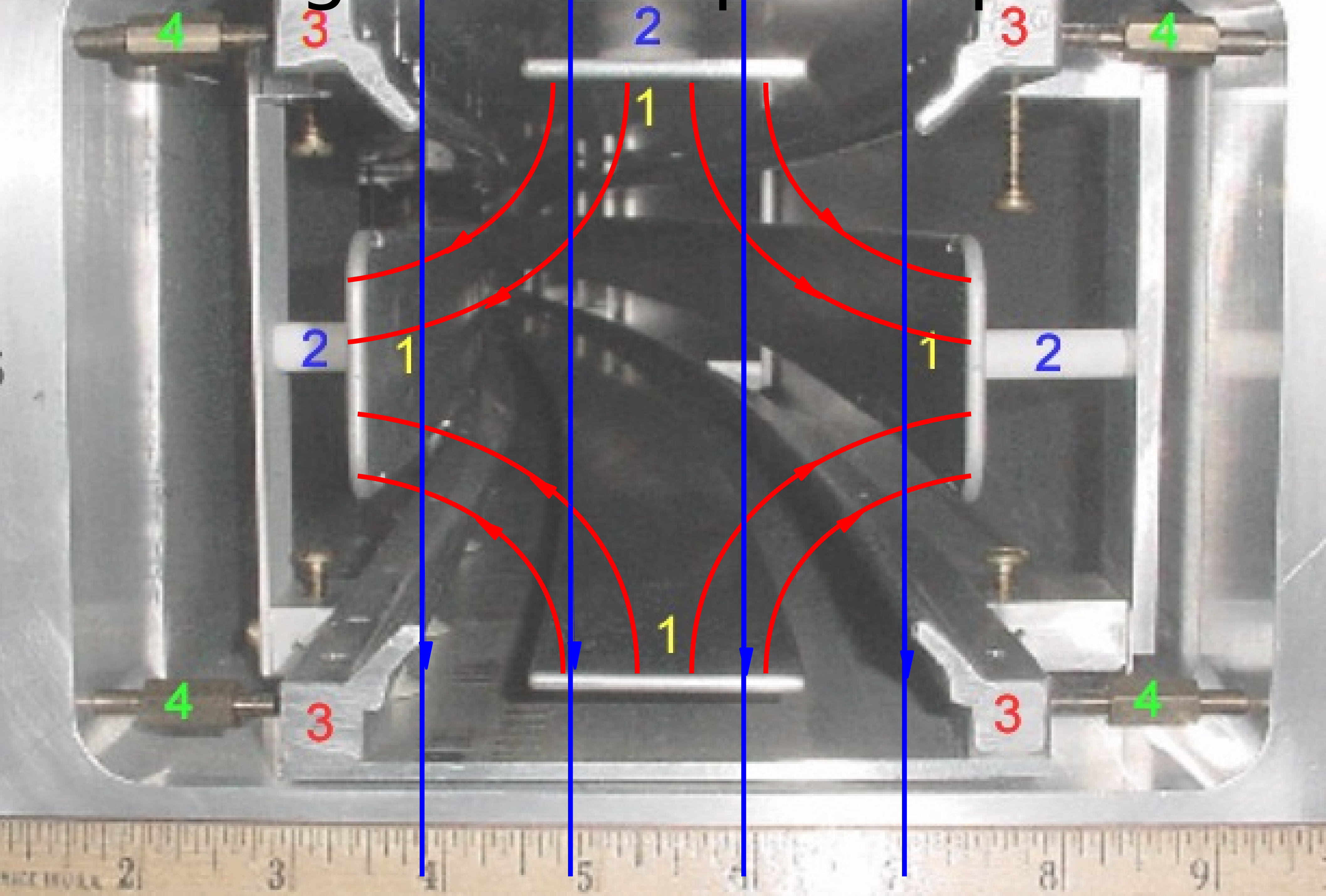
- inflector null's ring’s 1.5T field in beamline entrance using superconducting coil.

- kicker displaces the injected beam by ~0.8 mrad to place on ring's central orbit.

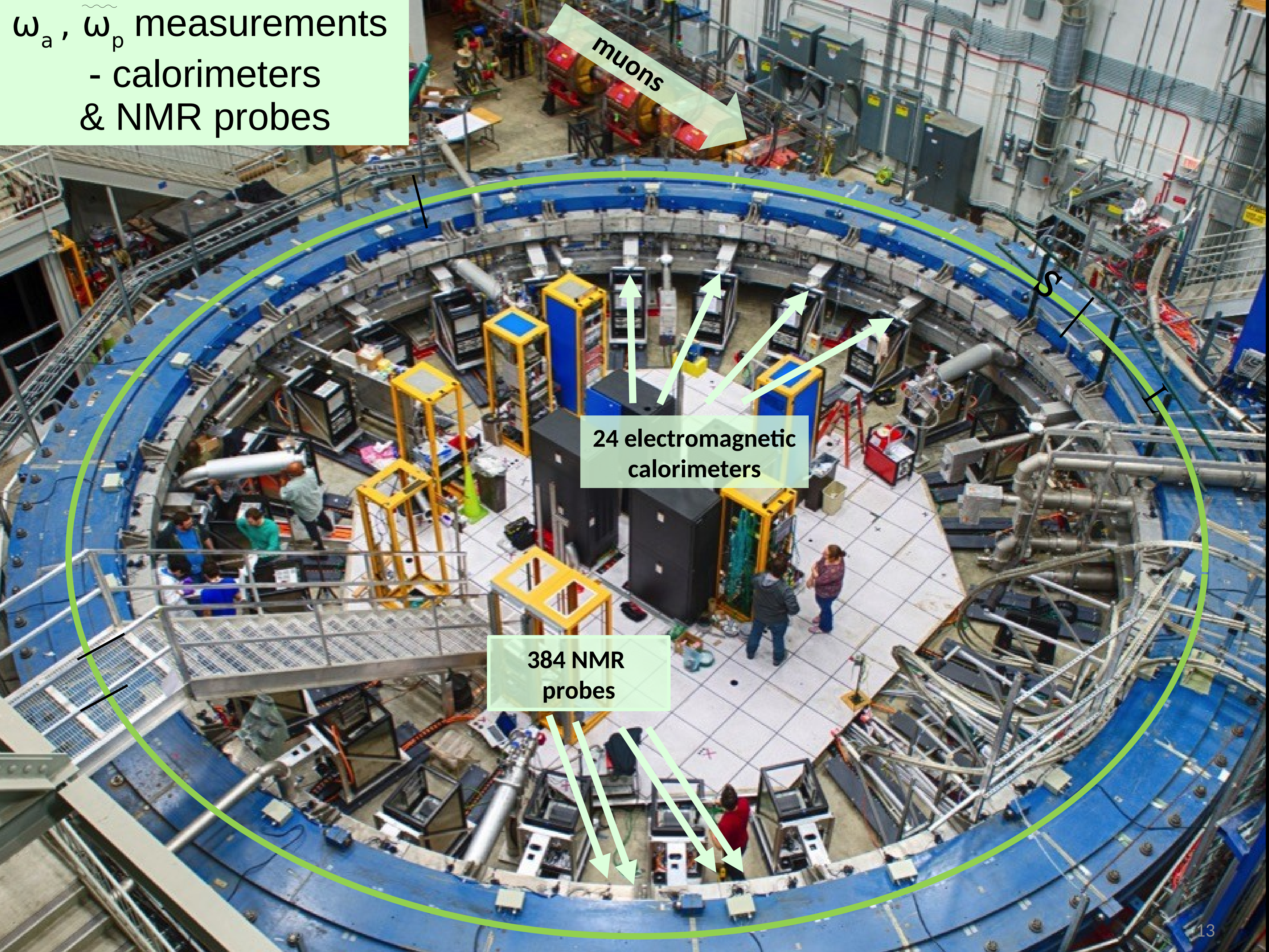
Muon storage
- electrostatic quadrupoles



