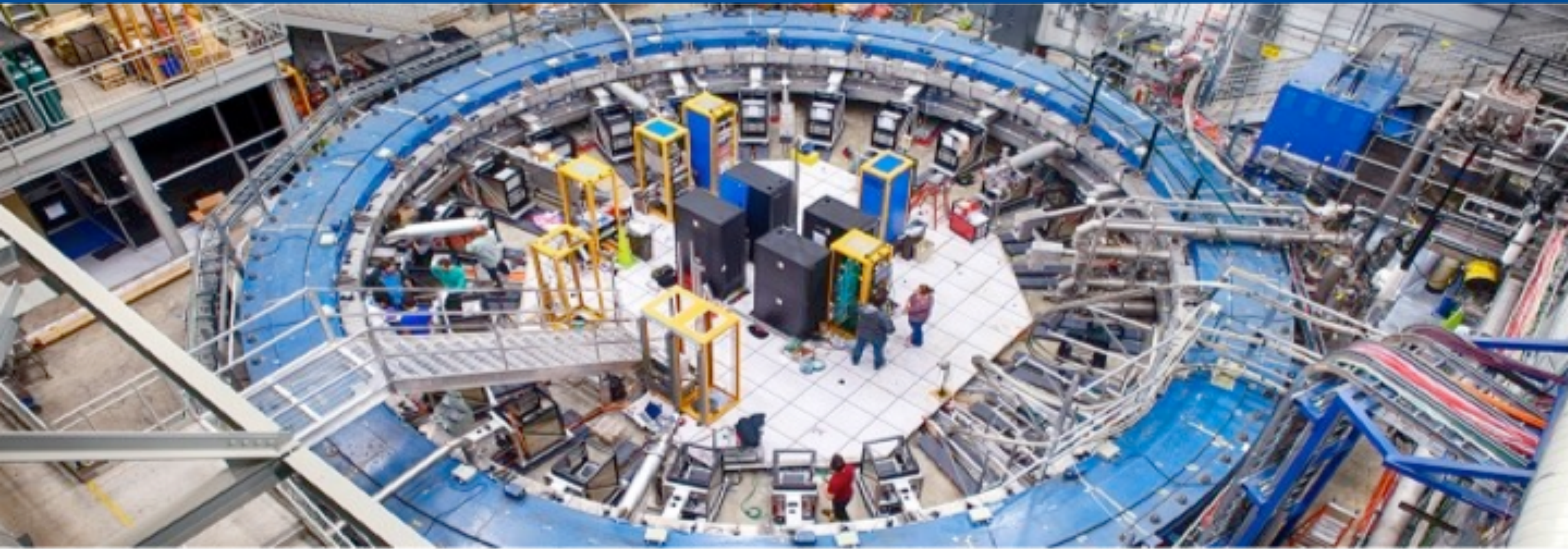


# Status of the Muon g-2 at Fermilab

Graziano Venanzoni– INFN Pisa

SIF 21/Sept/2018

# Outline

- The Muon g-2: summary of the present status
- The Muon g-2 experiment at Fermilab
- Conclusions

# Muon g-2: summary of the present 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 ~3σ deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659180.2(4.9)\times 10^{-10}(DHMZ)$$

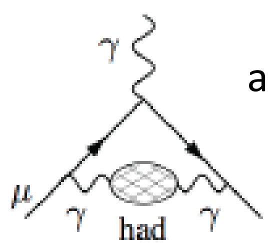
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

$$a_\mu^{E821} - a_\mu^{SM} \sim (28\pm 8)\times 10^{-10}$$

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

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

Hadronic Vacuum polarization (HLO)



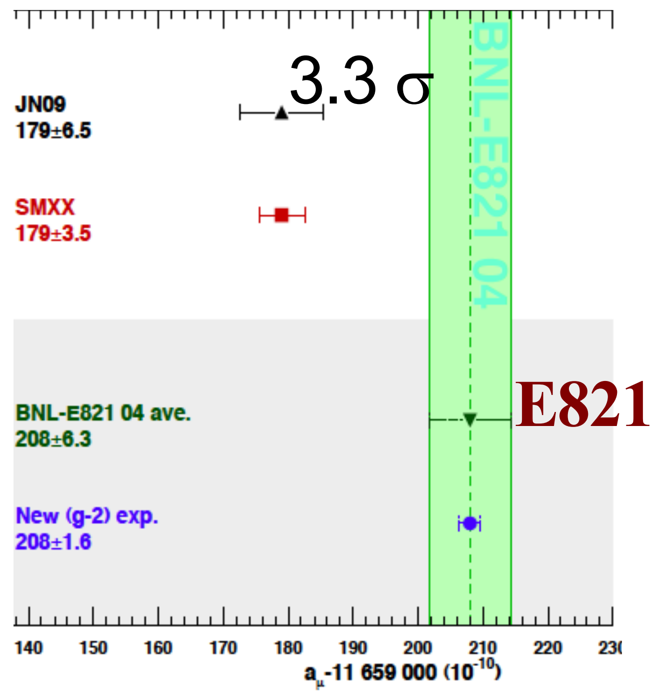

$a_\mu^{HLO} = (692.3\pm 4.2)10^{-10}$

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

# $(g\text{-}2)_\mu$: 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.

$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)

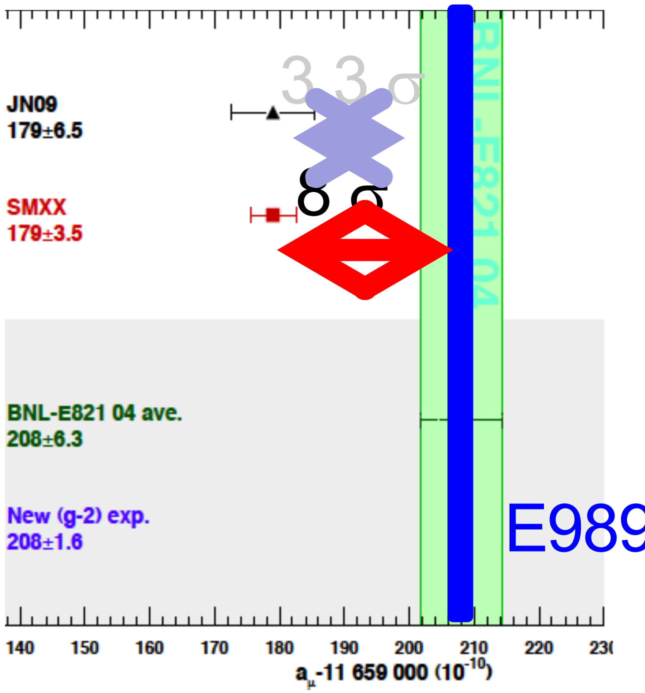



# $(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

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


→ $\delta a_\mu$ x4 improvement (0.14ppm)

If the central value remains the same ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)



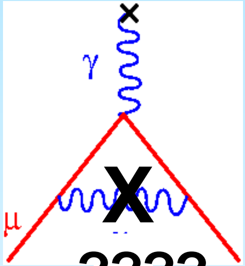

***Depending on the progress on Theory**

Thomas Blum; Achim Denig; Ivan Logashenko; Eduardo de Rafael; Lee oberts, B.; Thomas Teubner; Graziano Venanzoni (2013). "The Muon (g-2) heory Value: Present and Future". arXiv:1311.2198 [hep-ph].

Complementary proposal at J-PARC in progress

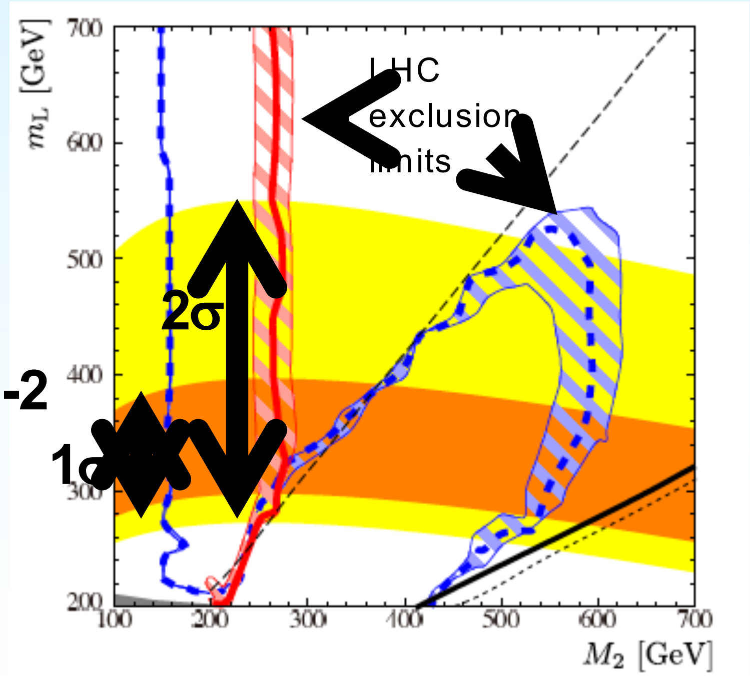
# New Physics?

$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$




(BNL) (SM)

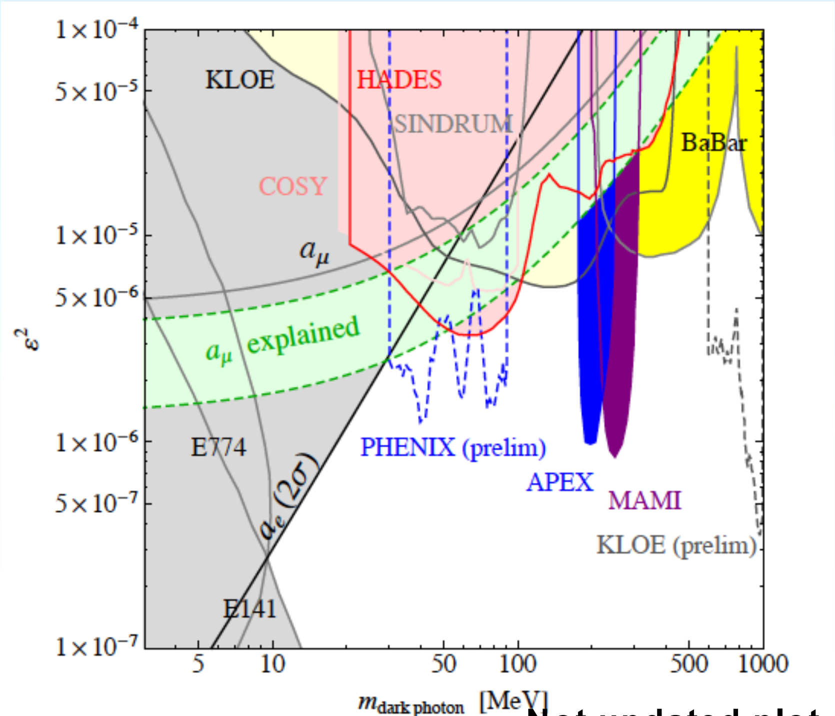
## SUSY?




(d) $\mu = 2\,\text{TeV}$, $m_R = 1.5 m_L$

[Endo,Hamaguchi,Iwamoto,Yoshinaga '13]

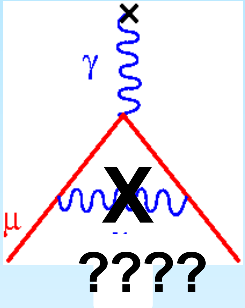
## Dark Photons?



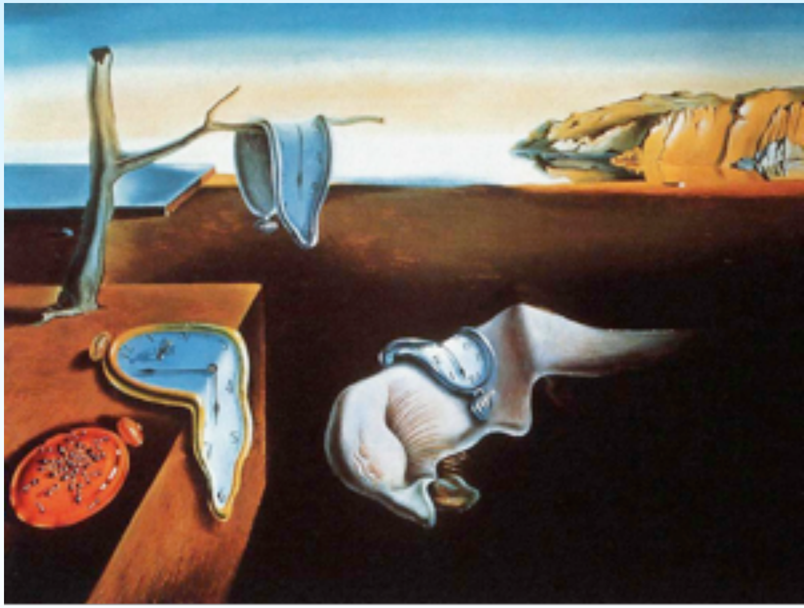

Not updated plot

# New Physics?

$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$




**Maybe an unknow “unknown” ?**

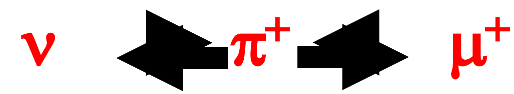


**In any case 3σ are not enough to claim a discovery.**

**We need a new (possible more) experiment with better precision!**

# How to measure g-2 in a storage ring

## (1) Polarized muons

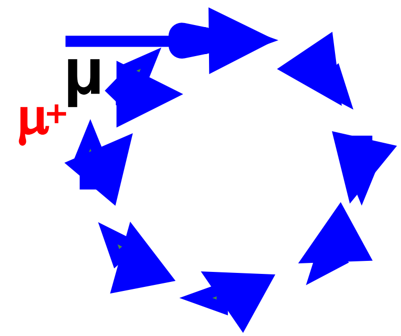



~97% polarized for forward decays

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

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

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



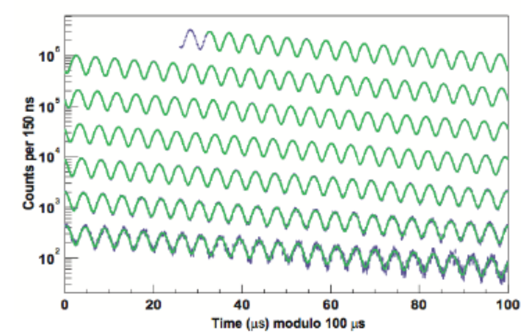

## (3) F$_\mu$ magic momentum = 3.094 GeV/c

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

*E* field doesn't affect muon spin when $\gamma$ = 29.3

## (4) Parity violation in the decay gives average spin direction

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



# How to measure g-2 in a storage ring

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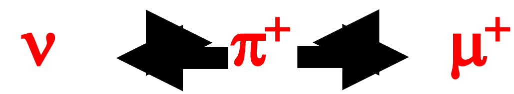


~97% polarized for forward decays

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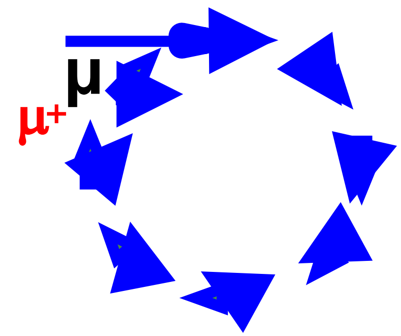
$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

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

Measure 2 quantities




## (3) $P_\mu$ magic momentum = 3.094 GeV/c

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

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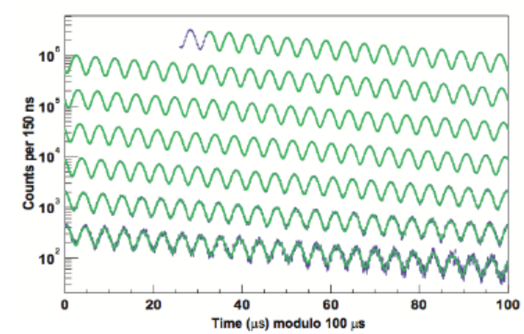


# 4 key elements for E989 at FNAL

- Consolidated method
- More muons (x20)
- Reduced systematics (ring and detector)
- New crew

- **E821 at Brookhaven**

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

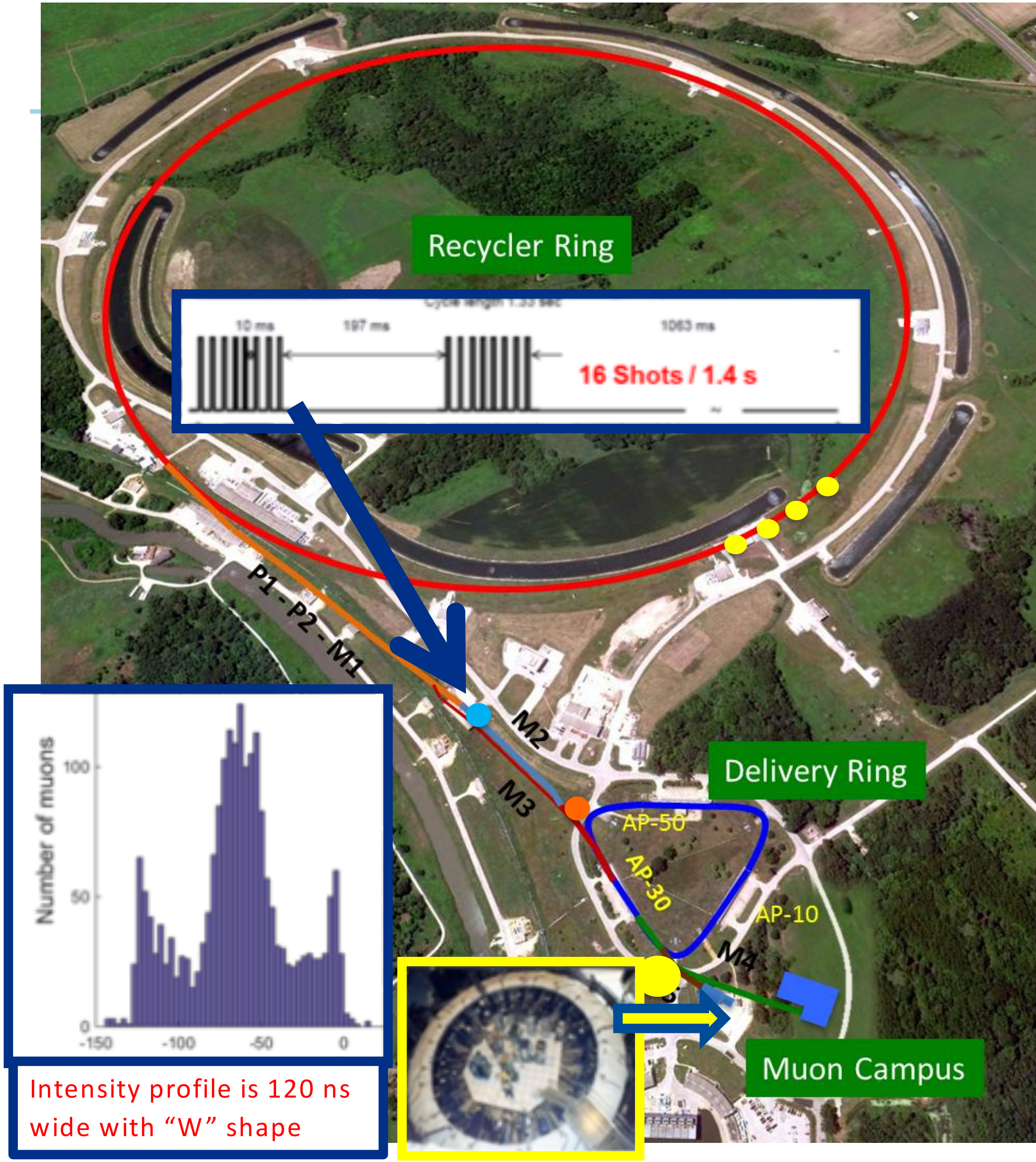
➔ $0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

$$\left.\begin{array}{l}\sigma_{\rm stat} = \pm 0.1 \text{ ppm} \\ \sigma_{\rm syst} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

