The Calibration System For The Muon g-2 Experiment @ *Fermilab*

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(On behalf of the g-2 collaboration)

INFN – Sezione di Napoli

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INFN Istituto Nazionale di Fisica Nucleare

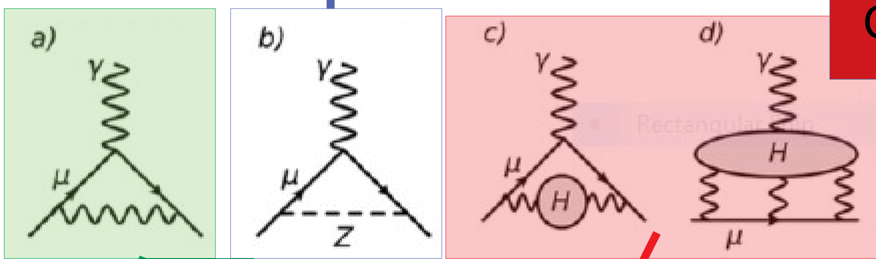
μ g–2

Overview...

- *g-2 and the experiments...*
- *Why LASER Calibration System ?*
- *Structure and components of the calibration system.*
- *Source Monitors in details*
- *Naples' DAQ : On-line and Off-line Monitoring*
- *Performance and stability*

g-2 and the experiments...

Theoretical Status



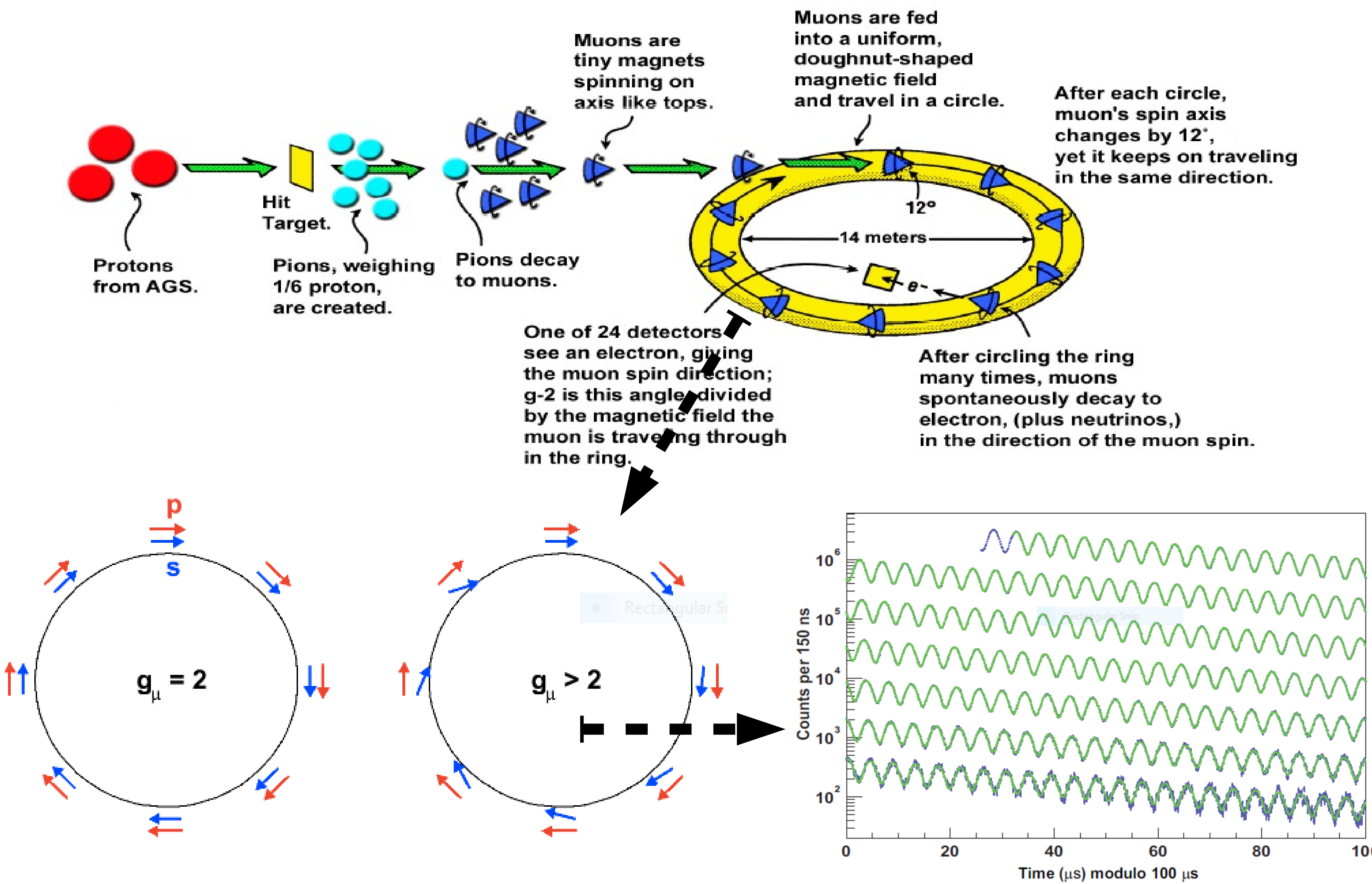
$$a_\mu = (g_\mu - 2)/2$$

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [71]	$6\,923 \pm 42$
HVP(lo) [72]	$6\,949 \pm 43$
HVP(ho) [72]	-98.4 ± 0.7
HLbL	105 ± 26
EW	153.6 ± 1.0
Total SM [71]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [72]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

SM Average

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had.} = (116591802 \pm 49) \times 10^{-11}$$

g-2 Experiment @ *BNL*



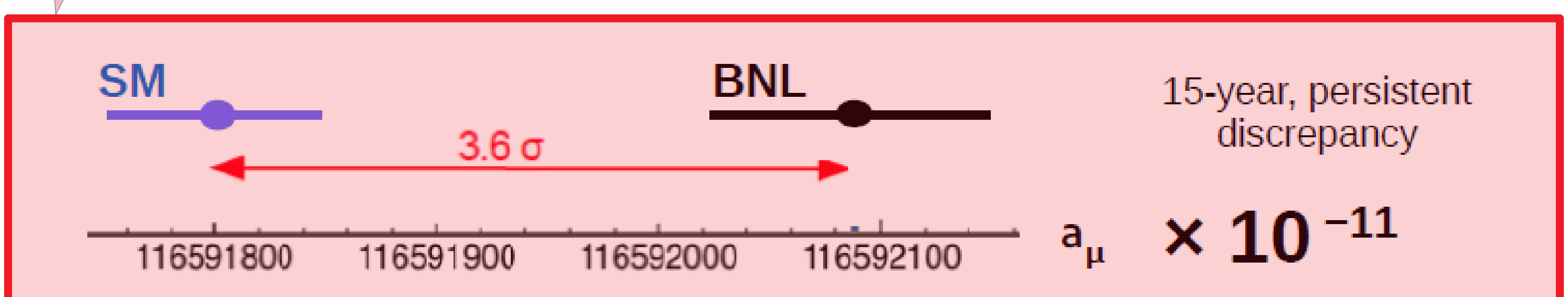
Earlier Experimental Results

Experiment	Year	Polarity	$a_\mu \times 10^{10}$	Pre. [ppm
CERN I	1961	μ^+	11 450 000(220000)	4300
CERN II	1962-1968	μ^+	11 661 600(3100)	270
CERN III	1974-1976	μ^+	11 659 100(110)	10
CERN III	1975-1976	μ^-	11 659 360(120)	10
BNL	1997	μ^+	11 659 251(150)	13
BNL	1998	μ^+	11 659 191(59)	5
BNL	1999	μ^+	11 659 202(15)	1.3
BNL	2000	μ^+	11 659 204(9)	0.73
BNL	2001	μ^-	11 659 214(9)	0.72

BNL Average

$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{syst}(63)_{tot} \times 10^{-11} \quad (\pm 0.54\,\text{ppm})$$

Theory – Expt. Discrepancy



g-2 Experiment @ *FNAL* : *Goals*

E821 at Brookhaven

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

21x more stat.

Overall 4x
More precise

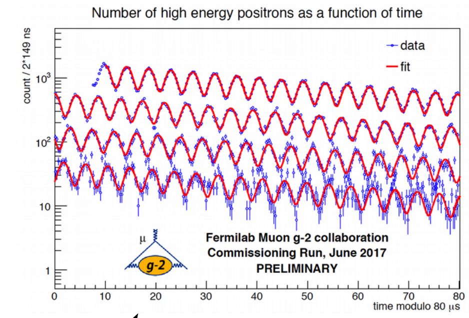
$$\left.\begin{array}{l}\sigma_{stat} = \pm 0.1 ppm \\ \sigma_{syst} = \pm 0.1 ppm\end{array}\right\} \Longrightarrow \sigma = 0.14 ppm$$

E989 at Fermilab

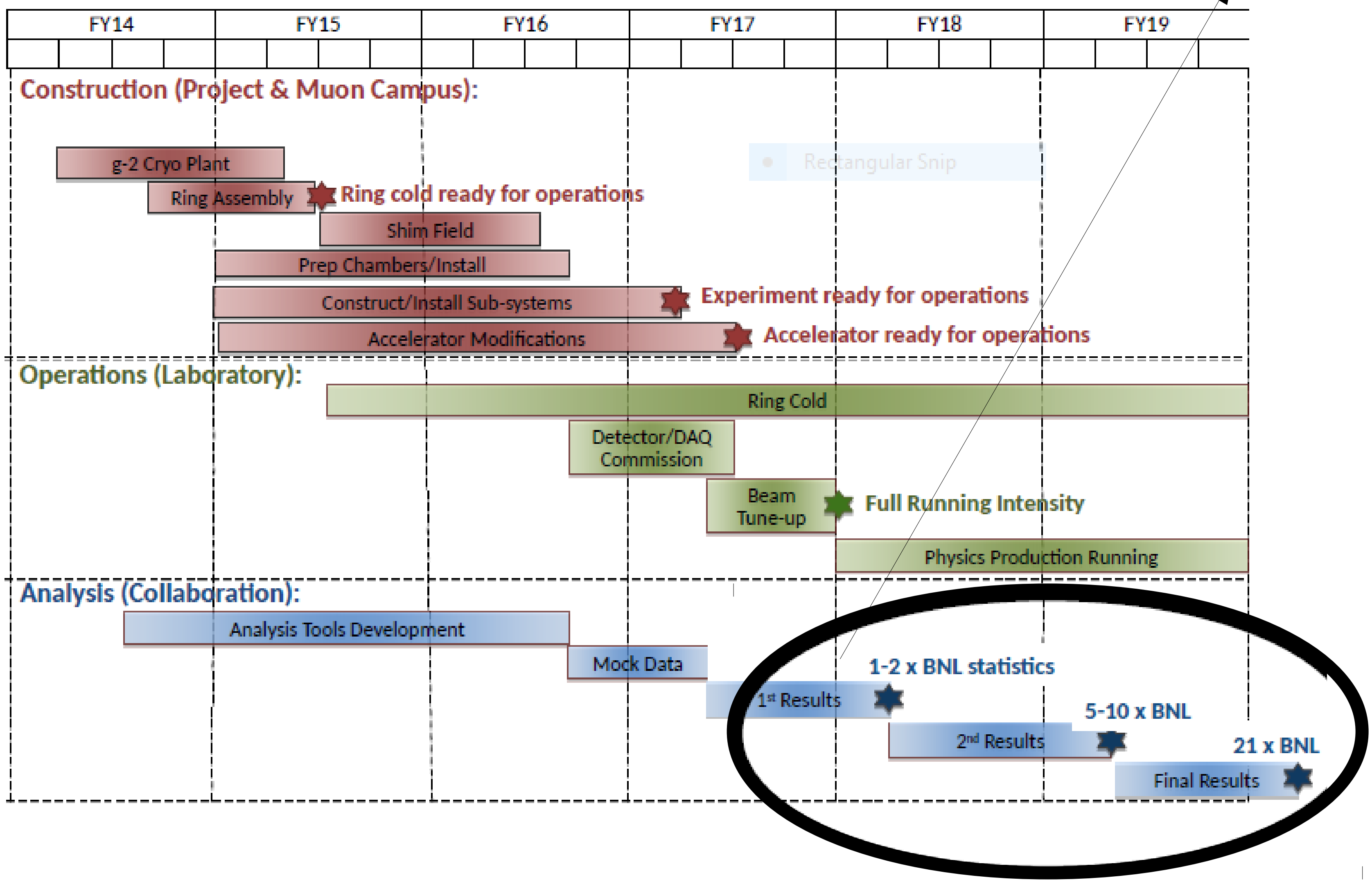
Improvements over *BNL*

- More muons => **more statistics (21x)**.
- Long decay channel **=>** **Less pion contamination.**
- Electrostatic quadrupoles to **focus the muon beam**.
- Segmented calorimeters (24 SiPM's) => **less pileup**.
- Laser Calibration System (Italian) => **long and short term stability**.

