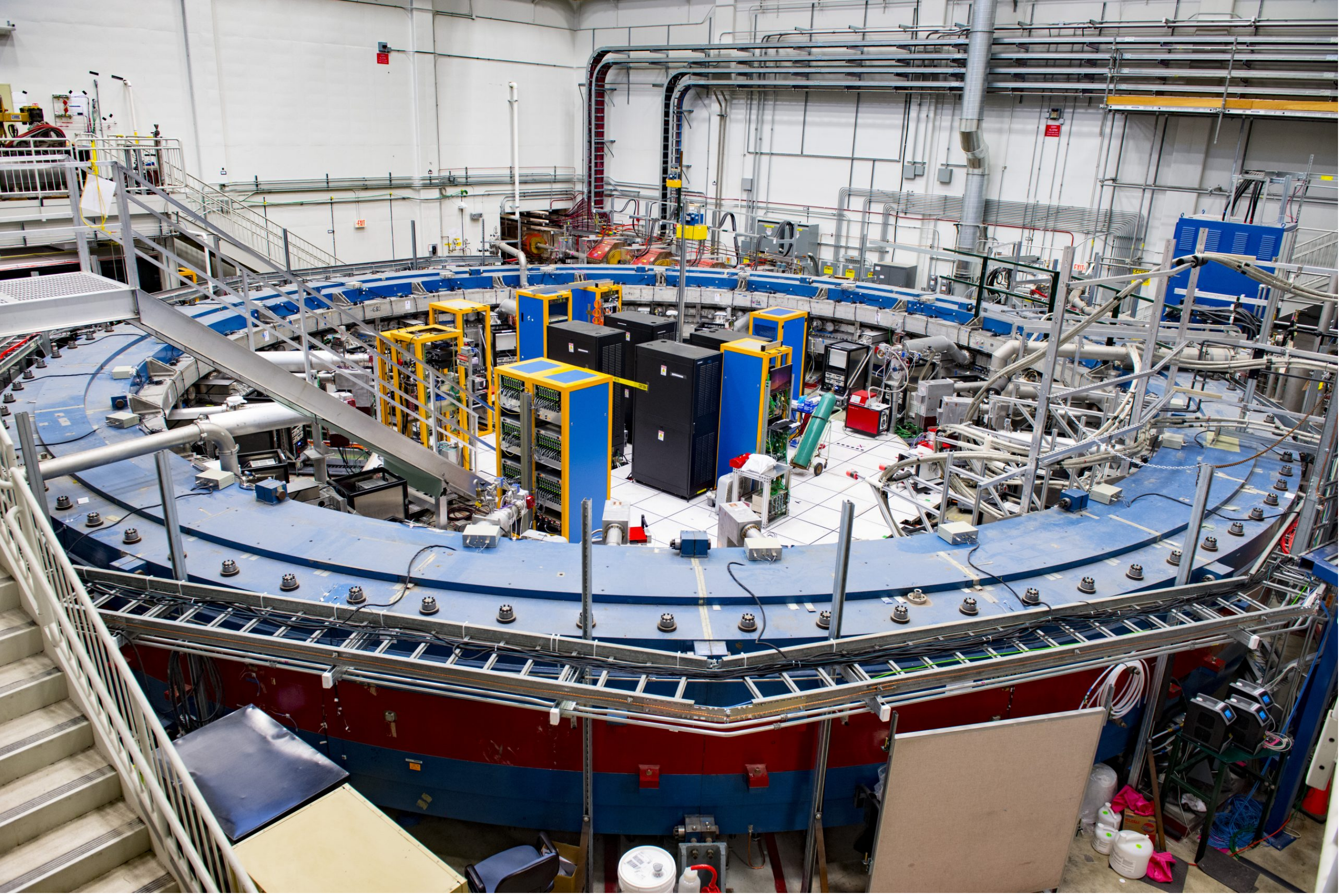


The Muon g-2 Experiment at Fermilab

Matteo Sorbara *on behalf of the Muon g-2 collaboration*
PHOTON 2019 conference @ LNF
7^{th} of June 2019

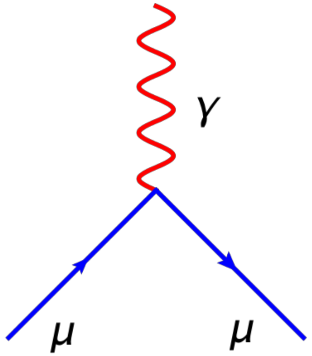
Overview

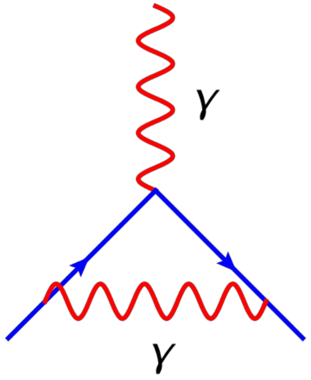
- The g-2 value: Standard Model vs Experiments
- The E989 Experiment Setup
  - Ring
  - Calorimeters
  - Trackers
- Precession Frequency Analysis
- Conclusions

The g-2 value: Standard Model

- Dirac's equation naturally predicts $g = 2$
- Standard Model corrections contribute $\sim 0.1\%$ to the value

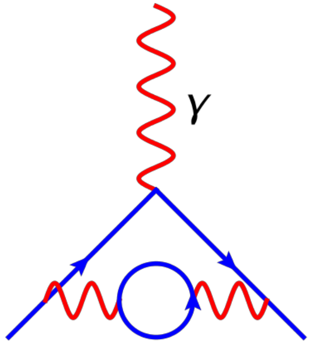
$$a_\mu = \frac{g-2}{2} = a_\mu^{QED} + a_\mu^{Weak} + a_\mu^{HVP} + a_\mu^{HLbL}$$





Schwinger: $\sim \frac{\alpha}{2\pi}$

+



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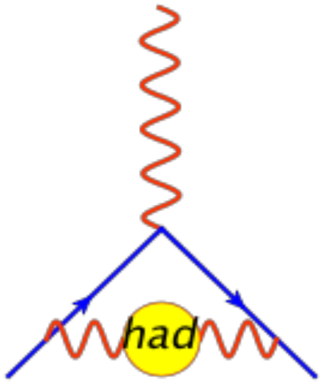
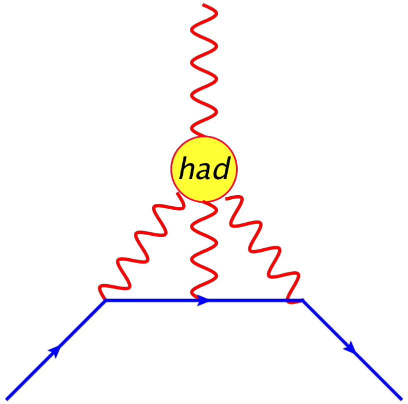


$$a_\mu^{HVP} \propto \int_{4M_\pi^2}^{+\infty} \frac{K(s)}{s} R(s) ds$$

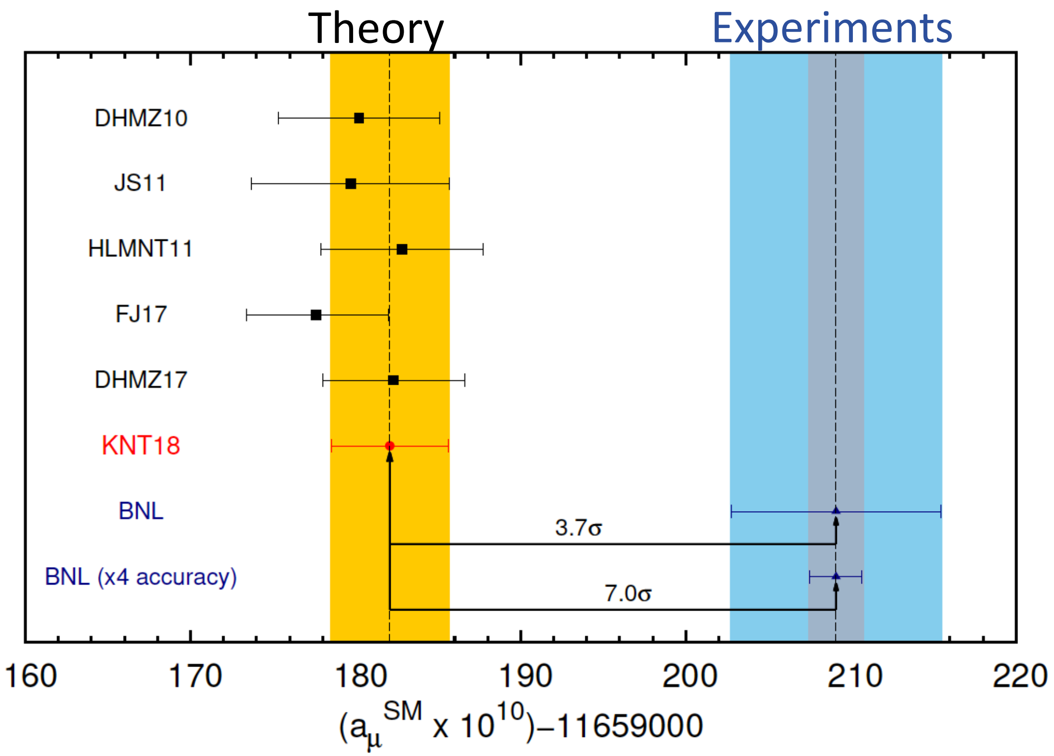


The g-2 value: Experimental Value

BNL value between 2001 and 2006:

$$a_\mu^{BNL} = 11\,659\,208.0(5.4)(3.3)\times 10^{-10} \qquad [0.54\;ppm] \qquad \text{(Phys.Rev.D73:072003,2006)}$$

The measured value shows a 3.7σ discrepancy with the SM prediction. This can be a hint of new physics in the $g-2$ value. It worths the effort (both from theoretical and experimental side) to reduce the uncertainties in order to clarify the origin of this difference.



