The Muon g-2 Experiment at FNAL

Franco Bedeschi, INFN – Pisa

MUSE Workshop

Pisa, September 2016

Outline

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


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 54 NUMBER 9 NOVEMBER 2014
Fermilab
BROOKHAVEN
NATIONAL LABORATORY

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)

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

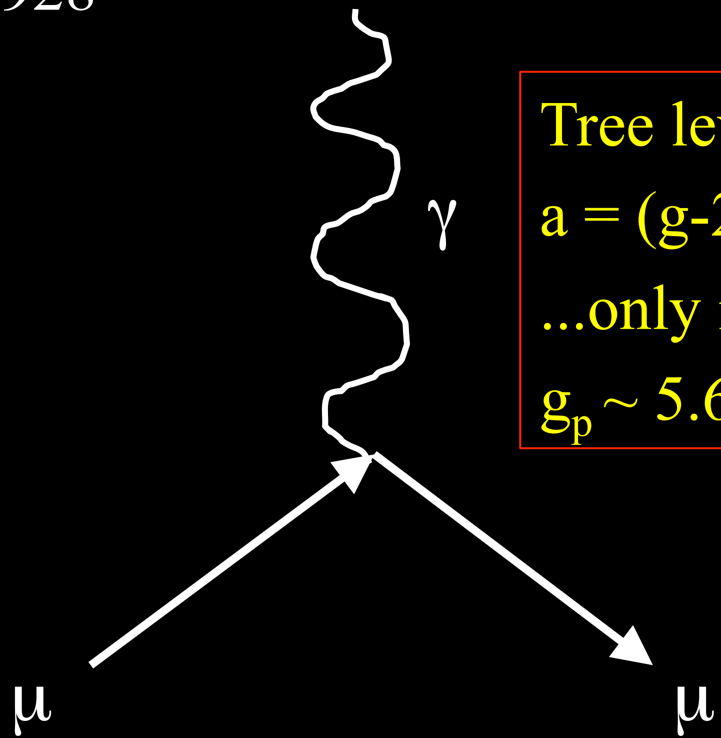
G. W. Bennett et al., PRL 92, 161802 (2004).
L. Roberts, Chinese Phys. C 34, 741 (2010).

  - Error statistics limited
  - Difference wrt. SM ~ 3σ (theory error ~ 5×10^{-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

Basic definitions

- Magnetic moment related to lepton spin, mass and charge
- Tree level QED : g = 2 for all leptons
  - Explained by Dirac in 1928

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

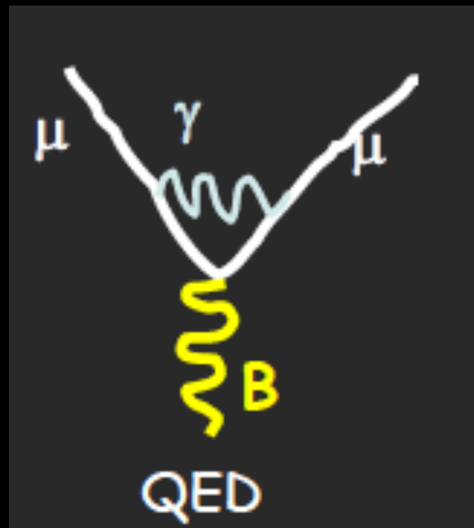


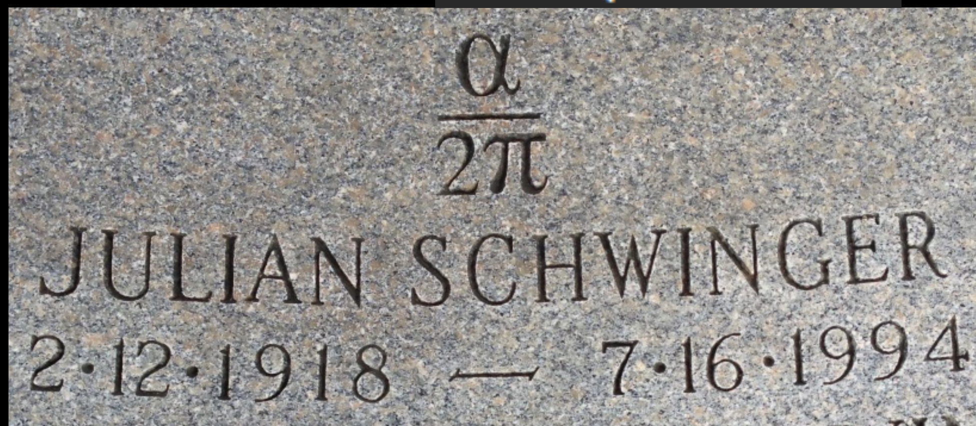
Tree level anomaly:
a = (g-2)/2 = 0
...only if pointlike
$g_p \sim 5.6$, $g_n \sim -3.8$

Higher orders (1)

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

$$a_\mu = \alpha/2\pi$$





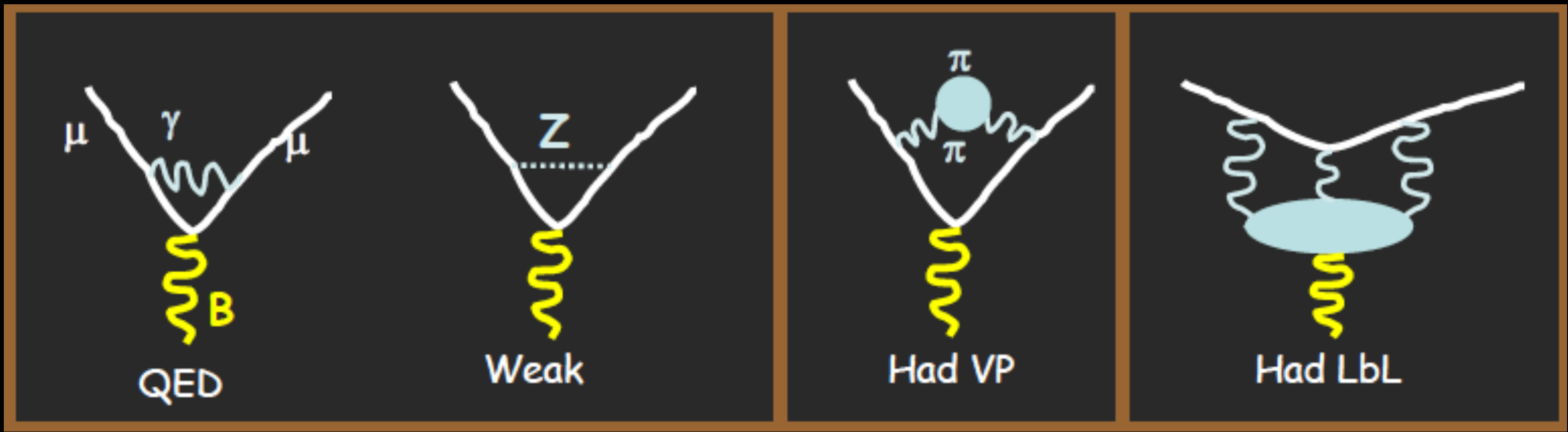
Higher orders (2)

- Higher order corrections depend on lepton mass

- 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

Other corrections

- a_μ is affected by loops with W/Z or quarks (hadrons)



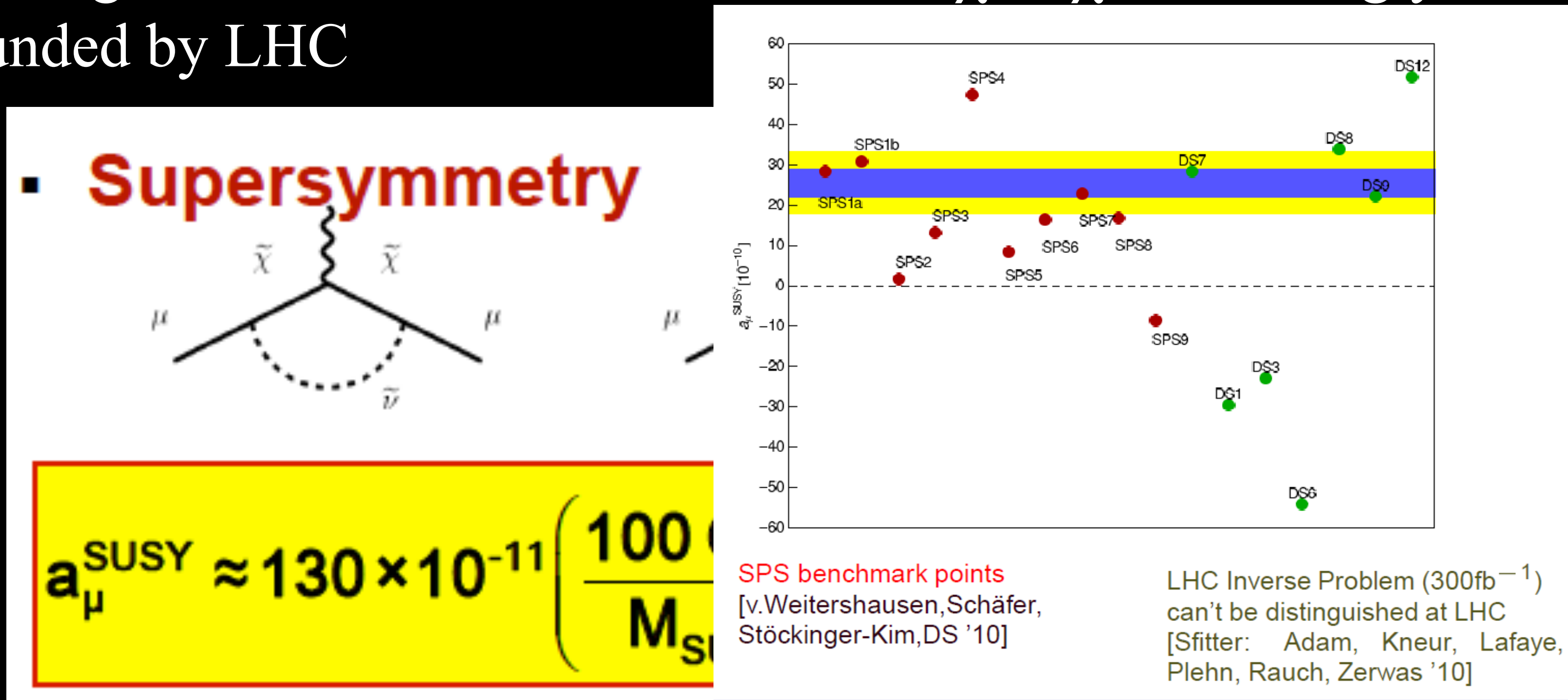
- Weak contribution small and precisely calculated
- Had VP and Had LBL are hard .... however
  - Improvements and new approaches expected

