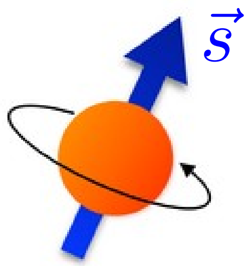
First result of the
Muon g-2 Experiment E989 at Fermilab

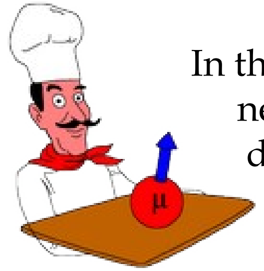
Vladimir Tishchenko
Brookhaven National Laboratory
Muon g-2 collaboration

Colloquium
Physics Department
Brookhaven National Laboratory
April 9, 2021

What is a muon?

- Elementary particle
- Same electric charge as the electron
- Like the electron, behaves like it is *intrinsically* spinning
- Approximately **200** times heavier than an electron





In the mid-1930s, physicists thought they knew all the subatomic particles of nature – the proton, neutron, and electron of the atom. However, in 1936 the muon was discovered which deeply disturbed the existing elegant picture of subatomic world . Its discovery was so unexpected that, Nobel laureate Isidor Isaac Rabi famously quipped, *"who ordered that?"* when informed of the discovery.

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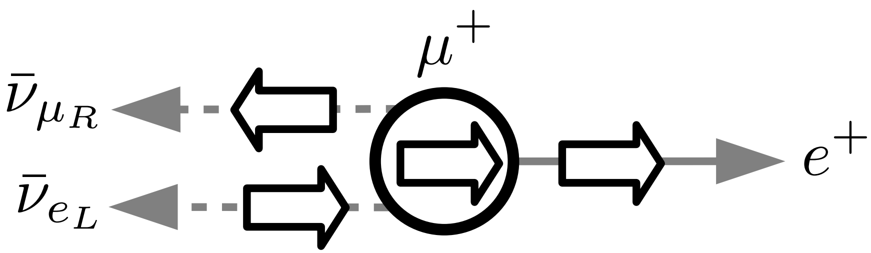
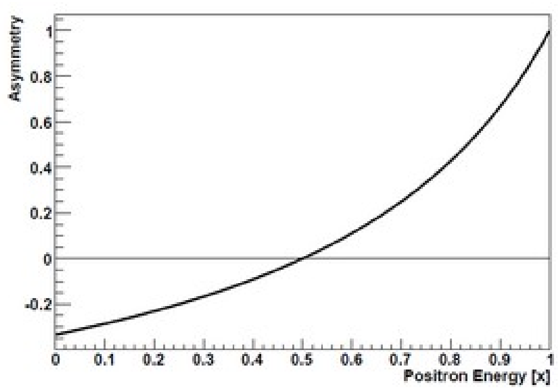
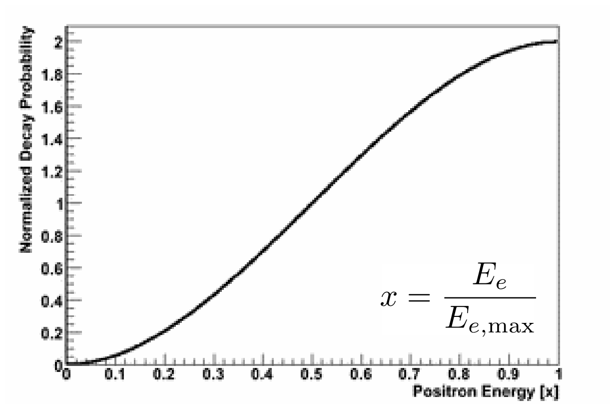
$$\tau_\mu \approx 2.2\,\mu\mathrm{s}$$

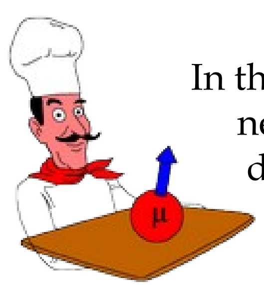
$$\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$$







- muons decay (to positrons or electrons)
- energy and angular distribution of decay positrons are highly correlated to the muon spin direction → muons are self-analyzing polarimeters



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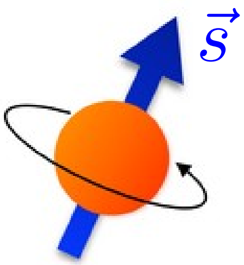
What is a muon?



- Elementary particle
- Same electric charge as the electron
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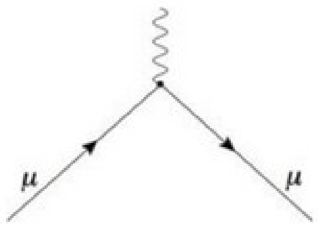
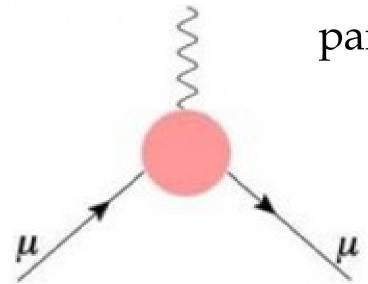
Spin and charge produce another important quantum-mechanical property of the muon, the magnetic moment:

$$\vec{\mu} = g \left(\frac{e}{2m_\mu} \right) \vec{s}$$

Dirac theory predicts g=2:



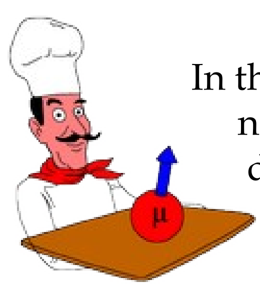


Quantum effects give additional contribution which arise from virtual particles, known and **unknown**:

$$g = 2(1 + a_\mu)$$

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

Comparison of a_μ from theory and experiment provides a stringent test of the Standard Model.



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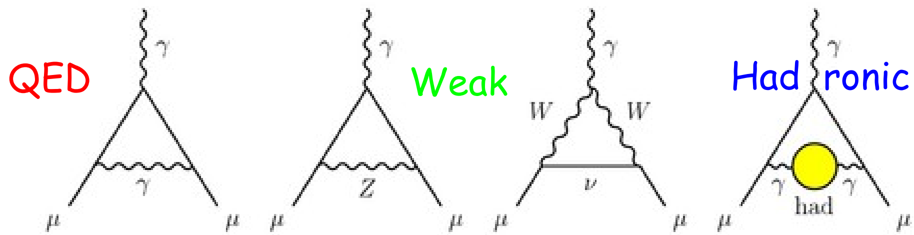
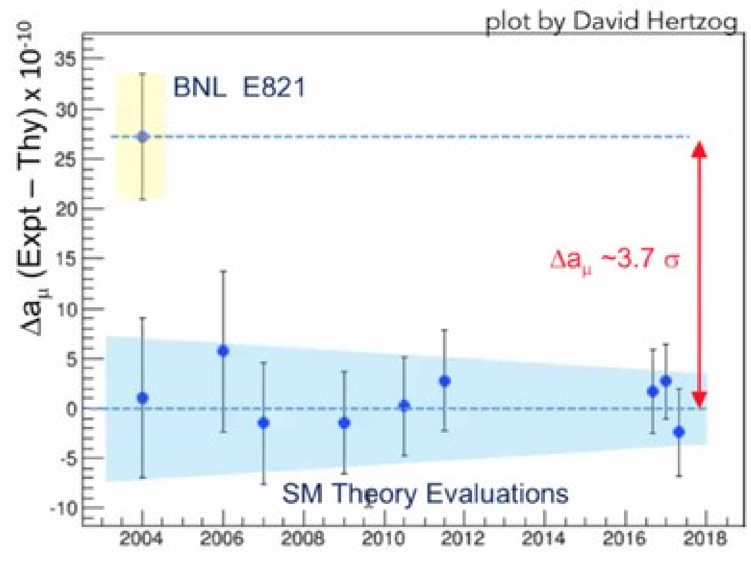
anomalous magnetic moment $a_\mu \equiv \frac{g_\mu - 2}{2}$

$$\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu}$$

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{Had}}$$



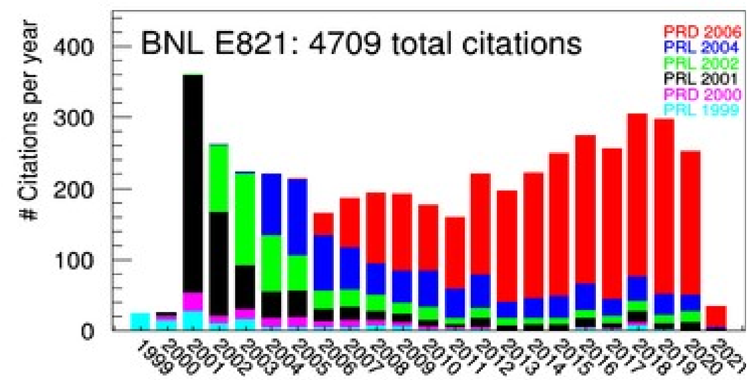
Source	value ($a_\mu \times 10^{-11}$)	error
QED	116 584 718.93	0.10
EW	154	1
HVP	6845	40
HLBL	92	18



$$a_\mu^{\mathrm{SM}} = 116\,591\,810(43) \times 10^{-11}$$ Theory Initiative Phys. Rep. 887 (2020)

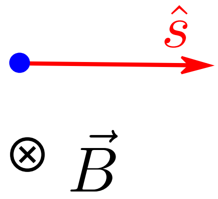
$$a_\mu^{\mathrm{exp}} = 116\,592\,089(63) \times 10^{-11}$$ BNL E821 (2004)

$$\Delta a_\mu = a_\mu^{\mathrm{SM}} - a_\mu^{\mathrm{exp}} \approx 3.7\sigma$$



B.L. Roberts

Muon g-2 experiment in a nutshell



$$\omega_s = \frac{e}{m} B(1 + a_\mu)$$

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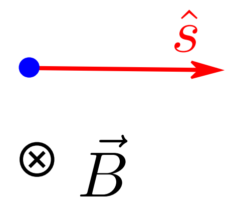


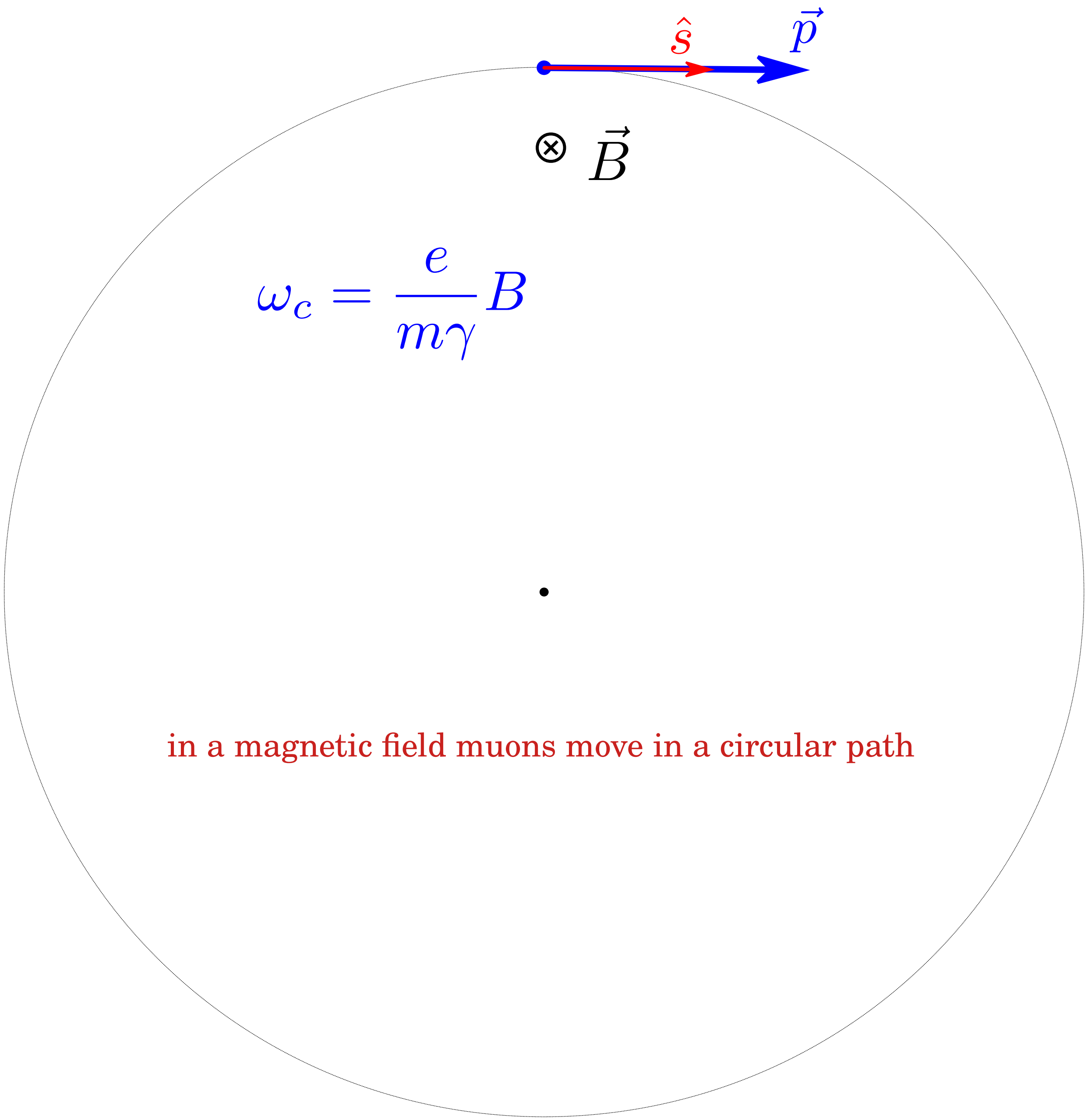
$$\omega_s = \frac{e}{m} B(1 + a_\mu)$$

$$\frac{\sigma_{a_\mu}}{a_\mu} \approx \frac{1}{a_\mu} \frac{\sigma_{\omega_s}}{\omega_s}$$

$$a_\mu \approx 0.001$$

$\frac{\sigma_{a_\mu}}{a_\mu}$	$\frac{\sigma_{\omega_s}}{\omega_s}$
1%	0.001%

Muon g-2 experiment in a nutshell



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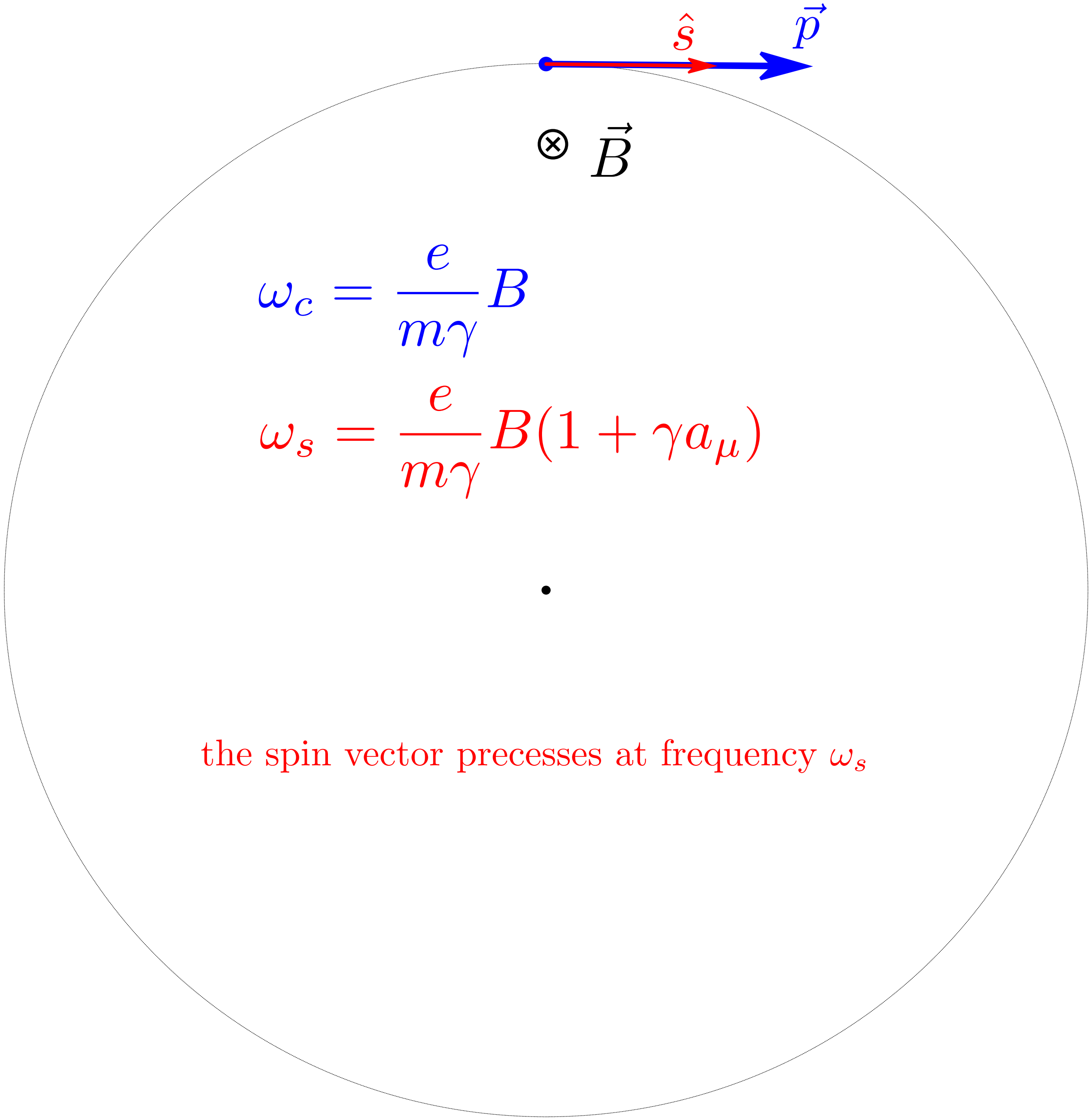
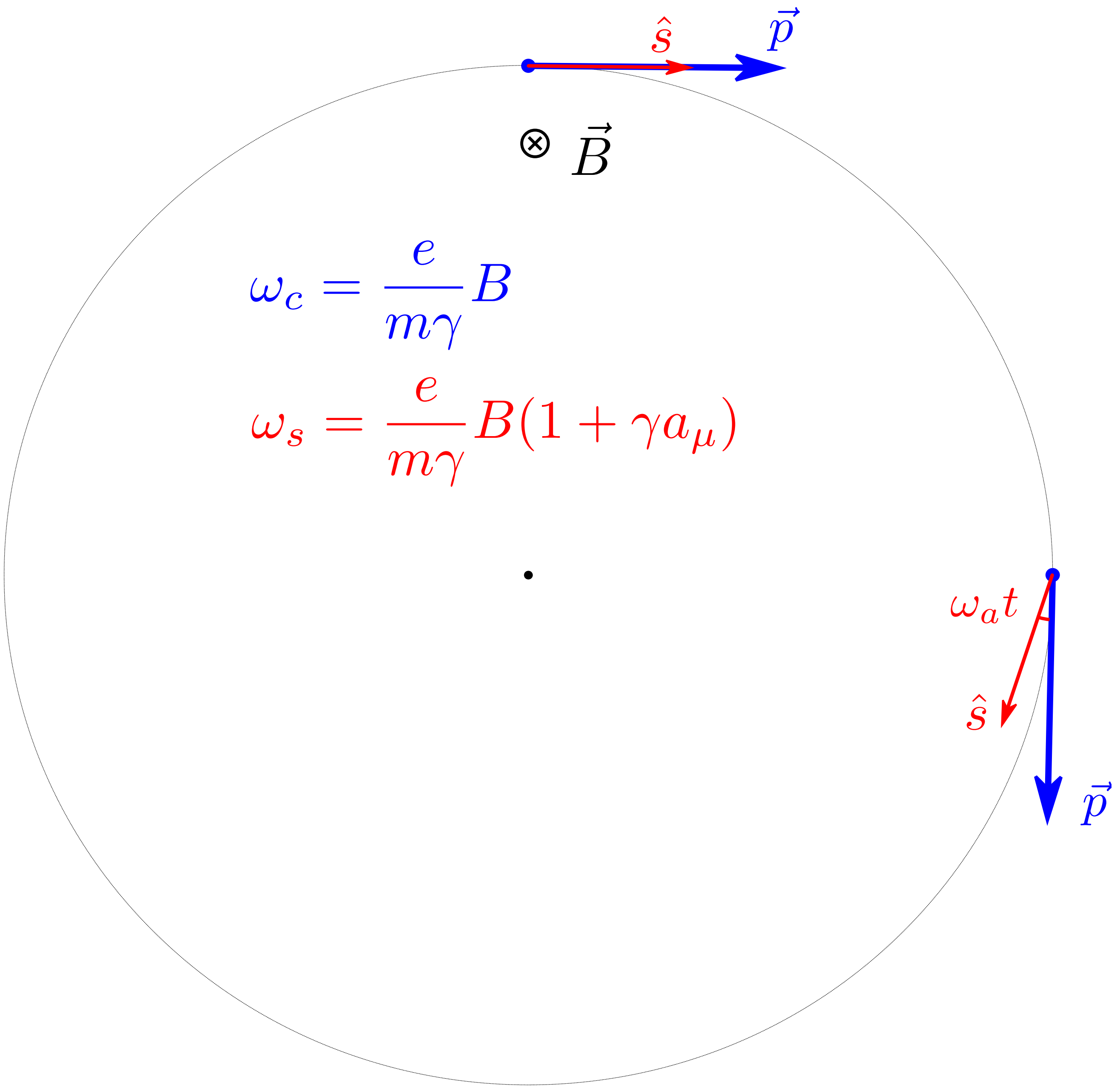


