

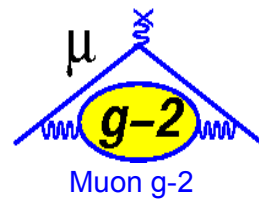


First results from Fermilab muon g-2 experiment

FCCP 2021, 17 September 2021

Tim Gorringer, 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



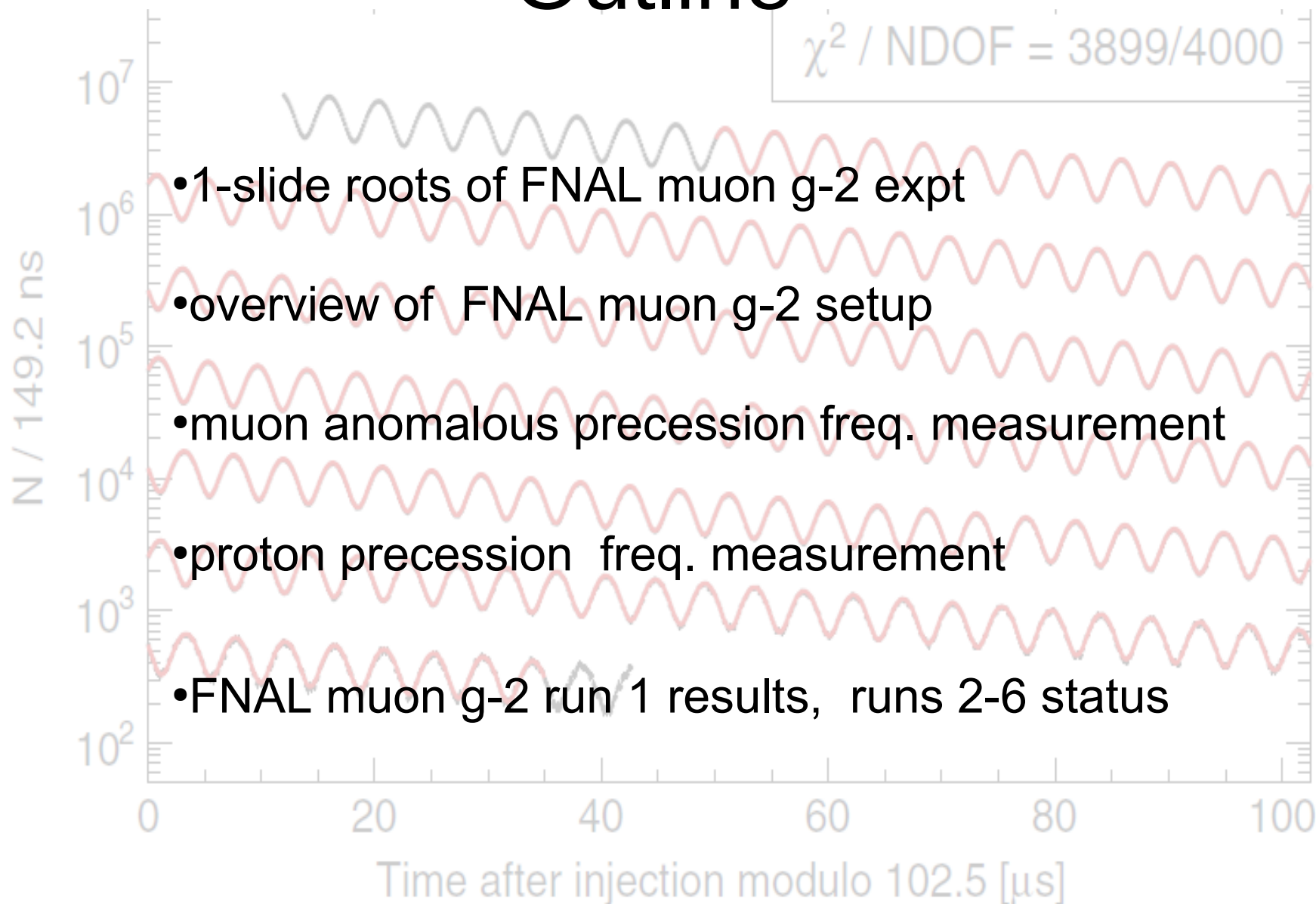
United Kingdom

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



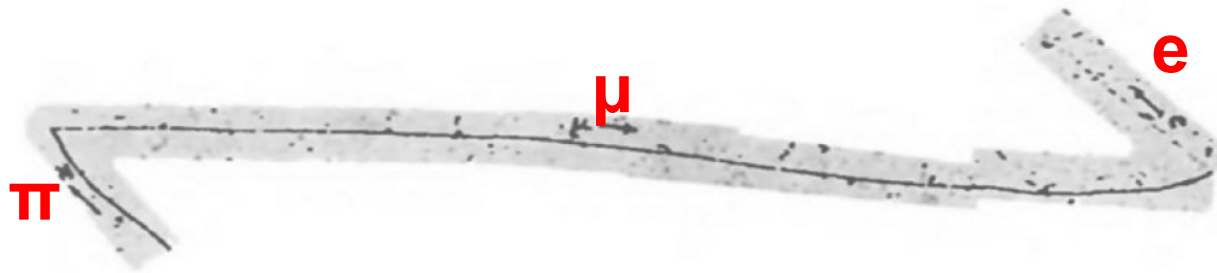
200 collaborators
35 Institutions
7 countries

Outline

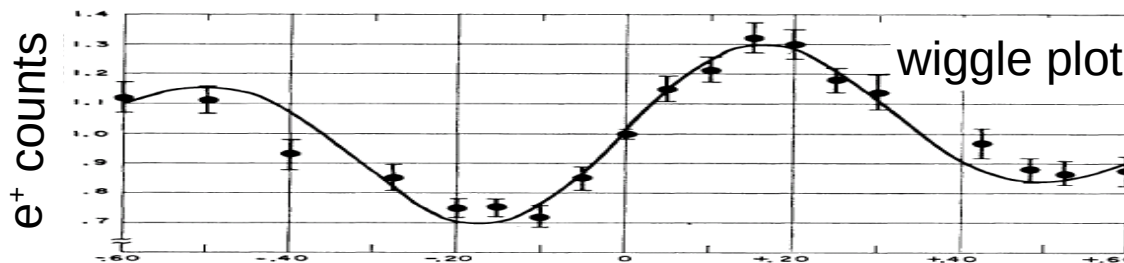


Roots of muon g-2 experiments.

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



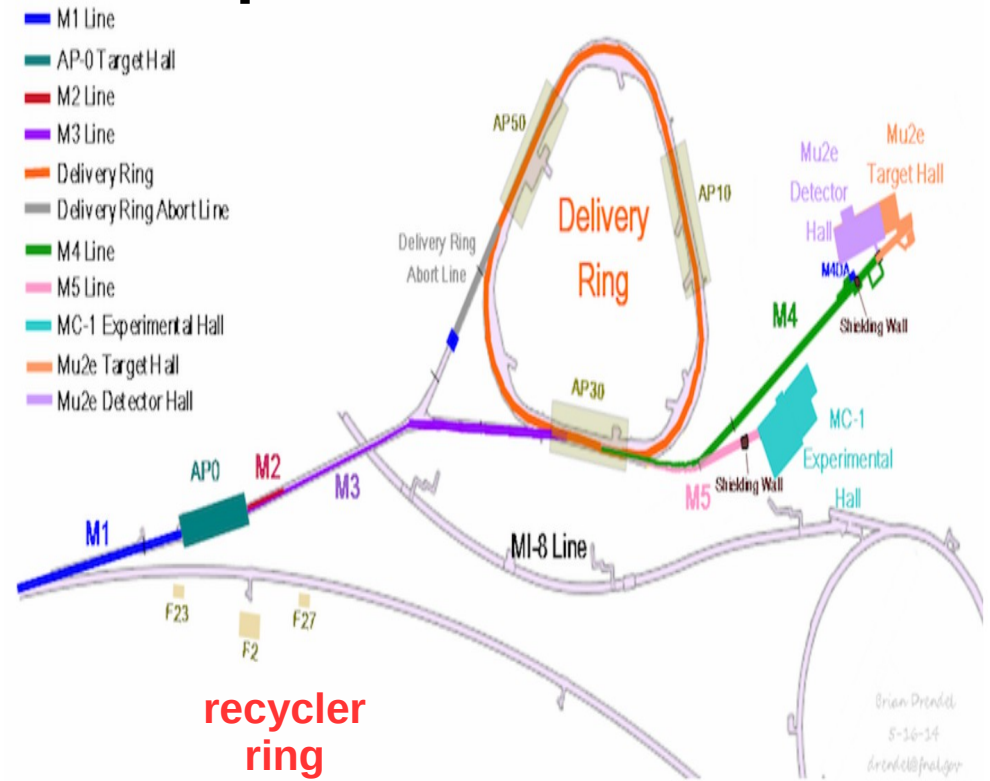
1960 – measurement of muon anomaly $a_\mu = (1.22 \pm 0.08) \times 10^{-3}$ in accord with $\alpha/2\pi$ self-interaction term and a_e

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

A photograph of the Fermilab g-2 experiment building, a large, modern concrete structure with a central glass facade, reflected in a body of water under a dramatic, cloudy sky. The building is situated on a grassy area with some trees and other structures in the background.

**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 , ρ separation
- ▶ muons extracted to g-2 storage ring



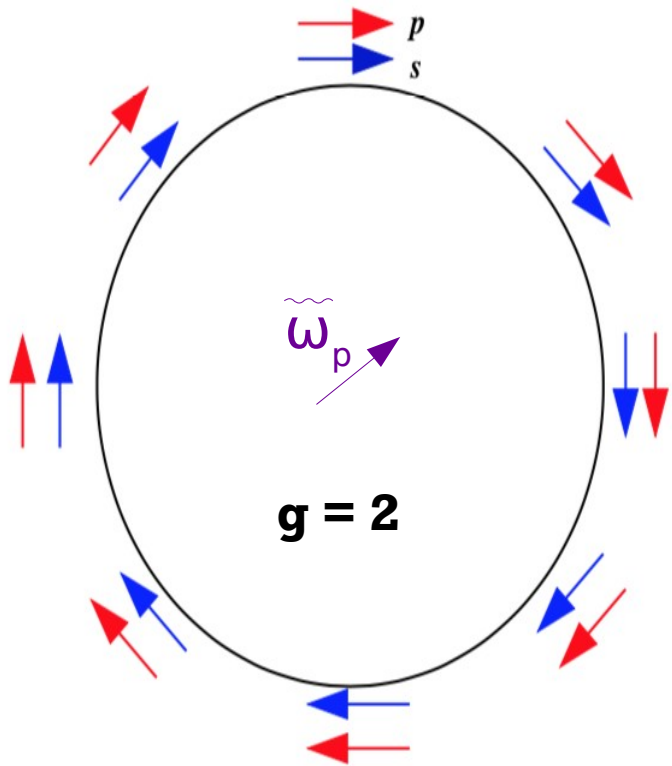
Shoulders of BNL E821

Assembly of storage ring



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

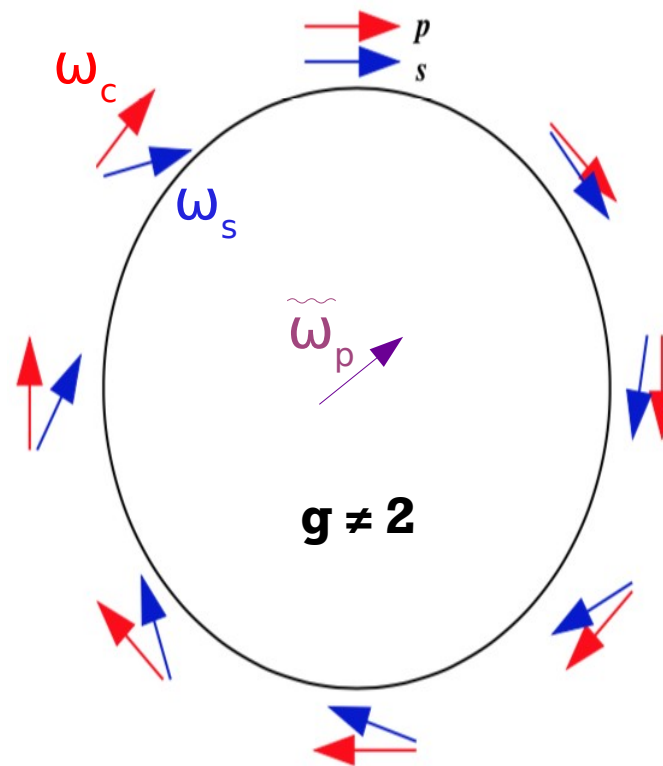
1. Store 3.094 GeV/c, polarized muons in uniform B-field
2. measure muon anomalous precession freq $\omega_a = \omega_s - \omega_c$ in \vec{B} field
3. measure proton Lamor precession freq $\tilde{\omega}_p$ to determine \vec{B}