Schedule



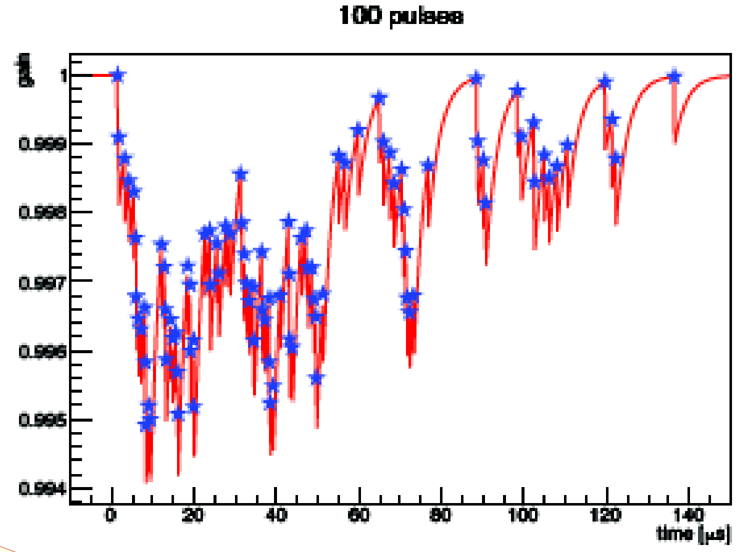
Number of high energy positrons as a function of time
data
fit
Fermilab Muon g-2 collaboration
Commissioning Run, June 2017
PRELIMINARY
time modulo 80 μs



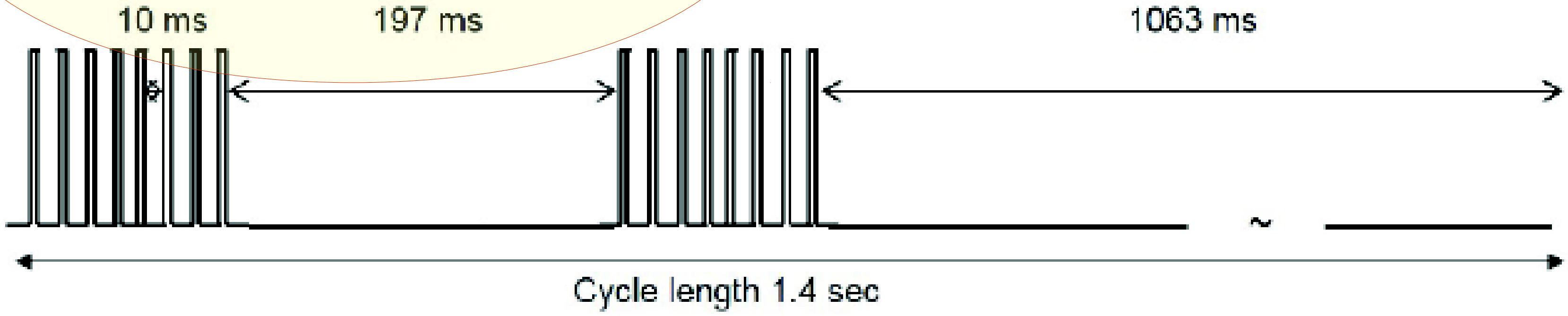
FY14
FY15
FY16
FY17
FY18
FY19
Construction (Project & Muon Campus):
g-2 Cryo Plant
Ring Assembly
Ring cold ready for operations
Shim Field
Prep Chambers/Install
Construct/Install Sub-systems
Experiment ready for operations
Accelerator Modifications
Accelerator ready for operations
Operations (Laboratory):
Ring Cold
Detector/DAQ Commission
Beam Tune-up
Full Running Intensity
Physics Production Running
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1-2 x BNL statistics
1st Results
5-10 x BNL
2nd Results
21 x BNL
Final Results

Why LASER Calibration System ?

