# The Muon g-2 Experiment at FNAL

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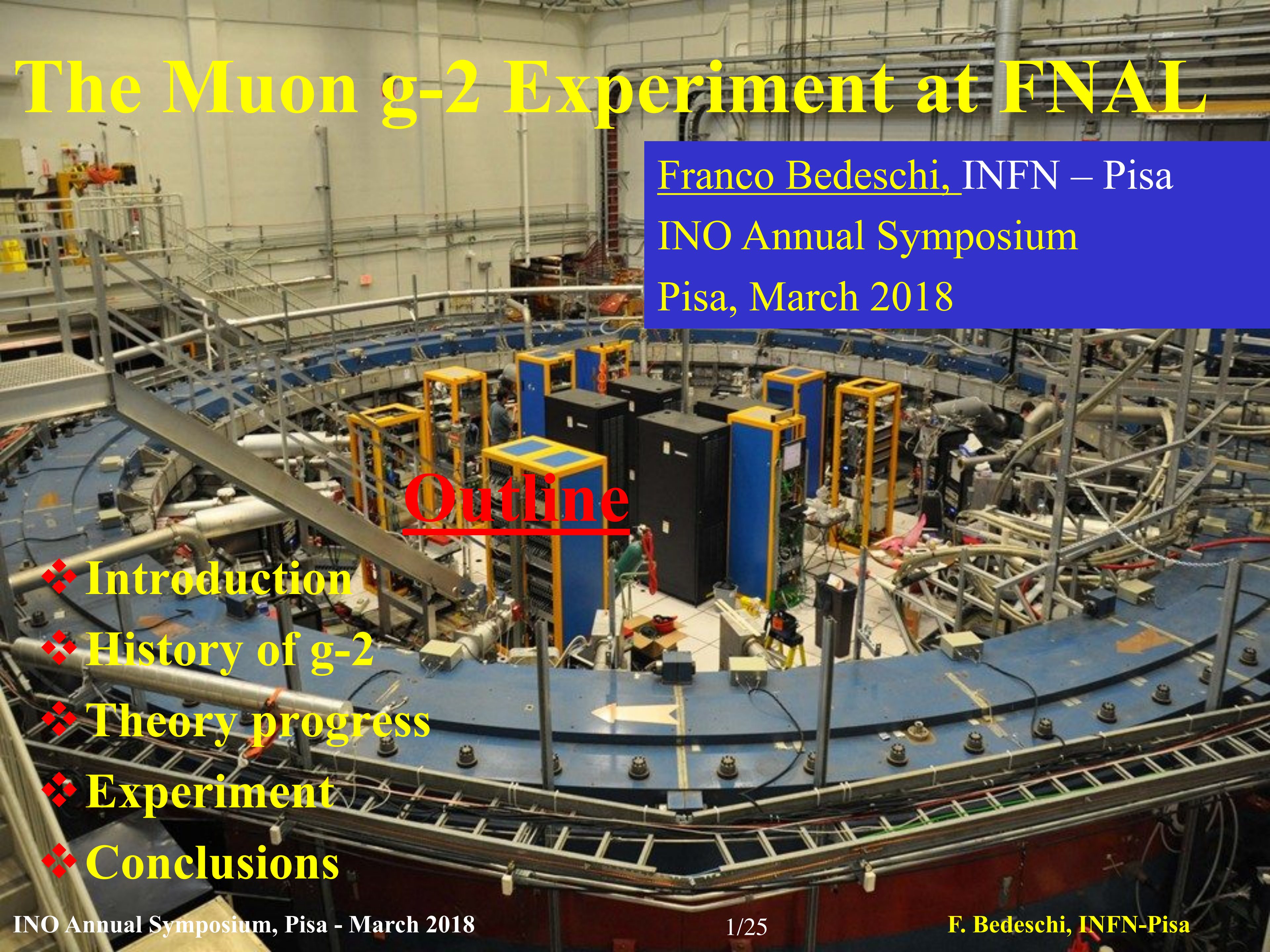
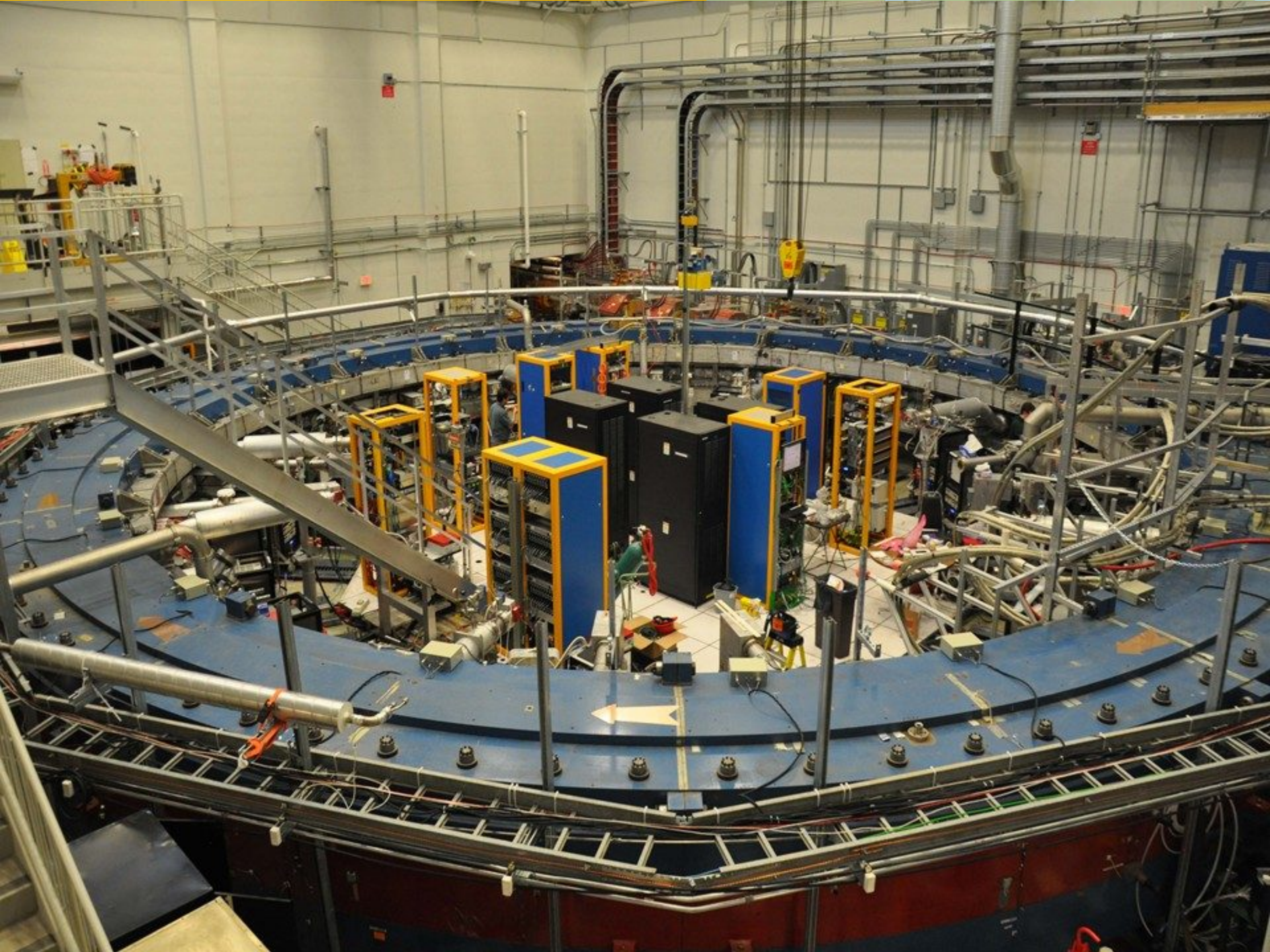
INO Annual Symposium

Pisa, March 2018



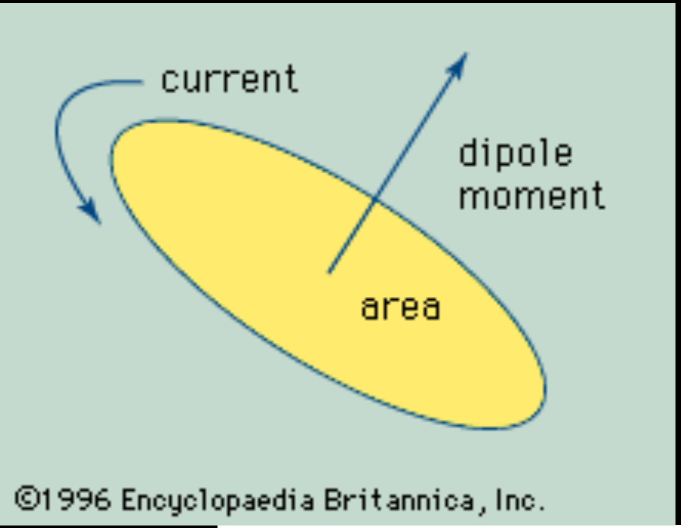
## Outline

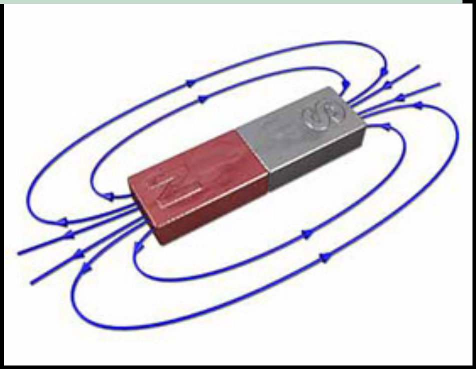
- Introduction
- History of g-2
- Theory progress
- Experiment
- Conclusions



# Magnetic moment: classical description

- Magnetic moment of current loop
  - $\mu = I\,A = I\,\pi r^2$
- Current from single particle:
  - $I = qv/(2\pi r)$
  - $\mu = qv/(2\pi r)\,.\,\pi r^2 = qrv/2$
- Relation to angular momentum
  - $S = mrv = 2m/q\,.\,\mu$
  - $\boxed{\mu = q/(2m)\,.\,S}$



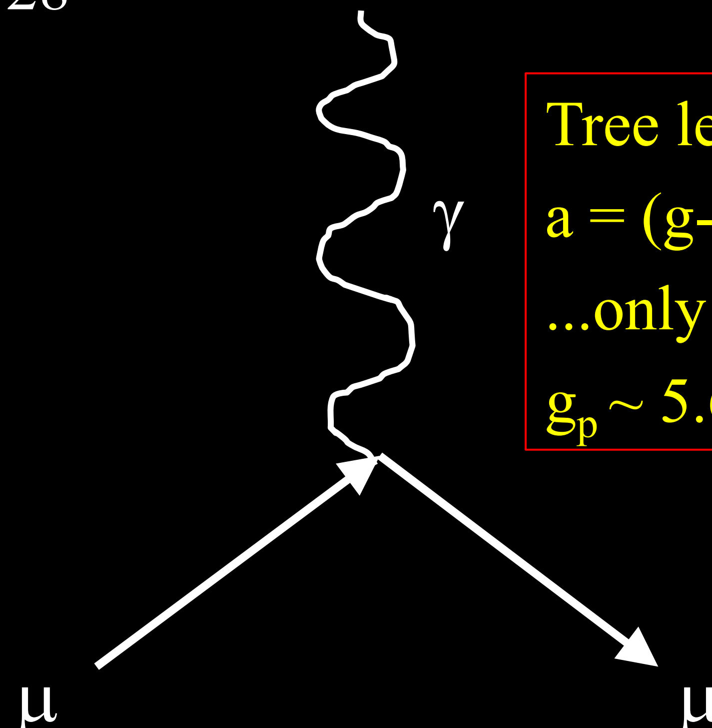



- Magnetic moment proportional to spin also for elementary particles, …. but quantum mechanics kicks in

# Basic definitions

- Magnetic moment relation to point-like particle spin different from classical phys.
- Tree level QED : g = 2 for all leptons
  - Explained by Dirac in 1928

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

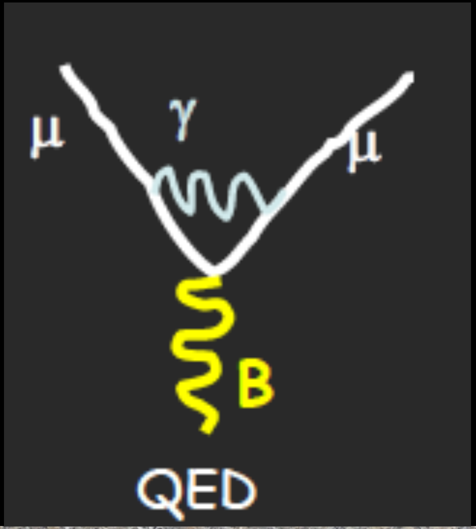


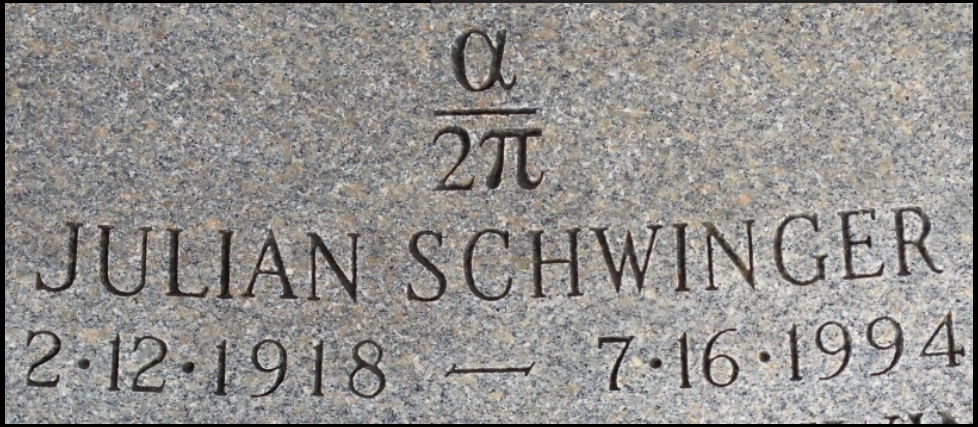

Tree level anomaly:
a = (g-2)/2 = 0
...only if pointlike
$g_p \sim 5.6$, $g_n \sim -3.8$

