Status of the muon g-2 at FNAL (E989)

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University «Federico II» and INFN- Naples
On behalf of the g-2 Coll.

MWPF 2017, October 22-27
Puerto Vallarte, Mexico

Muon g-2 experiment at Fermilab.

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab

Italy

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

China:

- Shanghai

Netherlands:

- Groningen

Germany:

- Dresden

Russia:

- Dubna
- Novosibirsk

United Kingdom

University College London

Liverpool

Oxford

Korea

KAIST

~33 institution,
~150 members

D.W. Hertzog, C. Polly,
co-spokesperson

Outline: Why, How and When

- Motivations for a number
- Status on g-2
- Introduction to the experimental technique
  - spin equations
  - magic g
- E989 goals and improvements
- What's done and what's going on
- First muons
- Schedule of E989
- Conclusions

Why

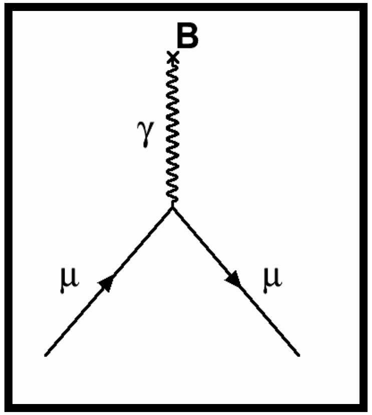
Muon magnetic moment

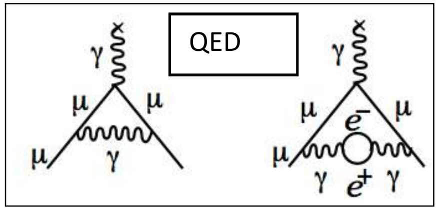
$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

Dirac theory: a charged, spin ½ elementary point particle has

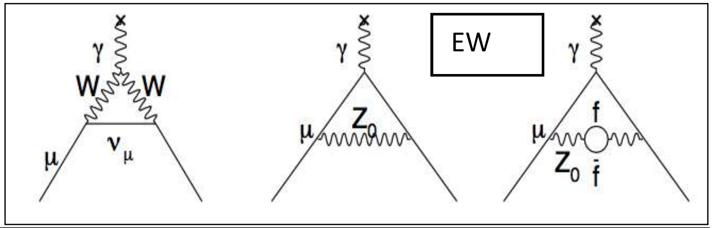
$g \equiv 2$

But expt: $g > 2 \rightarrow a_\mu = (g_\mu - 2)/2$

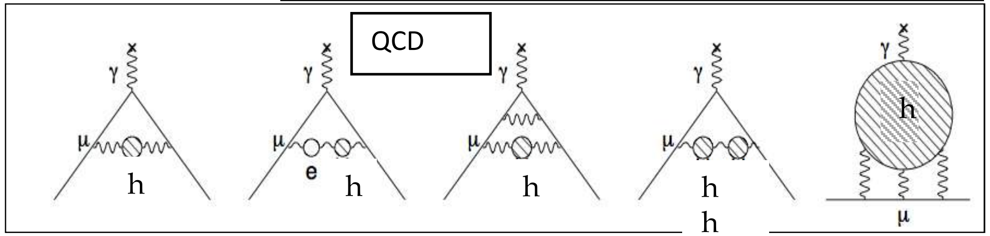




$\delta a_\mu^{QED} = 0.08 \times 10^{-11}$



$\delta a_\mu^{EW} = 1 \times 10^{-11}$



$\delta a_\mu^{QCD} = 50 \times 10^{-11}$

$$a_\mu^{SM} = (g_\mu^{SM} - 2)/2 = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$$

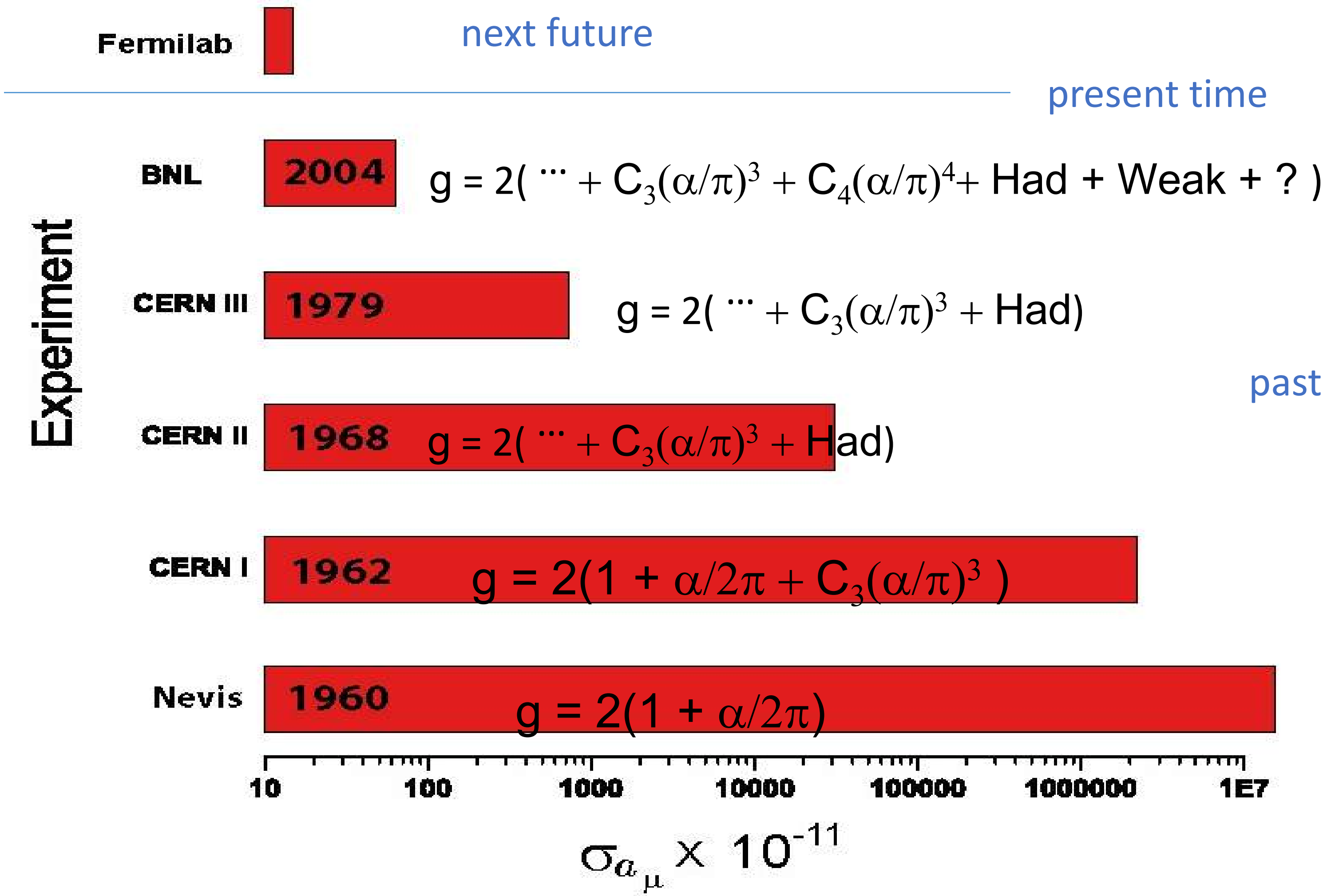
Results from E821 (BNL):

$$a_\mu^{Expt.} - a_\mu^{SM} = (260 \pm 78) \times 10^{-11} \quad (3.3\ \sigma)$$

$$a_\mu^{Expt.} = a_\mu^{SM} + a_\mu^{New\ Physics}$$

→ Hint for BSM Physics

.. as of things on experimental side



FCCP 2017

Daisuke Nomura

	2011		2017	*to be discussed
QED	11658471.81 (0.02)	⟶	11658471.90 (0.01)	[Phys. Rev. Lett. 109 (2012) 111808]
EW	15.40 (0.20)	⟶	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	⟶	9.80 (2.60)	[EPJ Web Conf. 118 (2016) 01016]*
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]*
	HLMNT11		KNT17	Davier et al (2017
LO HVP	694.91 (4.27)	⟶	692.23 (2.54)	this work* 693.1 (3.4
NLO HVP	-9.84 (0.07)	⟶	-9.83 (0.04)	this work*
NNLO HVP			1.24 (0.01)	[Phys. Lett. B 734 (2014) 144] *
Theory total	11659182.80 (4.94)	⟶	11659181.00 (3.62)	this work
Experiment			11659209.10 (6.33)	world avg
Exp - Theory	26.1 (8.0)	⟶	28.1 (7.3)	this work
Δa_μ	3.3σ	⟶	3.9σ	this work

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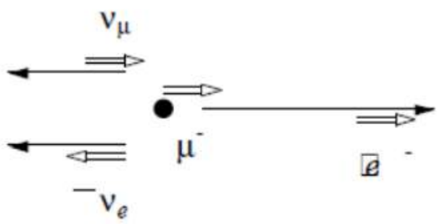
How

Mile stones for g-2 measurement

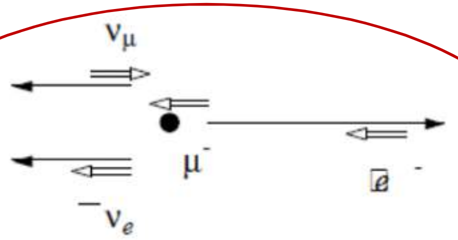
$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Pion Decay : $\pi^- \rightarrow \mu^-$ + anti ν_μ (99.98%).
In reference frame of π's CM , muon and neutrino in opposite directions.
As elicity(anti ν_μ)= +1 and π's spin is 0
→ $spin_\mu$ e p_μ are parallel ovvero elicity(μ^-)= +1 → **μ polarized**
For m_μ=0 allowed only elicità(μ^-)= -1, m_μ not zero allows elicity(μ^-)= +1.
From kinematic $\pi \rightarrow e$ + anti ν_e is favored, instead only ($\sim 2.5\ 10^{-5}$) (phase space spazio). If $m_\mu = m_e = 0$, π stable.

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$



a



b

Muon decay is three bodies decay
$\mu^- \rightarrow e^-$ + anti $\nu_e + \nu_\mu$.
In CM, p_e^{max} of electron is for per neutrinos parallel and both in opposite direction to p.
For neutrino with 0 mass we have elicity(ν_μ)= -1 and elicity(anti ν_e)= +1.
→ Total Spin of neutrinos (antiaparallel) is 0 for p_e^{max} .
→ Electron Spin coincide with μ spin
→ Therefore :
a) electron spin along p_e^{max} : forbiden as m_e=0 (elicità(e-)= -1), instead here +1! Actually strongly suppressed with respect to case b)
b) (elicity(e-)= -1) is favored. Only possibility for m_e=0

→ In Lab frame, electron with high p (energy) goes // to $spin_\mu$

Motion in a Magnetic Field

Particle: q = Qe moving in a magnetic field:

momentum turns with cyclotron frequency ω_C,

spin turns with ω_S

$$\omega_C = -\frac{QeB}{m\gamma}; \qquad \omega_S = -g\frac{QeB}{2m} - (1-\gamma)\frac{QeB}{\gamma m}$$

Spin turns relative to the momentum with ω_a

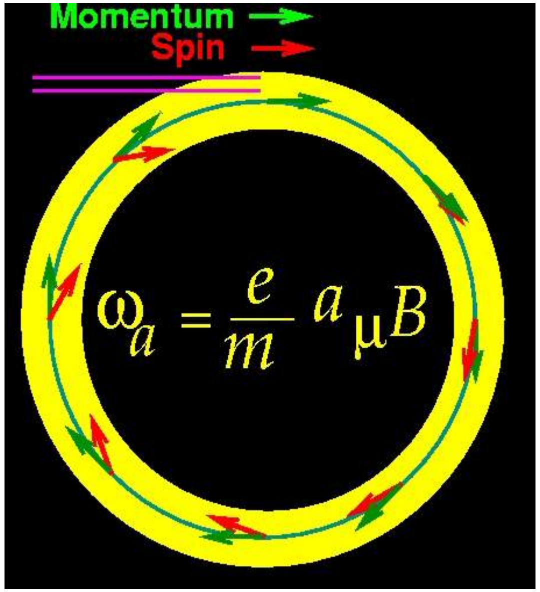
$$\omega_a = \omega_S - \omega_C = -\left(\frac{g-2}{2}\right)\frac{QeB}{m} = -a\frac{QeB}{m}$$

In a storage ring, with vert. focusing (E)