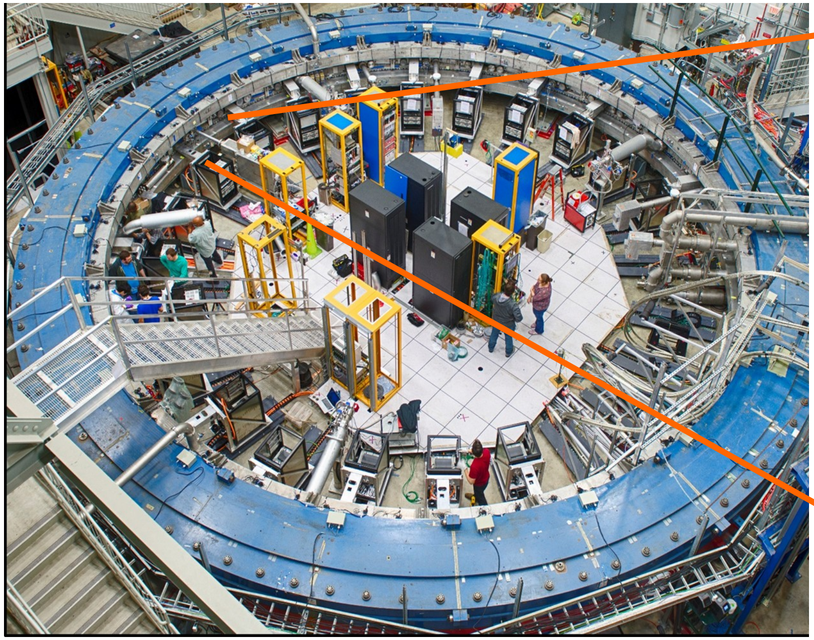
Magnet and quadrupoles

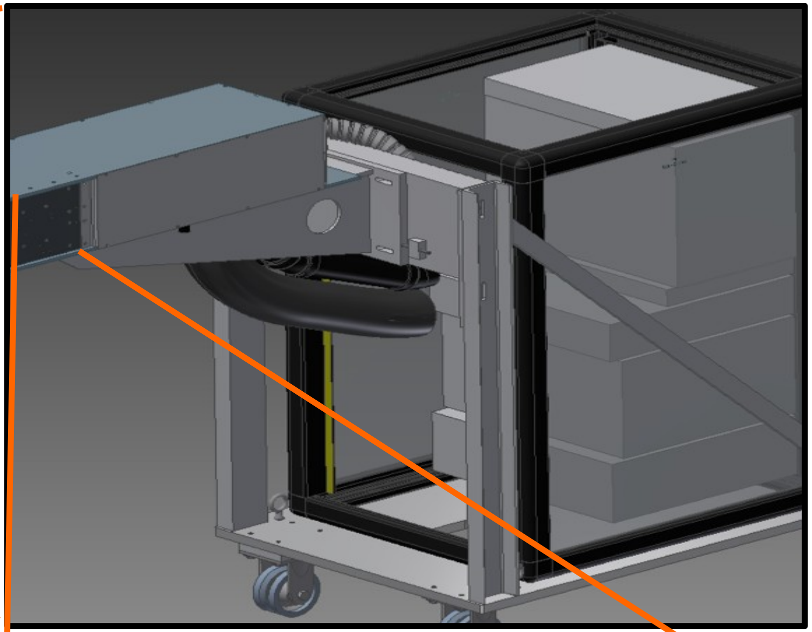


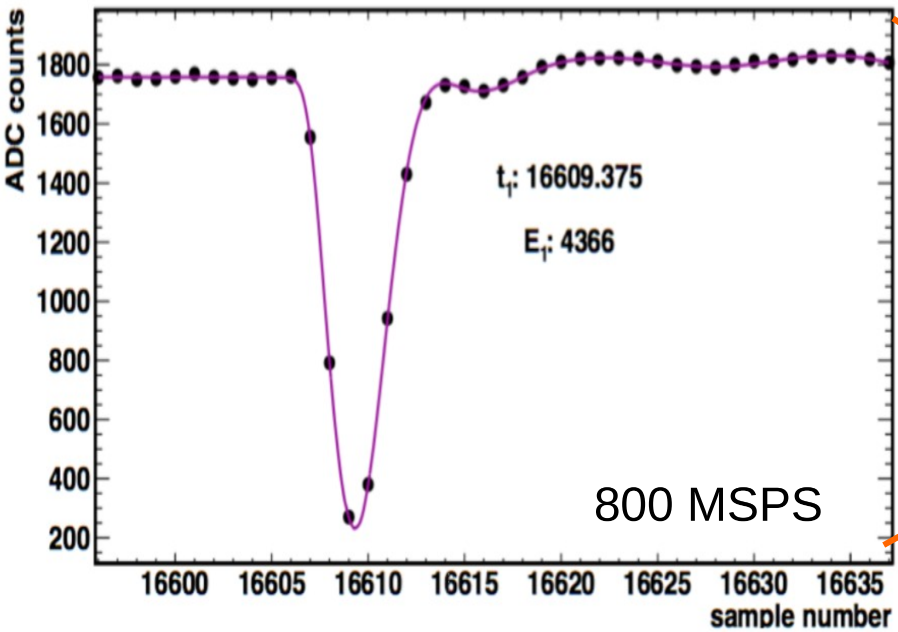
ω_a , $\tilde{\omega}_p$ measurements
- calorimeters
& NMR probes