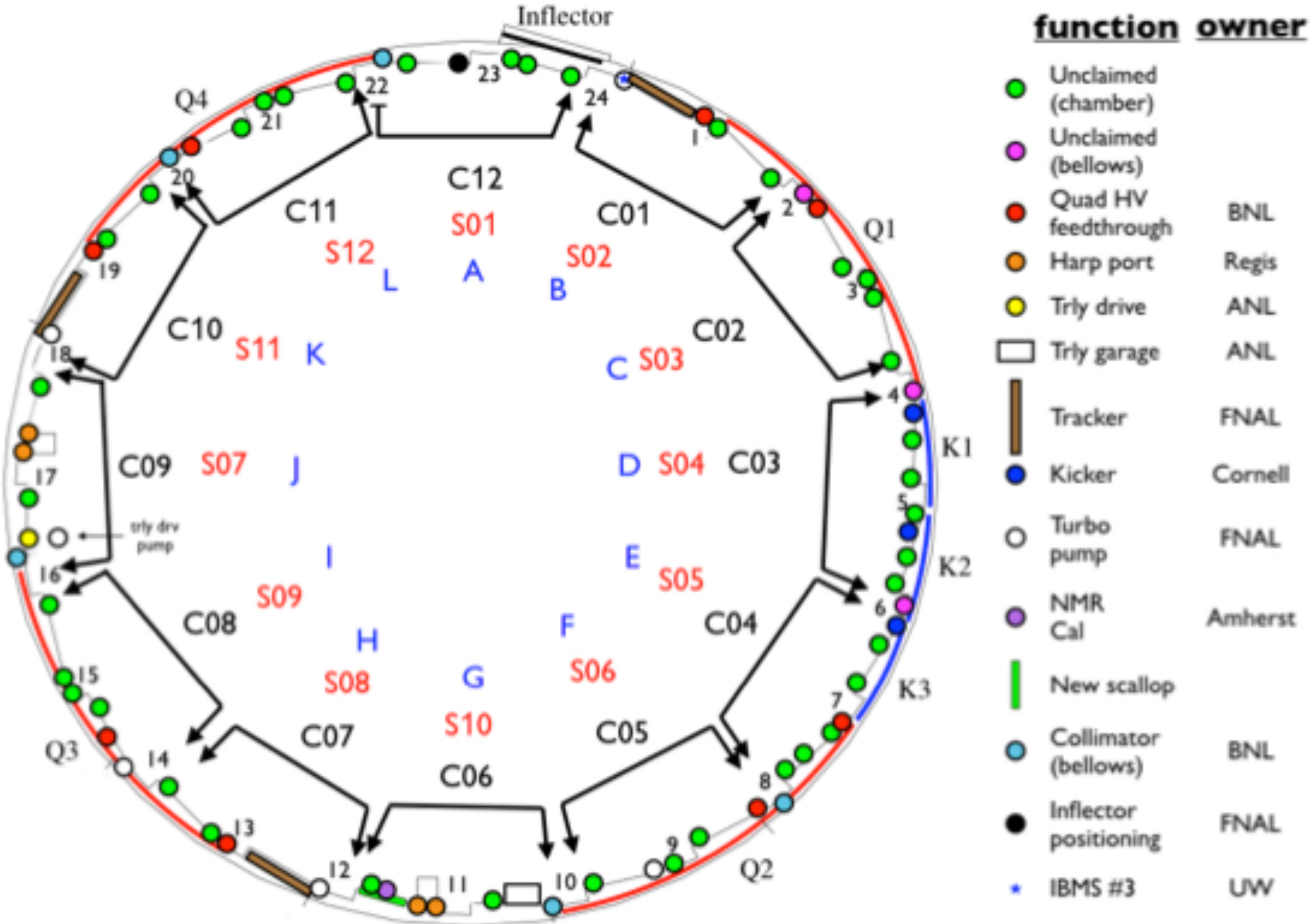
➔ $0.07\omega_a \oplus 0.07\omega_p$

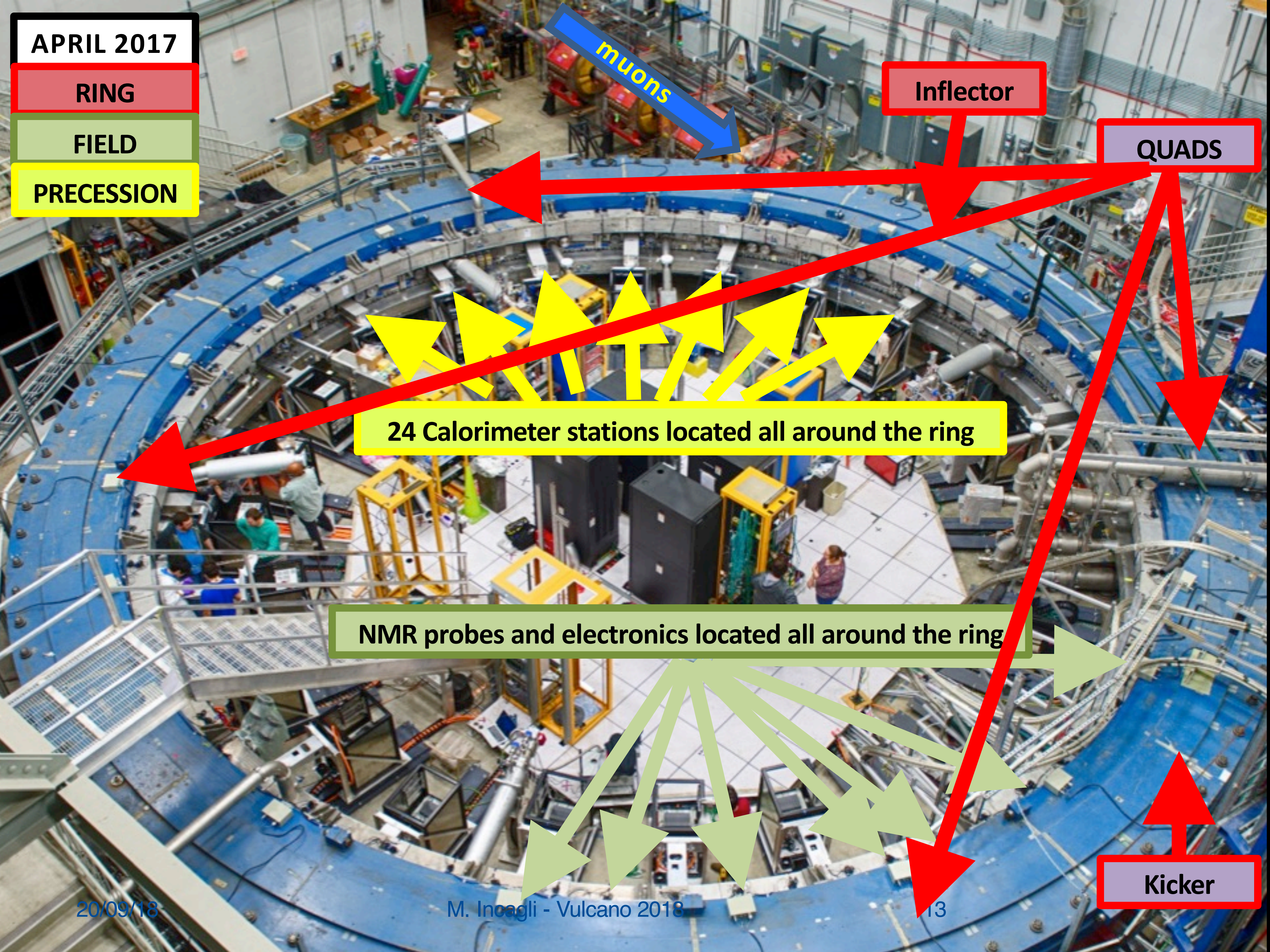
# Creating the Muon Beam for g-2




- 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; $\pi$ decay away
- $\mu$ enter storage ring

# The ring


Inflector
Q1
Q2
Q3
Q4
K1
K2
K3
C01
C02
C03
C04
C05
C06
C07
C08
C09
C10
C11
C12
S01
S02
S03
S04
S05
S06
S07
S08
S09
S10
S11
S12
A
B
C
D
E
F
G
H
I
J
K
L
trly drv
pump
function owner
Unclaimed (chamber)
Unclaimed (bellows)
Quad HV feedthrough BNL
Harp port Regis
Trly drive ANL
Trly garage ANL
Tracker FNAL
Kicker Cornell
Turbo pump FNAL
NMR Cal Amherst
New scallop
Collimator (bellows) BNL
Inflector positioning FNAL
IBMS #3 UW

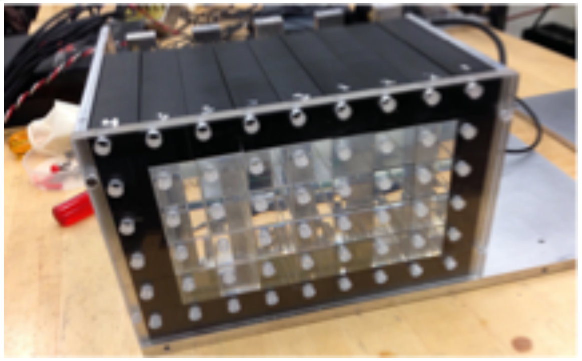

APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

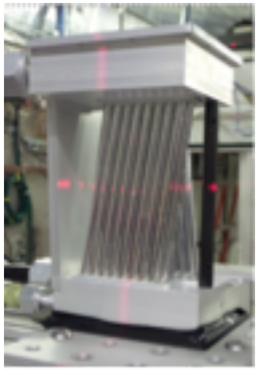
# $\omega_a$ systematics

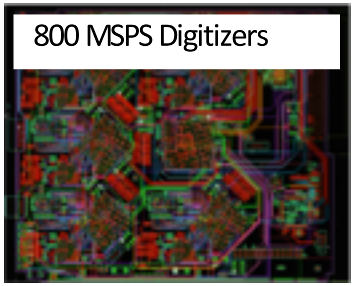
| Category | E821 [ppb] | E989 Improvement Plans | Goal [ppb] |
|---|---|---|---|
| Gain changes | 120 | Better laser calibration | |
| | | low-energy threshold | 20 |
| Pileup | 80 | Low-energy samples recorded | |
| | | calorimeter segmentation | 40 |
| Lost muons | 90 | Better collimation in ring | 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 |

- Tackling each of the major systematic errors with knowledge gained from BNL E821 and improved hardware

# New detector systems

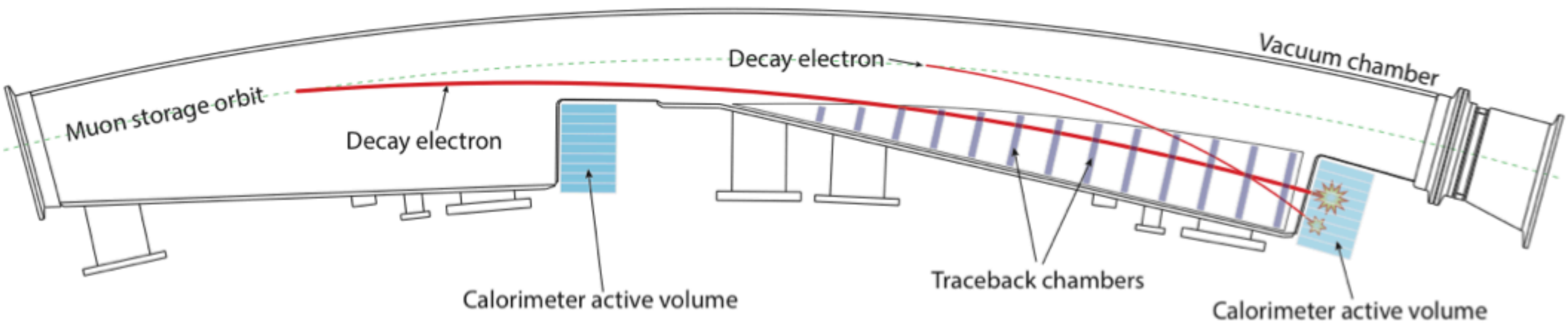




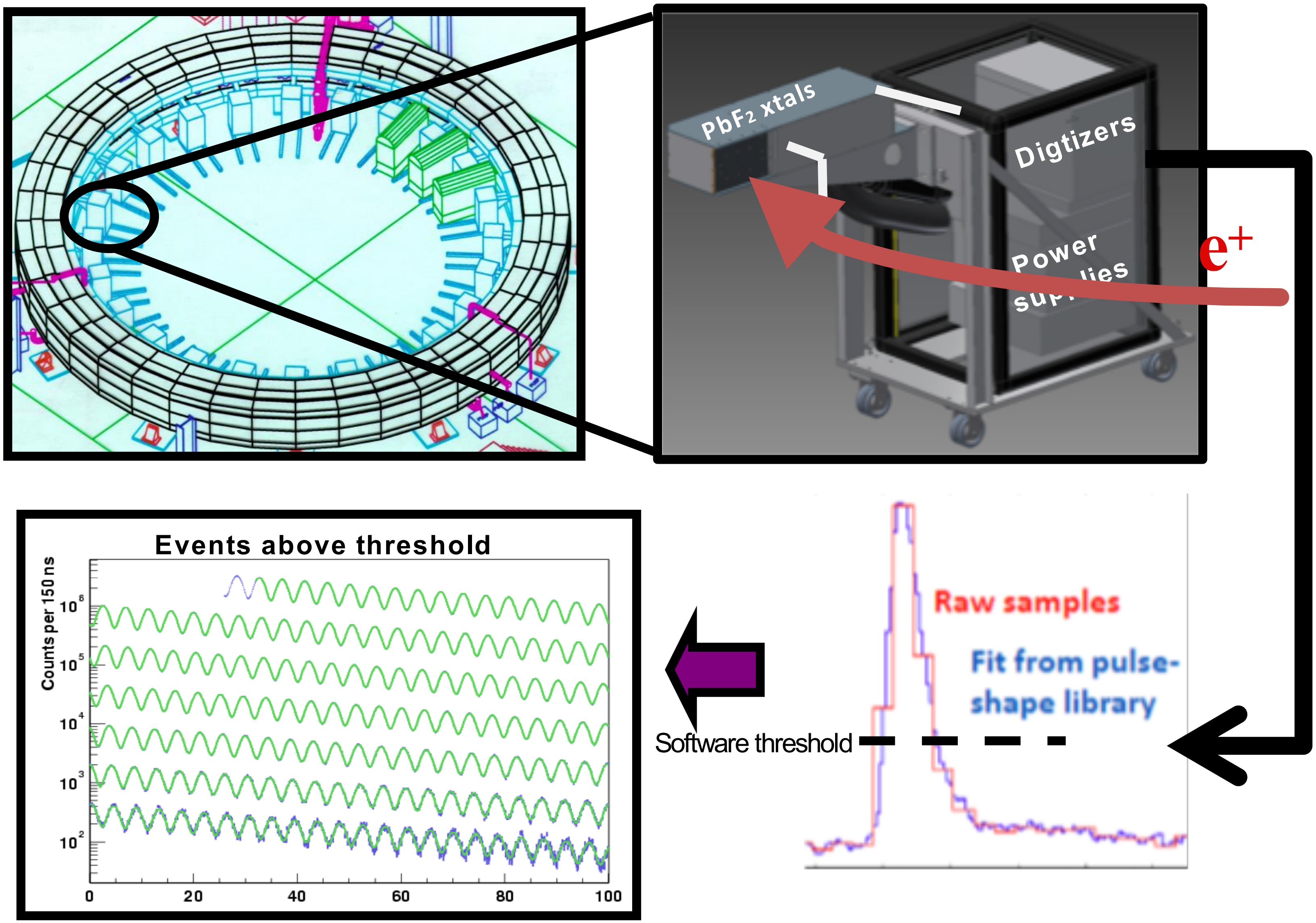



- Calorimeters 24 6x9 $PbF_2$ crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant UK contributions
- New laser calibration system from INFN crucial for untangling gain from other systematics

Top view of 1 of 12 vacuum chambers



# An “event” is an isolated positron above a threshold



# $\omega_p$ systematics

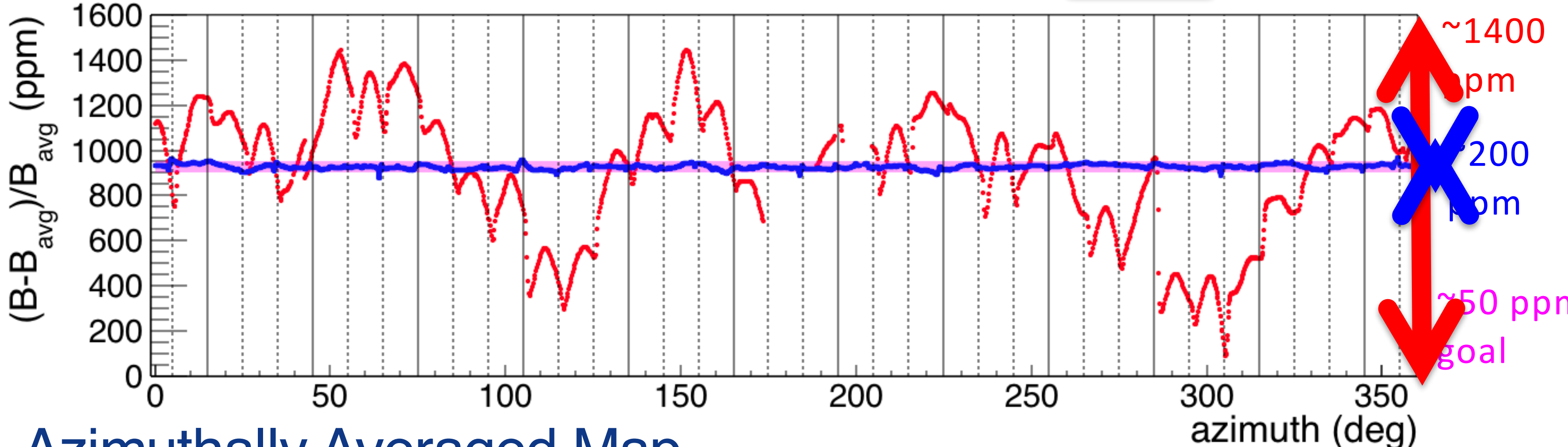
| Category | E821 [ppb] | Main E989 Improvement Plans | Goal [ppb] |
|---|---|---|---|
| Absolute field calibration | 50 | Improved $T$ stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes | 35 |
| Trolley probe calibrations | 90 | 3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes | 30 |
| Trolley measurements of $B_0$ | 50 | Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients | 30 |
| Fixed probe interpolation | 70 | Better temp. stability of the magnet, more frequent trolley runs, more fixed probes | 30 |
| Muon distribution | 30 | Improved field uniformity, improved muon tracking | 10 |
| External fields | – | Measure external fields; active feedback | 5 |
| Others † | 100 | Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce $O_2$ and image effects | 30 |
| Total syst. unc. on $\omega_p$ | 170 | | 70 |