$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

the spin vector precesses at frequency ω_s

Muon g-2 experiment in a nutshell



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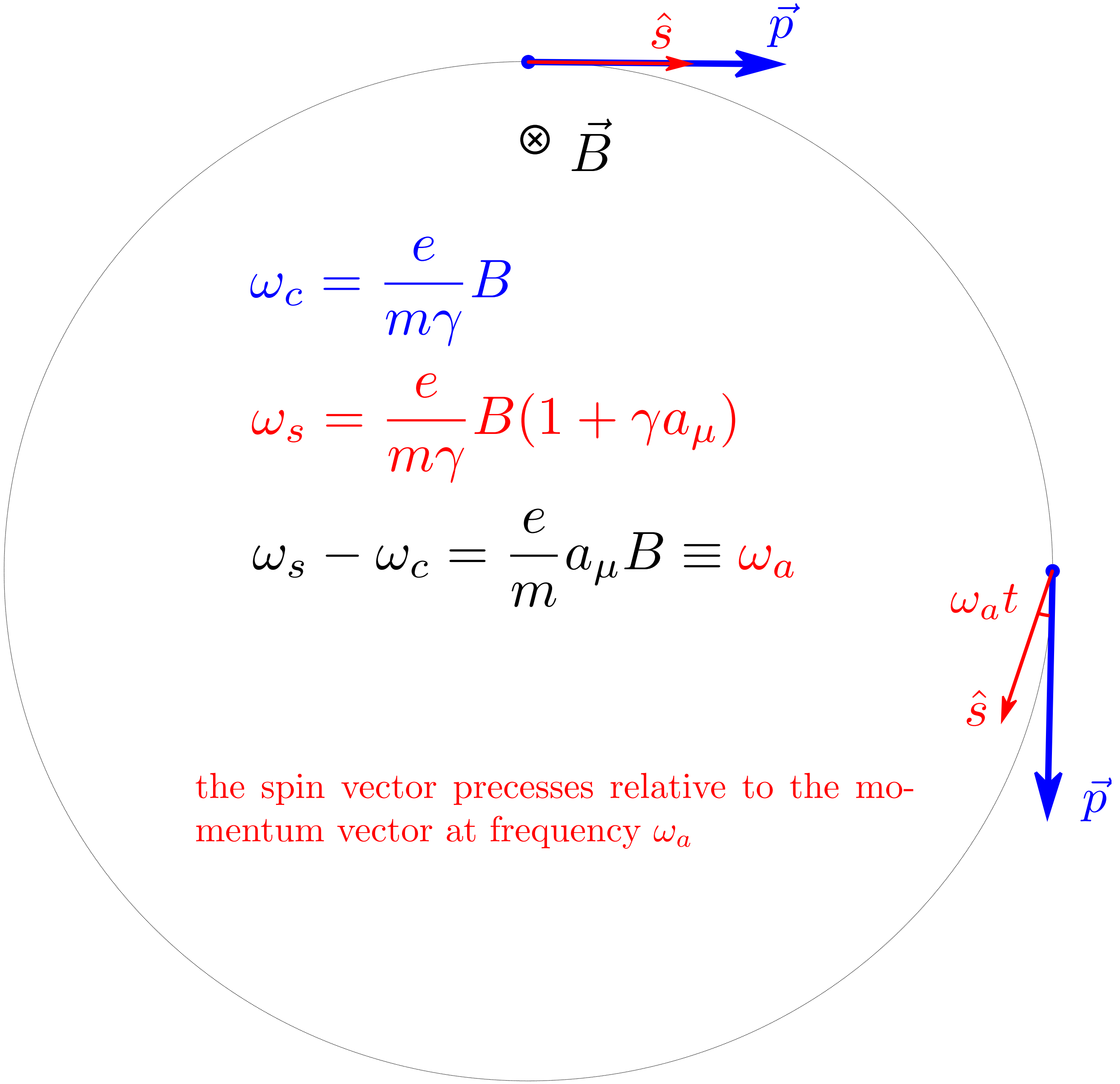


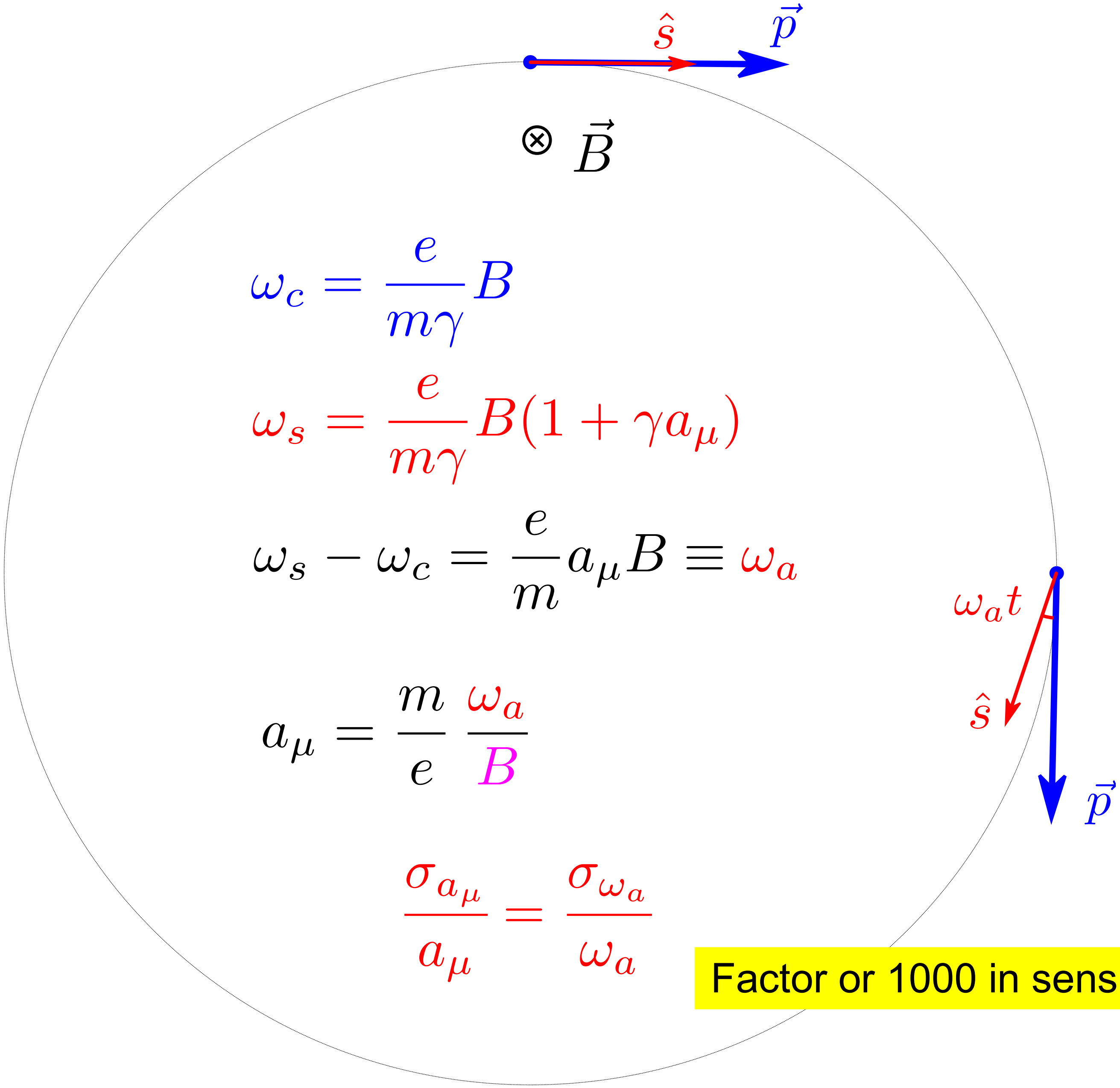
$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

$$\omega_s - \omega_c = \frac{e}{m} a_\mu B \equiv \omega_a$$

the spin vector precesses relative to the momentum vector at frequency ω_a

Muon g-2 experiment in a nutshell



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$$\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$$

$$\omega_s - \omega_c = \frac{e}{m}a_\mu B \equiv \omega_a$$

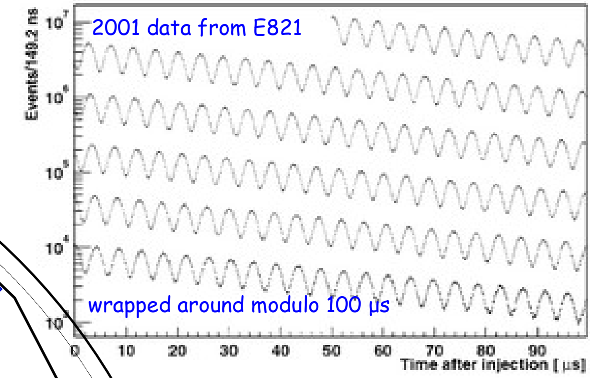
$$a_\mu = \frac{m}{e}\frac{\omega_a}{B}$$

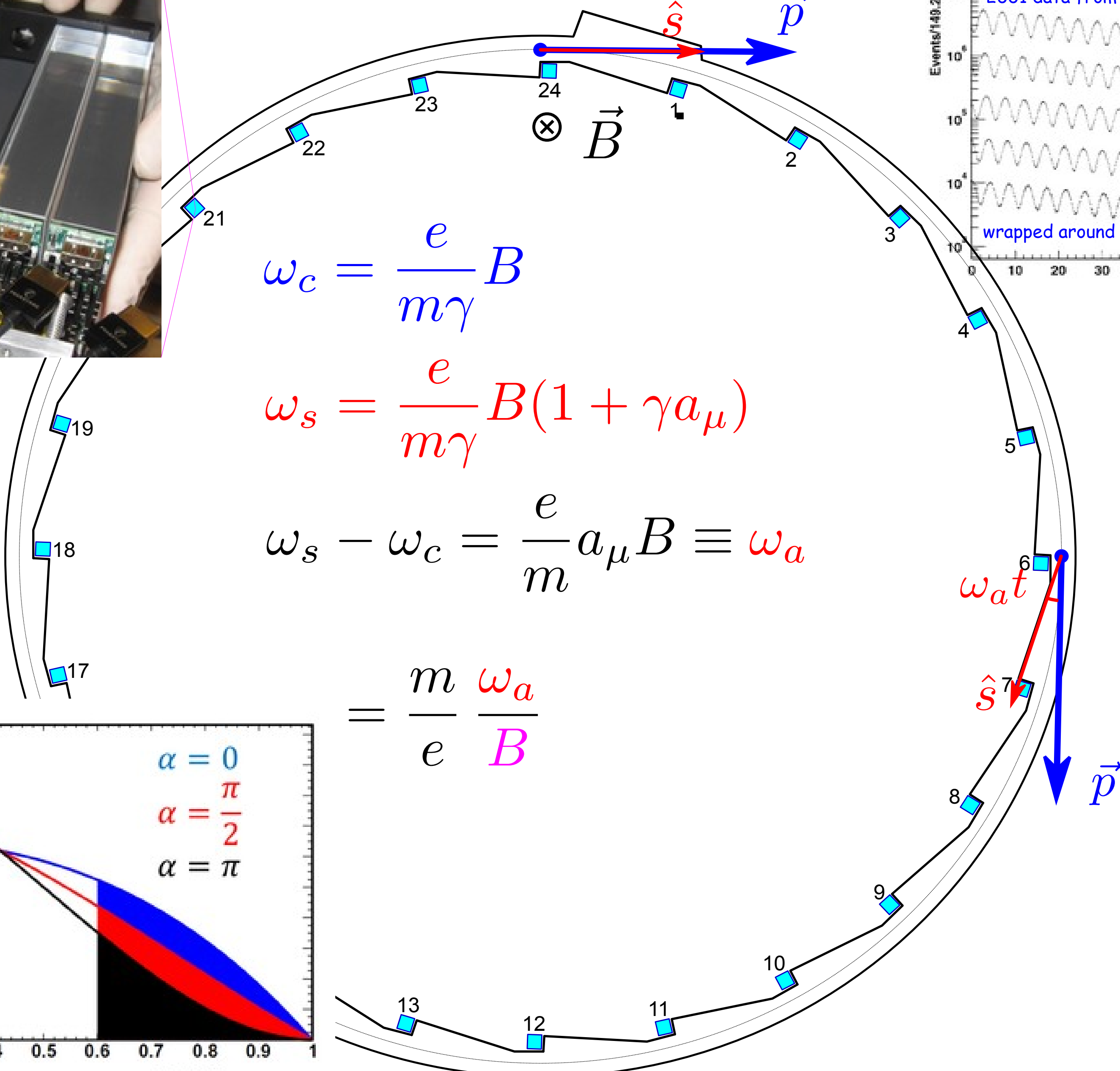
$$\frac{\sigma_{a_\mu}}{a_\mu} = \frac{\sigma_{\omega_a}}{\omega_a}$$

Factor or 1000 in sensitivity!

Muon g-2 experiment in a nutshell

calorimeter





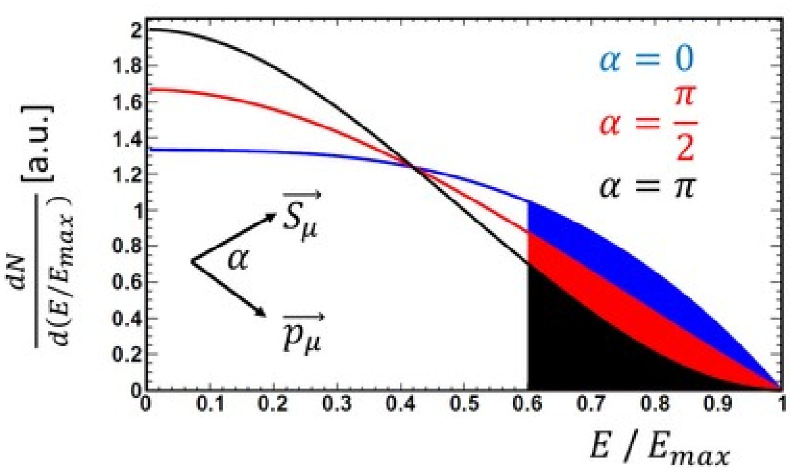
$$\omega_c = \frac{e}{m\gamma} B$$

$$\omega_s = \frac{e}{m\gamma} B(1 + \gamma a_\mu)$$

$$\omega_s - \omega_c = \frac{e}{m} a_\mu B \equiv \omega_a$$

$$= \frac{m}{e} \frac{\omega_a}{B}$$

$\hat{s}$ $\vec{p}$ $\otimes \vec{B}$ $\omega_a t$



E989 timeline: proposal submition

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

E989 Proposal

The New (g – 2) Experiment:

A Proposal to Measure the Muon Anomalous

Magnetic Moment to ±0.14 ppm Precision

Request: 4×10^{20} **protons on target in 6 of 20 Booster batches during 15 Hz operation**

February 9, 2009

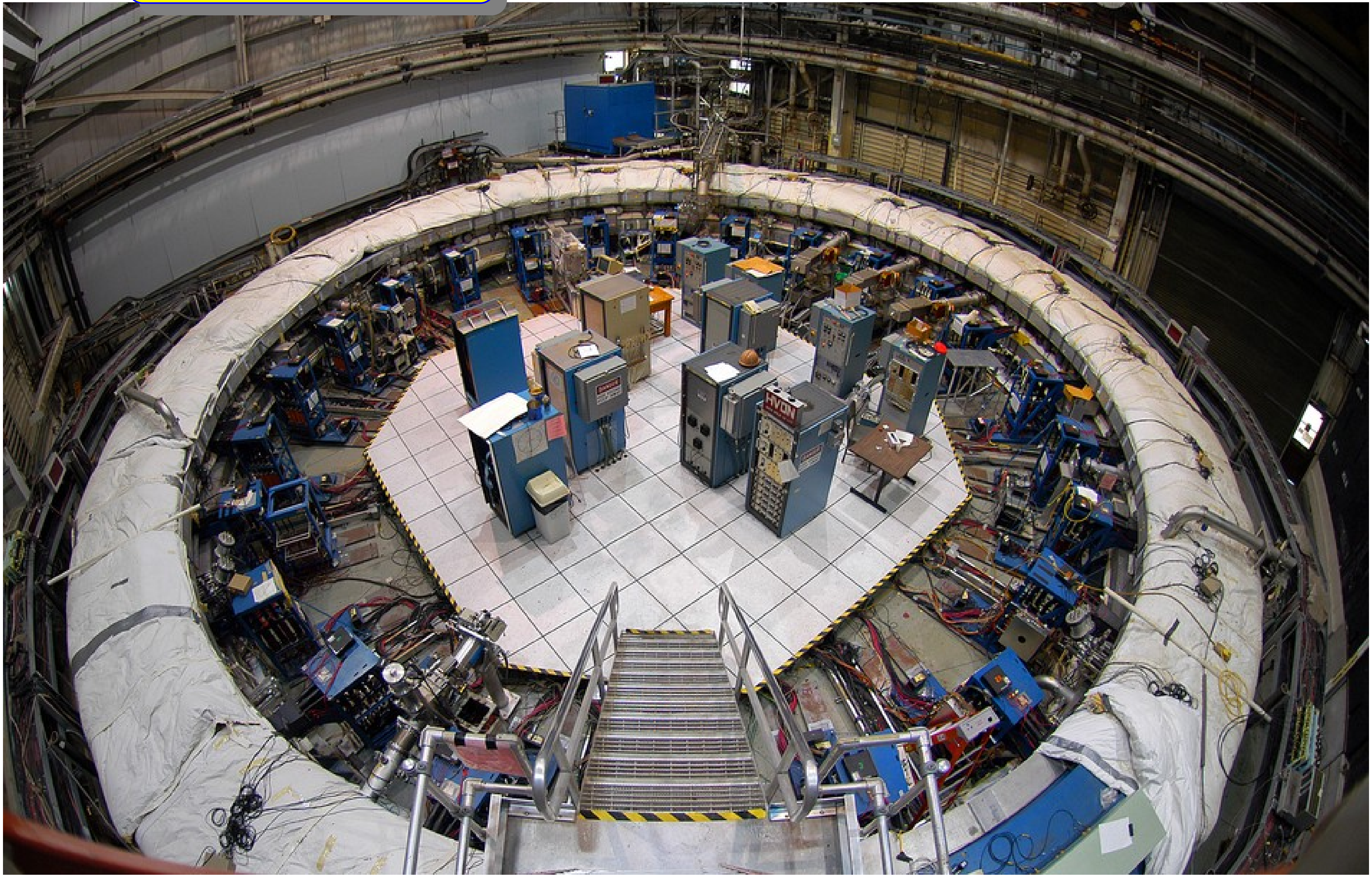
Contactpersons: David W. Hertzog (hertzog@illinois.edu, 217-333-3988)

B. Lee Roberts (roberts@bu.edu, 617-353-2187)

g-2 storage ring at BNL

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

storage ring at BNL



BROOKHAVEN NATIONAL LABORATORY

Experiment timeline

2009 | 2010 | **2011** | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

Jan.: Stage 1 approval by FNAL director
May: FY 11 Field Work Proposal granted to develop CDR

Dear Lee and Dave,

Following the recommendation of the PAC and discussions with the Department of Energy on funding projections over the period when we could run the New g-2 Experiment, I grant Stage I approval to g-2. Of course, there is still a lot of work to do to develop a detailed plan for the funding and various further approval processes which will be required to execute the experiment.

