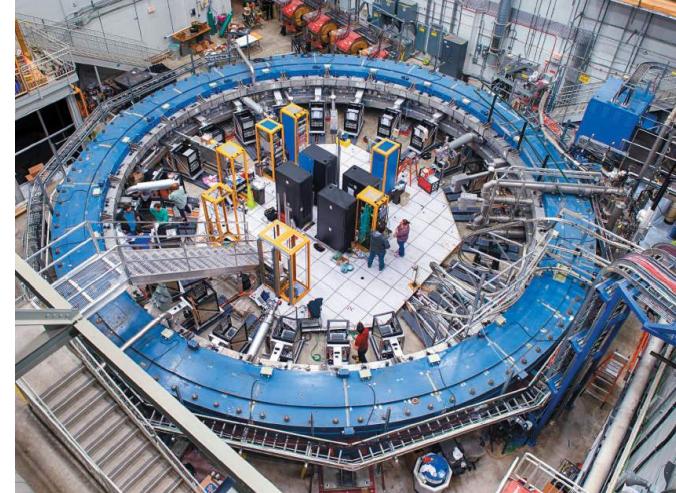


Misura del momento magnetico anomalo del muone ad altissima precisione

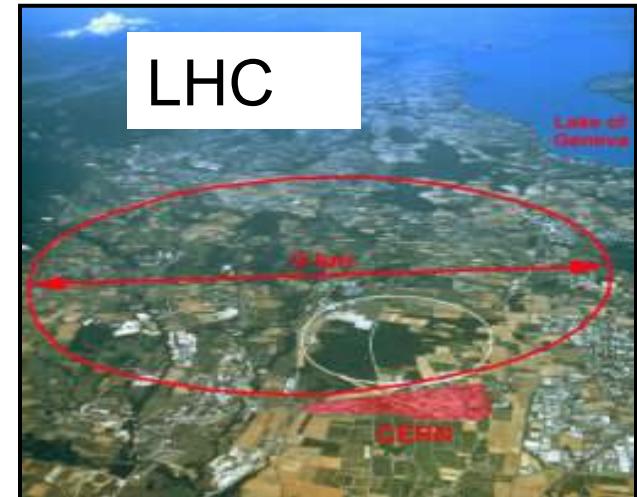
Graziano Venanzoni
INFN/PI



Seminario al CdS Pisa, 31/05/17

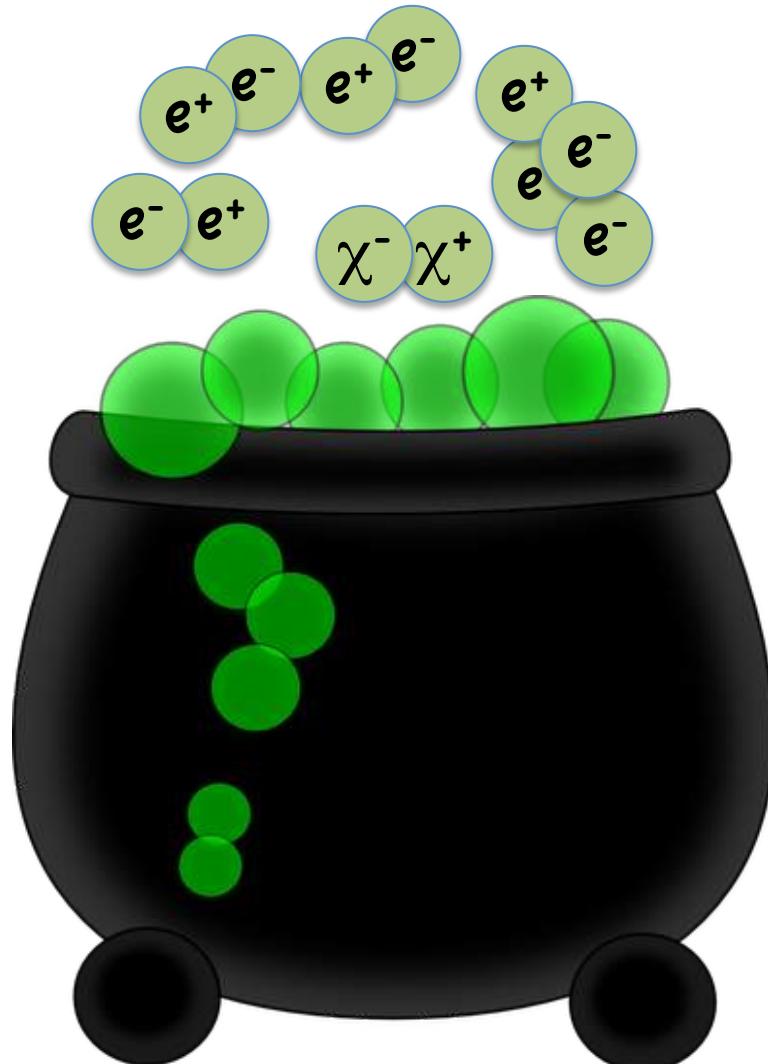
Due strade per scoprire nuova fisica

- **L'Alta Energia:** si progettano macchine a sempre più alta energia (LHC, ILC/Fcc) e si cercano nuove “particelle” di alta massa (osservazione diretta). Grandi apparati e collaborazioni.
- **L'Alta Intensità**: attraverso misure di precisione si cercano effetti di nuova fisica a bassa energia (si misurano parametri noti e si cercano deviazioni dalla teoria). Apparati e collaborazioni di dimensioni modeste, altissima statistica



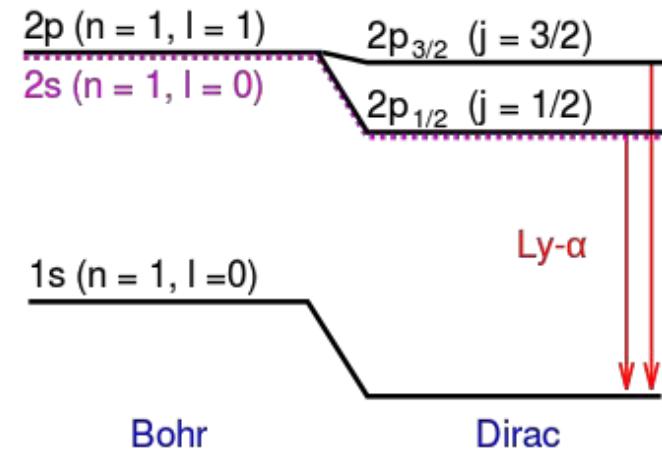
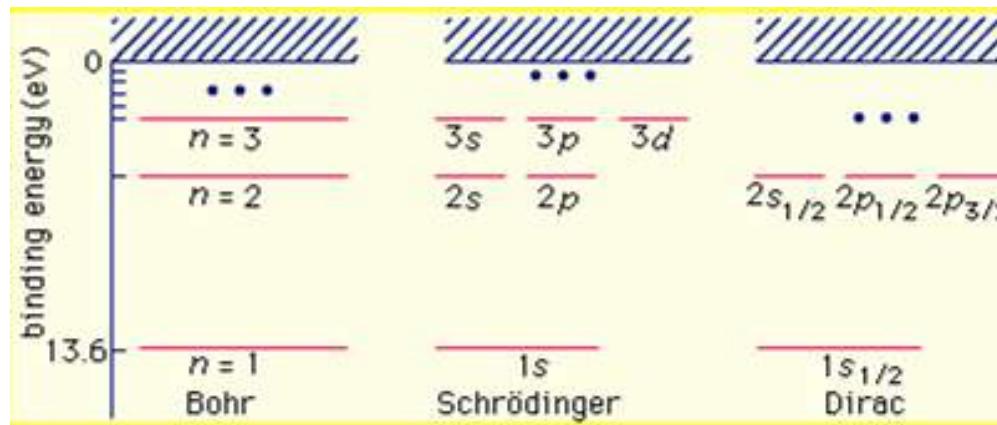
Perché “funziona” l’alta intensità?

- La teoria dei campi (Relatività+ Meccanica Quantistica) ci insegna che il vuoto e’ riempito di coppie di particelle e di antiparticelle che esistono per tempi brevissimi e sono perciò dette virtuali. Così come le bolle d’aria che si formano alla base di una pentola messa a riscaldare risalgono per venire a contatto con la superficie dell’acqua, queste particelle virtuali producono effetti tangibili ai processi fisici che coinvolgono particelle elementari reali.



1947: Effetto di spostamento del livello $2S_{1/2}$ ("Lamb shift")

- Spostamento dello stato $2S_{1/2}$ di + 1050 MHz (4 μeV , rispetto ai $\sim 10 \text{ eV}$ dello stato $2S_{1/2}$)

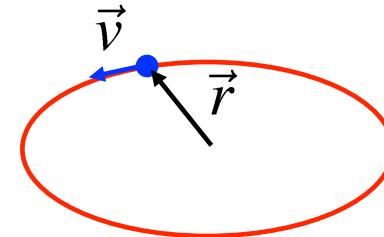


- Lo spostamento era dovuto all'interazione dell'elettrone con le particelle **virtuali** del **vuoto** (γ ed elettroni virtuali che producevano correzioni di massa, carica e di momento magnetico)
- Tuttavia queste **correzioni** non erano facili da calcolare

Il fattore giromagnetico dell'elettrone g

- Una particella carica che ruota ha un momento angolare L e un momento magnetico μ

$$\mu = \frac{q}{2m} \vec{L}$$



- Il rapporto tra $\mu/(q/2m)L$ e' chiamato fattore giromagnetico g . Classicamente **$g=1$**
- Per un'elettrone l'eq. di Dirac predice un momento magnetico *intrinseco* (ossia dovuto allo spin)) **2** volte quello atteso classicamente, ossia **$g=2$**

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

- Predizione in accordo con la congettura di Goudsmit e Uhlenbeck. Grande trionfo dell'equazione di Dirac!

1947: Misura del momento magnetico (anomalo) dell'elettrone

- Kusch e Foley studiando la risposta degli atomi di Gallio ad un campo magnetico esterno trovarono un valore per il fattore giromagnetico **g** dell'elettrone di ~0.1% piu' grande di quanto predetto dalla teoria di Dirac

PHYSICAL REVIEW

VOLUME 74, NUMBER 3

AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY

Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and 2P_1 states, In in the 2P_1 state, and Na in the 2S_1 state has been made by a measurement of the frequencies of lines in the hfs spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

$$g = 2(1.00119 \pm 0.00005); a = \frac{(g - 2)}{2} = 0.00119 \pm 0.00005$$

a= 0 secondo l'equazione di Dirac

Premi Nobel

- La crisi e il trionfo della QED negli anni del dopoguerra fu uno dei capitoli piu' avvincenti della fisica moderna che ebbe diversi protagonisti i quali furono tutti insigniti del premio Nobel.
- E sicuramente un luogo: la conferenza di Shelter Island (1947)



Julian Schwinger
Premio Nobel 1965



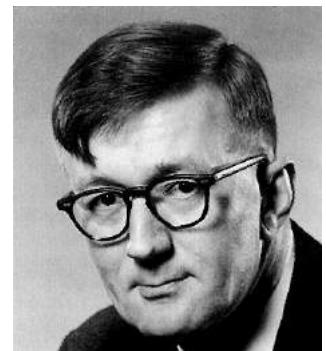
Richard P. Feynman
Premio Nobel 1965



Sin-Itiro Tomonaga
Premio Nobel 1965



Willis E. Lamb
Premio Nobel 1955



Polykarp Kusch
Premio Nobel 1955

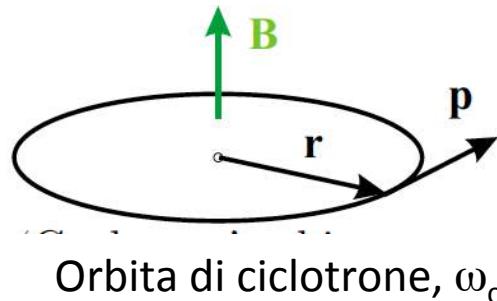
Il momento magnetico anomalo dell'elettrone e del muone ($a=(g-2)/2$)

- Dal 1947 nei successivi 60 anni la misura del momento magnetico anomalo dell'elettrone e del muone (suo fratello maggiore, con una massa 210 volte quella dell'e-) è andata raffinandosi, migliorando in precisione di un fattore 10^8 (passando da una precisione del 4×10^{-2} a 2×10^{-10} (nel caso dell'elettrone), 5×10^{-7} nel caso del muone)
- Anche la predizione teorica è andata via via raffinandosi raggiungendo una precisione simile
- Nonostante a_μ sia stato misurato ad una precisione più bassa (~ 1000) rispetto all'elettrone è $\sim 4 \times 10^4$ ($= m_\mu^2/m_e^2$) volte più sensibile ai contributi di nuova fisica. Quindi più interessante (al momento)!
- Come si misura il momento magnetico anomalo del muone (ed elettrone) e che cosa sono questi contributi di nuova fisica?

Come si misura l'anomalia magnetica?

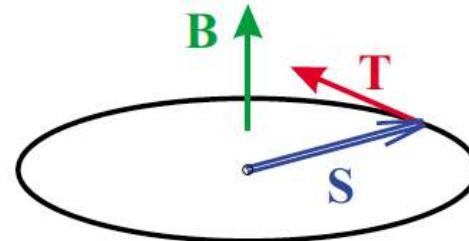
- Una particella carica con spin posta in campo magnetico (uniforme) ruota in un orbita circolare con frequenza angolare (chiamata di ciclotrone):

$$\omega_c = \frac{qB}{m}$$



- La presenza del campo magnetico agisce sullo spin facendolo ruotare intorno alla direzione del campo (frequenza di precessione dello spin)

$$\omega_s = g \frac{qB}{2m}$$



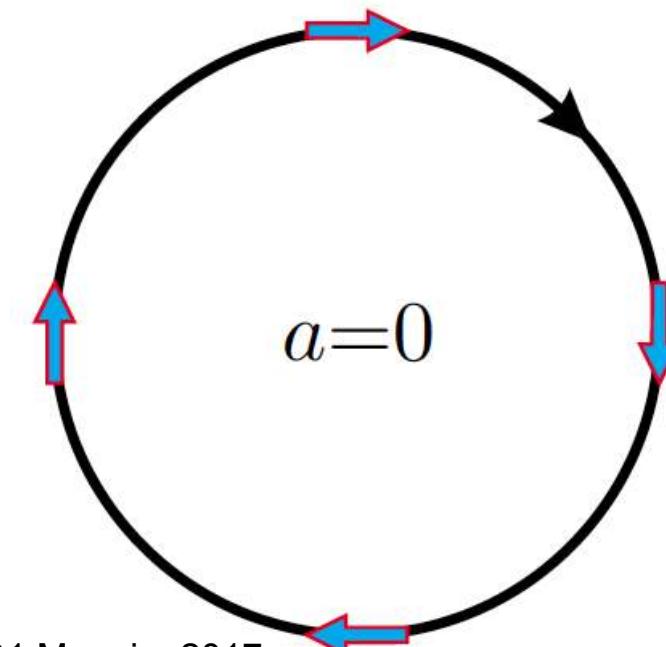
Precesione dello spin, ω_s

Come si misura l'anomalia magnetica?

- La frequenza con cui lo spin avanza rispetto all'impulso (frequenza di precessione anomala ω_a) e':

$$\omega_a = \omega_s - \omega_c = a \frac{eB}{m} \quad a=(g-2)/2$$

- Se $g=2$ ($a=0$) lo spin rimane ancorato all'impulso

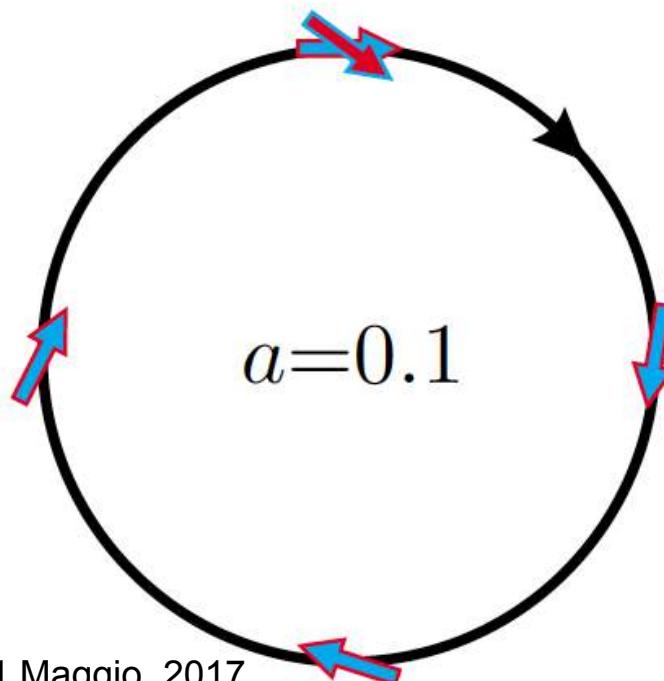


Come si misura l'anomalia magnetica?

- La frequenza con cui lo spin avanza rispetto all'impulso (frequenza di precessione anomala ω_a) e':

$$\omega_a = \omega_s - \omega_c = a \frac{eB}{m} \quad a=(g-2)/2$$

- Se $g > 2$ ($a > 0$) lo spin avanza rispetto all'impulso



Come si misura l'anomalia magnetica?

