# The anomalous magnetic moment of the muon: a crack in the Standard Model?

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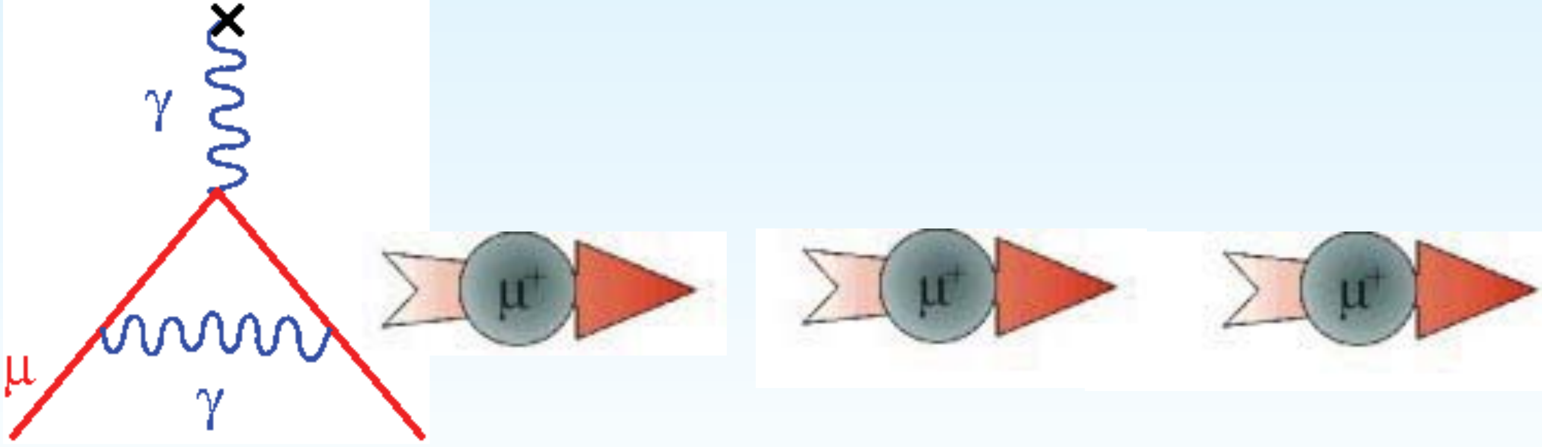
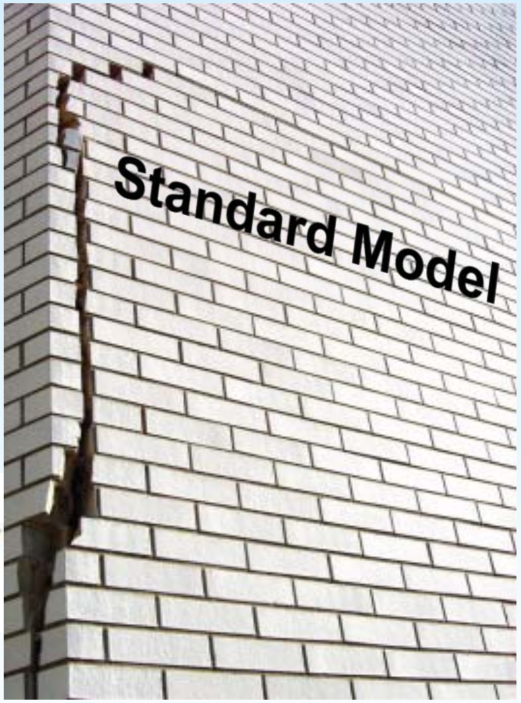




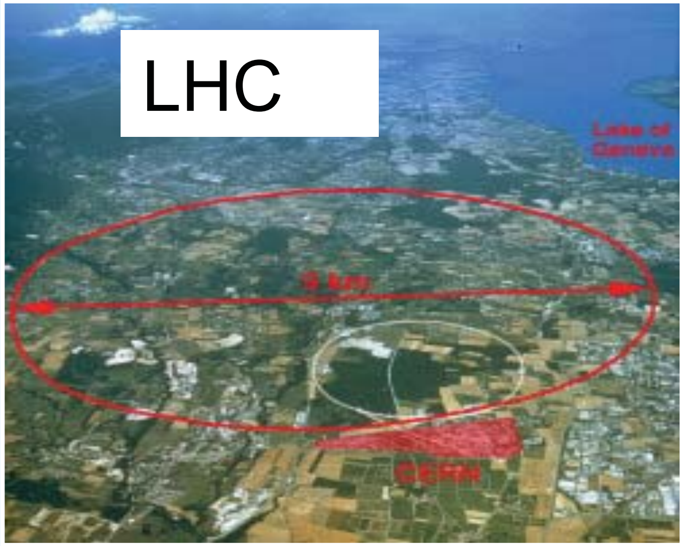
**Seminar at INO, Pisa, 16 Jan 2014**

# Particle Physicists ask only a few questions:

1. **Why mass?**
   - Higgs field
2. **Why matter?**
   - New sources of CP Violation
3. **Why this standard model?**
   - SUSY, Alternate Higgs models, Technicolor, …

wait

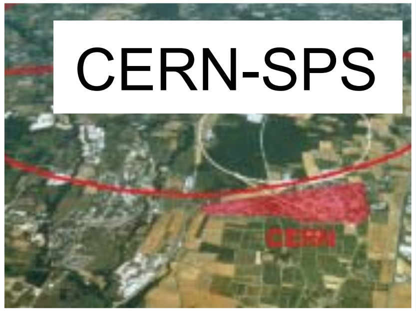
# Often: Direct answers are found at the *Energy Frontier*



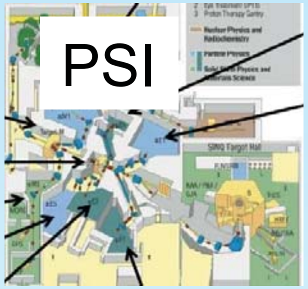
1. Higgs !!
2. But, sources of CP?
3. And, so far data is almost behaving as expected …

**And, if it was the case: How would we interpret some kind of BUMP at hundreds of GeV or at a TeV?**

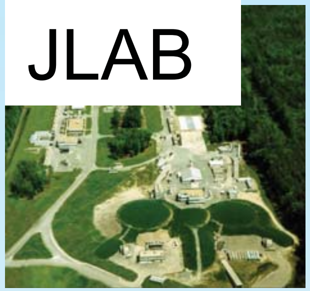
# Today: Indirect evidence from the *Precision Frontier*

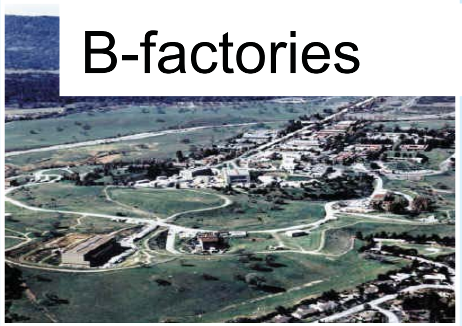

CERN-SPS


Underground

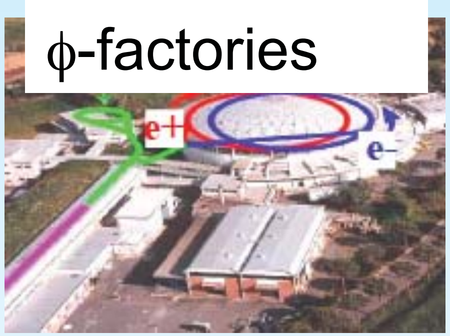

PSI


BNL


JLAB


B-factories


$\tau$/c-factories


$\phi$-factories


Mainz

1. **Higgs (just a bit on mass range from EW)**
2. **CP: CKM, EDMs, $0\nu\beta\beta$**
3. **New Physics? Maybe: g-2; Limits: many other expts.**

**Will require a model that addresses all data from high- and low-energy observables to really nail down any new physics**

# Often the two activities are interlinked: An example

Correlation between the Higgs Decay Rate to Two Photons and the Muon $g-2$

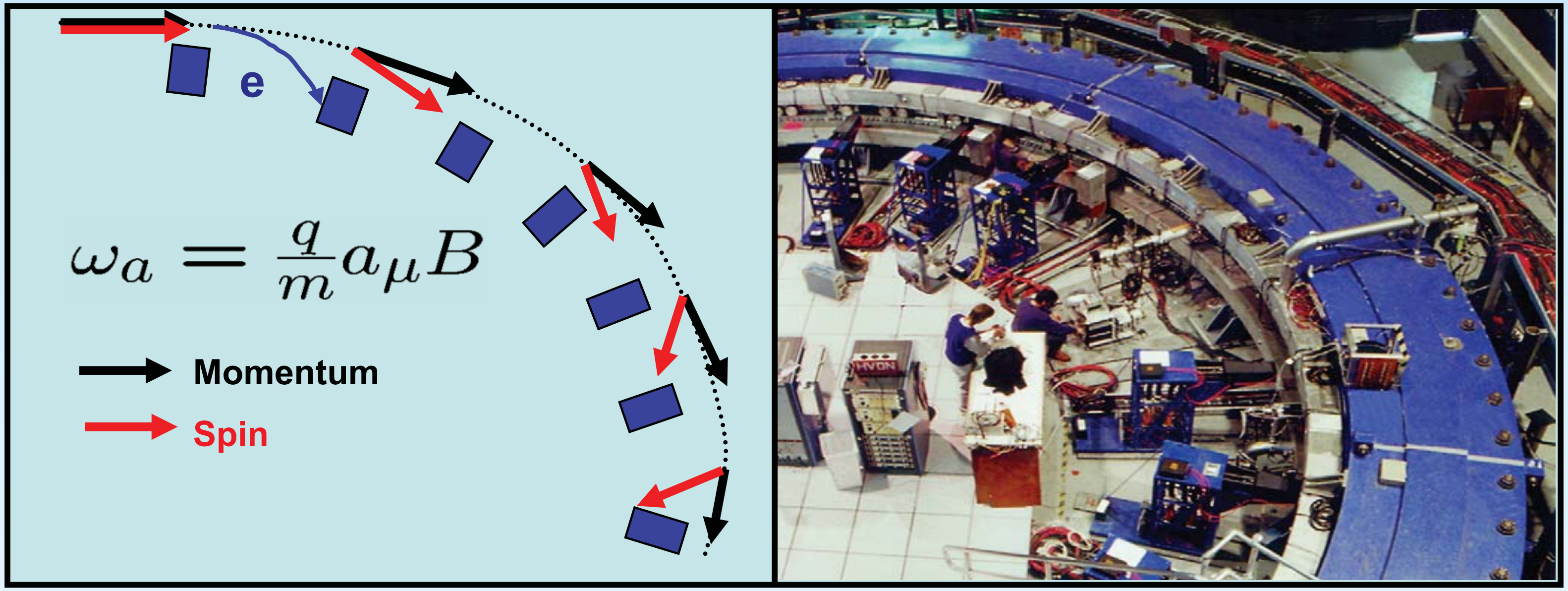
Gian F. Giudice[a], Paride Paradisi[a] and Alessandro Strumia[a,b]

arXiv:1207.6393v1

Post Higgs paper

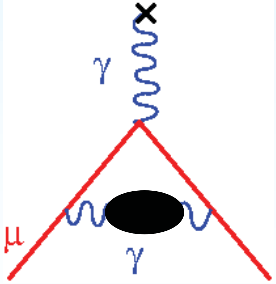
- Observations:
  - production rate is too high by ~40-50%
  - Higgs rates in ZZ* and WW* are consistent with the SM
  - Muon anomaly differs from SM by ~ +280 x $10^{-11}$
- Theoretical SUSY model that fits observations
  - light stau with large left-right mixing
  - light Bino
  - heavy higgsinos
- Other consequences
  - ✓ Predicts Muon Anomaly exactly **G-2**
  - ✓ Compatible with thermal dark matter **Underground**
  - ✓ Predicts small deviations in h → $\gamma$Z and h → $\tau\tau$ **LHC**
  - ✓ Predicts measureable violations of Lepton Non-Universality in $\tau-\mu$ and $\tau$-e **(Super)B/$\tau$-factories**
  - ✓ Predicts NO violation in the $\mu$-e sector **MEG,M2E**

# A Case for Challenging the Standard Model: Muon g-2



$$a_\mu\left(\text{Expt.}\right) = 116592089\left(63\right) \pm 10^{-11} \qquad \left(0.54\ \text{ppm}\right)$$

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)$$



# The giromagnetic factor

By definition, the gyromagnetic ratio g of a state of angular momentum J and magnetic moment μ is:

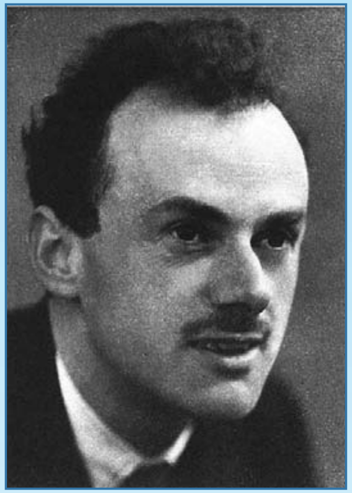
$$g = \frac{\mu}{\mu_0} \Big/ \frac{J}{\hbar}$$

In “classical” E.M. for a particle of charge *e* in a state of orbital angular momentum L:

$$\vec{\mu} = \mu_0 \vec{L}, \quad \mu_0 = \frac{e}{2m}, \quad g = 1$$

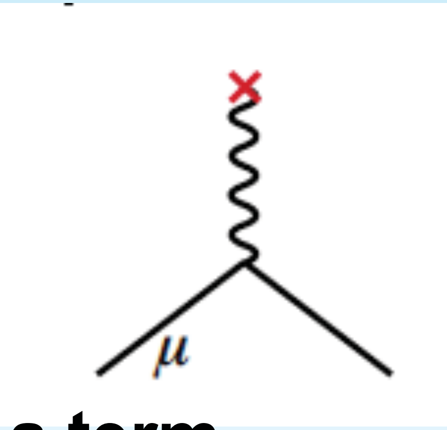
For an electron $\mu_0 = \mu_B = 5.788 \ldots \times 10^{-11}$ MeV $T^{-1}$

# “g” from Dirac equation (QED)



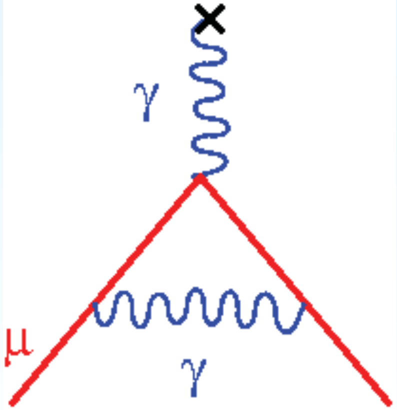
The Dirac equation of an electron interacting with an electromagnetic field predicts g=2 (due to spin)!

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma} \equiv g\mu_B \vec{S}; \quad \vec{S} = \vec{\sigma}/2, \quad g = 2$$



**However, experimentally g > 2; need to add a term**

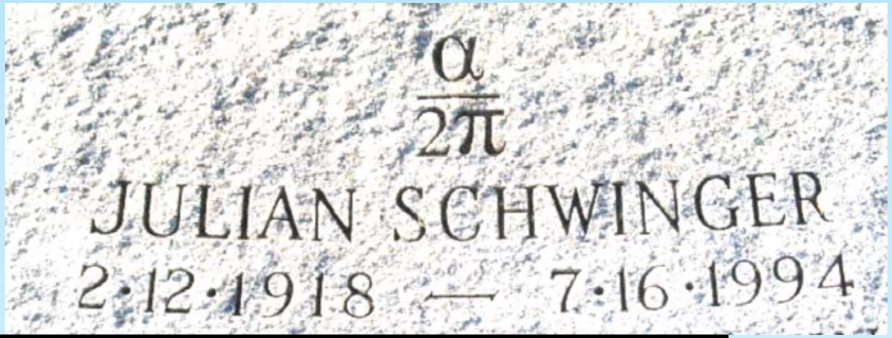
$$g = 2(1 + a)\,; \quad a = \frac{(g-2)}{2}$$

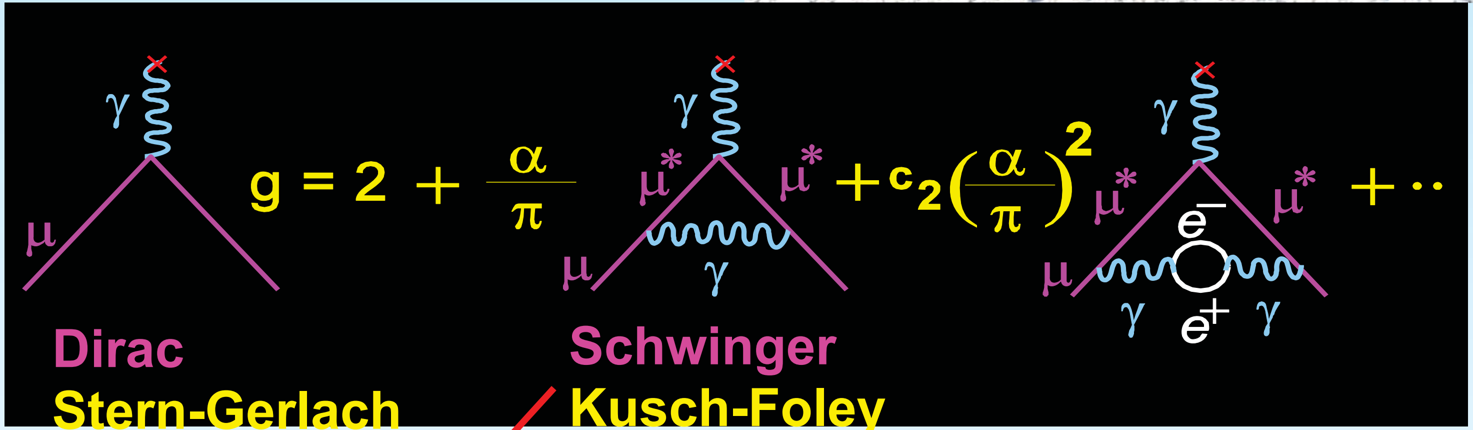


**a is the anomaly and it’s mostly due to emission and absorption of virtual photon (“Loop”)**

# In the QED, a becomes an expansion in (α/π) from loops

$$a = \sum_{j=1} C_j \left(\frac{\alpha}{\pi}\right)^j$$





$$g = 2 + \frac{\alpha}{\pi} + c_2\left(\frac{\alpha}{\pi}\right)^2 + \cdots$$

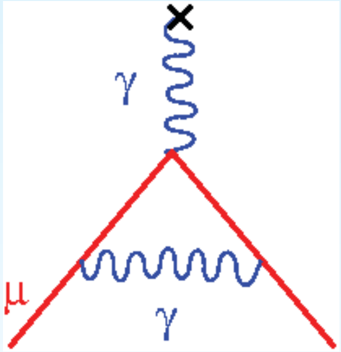
**Dirac**
**Stern-Gerlach**

**Schwinger**
**Kusch-Foley**

$$\mu_e^{\mathrm{th}} = \frac{e\hbar}{2mc}\left(1 + \frac{\alpha}{2\pi}\right) = \frac{e\hbar}{2mc} \times 1.00116$$

**Kusch and Foley 1948:**

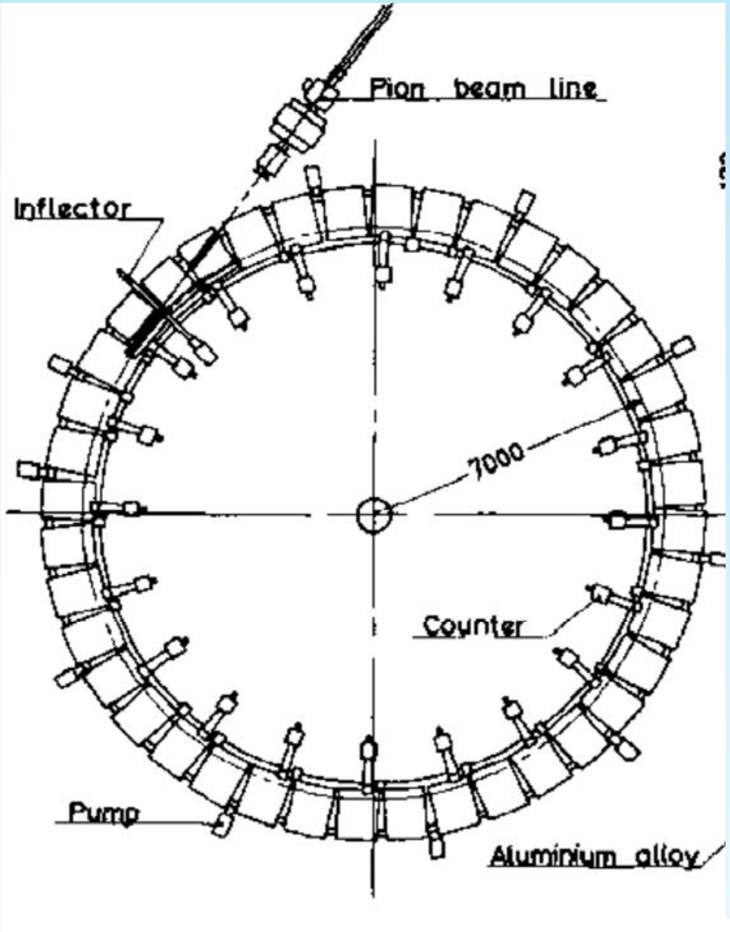
$$\mu_e^{\mathrm{exp}} = \frac{e\hbar}{2mc}(1.00119 \pm 0.00005)$$

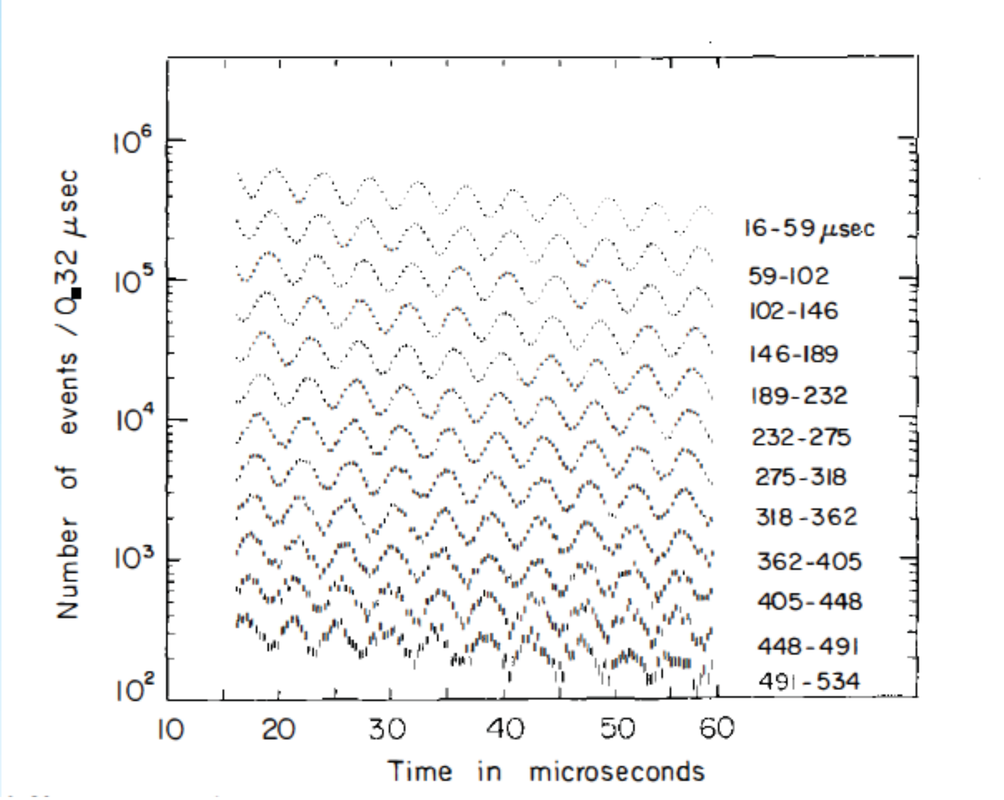


**triumph of QED!**

***However there are also other (important) contributions***

# Cern experiment in ‘70: a triumph for the QED





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

| 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) | | |

But how was possible to measure g-2 to such an accuracy?