simplified
relations

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

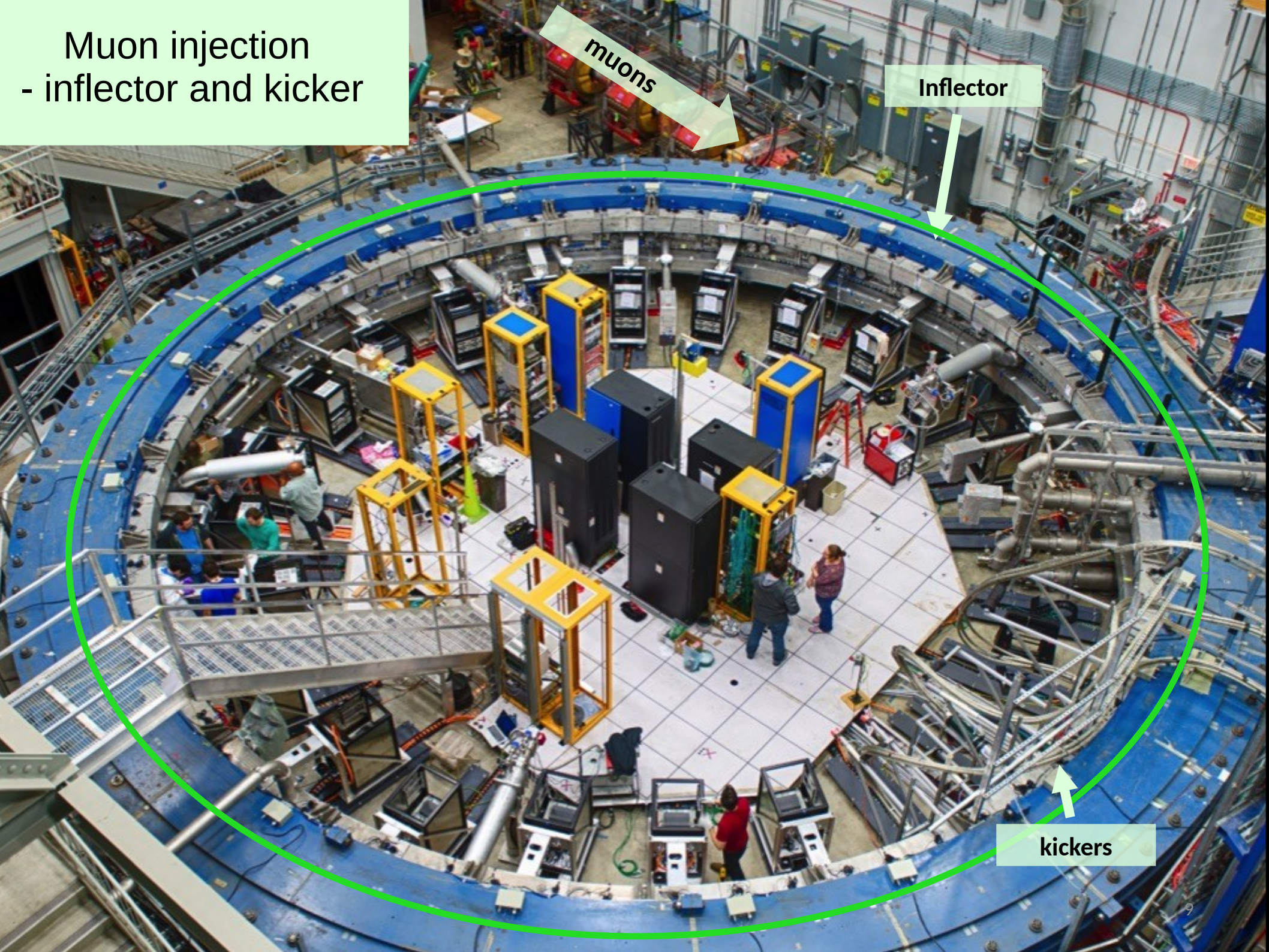
@ magic
momentum



Cyclotron
Period,
 $T_C = 149$ ns.

Anomalous
Period,
 $T_A = 4.37$ μ s.

Muon injection - inflector and kicker



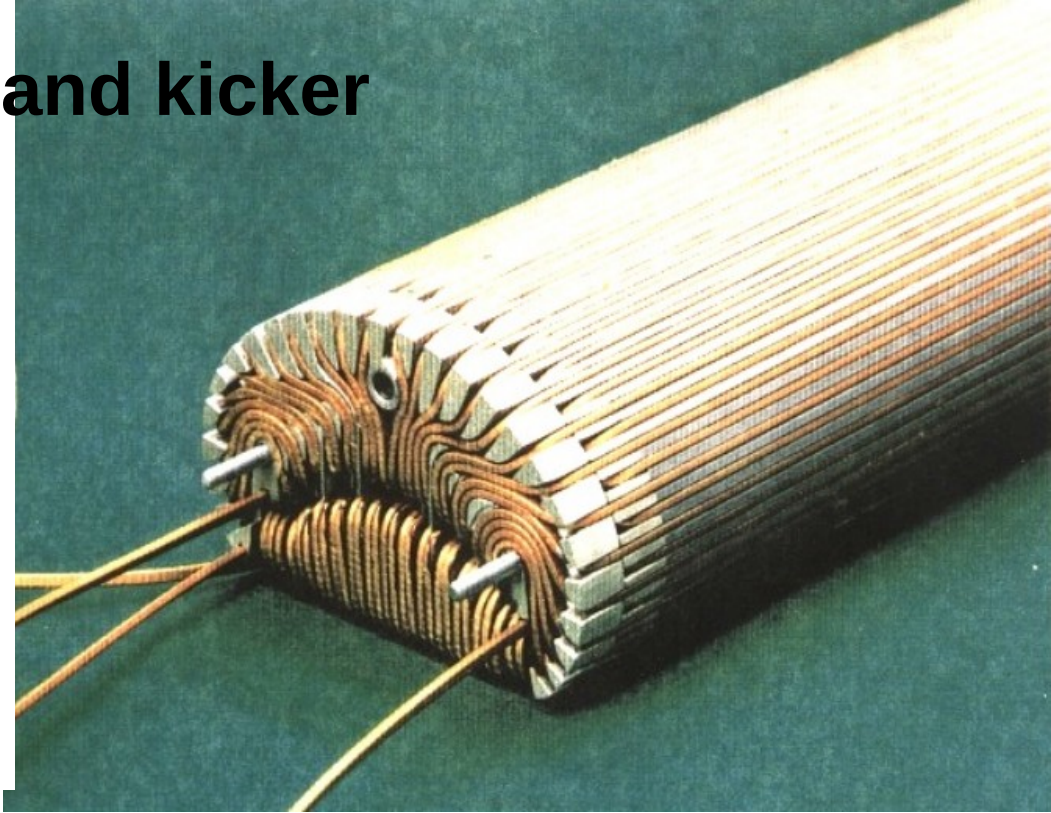
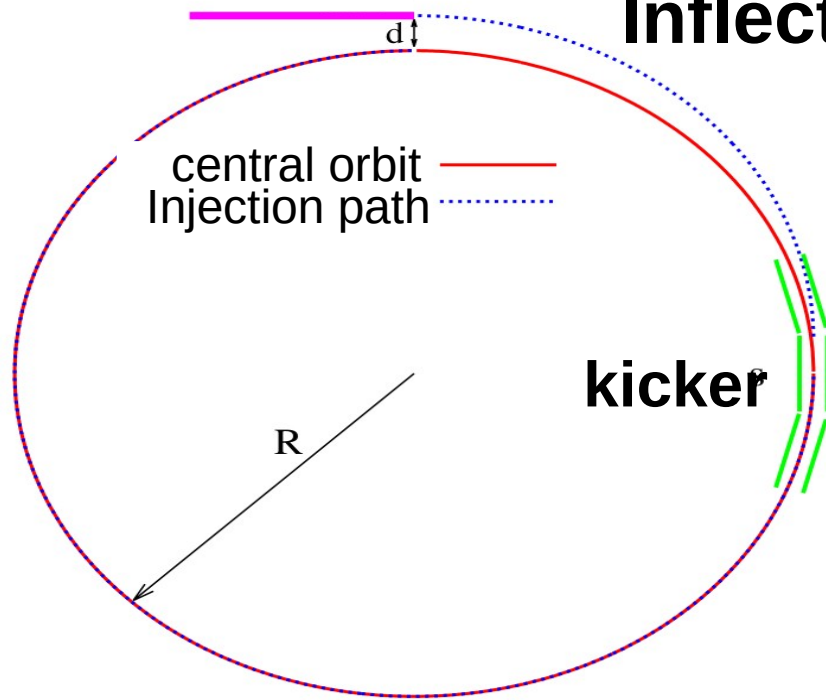
muons

Inflector

kickers

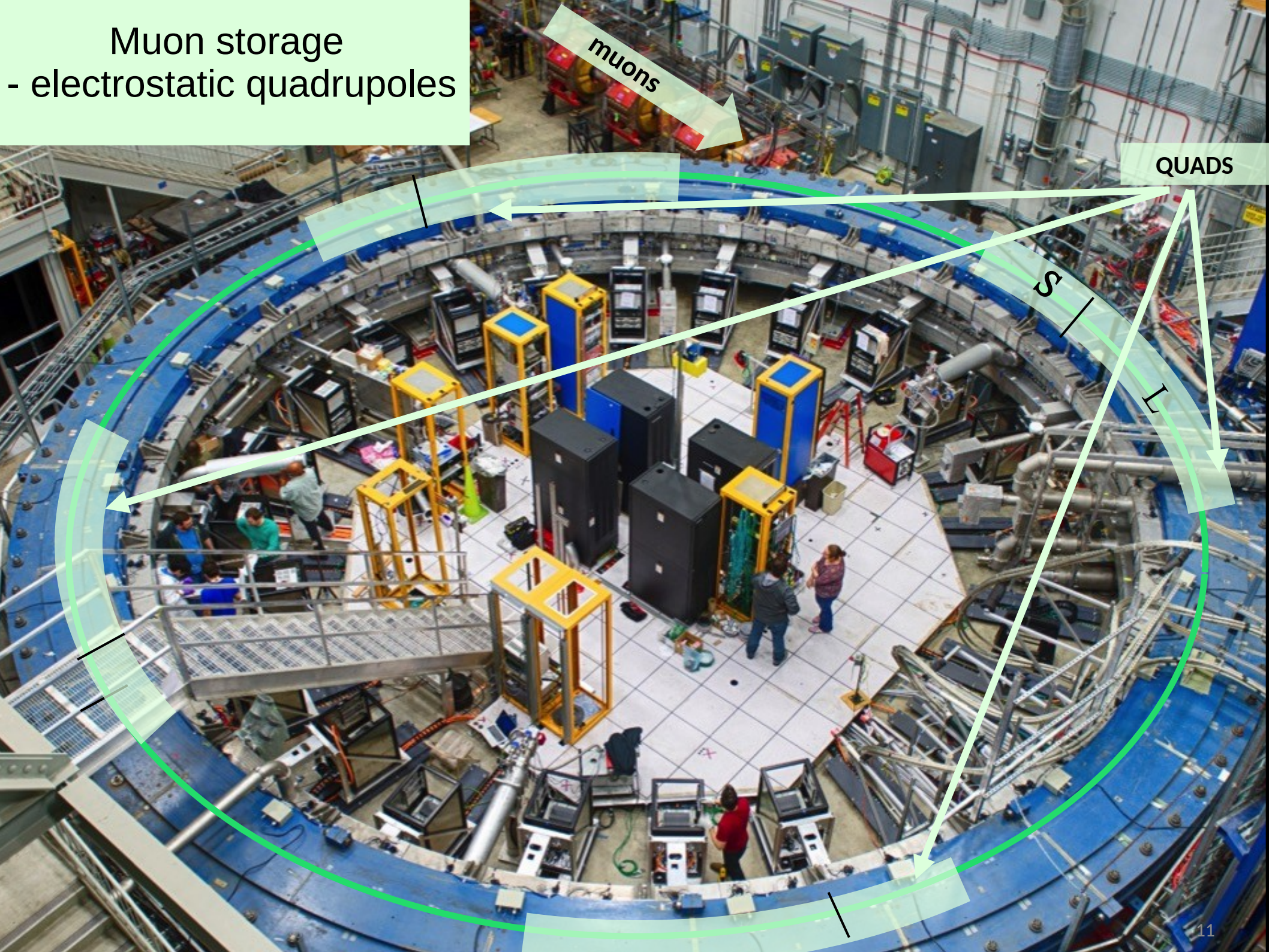
inflector

Inflector and kicker

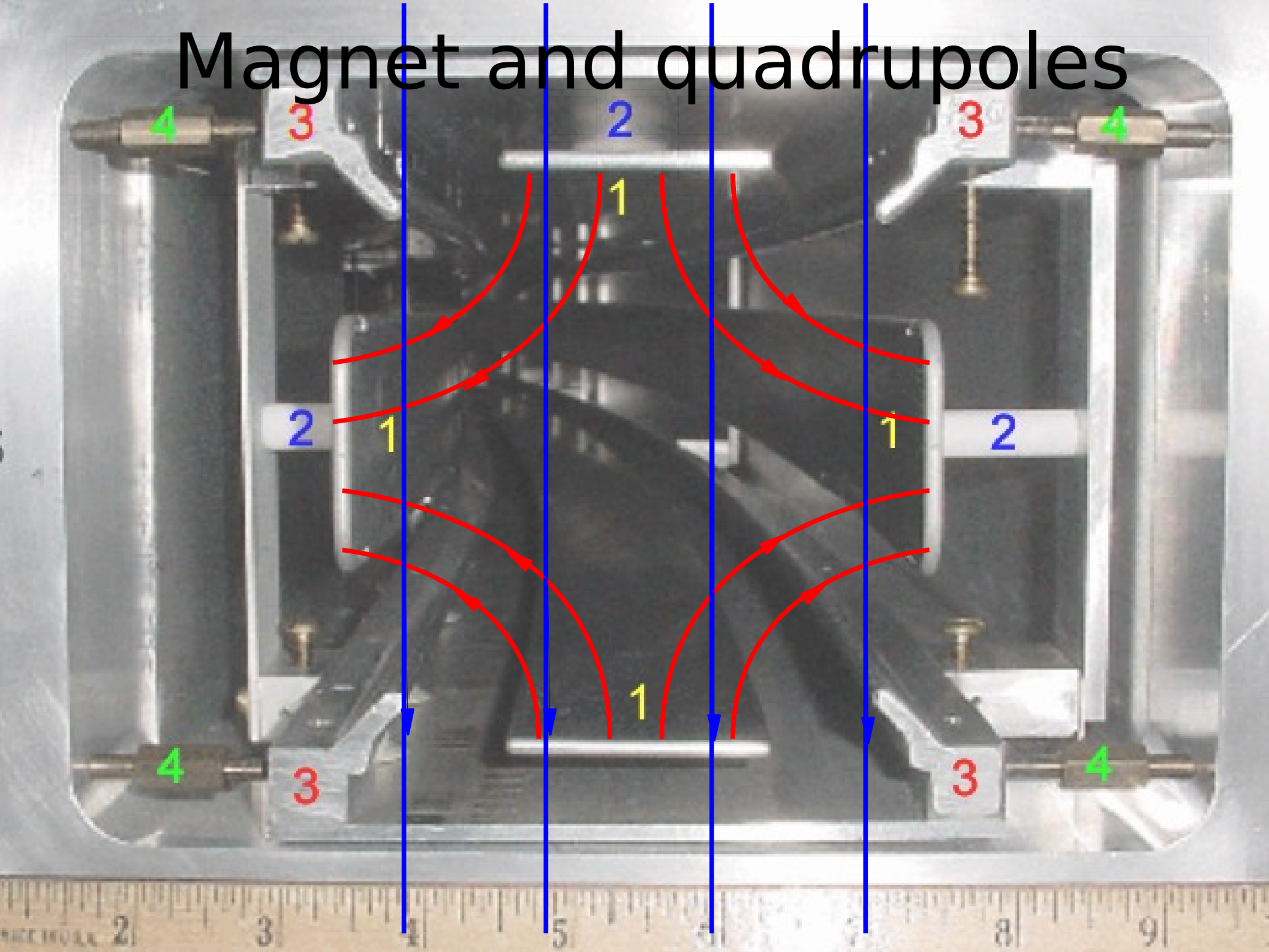


- inflector null's ring's 1.5T field in beamline entrance using superconducting coil.
- kicker displaces the injected beam by ~ 0.8 mrad to place on ring's central orbit.