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

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

New physics sensitivity

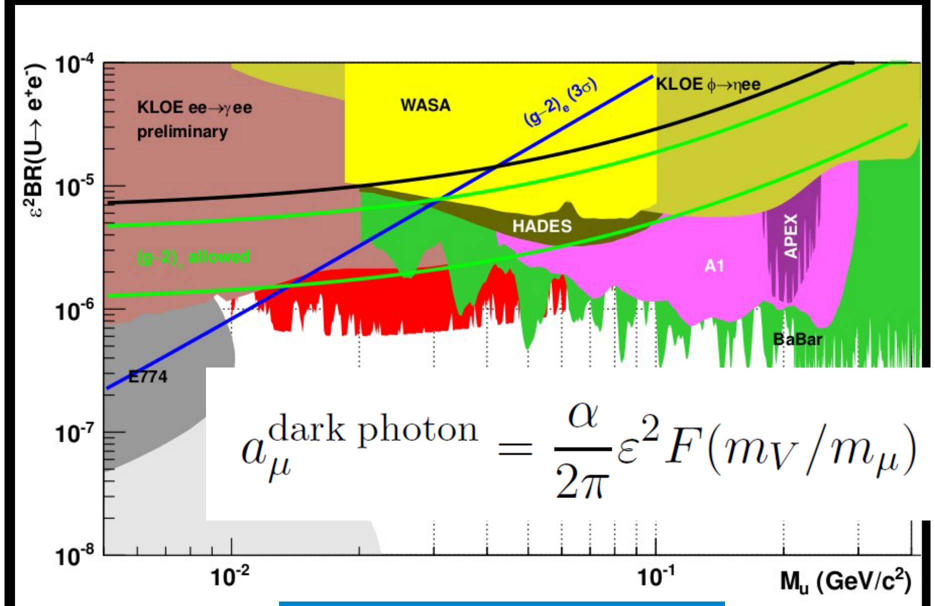
- New physics effects similar to weak contributions
  - SUSY gives relevant contributions from $\chi^{\pm}$ e χ^{0} not strongly bounded by LHC



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

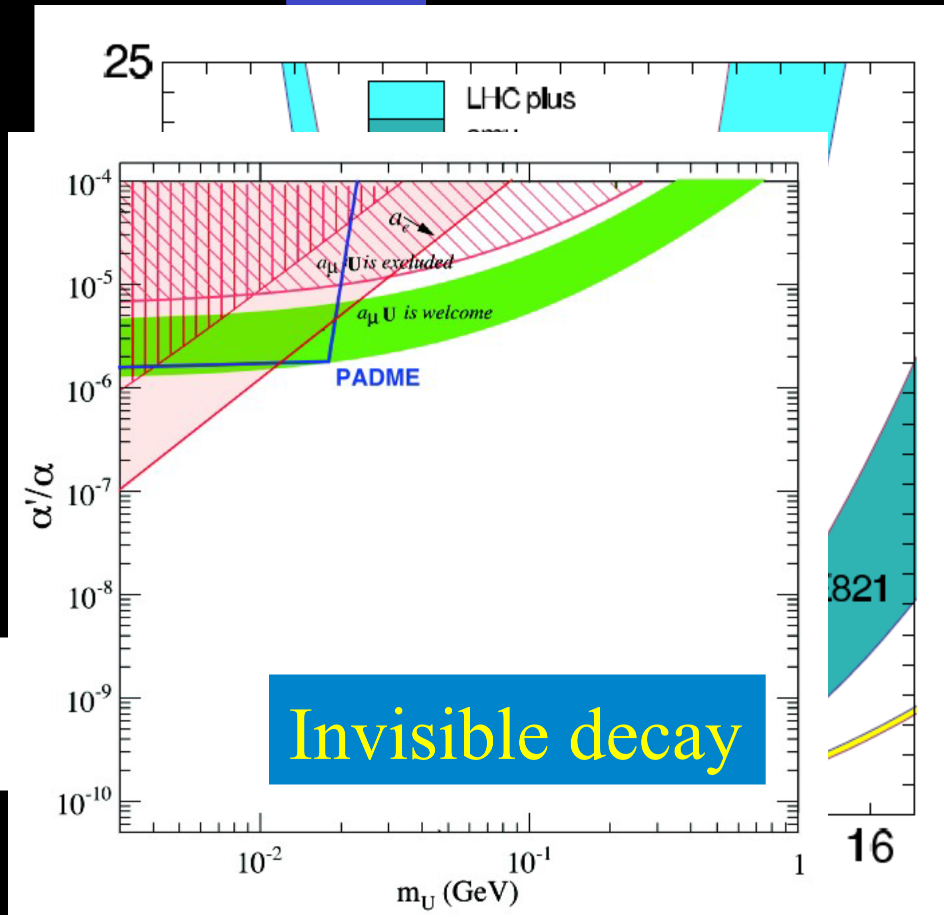
Relation with other measurements

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

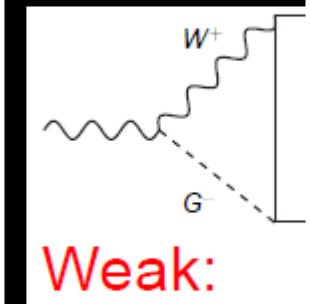


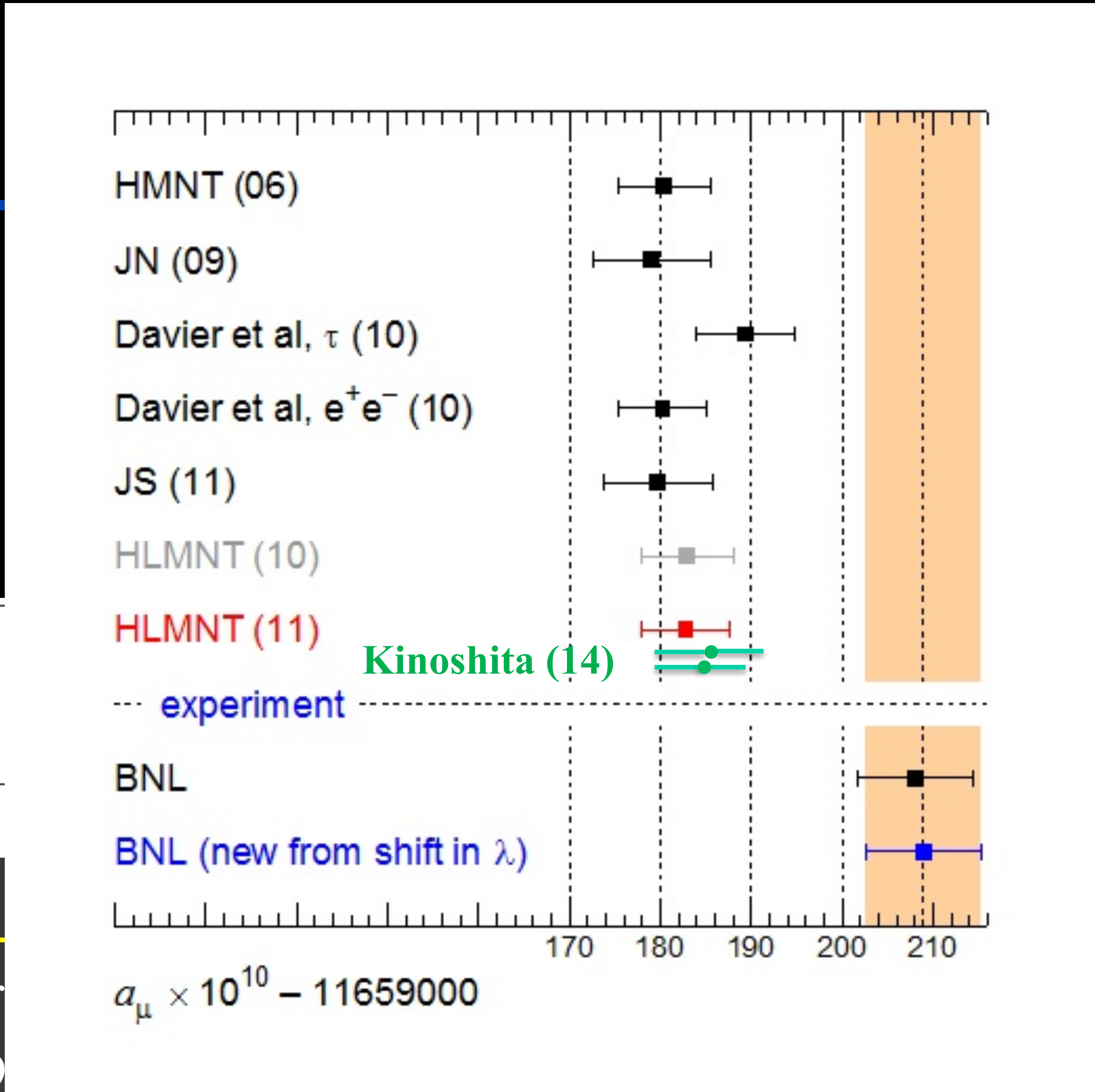
$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)$$