# Higher orders (1)

- Radiative corrections (challenging!) change the picture
  - $a \neq 0$
- Schwinger (1948): 1 loop correction

$$a_\mu = \frac{\alpha}{2\pi}$$



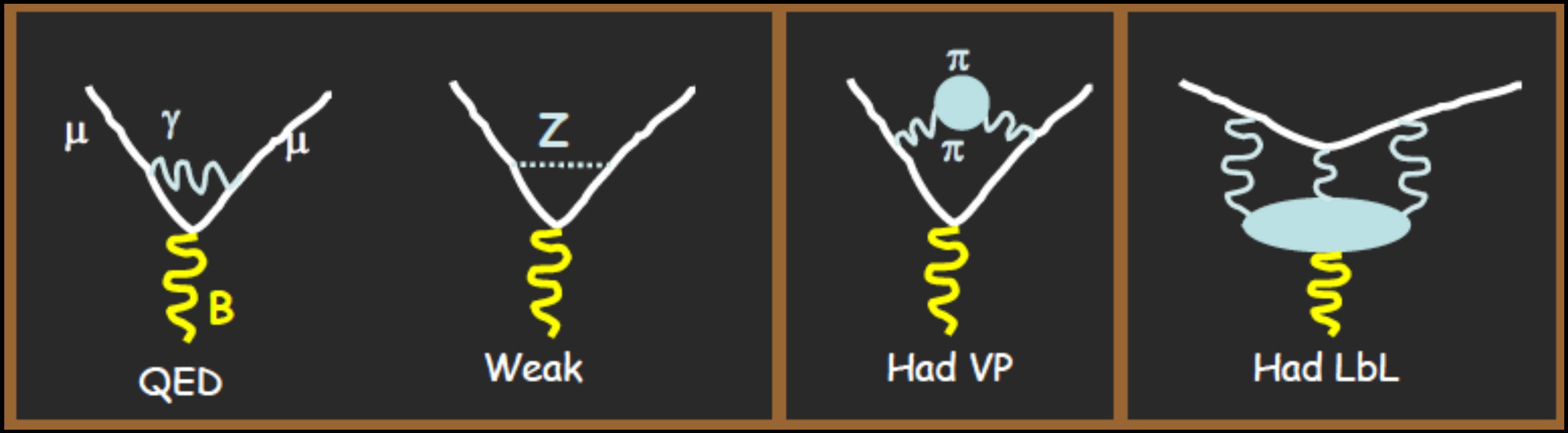



# Higher orders (2)

- QED calculations becomes more complex:
  - 1 loop → 1 diagram analytic calculation
  - 2 loop → 7 diagrams analytic calculation
  - 3 loop → 72 diagrams analytic calculation
  - 4 loop → 891 diagrams numerical calculation
  - 5 loop → > 12,000 diagrams numerical calculation
    - Contribution irrelevant compared to current experimental errors
- Higher order corrections depend on lepton mass

# Other corrections

- $a_\mu$ is affected by loops with W/Z or quarks (hadrons)




- Weak contribution small and precisely calculated
- Had VP and Had LBL are hard .... however
  - Improvements and new approaches expected

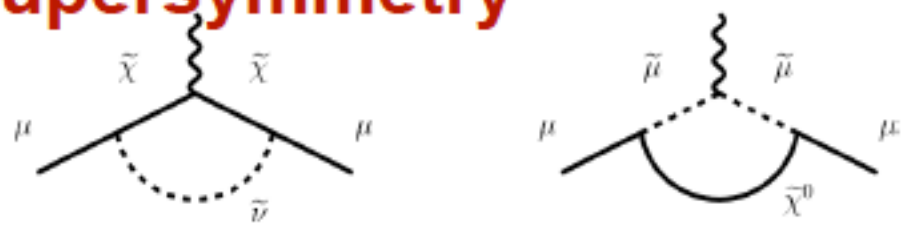
$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 40,000$$

- Contributions of virtual heavier particles (including new physics!) scale with lepton mass squared

# New physics sensitivity

- New physics effects similar to weak contributions
  - eg. SUSY gives relevant contributions from $\chi^{\pm}$ e $\chi^{0}$ not strongly bounded by LHC

- **Supersymmetry**

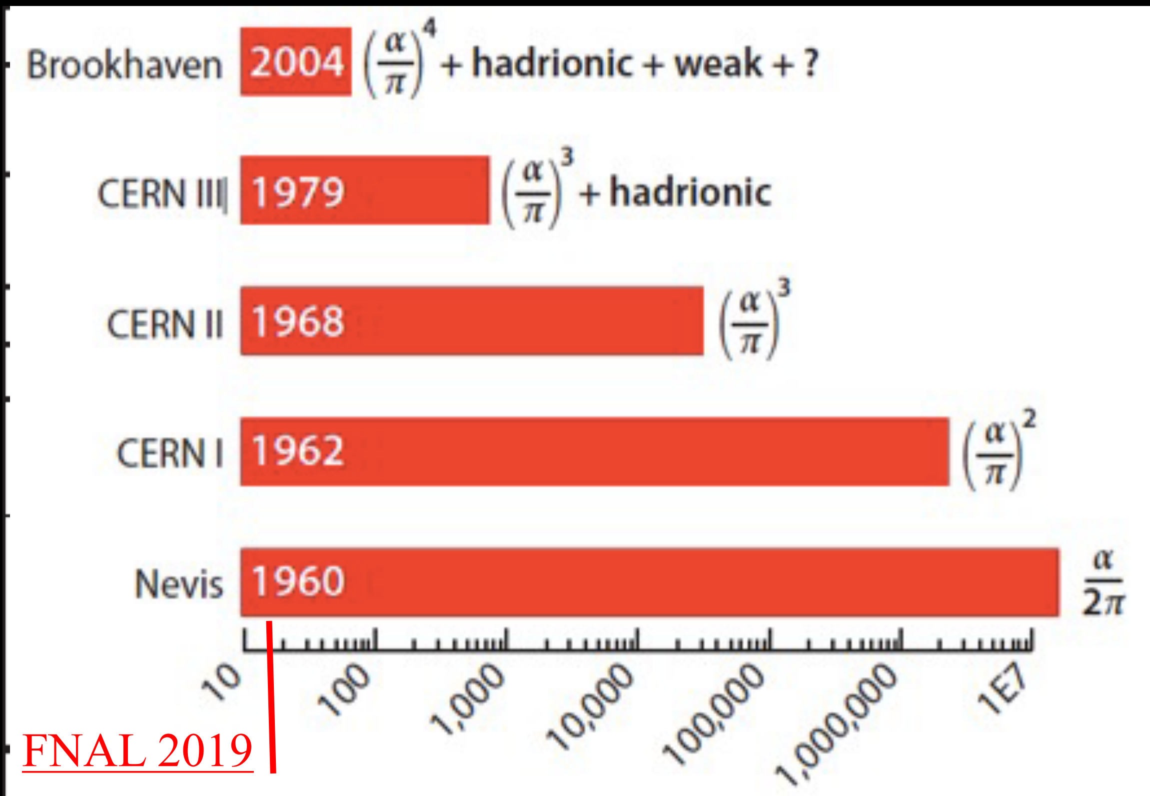



$$\boxed{a_\mu^{SUSY} \approx 130 \times 10^{-11} \left( \frac{100 \text{ GeV}}{M_{SUSY}} \right)^2 \tan\beta \, \mathrm{sign}(\mu)}$$

  - Presently $a^{exp} - a^{th} \sim (245 \pm 81) \times 10^{-11}$ (Kinoshita, Jul. 2014)
  - Experimental precision close to new physics effects

# A lot of history

- Experimental summary




| Reference |
|---|
| Garwin *et al*[30], Nevis (1957) |
| Garwin *et al*[33], Nevis (1959) |
| Charpak *et al*[34] CERN 1 (SC) (1961) |
| Charpak *et al*[35] CERN 1 (SC) (1962) |
| Bailey *et al*[36] CERN 2 (PS) (1968) |
| Henry *et al*[46] solenoid (1969) |
| Bailey *et al*[37] CERN 3 (PS) (1975) |
| Bailey *et al*[38] CERN 3 (PS) (1979) |
| Brown *et al*[48] BNL (2000) |
| Brown *et al*[49] BNL (2001) |
| Bennett *et al*[50] BNL (2002) |
| Bennett *et al*[51] BNL (2004) |
| Bennett *et al*[51, 26] BNL WA (2004) |

# Muon g-2 experiment at FNAL

- Improved measurement of the μ anomalous magnetic moment: $a_\mu = (g_\mu - 2)/2$
- Best previous measurement BNL-E821 (1997-2001)

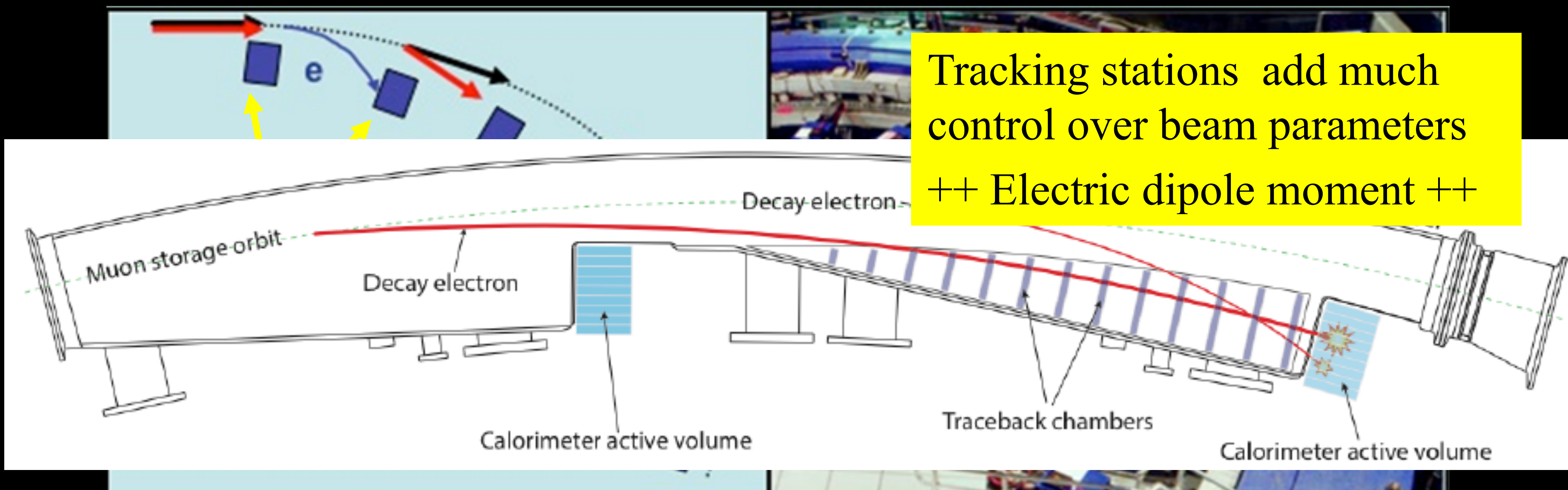
$$a_\mu^{\mathrm{exp}} = (11\,659\,208.9(5.4)_{\mathrm{stat}}(3.3)_{\mathrm{syst}}(6.3)_{\mathrm{tot}}) \times 10^{-10}$$

G. W. Bennett et al., PRL 92, 161802 (2004).
L. Roberts, Chinese Phys. C 34, 741 (2010).

  - Error statistics limited
  - Difference wrt. SM ~ 3σ (theory error ~ $5 \times 10^{-10}$)
- Goal of new FNAL experiment (E989) (x4 better)
  - $\sigma_{tot} = (1.2 \text{ stat.} \oplus 1.3 \text{ syst.}) \times 10^{-10} = 1.6 \times 10^{-10}$
- Assuming same central values (exp. & theory):
  - SM – exp. difference:
    - ~ 5σ if no improvement in theoretical determination
    - ~ 8σ if theory improved by x2

# FNAL E-989: how it works

- $a_\mu$ proportional to difference between precession and rotation frequency




Tracking stations add much control over beam parameters

++ Electric dipole moment ++

- Measure:
  - $\omega_a$ e B

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

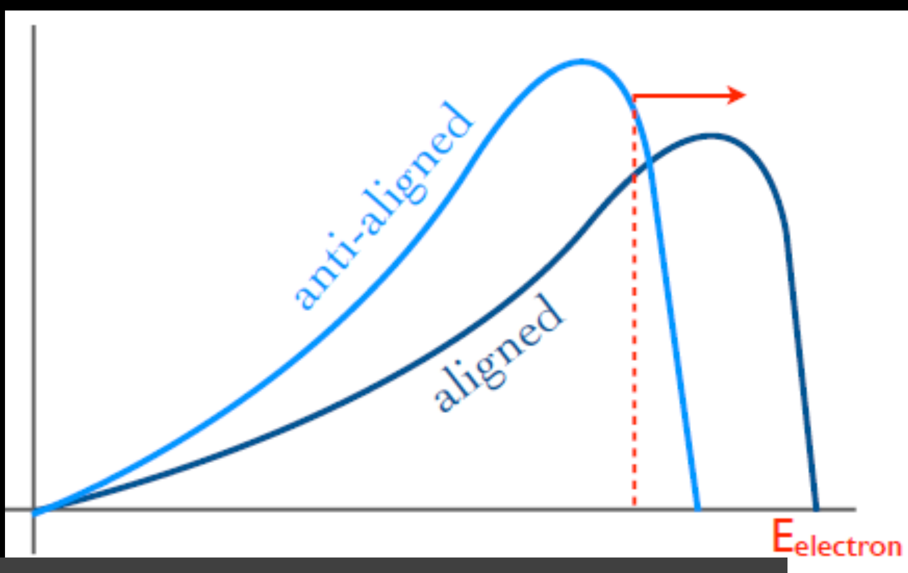
Magic momentum

3.094 GeV

$\gamma$=29.3

# How it works: $\omega_a$

- Inject polarized muons into the ring
- Observe decay electrons
  - Count electrons above energy threshold (1.9 GeV optimal)