Keshavarzi et al., arXiv:1802.02995

How to measure a_μ

The measure is based on the anomalous spin precession frequency of a muon in a uniform magnetic field:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c$$

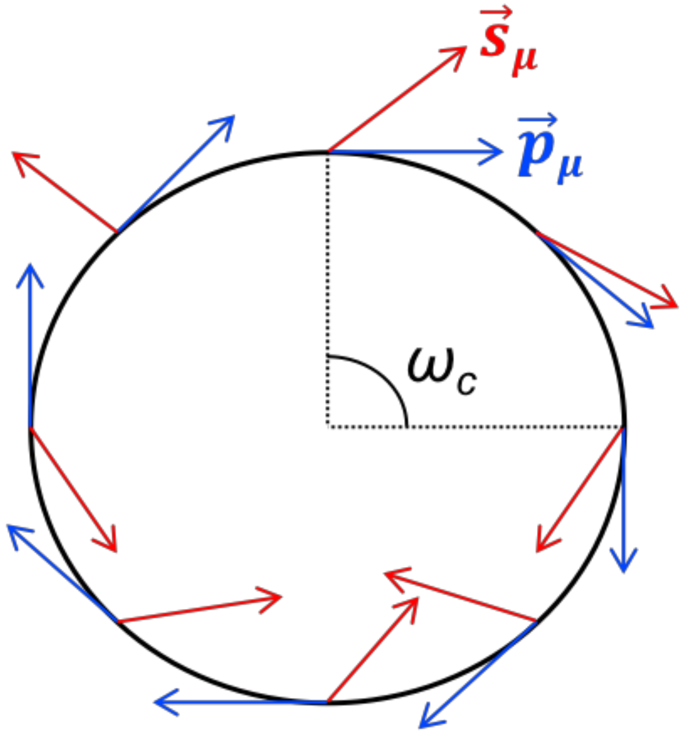
For relativistic particles it becomes:

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

Where the E-field term is caused by focussing electrostatic quadrupoles (more later). For $\gamma = 29.3$ (CERN III) the E-field term vanishes leaving us with:

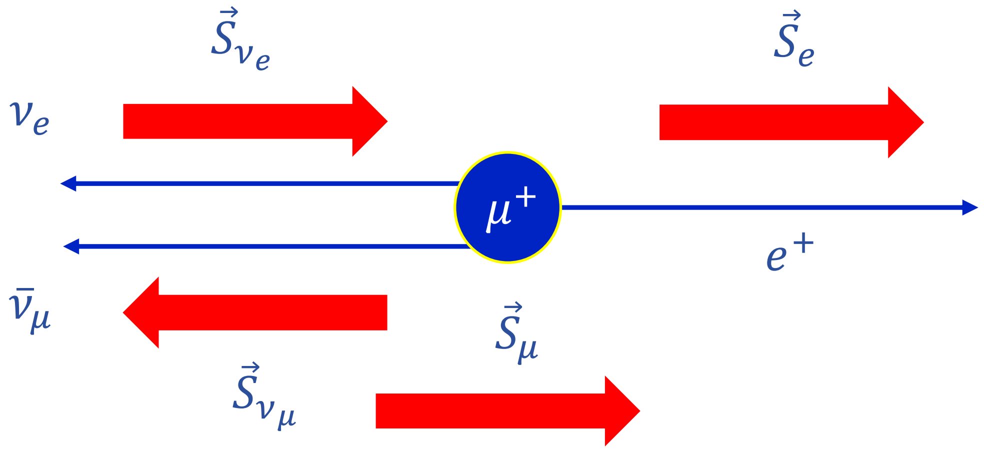
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

We need to measure precisely ω_a and the B-field.



How to measure a_μ

To measure the muon's spin we use the parity violating muon's decay. High energy positrons are emitted opposite to neutrinos and behave like a massless particle (so they are righthanded). Because of the angular momentum conservation, the muon and positron's spin are aligned.



Counting the number of decay positrons in a fixed direction gives a decay exponential modulated by the spin precession frequency.

Muon $g-2$ ($E989$) at Fermilab

The Muon g-2 (E989) at Fermilab aims to reduce the uncertainty on the anomalous magnetic moment by a factor 4 ($0.54\ \mathrm{ppm} \rightarrow 0.14\ \mathrm{ppm}$):

- Fermilab’s accelerator to produce muon beam
  - higher rate, more clean beam, better muon storage
- 21 times BNL statistics to reduce statistical uncertainty
- More uniform magnetic field
  - magnet shimming and wedging, field intensity measured with NMR probes
- Improved detectors
  - fast and segmented Čerenkov scintillators for EM calorimeter
- Better Beam tracking
  - in-vacuum tracker detector to reconstruct the beam profile

The E989 Goal

Category	Improvements	Goal [ppb]	BNL [ppb]
Gain changes	laser gain calibration	20	120
Pileup	calorimeter segmentation, low noise electronics	40	80
Lost muons	beam collimation, precise simulation	20	90
Coherent betatron oscillation	Better kicker, higher n value	< 30	70
E-field and pitch	tracker, precise simulation	30	50
Total	Quadrature sum	70	180

But… Same magnet!

