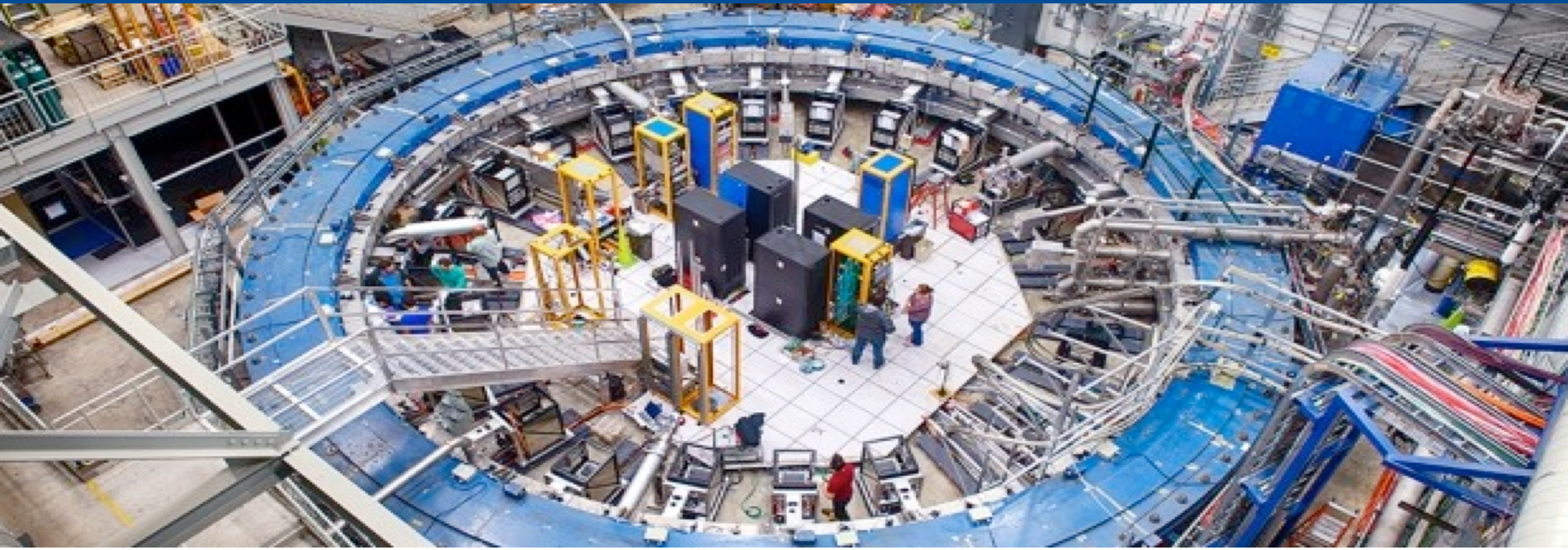


First results from the Muon g-2 Experiment at Fermilab

Graziano Venanzoni– INFN Pisa
(on behalf of the Muon g-2 Collaboration)

LNF 15 April 2021

Outline

- How to measure g-2 in a storage ring
- The Muon g-2 experiment at Fermilab
  - RUN1 Analysis
  - Results and comparison with BNL
- Italian contribution
- Future
- Conclusions

Antonio Anastasi (18/9/1989-23/3/2020)

Muon g-2

(Antonio in Seattle in 2015)

- Summer student at Fermilab 2013
- Master Thesis on the Laser Calibration system in 2013 (first Italian master student in g-2)
- PhD Thesis on the Laser Calibration system in 2017 (**first PhD in E989**, see https://gm2-docdb.fnal.gov/cgi-bin/private/RetrieveFile?docid=4911&filename=Thesis_anastasi.pdf&version=1)
- TB at SLAC in 2014 and at Frascati in 2016 (leading the efforts)
- Many helps and contributions on the finalization of the laser system.
- Author of "calorimeter/laser" Technical papers (NIM/JINST)

Antonio was an exceptional person in his freshness and with his enthusiasm and talent. His positive being was contagious. He was full of life and love for what he did and he was a person of great faith and very sunny. The strength with which he has faced the last years of his life during the illness will remain an indelible teaching. No words can express how we miss him.

DOTTORATO DI RICERCA IN FISICA *XXIX* CICLO

The Calibration System of the E989 Experiment at Fermilab
PhD Thesis
Antonio ANASTASI

SSD:FIS04

PhD Coordinator:
Prof. Lorenzo TORRISI

Tutor:
Dr. Giuseppe MANDAGLIO
Co-Tutor:
Dr. Graziano VENANZONI
Co-Tutor:
Prof. David HERTZOG

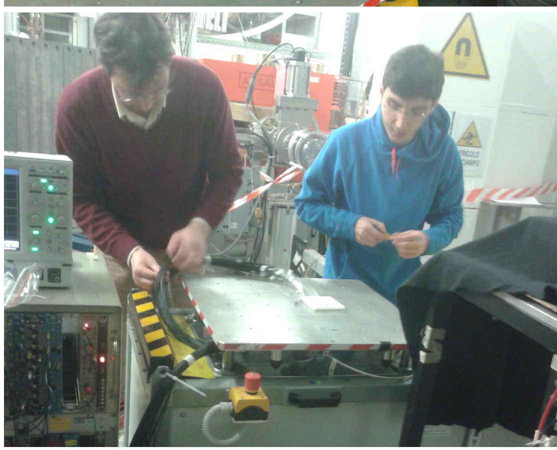
Triennio 2014/2016

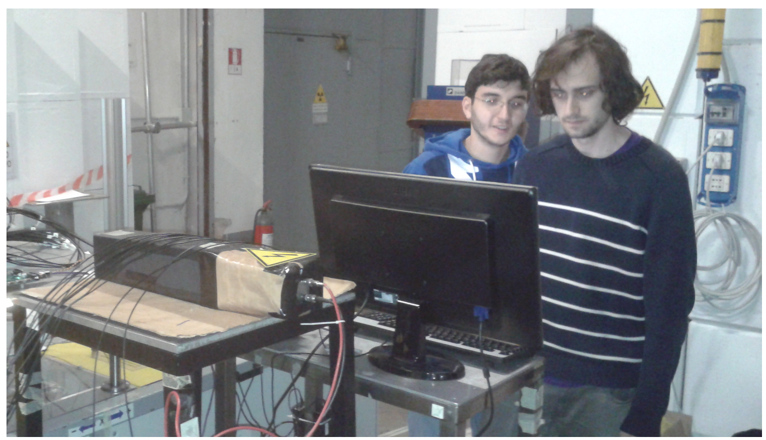
At Mephi (December 2015)

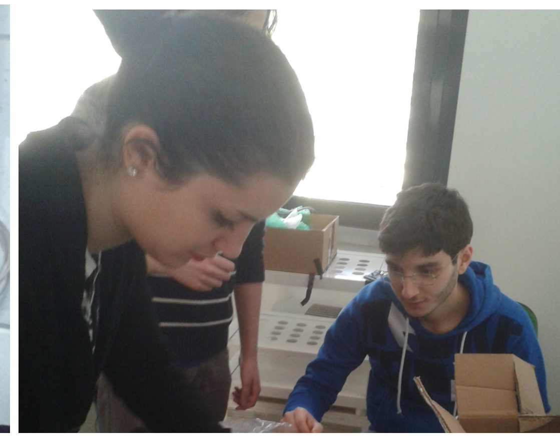
...one flash of memory...

Wonderful experience

TB at LNF- Frascati February 2016







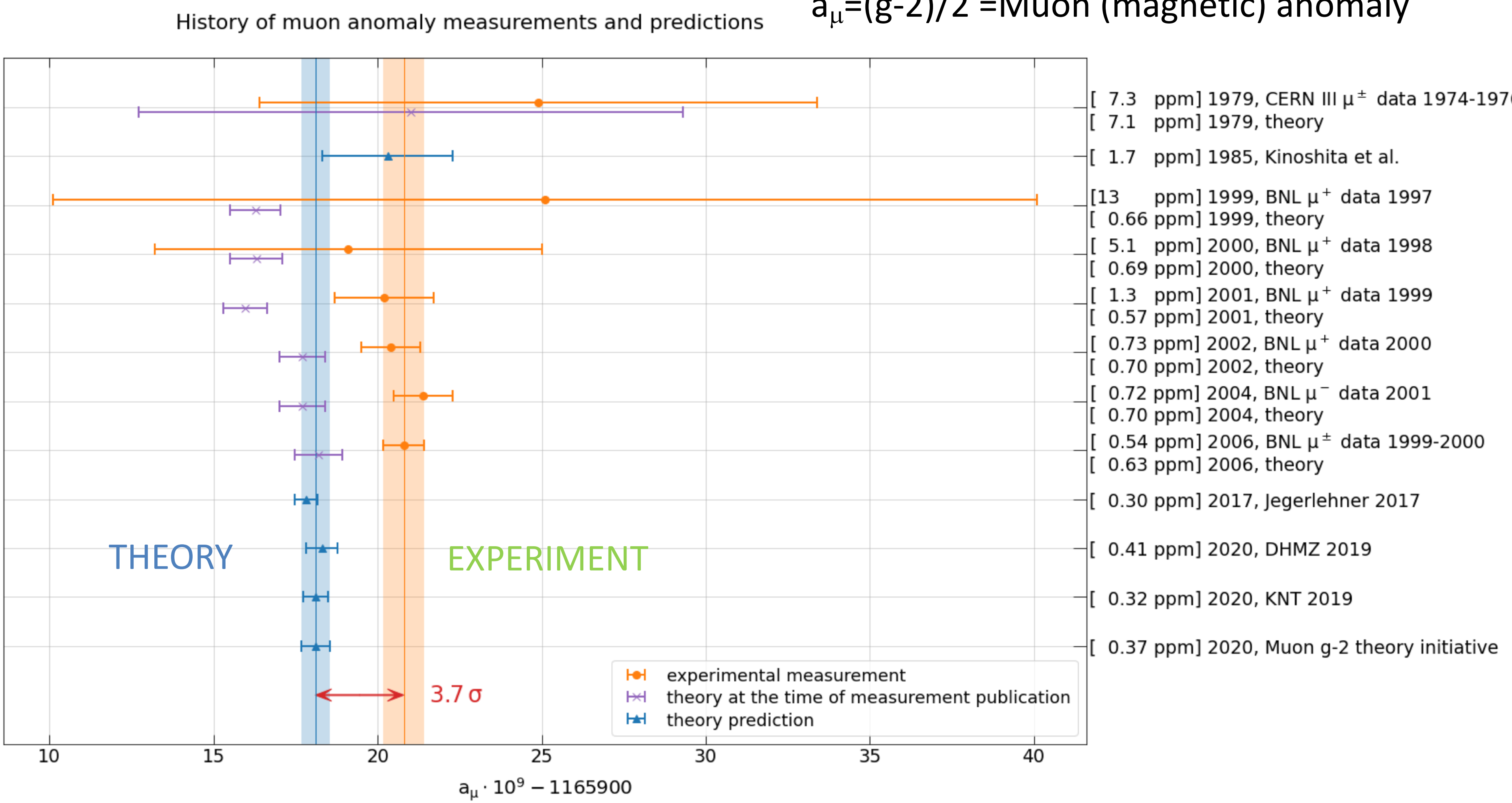
Nucl.Instrum.Meth.A 842 (2017) 86-91 • e-Print: [1610.03210](1610.03210)

Caveat

In the following I will refer to $\mathbf{a_\mu = (g\text{-}2)_\mu/2}$
as: the muon anomaly,
the anomalous magnetic moment,
or simply "the muon g-2"

A rich history of g-2 Theory and measurements

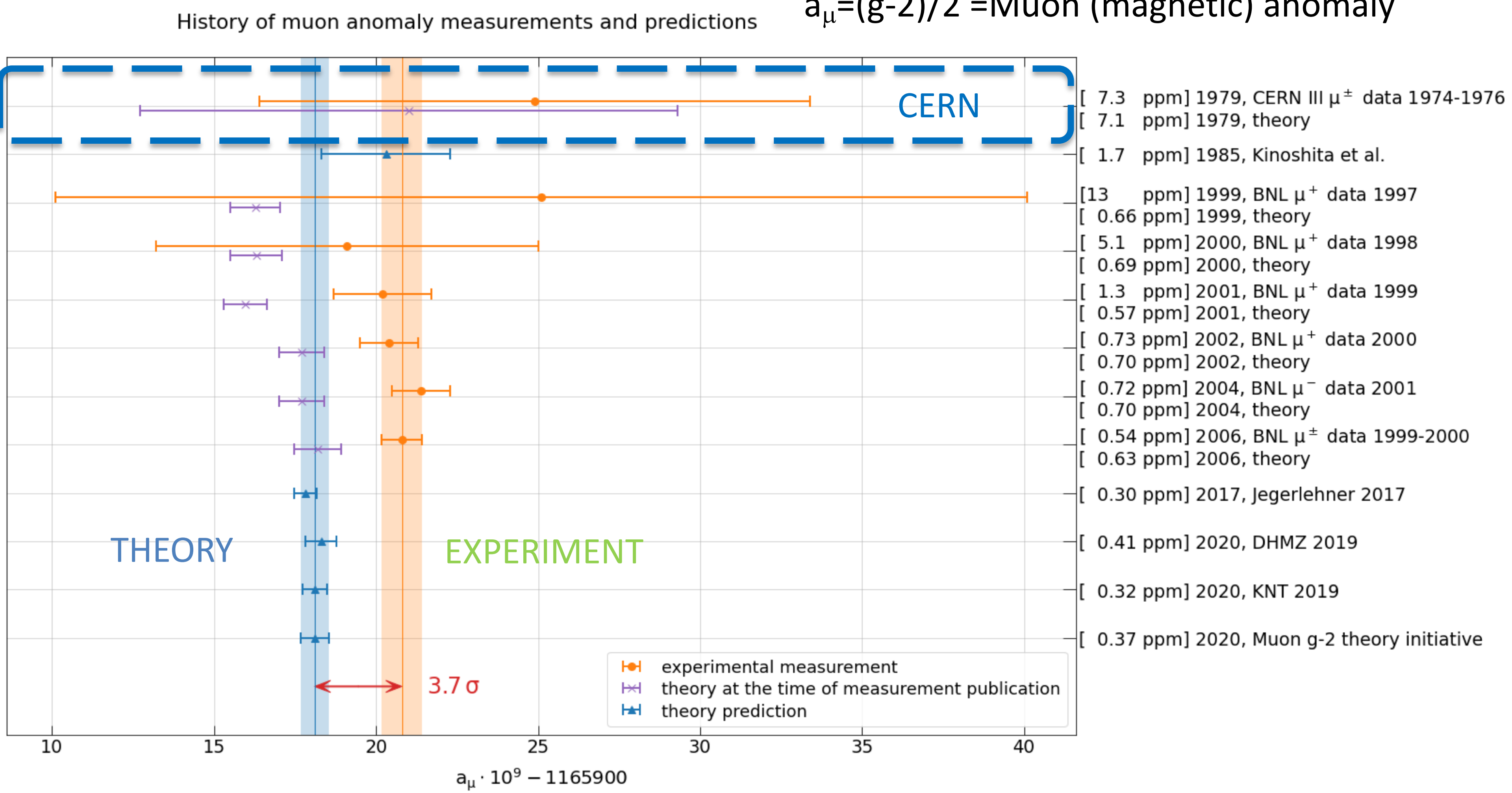
$a_\mu = (g-2)/2$ = Muon (magnetic) anomaly



G. Venanzoni, LNF- Frascati, 15 April 2021

A rich history of g-2 Theory and measurements

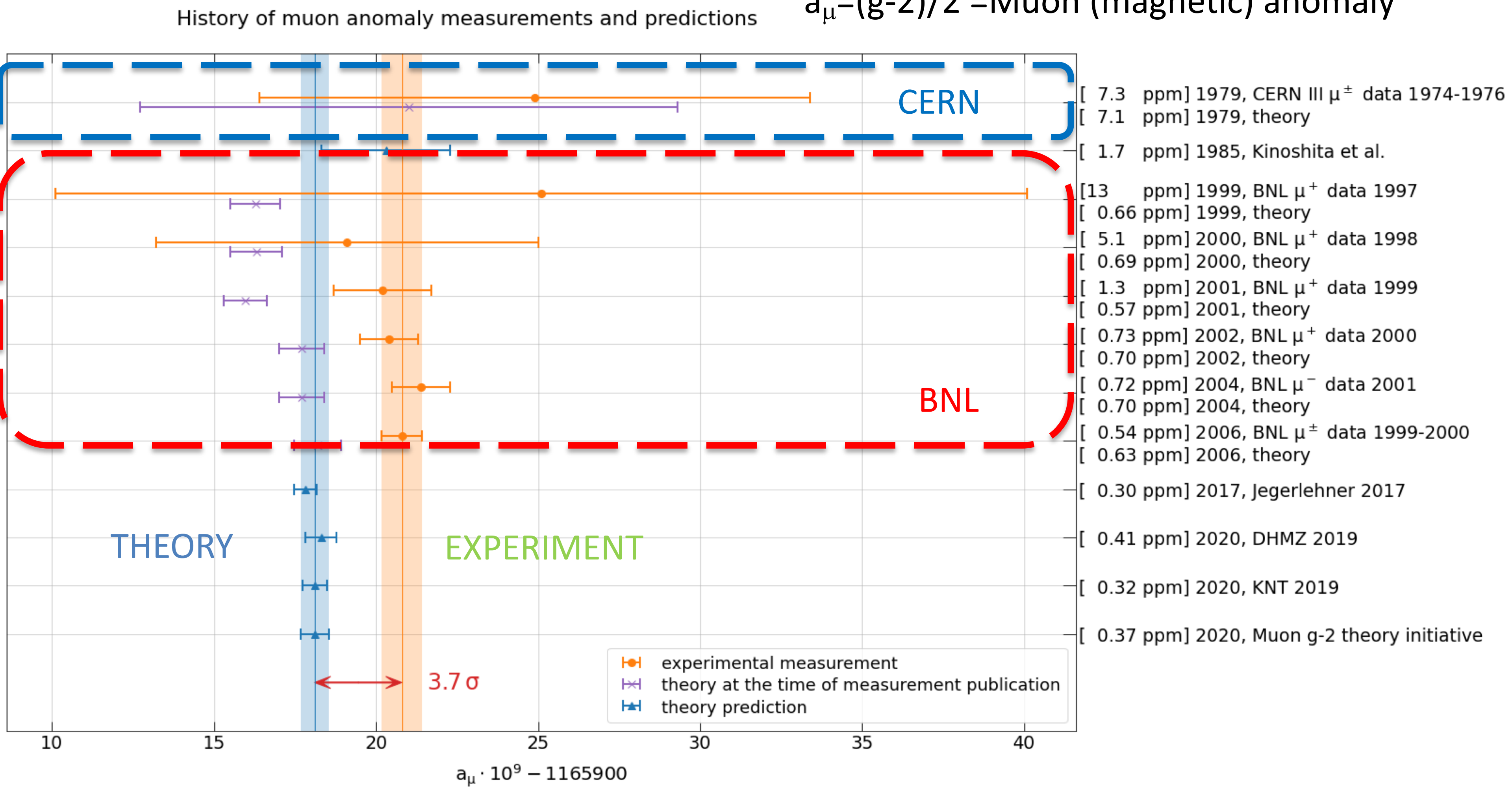
$a_\mu = (g-2)/2$ = Muon (magnetic) anomaly



G. Venanzoni, LNF- Frascati, 15 April 2021

A rich history of g-2 Theory and measurements

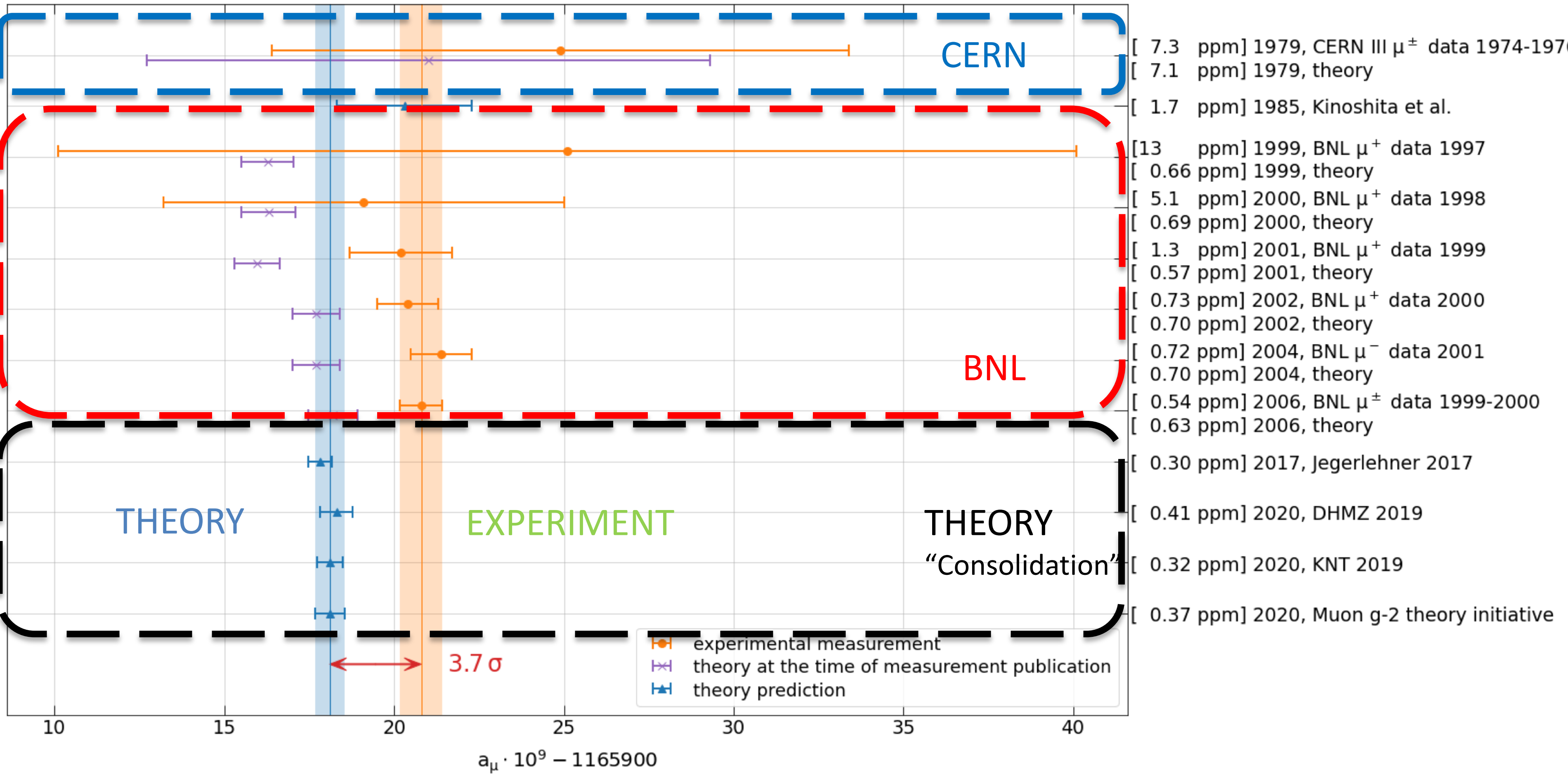
$a_\mu = (g-2)/2$ = Muon (magnetic) anomaly



A rich history of g-2 Theory and measurements

$a_\mu=(g-2)/2$ =Muon (magnetic) anomaly

History of muon anomaly measurements and predictions



A rich history of g-2 Theory and measurements

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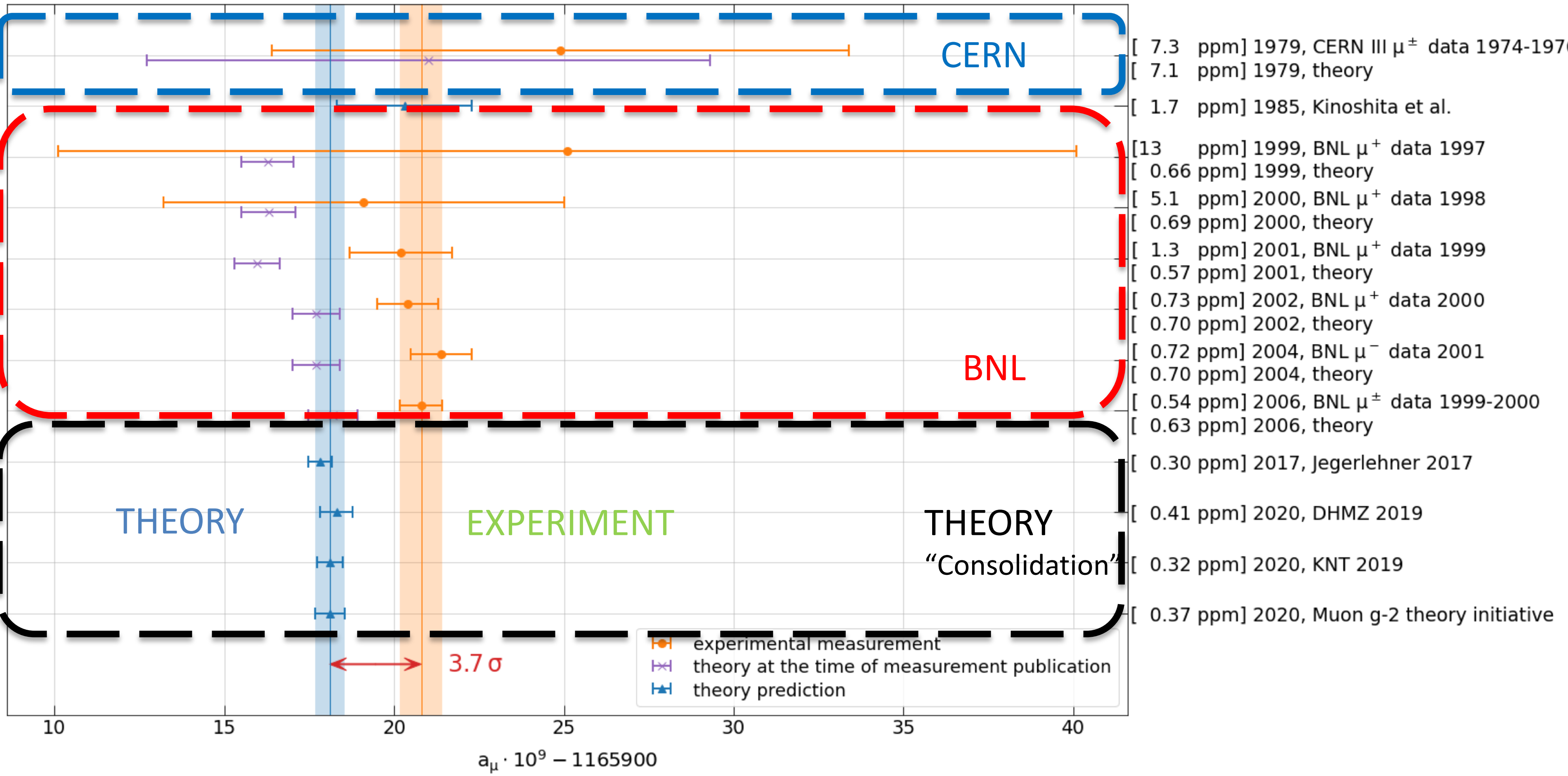
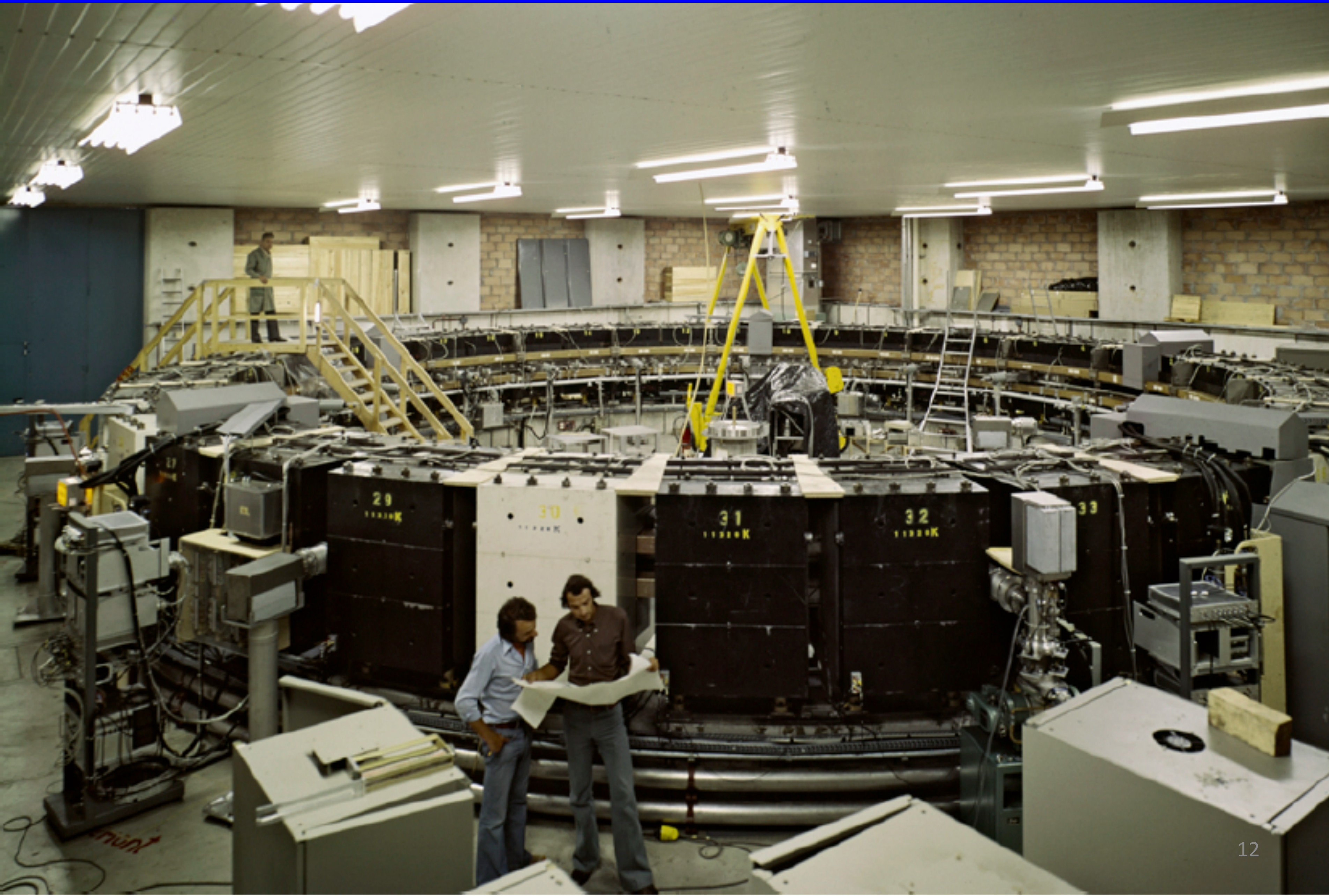
History of muon anomaly measurements and predictions

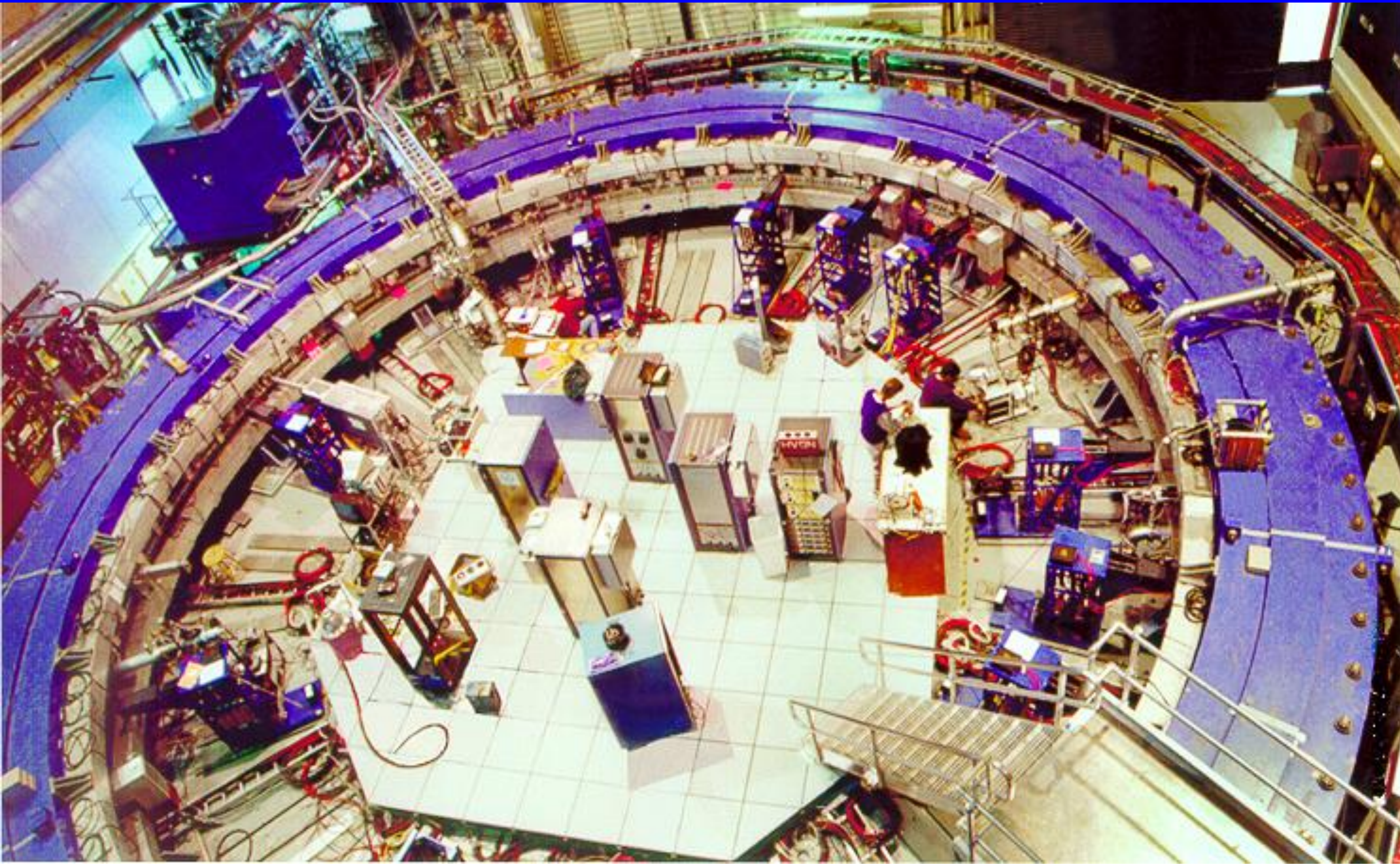


Why is possible to measure a_μ so precisely?