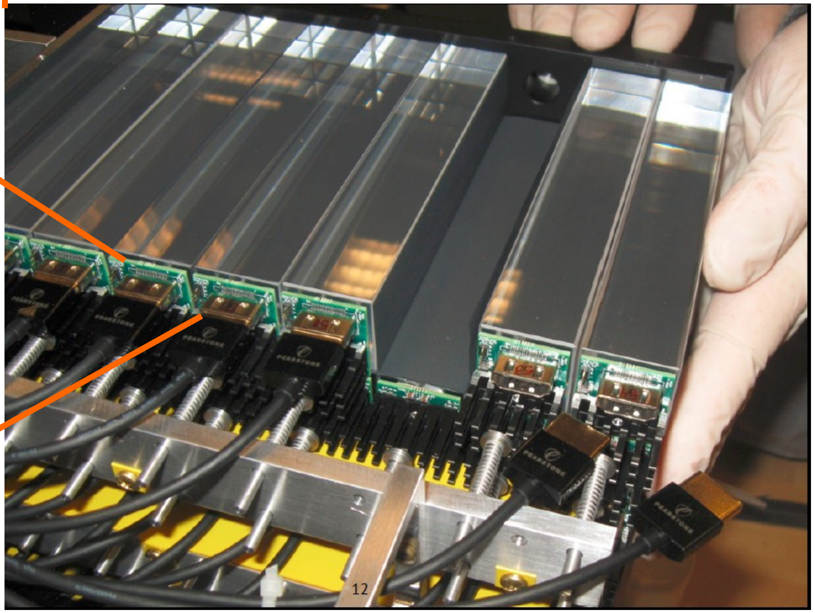


Twenty four electromagnetic calorimeters

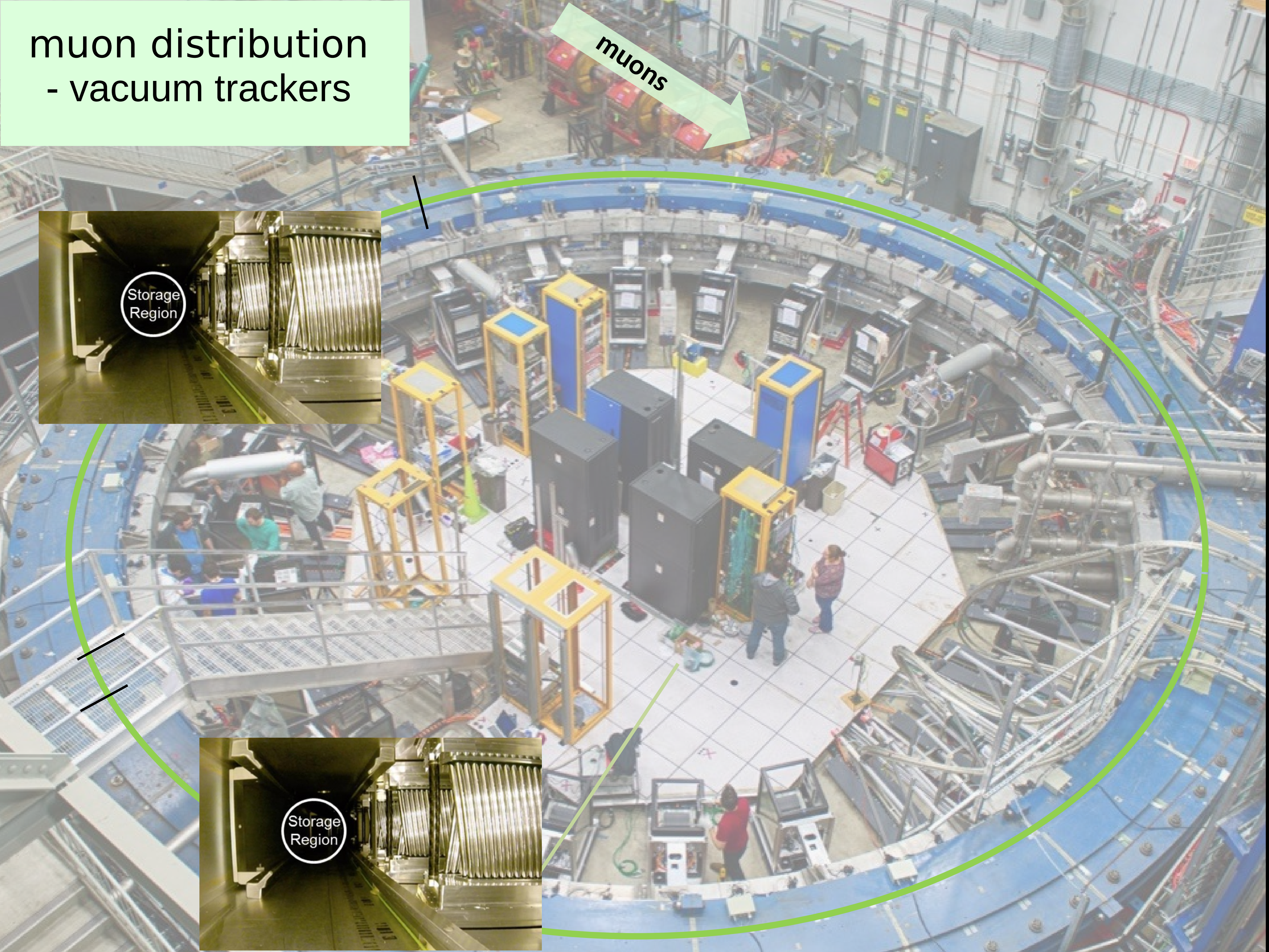






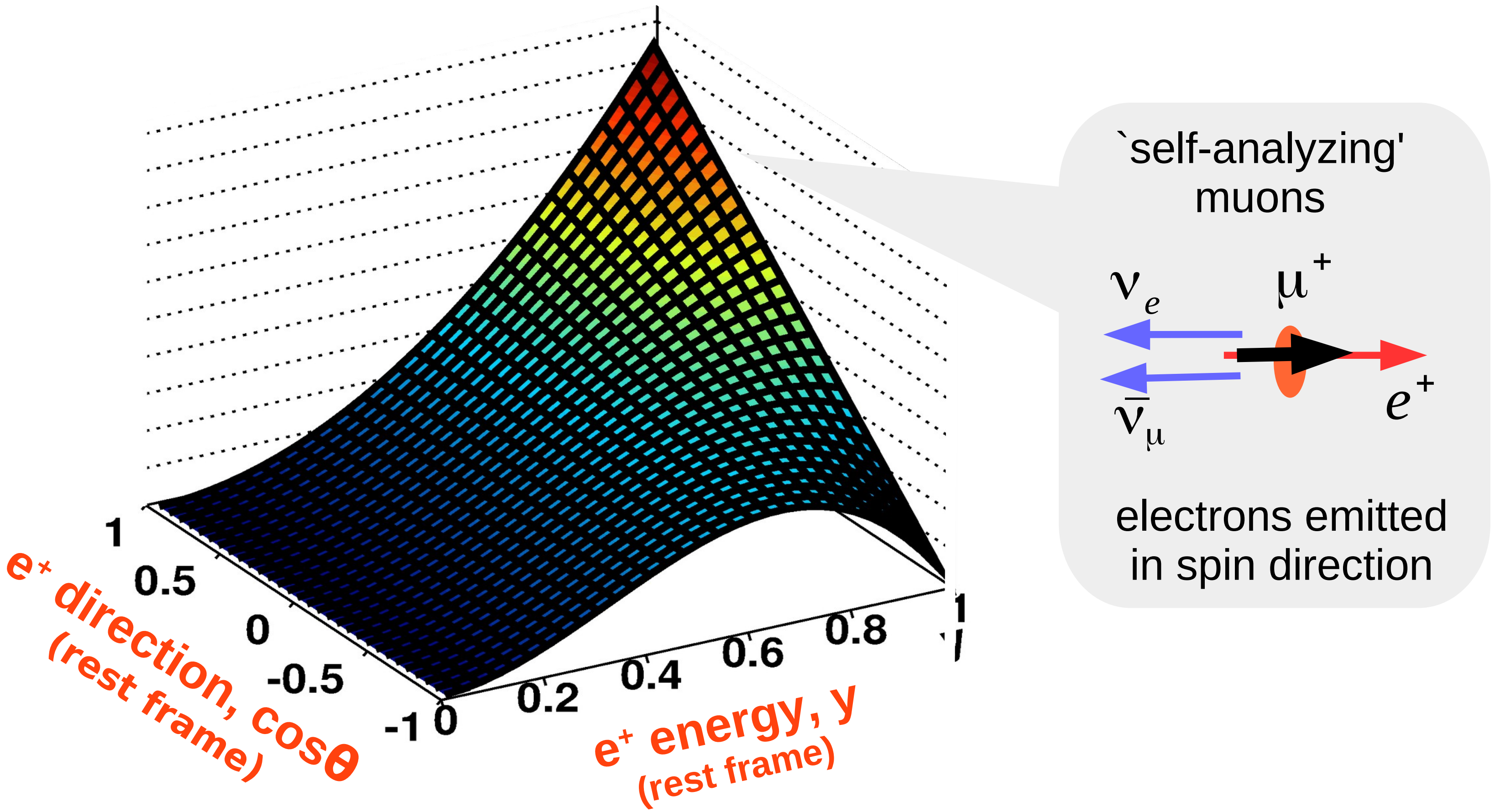


muon distribution
- vacuum trackers



ω_a, $\tilde{\omega}_p$ frequency measurements

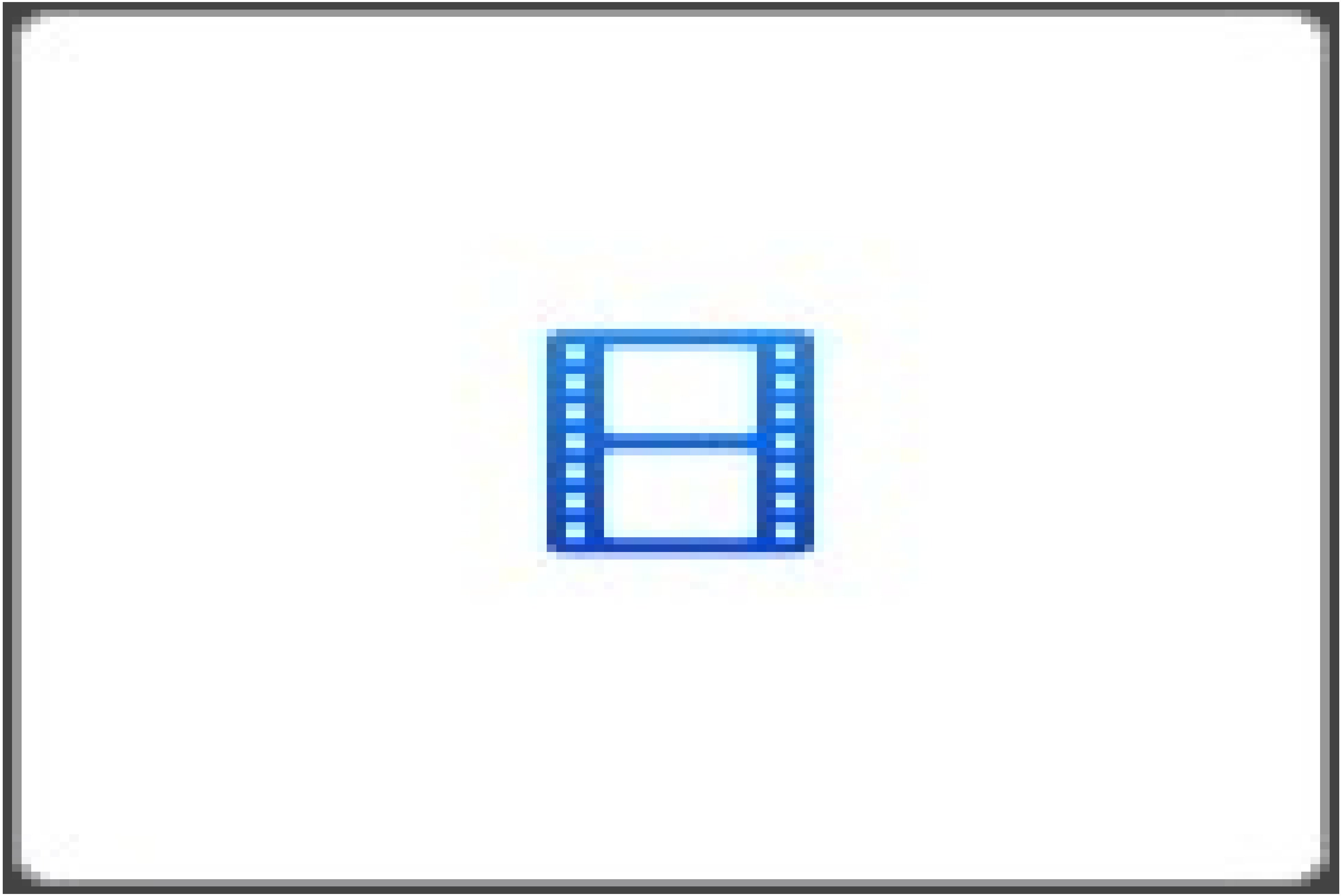