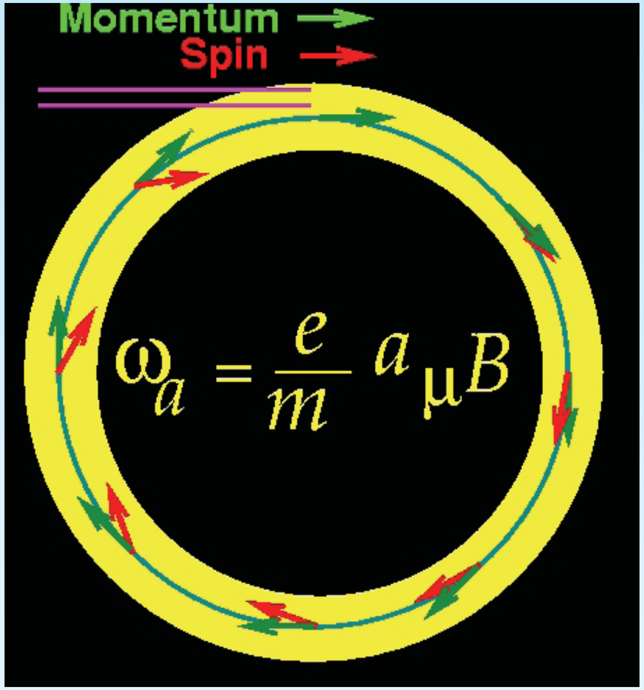
# Third Cern experiment (1979)

# The $a_\mu$ Experiment:

- Place polarized muons in a B field
  - spin precession frequency (q = ± e)

$$\vec{\omega}_S = -g\frac{q\vec{B}}{2m} - \frac{q\vec{B}}{\gamma m}(1-\gamma)$$

  - cyclotron frequency

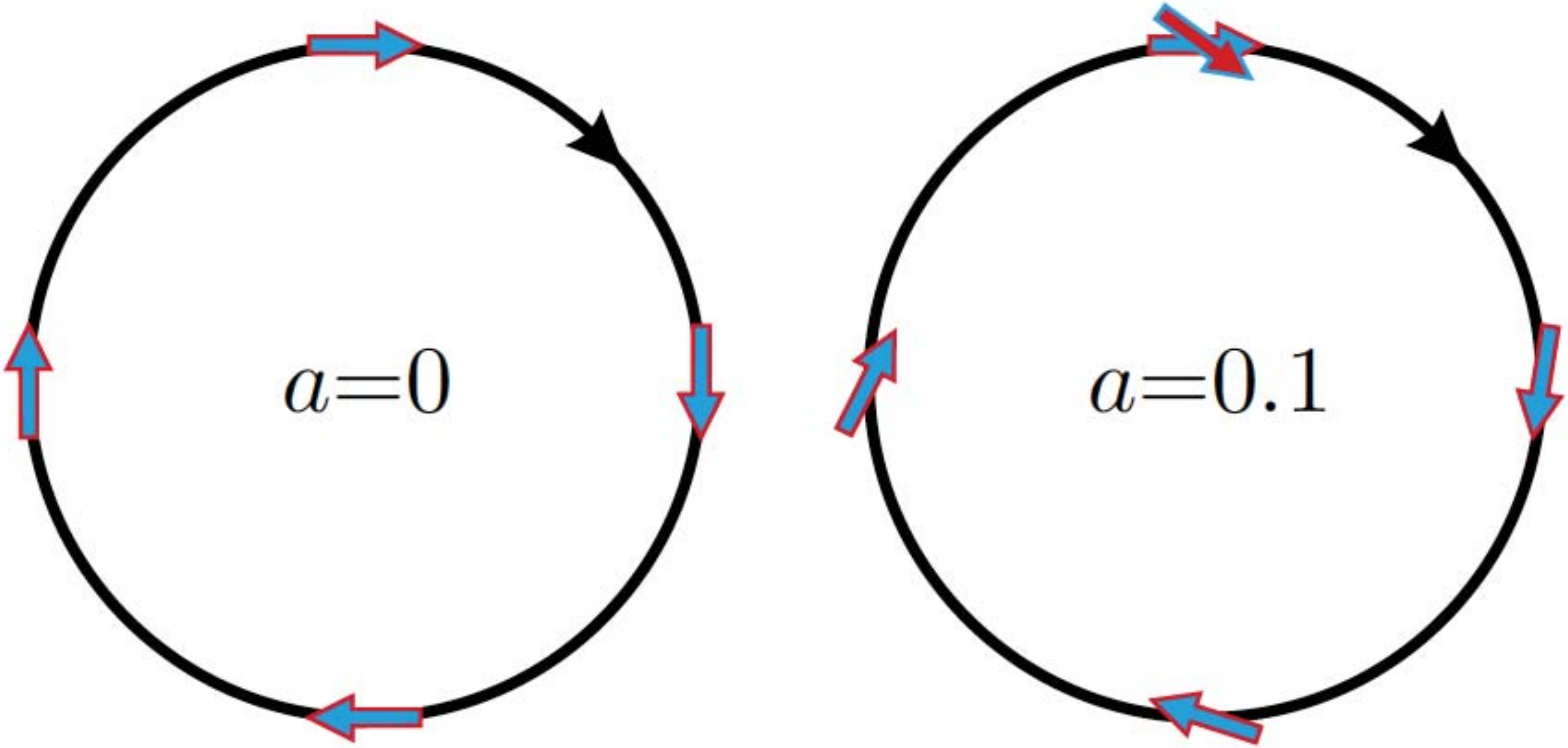


$$\vec{\omega}_C = -\frac{q\vec{B}}{m\gamma}$$

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

Since g > 2, the spin gets ahead of the momentum

**Measuring $\omega_a$ and B → $a\mu$**



For $a = 1$ ($\gamma$=1), spin rotates wrt momentum by 1/10 turn per turn.

# Need of Electric field for Vertical Focusing

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

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV/c}$$

**If $p_\mu$= 3.09 GeV (magic momentum) there is no effect of the electric field on the precession frequency!**

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

**Measure (precisely) $\omega_a$ and B and get $a_\mu$!**

**But…how to measure $\omega_a$?**

**Produce polarized muons and let them decay…**

# The Muons

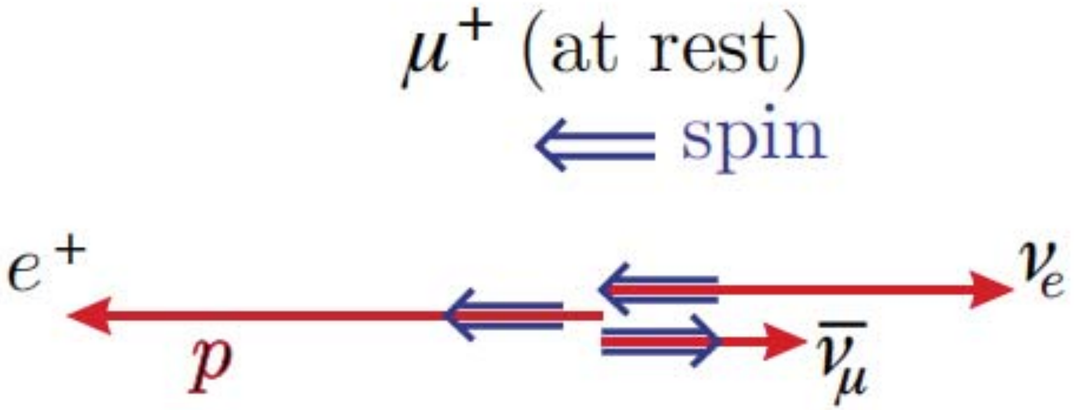
- **produced polarized in "forward" direction**

$$\pi^- \longrightarrow \mu^- \ \bar{\nu}_\mu$$

- **decay with information on where their spin was at the time of decay**

$$\mu^- \longrightarrow e^- \ \bar{\nu}_e \ \nu_\mu$$

**S**-**p** correlation fundamental to all muon anomaly experiments



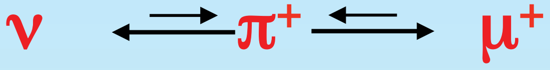
High energy positrons have momentum along the muon spin. The opposite is true for electrons from $\mu^-$.

Detect high energy electrons. The time dependence of the signal tracks muon precession.

**highest energy $e^\pm$ carry $\mu$ spin information**

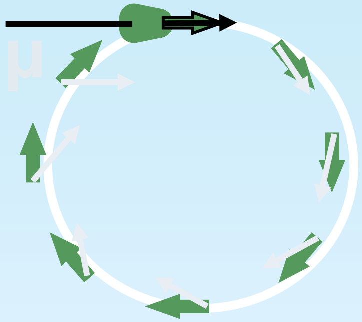
# 4 Key elements of modern storage-ring g-2 measurements

## (1) Polarized muons



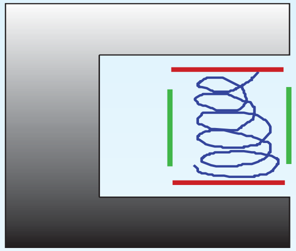
~97% polarized for forward decays

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



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

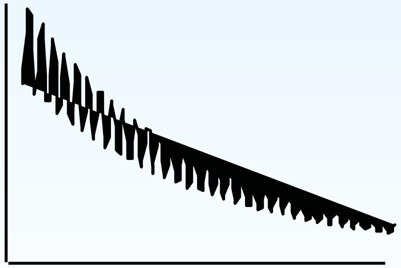
## (3) $P_\mu$ magic momentum = 3.094 GeV/c



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

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

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



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

*Note: this carries a tiny systematic error of < 0.05 ppm in past experiment

# CERN experiment ('70) # of high energy electrons vs time:

$\omega_a$

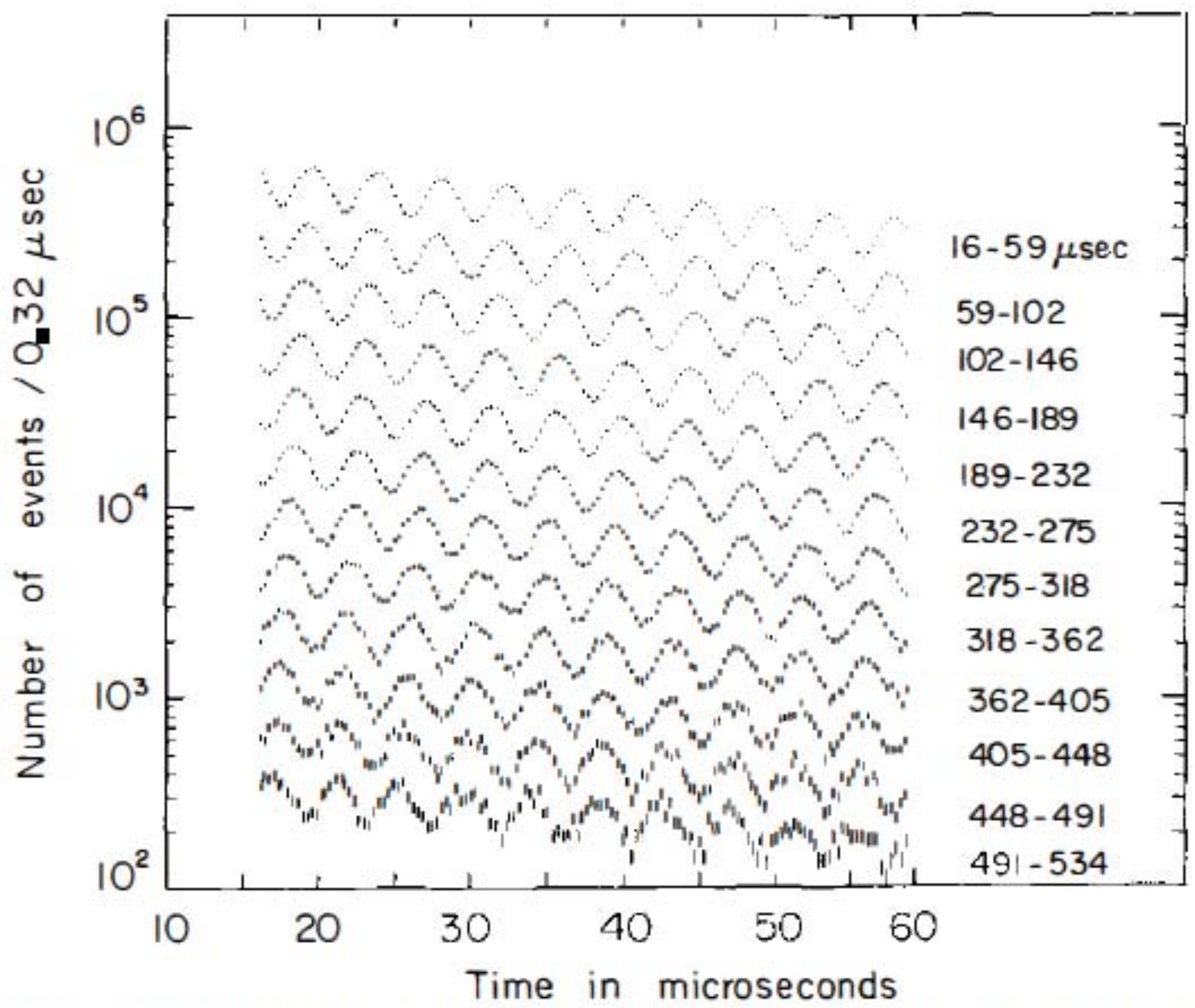


*Figure 13* Muon Storage Ring II: decay electron counts versus time (in microseconds) after injection. Range of time for each line is shown on the right (in microseconds).

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

**This was the results of CERN exp ('70). Since that many progress on the Experiment (BNL E821) and Theory**

# Setting the stage for Brookhaven E821

In 1984 QED was calculated to fourth order

Hadronic uncertainties were greatly reduced

Time for new experiment at Brookhaven AGS at sub ppm

Improvements:

Much higher intensity

3 superconducting coils

Circular aperture

Inject muons into ring with inflector and kicker

In-situ B measurements with NMR probes

# E821 exp at BNL: Muon (g-2) storage ring

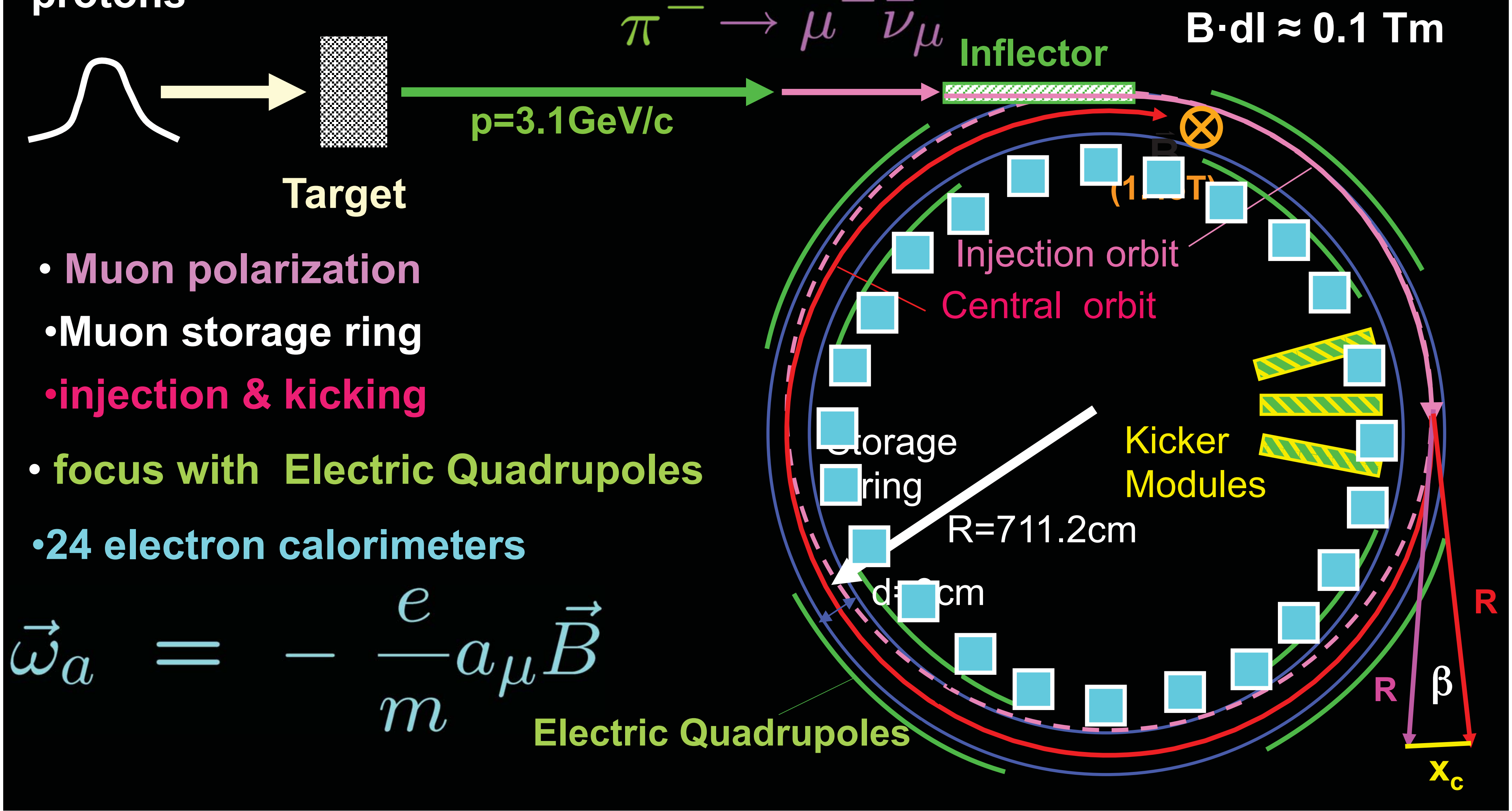
# Experimental Technique

25ns bunch of $\geqslant$ 1 X $10^{12}$ protons

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

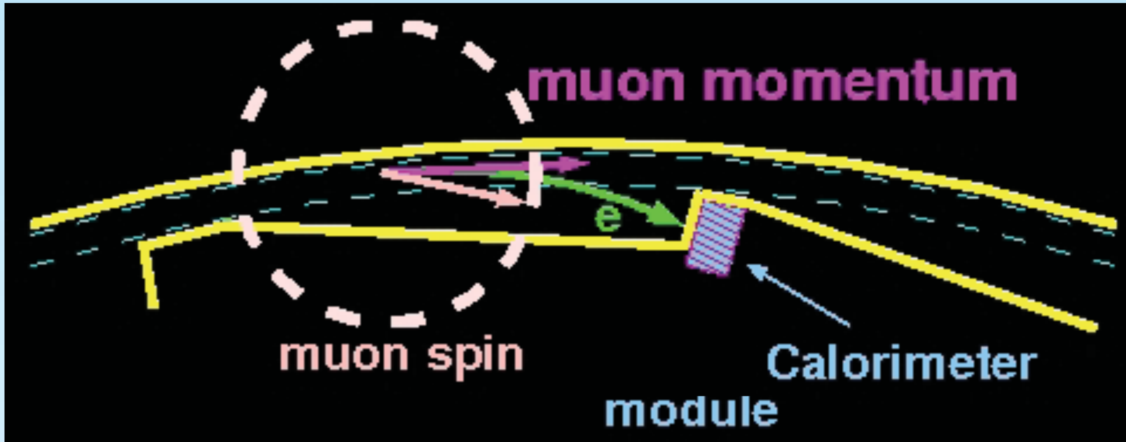
B·dl ≈ 0.1 Tm



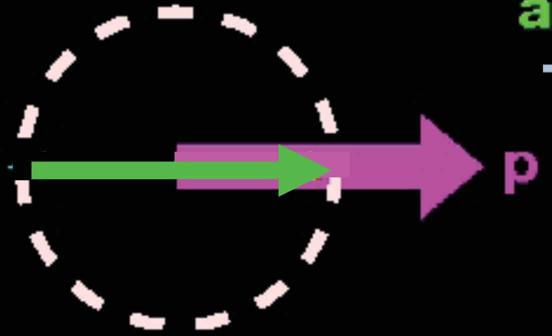
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

# $e^{\pm}$ from $\mu^{\pm} \rightarrow e^{\pm}\nu\bar{\nu}$ are detected

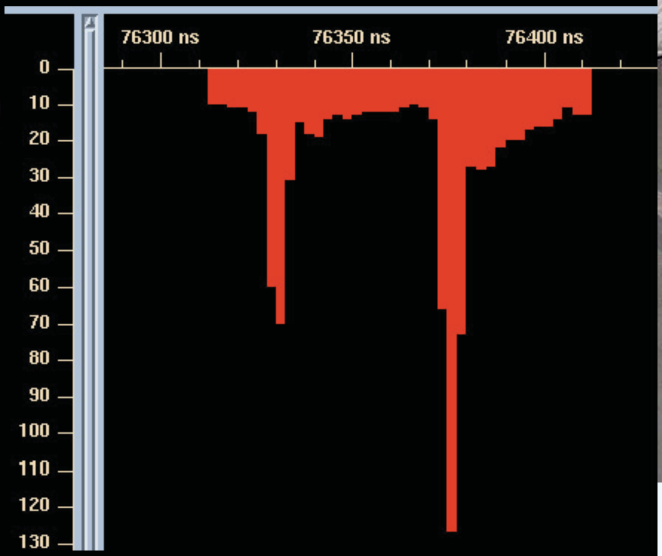


Measures Energy
and time



spin forward, more
high energy e

spin backward, less
high energy e

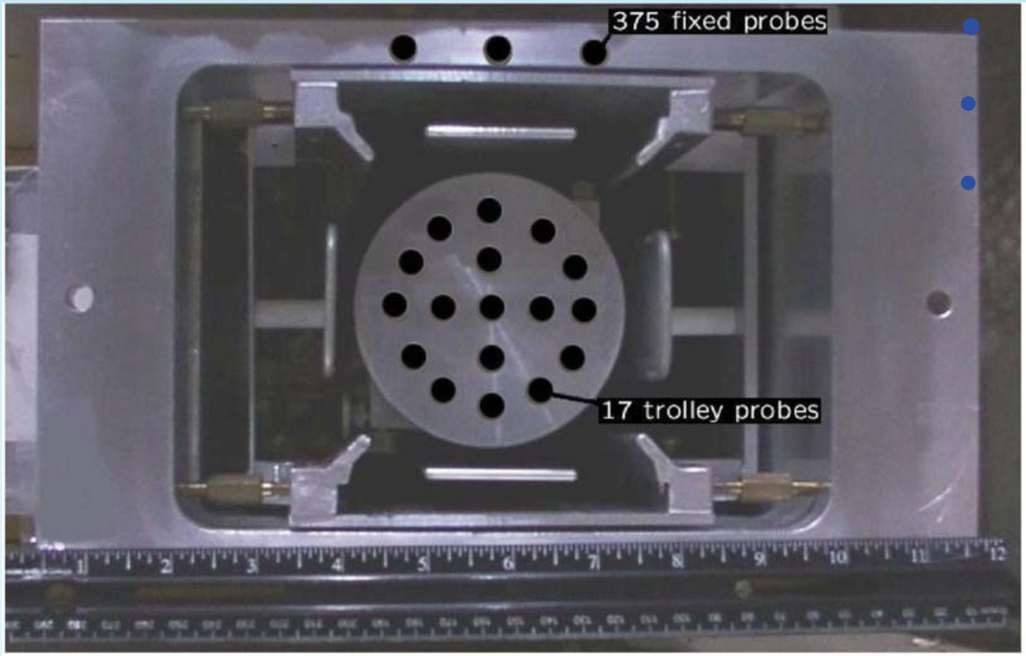


Waveform digitizer
gives t, E

Picture of a Lead-Scifi
Calorimeter from E821

# The magnetic field is measured and controlled using pulsed NMR and the free-induction decay.

$\omega_p$

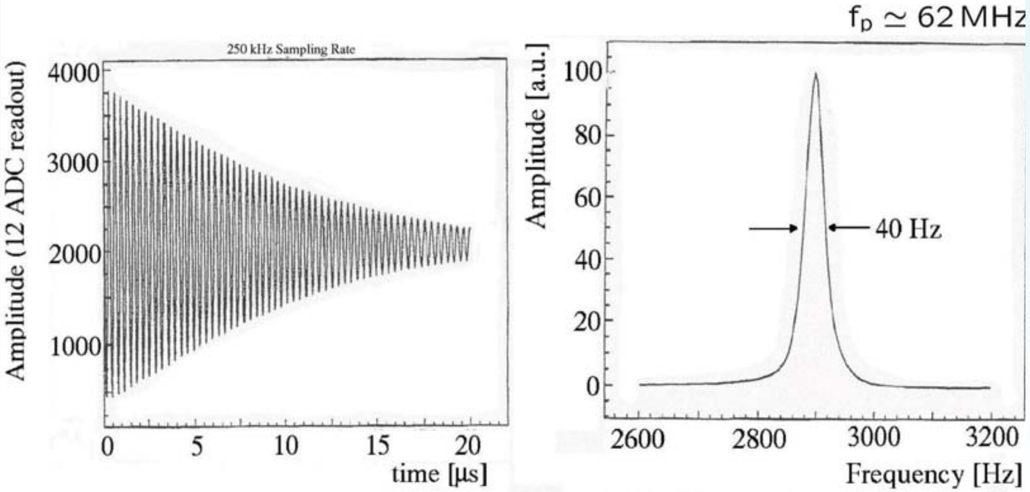


- $\omega_p$= Larmor frequency of the free p
- We measure $\omega_a$ and $\omega_p$ independently
- Use $\lambda = \mu_\mu/\mu_p$ as the "fundamental constant"

**Blind analysis**

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

Free induction decay signals:



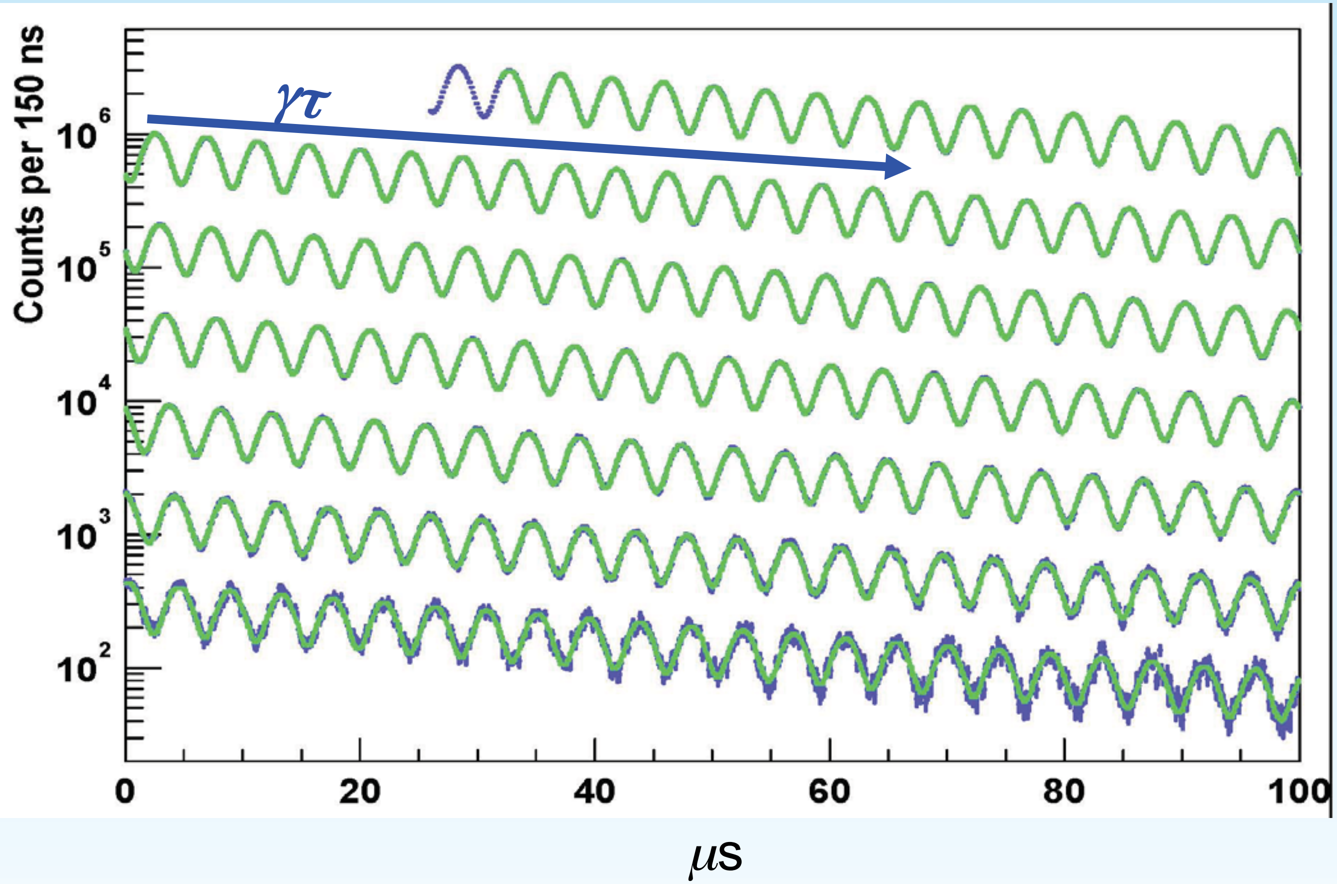
So which was the result for aμ?