Visible decay



[Hertzog, Miller, de Rafael, Roberts, DS '07]





+ exp.

x10^{-10}

= 2.3×10^{-10}

= 3.7×10^{-10}

= 4.4×10^{-10}

= 3.3×10^{-10}

10^{-10} JN'09

Results –

= 4.0×10^{-10}

Had LbL fr

10^{-10} PRV'09

✓ JN'09

= 2.6×10^{-10}

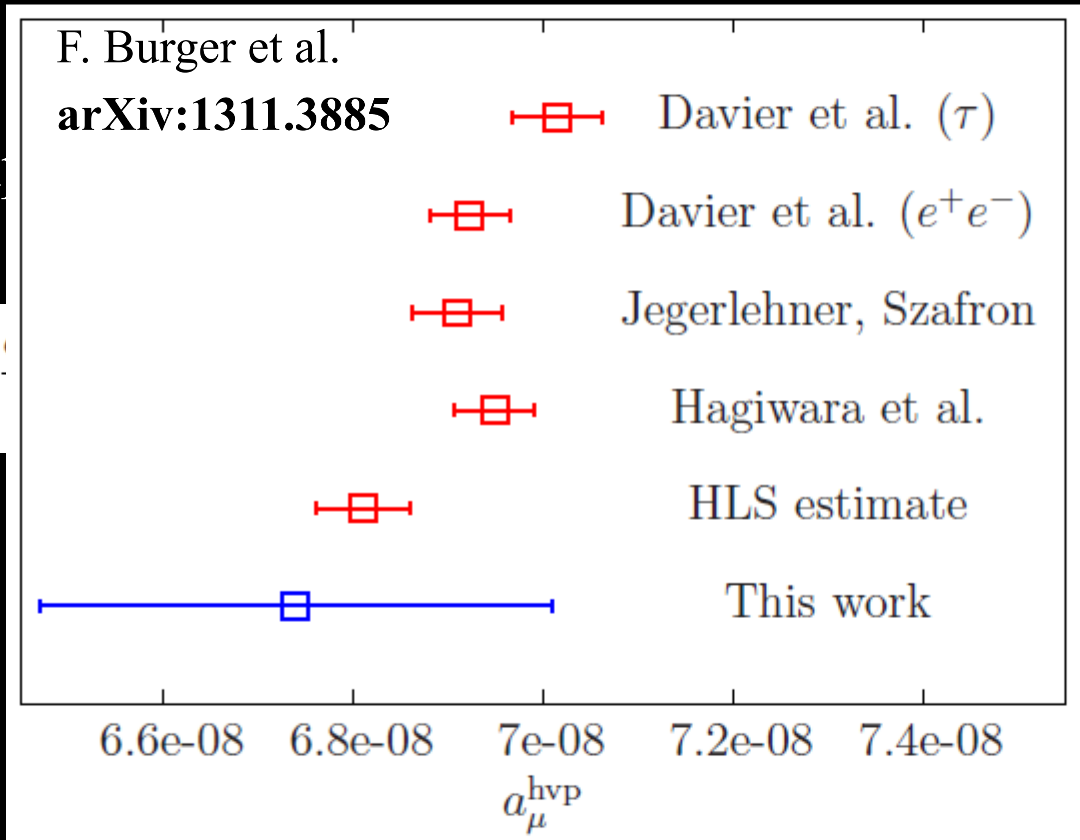
✓ PRV'09: (11'659'184.4 ± 5.1) x10^{-10} → 11'659'181.9 ± 4.2 (Davier16)

Potential theory improvements VP

❖ Had. VP:

- x2 on ex... ns from KLOE2, ... hi, this wrksp)

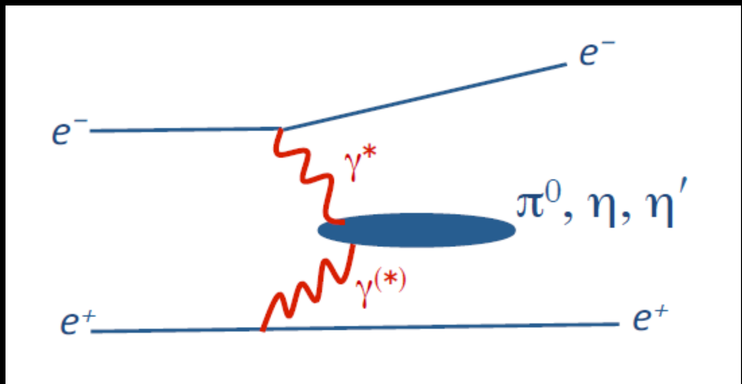
$a_\mu^{\text{had;LO}} = ($ ... $\text{hadrons})$ / $\mu^+\mu^-)$

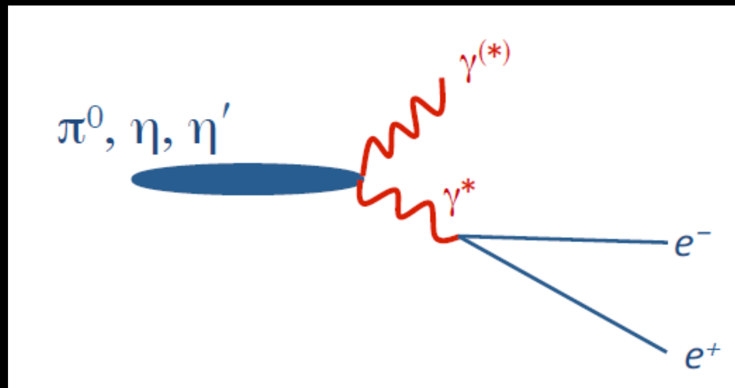


- Improved radiative corrections in MC
- 4 flavor lattice calculations presently 5 times worse, but are improving. arXiv:1311.3885v1 15 Nov ’13