We will consider the experiment ready for the Stage II approval when we determine that the available funding is sufficient for the proposal scope of the experiment and there is a detailed MOU between Fermilab and the experiment.

Despite the cautionary words, we are very pleased that your experiment has met a rather high standard, and we very much hope that this approval can lead to establishment of a soundly based plan. If there is any way we can be of assistance in this, please let us know.

Sincerely,

Piermaria Oddone

Disassembly of g-2 storage ring at BNL

2009 | 2010 | 2011 | **2012** | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

Disassembly of g-2 storage ring started
First yoke piece removed (Sept.)

transportation of coils from BNL to Fermilab

2009 | 2010 | 2011 | 2012 | **2013** | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

more photos and info: http://muon-g-2.fnal.gov/bigmove

BROOKHAVEN NATIONAL LABORATORY

Ring reassembly at Fermilab

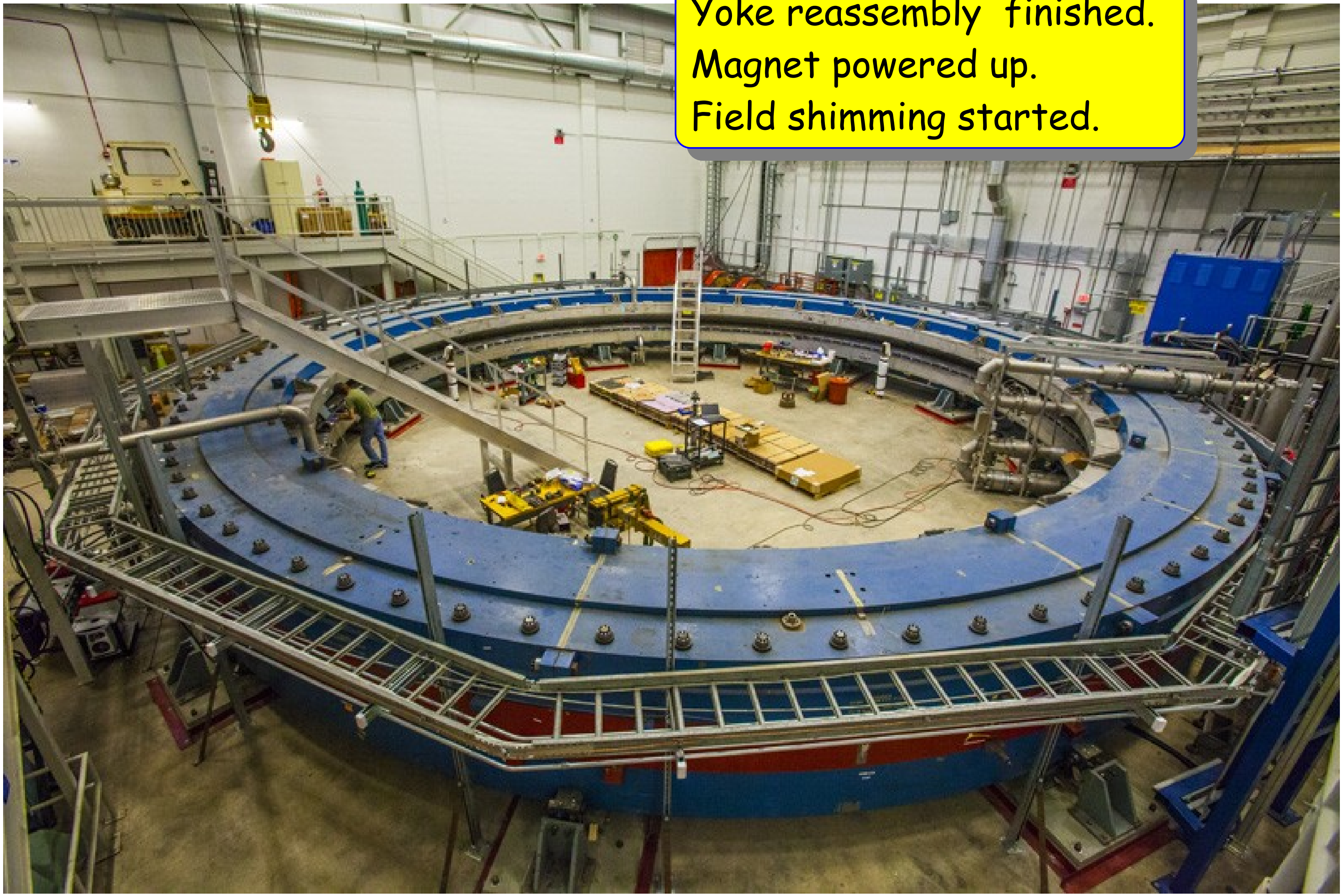
2009 2010 2011 2012 2013 **2014** 2015 2016 2017 2018 2019 2020 2021

June 23, 2014. Bottom yoke. Reassembly progresses well. Superconducting coils will be moved into the experimental hall end of July 2014

g-2 storage magnet reassembled at FNAL

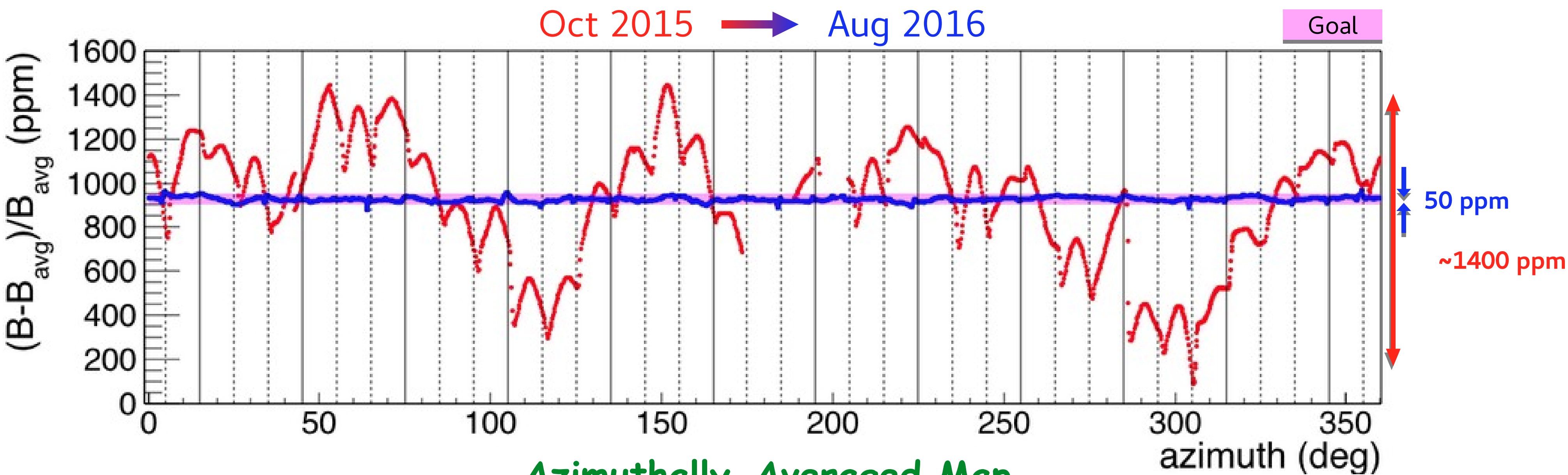
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | **2015** | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

Yoke reassembly finished.
Magnet powered up.
Field shimming started.

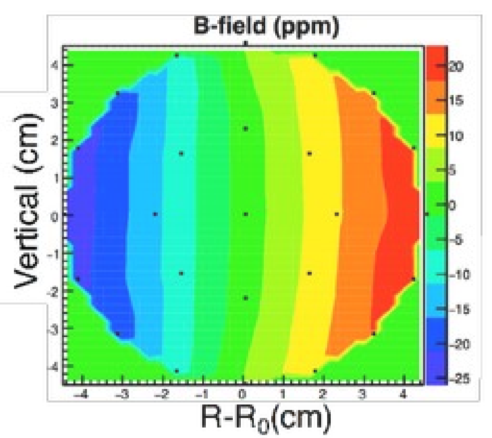


Rough Shimming Results

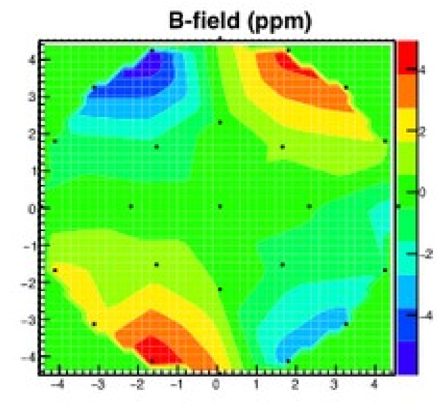
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | **2016** | 2017 | 2018 | 2019 | 2020 | 2021



Azimuthally-Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

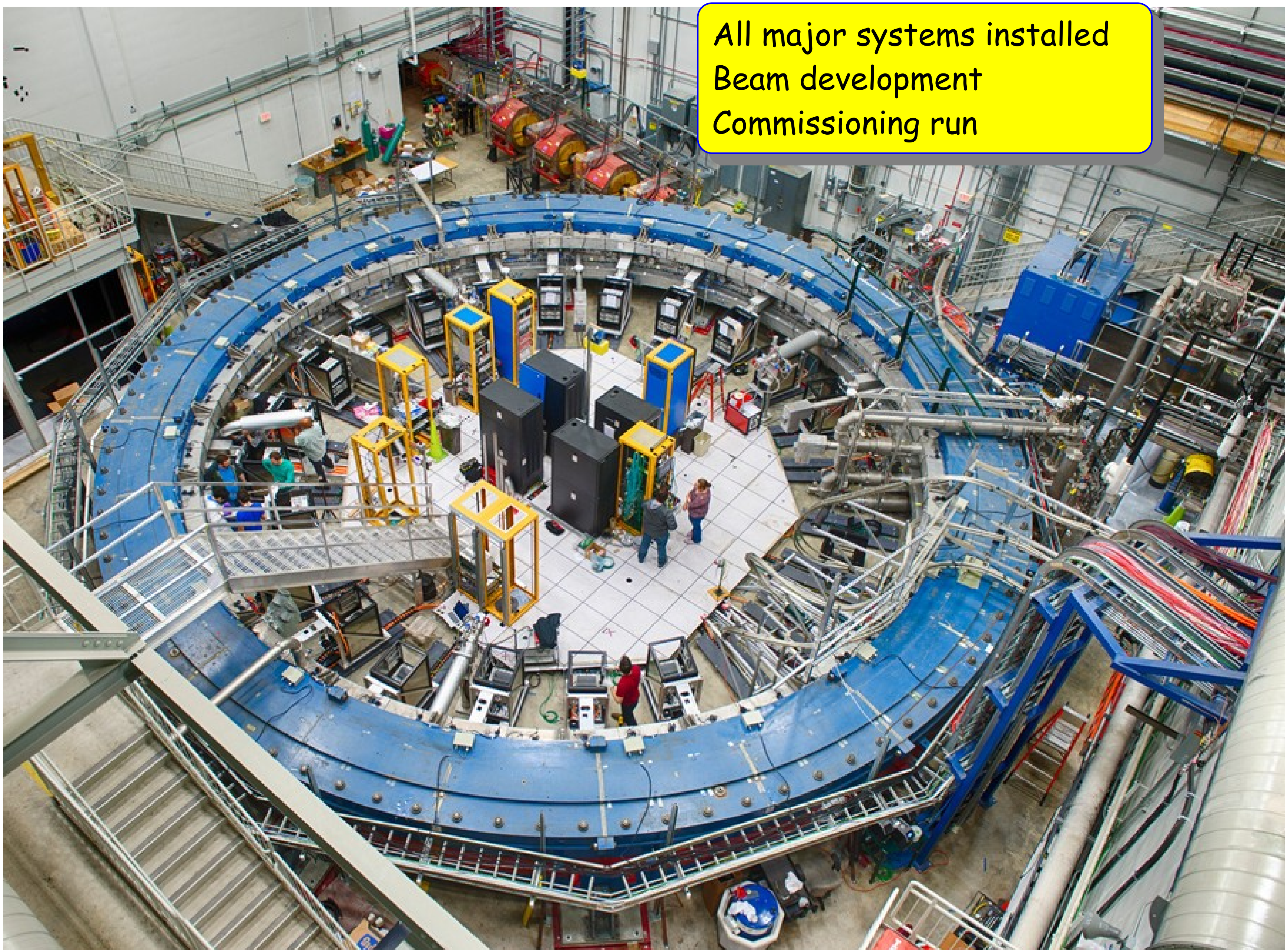
D. Flay

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

Commissioning run

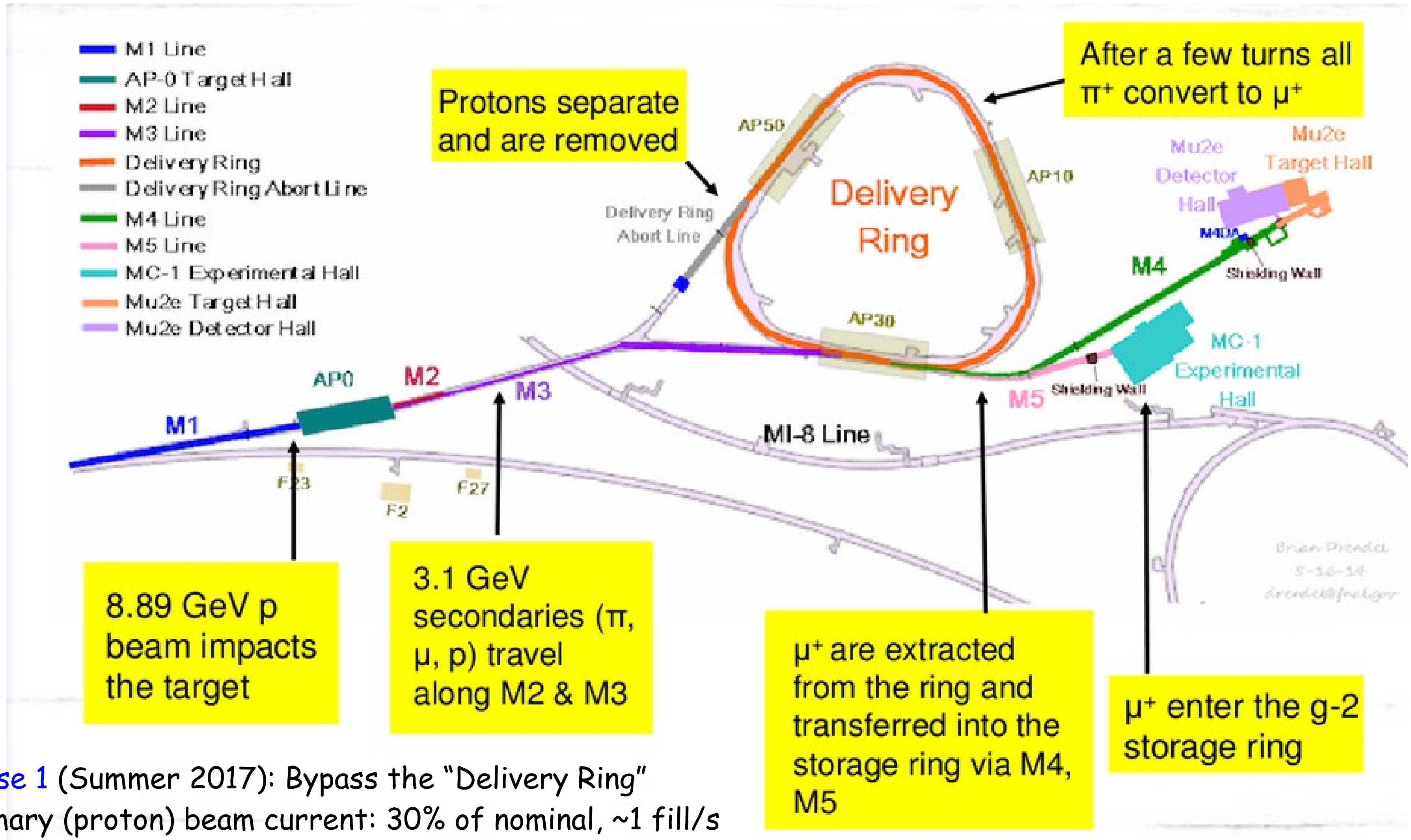
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018 | 2019 | 2020 | 2021

All major systems installed
Beam development
Commissioning run



First Beam Development

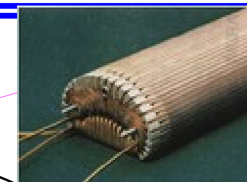
2009 2010 2011 2012 2013 2014 2015 2016 **2017** 2018 2019 2020 2021

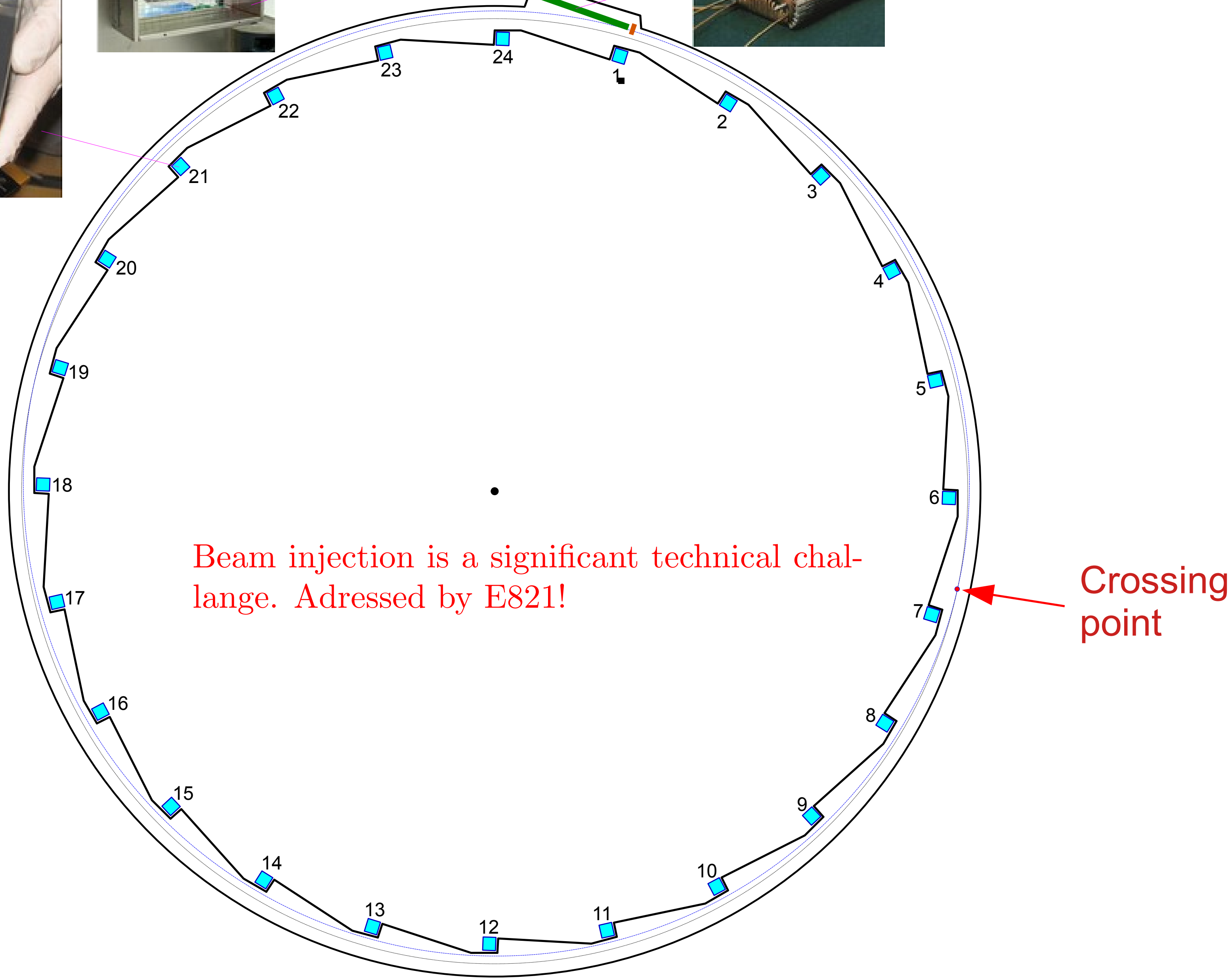


Phase 1 (Summer 2017): Bypass the "Delivery Ring"
Primary (proton) beam current: 30% of nominal, ~1 fill/s (vs. 12 Hz nominal)
Secondary beam: proton contamination

Phase 2 (Fall 2017 – Spring 2018): commissioning the entire beam line, beam development; ramping up to full current

g-2 storage ring anatomy

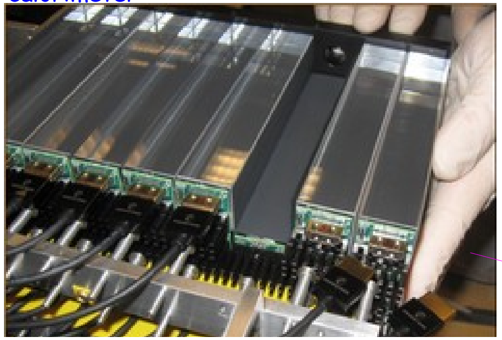




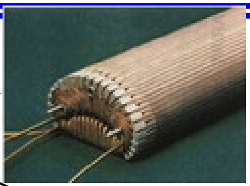
Beam injection is a significant technical challange. Adressed by E821!