- Mapping the short-term (700 mic. s) gain
  - *In-fill* pulses

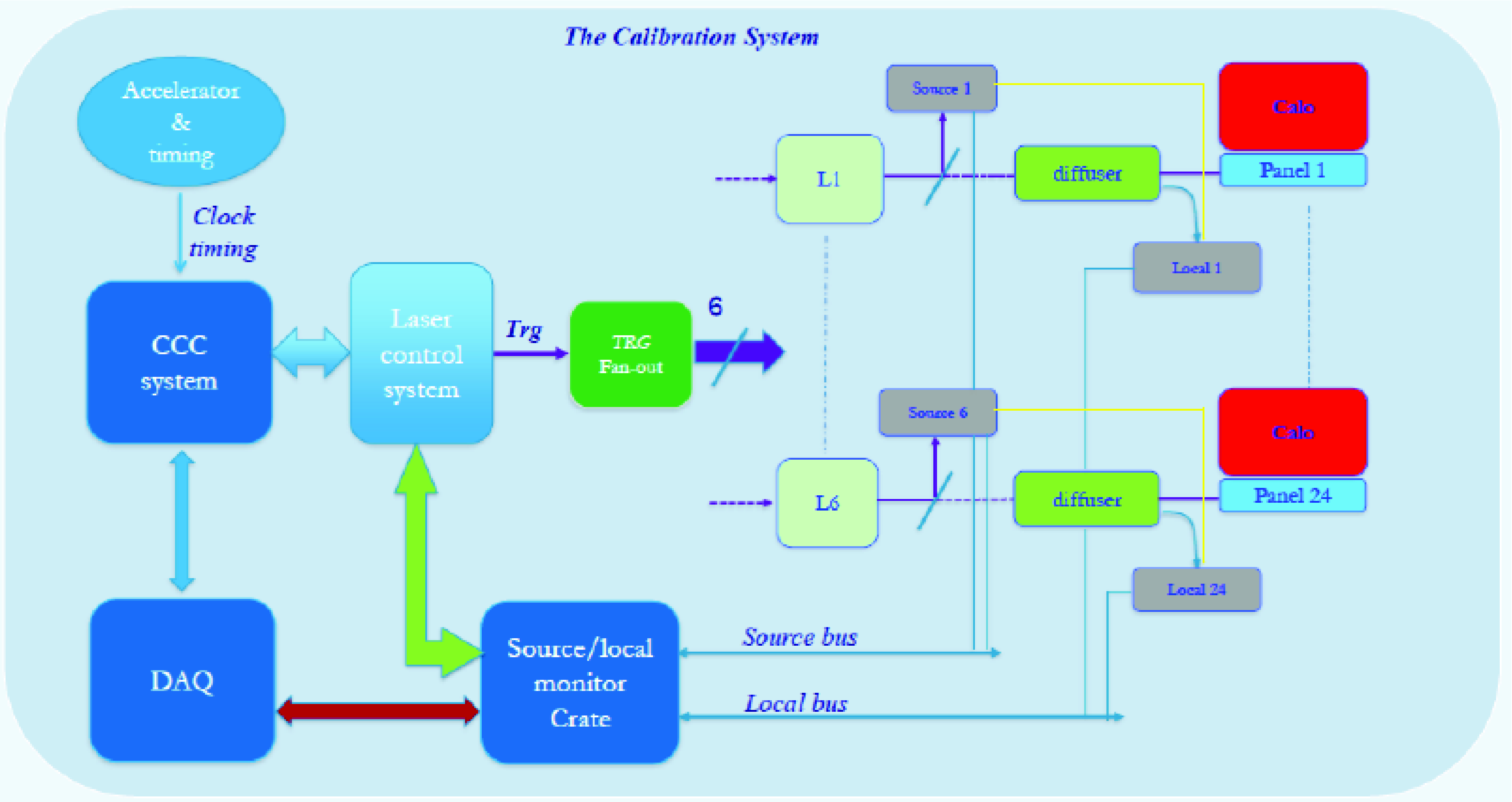


- Long term stability
  - *Out of fill* pulses

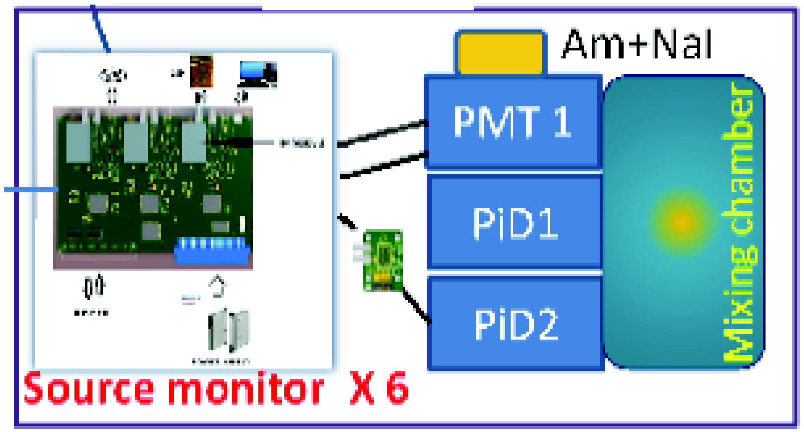


Structure and Components of The Calibration System

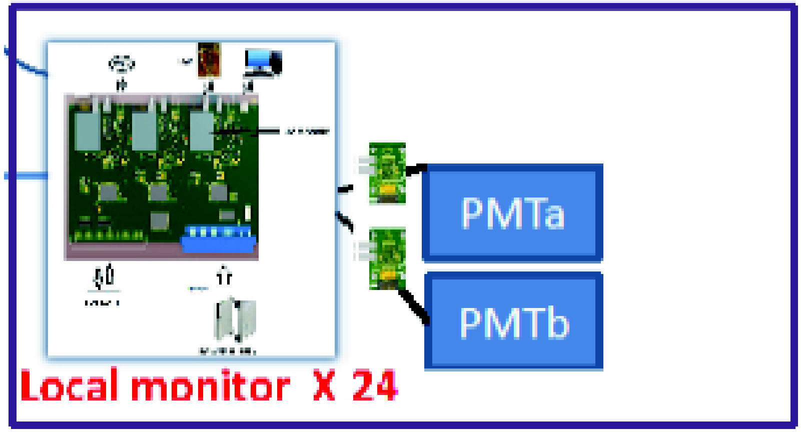
Laser Calibration System



Monitoring DAQ



6 SMs monitoring 6 laser sources



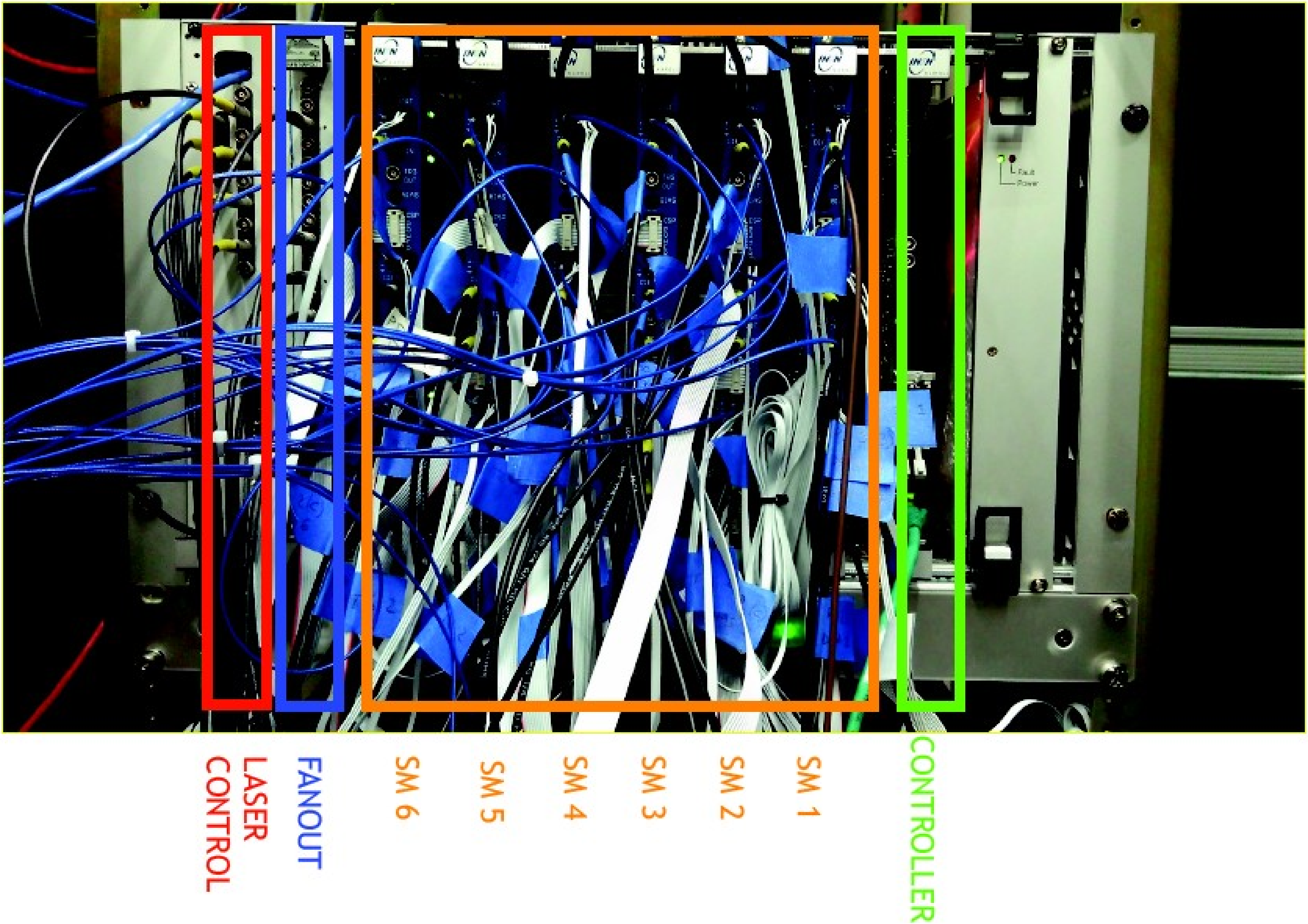
24 LMs connected to 24 calorimeters

Laser Control System

- Synced with the ***clock***, ***control*** and ***command*** system (CCC).
- Programmable generation of ***in-fill*****/*****out-of-fill*** pulses.
- ***Flight simulator*** : simulates a positron event.

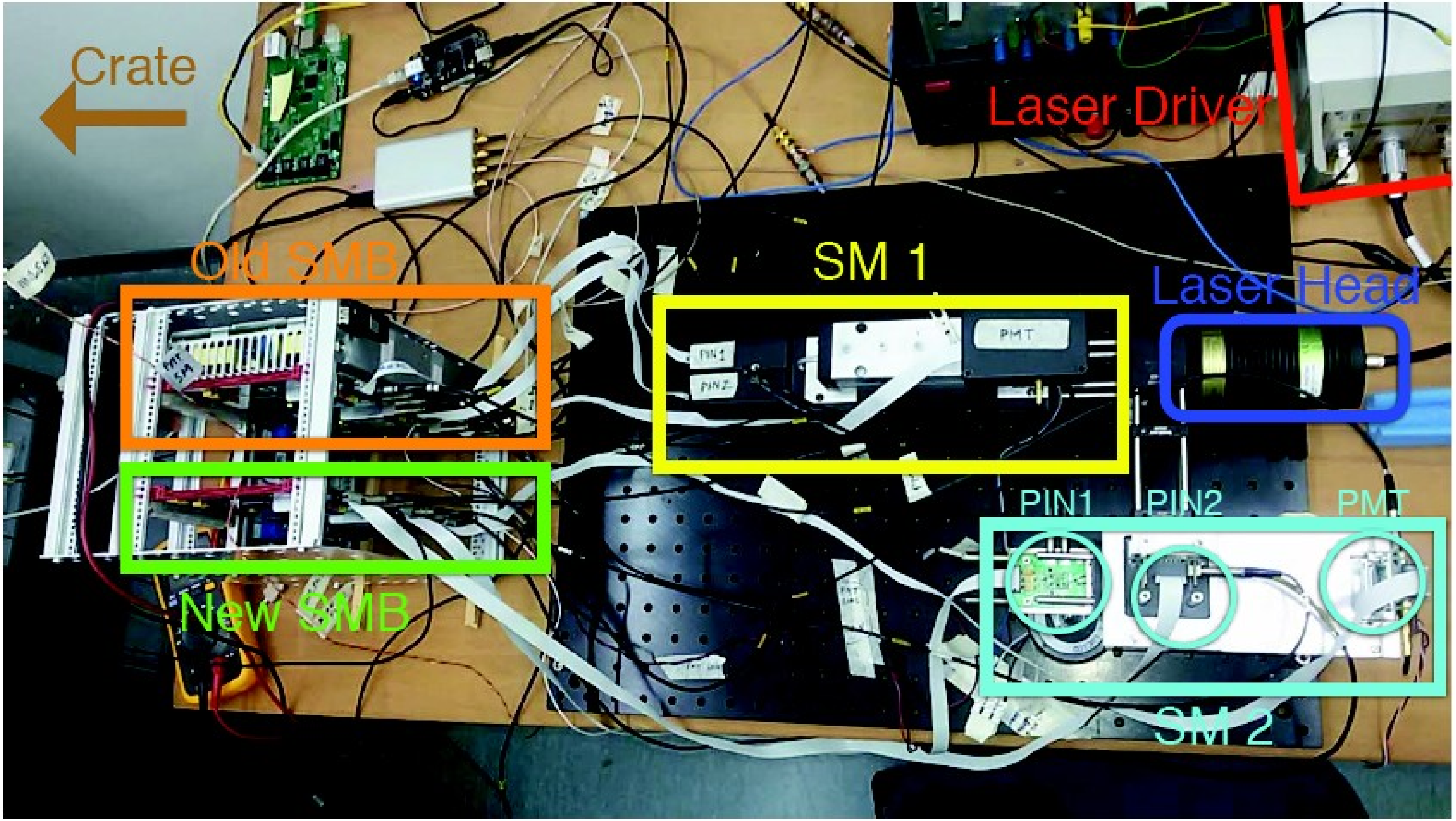
Source Monitors In Details

6 source Monitors (SM) @ *FNAL*



Test Stand @ *Napoli*

Test Stand @ *Napoli*

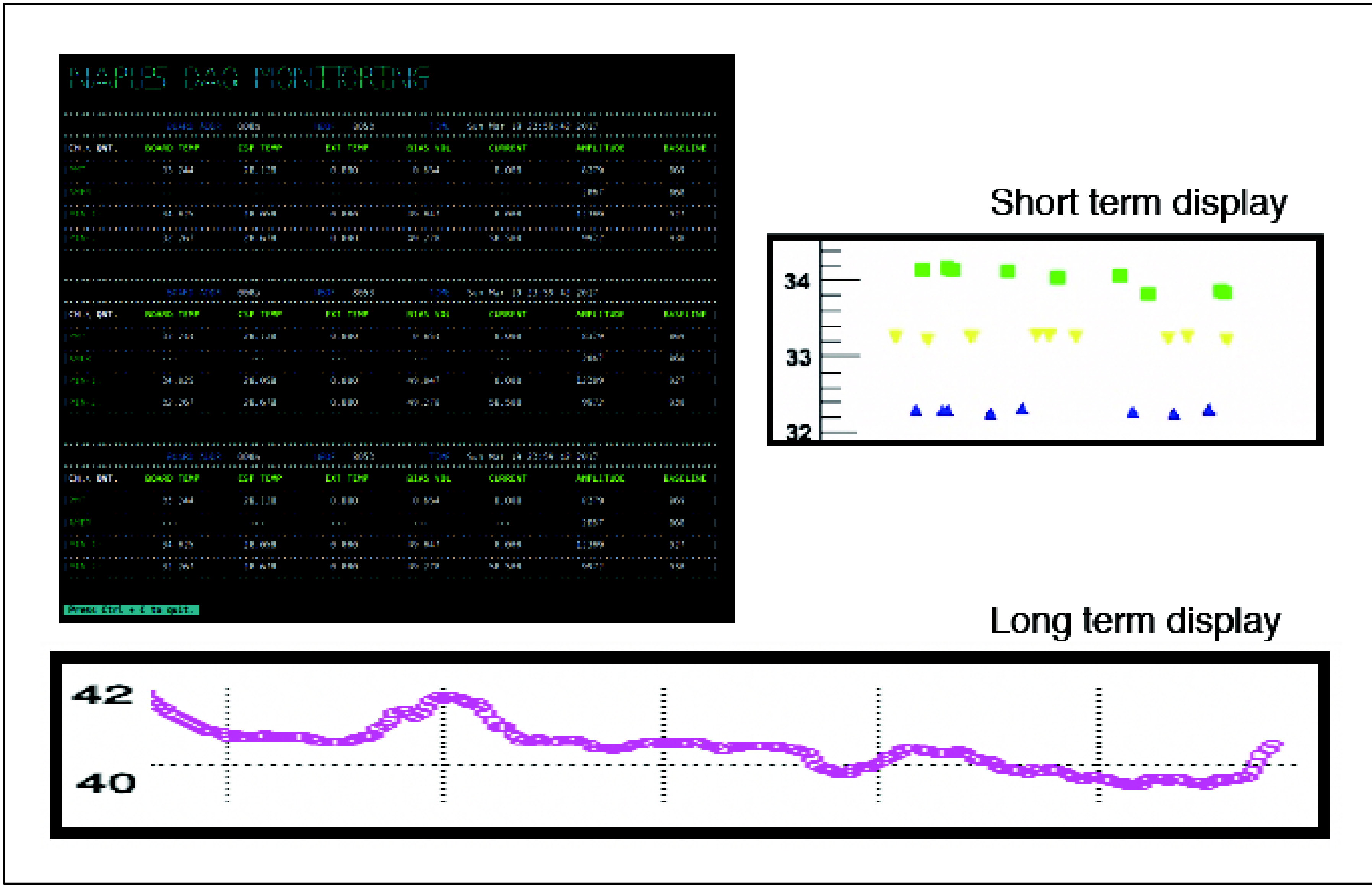


Naples' DAQ : On-line and Off-line Monitoring

Naples' DAQ @ *FNAL*

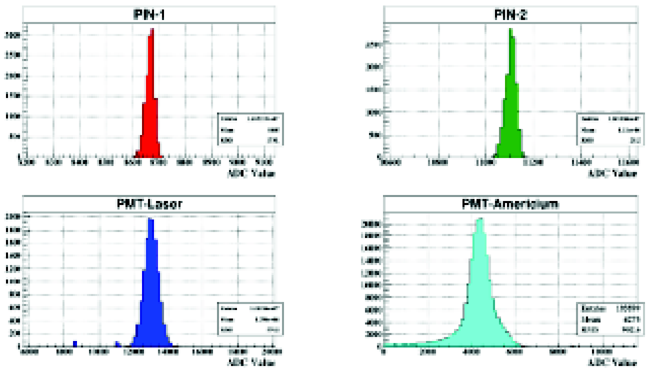
- Source monitoring **DAQ** is collecting data **continuously** even when there is **no external trigger** or the laser signals (Collecting **Americium**).
- We have powerful softwares that can :
  - Decode both online and offline data
  - Analyze both online and offline data