Potential theory improvements HLbL

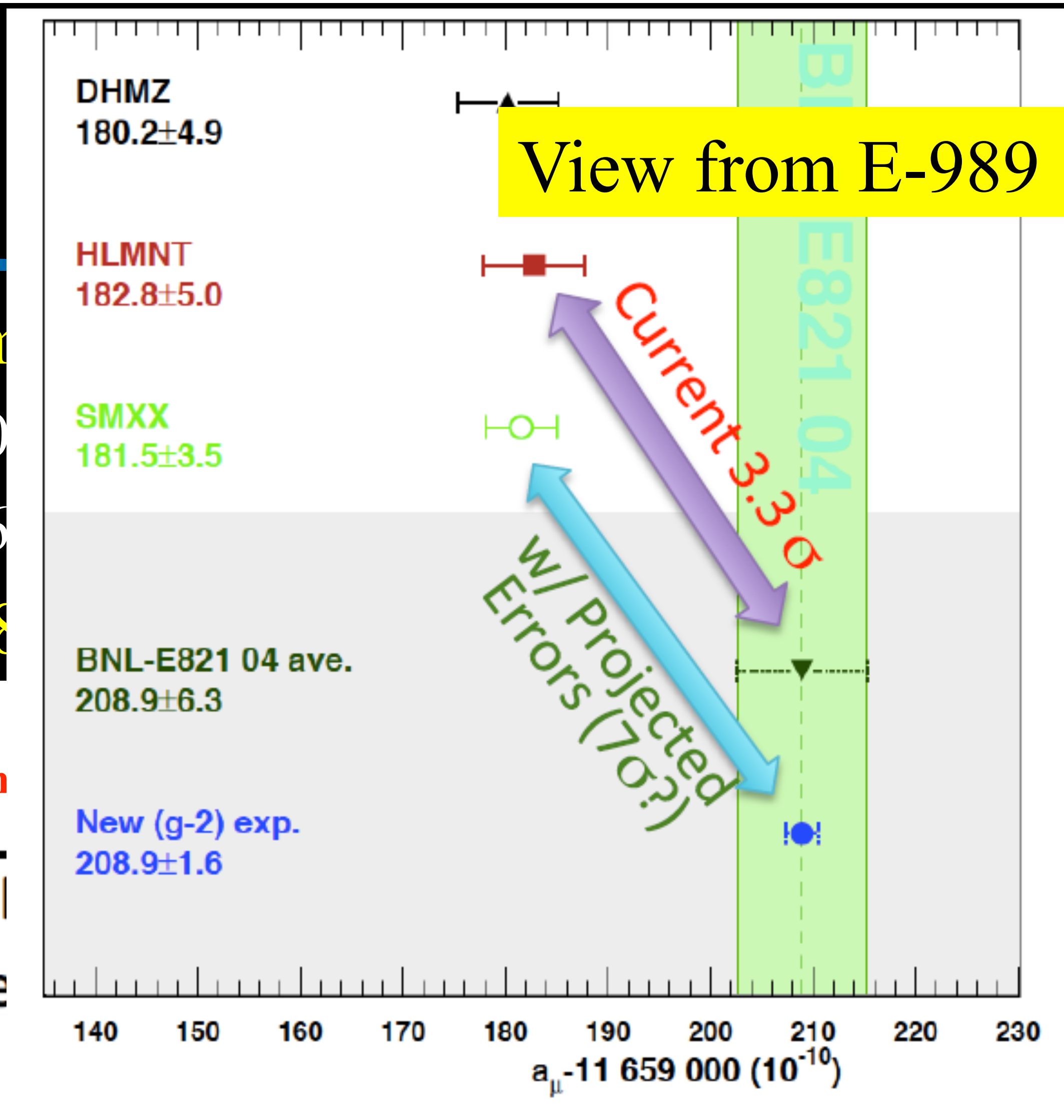
- Had. LbL:
  - Use dispersion relations to connect Had LbL contributions to experimental results.
    - G. Colangelo et al., ‘Towards a data-driven analysis of hadronic light-by-light scattering’, Phys. Lett. B738, (2014) 6 (10 Nov. 2014)
    - G. Colangelo et al., ‘Dispersion relation for hadronic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





  - Need $\gamma\gamma$ production or decay to 2γ → 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… …$e^- \lozenge \mu^+\mu^-$)



$\Delta=(a_{exp}-a_{th}$…						… 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

Back to history

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

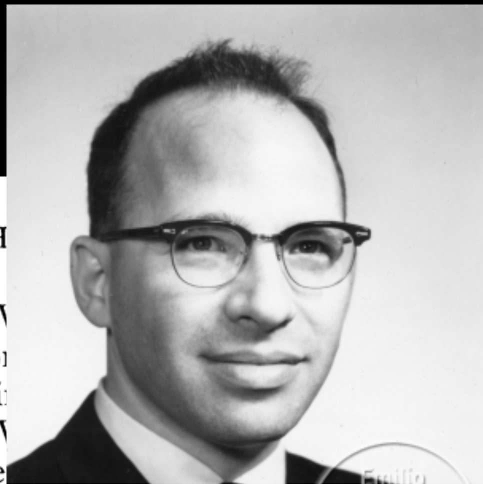
Garwin/Lederman (1957)

- 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.



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

$a_\mu = 0.00113 \pm 0.000014$

(Received October 1, 1957)

The magnetic moment of the positive μ 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 radio-frequency 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

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

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 ~ 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.

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

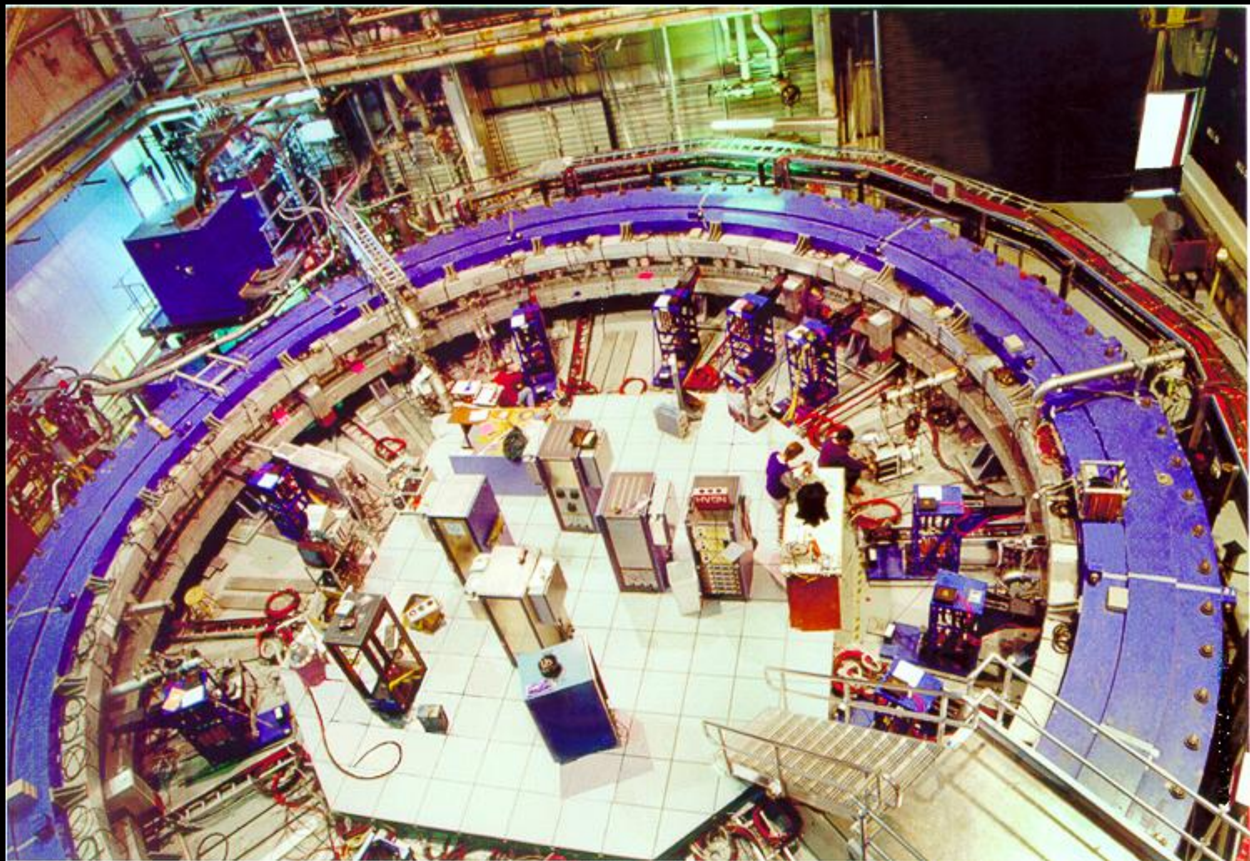
CERN-II-III (1968-1979)

- 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

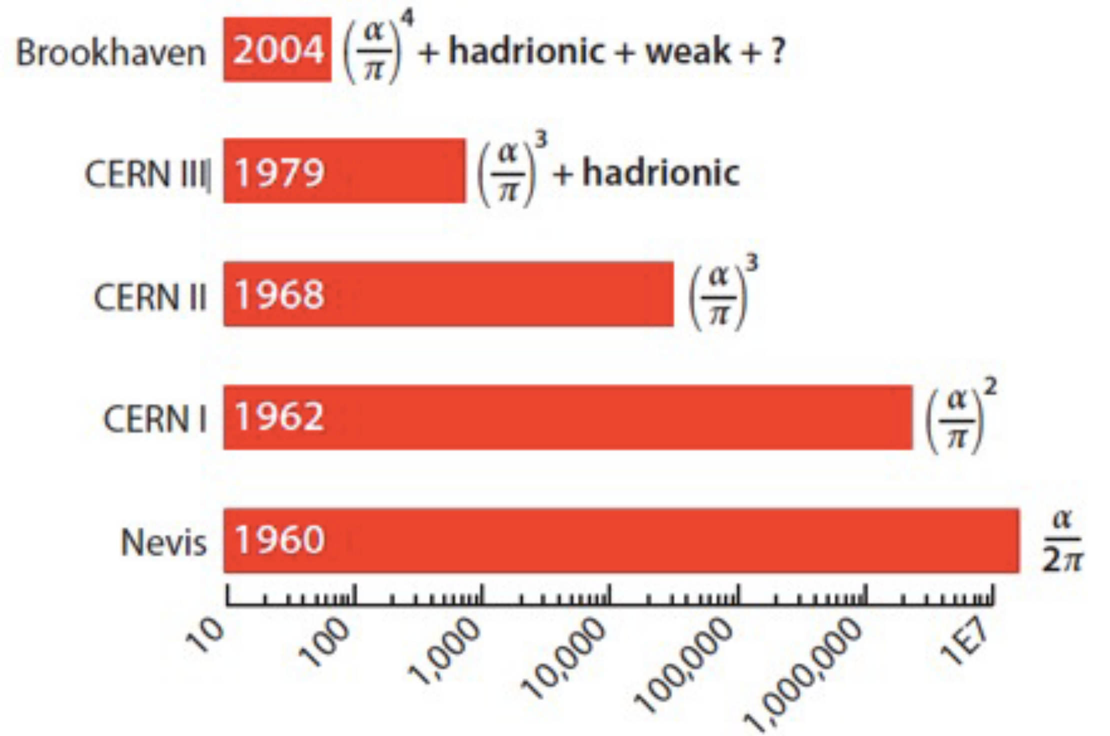
BNL-E821 (1997-2001)