With an electric quadrupole field for vertical focusing and the magic γ

$$\vec{\omega}_a = -\frac{Qe}{m}\left[a\vec{B} - \cancelto{0}{\left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

$$\gamma_m = 29.3\,, \quad p_m = 3.09\ \mathrm{GeV}/c$$



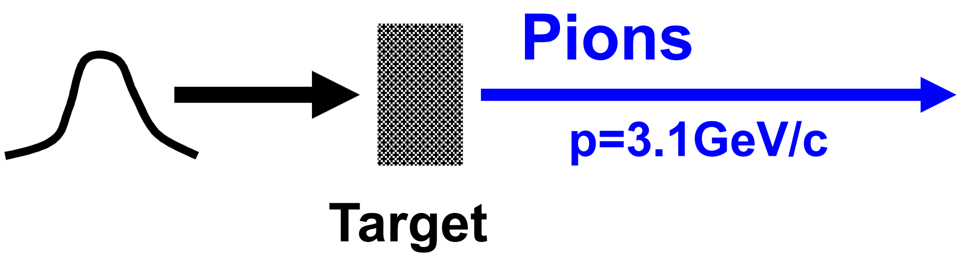
→Measure two quantities

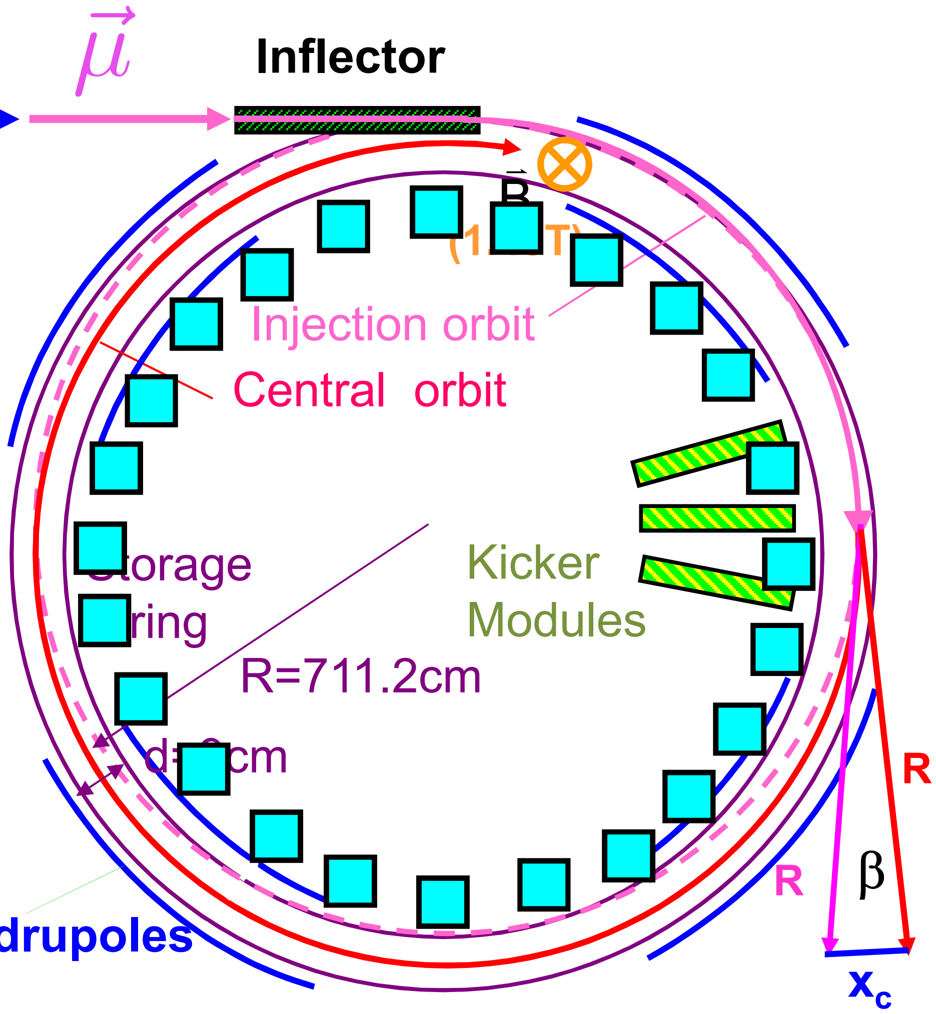
where **B** is expressed in terms of the Larmor frequency of a free proton ω_p

Experimental Technique

narrow time bunch of protons

$x_c \approx 77$ mm
$\beta \approx 10$ mrad
$B\cdot dl \approx 0.1$ Tm





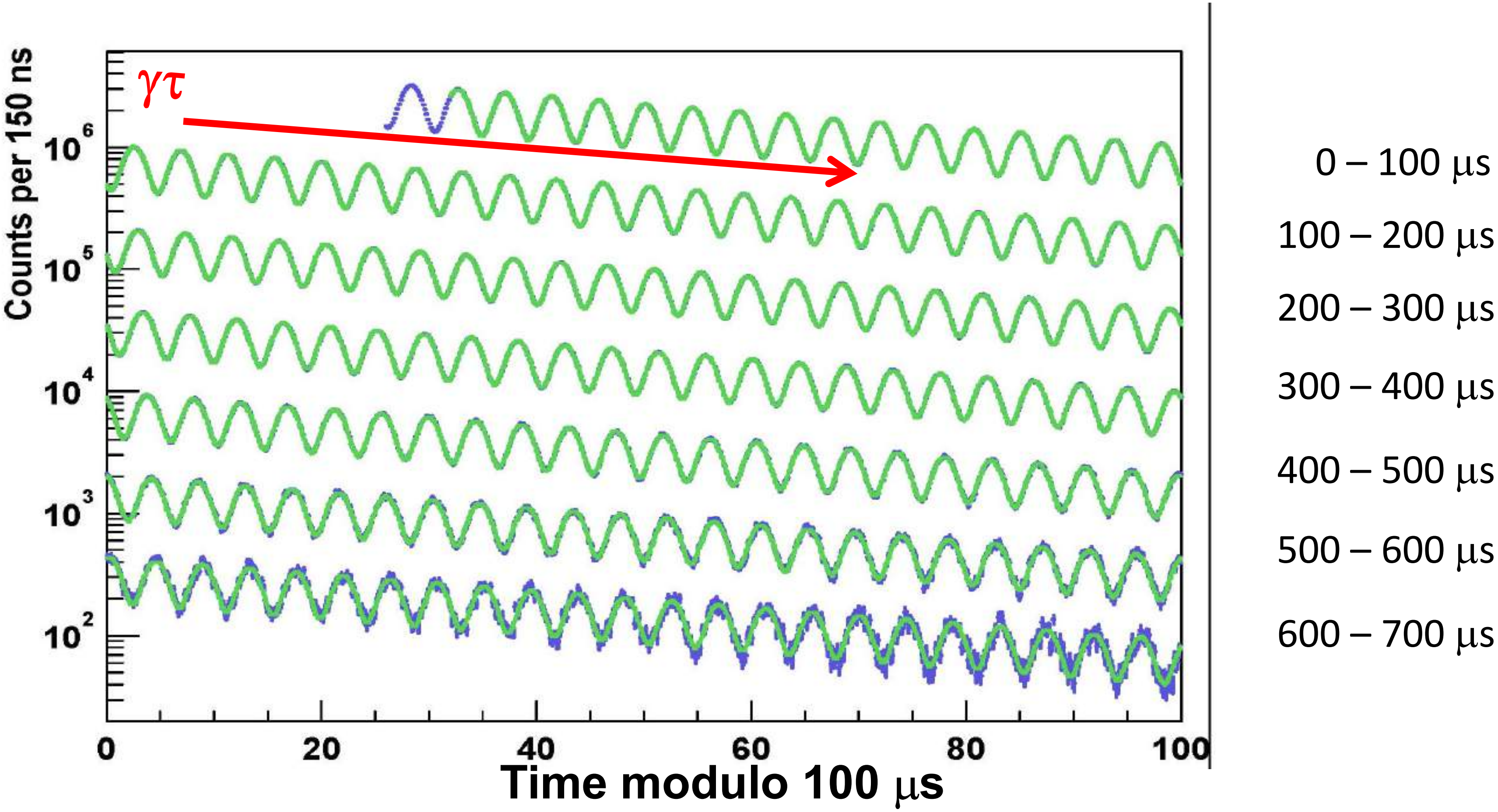
- Muon storage ring – weak focusing betatron
- Muon polarization
- Injection & kicking
- Focus with electric quads
- 24 electron calorimeters

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

E821 arrival-time spectrum

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

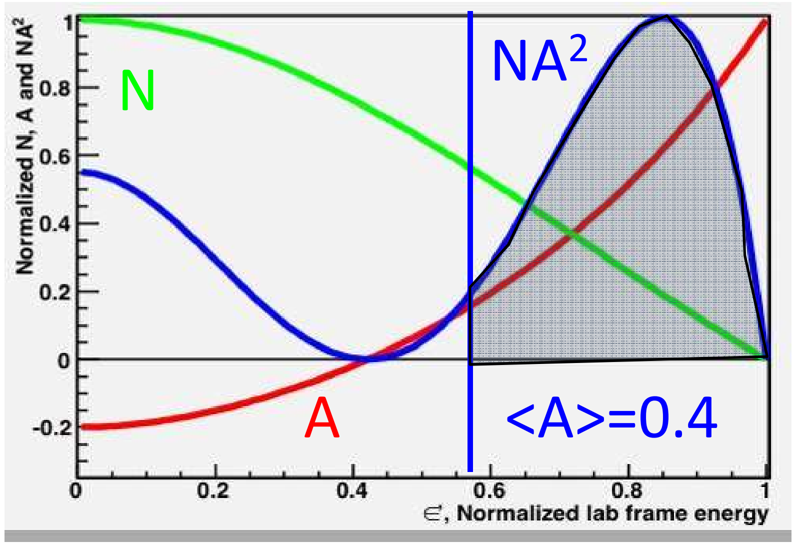
$$4 \times 10^9\ e^-,\ E_{e^-} \geq 1.8\ \mathrm{GeV}$$



Setting the energy threshold

- Polarized muons born from pion decay
- The highest energy positrons are correlated with the muon spin.
- As the spin rotates forward and backward the number of e^+ is modulated by ω_a

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

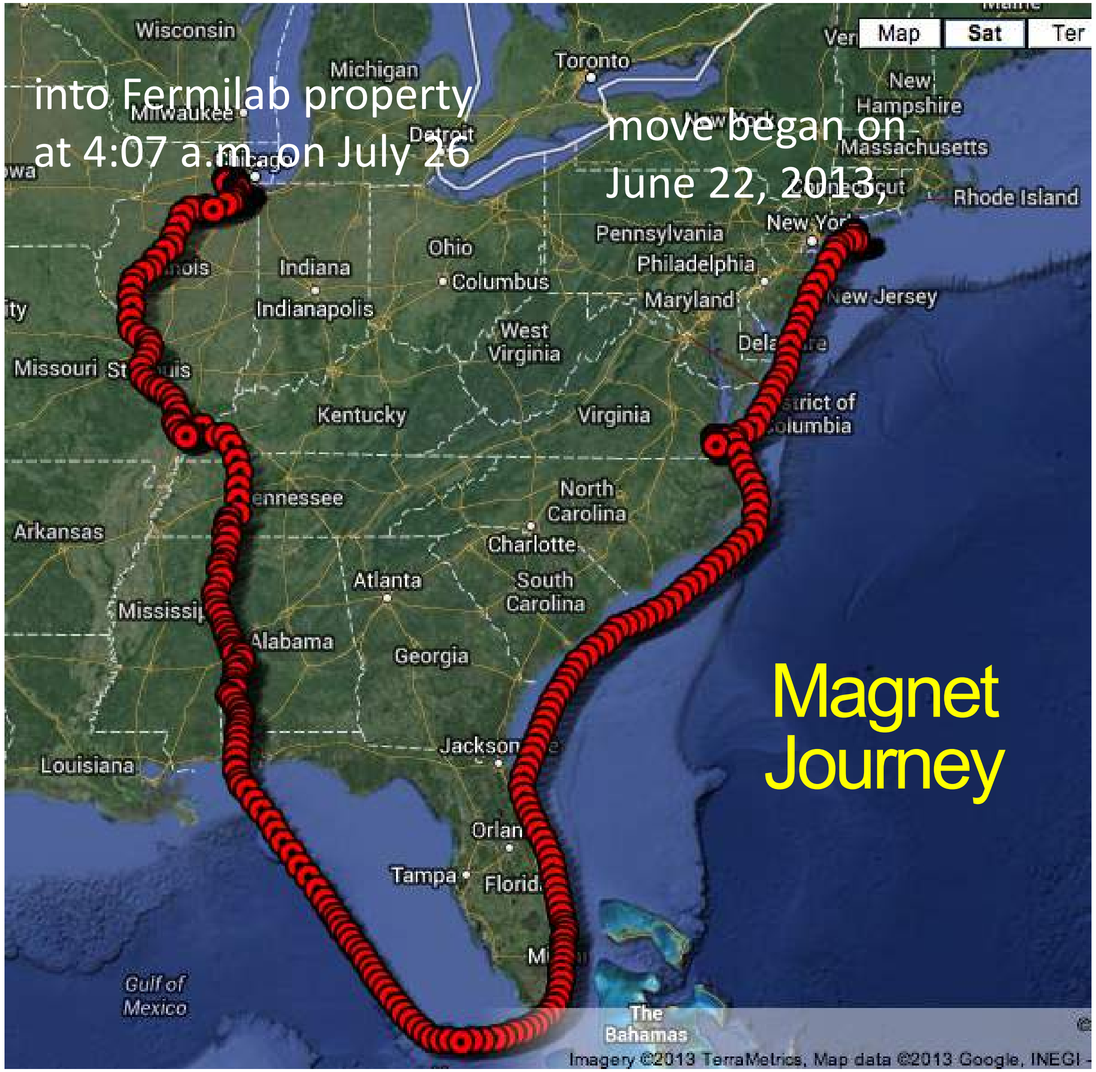


When

In 2004 Fermilab hosted a proton driver workshop

- We had a muon working group, where the usual cast of characters appeared. John Ellis was our theory leader
- We quickly realized that the Fermilab complex could provide the perfect beam to a new g-2 experiment, but only if the Tevatron was not operational.
- I think the physics conclusions that the muon group presented are certainly interesting and relevant now, and show why this meeting is so very important.

In the meantime, magnet goes from Long Island to Chicago



Moving 50 ft diameter Al rings without flexing by >1/8”. . .