- La frequenza con cui lo spin avanza rispetto all'impulso (frequenza di precessione anomala ω_a) e':

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

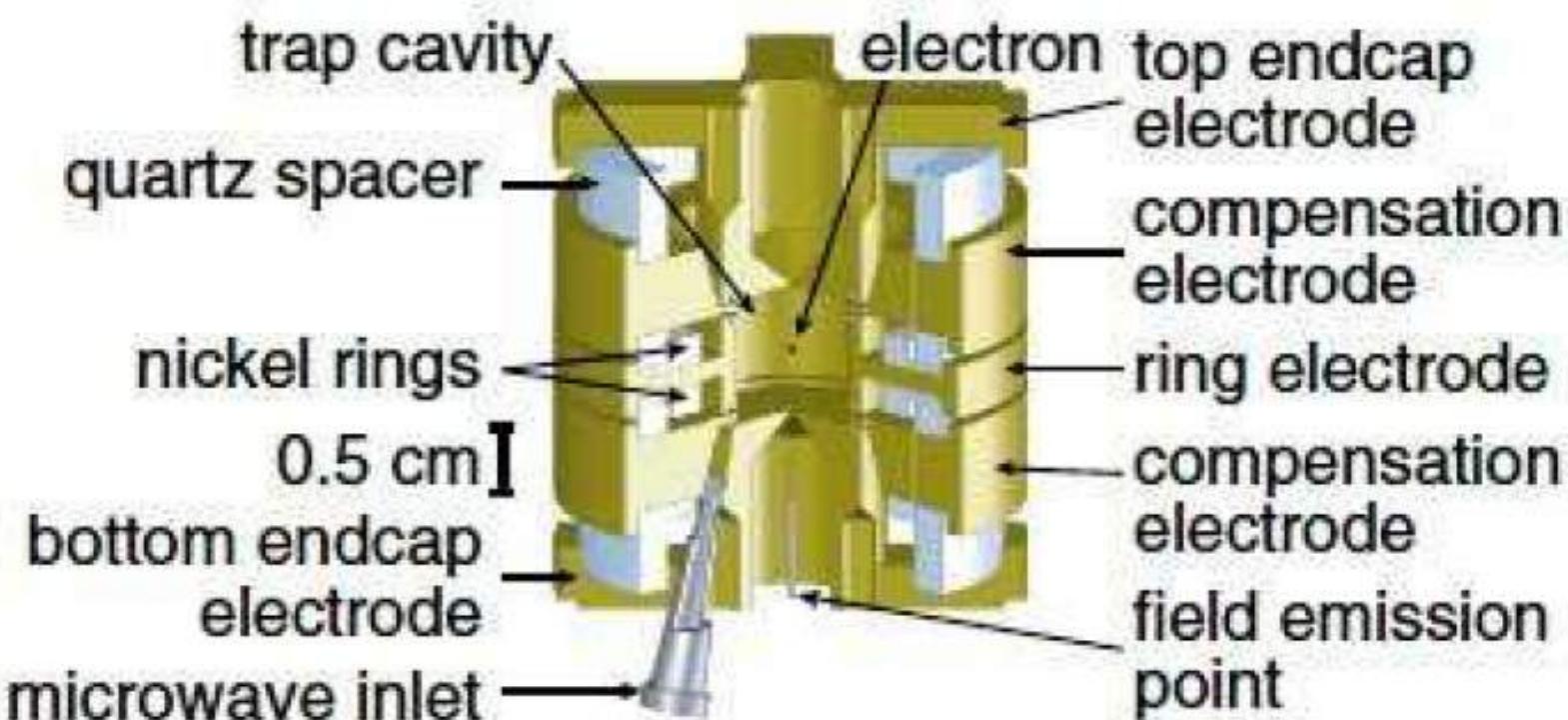
- Se $g > 2$ ($a > 0$) lo spin avanza rispetto all'impulso
- Si misura quindi la frequenza di precessione anomala ω_a e il campo magnetico B ricavando **a**:

$$a = \frac{(g - 2)}{2} = \frac{m\omega_a}{eB}$$

Misura del momento magnetico anomalo dell'elettrone

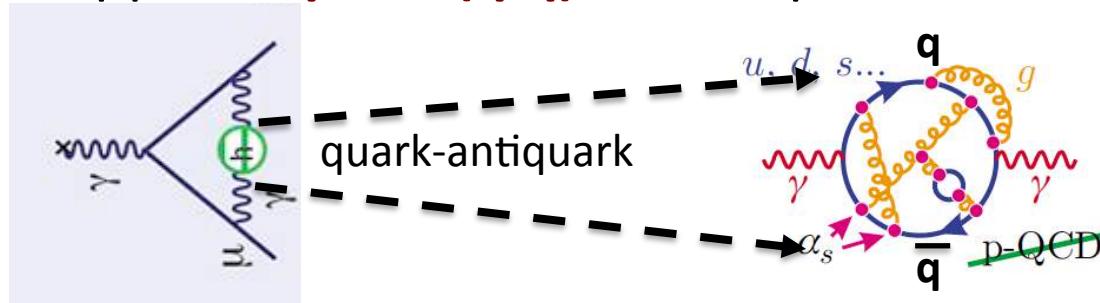
- L'elettrone viene confinato in una regione utilizzando delle trappole magnetiche. Si e' ottenuto:

$$a_e(\text{exp}) = 1\ 159\ 652\ 180.73 (0.28) \times 10^{-12} \quad [0.24 \text{ ppb}]$$



Misura del momento magnetico anomalo del muone

- La misura del momento magnetico anomalo del muone richiede apparati molto più grandi che per l'elettrone. I muoni vengono intrappolati in una un anello di ~ 14 mt di diametro con campo magnetico $B=14500$ Gauss. La misura dello spin del muone si ricava guardando la direzione dell' e^- emesso nel decadimento del muone $\mu^\pm \rightarrow e^\pm \nu\nu$
- Esperimenti (epici) al Cern negli anni 70 hanno messo in evidenza come all'anomalia del muone contribuissero anche le coppie di **quark (q, \bar{q})** virtuali prodotte dal vuoto quantistico



- In questa serie di esperimenti ebbe un ruolo cruciale Emilio Picasso (1927-2014)

How to measure g-2 in a storage ring

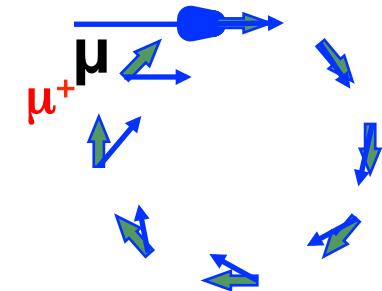
(1) Polarized muons



~97% polarized for forward decays

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

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

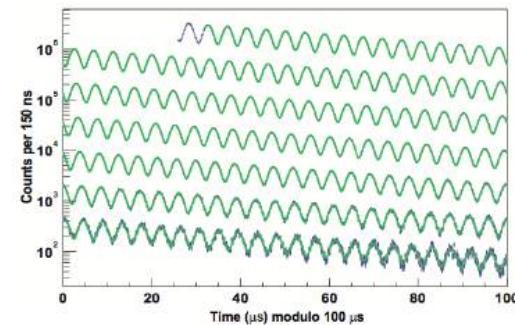


(3) P_μ magic momentum = 3.094 GeV/c

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

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

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



How to measure g-2 in a storage ring

(1) Polarized muons

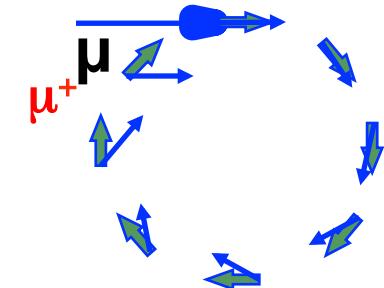


~97% polarized for forward decays

(2) Precession proportional to (g-2)

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

Measure 2 quantities

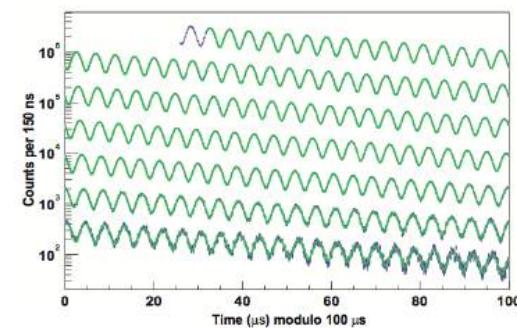


(3) P_μ magic momentum = 3.094 GeV/c

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

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

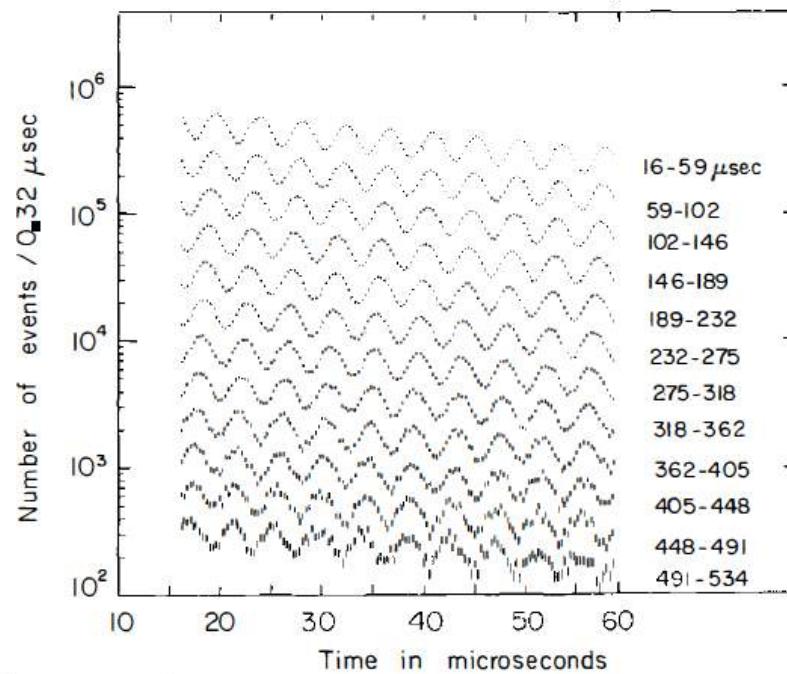
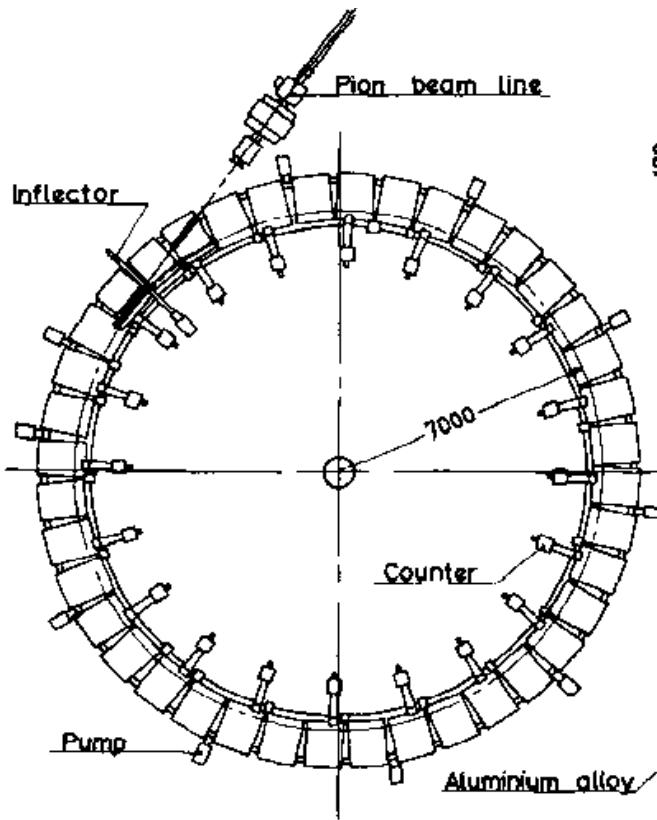
(4) Parity violation in the decay gives average spin direction



Esperimento g-2 del muone al Cern (1979)



L'esperimento al CERN: un trionfo per la QED



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

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

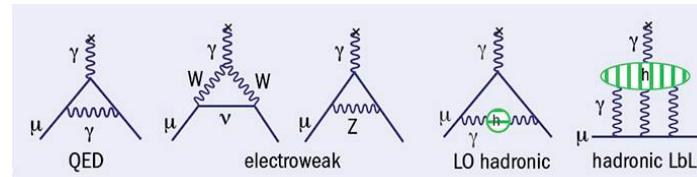
1984-2001: Misura del momento magnetico anomalo del muone a BNL

La misura del g-2 del muone è stata ripetuta al laboratorio di Brookhaven (USA) con una precisione ancora maggiore (15 x Cern)



Il risultato (che raggiunse una precisione di 0.54 parti per milione) fu sorprendente e mostrò:

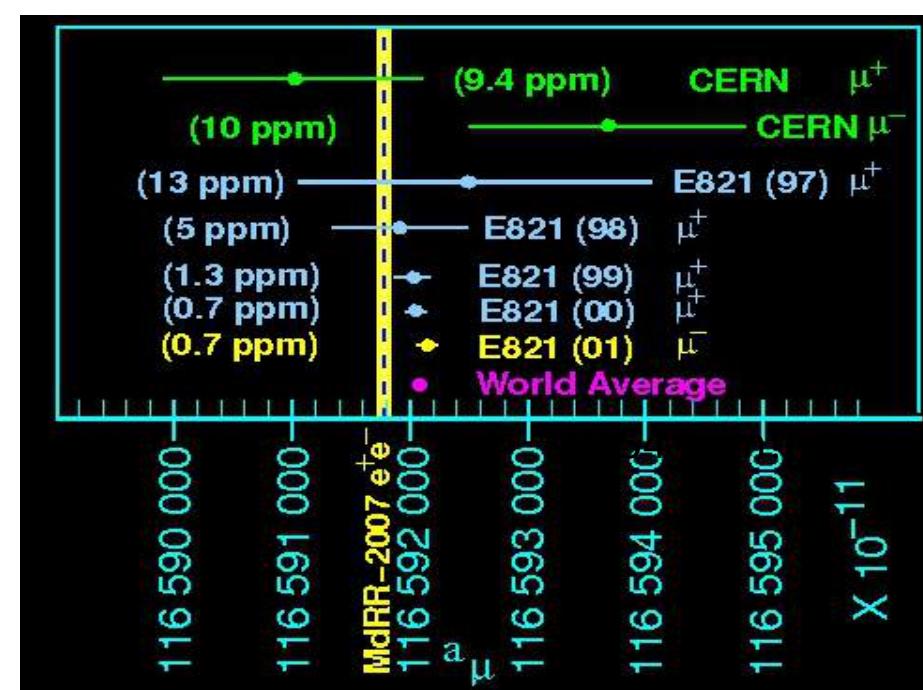
- 1) che alla anomalia magnetica contribuivano non solo gli e-, i quark, ma anche i messaggeri dell'interazioni elettrodebole e perfino il bosone di Higgs



- 2) una “discrepanza” con la previsione teorica del Modello Standard di 3 deviazioni standard (la probabilità che questo accada a causa di una fluttuazione statistica è dello 0,1%)

$$a_{\mu}^{E821} - a_{\mu}^{SM} = (287 \pm 80) \times 10^{-11} \text{ (3.6 } \sigma)$$

Questa discrepanza, per quanto non conclusiva, potrebbe essere spiegata dal contributo all'anomalia del muone di particelle tuttora ignote, come le particelle supersimmetriche (che si cercano ora in LHC) o di nuove particelle che potrebbero spiegare la materia oscura dell'Universo)



$g(\text{expt})$

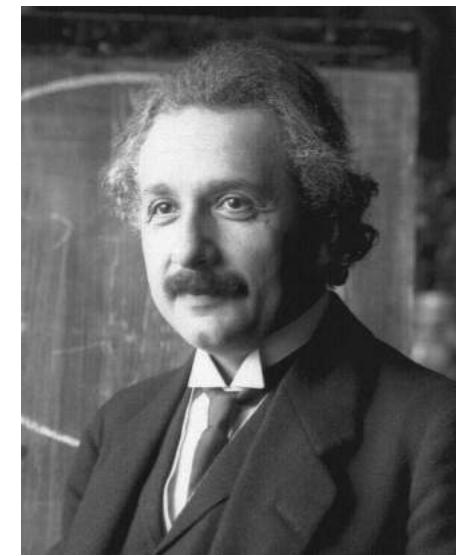
$g(\text{theory})$

$\frac{2}{2}$



$$\left(\frac{1}{2m} (\vec{P} + e\vec{A})^2 + \frac{e}{2m} \vec{\sigma} \cdot \vec{B} - eA^0 \right) \psi_A = (E - m) \psi_A$$

**La meccanica quantistica
incontra la relatività->
antimateria**





$g(\text{expt})$

2.00

$g(\text{theory})$

2.00

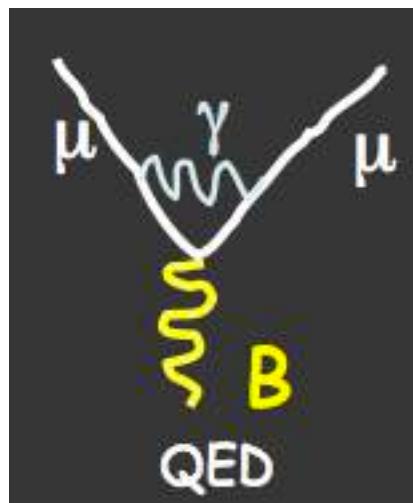


$g(\text{expt})$

$g(\text{theory})$

2.002331

2.002331



Elettrodinamica
quantistica->
Elettricità &
Magnetismo

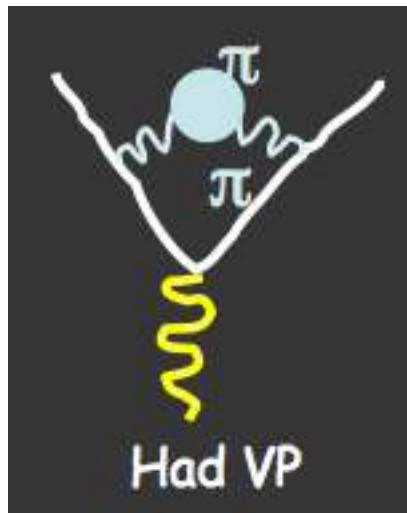


$g(\text{expt})$

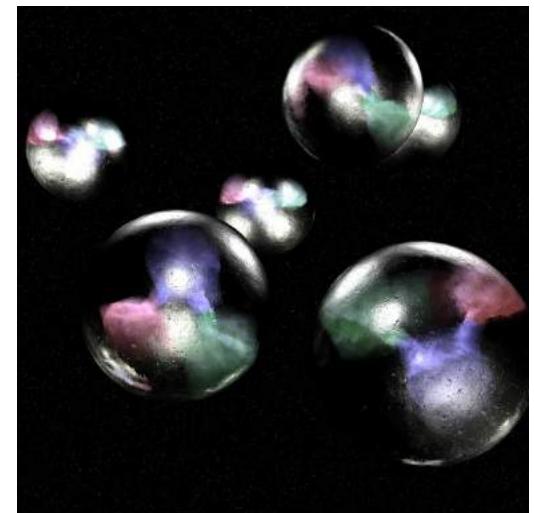
$g(\text{theory})$

2.00233184

2.00233183



Cromodinamica
quantistica->
L'interazione forte che
tiene legati I nuclei
(quark)

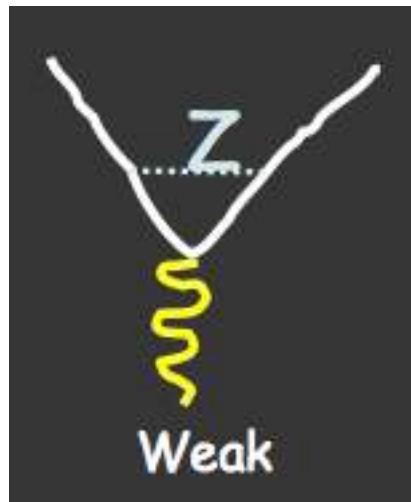


$g(\text{expt})$

2.002331841

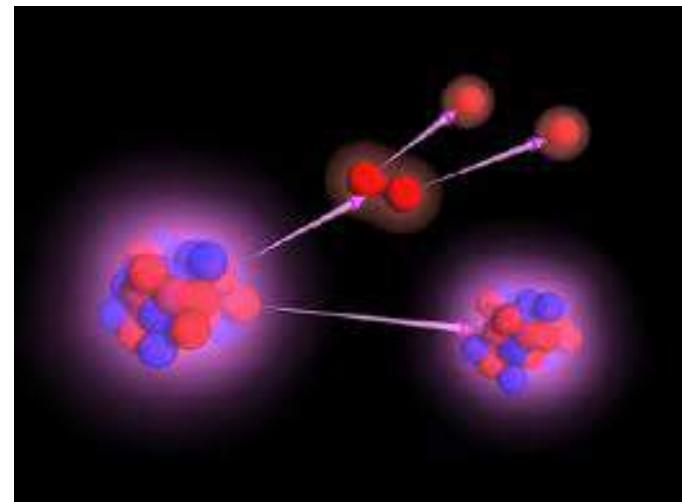
$g(\text{theory})$

2.002331836



Weak

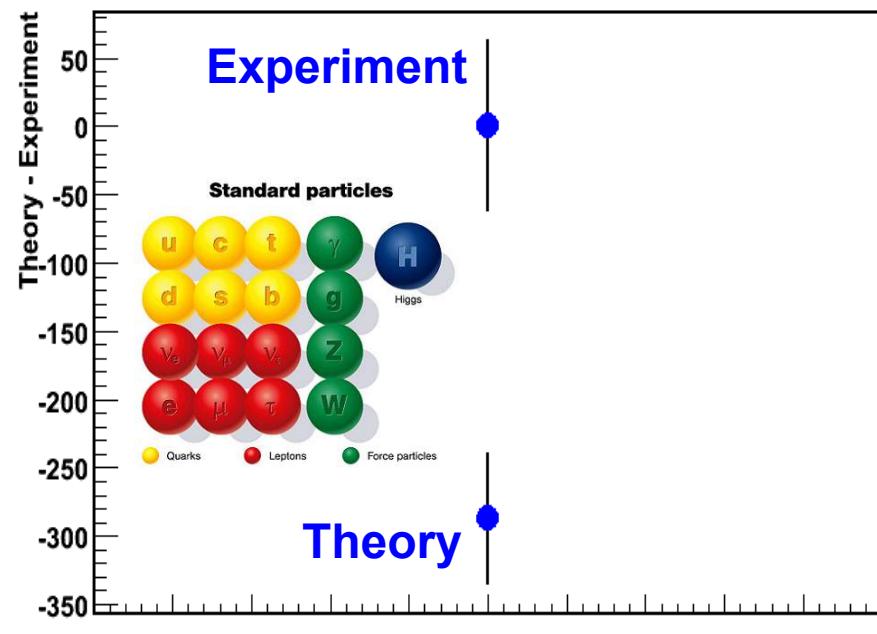
Teoria Elettrodebole->
La forza debole che
rende i nuclei e i
muoni instabili



25

$g(\text{expt})$
 $g(\text{theory})$

2.002331841⁷⁸
2.002331836³⁰



Una possibile crepa nel Modello Standard?