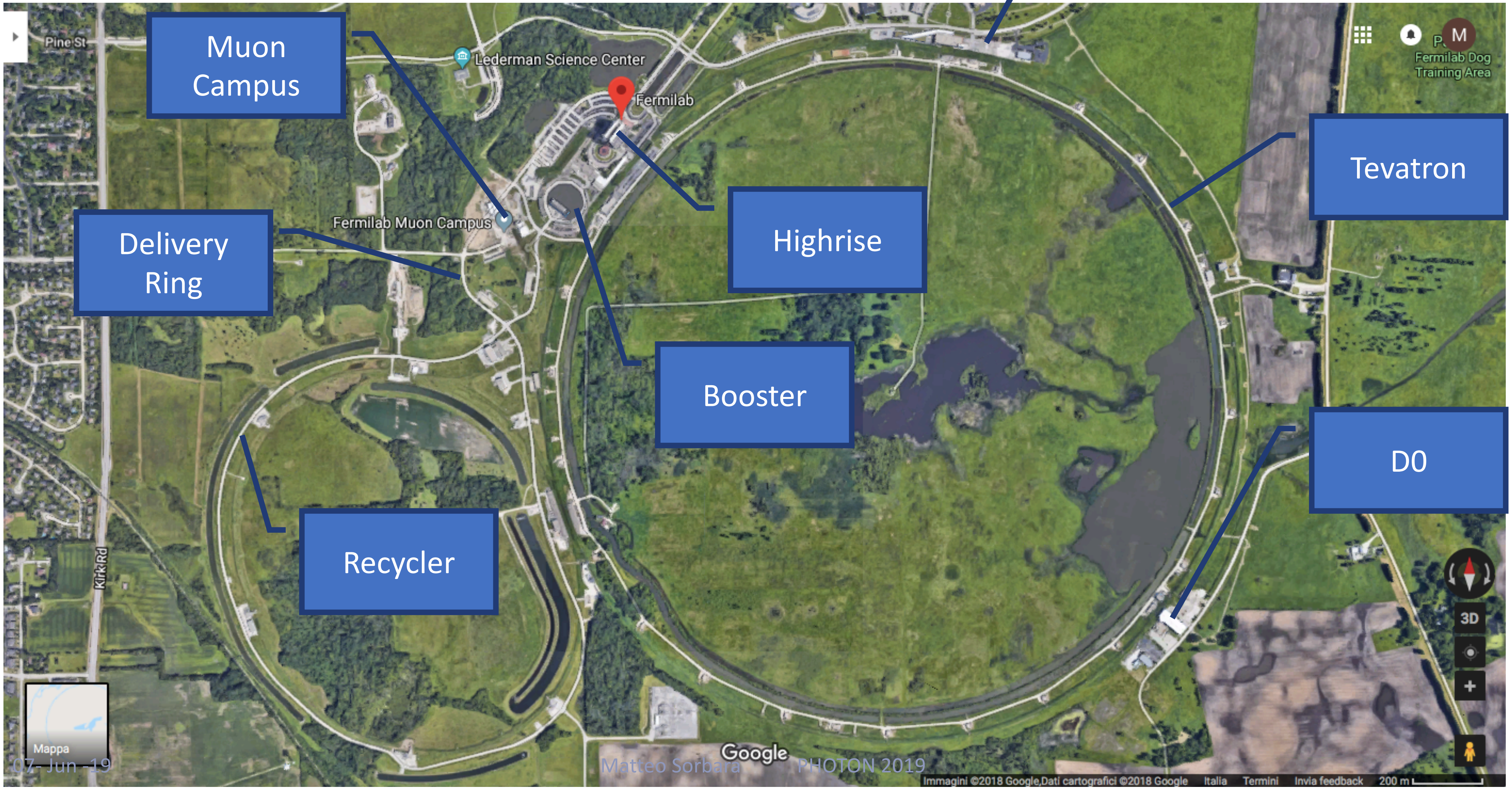
Near St. Louis

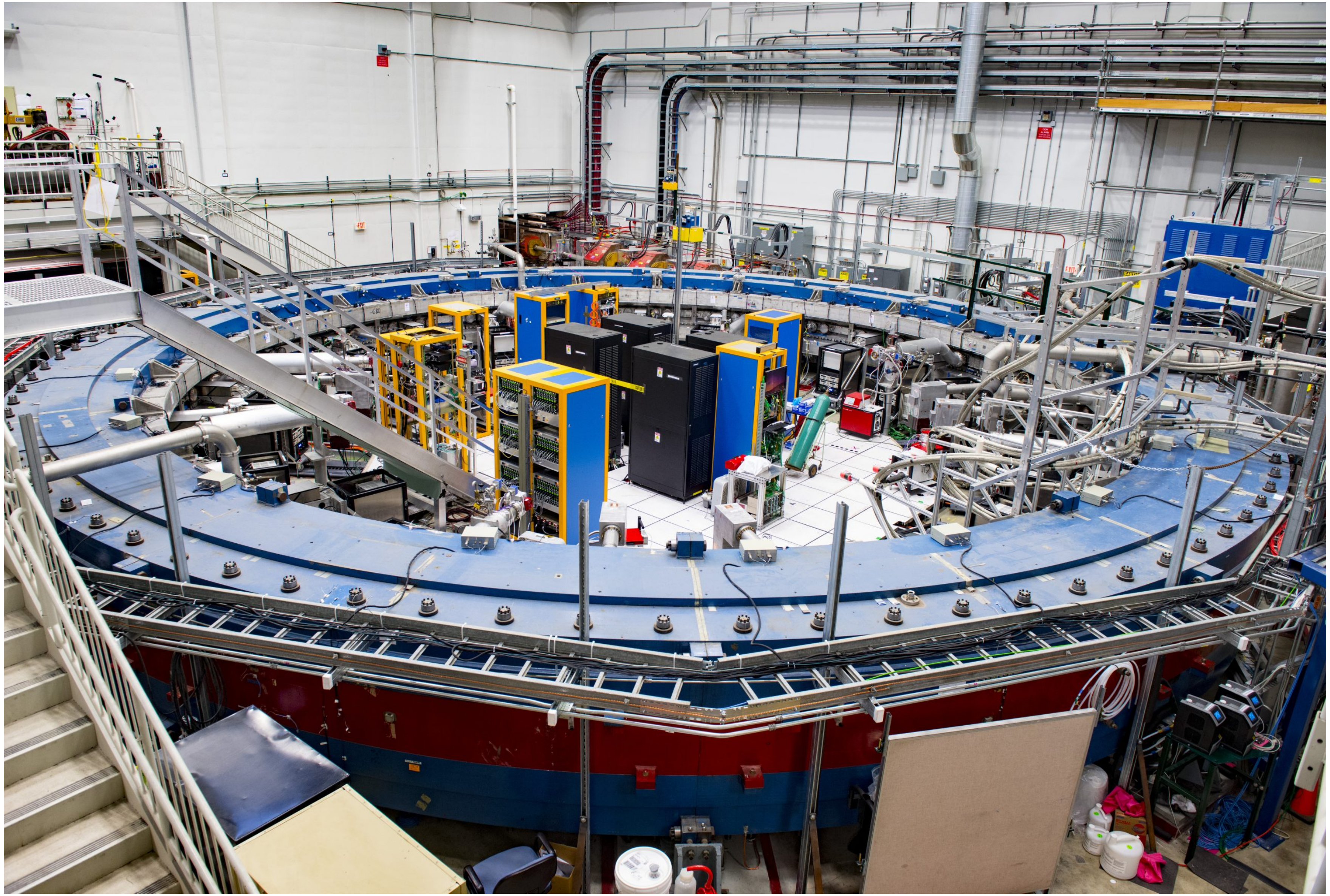
Right behind Fermilab

Fermilab Complex

Batavia ←

Warrenville →

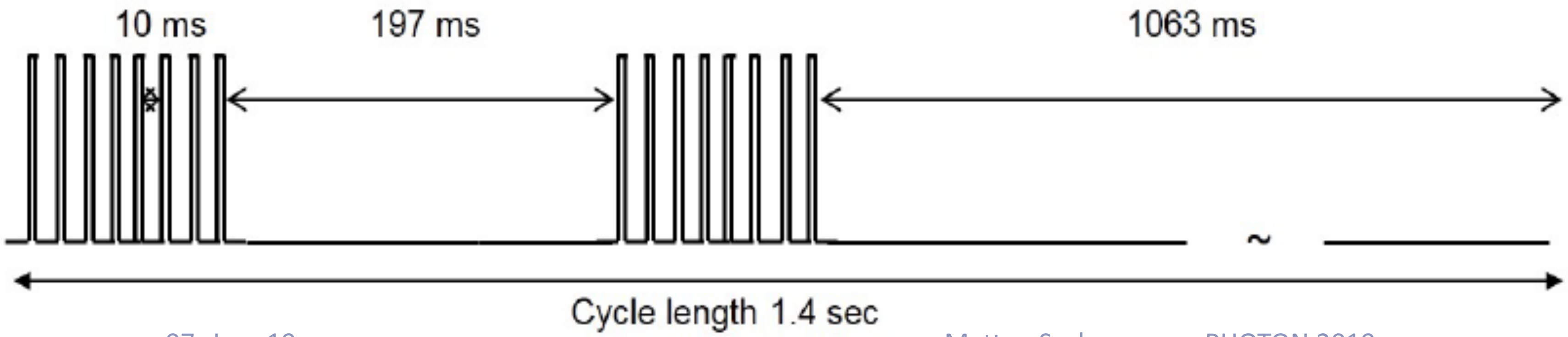


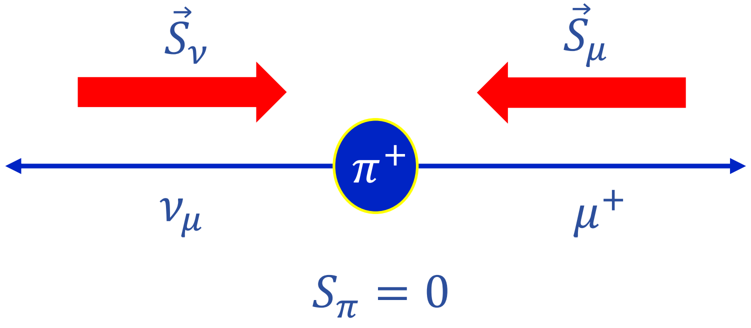


One Ring to rule them all, One Ring to find them, One Ring to bring them all, and in the Darkness blind them. **J. R. R. Tolkjen - Lord Of The Rings**

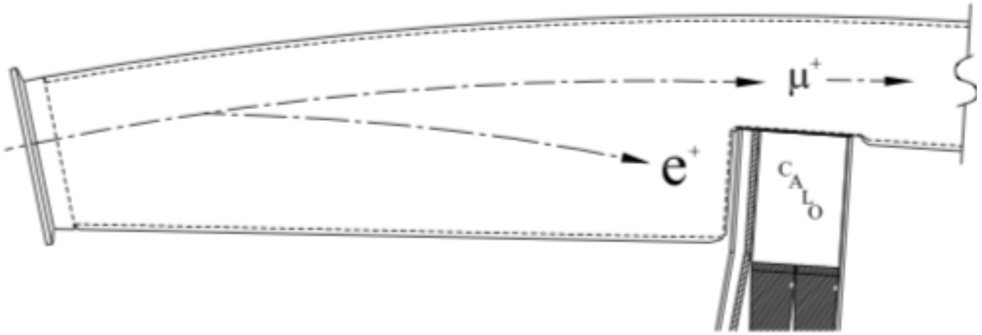
Producing μ^+

- 8 GeV protons from the recycler ring hit a Nickel/Chromium target
- 3.1 GeV π^+ are extracted and sent into the delivery ring
- Delivery ring collects π^+, μ^+ and leftover protons
- π^+ decay, protons are separated and dumped
- A pure polarized (>90%) 3.1 GeV μ^+ beam is sent into the storage ring trough an inflector magnet