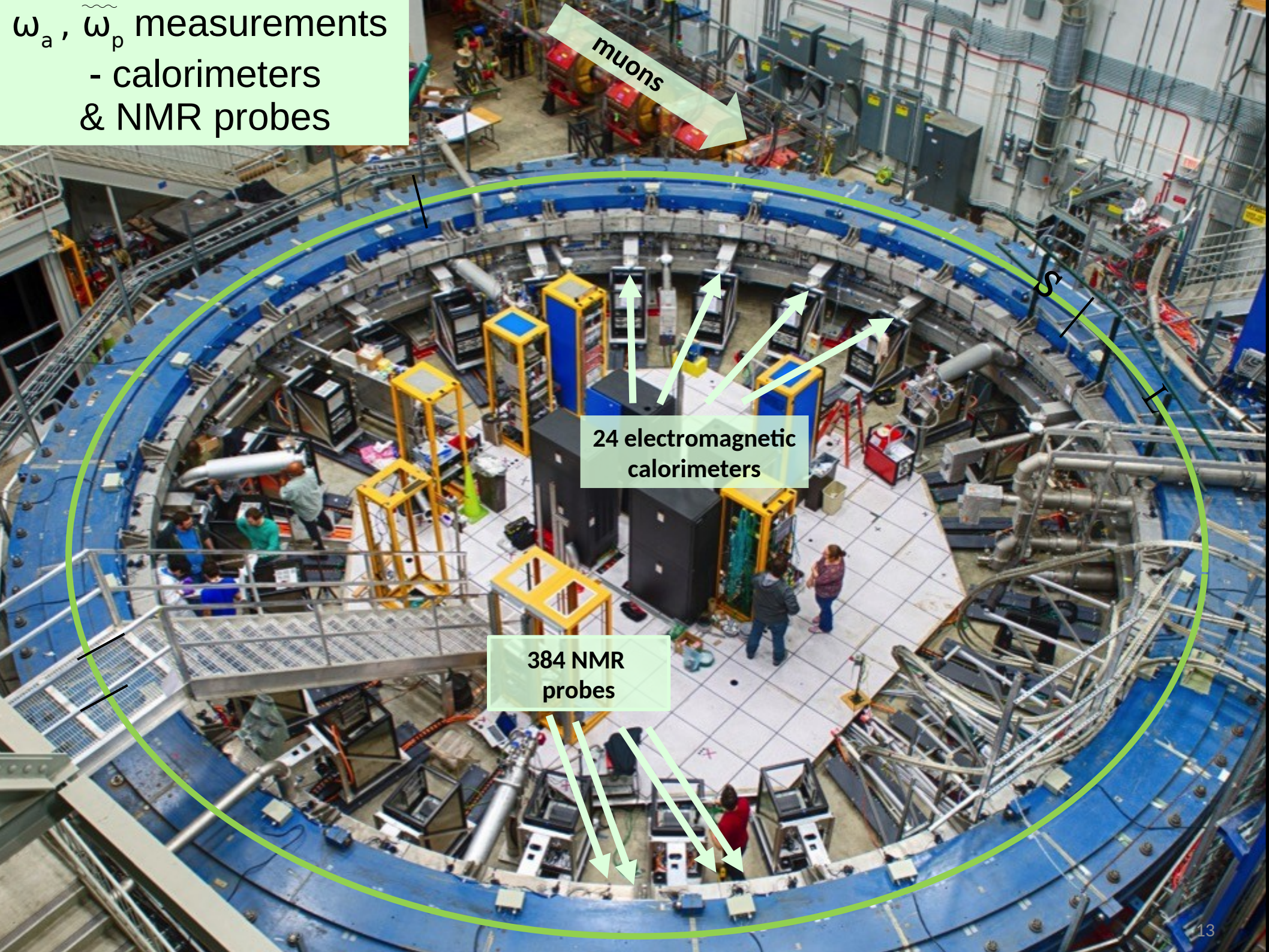
Muon storage
- electrostatic quadrupoles



Magnet and quadrupoles



ω_a , ω_p measurements
- calorimeters
& NMR probes

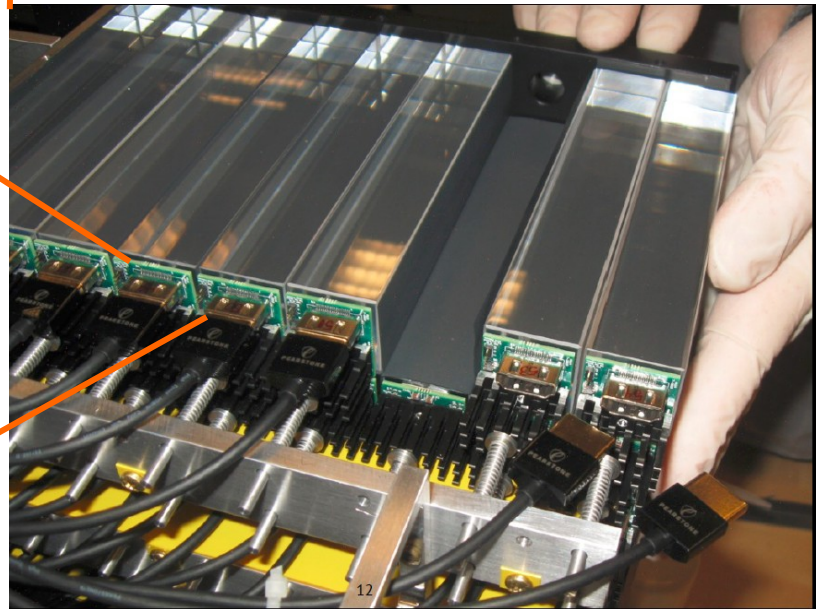
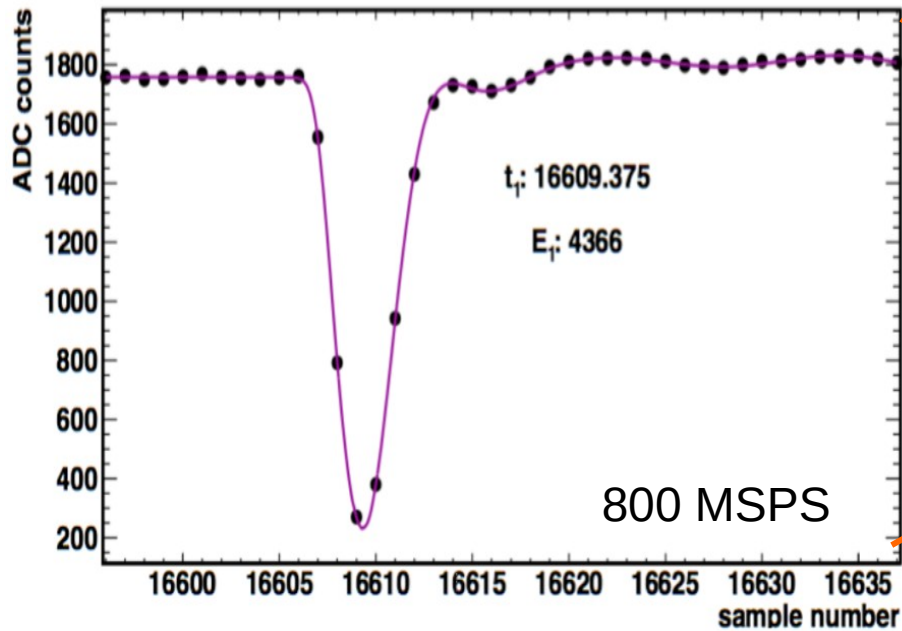
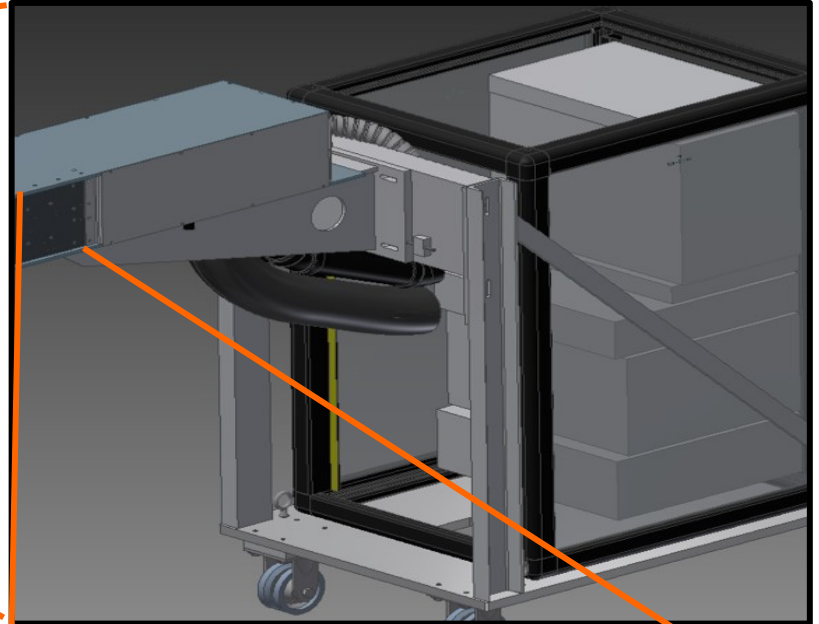
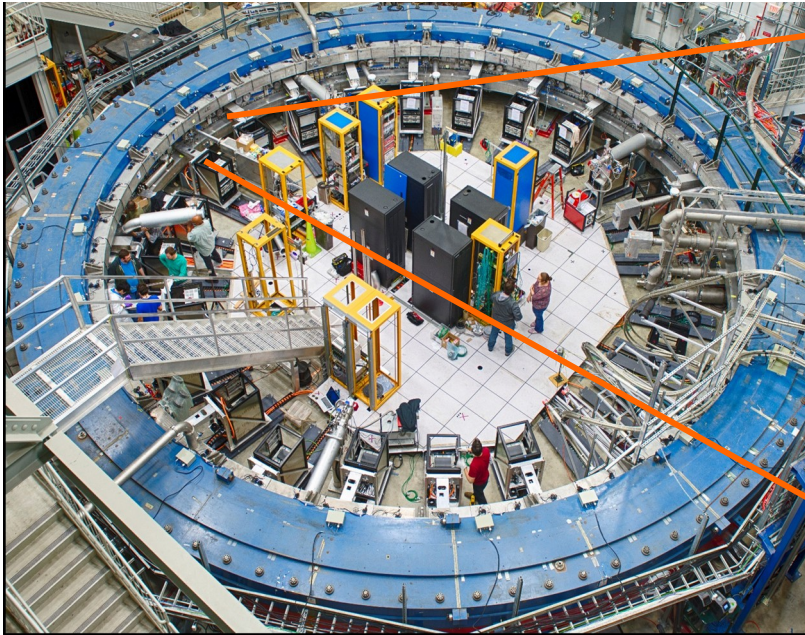