Closing two interstates in Chicago…

into Fermilab property at 4:07 a.m. on July 26, 2013

The (new) muon g-2 experiment at Fermilab (E989)

Goal

- A factor of 4 reduction in total error in a_μ over BNL (0.54 ppm)

$$a_\mu^{exp} = 116\,592\,089(54)_{st}(33)_{sy}(63)_{tot} \times 10^{-11}$$

± 0.54 ppm total error

- Two things to notice:
  – statistical error dominates
  – systematic error is only 2.5 to 3 times larger than E989 goal
- How to improve:
  – get a hotter beam (Fermilab) (21 × statistics of BNL)
  – improve everything in systematics, which have many contributing factors
- Fermilab Goal: Equal statistical and systematic errors
  – ± 70 ppb for ω_a and ω_p. total: ± 100 ppb
  – ± 100 ppb for statistics
  – Total error 140 ppb (0.14 ppm)

What has been done …

- 4 Major Steps
  - Transport BNL storage ring and associated equipment to Fermilab
  - Construct a new experimental hall to house the storage ring
  - Modify anti-proton complex to provide a high-purity, intense beam of 3.094 GeV/c muons
  - Upgrade various subsystems (injection devices, field monitoring, detectors & DAQ) to meet requirements for rates and systematics

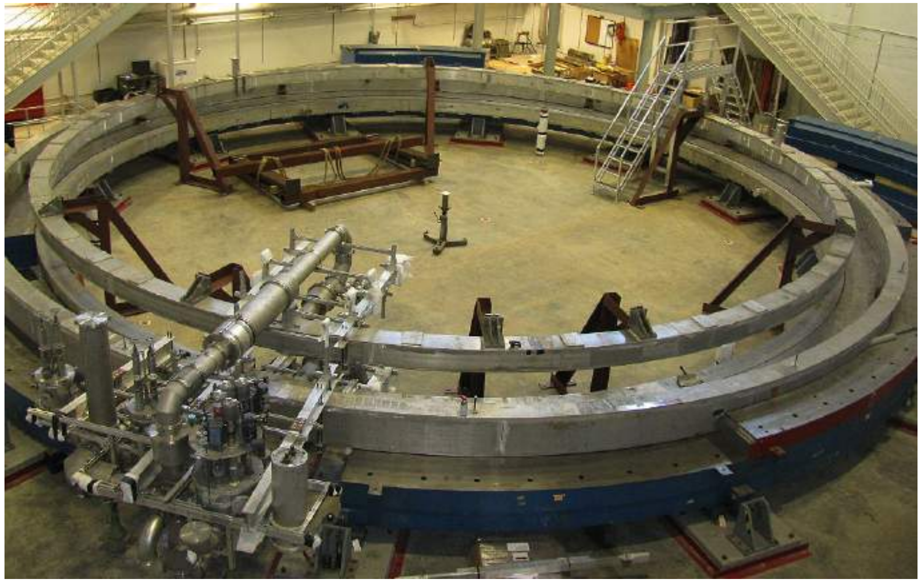
Fermilab Muon Campus Vision, circa 2012

- Convert FNAL anti-proton source to produce customized muon beams for experiments like Muon g-2 and Mu2e

Muon Campus Reality – View from Wilson Hall Today

- Muon g-2 hall complete, BNL storage ring installed and operational
- Mu2e civil construction complete, building outfitting underway
- Conversion of accelerator complex to muon source nearing completion

Putting the storage ring back together again (July 2014 – June 2015)

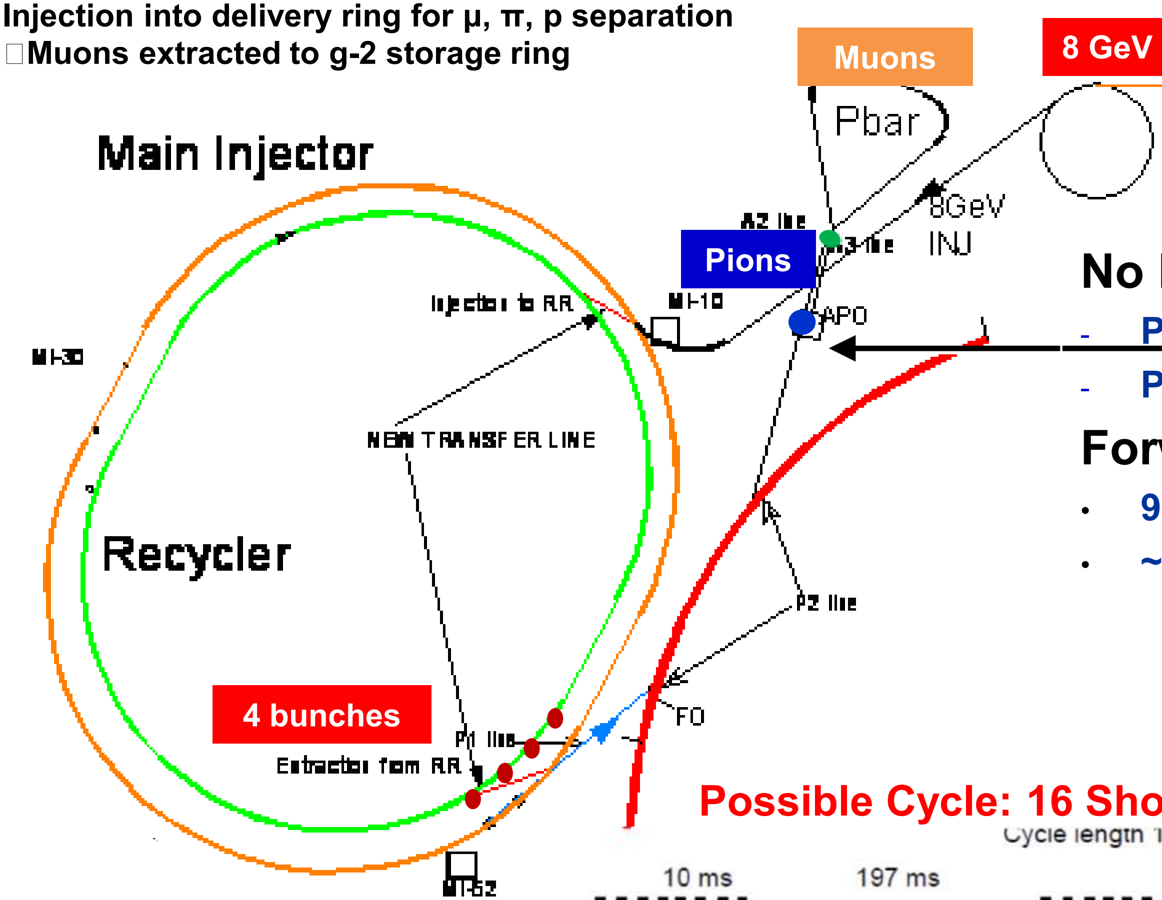


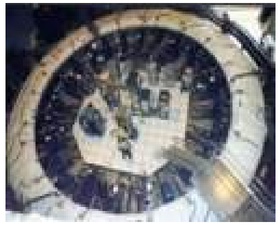
June 2015: Cool down has begun! Magnet Powered on June 25th 2016

22 September 2015: Magnet on (5300 A, 1.45 T)

Pure beam of muon of 3.1 GeV

- 8 GeV protons to recycler ring for rebunching
- extracted bunch and strike the π-production target
- decay of π's to polarized μ's in decay line
- Injection into delivery ring for μ, π, p separation
- Muons extracted to g-2 storage ring





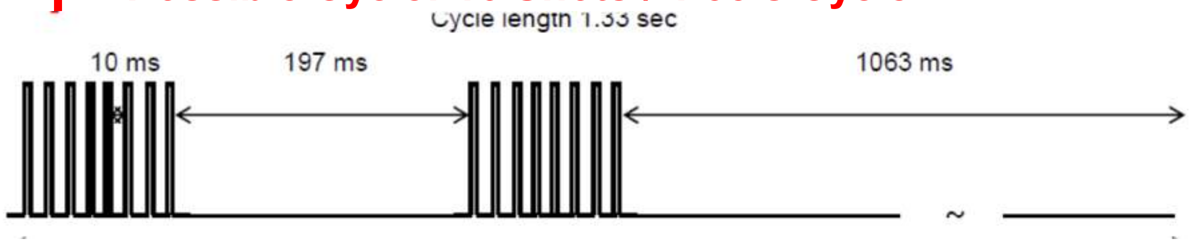
No hadronic flash

- Pions all decay
- Protons removed by a DR kicker

Forward muons collected

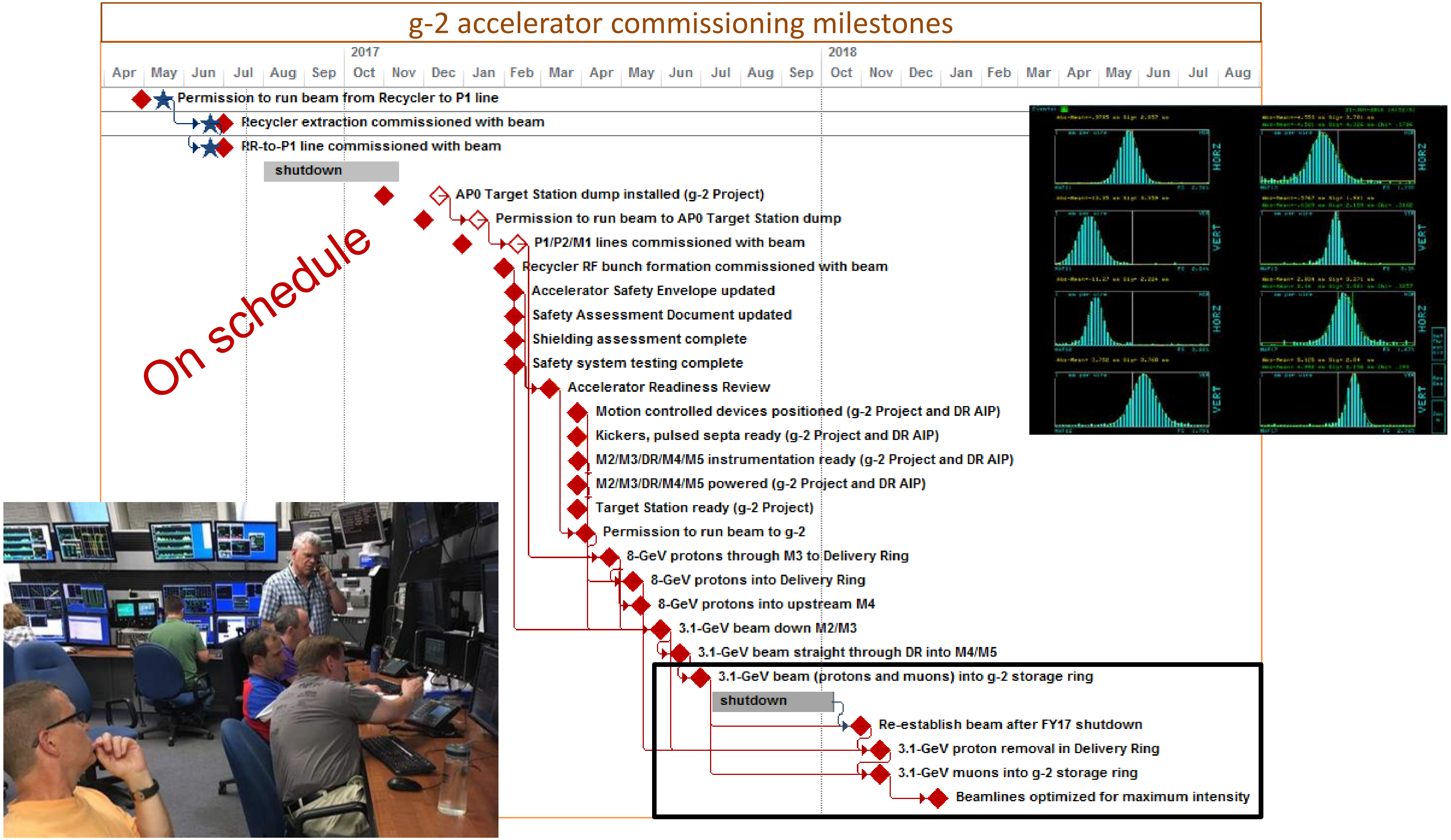
- 95% polarized
- ~800,000 μ^+/fill ($\delta P/P$ 2%) at ring

Possible Cycle: 16 Shots / 1.33 s Cycle



All protons are "excess" from those used for NOvA ν Program

Machine Plan: first muons on June 2017



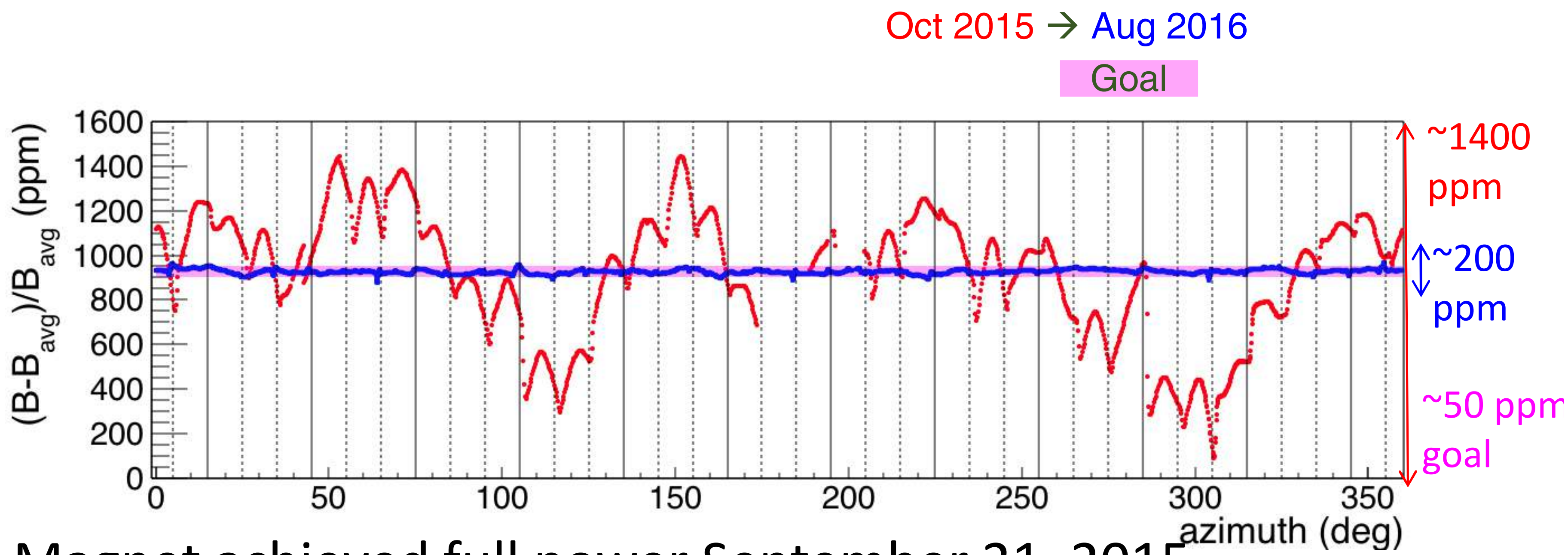
Start of data taking autumn 2017

ω_p(B) 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 ω_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
  - Has been our main thrust over the last 9 months

Progress on B Field



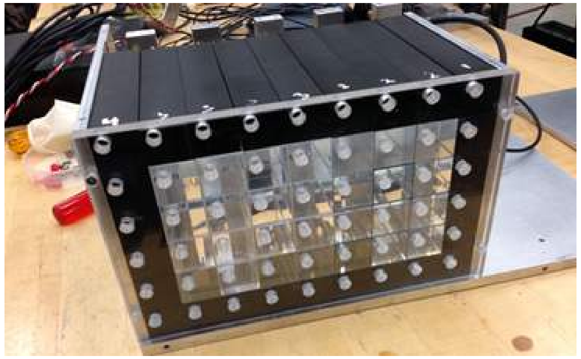
- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- June 2016 peak to peak variation was reduced to 200 ppm
- The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an averaged field uniformity of +- 1ppm. They estimated their systematic uncertainty of 140 ppb. We would like to improve of a factor 2!