**Harder electron spectrum when spin is aligned with momentum**

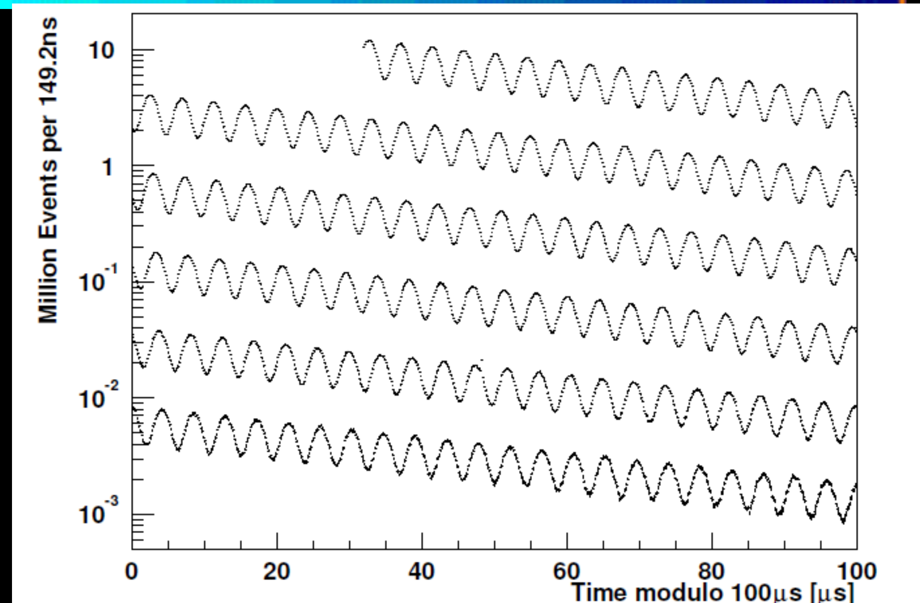
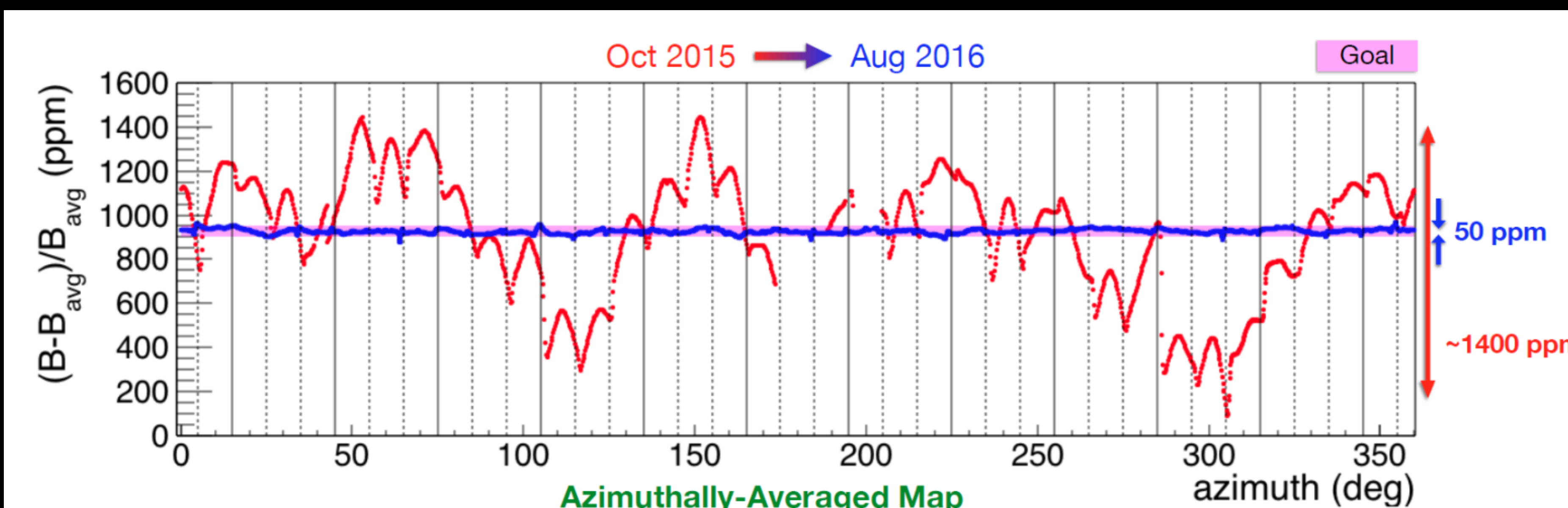



Figure 2: Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 $\mu s$ [9].

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

# How it works: $B/\omega_p$

- B measured with NMR probes (precision ~10 ppb)→
  - $\omega_p$ = free proton precession frequency $\propto$ B
  - Probes in several fixed positions and on trolley that can move around the ring
    - What matters is average field around ring
    - Max deviation 15 ppm demonstrated in ring section with laminations



# How it works: all together

- The whole measurement is reduced to the measurement of two frequencies: $\omega_a$ and $\omega_p$
  - With a little math:

$$\boxed{a_\mu = \frac{\omega_a/\omega_p}{\lambda - \omega_a/\omega_p}}$$

- $\lambda = \mu_\mu/\mu_p$ is the ratio of the magnetic moments of the muon and the proton
  - Measured with 120 ppb (26 ppb indirect) precision with spectroscopy of muonic hydrogen like atoms in a magnetic field monitored with NMR probes

W. Liu et al, Phys. Rev. Lett. 82, 711 (1999)

S. Karshenboim and V. Ivanov, Can. J. Phys. 80, 1305 (2002)

# $\omega_a$ systematics

❖ Most relevant: calorimeter gain variations within muon fill

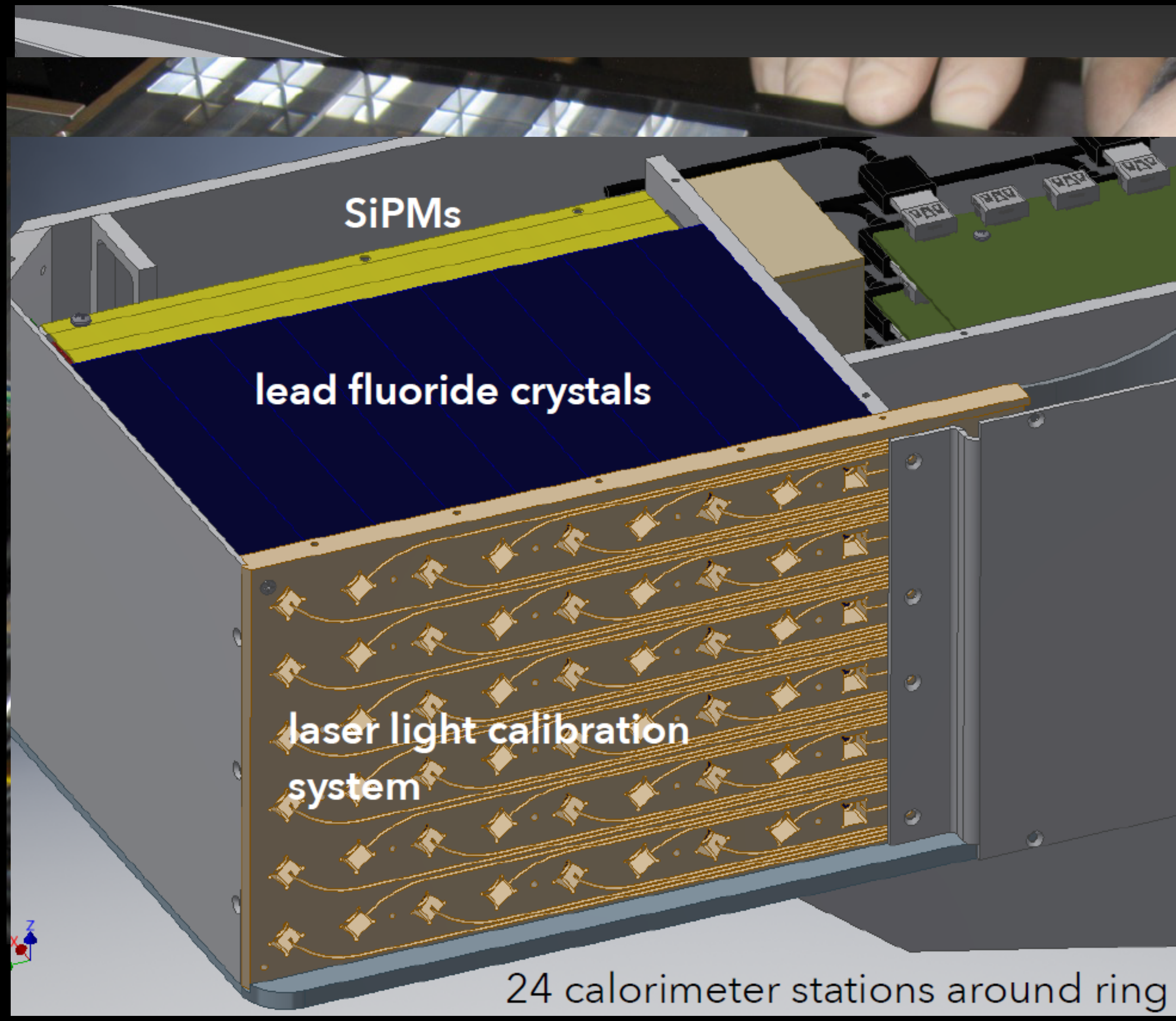
## Improving $\omega_a$

| 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 |

Coherent Betatron Oscillations

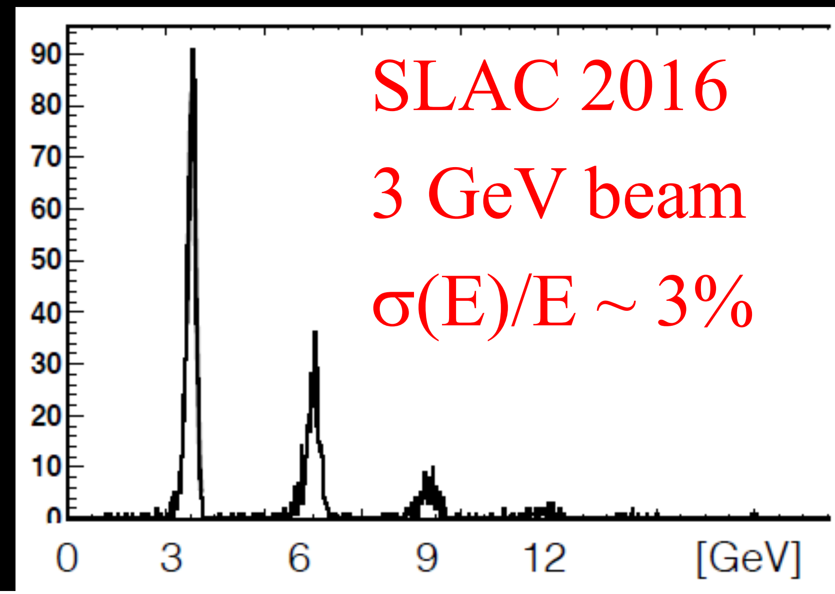
# Calorimetry (1)

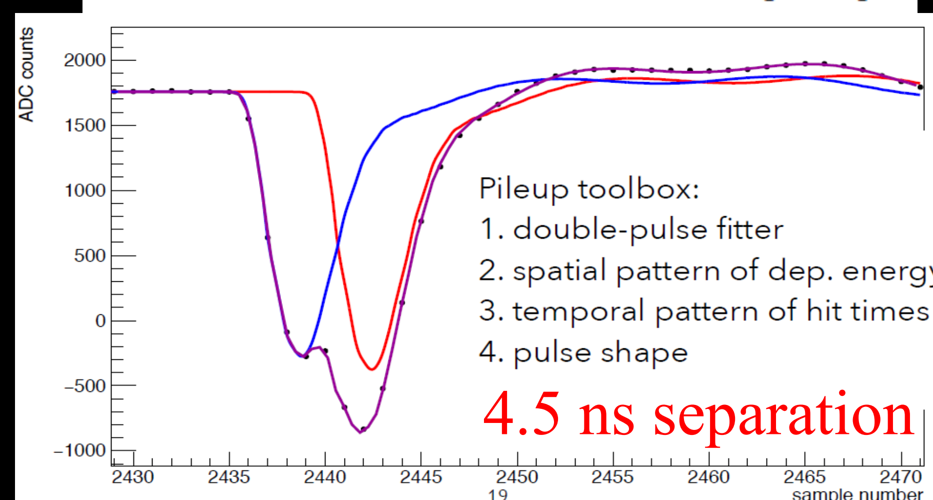
- 24 stations
- Fast:
  - Crystals $PbF_2$
    - Cherenkov
  - SiPM readout
- Laser calibration
  - Reduce systematics



# Calorimetry (2)

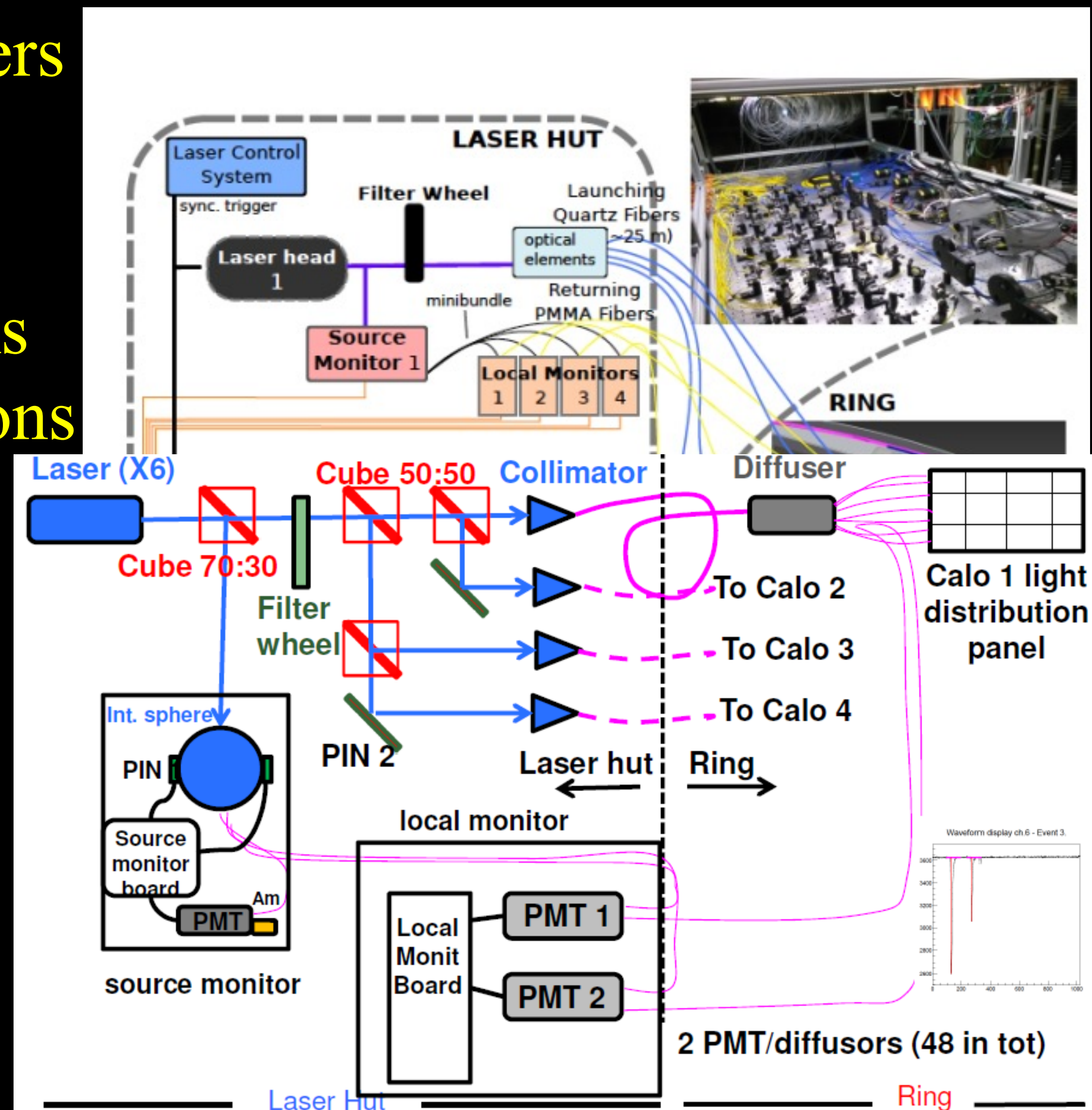
- Energy resol. ~ 3%
  - Optimized for good timing
- Timing resolution
  - 25 ps intrinsic
  - Digitizer bin 1.25 nsec
- Pile up
  - Resolve up to 4.5 ns separation