- Need to know the average field observed by a muon in the storage ring absolutely to better than 70 ppb, many hardware improvements
- Very challenging…first major step is making the field as uniform as possible

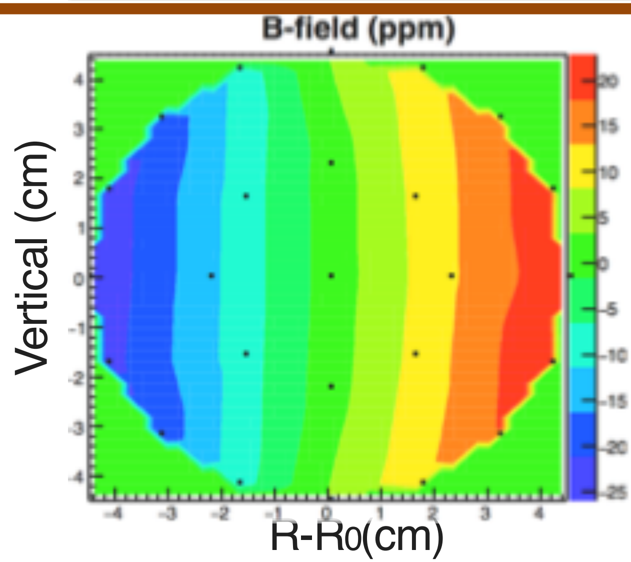
# Progress on Field

Oct 2015 → Aug 2016

Goal

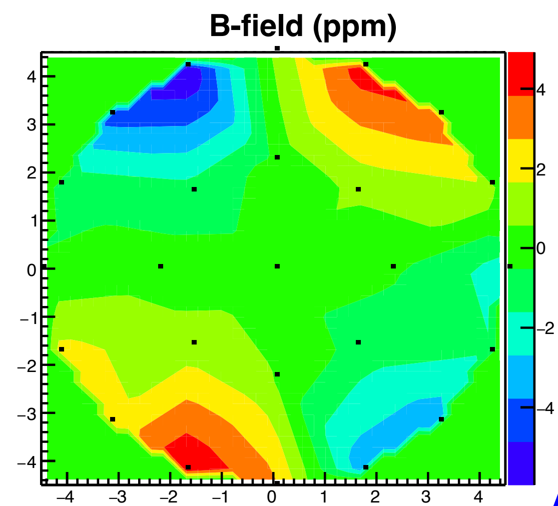



## Azimuthally Averaged Map




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

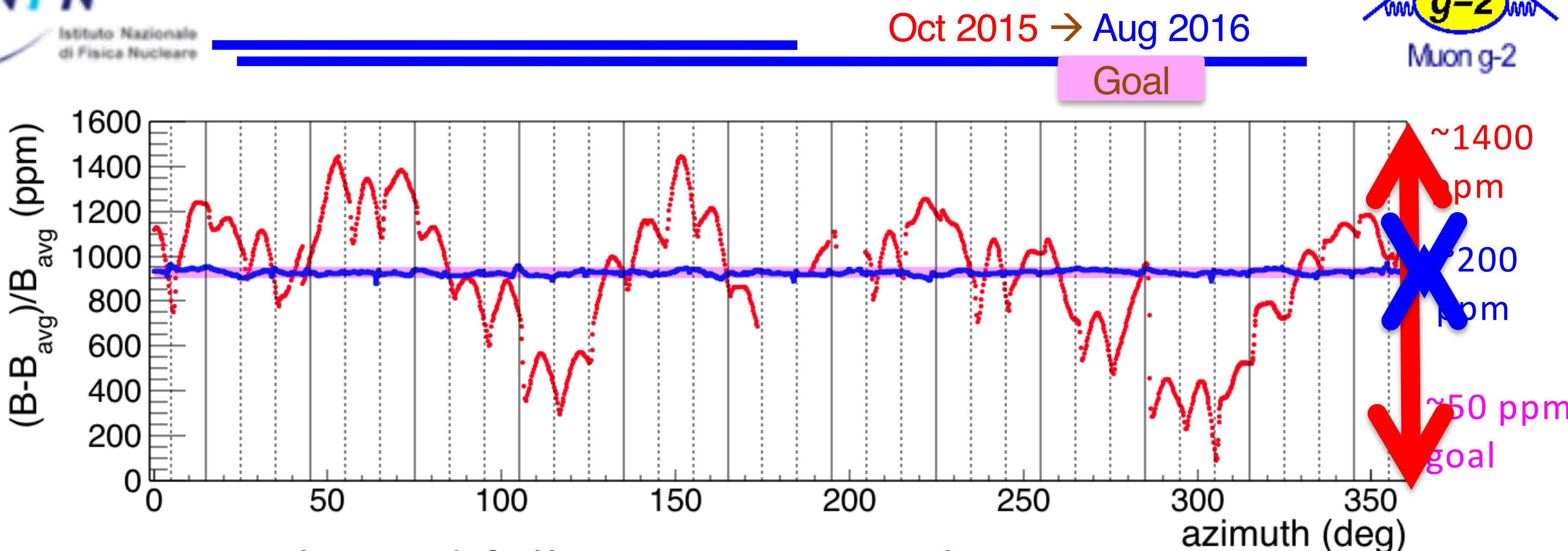
Oct 2015




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

Aug 2016

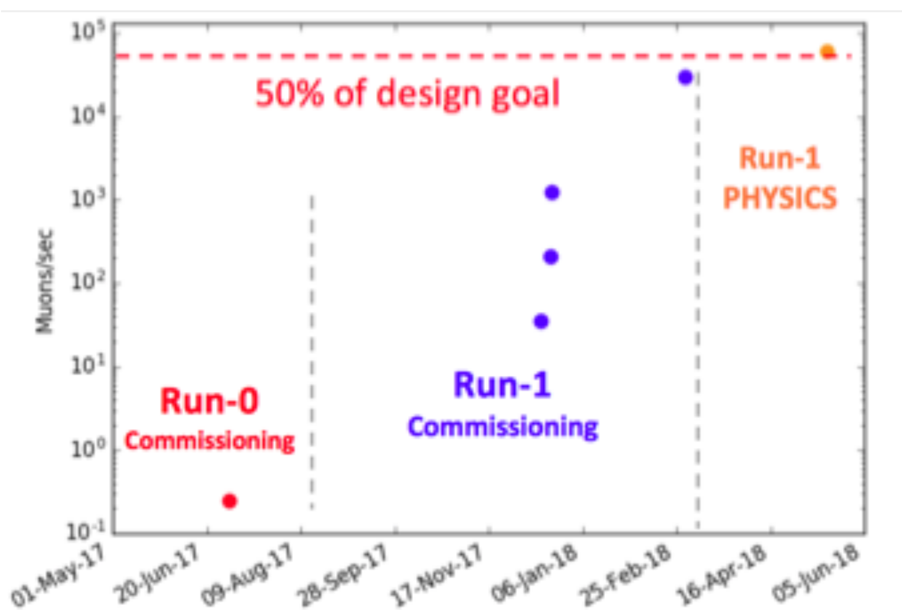
# Progress on Field

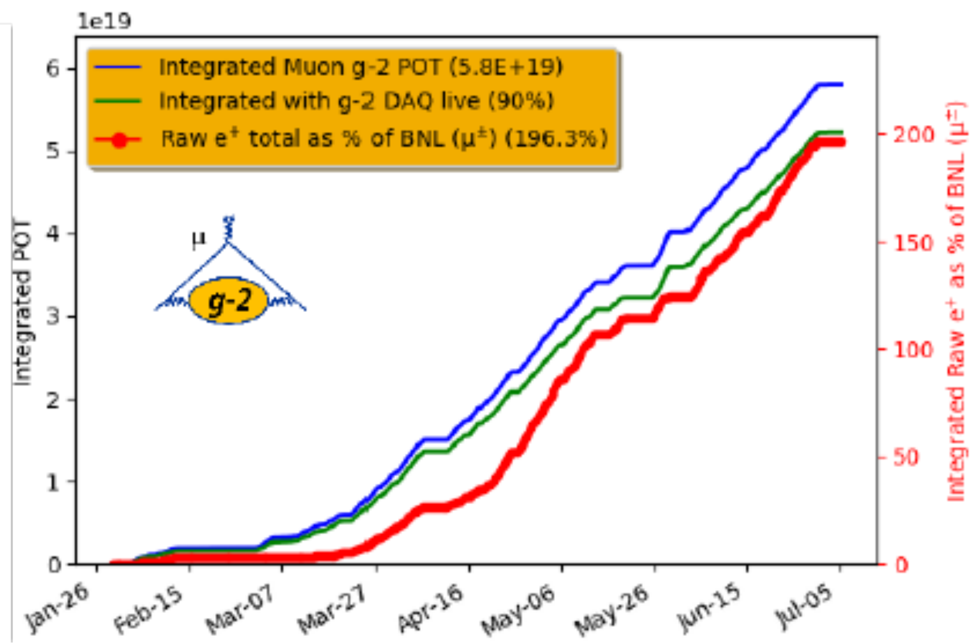



- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- Shimming of the magnet achieved 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an averaged field uniformity of +- 1ppm. They estimated their systematic uncertainty of 140 ppb. We improved of a factor 2!

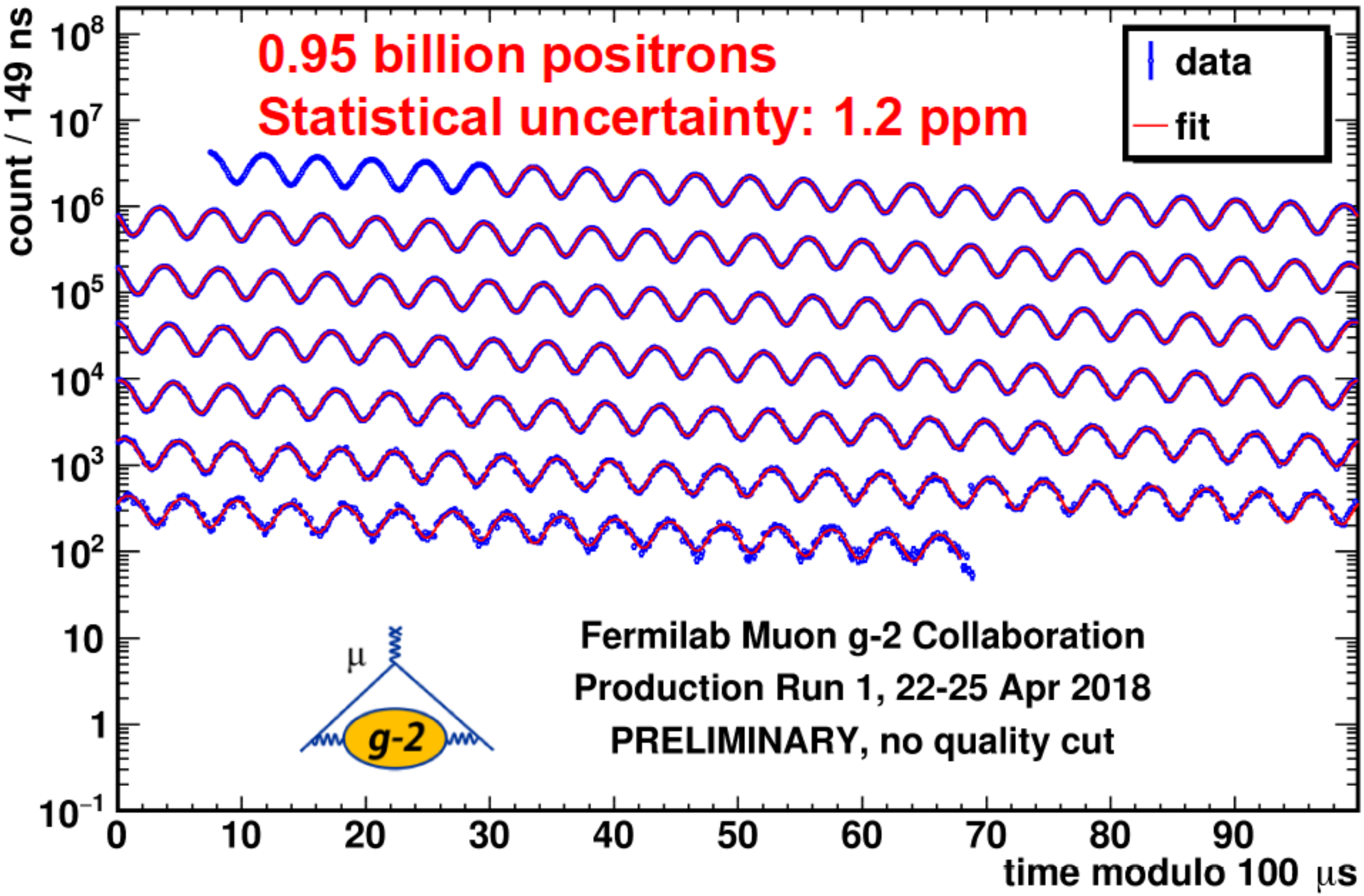
# RUN 1: March-July 2018

- 10/17 – 2/18: Commissioning Run
- 3/18 – 7/18: Physics run (**Run 1**): 18.5B $e^+$ recorded (compared to 9B $e^\pm$ that BNL recorded in 5 years of data taking).
- Achieved x2 BNL stat, 50% of TDR flux (~500$e^+$/fill)

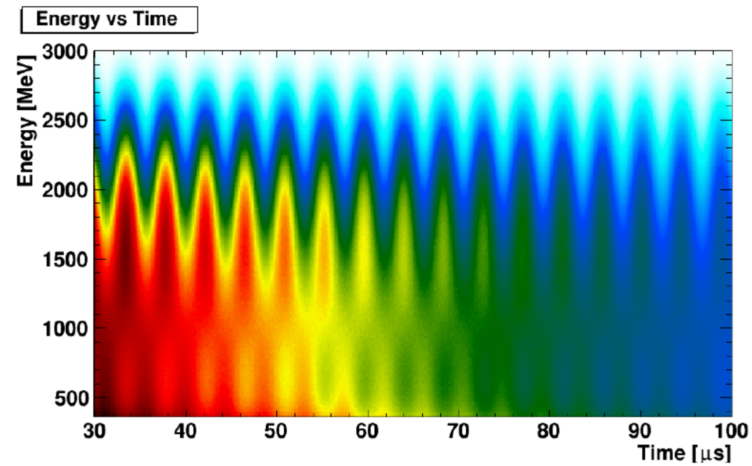


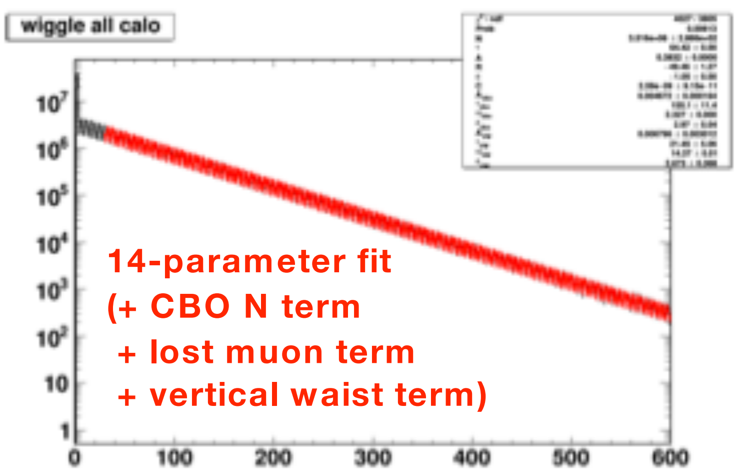
# Wiggle plot: A few days in April



# A typical $\omega_a$ analysis chain



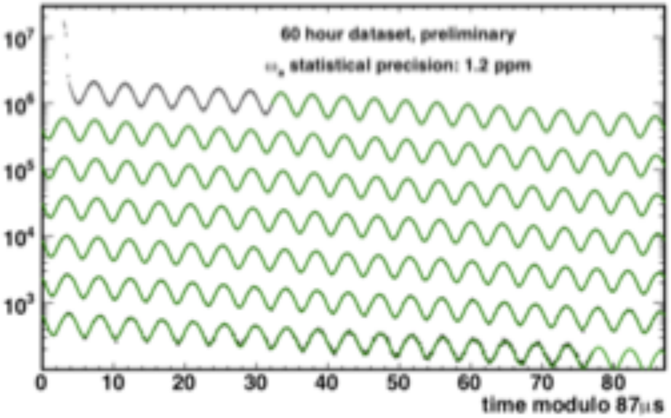

- In-fill gain correction
- Pileup subtraction
- Lost muon
- Coherent betatron oscillation (CBO)
- Fitting "wiggle plot" → Blinded $\omega_a$ (ppm)




→

| Fit type |
|---|
| **14 par** |
| Chi2/NDF |
| lifetime (μs) |
| Blinded R (ppm) |
| CBO lifetime (μs) |
| VW lifetime (μs) |