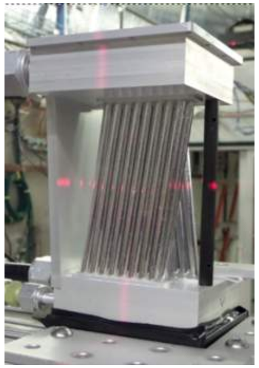
ω_a systematics

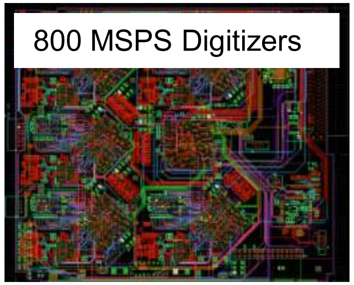
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to 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

New detector systems to be installed by March 2017

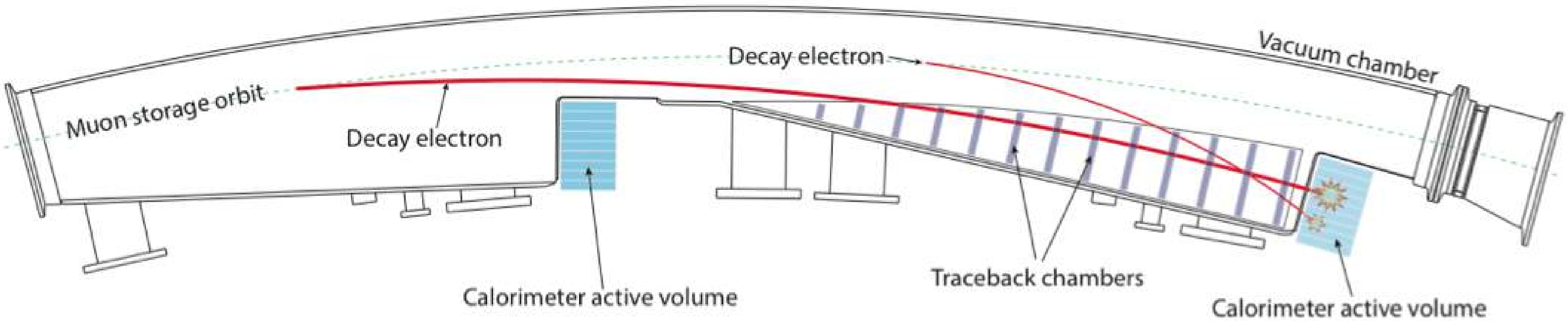




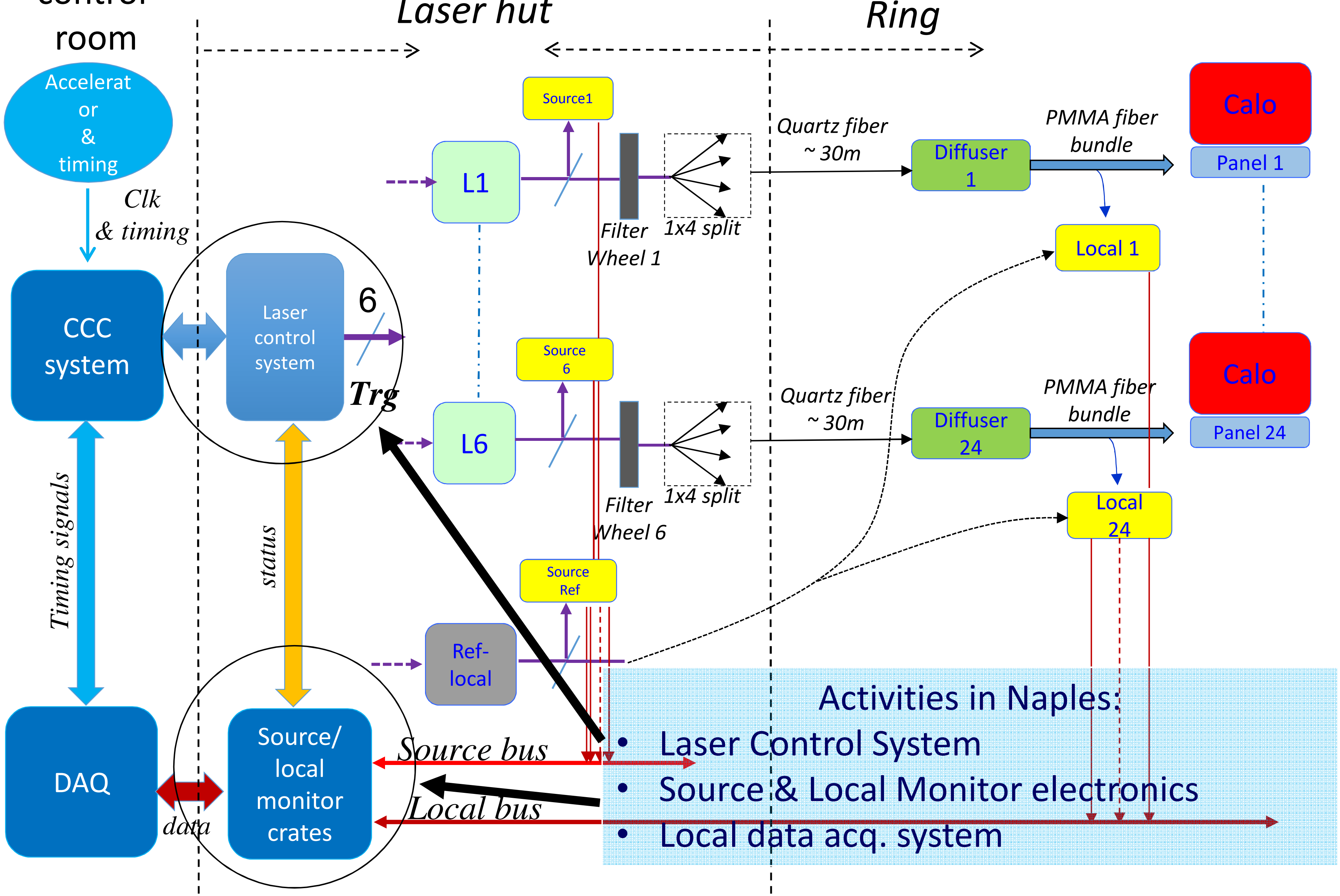


- Calorimeters 24 6x9 PbF2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant UK contributions
- New laser calibration system from INFN crucial for untangling gain from other systematics

Top view of 1 of 12 vacuum chambers



Laser Calibration Scheme



Activities in Naples:

- Laser Control System
- Source & Local Monitor electronics
- Local data acq. system

Aim of the Laser Calibration system

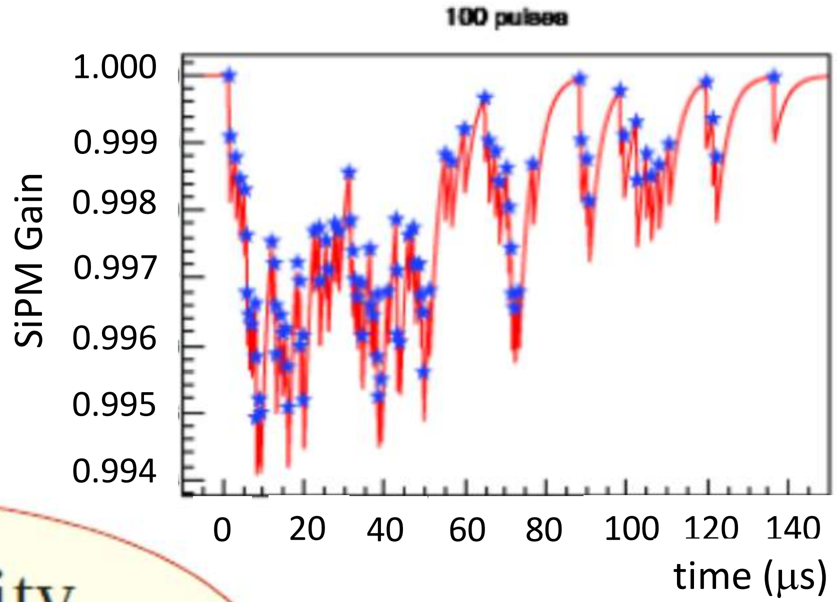
- *Main goal*: *stability monitor*
- Monitor short – term calorimeter gain fluctuations at the 10^{-4} level both during spills (in-fill) & between spills.

Also, to:

- Test/calibrate the calorimeters.
- In "Flight simulator mode" the experiment can be simulated
- Provide a time reference for the DAQ
- Pile-up studies

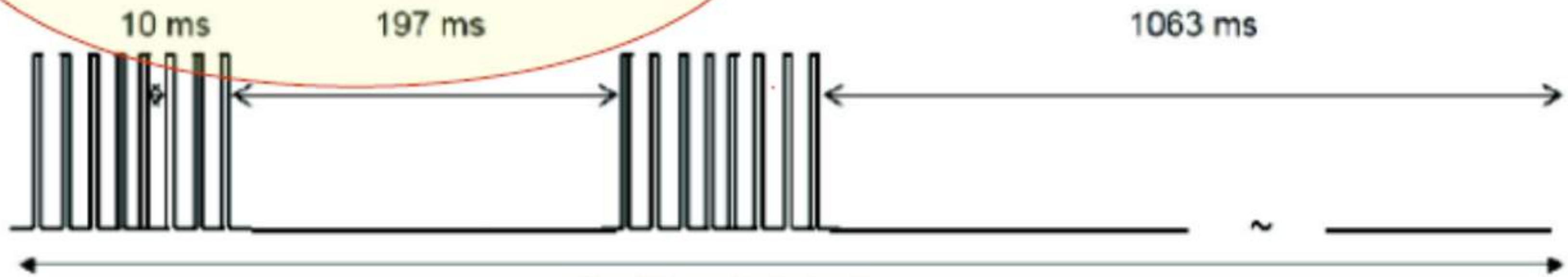
Mapping the short-term (700 mic. s) gain