# The arrival time spectrum of high-energy e$^-$ $\omega_a$

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

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

**$E_e \geq 1.8$ GeV**



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

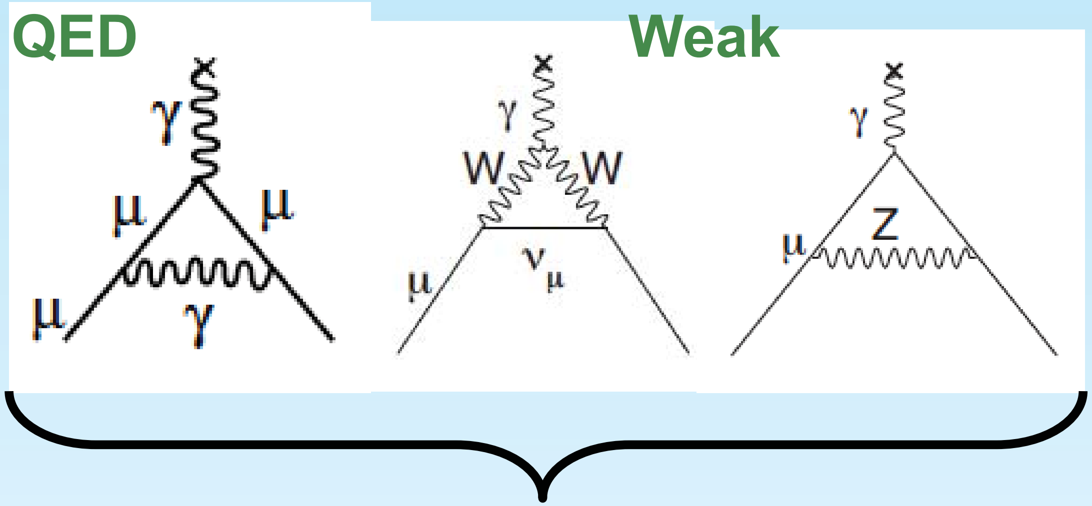
**Fitting this function gives $\omega_a$. Together with the magnetic field one get $a_\mu$:**

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

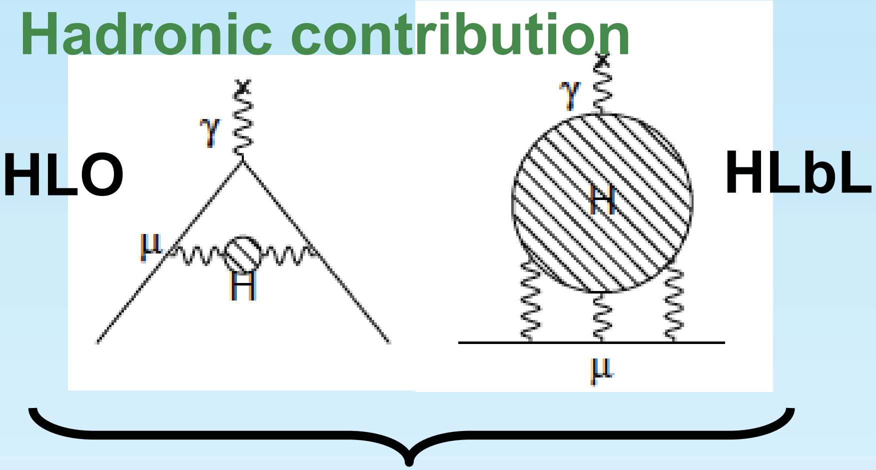
**(0.5 ppm)**

***What's the Standard Model prediction?***

# Standard Model contribution to (g-2)



Precisely known



Large uncertainty

(significant work going on)

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

$a_\mu^{QED} \sim \alpha/2\pi \sim O(10^{-3})$ $a_\mu^{Weak} \sim O(10^{-9})$ $a_\mu^{HAD} \sim O(10^{-8})$

$\delta a_\mu^{QED} \sim 1.4\times10^{-12}$ $a_\mu^{Weak} \sim 2\times10^{-11}$ $\delta a_\mu^{HAD} \sim 5\times10^{-10}$

In the '70 at CERN $a_\mu$ was measured with an uncertainty of $8\times10^{-9}$ (7ppm), of the same order of $\delta a_\mu^{SM}$ (sensitive to hadronic contribution)

**Today:**

# $a_\mu^{SM}$: the QED contribution

$$a_\mu^{QED} = (1/2)(\alpha/\pi)$$ Schwinger 1948

$$+\ 0.765857408\ (27)\ (\alpha/\pi)^2$$

Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '04

$$+\ 24.05050959\ (42)\ (\alpha/\pi)^3$$

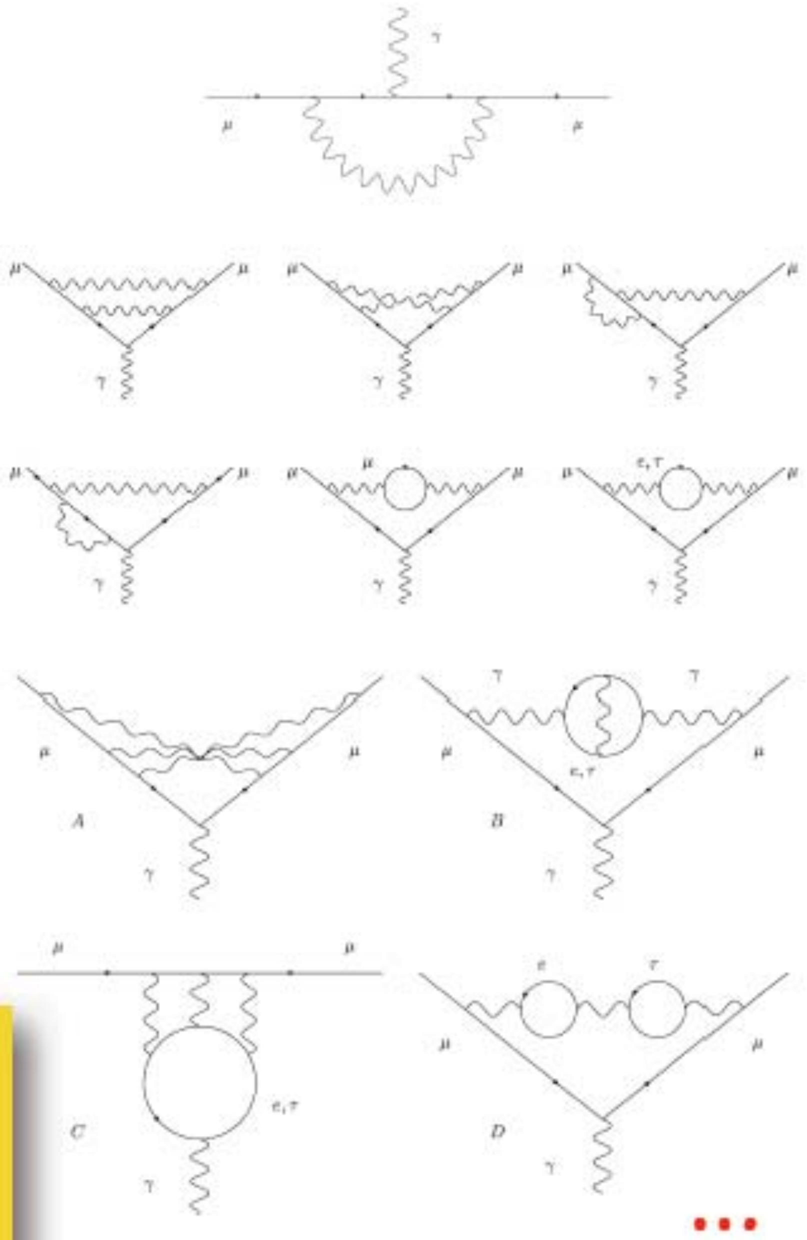
Remiddi, Laporta, Barbieri … ; Czarnecki, Skrzypek; MP '04;
Friot, Greynat & de Rafael '05, Mohr,Taylor & Newell '08

$$+\ 130.805\ (8)\ (\alpha/\pi)^4$$

Kinoshita & Lindquist '81, … , Kinoshita & Nio '04, '05;
Aoyama, Hayakawa, Kinoshita & Nio, June & Dec 2007

$$+\ 663\ (20)\ (\alpha/\pi)^5$$ In progress…

Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,
Karshenboim,…, Kataev, Kinoshita & Nio '06, Kinoshita et al. 2011



...

**Adding up, we get:**

$$a_\mu^{QED} = 116584718.08\ (14)(04) \times 10^{-11}$$

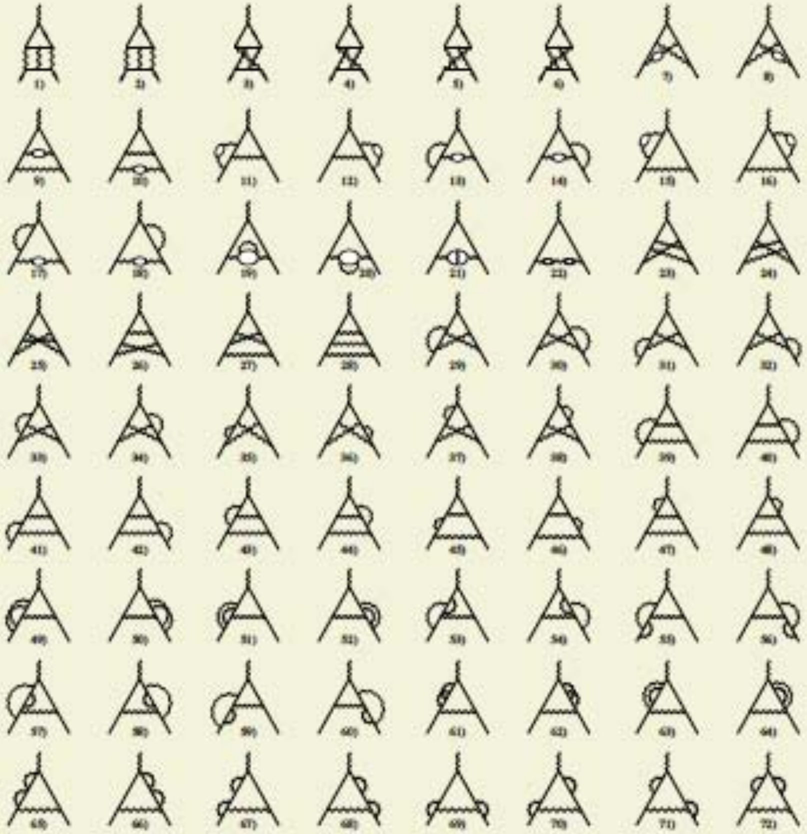
from coeffs, mainly from 5-loop unc ⇦ ⇨ from δα('08)

with $\alpha = 1/137.035999084(51)$ [0.37 ppb]

$\delta a_\mu^{QED}$ =0.001ppm

# Impressive calculation…hundreds of diagrams

**Note on 3–loop contribution** (Remiddi et al., Remiddi, Laporta 1996 [after 27 years]):



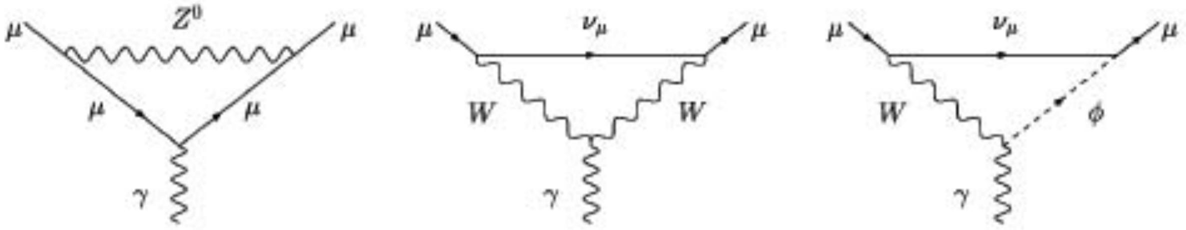
Result turned out to be surprisingly compact

$$A_{1\,\mathrm{uni}}^{(6)} = \frac{28259}{5184} + \frac{17101}{810}\pi^2 - \frac{298}{9}\pi^2\ln 2 + \frac{139}{18}\zeta(3) + \frac{100}{3}\left\{\mathrm{Li}_4(\tfrac{1}{2}) + \frac{1}{24}\ln^4 2 - \frac{1}{24}\pi^2\ln^2 2\right\}$$

$$-\frac{239}{2160}\pi^4 + \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5) = 1.181\,241\,456\,587\ldots$$

# $a_\mu^{SM}$: the Electroweak contribution

- **One-loop term:**



$$a_\mu^{EW}(1\text{-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

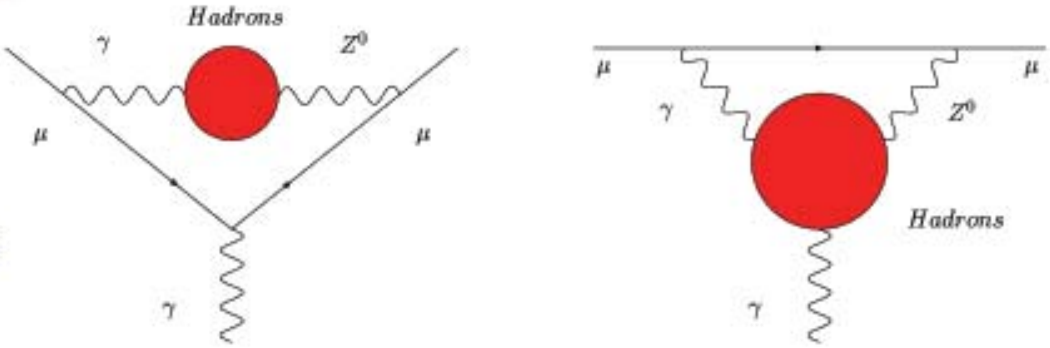
- **One-loop plus higher-order terms:**

$$a_\mu^{EW} = 154\ (2)\ (1) \times 10^{-11}$$

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano, Vainshtein '02; Degrassi, Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk, Czarnecki '05; Vainshtein '03.

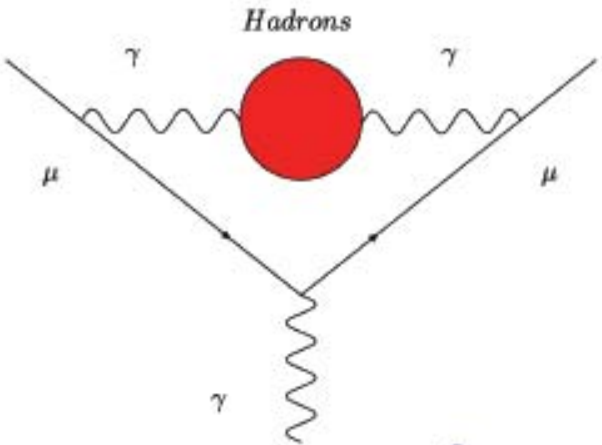
Higgs mass variation, $M_{top}$ error, 3-loop nonleading logs

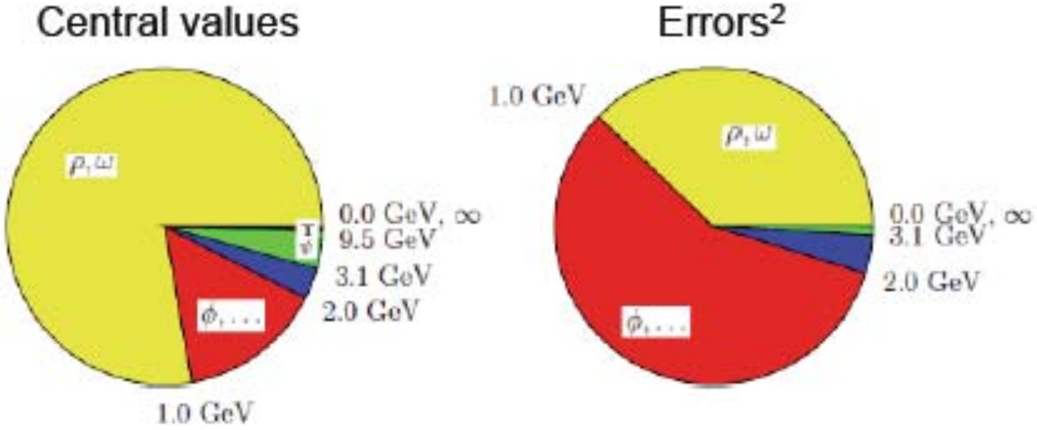
Hadronic loop uncertainties:



$\delta a_\mu^{Weak} = 0.02$ ppm

# $a_\mu^{SM}$: the hadronic leading-order (HLO) contribution





F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)s/m_\mu^2}$$

$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s)$$

$a_\mu^{\mathrm{HLO}} = 6903\ (53)_{\mathrm{tot}} \times 10^{-11}$ F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1

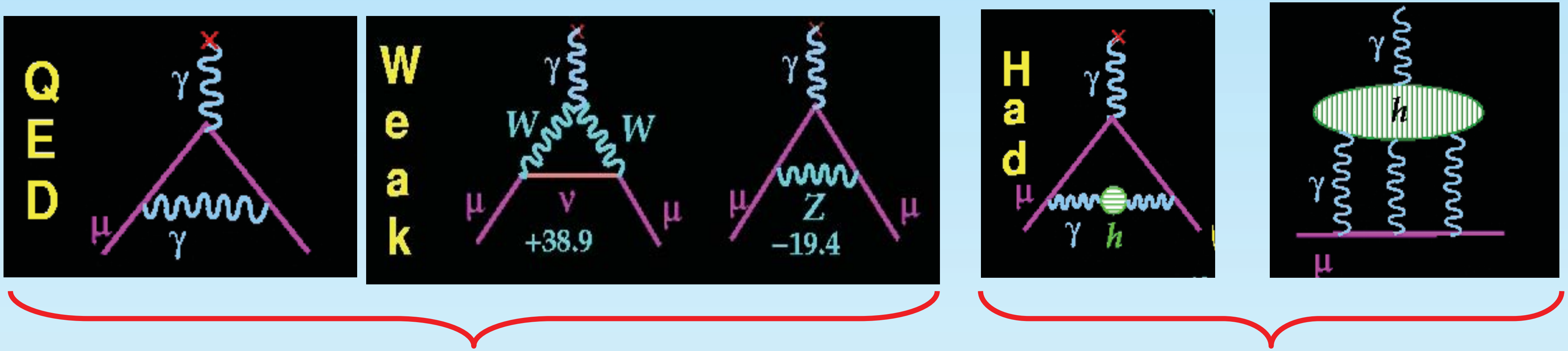
$= 6923\ (42)_{\mathrm{tot}} \times 10^{-11}$ Davier et al, arXiv:1010.4180 (incl. BaBar & KLOE10 2π)

$= 6949\ (37)_{\mathrm{exp}}\ (21)_{\mathrm{rad}} \times 10^{-11}$ Hagiwara et al. (HLMNT11), arXiv:1105.3149

**$\delta a_\mu^{\mathrm{HLO}}$ =0.4 ppm**

**Radiative Corrections are crucial!** S.Actis et al, Eur. Phys. J. C66 (2010) 585

# The SM Value for $a_\mu$



**well known**

**significant work ongoing**

| CONTRIBUTION | RESULT ($\times 10^{-11}$) UNITS |
|---|---|
| QED (leptons) | $116\ 584\ 718.09 \pm 0.14 \pm 0.04_\alpha$ |
| HVP(lo) | $6\ 923 \pm 42$ |
| HVP(ho) | $-97.9 \pm 0.9$ |
| HLxL | $105 \pm 26$ |
| EW | $154 \pm 2_{Higgs} \pm 1_{had}$ |
| Total SM | $116\ 591\ 802 \pm 42 \pm 26 \pm 2 \, (49_{tot})$ |

$\sigma_{\exp} = \pm 63$

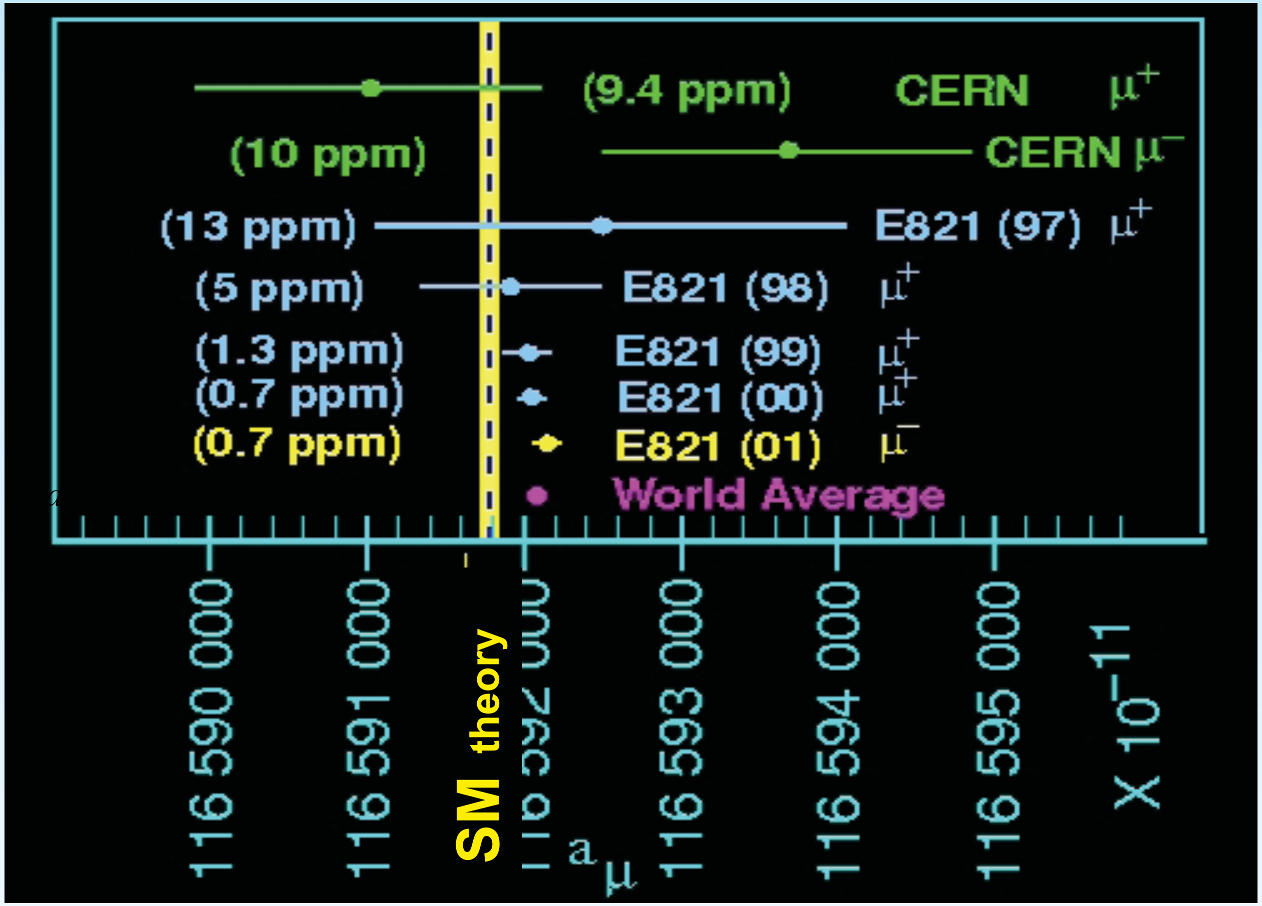
$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot}\times 10^{-11}$$