muons

24 electromagnetic
calorimeters

384 NMR
probes

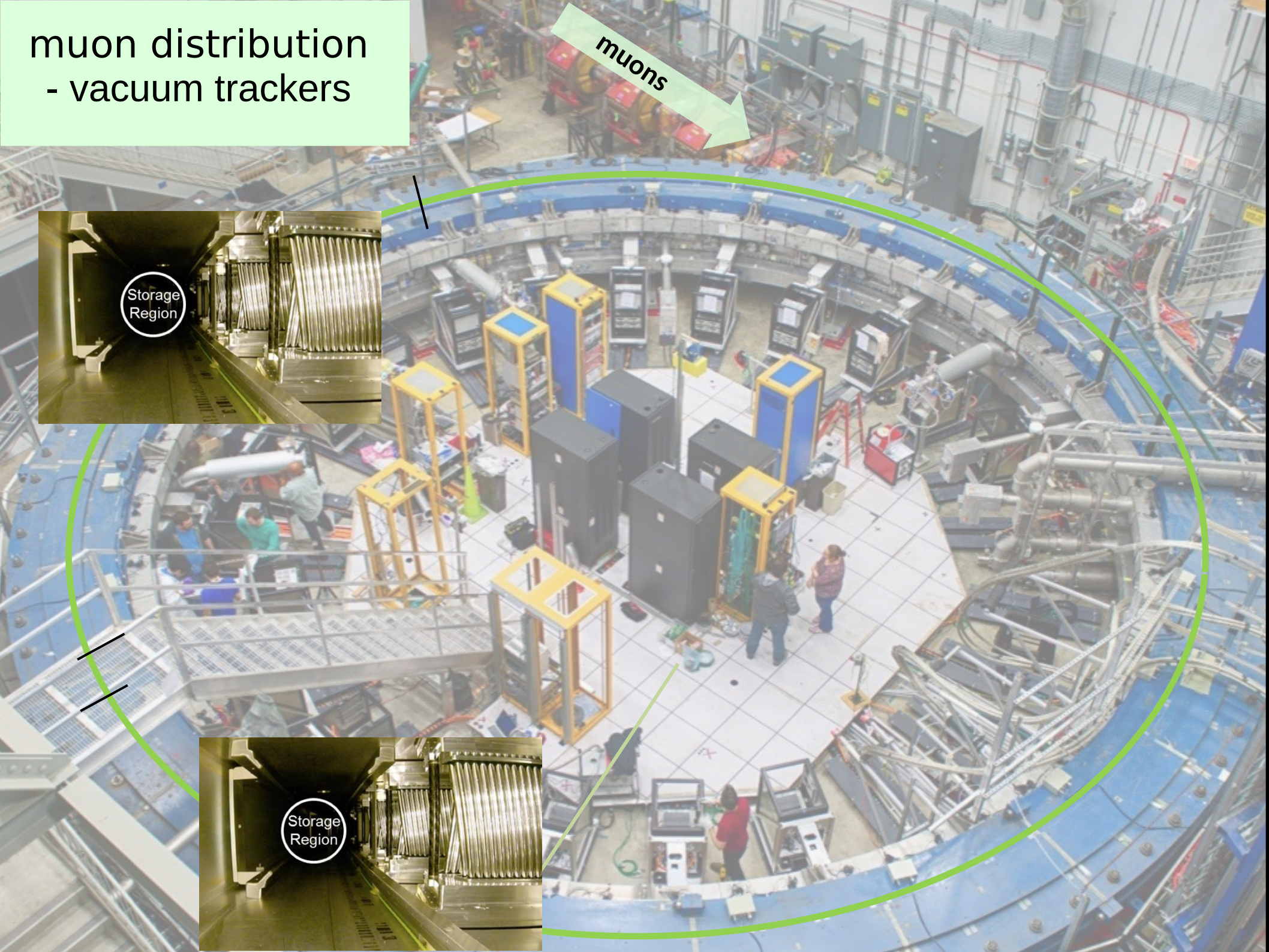
Twenty four electromagnetic calorimeters



muon distribution

- vacuum trackers

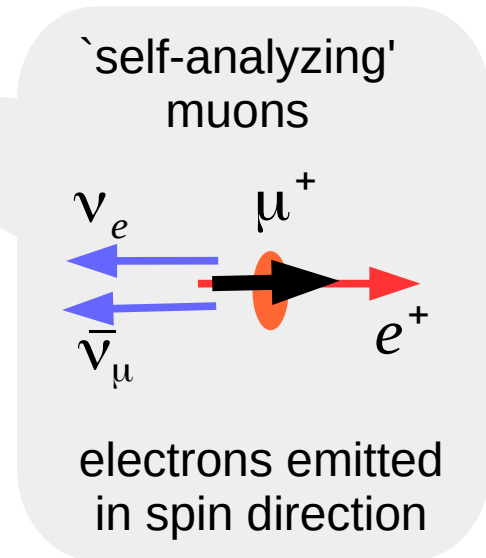
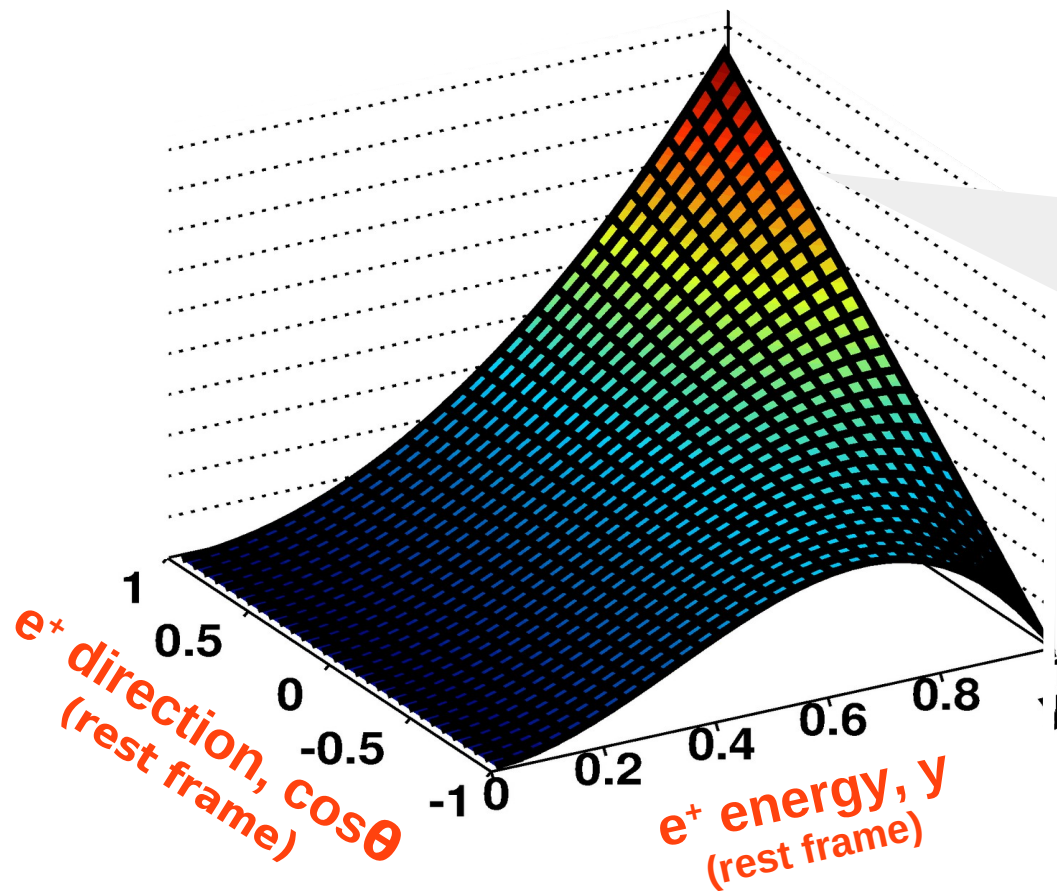
muons





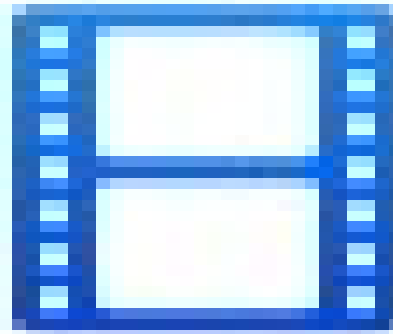
ω_a , $\tilde{\omega}_p$ frequency
measurements

Positron asymmetry and lab. energy distribution

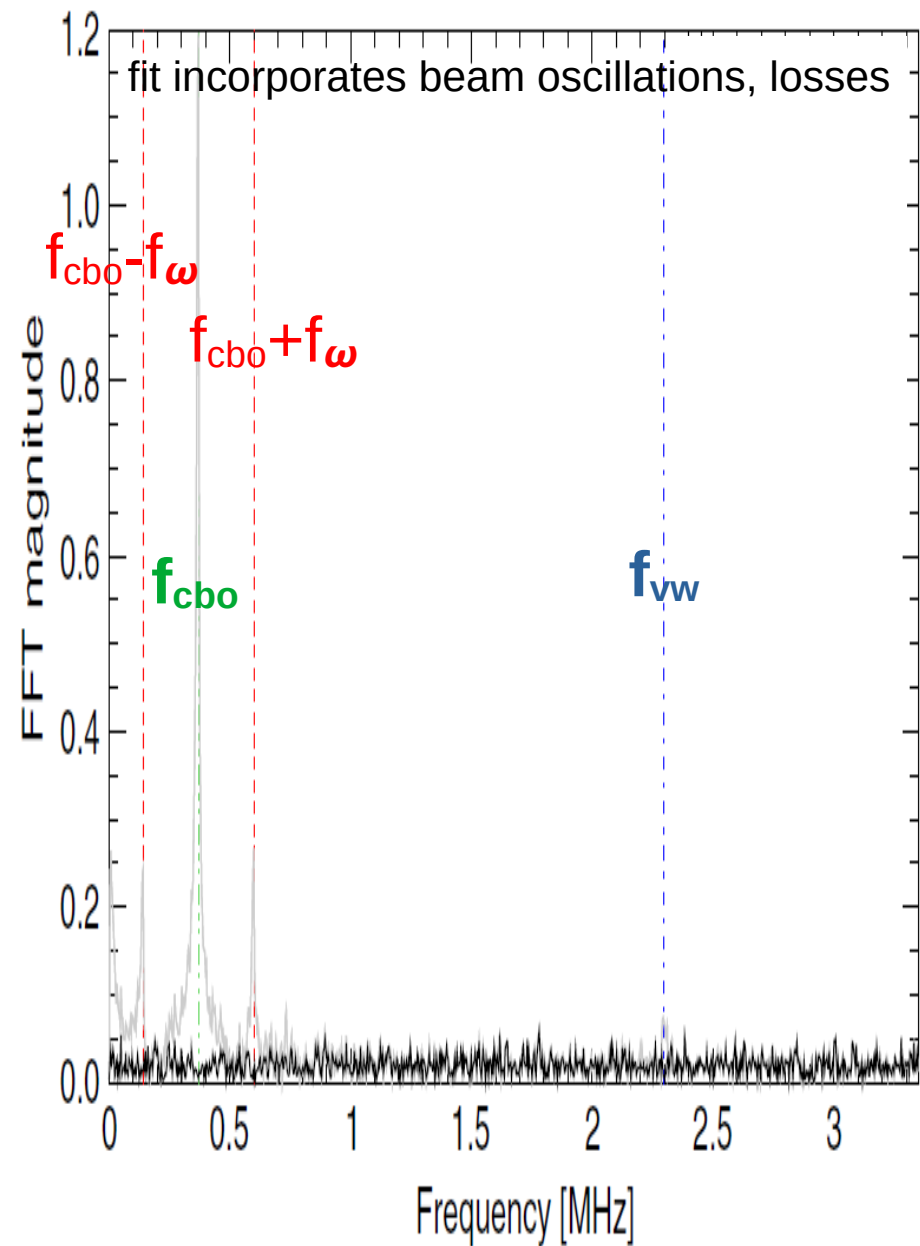
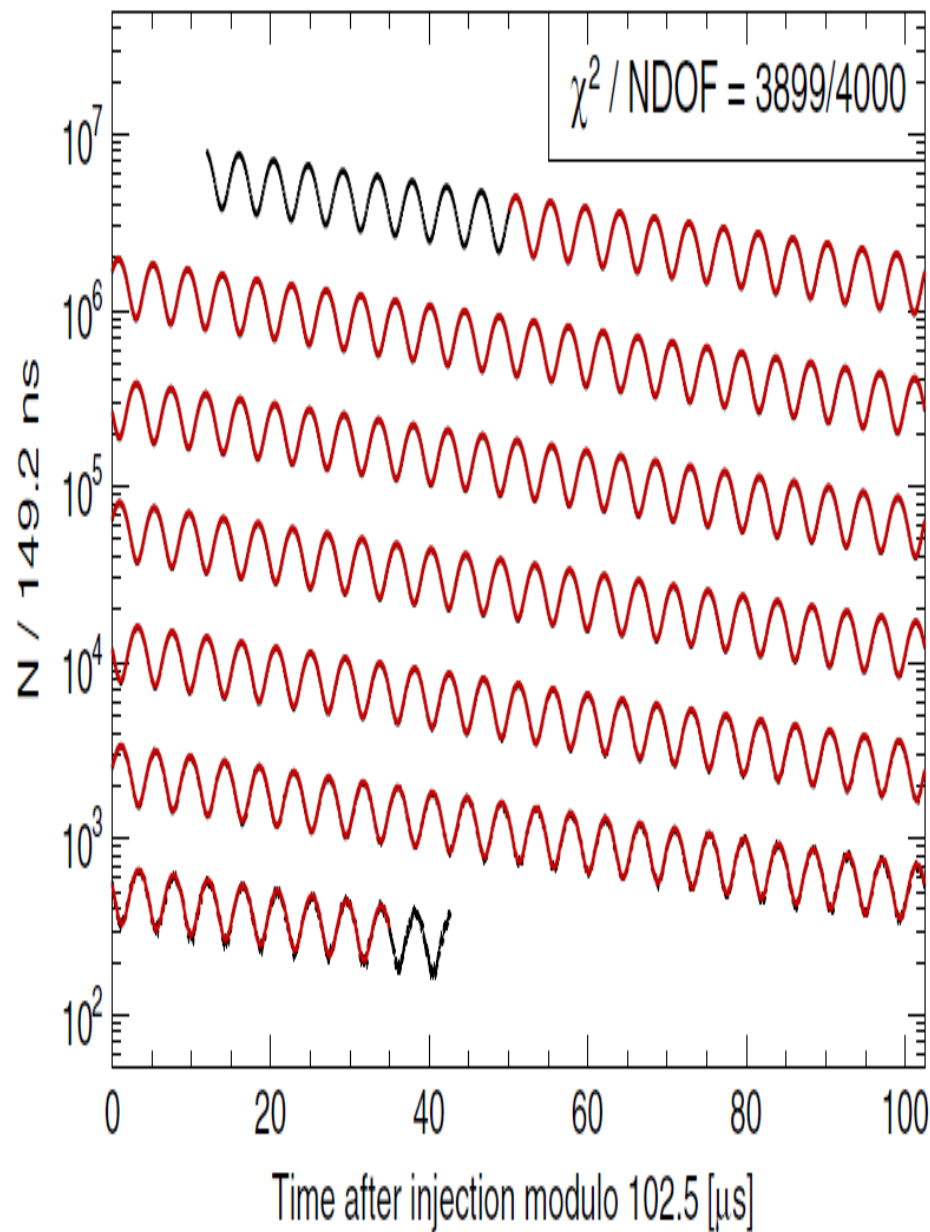