Naples' DAQ Monitoring @ *FNAL*

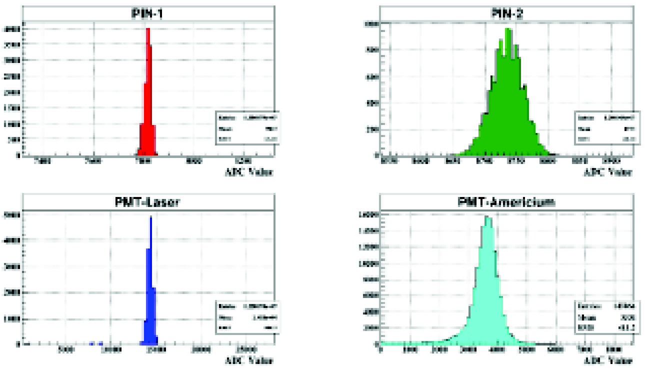


Performance and Stability

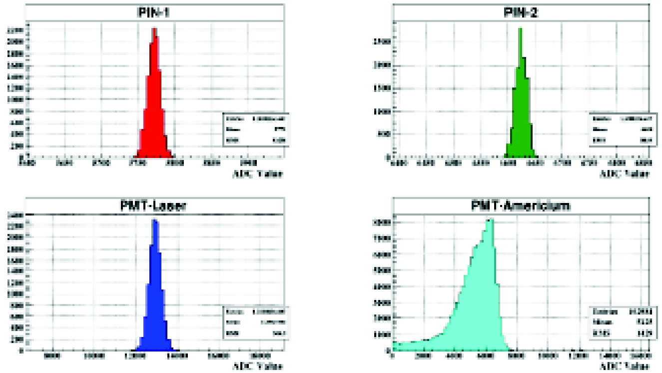
Board # 0001



Board # 0002

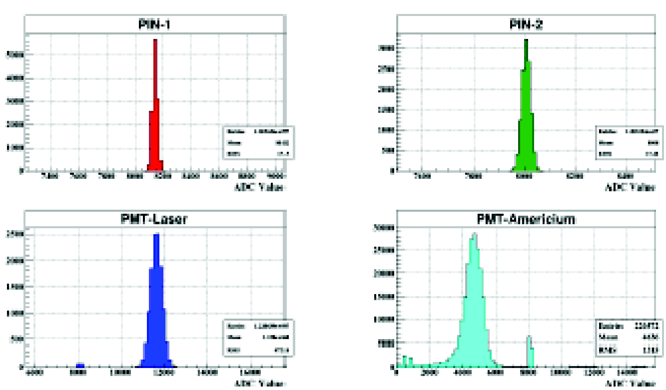


Board # 0003

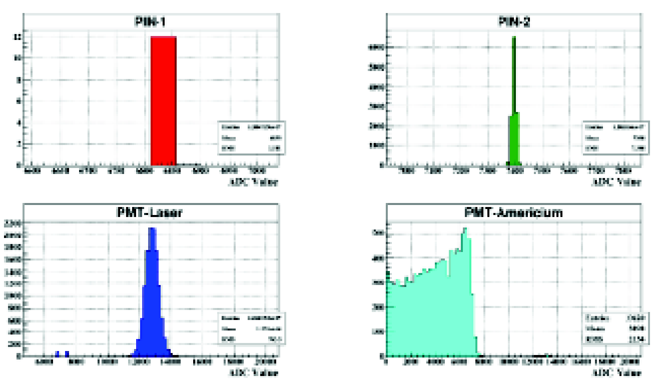


ALL SIX BOARDS

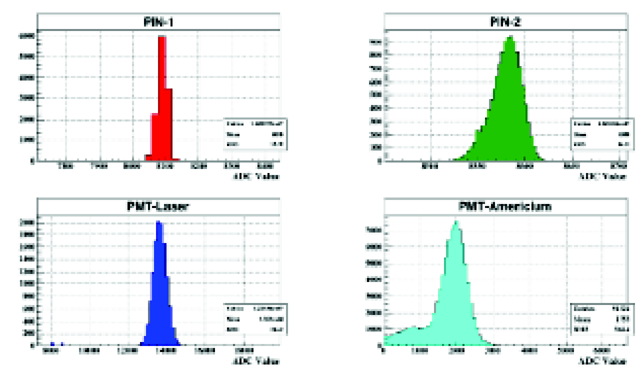
Board # 0004



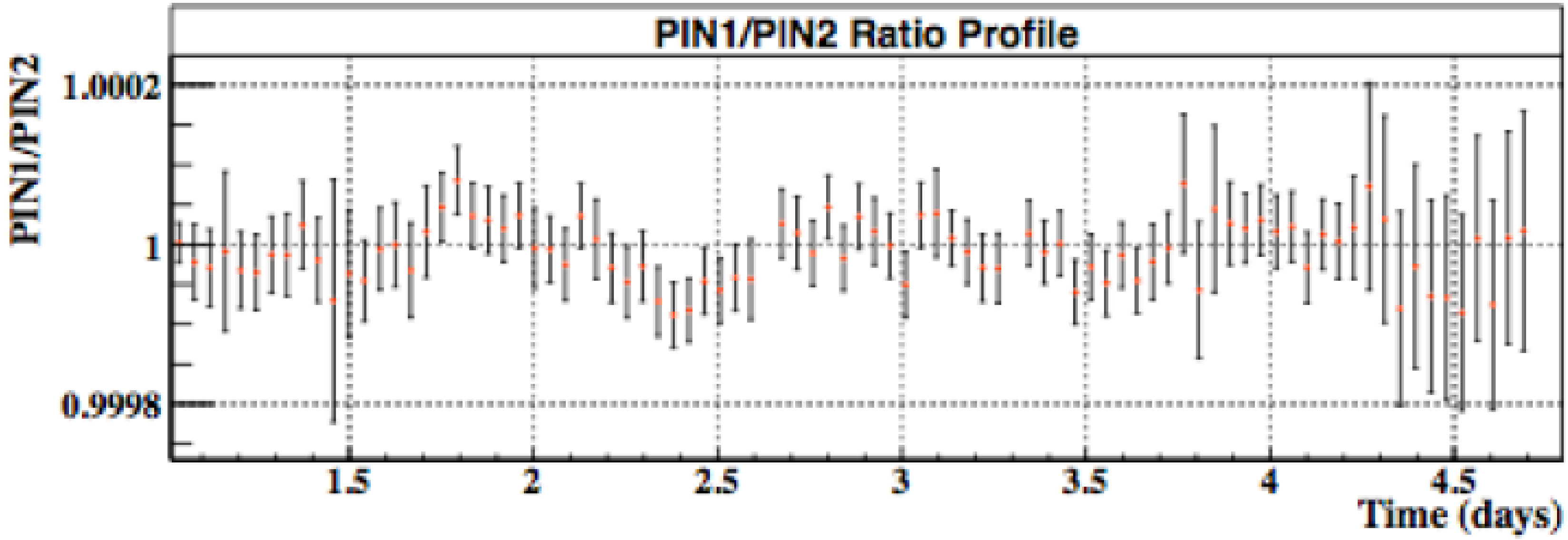
Board # 0005

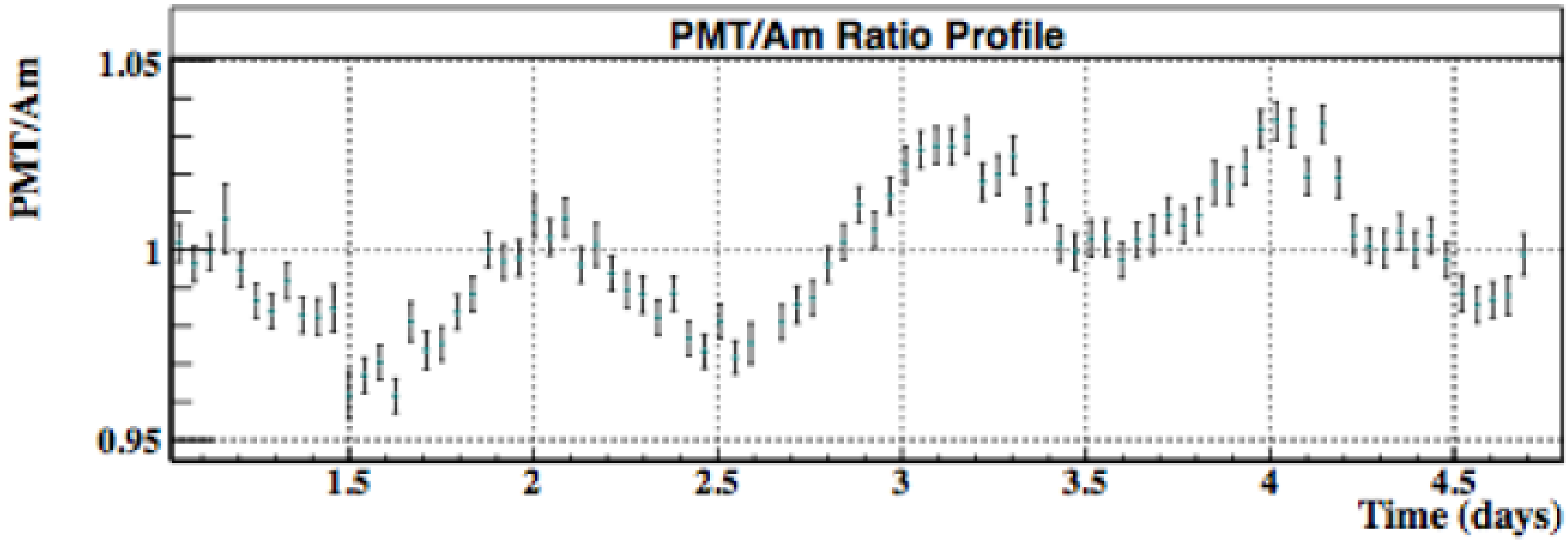


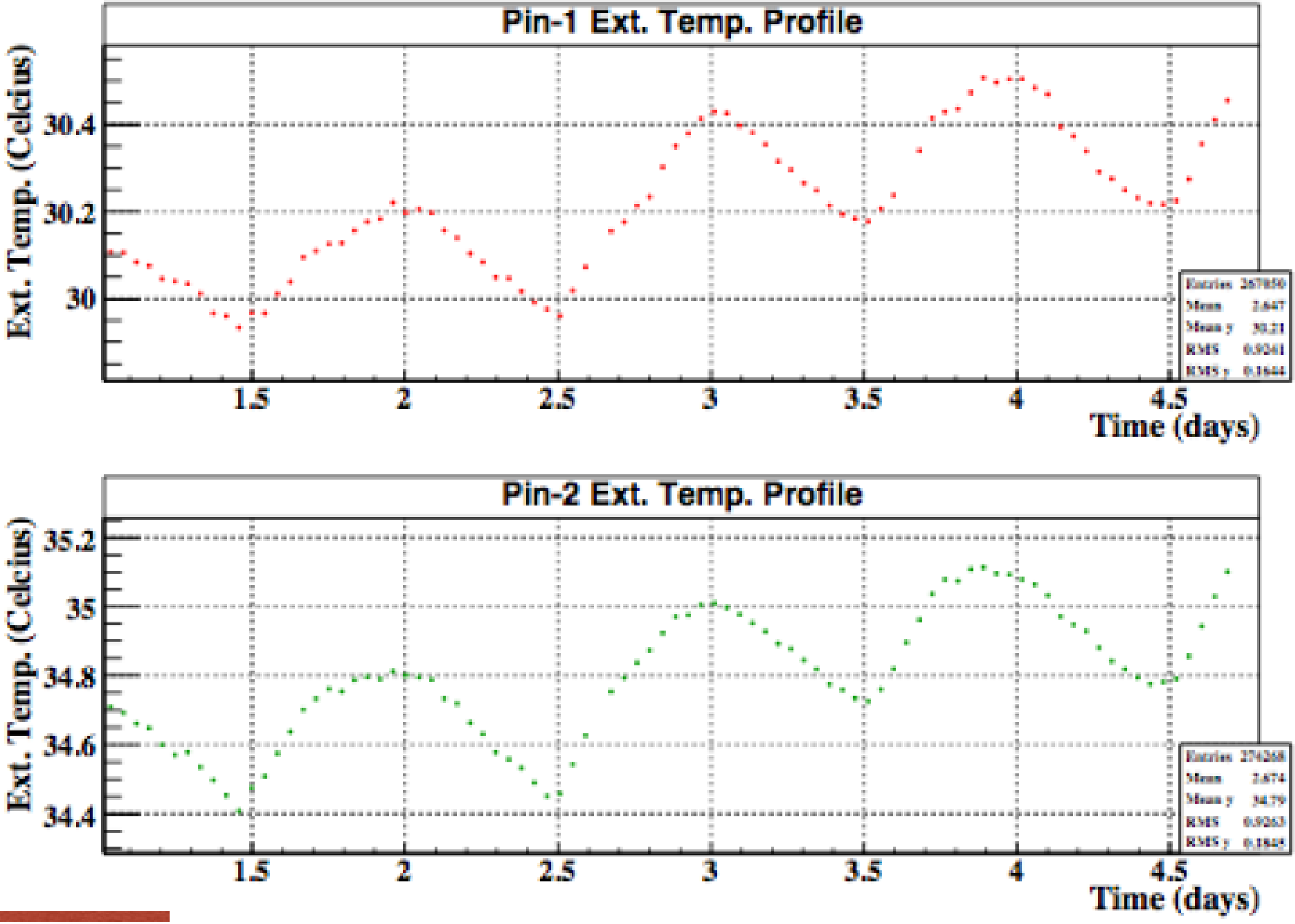
Board # 0006



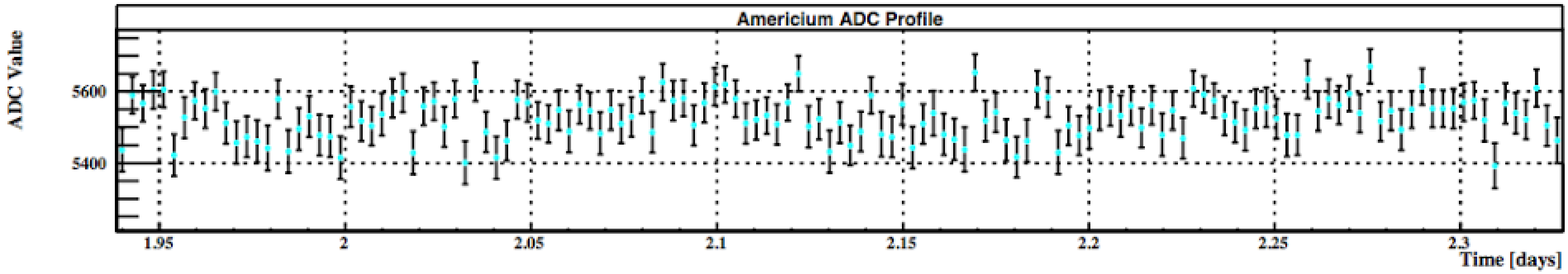