- *In-fill* pulses

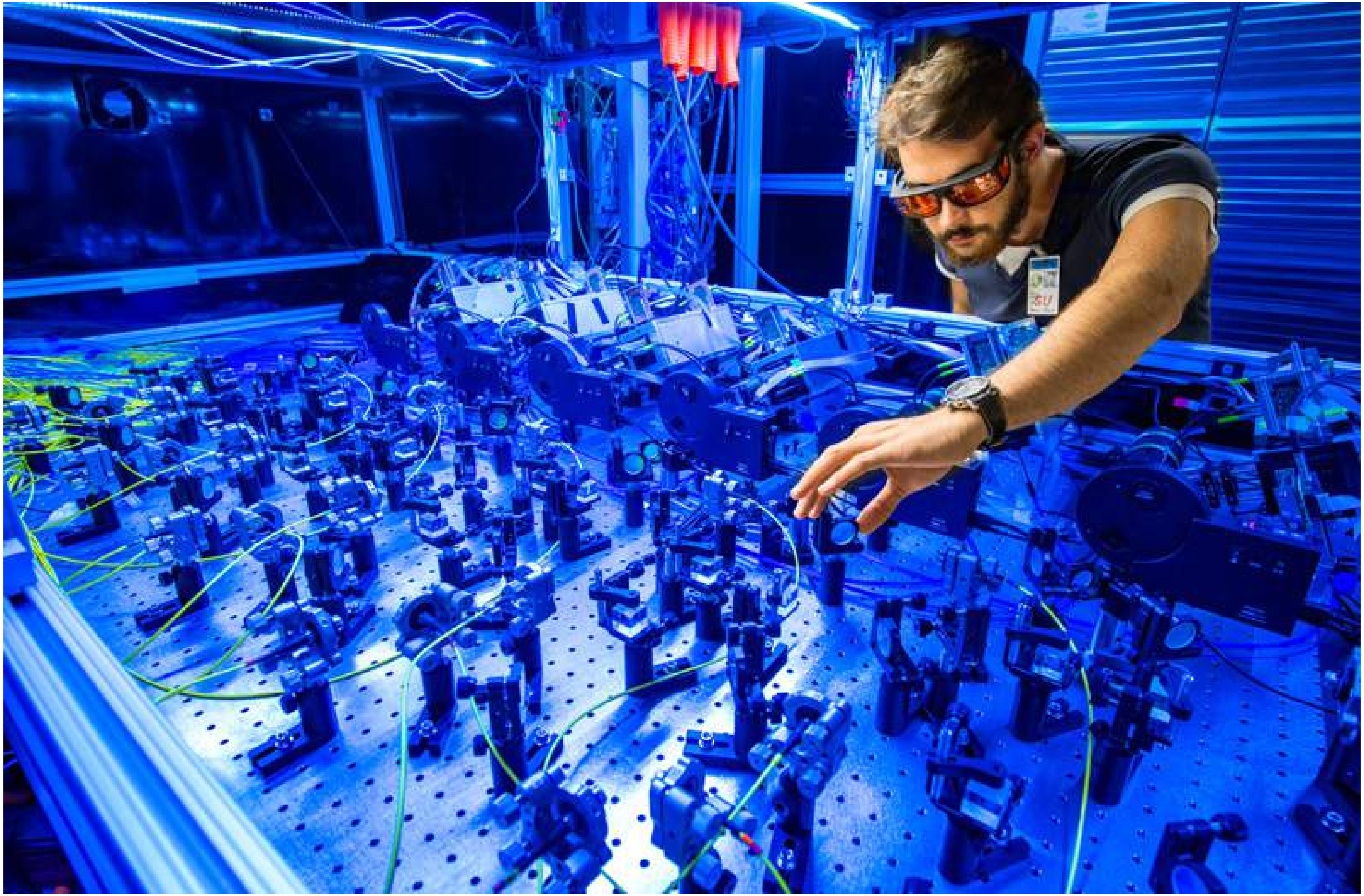


Long term stability

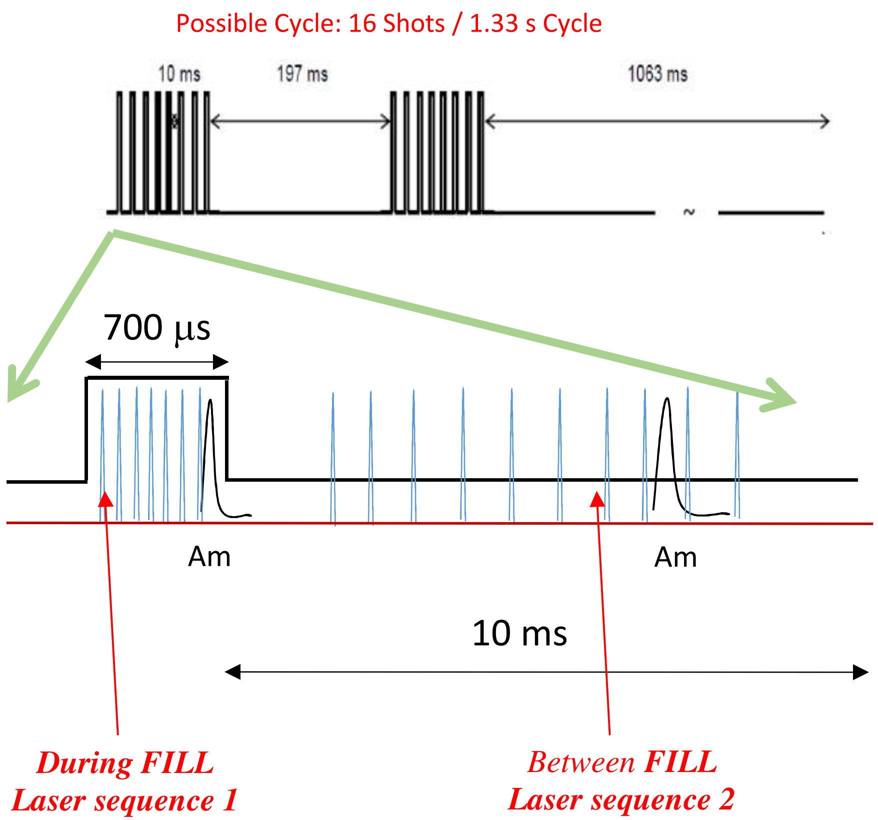
- *Out of fill* pulses

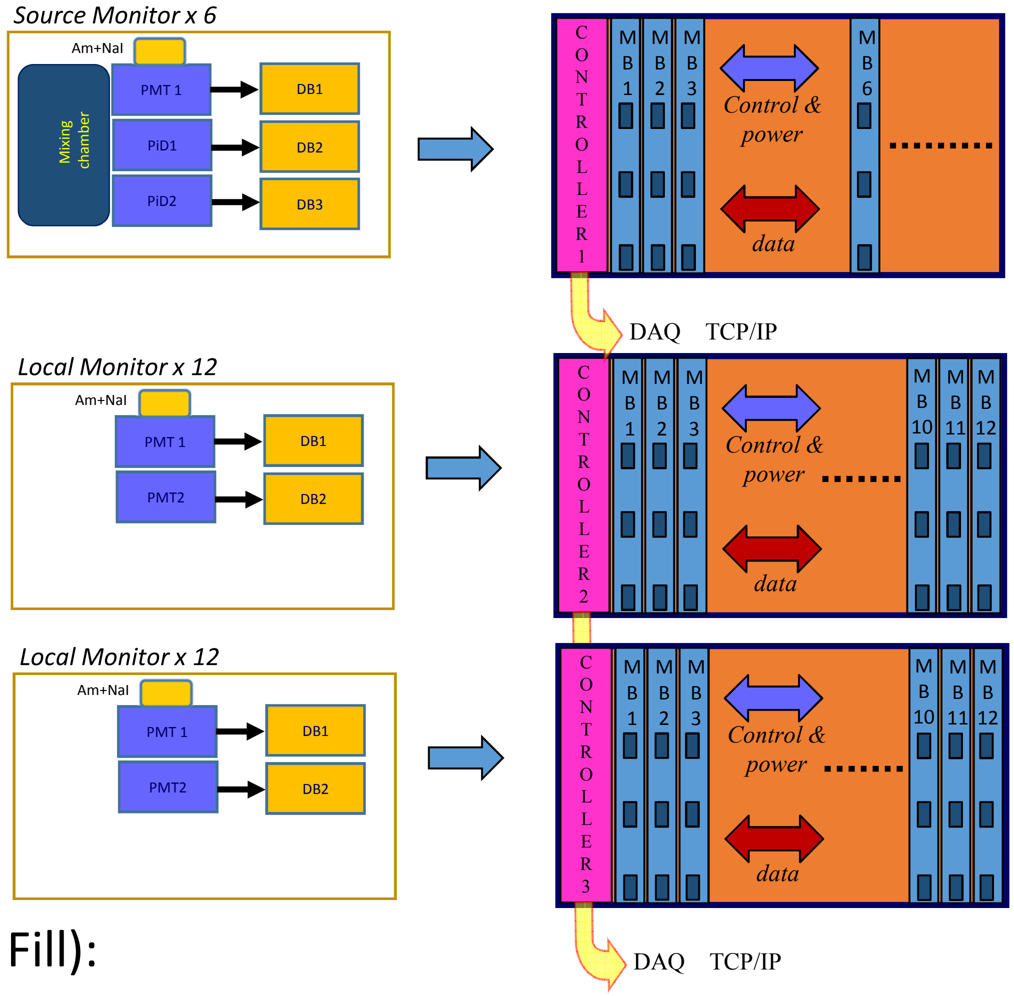


The Laser Calibration System



Monitoring Electronics: (Source & Local M.)





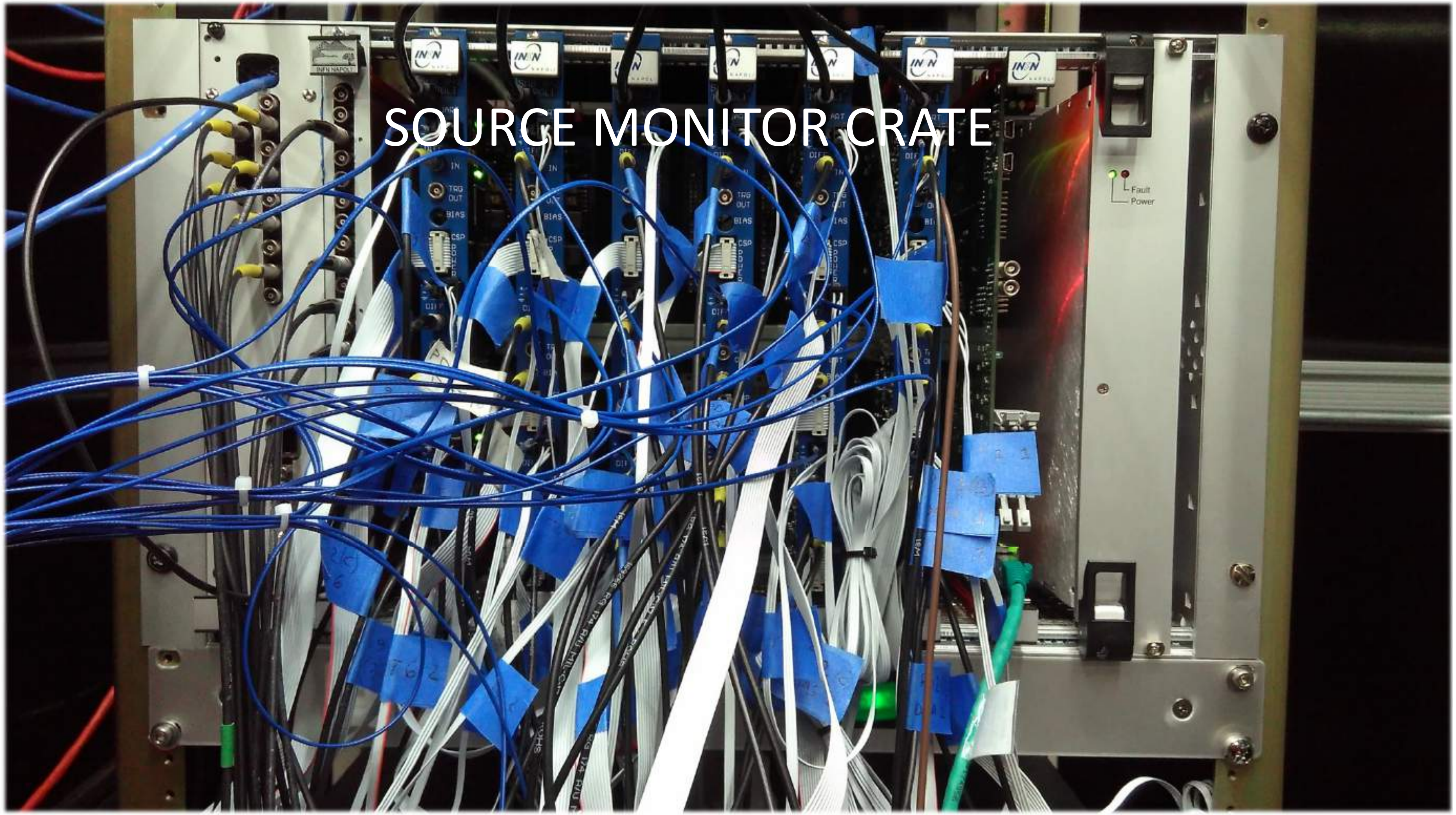
For each laser pulse (in Fill and between Fill):

- Time information (local & global ref)
- Charge integral (14 bit ADC)
- Operational parameters (Voltage)
- Temperature (local/remote/env.)
- Self calibration (electronics)

Event builder:

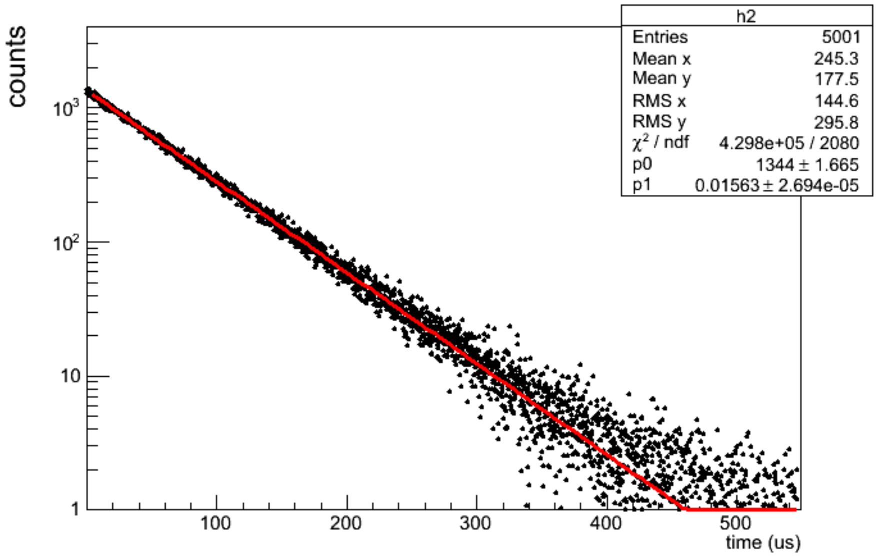
- Hardware inside crate
- Software between crates

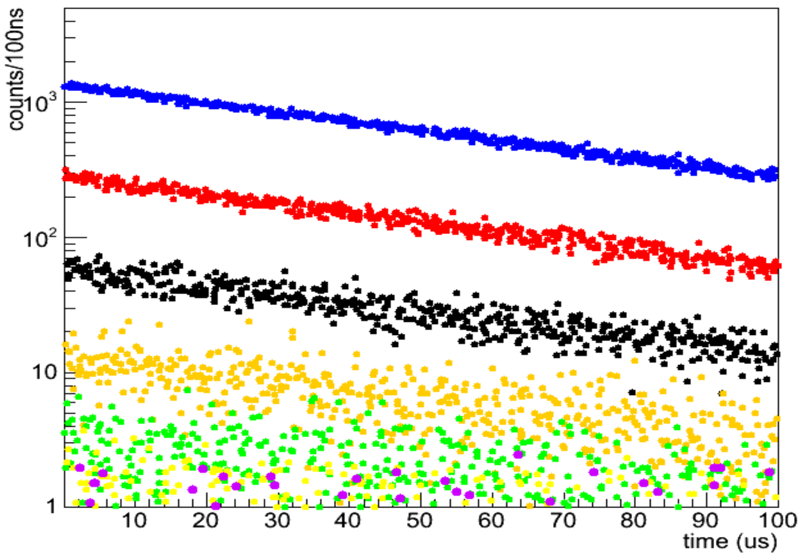
Readout doubled with WFD (800 MHz/12 bit)