- rest→lab frame boost yields higher energy positrons when emitted along μ -direction
- rest→lab frame boost yields lower energy positrons when emitted opposite μ -direction

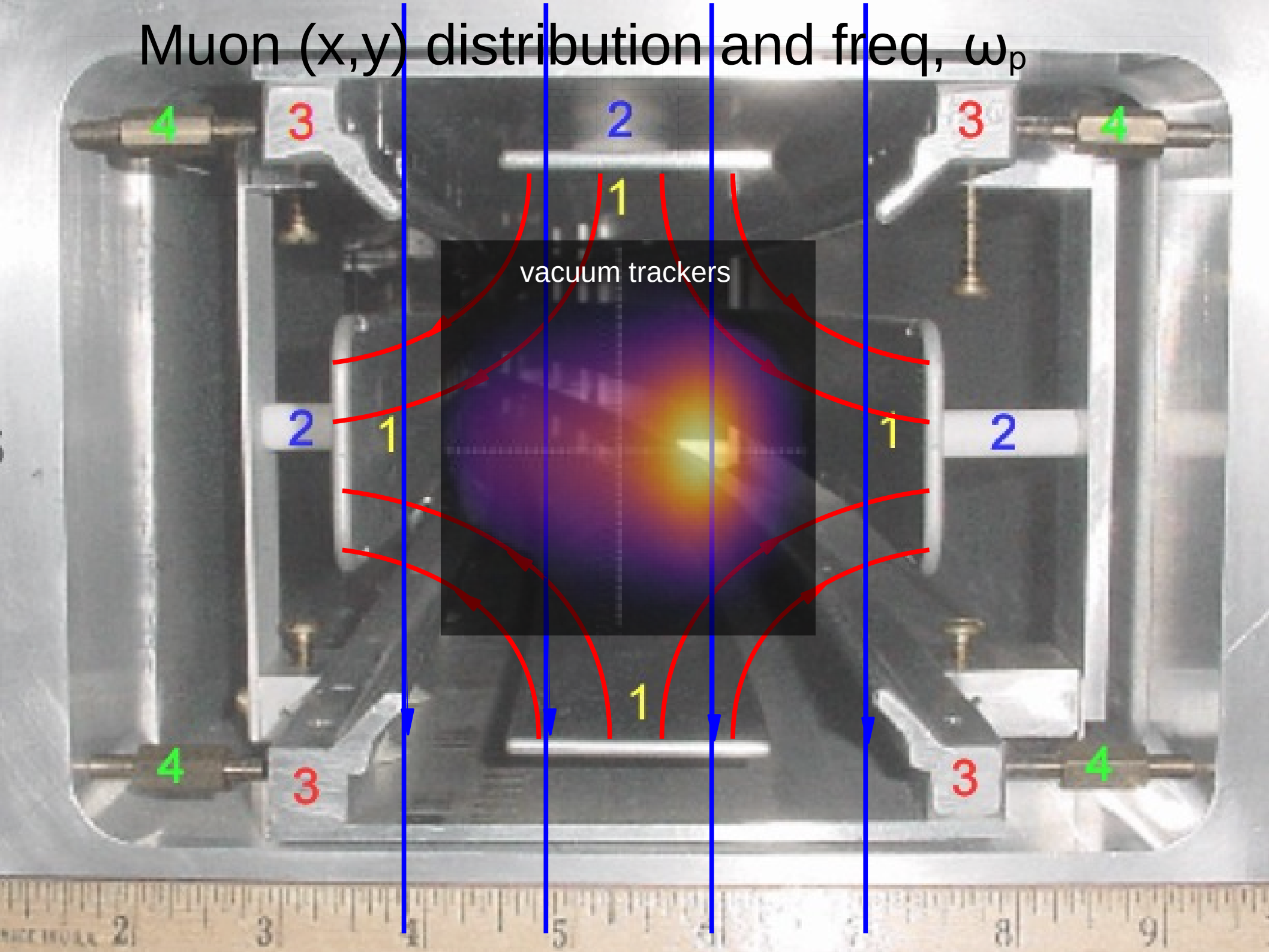
Positron energy versus time and freq, ω_a



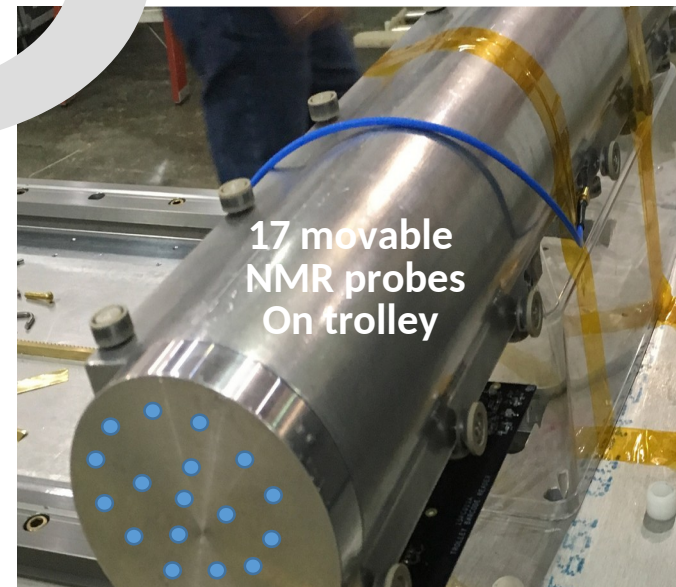
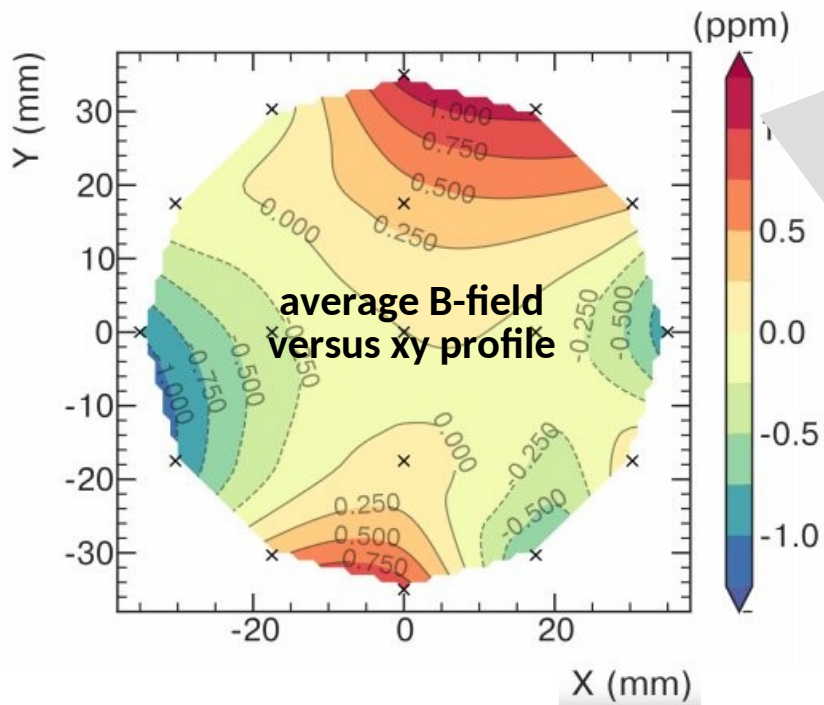
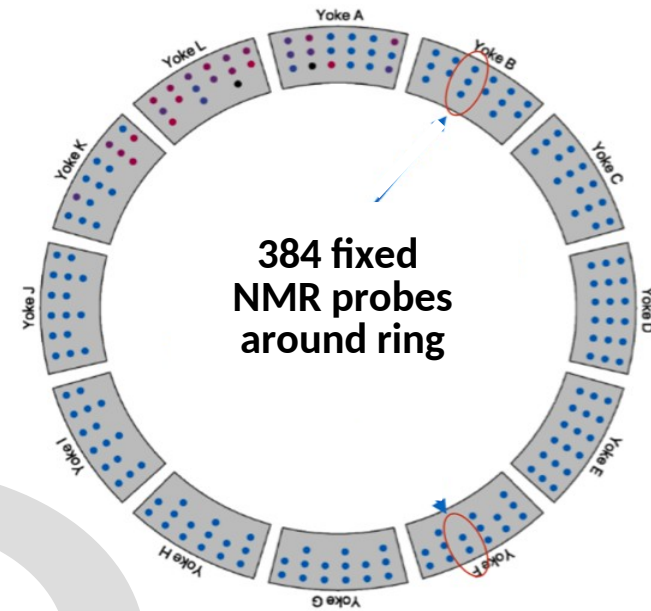
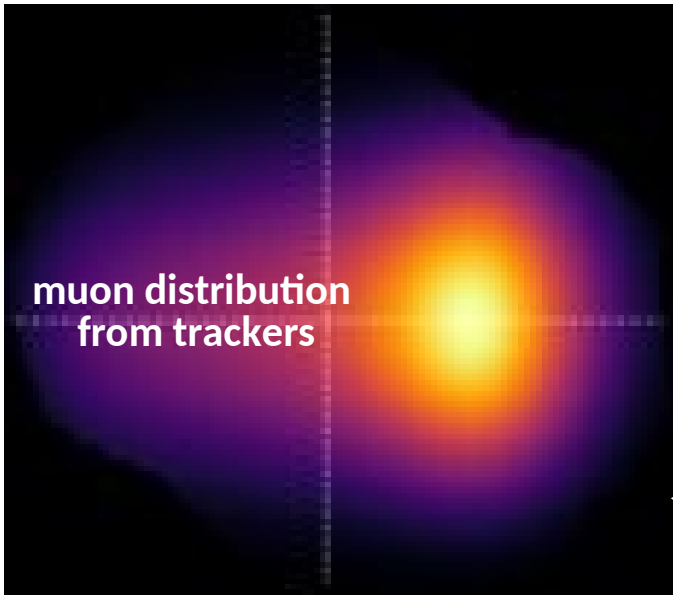
Sample fit to time distribution and freq, ω_a



Muon (x,y) distribution and freq, ω_p



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

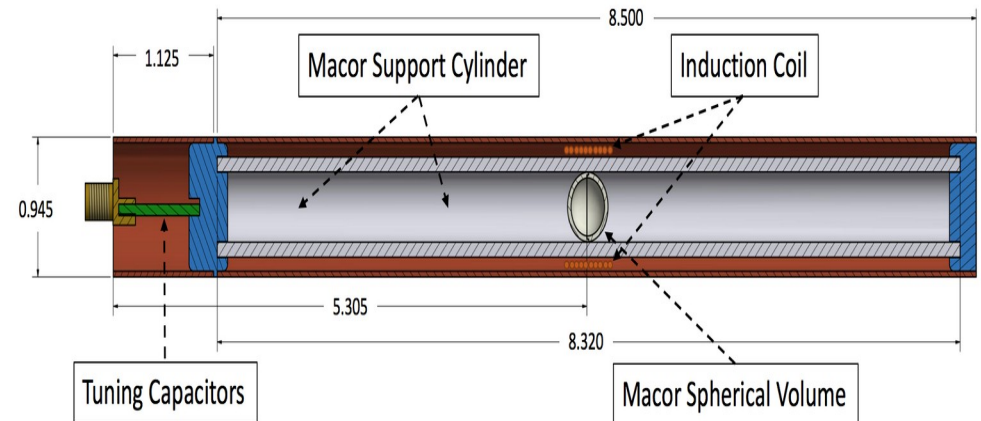


$\omega_p(r,t)$ absolute calibration

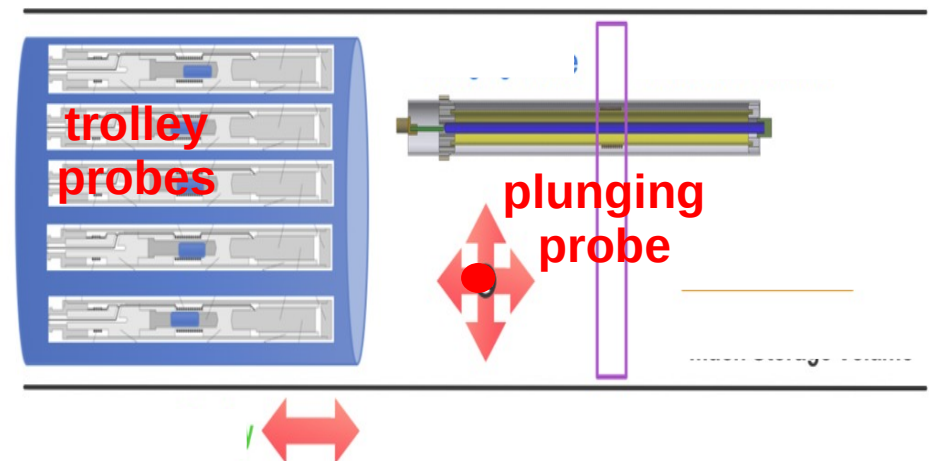
- 15 ppb absolute calibration uses spherical H_2O probe
- MRI studies account for sample shape, temp, magnetization corrections
- plunging probe used to transfer calibration to trolley probes