G-2 muon experiment at CERN (Seventies)



G-2 muon experiment at Brookhaven (2000’s)

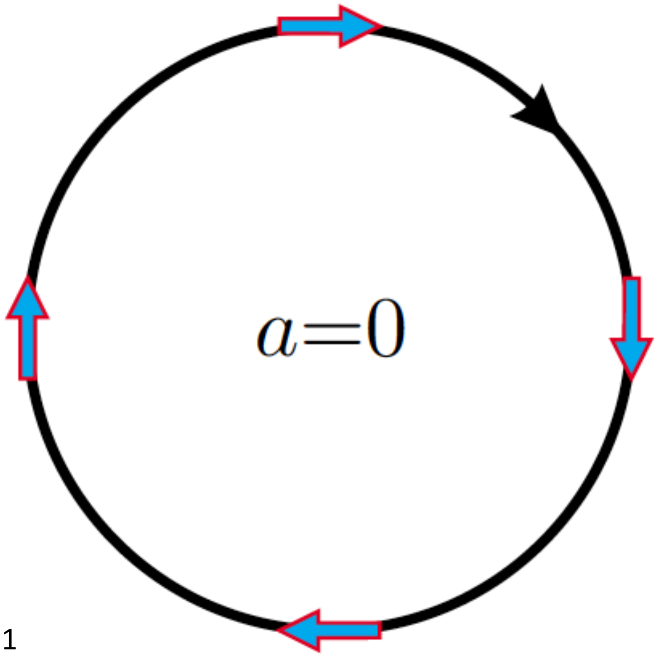


Why is possible to measure g-2 so precisely?

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g=2 (a=0) spin remains locked to momentum

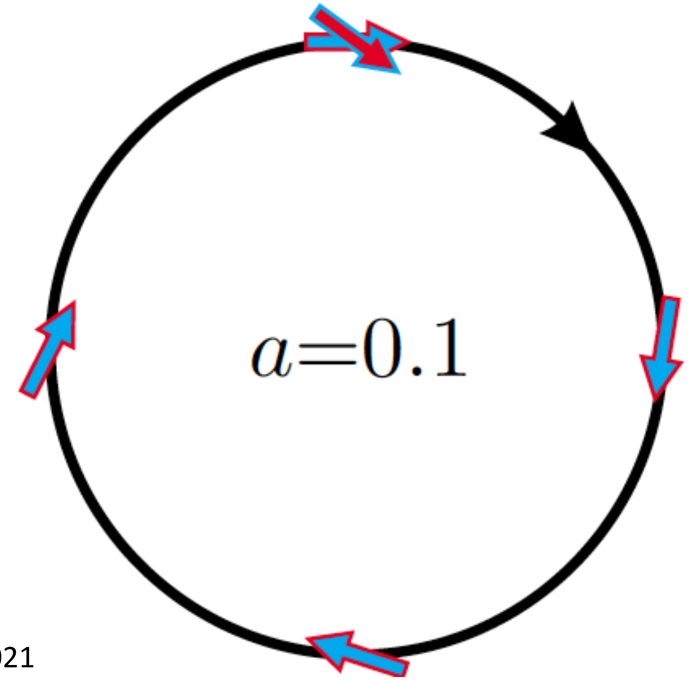


Why is possible to measure g-2 so precisely?

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin advances respect to the momentum

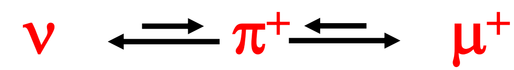


By measuring directly a_μ x800 more sensitive than an experiment which measures g

Key ingredients

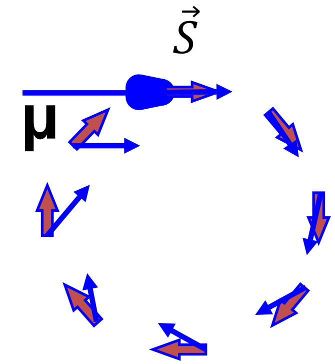
Muon g-2

1) Polarized muons



~95% polarized for forward decay

2) Precession proportional to (*g*-2)



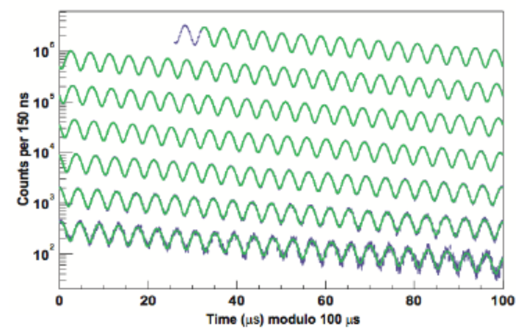
$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

$a_\mu=(g-2)/2$

3) P_μ magic momentum = 3.09 GeV/c

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

4) Decay e^+ emitted preferably in spin direction of the muon

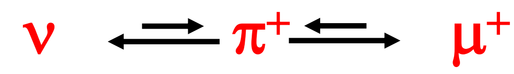


$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

Key ingredients

1) Polarized muons

~95% polarized for forward decay

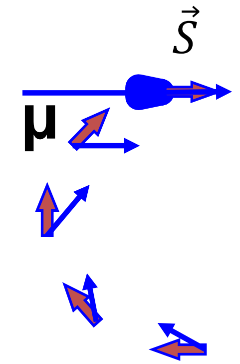


2) Precession proportional to (*g*-2)

$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

Measure 2 quantities

$a_\mu=(g-2)/2$

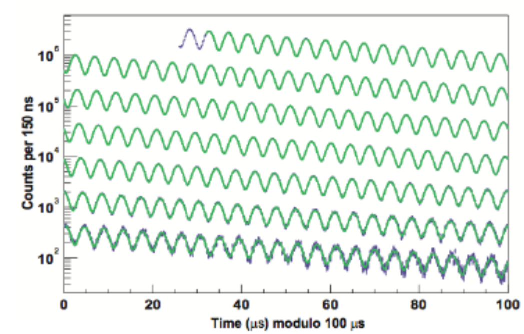


3) P_μ magic momentum = 3.09 GeV/c

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

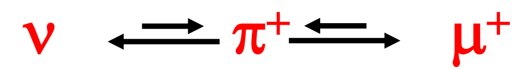
4) Decay e⁺ emitted preferably in spin direction of the muon

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



G. Venanzoni, LNF- Frascati, 15 April 2021

Key ingredients



1) Polarized muons

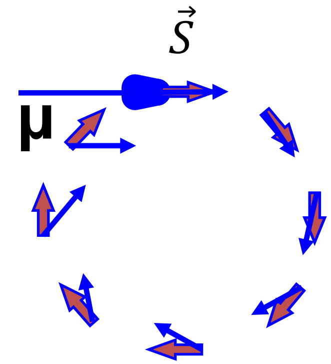
~97% polarized for forward decay

2) Precession proportional to (g-2)

$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

Measure 2 quantities

$a_\mu = (g-2)/2$



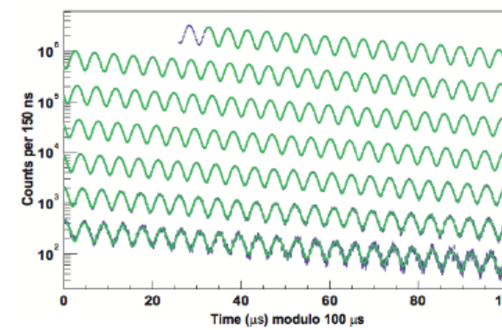
3) P_μ magic momentum = 3.09 GeV/c

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

E field doesn't affect muon spin when γ = 29.3

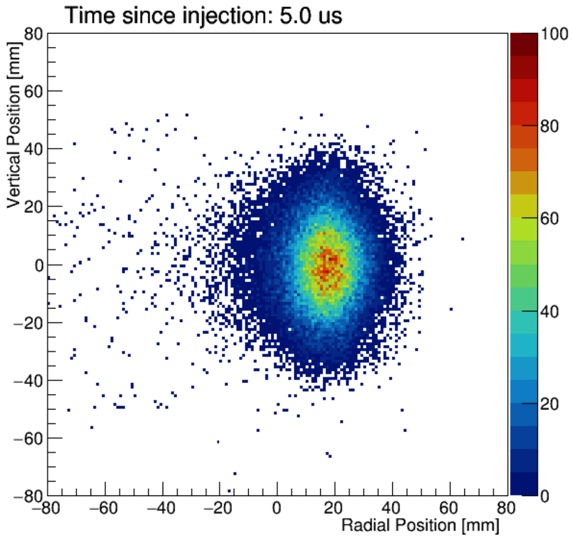
4) Decay e^+ emitted preferably in spin direction of the muon

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



However there are beam dynamics effects

- The muon beam oscillates and breathes as a whole
- The full equation is more complex and corrections due to radial (x) and vertical (y) beam motion are needed



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

- Running at γ_{magic}=29.3 (p=3.094 GeV/c) this coefficient is null
- Because of momentum spread (<0.2%)→ **E-field Correction**

- Vertical beam oscillation → **Pitch correction**

We will come back to these corrections in the following

Extracting a_μ(simplified)

By expressing B in terms of the precession frequency ω_p' of a proton shielded in a spherical water sample:

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p'} \frac{\mu_p'}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

External (precise) data

$$B = \frac{\hbar \omega_p'}{2\mu_p'}$$

$$e = \frac{4 m_e \mu_e}{\hbar g_e}.$$

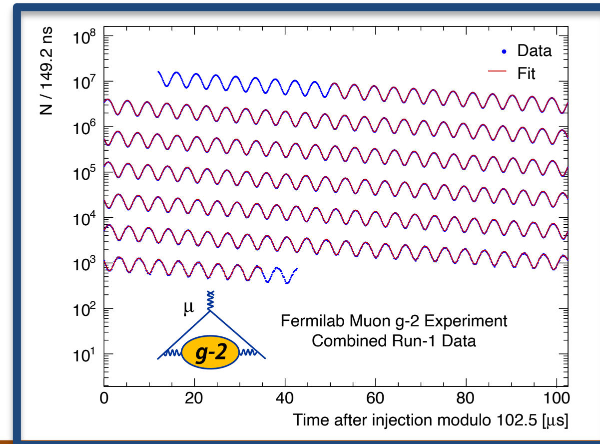
$$R' = \frac{\omega_a}{\tilde{\omega}_p'}$$ ratio of muon to proton precession in the same magnetic dipole field

$\tilde{\omega}_p'$ =Proton Larmor precession frequency **weighted for the muon distribution**

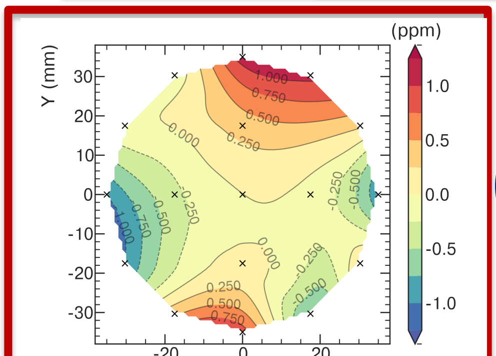
Extracting a_μ(simplified)

ω_a=muon spin precession respect to momentum (in B field)

$\boldsymbol{\omega_a}$

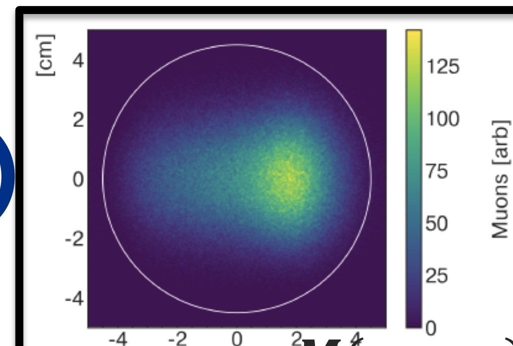


$$R' = \frac{\omega_a}{\tilde{\omega}_p'} \sim$$



$\boldsymbol{\omega_p(x, y, \varphi)}$

$\otimes$



$\boldsymbol{M(x, y, \varphi)}$

$$\tilde{\omega}_p' = \omega_p'(x, y, \varphi) \otimes M(x, y, \varphi)$$

ω_p=proton precession frequency

M=muon spatial (and time) **distribution**

Extracting a_μ(more realistic)

Corrections due to beam dynamics

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

Corrections due to transient magnetic fields

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

All these quantities have been evaluated throughout in the analysis of RUN1 data

Extracting a_μ(more realistic)

$$\frac{\mu_e(H)}{\mu'_p(T)}$$

Measured to 10.5 ppb accuracy at T = 34.7°C

Metrologia **13**, 179 (1977)

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

Known to 22 ppb from muonium hyperfine splitting

Phys. Rev. Lett. **82**, 711 (1999)

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

Bound-state QED (exact)

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

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

Measured to 0.28 ppt

Phys. Rev. A **83**, 052122 (2011)

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

Total uncertainty of 25 ppb

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

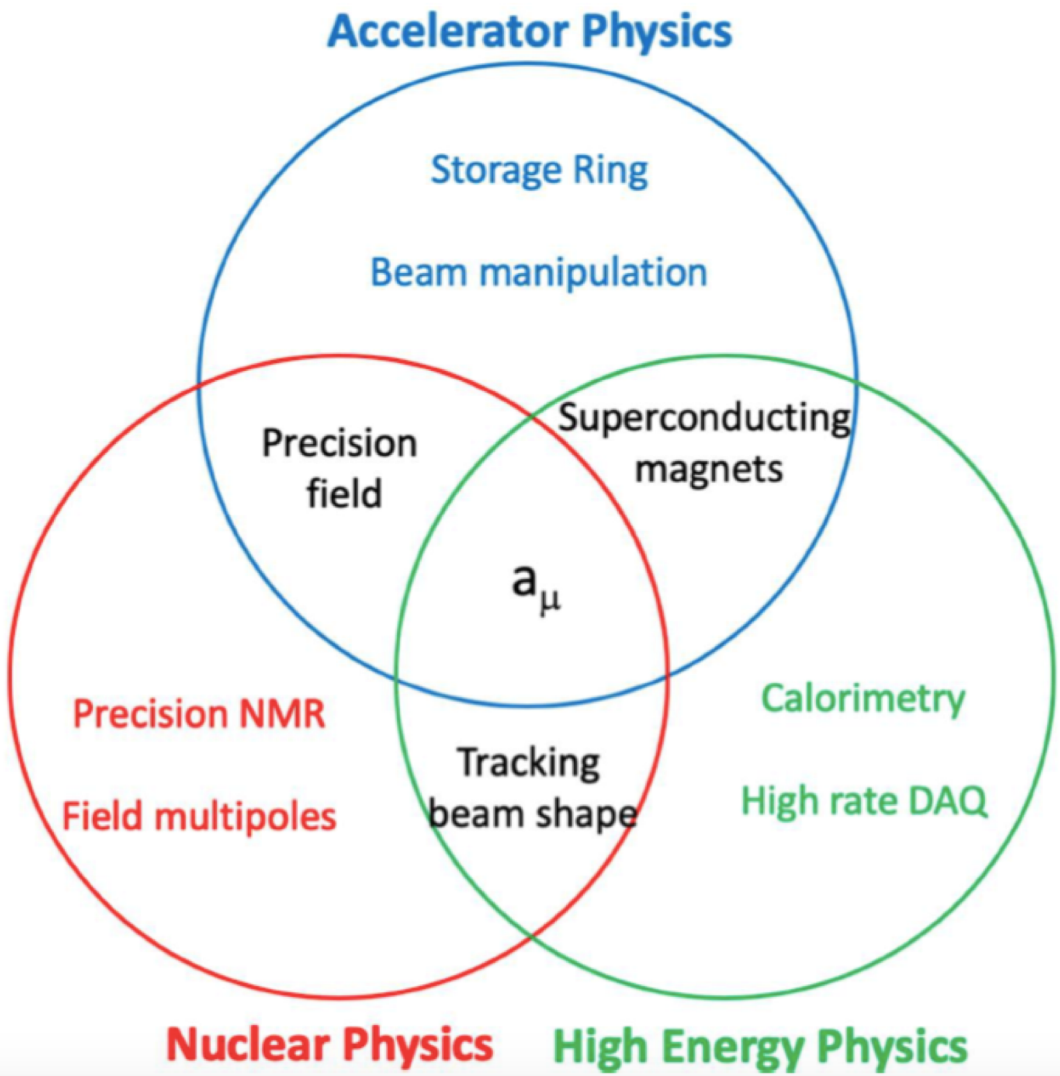
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

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

>200 collaborators
35 Institutions
7 countries

Three different communities to measure a_μ



June 2013: The ring leaves from BNL

2013: The Big Move

2013: The Big Move

26 July 2013:…the ring arrives to FNAL

[redacted]

4 key elements for E989 at FNAL

- Consolidated method (same ring of the BNL experiment)
- More muons (x20)
- improved beam and detector → Reduced systematics
- New crew → new ideas

- **E821 at Brookhaven**

$$\left.\begin{aligned}\sigma_{stat} &= \pm 0.46 \text{ ppm} \\ \sigma_{syst} &= \pm 0.28 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.54 \text{ ppm}$$

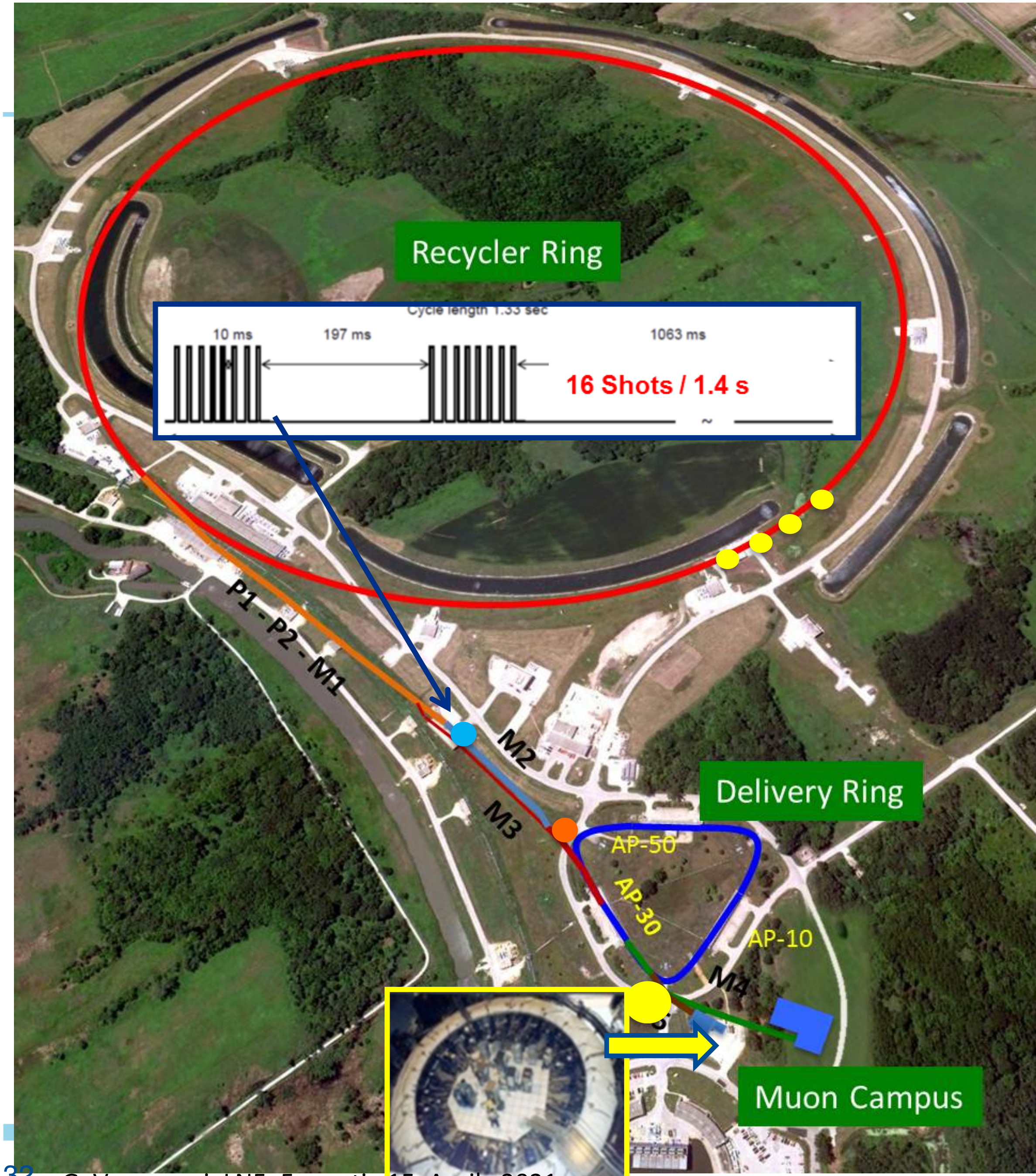
↳ $0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

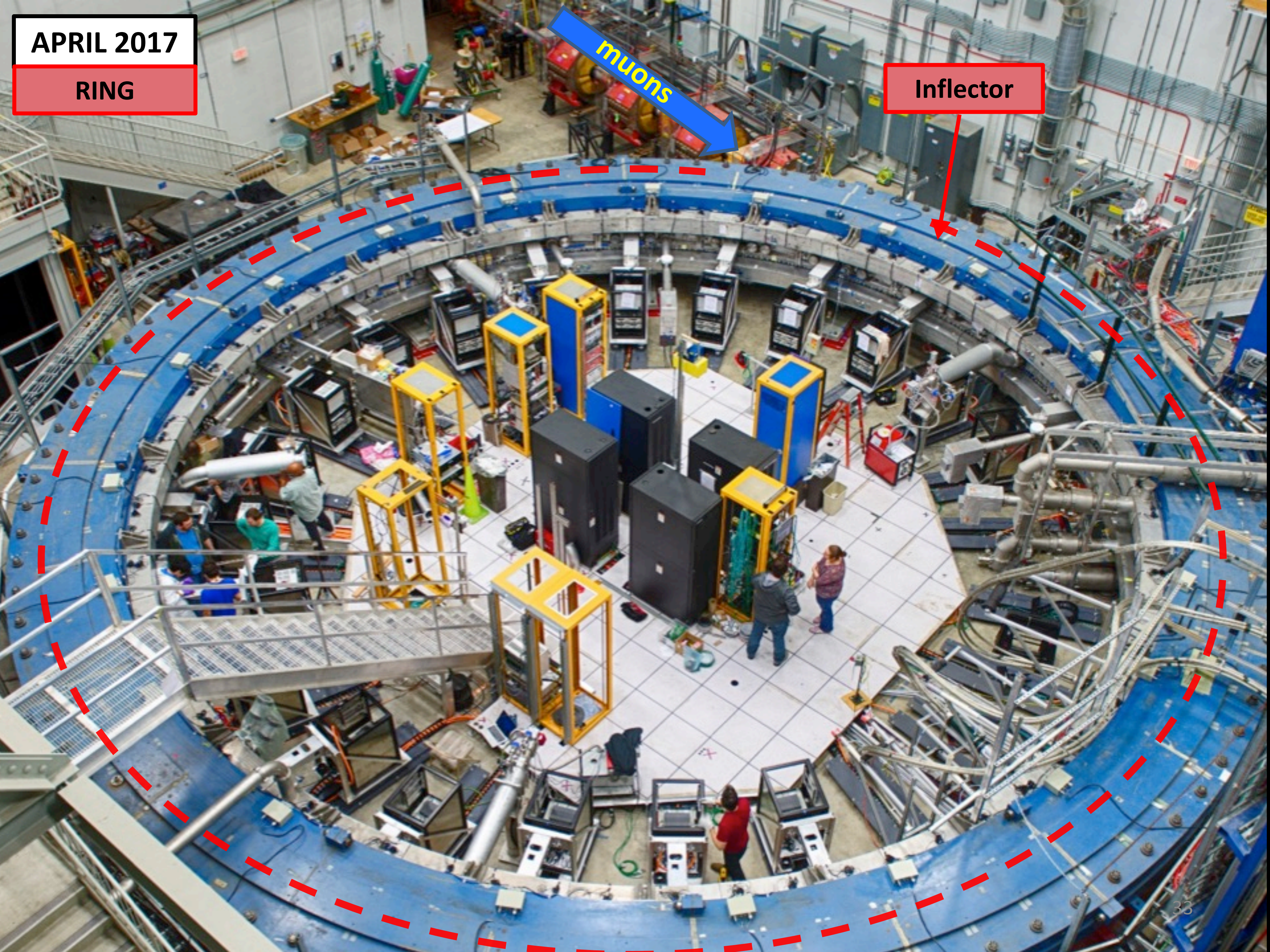
$$\left.\begin{aligned}\sigma_{stat} &= \pm 0.1 \text{ ppm} \\ \sigma_{syst} &= \pm 0.1 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.14 \text{ ppm}$$