News Release

For more information, contact:
Karen McNulty Walsh, (631)344-8350, kmcnulty@bnl.gov or
Mona S. Rowe, (631)344-5056, mrowe@bnl.gov



01-12
February 8, 2001

Physicists Announce Possible Violation of Standard Model of Particle Physics

UPTON, NY -- Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, in collaboration with researchers from 11 institutions in the U.S., Russia, Japan, and Germany, today announced an experimental result that directly confronts the so-called Standard Model of particle physics. "This work could open up a whole new world of exploration for physicists interested in new theories, such as supersymmetry, which extend the Standard Model," says Boston University physicist Lee Roberts, co-spokesperson for the experiment.



The g-2 muon storage ring at Brookhaven National Lab. ➤ [Hi-Res](#)

More information

Updates:
[December 12, 2001](#)
[July 30, 2002](#)

The [Physical Review Letters paper](#).

[Full background information](#)

[May 2000](#) and [February 2001](#) stories on g-2 from the Brookhaven Bulletin

Additional [pictures](#)

What is a Muon?
Essentially, a "heavy" electron. The muon, electron, and tau particles are generically referred to as charged leptons, and they have the

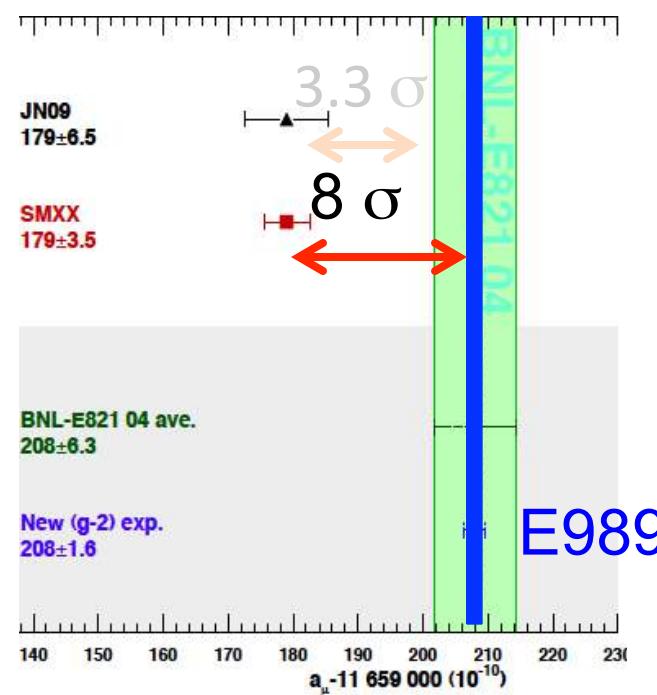
The Muon g-2 experiment at FNAL (E989)

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat.** w.r.t. E821.
Relocate the BNL storage ring to FNAL.
→ $\delta a_\mu \times 4$ improvement (0.14 ppm)

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

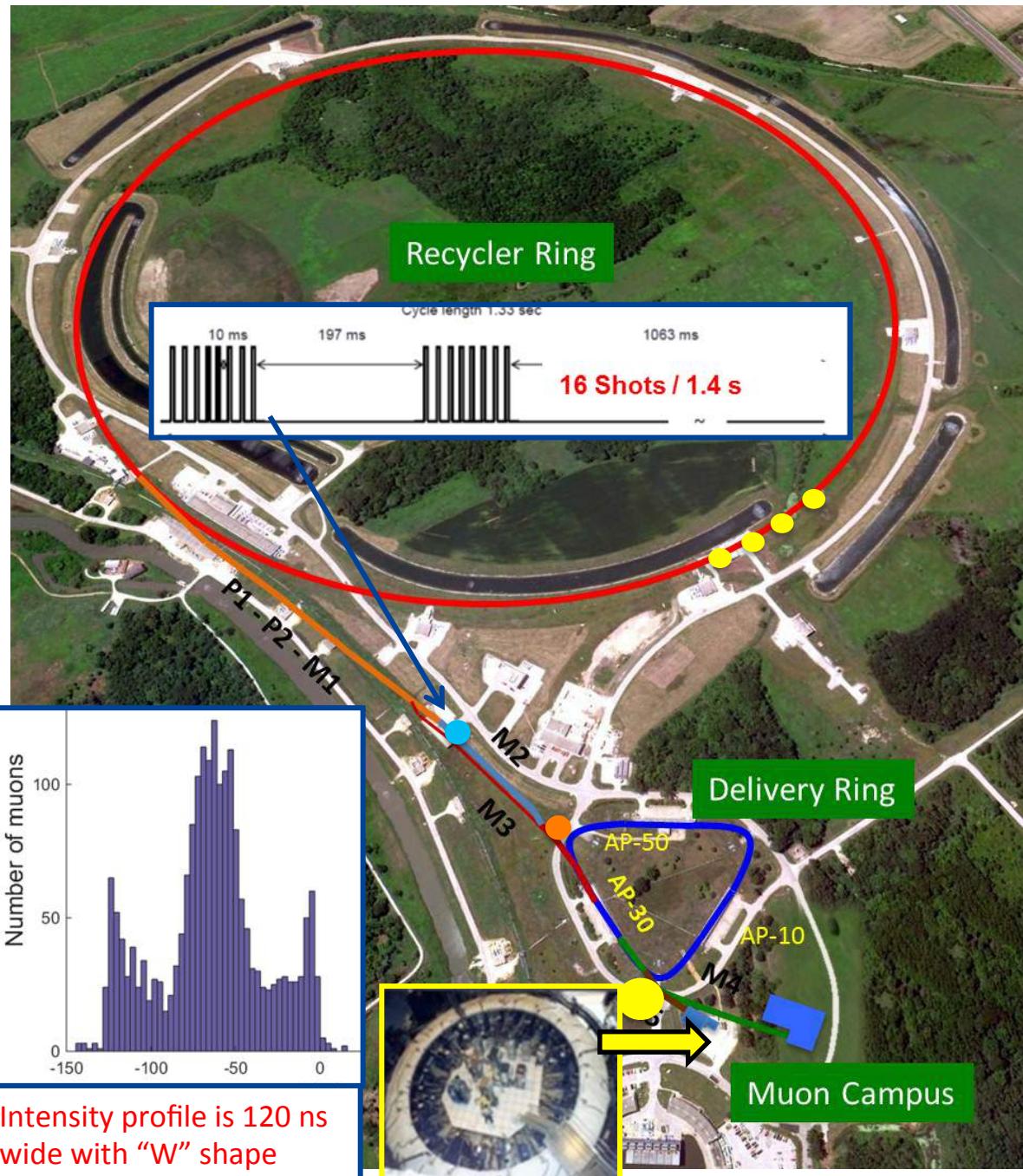
*Depending on the progress on Theory

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

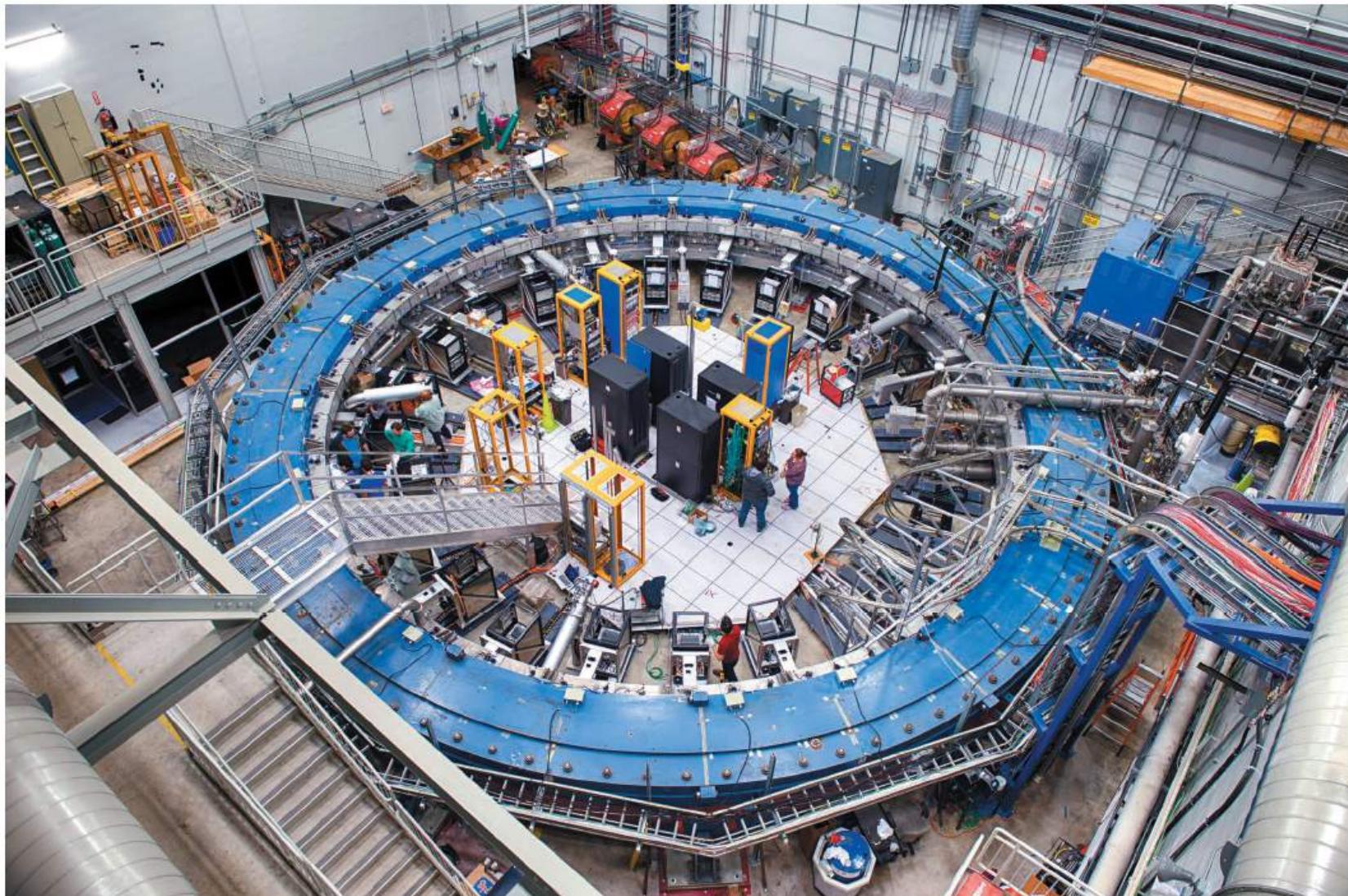


Complementary proposal at J-PARC in progress

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/ π / μ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

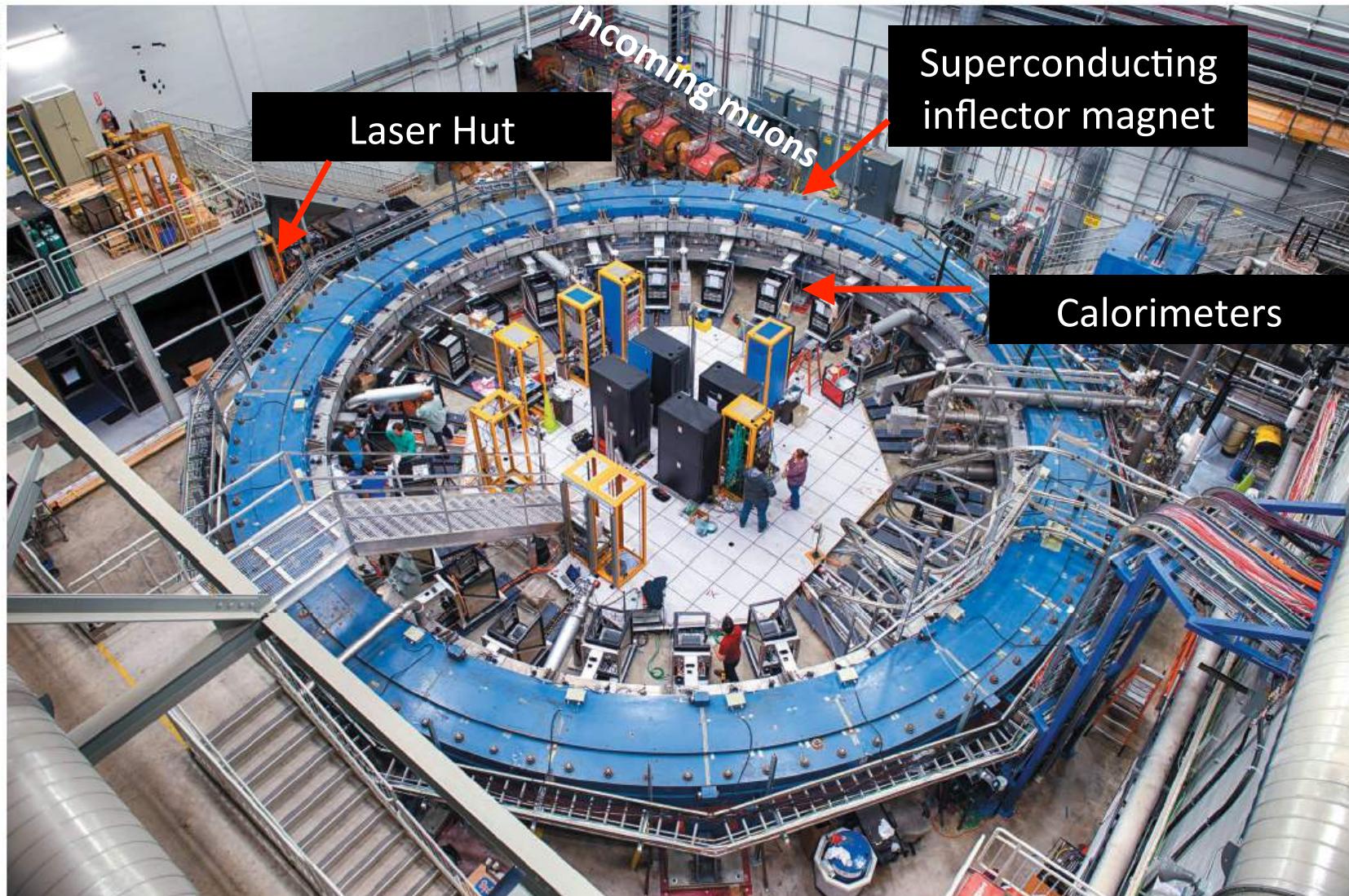


The Muon g-2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

<http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811>

Muons' big moment

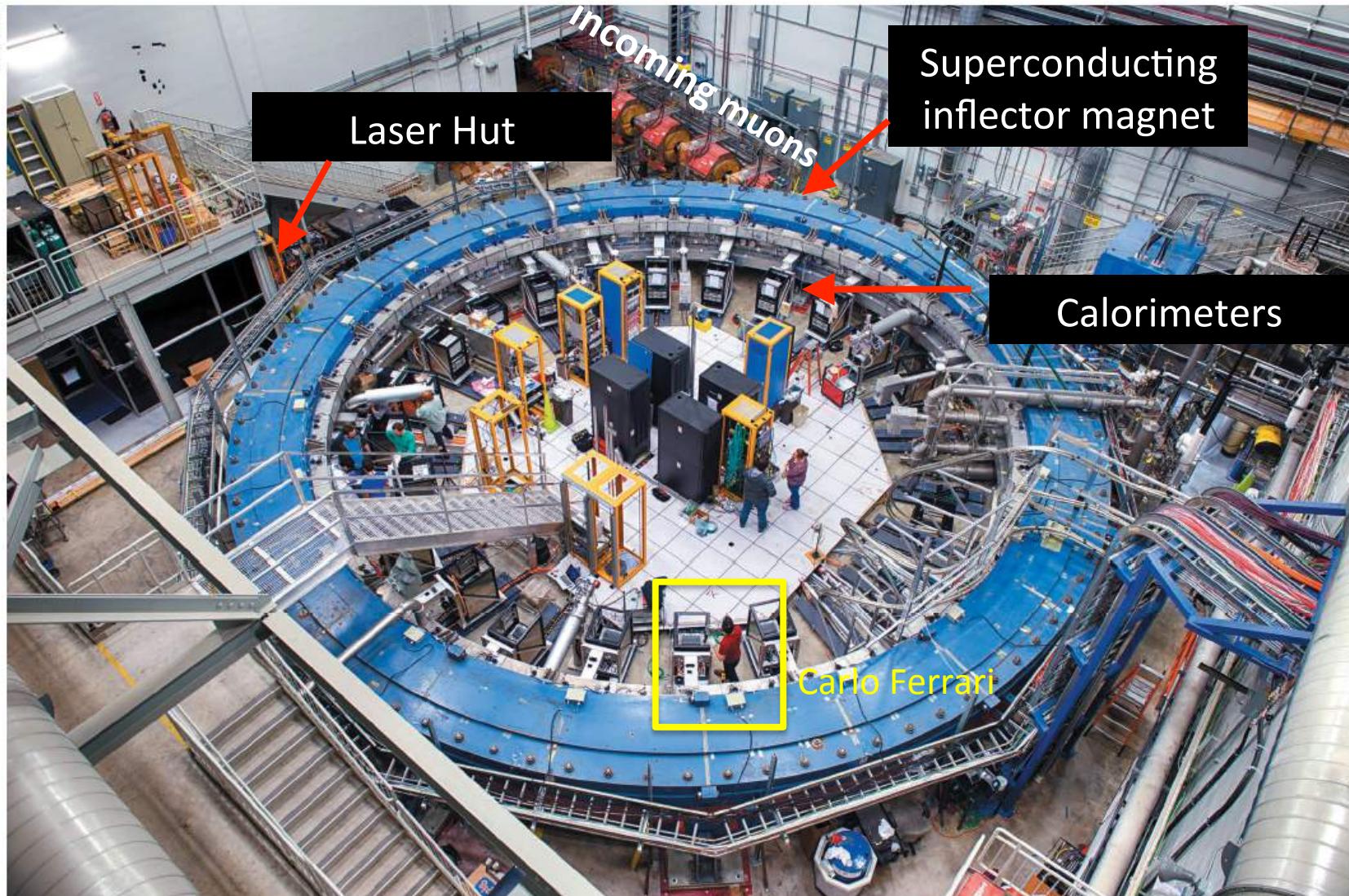


The Muon g-2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

<http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811>

Muons' big moment



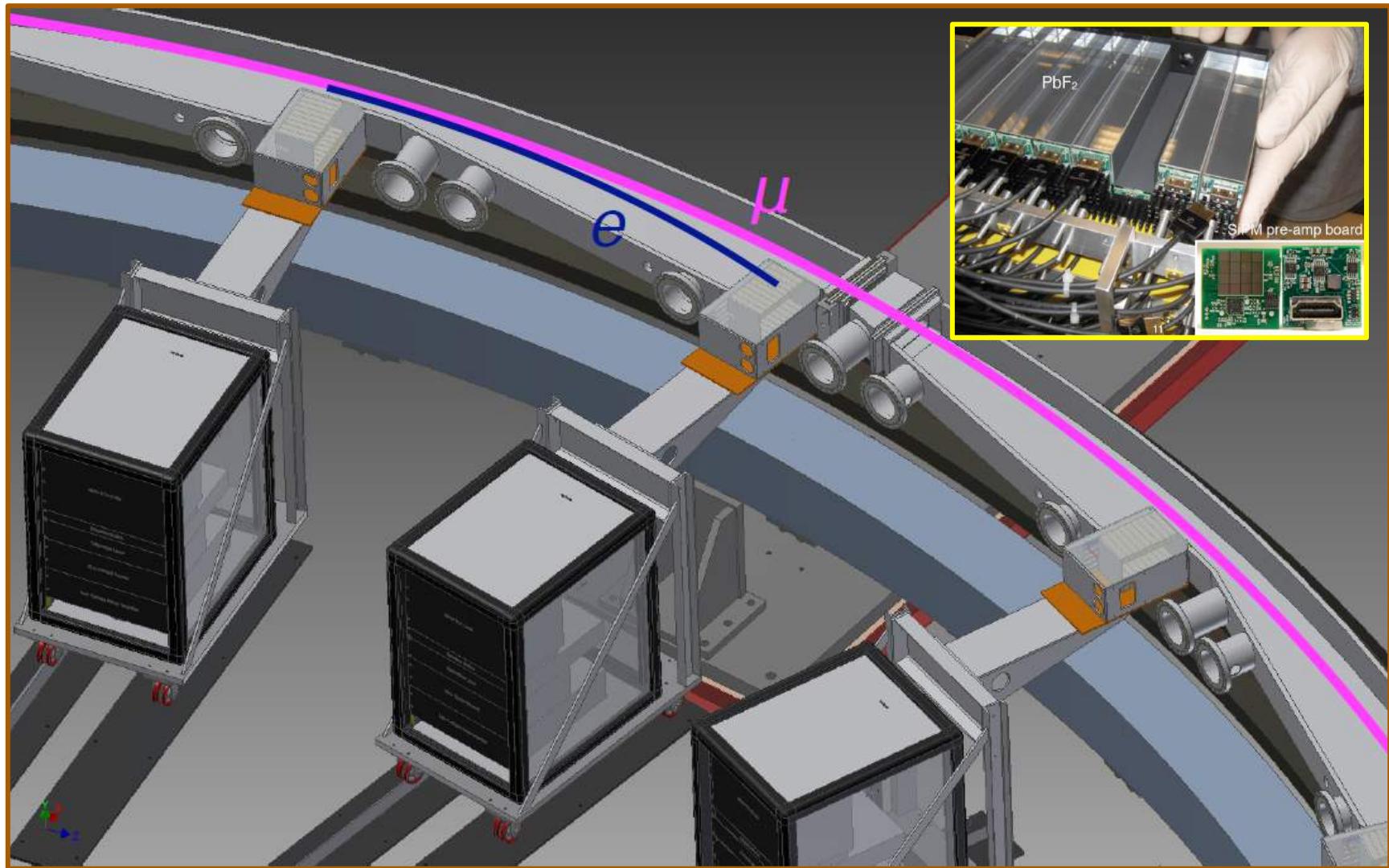
The Muon g-2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