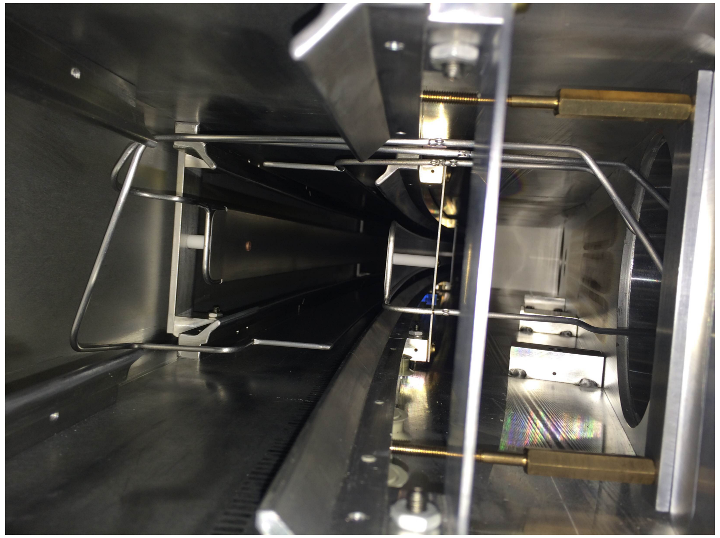


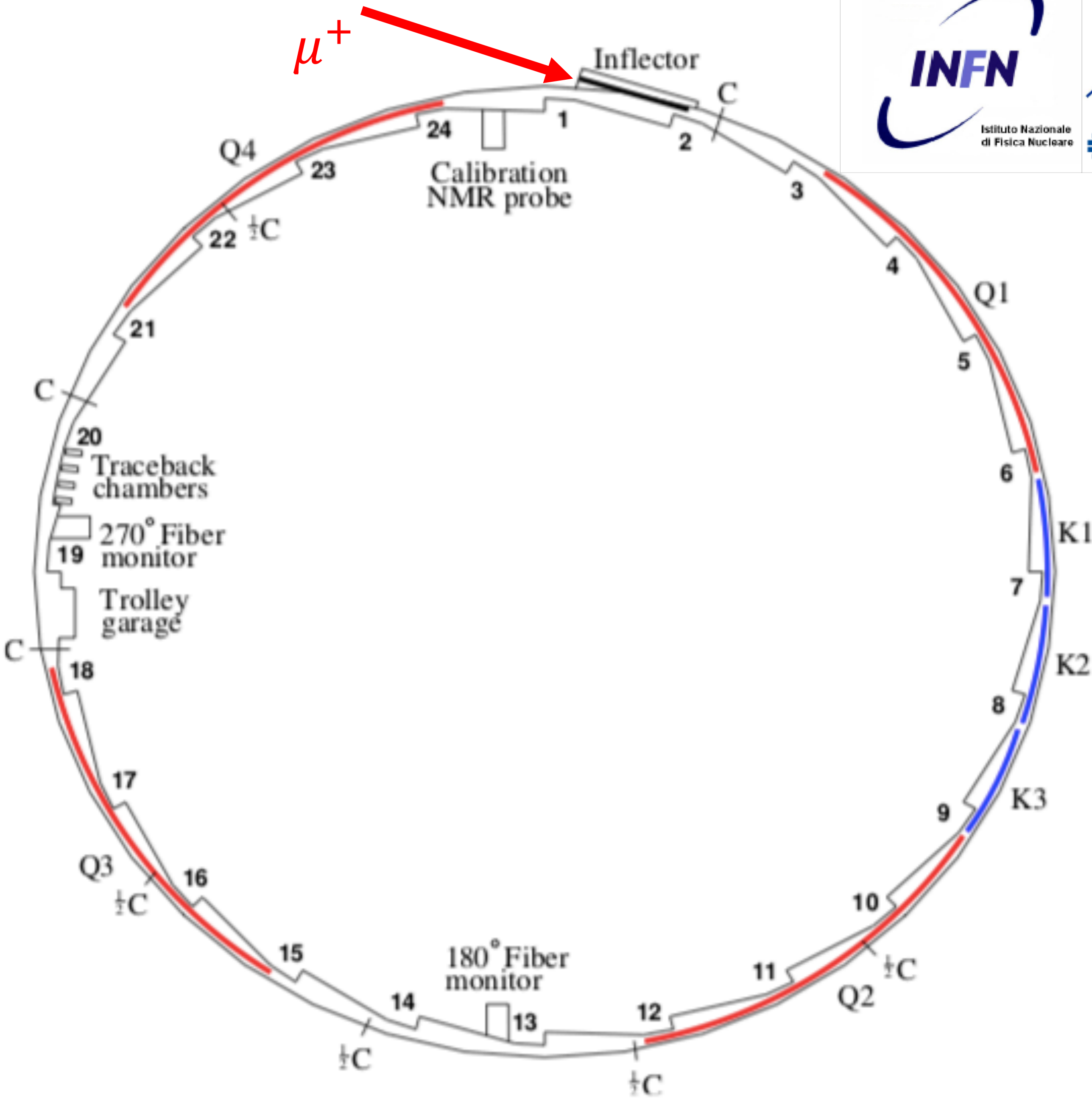


The Ring



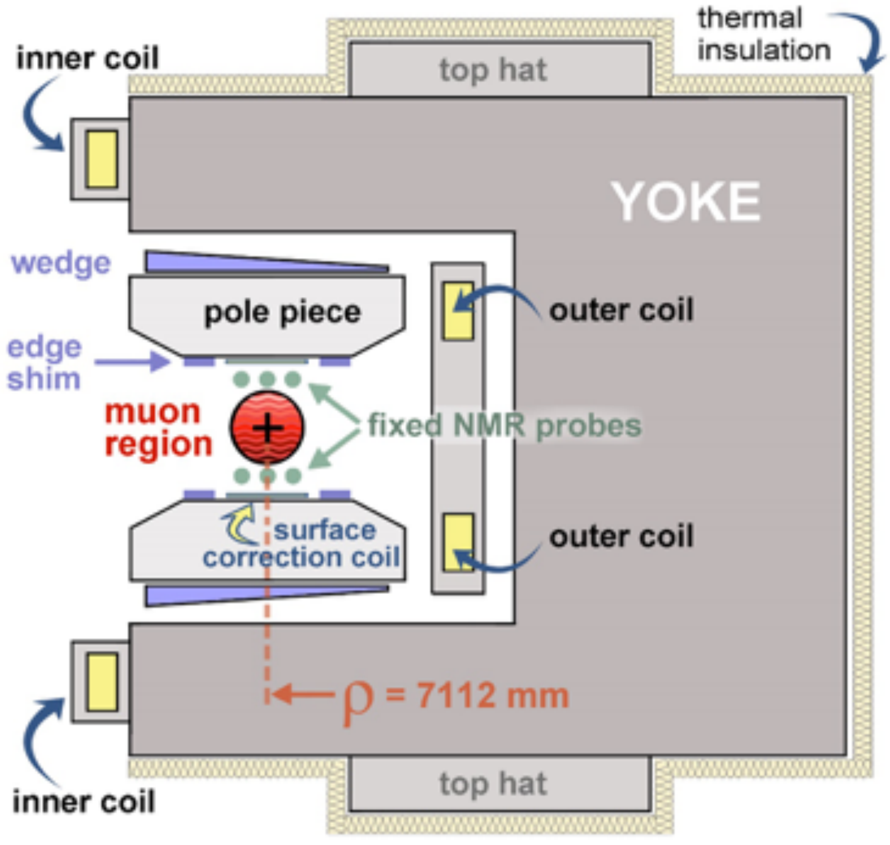
μ+
e+
CALO



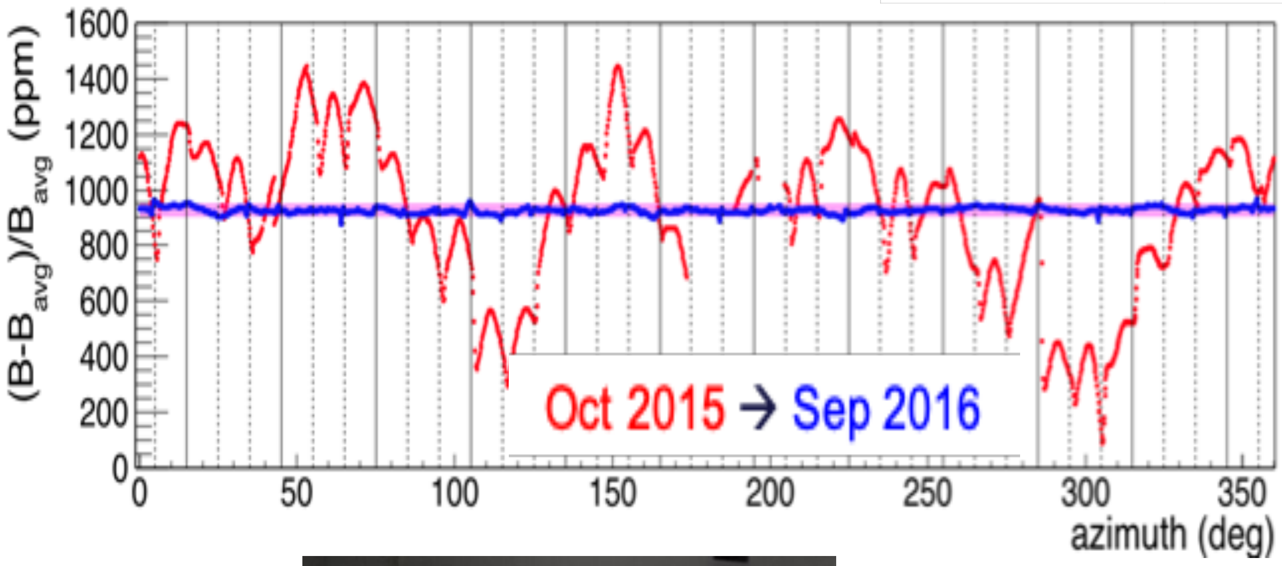


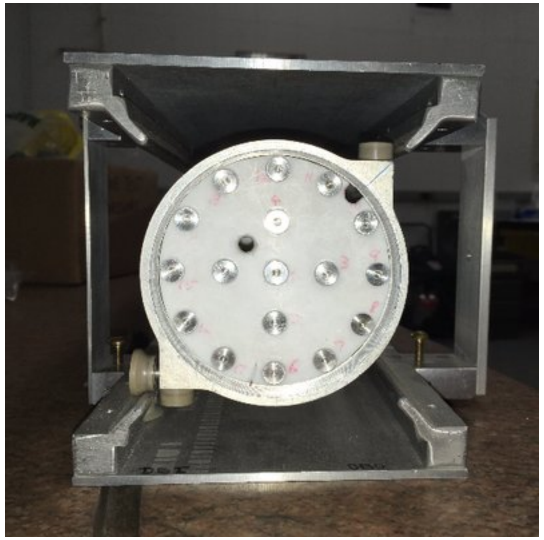
μ^+
Inflector
C
Calibration NMR probe
Q4
Q1
½C
K1
K2
K3
C
Traceback chambers
270° Fiber monitor
Trolley garage
C
Q3
½C
180° Fiber monitor
½C
½C
Q2
½C
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Field