# Systematics on $\omega_a$: phase shift



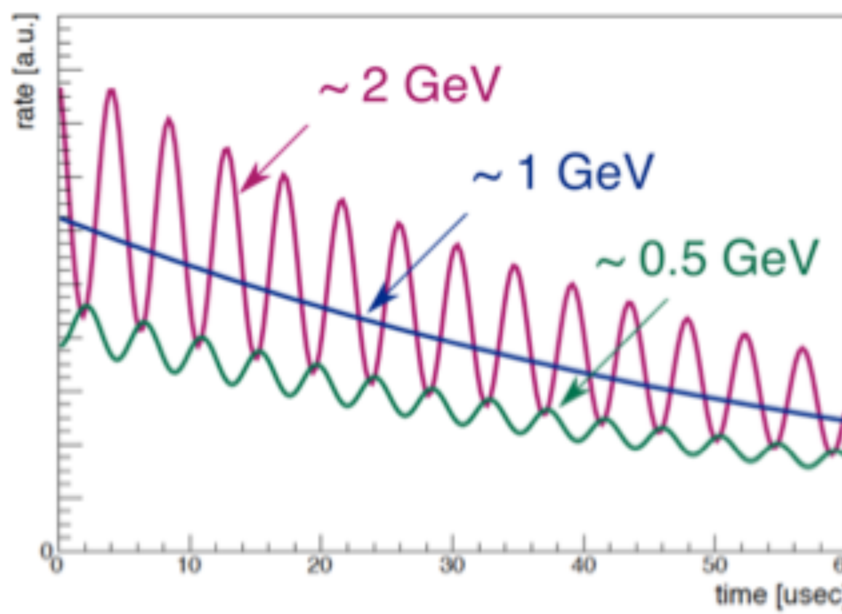

$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$

**If the phase is time dependent ("early-to-late" effect)**

$$\omega t + \phi = \omega t + \phi(t) = (\omega + \phi')t + \phi_0$$

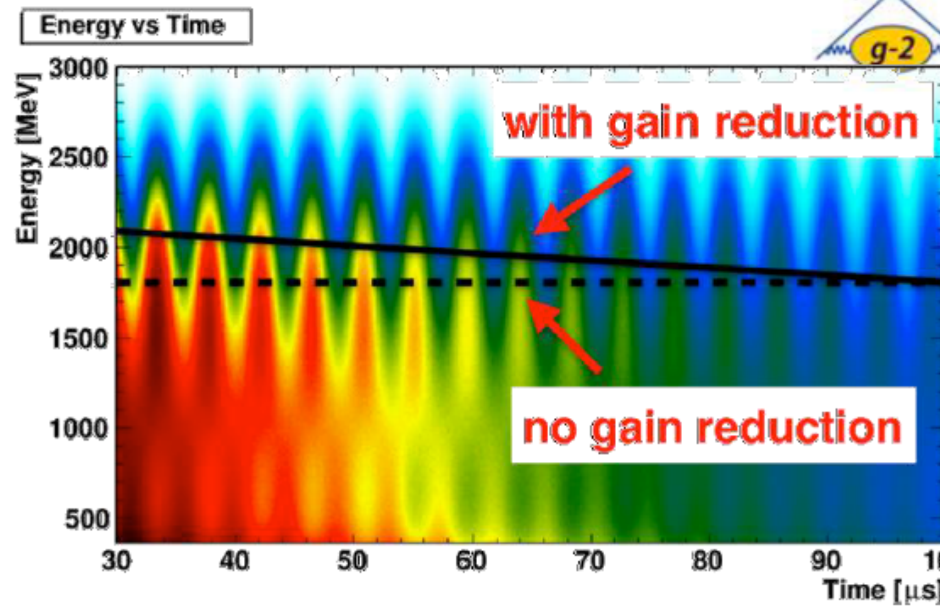
**Frequency shifted!**

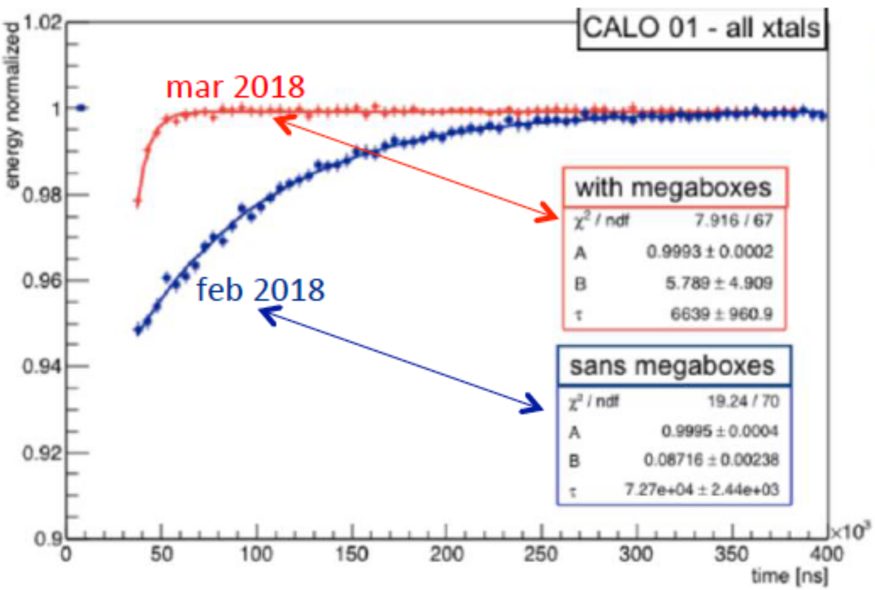
- since *phase* and *amplitude* are energy dependent, any effect that *combines together different energies within the same fill* can cause a "phase shift"



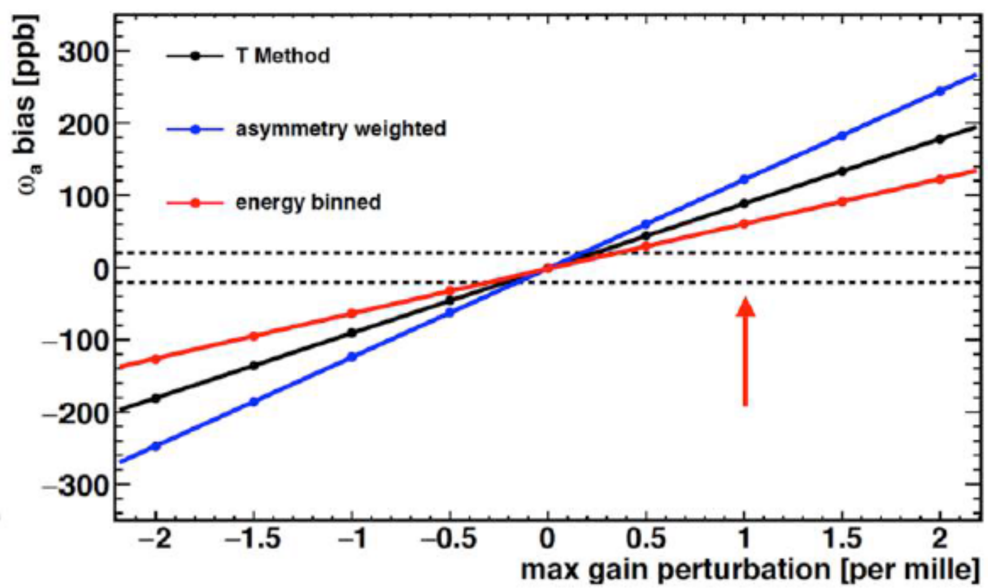
# Gain stability

- Gain variation during fill "mixes" different energies
- Laser system: fundamental tool
- Analysis totally performed by INFN, correction functions in official production



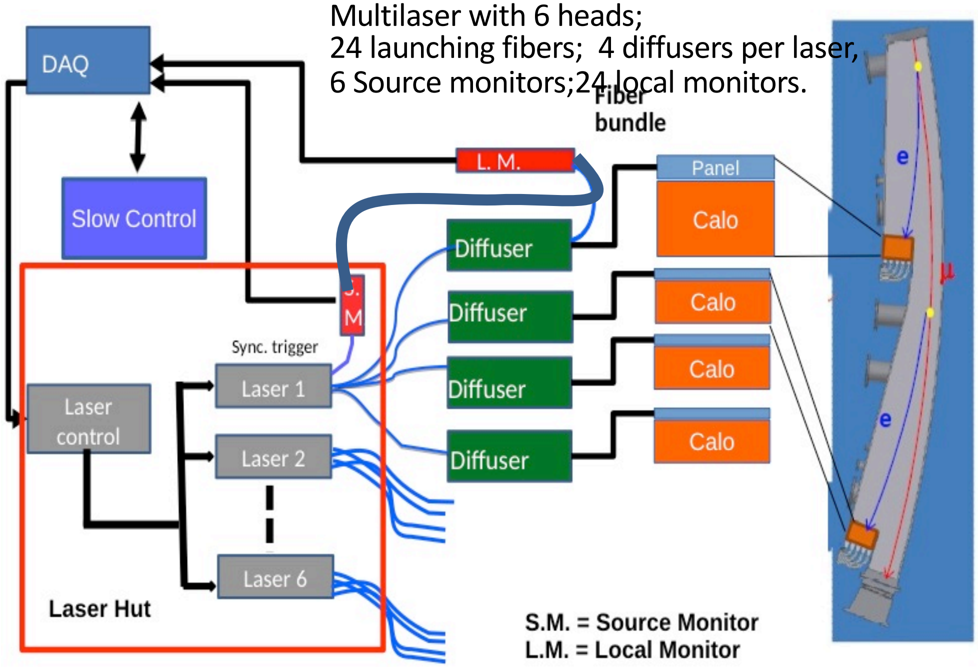

**laser gain monitoring system measured 0.1% perturbation at 30 us**

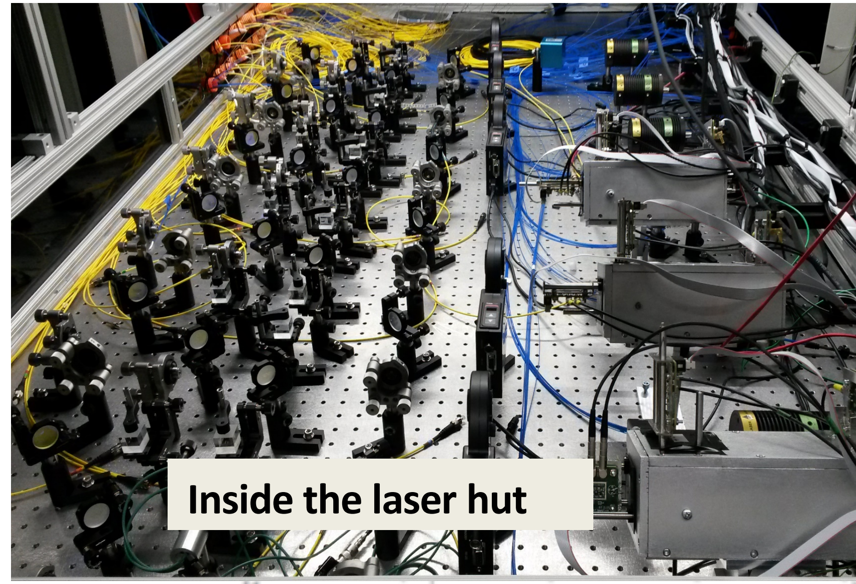


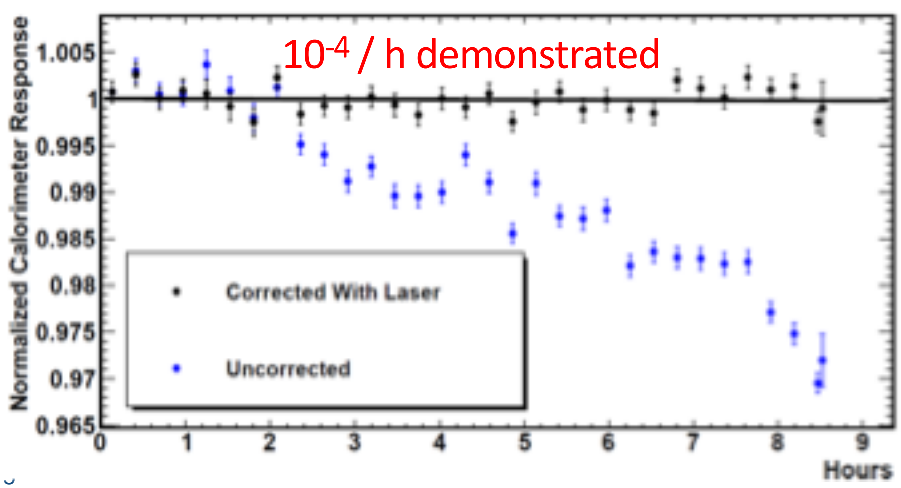

**50-150 ppb bias is expected for uncorrected in-fill gain perturbation**

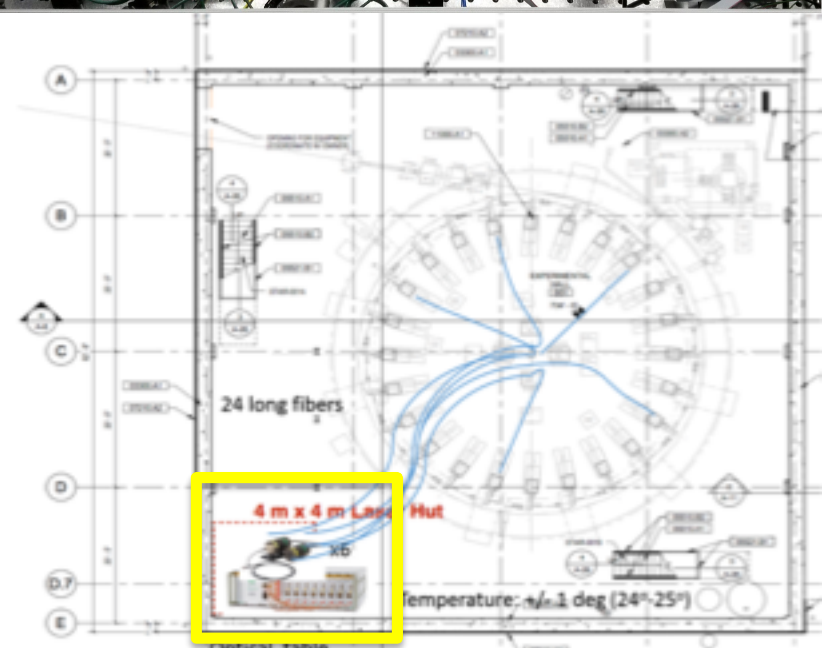
# The g-2 laser calibration system

Multilaser with 6 heads;
24 launching fibers; 4 diffusers per laser,
6 Source monitors;24 local monitors.



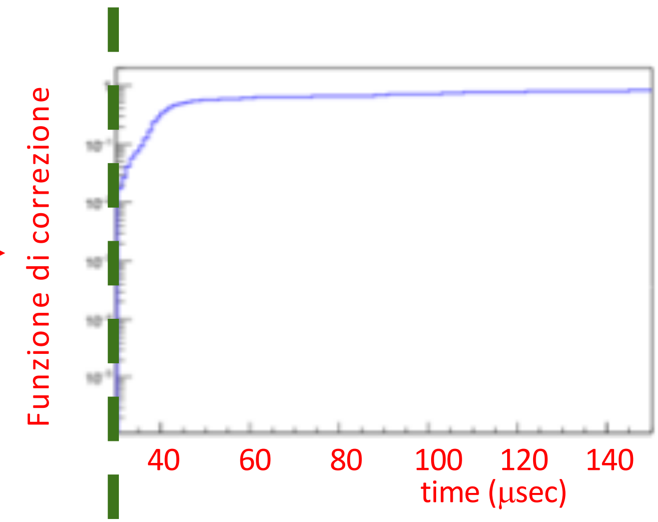



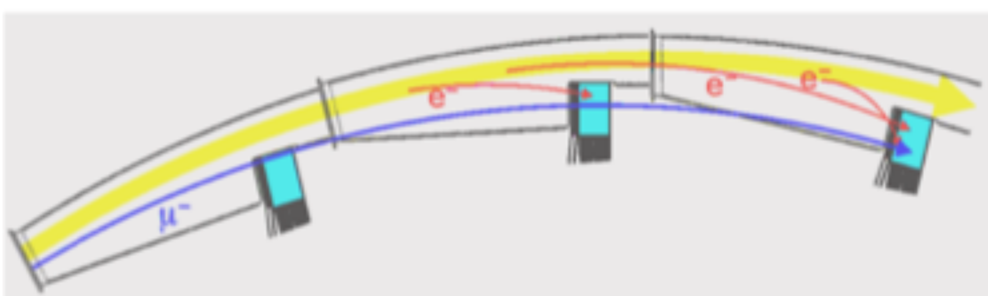
# Distorting muon life time: lost muons

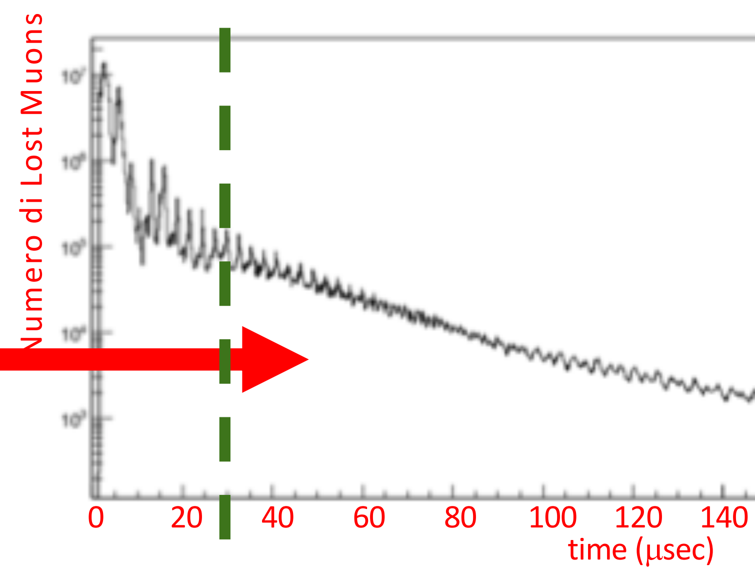
- Muons with *r > 45mm* wrt magic radius hit the collimators and bend (tipically) inward
- Correction to "wiggle function"

$$N(t) = N_0 e^{-t/\tau} \cdot \left(1 - A_{LM} I(t)\right) \cdot \left(1 + A\cos(\omega_a t + \varphi)\right)$$




- Lost muons selected as MIP particles which hit 2 (or 3) calos with Δt=6.2 ns

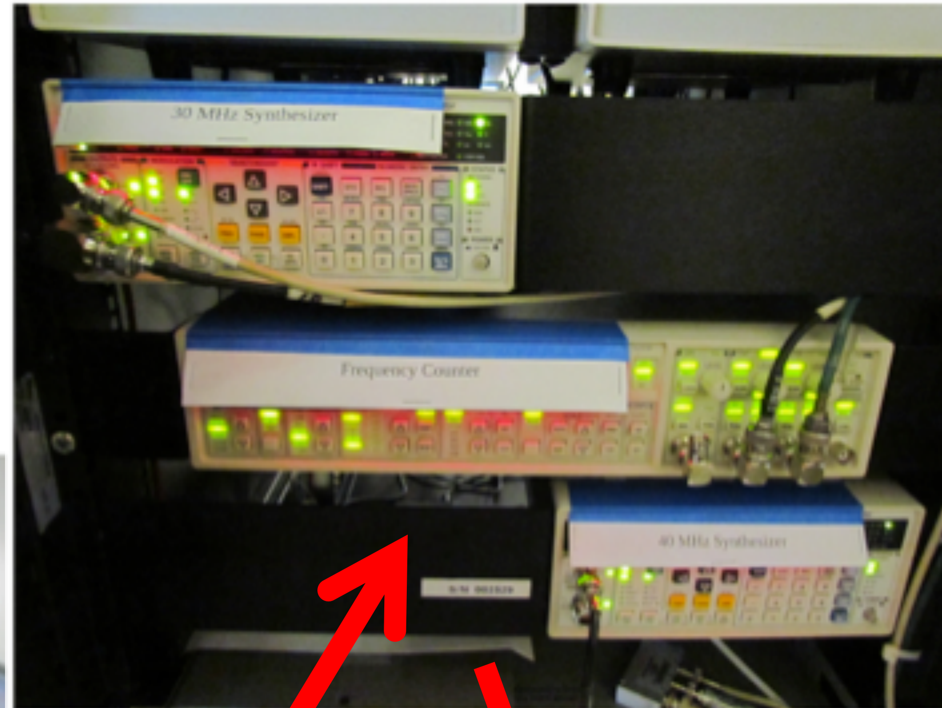



- Fraction of lost muons for t>30μs is $<10^{-4}$
- *wa-europa: Sorbara, Gioiosa, Driutti*

# Digression: blinding

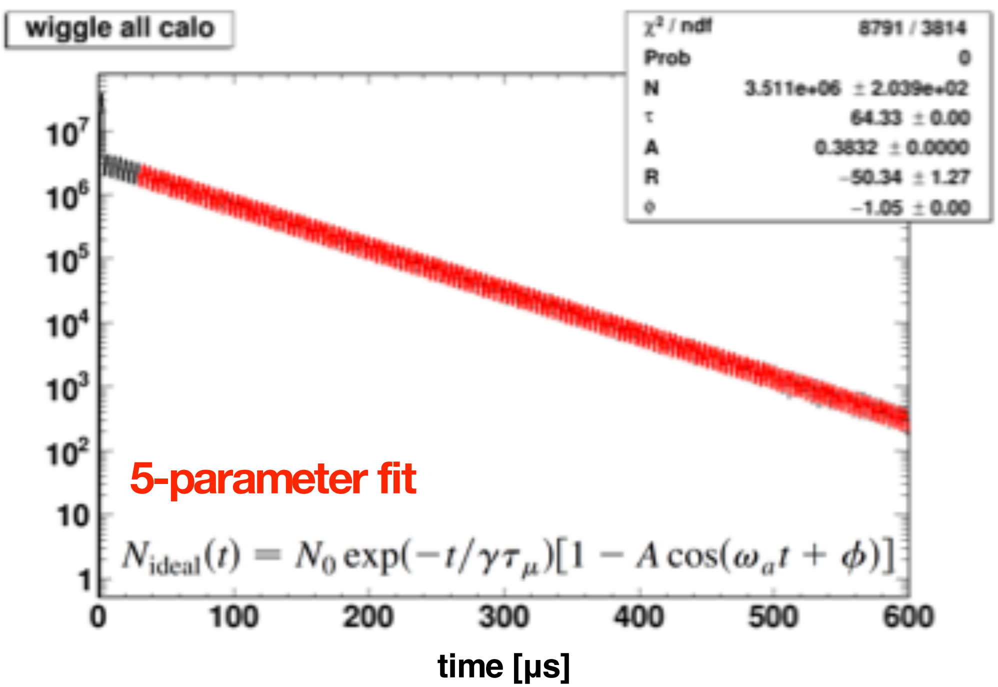
- Greg and Joe enthusiastically blinding the clock