Data (July 1 – 4, 2017) Analysis

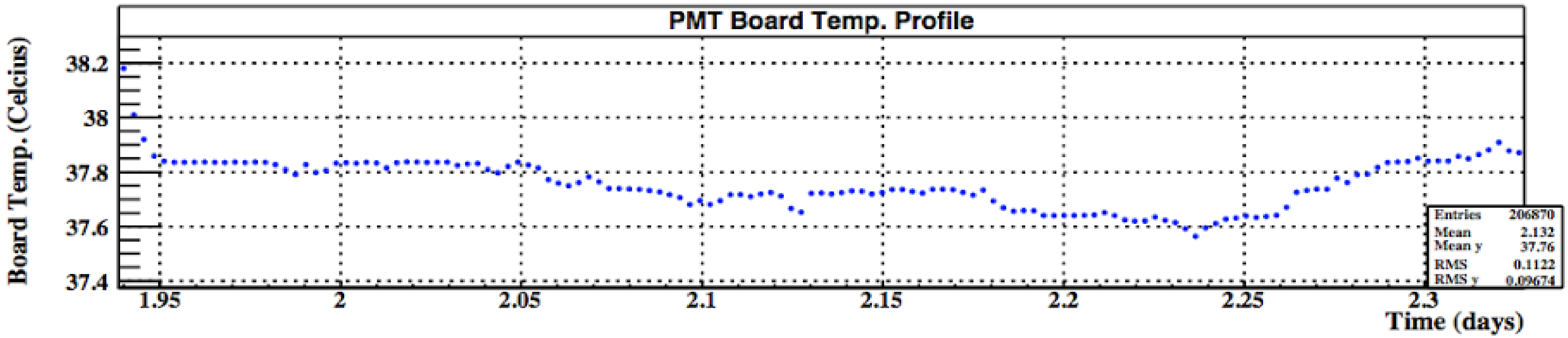




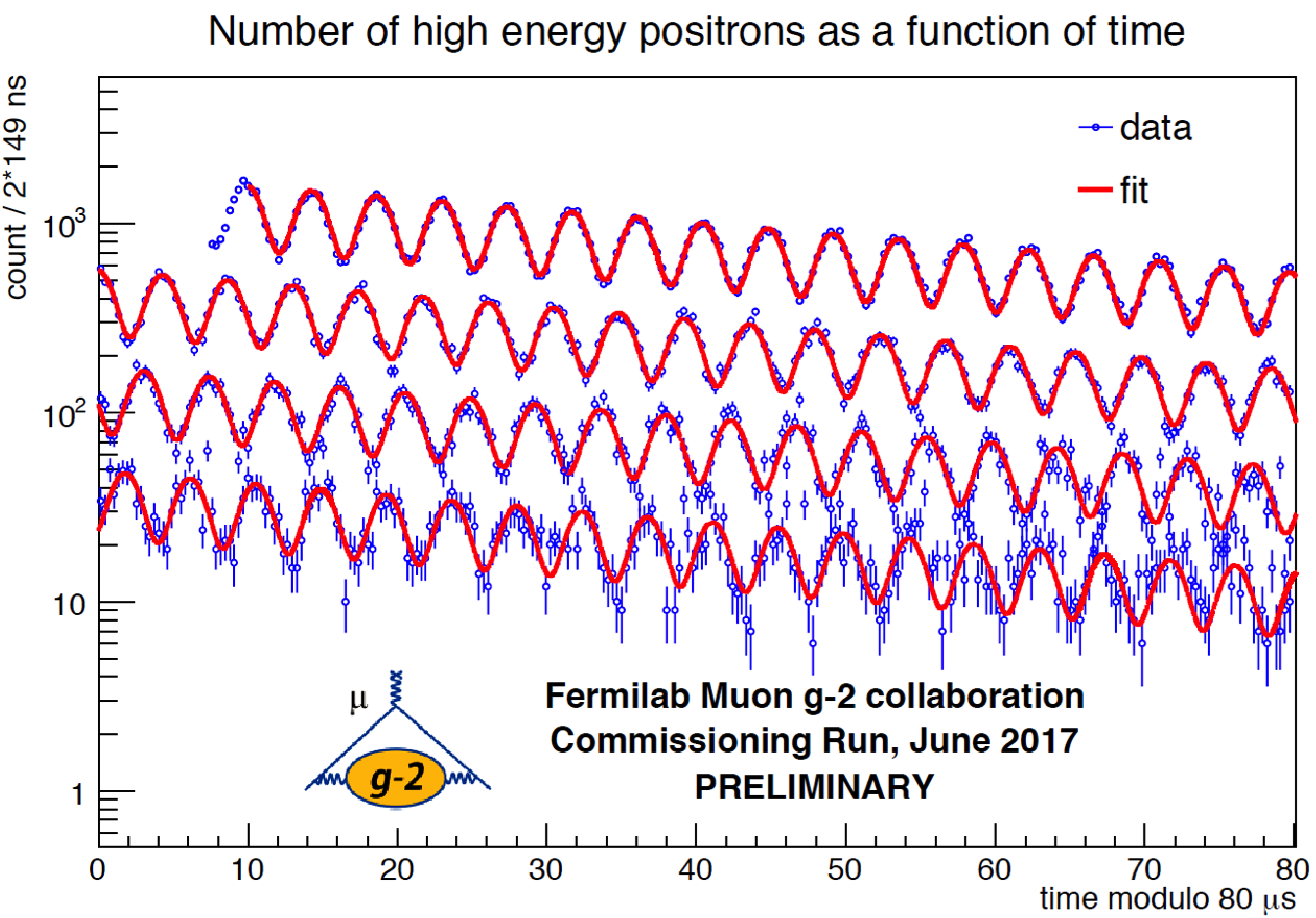

Pin-1 Ext. Temp. Profile
Ext. Temp. (Celcius)
Time (days)
Pin-2 Ext. Temp. Profile
Ext. Temp. (Celcius)
Time (days)

A Sample of the Americium Data Collected Over The Vacation





The First Wiggle Plot
June 2017



Number of high energy positrons as a function of time
count / 2*149 ns
data
fit
10^3
10^2
10
1
0
10
20
30
40
50
60
70
80
time modulo 80 μs
μ
g-2
Fermilab Muon g-2 collaboration
Commissioning Run, June 2017
PRELIMINARY

Summary...