<http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811>

Muons' big moment

24 Calos with 54 PbF₂ crystals and fast SiPMs



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

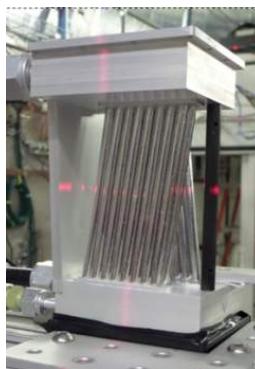
- Tackling each of the major systematic errors with knowledge gained from BNL E821 and improved hardware

ω_a systematics

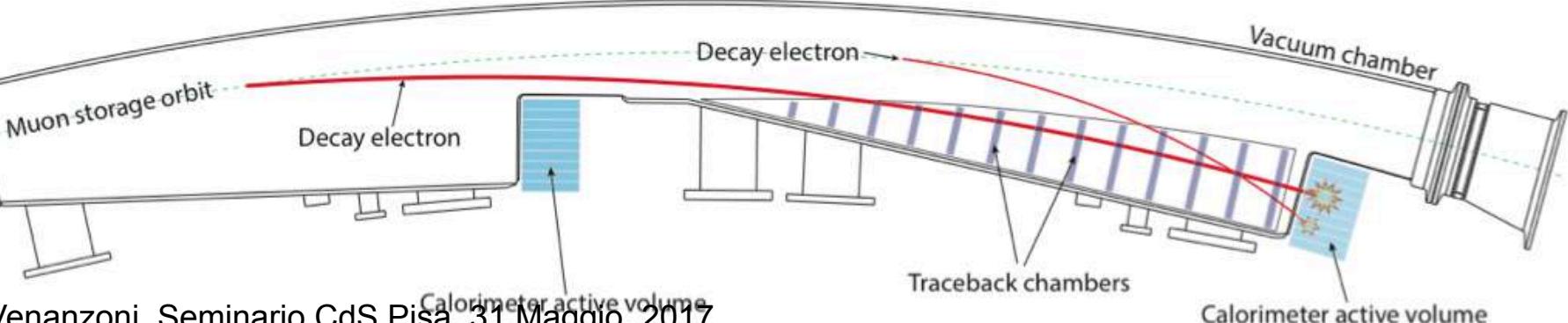
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration low-energy threshold	20
Pileup	80	Low-energy samples recorded calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency) Better match of beamline to ring	< 30
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 and improved hardware

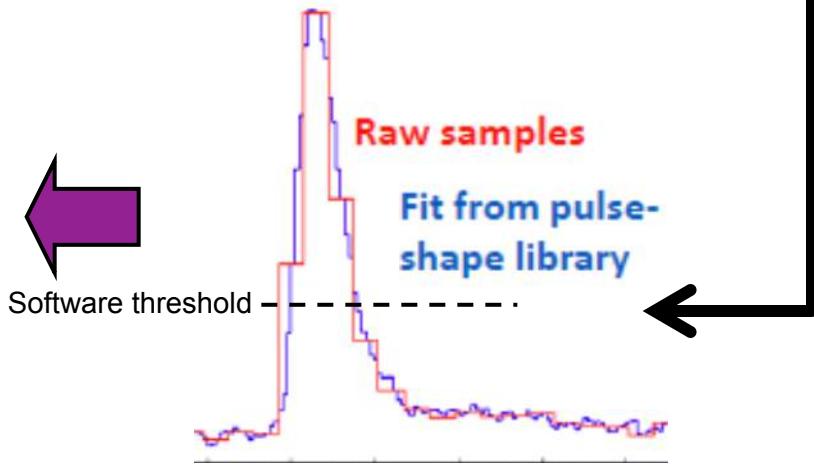
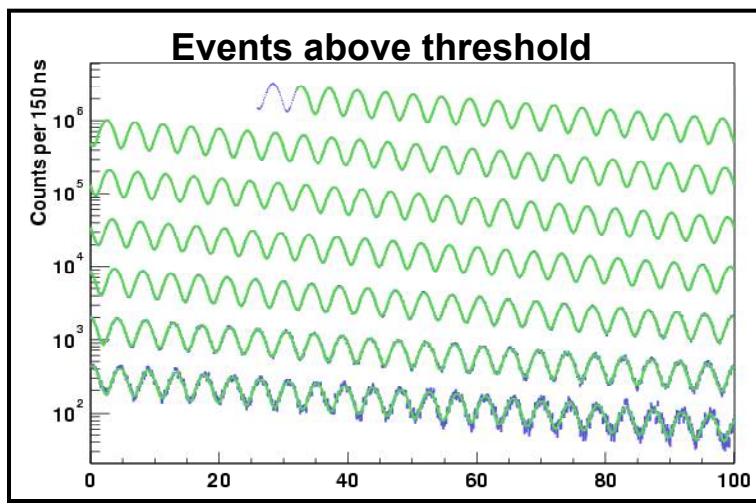
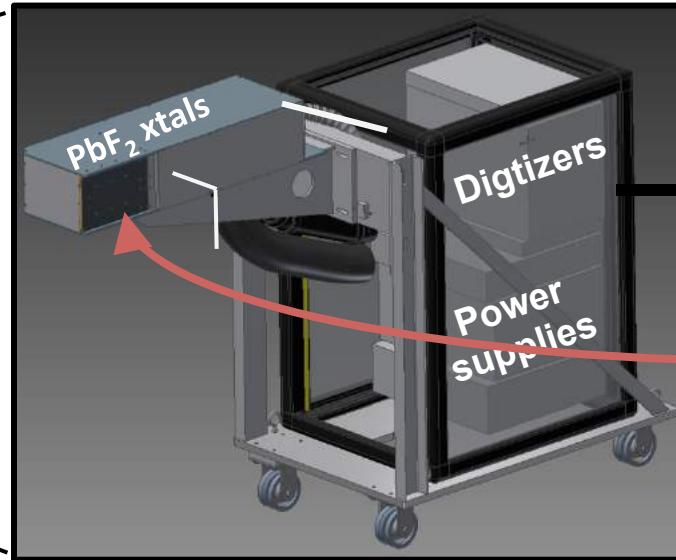
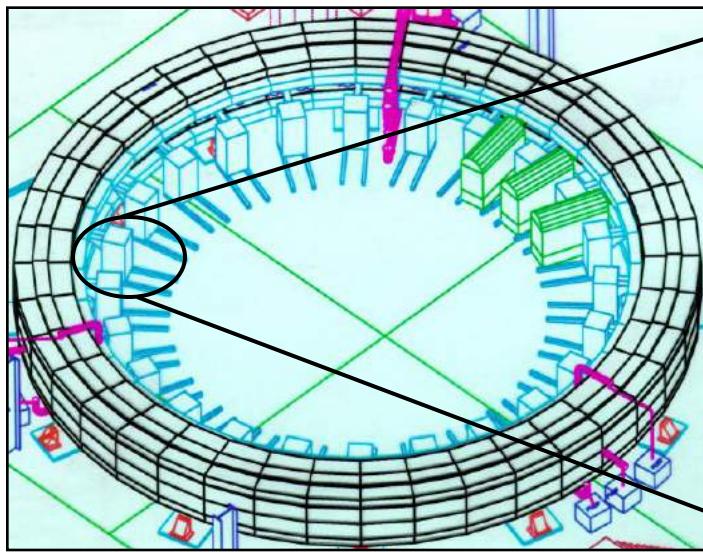
New detector systems



Top view of 1 of 12 vacuum chambers



An “event” is an isolated positron above a threshold

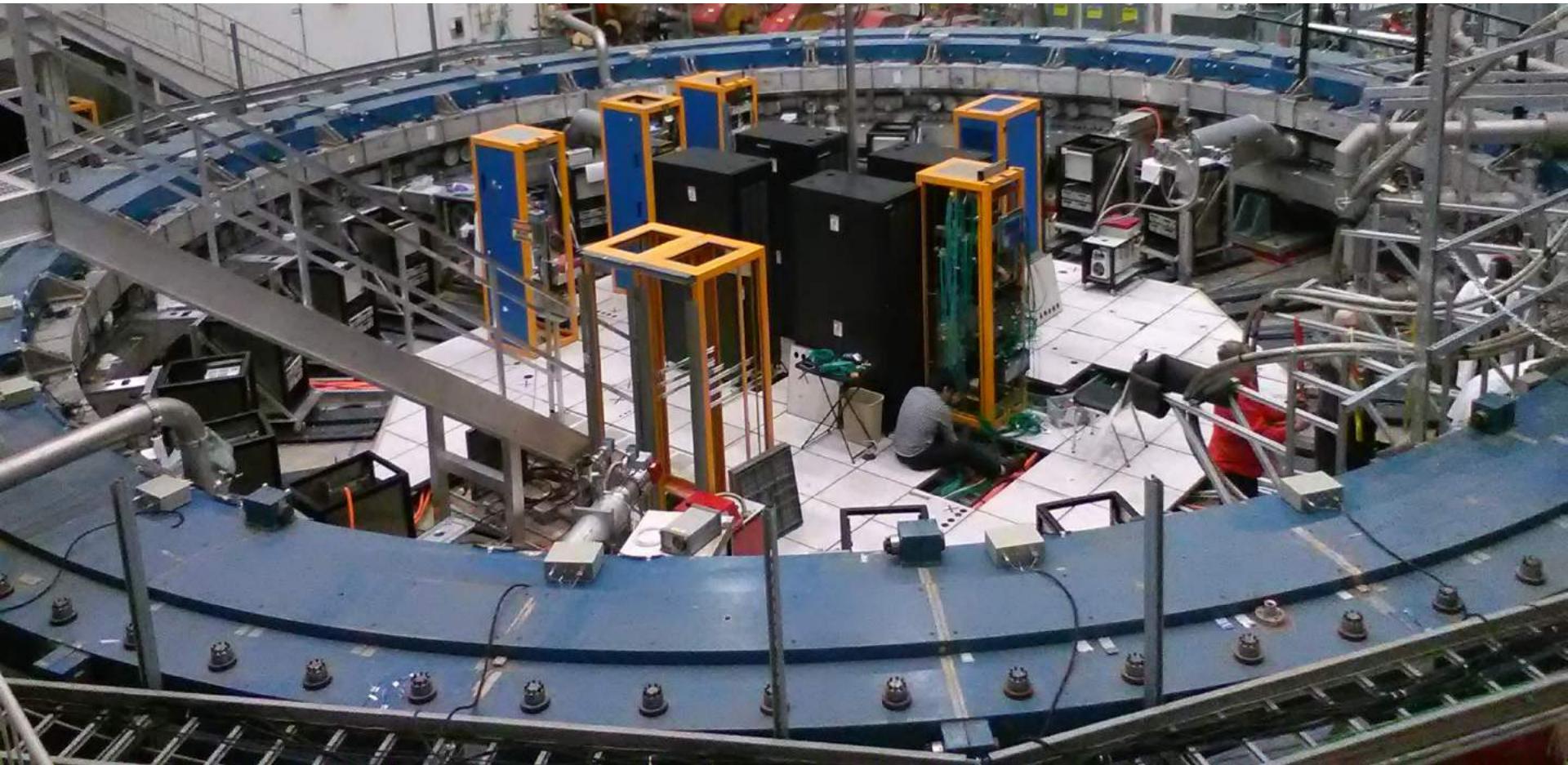


Installation status

24 trolleys in the ring

24 calorimeter in the ring

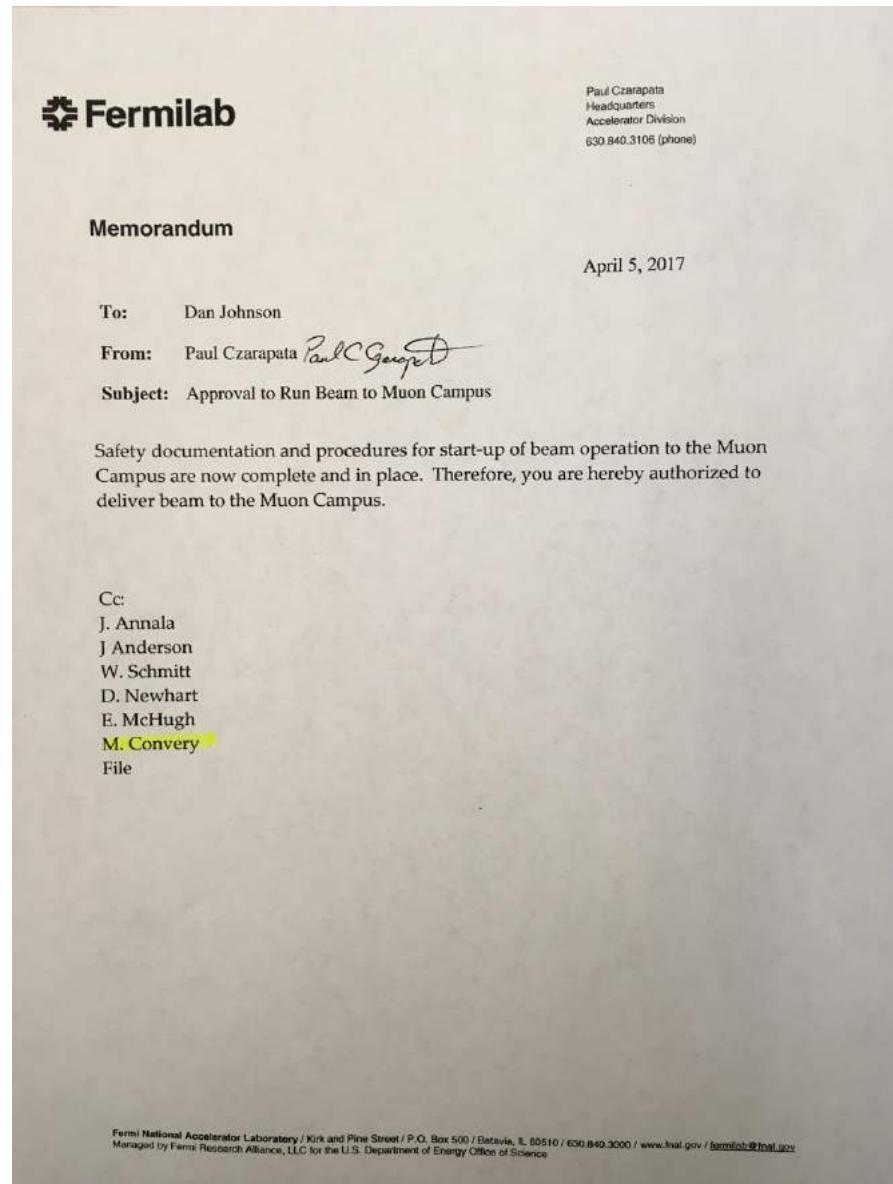
1 tracker module installed



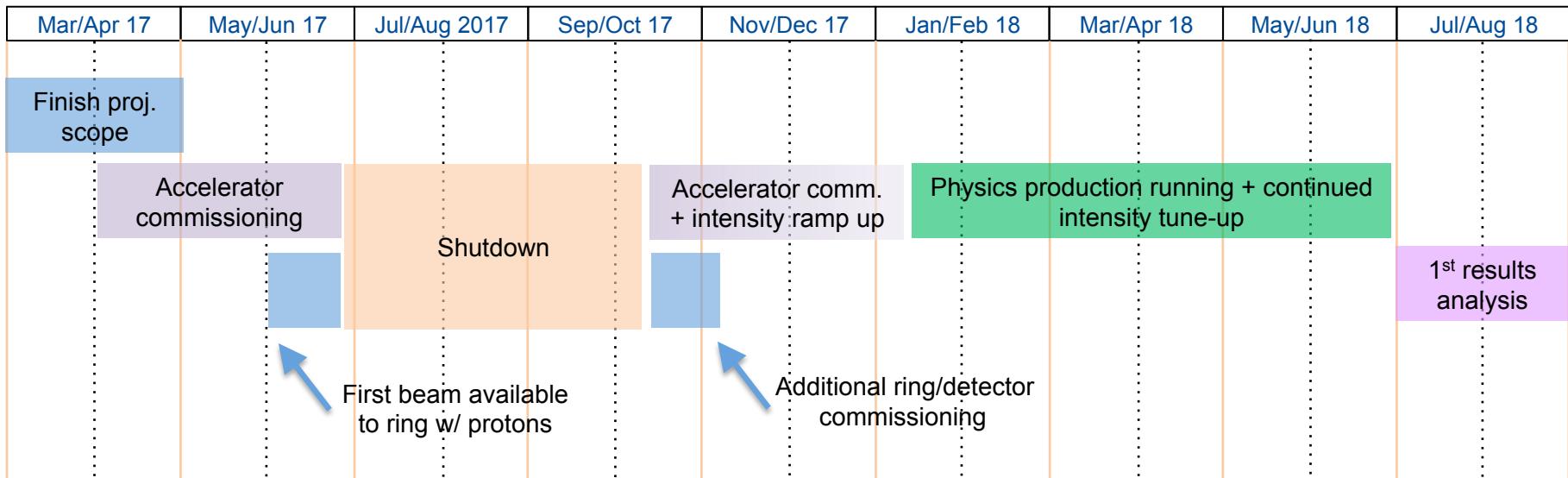
We have started acquiring laser signals from calorimeters