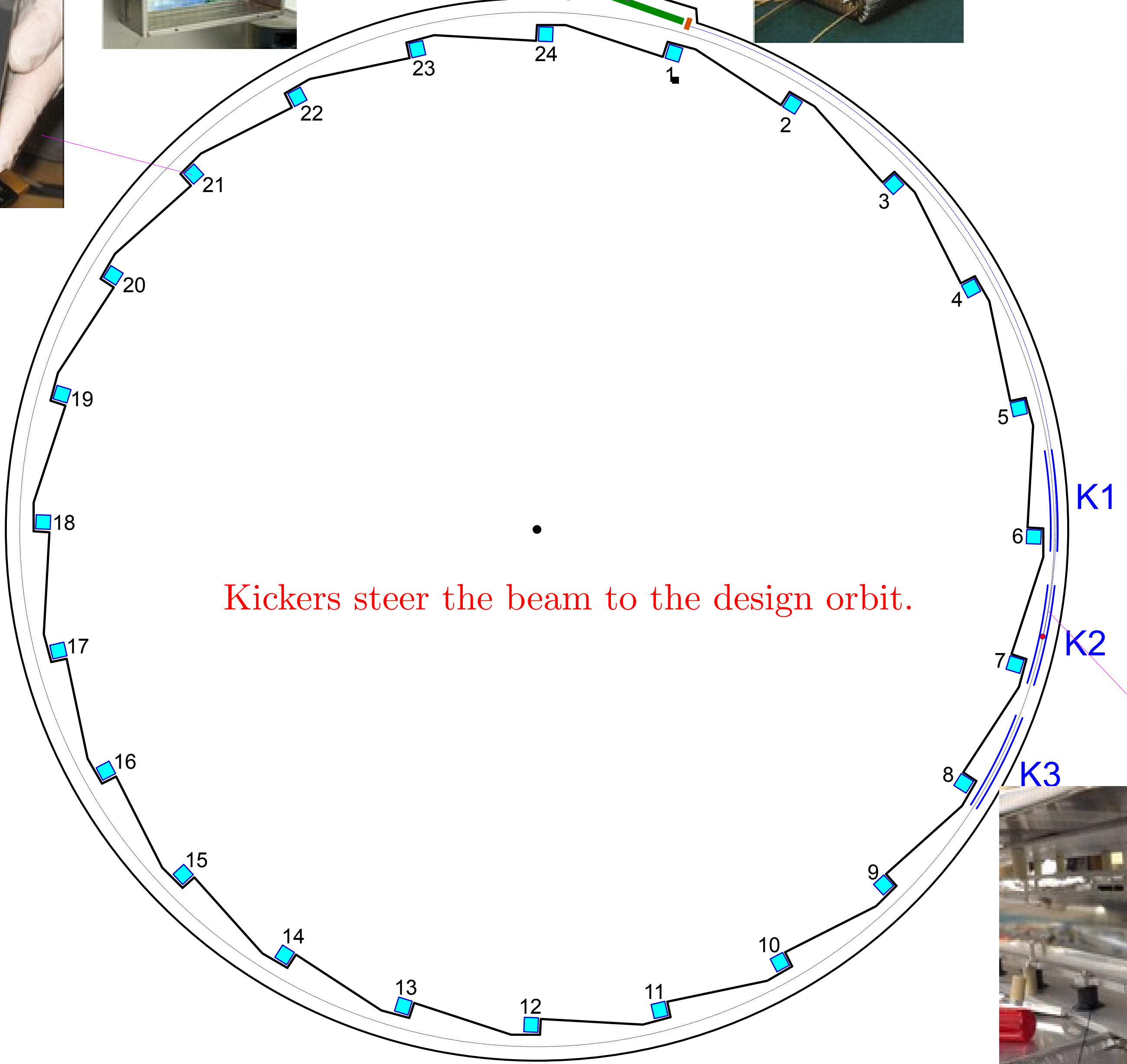
g-2 storage ring anatomy

calorimeter

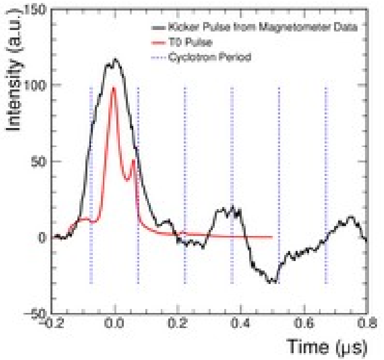


beam monitor

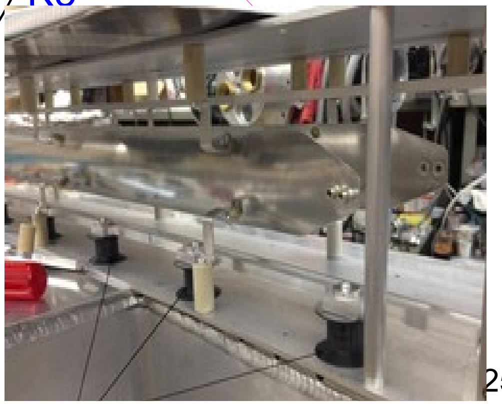




Kickers steer the beam to the design orbit.



Kickers



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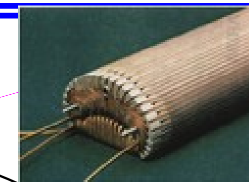

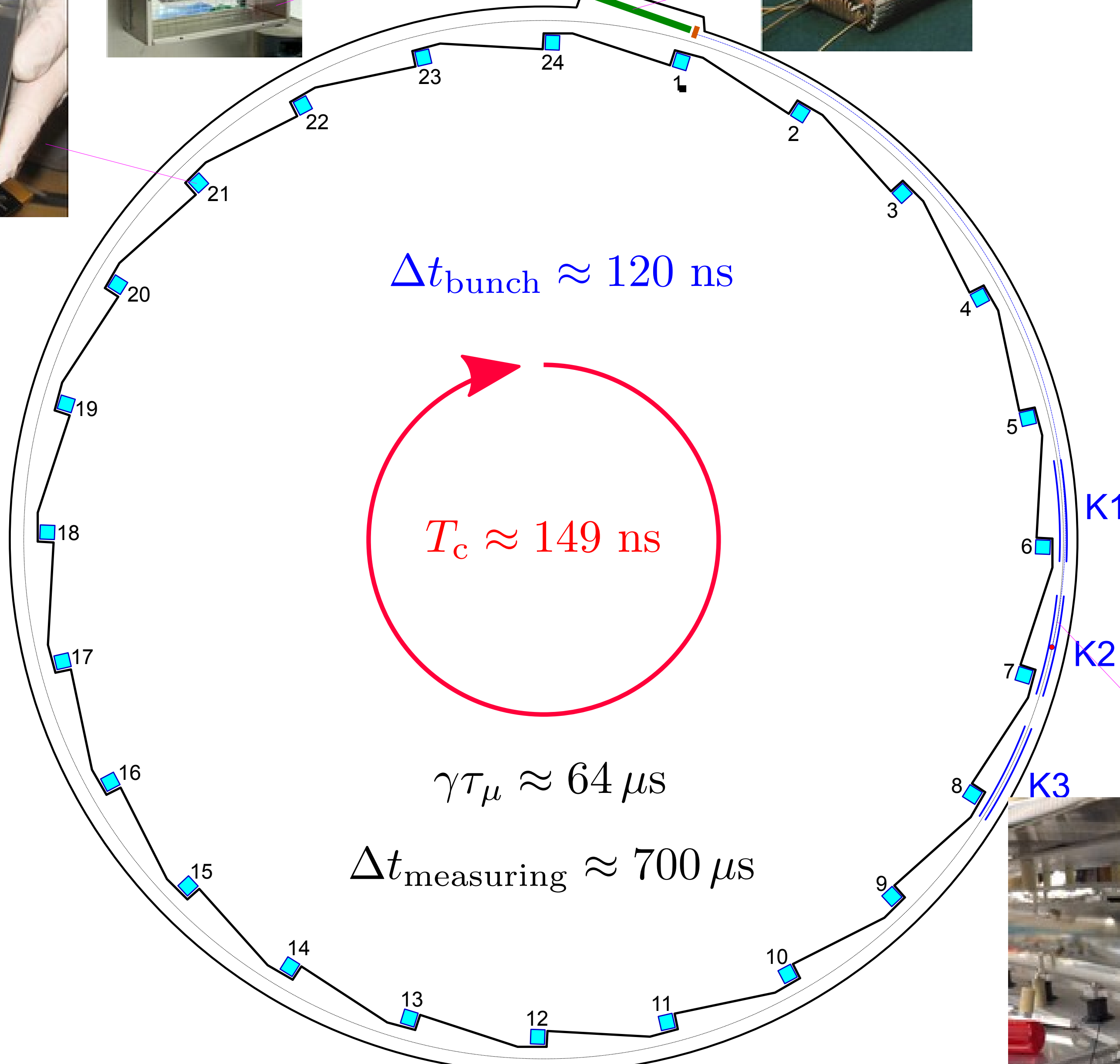

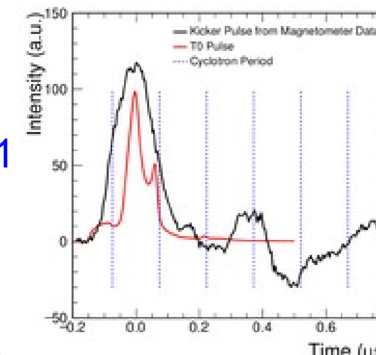

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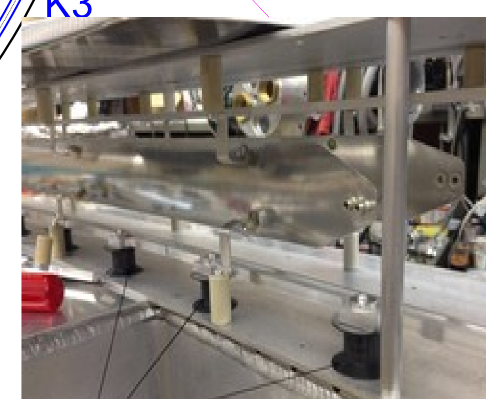

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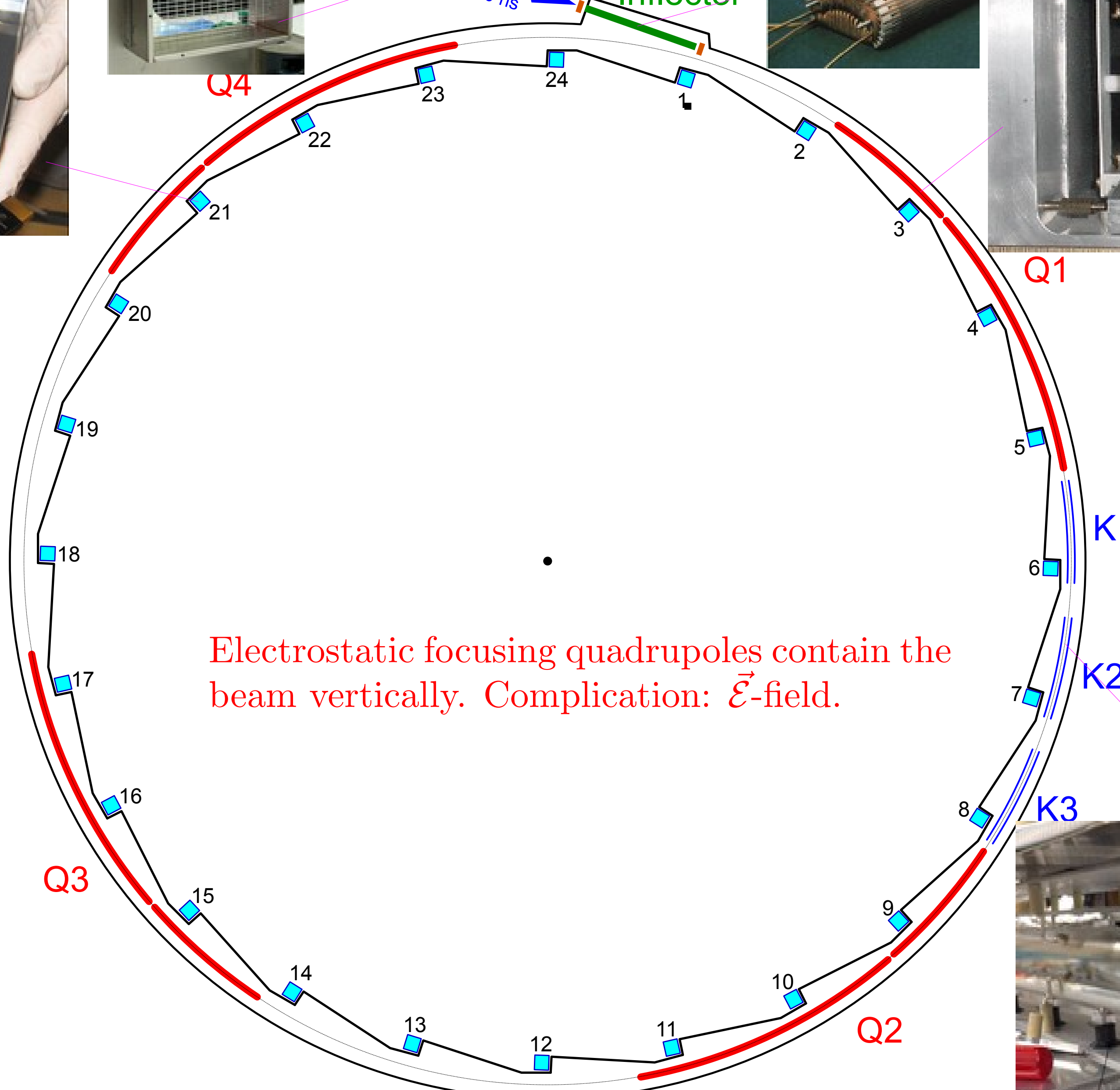
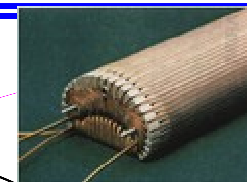
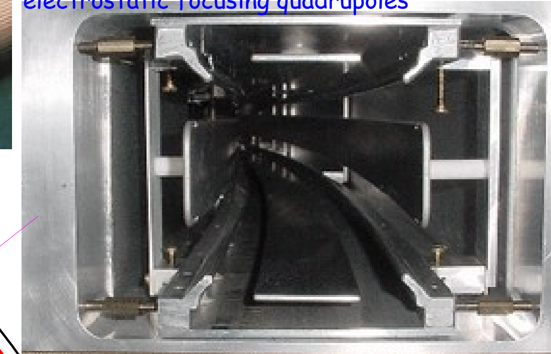
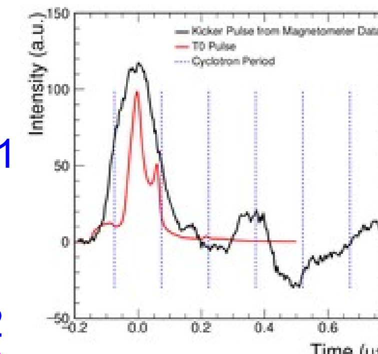




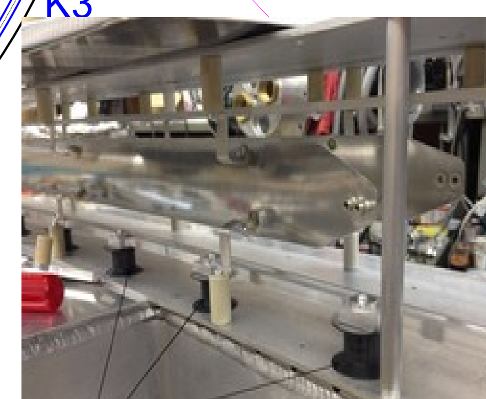
electrostatic focusing quadrupoles





Electrostatic focusing quadrupoles contain the beam vertically. Complication: $\vec{\mathcal{E}}$-field.

Kickers



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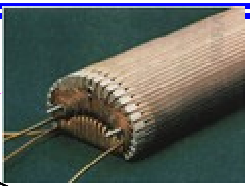
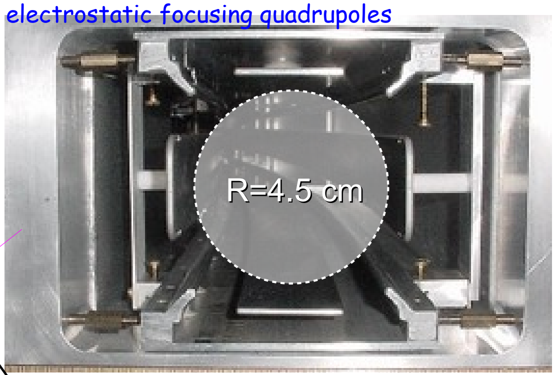
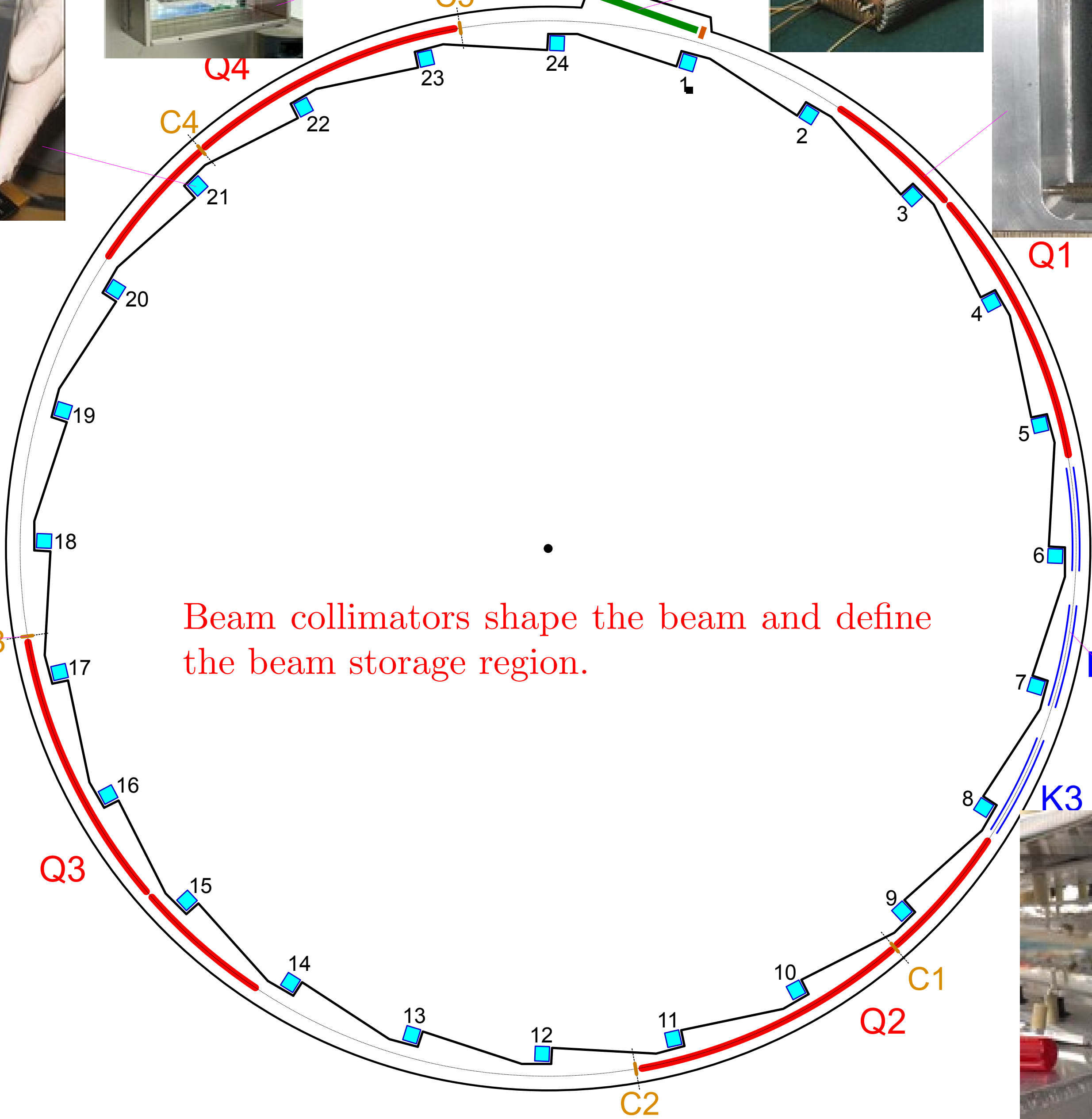
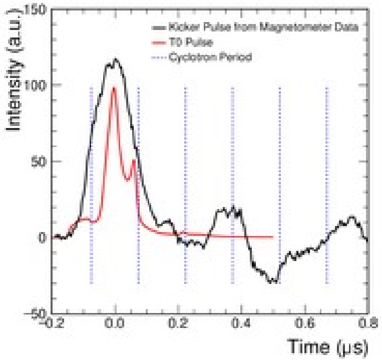