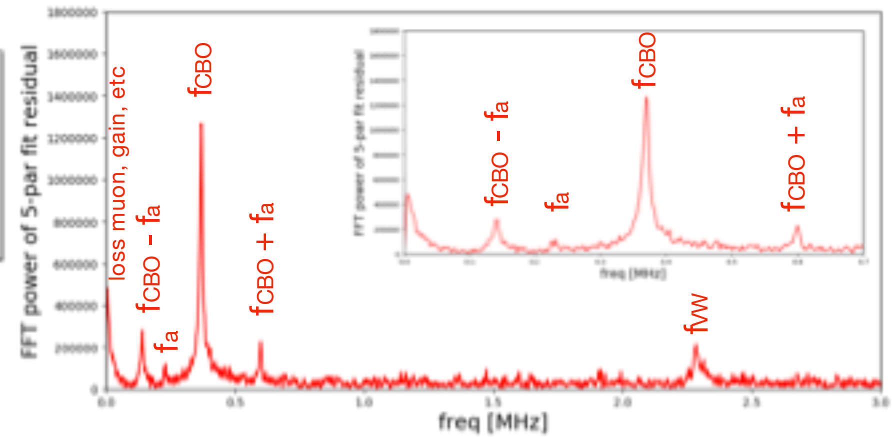



Locked Clock Panel

# T-method preliminary fitting results (5-par)

*in-fill gain correction and pileup correction not yet included

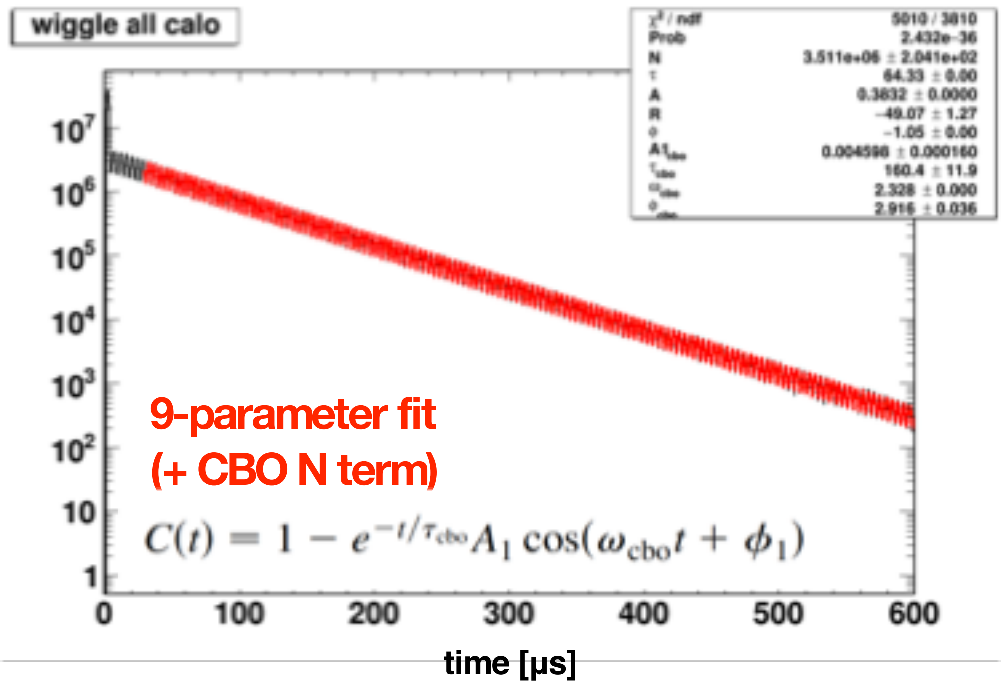


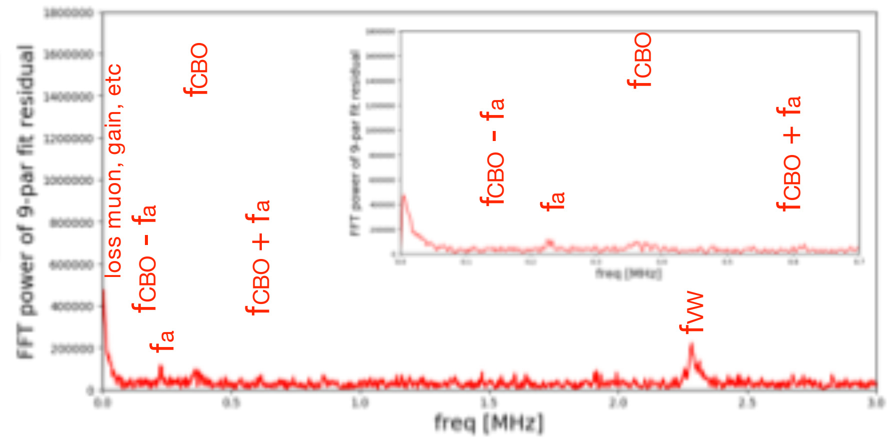

| Physical frequency | Variable | Frequency (MHz) | Period (μs) |
|---|---|---|---|
| Anomalous precession | fa | 0.23 MHz | 4.37 |
| Cyclotron | fc | 6.70 MHz | 0.149 |
| Horizontal Betatron | fx | 6.34 MHz | 0.158 |
| Vertical Betatron | fy | 2.2 MHz | 0.455 |
| CBO | fCBO | 0.37 MHz | 2.70 |
| Vertical Waist | fW | 2.3 MHz | 0.435 |

# T-method preliminary fitting results (9-par)

*in-fill gain correction and pileup correction not yet included



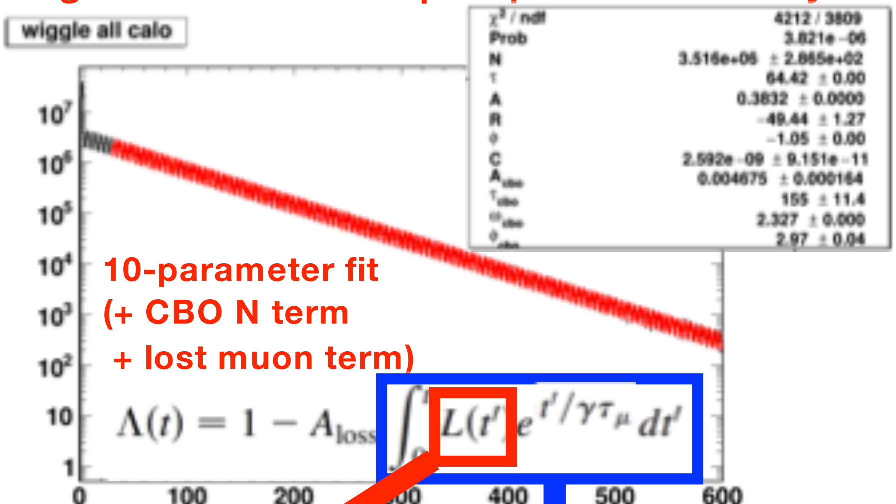

** CBO asym (A2) and phase (A3) terms also attempted but effect too small to be fitted



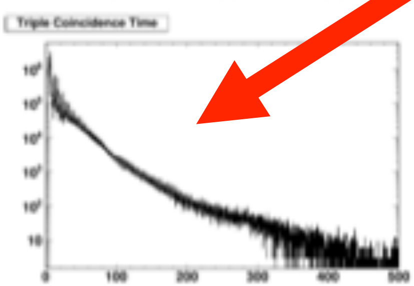

| Physical frequency | Variable | Frequency (MHz) | Period (μs) |
|---|---|---|---|
| Anomalous precession | fa | 0.23 MHz | 4.37 |
| Cyclotron | fc | 6.70 MHz | 0.149 |
| Horizontal Betatron | fx | 6.34 MHz | 0.158 |
| Vertical Betatron | fy | 2.2 MHz | 0.455 |
| CBO | fCBO | 0.37 MHz | 2.70 |
| Vertical Waist | fW | 2.3 MHz | 0.435 |

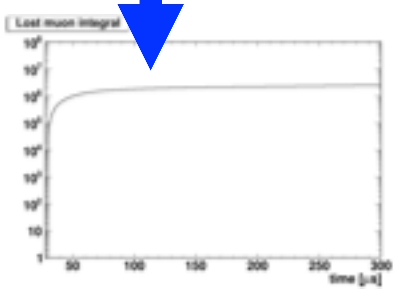
# T-method preliminary fitting results (10-par)

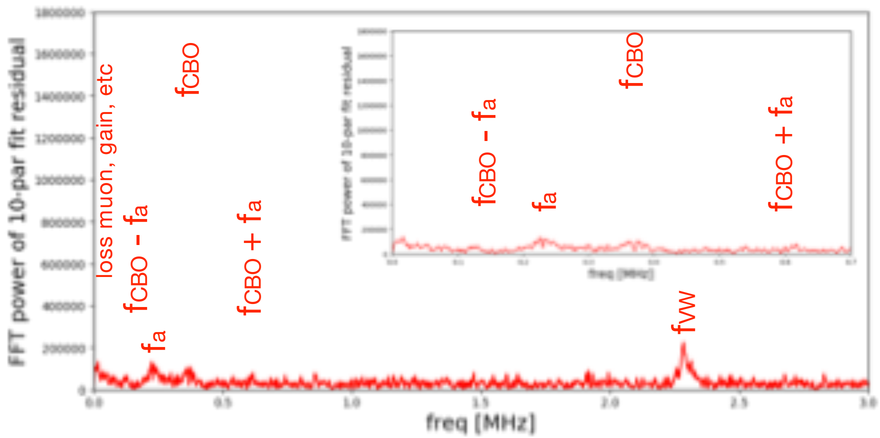
*in-fill gain correction and pileup correction not yet included




$$\Lambda(t) = 1 - A_{loss}\int_0^t L(t')e^{t'/\gamma\tau_\mu}\,dt'$$




| Physical frequency | Variable | Frequency (MHz) | Period (μs) |
|---|---|---|---|
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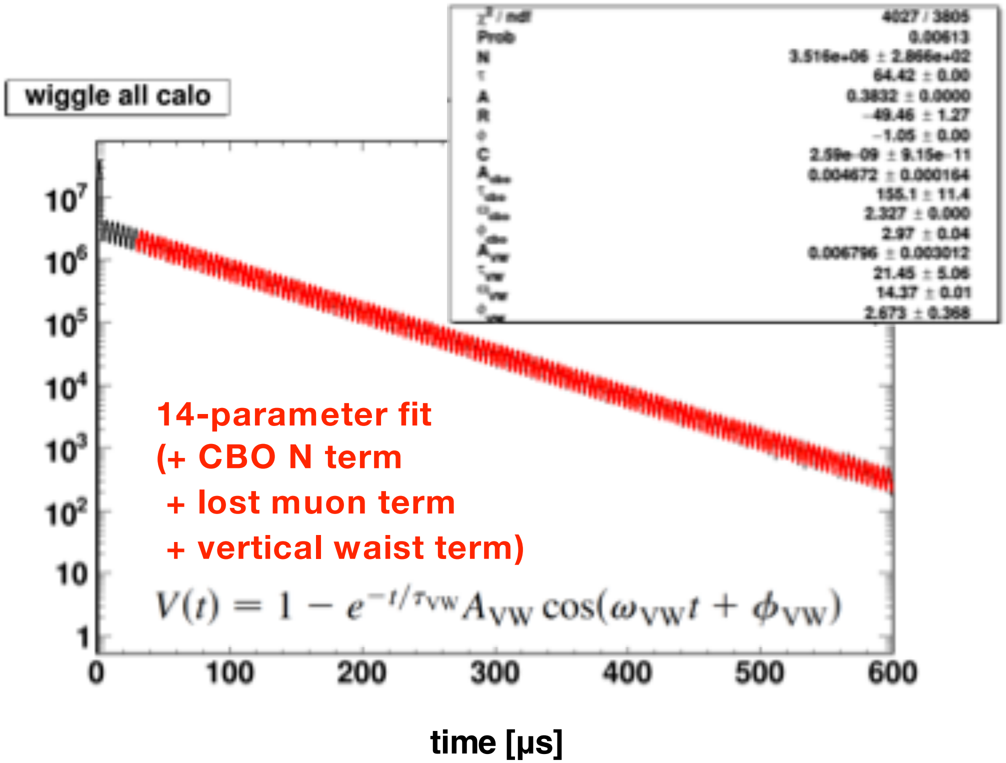
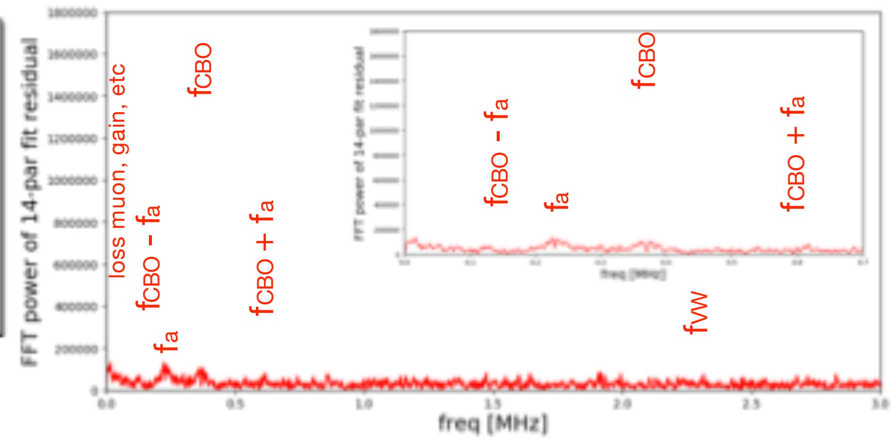
| Vertical Betatron | fy | 2.2 MHz | 0.455 |
| CBO | fCBO | 0.37 MHz | 2.70 |
| Vertical Waist | fW | 2.3 MHz | 0.435 |

# T-method preliminary fitting results (14-par)

*in-fill gain correction and pileup correction not yet included



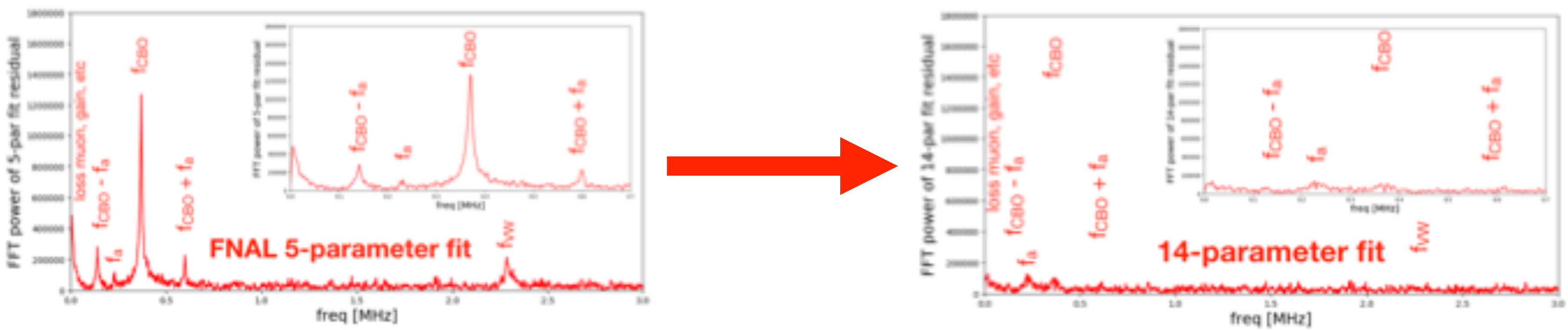




| Physical frequency | Variable | Frequency (MHz) | Period (μs) |
|---|---|---|---|
| Anomalous precession | fa | 0.23 MHz | 4.37 |
| Cyclotron | fc | 6.70 MHz | 0.149 |
| Horizontal Betatron | fx | 6.34 MHz | 0.158 |
| Vertical Betatron | fy | 2.2 MHz | 0.455 |
| CBO | fCBO | 0.37 MHz | 2.70 |
| Vertical Waist | fW | 2.3 MHz | 0.435 |

# T-method preliminary fitting results (comparison)

- With 2.5 days of Run1, the value of wa is determined with a statistical error of 1.27 ppm
- Still work to be done on systematics!