**(0.54 ppm!)**

**A factor 15 improvement in accuracy respect to CERN!**

**~3.5 “standard deviations” with SM**

**Error dominated by experimental uncertainty!**



$$a_\mu^{SM} = 116\,591\,802 \pm 49 \times 10^{-11}$$

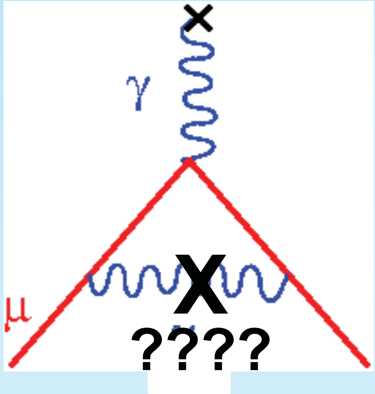
**M. Davier et al. 2011**

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

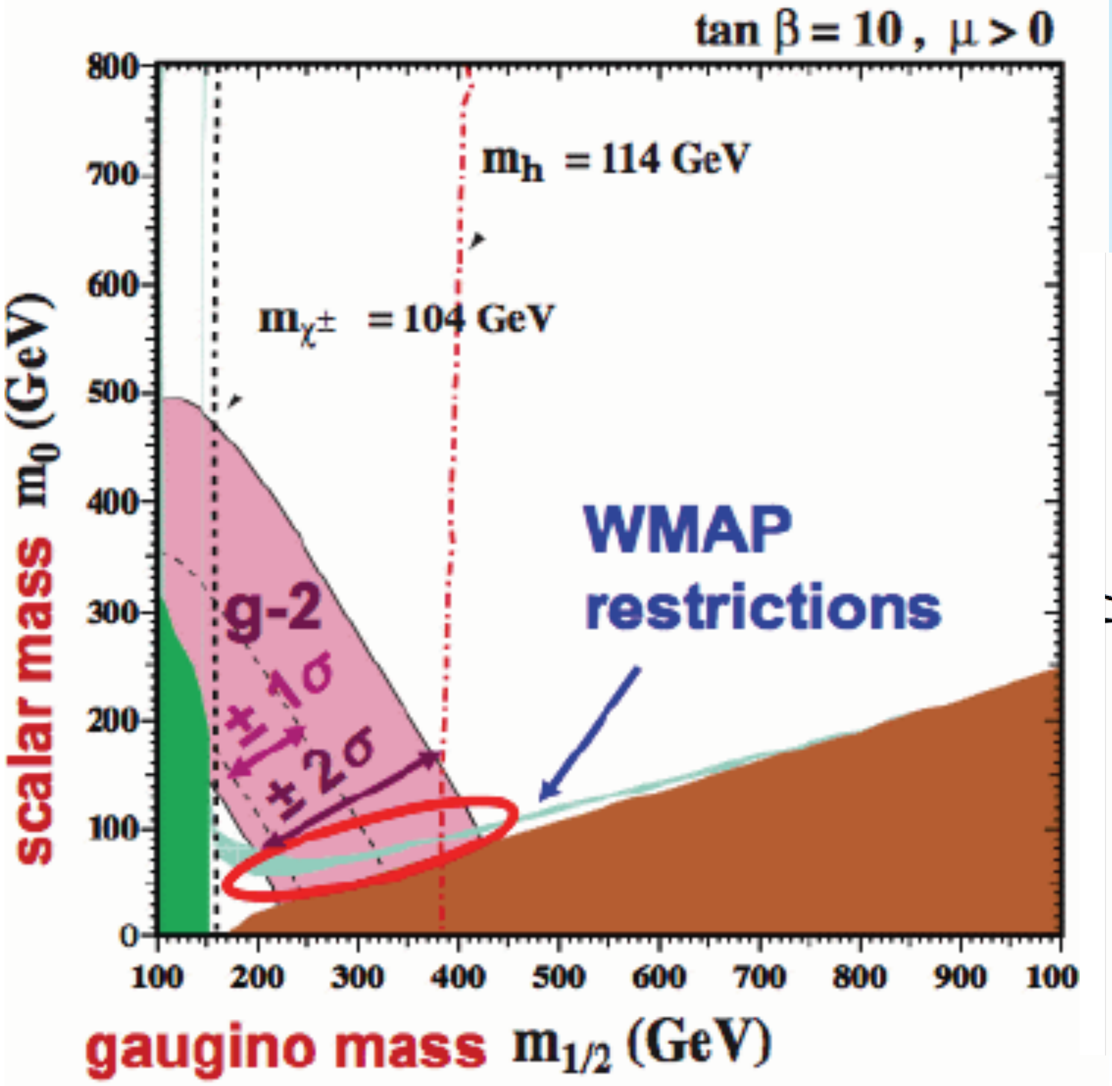
**Hint of new physics?**

# New Physics?

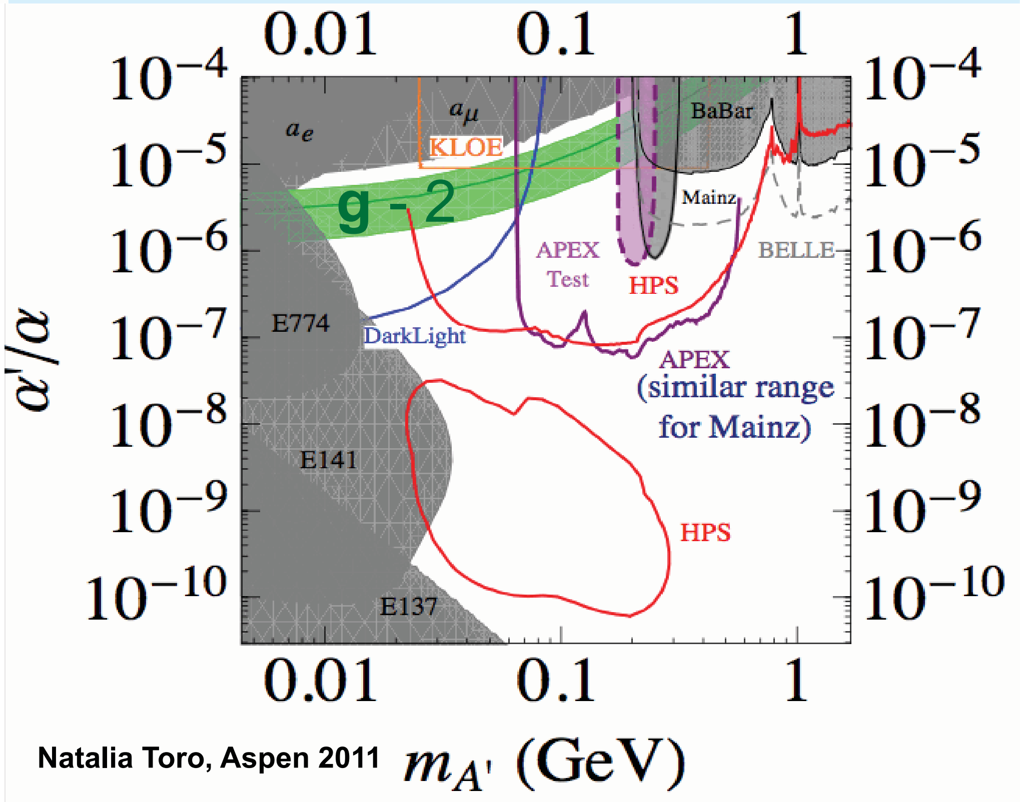
$$a_\mu^{TH} = a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{Weak} + a_\mu^{???}$$



**SUSY?**



**Dark Photons?**

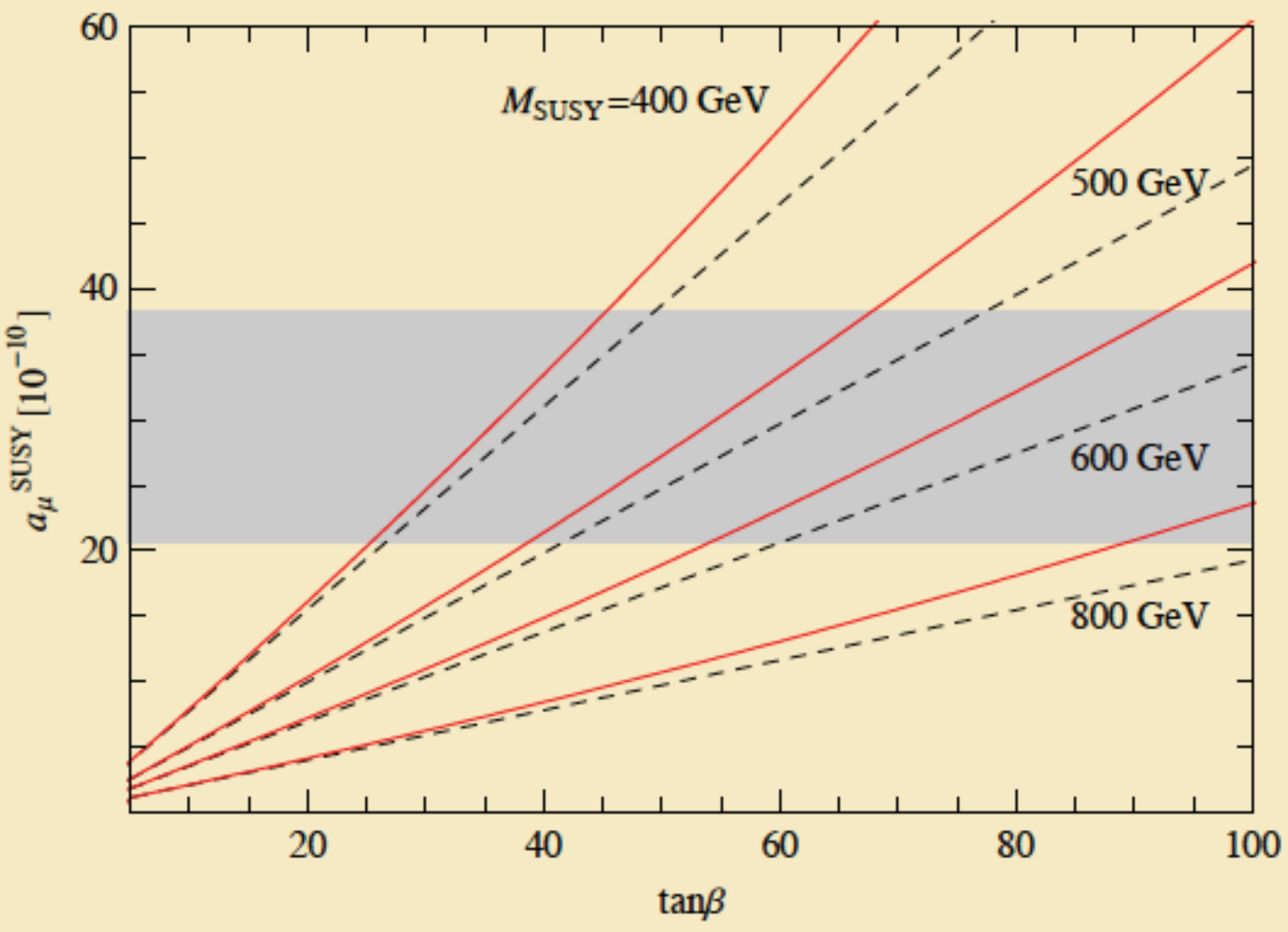


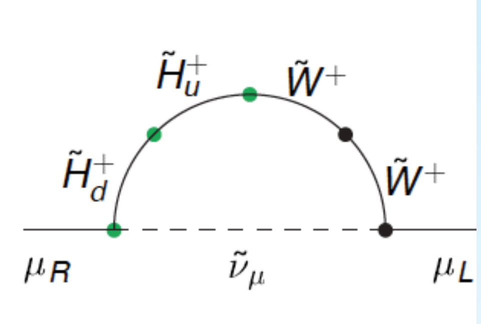
Natalia Toro, Aspen 2011

# SUSY?

**SUSY with mass scale of several 100 GeV is consistent with discrepancy**

$$\Delta a_\mu^{SUSY} \approx 13\cdot 10^{-10} \left(\operatorname{sgn}\mu\right) \tan\beta \left(\frac{100\ GeV}{M_{SUSY}}\right)^2$$





**Large tanβ, μ>0 prefer.**

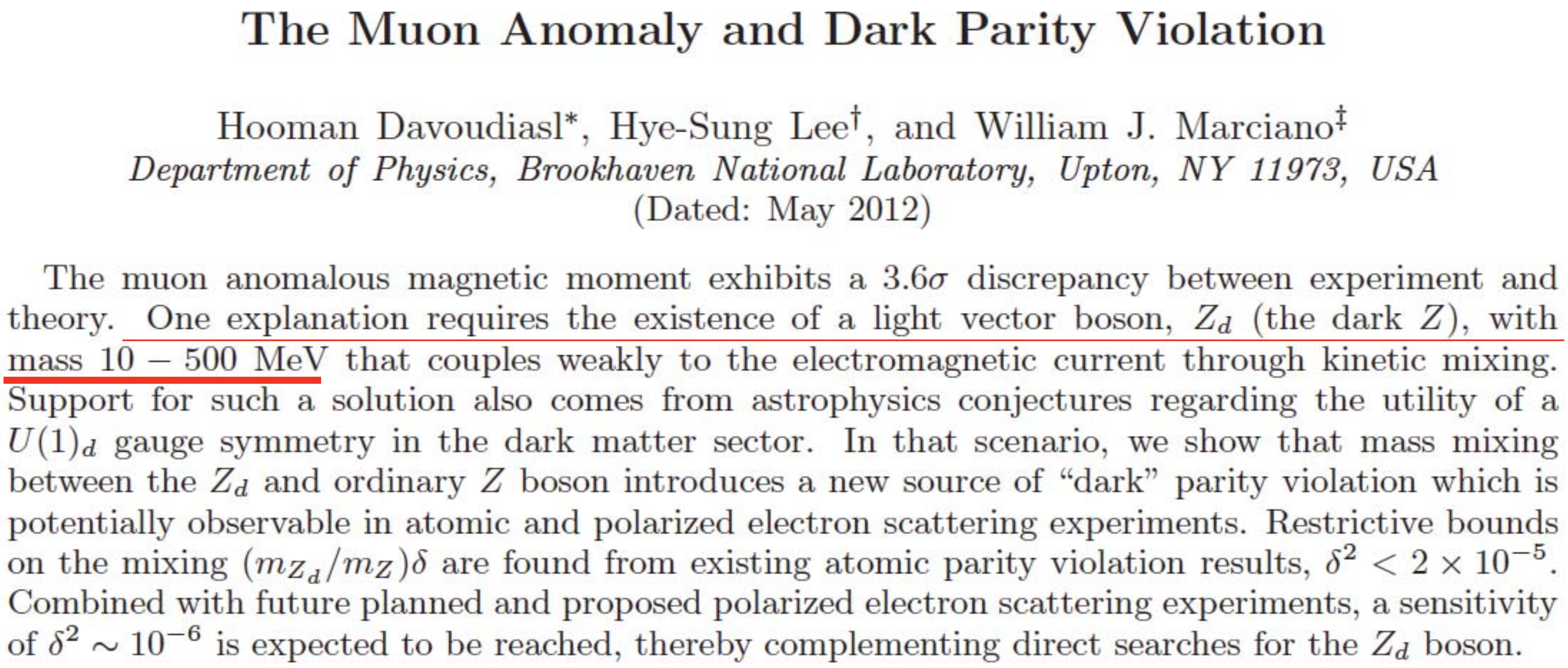
**strong limit on $M_{SUSY}$**

**Important constraint for interpretation of BSM physics searches at LHC**

# Dark Photons?

**15 May 2012**

**arXiv:1205.2709v1**

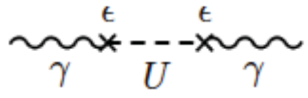


### The Muon Anomaly and Dark Parity Violation

Hooman Davoudiasl*, Hye-Sung Lee†, and William J. Marciano‡
*Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*
(Dated: May 2012)

The muon anomalous magnetic moment exhibits a 3.6$\sigma$ discrepancy between experiment and theory. One explanation requires the existence of a light vector boson, $Z_d$ (the dark $Z$), with mass 10 – 500 MeV that couples weakly to the electromagnetic current through kinetic mixing. Support for such a solution also comes from astrophysics conjectures regarding the utility of a $U(1)_d$ gauge symmetry in the dark matter sector. In that scenario, we show that mass mixing between the $Z_d$ and ordinary $Z$ boson introduces a new source of "dark" parity violation which is potentially observable in atomic and polarized electron scattering experiments. Restrictive bounds on the mixing $(m_{Z_d}/m_Z)\delta$ are found from existing atomic parity violation results, $\delta^2 < 2 \times 10^{-5}$. Combined with future planned and proposed polarized electron scattering experiments, a sensitivity of $\delta^2 \sim 10^{-6}$ is expected to be reached, thereby complementing direct searches for the $Z_d$ boson.

$$\mathscr{L}_{\mathrm{mix}} = -\frac{\epsilon}{2} F^{\mathrm{em}}_{\mu\nu} F^{\mu\nu}_{\mathrm{DM}} \qquad (\epsilon \ll 1)\ .$$



**Searches for dark photons are currently underway at $e^+e^-$ colliders (B-,tau/ charm-, $\phi$-factories)and fixed target experiments (JLAB, MAMI, etc…)**

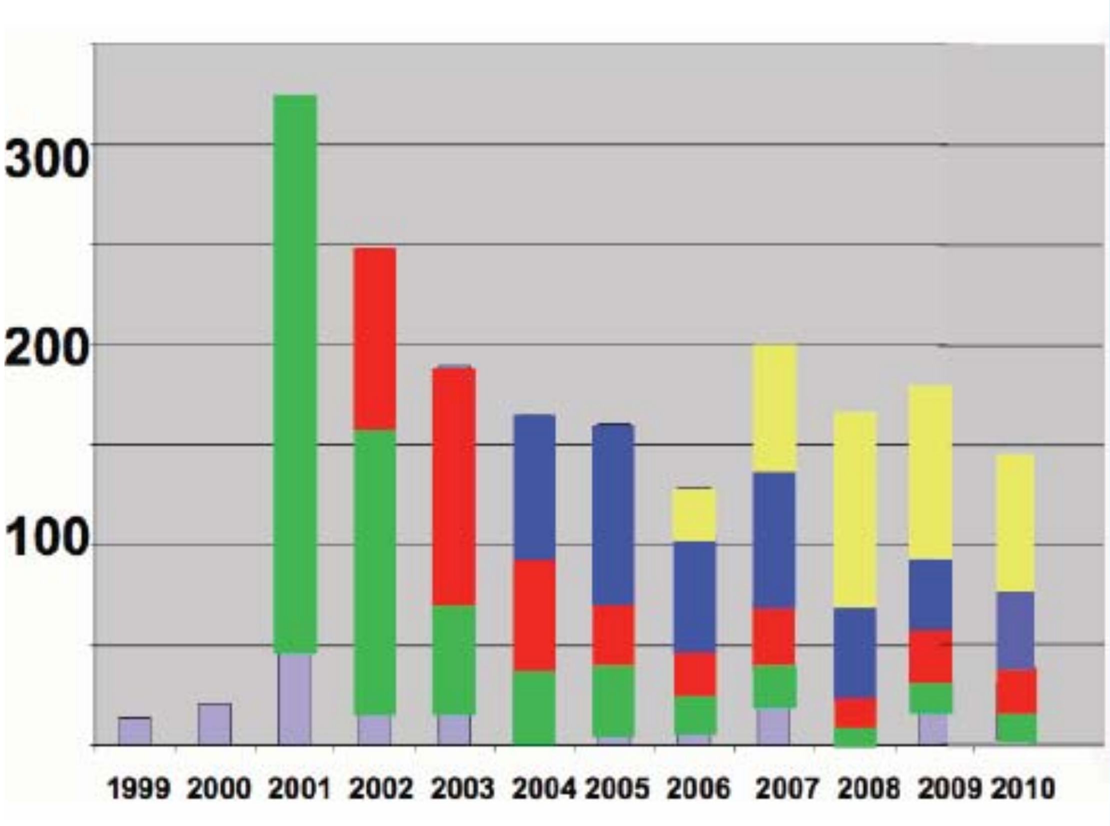
# Summary of present status

**E821 experiment at BNL has generated enormous interest**

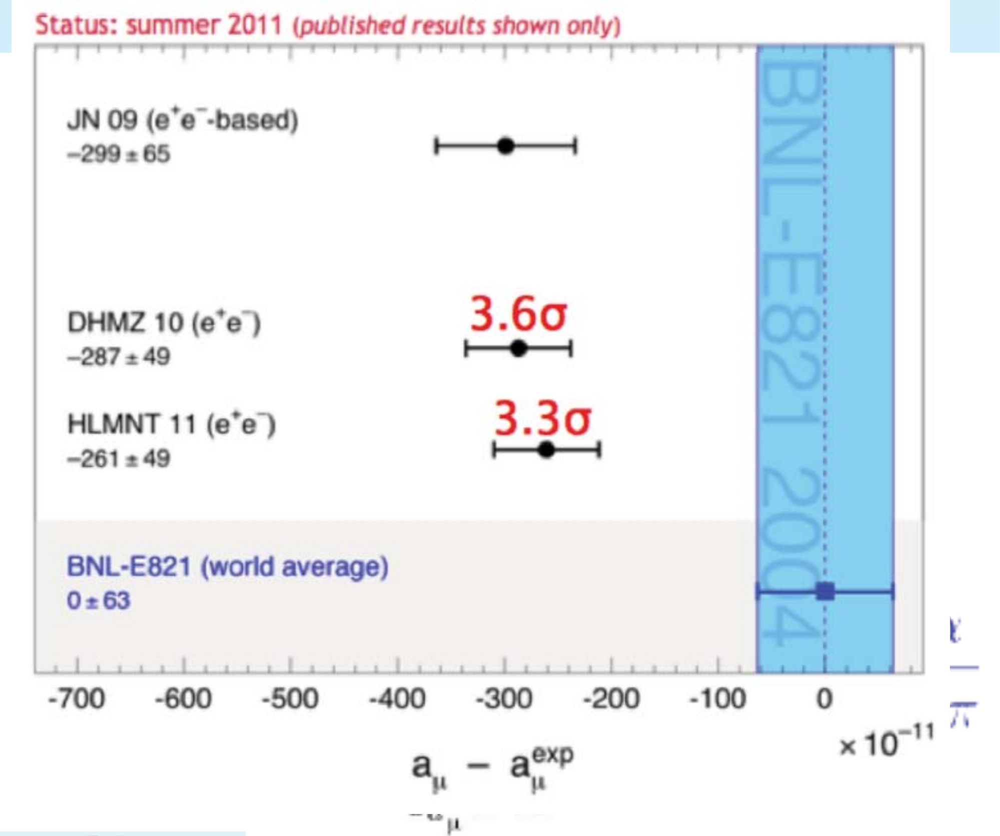
**Tantalizing deviation with SM (although persistent since 10 years) is ~3$\sigma$**

**Current discrepancy limited by experimental uncertainty (BNL)**

**BNL E821 citations**



**Present**

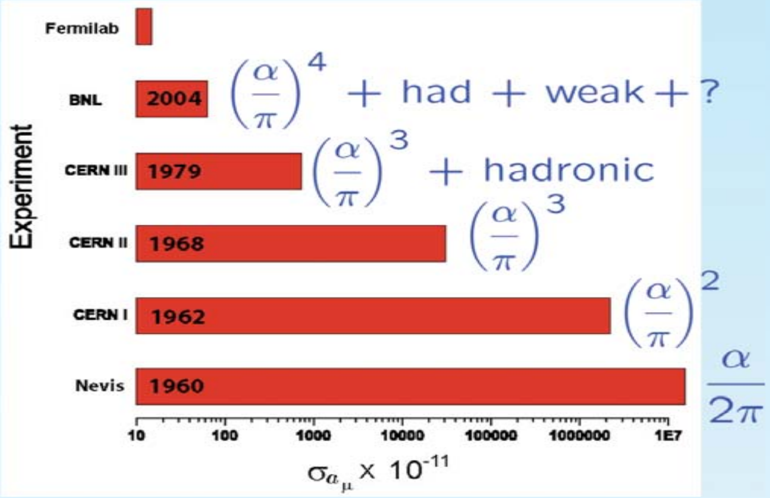


**>1850 total citations to our results**

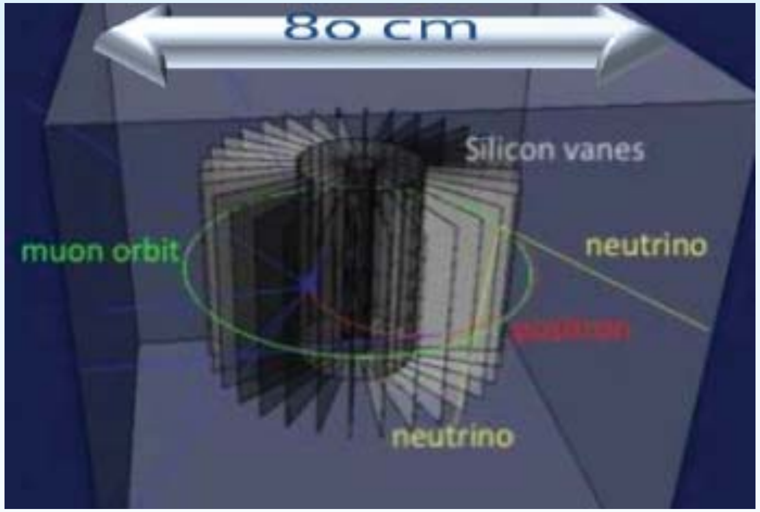
***We need a new experiment!***

# We need a new (possibly more) $(g\text{-}2)_\mu$ experiment(s)!

**Current discrepancy limited by experimental uncertainty. Two proposals to improve it x4:**



- New experiment at FNAL (E989) at magic momentum, consolidated method. 20 x $\mu$ w.r.t. E821. Relocate the BNL storage ring to FNAL. Has got a Stage-1 approval!



- Alternative proposal at J-PARC w/ out magic momentum and no E field, requiring ultra-slow muons generated from laser-ionised muonium atoms

**Precision target ~ $16 \times 10^{-11}$ (0.14 ppm) . If the central value remains the same ⇒ >7σ from SM!**

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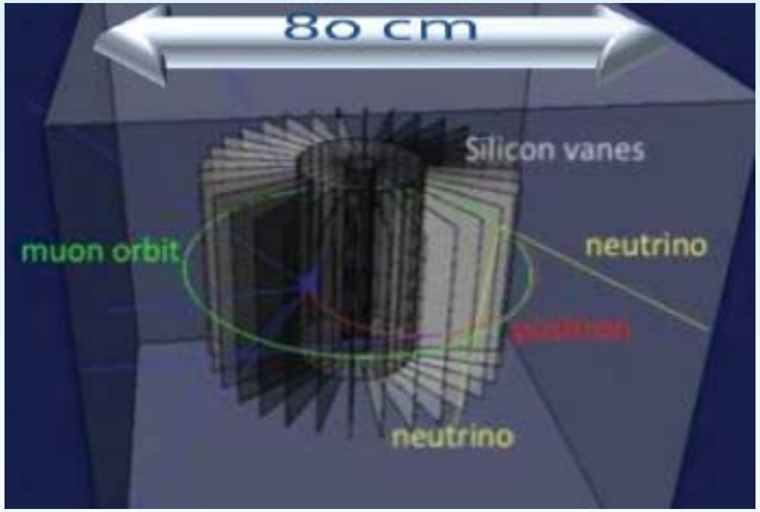

**Precision target ~ $16\times10^{-11}$ (0.14 ppm) . If the central value remains the same $\Rightarrow$ >7$\sigma$ from SM!**

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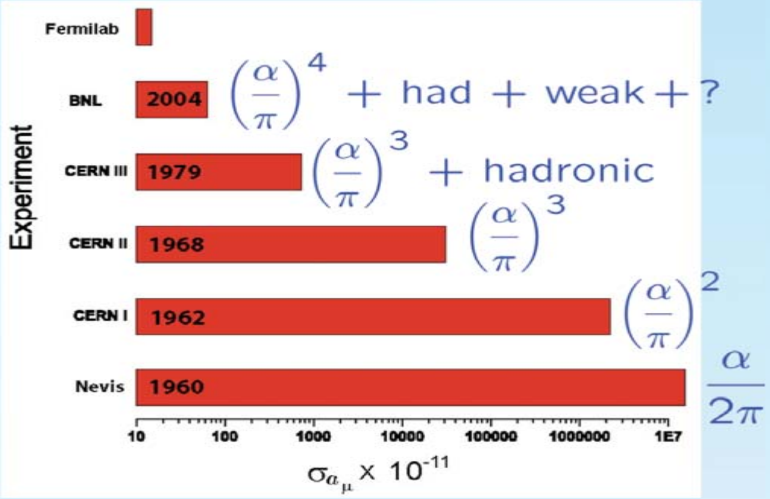
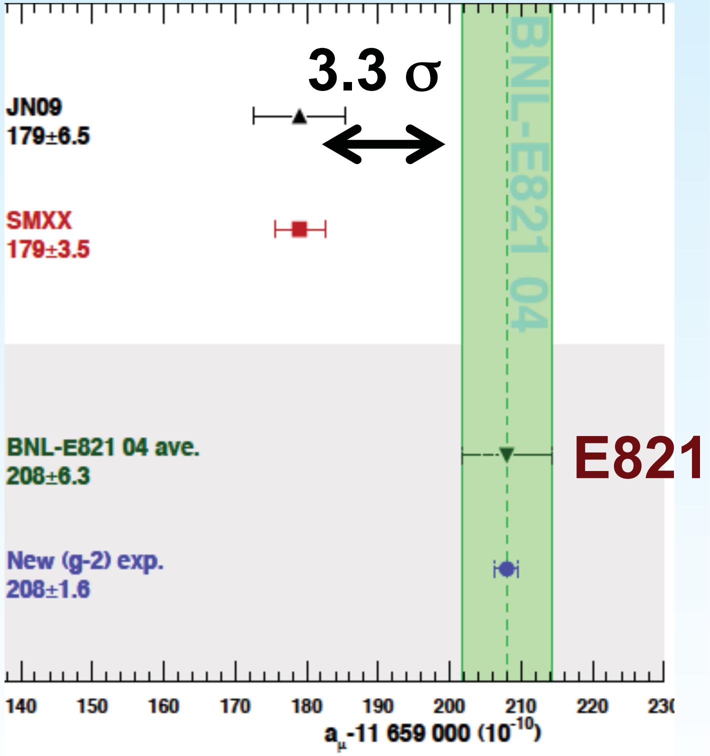