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



History of experiments

❖ 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)

$\mu^{\pm}$	0.001 165 920 80(63)	0.54 ppm	$\left(\frac{\alpha}{\pi}\right)^4$ + Weak + ?	Bennett *et al*[51, 26] BNL WA (2004)

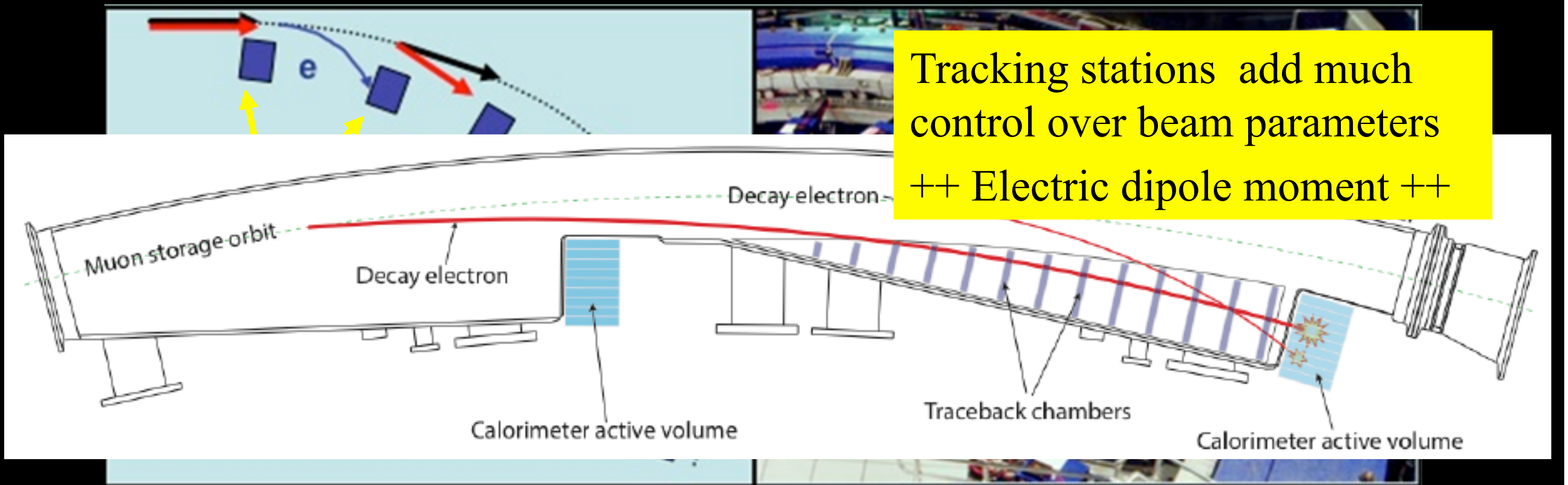
Future FNAL experiment

- 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 E-989: how it works

- a_μ proportional to difference between precession and rotation frequency



Tracking stations add much control over beam parameters
++ Electric dipole moment ++

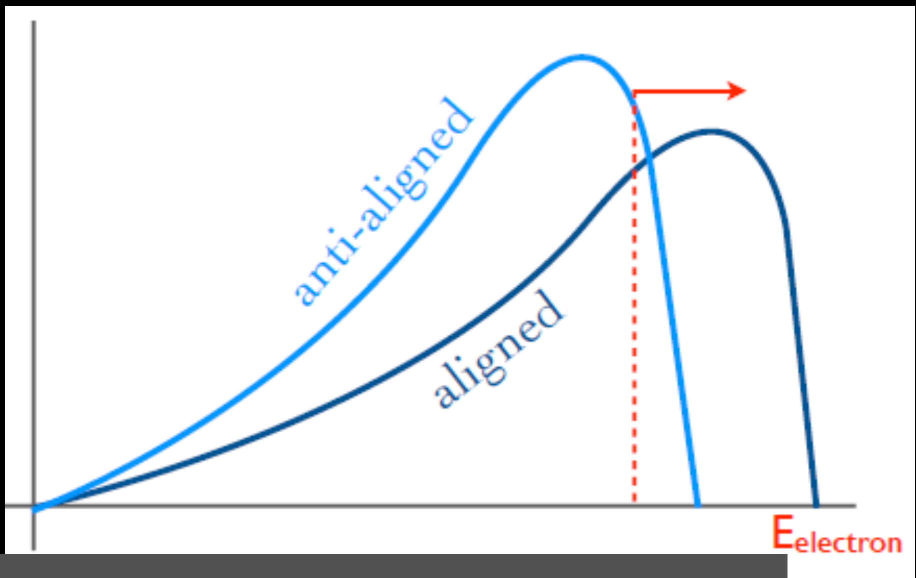
- Measure:
  - ω_a e B

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

Magic momentum
3.094 GeV
γ=29.3

How it works: ω_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

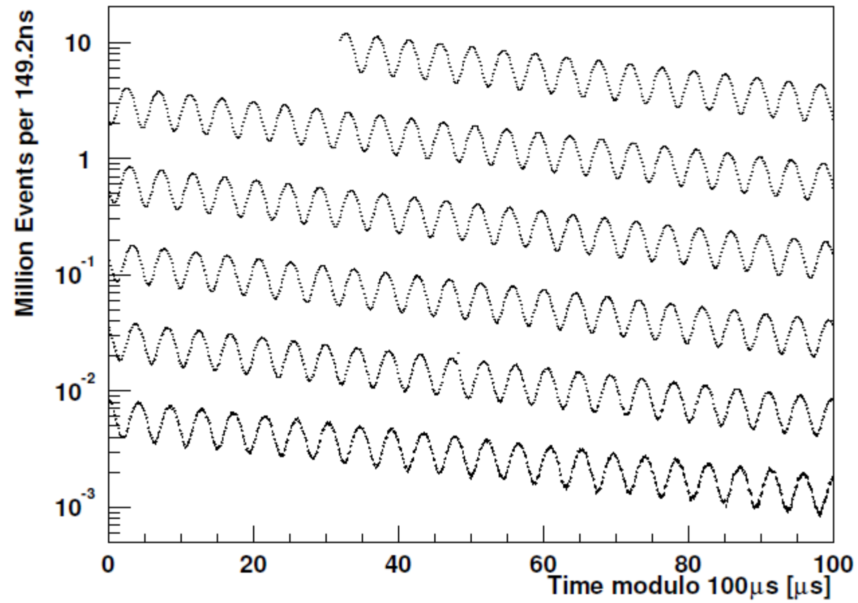
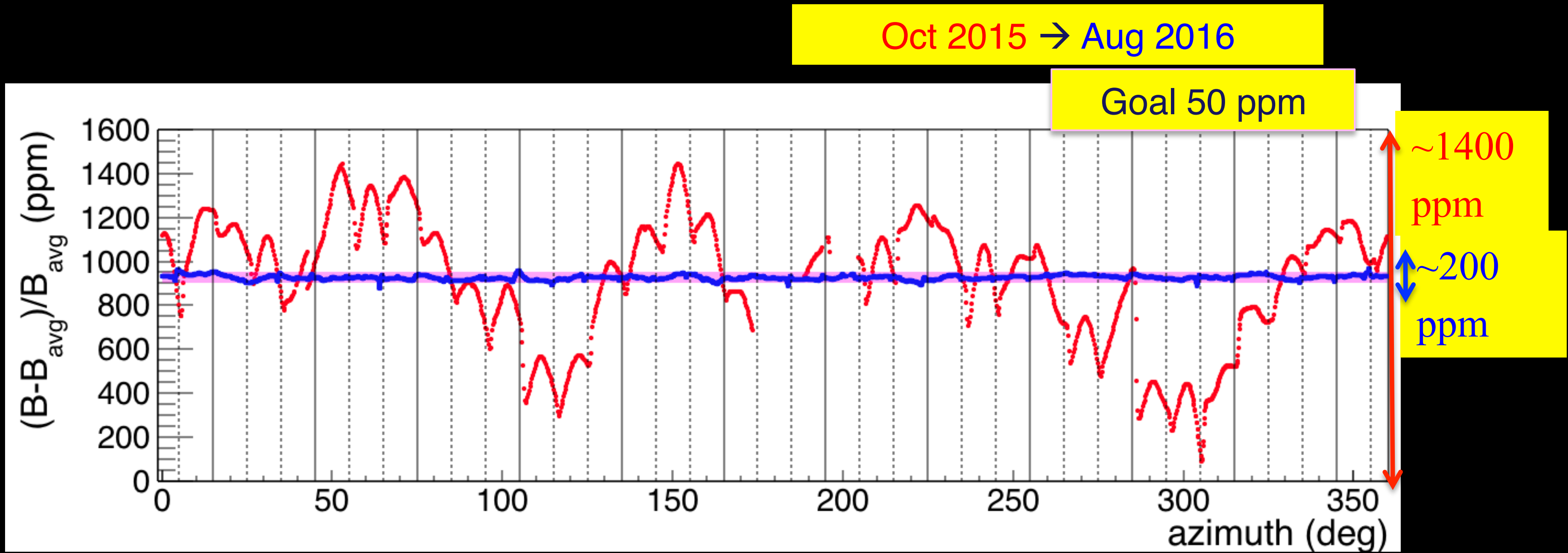


Figure 2: Distribution of electron counts versus time for 3.6 billion muon decays from the E821 experiment. The data are wrapped around modulo 100 μs [9].