- SM – *BNL* ~ **3.6 Sigma**, *FNAL* aims for **21 times** more statistics and will be **4 times** more precise hence a **7.5 Sigma** discrepancy (if central values stay fixed) is expected.
- All the **Source and Local Monitors** are in place and collecting data since last March. **Naples' DAQ** is collecting **Americium** data even when there's no **external trigger** or **Laser signal**.
- The **DAQ**, **Decoding**, **Analysis** and **Online Monitoring** softwares are ready and are currently in use**.**
- First **muon data** has already arrived and we have a ***wiggle plot.***

GRAZIE

BACKUP SLIDES

THEORY

Dirac equation and the magnetic moment of a lepton

Dirac equation in its covariant form looks like this:

$$[i\gamma^\mu \mathcal{D}_\mu - m_l]\ \Psi = 0 \tag{9}$$

where we have covariantized the derivative through minimal coupling to the external field $\mathcal{A}$, $\mathcal{D}_\mu = \partial_\mu - i\,e\,\mathcal{A}_\mu$ (covariant derivative with 4-potential $\mathcal{A}$), m_ℓ the mass of the lepton ℓ and Ψ ($= \{\psi_+, \psi_-\}$ column) is its 4-component spinor.

Dirac $\mapsto$Pauli : the "$g = 2$" factor

Pauli's theory can be shown to be a non-relativistic limit of the Dirac's theory. Equation (9) can be caste into the following form:

$$\begin{array}{rcrcl} (E - e\,\mathcal{A}_0)\,\psi_+ & - & \boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\,\boldsymbol{\mathcal{A}})\,\psi_- & = & m_\ell\,\psi_+ \\ -(E - e\,\mathcal{A}_0)\,\psi_- & + & \boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\,\boldsymbol{\mathcal{A}})\,\psi + - & = & m_\ell\,\psi_- \end{array} \tag{10}$$

where ψ_+ represents the particle part and the ψ_- is for the anti-particle. Where we have replaced the differential operators by their symbols, e.g. $E \equiv i\partial_0$ and $\boldsymbol{p} = -i\boldsymbol{\nabla}$, a weak-field limit $E - e\,\mathcal{A}_0 \approx m_\ell$ and the non-relativistic limit $\boldsymbol{p} \approx m_\ell\,\boldsymbol{v}$ of the second equation will look like:

$$\psi_- = \frac{1}{2m_\ell}\,\boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\,\boldsymbol{\mathcal{A}})\,\psi_+ \tag{11}$$

Plugging this in the first equation of (10) we get:

$$(E - m_\ell)\,\psi_+ = \frac{1}{2m_\ell}\left[\boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\,\mathcal{A})\right]^2\psi_+ + e\,\mathcal{A}_0\,\psi_+ \tag{12}$$

Where the classical non-relativistic energy is just the mass-energy subtracted part, so we can take $E - m = E_{non-rel} = i\partial_t$ and if we expand the red part keeping in mind that the **it** is a composite operator that operates on the wave-function ψ_+,

$$\left[\boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\,\mathcal{A})\right]^2\psi_+ = (\boldsymbol{p} - e\,\mathcal{A})^2\,\psi_+ + i\boldsymbol{\sigma}\cdot(\boldsymbol{p}\times\mathcal{A})\,\psi_+ + i\,e\,\sigma_k\,\underbrace{\epsilon_{kij}\,\mathcal{A}_i\,\mathcal{A}_j}_{\to 0}\,\psi_+ \tag{13}$$

the last term vanishes because $\mathcal{A}_i\mathcal{A}_j$ is symmetric while the Levicivita is not ! Plugging this result to Eq. (12) we arrive at the following final non-relativistic equation:

$$i\,\frac{\partial}{\partial t}\,\psi_+ = \frac{1}{2m_\ell}\left[(\boldsymbol{p} - e\,\mathcal{A})^2 - e\,\boldsymbol{\sigma}\cdot\boldsymbol{B}\right]\psi_+ + e\,\mathcal{A}_0\,\psi_+ \tag{14}$$

where the magnetic field is given by $(\boldsymbol{B})_k = i\,(\boldsymbol{p}\times\mathcal{A})_k = i\,\epsilon_{kij}\,\mathcal{F}_{ij}$, with $\mathcal{F}$ being the electromagnetic field-strength tensor. anyway second term inside the square-bracket is the interaction Hamiltonian of a lepton with spin $\boldsymbol{\sigma}/2$ in a magnetic field $\boldsymbol{B}$, let's write it down separately:

$$\mathcal{H} = -\frac{e}{m_\ell}\,\boldsymbol{s}\cdot\boldsymbol{B} \tag{15}$$

And we know that the interaction energy of a magnetic dipole with moment $\boldsymbol{\mu}$ in a magnetic field $\boldsymbol{B}$ is:

$$\mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} \tag{16}$$

Equating Eq. (15) and (17) we get:

$$\boldsymbol{\mu} = \frac{e}{m_\ell}\,\boldsymbol{s} = 2\times\frac{e}{2m_\ell}\,\boldsymbol{s} \tag{17}$$

Therefore, Dirac's equation predicts:

$$g = 2 \tag{18}$$

ANOMALOUS MAGNETIC MOMENT

$$g_{1-loop} = \frac{\alpha_{QED}}{\pi} \tag{20}$$

Therefore,

$$g_{QED} = 2 + \frac{\alpha_{QED}}{\pi} + \mathcal{O}(\alpha^2_{QED}) \tag{21}$$

And according to renormalization theory, g_{QED} is a series in α_{QED}. But we are interested in the deviation from $g = 2$, hence we define the anomalous magnetic moment:

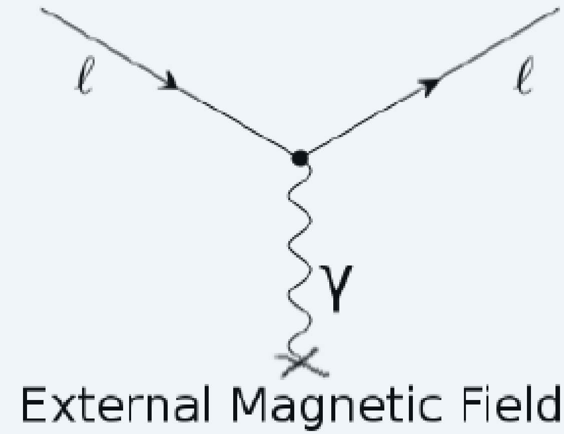
$$a_\ell = \frac{|\boldsymbol{\mu_\ell}|}{\mu_B} - 1 = \frac{g_\ell - 2}{2} \tag{22}$$

where μ_B is the Bohr-magnetin $(= e/m_\ell)$, $|\mu|_\ell$ and g_ℓ are the magnetic moment and g factor of lepton ℓ respectively. Therefore complete QED contribution to a_ℓ will be:

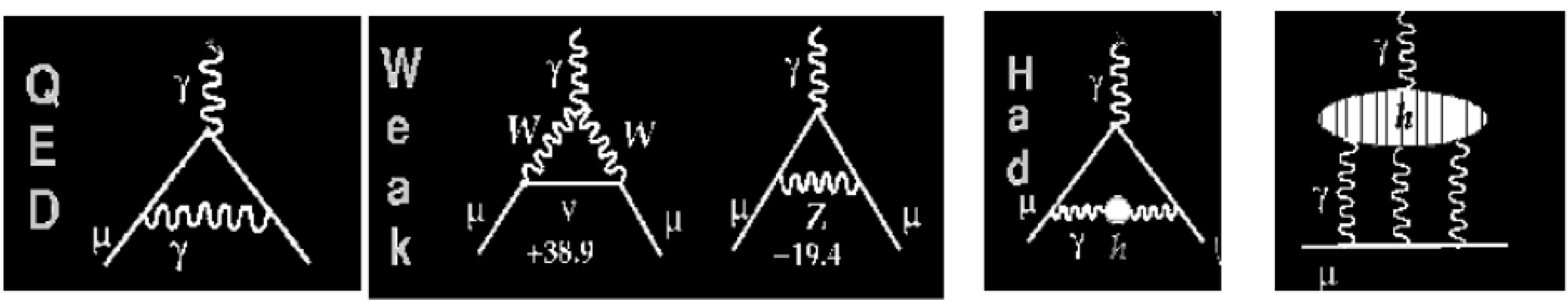
$$a_\ell = \sum_{n=0}^{\infty} C_n \, (\frac{\alpha_{QED}}{\pi})^n \tag{23}$$

Of course $C_0 = 0$ coming from the Dirac term and $C_1 = 1/2$ from the Schwingers'.

Tree level
contribution (g = 2)



Loop contributions (g – 2 =/= 0)



well known

significant work ongoing

HEAVY VIRTUAL PARTICLES

$$\delta a_\ell = F\left(\frac{m_\ell^2}{m_{\ell'}^2}\right)\left[\frac{\alpha_{QED}}{\pi}\right]^2 \tag{24}$$

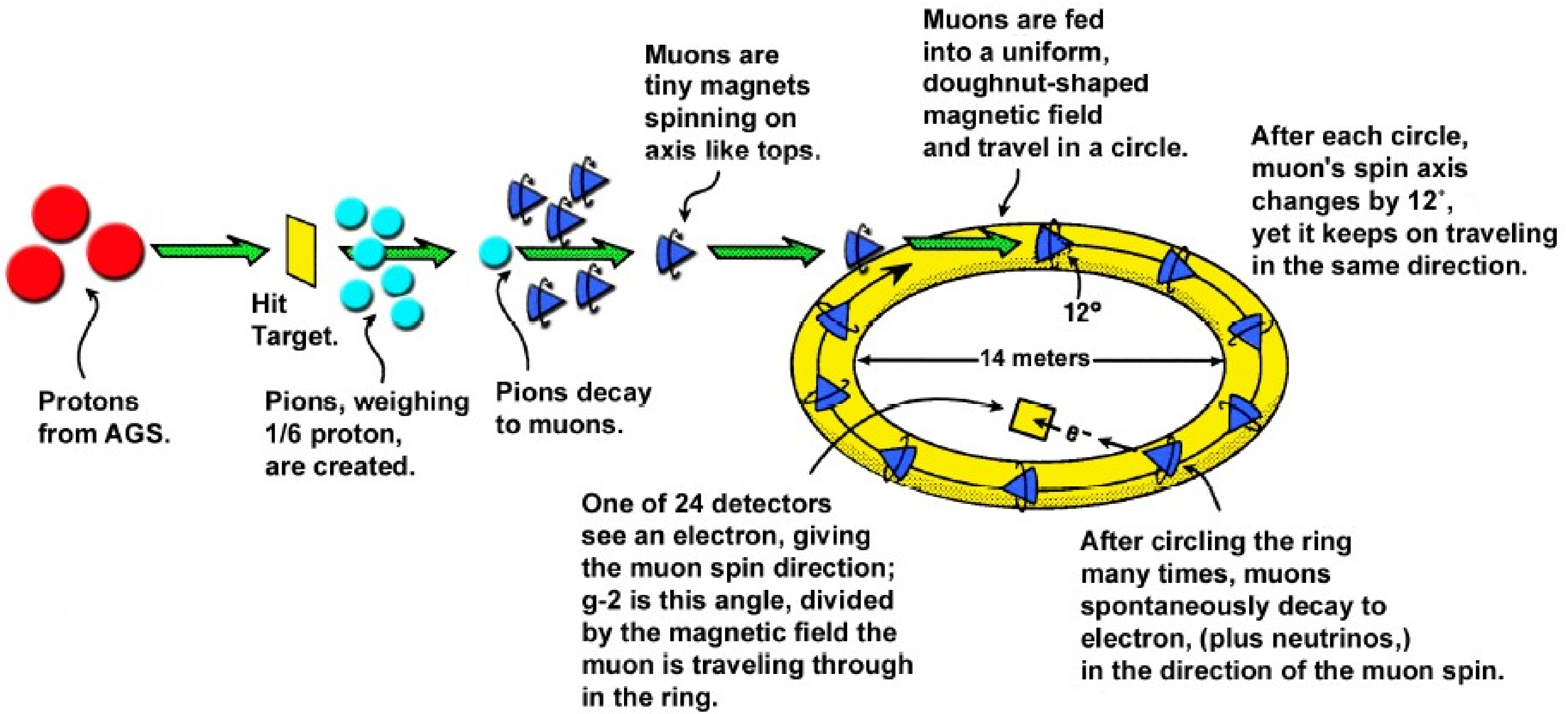
3 Anomalous Magnetic Moment of Muons

If we consider an unknown particle beyond standard model with mass M flowing in a loop (instead of a muon or a tau) as in the case of Fig. (4), such a particle will also have a contribution similar to the one described in Eq. (24),

$$\delta a_\ell \propto F'\left(\frac{m_\ell^2}{M^2}\right) \tag{25}$$

we can guess the properties (mass in this example) of such a particle by measuring anomalous magnetic moment of ℓ experimentally and then comparing with the theory. But, anomalous magnetic moment of an electron will of course be insensitive to new physics due to extremely low mass of electrons and τ is so short-lived ($2.906(10) \times 10^{-13}$ s) that designing such an experiment to measure a_τ is beyond the current technology.