Positron asymmetry and lab. energy distribution



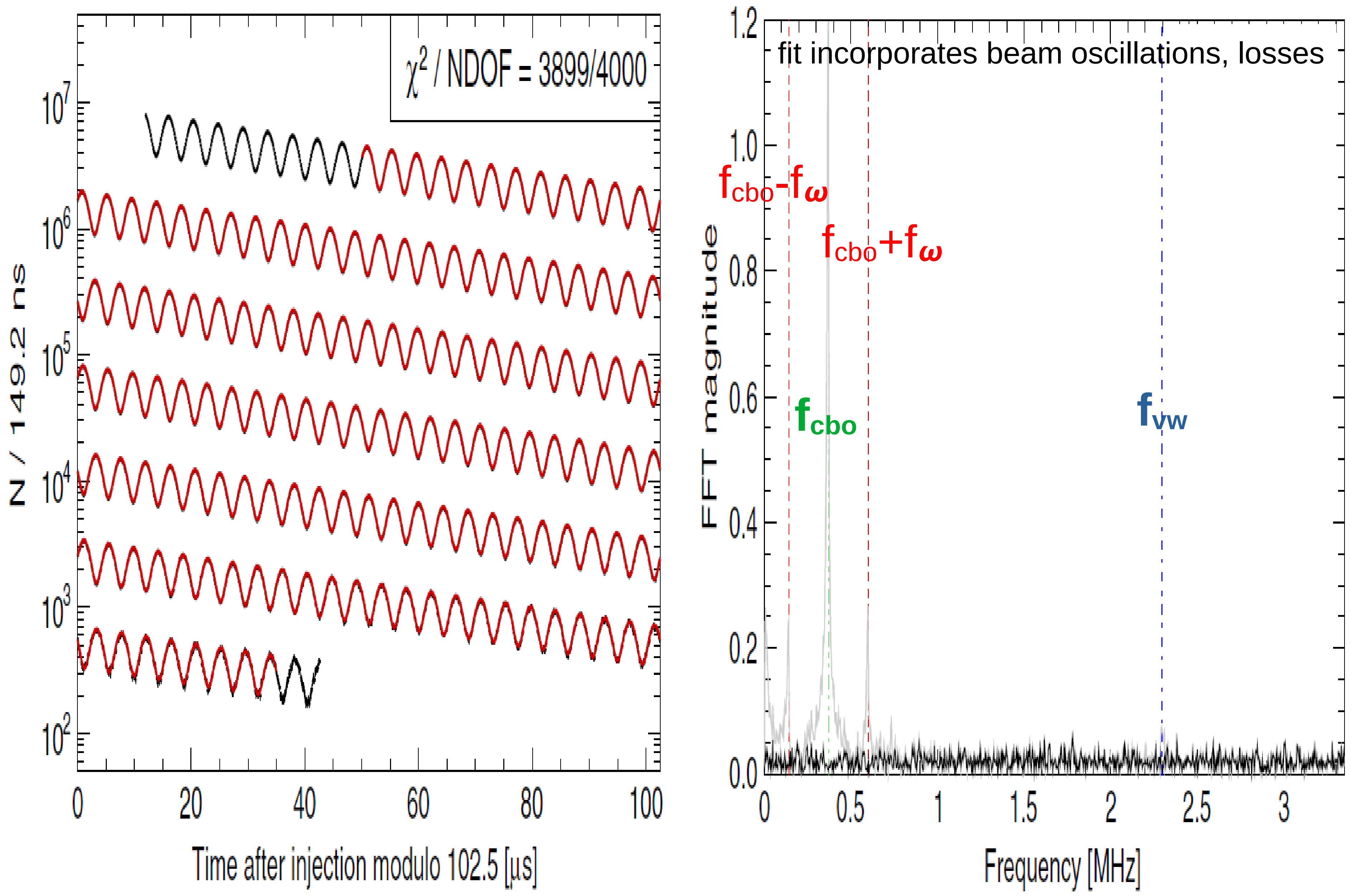
- rest→lab frame boost yields higher energy positrons when emitted along μ-direction

- rest→lab frame boost yields lower energy positrons when emitted opposite μ-direction

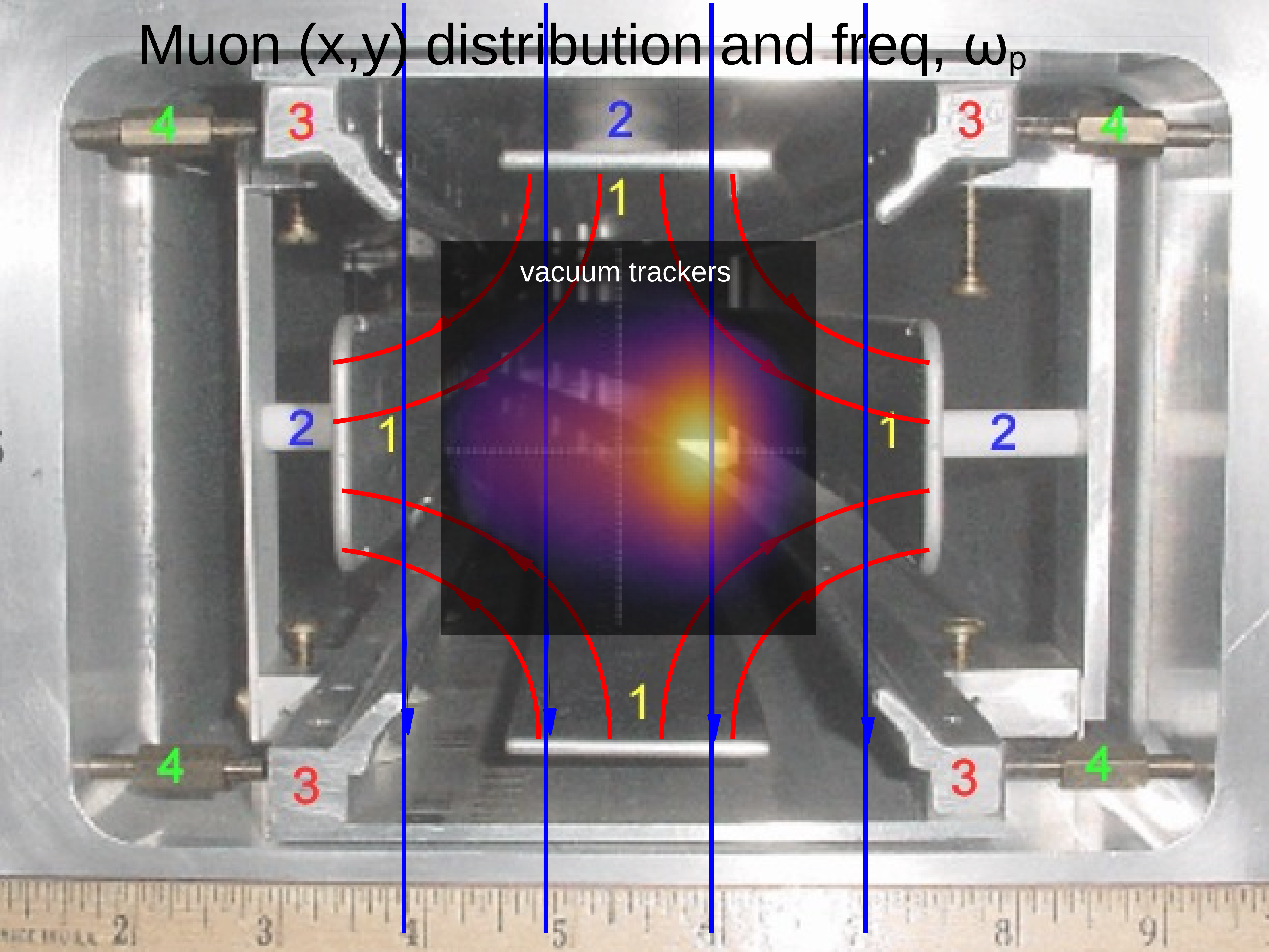
Positron energy versus time and freq, ω_a