**Precision target ~ $16 \times 10^{-11}$ (0.14 ppm) . If the central value remains the same ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)**



***Depending on the progress on Theory**

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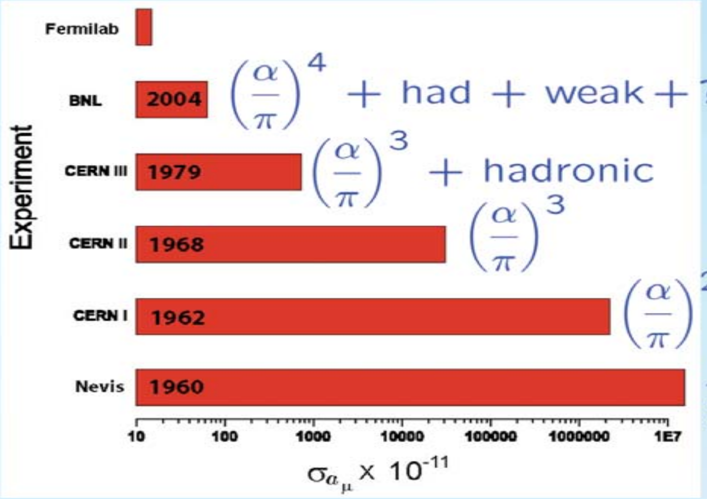

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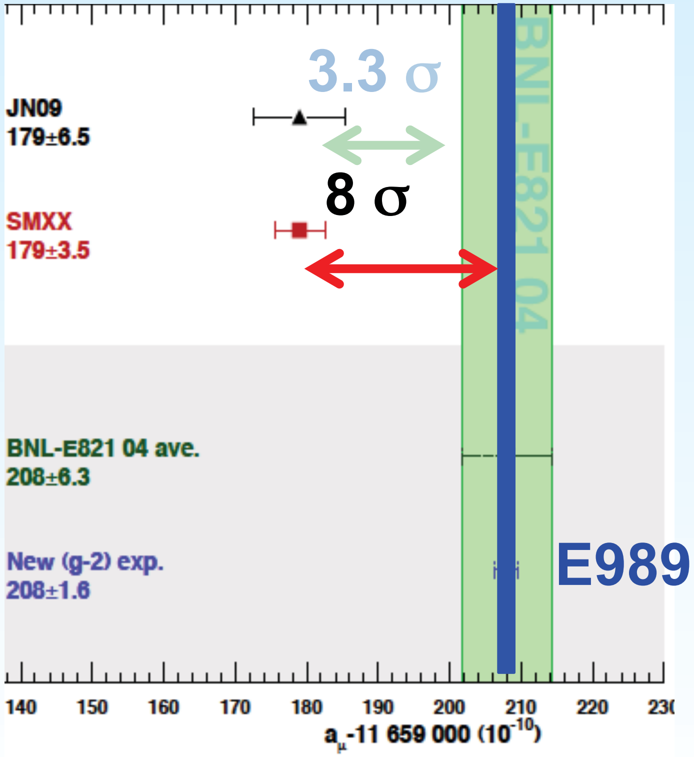


***Depending on the progress on Theory**

# Fermilab (g-2) Experiment:

- **E821 at Brookhaven**

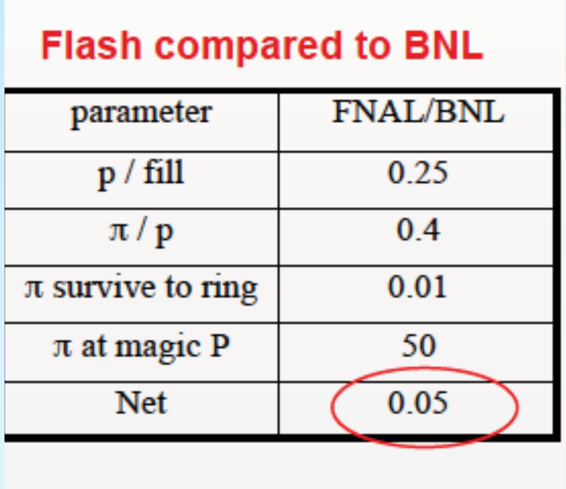
$$\left.\begin{array}{l}\sigma_{\text{stat}} = \pm 0.46\ \text{ppm} \\ \sigma_{\text{syst}} = \pm 0.28\ \text{ppm}\end{array}\right\} \quad \sigma = \pm 0.54\ \text{ppm}$$

- **E989 at Fermilab**
  - **move the storage ring to Fermilab, improved shimming, new detectors, electronics, DAQ**
  - **new beam structure that takes advantage of the multiple rings available at Fermilab, more muons per hour, less per fill of the ring**

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

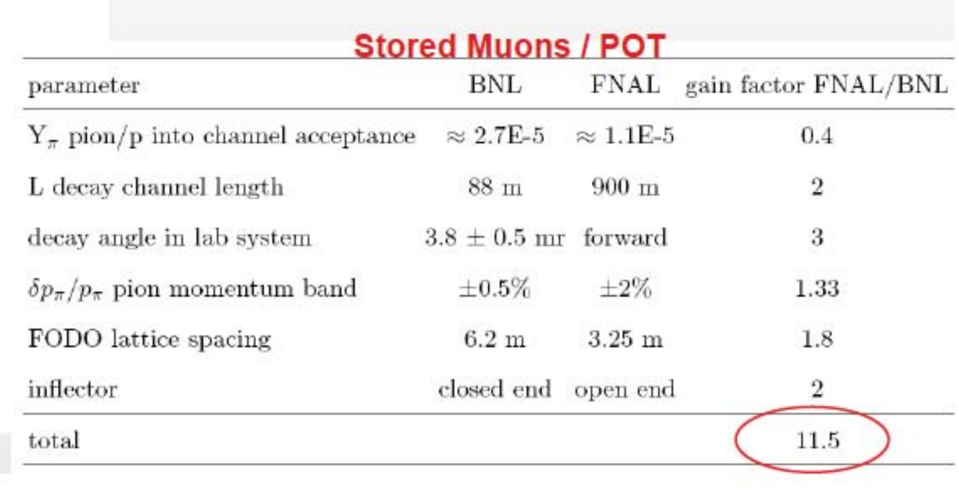
# Why Fermilab?

- The existence of many storage rings that are interlinked permits us to make the "ideal" beam structure.
  - proton bunch structure:
    - BNL 4 X $10^{12}$ p/fill: repetition rate 4.4 Hz
    - FNAL $10^{12}$ p/fill: repetition rate 15 Hz
  - using antiproton rings as an 900m pion decay line
    - 20 times **less** pion flash at injection than BNL
  - $0^o$ muons
    - ~5-10x increase $\mu$/p over BNL
  - Can run parasitic to main injector experiments (e.g. to NOVA) or take the booster cycles
- Expected data taking in 2016



**Flash compared to BNL**

| parameter | FNAL/BNL |
|---|---|
| p / fill | 0.25 |
| $\pi$ / p | 0.4 |
| $\pi$ survive to ring | 0.01 |
| $\pi$ at magic P | 50 |
| Net | 0.05 |



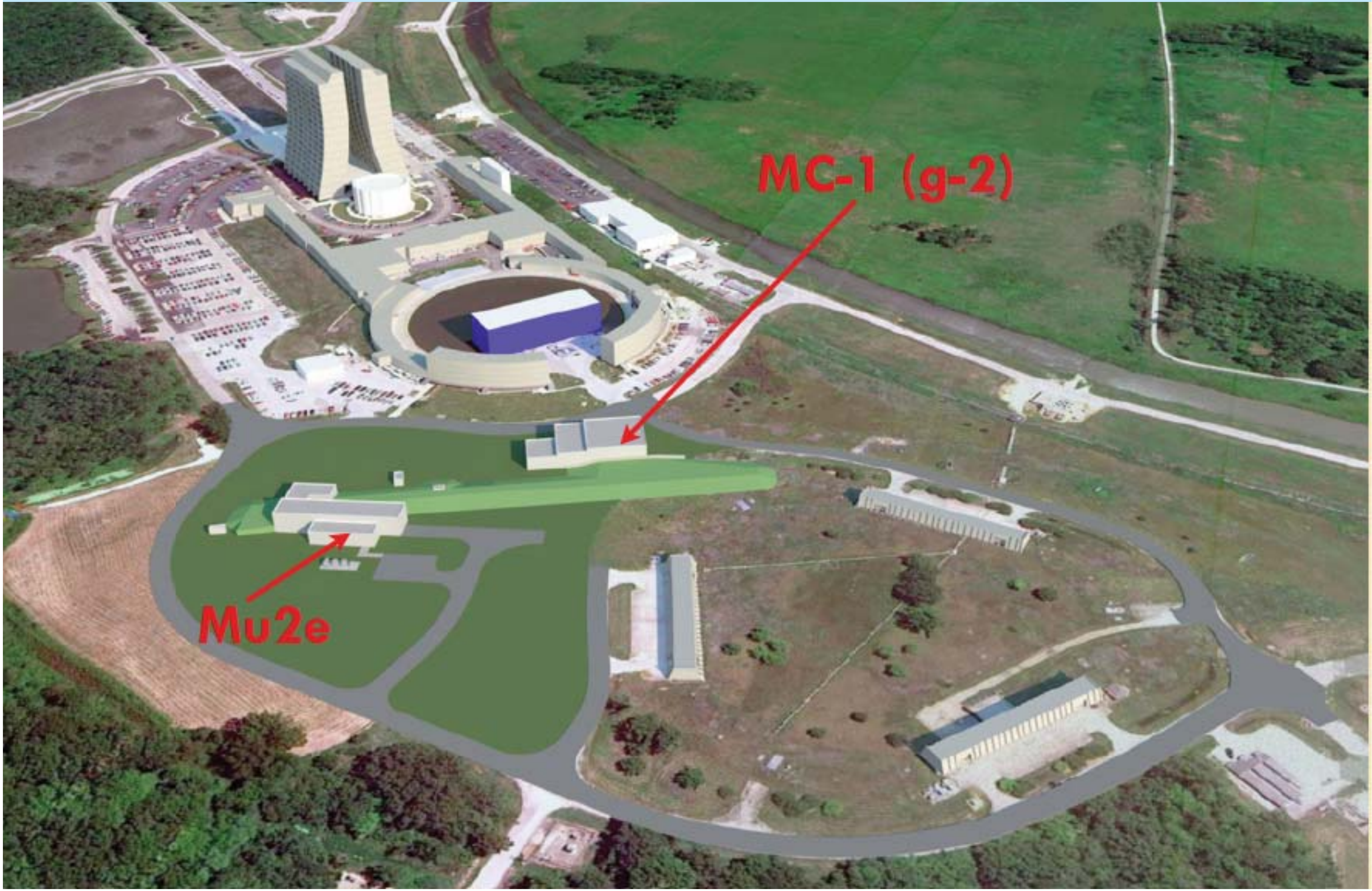
**Stored Muons / POT**

| parameter | BNL | FNAL | gain factor FNAL/BNL |
|---|---|---|---|
| $Y_\pi$ pion/p into channel acceptance | $\approx$ 2.7E-5 | $\approx$ 1.1E-5 | 0.4 |
| L decay channel length | 88 m | 900 m | 2 |
| decay angle in lab system | 3.8 $\pm$ 0.5 mr | forward | 3 |
| $\delta p_\pi / p_\pi$ pion momentum band | $\pm 0.5\%$ | $\pm 2\%$ | 1.33 |
| FODO lattice spacing | 6.2 m | 3.25 m | 1.8 |
| inflector | closed end | open end | 2 |
| total | | | 11.5 |

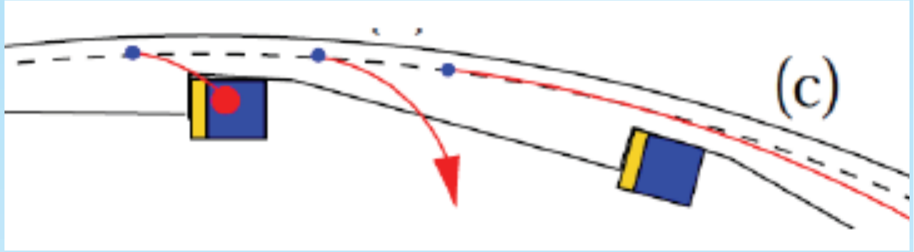
# Beam delivery to g-2

- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

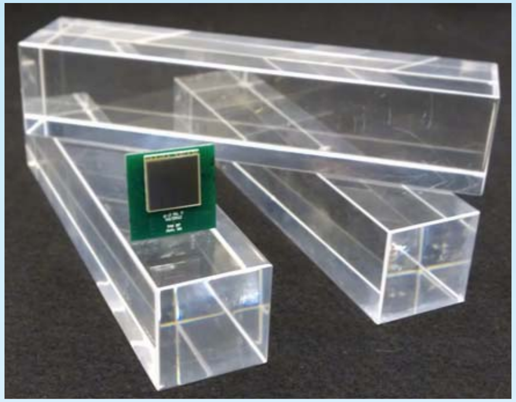
# Fermilab Muon Campus



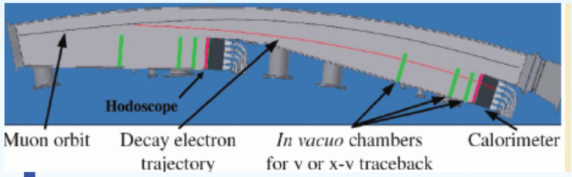
# Upgrades at Fermilab



- New segmented detectors to reduce pileup
  - PbF2 Crystals with SIPM
  - $X_0$ = 0.93 cm
  - $\sigma/E \sim 3.5\% / \sqrt{E}$
  - 4 ns pulse width

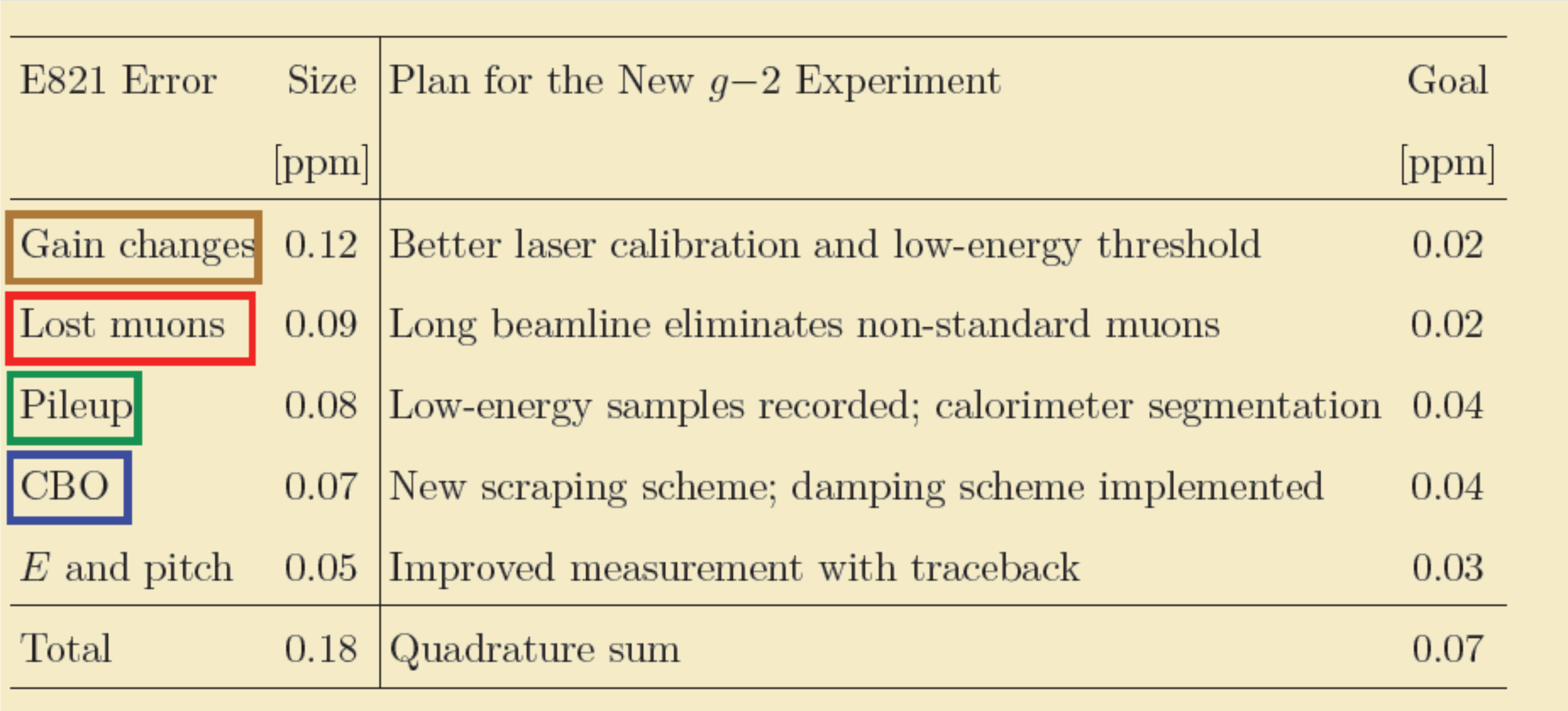


- Calorimeter stability tracked with laser pulsing system (Italian contribution)
- New electronics
  - 500 MHz 12-bit WFDs, with deep memories
- New tracking stations (in vacuum)



- Improvements in the magnetic field calibration, measurement and monitoring.

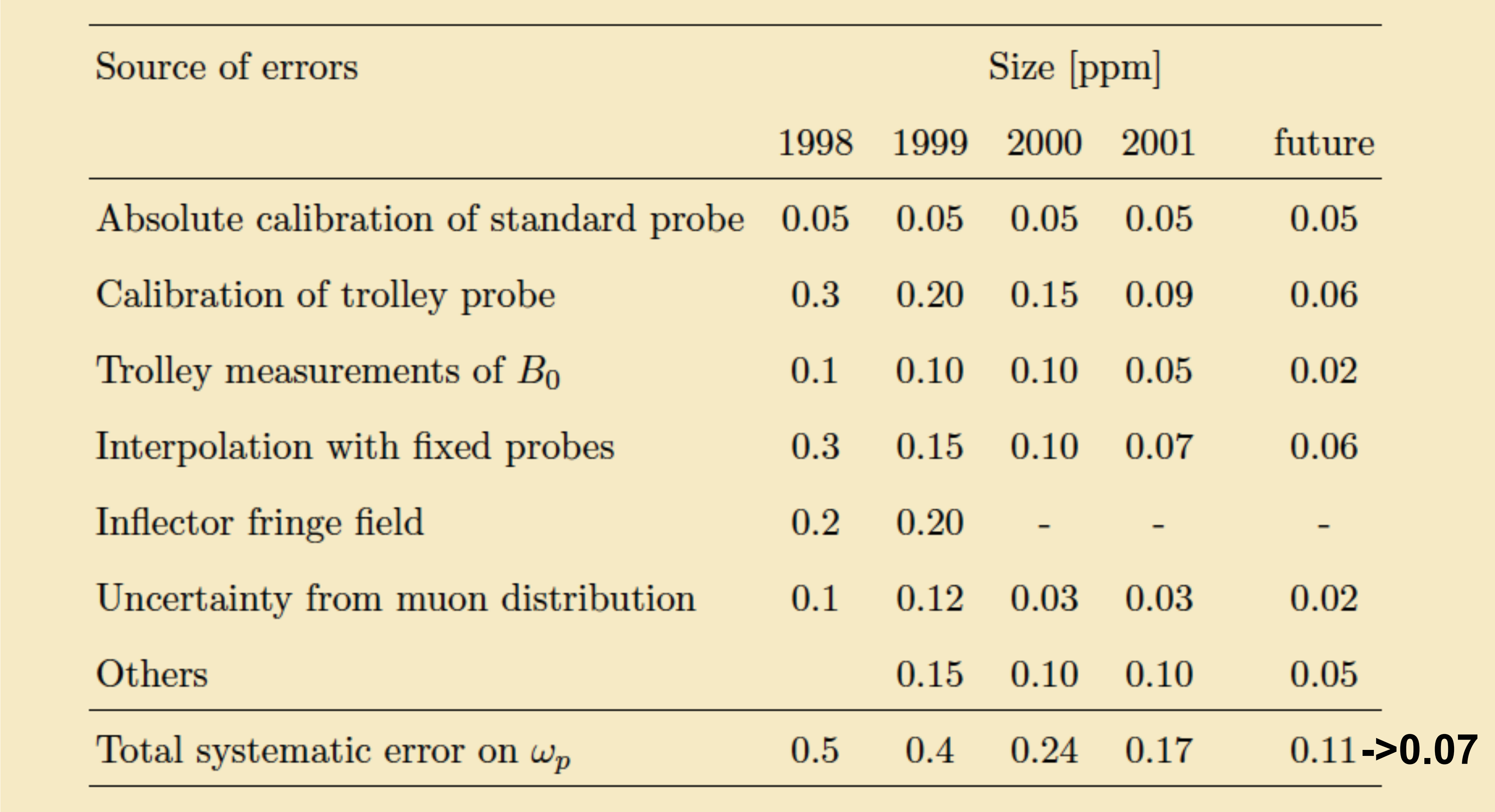
# Improving $\omega_a$



| E821 Error | Size [ppm] | Plan for the New $g-2$ Experiment | Goal [ppm] |
|---|---|---|---|
| Gain changes | 0.12 | Better laser calibration and low-energy threshold | 0.02 |
| Lost muons | 0.09 | Long beamline eliminates non-standard muons | 0.02 |
| Pileup | 0.08 | Low-energy samples recorded; calorimeter segmentation | 0.04 |
| CBO | 0.07 | New scraping scheme; damping scheme implemented | 0.04 |
| $E$ and pitch | 0.05 | Improved measurement with traceback | 0.03 |
| Total | 0.18 | Quadrature sum | 0.07 |

Systematic uncertainty on $\omega_a$ expected to be reduced by 1/3 at E989 (compared to E821) thanks to **reduced** pion contamination,the **segmented** detectors, and an **improved** storage ring kick of the muons onto orbit.

# Improving $\omega_p$

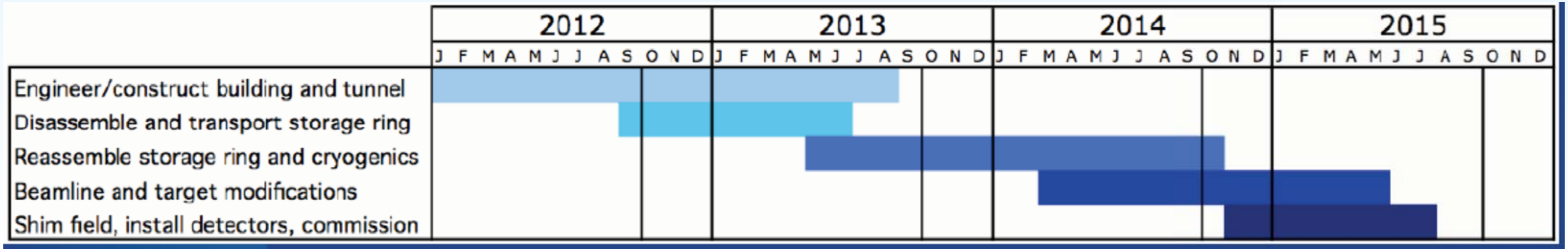


| Source of errors | Size [ppm] | | | | |
|---|---|---|---|---|---|
| | 1998 | 1999 | 2000 | 2001 | future |
| Absolute calibration of standard probe | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Calibration of trolley probe | 0.3 | 0.20 | 0.15 | 0.09 | 0.06 |
| Trolley measurements of $B_0$ | 0.1 | 0.10 | 0.10 | 0.05 | 0.02 |
| Interpolation with fixed probes | 0.3 | 0.15 | 0.10 | 0.07 | 0.06 |
| Inflector fringe field | 0.2 | 0.20 | - | - | - |
| Uncertainty from muon distribution | 0.1 | 0.12 | 0.03 | 0.03 | 0.02 |
| Others | | 0.15 | 0.10 | 0.10 | 0.05 |
| Total systematic error on $\omega_p$ | 0.5 | 0.4 | 0.24 | 0.17 | 0.11 **->0.07** |

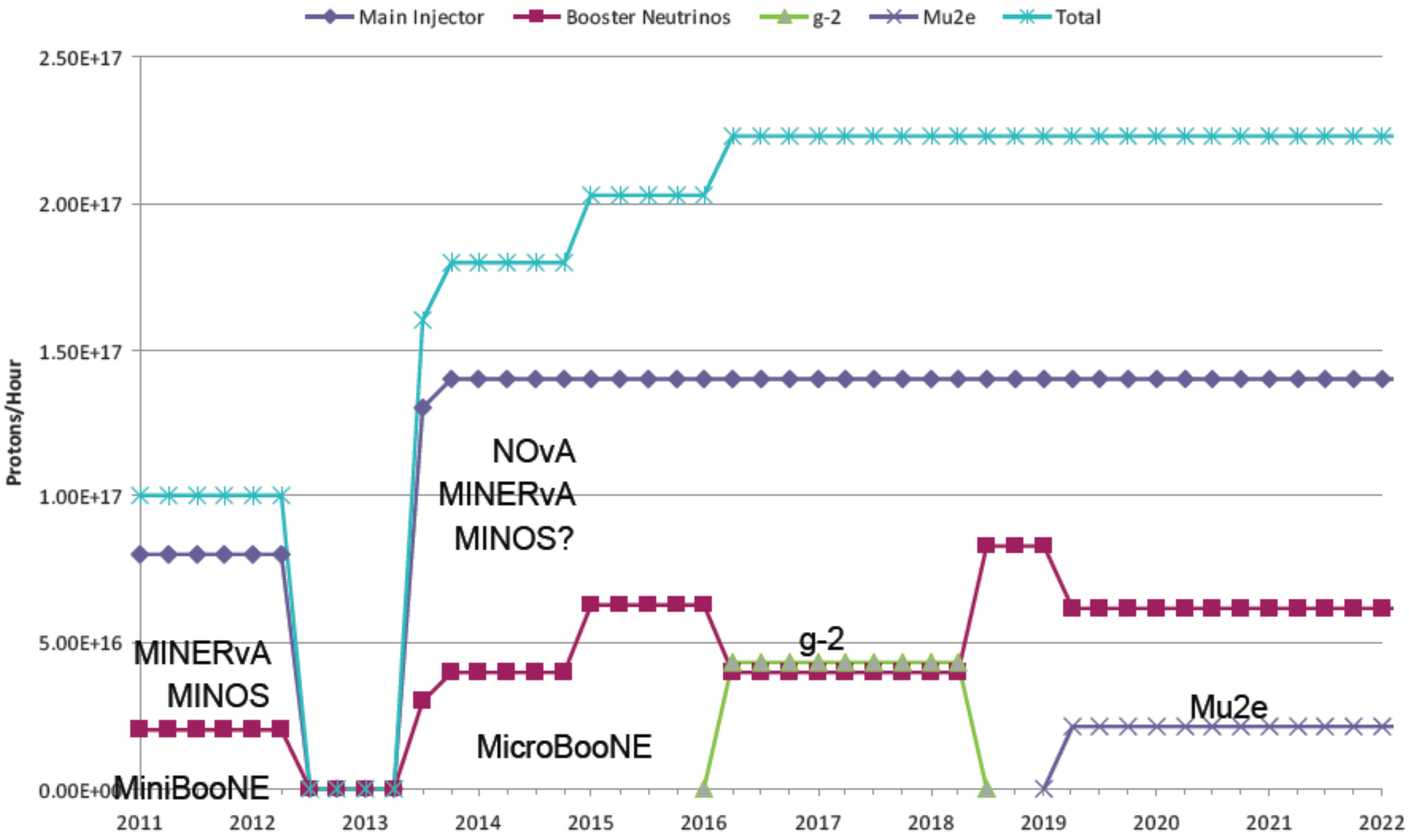
Systematic uncertainty on $\omega_p$ expected to be reduced by a factor 2 thanks to **better** shimming (uniformity of B), **relocations** of critical NMR probes, and **other** incremental changes

# Time schedule of the Experiment

- Proposal submitted to FNAL, February 2009 (66 authors)
  Positive response from PAC, April 2009
- Stage-I approval January 2010
- CD0 obtained on Settembre 2012
- CD1 obtained on December 2013, CDR with>100 authors
- CD2/CD3 in 2014/15
- Expected beam in 2017



# Who gets beam when?



Fermilab Today

Wednesday, Sept. 19, 2012

Feature

# Second muon experiment receives Mission Need approval from DOE

Fermilab's plans for creating a Muon Campus with top-notch Intensity Frontier experiments have received a big boost. The Department of Energy has granted Mission Need approval to the Muon g-2 project, one of two experiments proposed for the new Muon Campus. The other proposed experiment, Mu2e, is a step ahead and already received the next level of DOE approval, known as Critical Decision 1.