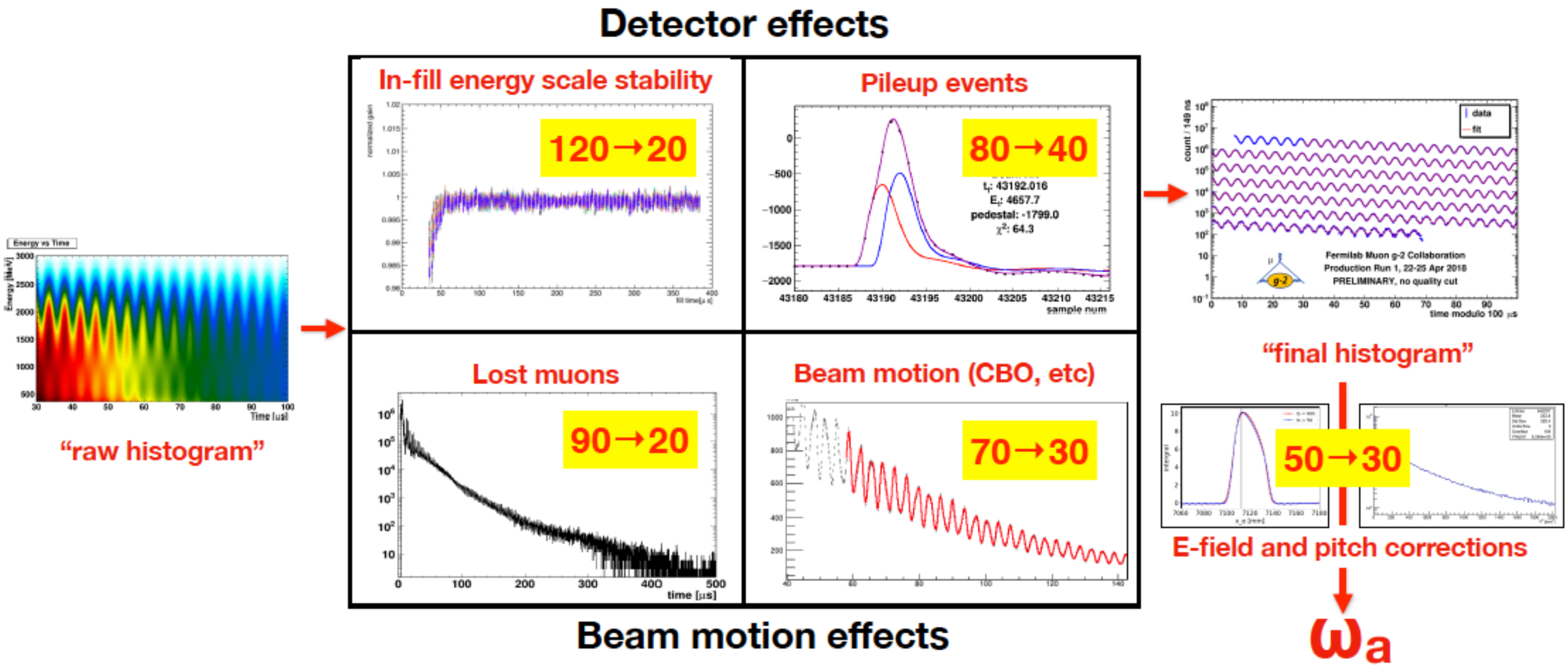
*in-fill gain correction and pileup correction not yet included




| Fit type | 5-par | 9-par | 10-par | 14-par |
|---|---|---|---|---|
| Physics | $\omega_a$ | CBO (N) | lost muon | vertical waist |
| Chi2/NDF | 8791/3814<br>~ 2.30 | 5010/3810<br>~ 1.31 | 4212/3809<br>~ 1.11 | 4027/3805<br>~ 1.06 |
| lifetime (μs) | 64.335(2) | 64.334(2) | 64.424(4) | 64.424(4) |
| Blinded R (ppm) | -50.34(1.27) | -49.07(1.27) | -49.44(1.27) | -49.46(1.27) |
| CBO lifetime (μs) | - | 160(12) | 155(11) | 155(11) |
| VW lifetime (μs) | - | - | - | 21(5) |


G. Venanzoni, SIF, 21 Sett 2018

# Where we are on systematic uncertainties




- Goal: stat and syst error ~ BNL ($0.46_{stat} \oplus 0.18_{sys\_\omega a}$ ppm)
- Hoping to unblind sometime in 2019

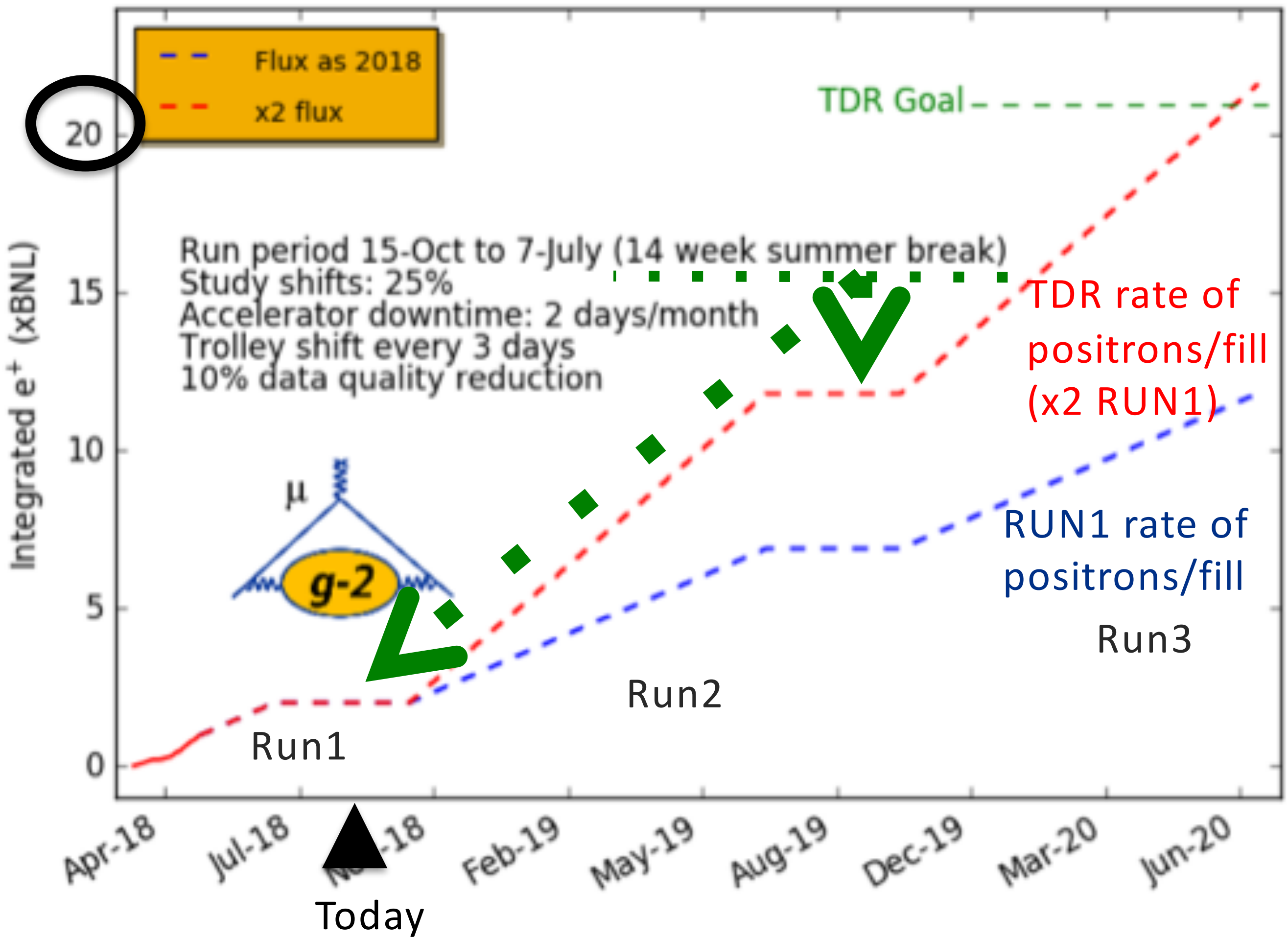
# Run1 + Run2 + Run3 = 21*BNL (statistics)

- Shutdown: Luglio-Settembre 2018
- Run II: Ott 2018-Lug 2019
- Run III:Ott 2019-Lug 2020

statistics: collect 21xBNL → reduce to **±100 ppb**
systematics on $\omega_a$, $\omega_p$ → reduce a factor ~2.5 to **±70 ppb** each

Miglioramenti attesi:

- 10-30% da miglioramento linea di fascio $\mu$
- 10-30% da Kicker piu' forte
- 10% da Quadrupoli (higher HV)
- 30-40% Nuovo inflector (shutdown estivo del 2019)
- Attesa x1.5 lujminosita' specifica nel RUN2; x2 nel RUN3 (Nuovo inflector)



# Fermilab E989: 34 Institutes; >150 Members

## Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Northwestern (thy)
- Regis
- Texas
- Virginia
- Washington
- York College

## National Labs

- Argonne
- Brookhaven
- Fermilab

## Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste
- Molise

## China:

- Shanghai

## The Netherlands:

- Groningen

## England

University College London
Liverpool
Oxford

## Korea

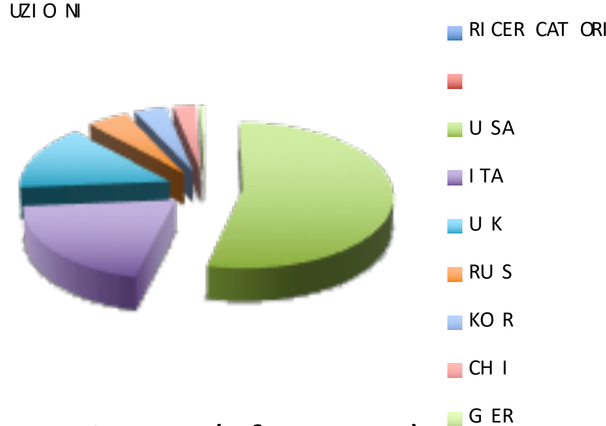
KAIST

## Russia:

Dubna
Novosibirsk

## Germany:

Dresden (thy)



**C. Polly, , Co-Spokesperson**
**M. Lancaster, Co-Spokesperson**


Italy is the second largest group in g-2 (after USA)

# Conclusioni

- Exciting period for g-2!
- E989 at Fermilab plans to achieve **140 ppb (or 16 x $10^{-11}$) on $a_\mu$** EDM parasitically
- RUN1 finished: Achieved ~2x BNL statistics in FY18…5-10% of ultimate goal (depending on the selection cuts).
- Analysis structure well defined, both for $\omega_p$ and for $\omega_a$

→ Goal is to publish in 2019 (~summer) on data collected in 2018 with error similar to BNL → important check of central value!

# Conclusioni

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- E989 at Fermilab plans to achieve **140 ppb (or 16 x $10^{-11}$) on $a_\mu$** EDM parasitically
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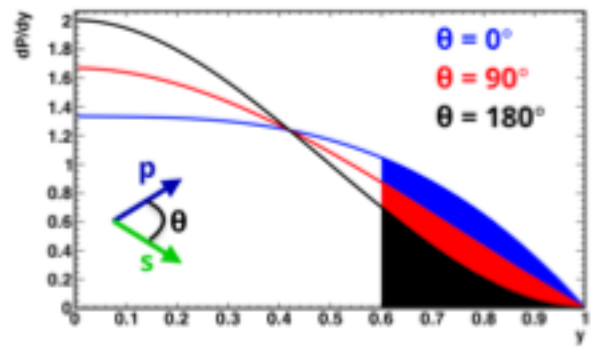
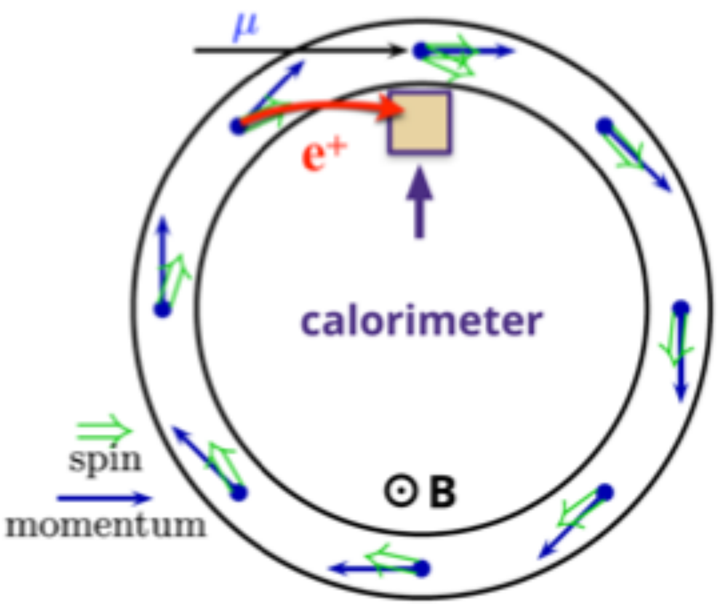
Will $a_\mu$ be inside or outside of the SM?

# THE END

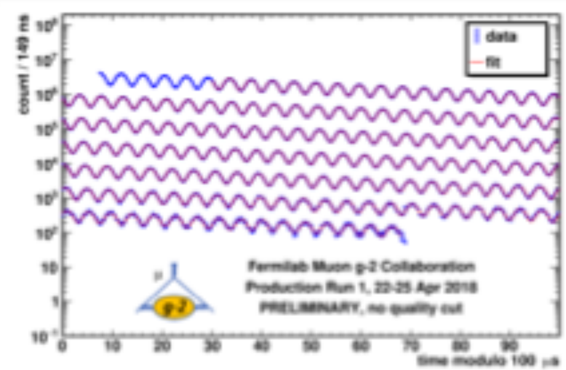
# $\omega_a$ Analysis

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m}$$




$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$




~ 0.23 MHz

~ 4.37 μs

Idealmente fit a 5 parametri. Realmente O(10) par:

$$N(t) = f^{loss}(t) \bullet f^{CBO}(t) \bullet f^{VW}(t) \bullet f^{acc}(t) \bullet \frac{N_0}{\gamma\tau_\mu} e^{-t/\gamma\tau_\mu} \bullet \left[1 - A(t)\cos(\omega_a^{calo} t + \phi(t))\right]$$

# The analysis strategy

- 7 independent analysis groups using different *Reconstruction algorythms* and different *Fit methods*
- 3 Independent Reconstruction algorythms developed (Q, East, West); a 4$^{th}$ one under construction by the Europa team

| Team | Reconstruction | Analysis |
|---|---|---|
| UKy | Q | Q |
| CU | East | T,E |
| Miss/UIUC | East | T |
| Europa | West/Europa | T,E |
| UW | West | T,E |
| SJTU | West | T |
| BU | West | R |

# The Europa group (coordinated by M. Incagli)

**Muon g-2**

Search: Muon g-2

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Wiki »

New wiki page Edit Watch History

## wa_europa

8 Italian people (mostly students, postdoc) involved

- coordinators: M. Incagli, J. Price
- fitting procedure: J. Price, A. Driutti
- gain functions: M. Smith, P. Girotti
- lost muons: M. Sorbara, A. Gioiosa, A. Driutti
- CBO studies: J. Price, T. Halewood-Leagas
- pileup: M. Smith, tracker-group
- calorimeter energy calibration: M. Sorbara, A. Gioiosa, G. Venanzoni
- calorimeter time calibration: P. Girotti, R. Ribatti, M. Incagli
- calorimeter clustering: ..
- track-cluster association: G. Hesketh,J. Price, M. Sorbara
- temperature correction: A. Nath, N. Raha
- ..

### HowTo

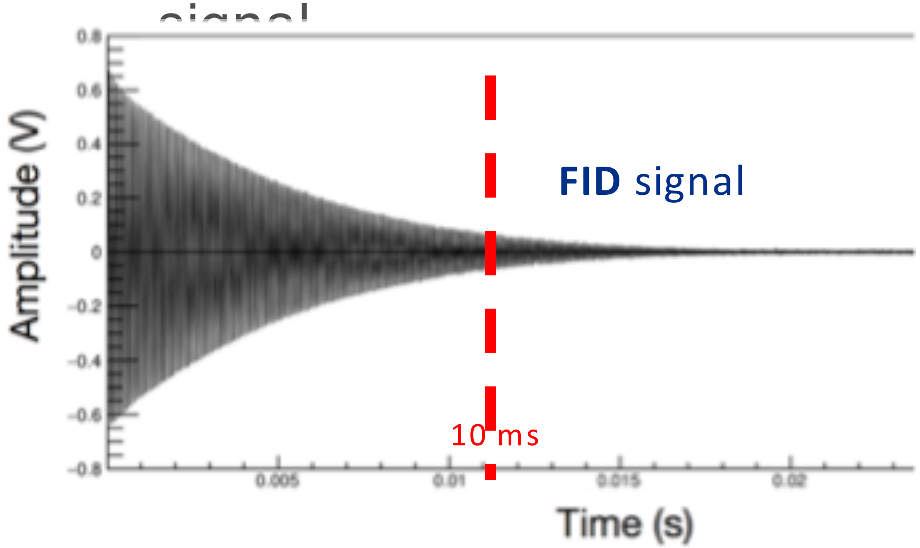
- General workflow: Basic overview from data to fit
- DST or reduced rples: where are they and what is inside
- Reading software: how to read the ntuples using the maintained code
- Fitting software: git branch and examples on how to fit (and how to blind)
- Correction functions: laser gain functions, lost muons, CBO, pileup, ...
- Cluster reconstruction: island fitting, energy and time calibration, clustering, ...
- Tracks and clusters: track-cluster association and related studies

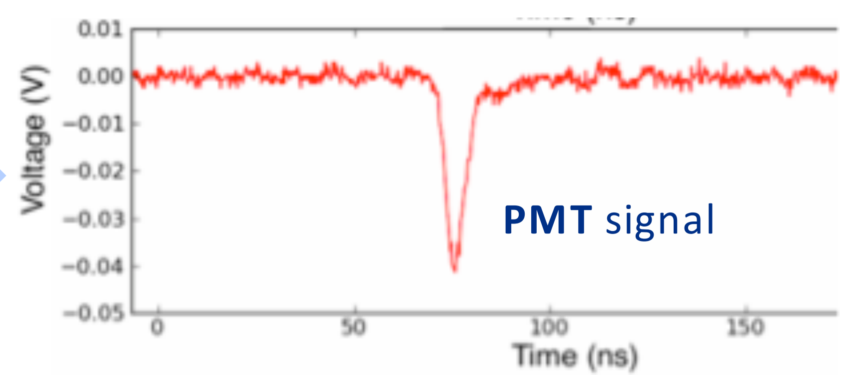
Wiki

Start page
Index by title
Index by date

# how do we measure $\omega_p$ - 1

- *Pulsed Nuclear Magnetic Resonance on "free" protons:*
  - Protons are aligned in magnetic field
  - Apply a $\pi/2$ shift by an external pulse
  - With the same coil, pick up the *Free Induction Decay (FID)* signal

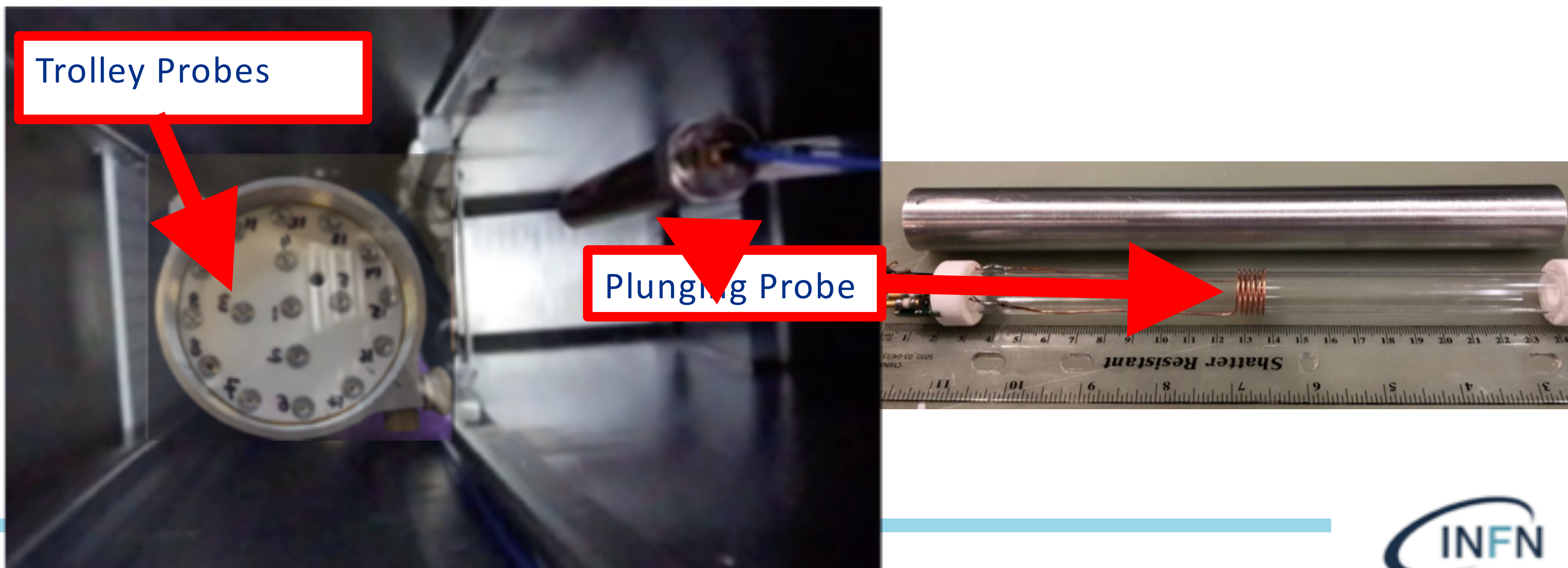



- The FID signal is the basis of the magnetic field measurement as a PMT pulse for the energy measurement