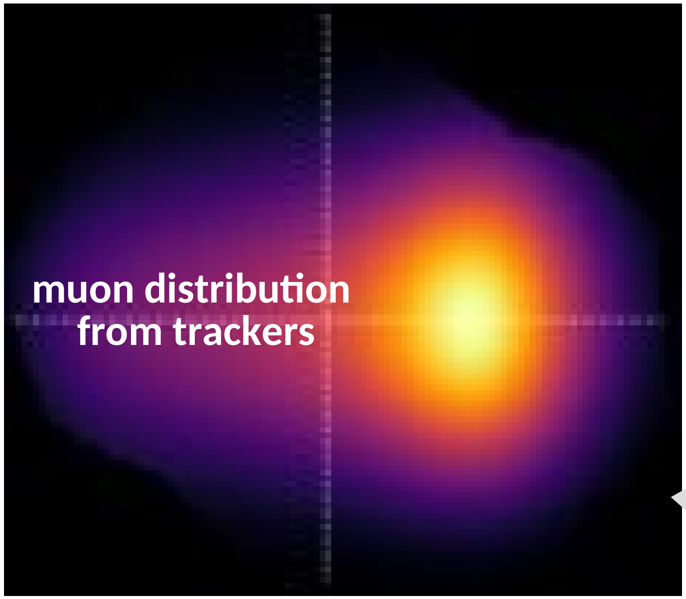
Sample fit to time distribution and freq, ω_a

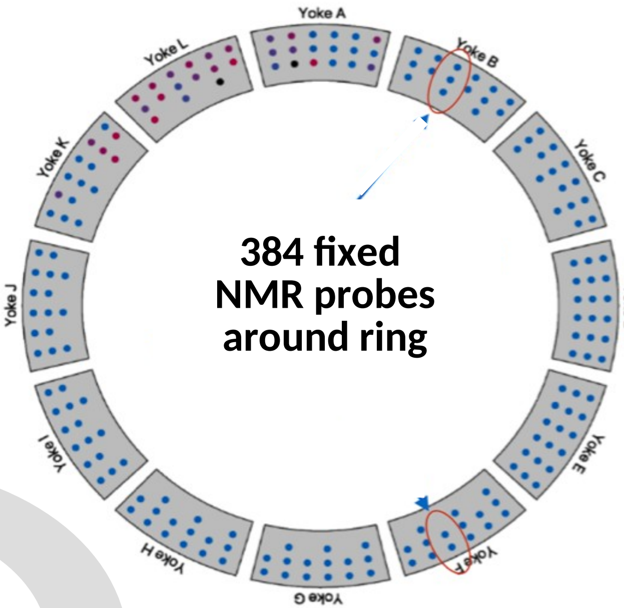


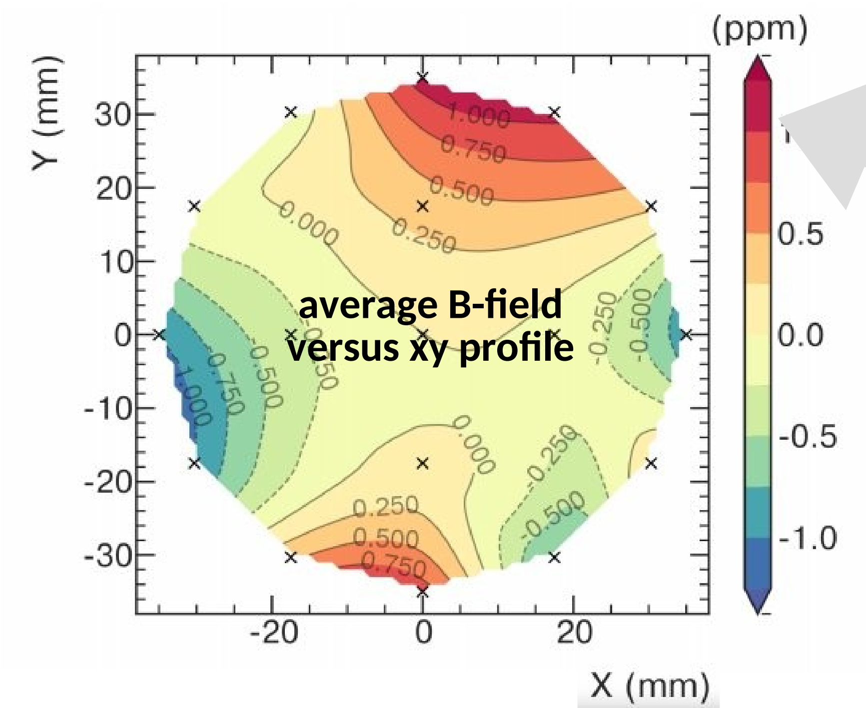
Muon (x,y) distribution and freq, ω_p

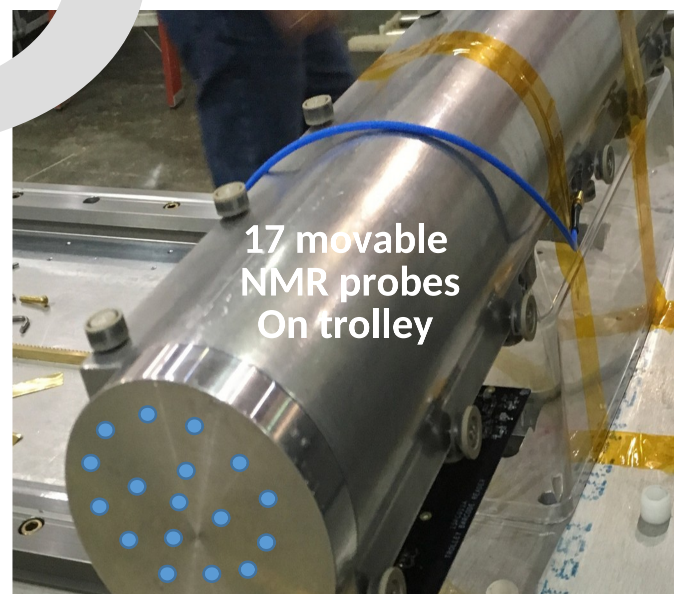


Bootstrapping of $\tilde{\omega}_p(r,t)$ determination



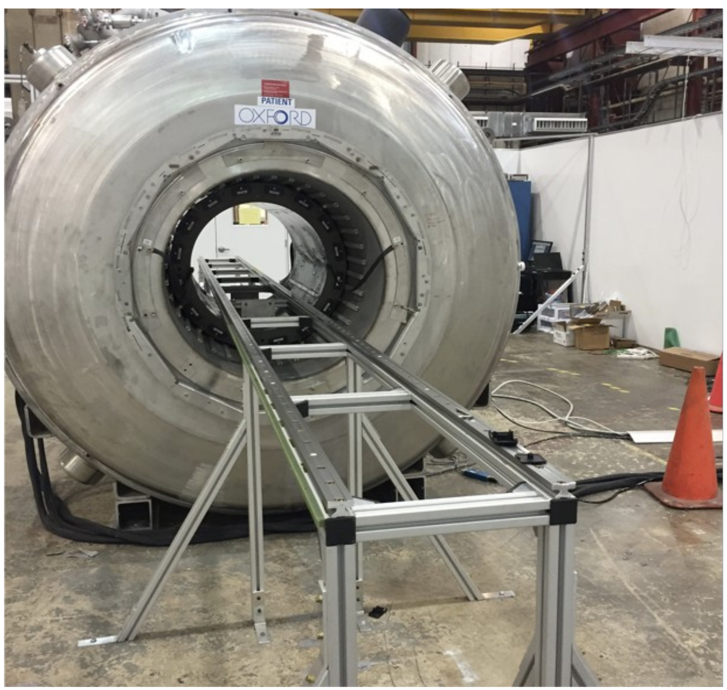




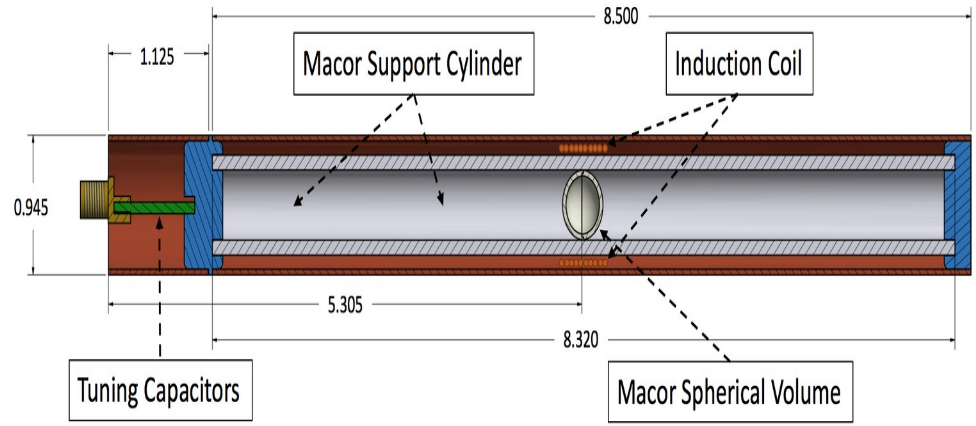


$\tilde{\omega}_p$ (r,t) absolute calibration

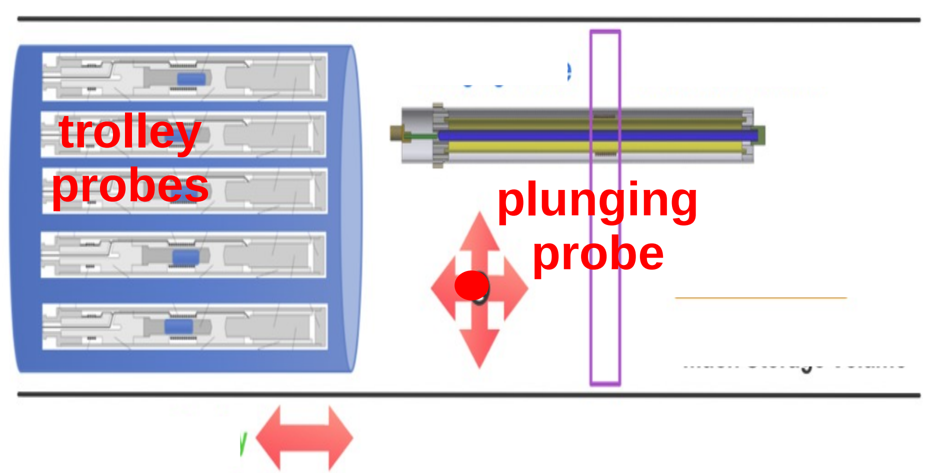
- 15 ppb absolute calibration uses spherical H_20 probe
- MRI studies account for sample shape, temp, magnetization corrections
- plunging probe used to transfer calibration to trolley probes