"We now are officially on DOE's roadmap," said Lee Roberts, professor at Boston University and co-spokesperson for the roughly 100 scientists collaborating on the Muon g-2 (pronounced gee minus two) experiment. "This should make it easier to increase the size of our collaboration and foster international participation. Potential collaborators supported by the National Science Foundation or foreign funding agencies will be happy to see that we now have DOE's official Mission Need approval."

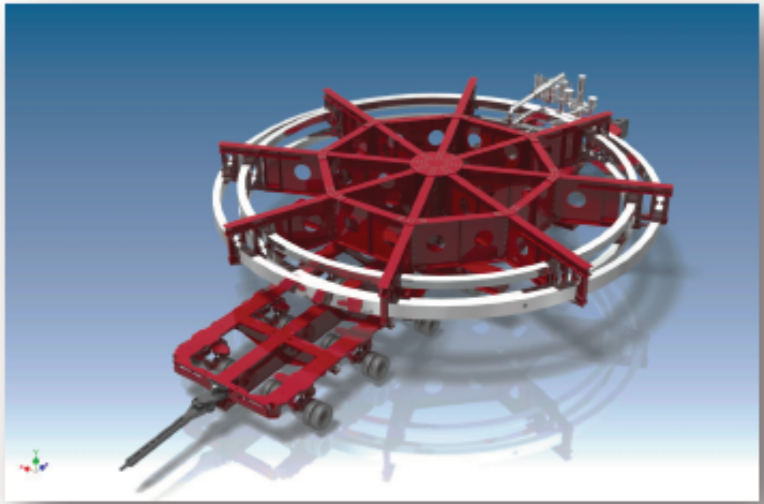
This rendering shows the location of the proposed Muon Campus at Fermilab. The arrow points to the proposed site of the planned Muon g-2 experiment. Click to enlarge. *Image: Muon Department/FESS*

At present, the Muon g-2 collaboration includes scientists from institutions in China, Germany, Italy, Japan, the Netherlands and Russia as well as 16 institutions in the United States. Physicists from several institutions in the United Kingdom are in the process of joining the collaboration.

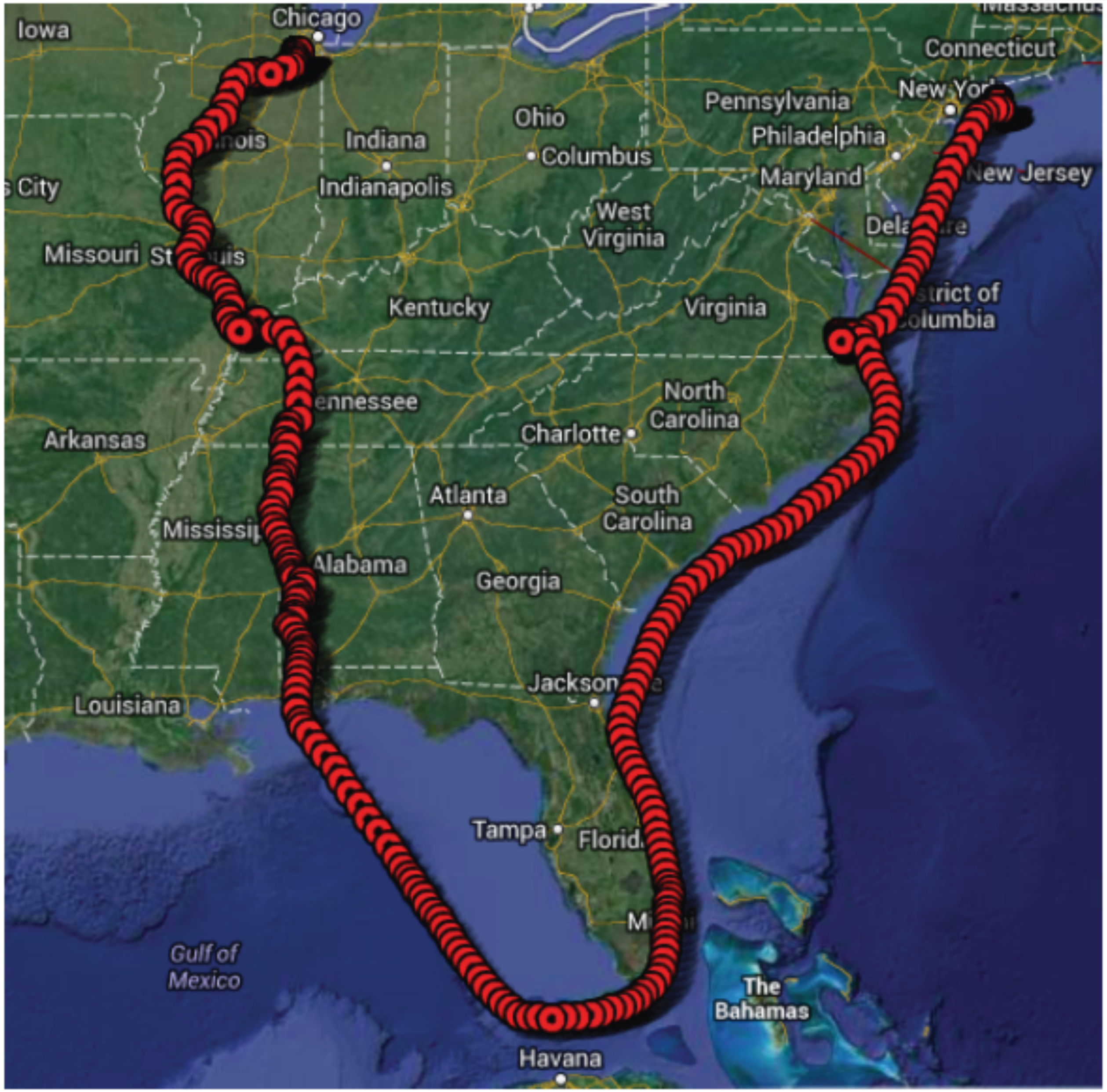
**CD0 received in September!**

# WBS 476.5 Disassembly & Transport

- Most difficult part of transport is delivery of 50 ft diameter superconducting coils
- Emmert International contracted to transport coils
- Coils left BNL Jun 23



# WBS 476.5 Disassembly & Transport



- Ended up choosing Southern route for transport
    - Longer, but…
    - Average wave height less than N. Atlantic
    - Never more than 12 hrs from safe harbor
    - $300k cheaper

- Live GPS used to follow ring and engage public
    - Website had more hits than any other special FNAL webpage
    - People came out all along the riverway to see the magnet pass by

# WBS 476.5: Start of Chicago ground transport

# WBS 476.5: Arrival at FNAL to 3000+ crowd

# BNL ring arrived at FNAL for the new g-2 experiment

July 26 2013

# Fermilab E989 Experiment (not updated):

**Argonne**
**Boston University**
**Brookhaven**
**CUNY Queens**
**Cornell**
**Fermilab**
**Illinois**
**James Madison**
**Kentucky**
**Massachusetts**
**Michigan**
**Muons Inc.**
**Northwestern**
**NIU?**
**Regis**
**Virginia**
**Washington**

**Shanghai**

**Dresden**

**KVI**

**Frascati**
**Rome**

**KEK**
**Osaka**

**Dubna**
**Novosibirsk**
**PNPI**

**UK Consortium?**

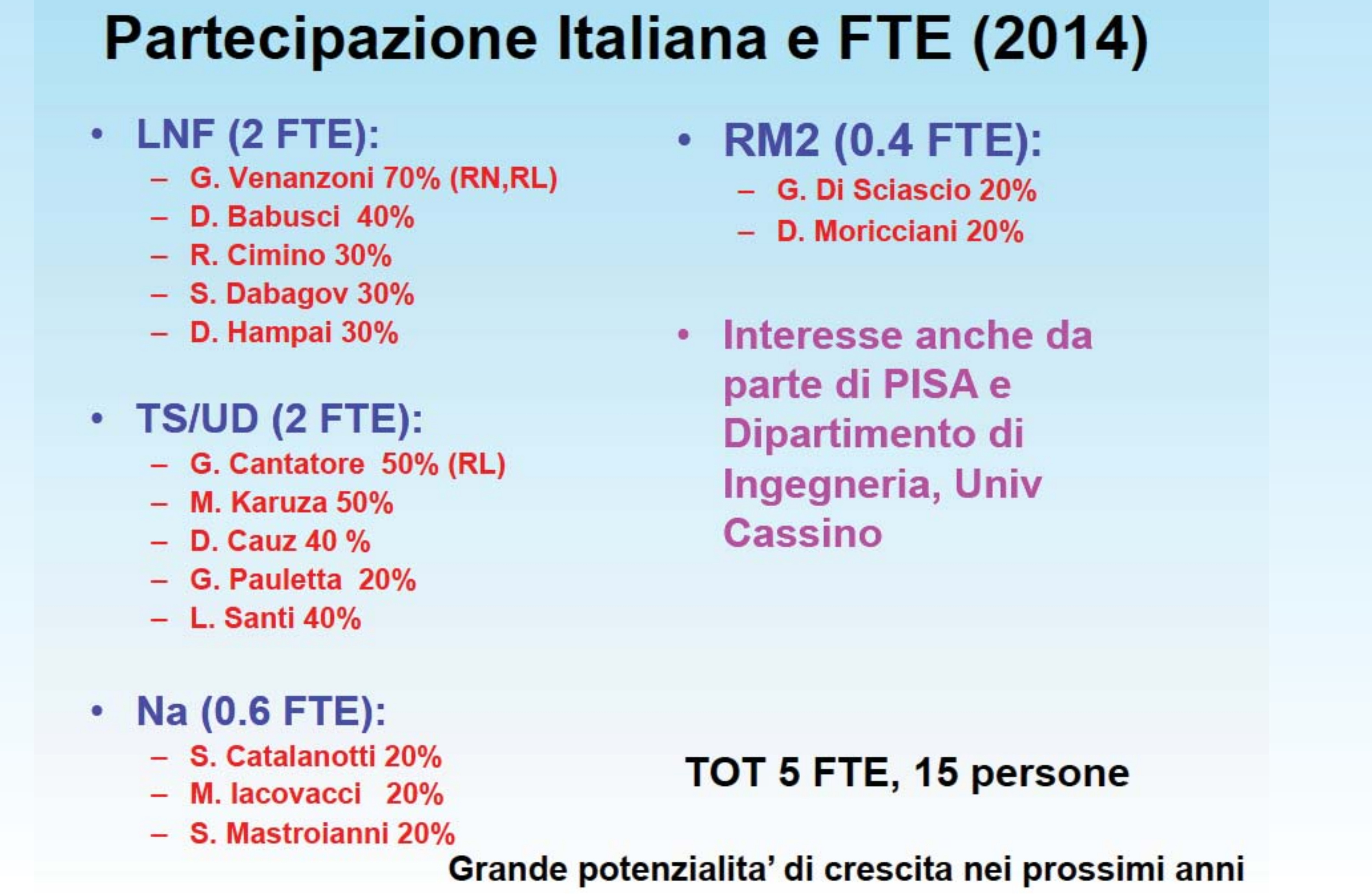
**>100 Collaborators,**

**~30 Institutions**

**"Collaboration has attained critical mass…have to put all this expertise to good use by matching tasks onto interests and capabilities"**

**C. Polly, Project Manager, June 12**

# Slide mostrata alla riunione della CSN1/INFN Settembre 2013



## Partecipazione Italiana e FTE (2014)

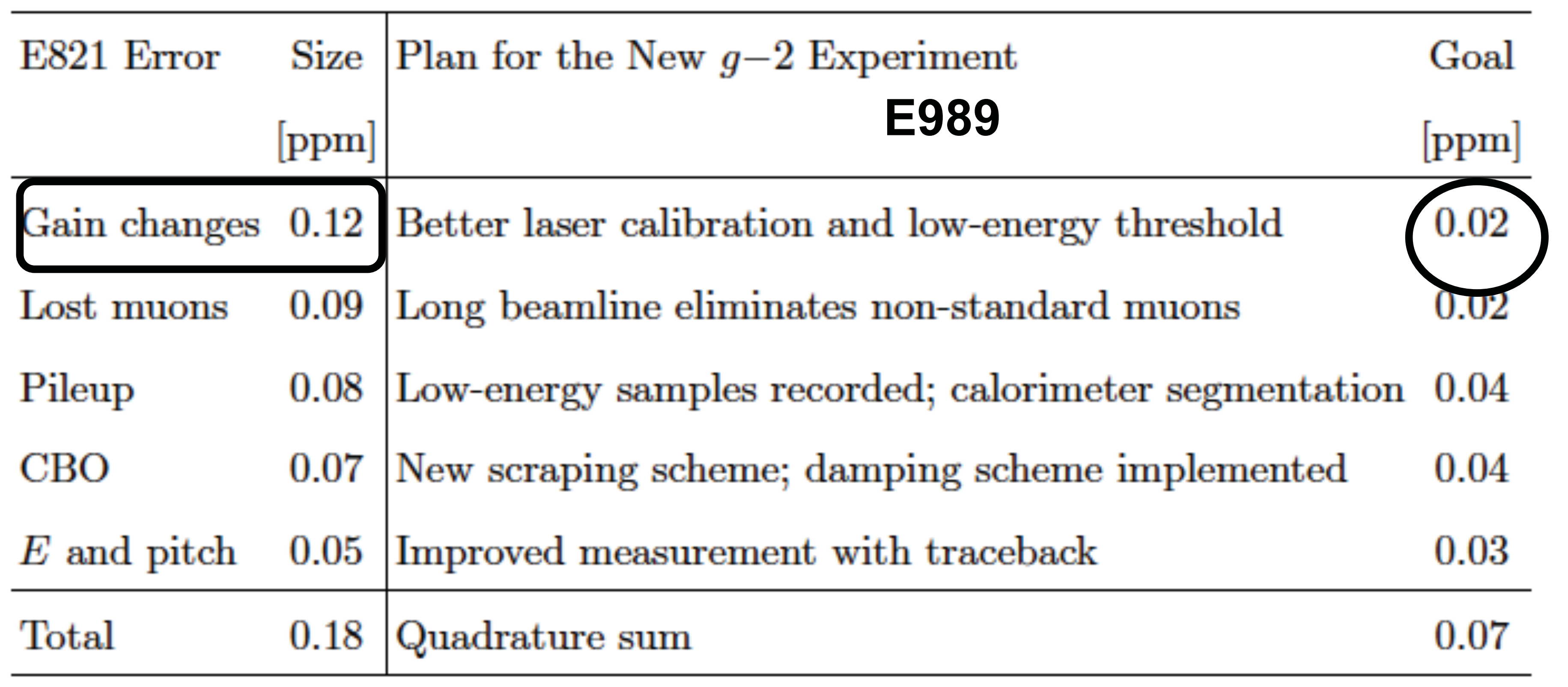
- **LNF (2 FTE):**
  - G. Venanzoni 70% (RN,RL)
  - D. Babusci 40%
  - R. Cimino 30%
  - S. Dabagov 30%
  - D. Hampai 30%
- **TS/UD (2 FTE):**
  - G. Cantatore 50% (RL)
  - M. Karuza 50%
  - D. Cauz 40 %
  - G. Pauletta 20%
  - L. Santi 40%
- **Na (0.6 FTE):**
  - S. Catalanotti 20%
  - M. Iacovacci 20%
  - S. Mastroianni 20%
- **RM2 (0.4 FTE):**
  - G. Di Sciascio 20%
  - D. Moricciani 20%
- Interesse anche da parte di PISA e Dipartimento di Ingegneria, Univ Cassino

**TOT 5 FTE, 15 persone**

**Grande potenzialita' di crescita nei prossimi anni**

# Errore sistematico a $\omega_a$ e Calibrazione

**Errori sistematici per l'esperimento precedente (E821) e a FNAL**

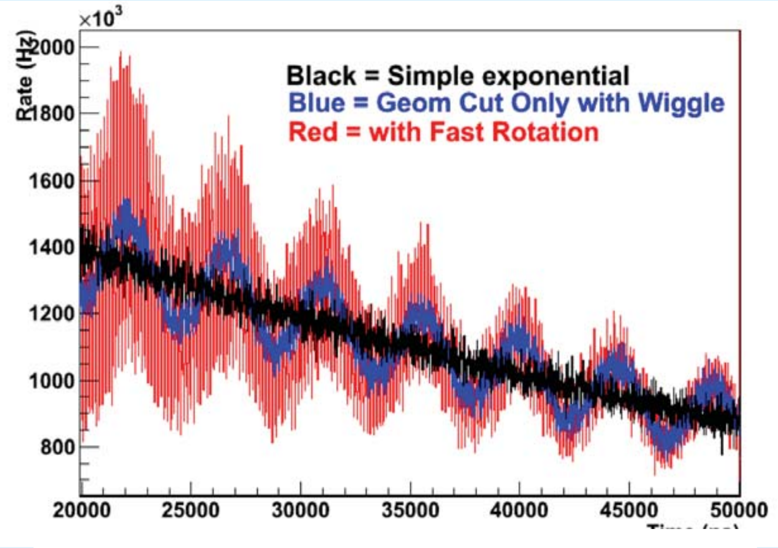


| E821 Error | Size [ppm] | Plan for the New $g-2$ Experiment **E989** | Goal [ppm] |
|---|---|---|---|
| Gain changes | 0.12 | Better laser calibration and low-energy threshold | 0.02 |
| Lost muons | 0.09 | Long beamline eliminates non-standard muons | 0.02 |
| Pileup | 0.08 | Low-energy samples recorded; calorimeter segmentation | 0.04 |
| CBO | 0.07 | New scraping scheme; damping scheme implemented | 0.04 |
| $E$ and pitch | 0.05 | Improved measurement with traceback | 0.03 |
| Total | 0.18 | Quadrature sum | 0.07 |

- Sistematico piu' importante (dovuto alle fluttuazioni di guadagno dei fotorivelatori)
- Calibrazione centrale per goal in accuratezza (insieme al miglioramento del rivelatore e fascio)
- Necessita' di un sistema di calibrazione laser impulsato ad altissima precisione
- Il sistema deve essere completato (e spedito) entro il 2016

# Fluttuazioni di Guadagno “Short term”

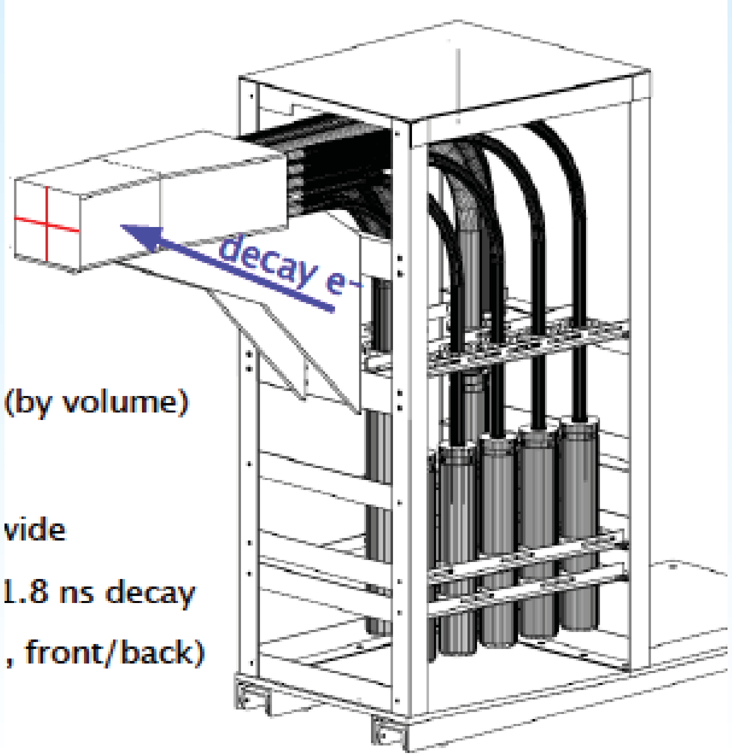
- Il rate cambia di vari ordini di grandezza tra l’inizio e la fine del fill (O(MHz)→O(100) Hz)



- **In E821 ciascun calorimetro era diviso in 4 quadranti ciascuno letto da un PMT. Il segnale analogico che veniva digitalizzato era dato dalla somma dei 4 PMT➔ Calorimetro sostanzialmente monolitico.**

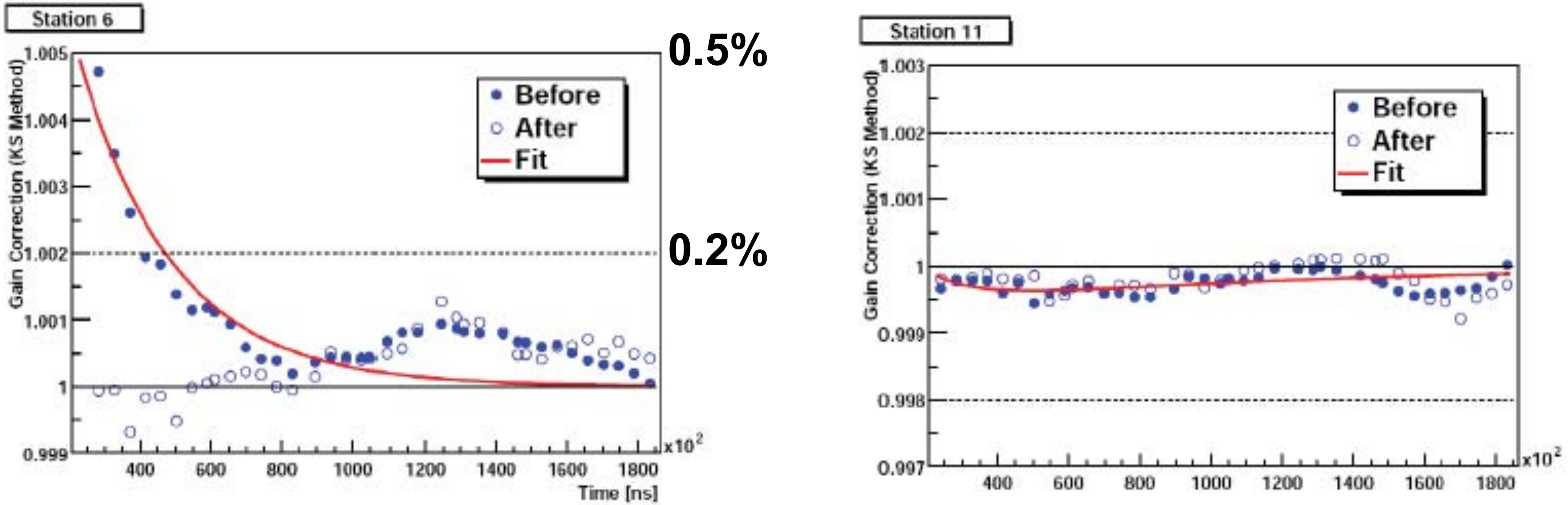
- **A causa dell’alto rate di pioni, i PMT venivano spenti per i primi 30 μs**

- **Drift di guadagno dominato dal tempo di recovering e pileup (due elettroni nello stesso istante).**