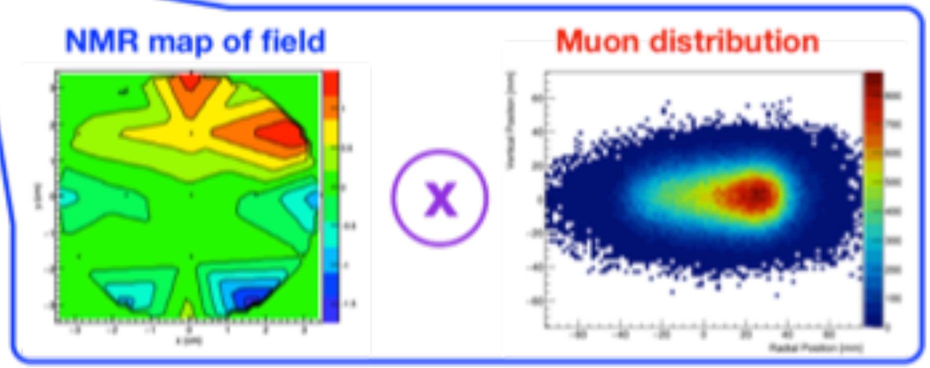
# how do we measure $\omega_p$ - 2

- local measurement with a set of 17 probes mounted on a trolley ~1 run every 3 days (1 run takes 2-3 hours)
- time interpolation: a set of 378 fixed probes measure the field
- the fixed probes are not at the same location as the trolley probes → space interpolation
- absolute calibration: a *plunging probe* is inserted periodically in the trolley garage to measure the field in the same location (with ~mm precision)



# How do we measure $\omega_p$ - 3

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




**Field**

$$B(r,\theta) = \sum_{n=1}^{\infty} r^n (c_n \cos n\theta + s_n \sin n\theta)$$

**Beam**

$$I_0 = \int_0^{r_0}\int_0^{2\pi} M(r,\theta) r dr d\theta$$

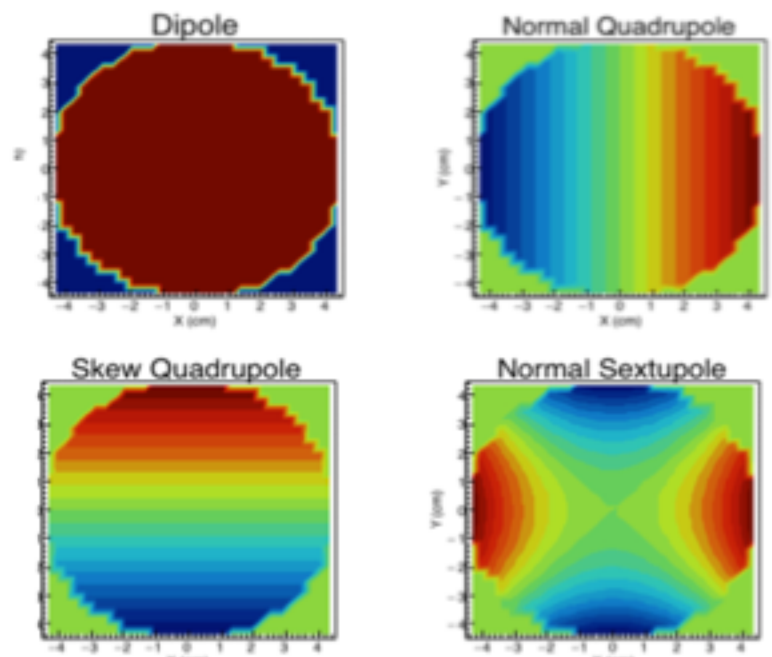
$$I_n = \int_0^{r_0}\int_0^{2\pi} r^n M(r,\theta) \cos n\theta\, r dr d\theta$$

$$J_n = \int_0^{r_0}\int_0^{2\pi} r^n M(r,\theta) \sin n\theta\, r dr d\theta.$$

The average field seen by the muons is then given by

**Convolution**

$$\bar{B} = c_0 + \frac{1}{I_0}\sum_{n=1}^{\infty}(c_n I_n + s_n J_n).$$



# Three Recent papers relevant for g-2!

20 years effort!

25 April 2017

## High-precision calculation of the 4-loop contribution to the electron $g$-2 in QED

Stefano Laporta*

*Dipartimento di Fisica, Università di Bologna,*
*Istituto Nazionale Fisica Nucleare, Sezione di Bologna,*
*Via Irnerio 46, I-40126 Bologna, Italy*

**Abstract**

I have evaluated up to 1100 digits of precision the contribution of the 891 4-loop Feynman diagrams contributing to the electron $g$-2 in QED. The total 4-loop contribution is

$$a_e = -1.912245764926445574152647167439830054060873390658725345\ldots\left(\frac{\alpha}{\pi}\right)^4 .$$

I have fit a semi-analytical expression to the numerical value. The expression contains harmonic polylogarithms of argument $e^{\frac{i\pi}{3}}$, $e^{\frac{2i\pi}{3}}$, $e^{\frac{i\pi}{2}}$, one-dimensional integrals of products of complete elliptic integrals and six finite parts of master integrals, evaluated up to 4800 digits.

## The hadronic vacuum polarization contribution to the muon $g-2$ from lattice QCD

M. Della Morte[a], A. Francis[b], V. Gülpers[c], G. Herdoíza[d], G. von Hippel[e], H. Horch[e], B. Jäger[f], H.B. Meyer[e,g], A. Nyffeler[e], H. Wittig[e,g]

[a] CP3-Origins, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
[b] Department of Physics and Astronomy, York University, Toronto, ON, Canada, M3J1P3
[c] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[d] Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain
[e] PRISMA Cluster of Excellence and Institut für Kernphysik, Johann Joachim Becher-Weg 45, University of Mainz, D-55099 Mainz, Germany
[f] ETH Zürich, Institute for Theoretical Physics, Wolfgang-Pauli-Str. 27, 8093 Zürich, Switzerland
[g] Helmholtz Institute Mainz, University of Mainz, D-55099 Mainz, Germany

**Abstract**

We present a calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment, $a_\mu^{\rm hvp}$, in lattice QCD employing dynamical up and down quarks. We focus on controlling the infrared regime of the vacuum polarization function. To this end we employ several complementary approaches, including Padé fits, time moments and the time-momentum representation. We correct our results for finite-volume effects by combining the Gounaris-Sakurai parameterization of the timelike pion form factor with the Lüscher formalism. On a subset of our ensembles we have derived an upper bound on the magnitude of quark-disconnected diagrams and found that they decrease the estimate for $a_\mu^{\rm hvp}$ by at most 2%. Our final result is $a_\mu^{\rm hvp} = (654 \pm 32\,^{+21}_{-23}) \cdot 10^{-10}$, where the first error is statistical, and the second denotes the combined systematic uncertainty. Based on our findings we discuss the prospects for determining $a_\mu^{\rm hvp}$ with sub-percent precision.

$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 6\%$

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

## Measuring the leading hadronic contribution to the muon $g$-2 via $\mu e$ scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,f], M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]

[1] INFN Bologna, Viale Carlo Berti-Pichat 6/2, 40127 Bologna, Italy
[2] INFN Pavia, Via Agostino Bassi 6, 27100 Pavia, Italy
[3] INFN Bologna, Via Irnerio 46, 40126 Bologna, Italy
[4] INFN Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy
[5] Dipartimento di Fisica, Università di Pavia, Via A. Bassi 6, 27100 Pavia, Italy
[6] INFN Padova, Via Francesco Marzolo 8, 35131 Padua, Italy
[7] INFN Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[8] Dipartimento di Fisica e Scienze della Terra "M. Melloni", Parco Area delle Scienze 7/A, 43124 Parma, Italy
[9] INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, RM, Italy

$\delta a_\mu^{HLO}/a_\mu^{HLO} \rightarrow 0.3\%_{\rm stat}$

**MUonE proposal**

Received: 17 October 2016 / Accepted: 17 January 2017 / Published online: 1 March 2017

## Measurement of $\omega_p$ to 70 ppb using Pulsed Proton NMR

⇒ Want Larmor frequency of free protons $\omega_p$ in storage volume while muons are stored

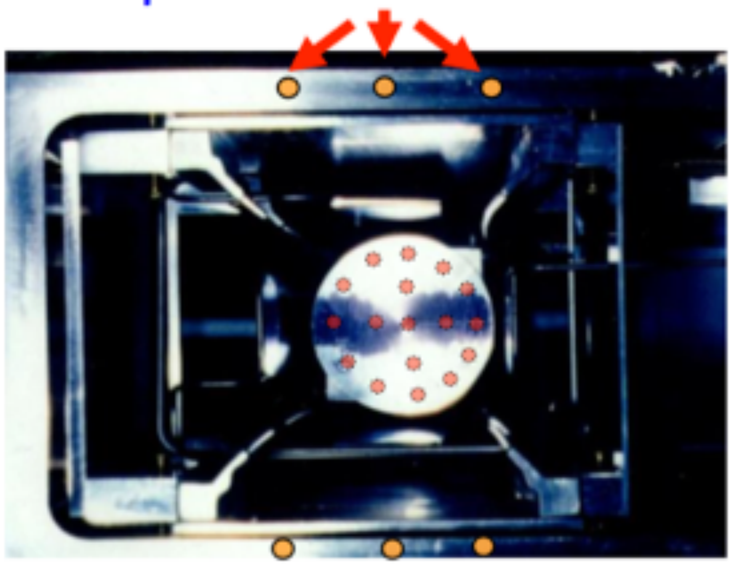
- Can't have NMR probes in storage volume at same time/place as muons!

(1) 387 Fixed probes measure field at same time as muons stored, but outside storage volume

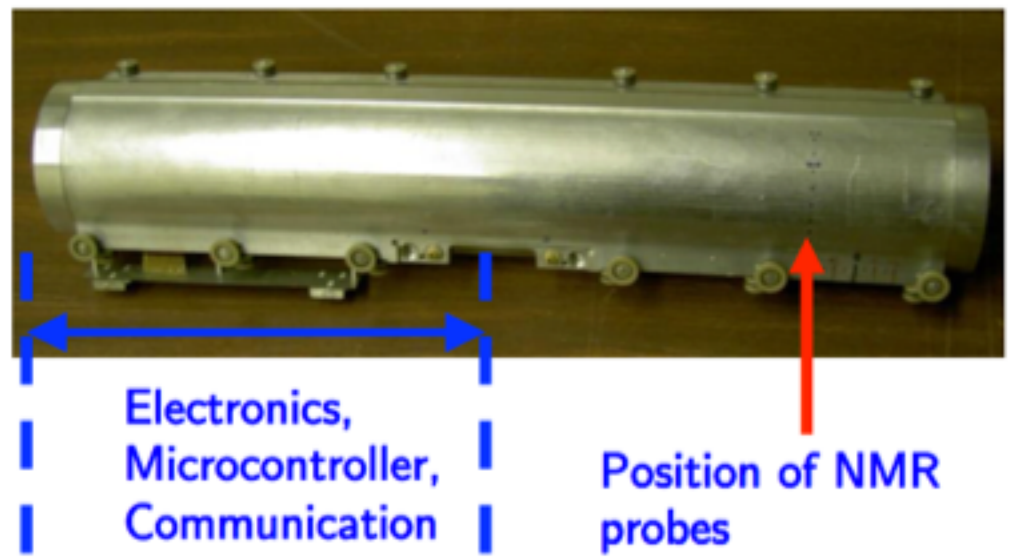
(2) Field inside storage volume measured by NMR trolley, but not when muons stored

- Fixed probes are cross-calibrated when trolley goes by; can infer field inside storage volume when muons stored from fixed probes

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes



# Summary

- ***FNAL: status and the plan going forward …***
  - Design complete and implementation well along
  - Beam on; magnetic field ready
  - Detector almost ready; starting commissioning
  - Beam expected in late 2017
  - Goal remains **140 ppb (or 16 x $10^{-11}$) on $a_\mu$**
  - EDM parasitically

- ***J-PARC: novel method being developed***
  - Working out key new issues: source; magnet; detectors, etc.
  - Concept has greater reach for EDM owing to detector coverage
  - Aiming at 2019 Phase 1 start with
    - **g-2 to ~400 ppb**,
    - EDM ~$10^{-21}$ e-cm;

# First challenge…getting the statistics

| Item | Estimate |
|---|---|
| Protons per fill on target | $10^{12}$ p |
| Positive-charged secondaries with $dp/p = \pm 2\%$ | $4.8 \times 10^7$ |
| $\pi^+$ fraction of secondaries | 0.48 |
| $\pi^+$ flux entering FODO decay line | $> 2 \times 10^7$ |
| Pion decay to muons in 220 m of M2/M3 line | 0.72 |
| Muon capture fraction with $dp/p < \pm 0.5\%$ | 0.0036 |
| Muon survive decay 1800 m to storage ring | 0.90 |
| Muons flux at inflector entrance (per fill) | $4.7 \times 10^4$ |
| Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$ | $0.10 \pm 0.04$ |
| Stored muons per fill | $(4.7 \pm 1.9) \times 10^3$ |
| Positrons accepted per fill (factors 0.15 x 0.63) | $444 \pm 180$ |
| Number of fills for 1.8 $\times 10^{11}$ events | $(4.1 \pm 1.7) \times 10^8$ fills |
| Time to collect statistics | $(13 \pm 5)$ months |
| Beam-on commissioning | 2 months |
| Dedicated systematic studies periods | 2 months |
| Net running time required | $17 \pm 5$ months |

Achieving required statistics is a primary concern

- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

Need a factor of 85 improvement in integrated beam coming from many other factors

Ratio of beam powers BNL/FNAL:

$$\frac{\text{4e12 protons/fill} * (\text{12 fills / 2.7s}) * \text{24 GeV}}{\text{1e12 protons/fill} * (\text{16 fills / 1.3s}) * \text{8 GeV}} = 4.3$$

Fermilab

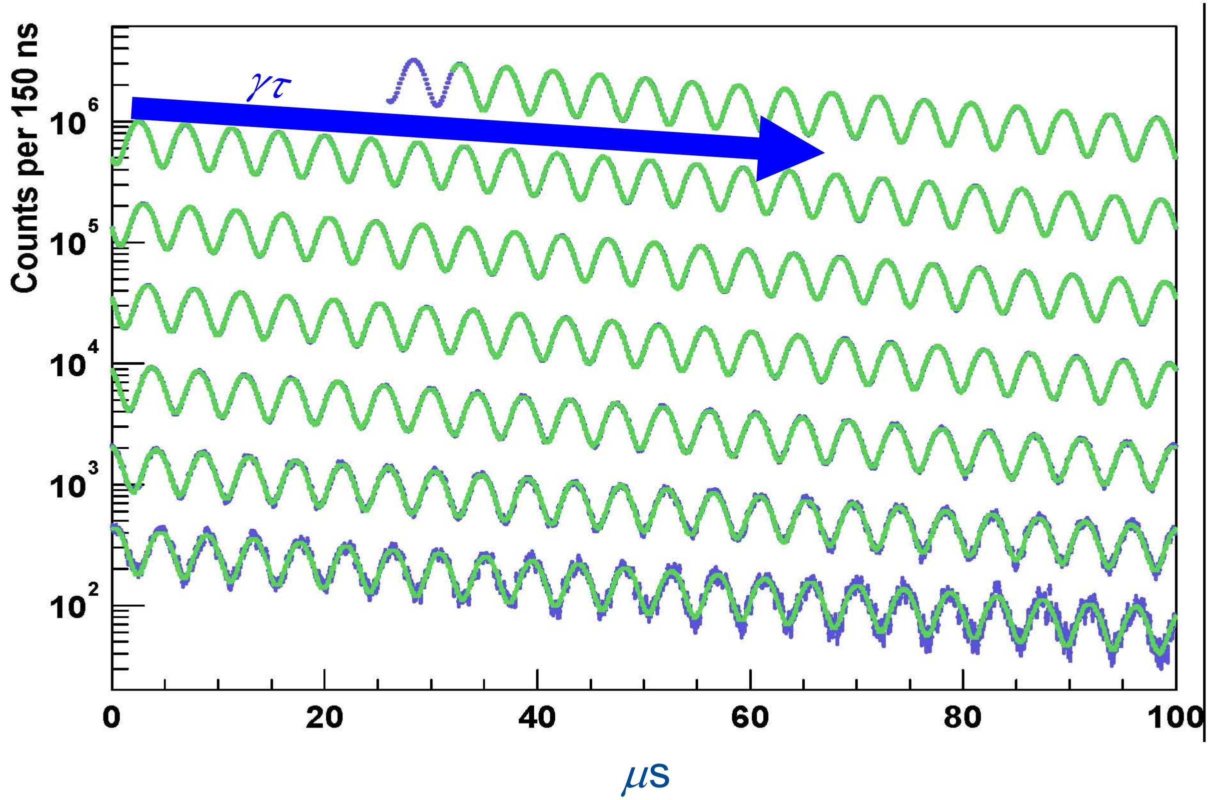
$\omega_a$

# The arrival time spectrum of high-energy e⁻

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

$3.6 \times 10^9\ e^-$

**$E_e \geq 1.8$ GeV**




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

Fitting this function gives $\omega_a$. Together with the magnetic field one get $a_\mu$:

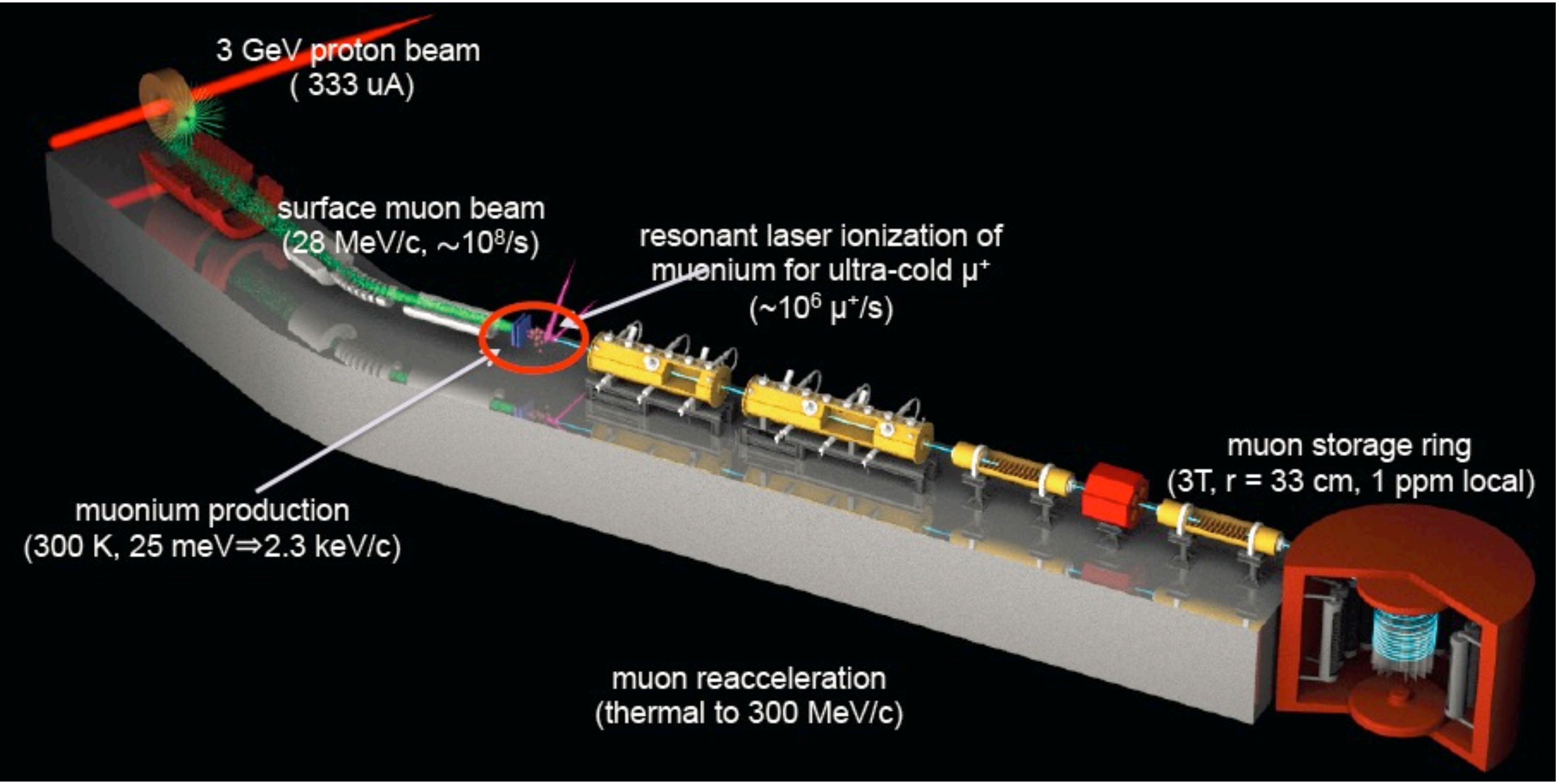
$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot} \times 10^{-11}$$