EXPERIMENTS



EXPERIMENTS

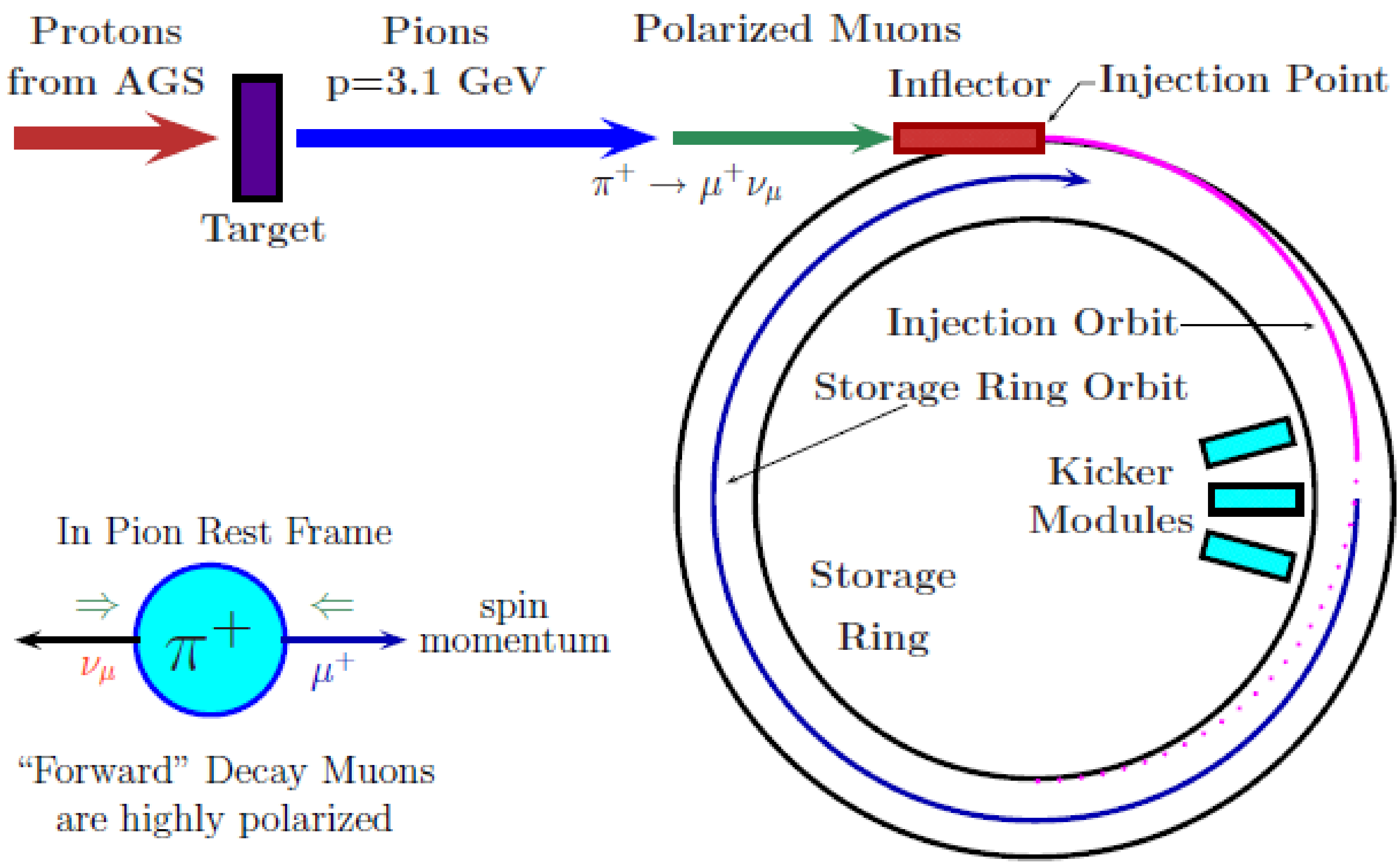


Fig. 4. The schematics of muon injection and storage in the $g-2$ ring.

Jegerlehner, Nyffeler, arXiv:0902.3360v1 [hep-ph]

$$\omega_a = \omega_s - \omega_c$$

$$\omega_c = \frac{eB}{m_\mu \gamma}, \quad \omega_s = \frac{eB}{m_\mu \gamma} + a_\mu \frac{eB}{m_\mu}, \quad \omega_a = a_\mu \frac{eB}{m_\mu}$$

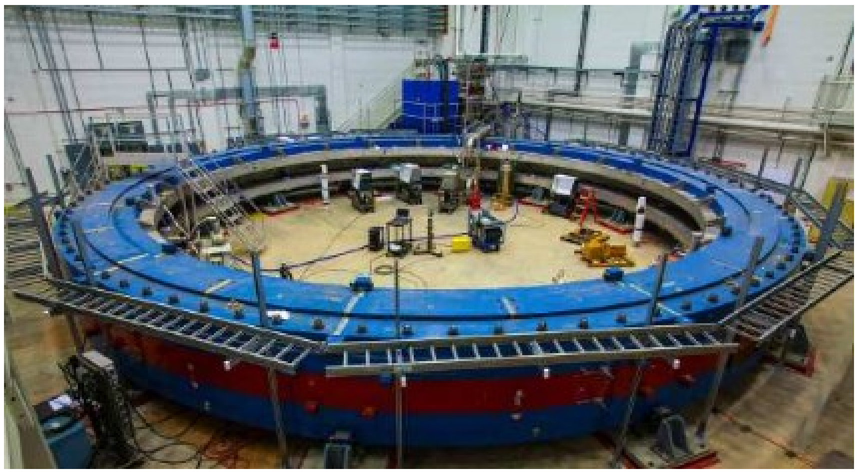
0

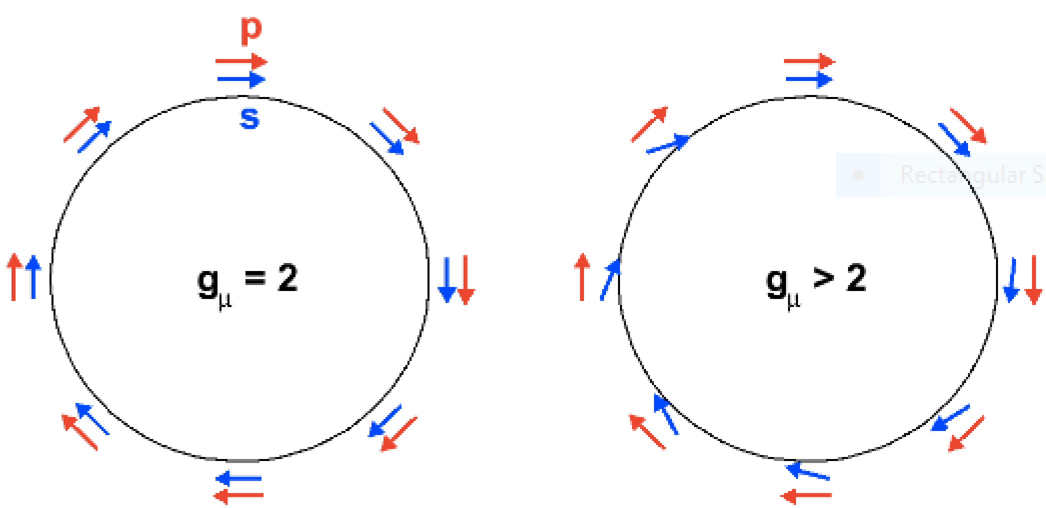
$$\vec{\omega_a} = \frac{e}{m_\mu}\left(a_\mu \vec{B} - \left[a_\mu - \frac{1}{\gamma^2 - 1}\right] \vec{v} \times \vec{E}\right)$$

$$\gamma = \sqrt{1 + 1/a_\mu} = 29.3$$

$$E_{\text{magic}} = \gamma m_\mu \simeq 3.098 \text{ GeV}$$

g-2 Experiment Basics...





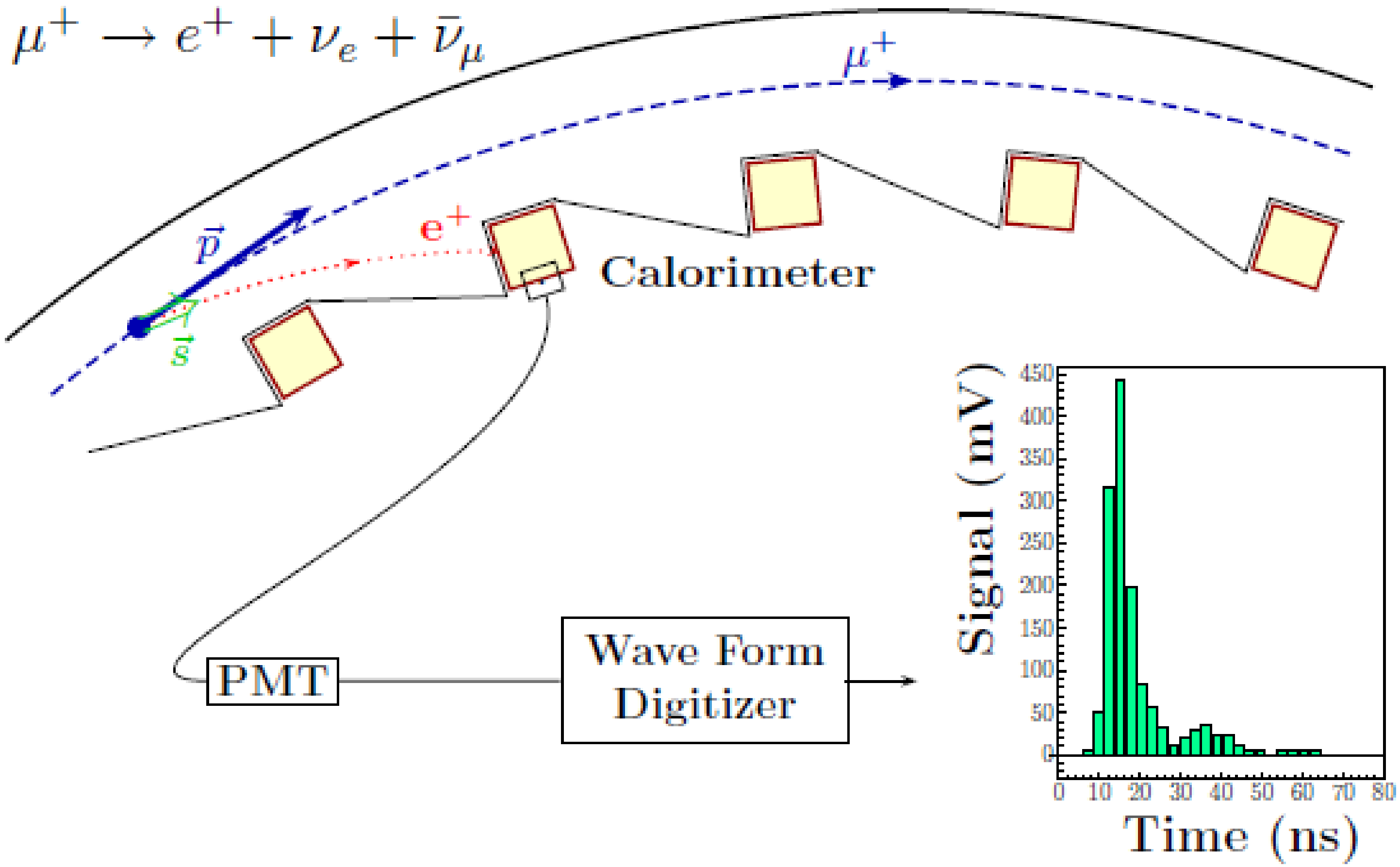


Fig. 5. Decay of μ^+ and detection of the emitted e^+ (PMT=Photomultiplier).