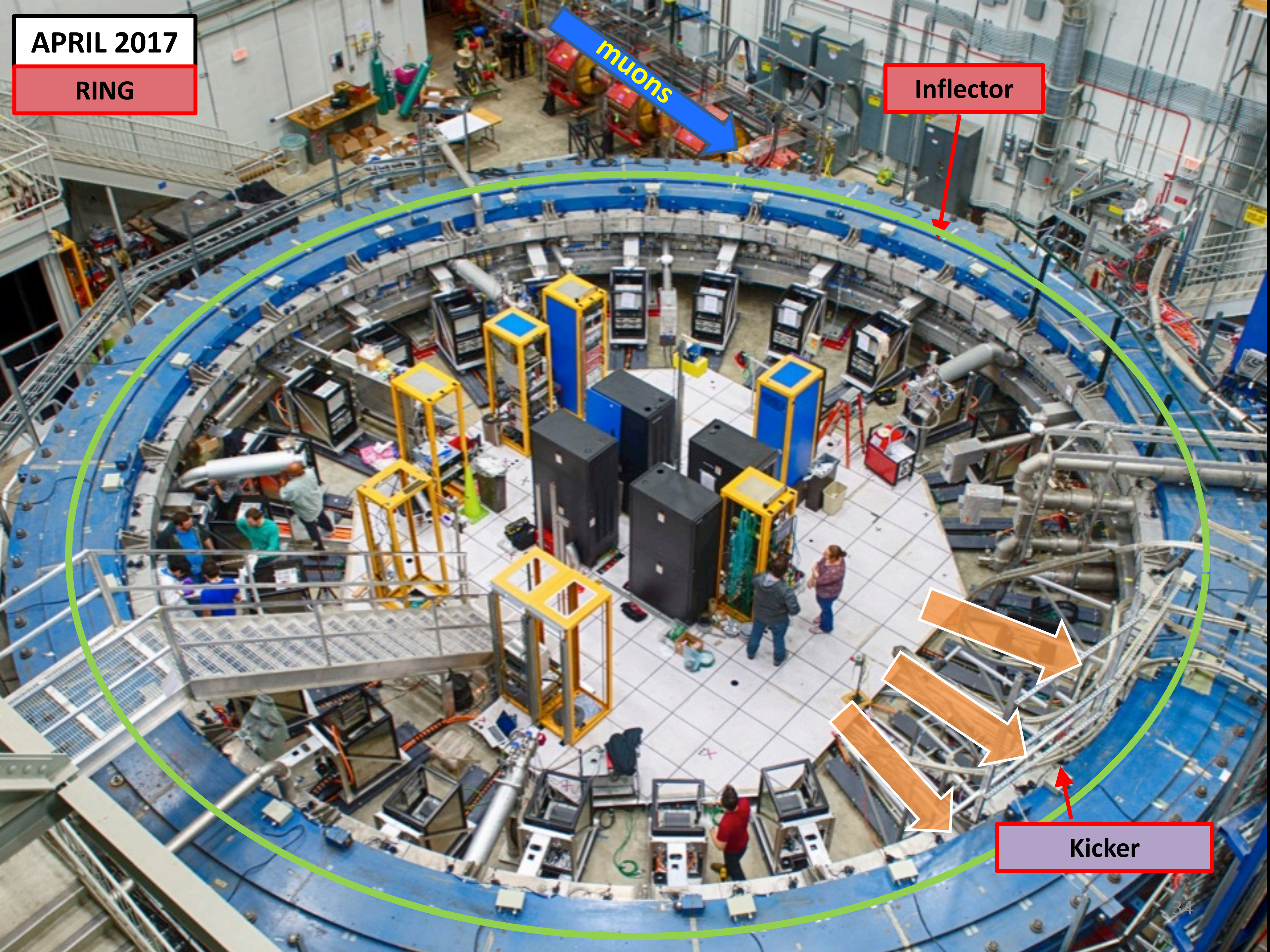
$0.07\omega_a \oplus 0.07\omega_p$

Creating the Muon Beam for g-2

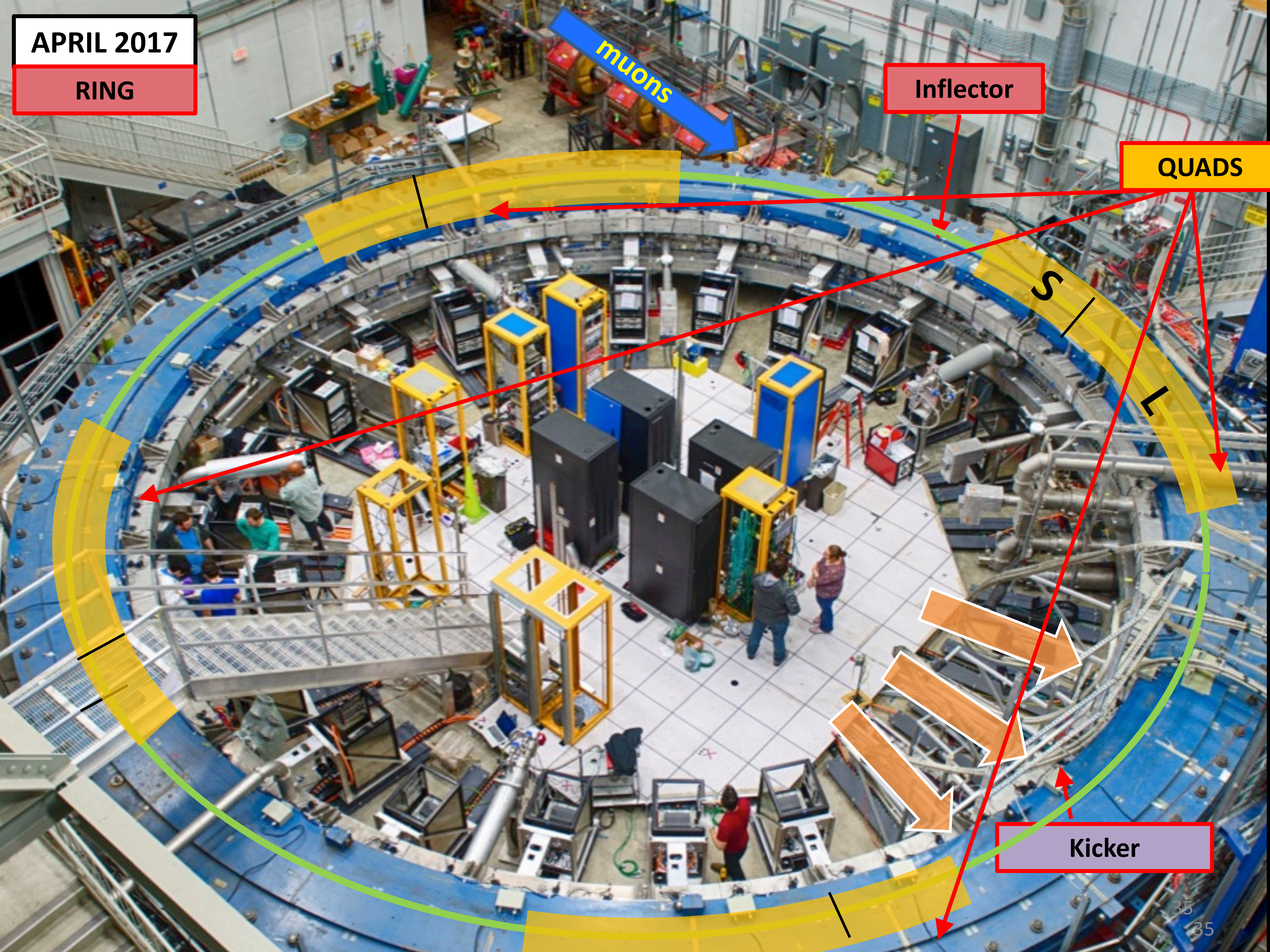


- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

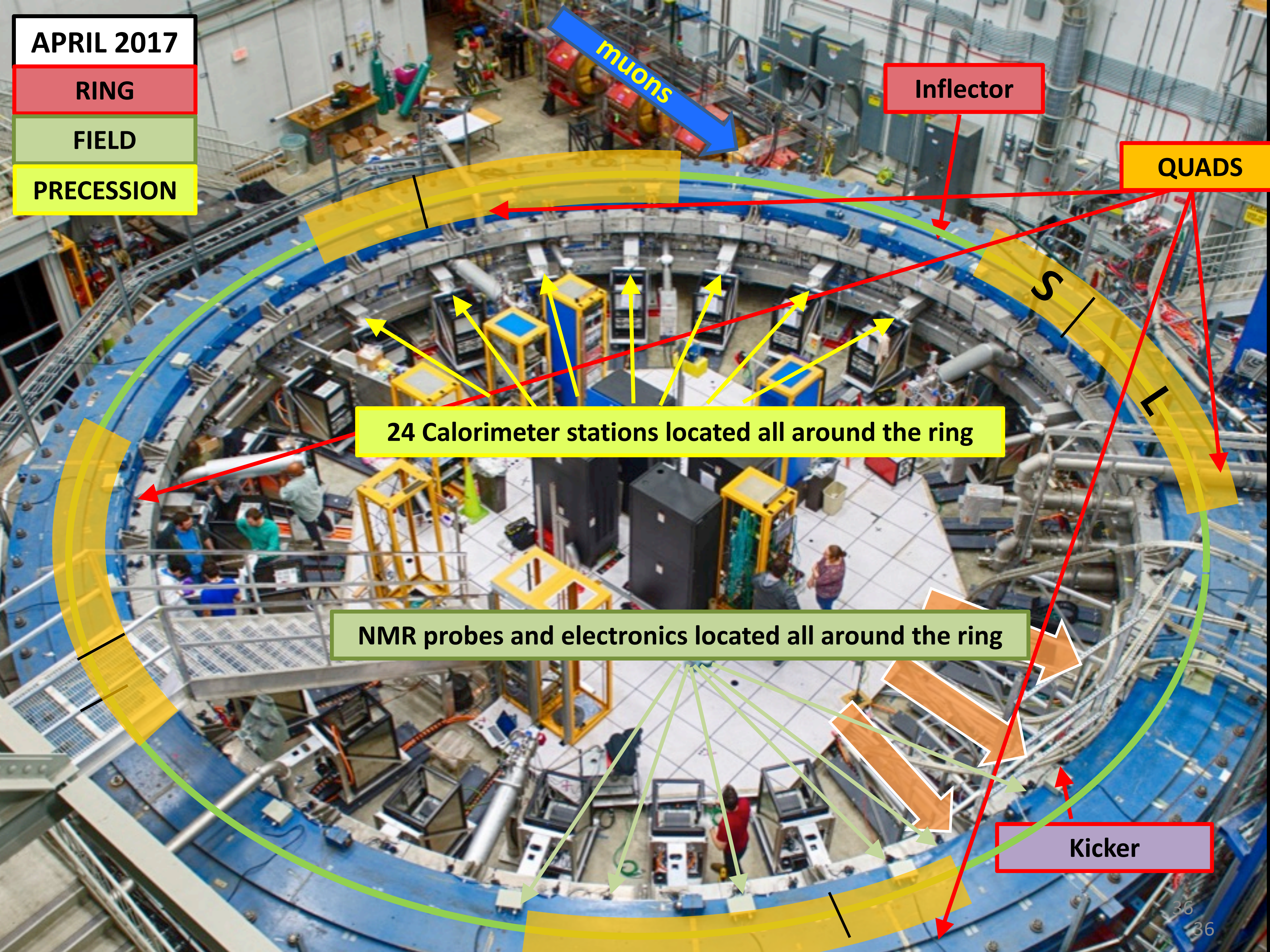

APRIL 2017
RING
muons
Inflector



APRIL 2017
RING
muons
Inflector
Kicker



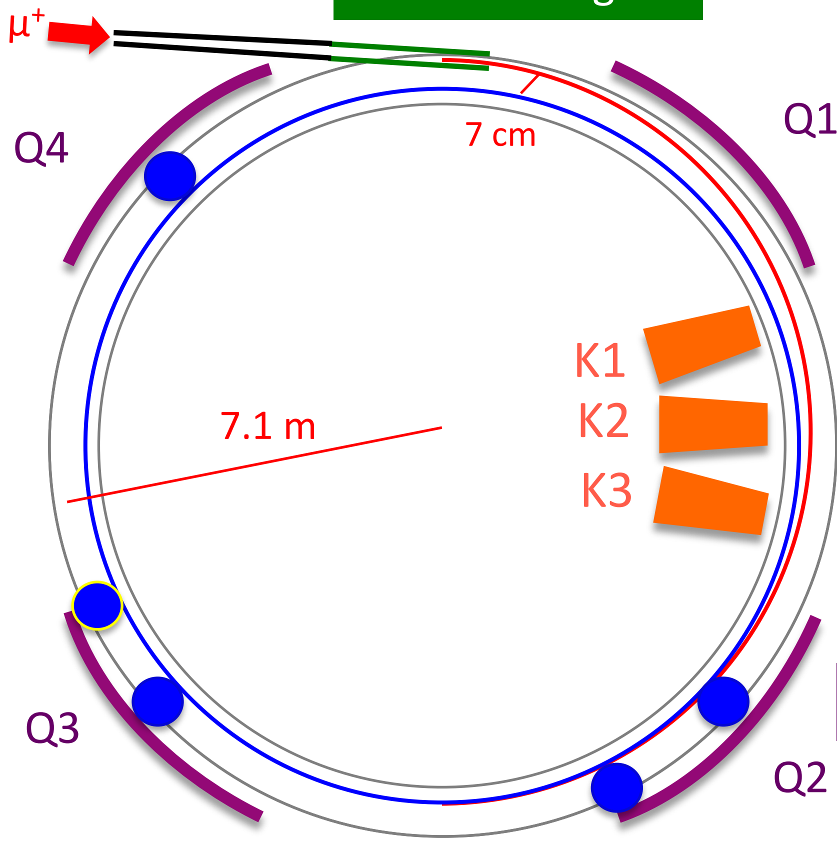
35


APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
S
L
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

Injection / storage

Inflector Magnet

cancels 1.45 T main field



Kicker magnets **x3 (40-55 kV)**

radially centers beam

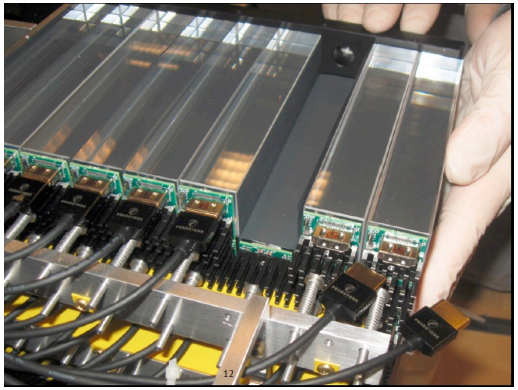
Focussing quadrupoles **15-28 kV**

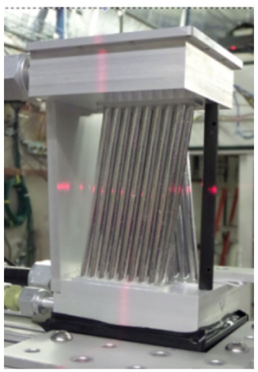
vertically focusses beam

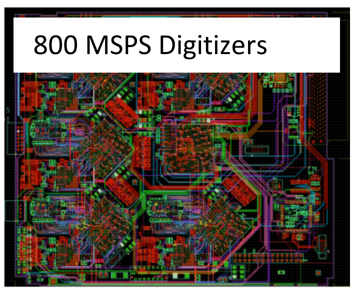
Collimators

R_{fill}~13Hz
N_{μ}/fill (TDR)~ 10^4
N_{μ}/sec(TDR)~ $1.3\text{x}10^5$
$N_{e+\ E>1.8\ GeV}$/fill (TDR)~ 10^3

Detector systems

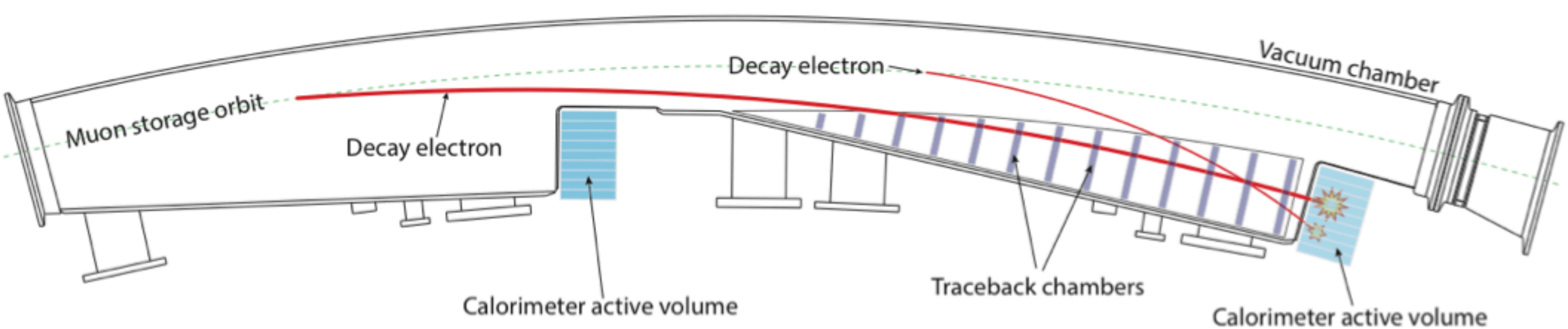




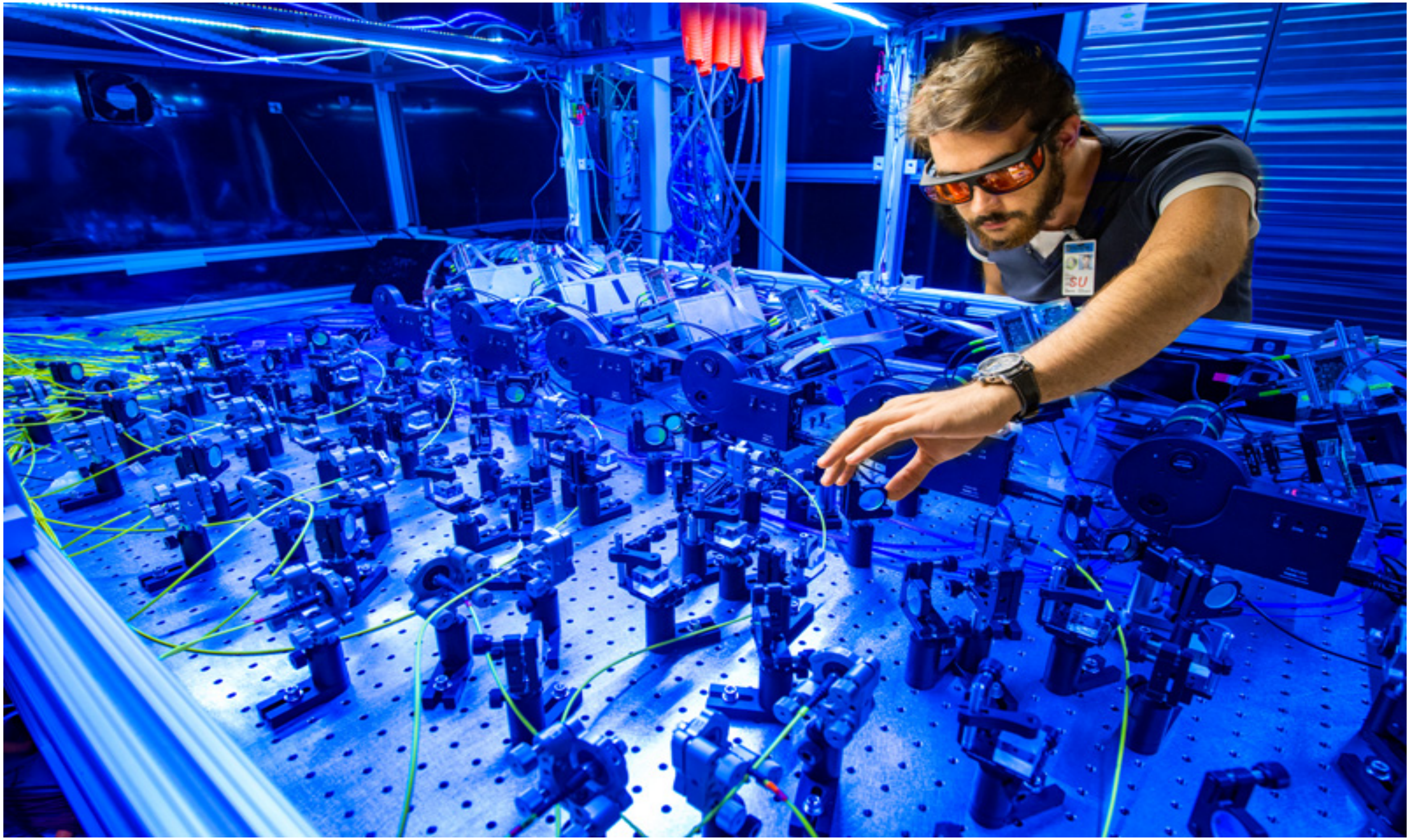


- Calorimeters: fast PbF_2 crystal arrays with SiPM readout → greatly reduce pileup
- State of the art laser calibration system
- WFD electronics → greatly reduced energy threshold
- Two straw tube trackers to precisely monitor properties of stored muons

Top view of 1 of 12 vacuum chambers



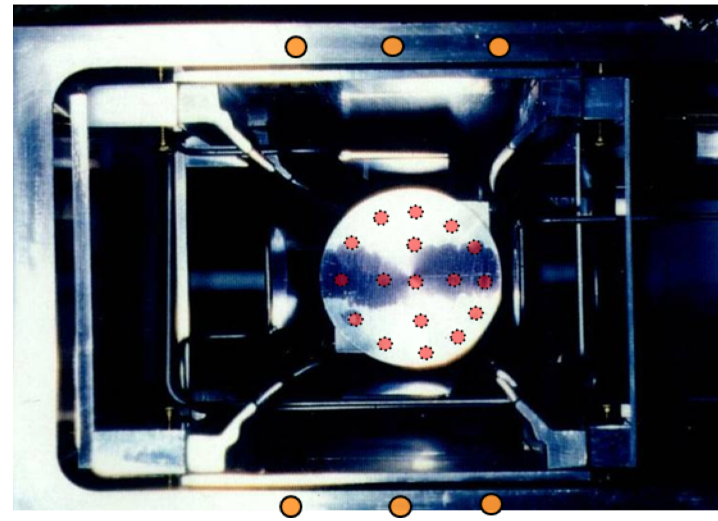
Sistema laser (~2018)

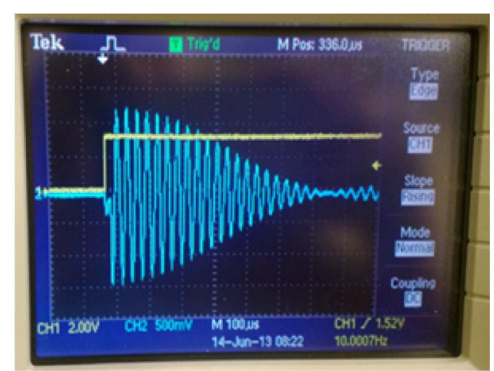


JINST 14 (2019) P11025 (1906.08432)

Measuring the magnetic field

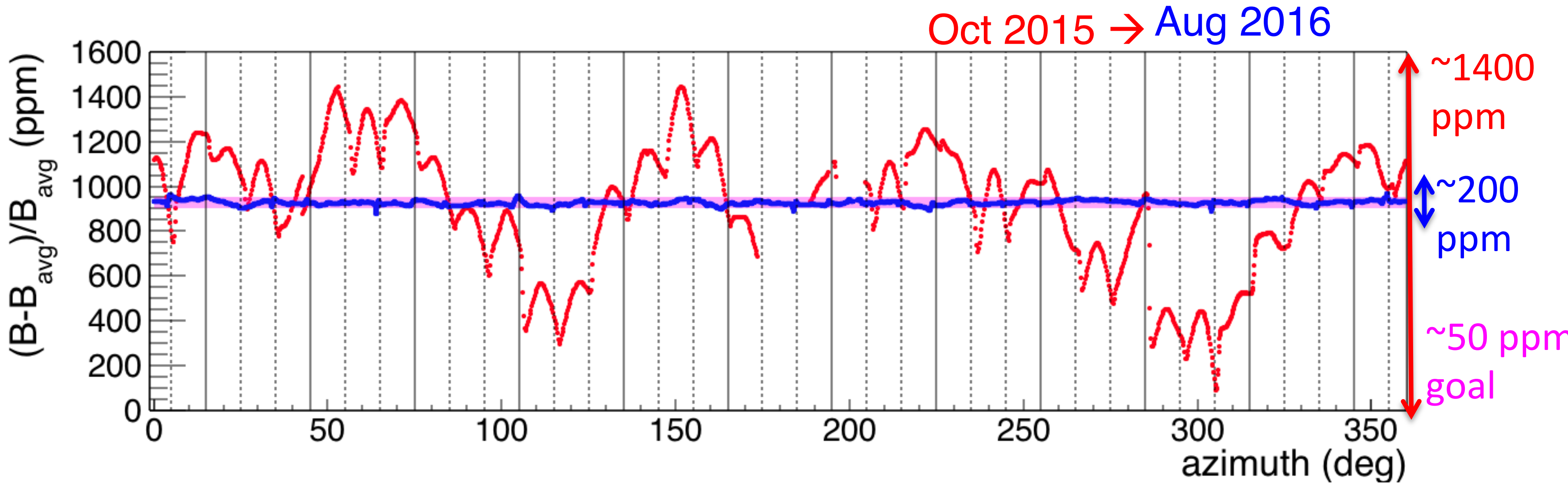
- 378 Fixed probes monitor field 24/7
- 17-probe NMR trolley maps the magnetic field over the muon storage region
  - Trolley runs every 2-3 days
- Free induction decay signal of the probes digitized and analyzed to extract a precession frequency



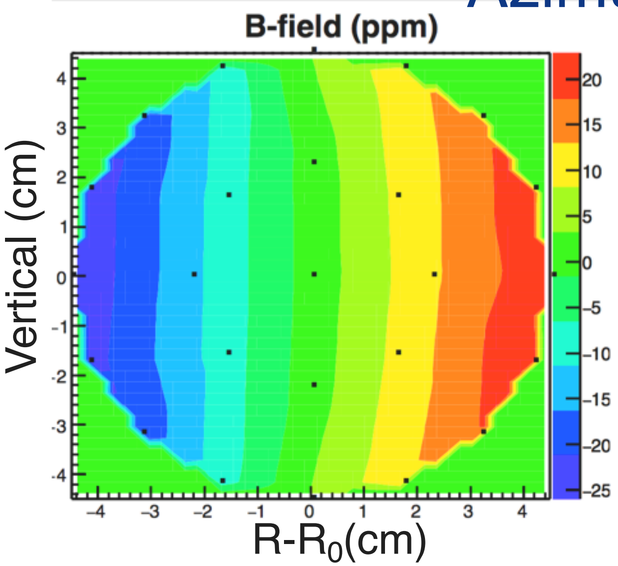


B Field shimmed at 3x finer uniformity than BNL

Muon g-2

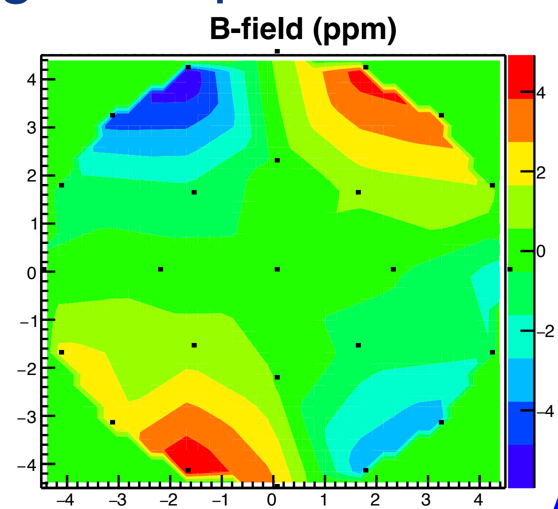


Azimuthally Averaged Map



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

Oct 2015

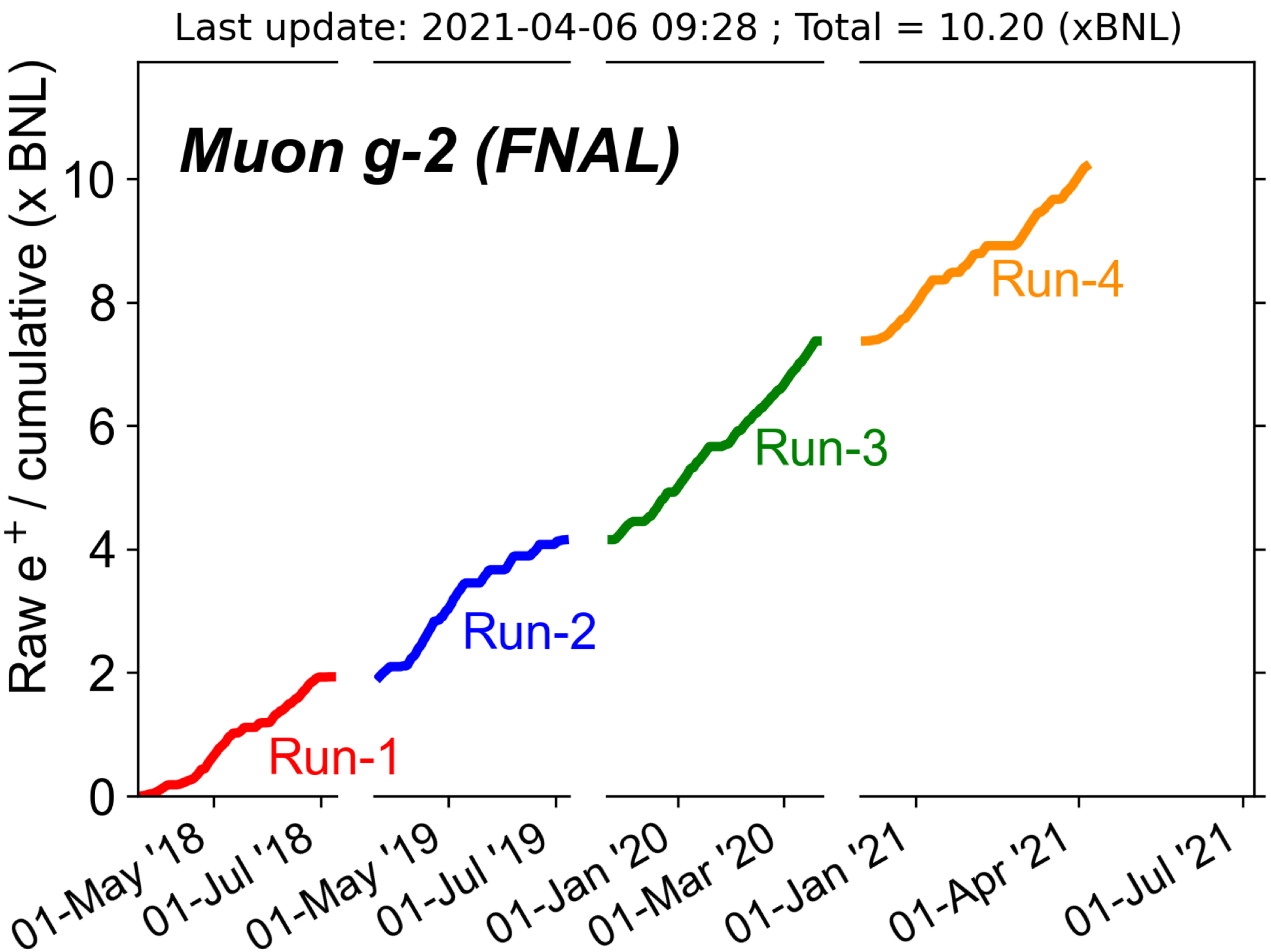


	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

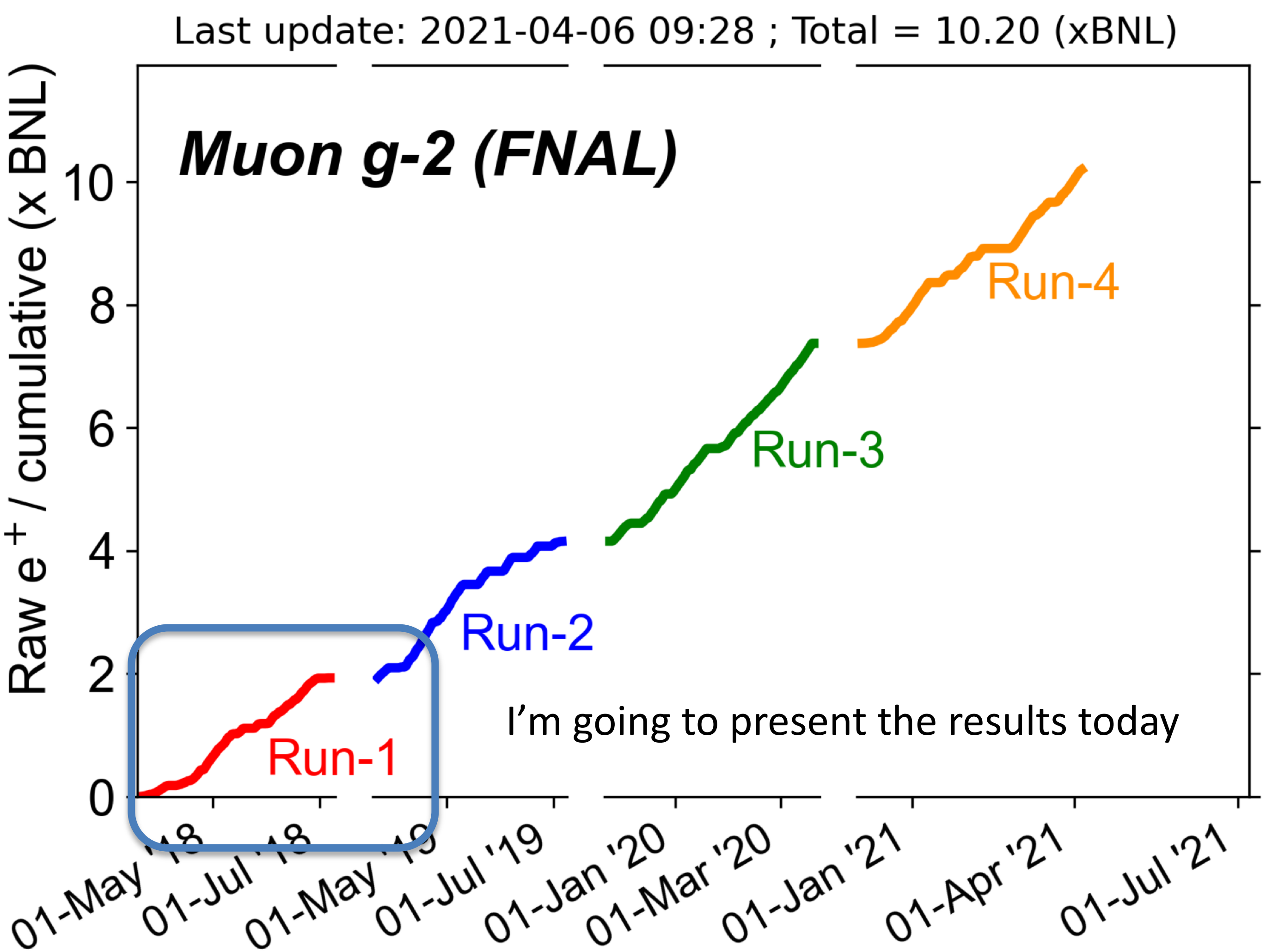
E989 collected data

We have collected plenty of data over the last 3 years:



E989 collected data

We have collected plenty of data over the last 3 years:



Run 1 Datasets

Run 1 collected in spring 2018. 4 datasets based on the storage parameters (quadrupoles field index, kickers voltage)

Dataset	Acquisition	Quad kV (field #)	Kicker [kV]	Positrons
1a	22 – 25 Apr	18.3 (0.108)	130	0.9B
1b	26 Apr – 2 May	20.4 (0.120)	137	1.3B
1c	4 – 12 May	20.4 (0.120)	132	2.0B
1d	6 – 29 Jun	18.3 (0.108)	125	4.0B

Total statistics =8.2B e^+ ~1.2x BNL one

RUN1: analysis structure

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

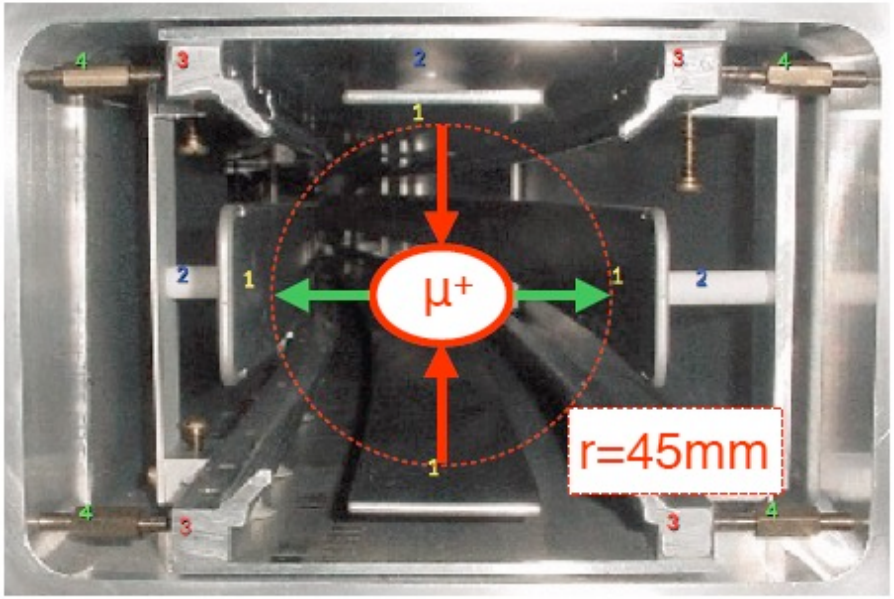
- Multiple analysis groups with different methodologies:
  - Six groups analyse ω_a with 2 different energy and time reconstructions and 4 different analysis methods
  - Two groups for the analysis of ω_p + one group for calibration
  - Different groups for beam dynamics corrections

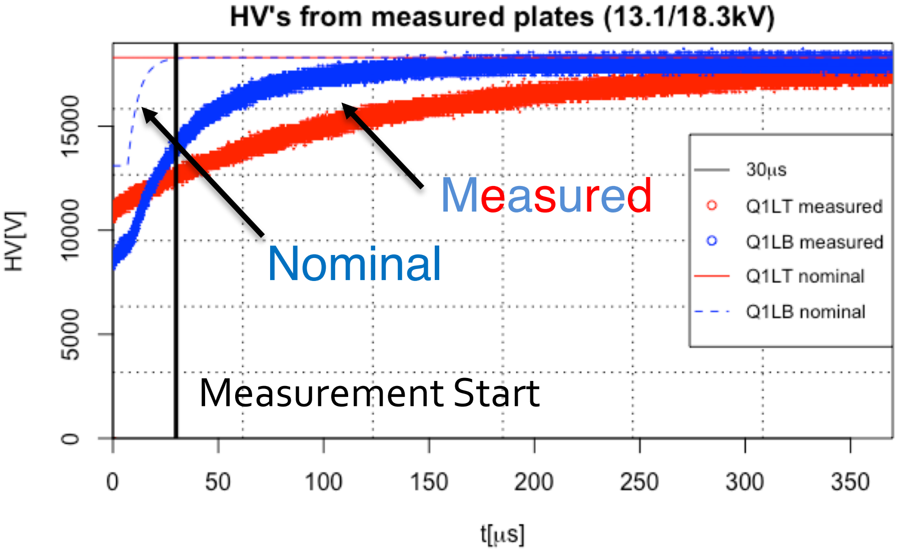
RUN1 analysis Italian contribution

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Beam in Run 1 challenges: ESQ

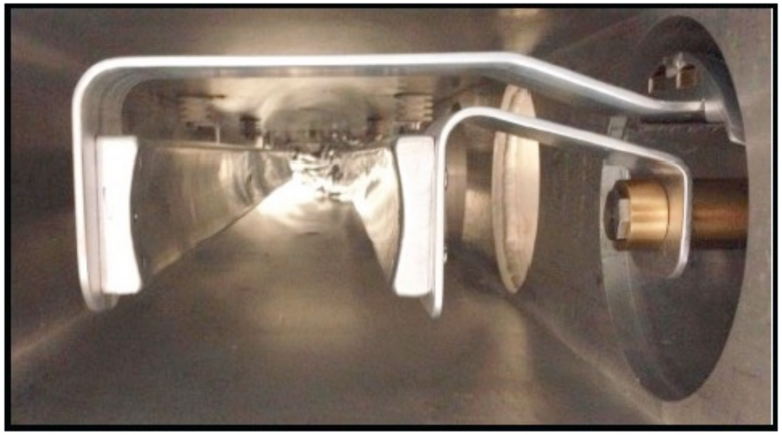
- Two resistors of one Electrostatic Quadrupole (ESQ1) were damaged: slower recovery time
- Beam moving down and increasing its RMS
- Effect on ω_a:
  - time-dependent phase
  - Increase of the amplitude of Coherent Betatron Oscillation (CBO)
  - Increase of the muon loss
- Fixed before RUN2

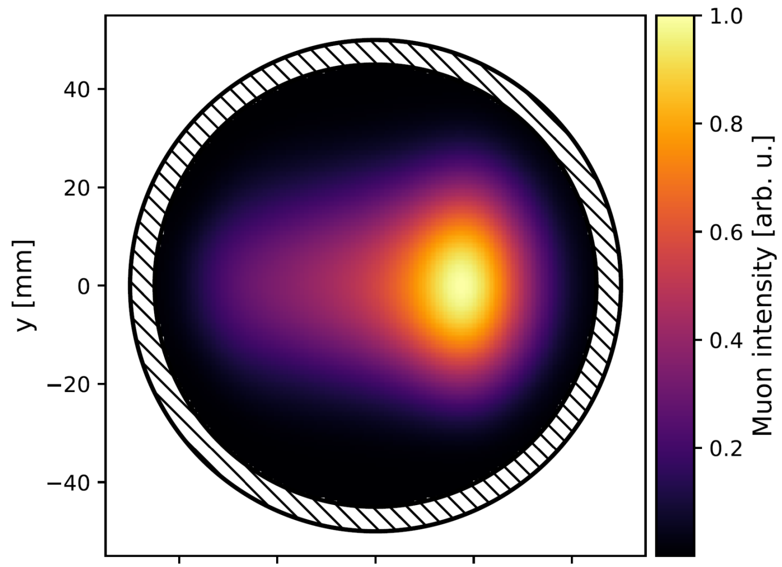


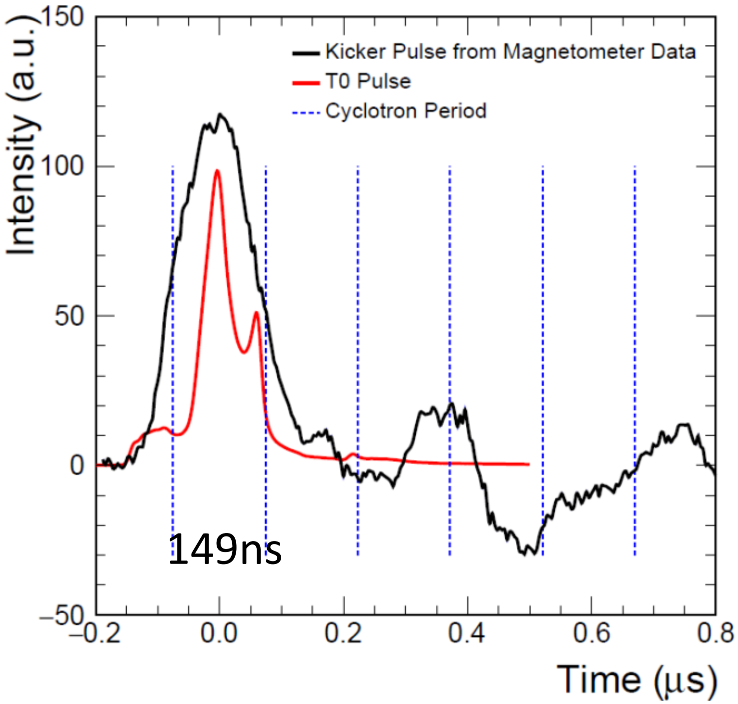


Beam in Run 1 challenges: Kicker

- Sub-standard and not uniform kick
- Muon equilibrium orbit displaced by~ 6mm
- Larger E-field correction
- Larger CBO amplitude







ω_a systematic effects

- Many systematics come from effects that **change the phase** of the detected e^+ over time and introduce a bias on ω_a

$$cos(\omega_a t + \phi(t)) = cos(\omega_a t + \phi_0 + \phi' t + ...)$$
$$= cos((\omega_a + \phi')t + \phi_0 + ...)$$

- In general, anything that changes from **early-to-late** within each muon fill can be a cause of systematic error, as:
  - Beam distortion
  - Muon losses
  - Varying lifetime
  - Rate dependent reconstruction

Muon g-2

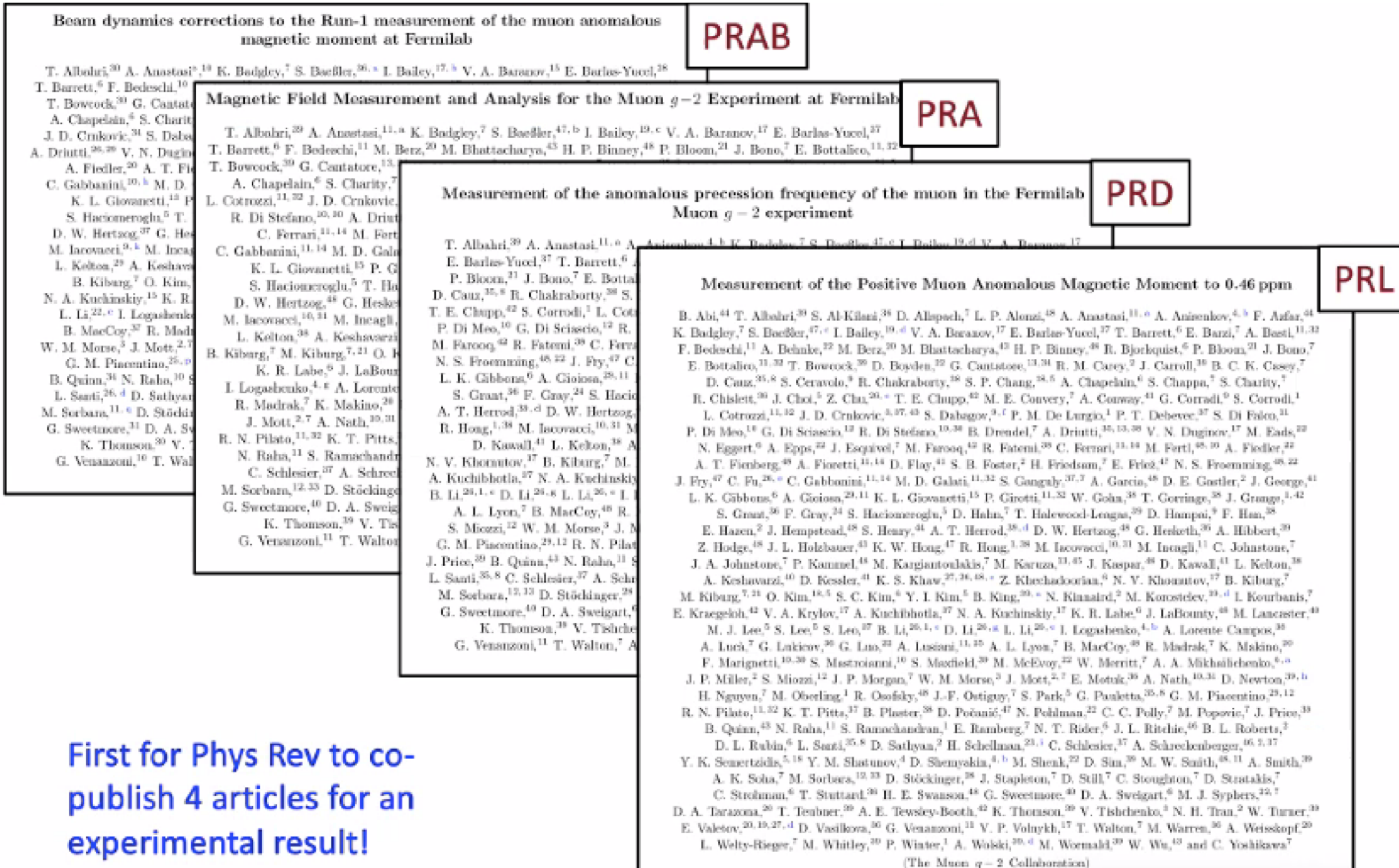
RUN1 challenges required a number of dedicated studies of systematic effects

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

In the following we will discuss some of these quantities.
If you are interested to all the details…(see next slide)

Four articles appeared today on ArXiv!

Muon g-2



First for Phys Rev to co-publish 4 articles for an experimental result!

“Master Formula”

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

A blinded analysis

- Two levels of blinding:
  - HW blinding (ω_a clock detuned)
  - SW (unknow offset in the analysis of ω_a)
- The HW blinding factor is known only to two people outside the collaboration

Locked Clock Panel

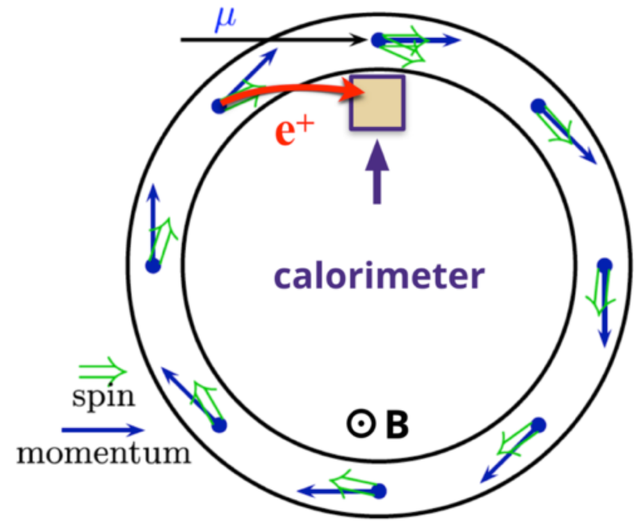
blinding the clock in 2018

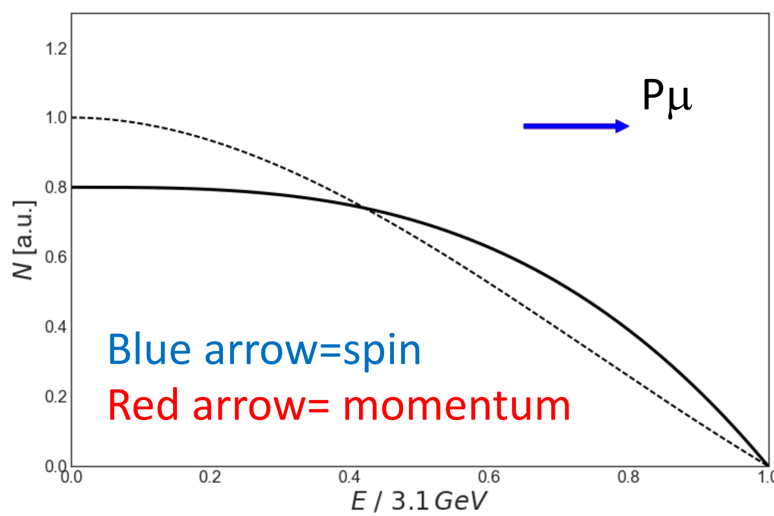
ω_a Measurement

- The number of positrons is modulated by the anomalous precession frequency

$$N_0 e^{-t/\tau}[1 - A\,cos(\omega_a t + \phi)]$$

- 4 different analysis methods:
  - T: simple energy threshold >1.7 GeV
  - A: asymmetry weighted with threshold >1.1 GeV
  - R: ratio method
  - Q: No clustering: total energy above minimal threshold





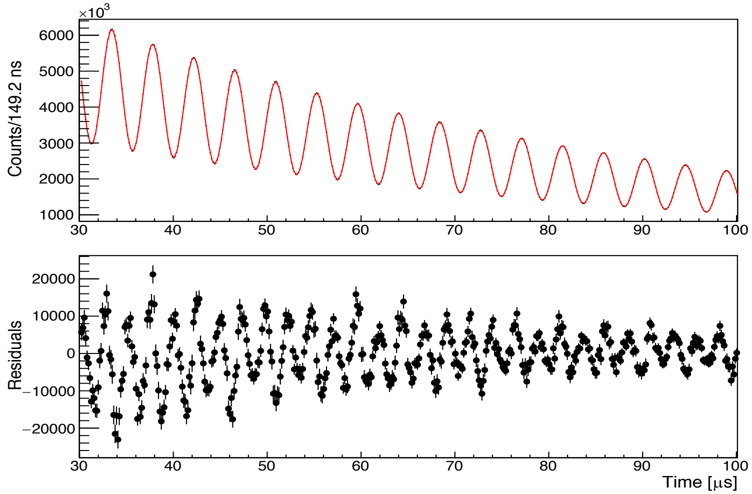
E and t are the measured observables.

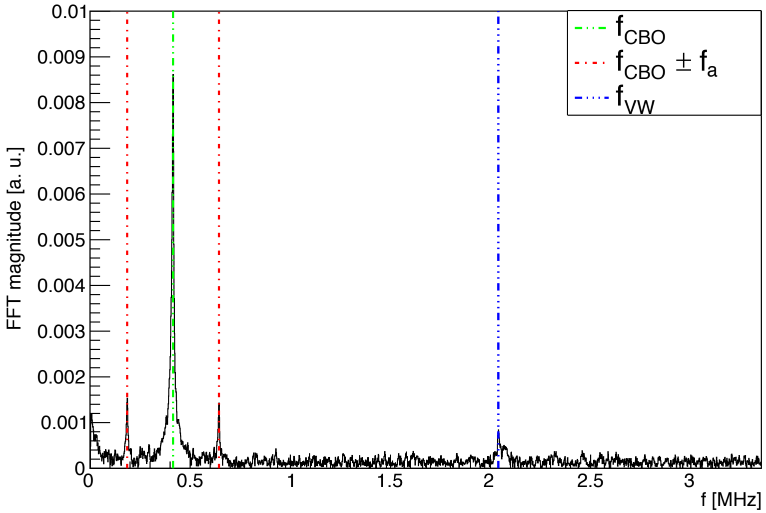
The ω_a fit

- The wiggle plot is fitted with a decay exponential modulated by the precession frequency:

$$f_5(t) = N_0 e^{-t/\tau}[1 - A\,cos(\omega_a t + \phi)]$$

- The 5 parameters function presents peaks in the Fast Fourier Transform (FFT) of the residuals due to beam dynamics effects
- Increasing the number of corrections in order to remove peaks

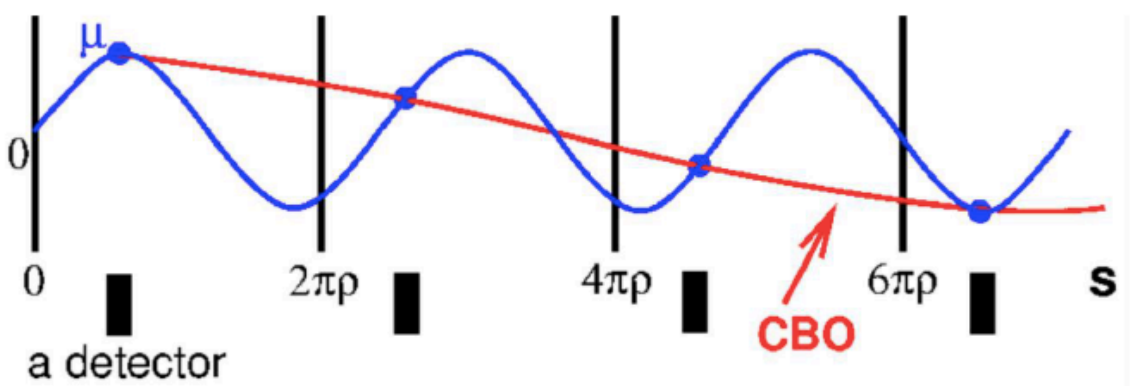


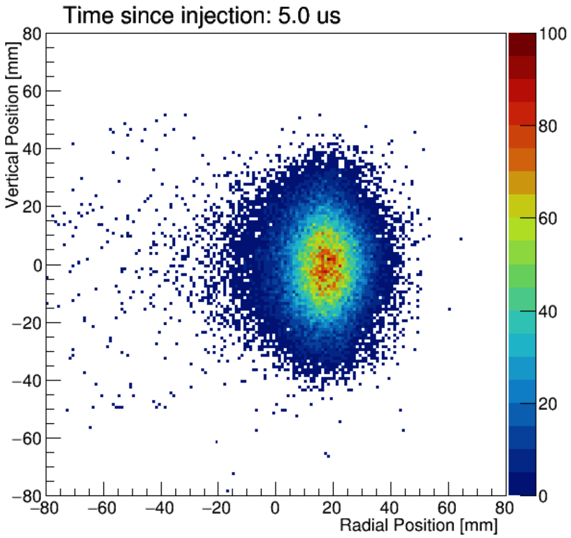


Structure in residual: Beam oscillation

- Coherent Betatron Oscillations (CBO) sampled by each detector at one point around the ring

$\lambda_{CBO} \simeq$ 14 turns





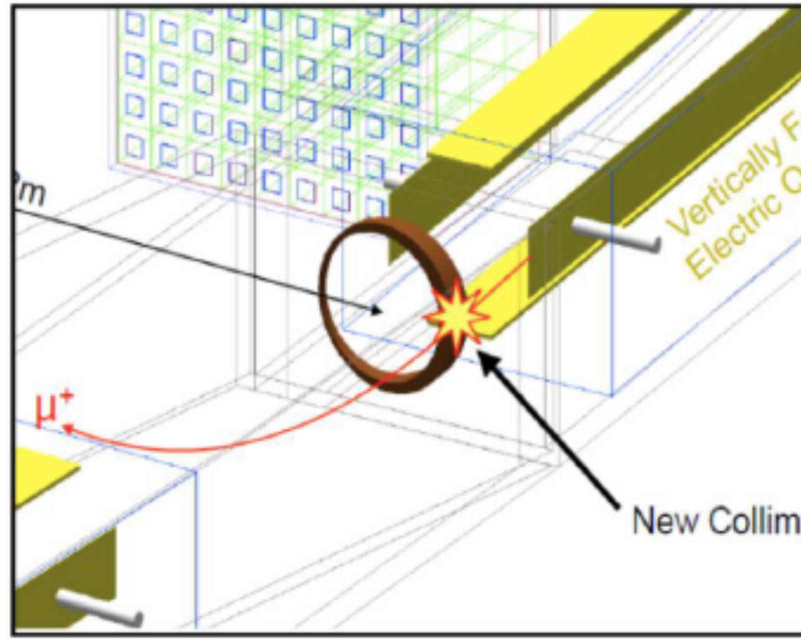
- Beating effects and additional radial and vertical frequencies

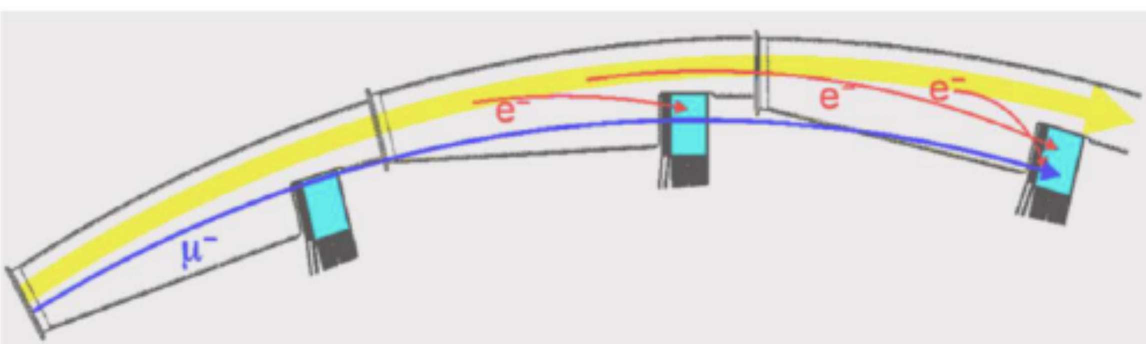
Lost Muons

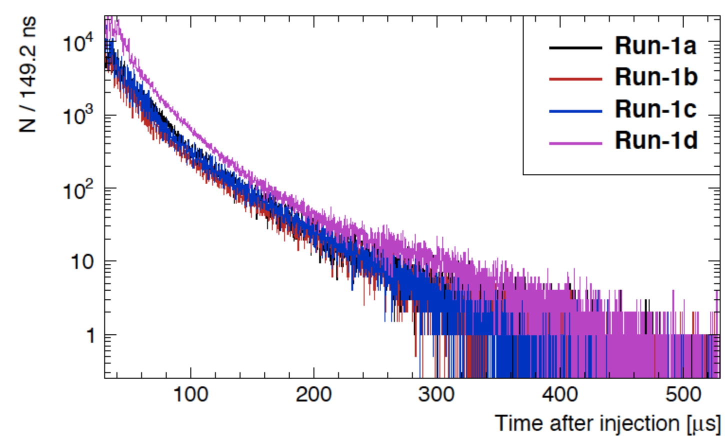
- Muon losses distort the exponential decay of the number of stored muons
- Muon Loss term :

$$J(t) = 1 - K_{LM} \int_0^t e^{\frac{t'}{\tau}} L(t') dt'$$

- $L(t)$ measured from the detection of Minimum Ionizing Particles in the calorimeters







The fit equation

$$N_0 e^{-\frac{t}{\gamma\tau}} (1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)$$

$$A_{\rm BO}(t) = 1 + A_A \cos(\omega_{\rm CBO}(t) + \phi_A) e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$\phi_{\rm BO}(t) = 1 + A_\phi \cos(\omega_{\rm CBO}(t) + \phi_\phi) e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$N_{\rm CBO}(t) = 1 + A_{\rm CBO} \cos(\omega_{\rm CBO}(t) + \phi_{\rm CBO}) e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$N_{\rm 2CBO}(t) = 1 + A_{\rm 2CBO} \cos(2\omega_{\rm CBO}(t) + \phi_{\rm 2CBO}) e^{-\frac{t}{2\tau_{\rm CBO}}}$$

$$N_{\rm VW}(t) = 1 + A_{\rm VW} \cos(\omega_{\rm VW}(t) t + \phi_{\rm VW}) e^{-\frac{t}{\tau_{\rm VW}}}$$

$$N_y(t) = 1 + A_y \cos(\omega_y(t) t + \phi_y) e^{-\frac{t}{\tau_y}}$$

Red = free parameters

Blue= fixed parameters

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

Muon Loss term

$$\omega_{\rm CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F \omega_{\rm CBO(t)} \sqrt{2\omega_c / F \omega_{\rm CBO}(t) - 1}$$

$$\omega_{\rm VW}(t) = \omega_c - 2\omega_y(t)$$

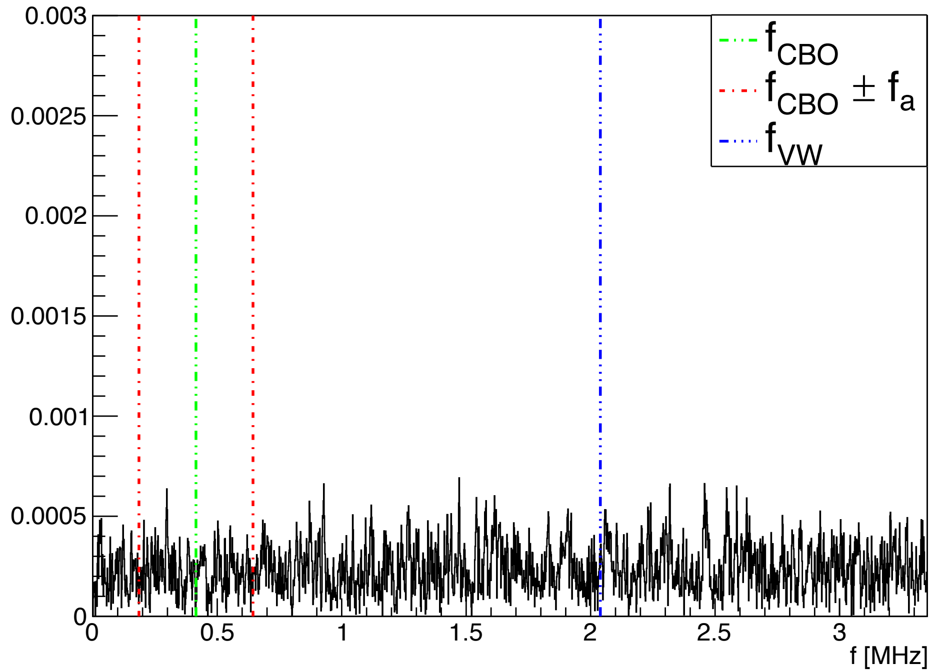
ω_y, ω_{vw} vertical oscillations

ω_{CBO}, ω_{2CBO}, radial oscillation

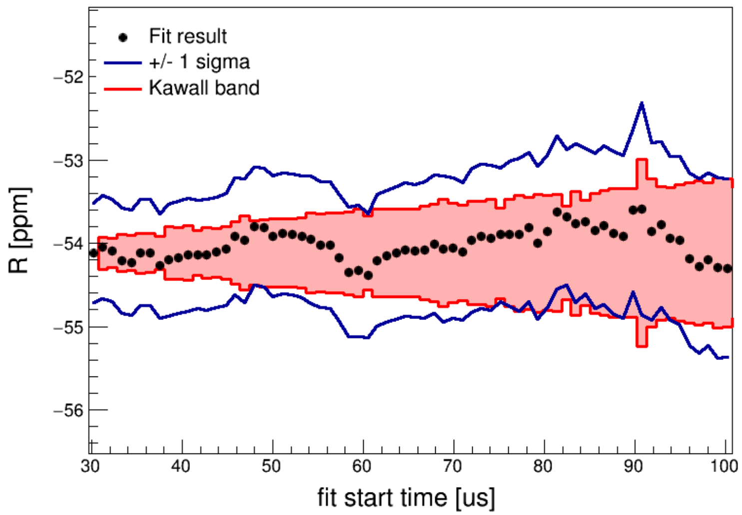
Final Fit

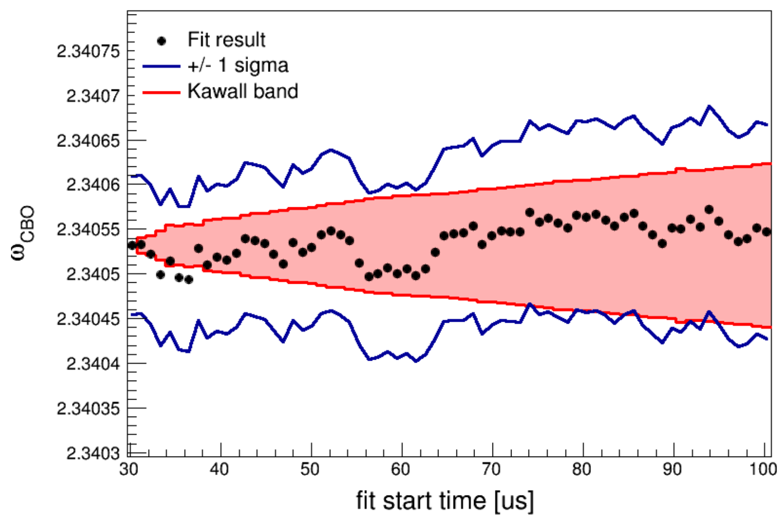
$$R_{(blinded)} = (1 + \omega_{blind} / \omega_{ref}) \text{ [ppm]}$$