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

How it works: B/ω_p

- B measured with NMR probes (precision ~10 ppb)→
  - ω_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



How it works: all together

- The whole measurement is reduced to the measurement of two frequencies: ω_a and ω_p
  - With a little math:

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

- $\lambda = \mu_\mu/\mu_p$ 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 (positive muon + electron) 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)

ω_a systematics

- Most relevant: calorimeter gain variations

Improving ω_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

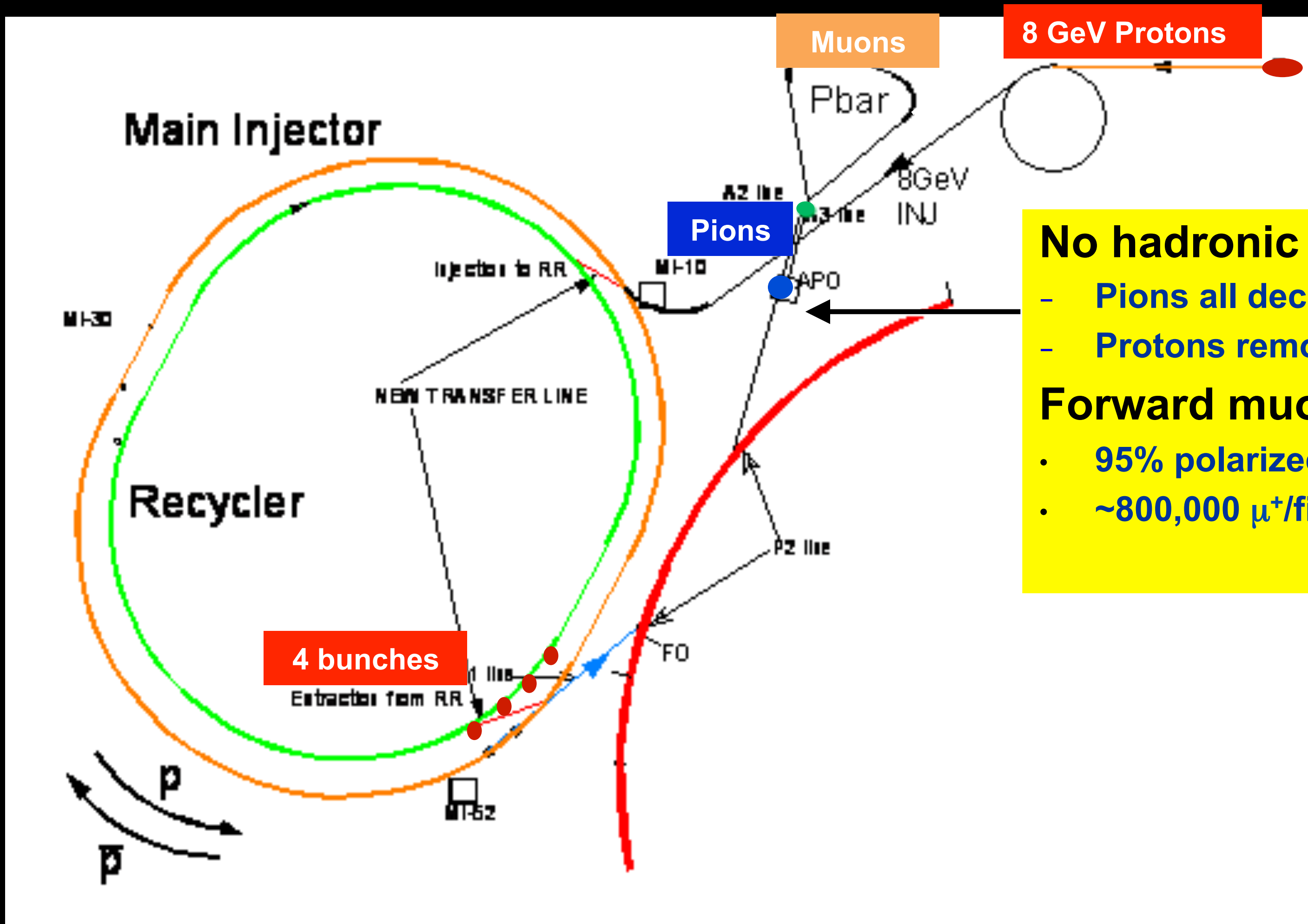
CBO: Coherent Betatron Oscillations

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

FNAL muon beam



No hadronic flash

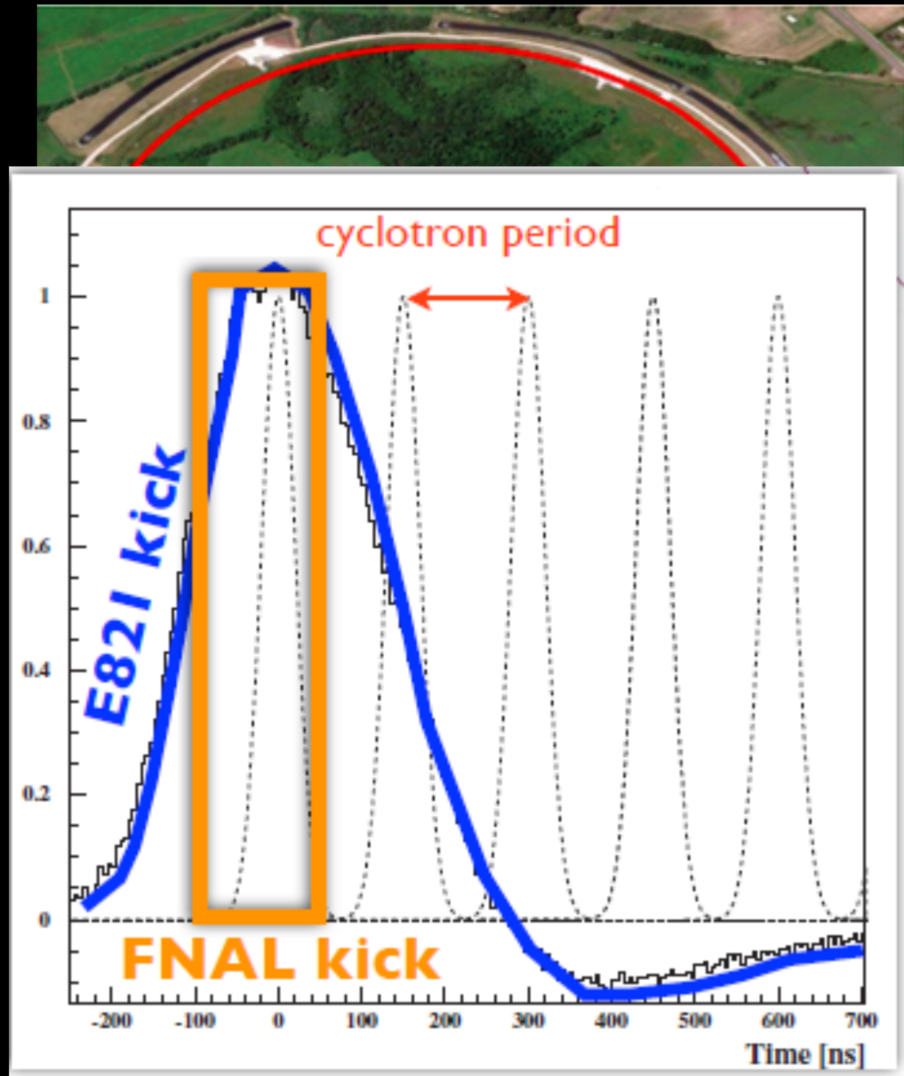
- Pions all decay
- Protons removed by a DR kicker