SOURCE MONITOR CRATE
Fault
Power
LASER CONTROL
FANOUT
SM 6
SM 5
SM 4
SM 3
SM 2
SM 1
CONTROLLER

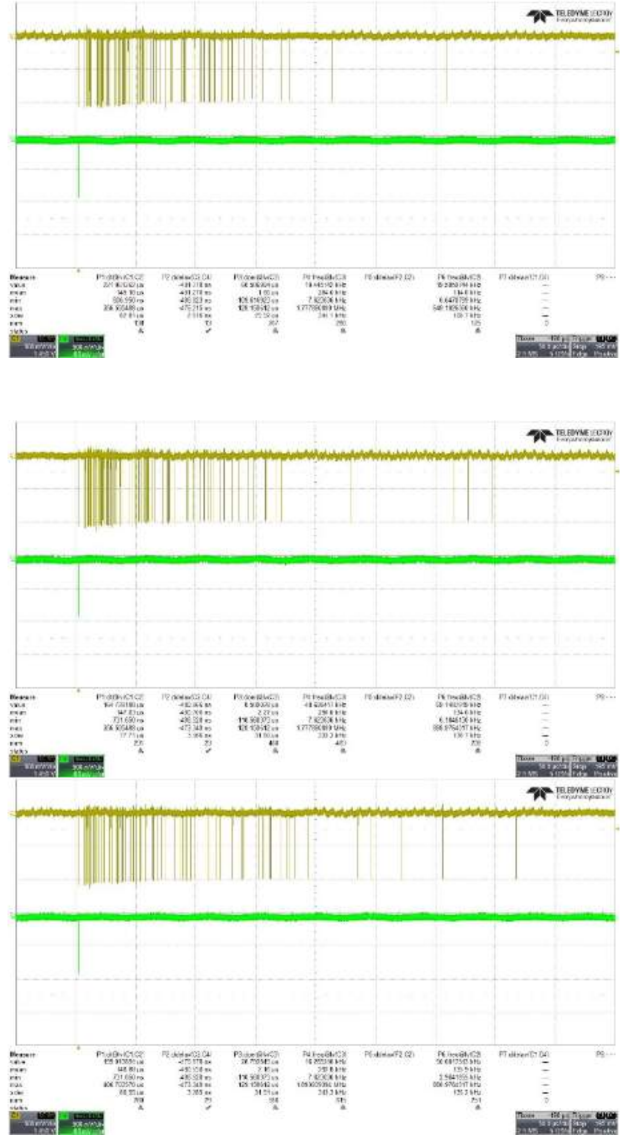
Laser Control Board: “flight simulator “

Laser control board used to simulate (g-2) fill (with no wiggles)

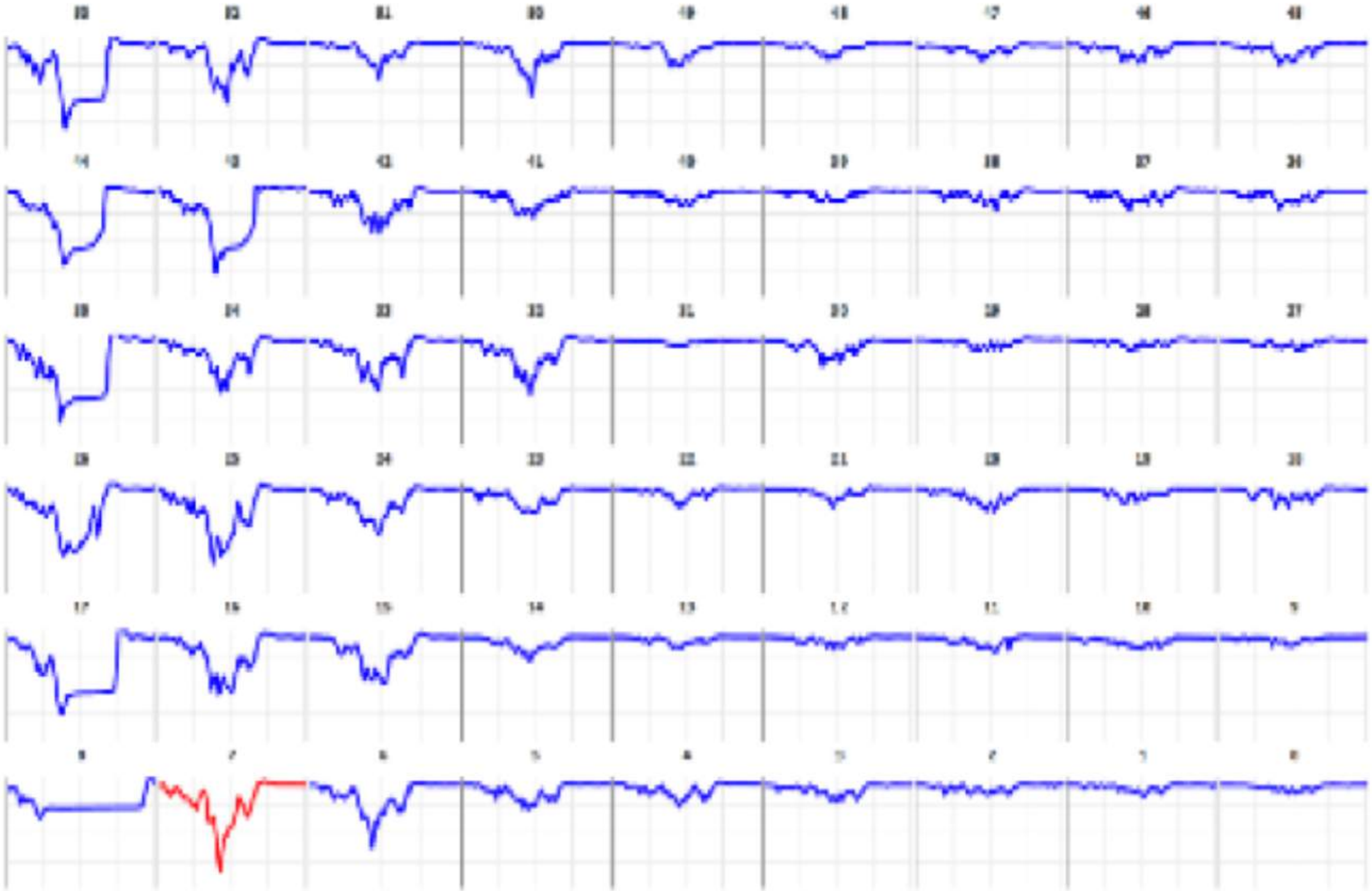




Average 96 hits; pulse width = 20ns



First fill – May 23, 2017 commissioning run



Beam/magnet Detector/DAQ performance:

- **Beam**: good success with FY17 commissioning run
  - Accomplished all pre-shutdown goals
  - Delivered ~3 billion muons to storage ring
  - Have a plan for repairs and improvements during shutdown

- Magnet: at 5280A – up most of the time with no problems

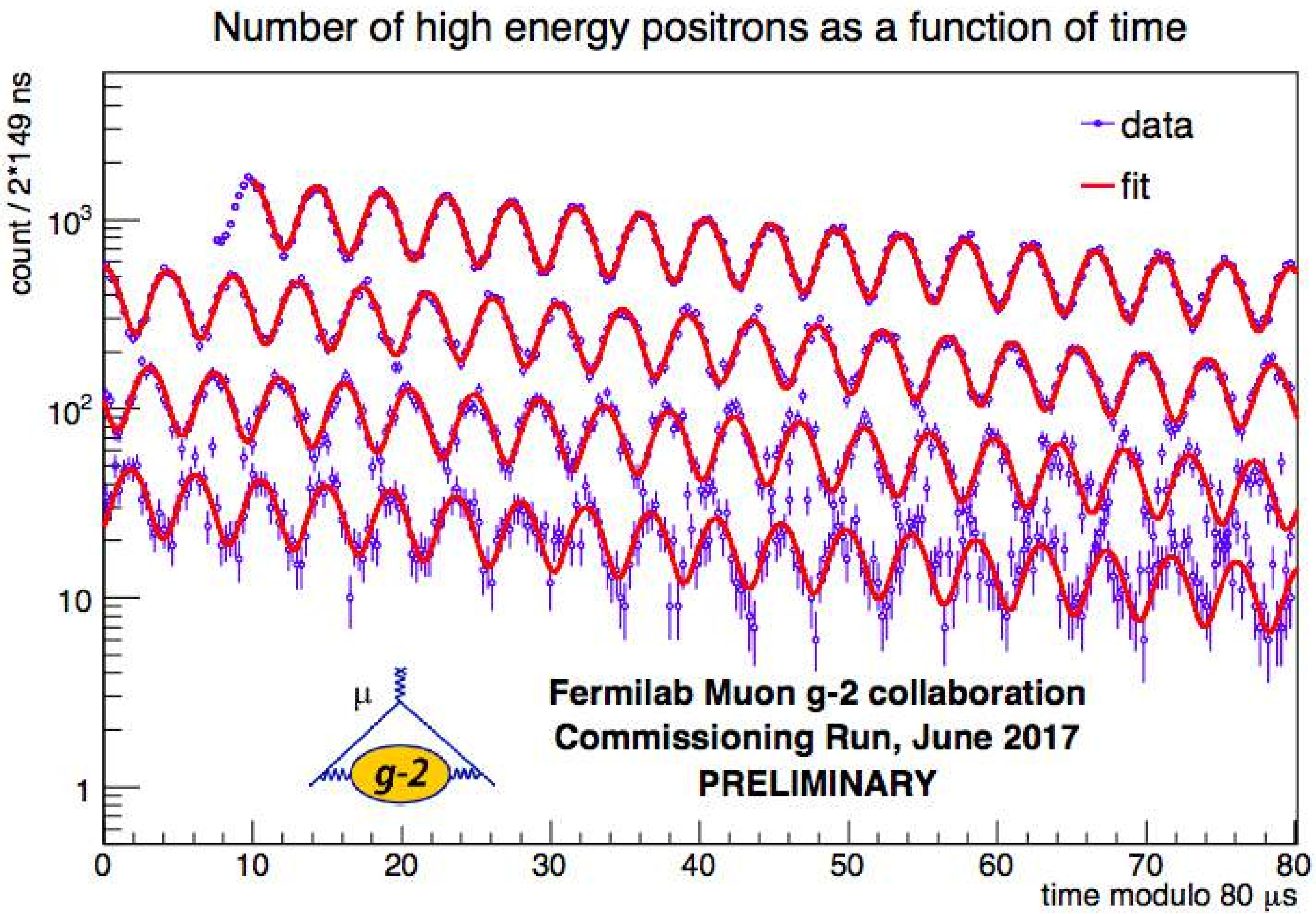
- **Inflector**: some instabilities and trips due to cooling problems

- **Quadrupoles**: sparkling mostly due to not perfect vacuum (10^{-6} torr, expected 2×10^{-7} torr)

- **Calorimeters**: The uptime was 100 % since day 0. Used to measured initial splash, "CBO", launch, for protons and spin precession, distribution of decay vertices, and losses for muons
- **Tracker**: mostly worked with only 1 HV trip in the commissioning run
- **Aux Detectors** (IBMS, Fiber harps) mostly working and very useful for beam diagnostic
- **Readout Electronics**: stable throughout runs
- **DAQ** and online monitoring performed well
- **Offline production**: Data reconstructed almost online (~4 hours delay). ~20 TB of data were reconstructed in 4 days.

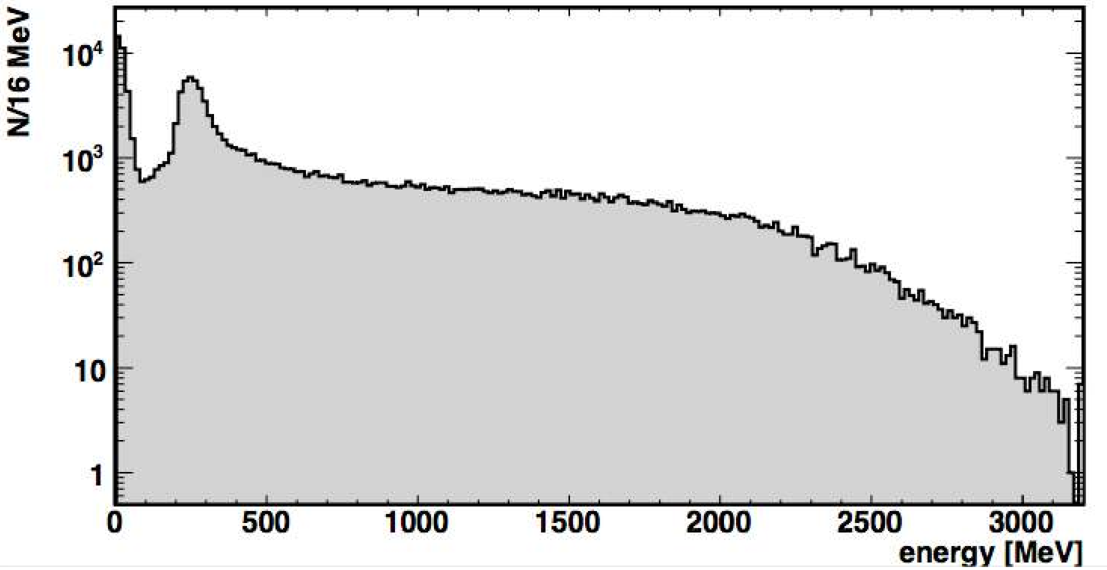
June 2017: first muons at FNAL

news INFN of June 2nd: **[In USA a caccia dell'anomalia del muone]**

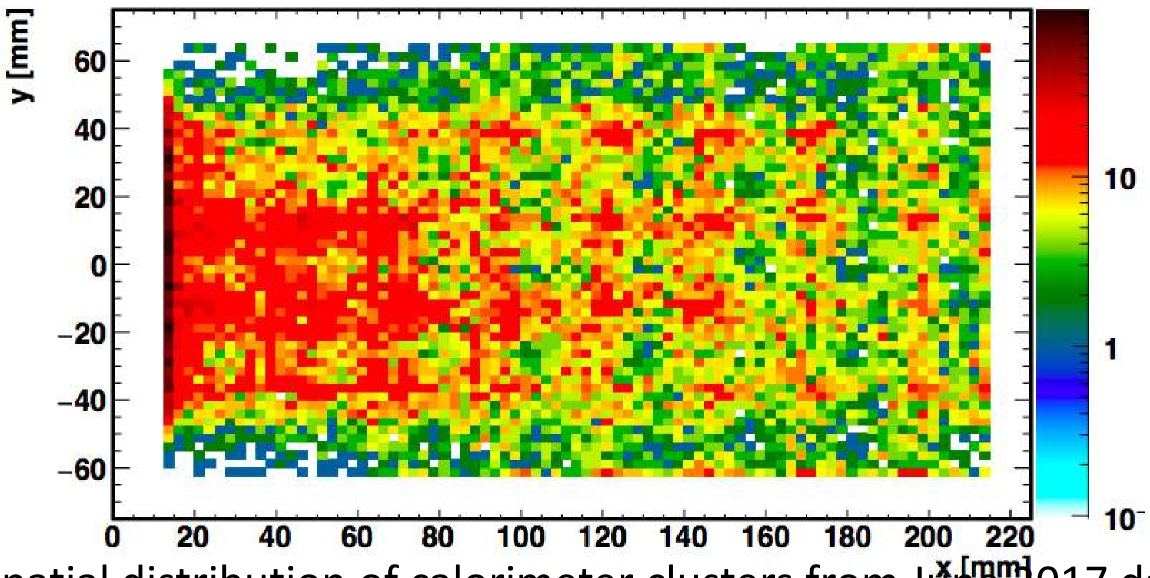


This figure was accumulated from two weeks of data accumulated in June 2017 and has approximately 700k positrons. The number of wiggles is somewhere between that achieved by CERN-II and CERN-III.