Milestones (last 6 months)

- 17 novembre 2016:
 - the E821 inflector has been cooled and powered to full current
- 24 gennaio 2017:
 - the final vacuum chamber installed in the magnet
- March 14-16 2017:
 - Successful beam readiness review
- April 5 2017:
 - Authorization to deliver beam to the Muon Campus



Short term schedule

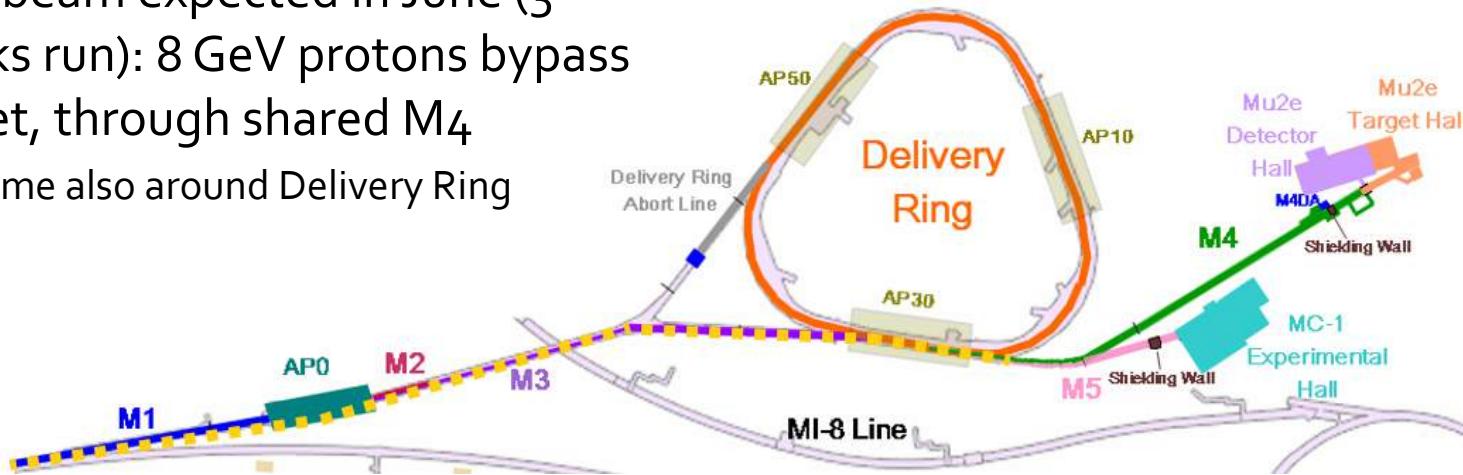


- After many years of design and construction, we are essentially ready for beam
- June: Commissioning
- Fall: Commission Delivery Ring and optimize Muon Storage
- CY2018: Efficient data taking
- Summer 2018: Our goal is a “BNL level” 1st result
- 2 years run for 4x reduction of error (final result expected ~2020)

Short term schedule

First beam expected in June (3 weeks run): 8 GeV protons bypass target, through shared M4

- If time also around Delivery Ring



- After many years of design and construction, we are essentially ready for beam
- June: Commissioning
- Fall: Commission Delivery Ring and optimize Muon Storage
- CY2018: Efficient data taking
- Summer 2018: Our goal is a “BNL level” 1st result
- 2 years run for 4x reduction of error (final result expected ~2020)

Contributo Italiano: Storia

- Il contributo Italiano è iniziato intorno al 2009 quando alcuni fisici (principalmente dei LNF) hanno iniziato a partecipare alle prime riunioni e alla stesura della Lol
- Nel 2012 la partecipazione si è consolidata coinvolgendo ricercatori di altre sezioni INFN e CNR/INO con apertura di sigla nel 2013 e approvazione nel 2014
- Vinto un RISE nel 2016 con Mu2e
- Situazione 2017: 28 fisici, 4 sezioni
- L'attività ha riguardato la progettazione e realizzazione di un sistema di calibrazione laser ad altissima precisione
- I primi studi sono stati fatti a Pisa (Scuri/Ferrari/Veronesi) e LNF

Submitted to FNAL

February 9, 2009

The New ($g - 2$) Experiment:
A Proposal to Measure the Muon Anomalous Magnetic Moment
to ± 0.14 ppm Precision

New ($g - 2$) Collaboration: R.M. Carey¹, K.R. Lynch¹, J.P. Miller¹,
B.L. Roberts¹, W.M. Morse², Y.K. Semertzidis², V.P. Druzhinin³, B.I. Khazin³,
I.A. Koop³, I. Logashenko³, S.I. Redin³, Y.M. Shatunov³, Y. Orlov⁴, R.M. Talman⁴,
B. Casey⁵, J. Johnstone⁵, D. Harding⁵, A. Klebaner⁵, A. Leveling⁵, J-F. Ostiguy⁵,
N. Mokhov⁵, D. Neuffer⁵, M. Popovic⁵, S. Strigov⁵, M. Syphers⁵, G. Velev⁵,
S. Werkema⁵, F. Happacher⁶, G. Venanzoni⁶, P. Debevec⁷, M. Grosse-Perdekamp⁷,
D.W. Hertzog⁷, P. Kammel⁷, C. Polly⁷, K.L. Giovanetti⁸, K. Jungmann⁹,
C.J.G. Onderwater⁹, N. Saito¹⁰, C. Crawford¹¹, R. Fatemi¹¹, T.P. Gorringe¹¹,
W. Korsch¹¹, B. Plaster¹¹, V. Tishchenko¹¹, D. Kawall¹², T. Chupp¹³,
C. Ankenbrandt¹⁴, M.A. Cummings¹⁴, R.P. Johnson¹⁴, C. Yoshikawa¹⁴, André
de Gouvêa¹⁵, T. Itahashi¹⁶, Y. Kuno¹⁶, G.D. Alkhazov¹⁷, V.L. Golovtsov¹⁷,
P.V. Neustroev¹⁷, L.N. Uvarov¹⁷, A.A. Vasilyev¹⁷, A.A. Vorobyov¹⁷, M.B. Zhalov¹⁷,
F. Gray¹⁸, D. Stöckinger¹⁹, S. Baefler²⁰, M. Bychkov²⁰, E. Frlež²⁰, and D. Počanicć²⁰

2013: primi studi

Status report on the design of the calorimeter calibration system

Part I

(calibration system and laser sources)

F. Scuri – I.N.F.N. – Sezione di Pisa – Italy

For the Italian group

G-2 detector meeting, March 19, 2013

LNF: F. Happacher, M. Martini, S. Miscetti, G. Venanzoni

Pisa : S. Donati, C. Ferrari, F. Scuri, F. Spinella, S. Veronesi

Roma 2: P. Camarri, G. Di Sciascio, D. Moricciani

Napoli: M. Iacovacci, S. Mastroianni

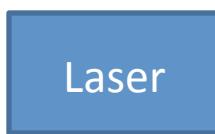
Trieste e UD: G. Cantatore, M Karuza, D. Cauz, G. Pauletta, G. Santi

Fiber length saving configurations (option II)

Many options, depending on the fiber-to-fiber uniformity we need

.... many “custom” arrangements needed to couple fibers to expanders

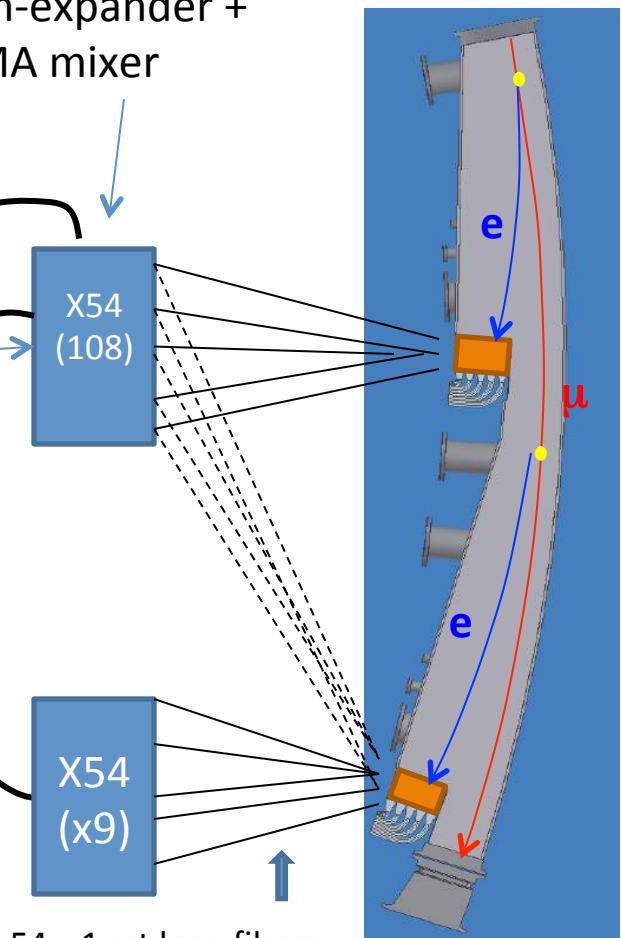
Low loss beam-expander
(Melles-Griot)



Total fiber length : about 400 mt

Savings in the total fiber length has a big impact in total cost !

Beam-expander +
PMMA mixer



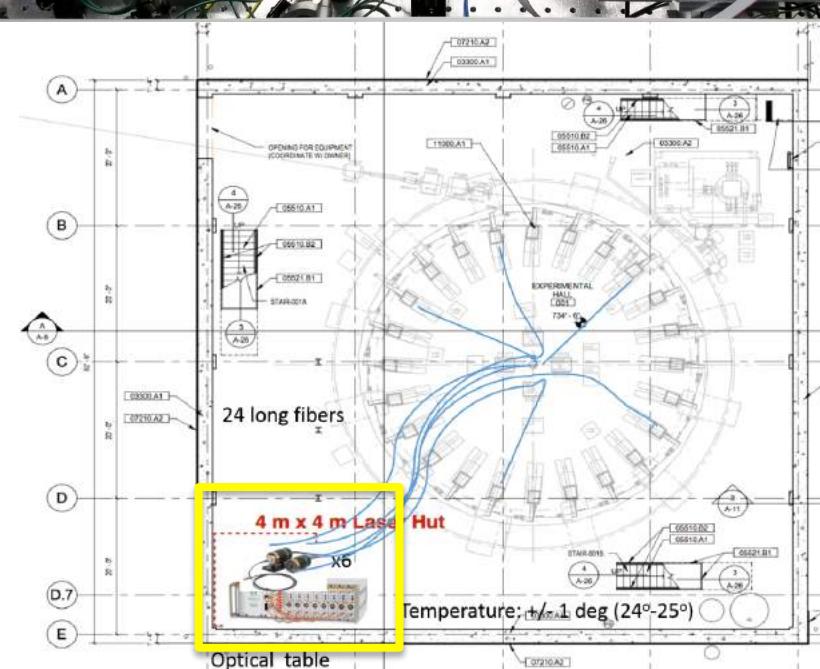
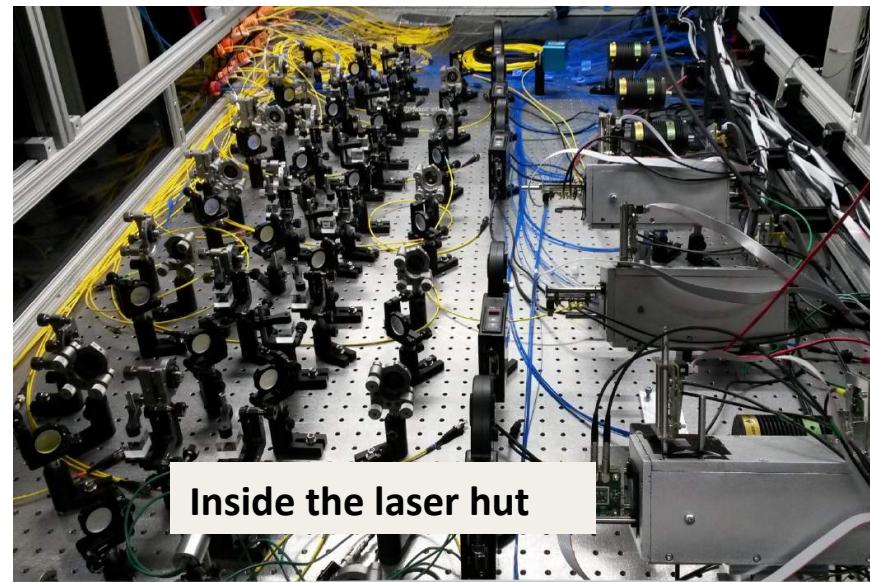
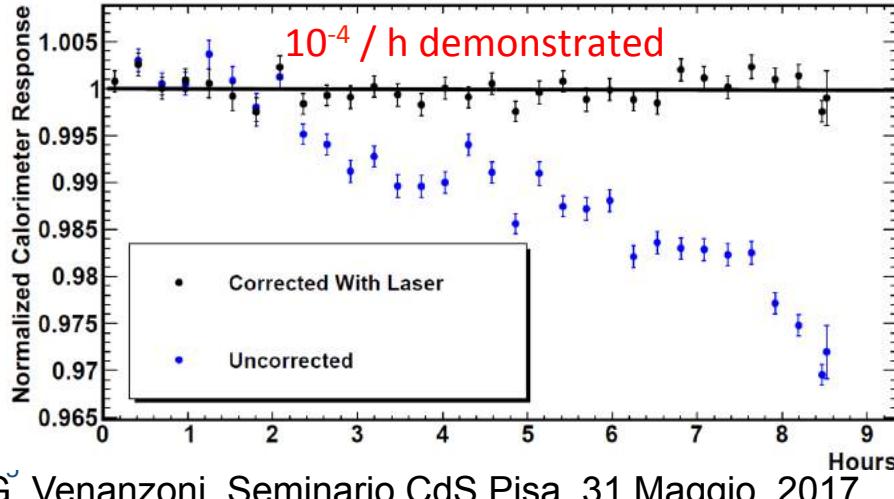
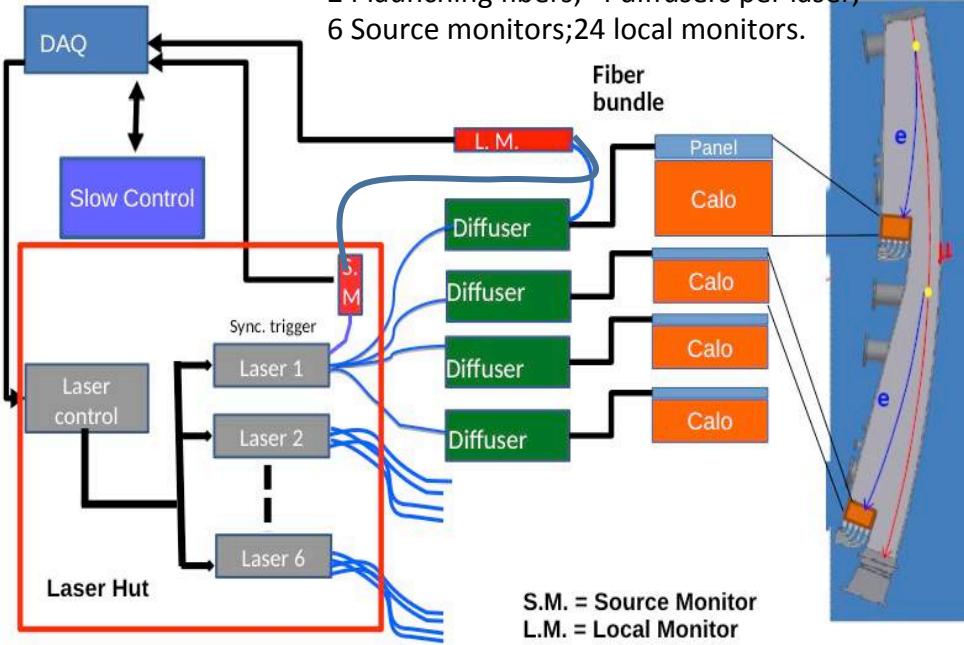
24 x 7 mt long fibers
(12 x7)

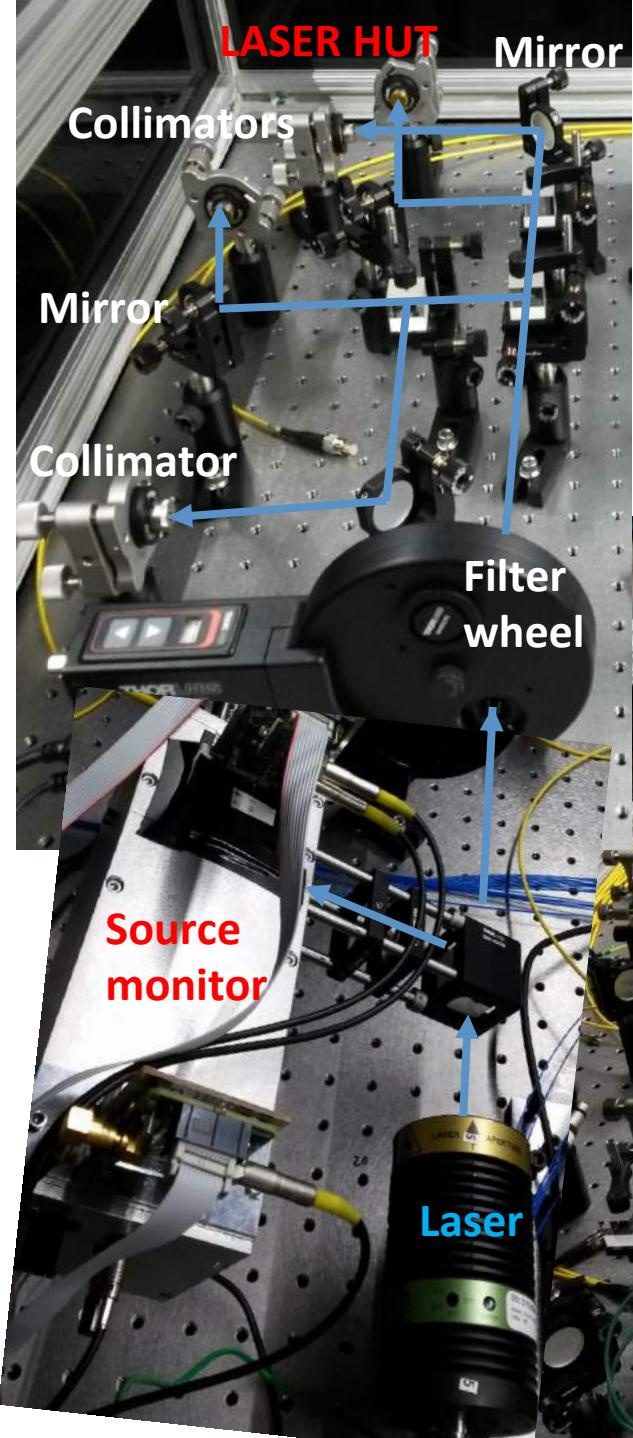
54 x 1 mt long fibers
(9 if use splitter strips
in the station box (see below))