Forward muons collected

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

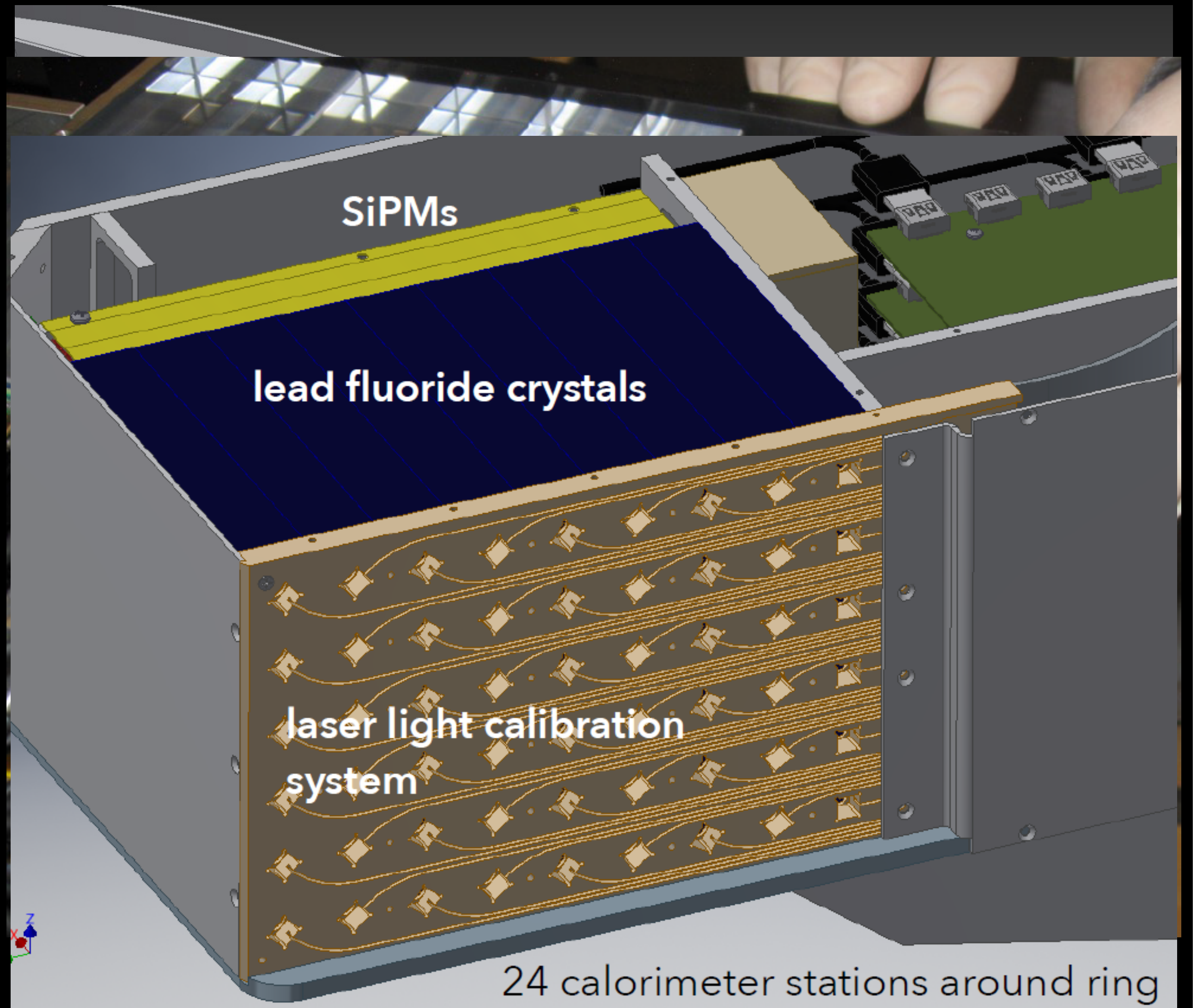
FNAL beam wrt. BNL

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



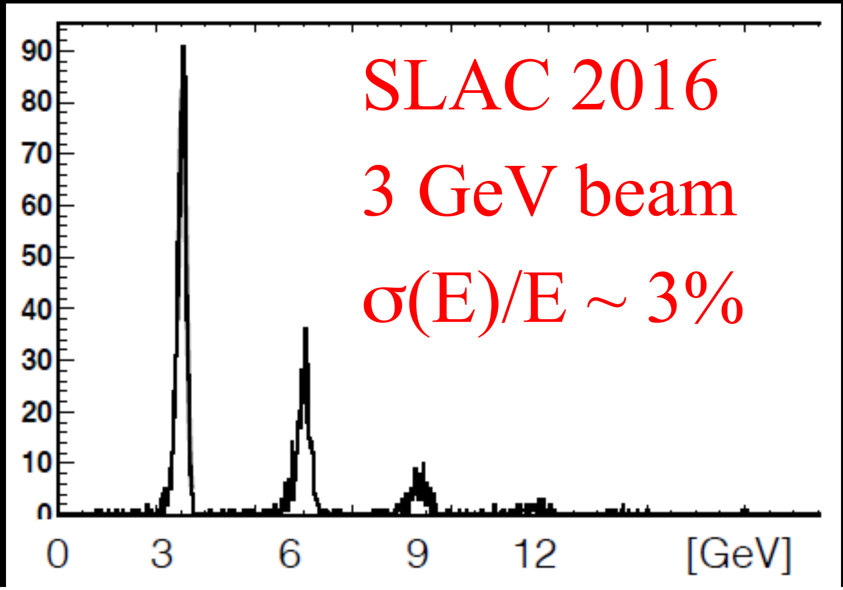
Calorimetry (1)

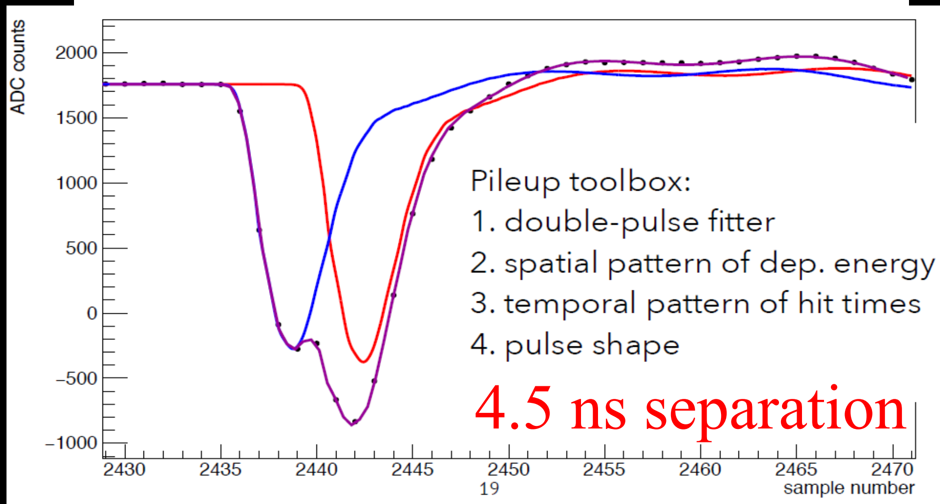
- 24 stations
- Fast:
  - Crystals PbF_2
    - Cherenkov
  - SiPM readout
- Laser calibration
  - Reduce systematics



Calorimetry (2)

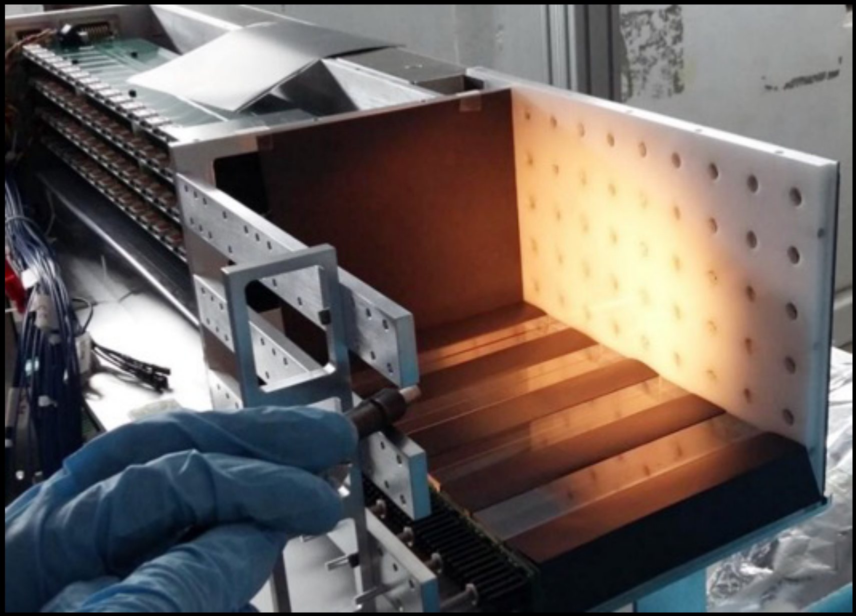
- Energy resol. ~ 3%
  - Optimized for good timing
- Timing resolution
  - 25 ps intrinsic
  - Digitizer bin 1.25 nsec
- Pile up
  - Resolve up to 4.5 ns separation