g-2 Magnet in Cross Section

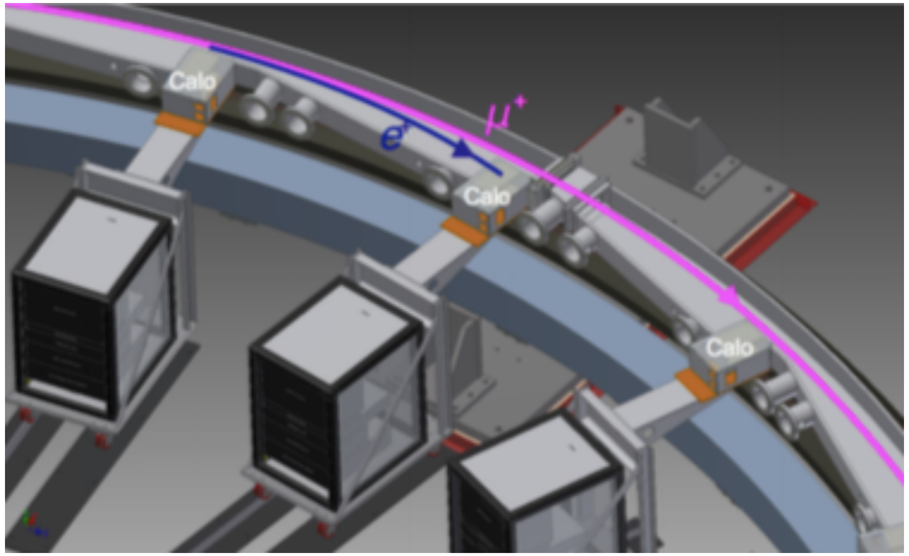


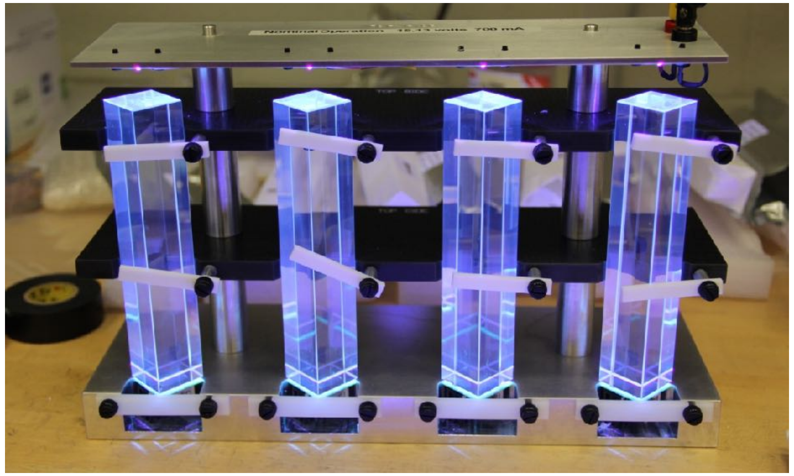


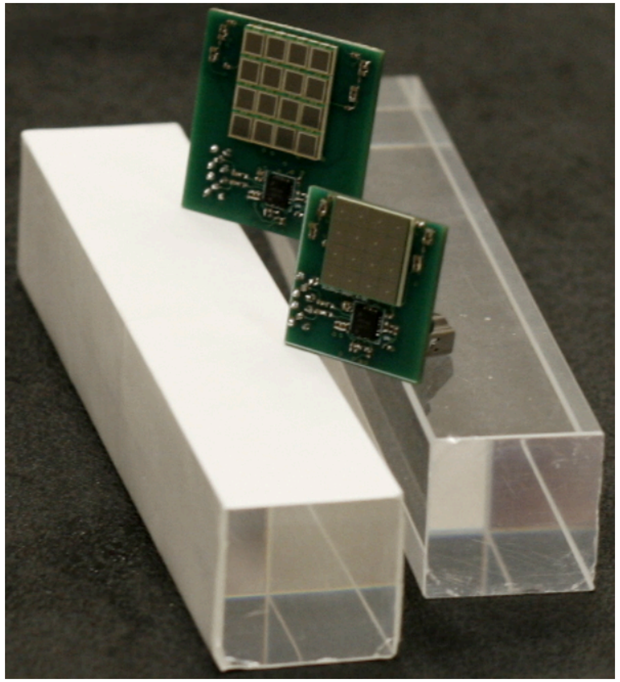
@trolley_tracker

Calorimeters

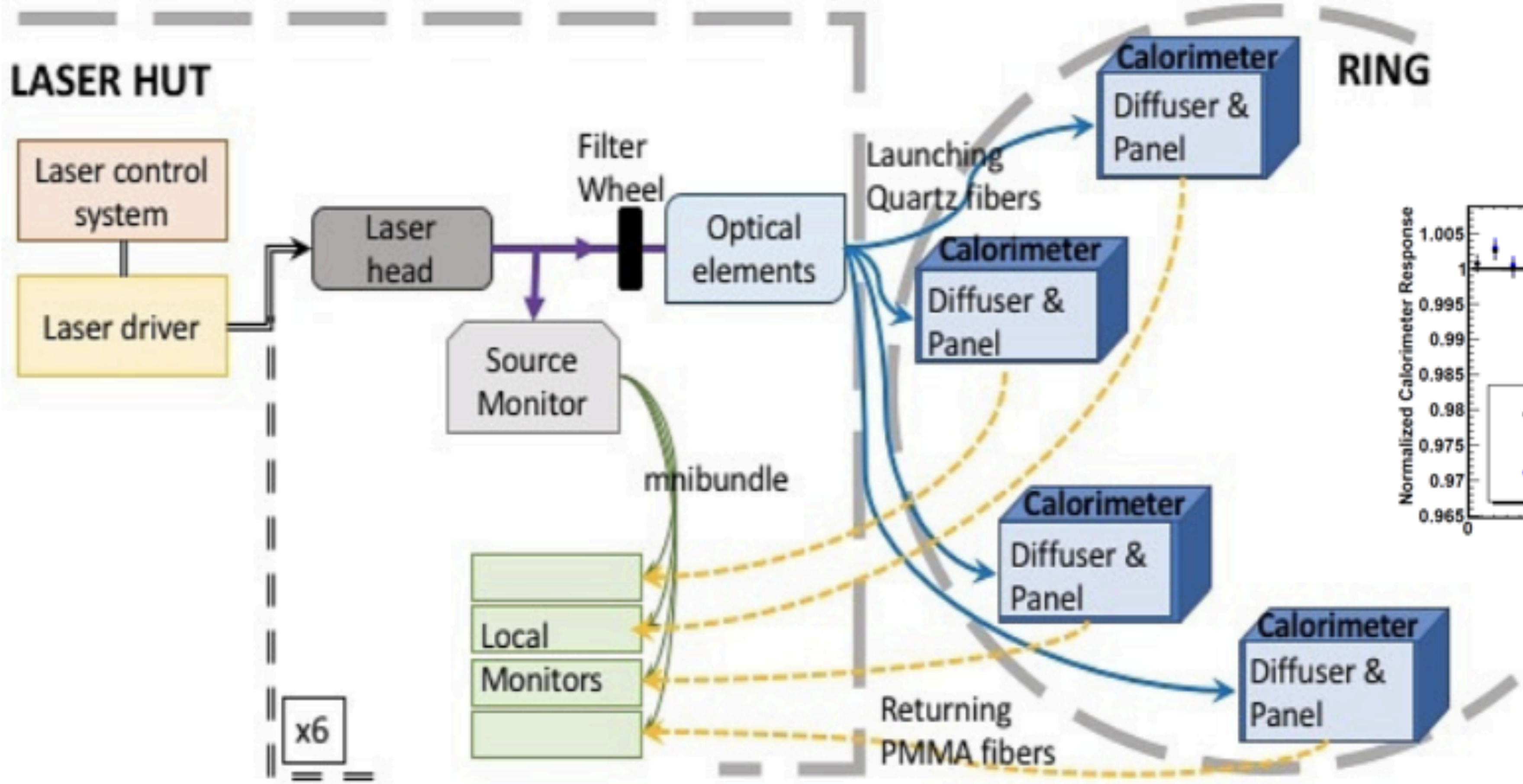
- 24 calorimeters along the inner radius of the ring
- Each calorimeter is a 6×9 array of PbF_2 crystals
- Each crystal is $2.5 \times 2.5\ cm^2$ and $14\ cm$ deep $(= 15\ X_0)$
- Čerenkov crystals >> Fast response >> Less Pile-Up
- Crystals are read by Large Area SiPM