2017

“Evoluzione” del sistema di calibrazione laser

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

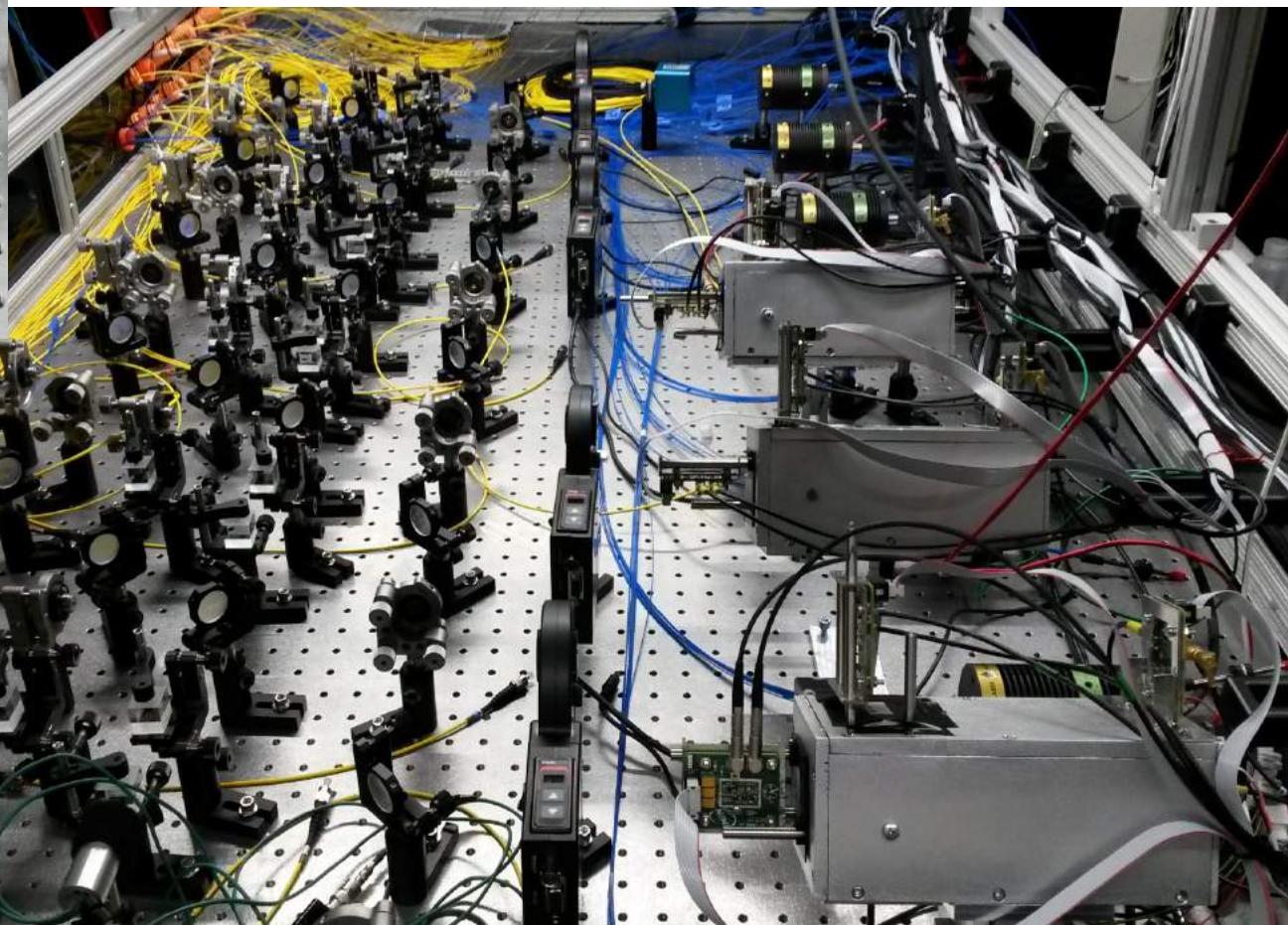




Laser Hut

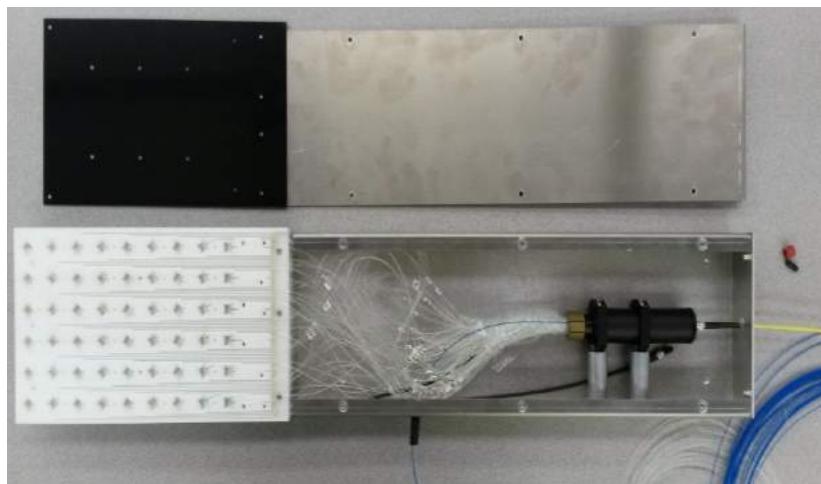
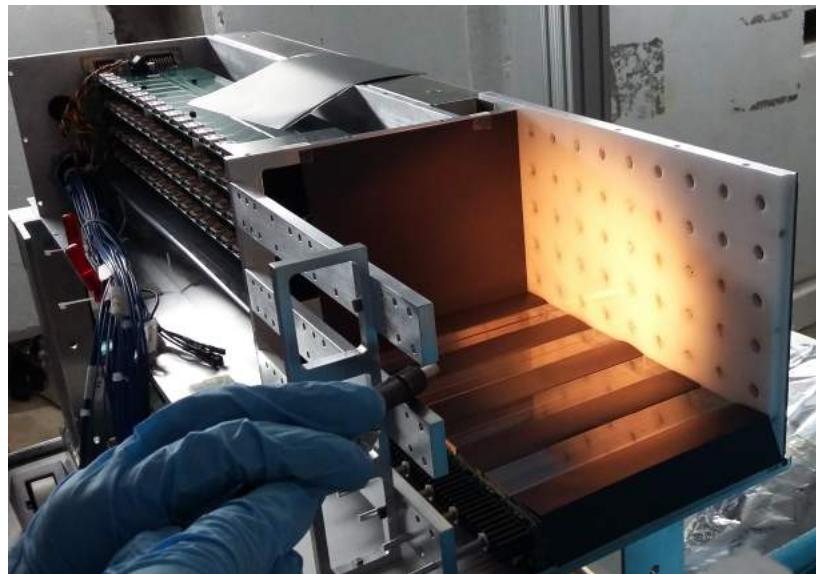
Installation complete:

- 6 laser heads
- 6 filter wheels (controlled remotely through beaglebone)
- Beam splitters, mirrors and collimators
- 6 source monitor with electronics



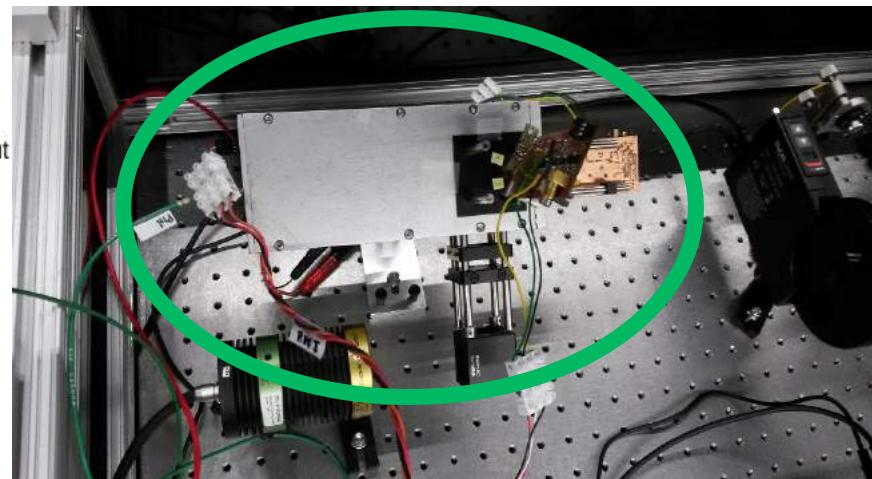
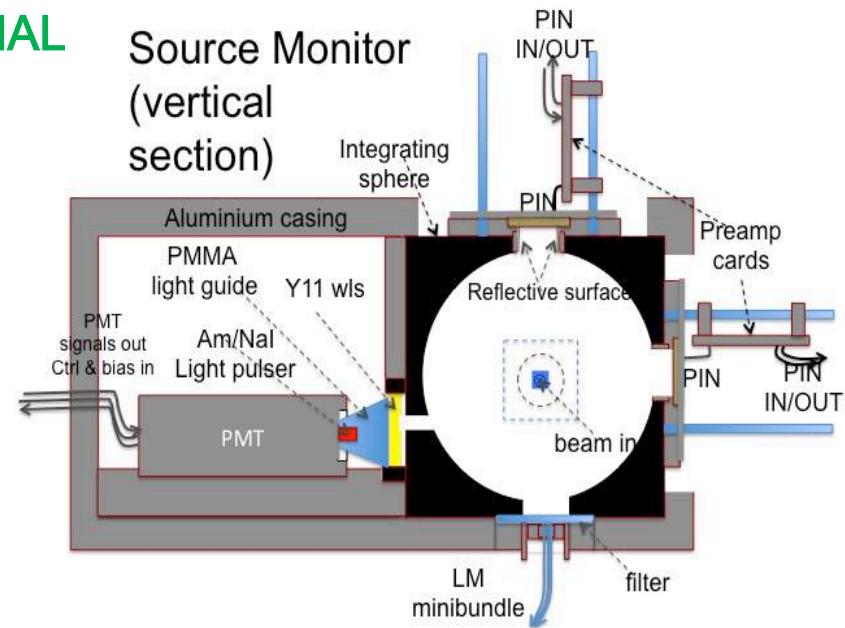
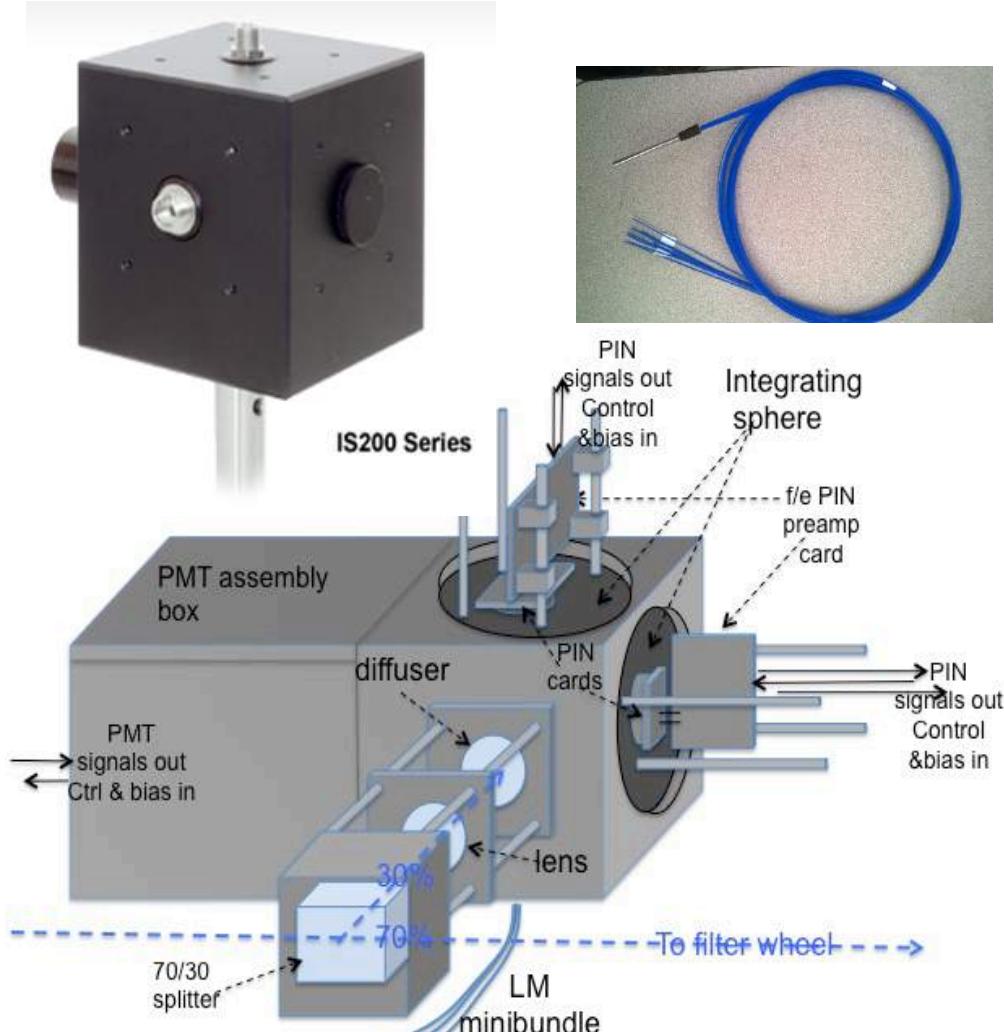
Distribution panels & boxes

25 pannelli progettati da A. Basti e realizzati nell'officina meccanica di Frascati



The Source Monitor

Fully tested in two test beams. **Six installed at FNAL**

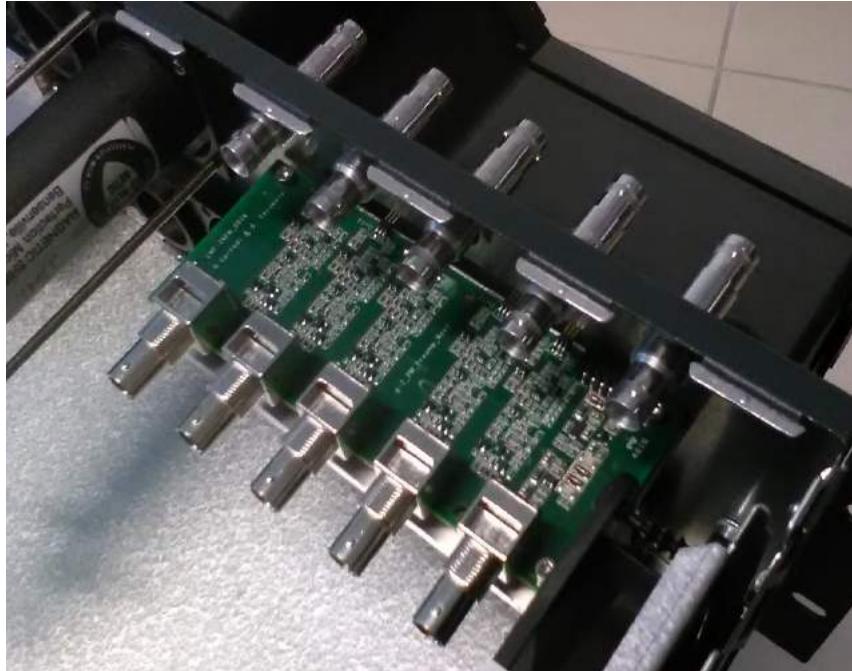


Local Monitor electronics

Scatola PMT disegnata da A.
Basti e realizzata a Pisa

It consists of 24 PMT, and its associated electronics boards for signal conditioning and make it differential.

2 optical fibers reach each PMT, bandpass filters reduce the ambient light.



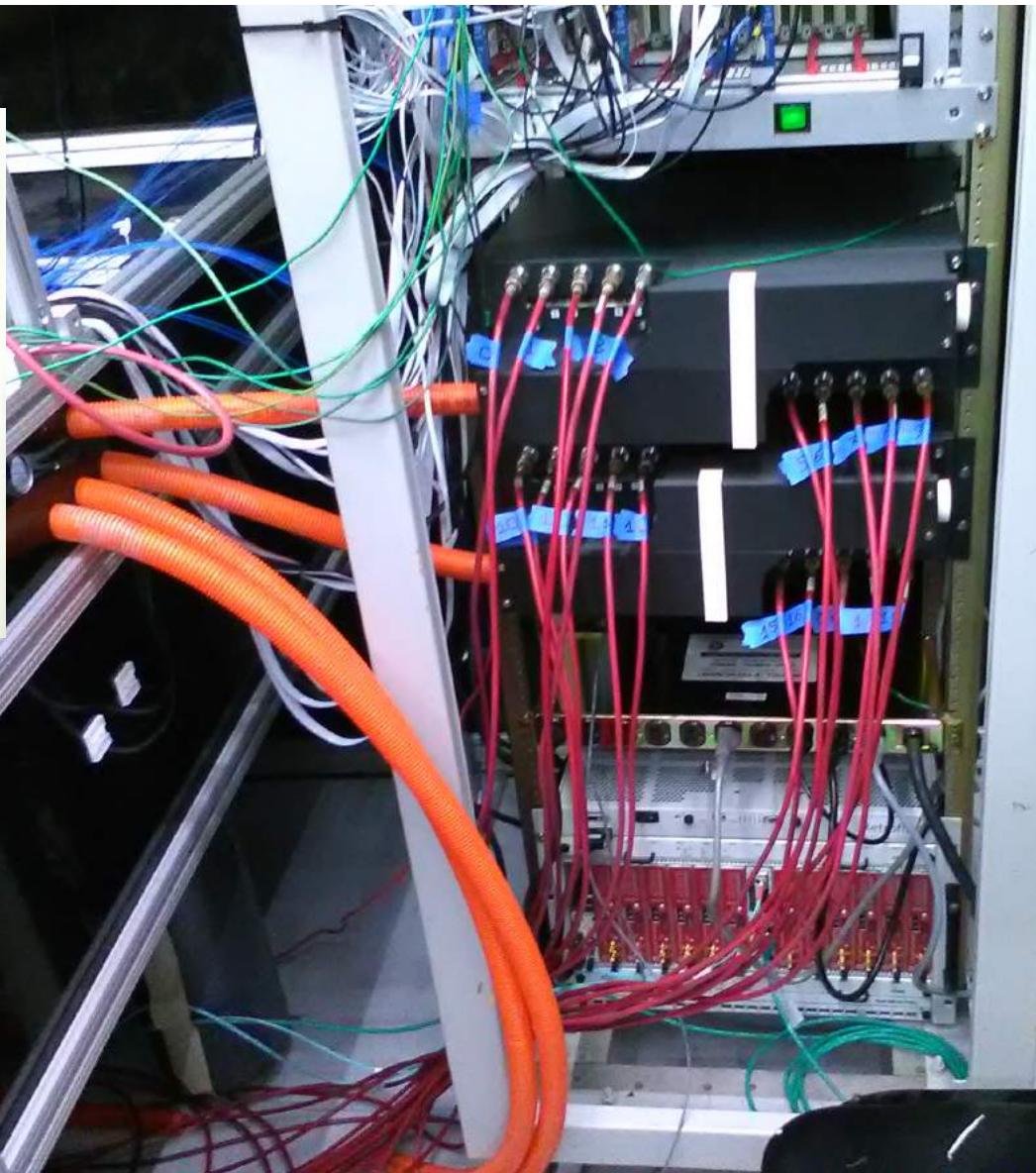
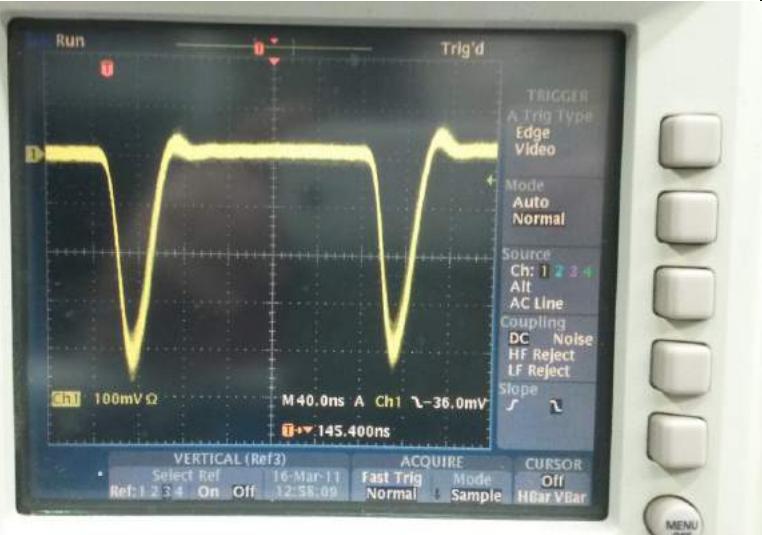
**The local monitor have been installed in
March**

The installation includes the electronic
boards to interface with the WFD.