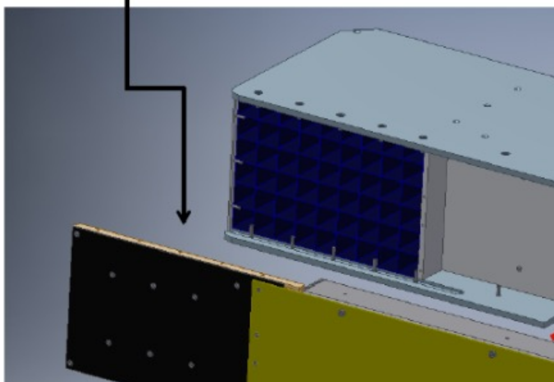



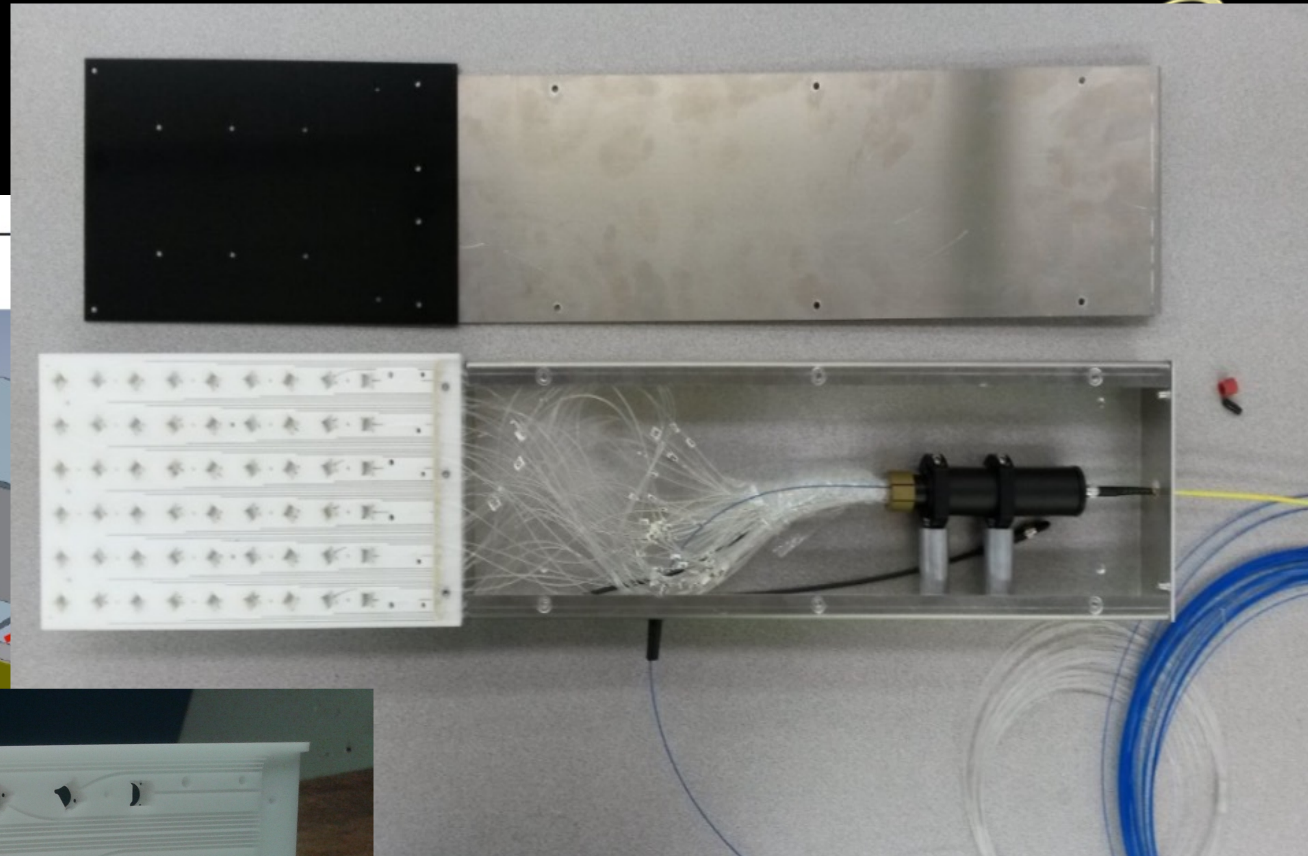
# Calibration system

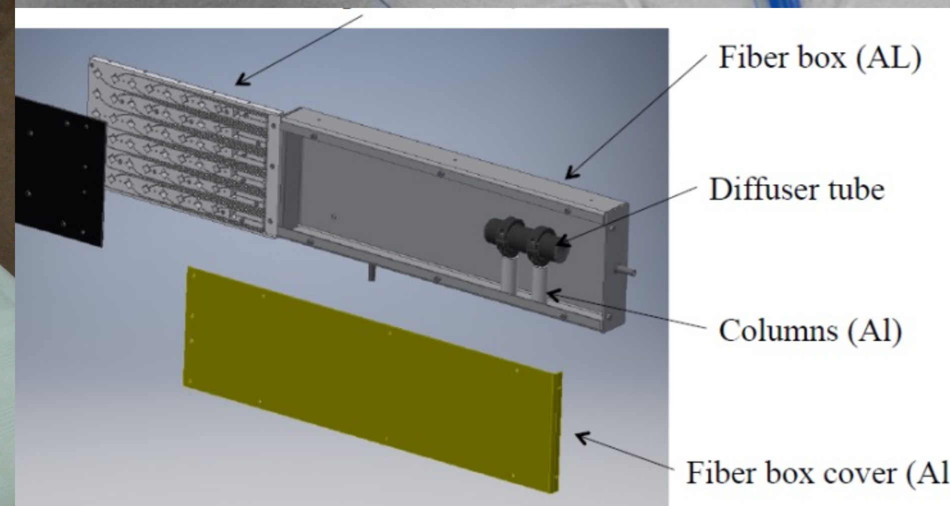
- Light from 6 blue lasers distributed to all calorimeter cells
- Source monitor: tracks laser intensity variations
- Local monitor: tracks distribution chain variations



- G-2 Calibration System –

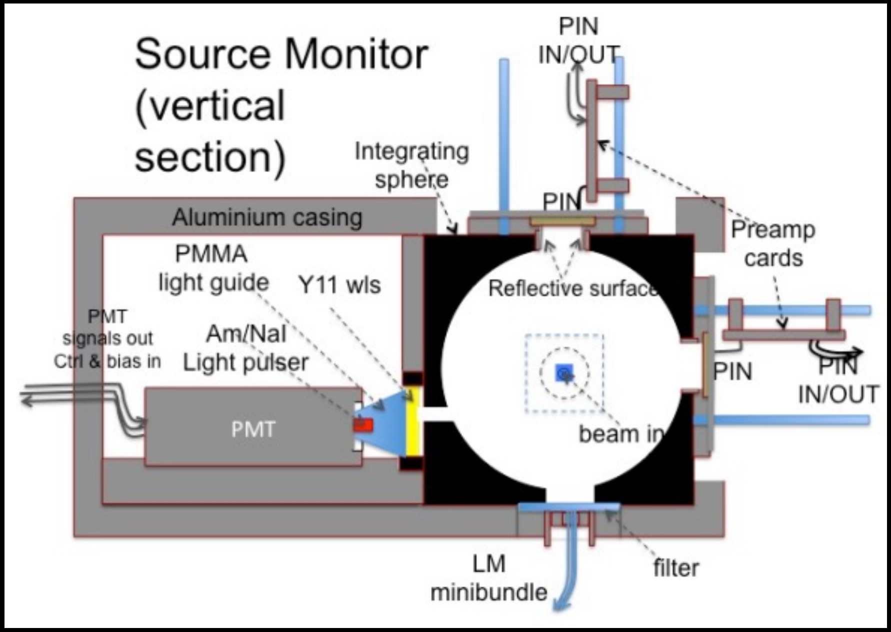


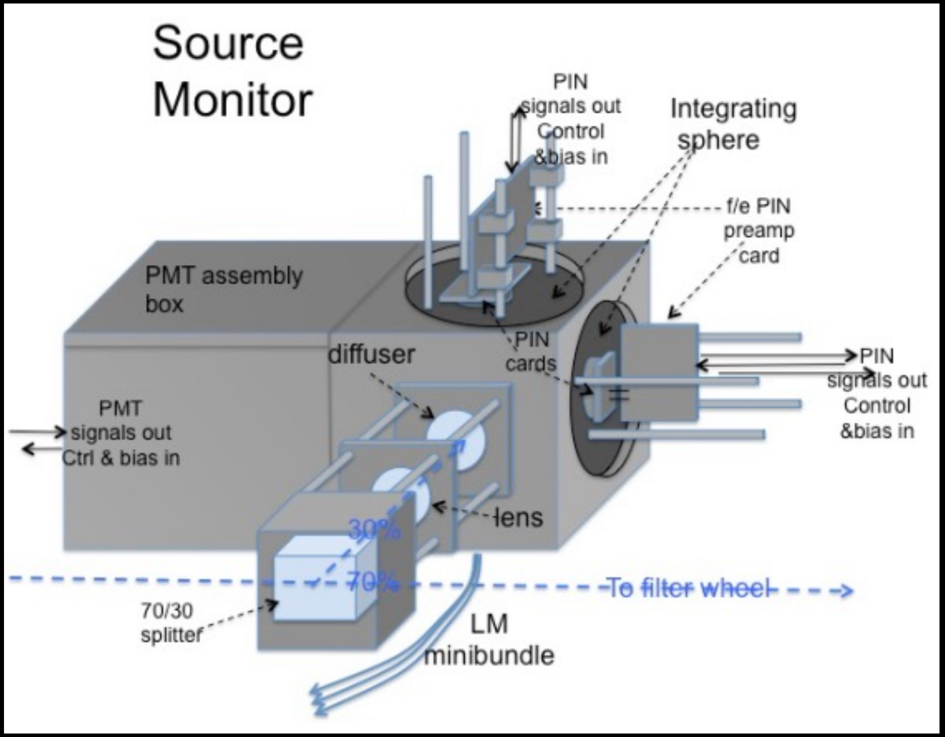




# Source monitor

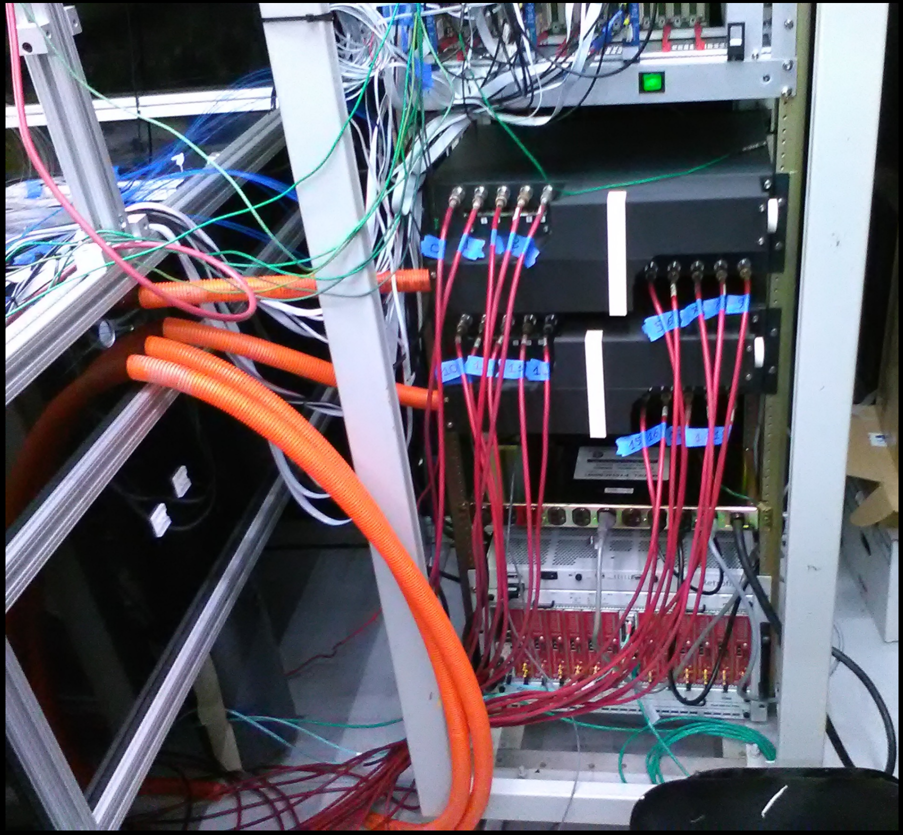
- Monitor laser fluctuations:
  - Fast reference → PIN diodes
  - Slow reference → NaI + Am source