electrostatic focusing quadrupoles



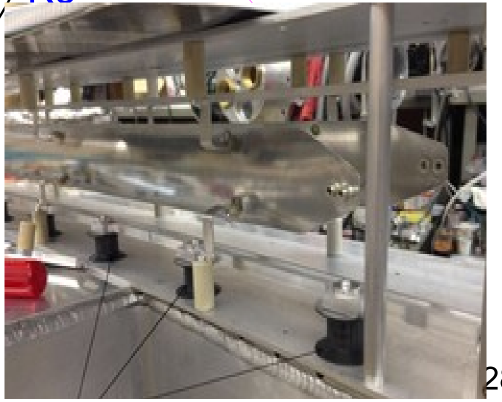




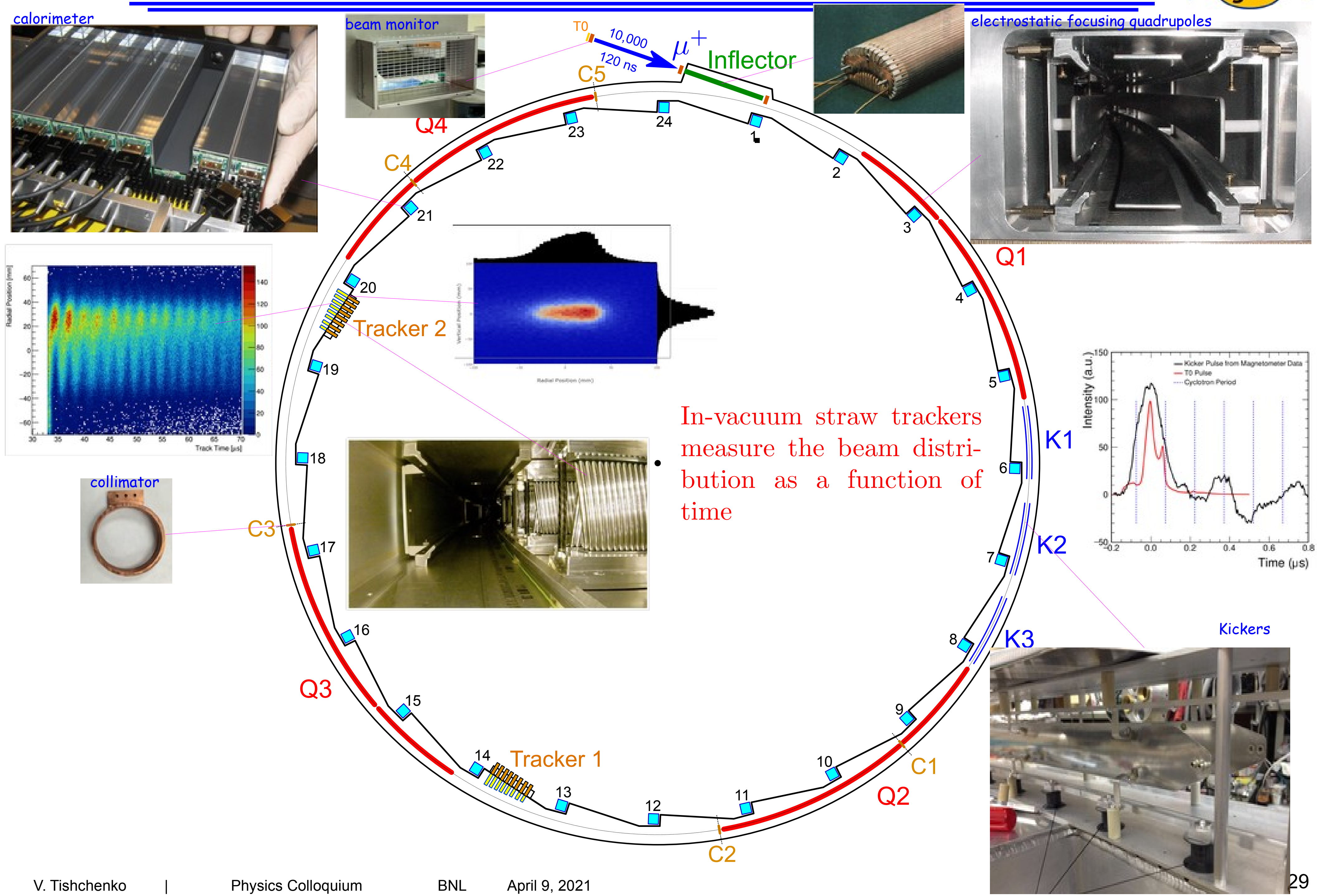
collimator

Beam collimators shape the beam and define the beam storage region.

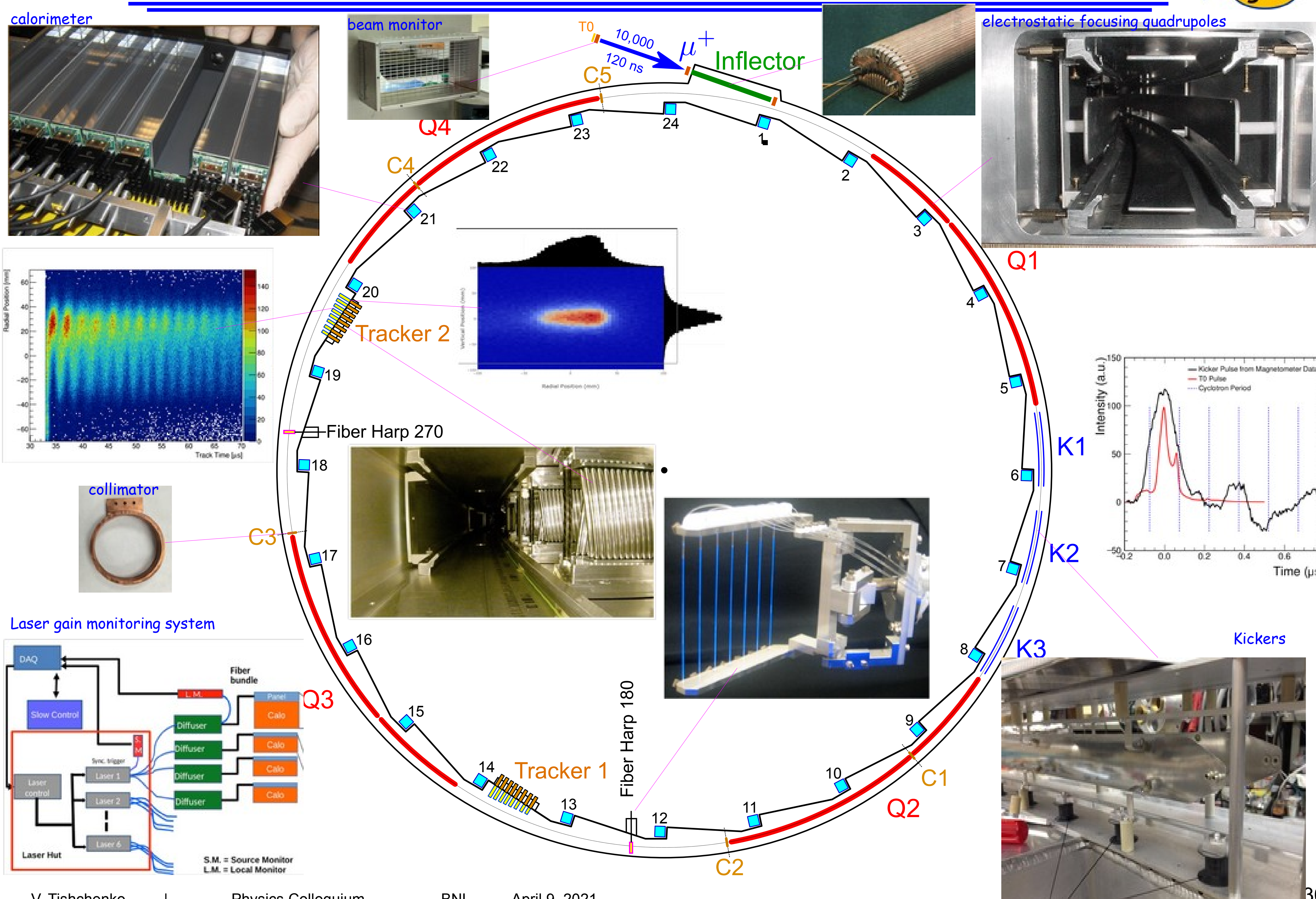
Kickers



g-2 storage ring anatomy



g-2 storage ring anatomy



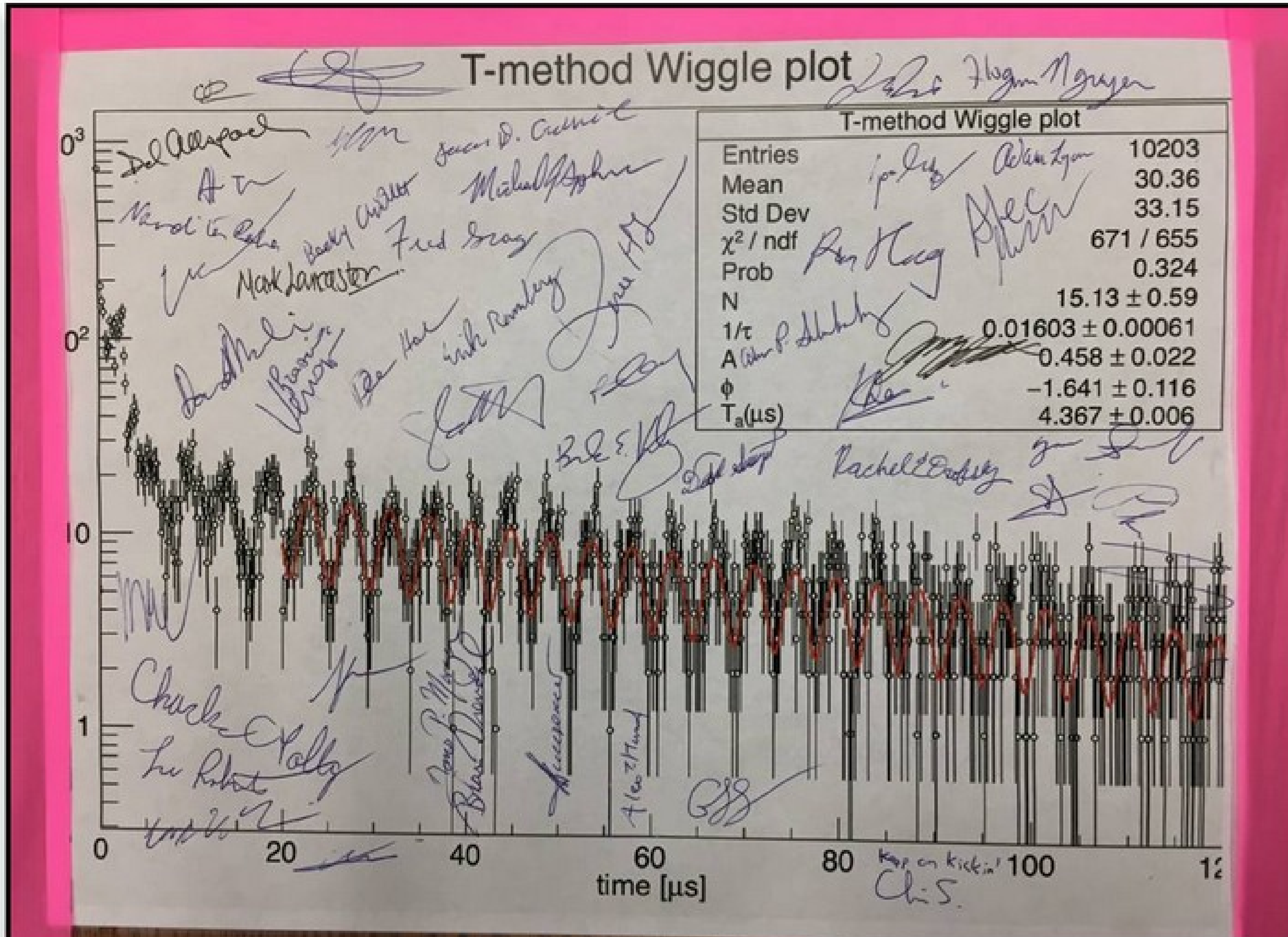
Commissioning run – Summer 2017

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018 | 2019 | 2020 | 2021

Withing a couple of weeks we had verified that:

- Detectors, electronics, DAQ worked to specification
- Injection systems could store the beam
- Generally, the observations were inline with expectations

First signal of muon spin precession – June 2017

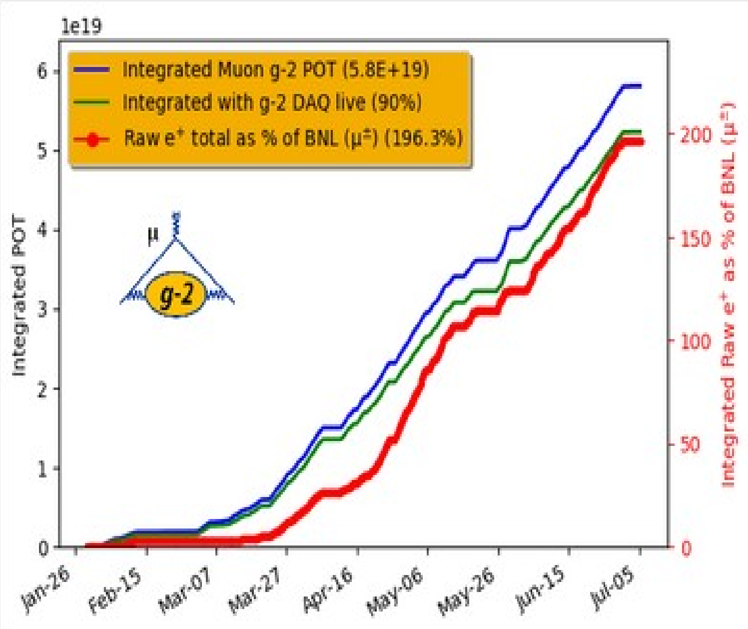


BNL roles in E989 project

- PO
  - W.M. Morse (Resident spokesman in E821, unique knowledge in all areas of the experiment, recognized for invaluable intellectual contributions in E989; g-2 ring transport L2 manager; Mentor)
  - J. Crnkovic (post-doc, ESQ operation expert, g-2 storage ring ops. coordinator)
  - V. Tishchenko (ESQ upgrade L3 manager, end-to-end beam simulations, beam and spin dynamics of stored muons)
  - A. Hoffman (technician, ESQ R&D)
- CAD
  - L. Snydstrup (Lead mechanical engineer in E821)
  - W. Meng (Superconducting inflector in E821)
  - J. Benante (Lead tech. in E821)
  - L. DeSanto (High-voltage systems engineer)
  - A. Zhang (Pulsed power engineer)

First Production run, 2018

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018** | 2019 | 2020 | 2021



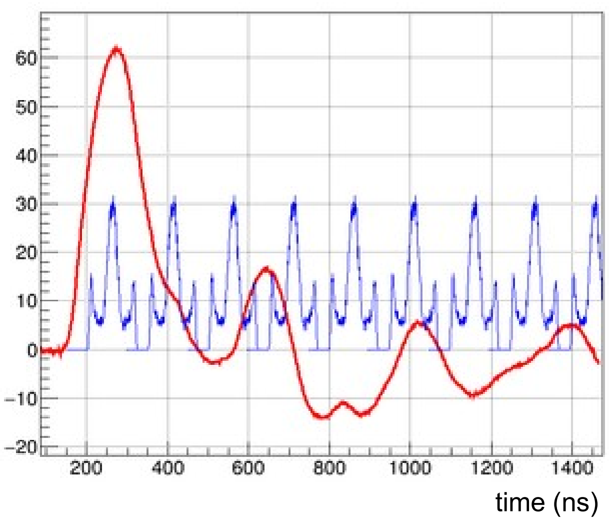
- Run 1: March 26 – July 7, 2018
- ~1.7xBNL statistics of raw data collected
- 8.2×10^9 e^+ after data quality cuts.

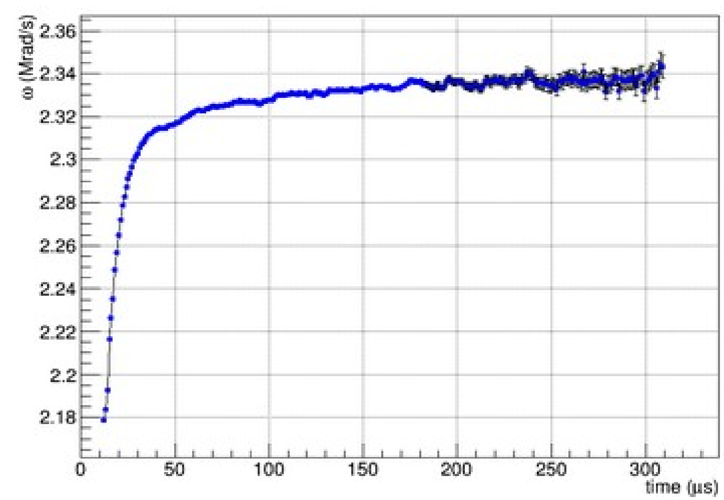
Challenges:

- Beam pulse is longer than design expectations
- Kicker current pulse: lower amplitude, ringing
- Non-ideal beam and kicker pulses affect
  - muon storage
  - stored beam momentum
  - stored beam dynamics (CBO)
- Kicker-quad interference
- Varying CBO frequency (2 damaged out of 32 HV resistors)

Run-1 data subset	ESQ (kV)	Kicker (HV)	$\delta\omega_a^m$ (stat) ppb
Run-1a	18.3	130	1206
Run-1b	20.4	137	1024
Run-1c	20.4	130	825
Run-1d	18.3	125	676†

† 50 μs fit start time



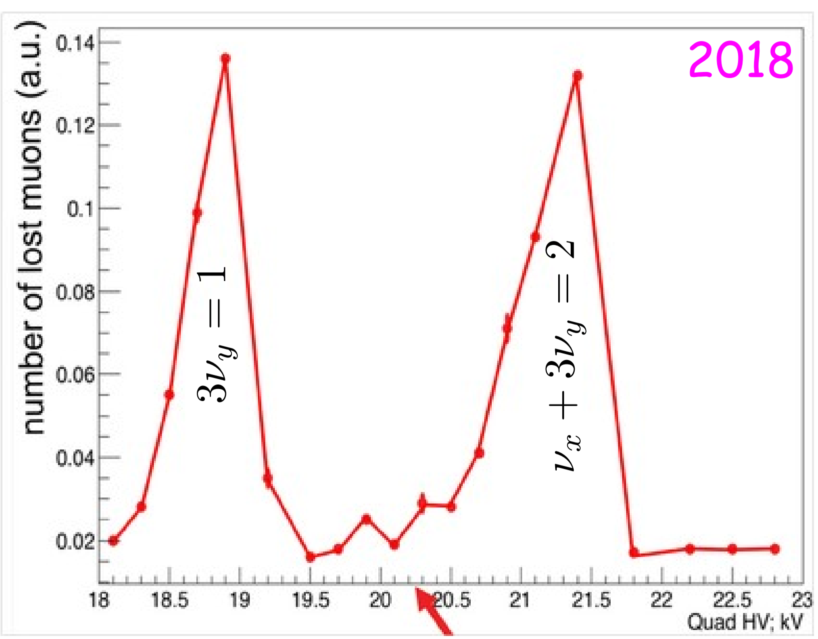


g-2 ring operating point for 2018 run

The ESQ system defines the operating point of muon g-2 storage ring, which must be chosen such that it is away from betatron and spin resonances. The theoretical analysis of resonance conditions was performed by BNL.