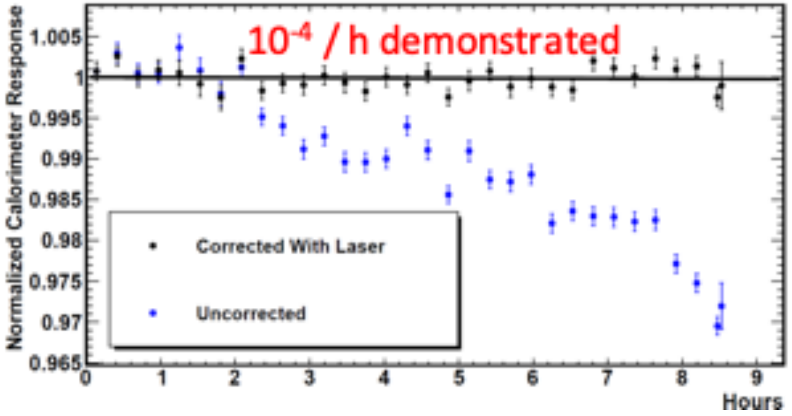


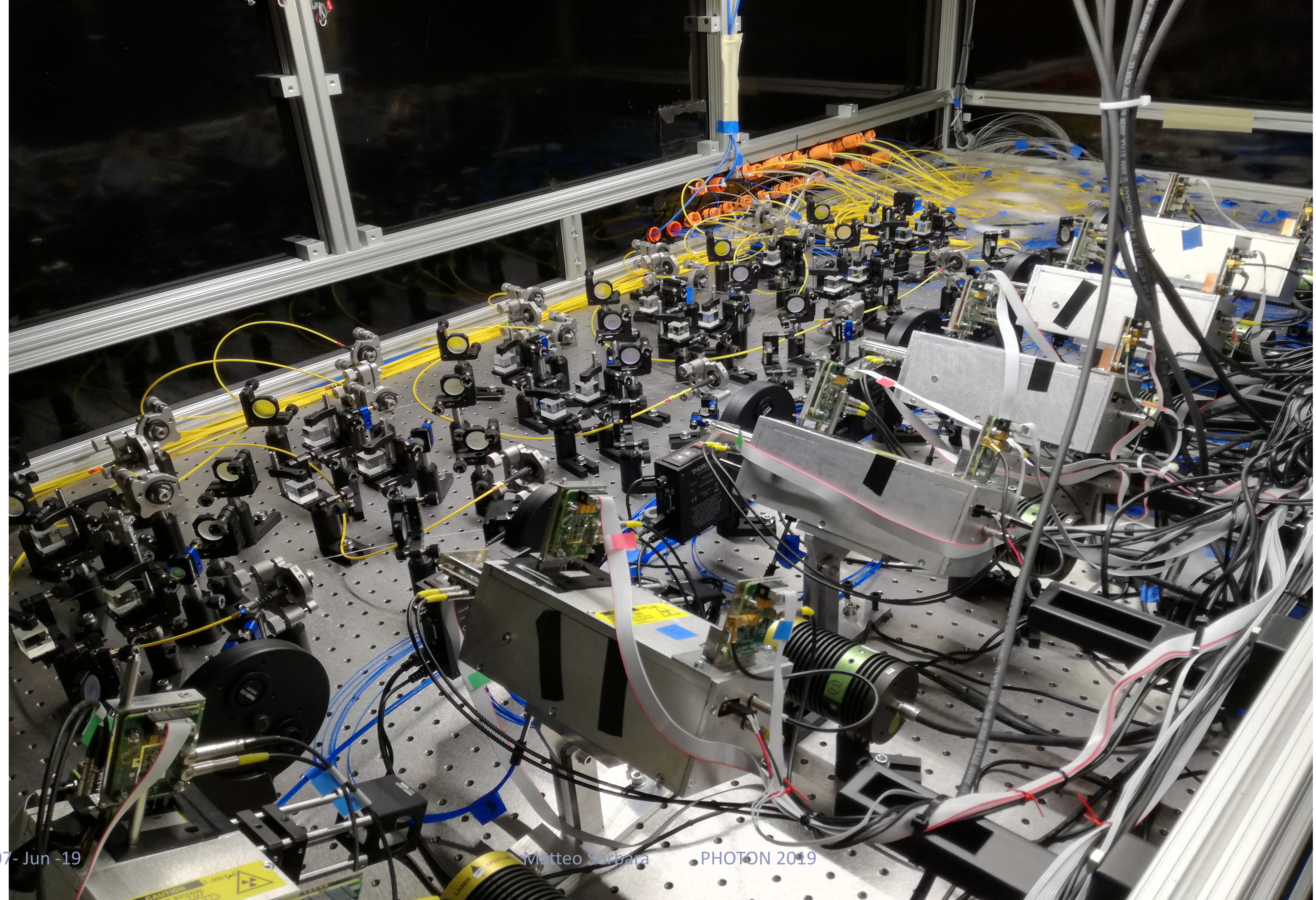




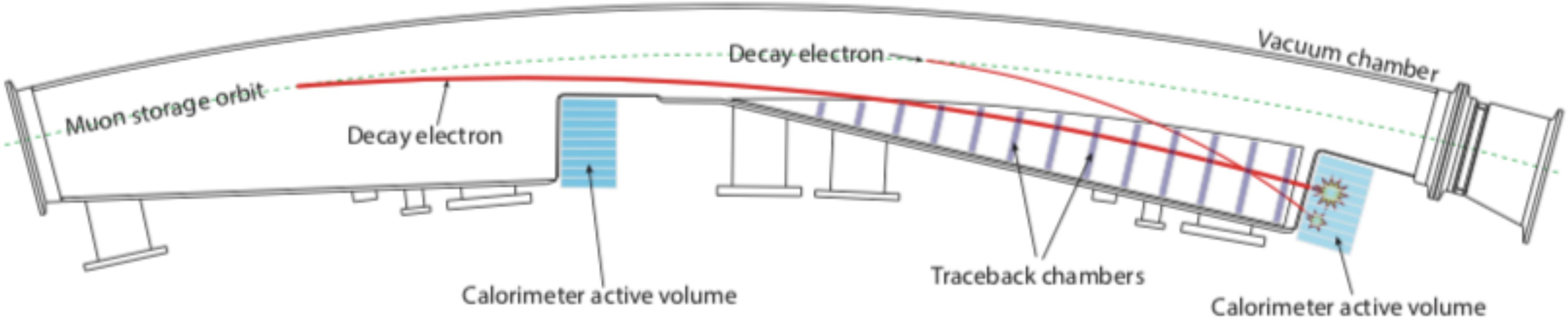
Gain Calibration: Laser system

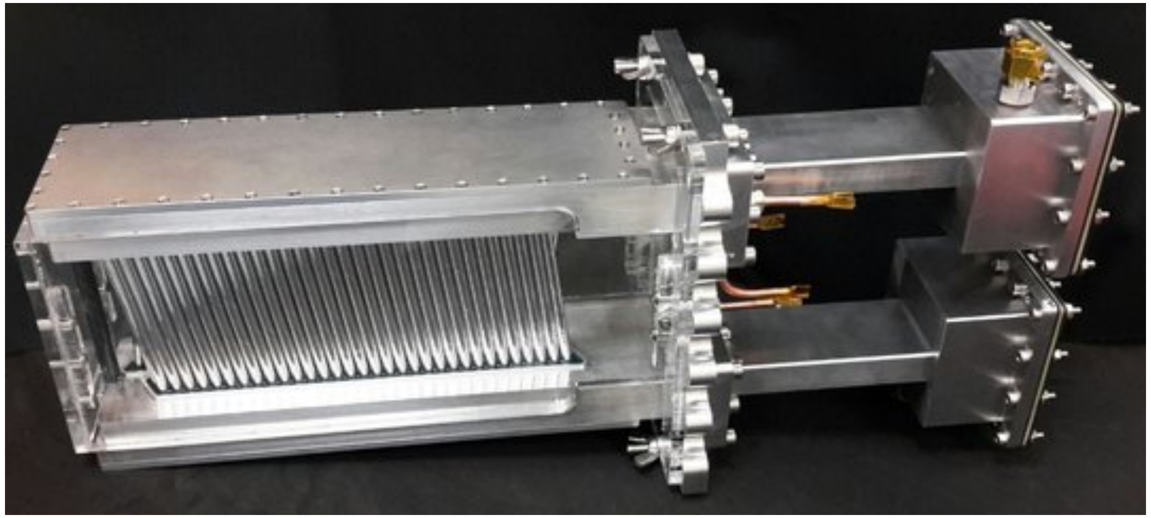






Tracker Detector



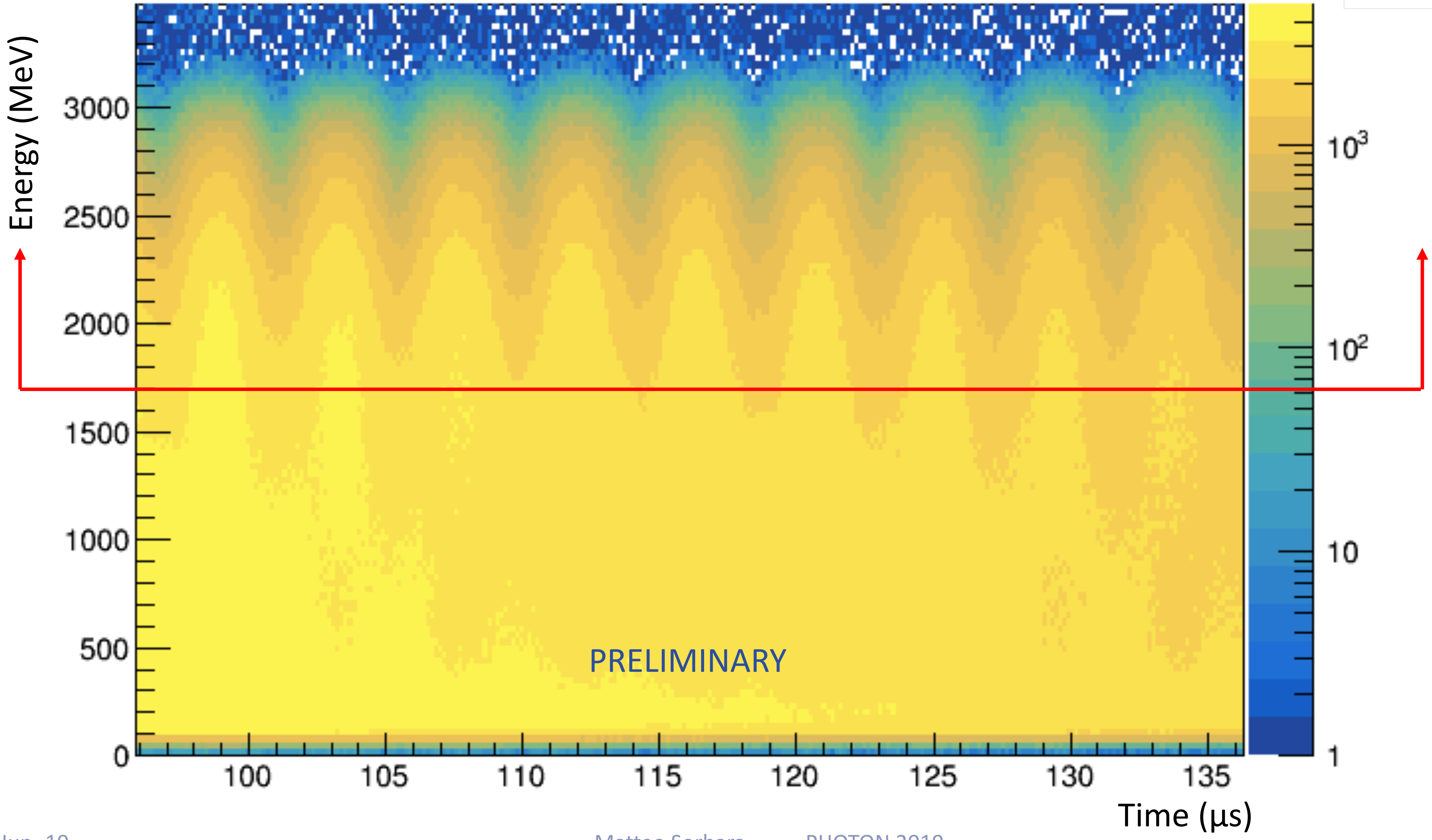


Straw tracker to reconstruct the track of particles (positrons and lost muons).

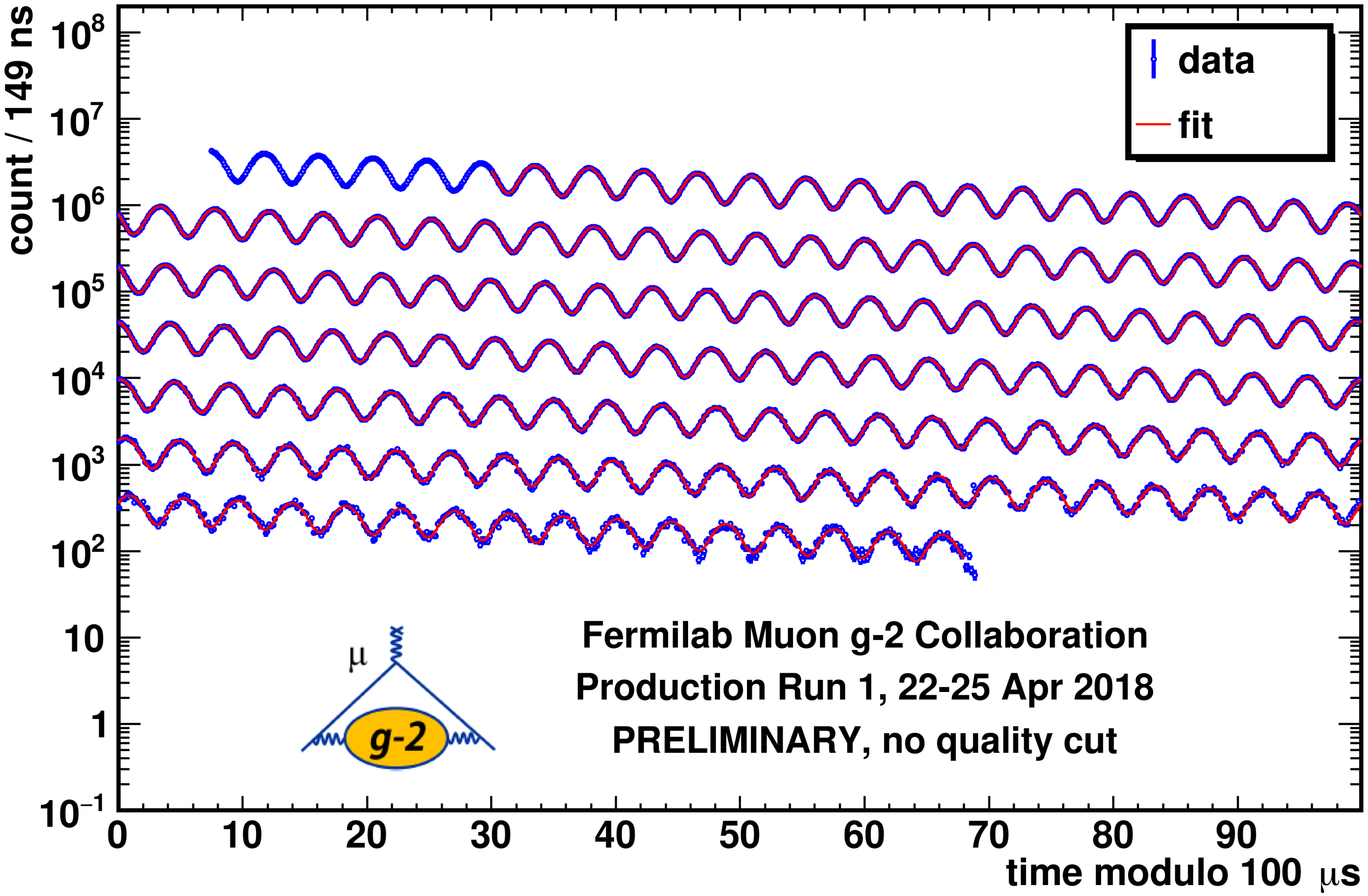
Used to reconstruct the beam position and profile from the decay positron's track.