$$N(t) = N_0(E)\ \exp\left(\frac{-t}{\gamma\tau_\mu}\right)\ [1 + A(E)\ \sin(\omega_a t + \phi(E))]$$

$$A(E_e) \doteq \frac{1 - 2x_e}{3 - 2x_e}$$

Jegerlehner, Nyffeler, arXiv:0902.3360v1 [hep-ph]

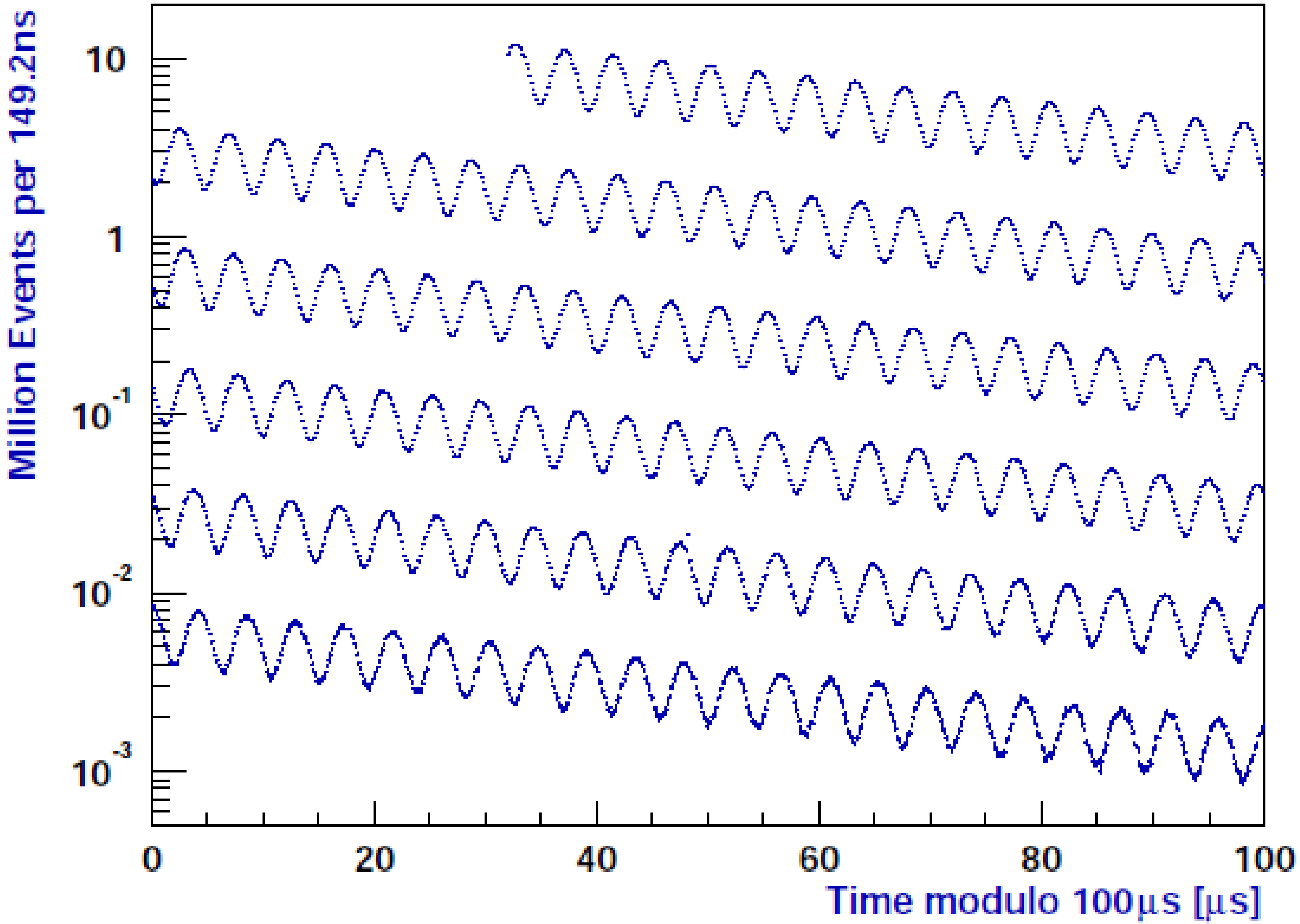


Fig. 6. Distribution of counts versus time for the 3.6 billion decays in the 2001 negative muon data–taking period [Courtesy of the E821 collaboration. Reprinted with permission from [92]. Copyright (2007) by the American Physical Society].

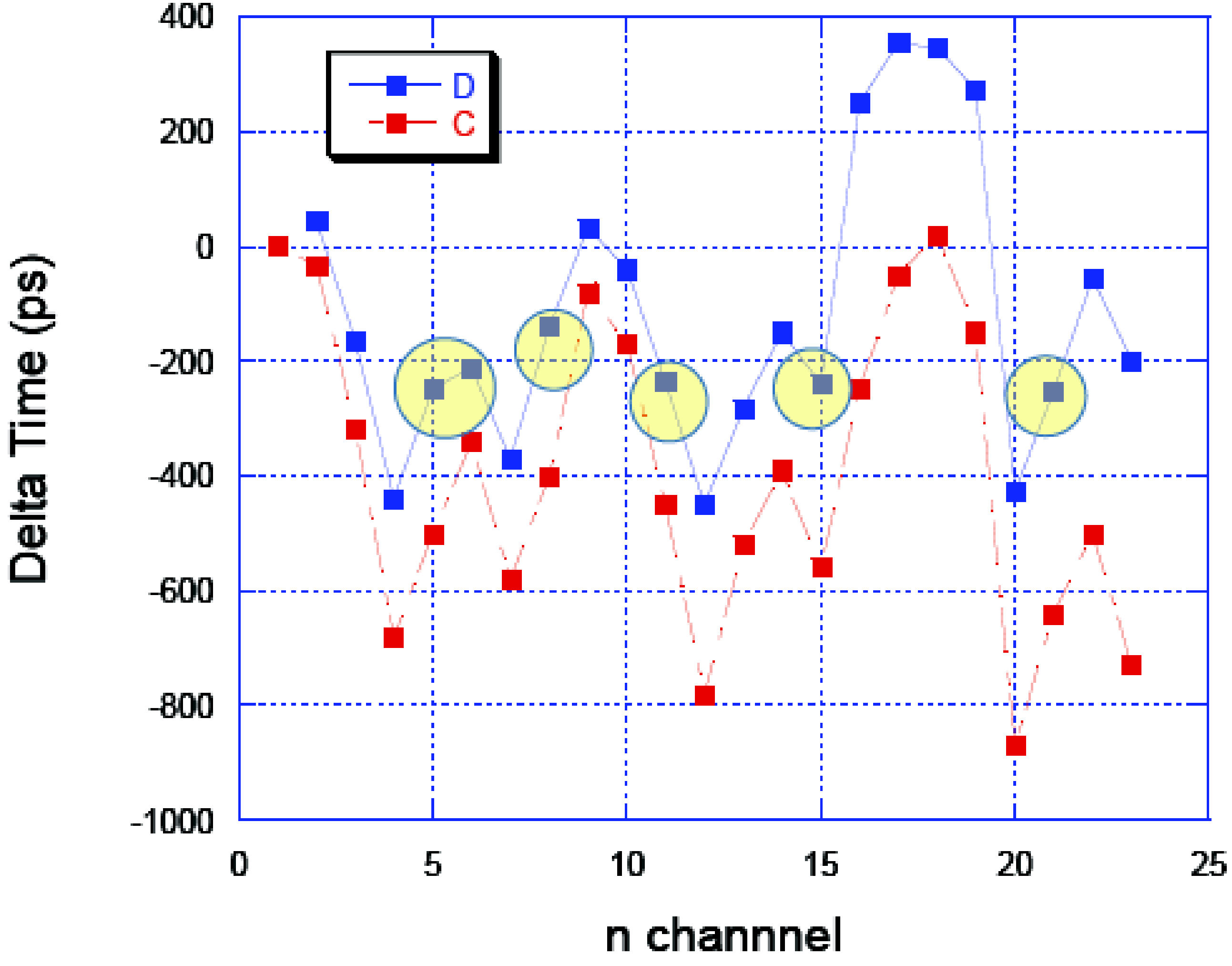
Jegerlehner, Nyffeler, arXiv:0902.3360v1 [hep-ph]

FCCP 2017

Daisuke Nomura

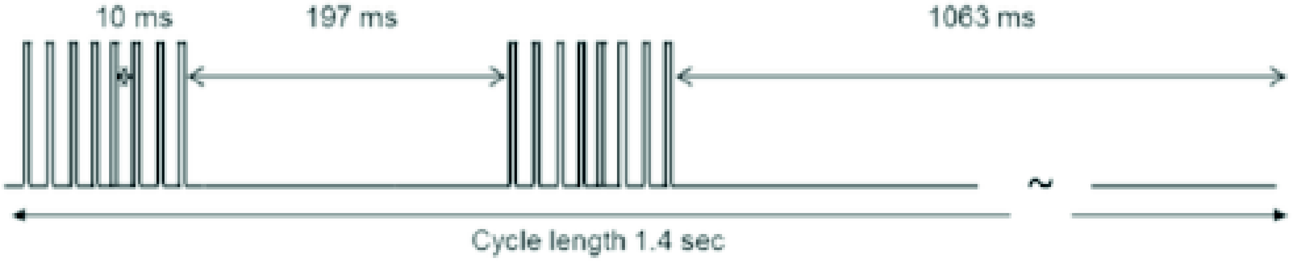
	2011		2017	*to be discussed
QED	11658471.81 (0.02)	⟶	11658471.90 (0.01)	[Phys. Rev. Lett. 109 (2012) 111808]
EW	15.40 (0.20)	⟶	15.36 (0.10)	[Phys. Rev. D 88 (2013) 053005]
LO HLbL	10.50 (2.60)	⟶	9.80 (**2.60**)	[EPJ Web Conf. 118 (2016) 01016]*
NLO HLbL			0.30 (0.20)	[Phys. Lett. B 735 (2014) 90]*
	HLMNT11		**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	

Fan-out



D
C
400
200
0
-200
-400
-600
-800
-1000
0
5
10
15
20
25
Delta Time (ps)
n channnel

Accelerator cycle @ FNAL



3 different time gaps between Fill windows

- 10 ms
- ~200 ms
- ~1000 ms

BOS pulse from CCC used to codify four different in-fill/inter-fill programs

New firmware/software update to manage the new interface with CCC system