# Correzioni di guadagno vecchio esperimento (E821)

Short timescale gain change (within one fill) matters

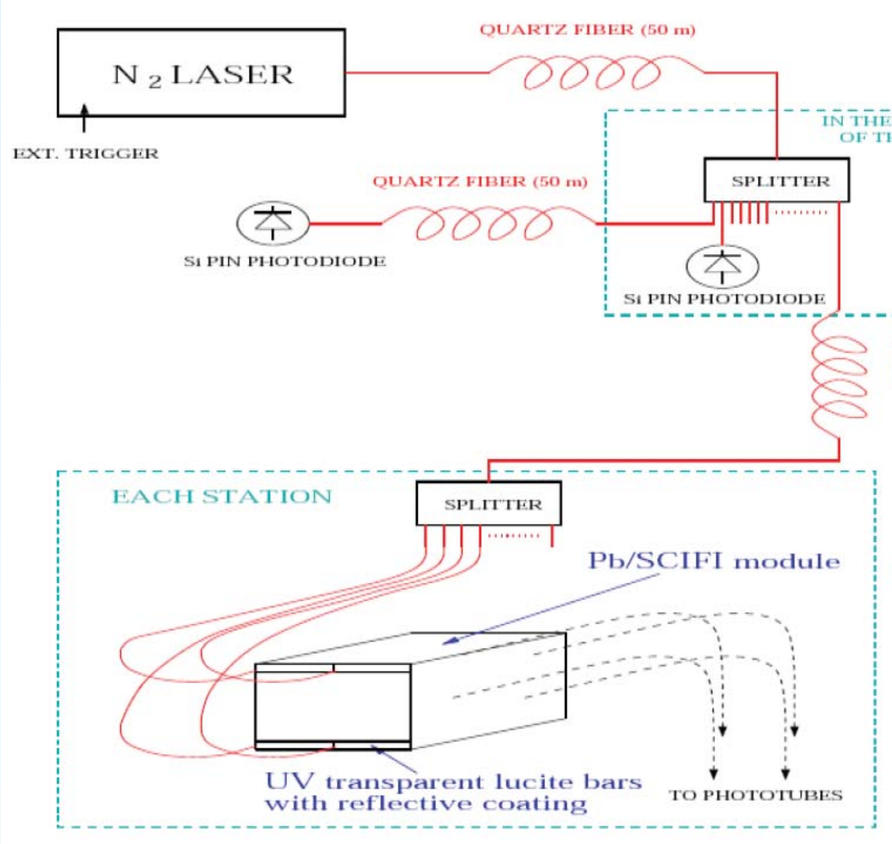


0.5%

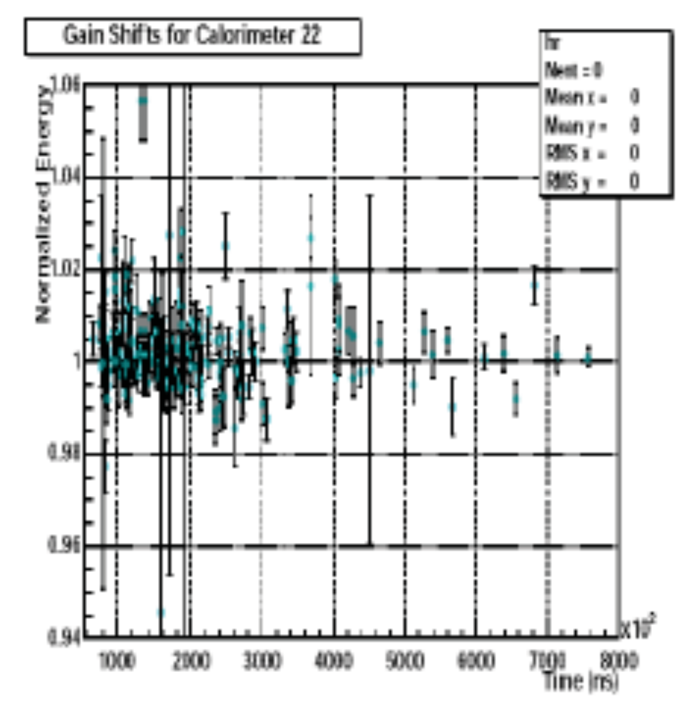
0.2%

- Variazioni di Guadagno con diverso andamento nel tempo. Effetto anche dello 0.5%. Dopo le correzioni effetti <~0.1%. Errore associato, transla in 0.12 ppm.
- Stima conservativa in quanto l'error budget e' dominato dal contributo statistico (0.46ppm)

# Sistema laser vecchio esperimento



- 330 nm laser system provided UV light to directly excite scintillator

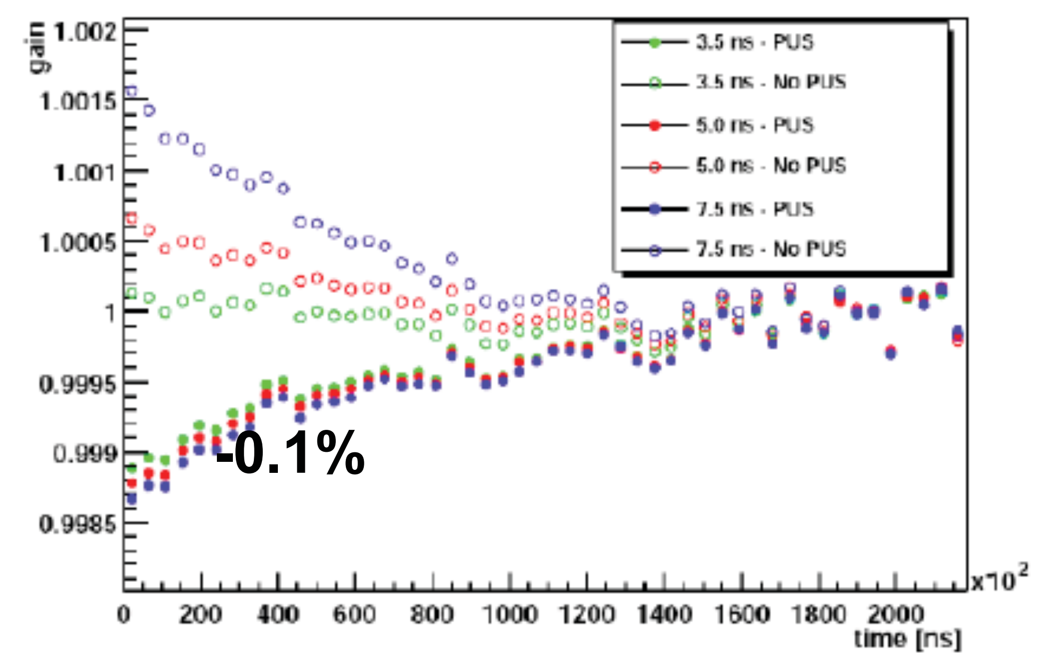


- Sistema laser impulsato ad azoto  (330 nm).
- L’impulso veniva distribuito attraverso un sistema di splitter box e fibre. Problemi di instabilita’ in tempo e temperatura. Variazioni per punto al %.
- Non usato per calibrazione guadagno. Usato per timestamp e debugging

# Miglioramenti nuova proposta

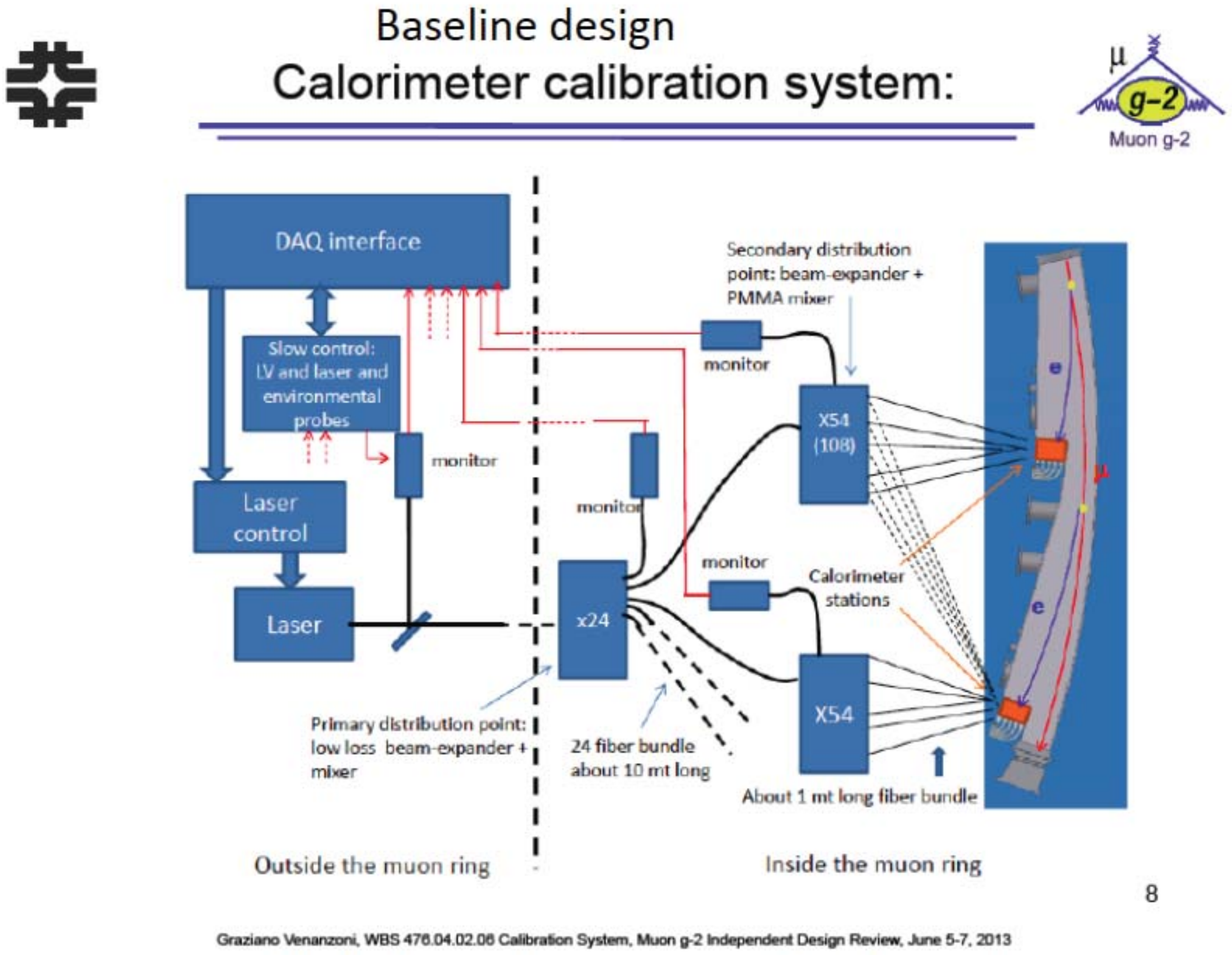
- In E821 effetto residuo su G(T)~0.1% che non si poteva verificare indipendentemente → errore associato su $\omega_a$ =0.12 ppm

- Il goal di 0.02 pm in E989 verra' ottenuto grazie a:
  - Il nuovo sistema laser dovra' permettere una misura indipendente delle fluttuazioni di guadagno "short term", al meglio dello 0.1% (possibilmente 0.04%). Esso dovra' mostrare una stabilita' (migliore) dello 0.1% su un periodo di 30' (run di calibrazione).
  - Pileup ridotto grazie a miglioramento del rivelatore ed elettronica associata



**→ Sistema laser centrale per l'esperimento! (altrimenti sistematico sulle fluttuazioni di guadagno non tollerabile)**

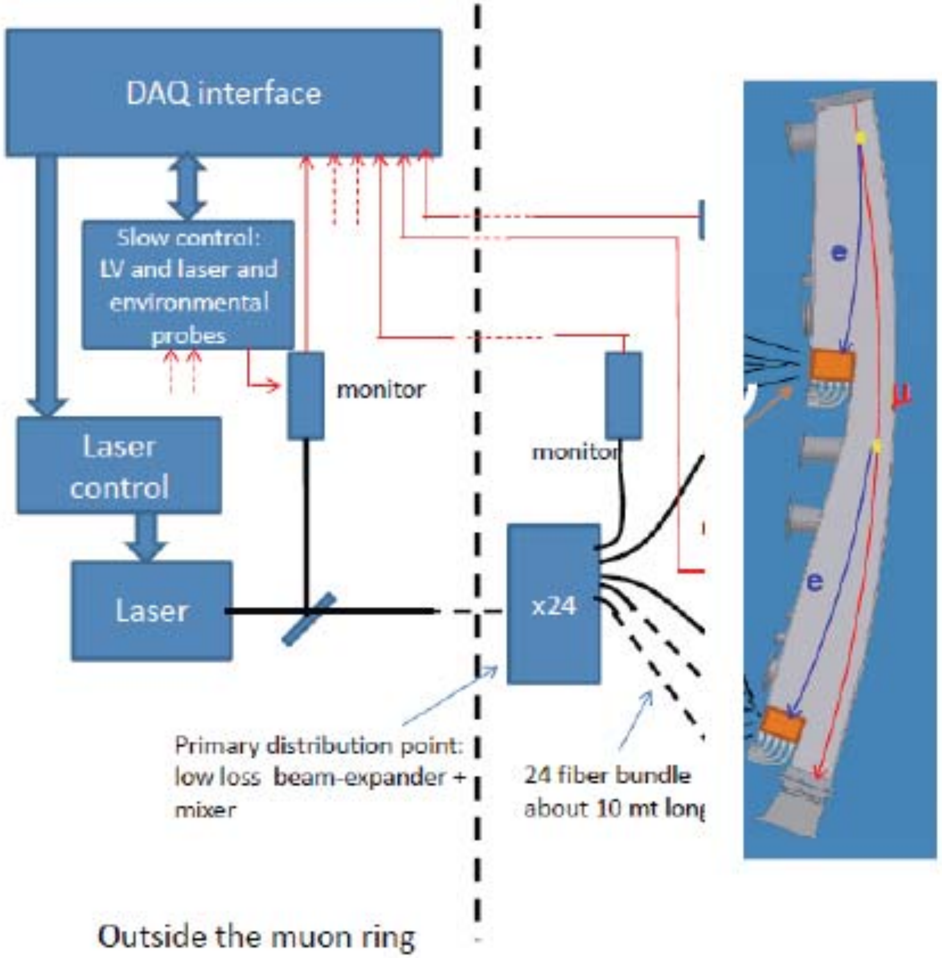
- Goal of 0.04% per singolo punto!!!



## Baseline design
## Calorimeter calibration system:

Two points of light distribution: 1 primary +[8-24] secondaries. 1300 fibers. Monitoring for each distribution point, ~15-30 in total

# Calibration system: Alternative solution (“Pisa Frame”)


DAQ interface

Slow control: LV and laser and environmental probes

monitor

Laser control

Laser

monitor

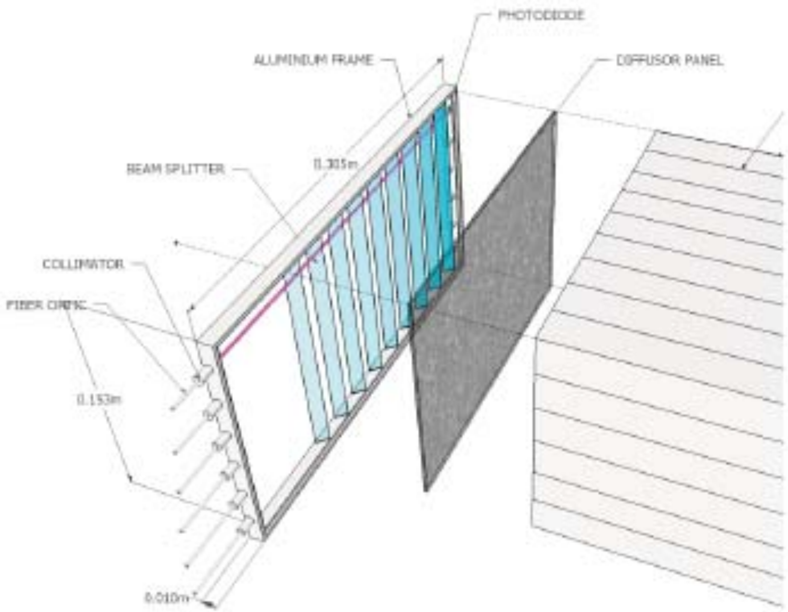
x24

Primary distribution point: low loss beam-expander + mixer

24 fiber bundle about 10 mt long

Outside the muon ring

- Simpler solution
- Possibility of monitoring of a single fiber
- Cost will depend very much on the monitoring element (6 PD / module, 6x24=150 total)
- Time/Mechanical Stability?

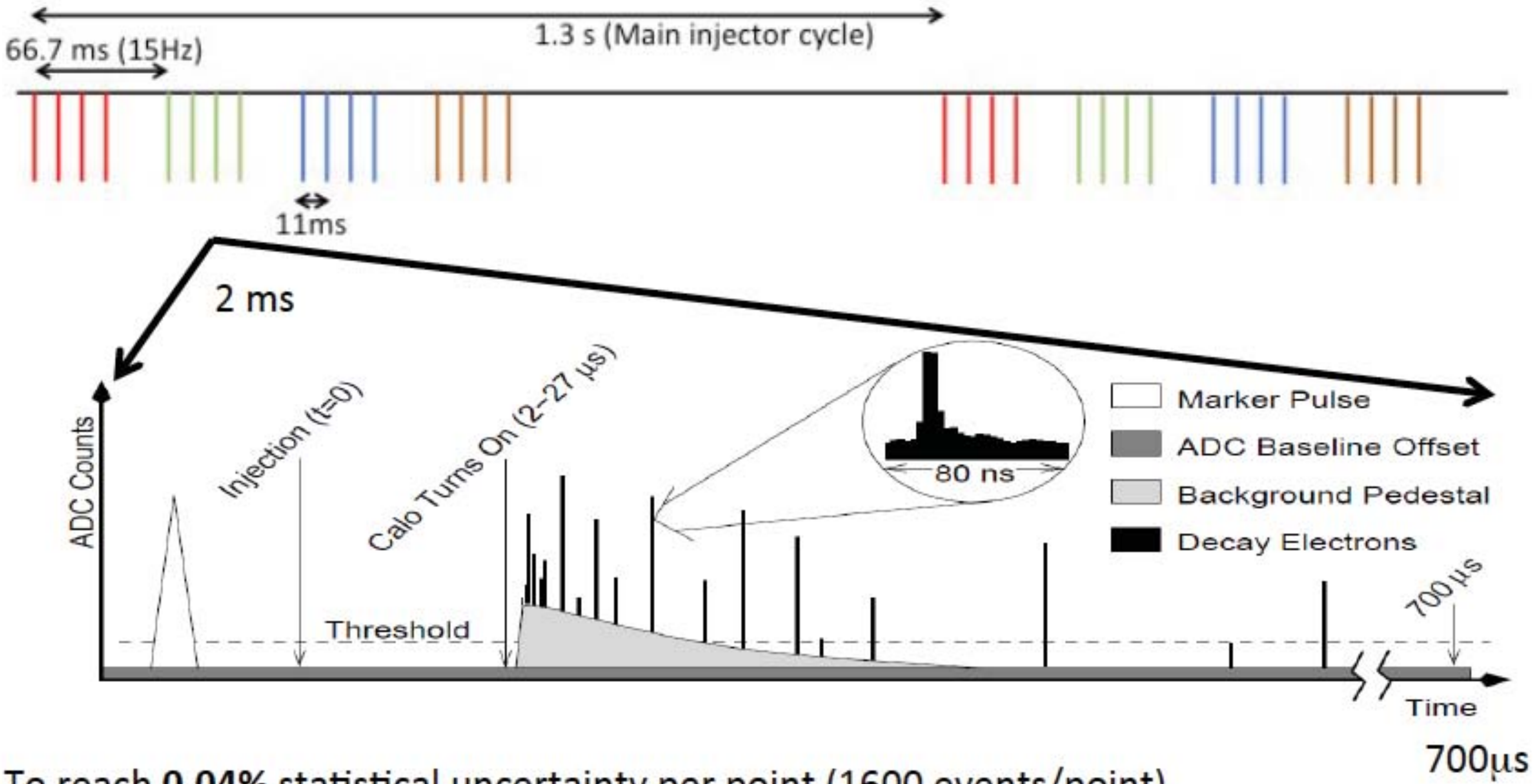


- A single primary distribution point with 150 fibers (instead of 1300), thanks to a different routing of fibers to crystals (“Pisa frame*”)

- The two options have different requests/implementations and critical points

- We will focus on the "baseline" solution (leaving for the future the possibility to work on the alternative one)

# Statistical Goal



To reach **0.04%** statistical uncertainty per point (1600 events/point)

- Let's assume 9 points per fill (1 every 80 **µs**, 12.5 kHz laser repetition rate)
- By moving the offset by 5 **µs** after a fill → 16 fills to have a single event calibration cycle (i.e. one point every 5 **µs** ), i.e. 1.3 s (1/2 hour to have full calibration cycle (1600 events every 5 **µs**).

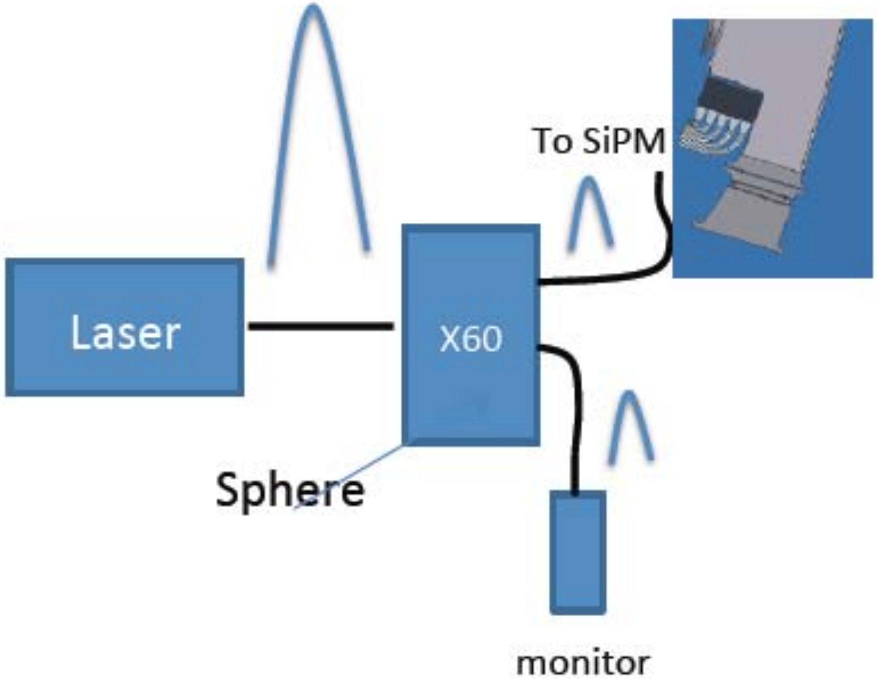
**30' calibration runs with ~10 kHz laser frequency → sampling of G(t) in 140 points between 0 and 700µs**

# Systematics: requests

- Monitoring and its electronics stable at $10^{-4}$
- Laser source and distribution system stable at $\sim 10^{-3}$

– What matters is **the SiPM/monitoring** signal ratio:

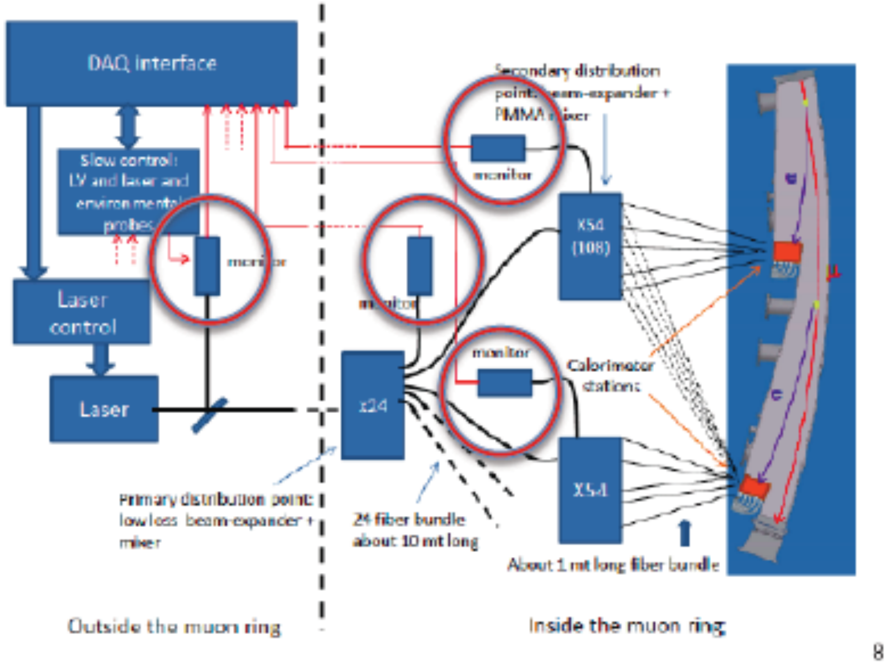
  - With a performing monitoring all the effects of beam pointing, source fluctuation, etc…, cancel in the ratio;
  - loss of uniformity (in time) and local effects (temperature gradients, mechanical stress) could modify the ratio

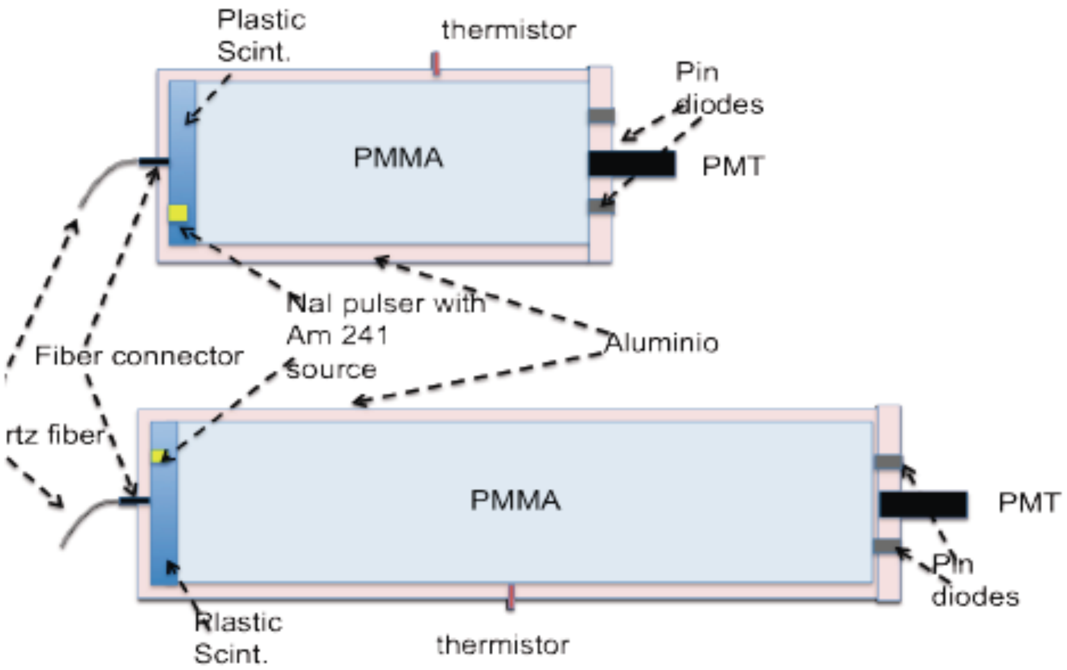


→ **Stable, redundant and self-calibrating monitoring system**

# Monitoring system (Trieste/Udine)

It's the heart of the calibration system. It MUST be stable against drifts of temperature/voltage/mechanical stress/Electronics etc…





The basic element is a Pin Diode.

Every monitor will have 2-3 PD and will be equipped with a NaI(Am) pulser for absolute calibration

The PD signal will be amplified by a commercial/home-made low-noise board.

The signal will be sent to: (i) g-2 WFD **or** (ii) commercial/home-made (Flash/ charge) ADC (to be defined within 2014).