In 2018 run, the operation point of g-2 storage ring was chosen to minimize muon losses. The measured muon loss vs. ESQ voltage curve agrees well with theory expectation.

Run-1 data subset	ESQ (kV)	Kicker (HV)	$\delta\omega_a^m$ (stat) ppb
Run-1a	18.3	130	1206
Run-1b	20.4	137	1024
Run-1c	20.4	130	825
Run-1d	18.3	125	$676^{\dagger}$



Sudeshna Ganguly, Muon g-2 internal note #11085

$$\nu_x = \omega_x/\omega_c \approx \sqrt{1-n} \qquad \nu_x^2 + \nu_y^2 \approx 1$$

$$\nu_y = \omega_y/\omega_c \approx \sqrt{n} \qquad n \equiv \frac{kR_0}{vB}$$

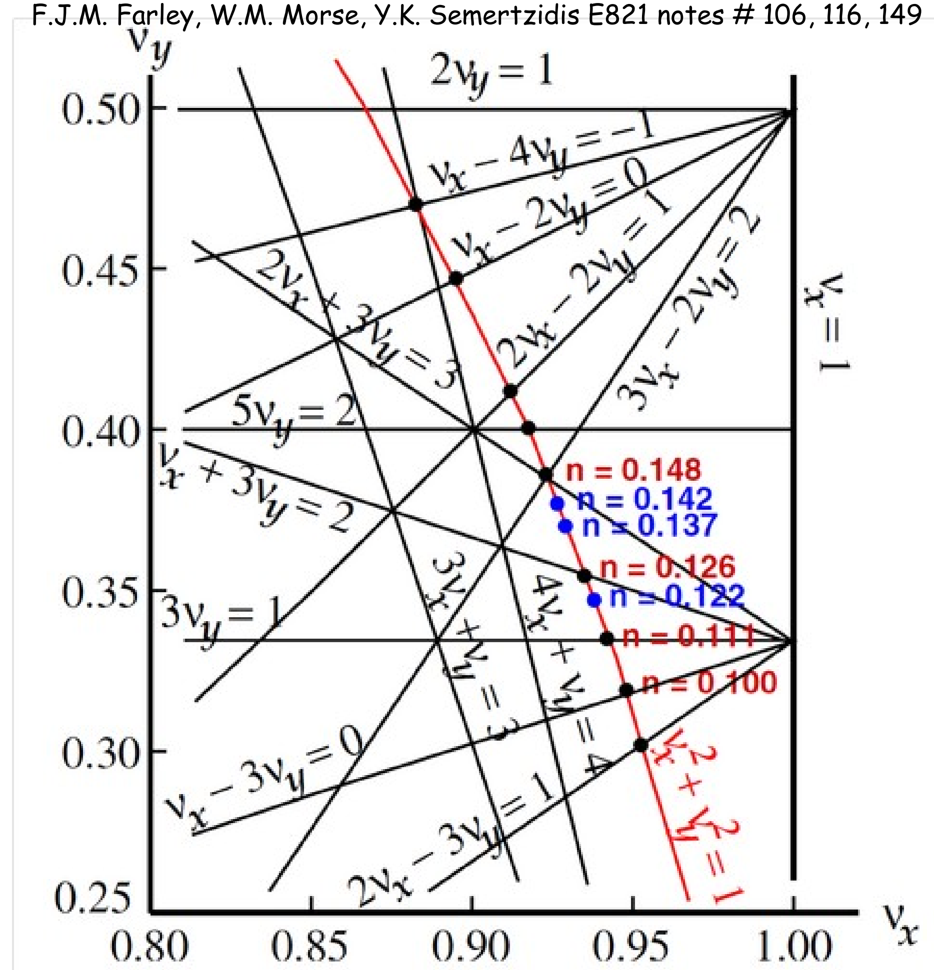
resonance conditions:

$$L\nu_x \pm M\nu_y \pm N = 0 \text{ (betatron)}$$

$$L\nu_x + M\nu_y \pm N = a_\mu\gamma \text{ (spin)}$$

where L, M, N are integers.

F.J.M. Farley, W.M. Morse, Y.K. Semertzidis E821 notes # 106, 116, 149



a_μ determination from data

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

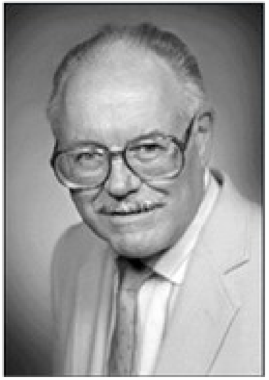
22 ppb
hyperfine splitting of muonium
CODATA

0.26 ppt
G. Gabrielse

10.5 ppb
$\mu'_p(T_\mathrm{r})$ proton shielded in a spherical water sample at $T_\mathrm{r} = 34.7°$ C
$\mu_e(H)$ electron bound in H
Metrologia, 13(4), 1977

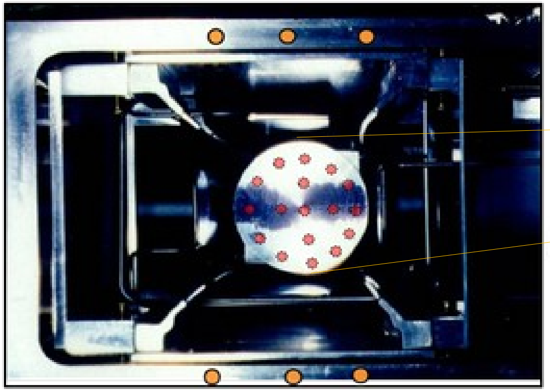
0.1 ppb
CODATA

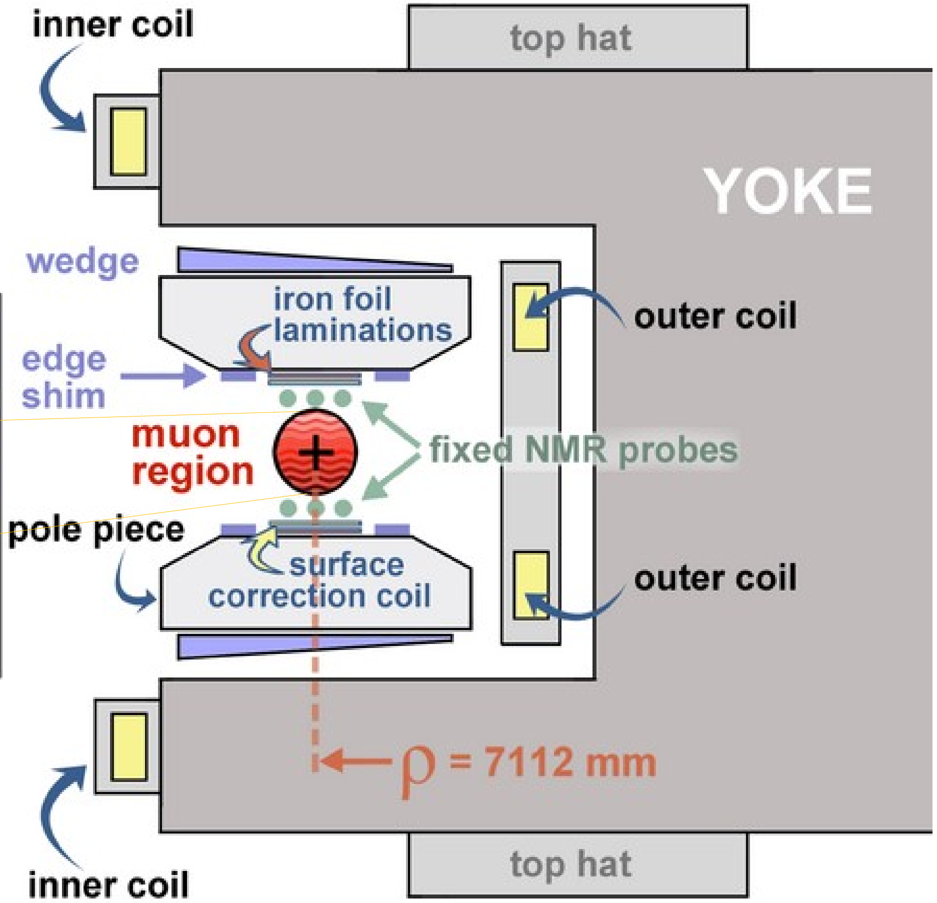
Magnet anatomy and $\omega'_p(T_r)$ measurement



Brilliant magnet design by Gordon Danby (BNL)

378 fixed NMR probes
17 NMR Trolley probes
A suit of shimming elements





12 C-shaped yokes
- 3 upper and 3 lower poles per yoke
- 72 total poles

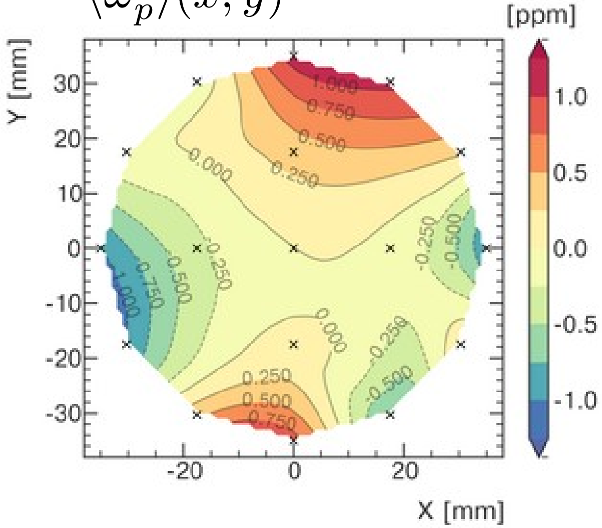
Shimming knobs
- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (dipole)
- Wedges (dipole, quadrupole)
- Edge shims (dipole, quadrupole, sextupole)
- Laminations (dipole, quadrupole, sextupole)
- Surface coils (quadrupole, sextupole,…)

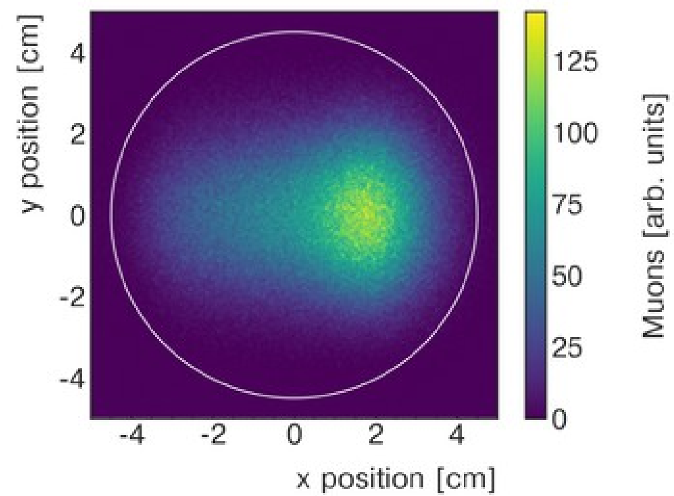
name	value
Magnetic field	1.45 T
Current	5200 A
Design orbit radius	7.112 m
Muon storoage region diameter	90 mm
Magnet gap	18 cm
Stored energy	6 MJ

NMR trolley maps the field at about 9000 locations over the entire azimuth every 3 days

$\tilde{\omega}'_p(T_r)$ determination

$$\tilde{\omega}'_p(T_\mathrm{r}) = \langle \omega'_p \rangle (x,y) \otimes \langle \rho^\mu \rangle (x,y)$$





Dataset	$\tilde{\omega}'_p(T_r)/2\pi$ (Hz)		Uncertainty (ppb)
Run-1a	61,791,871.2		115
Run-1b	61,791,937.8		127
Run-1c	61,791,845.4		125
Run-1d	61,792,003.4		108
Average Over All Datasets			
Field Measurements			56
ESQ Transient		(B_q)	92
Kicker Transient		(B_k)	37
Total			114

TABLE XIV: The final result for $\tilde{\omega}'_p(T_r)$ for each of the four datasets in Run-1. These numbers represent the Larmor precession frequency of protons in a spherical water sample in the same magnetic field experienced by the muons. The uncertainties are in ppb of 61.79 MHz.

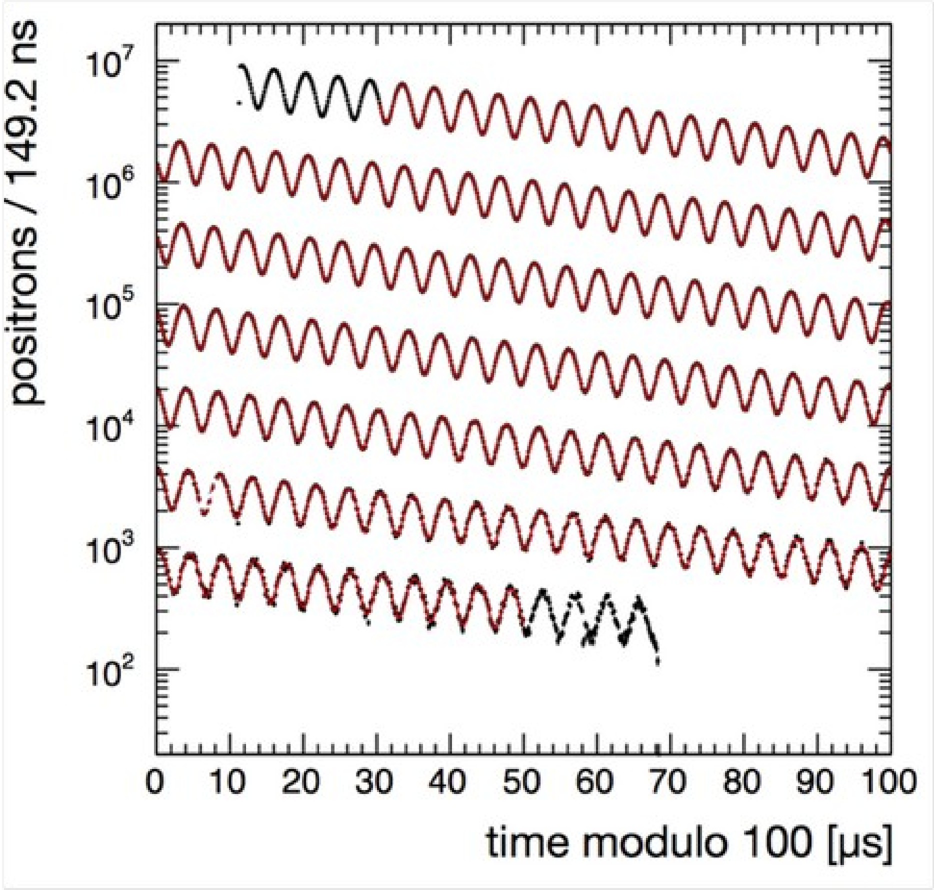
$$\tilde{\omega}'_p = \frac{\int_0^T \mathrm{d}t \int_0^{2\pi} \mathrm{d}\phi \int_{r_1}^{r_2} \mathrm{d}r \int_{-y_0}^{y_0} \mathrm{d}y \; r\rho^\mu(r,y,\phi,t)\omega'_p(r,y,\phi,t)}{\int_0^T \mathrm{d}t \int_0^{2\pi} \mathrm{d}\phi \int_{r_1}^{r_2} \mathrm{d}r \int_{-y_0}^{y_0} \mathrm{d}y \; r\rho^\mu(r,y,\phi,t)}$$

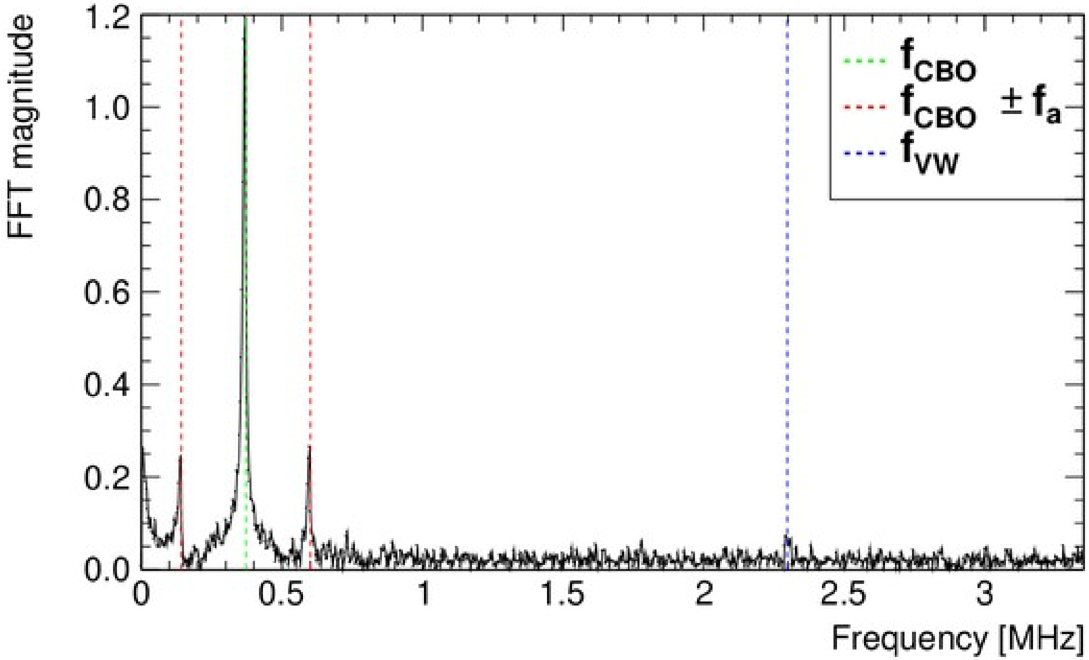
$$\times(1 + \underset{-17\ \mathrm{ppb}}{B_k} + \underset{-27\ \mathrm{ppb}}{B_q})$$

- Correction for transient fields from pulsed ESQ and Kicker
- Two different analysis methods
- Two independent analysis teams
- Total uncertainty: 114 ppb

ω_a^{m} extraction

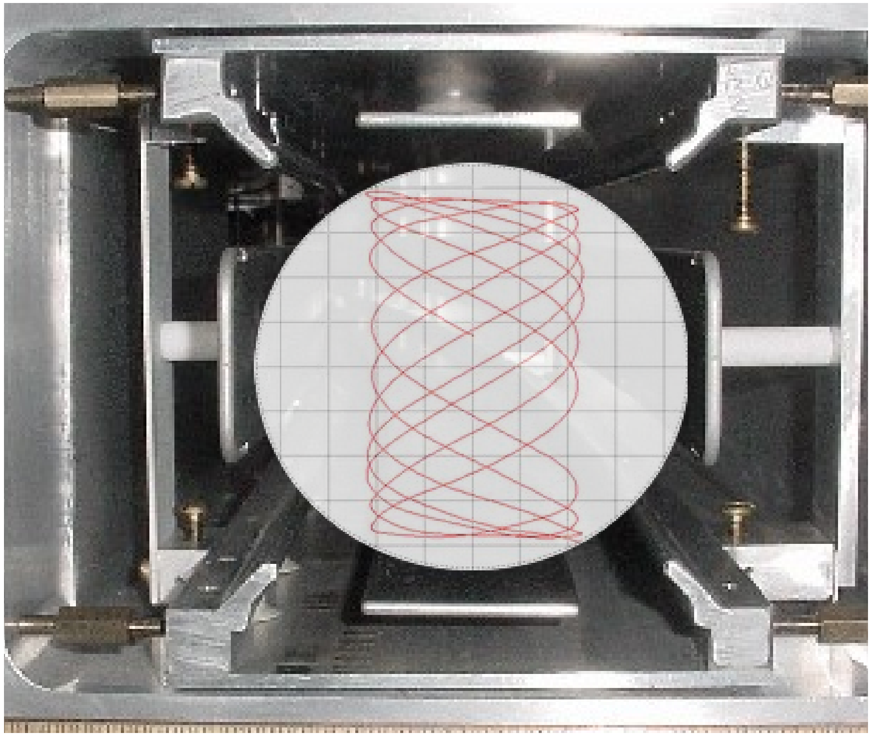
$$f_5(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot [1 + A \cdot \cos(\omega_a \cdot t + \varphi_0)]$$