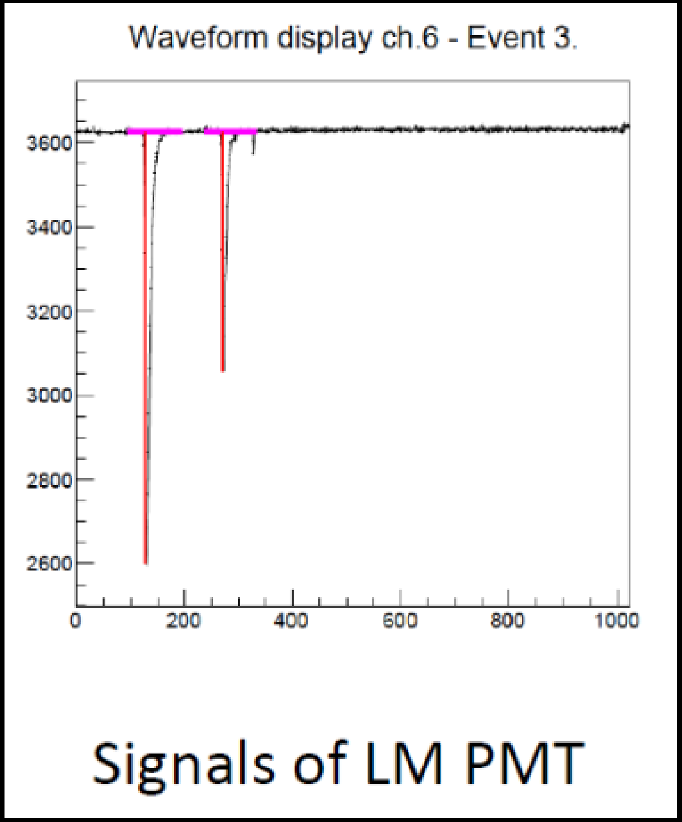


# Local monitor

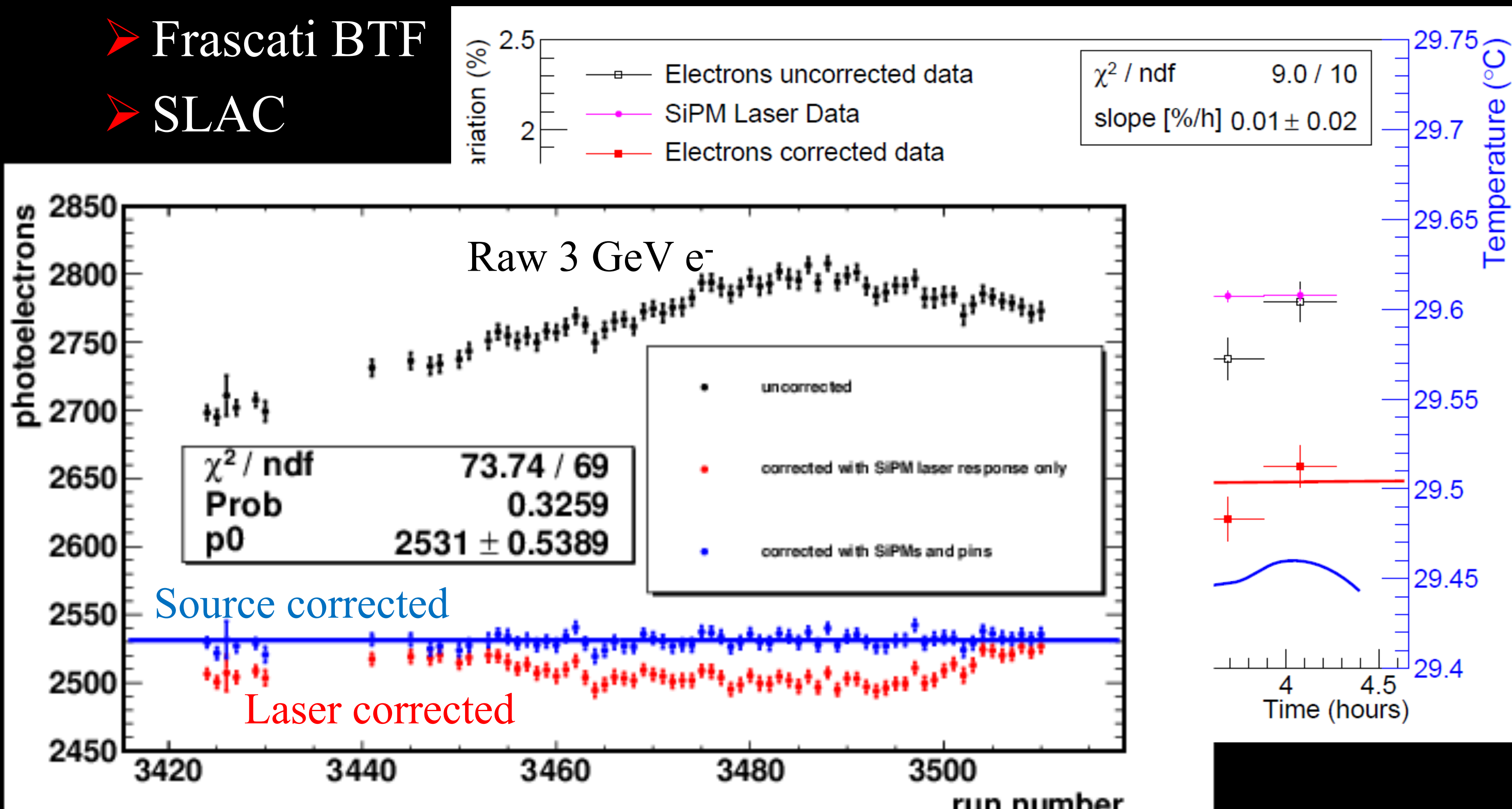
- Ratio of return light from calorimeter and direct pulse from source monitor (~250 nsec separation)





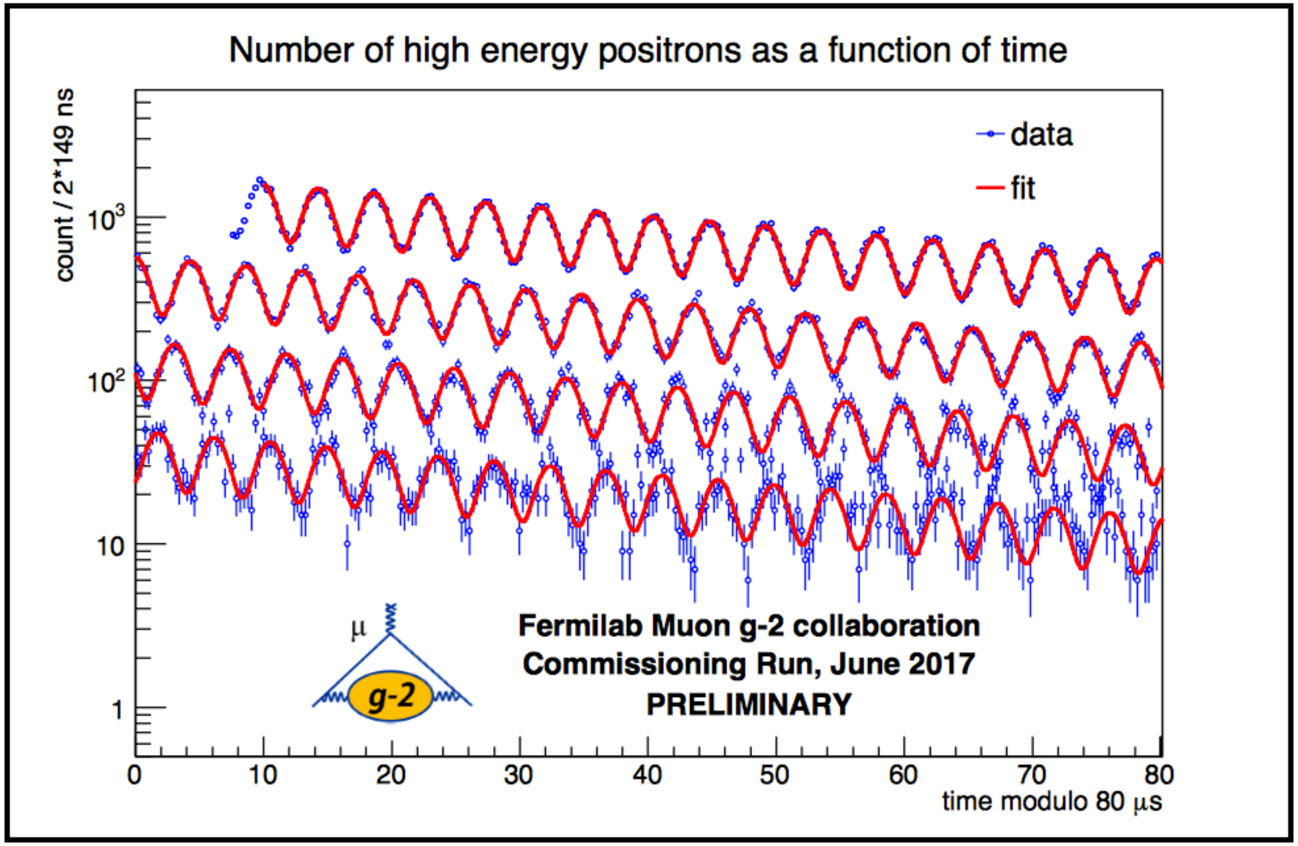
# Test beam results

- 1 laser system fully tested in 2016
  - Frascati BTF
  - SLAC



# Engineering run

- First results with short engineering run June 2017




Time spectrum from FY17

# Conclusions

- The muon anomaly has great history and interest.
  - Crucial test of higher order calc. and can signal new physics
  - Lots of new theory work started including major lattice projects
- Ring, detector  and beam for planned FNAL experiment are complete
  - Physics quality data taking is in progress now
- Superb laser calibration system from INFN!
  - Impossible without strong INO support → **THANKS!**
- First results are close .....
  - > 1 x BNL data by summer 2018

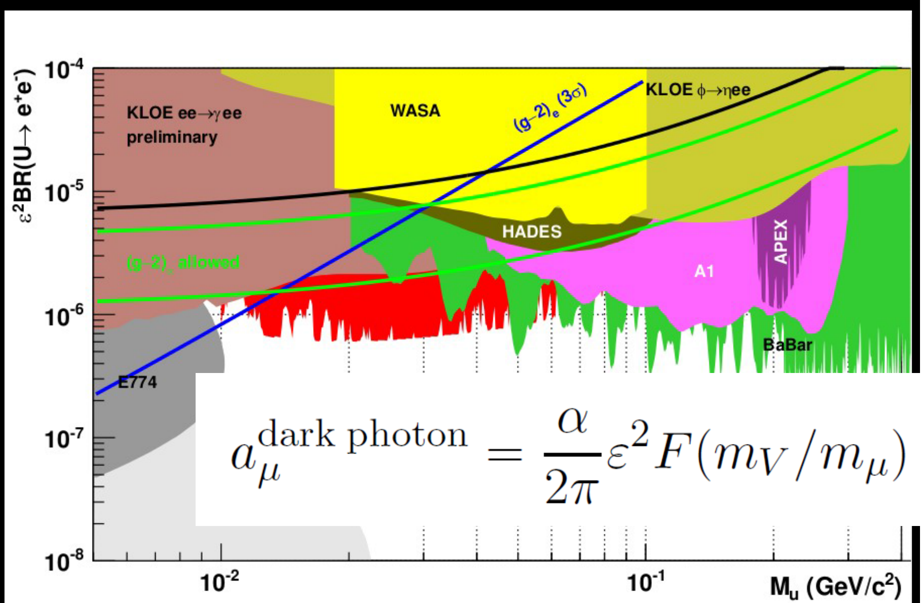

The end

# Backup slides

# MORE SLIDES

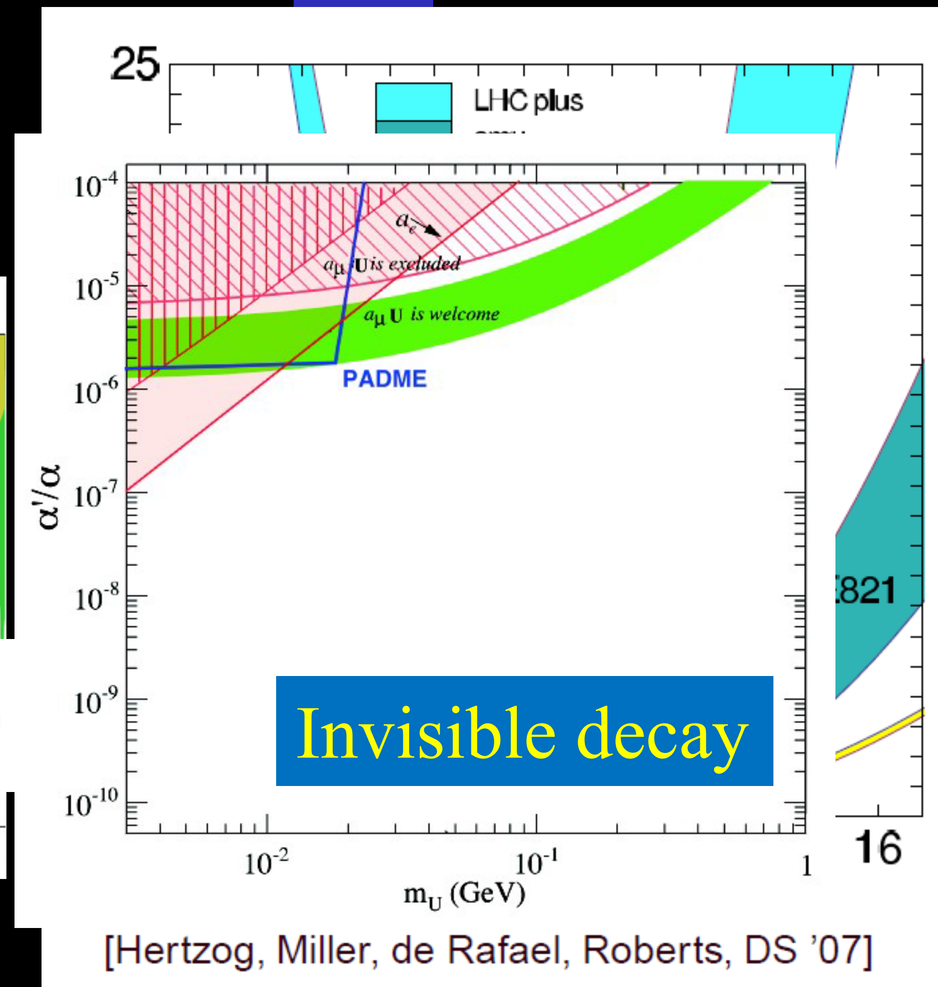
# Relation with other measurements

- Connected with other measurement of great interest
  - Bs→μμ, μ→eγ
  - SUSY/tan β
  - Dark photon