A prototype is in construction at Udine

# A first prototype

PMT

Sotto questo tappo
Sono contenutu 2 PIN diodes

NaI+Am
"pulser"

La fibra entrera' da
questo lato

Work is going on to arrive to 1% stablity within next couple months

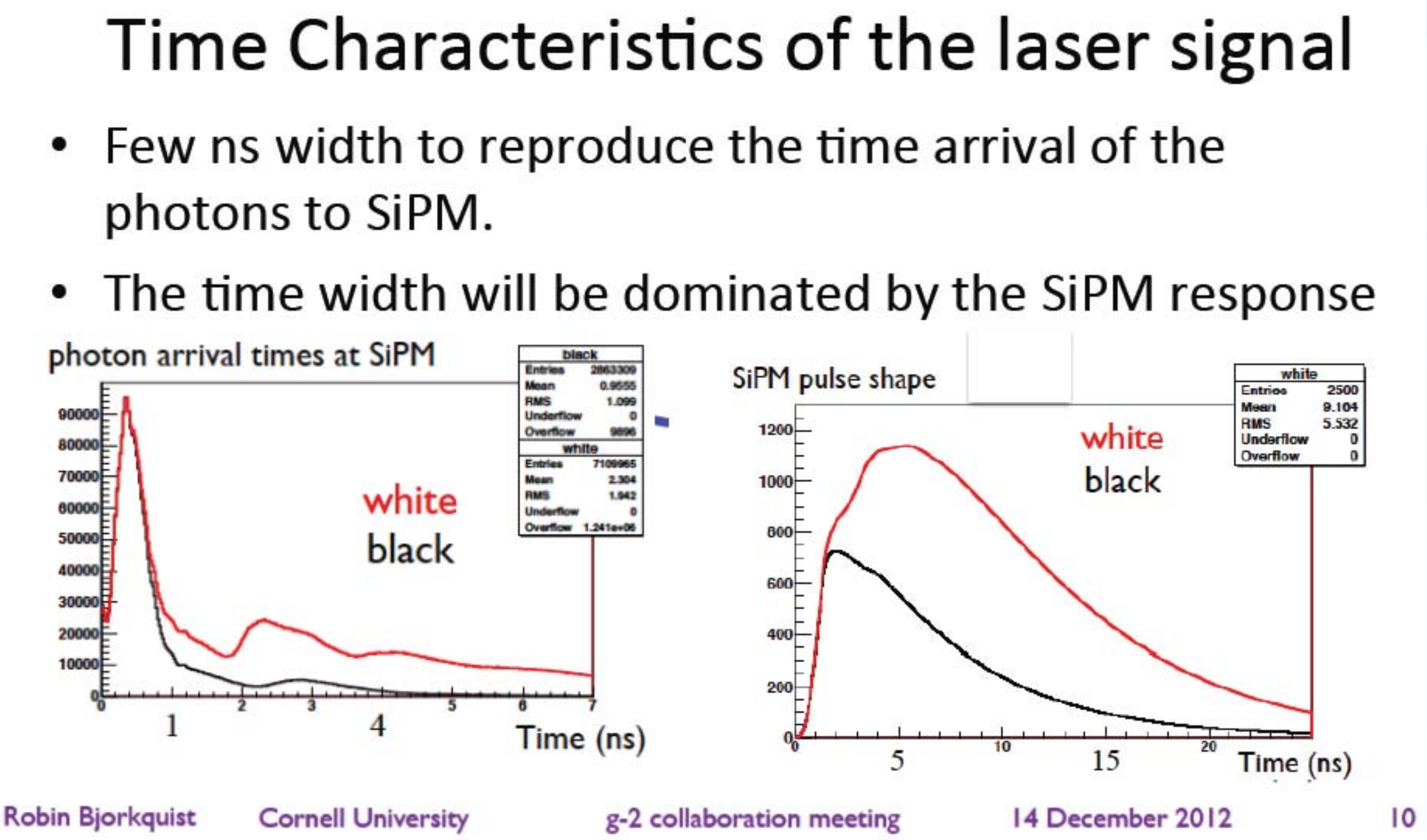
# Laser characteristics:

- Wavelength $\lambda$:[350-450 nm], 400 nm as reference
- Energy pulse equivalent to 2 GeV (assuming *up to* 2p.e./MeV, $\varepsilon_{SiPM}$~50%, light transmission factor T~$10^{-1}$):

$$E_{pulse}^{TOT} = \frac{24 \times 54 \times E_{pulse}^{crystal}}{T} = \frac{24 \times 54 \times 0.01pJ}{10^{-1}} = \frac{13pJ}{10^{-1}} \sim 0.1nJ$$

- Required laser power for 1 ns pulse width would be ~0.1 W
- Pulse width ~ns
- Repetition Rate O(10 KHz) (but also at MHz for debugging purposes)

The **"light transmission factor" T** includes light losses along the optical path: filters, diffusive elements, fiber coupling, light routing to calorimeter (T: $10^{-3} - 10^{-1}$)



# Time Characteristics of the laser signal

- Few ns width to reproduce the time arrival of the photons to SiPM.
- The time width will be dominated by the SiPM response

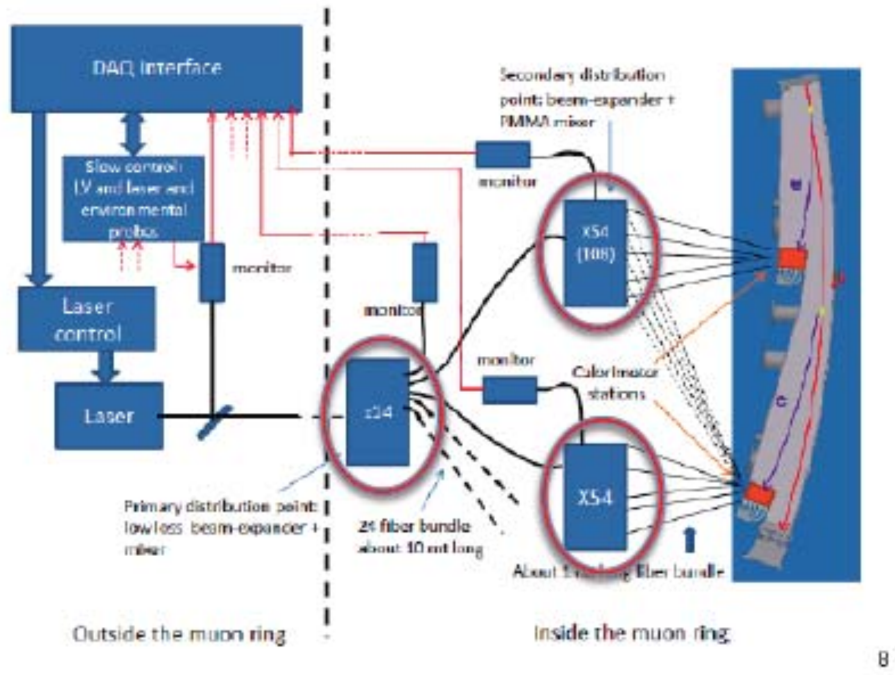
photon arrival times at SiPM

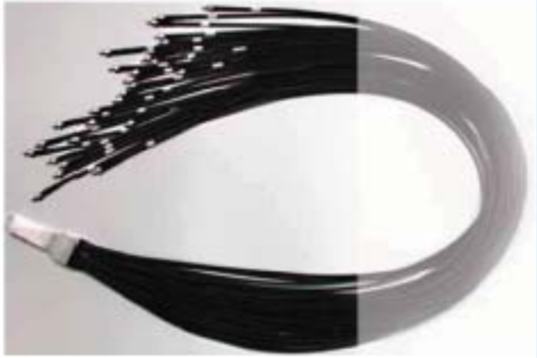
SiPM pulse shape

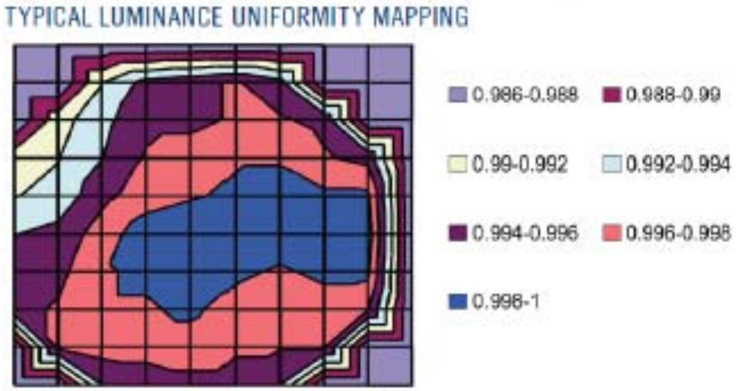
The laser pulse width will be modified by the distribution system (diffusive sphere)

# Light distribution system (LNF/RM2/INO PI)

Intensity and **uniformity MUST be** stable in time (during the 30’ of calibration run)







The basic element is a diffusive **sphere + fiber** bundles

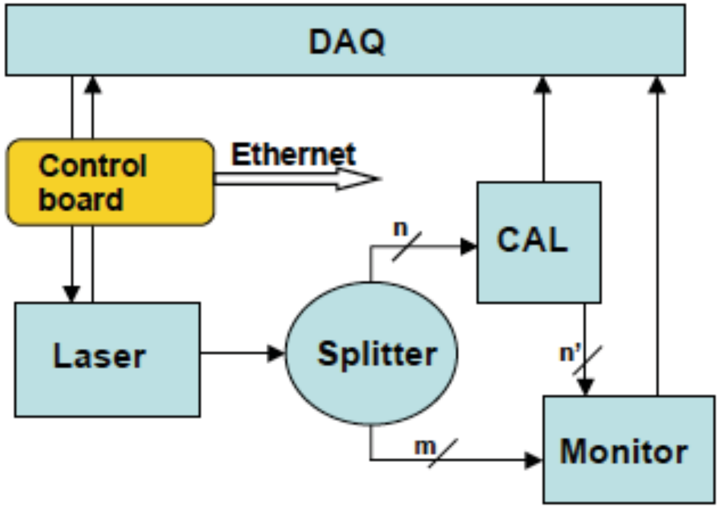
Each sphere has one input and three output windows. Each window can serve 60 fibers (200μm ø each). In principle 3 calorimeter stations for each sphere.

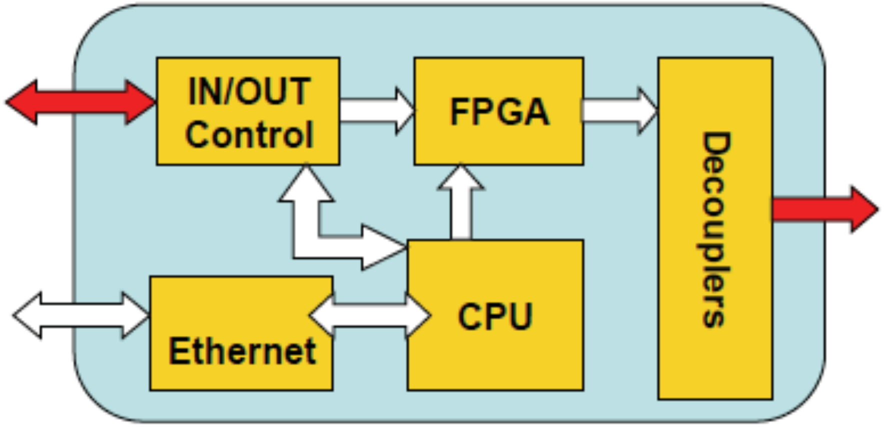
Optical components (Sphere, beam-splitters, fibers) already bought.

We will study the transmission efficiency (using a Pin diode+amplifier+DRS4 Board) and variation of pulse-shape.

We will study the the loss of uniformity over time. A possibility is to use a 16 bit CCD

# Laser Drive electronics (NA)





- The laser control board will communicate with DAQ and SC and drive the laser in 2 modes (see also Dave's presentation at Det. Meet 11/5/2013):
  - At fixed frequency (~10 kHz) for calibration purposes (during or between fills) with fixed or variable amplitudes
  - Pulse on command: triggered according to g-2 DAQ cycle, emulating beam structure by **Flight Simulator** (Modulate the frequency from O(MHz) to hundreds of Hz) for exercising electronics, DAQ, etc…

Work is going on comparing two possibilities:

(1) ML507 VIRTEX5

(2) FPGA with a μcontroller

# Milestones

- **Summer 2014:** complete the individual element tests and qualifications;
- **Summer 2014:** test beam with a calorimeter prototype fully equipped (SLAC)
- **Nov 2014:** Choice of the distribution system
- **Dec 2014:** Demonstration of 0.1% monitoring on a single module
- **July 2015:** select the final laser source and the optical devices, place the orders.
- **Fall 2015:** check of all components and full calibration system
- **2016:** delivery at FNAL, setup and test of the full system

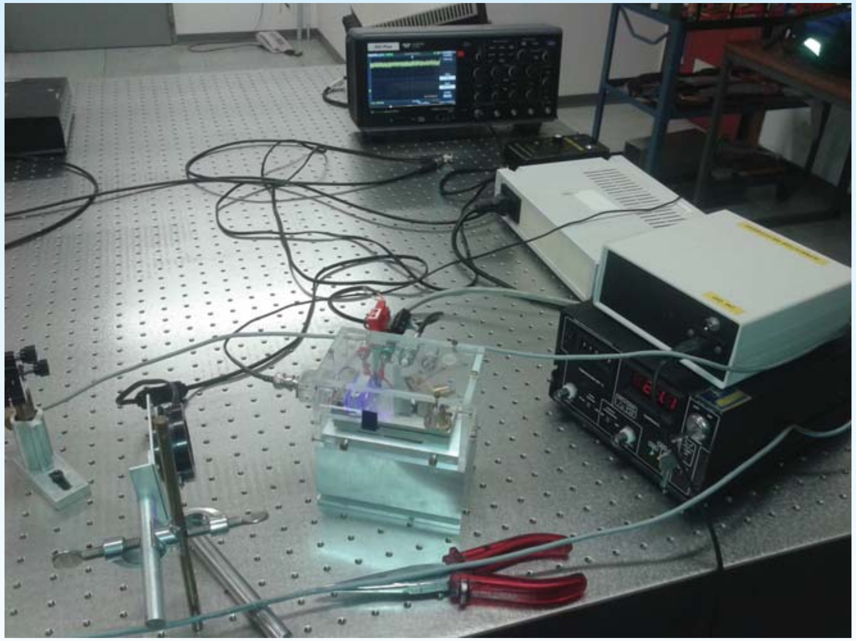
# Status of the Italian Participation

- In September INFN approved us for 2014 with an initial 100KEur contribution for first tests on the calibration system. Depending on the status of our activities and of E989 we will have definitive approval in 2014.
- Formal involvement :
  - Trieste (2 people 1FTE)
  - Udine (3 people 1FTE)
  - LNF (8 people 3 FTE)
  - Roma 2 (2 people 1 FTE)
  - Naples (4 people 2 FTE)

**C. Ferrari, A. Fioretti, C. Gabbanini associati a LNF per il 2014**

- We have completed the purchases for the tests planned in the first half of 2014
- We have also a PhD student (A. Anastasi who was summer student on g-2 this year) who plans to work on g-2

# Primi test all'INO (Gennaio 14)



Prime misure sull'eff. di trasmissione della sfera integratrice

# Conclusioni

- La misura del g-2 del muone rappresenta un benchmark solido per i test di fisica BSM. La discrepanza di 3.3 sigma tra il valore sperimentale e la predizione teorica non e' sufficiente a stabilire un chiaro segnale di nuova fisica.
- Nuova proposta E989 a FNAL. Schedule serrata con inizio presa dati nel 2017. Miglioramento di un fattore 4 dell'errore. Se la nuova misura dovesse confermare il valore di BNL, la discrepanza tra SM ed esperimento sarebbe tra 5-8$\sigma$ (scoperta!)
- Sigla G-2 aperta per il 2014 con 4 sezioni INFN coinvolte. Gruppo italiano di dimensioni giuste e ben motivato a raccogliere la sfida. Lavoro principale su un sistema laser ad altissima precisione
- Partecipazione e competenze dell'INO essenziali!!!!

# SPARES

# The present experimental values:

$$a_e = 1159652180.73\ (28) \times 10^{-12}$$

0.24 parts per billion !! Hanneke et al., PRL100 (2008) 120801

$$a_\mu = 116592089\ (63) \times 10^{-11}$$

0.5 parts per million !! E821 – Final Report: PRD73 (2006) 072003

$$a_\tau = -0.018\ (17)$$

DELPHI - EPJC35 (2004) 159 [$a_\tau^{SM} = 117721(5) \times 10^{-8}$, Eidelman & MP '07]

# [ A parenthesis on the electron g-2...

$a_e^{SM}$ = $(1/2)(\alpha/\pi)$ - $0.328\ 478\ 444\ 002\ 89(60)\ (\alpha/\pi)^2$

Schwinger 1948 Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '06

$A_2^{(4)}(m_e/m_\mu) = 5.197\ 386\ 78\ (26) \times 10^{-7}$

$A_2^{(4)}(m_e/m_\tau) = 1.837\ 62\ (60) \times 10^{-9}$

$+\ 1.181\ 234\ 016\ 827\ (19)\ (\alpha/\pi)^3$

Kinoshita, Barbieri, Laporta, Remiddi, … , Li, Samuel; Mohr,Taylor & Newell '08, MP '06

$A_2^{(6)}(m_e/m_\mu) = -7.373\ 941\ 73\ (27) \times 10^{-6}$

$A_2^{(6)}(m_e/m_\tau) = -6.5819\ (19) \times 10^{-8}$

$A_3^{(6)}(m_e/m_\mu, m_e/m_\tau) = 1.909\ 45\ (62) \times 10^{-13}$

$-\ 1.9144\ (35)\ (\alpha/\pi)^4$

Kinoshita & Lindquist '81, … , Kinoshita & Nio '05; Aoyama, Hayakawa, Kinoshita & Nio, 2007

$+\ 0.0\ (4.6)\ (\alpha/\pi)^5$ In progress (12672 mass ind. diagrams!)

Aoyama, Hayakawa, Kinoshita, Nio '07; Aoyama, Hayakawa, Kinoshita, Nio, Jan 2011

$+\ 1.676\ (20) \times 10^{-12}$ Hadronic

Krause 1997, Jegerlehner & Nyffeler 2009

$+\ 0.02973\ (52) \times 10^{-12}$ Electroweak

Mohr,Taylor & Newell, '08; Czarnecki, Krause, Marciano '96

# ... and the best determination of alpha ]

- **The 2008 measurement of the electron g-2 is:**

  $a_e^{exp} = 1159652180.73\ (28) \times 10^{-12}$ Hanneke et al, PRL100 (2008) 120801

  **vs. old (factor of 15 improvement, 1.8σ difference):**

  $a_e^{exp} = 1159652188.3\ (4.2) \times 10^{-12}$ Van Dyck et al, PRL59 (1987) 26

- **Equating $a_e^{SM}(\alpha) = a_e^{exp}$ → best determination of alpha to date:**

$\alpha^{-1} = 137.035\ 999\ 084\ (12)(37)(2)(33)\ [0.37\text{ppb}]$ Hanneke et al, '08

$\delta C_4^{qed}$ $\delta C_5^{qed}$ $\delta a_e^{had}$ $\delta a_e^{exp}$ (smaller than th!)

- **Compare it with other determinations (independent of $a_e$):**

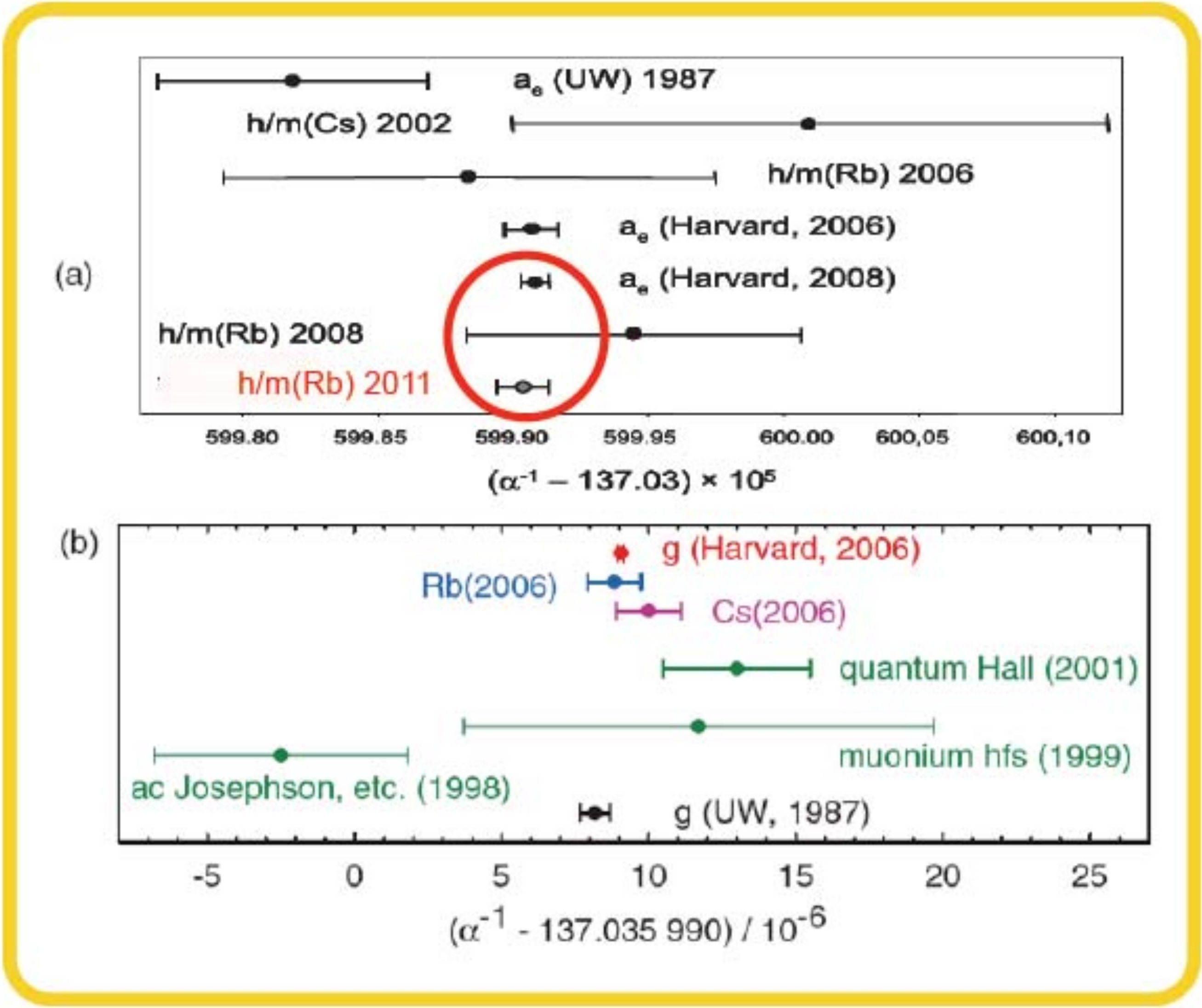
$\alpha^{-1} = 137.036\ 000\ 00\ \ (110)\ \ [7.7\text{ ppb}]$ PRA73 (2006) 032504 (Cs)

$\alpha^{-1} = 137.035\ 999\ 45\ \ (62)\ \ [4.6\text{ ppb}]$ PRL101 (2008) 230801 (Rb)

$\alpha^{-1} = 137.035\ 999\ 037\ \ (91)\ \ [0.7\text{ ppb}]$ PRL106 (2011) 080801 (Rb)

**Excellent agreement → beautiful test of QED at 4-loop level!**

# Old and new determinations of alpha



Gabrielse, Hanneke, Kinoshita, Nio & Odom, PRL99 (2007) 039902
Hanneke, Fogwell & Gabrielse, PRL100 (2008) 120801
Bouchendira et al, PRL106 (2011) 080801

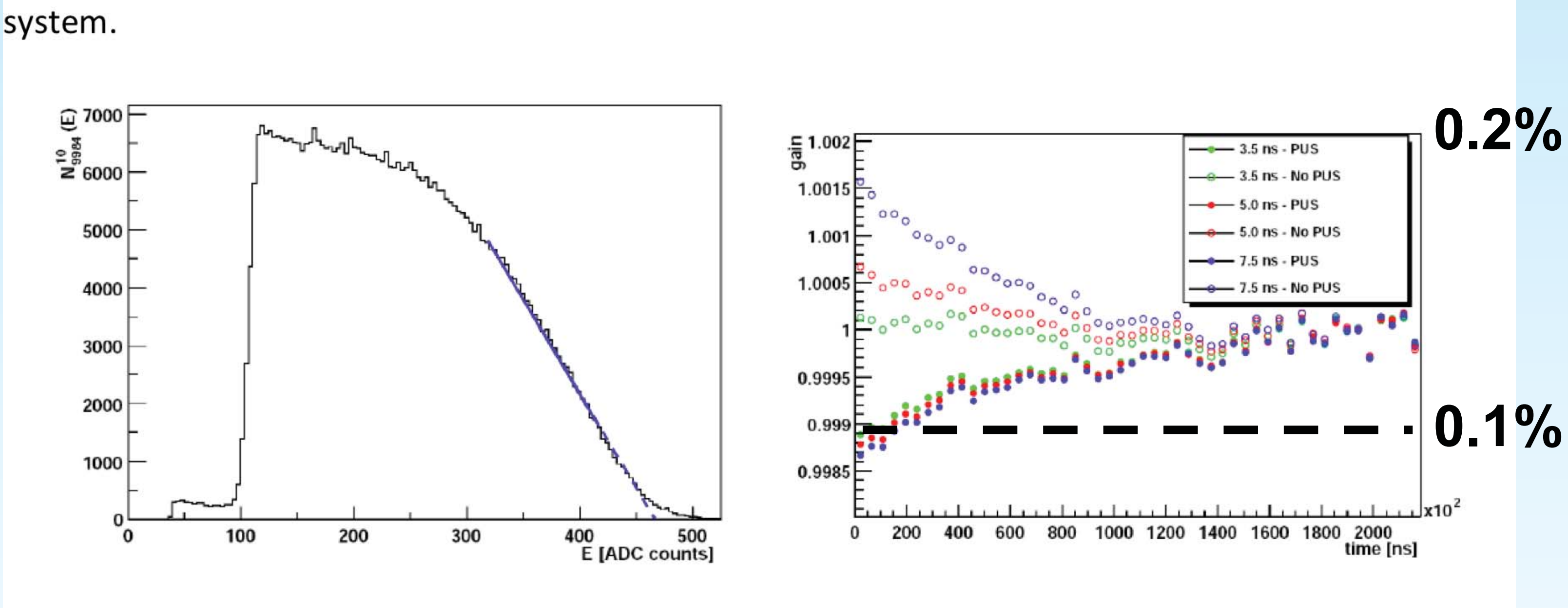
# Old friends, new teammates

# Conclusions

- The design of the laser calibration system (and its electronics) is in an advanced phase
- INFN approved a first R&D on the calibration system with 100kEur for 2014
- We are focusing on the baseline solution
- We are constructing a first prototype of the monitor
- We have purchased the components to perform the first tests of laser source, stability, transmission loss of the distribution and monitoring system.
- We plan to have a first prototype for a calorimeter module ready for SLAC TB.
- We plan to have definitive approval next year

# Monitoring delle fluttuazioni in guadagno in E821

- SW: Fit dell’endpoint (“EP”) dello spettro di decadimento degli e- in funzione del tempo
  - Incertezza nell’estrapolazione; correzioni di pileup



- HW: Sistema Laser (di fatto non ha funzionato al livello di stabilita’ richiesto)