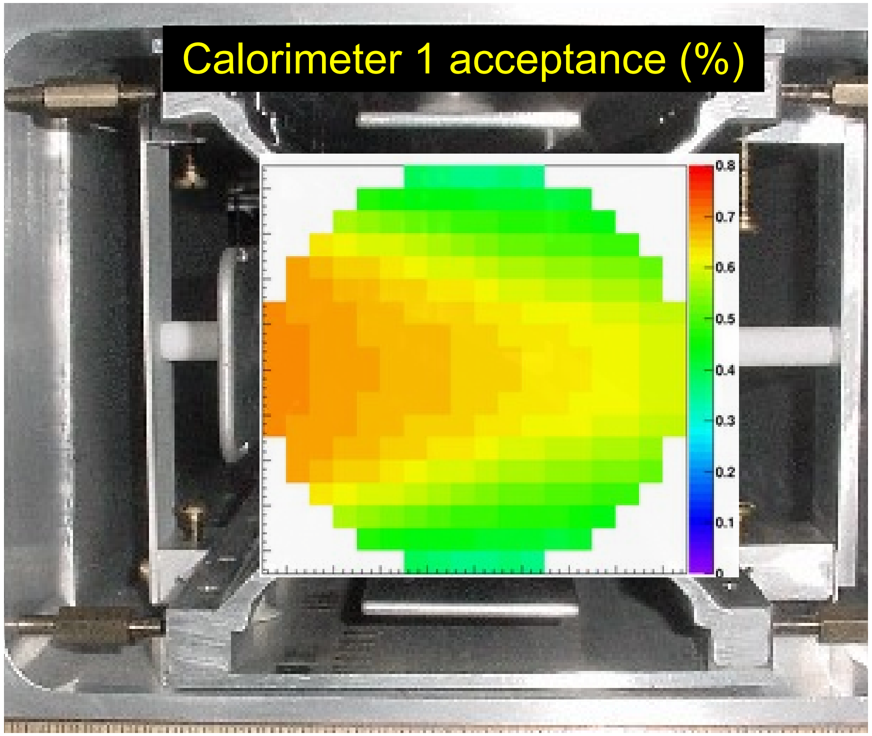




ω_a^{m} extraction

$$f_5(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot [1 + A \cdot \cos(\omega_a \cdot t + \varphi_0)]$$





$$N_0,\ A,\ \varphi_0 \ \rightarrow\ N_0(x,y),\ A(x,y),\ \varphi_0(x,y) \ \rightarrow\ N_0(t),\ A(t),\ \varphi_0(t)$$

ω_a^{m} extraction

$$f_5(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot [1 + A \cdot \cos(\omega_a \cdot t + \varphi_0)]$$

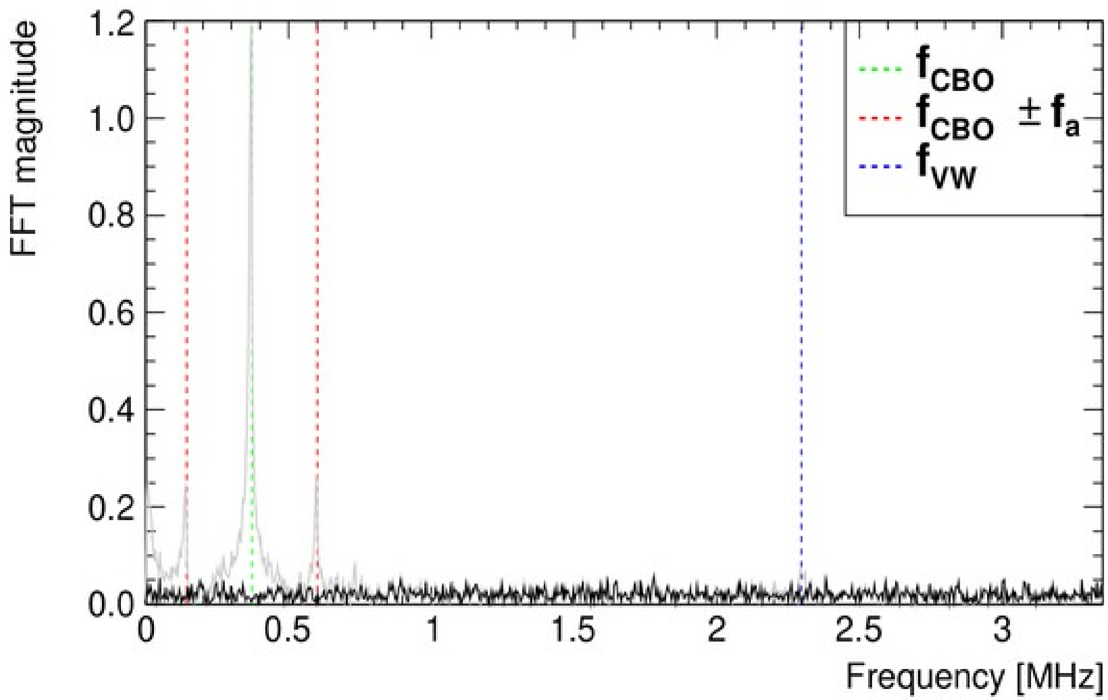
$$f_{22}(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\tau_\mu} [1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a \cdot t + \varphi_0 \cdot \phi_x(t))]$$

$$N_x(t) = 1 + e^{-1t/\tau_{\mathrm{CBO}}} A_{N,x,1,1} \cos(1\omega_{\mathrm{CBO}} t + \phi_{N,x,1,1}) + e^{-2t/\tau_{\mathrm{CBO}}} A_{N,x,2,2} \cos(2\omega_{\mathrm{CBO}} t + \phi_{N,x,2,2})$$

$$N_y(t) = 1 + e^{-1t/\tau_y} A_{N,y,1,1} \cos(1\omega_y t + \phi_{N,y,1,1}) + e^{-2t/\tau_y} A_{N,y,2,2} \cos(1\omega_{\mathrm{VW}} t + \phi_{N,y,2,2})$$

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

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



	N_0	τ_μ	A_0	φ_0	ω_{CBO}	τ_{CBO}	$A_{N,x,1,1}$	$\phi_{N,x,1,1}$	κ_{loss}	ω_y	τ_y
ω_a^m	-0.01	-0.00	0.00	-0.87	0.01	0.02	-0.03	-0.02	-0.01	0.00	-0.00

	$A_{N,y,2,2}$	$\phi_{N,y,2,2}$	$A_{N,x,2,2}$	$\phi_{N,x,2,2}$	$A_{A,x,1,1}$	$\phi_{A,x,1,1}$	$A_{\phi,x,1,1}$	$\phi_{\phi,x,1,1}$	$A_{N,y,1,1}$	$\phi_{N,y,1,1}$
ω_a^m	0.00	0.01	0.01	-0.00	0.02	-0.01	-0.00	-0.01	-0.00	-0.01

ω_a^{m} extraction

$$f_{22}(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu} \left[1 + A_0 \cdot A_x(t) \cdot \cos(\omega_a t + \varphi_0 \cdot \phi_x(t))\right]$$

$$N_x(t) = 1 + e^{-1t/\tau_{\rm CBO}} A_{N,x,1,1} \cos(1\omega_{\rm CBO} t + \phi_{N,x,1,1}) + e^{-2t/\tau_{\rm CBO}} A_{N,x,2,2} \cos(2\omega_{\rm CBO} t + \phi_{N,x,2,2}),$$

$$N_y(t) = 1 + e^{-1t/\tau_y} A_{N,y,1,1} \cos(1\omega_y t + \phi_{N,y,1,1}) + e^{-2t/\tau_y} A_{N,y,2,2} \cos(1\omega_{\rm VW} t + \phi_{N,y,2,2}),$$

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

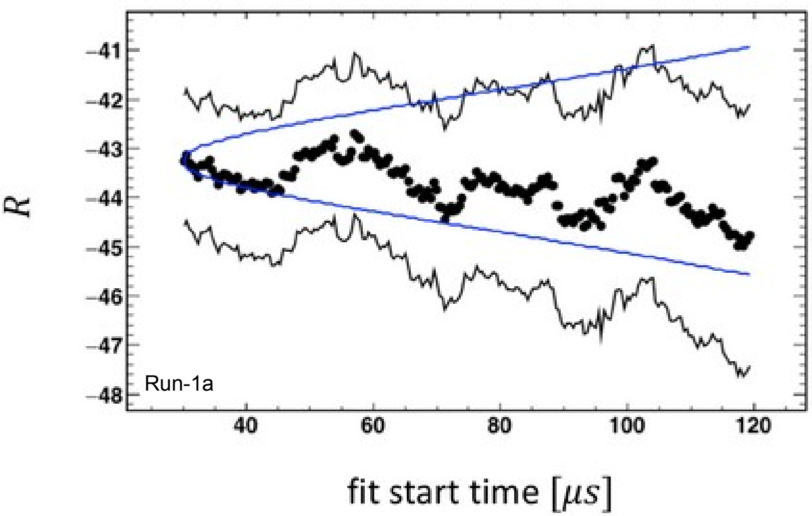
$$\phi_x(t) = 1 + e^{-1t/\tau_{\rm CBO}} A_{\phi,x,1,1} \cos(1\omega_{\rm CBO} t + \phi_{\phi,x,1,1})$$

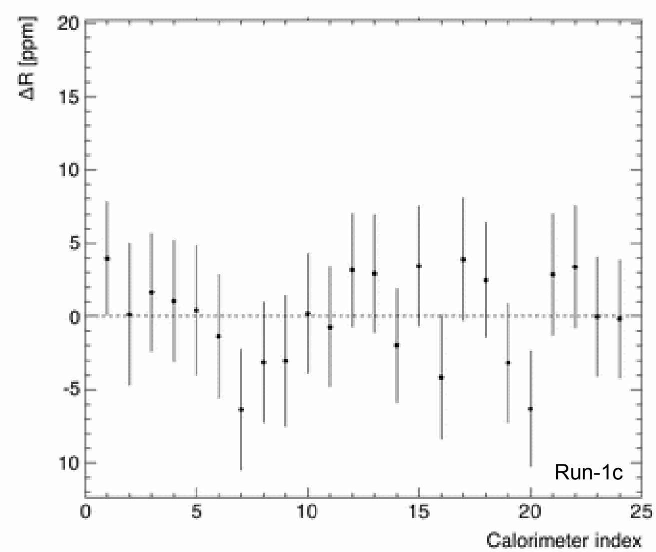
$$\Lambda(t) = 1 - K_{\rm loss} \int_0^t e^{t'/\gamma\tau} L(t') dt'$$

$\chi^2/\mathrm{NDF} = 3899/4000$

Run-1d

Parameter	Fit result	Parameter	Fit result
blinded R (ppm)	-16.01 ± 0.68	τ_y ()	168 ± 98
N_0	$(7249.8 \pm 3.5) \times 10^3$	$A_{N,y,2,2}$	0.00039 ± 0.00022
$\gamma\tau_\mu$ ()	64.4478 ± 0.0023	$\phi_{N,y,2,2}$	2.10 ± 0.65
A_0	0.355193 ± 0.000021	$A_{N,x,2,2}$	0.000198 ± 0.000059
ϕ_0	2.07519 ± 0.00013	$\phi_{N,x,2,2}$	-3.35 ± 0.30
$\omega_{\rm CBO}$ (s^{-1})	2.33593 ± 0.00030	$A_{A,x,1,1}$	0.00059 ± 0.00014
$\tau_{\rm CBO}$ ()	190 ± 11	$\phi_{A,x,1,1}$	-0.38 ± 0.24
$A_{N,x,1,1}$	0.003237 ± 0.000097	$A_{\phi,x,1,1}$	0.000108 ± 0.000072
$\phi_{N,x,1,1}$	-6.081 ± 0.029	$\phi_{\phi,x,1,1}$	-3.19 ± 0.66
$K_{\rm loss}$	0.00903 ± 0.00036	$A_{N,y,1,1}$	-0.000082 ± 0.000046
κ_y	1.01398 ± 0.00063	$\phi_{N,y,1,1}$	-5.98 ± 0.58



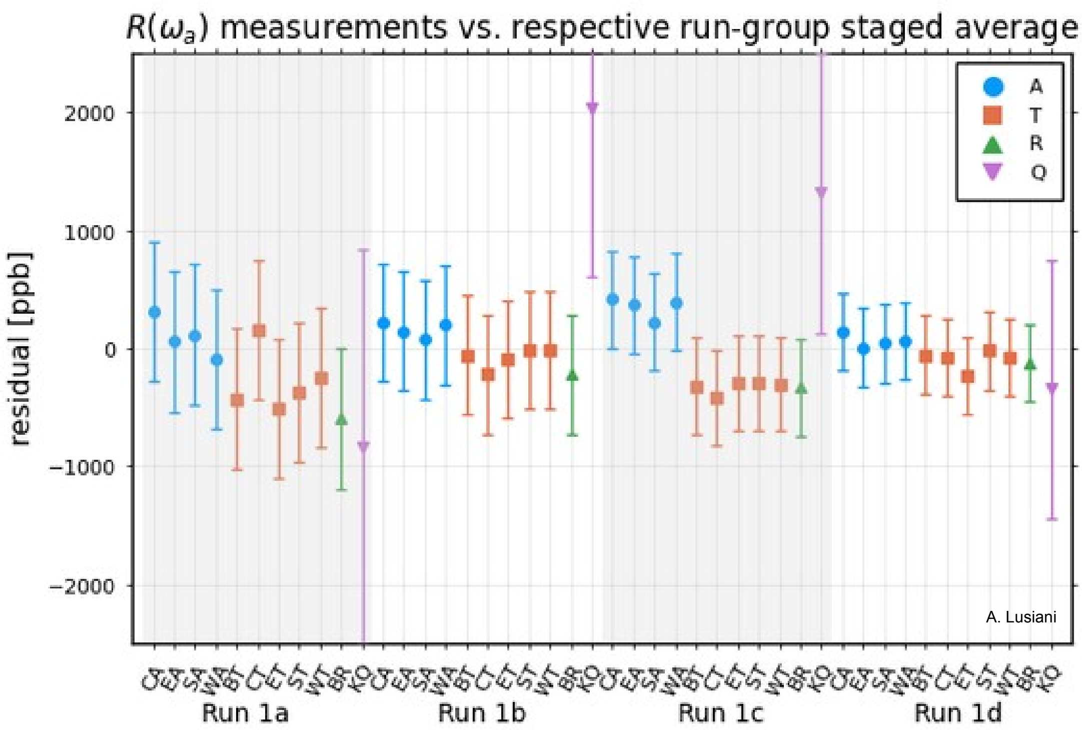


ω_a^{m} extraction

- 4 different analysis methods (T,Q,R,A)
- 6 independent analysis teams (Boston, Cornell, Kentucky, Washington, Europa, Shanghai)
  - unique mix of reconstruction, analysis and independent data-driven corrections to determine ω_a
  - varying sensitivities to potential systematic effects, as well as varying statistical sensitivities.
- Blind analysis
  - Frequency is measured in units of digitizer clock ticks
  - Each analyzer uses its own secret offset
- Two-step unblinding process
  - Relative unblinding (Feb. 7,2020) Excellent agreement between all 11 results
  - Absolute unblinding (Feb 25, 2021)

`

data set	1a	1b	1c	1d
$\omega_a^{m}/2\pi$ (s^{-1})	229080.957	229081.274	229081.134	229081.123
$\Delta(\omega_a^{m}/2\pi)$ (s^{-1})	0.277	0.235	0.189	0.155
statistical uncertainty (ppb)	1207	1022	823	675
Gain changes (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Time randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
total systematic uncertainty (ppb)	64	70	54	49
total uncertainty (ppb)	1209	1025	825	676



A-measurements are compared with TR- staged average
non-A measurements are compared with A staged average

staged average means
first average same-reco measurements with equal weigths
then average the first step averages with equal weights

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ω_a determination

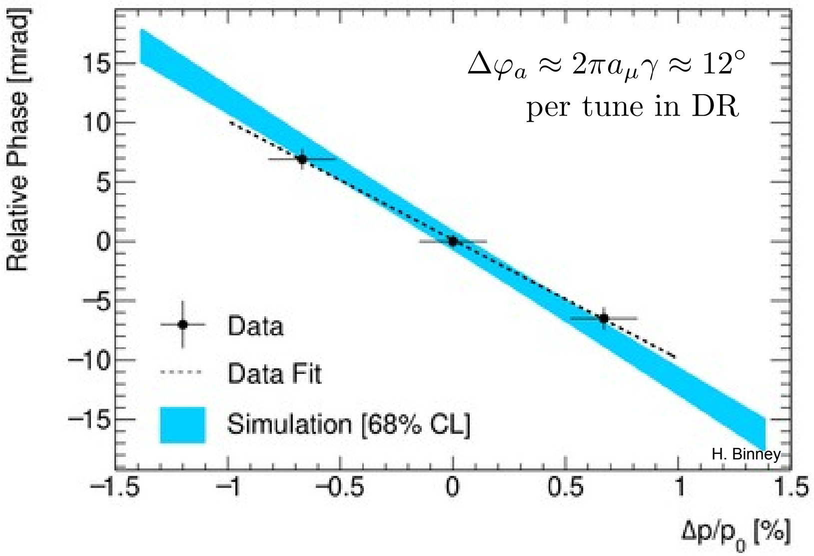
$$\frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s}_{\perp}\cdot\left[a_\mu\hat{\beta}\times\vec{B} + \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{0 \text{ at } p_\mu = 3.09 \text{ GeV/c}}\beta\vec{\mathcal{E}}\right]$$

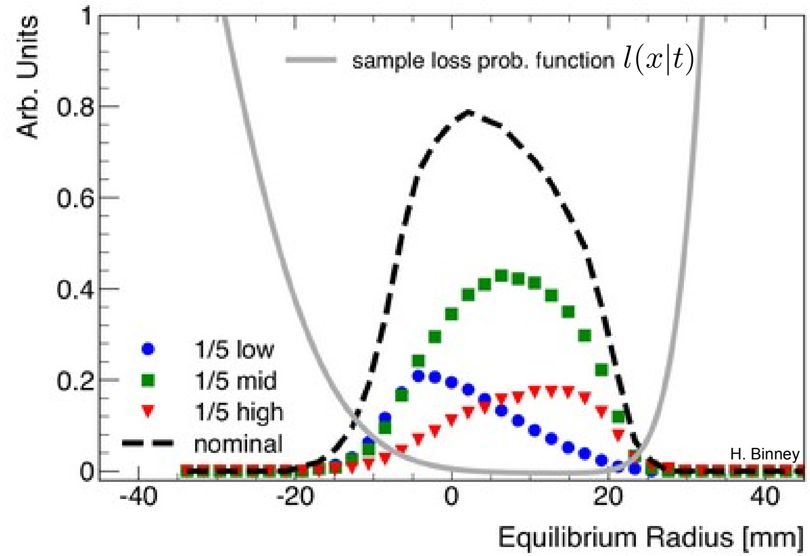
If $\mathcal{E} = 0$ and $\vec{\beta} \perp \vec{B}$: $\quad a_\mu = \frac{m}{e}\frac{\omega_a}{B}$

$$\omega_a = \omega_a^m \cdot (1 + C_\mathrm{p} + C_\mathrm{e} + C_\mathrm{ml} + C_\mathrm{pa})$$

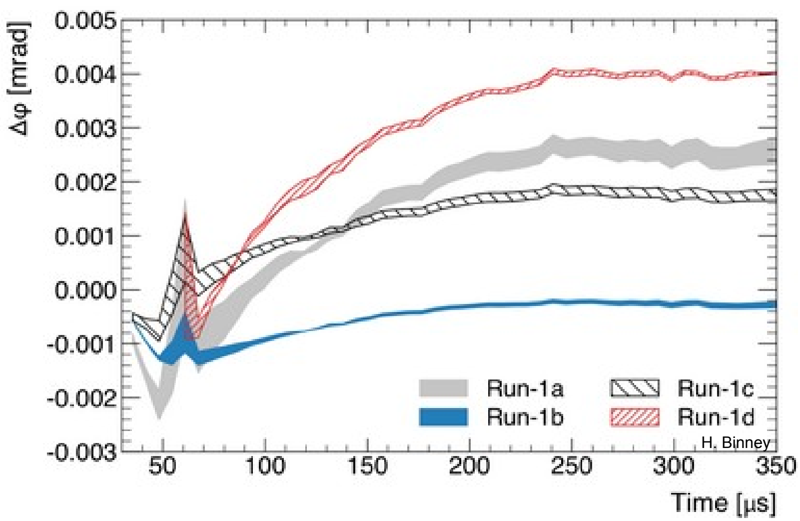
	Correction (ppb)	Uncertainty (ppb)
ω_a^m statistical	–	434
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
C_total	499	93

C_{ml}





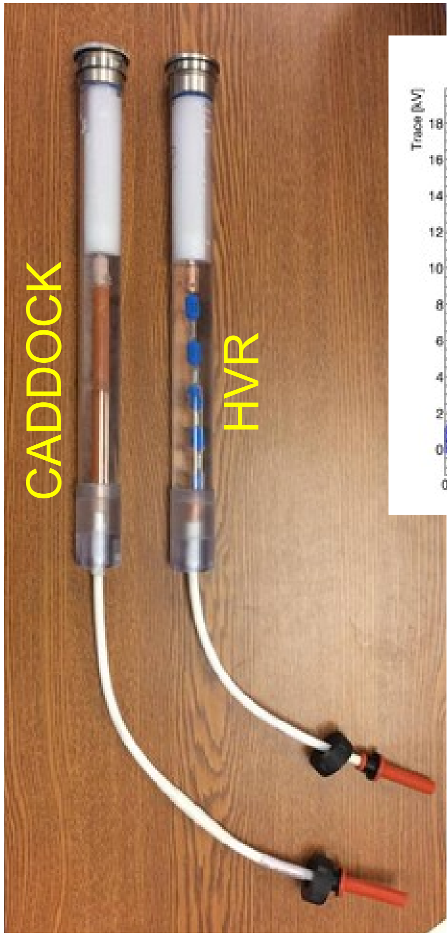
In this time window, the loss probability is greater at low momentum than at high momentum.