absolute probe

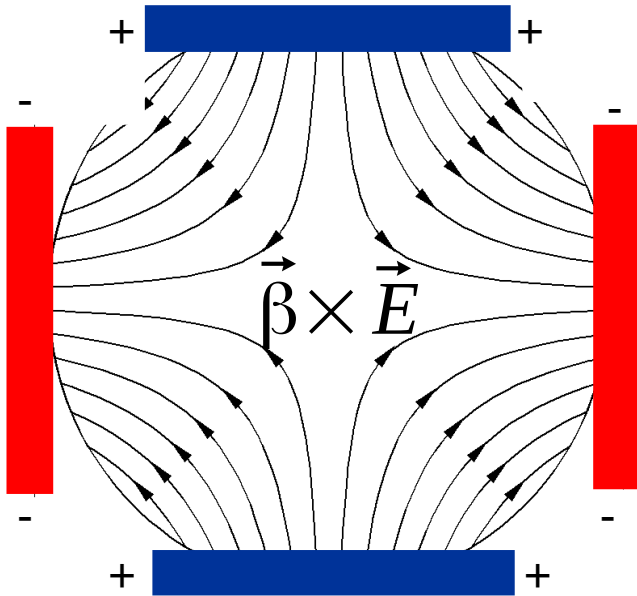


plunging probe

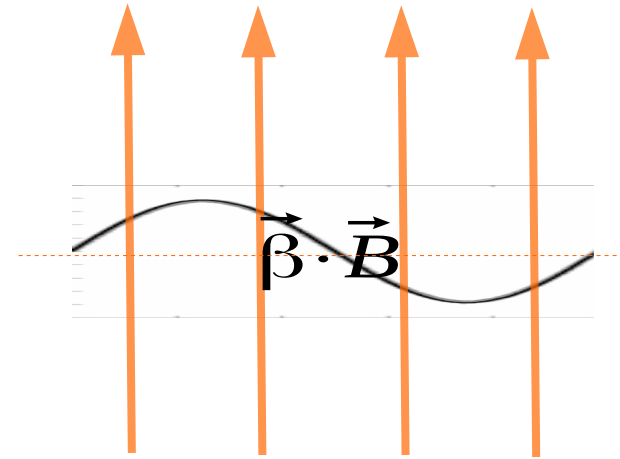


ω_a corrections C_E , C_P , C_{ML} , C_{PA}

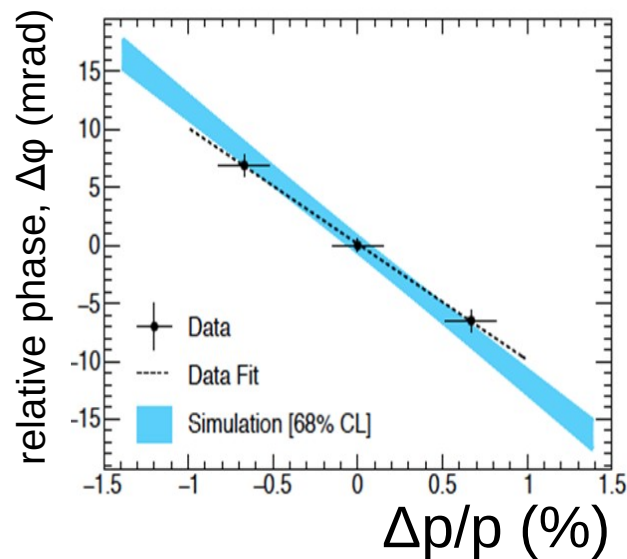
$C_E = 489 \pm 53$ ppb, motional B-field



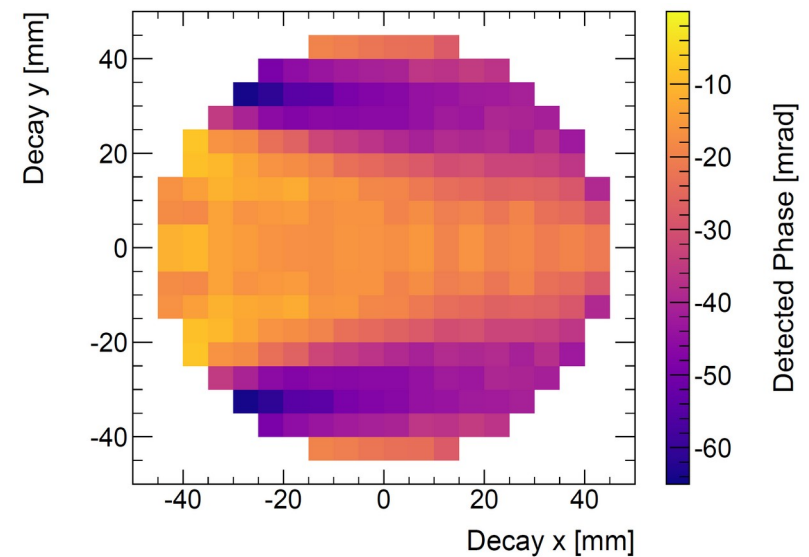
$C_P = 180 \pm 13$ ppb, B-field pitch



$C_{ML} = -11 \pm 5$ ppb, muon loss



$C_{PA} = -158 \pm 58$ ppb, beam changes

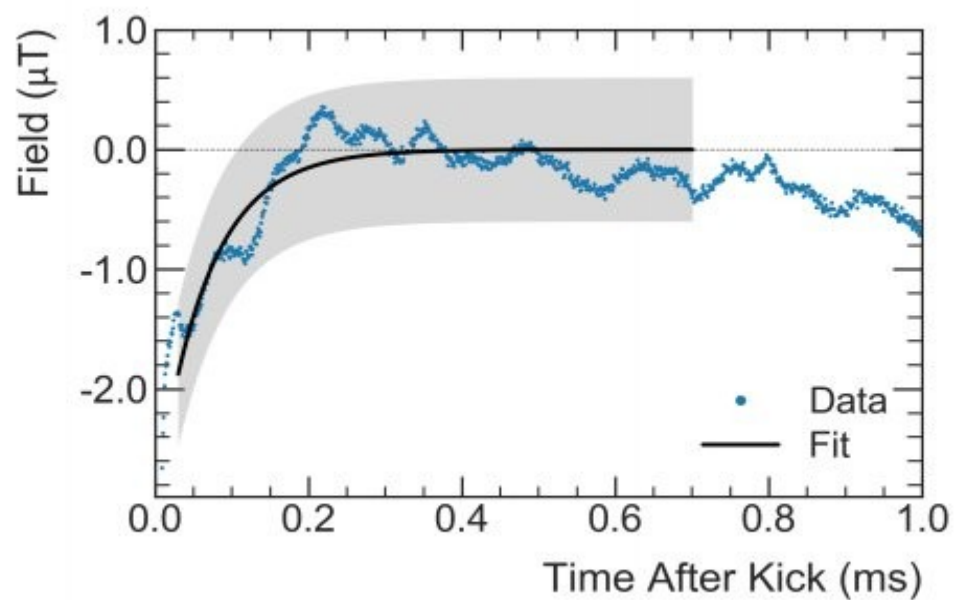
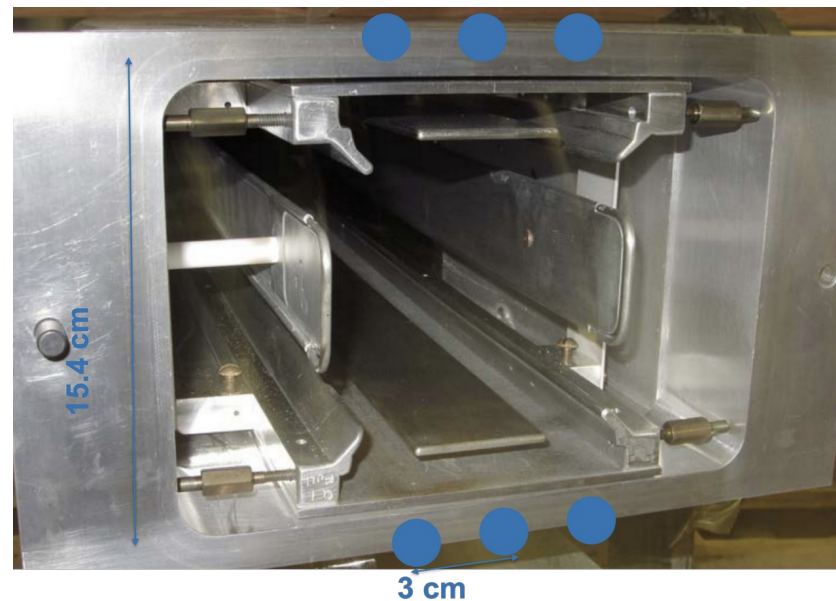


ω_p corrections B_K , B_Q

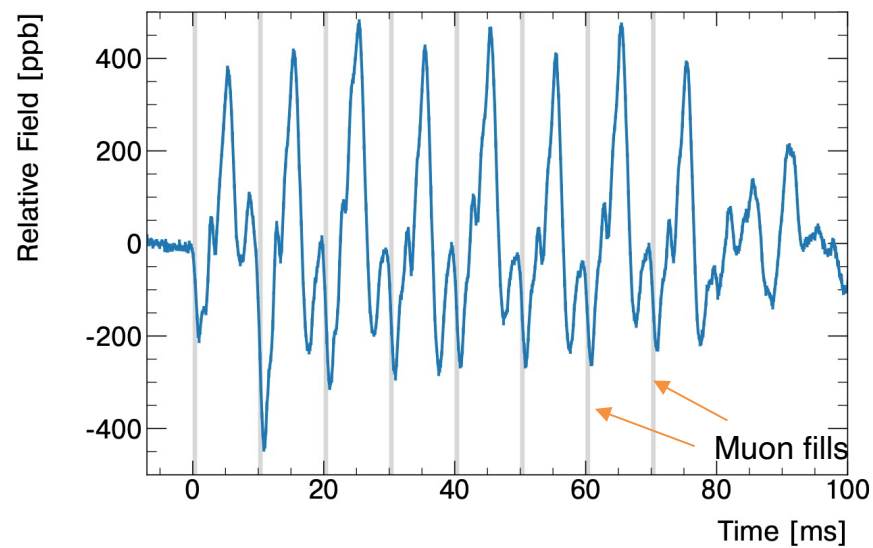
$B_K = -27 \pm 37 \text{ ppb}$, kicker transients