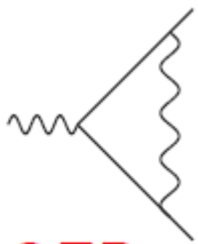



$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)$$

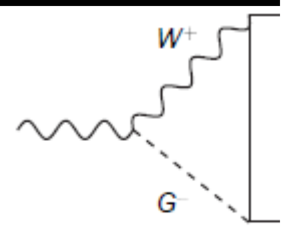
Visible decay



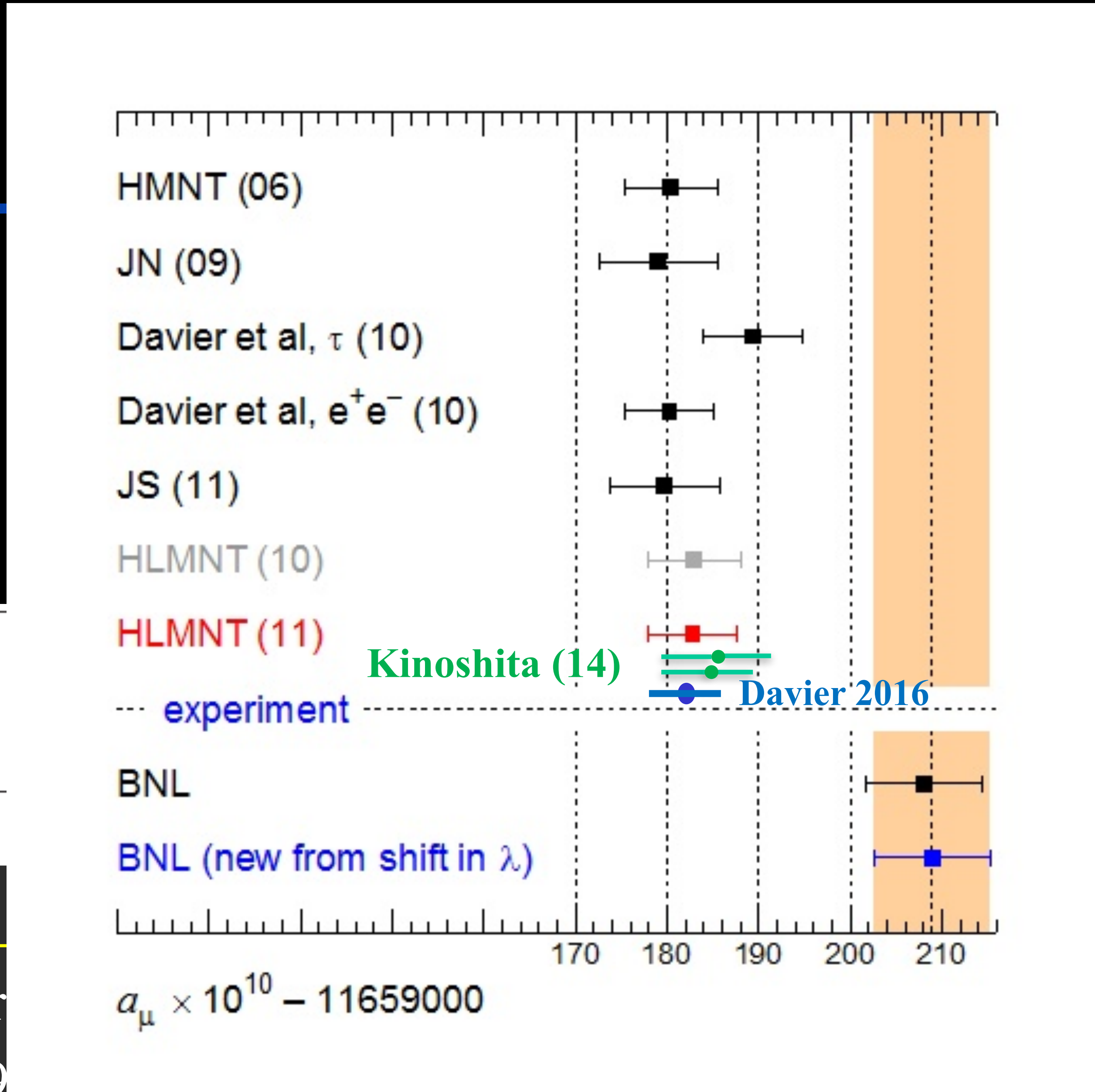

Invisible decay



QED:




Weak:




+ exp.

$\mathrm{x}10^{-10}$

$= 2.3\mathrm{x}10^{-10}$

$= 3.7\mathrm{x}10^{-10}$

$= 4.4\mathrm{x}10^{-10}$

$= 3.3\mathrm{x}10^{-10}$

$10^{-10}$ JN'09

## Results –

$= 4.0\mathrm{x}10^{-10}$

Had LbL fr

$10^{-10}$ PRV'09

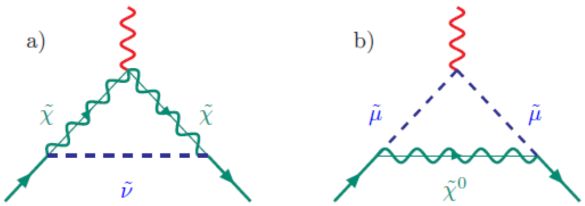
$= 2.6\mathrm{x}10^{-10}$

- ✓ JN'09
- ✓ PRV'09: (11'659'184.4 ± 5.1) $\mathrm{x}10^{-10}$ → 11'659'181.9 ± 4.2 (Davier16)

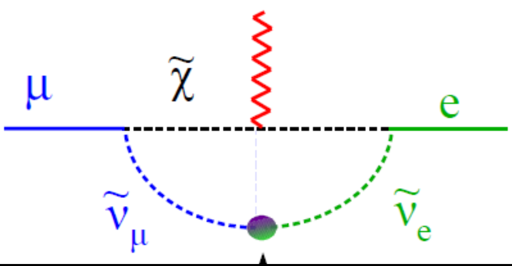
# Correlation with μ→eγ

→back

g-2

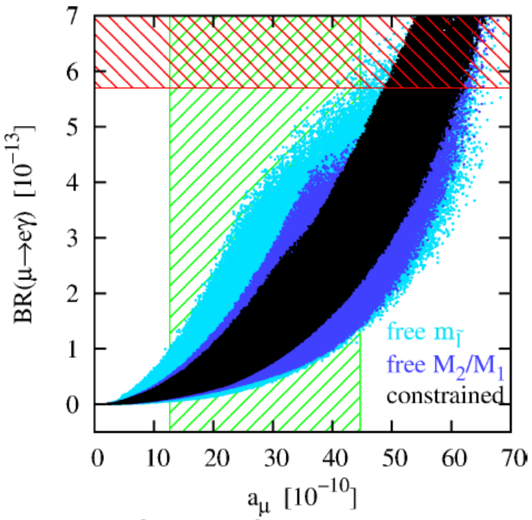



μ→eγ

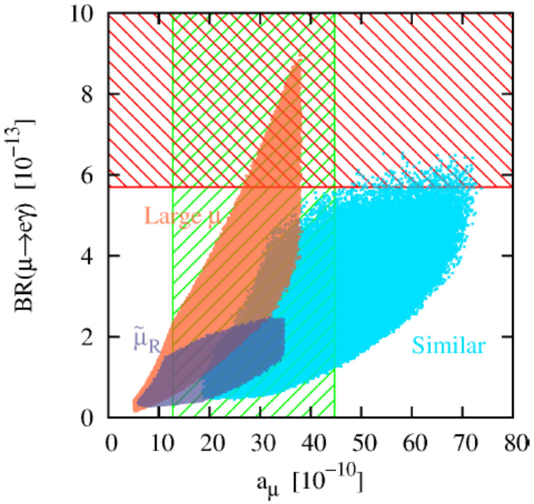



- study correlation for fixed $\delta_{LL} = 2 \times 10^{-5}$
- However: strong correlation of individual diagrams does not imply strong correlation of the sum! Strong correlations for strong parameter constraints or domination of certain diagrams

[Kersten,Park,DS,Velasco-Sevilla '14]




black: from [Isidori et al]; other regions have looser constraints




parameter regions where single diagrams dominate

# Back to history

- Measurements of g-2 started in 1957
- Continuous evolution of the technique until now

# Garwin/Lederman (1957)

- First experiments
  - Magnetic resonance

**$g = 2.00 \pm 0.10$**

LETTERS TO TH

[4] Their arguments are as follows: From the He[6] recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2) \lesssim \frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

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PHYSICAL REVIEW VOLUME 109, NUMBER 3 FEBRUARY 1, 1958

## Magnetic Moment of the Free Muon*†

T. Coffin, R. L. Garwin,‡ S. Penman, L. M. Lederman, and A. M. Sachs
*Columbia University,§ New York, New York*

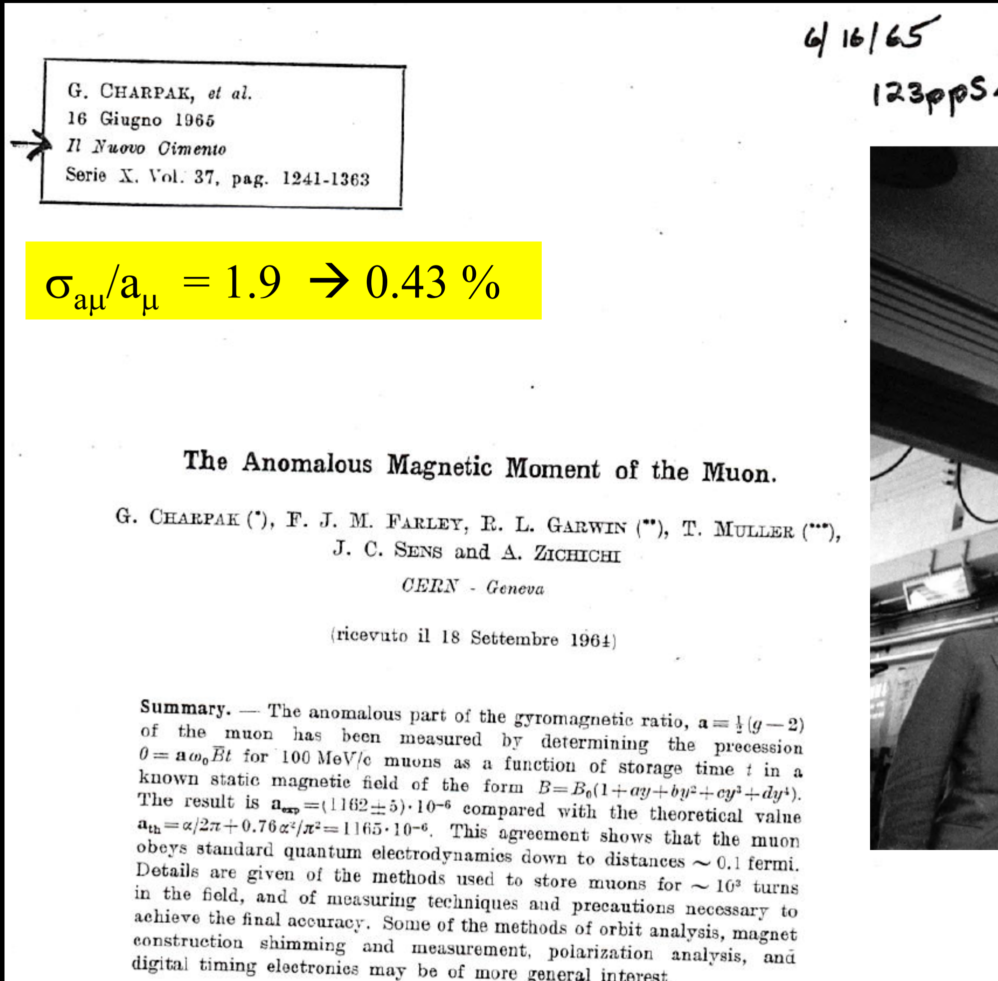
(Received October 1, 1957)

**$a_\mu = 0.00113 \pm 0.000014$**

The magnetic moment of the positive $\mu$ meson has been measured in several target materials by a magnetic resonance technique. Muons were brought to rest with their spins parallel to a magnetic field. A radiofrequency pulse was applied to effect a spin reorientation which was detected by counting the decay electrons emerging after the pulse in a fixed direction. Results are expressed in terms of a $g$ factor which for a spin $\frac{1}{2}$ particle is the ratio of the actual moment to $e\hbar/2m_\mu c$. The most accurate result obtained in a $CHBr_3$ target, is that $g=2(1.0026\pm0.0009)$ compared to the theoretical prediction of $g=2(1.0012)$. Less accurate measurements yielded $g=2.005\pm0.005$ in a copper target and $g=2.00\pm0.01$ in a lead target.

# CERN-I (1964)

## ❖ Precession in magnetic field



6/16/65

123pps.

G. CHARPAK, *et al.*
16 Giugno 1965
*Il Nuovo Cimento*
Serie X. Vol. 37, pag. 1241-1363

**The Anomalous Magnetic Moment of the Muon.**


G. CHARPAK (*), F. J. M. FARLEY, R. L. GARWIN (**), T. MULLER (***), J. C. SENS and A. ZICHICHI

*CERN - Geneva*



(ricevuto il 18 Settembre 1964)



**Summary.** — The anomalous part of the gyromagnetic ratio, $a = \frac{1}{2}(g-2)$ of the muon has been measured by determining the precession $\theta = a\omega_0 \bar{B} t$ for 100 MeV/c muons as a function of storage time $t$ in a known static magnetic field of the form $B = B_0(1 + ay + by^2 + cy^3 + dy^4)$. The result is $a_{exp} = (1162 \pm 5) \cdot 10^{-6}$ compared with the theoretical value $a_{th} = \alpha/2\pi + 0.76\alpha^2/\pi^2 = 1165 \cdot 10^{-6}$. This agreement shows that the muon obeys standard quantum electrodynamics down to distances $\sim 0.1$ fermi. Details are given of the methods used to store muons for $\sim 10^3$ turns in the field, and of measuring techniques and precautions necessary to achieve the final accuracy. Some of the methods of orbit analysis, magnet construction shimming and measurement, polarization analysis, and digital timing electronics may be of more general interest.


$\sigma_{a\mu}/a_\mu = 1.9 \rightarrow 0.43$ %

Farley, Sens, Charpak, Muller, Zichichi
**6-m g-2 magnet**

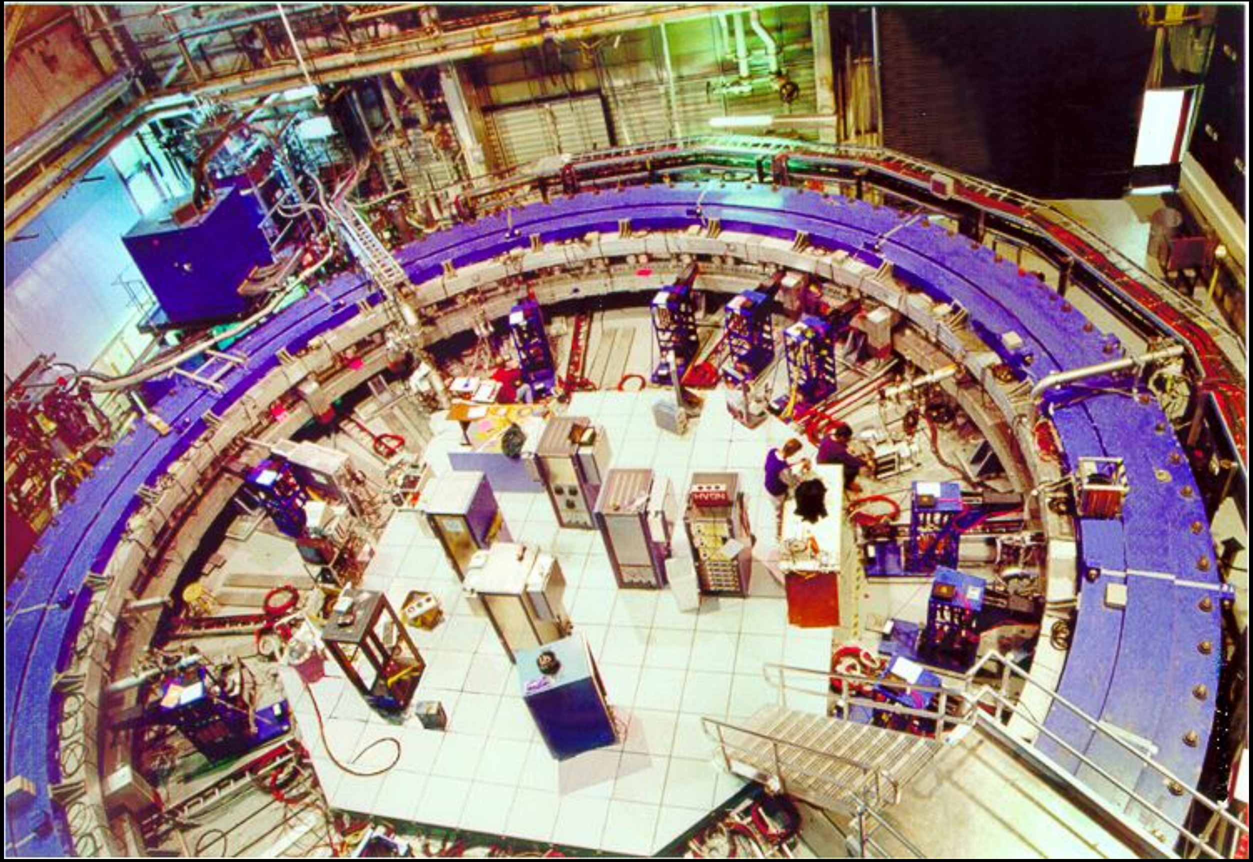
# CERN-II-III (1968-1979)