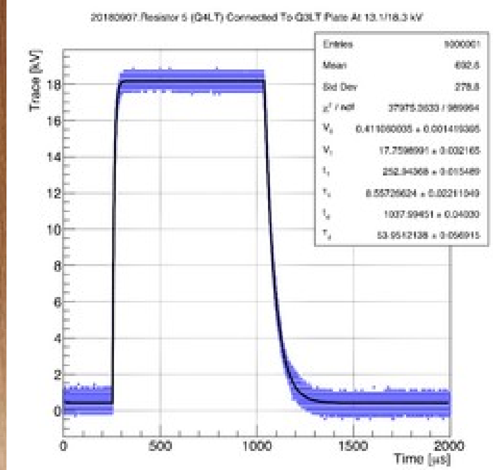
Data Set				
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6

C_{pa} and damaged HV resistors

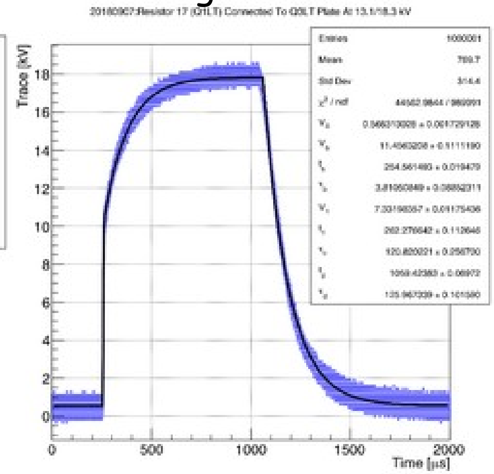
Degradation of two (out of 32) of HVR HV resistors in Q1-Long (top and bottom plates).

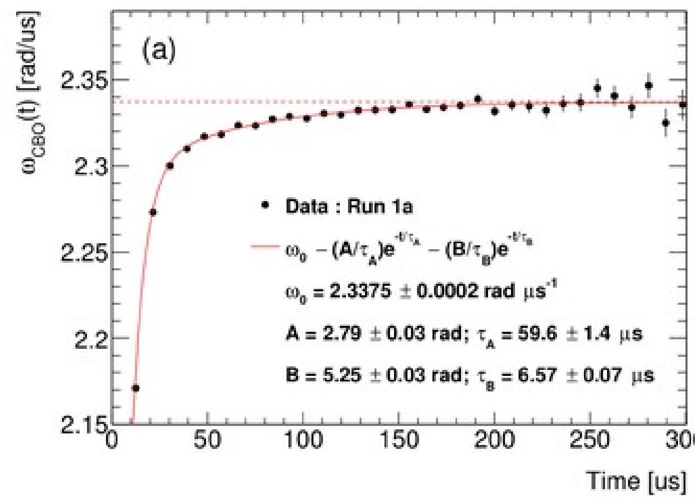


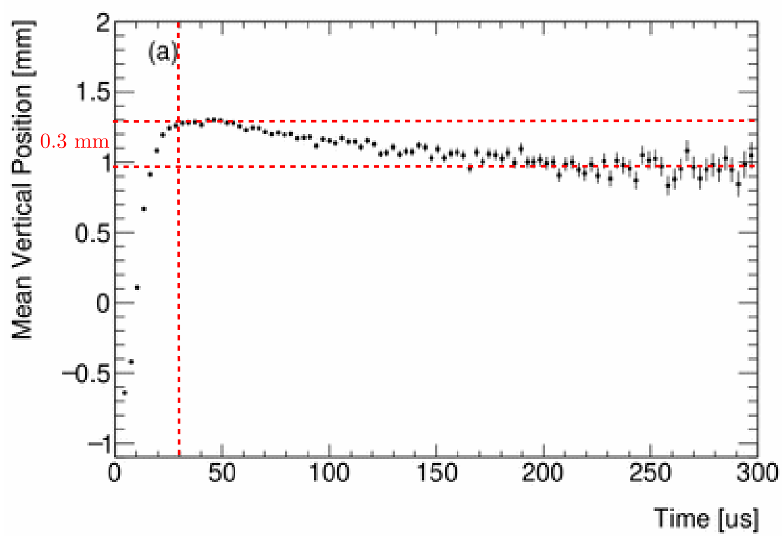
Nominal

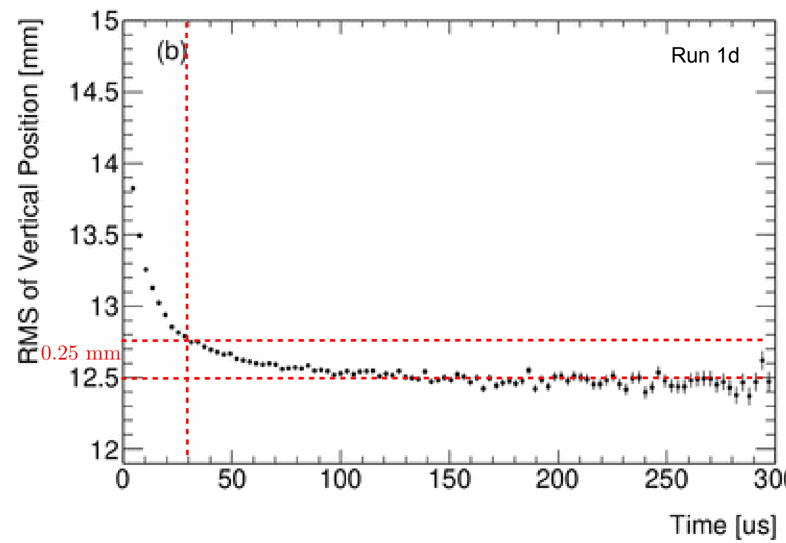


Damaged resistor



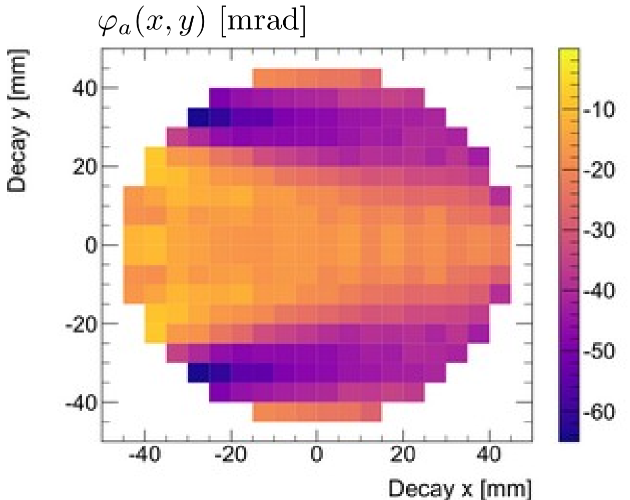






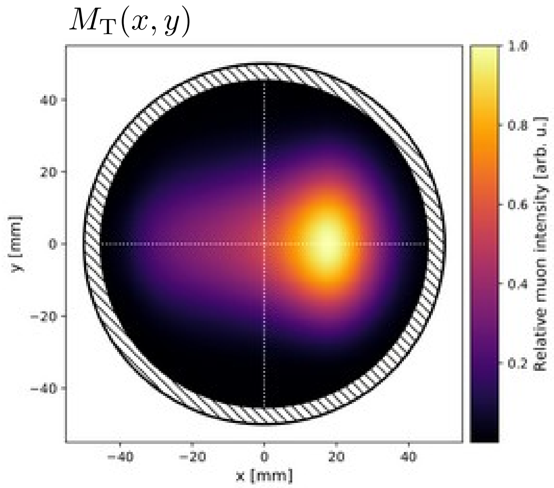
C_{pa}

$\varphi_a(x,y)$ [mrad]



$\otimes$

$M_{\mathrm{T}}(x,y)$



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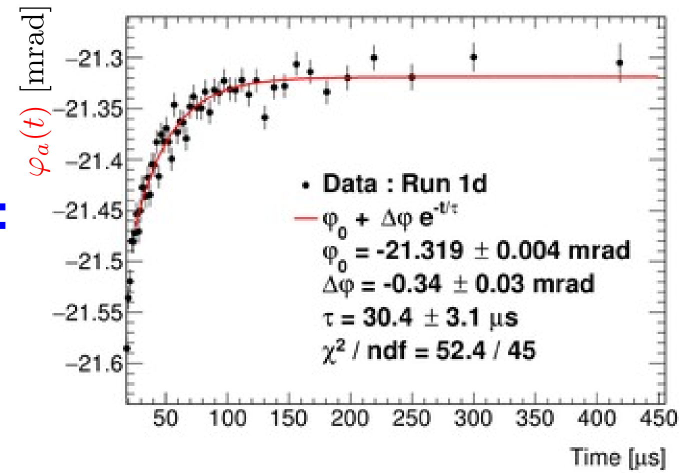
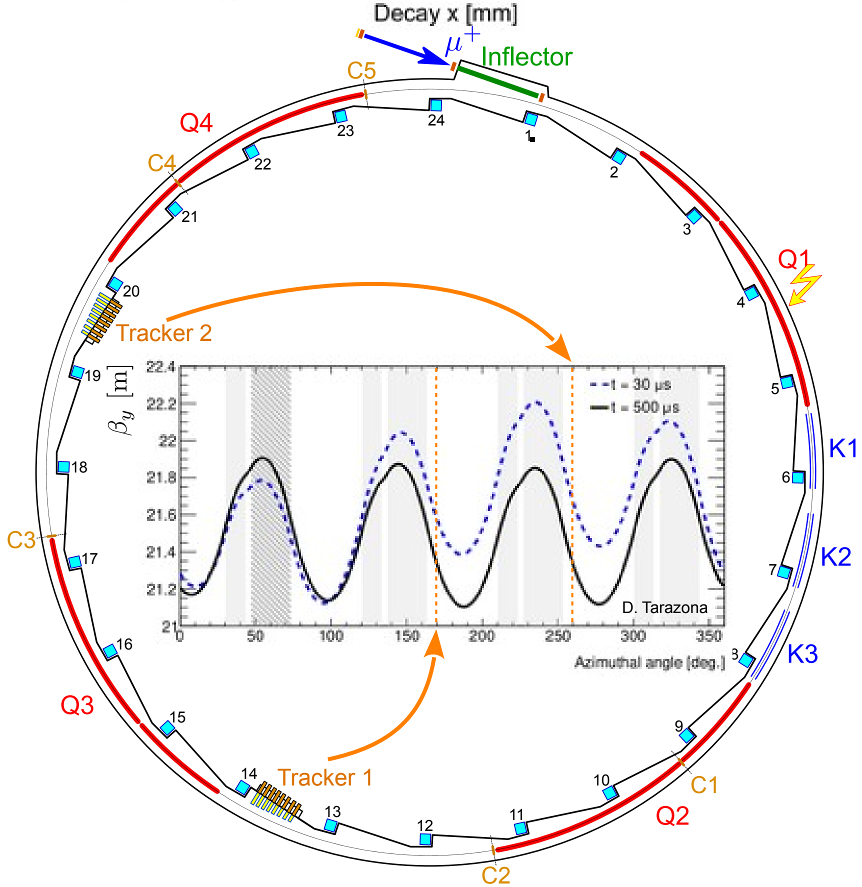




$$\varphi_a(t) = \arctan \frac{\sum_{ij} M_T(x_i,y_j,t)\cdot\varepsilon_c(x_i,y_j)\cdot A(x_i,y_j)\cdot\sin(\varphi_a(x_i,y_j))}{\sum_{ij} M_T(x_i,y_j,t)\cdot\varepsilon_c(x_i,y_j)\cdot A(x_i,y_j)\cdot\cos(\varphi_a(x_i,y_j))}$$

$$f_{22}(t) = N_0\cdot N_{xy\Lambda}(t)\cdot e^{-t/\tau_\mu}\left[1 + A(t)\cdot\cos(\omega_a\cdot t + \varphi_0\cdot\phi_x(t) + \varphi_a(t))\right]$$

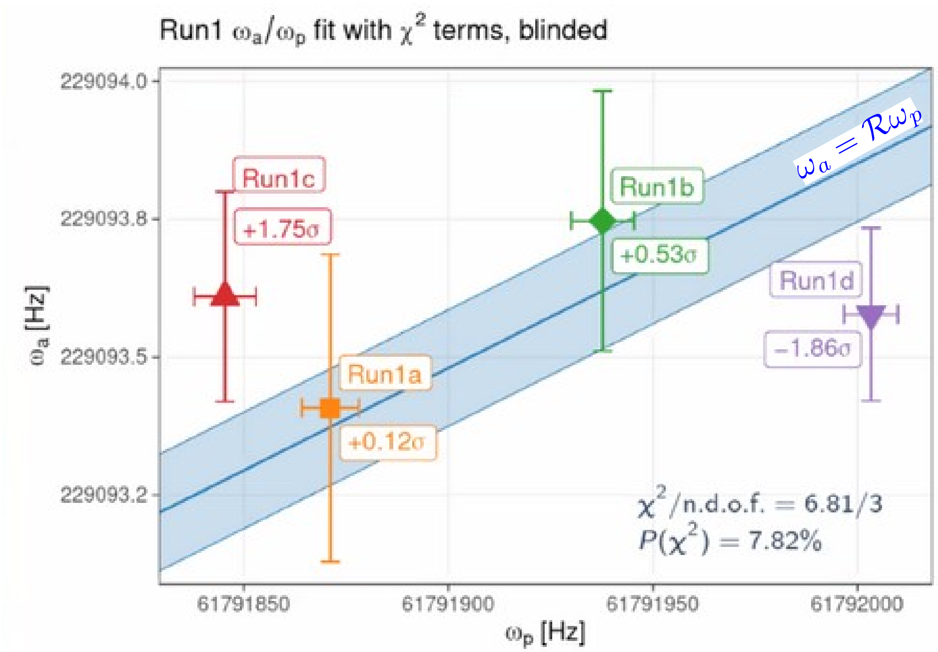
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

Summary of unblinded Run-1 measurements

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

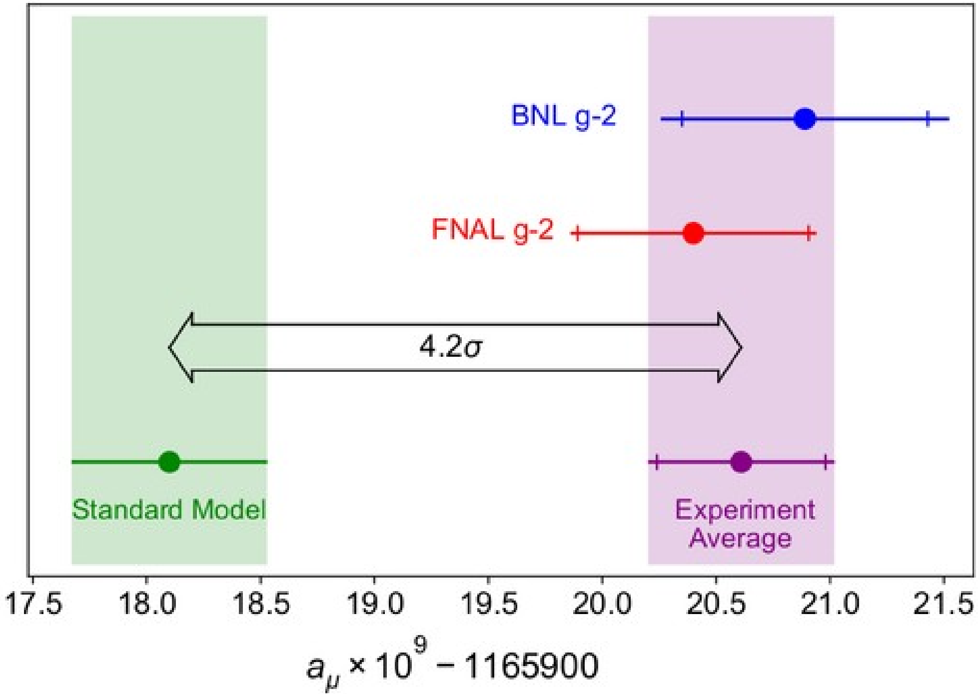
Run	$\omega_a/2\pi$ [Hz]	$\tilde{\omega}'_p/2\pi$ [Hz]	$\mathcal{R}'_\mu \times 1000$
1a	229081.06(28)	61791871.2(7.1)	3.7073009(45)
1b	229081.40(24)	61791937.8(7.9)	3.7073024(38)
1c	229081.26(19)	61791845.4(7.7)	3.7073057(31)
1d	229081.23(16)	61792003.4(6.6)	3.7072957(26)
Run-1			3.7073003(17)

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
$\mu'_p(34.7^\circ C)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462



Final result

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm}),$$
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm}).$$



From top to bottom: Experimental values of a_μ from BNL E821, FNAL E989 Run-1, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value for the Standard Model is also shown.

$$a_\mu(\text{FNAL}) - a_\mu(\text{SM}) = (230 \pm 69) \times 10^{-11}\ (3.3\sigma)$$
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}\ (4.2\sigma)$$

Summary

- The muon $g-2$ experiment E989 at Fermilab measured a_μ at 0.46 ppm in Run-1
- The result is consistent with the one obtained by E821 collaboration at BNL
- The combined experimental results differrs from current SM prediction by 4.2σ. However, there are new lattice results (yet to be confirmed by independent lattice calculatoins) suggesting smaller discrepancy between theory and experiment.

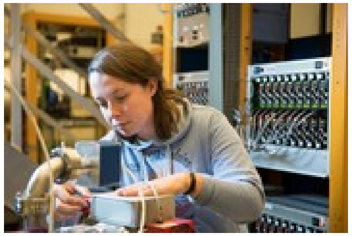
HET Lunch Seminar

Open g-2 discussion

Friday 9 Apr 2021, 12:30 → 13:30 US/Eastern – today!

https://indico.bnl.gov/event/10430/

Also, two more seminars in the JETP series at FNAL



- Saskia Charity (Fermilab) April 23rd
  Precision measurement of the magnetic field in Run 1

- Lawrence Gibbons (Cornell) April 30th
  The Run 1 anomalous muon precession frequency analysis