absolute probe

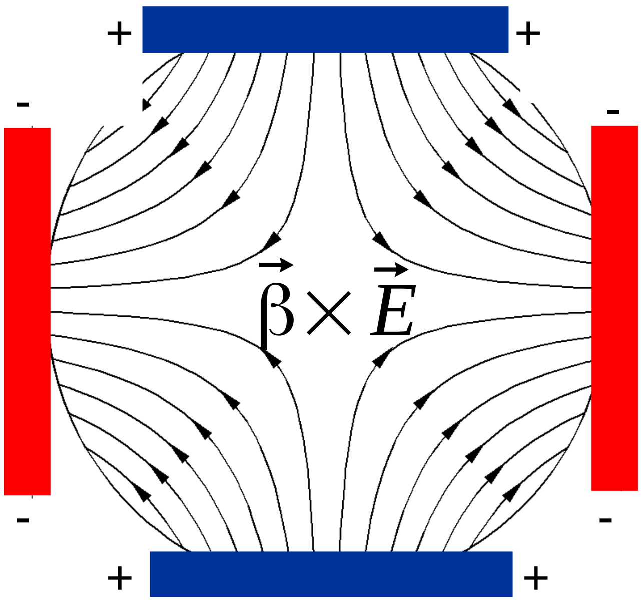


plunging probe

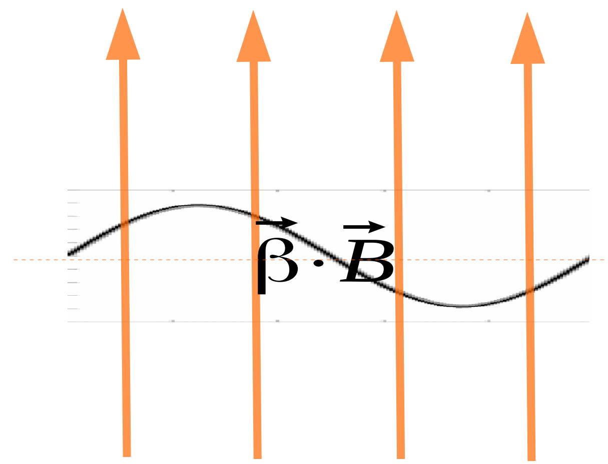


ω_a corrections C_E, C_P, C_{ML}, C_{PA}

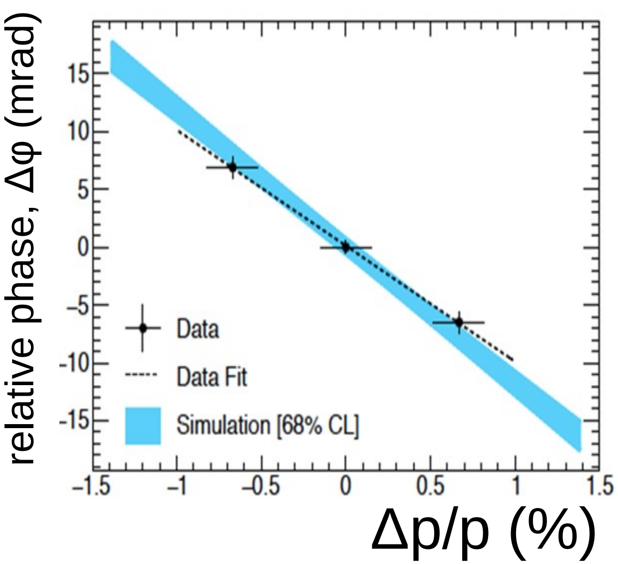
C_E = 489±53 ppb, motional B-field



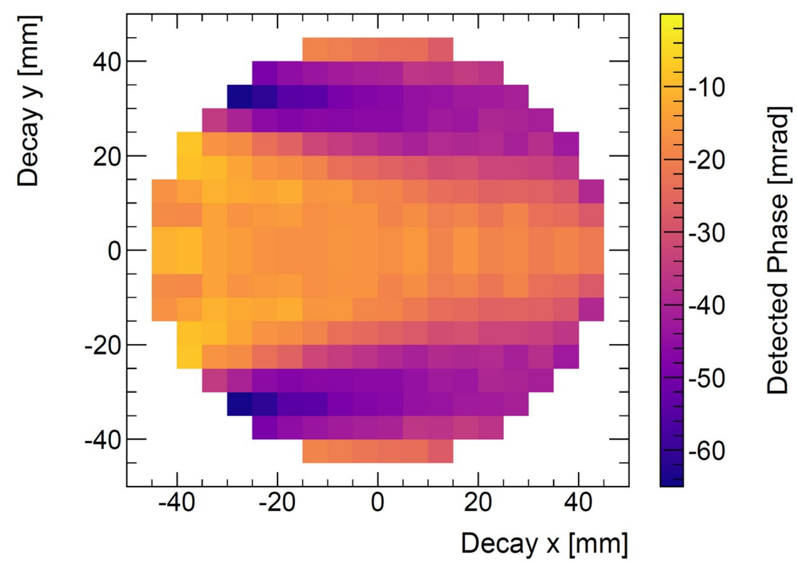
C_P = 180±13 ppb, B-field pitch



C_{ML} = -11±5 ppb, muon loss



C_{PA} = -158±58 ppb, beam changes

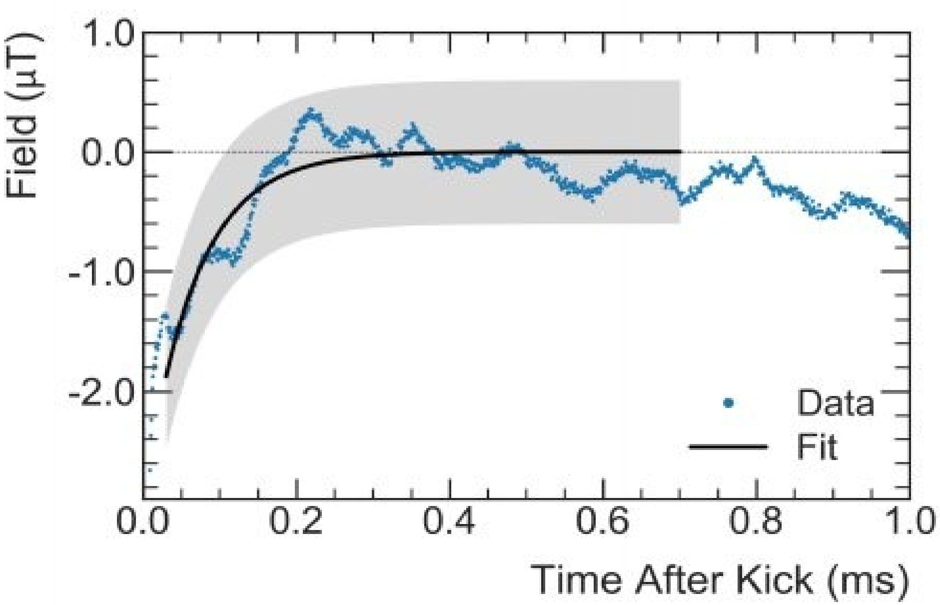


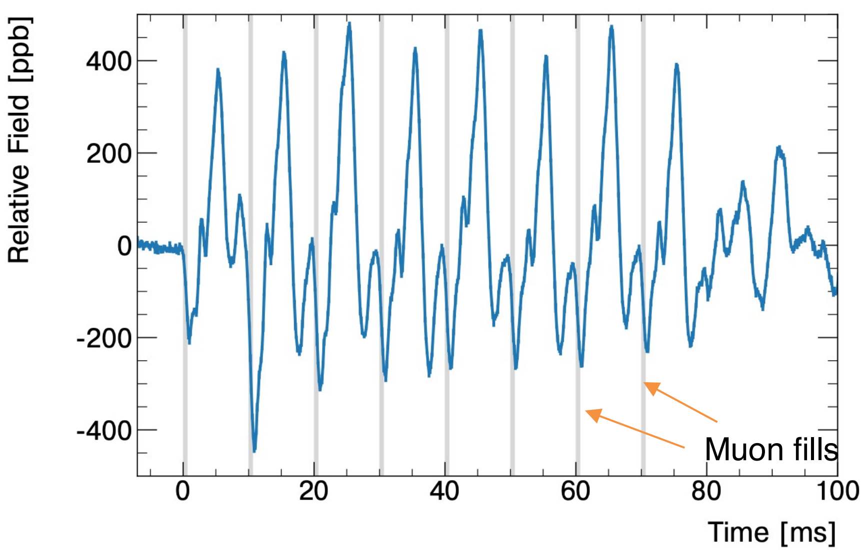
ω_p corrections B_K, B_Q

B_K = -27±37ppb, kicker transients

B_Q = -17±92ppb, quad transients

Quad Plates inside Vacuum Chamber

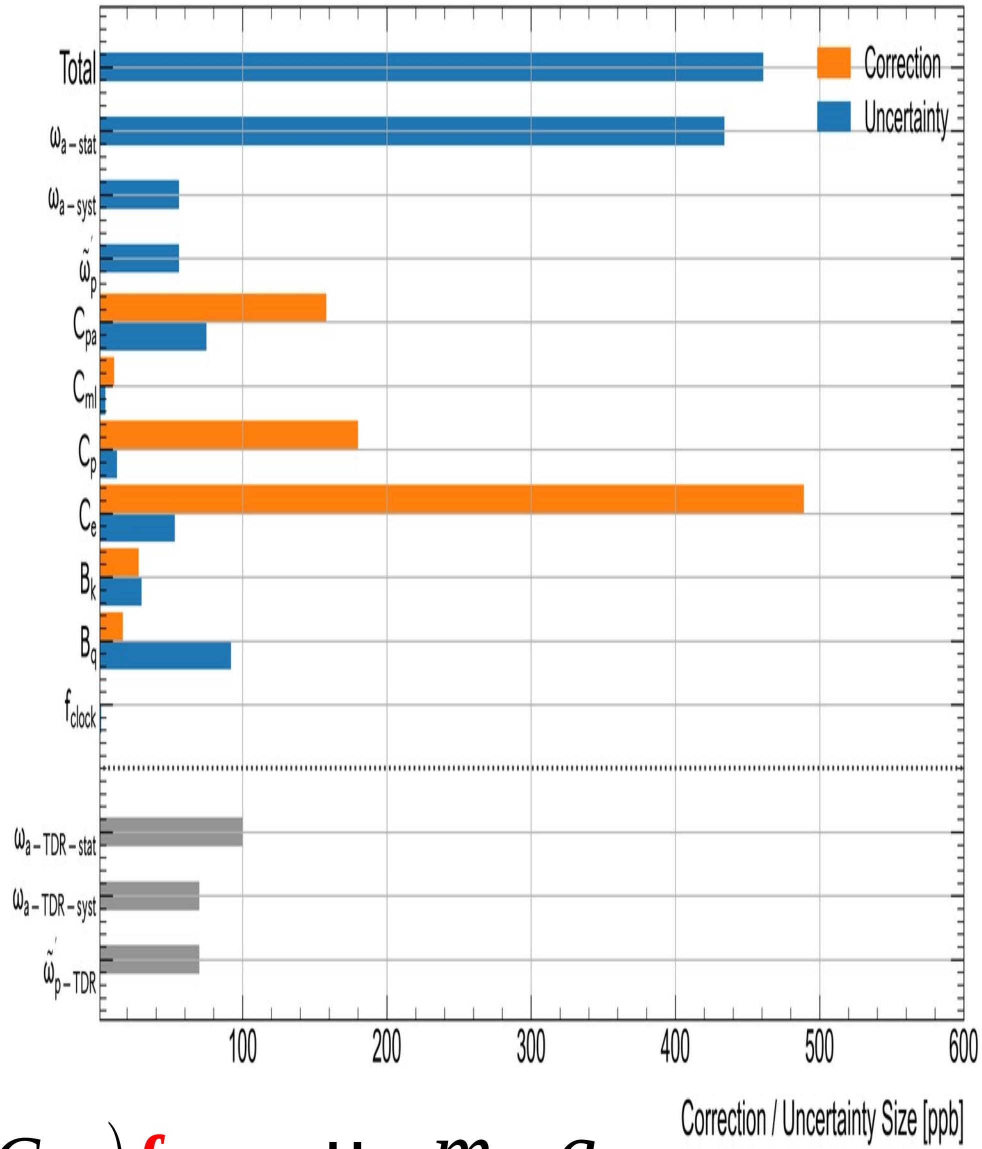




Run 1 results for muon anomaly a_μ

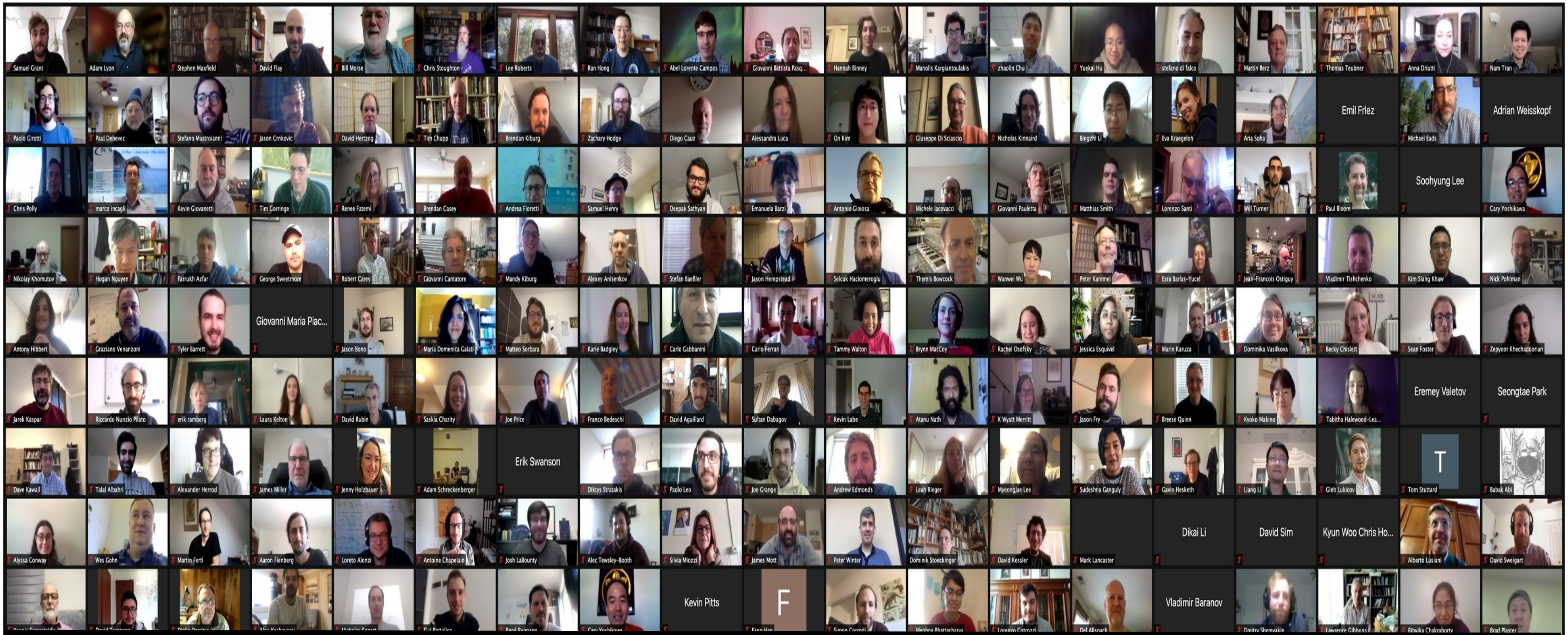
Run 1 statistical, systematics uncertainties

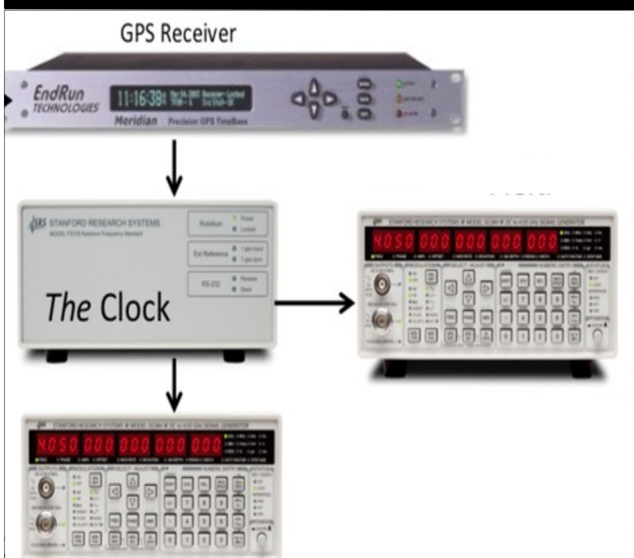
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}} \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$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

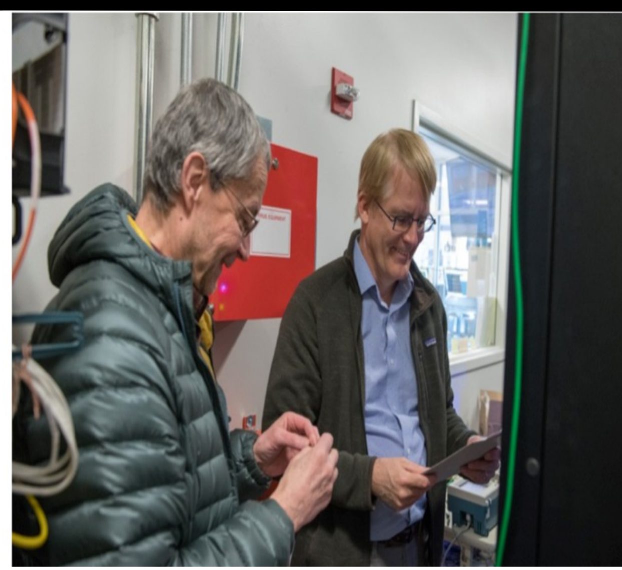


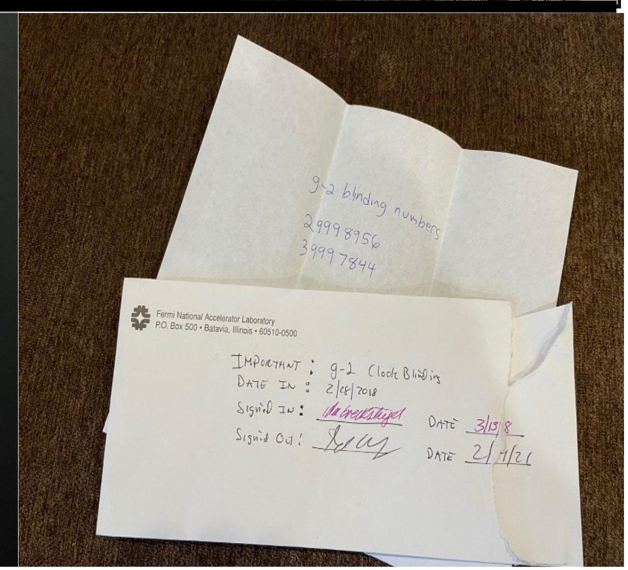
$$a_\mu = \frac{\omega_a (1 + C_E + C_P + C_{LM} + C_{PA}) f_{clock}}{\tilde{\omega}_p (1 + B_K + B_Q) f_{calib}} \left(\frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \right)$$