Local monitor installation

Installation and cabling (HV, LV, WFD) complete. Test in progress.

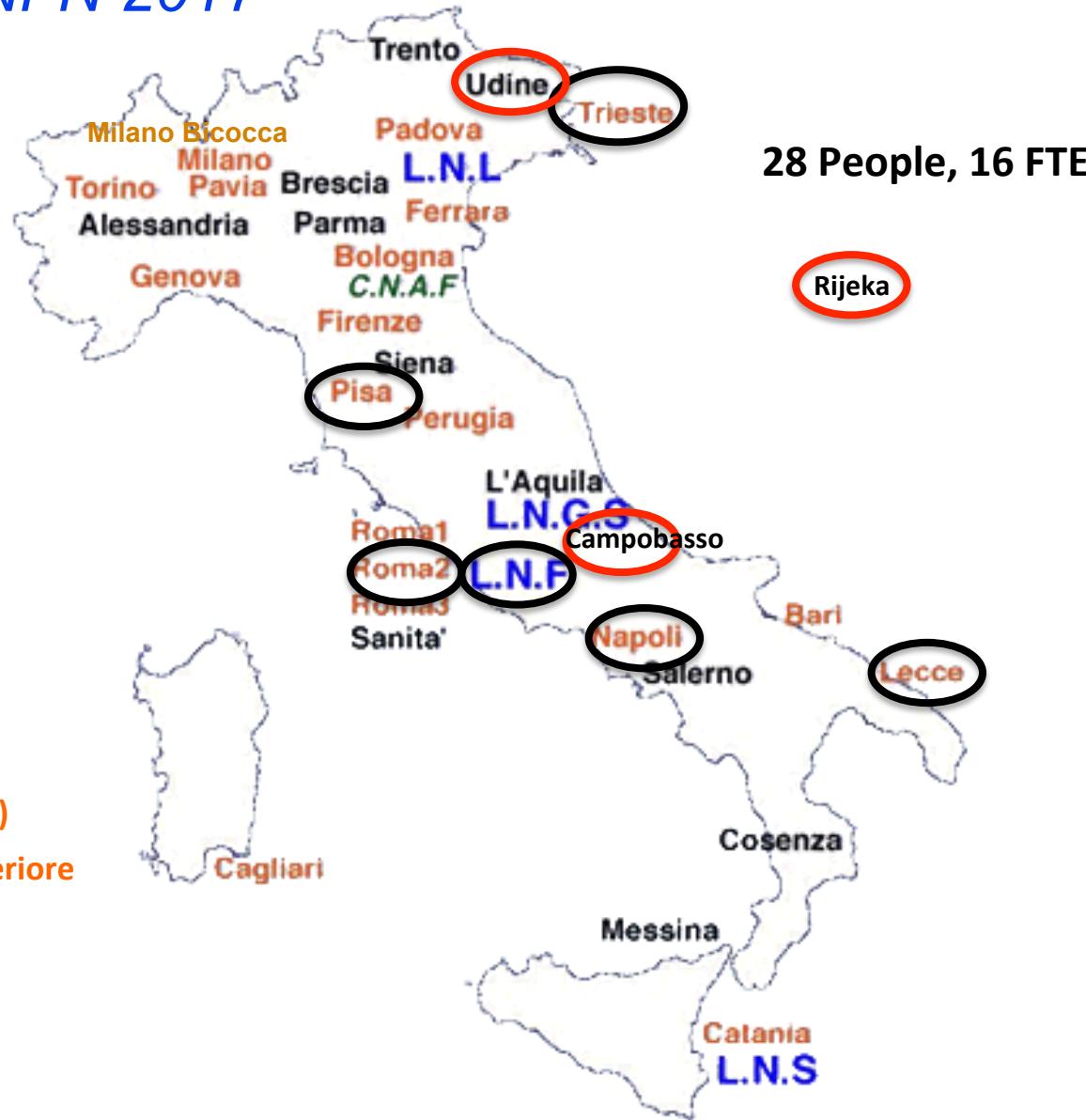


Low voltage supply for the preamplifier boards

A close-up view of a black electronic module, likely a low voltage power supply, mounted in a metal frame. It has several circular ports and a small control panel with a red LED and a green LED. Several white cables are connected to the back of the module.

6 INFN Sections:

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



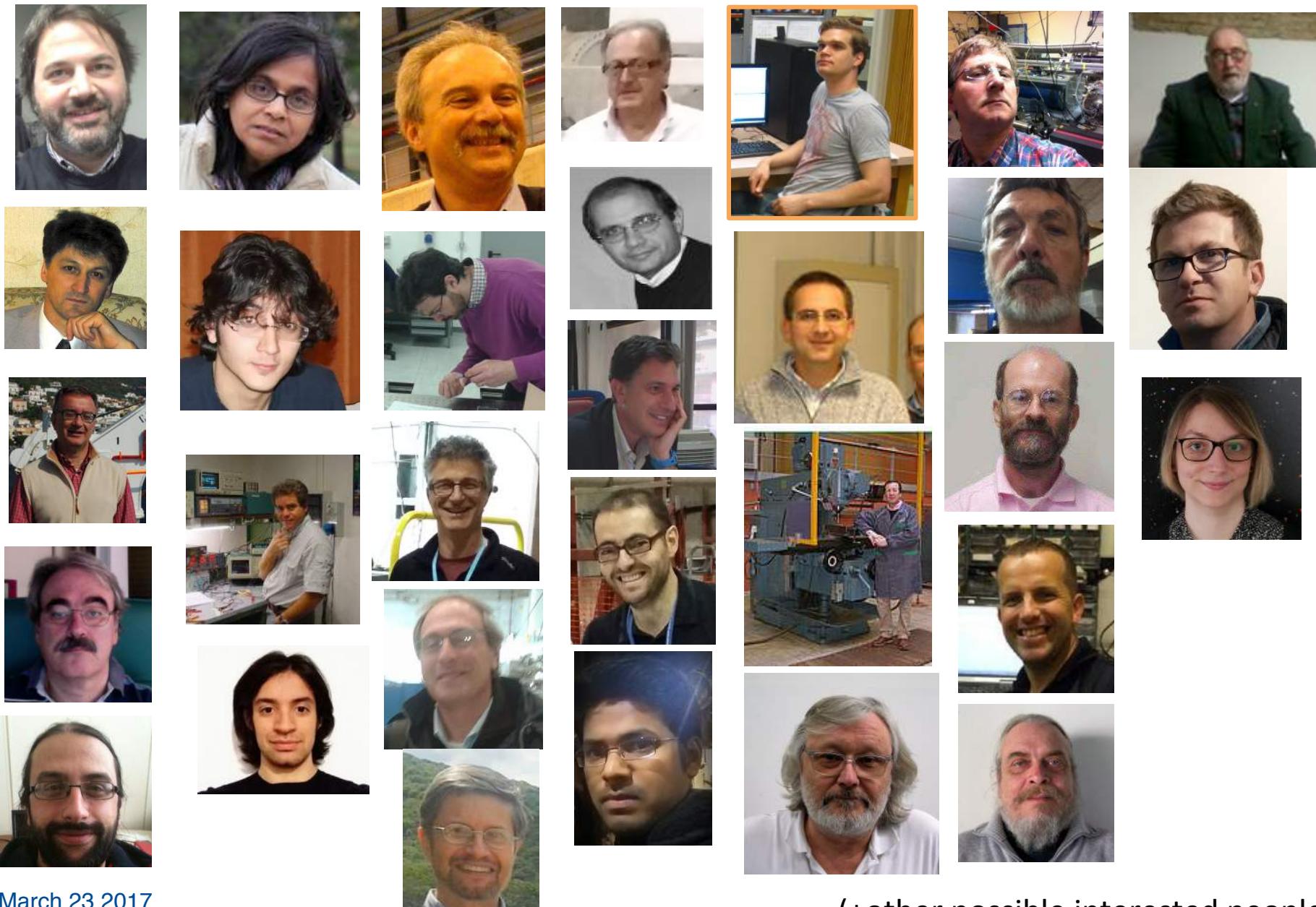
6 Universities:

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

CNR INO:

- Pisa

Laser Calibration team: 21 staff; 4 postdoc; 3 PhD students



First PhD Thesis in g-2!



Università degli Studi di Messina

DIPARTIMENTO DI SCIENZE MATEMATICHE E INFORMATICHE,
SCIENZE FISICHE E SCIENZE DELLA TERRA

DOTTORATO DI RICERCA IN FISICA XXIX CICLO

A. Anastasi,
University of Messina

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

SSD:FIS04

PhD COORDINATOR:
Prof. Lorenzo TORRISI

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

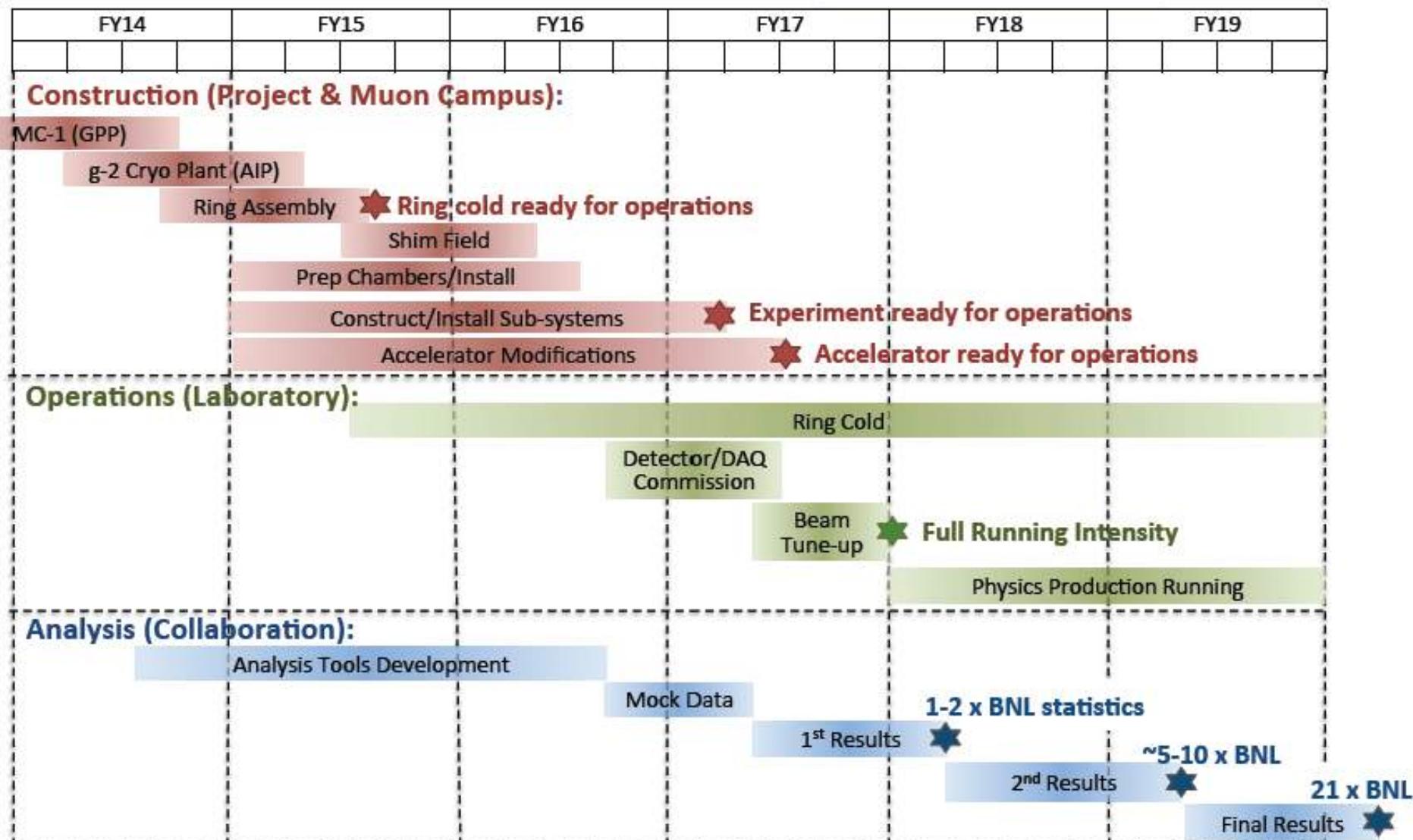
TRIENNIO 2014/2016

Contributo Italiano e Richieste di supporto in Sezione

- Non abbiamo richieste significative che non siano metabolismo del sistema e turni presa dati a Fermilab
- Possibile utilizzo computing a Pisa (TIER 2)?



Schedule overview



Futuro

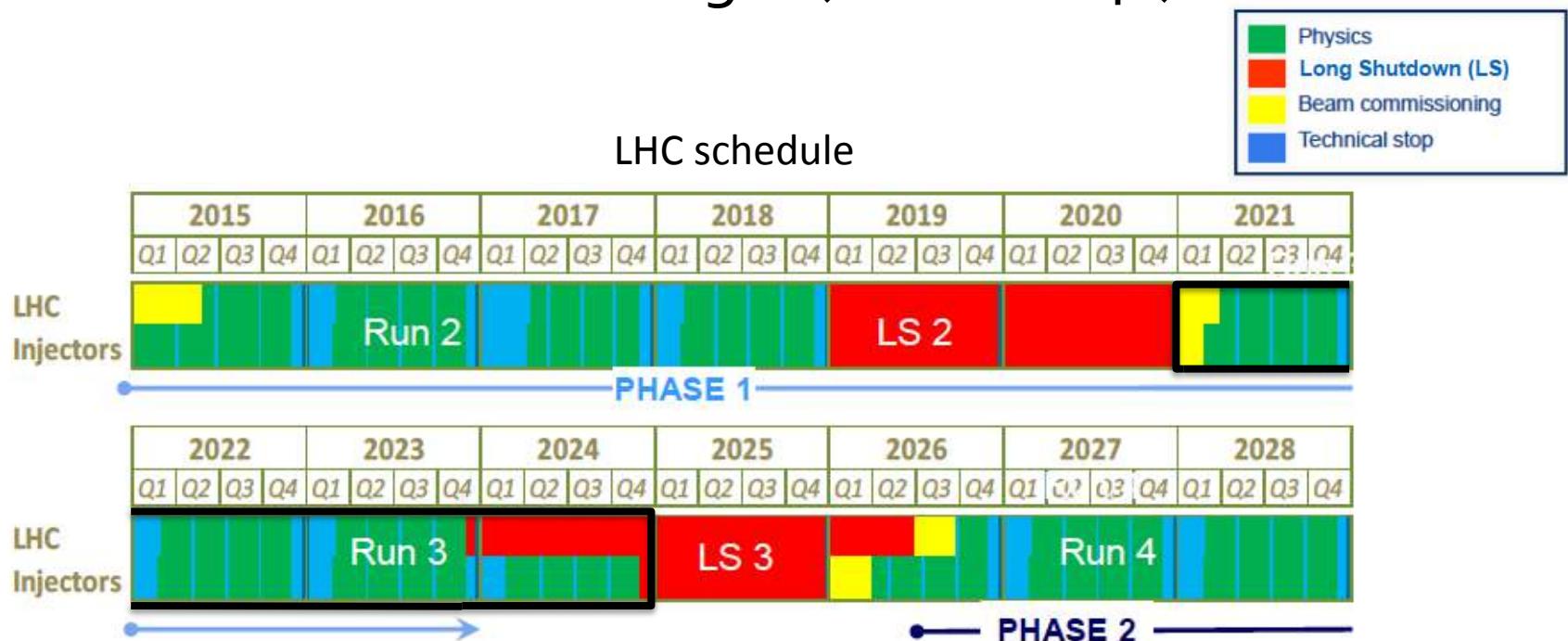
- 2018-2021: turni a Fermilab e analisi dati ω_a
- 2020-2022: possibile run con μ^- (da approvare)?



- Opportunity to propose μ^- in FY20-22, has to be coordinated with Mu2e start-up
- Simulation projects 24 months of μ^- run time, reduces to 16 months with new inflector

Futuro

- 2018-2021: turni a Fermilab e analisi dati ω_a
- 2020-2022: possibile run con μ^- (da approvare)?
- Meanwhile: Nuovo esperimento al CERN per la misura del contributo adronico al $g-2$ (2021-2024?)



High precision measurement of a_{μ}^{HLO} with a 150 GeV μ beam on e^- target at CERN

G. Abbiendi¹, C.M. Carloni Calame², M. Incagli³, U. Marconi¹, C. Matteuzzi⁴, G. Montagna^{2,5}, C. Patrignani^{1,6}, O. Nicrosini², M. Passera⁷, F. Piccinini², F. Pisani^{1,6}, R. Tenchini³, L. Trentadue^{4,8}, G. Venanzoni⁹

¹INFN, Sezione di Bologna, Bologna, Italy

²INFN, Sezione di Pavia, Pavia, Italy

³INFN, Sezione di Pisa, Pisa, Italy

⁴INFN, Sezione di Milano Bicocca, Milano, Italy

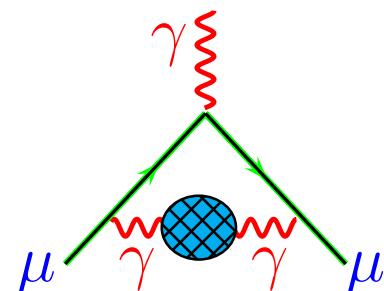
⁵Universita' di Pavia, Pavia, Italy

⁶Universita' di Bologna, Bologna, Italy

⁷INFN, Sezione di Padova, Padova, Italy

⁸Universita' di Parma, Parma, Italy

⁹INFN, Laboratori Nazionali di Frascati, Frascati, Italy



Articoli riferimento

Physics Letters B 746 (2015) 325–329



Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb



A new approach to evaluate the leading hadronic corrections to the muon $g-2$



C.M. Carloni Calame^{a,*}, M. Passera^b, L. Trentadue^{c,d}, G. Venanzoni^e

^a Dipartimento di Fisica, Università di Pavia, Pavia, Italy

^b INFN, Sezione di Padova, Padova, Italy

^c Dipartimento di Fisica e Scienze della Terra "M. Melloni", Università di Parma, Parma, Italy

^d INFN, Sezione di Milano Bicocca, Milano, Italy

^e INFN, Laboratori Nazionali di Frascati, Frascati, Italy

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

THE EUROPEAN
PHYSICAL JOURNAL C

Phys. Lett. B 746 (2015) 325

Regular Article - Experimental Physics



Measuring the leading hadronic contribution to the muon $g-2$ via μe 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 Marzollo 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

Eur. Phys. J C 77 (2017) 139

- E821 experiment at BNL has generated enormous interest:

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

- Tantalizing $\sim 3\sigma$ deviation with SM (persistent since >10 years):

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

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

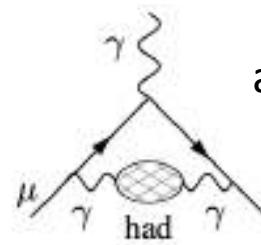
$$a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8) \times 10^{-10}$$

- Current discrepancy limited by:

- **Experimental** uncertainty → New experiments at FNAL and J-PARC $\times 4$ accuracy
- **Theoretical** uncertainty → limited by hadronic effects

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

Hadronic Vacuum polarization (HLO)

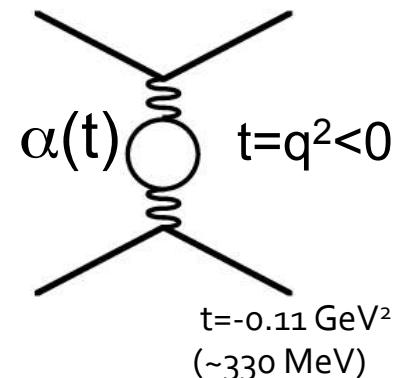


$$a_\mu^{\text{HLO}} = (692.3 \pm 4.2) 10^{-10}$$

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

L'idea: un nuovo modo di misurare il contributo adronico al g-2

$$a_{\mu}^{HLO} = -\frac{\alpha}{\pi} \int_0^1 (1-x) \Delta \alpha_{had} \left(-\frac{x^2}{1-x} m_{\mu}^2 \right) dx$$