ω_a Analysis

What do we see?



Wiggle Plot



*BLINDED

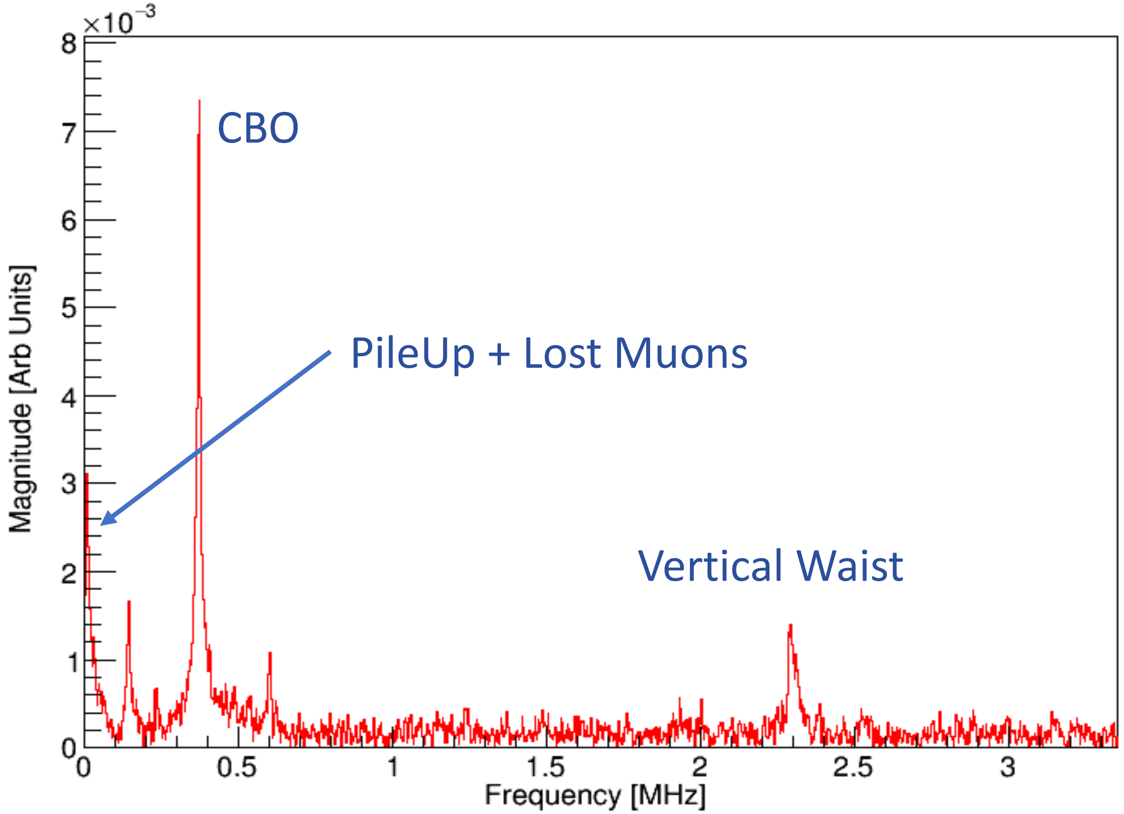
The ω_a fit

The ω_a value is extracted form the wiggle plot fit using:

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

But…

The residuals FFT shows peaks related to beam dynamics and pile up events, we need to account for them.



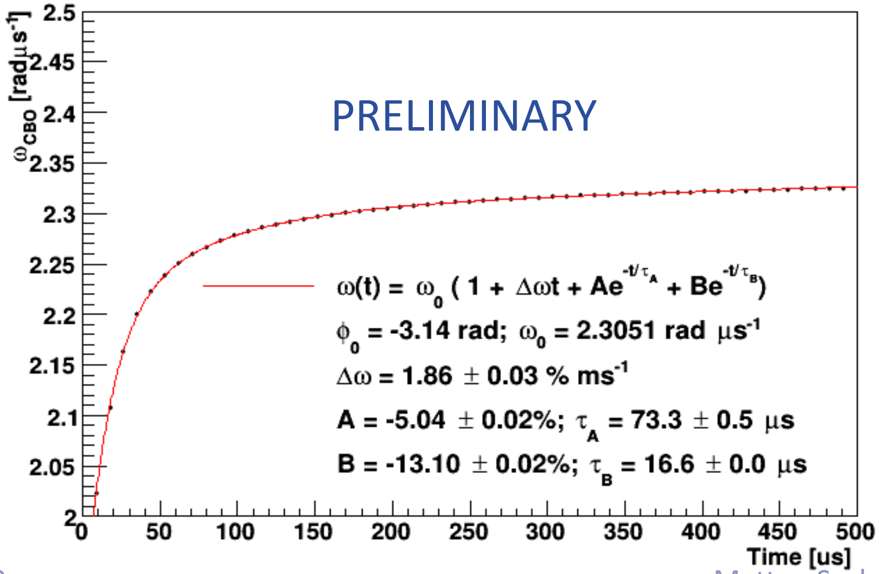
The ω_a fit: corrections

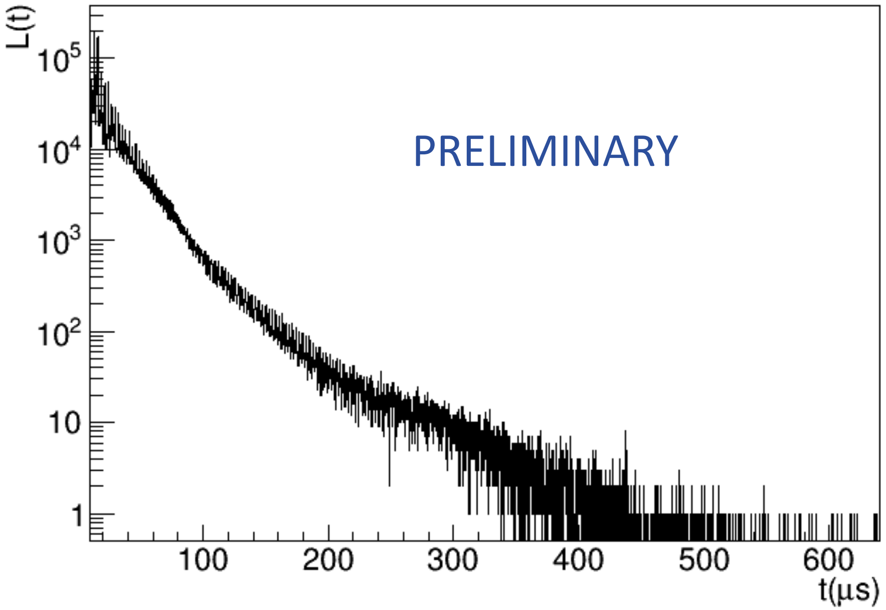
$$N(t) = N_0 e^{-t/\tau}[1 - A\cos(\omega_a t + \phi)] \cdot C(t) \cdot \Lambda(t) \cdot V(t)$$

$C(t)$: CBO correction

$V(t)$: vertical oscillations terms

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





Measuring a_μ

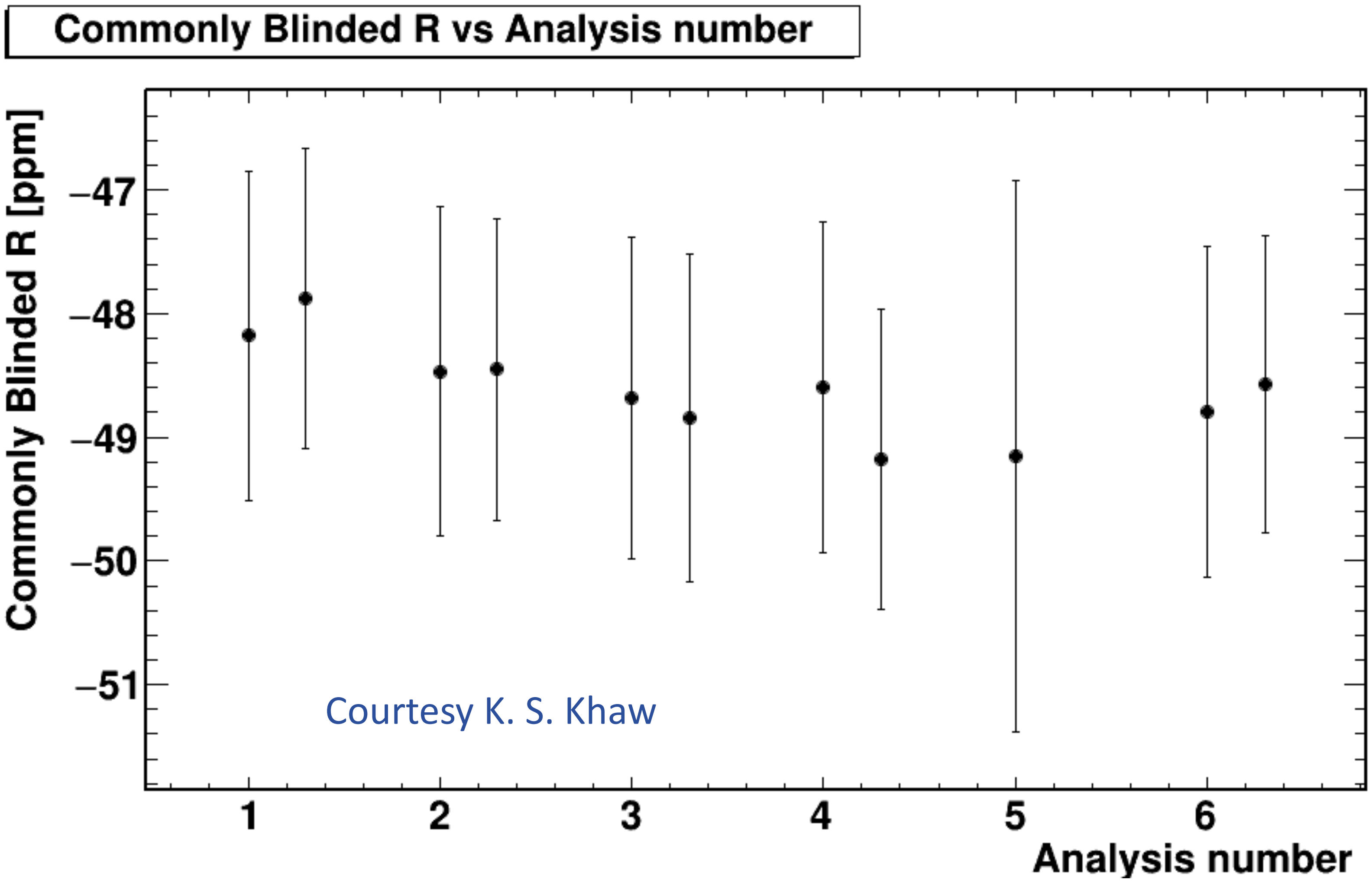
a_μ is finally the result from three different measures:

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

- ω_a from the precession frequency analysis
- ω_p from the NMR frequency analysis
- $\tilde{\omega}_p$ is the value from the magnetic field convoluted with the muons distribution inside the ring

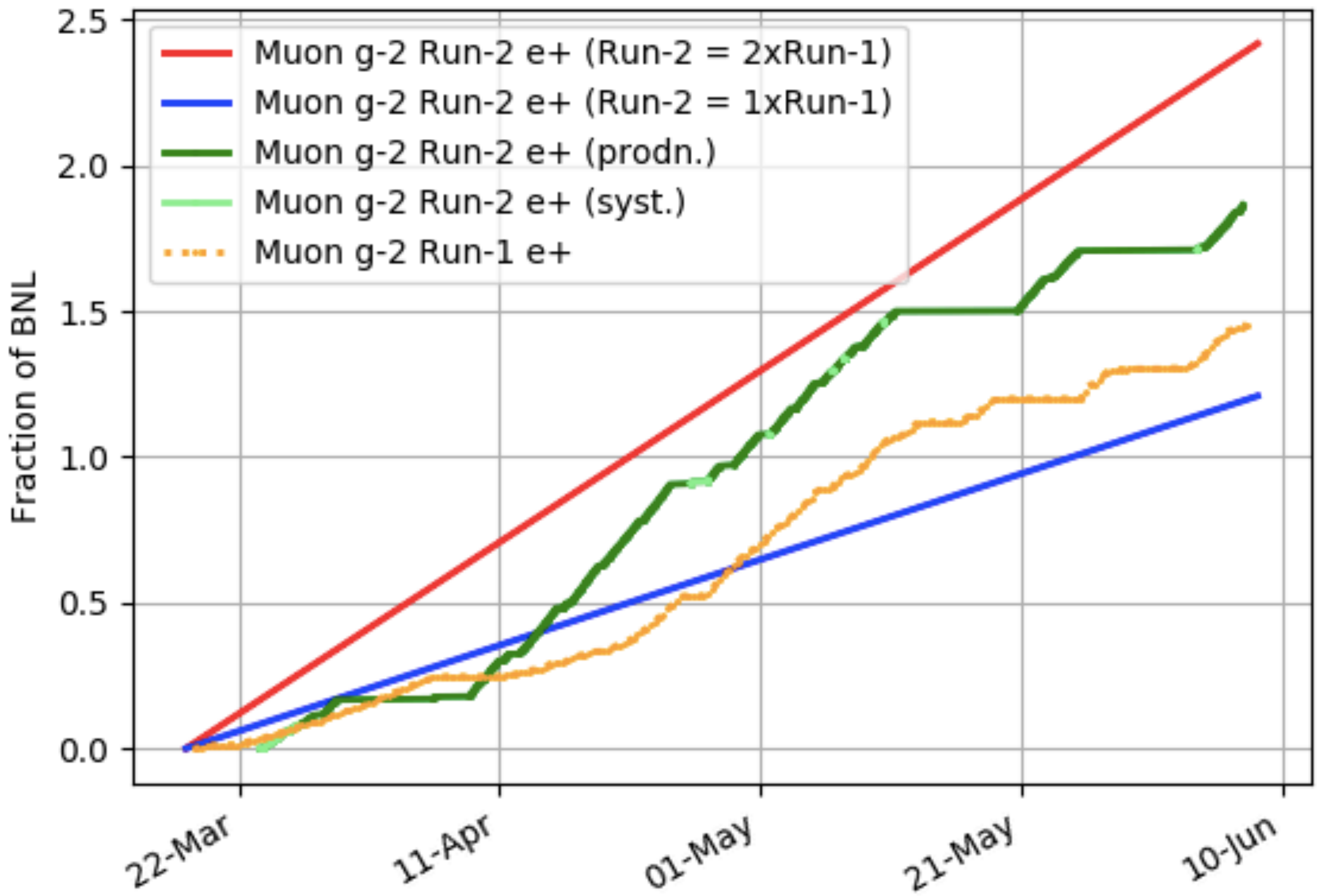
Unfortunately still no result is available, but…

60h Relative unblinding



1. Cornell
2. Washington
3. Boston
4. Shangai
5. Kentucky
6. Europa

Where are we now?

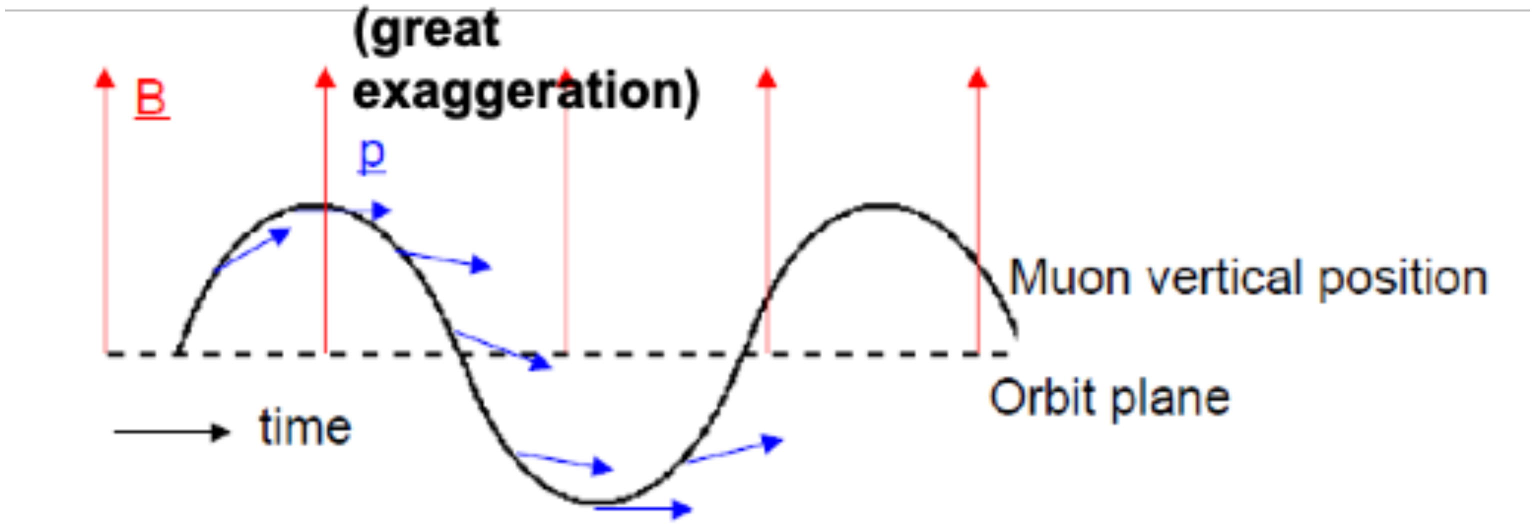


Updated this morning
1.84 BNL for Run 2

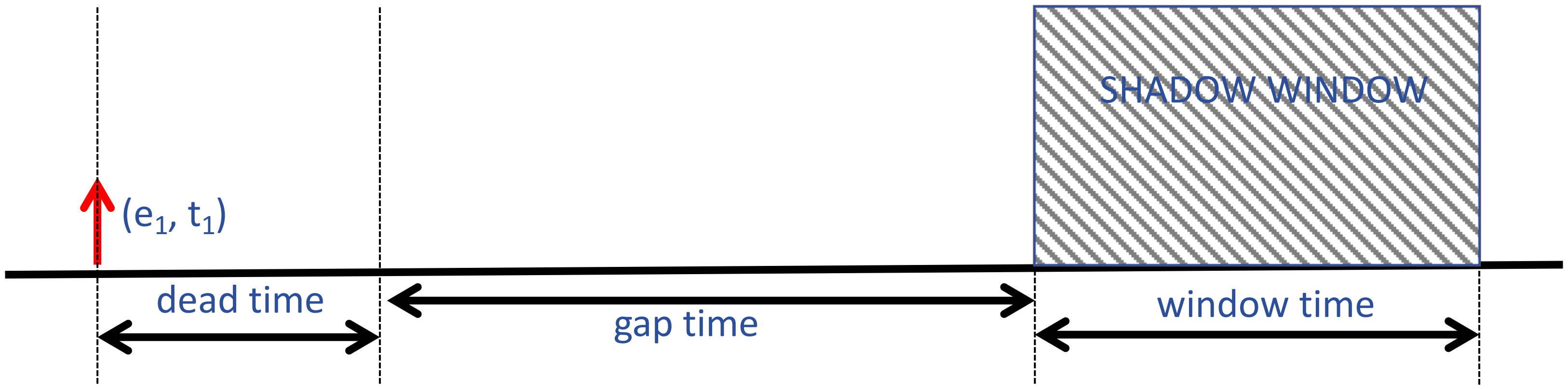
Run 2 will end up in July 2019;
Run 3 will start on October 1st 2019

SPARES

Pitch correction



Pile Up Subtraction



Asymmetry