- CERN-II: muon storage ring → $\sigma_{a\mu}/a_{\mu}$ = **265 ppm**
- CERN-III: magic mom./electr. quads → $\sigma_{a\mu}/a_{\mu}$ = **7.3 ppm**

S van der Meer, F J M Farley, M Giesch, R Brown, J Bailey, **E Picasso** and H Jöstlein

# BNL-E821 (1997-2001)

- Extremely good storage ring magnet! → B uniformity
- AGS higher statistics then CERN → $\sigma_{a\mu}/a_\mu = 5 \rightarrow 0.5$ ppm

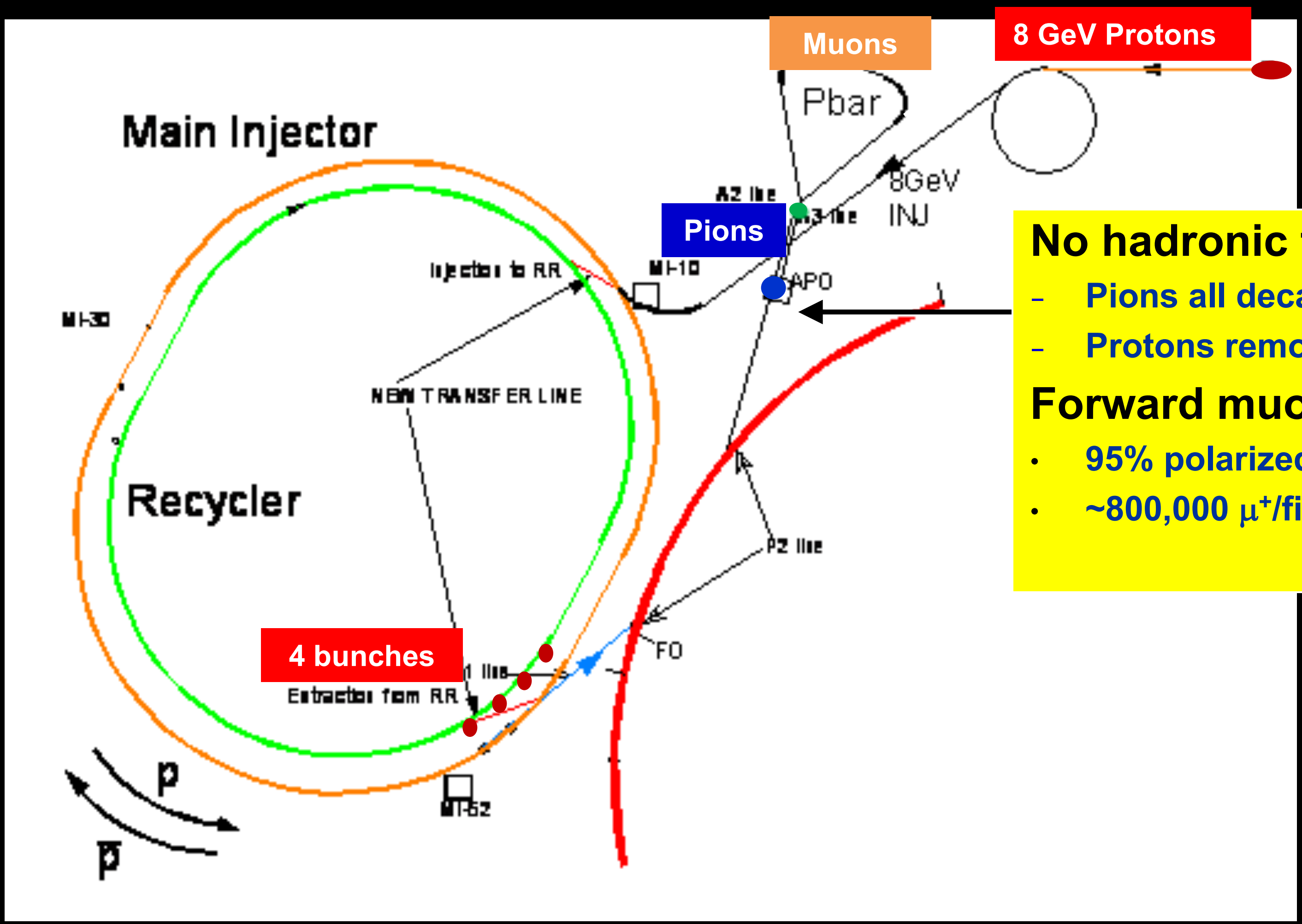


# Future FNAL experiment

- Ring magnet from BNL!
- 20x more muons
- Much cleaner beam
- Better calorimeter
- Tracking stations added
- Better B field measurements
- Miscellaneous improvements on systematics

- **Plan for error ~ 0.14 ppm**

# FNAL muon beam




**No hadronic flash**

- Pions all decay
- Protons removed by a DR kicker

**Forward muons collected**

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

# Misure di $\alpha_{EM}$

P.J. Mohr, B.N. Taylor, D.B. Newell, RMP 80, 633 (2008)
B.J. Mount, M. Redshaw, E.G. Myers, PRA 82, 042513 (2010)
R. Bouchendira, P. Clade, S. Guellati-Khelifa, F. Nez, F. Biraben, PRL 106, 080801 (2011)
P.J. Mohr, N.N. Taylor, D.B. Newell, RMP 84, 1527 (2012)

$$\alpha^{-1}(\textit{ac Josephson}) = 137.035\,987\,5\,(43) \quad [31\ ppb]$$

$$\alpha^{-1}(\textit{quantum Hall}) = 137.036\,003\,0\,(25) \quad [18\ ppb]$$

$$\alpha^{-1}(\textit{neutron wavelength}) = 137.036\,007\,7\,(28) \quad [21\ ppb]$$

$$\alpha^{-1}(\textit{atom interferometry}) = 137.036\,000\,0\,(11) \quad [7.7\ ppb]$$

$$\alpha^{-1}(\textit{Rb on optical lattice}) = 137.035\,999\,049\,(90) \quad [0.66\ ppb]$$

# Theory of g-2

Back

- $a_\mu$ may be expressed as

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{EW}) + a_\mu(\text{had}),$$

where

$$a_\mu(\text{QED}) = A_1 + A_2(m_\mu/m_e) + A_2(m_\mu/m_\tau) + A_3(m_\mu/m_e, m_\mu/m_\tau).$$

- Feynman-Dyson rules enables us to write $A_i$ as a power series

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_i^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + \ldots, \quad i = 1, 2, 3,$$

with finite expansion coefficients.

# $a_\mu$ (QED)

Back

- $a_\mu$(QED) including mass-dependent terms, is known up to $n = 10$.

$$a_\mu^{(2)}(QED) = 0.5$$
$$a_\mu^{(4)}(QED) = 0.765\,857\,425\,(17)$$
$$a_\mu^{(6)}(QED) = 24.050\,509\,96\,(32)$$
$$a_\mu^{(8)}(QED) = 130.877\,4\,(61) \qquad (A_1^{(8)} \text{ is updated})$$
$$a_\mu^{(10)}(QED) = 751.77\,(93) \qquad (A_1^{(10)} \text{ is updated})$$

- $\tau$-loop contribution to $a_\mu^{(8)}$(QED) is calculated by

A. Kurz, T. Liu, P. Marquard, M. Steinhauser, arXiv:1407.0267 (2014)

- Leading contribution to $a_\mu^{(12)}$(QED) will come from diagrams which contain one light-by-light subdiagram and three vacuum-polriztion loops. A crude estimate gives

$$a_\mu^{(12)}(QED)(\alpha/\pi)^6 \sim 0.08 \times 10^{-11}.$$

# $a_\mu$ (had) & $a_\mu$ (EW)

Back

- At present it is derived mostly from experimental data related to hadronic vacuum polarization. Recent evaluations are

$$a_\mu(\text{had.vp}) = 6949.1\ (37.2)_{exp}(21.0)_{rad}\ \times 10^{-11}$$
$$a_\mu(\text{had.vp.NLO}) = -98.4\ (0.6)_{exp}(0.4)_{rad}\ \times 10^{-11}$$
$$a_\mu(\text{had.vp.NNLO}) = 12.4\ (10)\ \times 10^{-11}$$
$$a_\mu(\text{had.lbyl}) = 116\ (40) \times 10^{-11}$$
$$a_\mu(\text{had.lbyl.NLO}) = 3\ (2) \times 10^{-11}$$

K. Hagiwara, R. Liao, A. D. Martin, D. Nomura, T. Teubner, J. Phys. G 38, 085003 (2011) [arXiv:1105.3149]
A. Kurz, T. Liu, P. Marquard, M. Steinhauser,PLB 734, 144 (2014)
J. Prades et al., in *Lepton Dipole Moments*, eds. B. L. Roberts and W. J. Marciano (World Scientific, Singapore,2009), p.303.
G. Colangelo, M. Hoferichter, A. Nyffeler, M. Passera, P. Stoffer, PLB 735, 90 ( 2014)

- Electroweak contribution has been calculated up to 2-loop order:

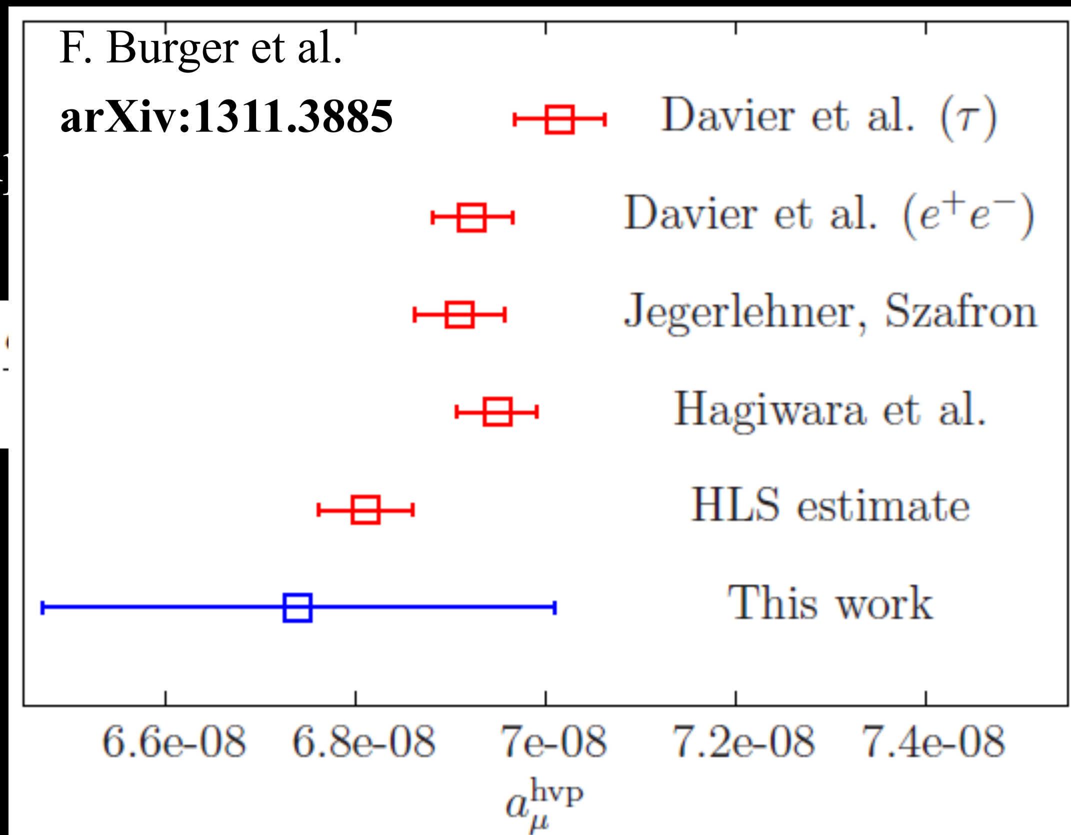
$$a_\mu(\text{EW}) = 154\ (2)\ \times 10^{-11}.$$

K. Fujikawa, B.W. Lee, A.I. Sanda, PRD 6, 2923 (1972).
A. Czarnecki, B. Krause, W.J. Marciano, PRL 76, 3267 (1996).
M. Knecht, S. Peris, A. Perrottet, E. de Rafael, J. High Energy Phys. 11 (2002) 003.
A. Czarnecki, W.J. Marciano, A. Vainshtein, PRD 67, 073006 (2003).

# Potential theory improvements VP

- Had. VP:
  - x2 on ex ... ns from KLOE2, ...