Calorimeters



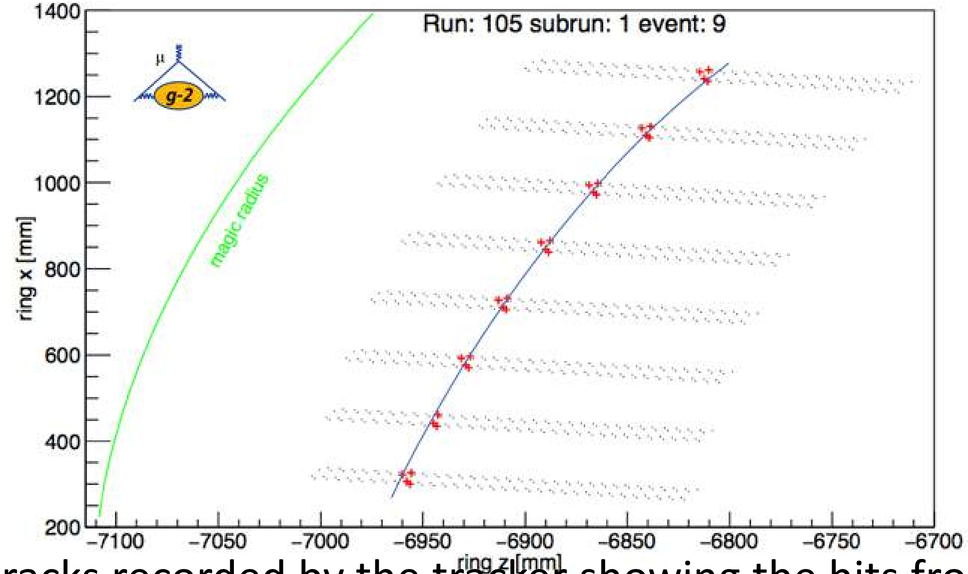
Energy distribution from June 2017 data recorded in the calorimeter.
The peaks are from protons and lost muons



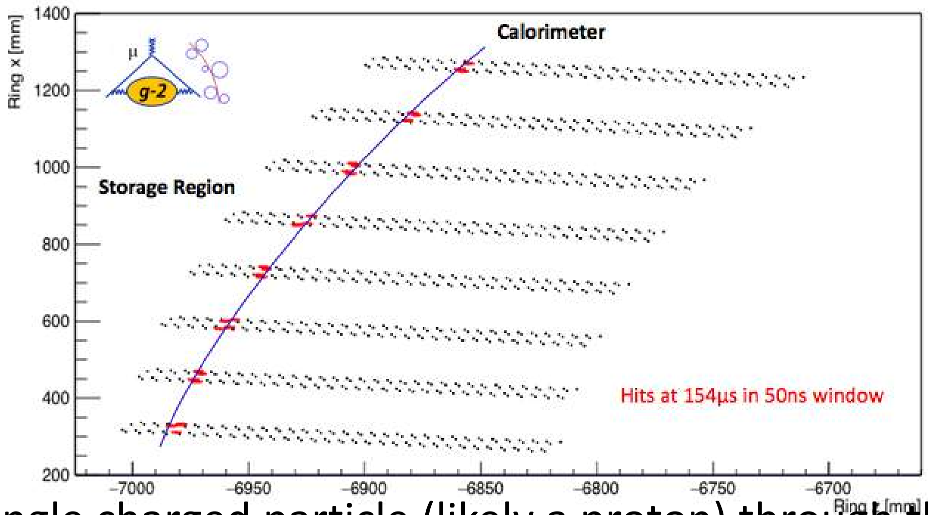
Spatial distribution of calorimeter clusters from June 2017 data recorded in the calorimeter.

first positron tracks at FNAL

Traking

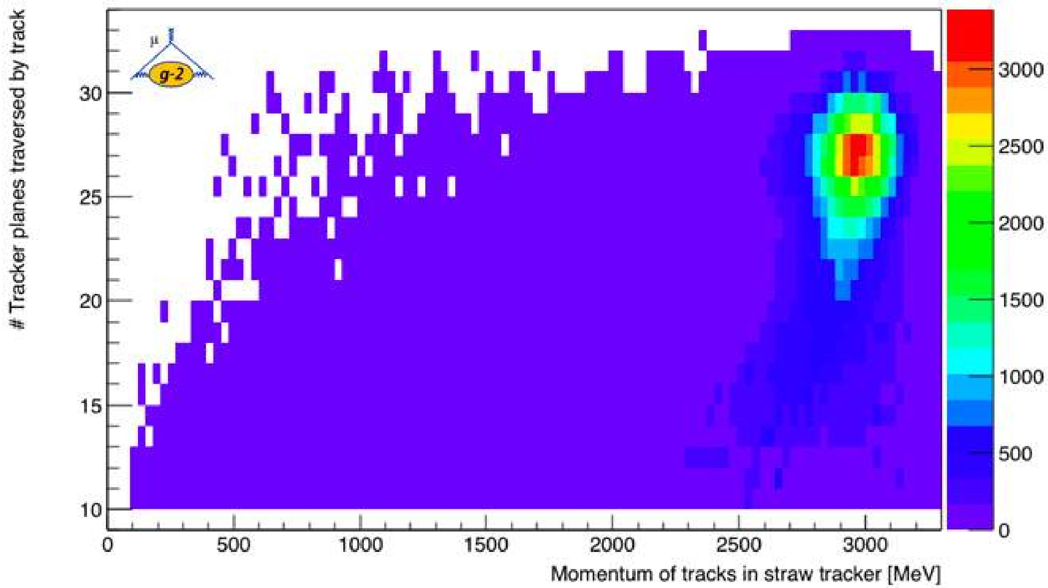


One of the first tracks recorded by the tracker showing the hits from a single charged particle (likely a proton) through the straw trackers and the (wire)-track fit and the magic radius

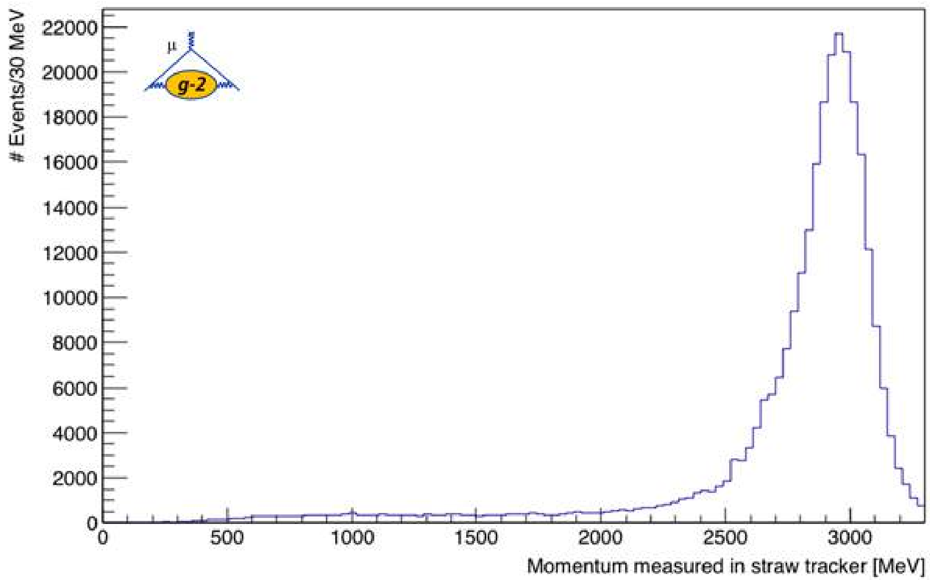


Hits from a single charged particle (likely a proton) through the straw trackers and the (wire)-track fit

Traking: pulse

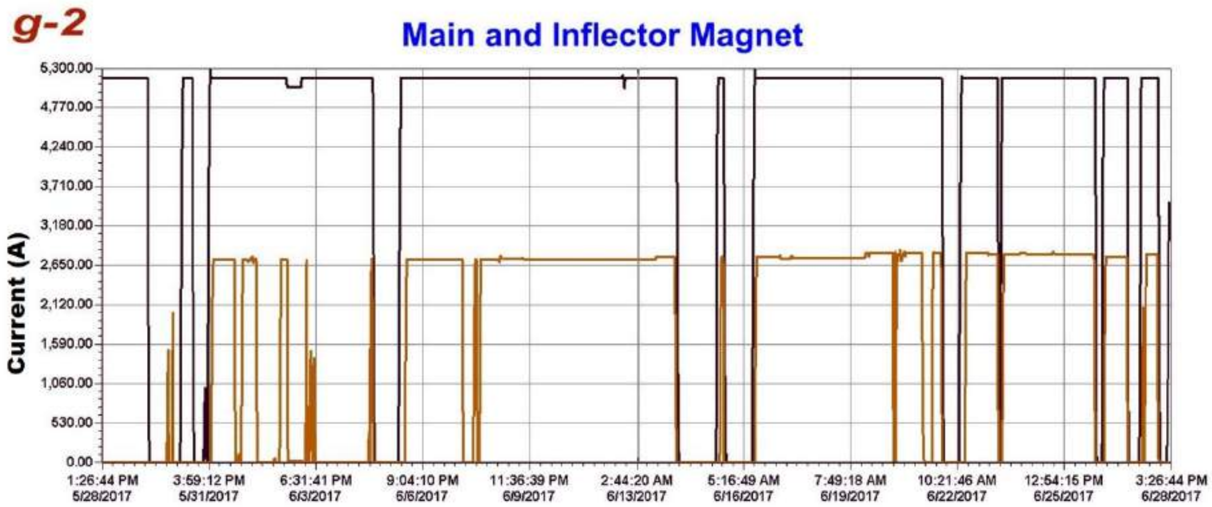


Momentum of tracks vs number of tracker planes with hits (max is 32)



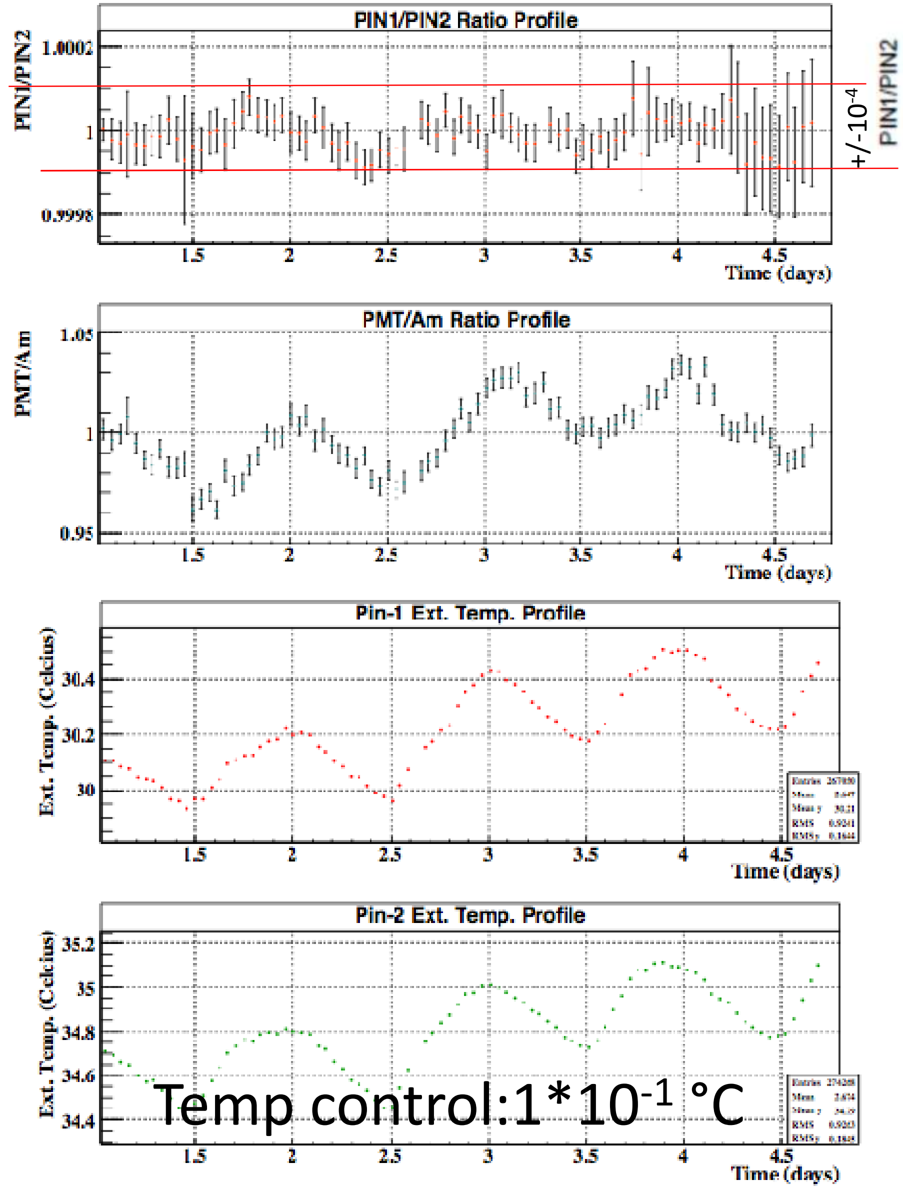
Momentum of tracks (there are approx 250k tracks in this plot)