Occorre misurare molto bene la costante di accoppiamento e.m. $\alpha(q^2)$ per q^2 bassi e negativi

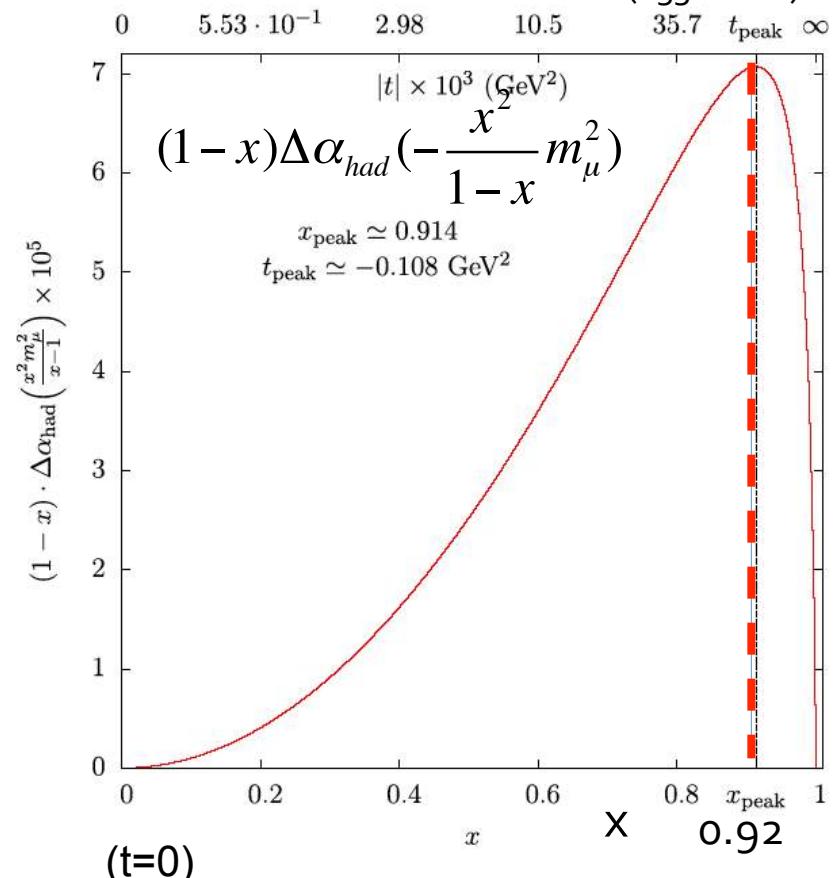
$$t = \frac{x^2 m_{\mu}^2}{x-1} \quad 0 \leq -t < +\infty$$

$$x = \frac{t}{m_{\mu}^2} \left(1 - \sqrt{1 - \frac{4m_{\mu}^2}{t}} \right); \quad 0 \leq x < 1;$$

$$f(t) = \frac{N_{\text{data}}(t)}{N_{\text{MC}}^0(t)} \propto \left(\frac{1}{1 - \Delta \alpha(t)} \right)^2.$$

N_{data} : canale di misura per $q^2 < 0$

N_{MC} : canale di normalizzazione

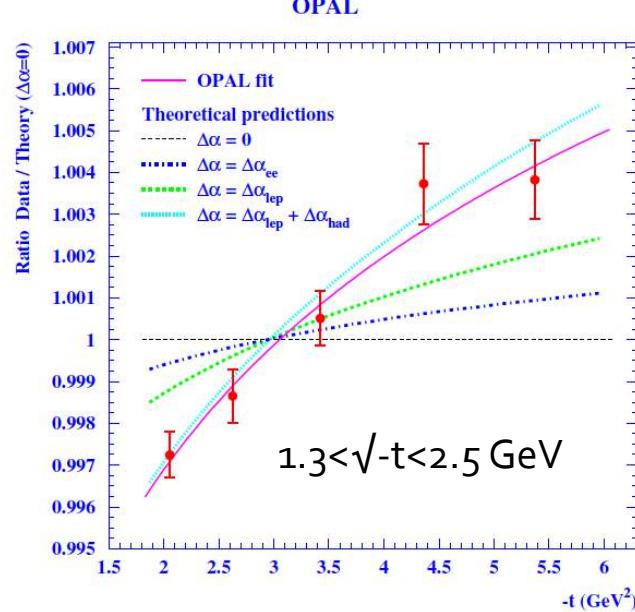


Measurement of $\Delta\alpha_{\text{had}}(t)$ spacelike at LEP

- $\Delta\alpha_{\text{had}}(t)$ ($t < 0$) has been measured at LEP using small angle Bhabha scattering

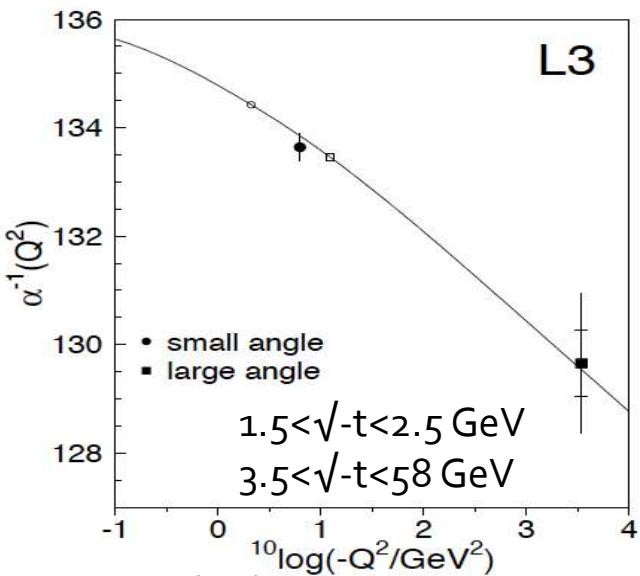
$$f(t) = \frac{N_{\text{data}}(t)}{N_{\text{MC}}^0(t)} \propto \left(\frac{1}{1 - \Delta\alpha(t)} \right)^2.$$

Accuracy at per mill level was achieved!



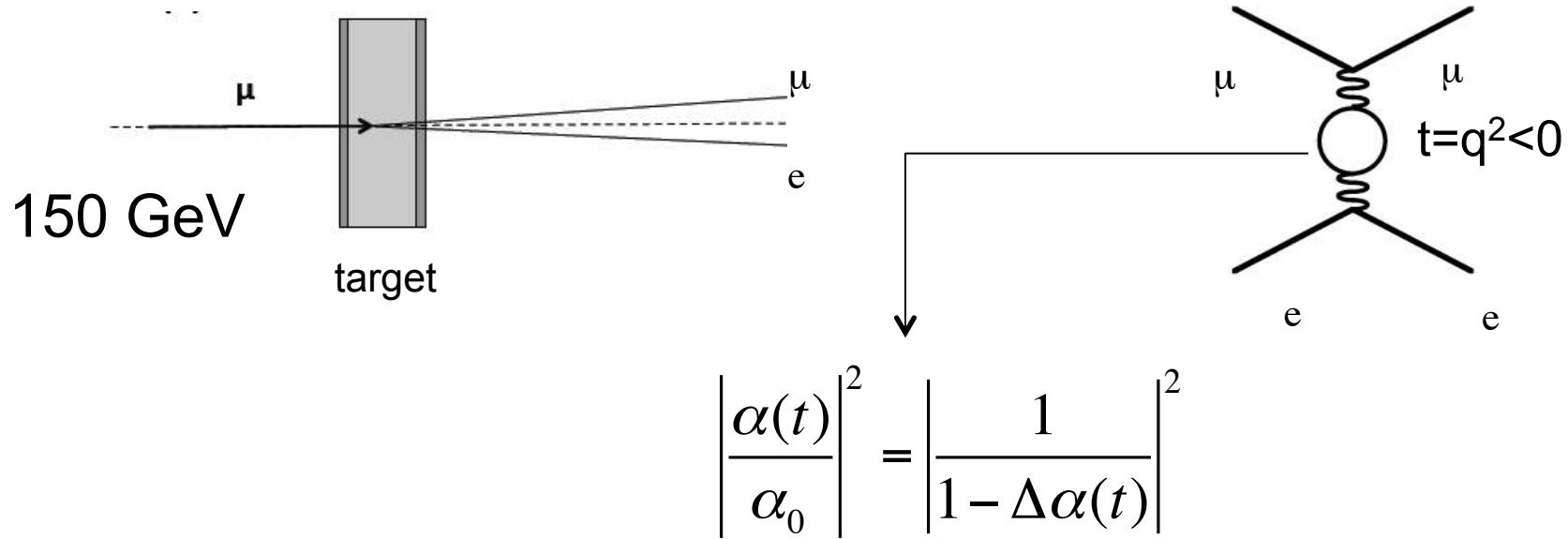
G. Abbiendi et al., Eur. Phys. J. C 45, 1–21 (2006)

- For low t values (≤ 0.11 GeV 2), like in our a different approach is needed!



Processo sperimentale:

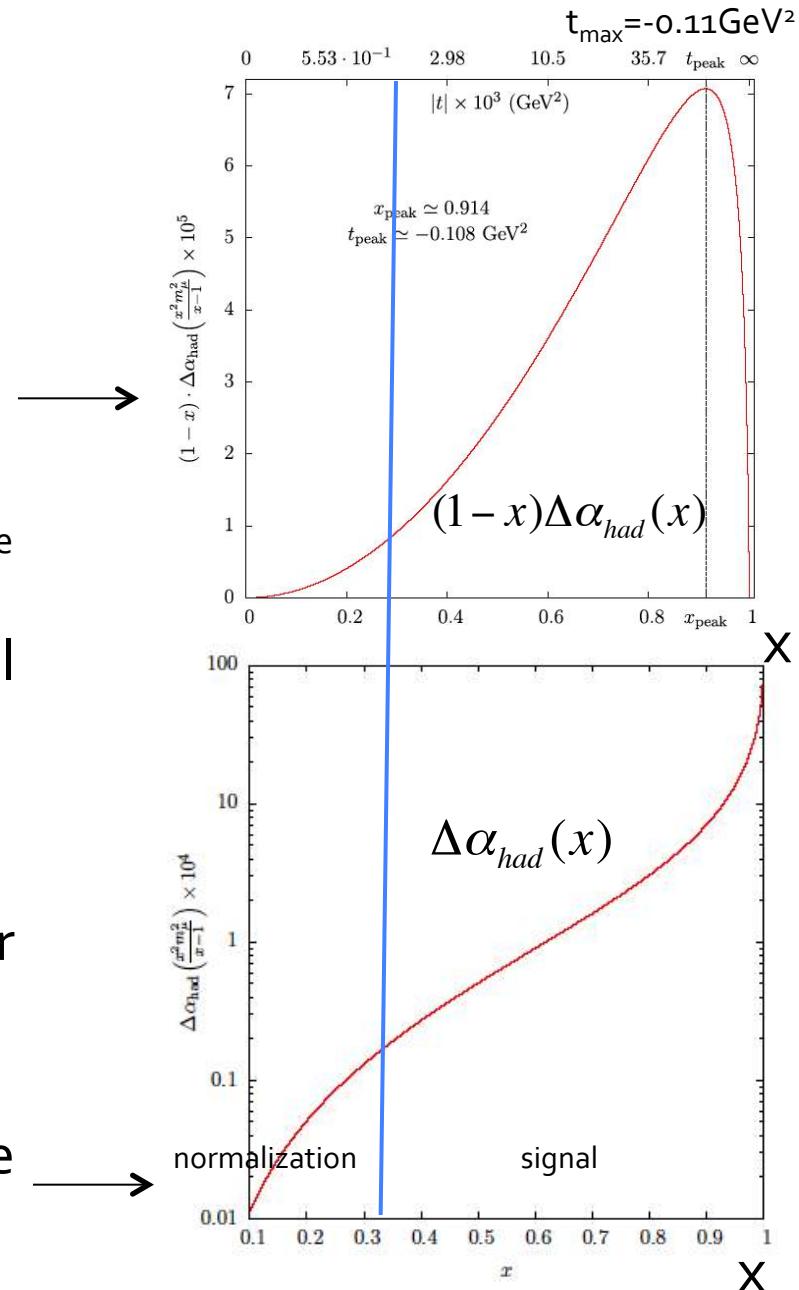
150 GeV μ beam on Be target at CERN
(through the elastic scattering $\mu e \rightarrow \mu e$)



Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

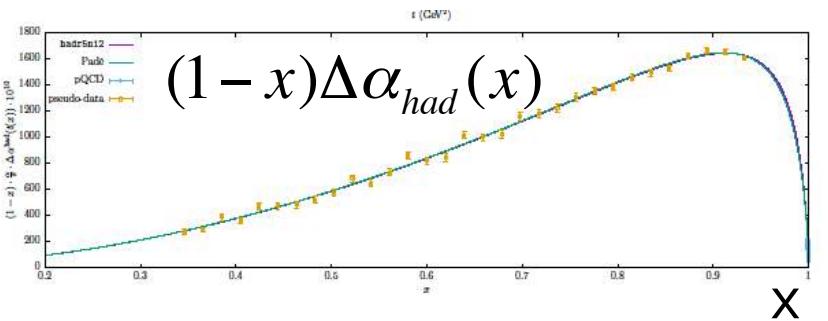
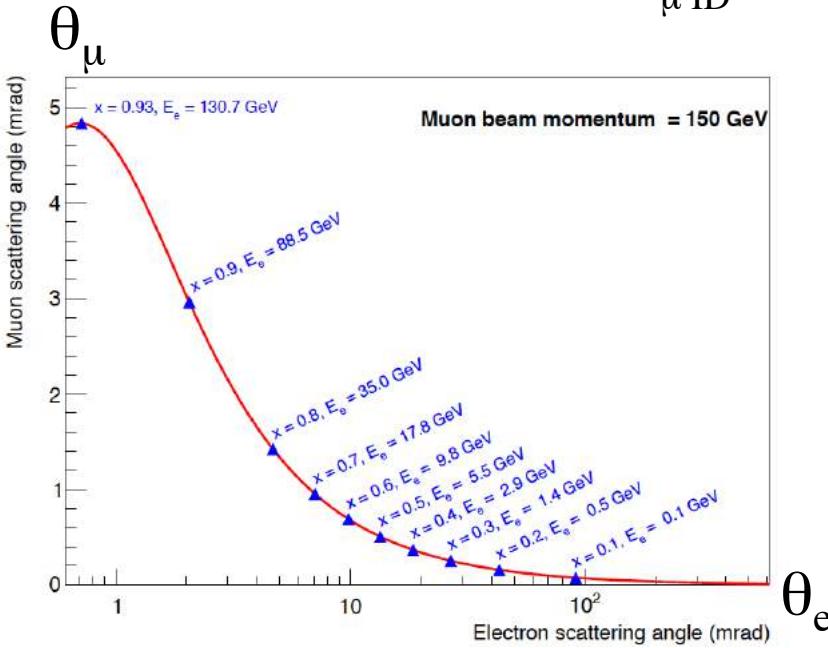
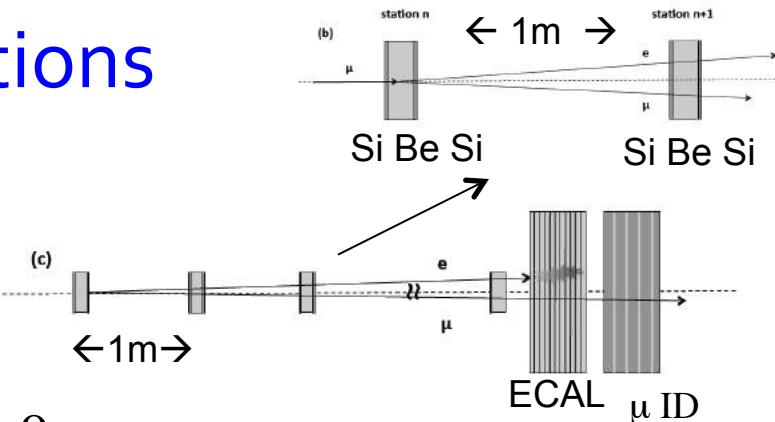
It looks an ideal process!

- $\mu e \rightarrow \mu e$ is pure t-channel (at LO)
- It gives $0 < -t < 0.161 \text{ GeV}^2$ ($0 < x < 0.93$) \rightarrow
- The kinematics is very simple: $t = -2m_e E_e$
- High boosted system gives access to all angles (t) in the cms region
 - $\theta_e^{\text{LAB}} < 32 \text{ mrad}$ ($E_e > 1 \text{ GeV}$)
 - $\theta_\mu^{\text{LAB}} < 5 \text{ mrad}$
- It allows using the same detector for signal and normalization
- Events at $x \sim 0.3$ ($t \sim -10^{-3} \text{ GeV}^2$) can be used as normalization ($\Delta\alpha_{had}(t) < 10^{-5}$) \rightarrow



Detector considerations

- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle
- The $t=q^2 < o$ of the interaction is determined by the electron (or muon) scattering angle (a` la NA7)
- ECAL and μ Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID
- It provides uniform full acceptance, with the potential to keep the systematic errors at 10^{-5} (main effect is the multiple scattering for normalization which can be studied by data)
- Statistical considerations show that a **0.3%** error can be achieved on a_μ^{HLO} in 2 years of data taking with $2 \times 10^7 \mu/\text{s}$ (available at CERN)



μ -e proposal: plans (next 2 years)

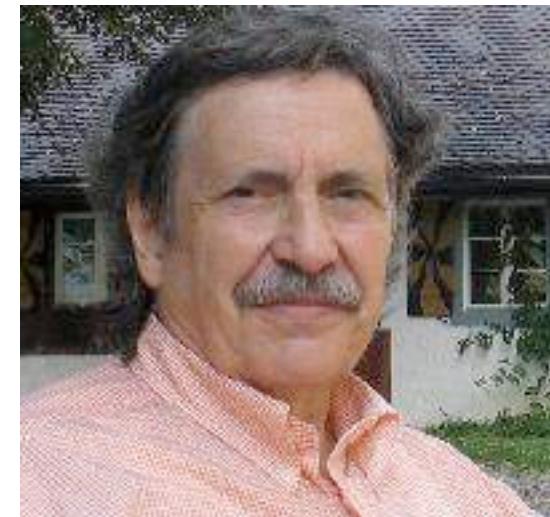
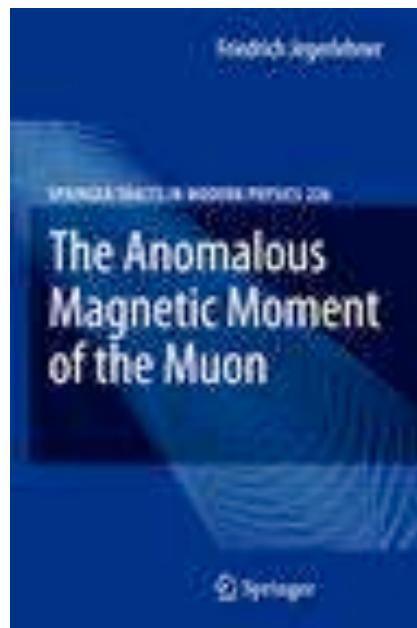
- Focus on Multiple Scattering (MSC) effects:
 - How non gaussian tails affects our measurement and can be monitored/controlled (2D plots and acoplanarity)
- Background subtraction and modeling in GEANT
- Optimization of target/detector and full detail simulation
- Test beam(s) and proto-experiment with a realistic module
- NNLO MC generation of μe process
- Design possible implementation in M2
- Consolidate the collaboration and write a CDR

Proposal part of the Physics Beyond Collider Working Group!

<http://pbc.web.cern.ch/>

Conclusione: g-2:

“The closer you look the more there is to see”
(Quanto più si guarda da vicino, tanto più c'è da vedere)



Fred Jegerlehner

Exciting period for g-2!!!

Se sarà o no nuova fisica ve lo diremo tra qualche anno!!



THE END