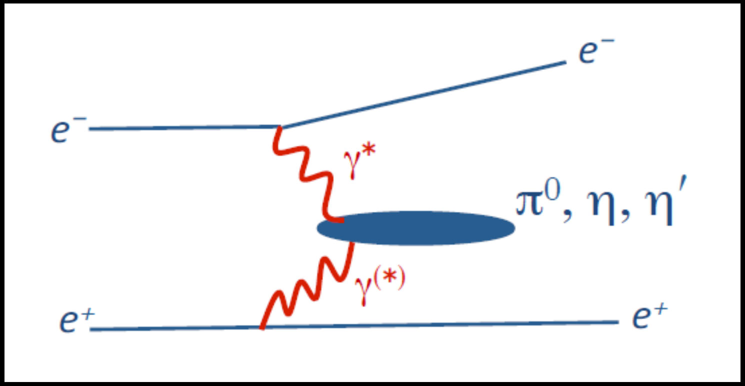
$a_\mu^{\mathrm{had;LO}} = ( \ldots \quad \ldots \mathrm{hadrons}) / \ldots \mu^+\mu^-)$

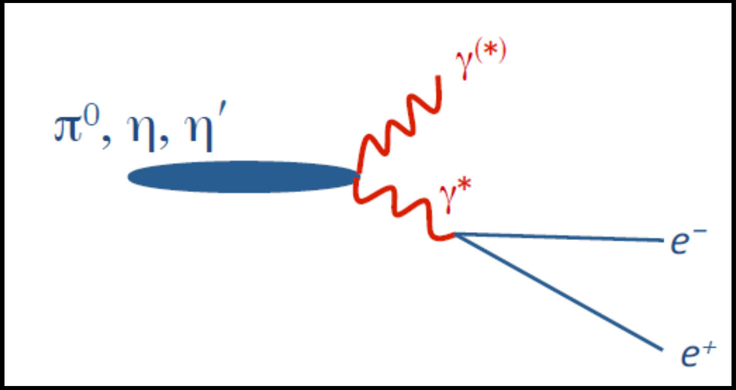



  - Improved radiative corrections in MC
  - 4 flavor lattice calculations presently 5 times worse, but are improving. arXiv:1311.3885v1 15 Nov ’13

# Potential theory improvements HLbL

- Had. LbL:
  - Use dispersion relations to connect Had LbL contributions to experimental results.
    - G. Colangelo et al., 'Towards a data-driven analysis of hadronic light-by-light scattering', Phys. Lett. B738, (2014) 6 (10 Nov. 2014)
    - G. Colangelo et al., 'Dispersion relation for hadronic light-by-light scattering and the muon g-2', PoS CD15 (2016) 008



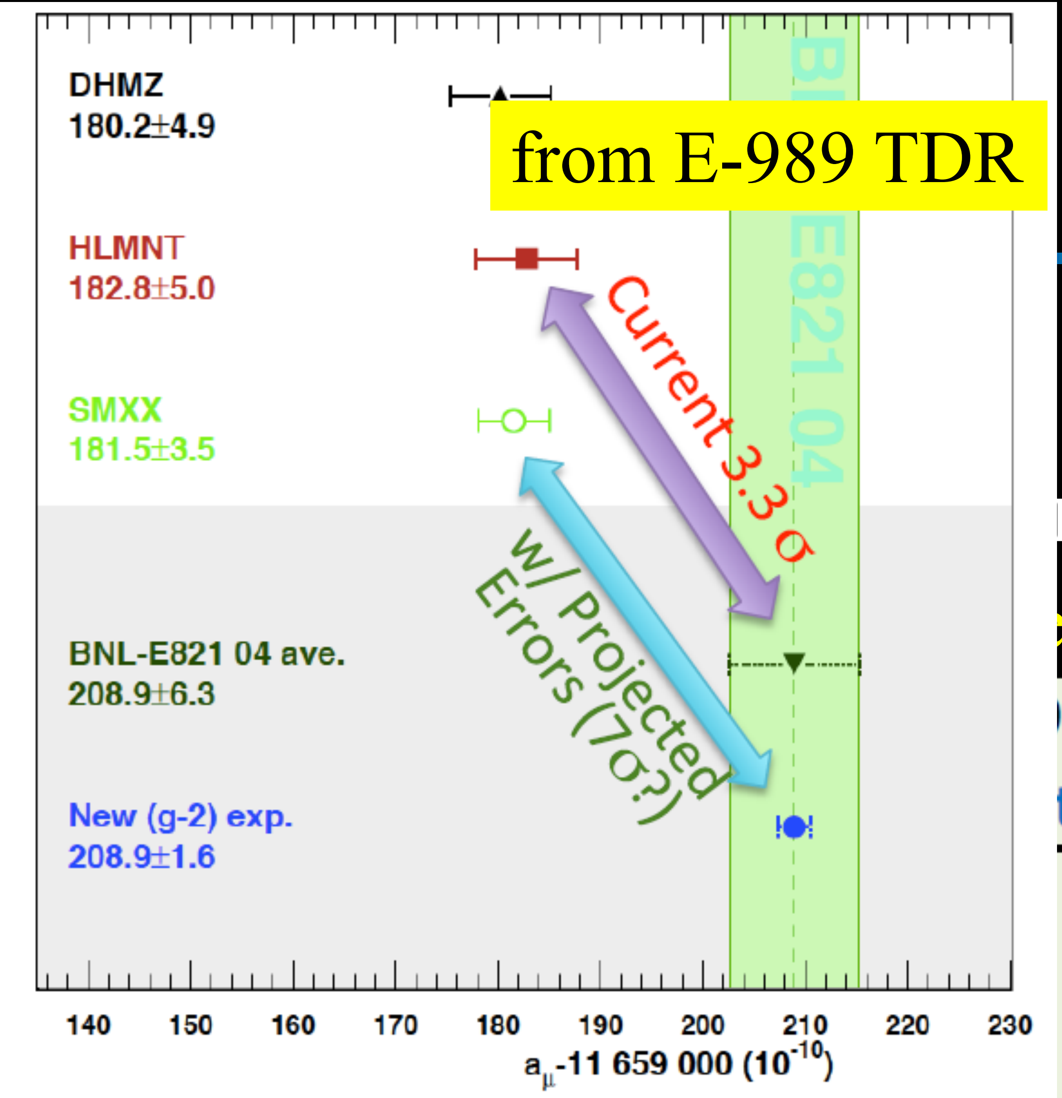

  - Need $\gamma\gamma$ production or decay to $2\gamma$ → x2 theory error reduction expected
  - Lattice calculations also started (Tom Blum 2014: arXiv:1407.2923)

❖ Two assum

➢ 11.6 ± 4.0

➢ 10.5 ± 2.6 RV'09]

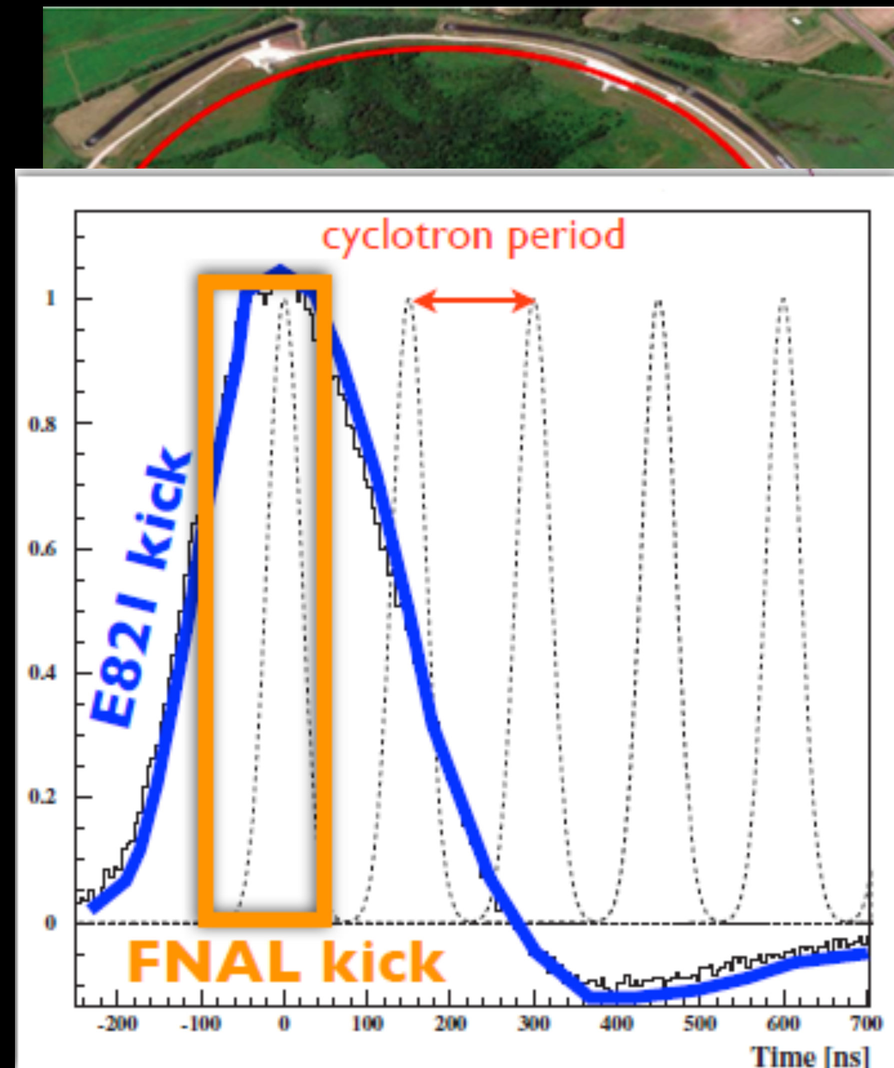
❖ FNAL E-98 $e^+e^- \rightarrow \mu^+\mu^-$)




| $\Delta=(a_{exp}-a_{th}$ | | | | | | th. syst. |
|---|---|---|---|---|---|---|
| Δ = Exp - JI | | | | | | 23.4 |
| σ = Total e | | | | | | 3.4 |
| Δ/σ | | | | | | 6.9 |
| Δ = Exp - PRV'09 | 27.0 | 24.5 | 27.0 | 24.5 | 27.0 | 24.5 |
| σ = Total error | 7.6 | 8.1 | 4.3-4.5 | 4.3 | 3.0 | 3.0 |
| Δ/σ | 3.6 | 3.0 | 6.3-6.0 | 5.7 | 9.0 | 8.1 |

# FNAL beam wrt. BNL

- Beam improved recycling p-bar source:
  - x20 total # muons
    - x6-12 #muons/proton on target
    - x4 fill frequency
  - Statistical error on $a_\mu$:
    - $5.4 \times 10^{-10} \rightarrow 1.2 \times 10^{-10}$
  - Removed pion flash
    - $L_{decay}$ 90 m → 2000 m
- Fast muon kicker
  - Turns off before one turn



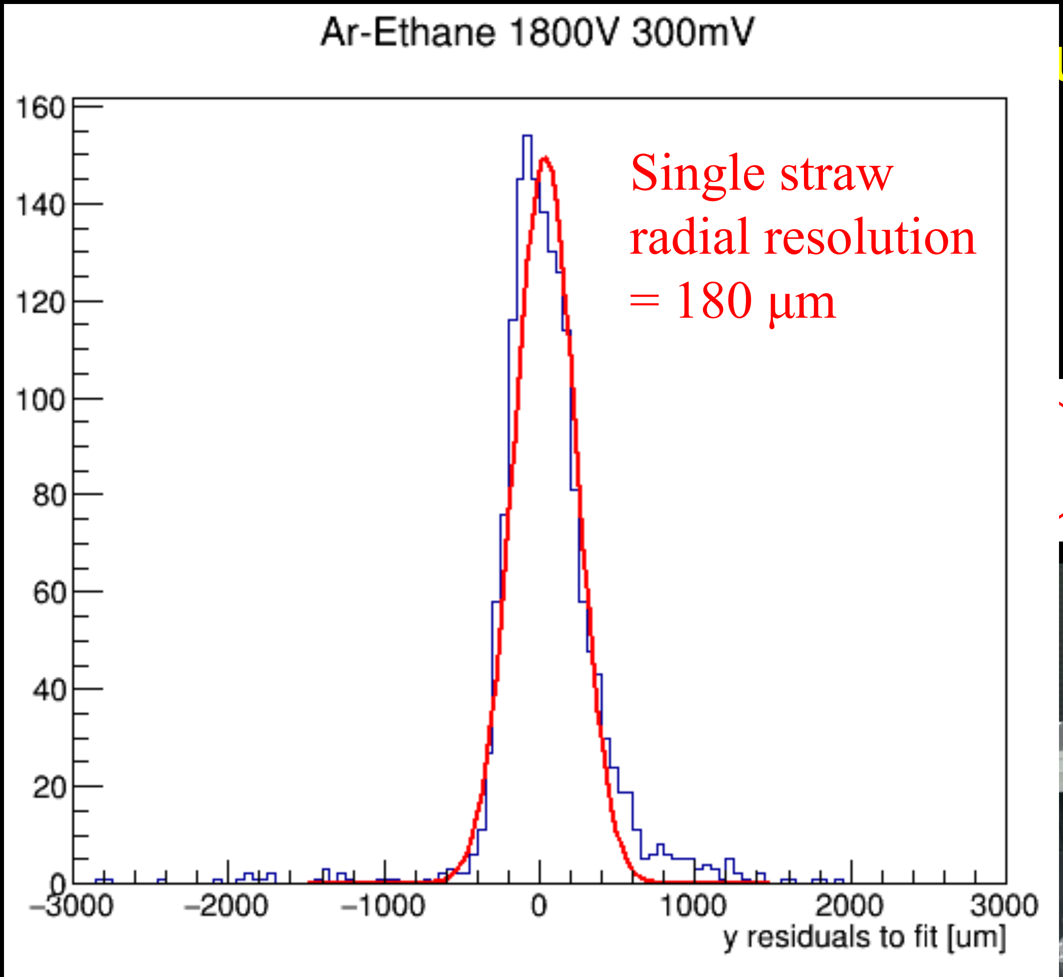
# B field systematics

- Mostly more and better probes/temperature stability

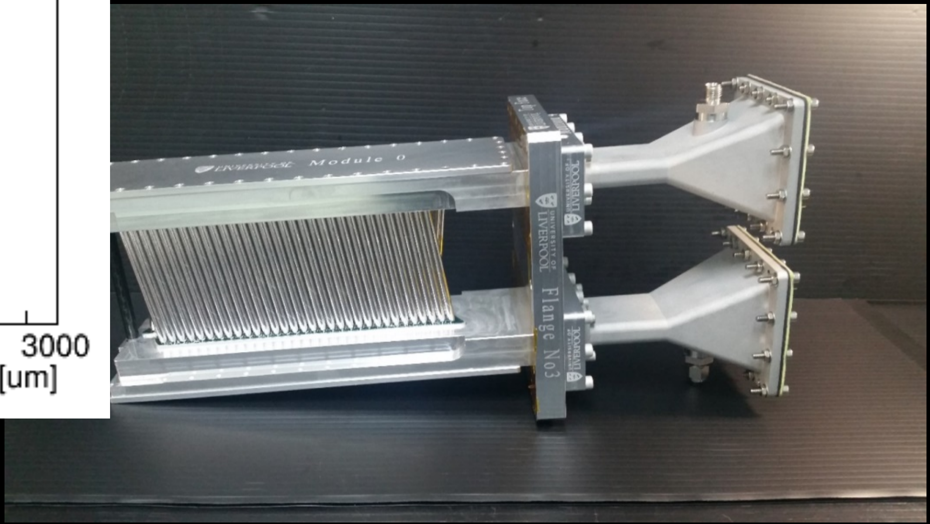
| E821 Error **BNL** | Size [ppm] | Plan for the E989 $g-2$ Experiment **FNAL** | Goal [ppm] |
|---|---|---|---|
| Absolute field calibrations | 0.05 | Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics | 0.035 |
| Trolley probe calibrations | 0.09 | Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations | 0.03 |
| Trolley measurements of $B_0$ | 0.05 | Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients | 0.03 |
| Fixed probe interpolation | 0.07 | More frequent trolley runs; more fixed probes; better temperature stability of the magnet | 0.03 |
| Muon distribution | 0.03 | Additional probes at larger radii; improved field uniformity; improved muon tracking | 0.01 |
| Time-dependent external B fields | – | Direct measurement of external fields; simulations of impact; active feedback | 0.005 |
| Others | 0.10 | Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients | 0.05 |
| Total | 0.17 | | 0.07 |

# Tracking system

ubes in stereo arrangement




$$\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\Bigg]$$



# Status and plan