$B_Q = -17 \pm 92 \text{ ppb}$, quad transients



Quad Plates inside Vacuum Chamber

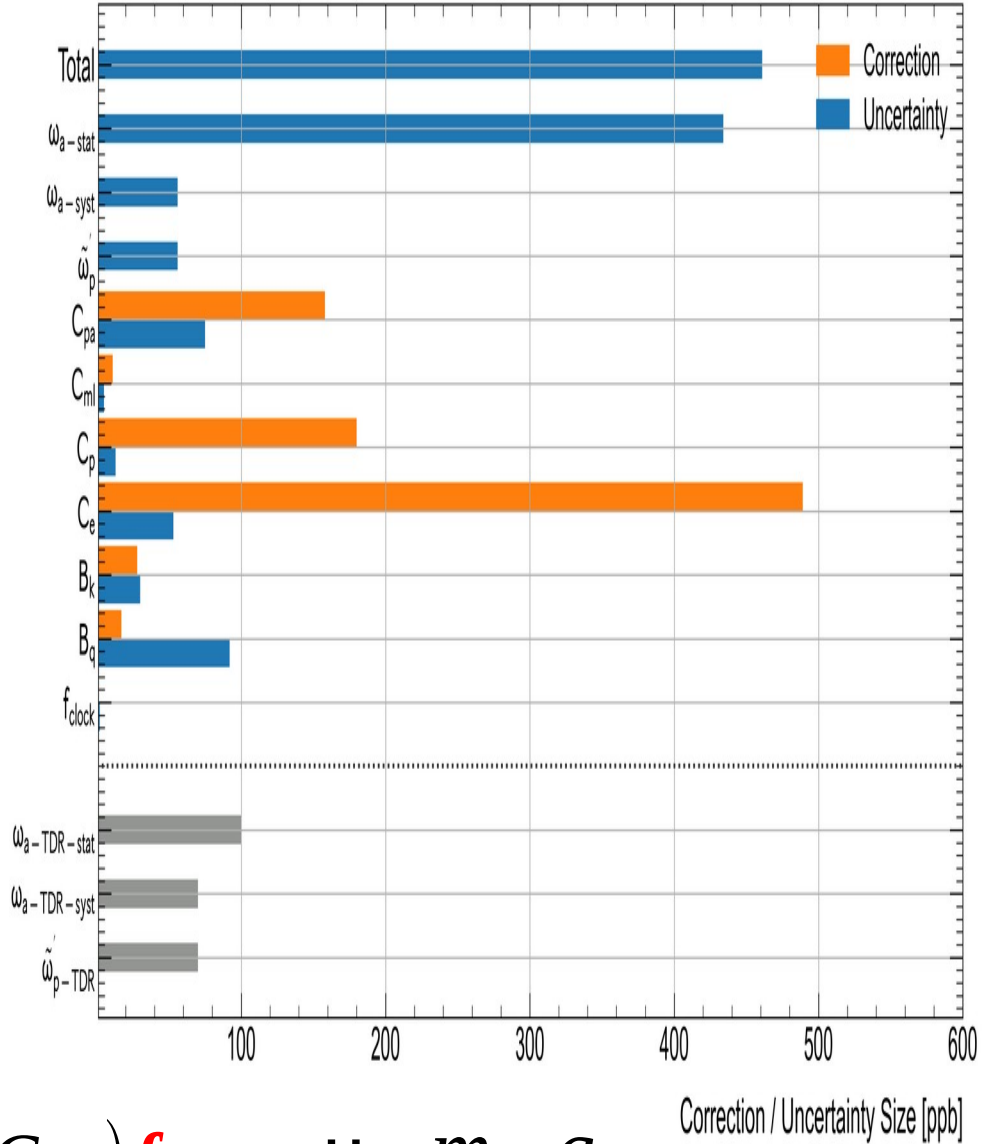




**Run 1 results for
muon anomaly a_μ**

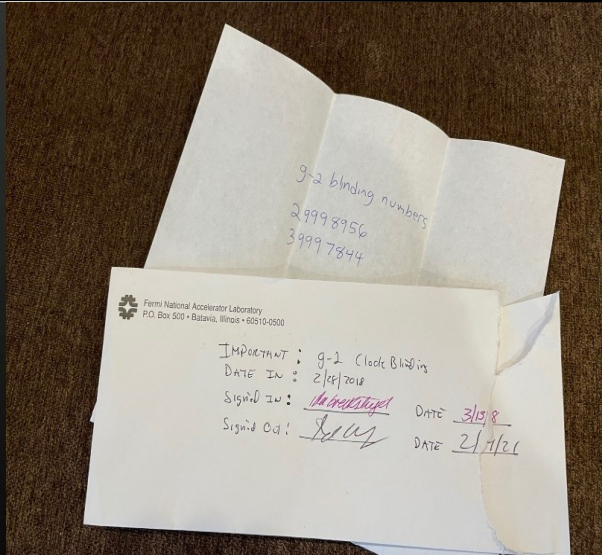
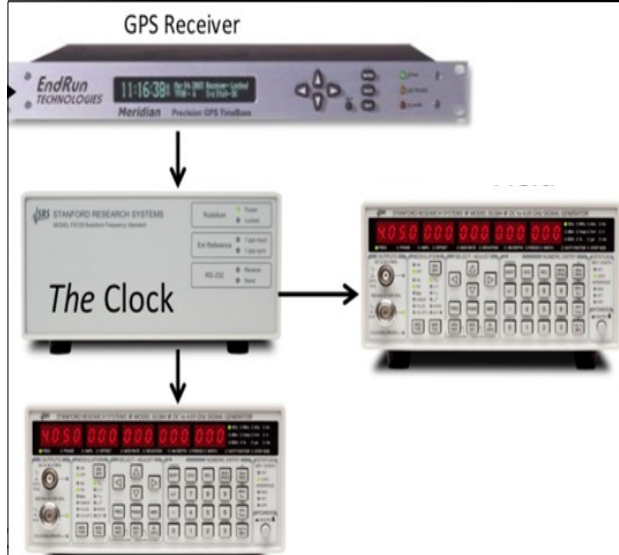
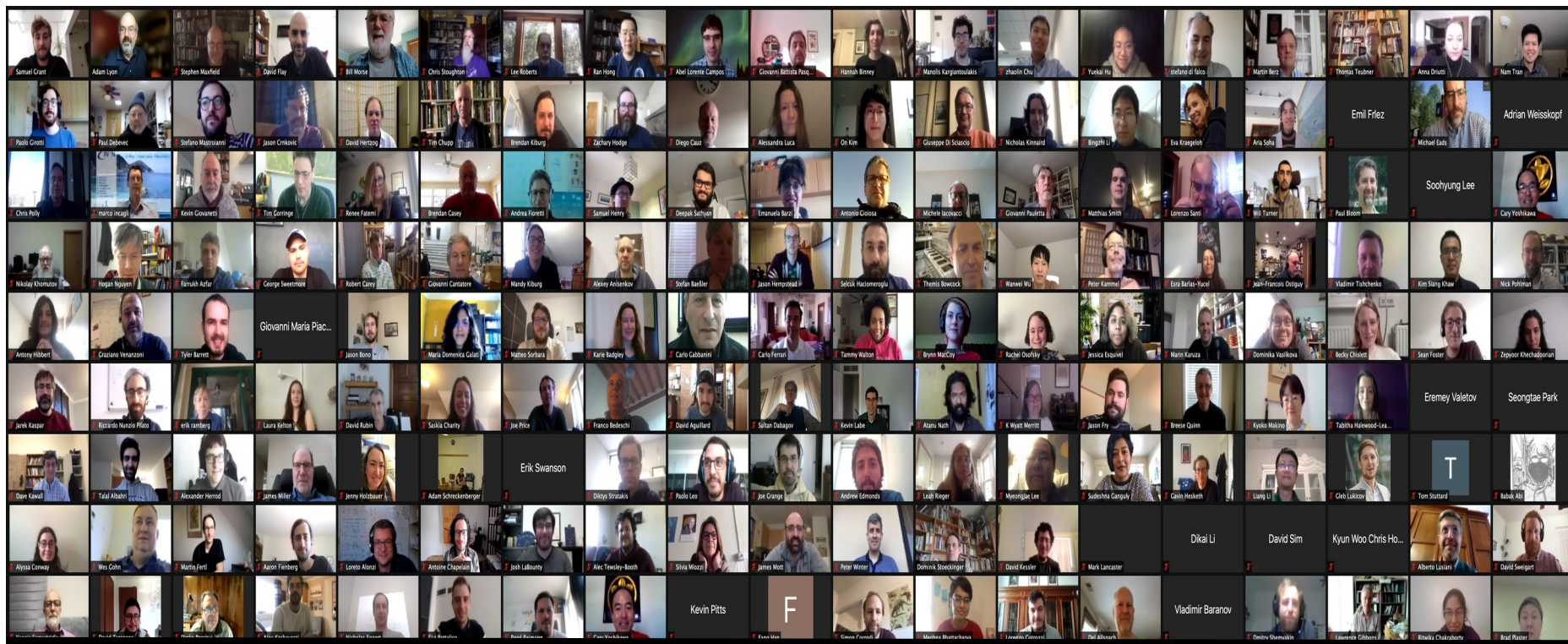
Run 1 statistical, systematics uncertainties

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
$f_{calib} \langle \omega'_p(x, y, \phi) \times M(x, y, \phi) \rangle$	–	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

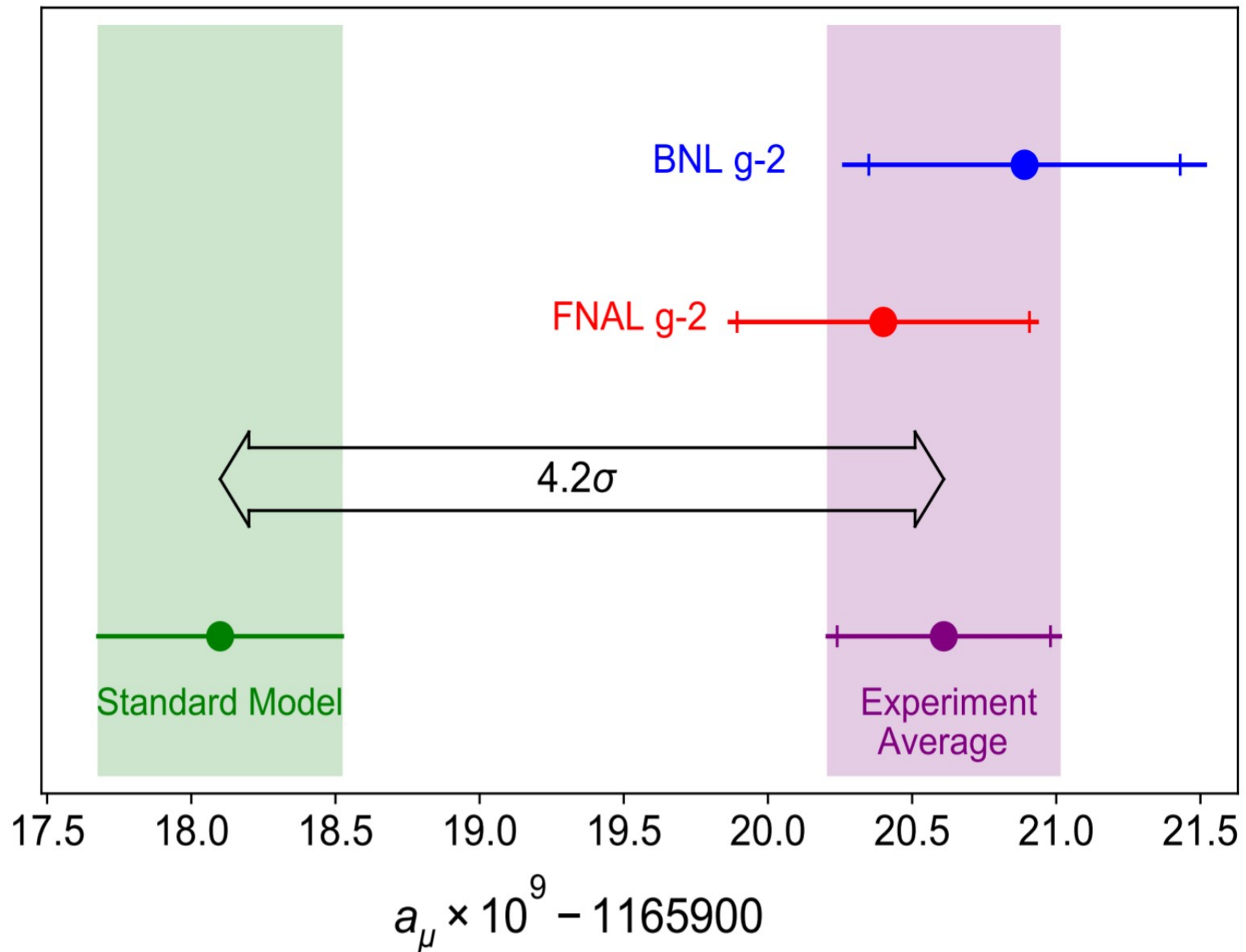


$$a_\mu = \frac{\omega_a (1 + C_E + C_P + C_{LM} + C_{PA}) \mathbf{f}_{clock}}{\tilde{\omega}_p (1 + B_K + B_Q) f_{calib}} \left(\frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \right)$$

f_{clock} unblinding meeting



f_{clock} 'unblinding moment'



Published simultaneously with run 1 release

PR-AB

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

← Beam Dynamics

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T. Gorringer,³⁸
D. Hampai,⁹ F. Ha
Z. Hodge,⁴⁸ J. L. H
M. Kargiantoulakis,
K. S. Khaw,^{27,26,}
Y. I. Kim,⁵ B. King,
J. LaBounty,⁴⁸ M
A. Lorente Campo
K. Makino,²⁰ F. M
A. Nath,^{10,31} D. Ne
R. N. Pilato,^{11,3}
B. Quinn,⁴³ N. Ra
L. Santi,^{35,8} D. Sath
M. Sorbara,^{12,33} D. S
G. Sweetmore,⁴⁰ D. A
K. Thomson,³⁵
G. Venanzoni,¹¹ T.

⁵Center for Axion andPHYSICAL REVIEW A **103**, 042208 (2021)

PRA

Featured in Physics

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

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

PRD

Editors' Suggestion

Featured in Physics

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

← Muon Precession

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

PRL

Editors' Suggestion

Featured in Physics

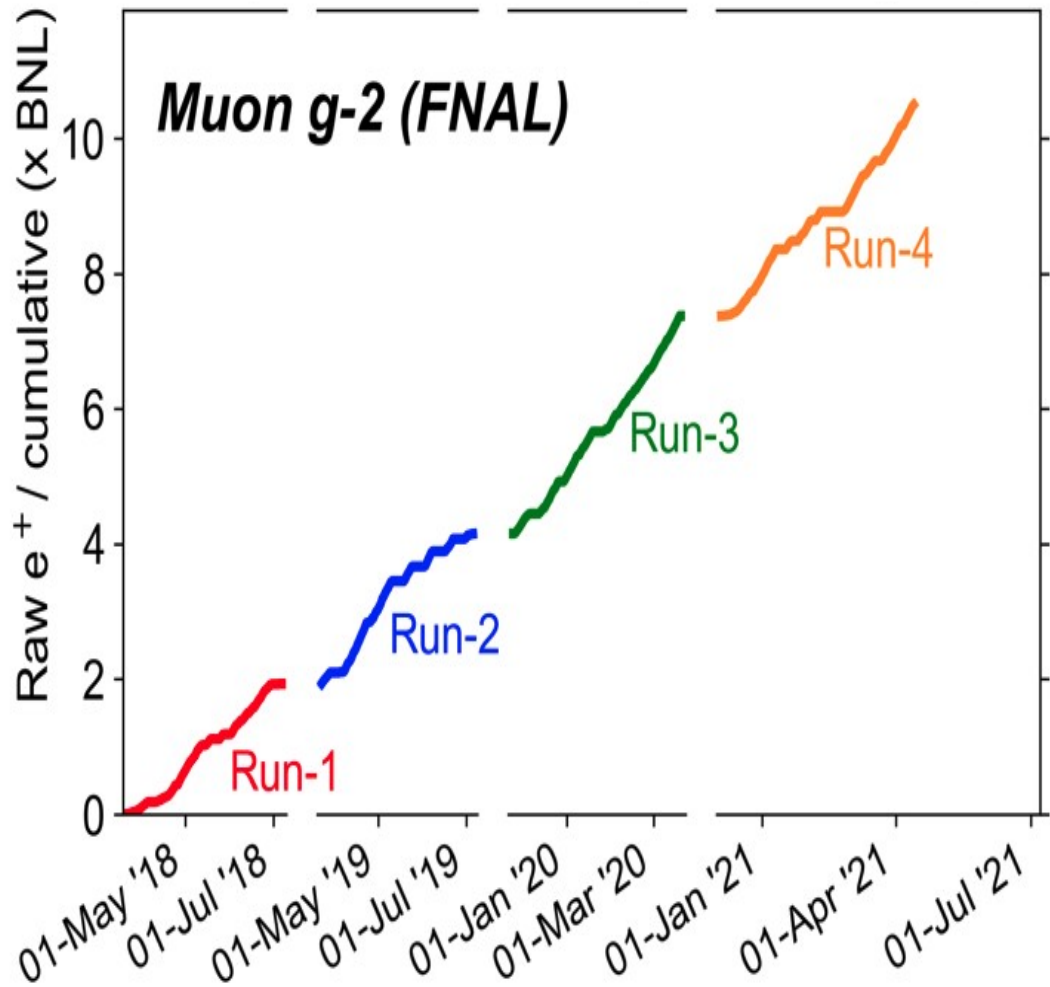
Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