(0.5 ppm)

*What's the Standard Model prediction?*

Fermilab

# The J-PARC approach




Injection of an ultra-cold, low-energy, muon beam into a small, but highly uniform magnet

# What makes them different?

- Eliminate electric focusing removes $\boldsymbol{\beta} \times \boldsymbol{E}$ term

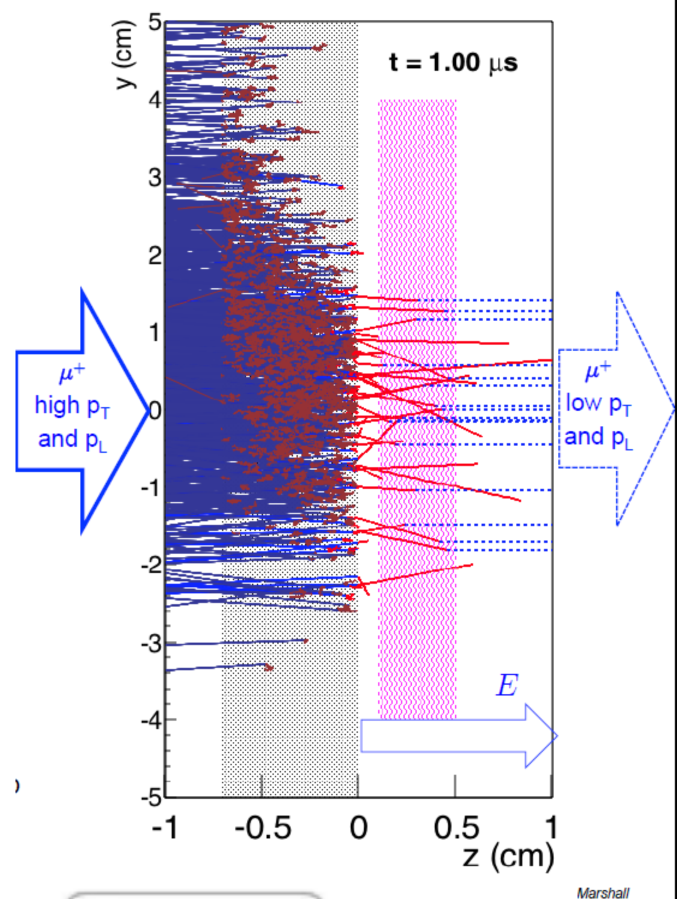
$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

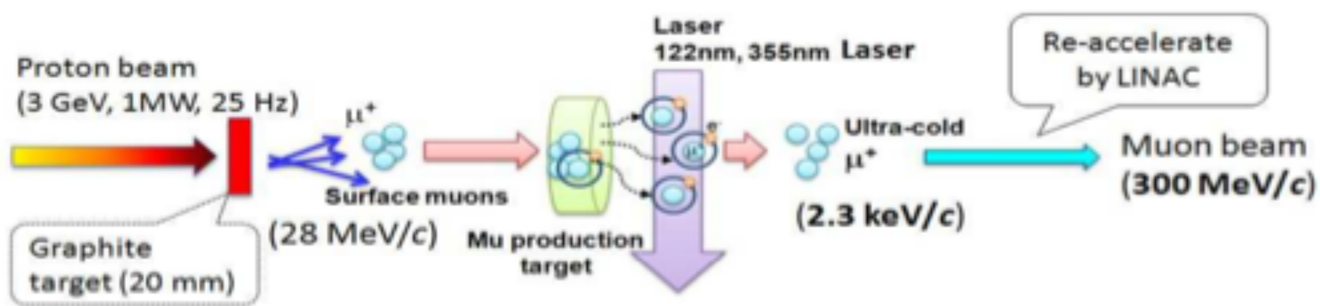
Do need ~zero $P_T$ to store muons

- → Not constrained to run at the "magic momentum"
- Create "ultra-cold" muon source; accelerate, and inject into compact storage ring.
- Consequences are quite interesting …
  - Smaller magnet; intrinsically more uniform
- Aim for BNL level precision as an important check

# Ultra-cold Muons

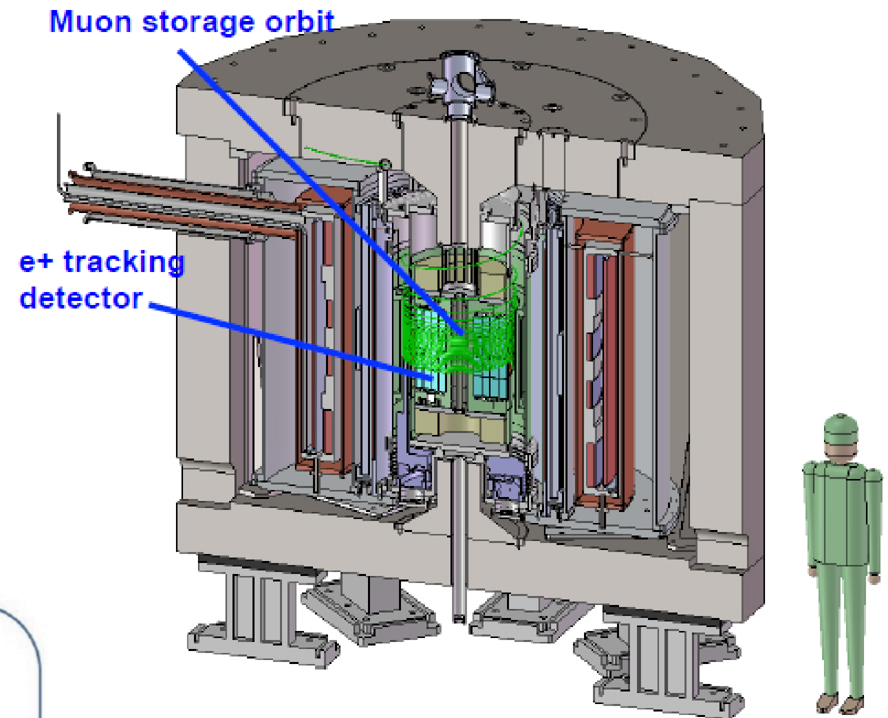
- Surface $\mu^+$
- Stop in Aerogel
- Diffuse Muonium ($\mu^+e^-$) atoms into vacuum
- Ionize
  - 1S → 2P→unbound
  - **Max Polarization 50%**
- Accelerate
  - E field, RFQ, linear structures
  - P = 300 MeV/c



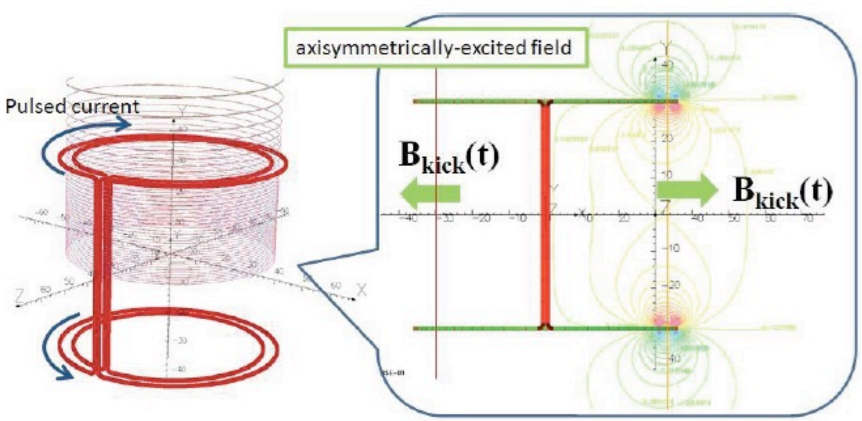



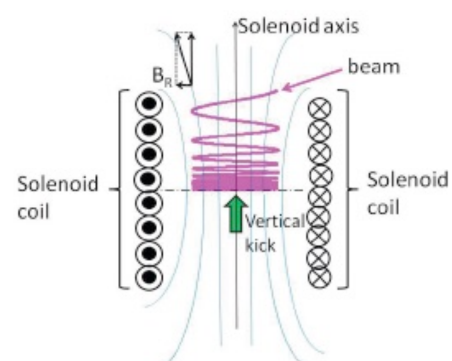
# Muon storage magnet

- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical $B$ = 3 Tesla, <1ppm locally
  - storage region r = 33.3±1.5 cm, h = ±5 cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - n = 1.5 × $10^{-4}$, r$B_r$(z) = -n z$B_z$(r) in storage region




a trapped orbit



# Detector system of silicon trackers

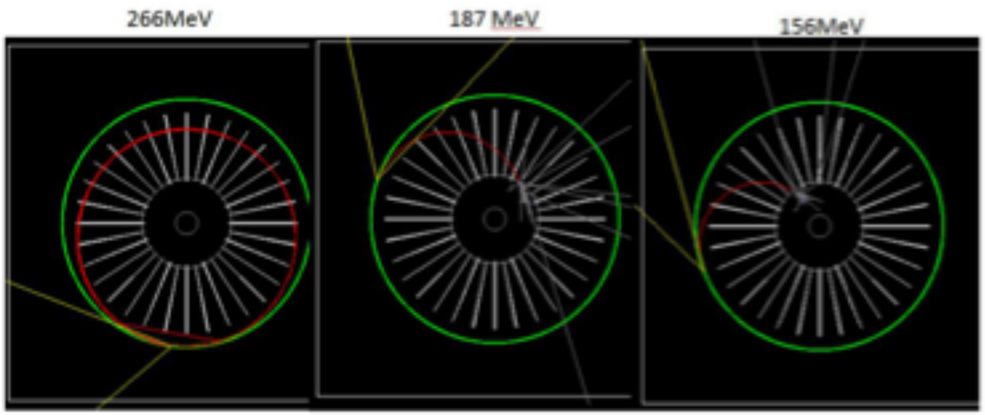
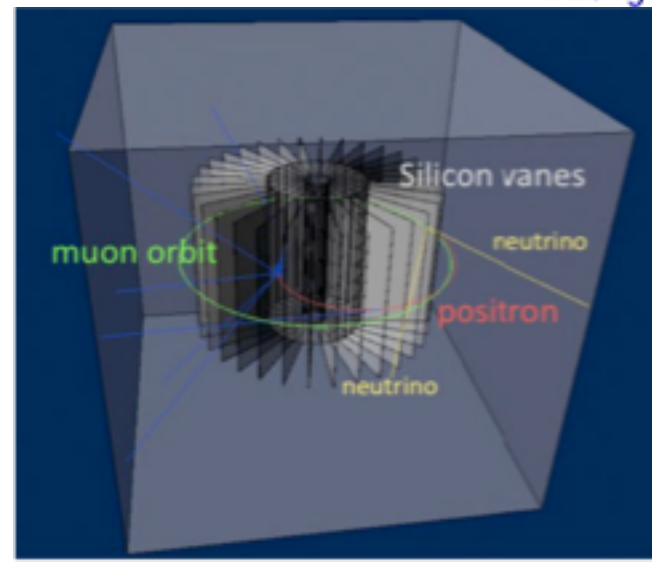
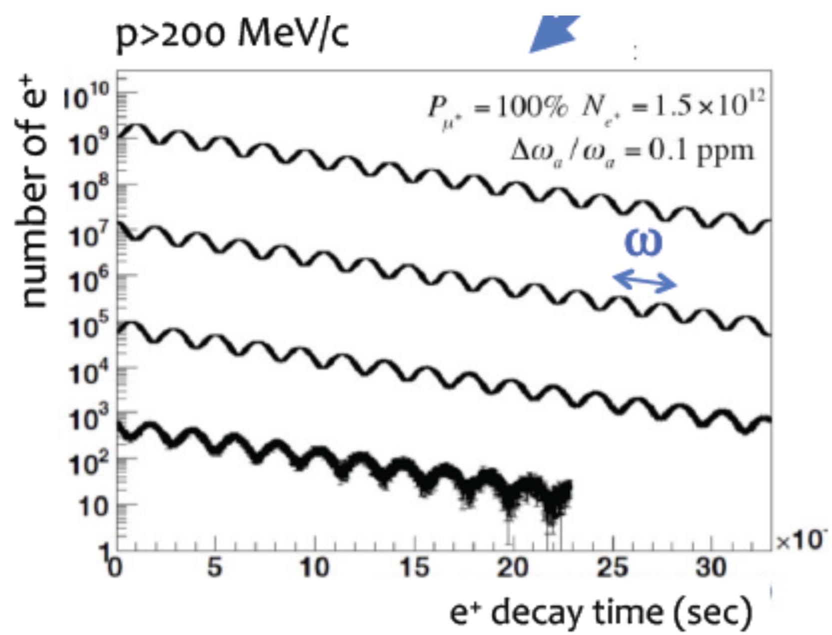



**Figure 6:** Example positron trajectories in the detector system at three different energies of positrons. The green circle is the muon beam orbit. The red trajectory is the trace of the positron track. The white tracks are photons.




Expected data. Note shorter lifetime at this momentum, and lower asymmetry owing to polarization of source

# Comparison

$$\delta\omega_a/\omega_a = \frac{1}{\omega_a \gamma \tau_\mu}\sqrt{\frac{2}{NA^2\langle P\rangle^2}},$$

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

| Parameter | Fermilab E989 | J-PARC E24 |
|---|---|---|
| Statistical goal | 100 ppb | 400 ppb |
| Magnetic field | 1.45 T | 3.0 T |
| Radius | 711 cm | 33.3 cm |
| Cyclotron period | 149.1 ns | 7.4 ns |
| Precession frequency, $\omega_a$ | 1.43 MHz | 2.96 MHz |
| Lifetime, $\gamma\tau_\mu$ | 64.4 $\mu$s | 6.6 $\mu$s |
| Typical asymmetry, $A$ | 0.4 | 0.4 |
| Beam polarization | 0.97 | 0.50 |
| Events in final fit | $1.8 \times 10^{11}$ | $8.1 \times 10^{11}$ |

# Summary of expected sensitivities

| Quantities | Description | Value |
|---|---|---|
| $T$ | Running time | $2 \times 10^7$ s |
| $P$ | Muon polarization | 0.5 |
| $\frac{dN_\mu}{dt}$ | Average muon rate in the storage magnet | $0.334 \times 10^6$/s |
| $N_\mu$ | Total number of muon in the storage magnet | $0.668 \times 10^{13}$ |
| $\epsilon_{acc}$ | Acceptance of the $e^+$ detector and momentum cut | 0.133 |
| $\epsilon_{trk}$ | Track reconstruction efficiency | 0.9 |
| $N_{e^+}$ | Total number of positrons ($N_\mu \epsilon_{acc} \epsilon_{trk}$) | $0.80 \times 10^{12}$ |
| $\frac{\Delta\omega_a}{\omega_a}$ | Uncertainty on anomalous spin precession frequency | 0.36 ppm |
| $\Delta d_\mu$ | Uncertainty on EDM | $1.3 \times 10^{-21} e \cdot$ cm |

- Statistical uncertainty estimates
  - $\Delta\omega_a/\omega_a$ = 0.36 ppm ($0.163/PN^{1/2}$)
    - BNL E821 $\sigma_{stat}$ = 0.46 ppm
  - $\Delta d_\mu = 1.3\times10^{-21}$ $e \cdot$ cm sensitivity
    - BNL E821 $(-0.1\pm0.9)\times10^{-19}$ $e \cdot$ cm
    - $\Delta d_e < 1.05\times10^{-27}$ $e \cdot$ cm

# J-PARC $g$–2 goals (Stage 1)

## Statistics

- Running time
  - measurement only: $2\times10^{7}$ s
- Muon rate from H-line
  - 1MW, SiC target: $3.32\times10^{8}$ $s^{-1}$
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization, $\mathcal{P} = 0.5$
  - $2.25\times10^{-3}$ (stage 2 goal is 0.01)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-$\beta$: 0.52
- Storage ring injection, decay, and kick
  - 0.92
- Stored muons
  - $3.34\times10^{5}$ $s^{-1}$ , total $6.68\times10^{12}$

## Systematics

- Estimations still in progress
  - simulations
  - need experience with prototypes and first stages
  - need running experience to make assessments similar to E989
- $\omega_p$ ($B$ measurement)
  - + smaller stored volume, higher local precision that E821
  - + all tracks to storage region
- $\omega_a$ (decay time measurement)
  - + all tracking detectors
  - – high rate differences between early and late decay times
    - + polarization flip
- Learning curve could be long and steep
  - we haven't done this experiment before…

# TDR Numbers

- 1.6 x $10^{11}$ good decay positrons (E>1.8GeV, t>30μs) for 22 BNL statistics (7x$10^9$)
- Needs 1.5 x $10^8$ fills (=7 months)

**→ 3BNL/month; ~$10^3$ $e^+$/fill; $10^4$ μ/fill**

| Item | Factor | Value per fill |
|---|---|---|
| Protons on target | | $10^{12}$ p |
| Positive pions captured in FODO, $\delta p/p = \pm 0.5\%$ | $1.2 \times 10^{-4}$ | $1.2 \times 10^{8}$ |
| Muons captured and transmitted to SR, $\delta p/p = \pm 2\%$ | 0.67% | $8.1 \times 10^{5}$ |
| Transmission efficiency after commissioning | 90% | $7.3 \times 10^{5}$ |
| Transmission and capture in SR | $(2.5 \pm 0.5)\%$ | $1.8 \times 10^{4}$ |
| Stored muons after scraping | 87% | $1.6 \times 10^{4}$ |
| Stored muons after 30 $\mu$s | 63% | $1.0 \times 10^{4}$ |
| Accepted positrons above E = 1.86 GeV | 10.7% | $1.1 \times 10^{3}$ |
| Fills to acquire $1.6 \times 10^{11}$ events (100 ppb) | | $1.5 \times 10^{8}$ |
| Days of good data accumulation | 17 h/d | 202 d |
| Beam-on commissioning days | | 150 d |
| Dedicated systematic studies days | | 50 d |
| Approximate running time | | $402 \pm 80$ d |
| Approximate total proton on target request | | $(3.0 \pm 0.6) \times 10^{20}$ |

# Beam structure