f_{clock} unblinding meeting

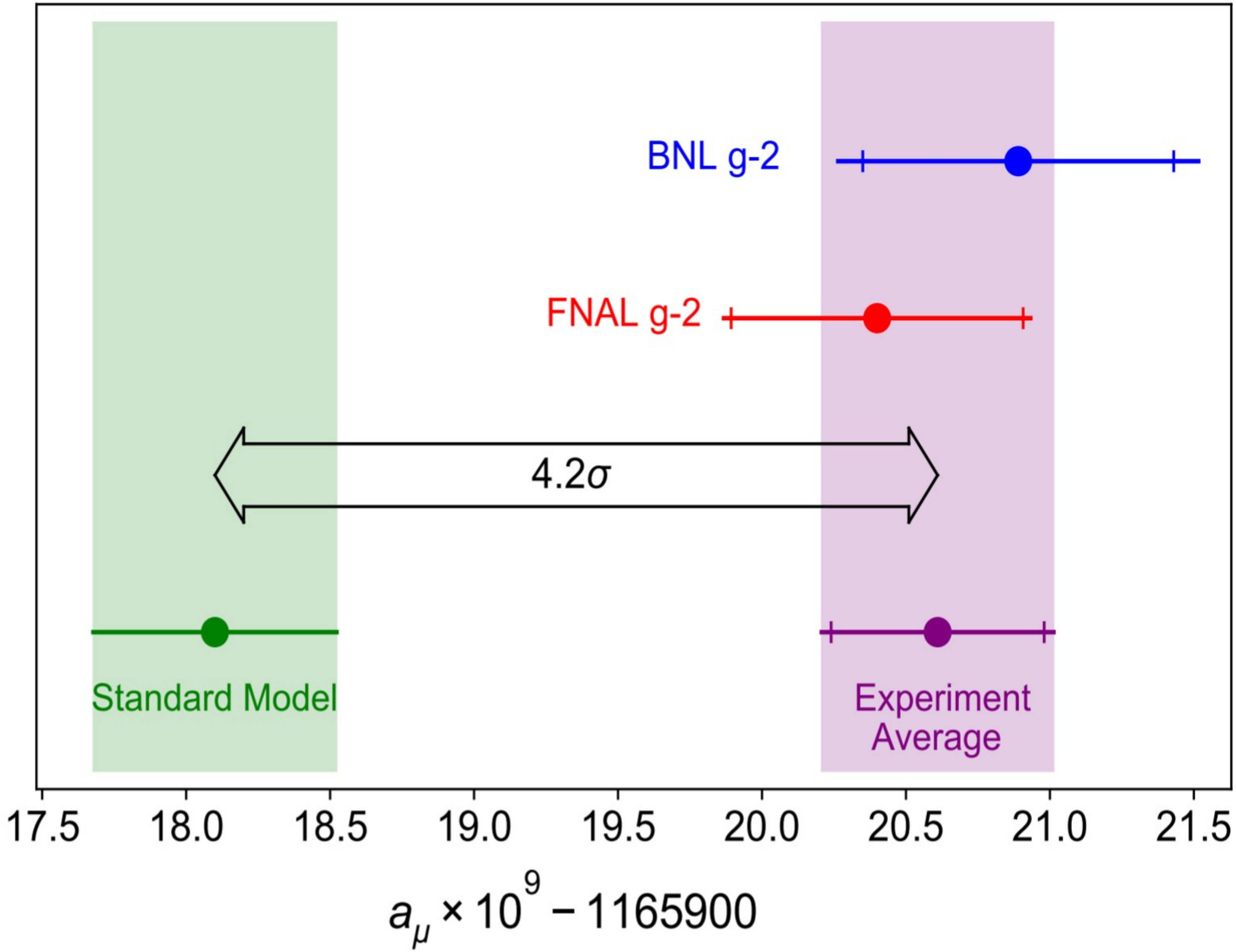




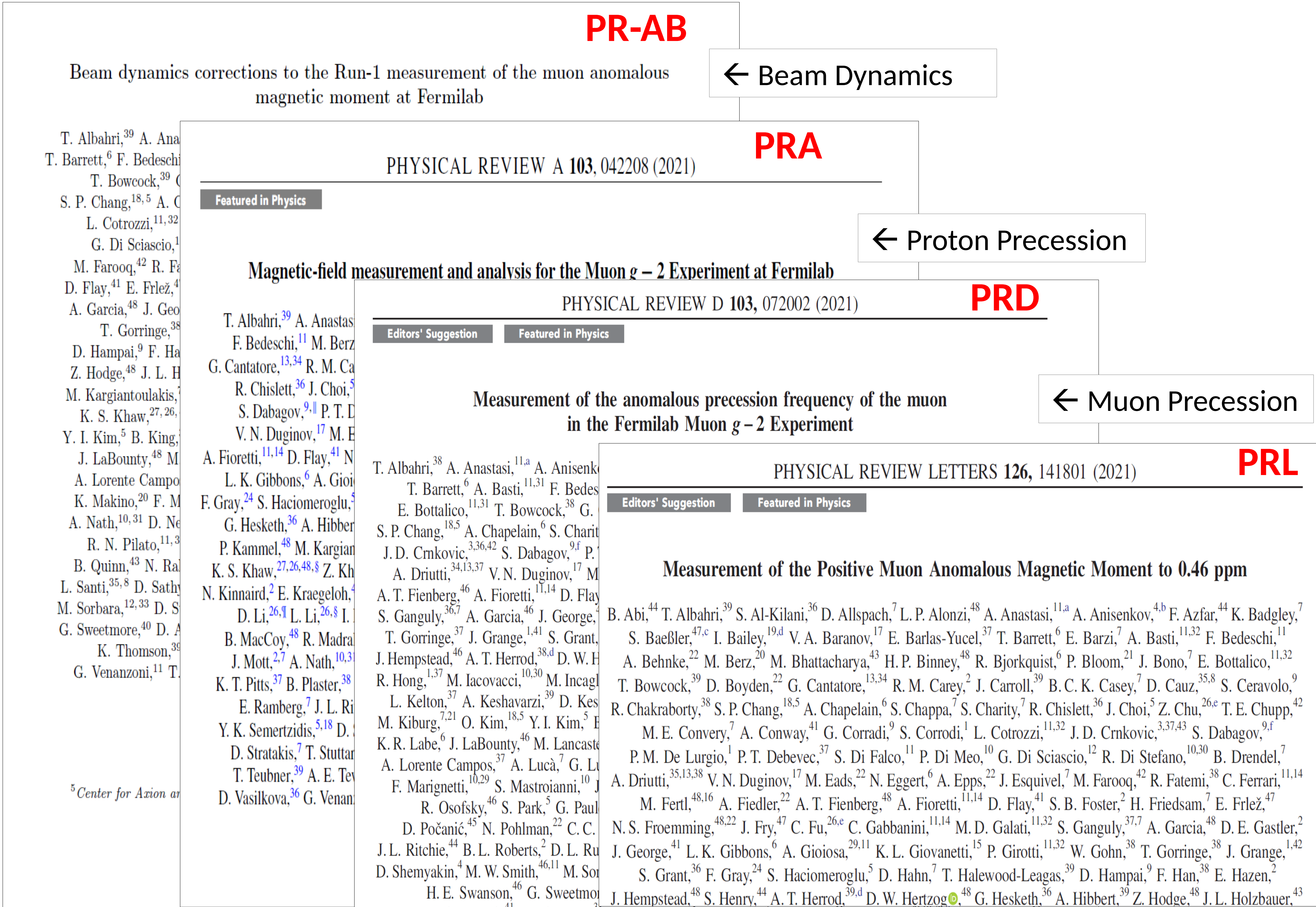




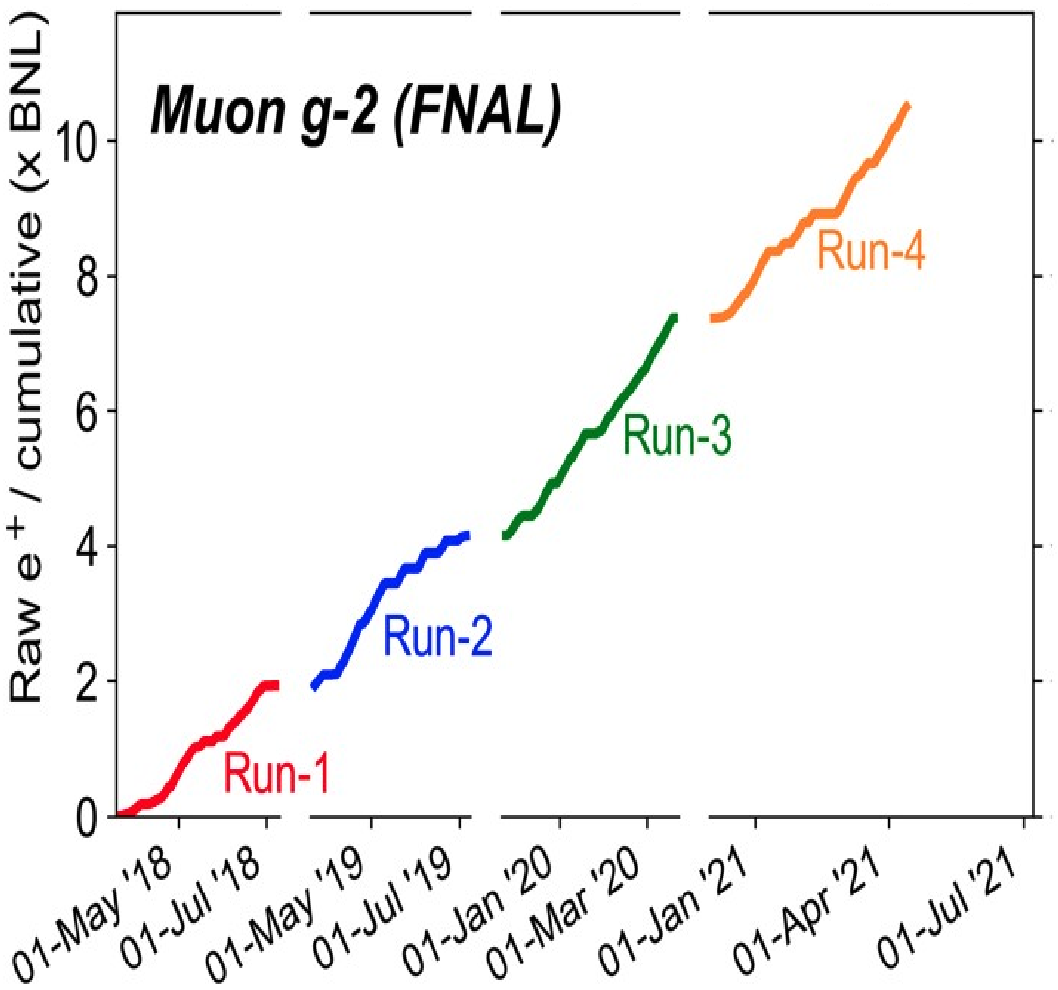
f_{clock} 'unblinding moment'



Published simultaneously with run 1 release



Runs 2-6 data taking, analysis status



run 1 was 6% of x20 BNL goal

run 2+3 has x4 statistics + improvements in stored beam, field stability. Summer 2022 publication target.

run 4 just completed and **run 5, 6** planned. Achieved x10 BNL statistics. Goal x20 BNL statistics and 120 ppb precision

Conclusion

we’ve reported our run 1 result for the muon anomaly,
a_{μ} = 116 592 040 (54) x 10^{-11} (0.46 ppm)

our new result & previous BNL result are consistent and together increase the discrepancy with theory to 4.2 σ