T. Albahr, ³⁹ A. Anastas
F. Bedeschi, ¹¹ M. Berz
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V. N. Duginov, ¹⁷ M. E
A. Fioretti, ^{11,14} D. Flay, ⁴¹ N
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F. Gray, ²⁴ S. Haciomeroglu, ⁴
G. Hesketh, ³⁶ A. Hibber
P. Kammel, ⁴⁸ M. Kargian
K. S. Khaw, ^{27,26,48,§} Z. Kh
N. Kinnaird, ² E. Kraegeloh, ⁴
D. Li, ^{26,9} L. Li, ^{26,§} I.
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H. E. Swanson,⁴⁶ G. Sweetmor

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. Botalico,^{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. Gorringer,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

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

our new result & previous BNL result are consistent and
together increase the discrepancy with theory to $4.2\,\sigma$

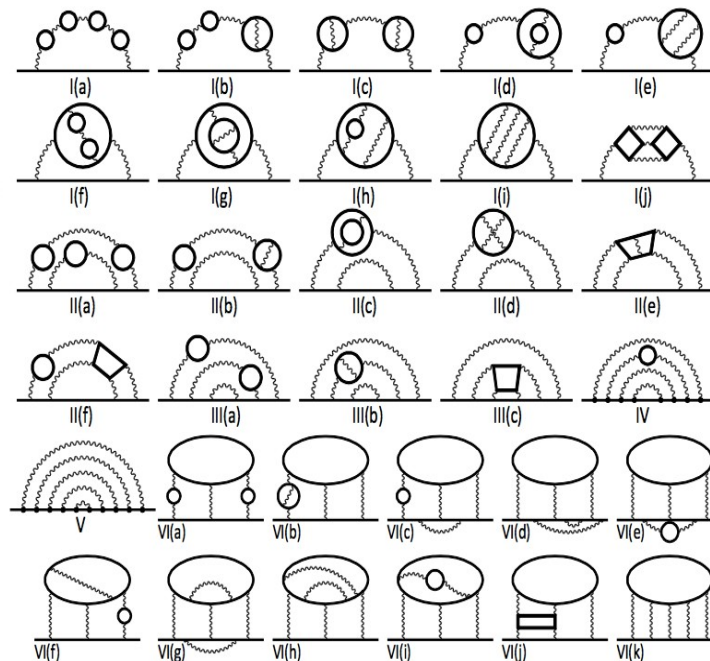
we expect $\sim 2\times$ improvement in precision from our run 2
+ 3 data and $\sim 4\times$ improvement from our run 4 + 5 + 6
data

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

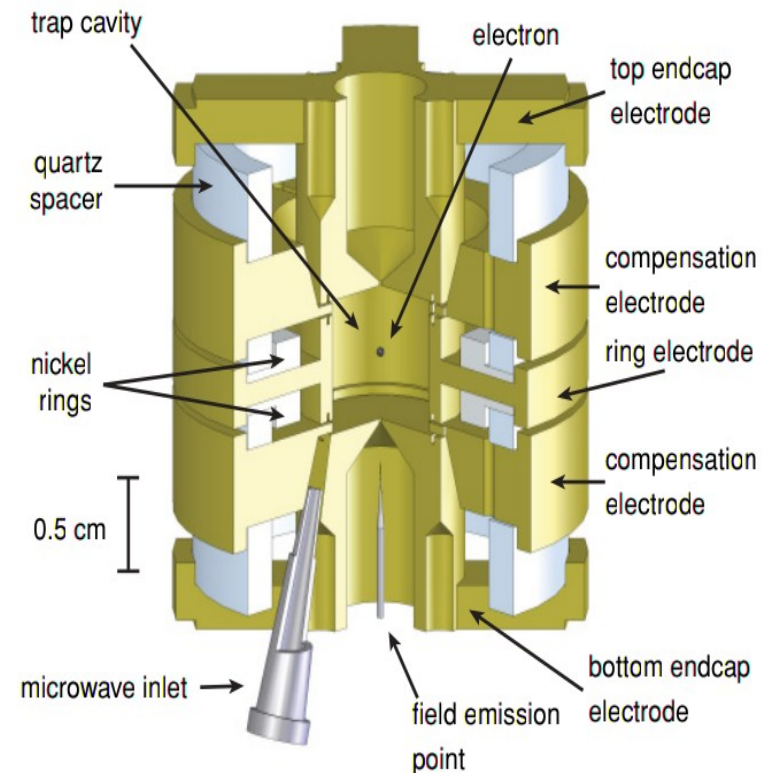
Gabrielse et al. suspended single electrons in magnetic field to measure the mag. moment to extraordinary 0.28 ppt precision.

SM



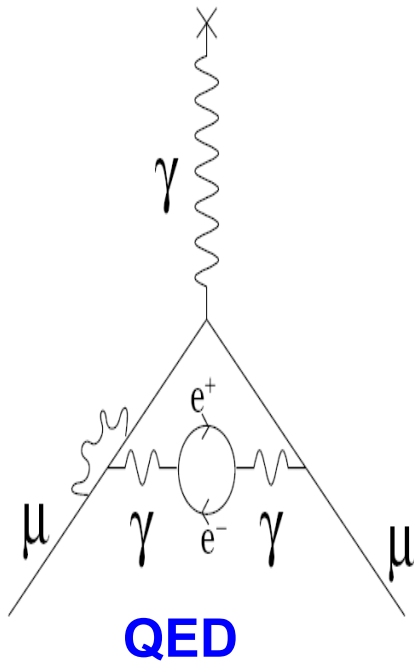
14,000 diagram

Expt.

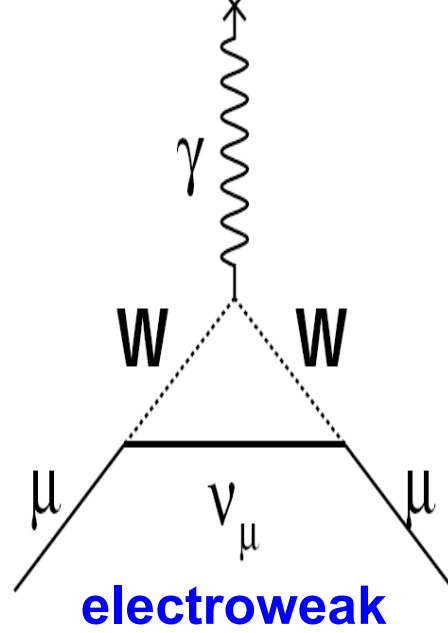


Present. Standard model and anomaly, $a = (g-2) / 2$

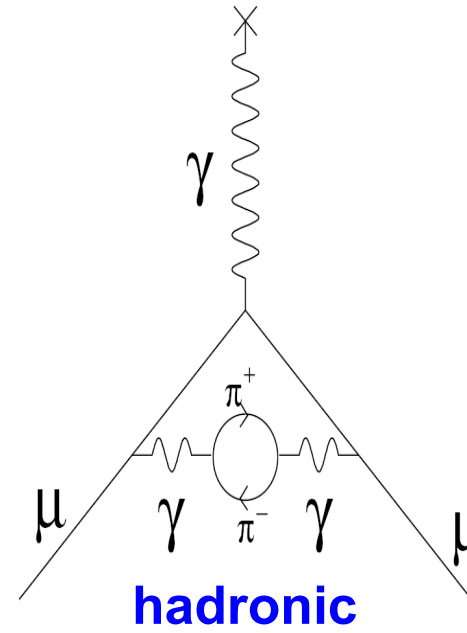
$$a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{Strong} + a_{\mu}^{Weak} + a_{\mu}^{NP}$$



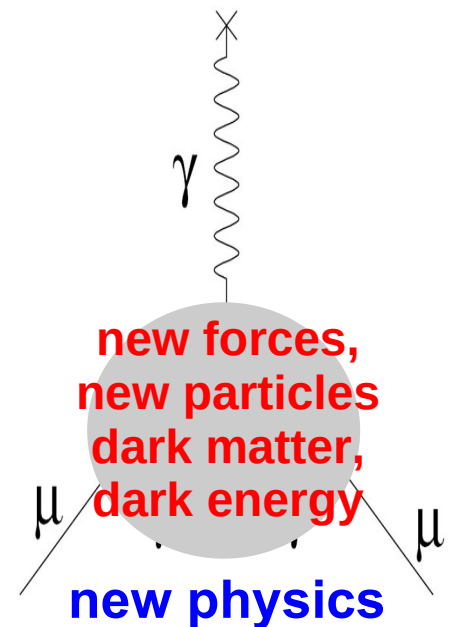
$$a_{\mu}^{QED} = 116\,584\,718.9 (0.1)$$



$$a_{\mu}^{EW} = 154 (1)$$



$$a_{\mu}^{Had} = 6939 (40)$$



$$a_{\mu}^{NP} = ? \times 10^{-11}$$

dispersion relations,
 $e^+e^- \rightarrow \text{hadrons}$
 for $a_{\mu}^{\text{hvp:LO}}$

scale
 $\sim m_l^2 / m_x^2$

Muon g-2 theory initiative

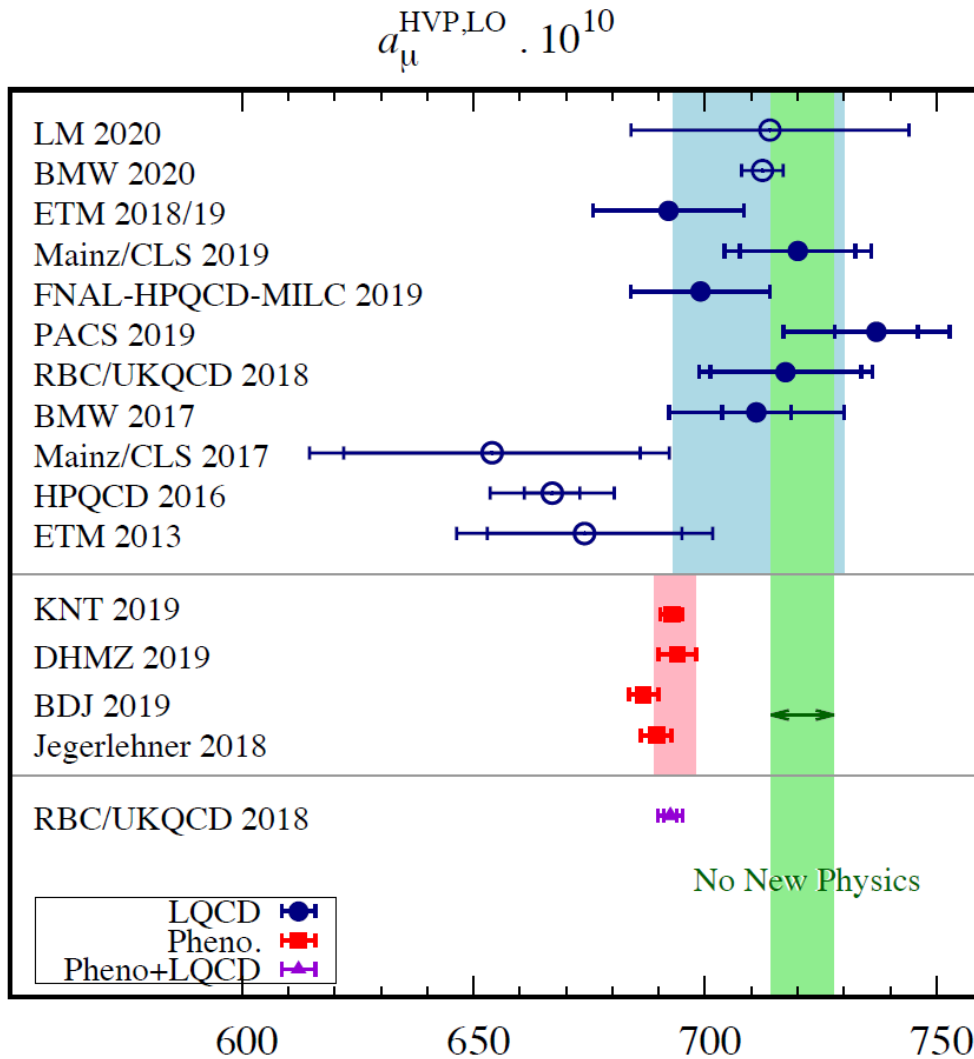
- 6 workshops 2017-2020
- 6/10/20 white paper, 132 authors, 82 institutions, 21 countries
- T. Aoyama et al, Phys. Reports 887 (2020) 1-166.
- consortium compiled theoretical inputs & recommend value ahead of FNAL expt.

The anomalous magnetic moment of the muon in the Standard Model

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Recent lattice QCD developments for hadronic vacuum polarization

adapted from [T. Aoyama et al, [arXiv:2006.04822](https://arxiv.org/abs/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

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