Currents in magnets

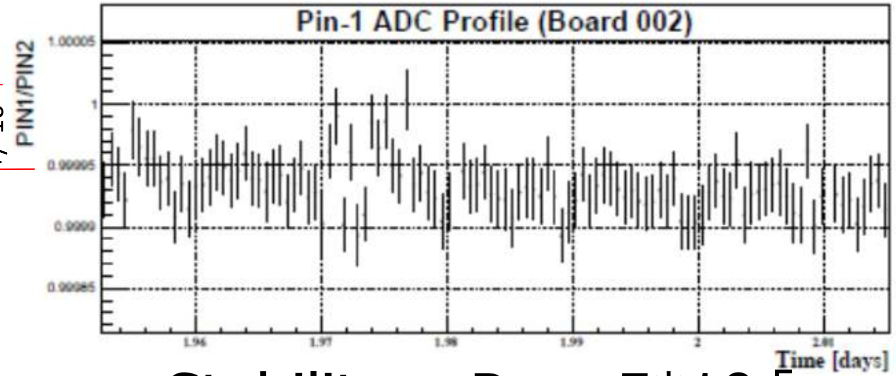


The currents in the storage ring magnet and inflector magnet for the first month of the June 2017 commissioning run

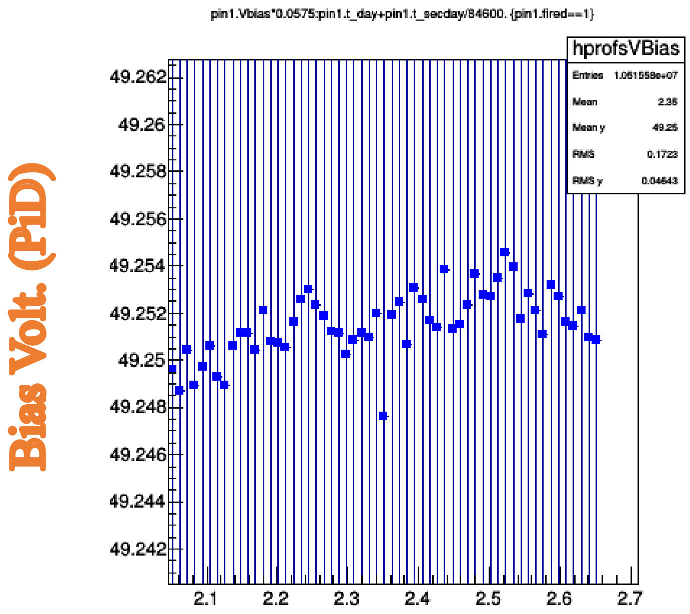
Performance of Laser Calibration



Temp control: $1*10^{-1}$ °C



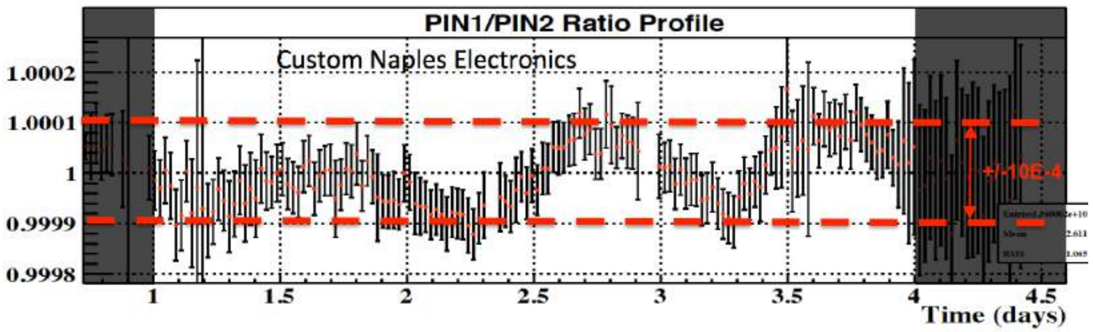
Stability: $\Delta R < 5*10^{-5}$

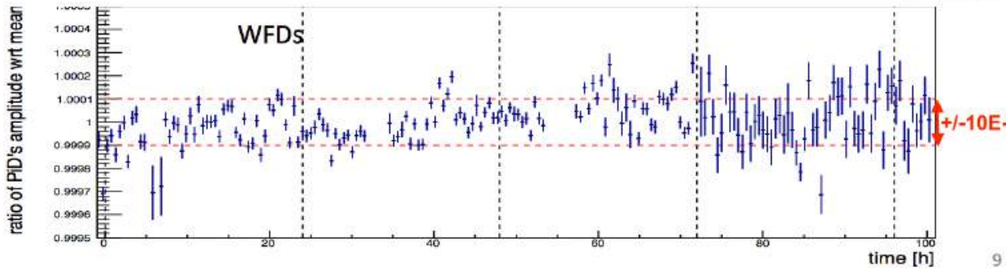


Bias Voltage control: $2*10^{-4}$

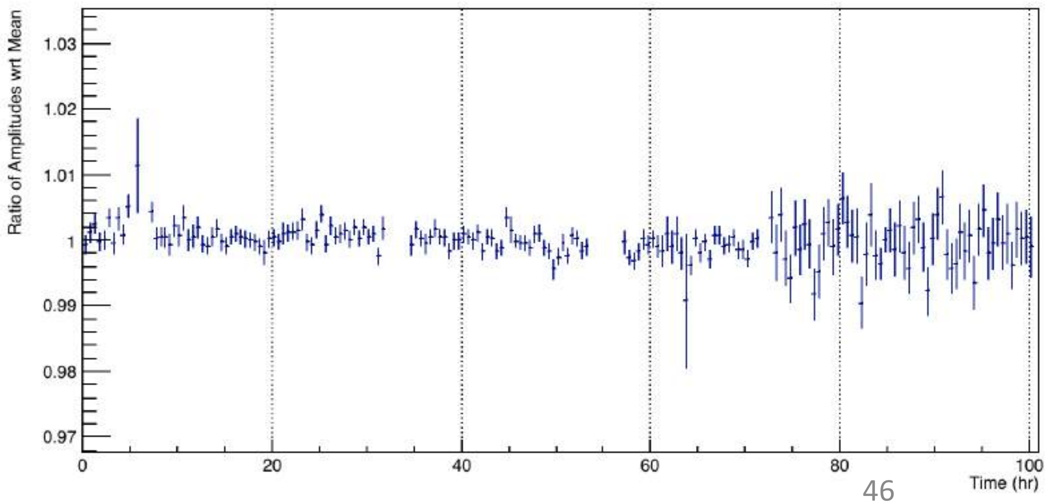
Cross check of Source e Local Monitor

- Stability is qualified by the two PiD signals in the SM – PIN1/PIN2. The comparison between ADC14 bits digitization and WDF (800 MHz/12 bit) shows capability of stability monitoring at $\leq 10^{-4}$

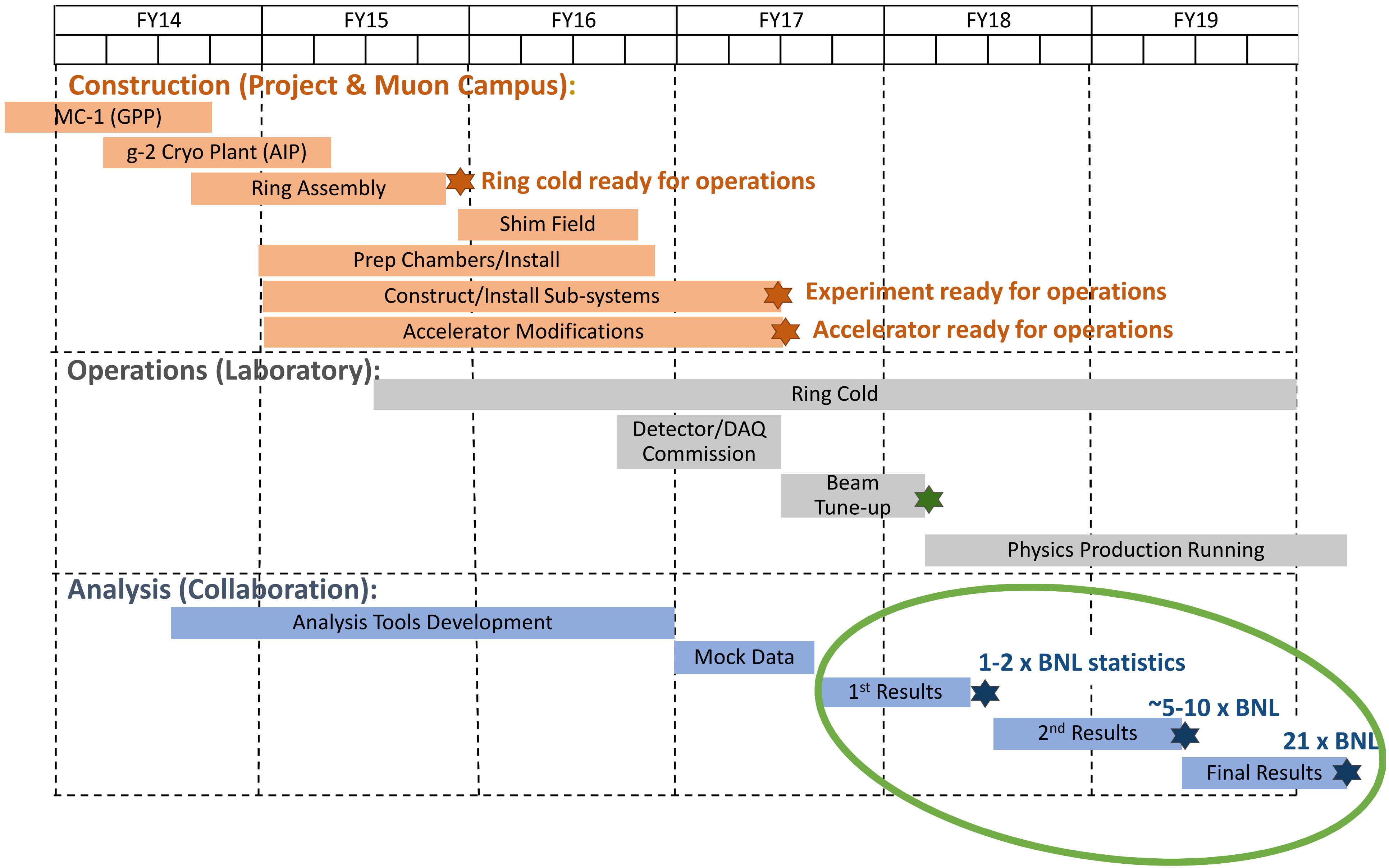




- Ratio of the two signals (PMT) of the LM. Within the uncertainty of the laser fluctuations and statistics of the photons no instability can be seen

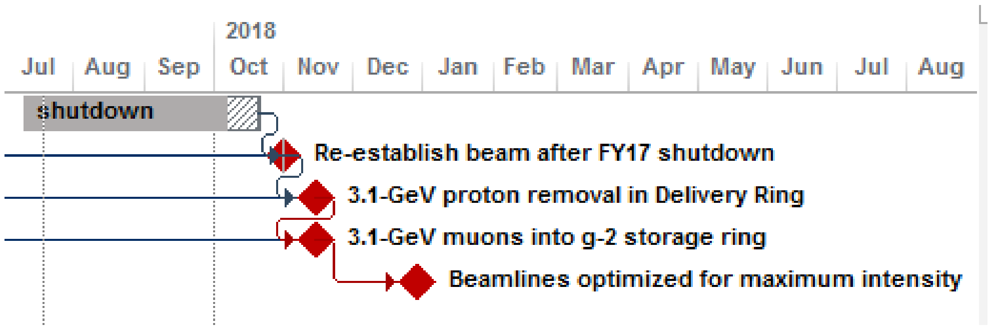


Project Timeline



Conclusions

- E989 is on schedule
- First runs in June-July 2017 very successfull
- Coming future very appealing:



- First Physics results expected by spring/ summer 2018
- Then Data Taking will go on for 2 years

Workshop on "Flavour changing and conserving processes" 2015 (FCCP2015)

Gran successo!!

10-12 September 2015 *Villa Orlandi, Anacapri, Capri Island, Italy*
Europe/Rome timezone

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List of registrants
Travel Information
Accommodation and fee
Social Programme

The workshop aims to discuss the status and prospects of the physics of "Flavour changing and conserving processes" and addresses the scientific community involved in experiments like g-2, mu2e, meg, meee, EDM and more generally to the physics of K and B mesons. It wants to be a "thinking effort" on the outlook, both theoretical and experimental, as well as a picture of the "state of art". Specifically aims to gather expertise gained in Italy on SM contributions to the g-2 of the muon and related subjects.

Dates: from 10 September 2015 08:00 to 12 September 2015 13:00
Timezone: Europe/Rome
Location: *Villa Orlandi, Anacapri, Capri Island, Italy*
International Centre for Scientific Culture - University of Napoli Federico II

First Workshop of the Muon g-2 Theory Initiative

3-6 June 2017 *Q Center*
US/Central timezone

Search

66 registered participants, 40 talks, 15 discussion sessions (525 minutes)

Workshop on "Flavour changing and conserving processes" 2017 (FCCP2017)

7-9 September 2017 *Villa Orlandi, Anacapri, Capri Island, Italy*

Overview

Timetable

Organizing committee

Local Organizing Committee

Contribution List

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Registration

└ Registration Form

List of registrants

Travel Information

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The workshop aims to discuss the status and prospects of the physics of "Flavour changing and conserving processes" and addresses the scientific community involved in experiments like g-2, mu2e, meg, meee, EDM and more generally to the physics of K and B mesons. It wants to be a "thinking effort" on the outlook, both theoretical and experimental, as well as a picture of the "state of art". Specifically aims to gather expertise gained in Italy on SM contributions to the g-2 of the muon and related subjects.

Dates:	from 07 September 2017 08:00 to 09 September 2017 16:30
Timezone:	Europe/Rome
Location:	*Villa Orlandi, Anacapri, Capri Island, Italy* International Centre for Scientific Culture - University of Napoli Federico II
Additional info:	Contacts For any information or question please contact the Local Organizing Committee at: loc_fccp2017@lists.na.infn.it

Thanks