Fourier transform of residuals



No unaccounted frequencies





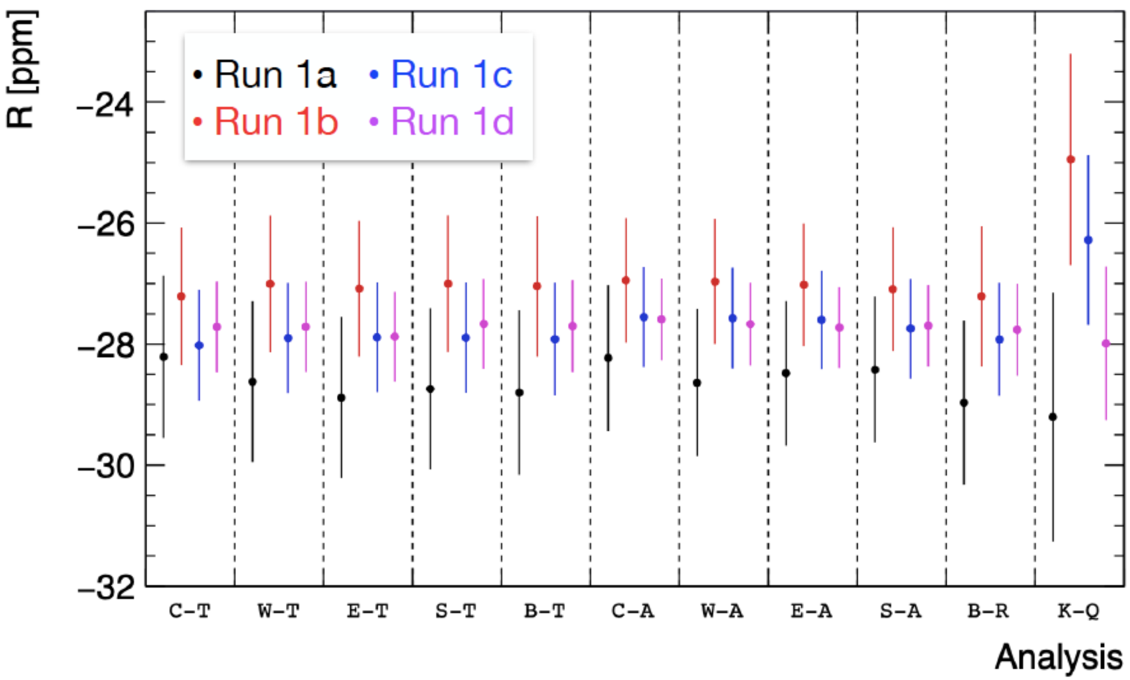
Systematic errors

Consistency check	Varied effects
start time scan	gain corr, μloss corr, pile up, betatron osc and ω_{cbo}-ω_a start-time phase
calorimeter scan	increases beta osc, changes ω_{cbo}-ω_a , ω_{c--} ω_a relative phases
different pileup separation, corrections	w/, w/o spatial separation + empirical, probability, shadow, rejection correction approaches
different kicker, quad settings	different freq, ampl, phase beam osc, different ampl. t-dependence μloss
ad-hoc correction on-off	fits with, without the leading unexplained term
R-T method comparision	different scales of μloss, igain, ad-hoc, pileup slow terms
ART-Q method comparision	with / without positron reconstruction, template fitting, xtal clustering

Software ω_a unblinding and combination

- Comparison of different analyses after software unblinding shows good consistency
- Final combination based on Asymmetry method:
  - statistically optimal one
  - negligible gain in total precision by including the other methods

Note: R is the blinded value for ω_a



- **434 ppb** statistical uncertainty (compare to 460 ppb for BNL)
- **56 ppb** systematic uncertainty

“Master Formula”

Beam Dynamics corrections

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

Electric Field correction C_e

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

The off-momentum muon spins are slightly affected by the radial *E* field

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

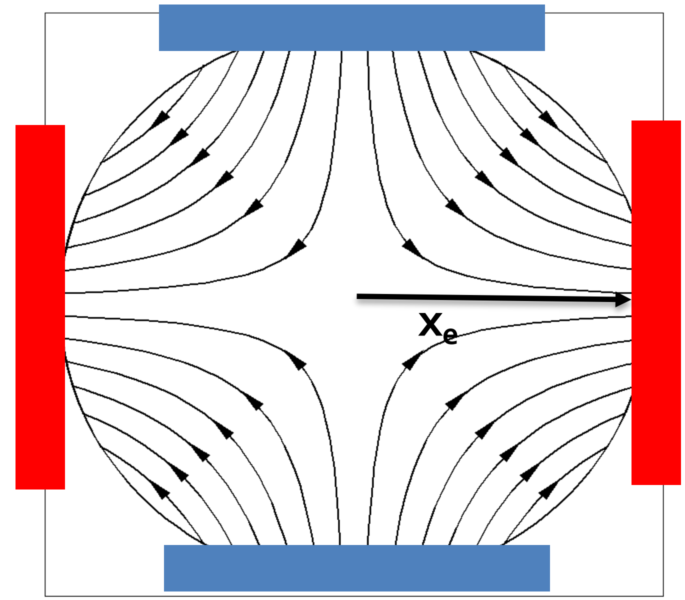
C_e depends on $\mathbf{x_e}$ (equilibrium radius)

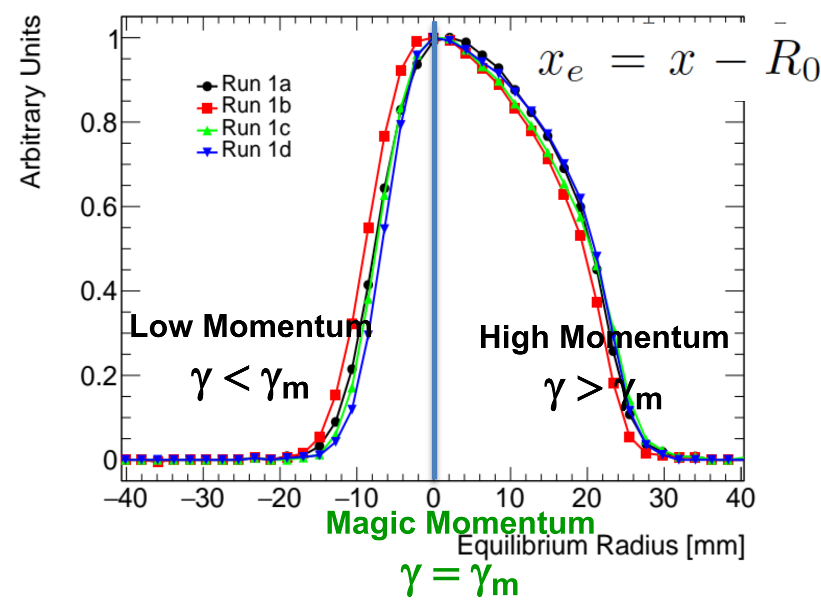
$$\langle x_e^2 \rangle = \sigma_{x_e}^2 + \langle x_e \rangle^2$$

x_e obtained by a Fourier analysis of arrival time of the positrons on the **calorimeter**

$$C_e \sim 450\ ppb,\ \delta_{C_e} \sim 50 ppb$$

Uncertainty driven by **momentum-time correlation** due to non-uniform kicker pulse

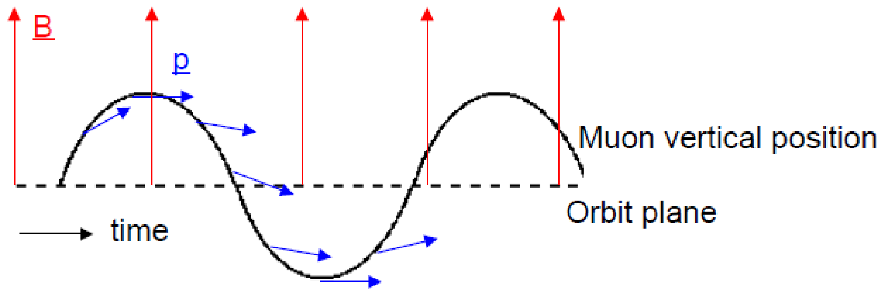




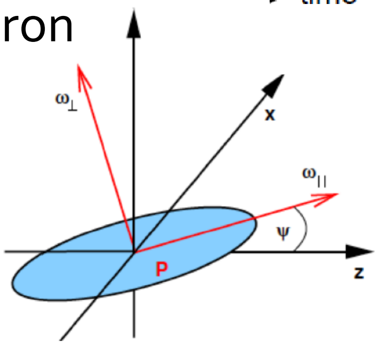
Pitch correction C_p (vertical betatron osc.)

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

(great exaggeration)



The precession plane oscillates harmonically with the vertical betatron frequency $\psi(t) = \psi_0 \cos\omega_y t$

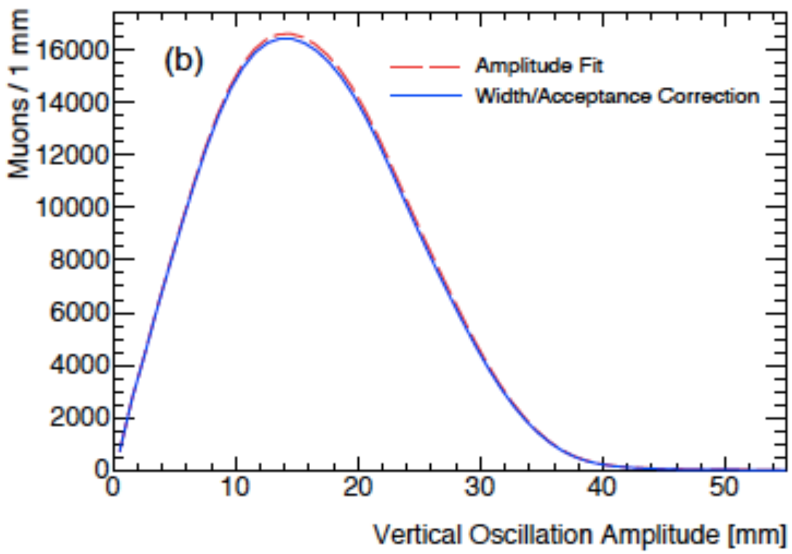


$$C_p = \frac{\psi_0^2}{4} = \frac{n}{4R_0^2}\langle A^2\rangle$$

A vertical oscillation amplitude

C_p obtained by the μ decay positions meas. by the **trackers** averaged on azimuth

$$\boldsymbol{C_p \sim 200\ ppb, \delta_{C_p} \sim 10ppb}$$



Uncertainty driven by tracker measurement systematic effects

Example of phase shift: Muon Loss-Phase correction C_{ml}

- Muon losses (ML) induce a (tiny) **phase shift** since: 1) Different momentum μ have different phase; 2) μ are lost depending on momentum

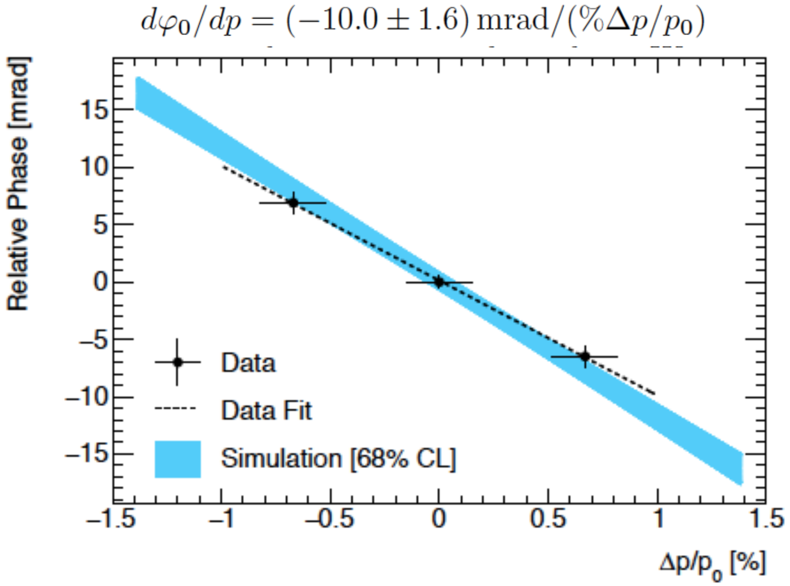
1) 2)

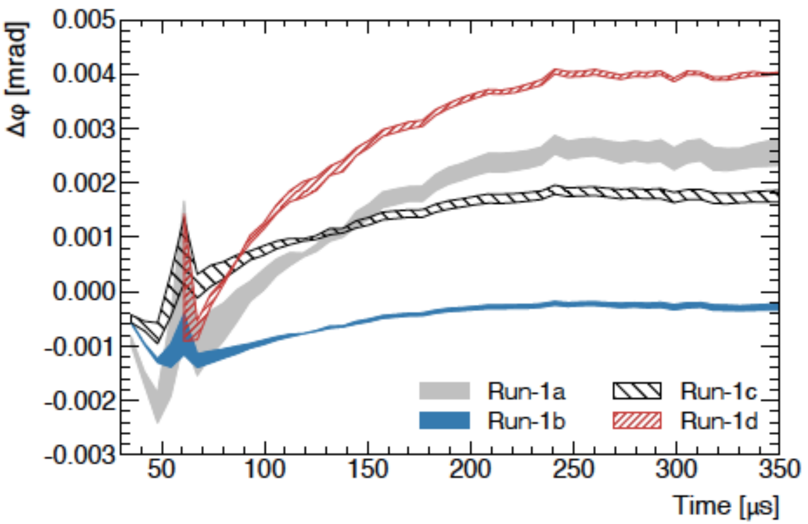
$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{d\phi}{dp} \cdot \frac{dp}{dt} \neq 0$$

- Data-driven special measurements (of biased momentum)

$$C_{ml} < 20\ ppb, \delta_{C_{ml}} \sim 5\ ppb$$

~Negligible uncertainty





Example of phase shift: Phase-Acceptance correction C_{pa}

- Variable phase due to 1) Beam changing from **early to late** coupled with 2) the measured phase depends on the decay coordinates

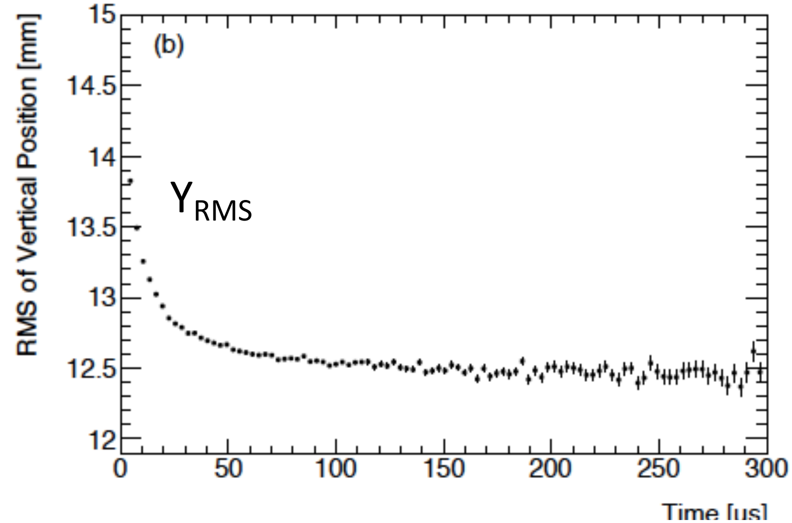
1) 2)

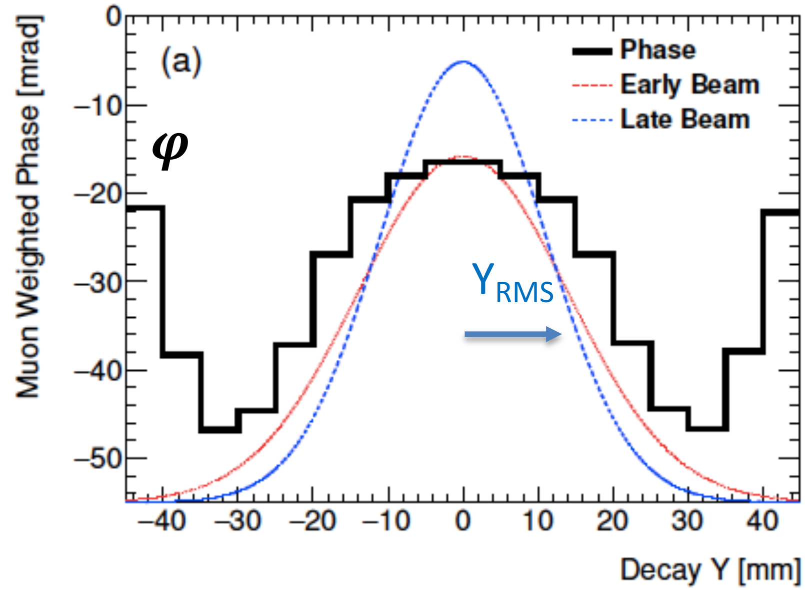
$$\Delta\omega_a = \frac{d\phi}{dt} = \frac{dY_{RMS}}{dt} \cdot \frac{d\phi}{dY_{RMS}} \neq 0$$

- Effect increases to RUN1 due to damaged QUAD resistors
- Extensive use of the simulation trained by data (**trackers** and **calorimeters**).

$$C_{pa} \sim 200\ ppb, \delta_{C_{pa}} \sim 80\ ppb$$

Expected Systematic effect <50 ppb in RUN2 (due to fix of EQS resistors)





φ is integrated in the Y distribution of muons

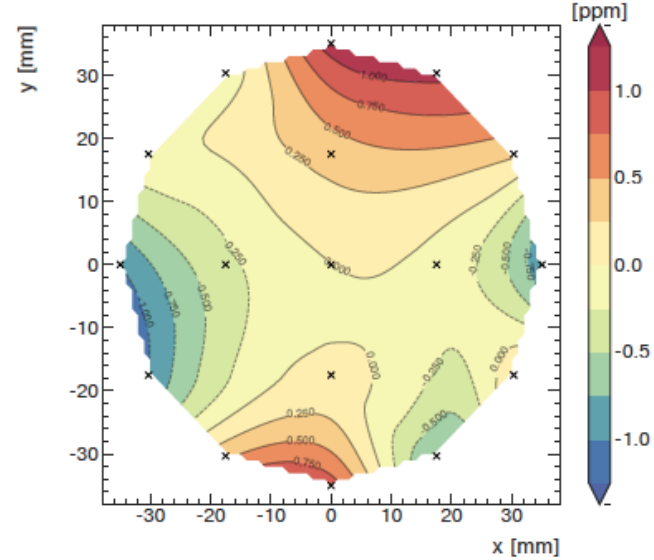
“Master Formula”

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

Field measurement

ω'_p measurement

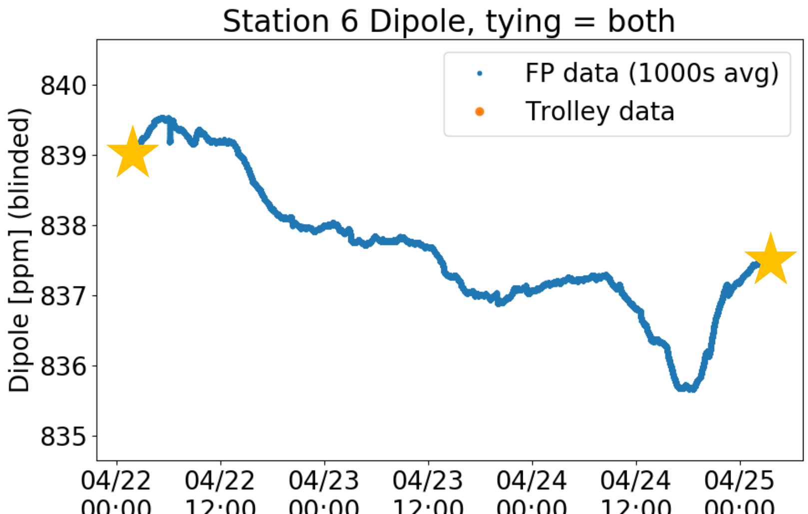
- Trolley maps of the magnetic field at about 9000 locations over the entire azimuth every 3 days
- Fixed probes to interpolate the field between the trolley runs
- Need calibration to convert the 17 NMR trolley to water sample



$$\delta_{\omega'_p} \sim 48ppb$$

Uncertainty due to:

1. Temperature Corrections
2. Configuration Corrections
3. Trolley Map Systematics
4. Fixed Probe Systematics
5. Tracking Drift Uncertainty

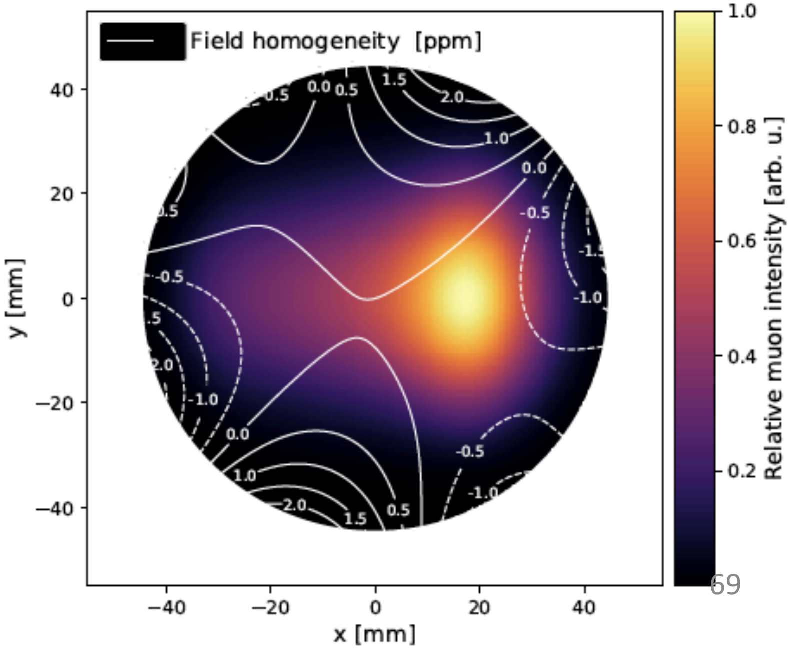


$\omega'_p \rightarrow \tilde{\omega}'_p$: muon weighted average

- Need field actually experienced by muons
- Muon decay point estimated from e+ track reconstructed by the two straw trackers inside storage vacuum
- Use beam dynamics models, tuned to the tracker data, to get distribution all around the ring
- Systematic uncertainty due to probe calibrations, field map, tracker alignment and BD model

$$\boldsymbol{\delta_{\widetilde{\omega'}_p} \sim 56\, ppb}$$

Muon's view of a tracker



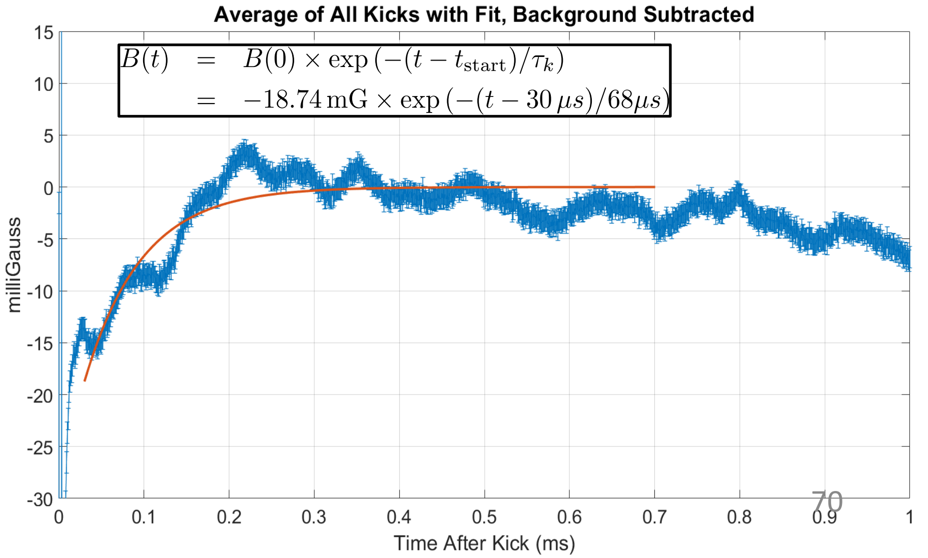
Kicker transient field B_k

- The kicker pulse (~ 200G) produces a transient magnetic field for 150ns in the storage volume → eddy currents
- **A Faraday magnetometer** installed between the kicker plates measured the rotation of polarized light in a crystal due to the transient field
- Signal was fitted with an exponential function

$$\Delta B(t) = \Delta B(0) \exp\left(-t/\tau_k\right)$$

$$\boldsymbol{B_k \sim 30\ ppb,\ \delta_{C_{pa}} \sim 40\ ppb}$$

Magnetometer between kicker plates



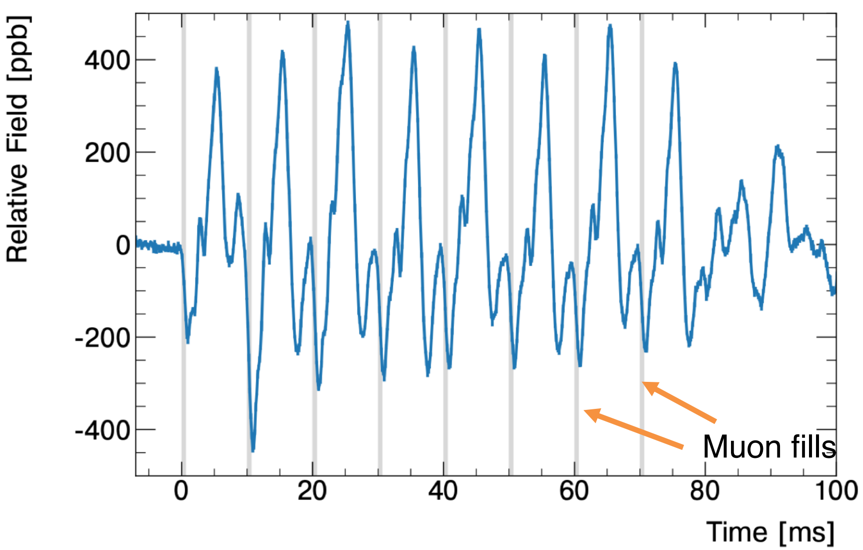
ESQ transient field B_q

- The ESQ are charged/discharged every muon fill (700μs)
- The electric pulse induces mechanical vibrations in the plates which generate magnetic perturbations
- Customized NMR probes measured B_q at several positions

$$\boldsymbol{B_q \sim 20\ ppb, \delta_{B_q} \sim 90\ ppb}$$

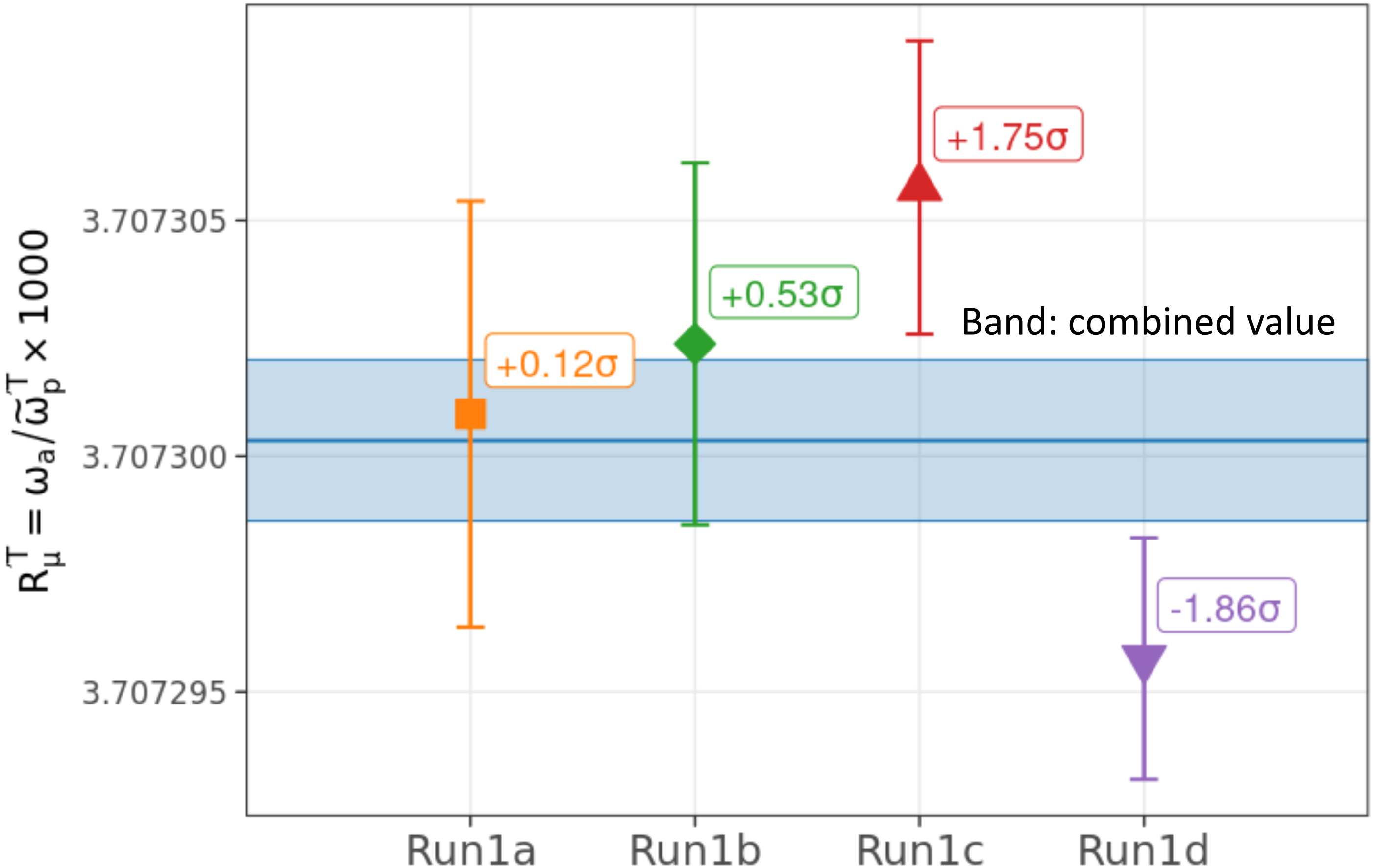
The uncertainty is determined by the full width of the measured effect due to the lack of measurements in run-1. (To be reduced in RUN2 by more measurement)