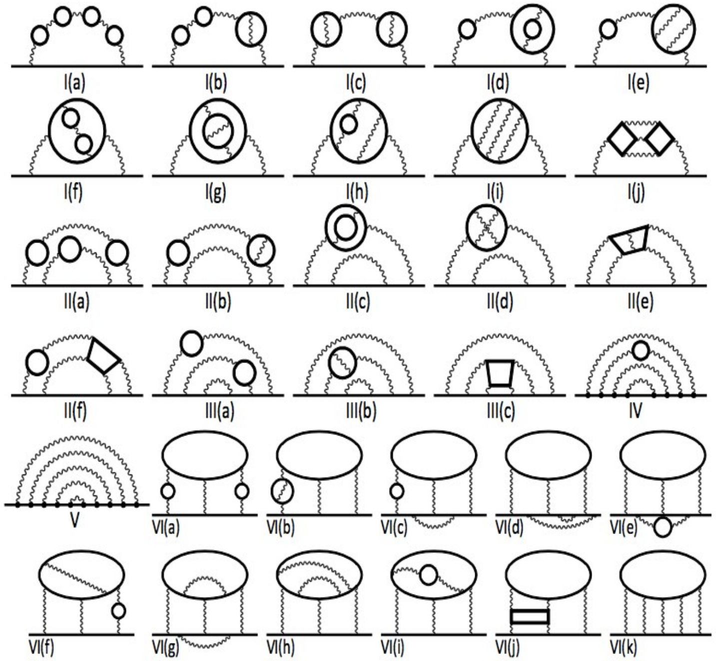
we expect ~2x improvement in precision from our run 2 + 3 data and ~4x improvement from our run 4 + 5 + 6 data

2008 Electron g-factor is now measured to 0.28 ppt!

vacuum isn't empty, it contains `foam' of virtual particles that contribute to electron's anomalous magnetism

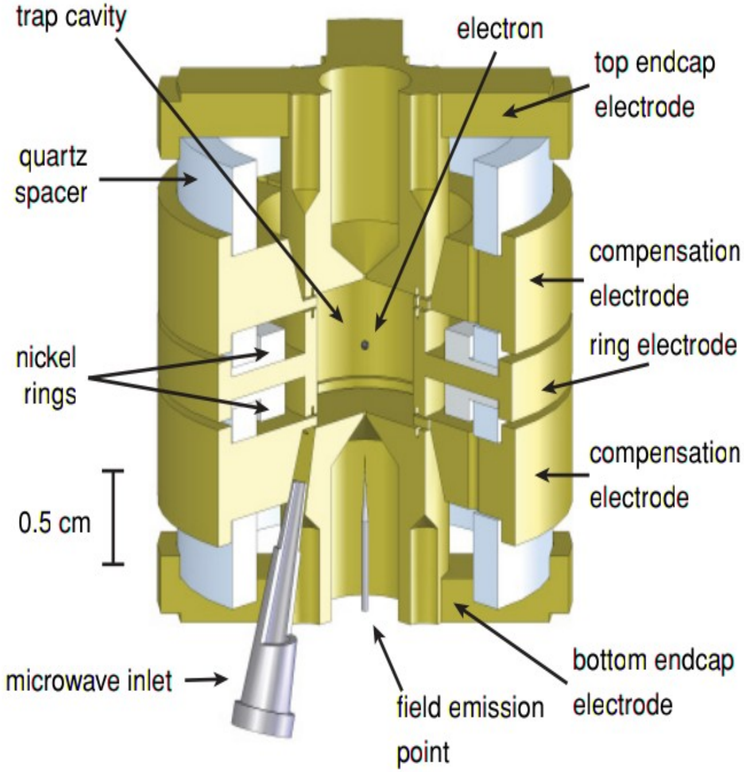
Gabrielse et al. suspended single electrons in magnetic field to measure the mag. moment to extraordinary 0.28 ppt precision.

SM



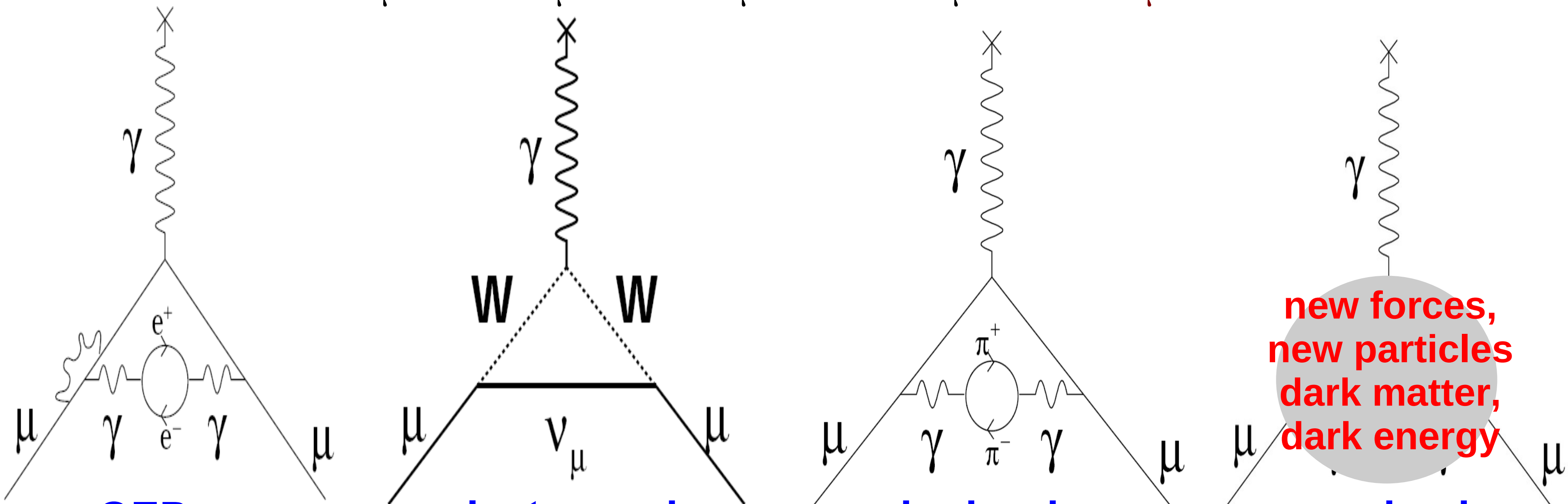
14,000 diagram

Expt.



Present. Standard model and anomaly, $a = (g-2)/2$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Strong} + a_\mu^{Weak} + a_\mu^{NP}$$



QED	electroweak	hadronic	new physics
a_μ^{QED} = 116 584 718.9 (0.1)	a_μ^{EW} = 154 (1)	a_μ^{Had} = 6939 (40)	a_μ^{NP} =?
			× 10^{-11}
		dispersion relations, $e^+e^- \rightarrow$ hadrons for $a_\mu^{hvp:LO}$	scale $\sim m_l^2/m_x^2$

Muon g-2 theory initiative

- 6 workshops 2017-2020
- 6/10/20 white paper, 132 authors, 82 institutions, 21 countries
- T. Aoyama et al, Phys. Reports 887 (2020) 1-166.
- consortium compiled theoretical inputs & recommend value ahead of FNAL expt.

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10],
C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18],
C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27],
M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33],
A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38],
L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37],
L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49],
A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53],
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M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19],
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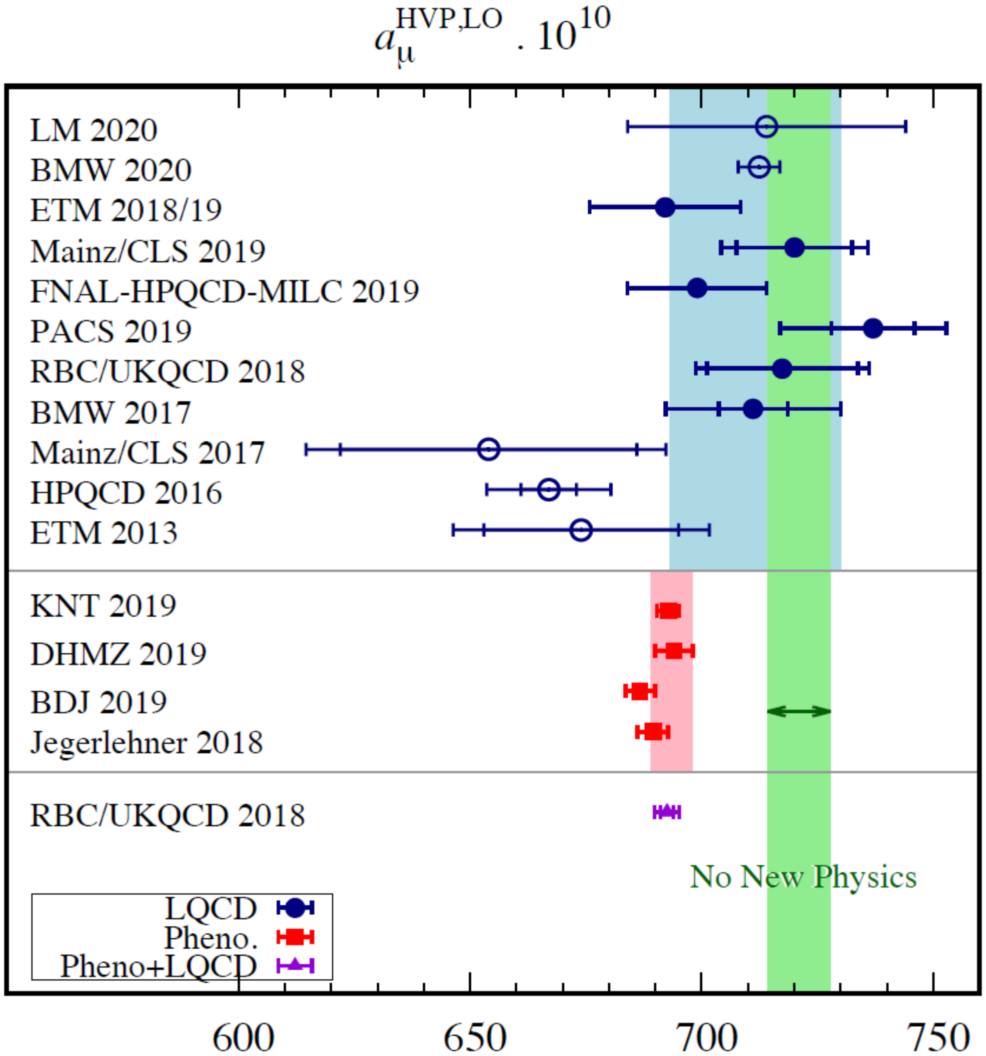
A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

Recent lattice QCD developments for hadronic vacuum polarization

adapted from [T. Aoyama et al, arXiv:2006.04822]



- The errors in (all but one of the) lattice QCD results are still large
- All results include contributions from connected ud, s, c, b + disconnected, QED + strong isospin breaking, and finite volume corrections.
- Lattice combination: included results shown with filled circles

$$a_\mu^{HVP,LO} = a_\mu^{HVP,LO}(ud) + a_\mu^{HVP,LO}(s) + a_\mu^{HVP,LO}(c) + a_{\mu \mathrm{disc}}^{HVP,LO} + \delta a_\mu^{HVP,LO} = 711.6\,(18.4) \times 10^{-10}$$