Quad Plates inside Vacuum Chamber



Results

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

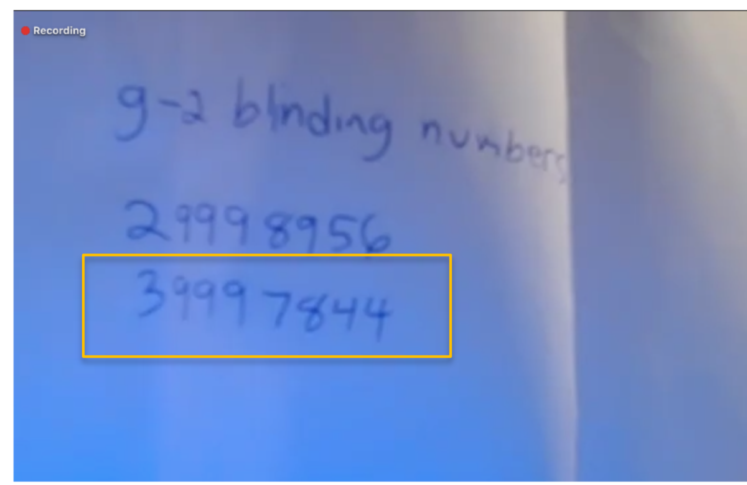


χ^2/ndf=6.8/3 P(χ^2)=7.8%

a_μ: Unblinding

On February 25 the collaboration met for the unblinding:

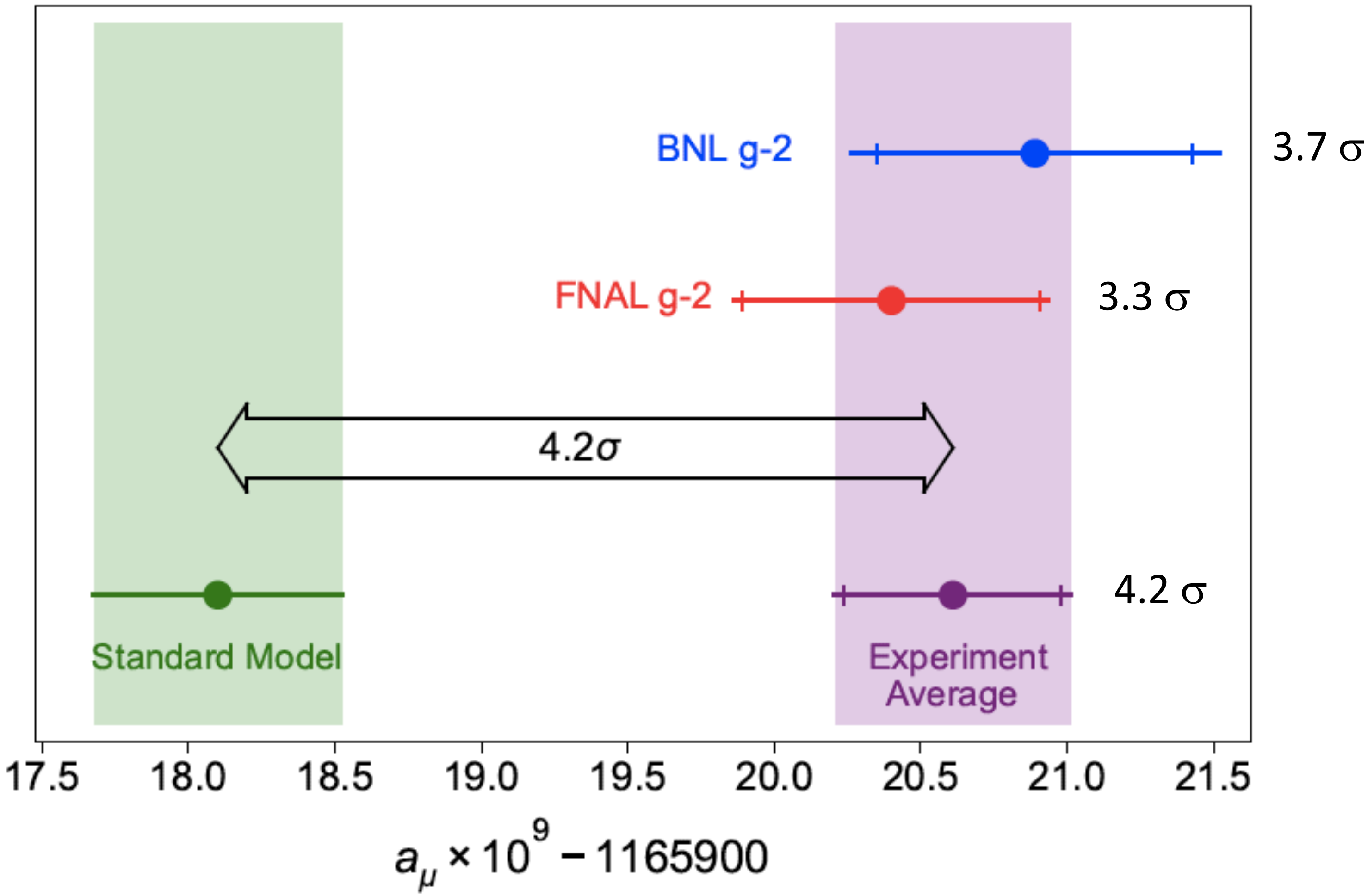
1) The box was opened
2) The number was plugged in two independent programs
3) And the result was….



Secret offset

a_μ: Unblinding meeting

a_μ: Unblinding



a_μ: Unblinding

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (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_q	-17	92
B_k	-27	37
$\mu'_p(34.7°)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–	462

434 ppb stat $\oplus$ 157 ppb syst error

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

Post April 7

- +8500 participants to the Fermilab release (7/4)
- 1300 participants to the CERN seminar (8/4)
- > 30 theoretical papers on ArXiv the day after the announcement (8/4)
- News reported in all newspapers, socials
- 2.7 billion people have read the news of the measure since the announcement on Wednesday 7 April at 12:00 on 9 April (fermilab press office)
- Millions of youtube views etc ...

First Page NYT

INFN Istituto Nazionale di Fisica Nucleare

Muon g-2

8 April 2021

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXX .... No. 59,022 — NEW YORK, THURSDAY, APRIL 8, 2021 — $3.00

Biden Tax Plan Aims to Curtail Use of Havens

Loophole Has Enriched Global Corporations

Contagious Variant Is Fueling Surge in Infections Across the U.S.

PAIR OF SETBACKS FOR ASTRAZENECA OVER ITS VACCINE

BLOOD CLOT CONCERNS

U.K. Curbs Use by Adults Under 30 as the E.U. Outlines Risks

ISIS and African Militants Join In a Marriage of Convenience

New York to Provide $2.1 Billion For Undocumented Immigrants

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental

REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A19

National journals

Muon g-2

Corriere

FERMILAB

Muone, la reazione «inattesa» della particella che può cambiare le leggi della fisica

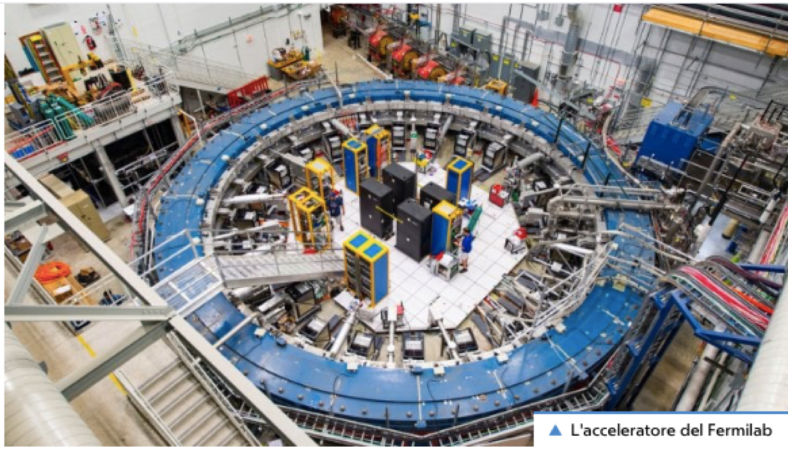
I dati dell'esperimento Muon g-2, con l'importante contributo italiano dell'Istituto nazionale di fisica nucleare, indicherebbero fenomeni non descritti dalle attuali teorie. Venanzoni (Infn): «Un successo in buona parte merito dei giovani ricercatori». Ma Nature frena

di **Paolo Virtuani**

News reported by the main National (> 30) newspapers.

Repubblica

L'anomalia del muone: l'esperimento che suggerisce l'esistenza di nuove forze della natura



▲ L'acceleratore del Fermilab

di Matteo Marini

L'acceleratore di particelle del Fermilab, a Chicago, ha misurato un'anomalia nel valore del momento magnetico del muone. Sembrerebbe un dettaglio riservato agli appassionati di fisica. Invece è una notizia che apre la porta alla presenza di nuove particelle. Perfino di un secondo bosone di Higgs

Italian contribution: a little of history

- We started (in an exploratory way) in 2009
- 2012 Consolidation of collaboration and CNR INO contribution
- In 2013 INFN sigla (~ 6 FTE)
- In 2021 we reached ~ 18 FTE> 30 employees

Submitted to FNAL

February 9, 2009

The New $(g-2)$ Experiment:

A Proposal to Measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm Precision

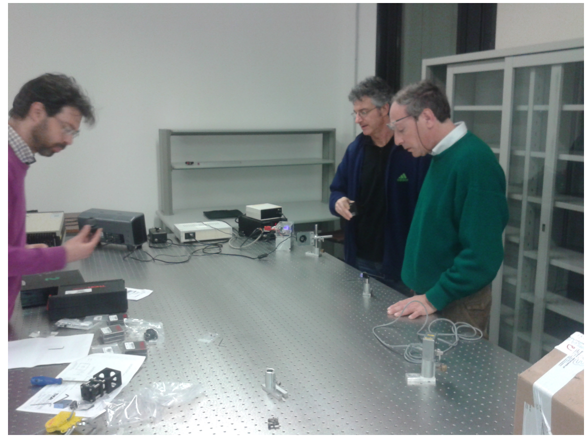
New $(g-2)$ Collaboration: R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], W.M. Morse[2], Y.K. Semertzidis[2], V.P. Druzhinin[3], B.I. Khazin[3], I.A. Koop[3], I. Logashenko[3], S.I. Redin[3], Y.M. Shatunov[3], Y. Orlov[4], R.M. Talman[4], B. Casey[5], J. Johnstone[5], D. Harding[5], A. Klebaner[5], A. Leveling[5], J-F. Ostiguy[5], N. Mokhov[5], D. Neuffer[5], M. Popovic[5], S. Strigonov[5], M. Syphers[5], G. Velev[5], S. Werkema[5], F. Happacher[6], G. Venanzoni[6], P. Debevec[7], M. Grosse-Perdekamp[7], D.W. Hertzog[7], P. Kammel[7], C. Polly[7], K.L. Giovanetti[8], K. Jungmann[9], C.J.G. Onderwater[9], N. Saito[10], C. Crawford[11], R. Fatemi[11], T.P. Gorringe[11], W. Korsch[11], B. Plaster[11], V. Tishchenko[11], D. Kawall[12], T. Chupp[13], C. Ankenbrandt[14], M.A Cummings[14], R.P. Johnson[14], C. Yoshikawa[14], André de Gouvêa[15], T. Itahashi[16], Y. Kuno[16], G.D. Alkhazov[17], V.L. Golovtsov[17], P.V. Neustroev[17], L.N. Uvarov[17], A.A. Vasilyev[17], A.A. Vorobyov[17], M.B. Zhalov[17], F. Gray[18], D. Stöckinger[19], S. Baeßler[20], M. Bychkov[20], E. Frlež[20], and D. Počanić[20]

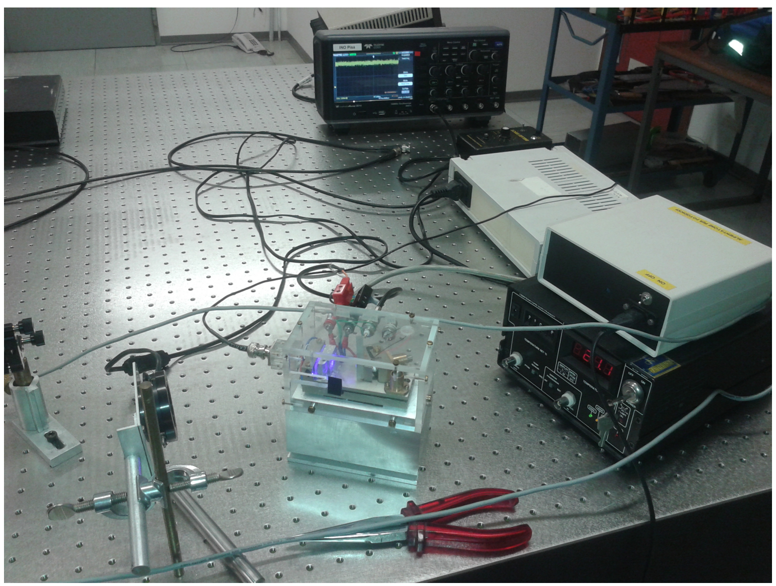
From where we started

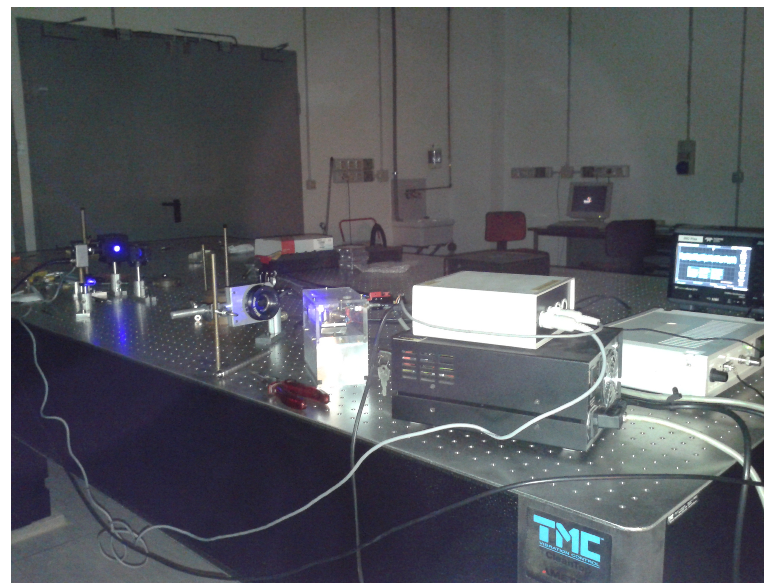
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

→ Un laser con controllo delle fluttuazioni di guadagno al di sotto del per mille. Sistematico dominante in BNL!

First tests 2013







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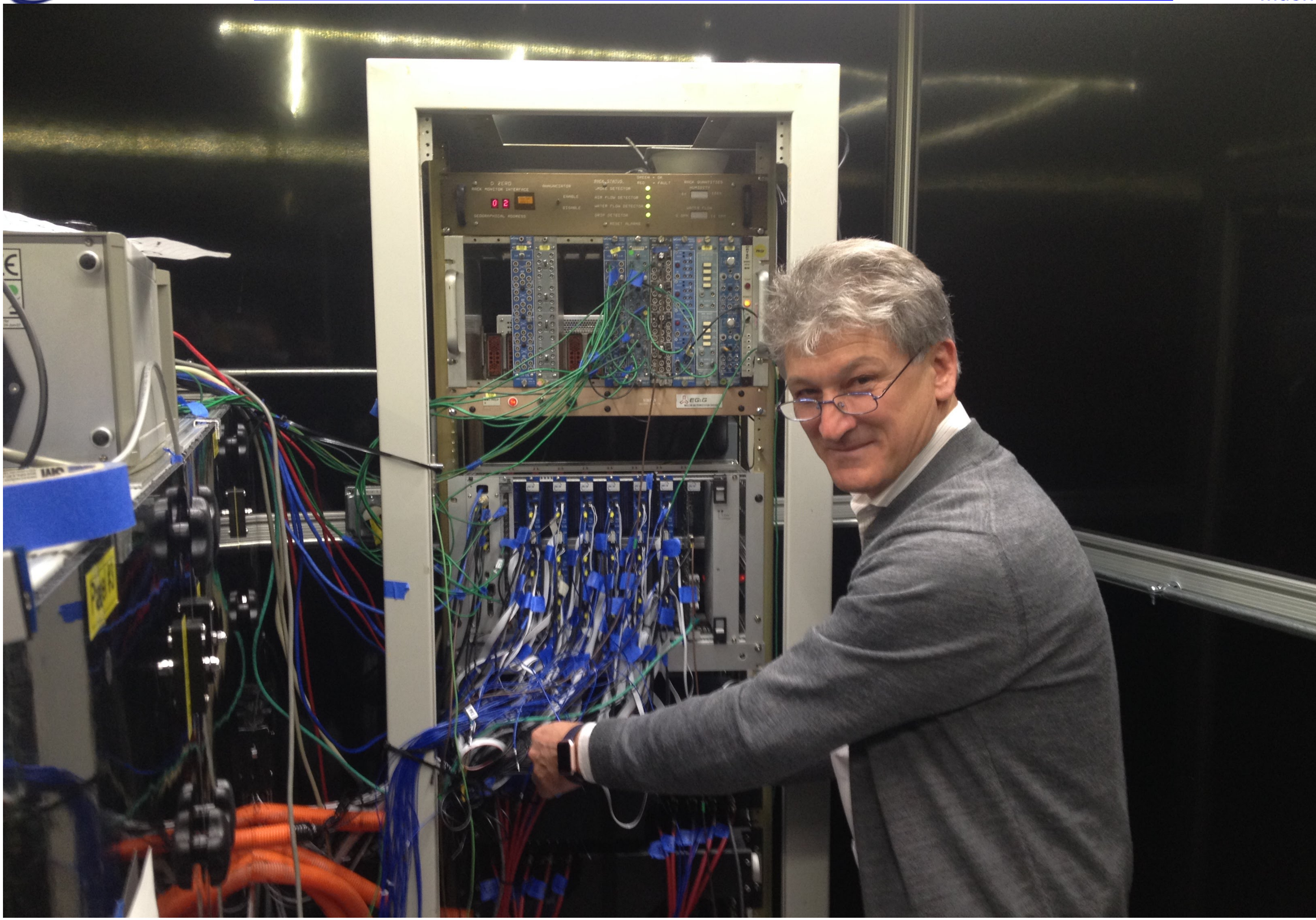
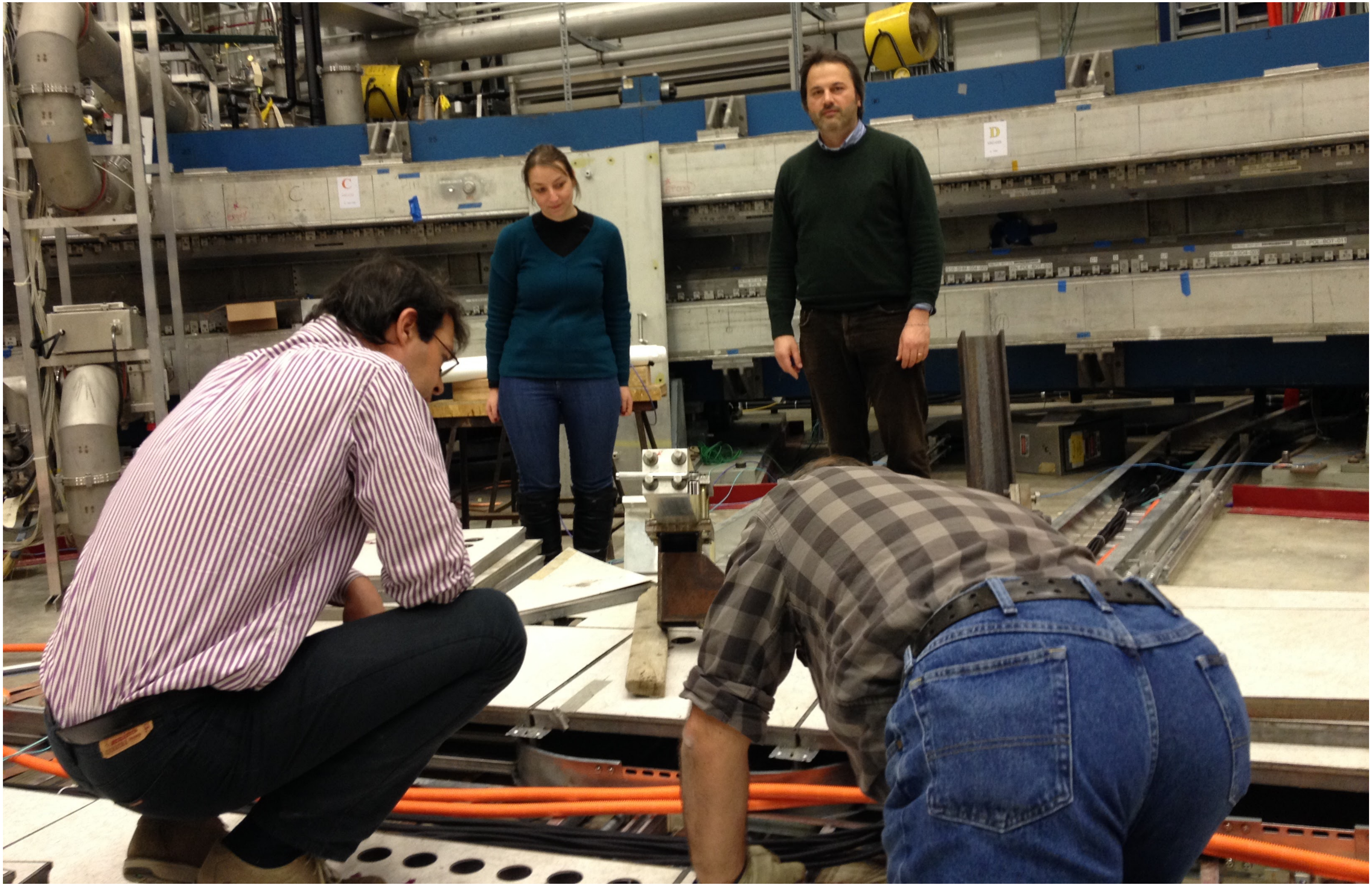
In the laser Hut

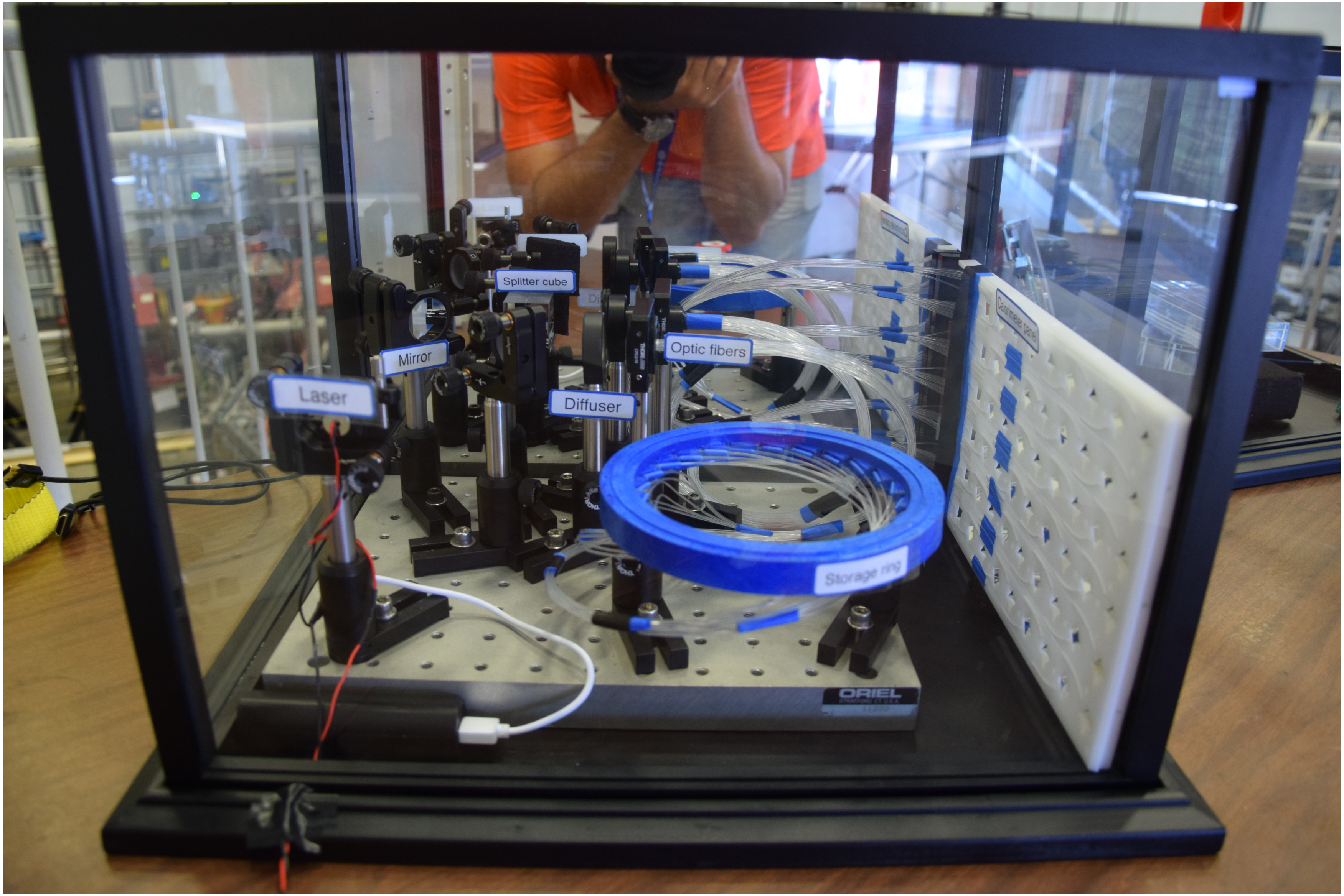
Muon g-2



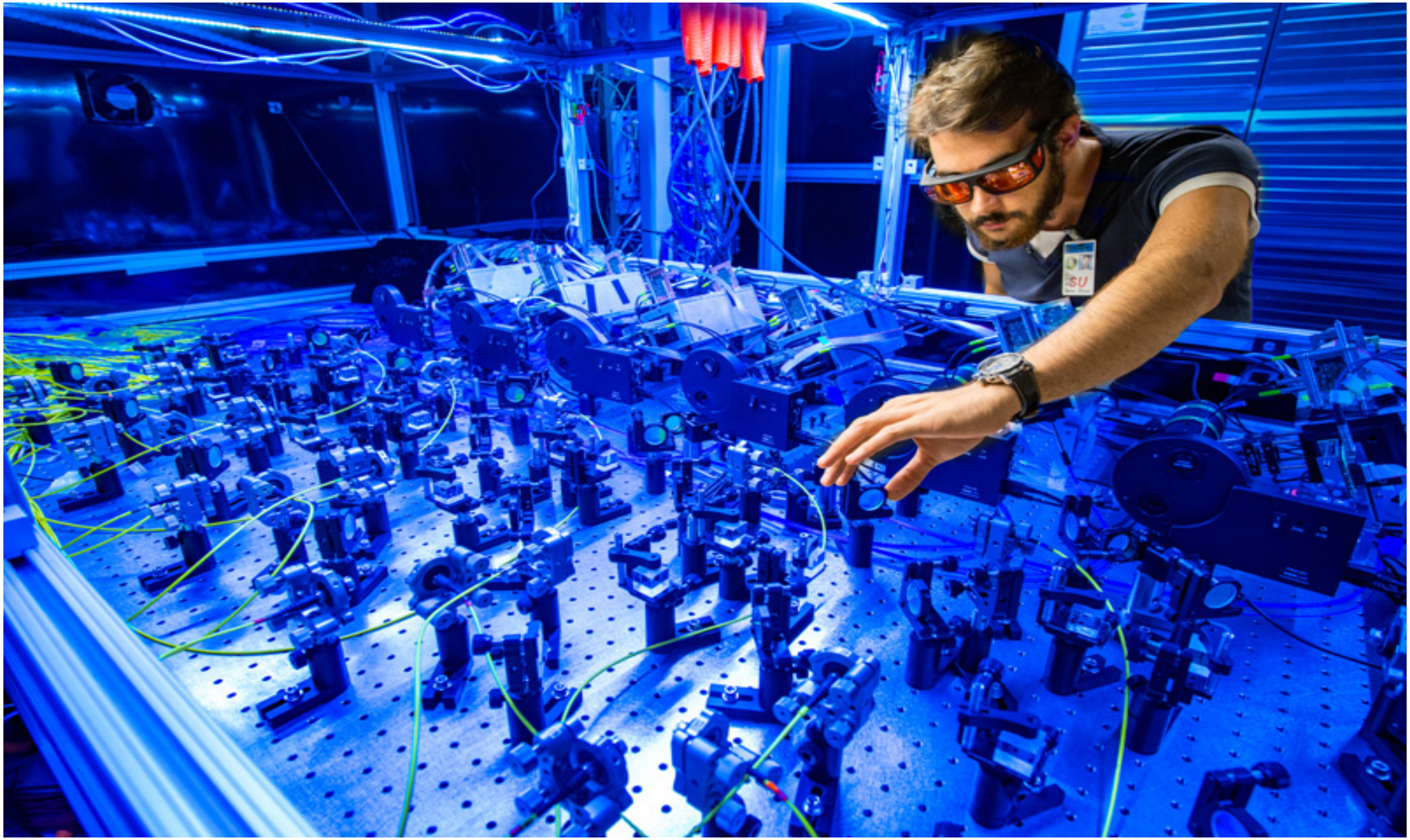
Bringing the fibers to the calorimeters



Finally… the calibration system is ready!



Finally… the calibration system is ready!



INFN Istituto Nazionale di Fisica Nucleare

JINST 14 (2019) P11025 (1906.08432)

Muon g-2

The laser-based gain monitoring system of the calorimeters in the Muon $g-2$ experiment at Fermilab

A. Anastasi,[a] A. Basti,[a,c] F. Bedeschi,[a] A. Bolano,[b] E. Bottalico,[a,c] G. Cantatore,[d,e] D. Cauz,[d,f] A.T. Chapelain,[g] G. Corradi,[h] S. Dabagov,[h,i,j] S. Di Falco,[a] P. Di Meo,[b] G. Di Sciascio,[k] R. Di Stefano,[b,l] S. Donati,[a,c] A. Driutti,[d,f] C. Ferrari,[a,m] A.T. Fienberg,[n] A. Fioretti,[a,m,1] C. Gabbanini,[a,m] L.K. Gibbons,[g] A. Gioiosa,[k,o] P. Girotti,[a,c] D. Hampai,[h] J.B. Hempstead,[n] D.W. Hertzog,[n] M. Iacovacci,[b,p] M. Incagli,[a] M. Karuza,[d,q] J. Kaspar,[n] K.S. Khaw,[n] A. Lusiani,[a,r] F. Marignetti,[b,l] S. Mastroianni,[b] S. Miozzi,[k] A. Nath,[b] G. Pauletta,[d,f] G.M. Piacentino,[k,o] N. Raha,[a] L. Santi,[d,f] M. Smith,[a,n] M. Sorbara,[k,s] D.A. Sweigart[g] and G. Venanzoni[a,1]

ABSTRACT: The Muon $g-2$ experiment, E989, is currently taking data at Fermilab with the aim of reducing the experimental error on the muon anomaly by a factor of four and possibly clarifying the current discrepancy with the theoretical prediction. A central component of this four-fold improvement in precision is the laser calibration system of the calorimeters, which has to monitor the gain variations of the photo-sensors with a 0.04% precision on the short-term (~ 1 ms). This is about one order of magnitude better than what has ever been achieved for the calibration of a particle physics calorimeter. The system is designed to monitor also long-term gain variations, mostly due to temperature effects, with a precision below the per mille level. This article reviews the design, the implementation and the performance of the Muon $g-2$ laser calibration system, showing how the experimental requirements have been met.

Errore su ω_a <20 ppb
(*Phys.Rev.D* 103 (2021) 7, 072002)

Physics Week at Elba 2019 (>100 participants)

Fermilab Nov 2019
a_μ=...

INFN g-2 Group (2021)

34 People, 18 FTE

6 INFN Sections:

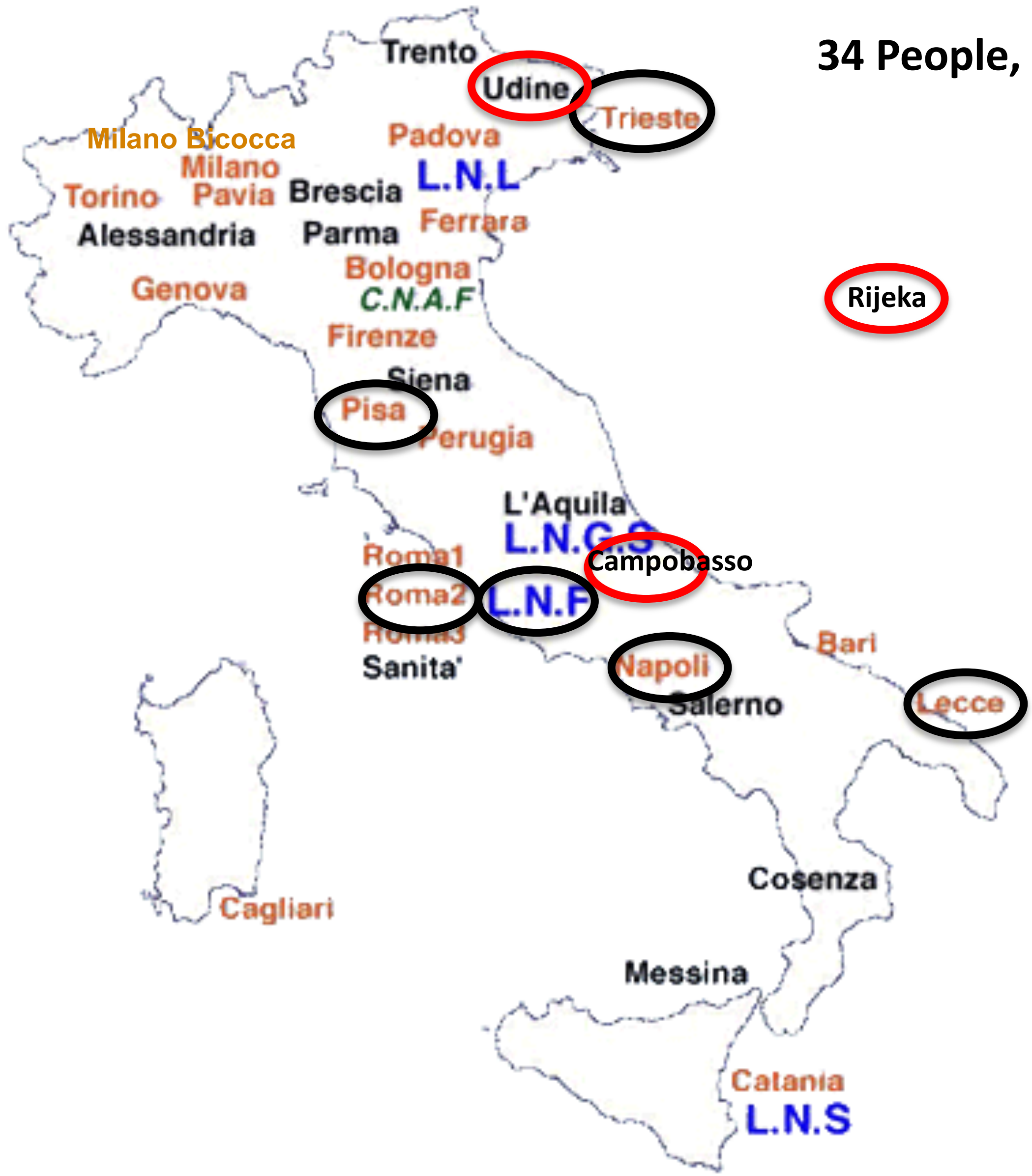
- LNF (Frascati)
- Napoli
- PISA
- Roma2
- Trieste
- Lecce

6 Universities:

- Udine
- Naples
- Trieste
- Rjeka
- Molise (Campobasso)
- Scuola Normale Superiore (Pisa)

CNR INO:

- Pisa



Roles of the Italian group

- G. Venanzoni: **co-spokesperson**
- F. Bedeschi: **member** of the talk committee
- M. Incagli: detector coordinator; **chair** Institution Board
- A. Lusiani: head of computing for Italy; **chair** combination a_μ
- M. Sorbara: head of the omega_a Europe Analysis Group
- E. Bottalico / P. Girotti: responsible for the laser system
- A. Gioiosa: slow control manager
- S. Mastroianni: DAQ expert
- N. Piacentino and E. Bottalico D&I committee members

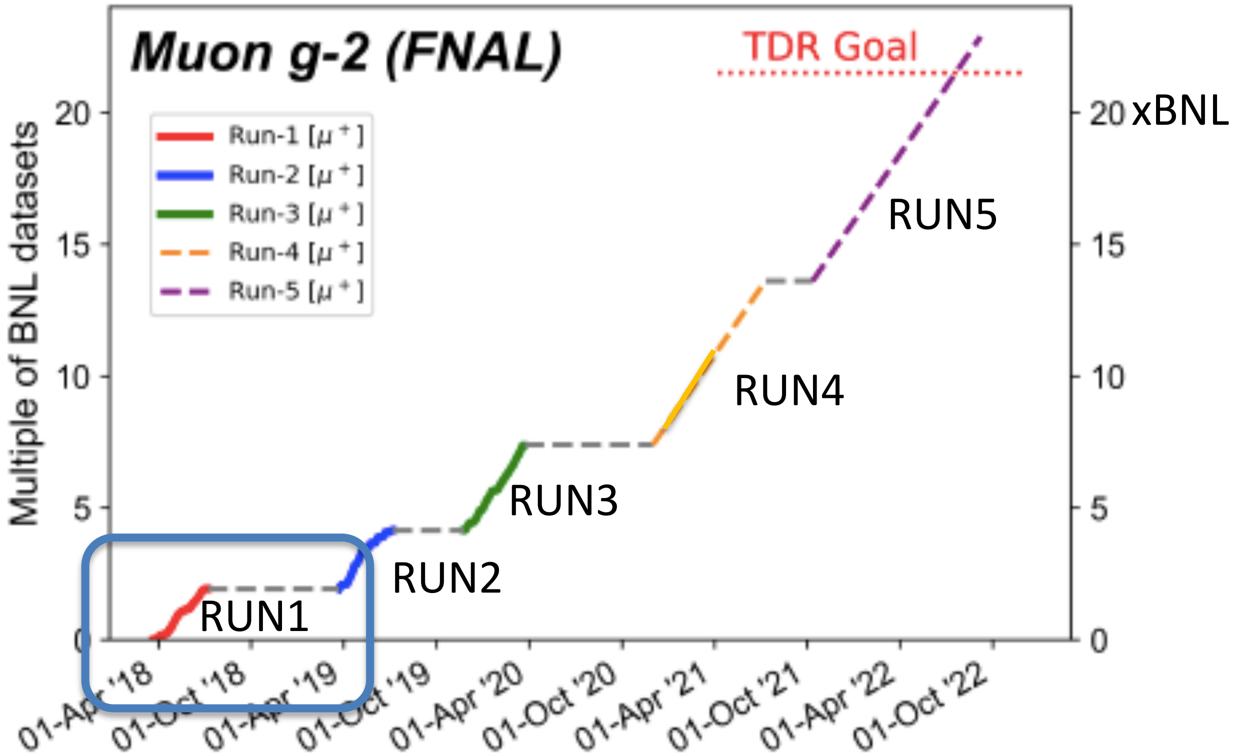
g-2 Young

- M. D. Galati (MSc. at UniPi): Magnetometer, Run2 analysis, lost muons and pileup studies;
- P. Leo (Msc. At UniPi): Run2 analysis, ReconIta;
- E. Bottalico (PhD. at UniPi): Phase acceptance systematics, Laser studies and beam dynamics;
- L. Cotrozzi (PhD at UniPi): Run2/3 analysis;
- P. Girotti (PhD. at UniPi): Gain corrections, Run 1 residual gain analysis, pileup studies;
- M. Sorbara (PhD. at UniRoma2): Run 1/2 analysis, result combination and calorimeter simulation.

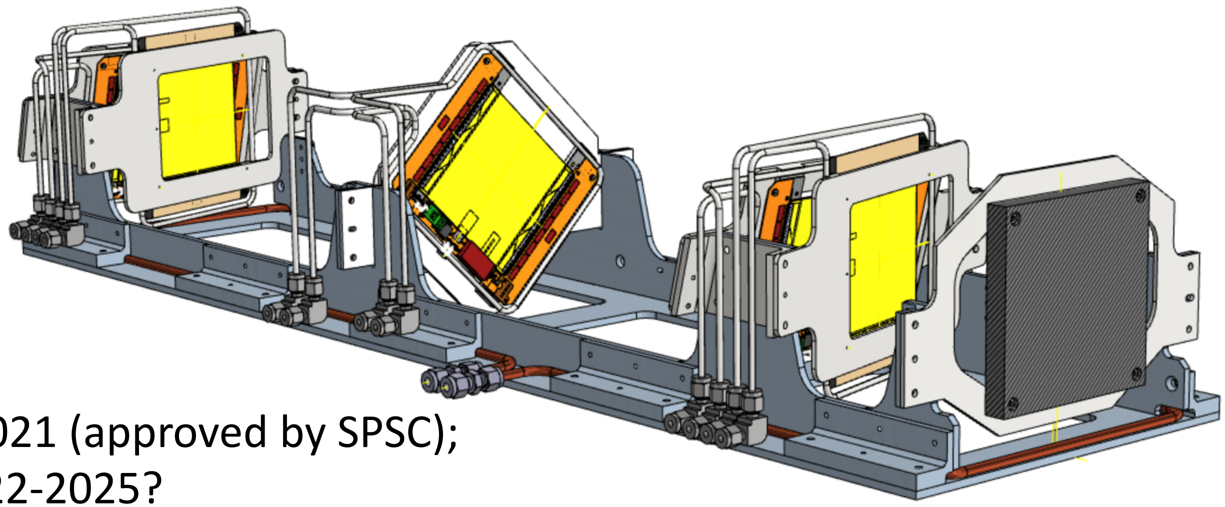
4 dottorandi 2 studenti di laurea magistrale

Future

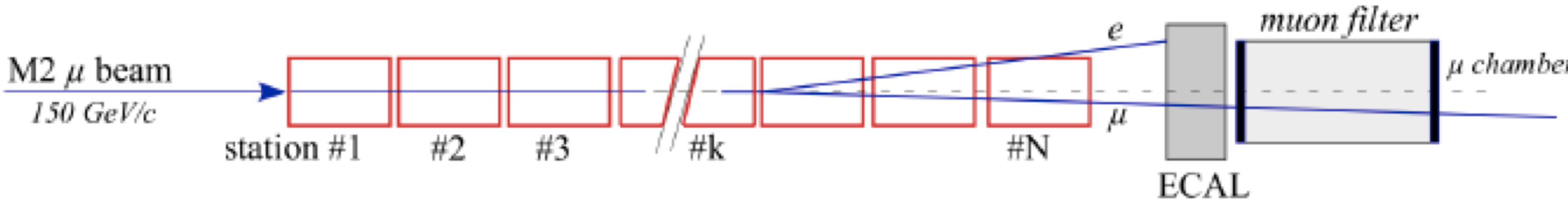
- RUN1 is only 6% of the final dataset
- Analysis of RUN2/3 (expect an improvement of a factor ~2 in precision)
- RUN4 (November 2020-July 2021) is expected to bring the statistics to ~13 BNL
- RUN5 in 2021-2022 should allow to achieve the x20 BNL project goal



MUonE al CERN



Test RUN 2021 (approved by SPSC);
Full run 2022-2025?



Alternative measurement of HVP for a_μ

-*A. Abbiendi et al Eur.Phys.J.C* 77 (2017) 3, 139
-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

Conclusions

- We have presented the first measurement of a_μ at 0.46 ppm
- Our result is consistent with the BNL one (within one standard deviation) with slightly better precision

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

- The discrepancy with the Standard Model prediction of the g-2 by the Theory Initiative is 4.2σ
- We expect an improvement in precision of a factor 2 from the RUN2/3 data and more from Run4 and 5.
- INFN played (and will play) an important role for this measurement!

Stay tuned!

The Muon g-2 Collaboration (Elba 2019)

Acknowledgements

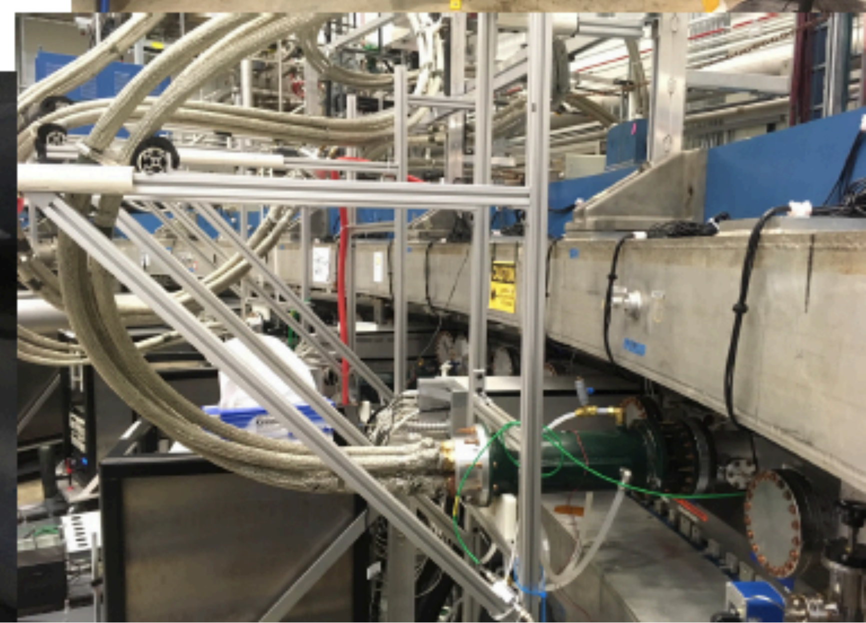
Department of Energy (USA),
National Science Foundation (USA),
Istituto Nazionale di Fisica Nucleare (Italy),
Science and Technology Facilities Council (UK),
Royal Society (UK),
European Union's Horizon 2020
National Natural Science Foundation of China,
MSIP, NRF and IBS-R017-D1 (Republic of Korea),
German Research Foundation (DFG)

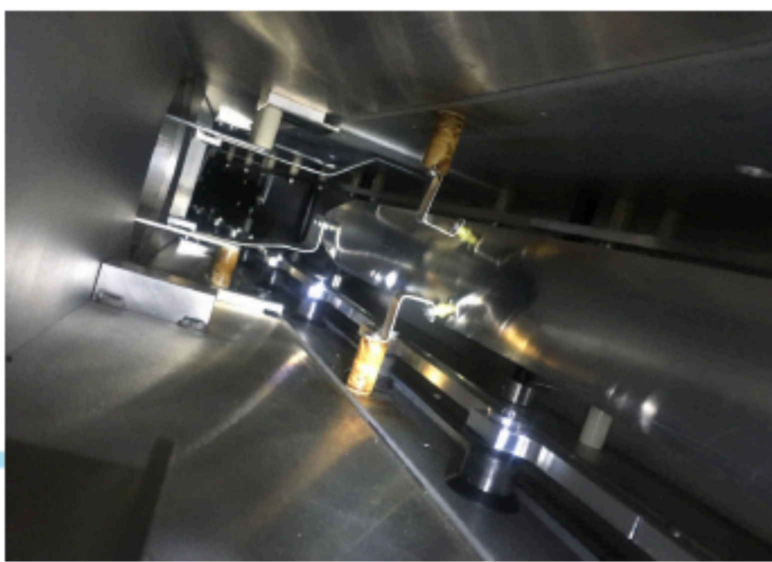
END

t [μs]

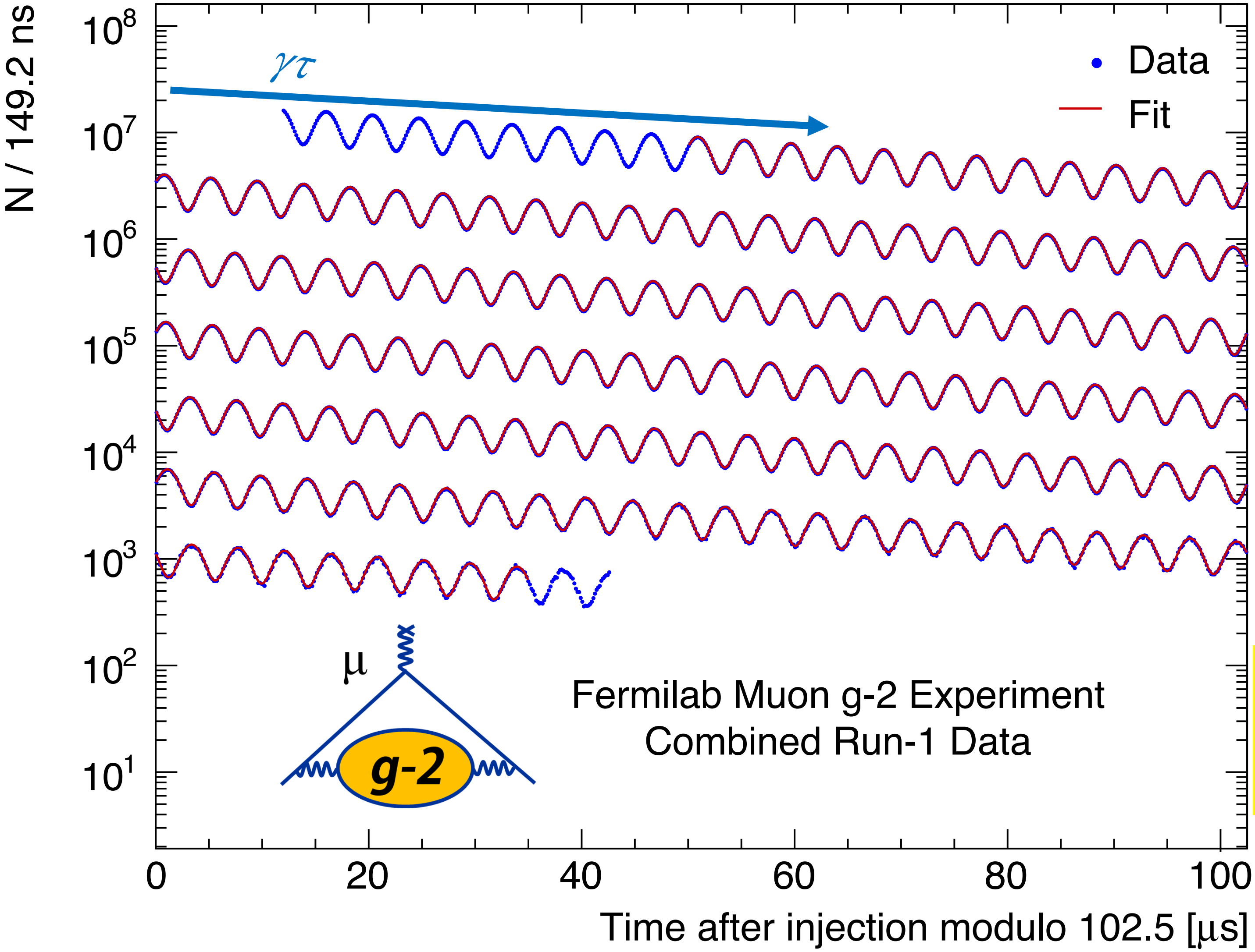
How a kick is made?

- a *charging power supply* charges up
- *capacitor bank* to low voltage (700 V) that is discharged
- through a *transformer* into
- a *Blumlein*, which is a HV capacitor (55 kV), that is discharged through
- four *50 Ohms resistors*, which convert high voltage into high current into
- in-vacuum *plates*, where the current generates magnetic field that rotates momentum vector of muons





RUN1 A-method Wiggle Plot



$8.2{\times}10^9\ e^+$

(combined RUN1 statistics)

$\gamma\tau_\mu$ = 64.4 μs;
(g-2): τ_a = 4.37 μs;
Cyclotron: t_C = 149 ns

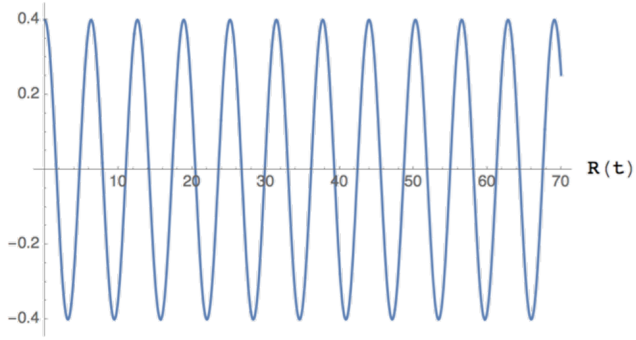
R-method (Ratio)

- Ratio method: randomly split dataset in 2 subsets shifted by ±half a g-2 period
- Build combinations of the 2 subsets which eliminates the exponential behaviour and leaves just a sinusoidal term

$$u^{\pm}(t) = N(t \pm \mathrm{T}/2) = N_0 e^{-t/\tau \mp T/2\tau}\left(1 + A\cos(\omega_a t \pm \omega_a \frac{T}{2} + \varphi)\right)$$

$$U(t) = u^{+}(t) + u^{-}(t)$$

$$R(t) = \frac{N(t) - U(t)}{N(t) + U(t)}$$

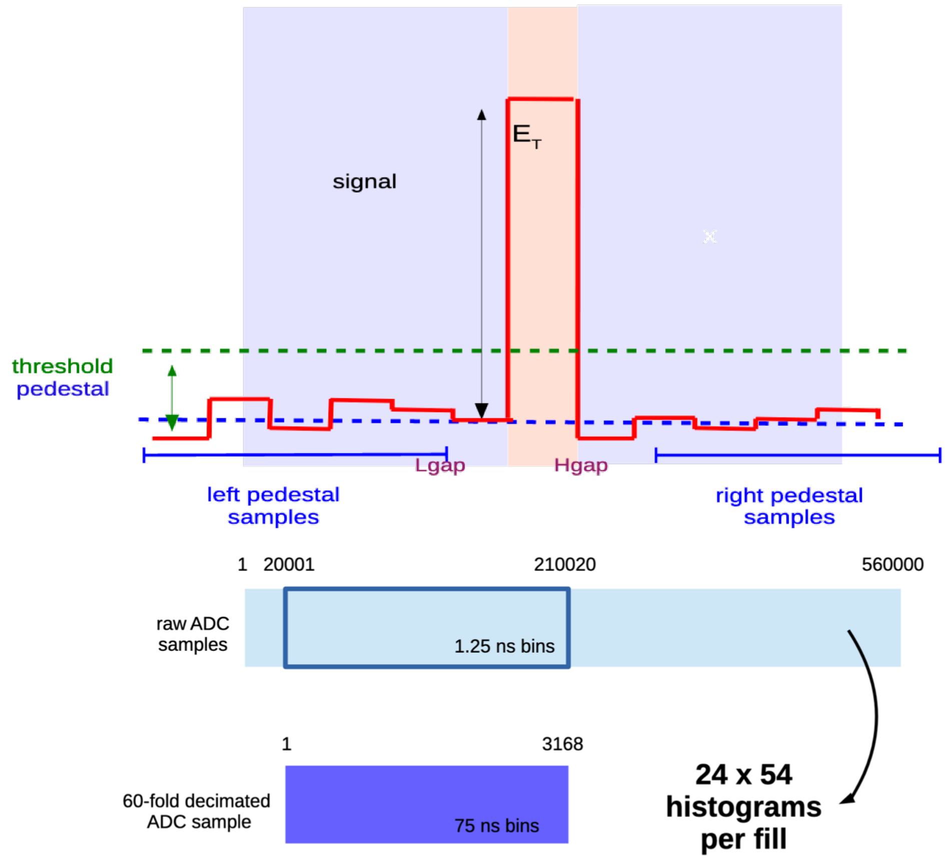


$$R(t) = A\cos(\omega_a t + \phi) - \frac{1}{16}(\frac{T}{\gamma\tau})^2 + (h.o.)$$

3 parameters fit: less sensitive to slow effects which divide out

Q-method

- No clustering: just integrate energy above threshold for each crystal (in principle no threshold should be applied)
- To reduce the amount of data stored offline, time bins are summed up in groups of 60
- The total energy per event fluctuates with ω_a frequency



Beam Frequencies in the Residuals

$$f_c = \frac{pc}{\gamma m} \cdot \frac{1}{2\pi r}$$

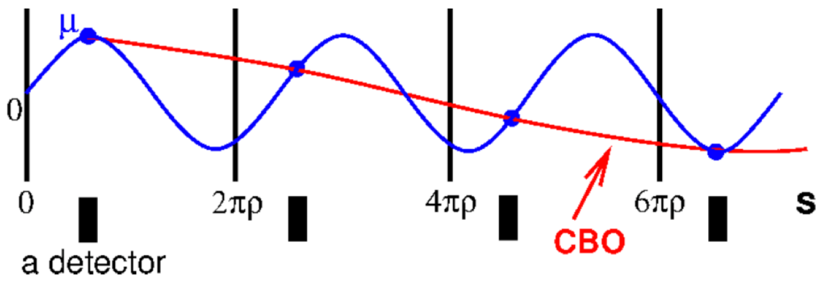
$$f_x = \sqrt{1-n}\, f_c$$

$$f_y = \sqrt{n}\, f_c$$

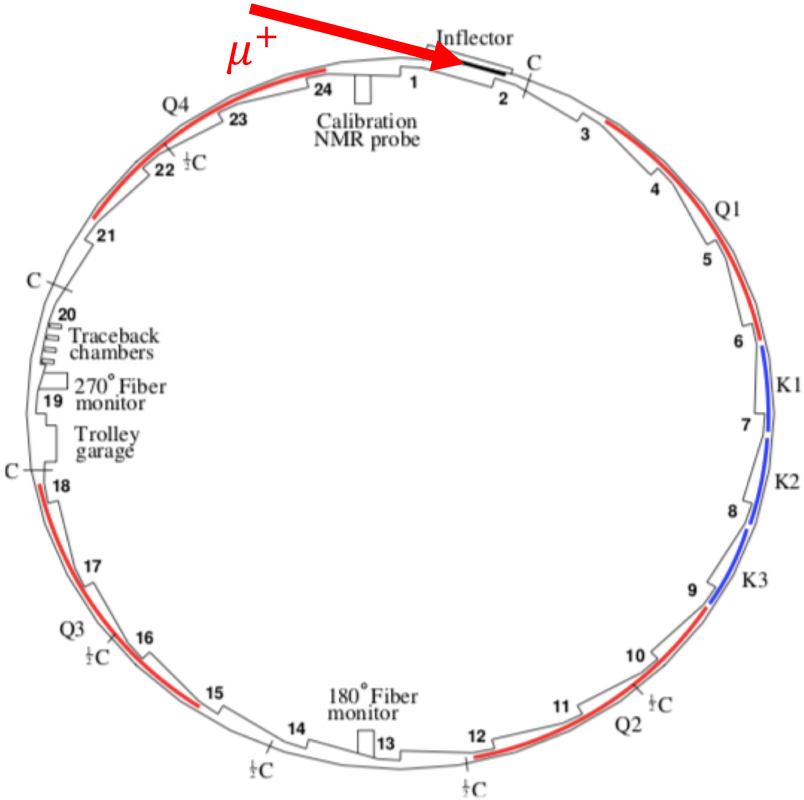
$$f_{CBO} = f_c - f_x$$

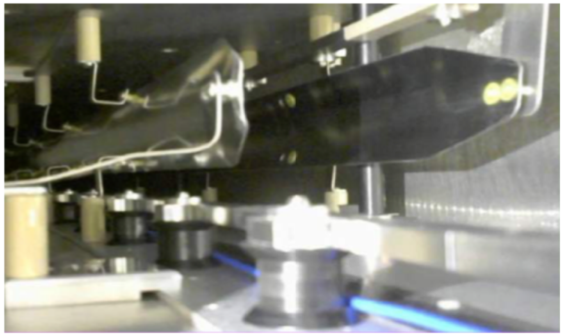
$$f_{VW} = f_c - 2f_x$$

$$f_{beat} = f_{CBO} \pm f_a$$

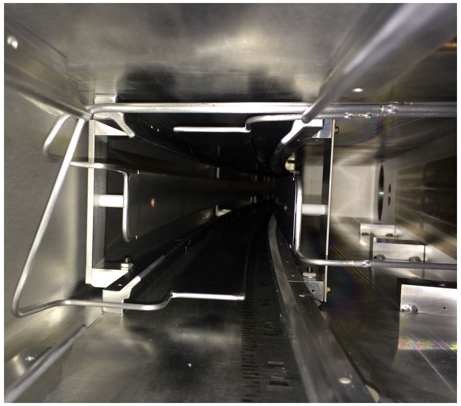


Beam Storage and Focussing



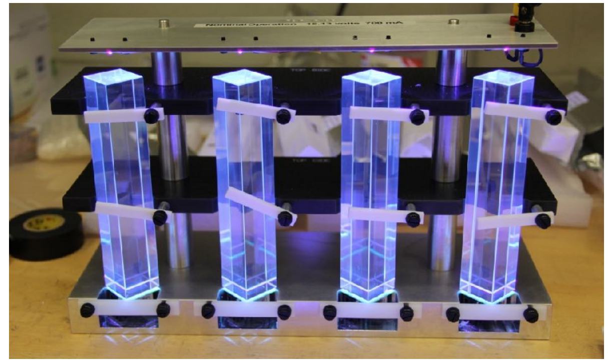


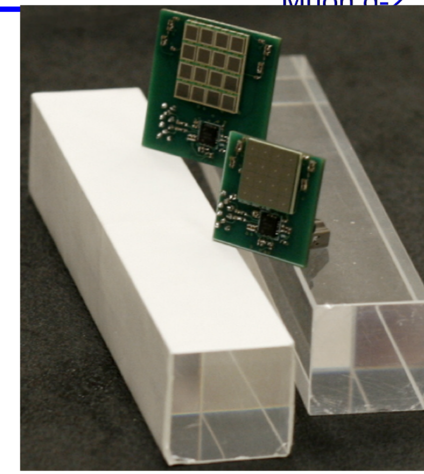
- 3 magnets
- 10.8 mrad kick
- 55 kV voltage each



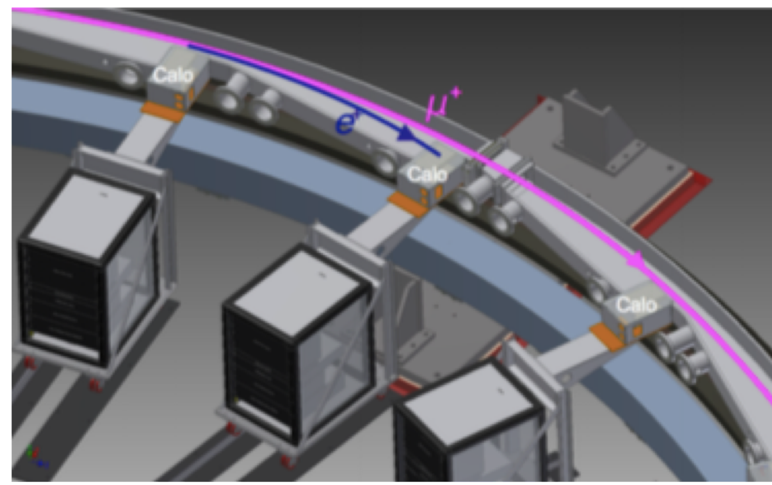
- 4 electrostatic quadrupoles
- each quadrupole divided in 2 regions (long and short)
- High Voltage determines the beam dynamics

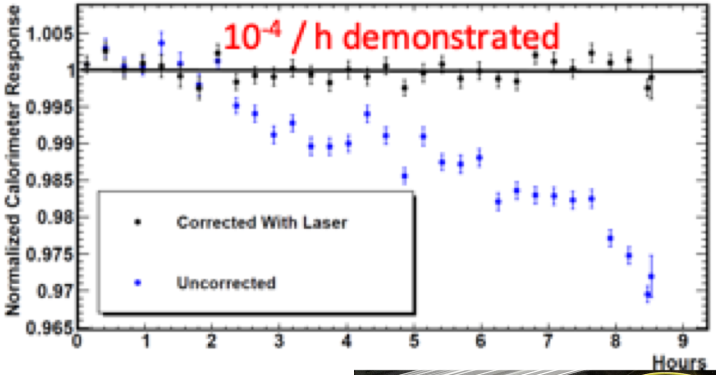
Calorimeters

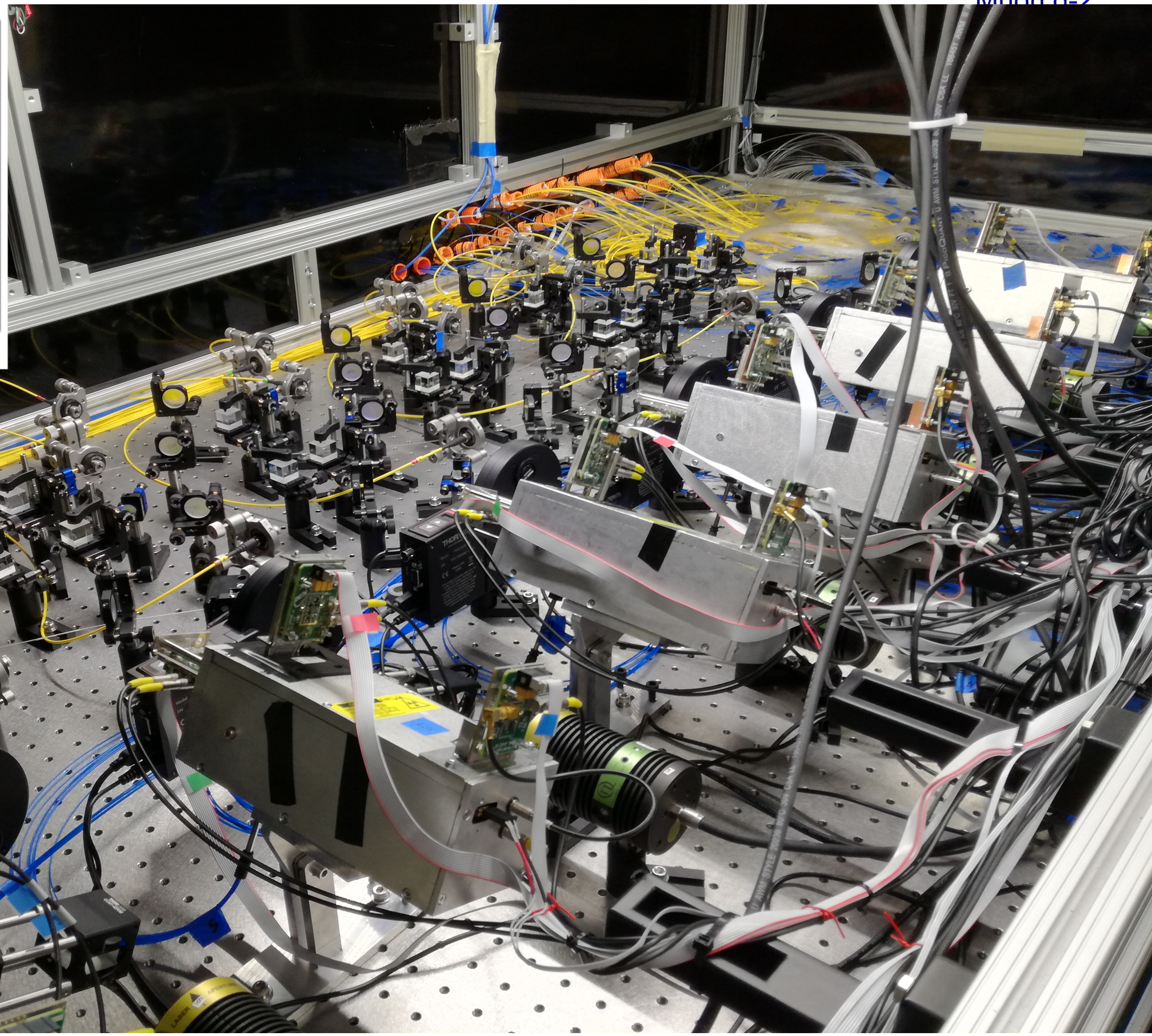




- 24 calorimeters along the inner radius of the ring
- Each calorimeter is a 6×9 array of PbF_2 crystals
- Each crystal is 2.5×2.5 cm^2 and 14 cm deep ($= 15\ X_0$)
- Čerenkov crystals: Fast response and less pile up
- Crystals are read by Large Area SiPM (1.2×1.2 cm^2)




10^{-4} / h demonstrated
Normalized Calorimeter Response
Corrected With Laser
Uncorrected
Hours
1.005
1
0.995
0.99
0.985
0.98
0.975
0.97
0.965
0
1
2
3
4
5
6
7
8
9



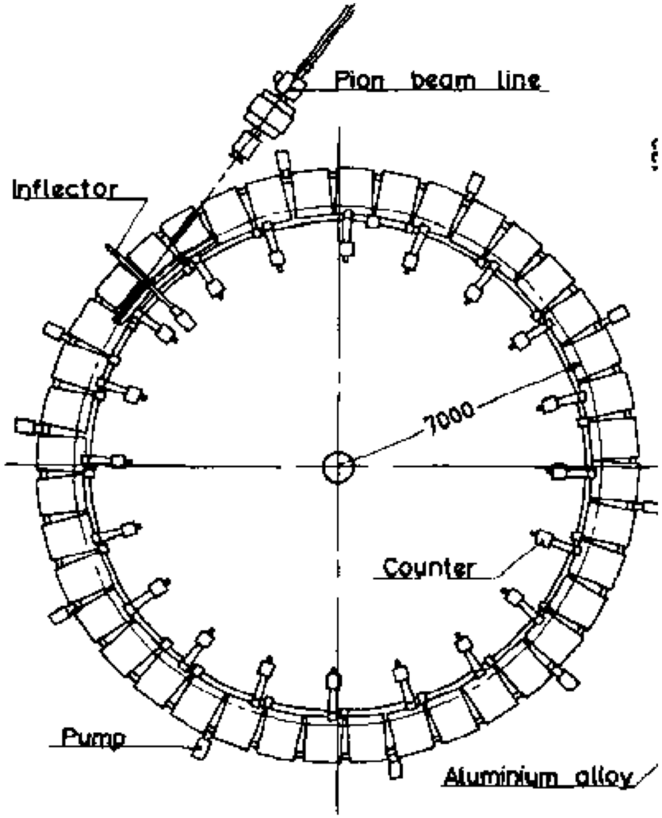
A blinded analysis

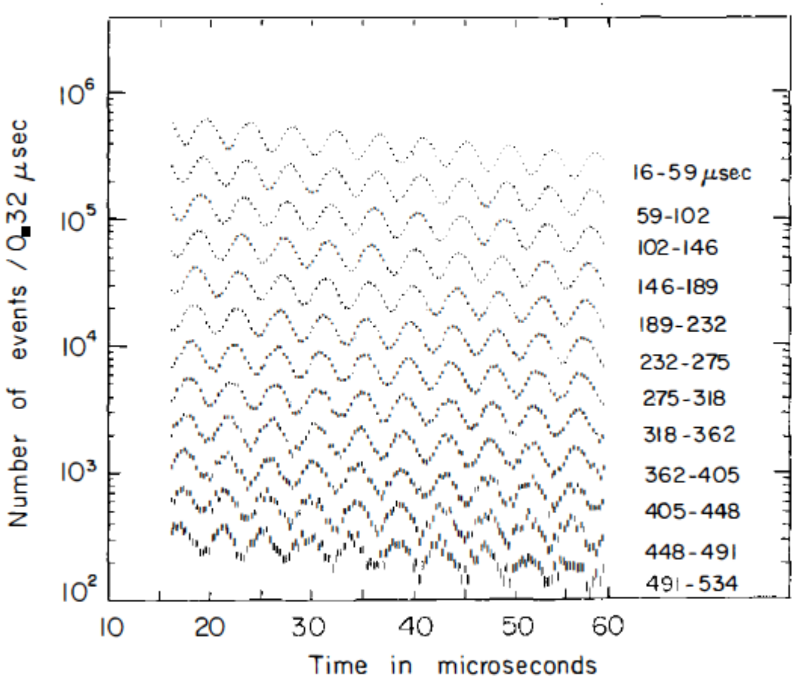
- Two levels of blinding: 1) HW (blinding of the precise digitization rate); 2) SW (unknow offset in the analysis of ω_a)
- HW blinding: ω_a clock detuned with with true frequency (40 –XMHz); blinding factor in the range of 25 ppm.
- The “blinding” factor is known only to two people outside the collaboration and stored in two sealed boxes (at FNAL and UW), and revealed after the completion of the analysis and agreement to proceed with the unblinding

(Greg Bock and Joe Lykken blinding the clock in 2018)

Locked Clock Panel

The g-2 experiment at CERN: a triumph for QED





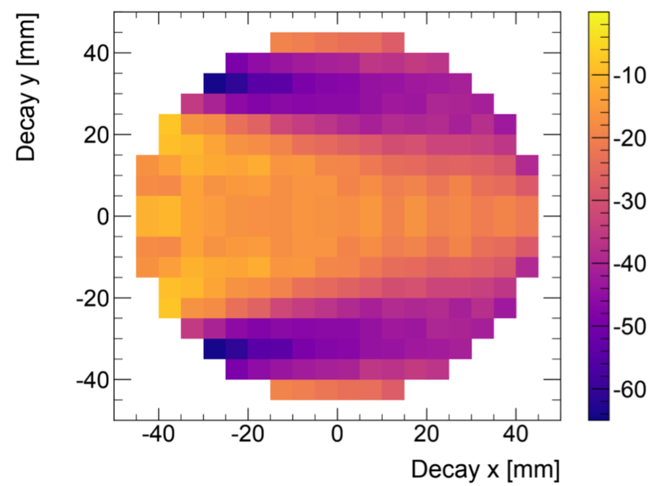
$$a_\mu^{EXP} = 1\,165\,924\,(8.5) \times 10^{-9}\ (7\ \text{ppm}).$$

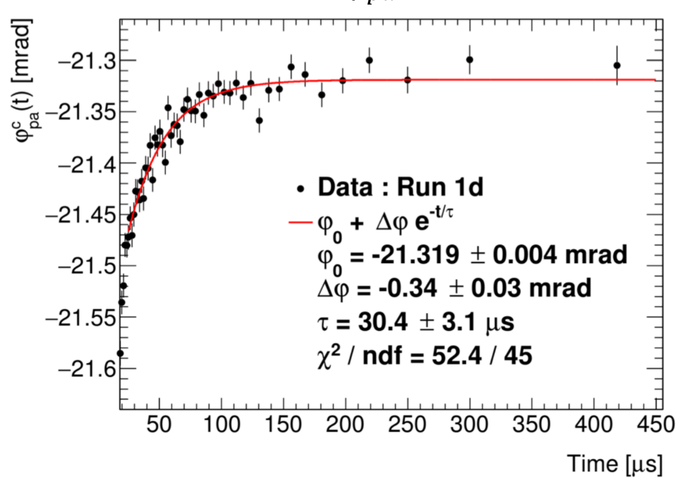
QED terms	Muon	Numerical values ($\times 10^9$)	
2nd order: A	0.5	Total QED:	1 165 852 (1.9)
4th order: B	0.765 782 23	Strong interactions:	66.7 (8.1)
6th order: C	24.452 (26)	Weak interactions:	2.1 (0.2)
8th order: D	135 (63)	Total theory:	1 165 921 (8.3)
10th order: E	420 (30)		

Acceptance correction

- A considerable study of this effect involved:

1. Generation of phase, asymmetry, and acceptance maps using our GEANT-based model of the ring
2. Folding the azimuthal beam distribution with the obtained maps to determine the phase shift - $\varphi^{c}_{pa}(t)$.
3. Application of this $\varphi^{c}_{pa}(t)$ to precession data fits to determine the phase-acceptance (pa) correction C_{pa}.





Muon g-2: Status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad (0.54\ \text{ppm})$$

- Tantalizing ~3.5 σ deviation with SM (persistent since ~20 years):

$$a_\mu^{SM} = 11659181.0(4.3)\times 10^{-10}$$

$$a_\mu^{E821} - a_\mu^{SM} = (27.9\pm 7.6)\times 10^{-10} = 3.7\sigma$$

$$(\Delta a_\mu \sim 2300\text{ppb})$$

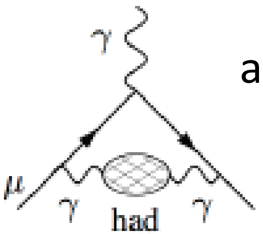
T. Aoyama «**The anomalous magnetic moment of the muon in the Standard Model**», June 8, 2020, 194 pages, e-print: 2006.04822 [hep-ph] (>40 citations)

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC x4 accuracy
  - Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

MUonE (see Marconi's talk)

Hadronic Vacuum polarization (HLO)

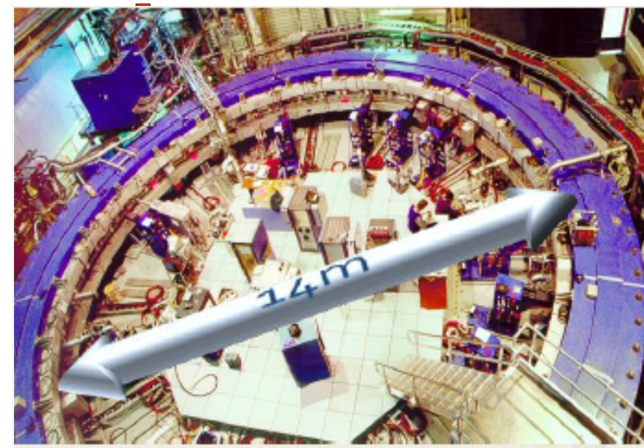


$a_\mu^{HLO} = (692.3\pm 4.0)10^{-10}$

$\delta a_\mu/a_\mu \sim 0.6\%$

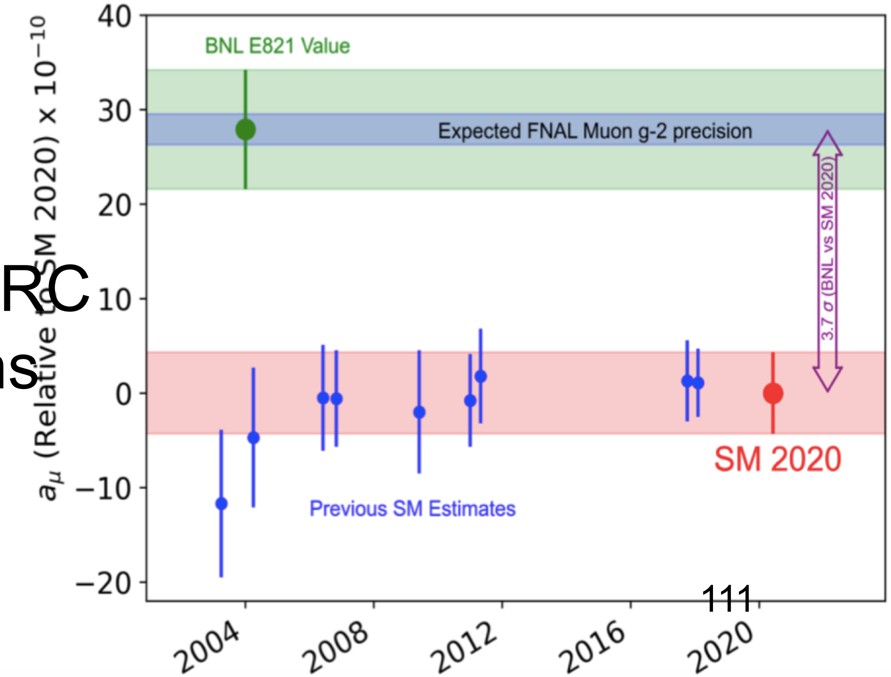
$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. Relocate the BNL storage ring to FNAL.

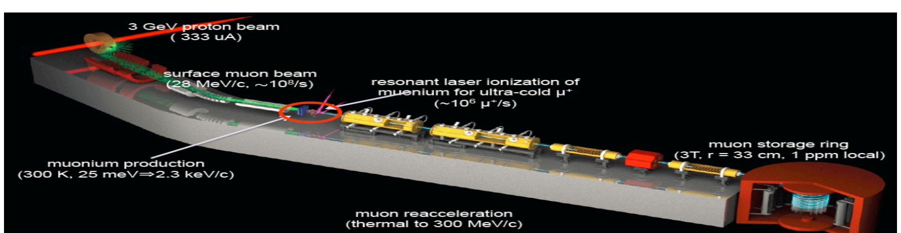


→ δa_μx4 improvement (0.14ppm)

If the central value remains the same > 5σ from SM (enough to claim discovery of New Physics!)

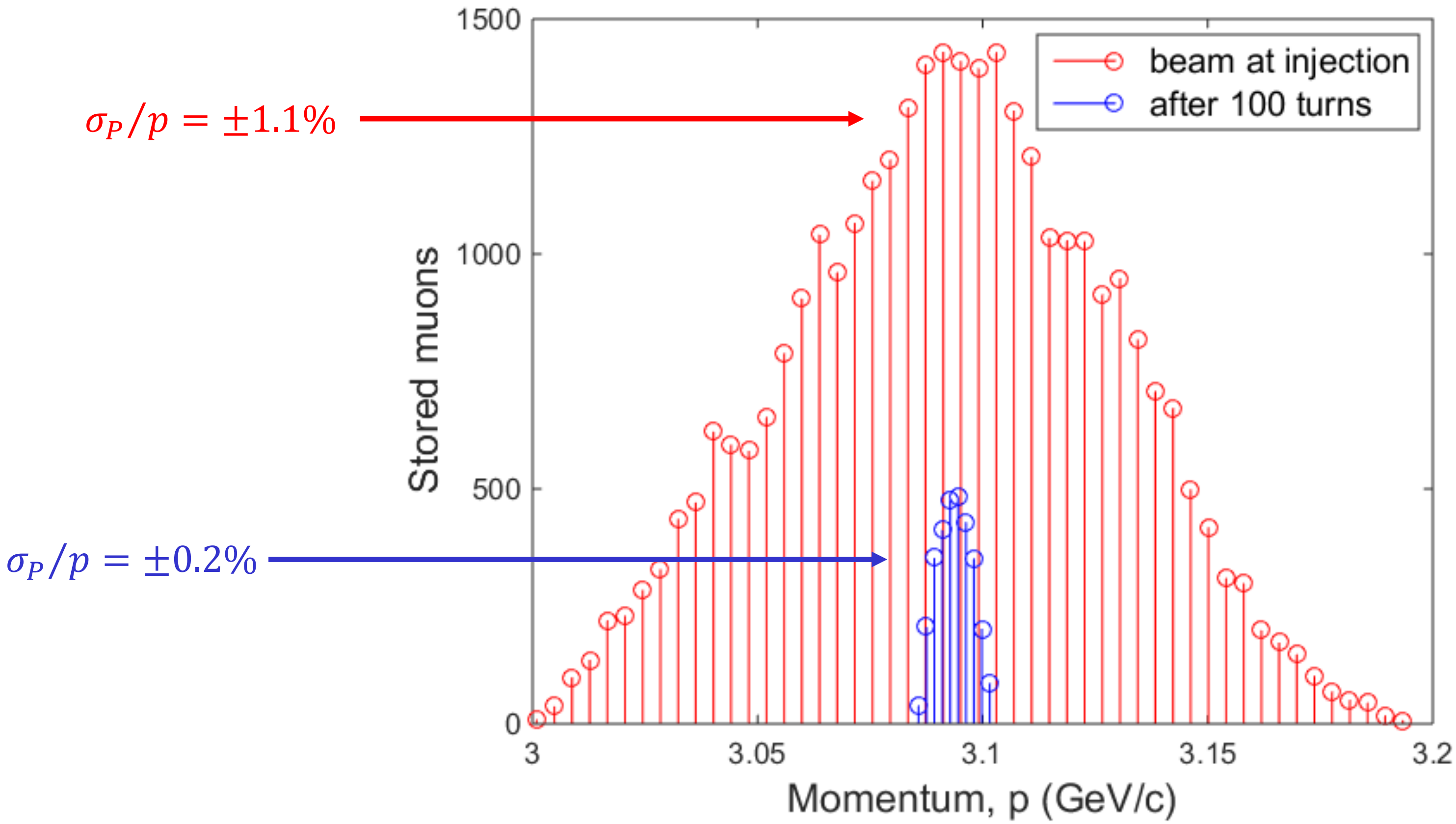


Complementary proposal at J-PARC in progress using ultra-cold muons



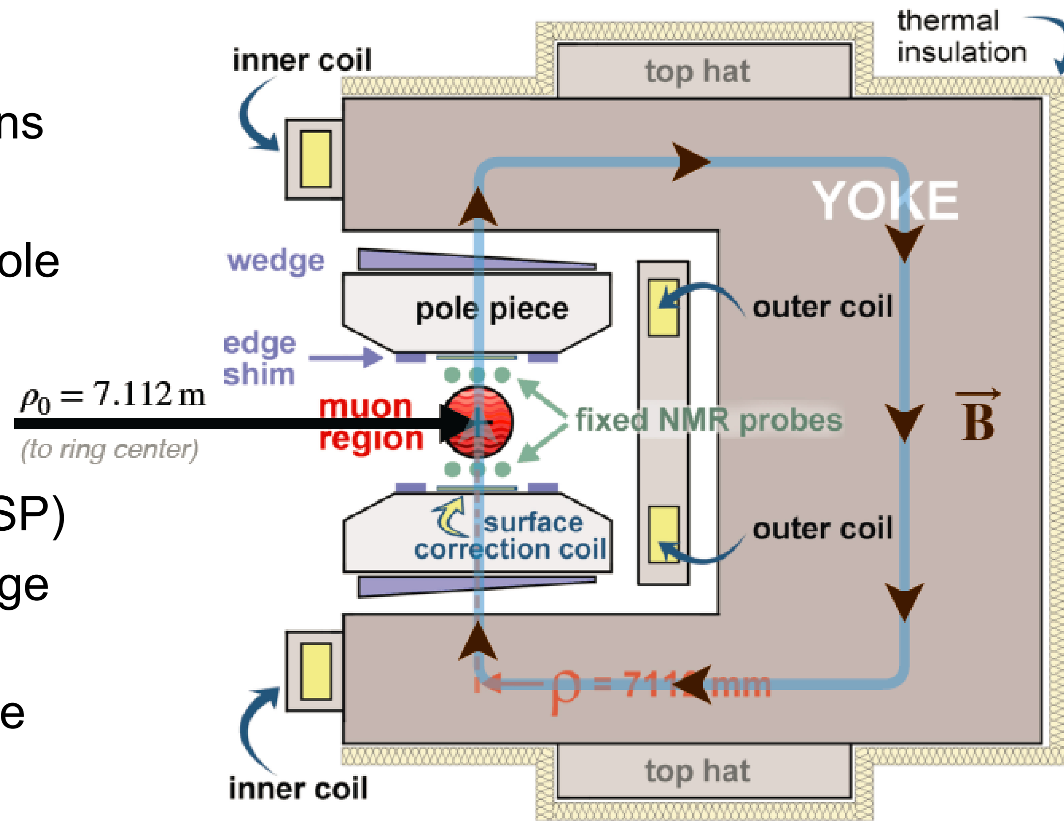
Beamline Wedges

- Muon g-2 storage ring accepts particles only within $\sigma_p/p = 0.2\%$
- Incoming beam loss of 80%
- **Goal**: Reduce the beam at injection to better match the accepted beam



Shimming tools for the Magnetic Field

- **B Field** 1.45T
- **12 Yokes**: C shaped flux returns
- **72 Poles**: shape field
- **864 Wedges:** angle - quadrupole (QP))
- **24 Iron Top Hats**: change effective mu
- **Edge Shims**: QP, sextupole (SP)
- **8000 Surface iron foils**: change effective mu locally
- **Surface coils**: will add average field moments (360 deg)



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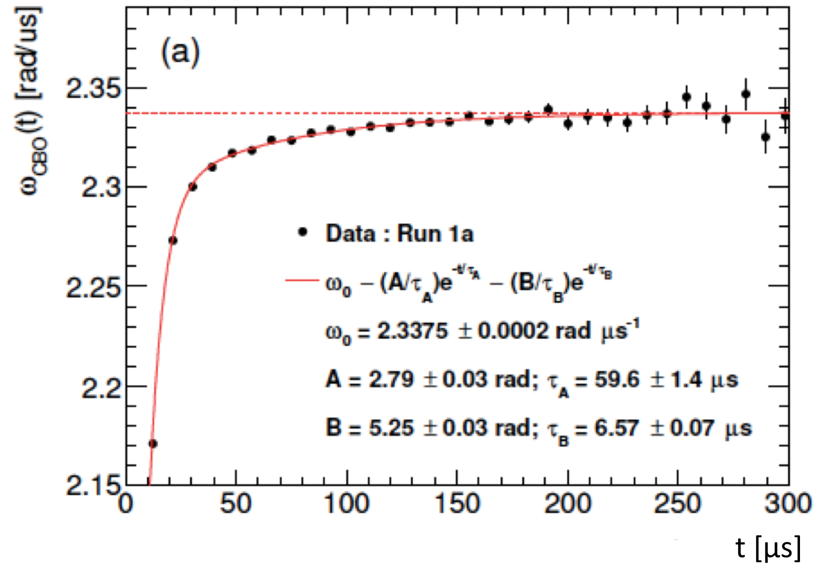
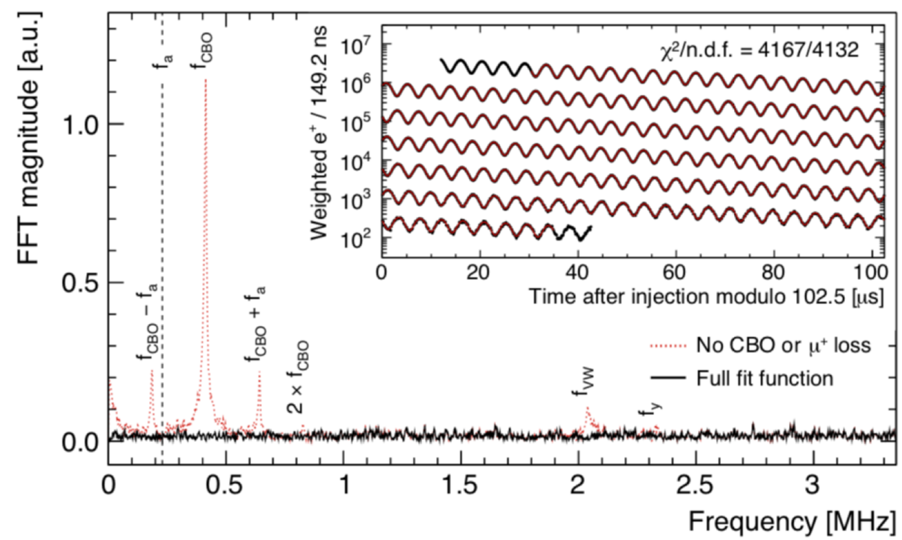
CBO amplitude

Muon g-2

- CBO is parametrized from tracker data as:
  - $\omega_{cbo}(t) = \omega_0 - \left(\frac{A}{\tau_A}\right) \cdot e^{-\frac{t}{\tau_A}} - \left(\frac{B}{\tau_B}\right) \cdot e^{-\frac{t}{\tau_B}}$
- The parameters τ_A and τ_B represent two recovery times, one short $\sim 5\mu s$ and one long $\sim 50\mu s$ due respectively to quadrupoles scraping and *damage resistors.*
- The parameters differ among different datasets mostly for Run 1a and 1d, where the *damaged resistors* effect was worse.
- Without the CBO term in ω_a model, strong signals emerge in the residuals at expected frequencies.





ω'_p : Calibration procedure

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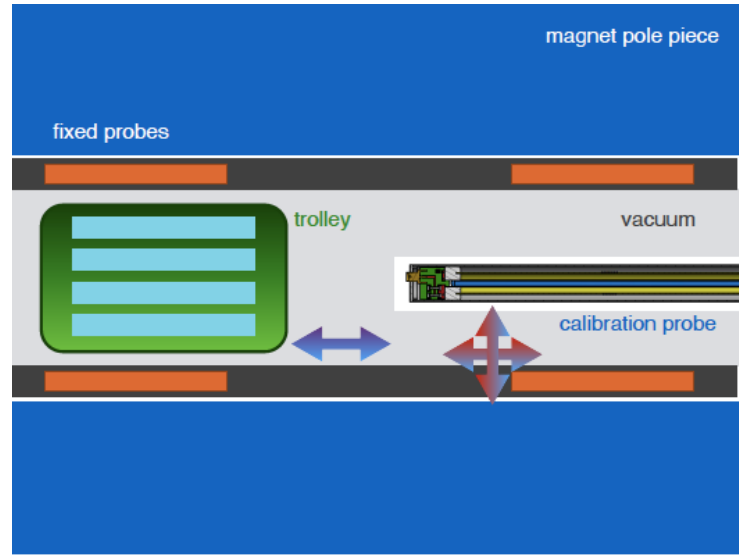
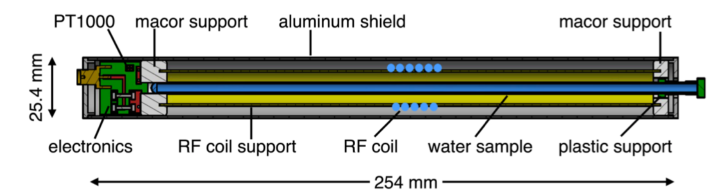
Muon g-2

- The Trolley has a complicated magnetic perturbation, which needs to be accounted for
- Use of a calibration probe to go from «measured» ω_p in the trolley to shielded proton frequency
- It is a Water-based NMR probe; Highly symmetrical construction => minimize B perturb
- Measure field perturbations of probe materials and orientation very precisely: (15.2 ± 12) ppb
- Careful comparisons to BNL's spherical probe and ^{3}He verify understanding

Quantity	Uncertainty (ppb)
Diamagnetic Shielding T dep	5
Bulk Magnetic Susceptibility	6
Material Perturbation	12
Water Sample and Sample Holder	2
Radiation Damping	3
Proton Dipolar Fields	2
TOTAL	15





Figure?

Towards 140ppb

δa_μ	BNL (ppb)	FNAL goal (ppb)	
ω_a statistic	480	100	**20 × BNL statistics**: more muons/sec, higher quality beam, less beam background
ω_a systematic	180	70	**new instrumentation for ω_a measurement**: segmented and fast EM calorimeters with laser calibration system
$\overline{\omega}_p$ systematics	170	70	**improved ω_p measurement:** new precise NMR probes and tracker system for beam distribution
Total	**540**	**140**	

From a muon's eyes