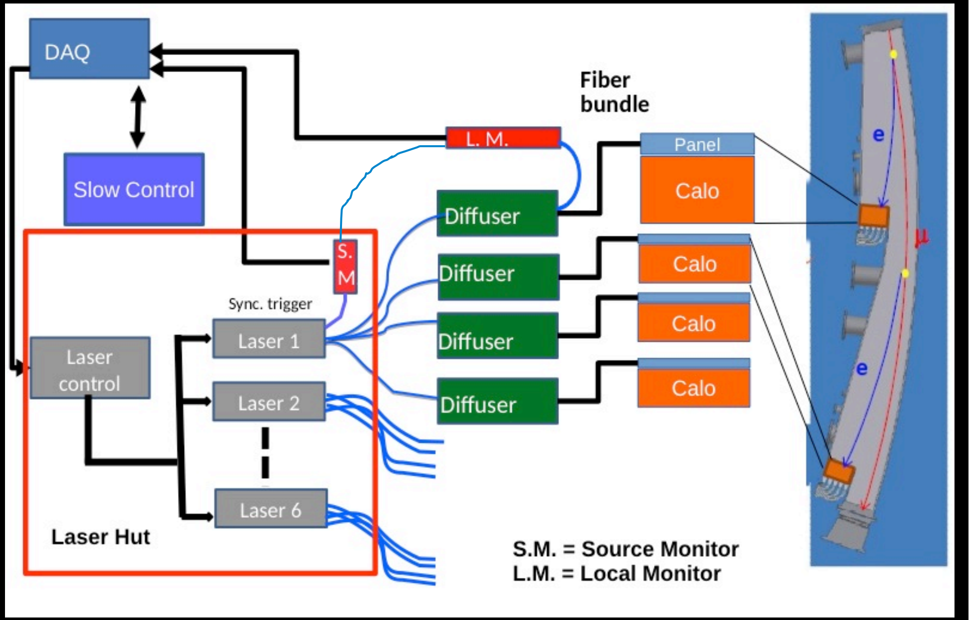




Calibration system (1)

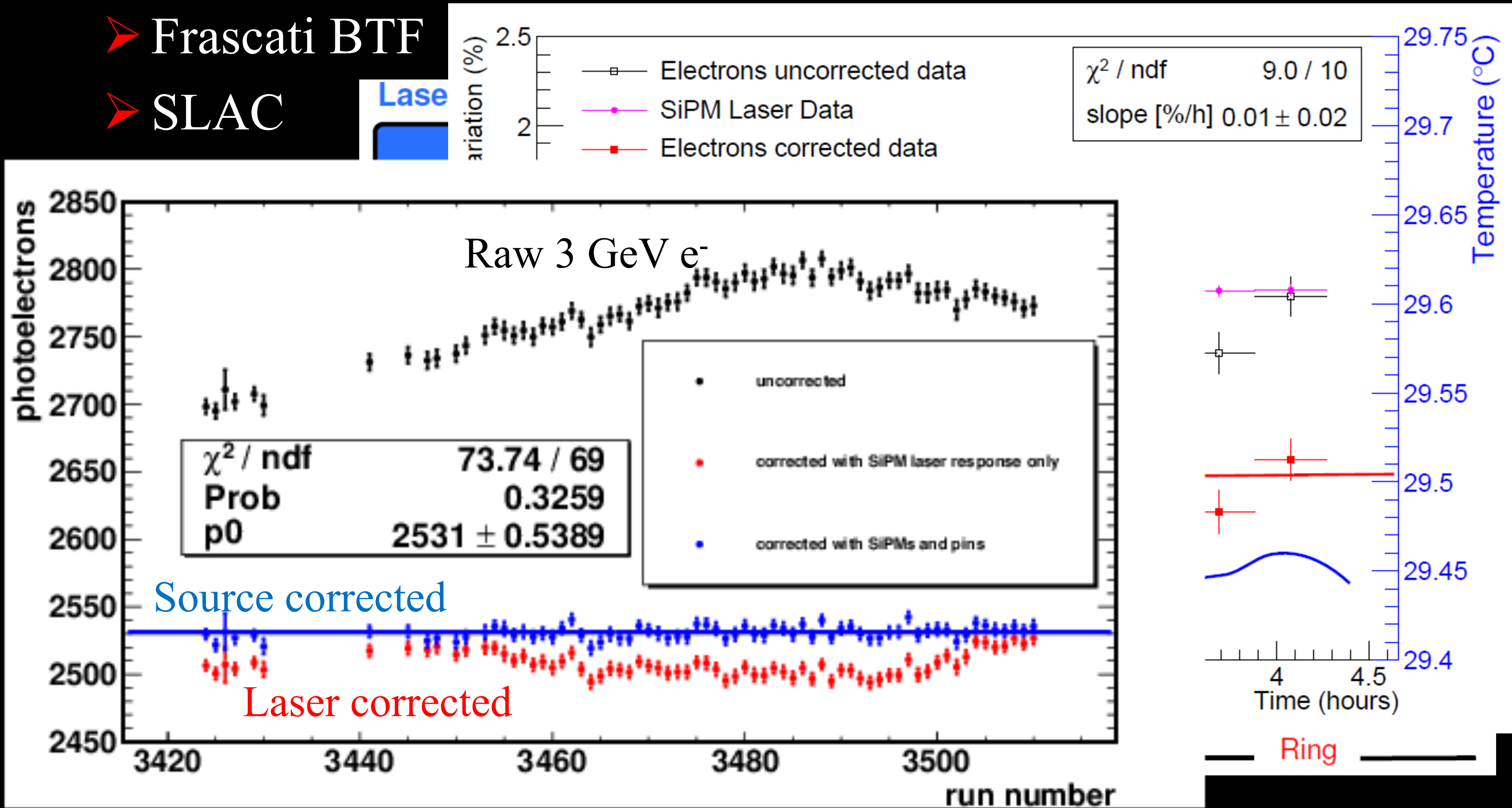
- Light from 6 blue lasers distributed to all calorimeter cells
- Source monitor: tracks laser intensity variations
- Local monitor: tracks distribution chain variations





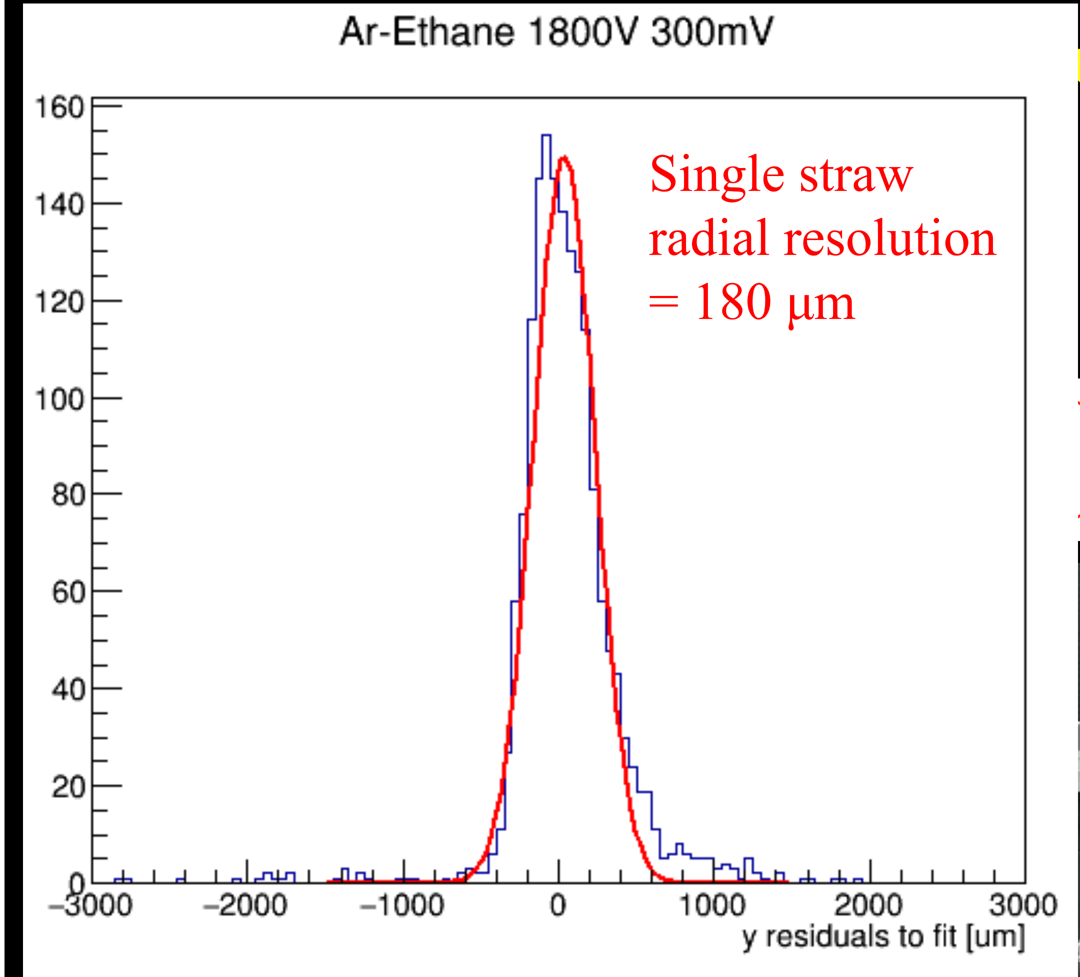
Calibration system (2)

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

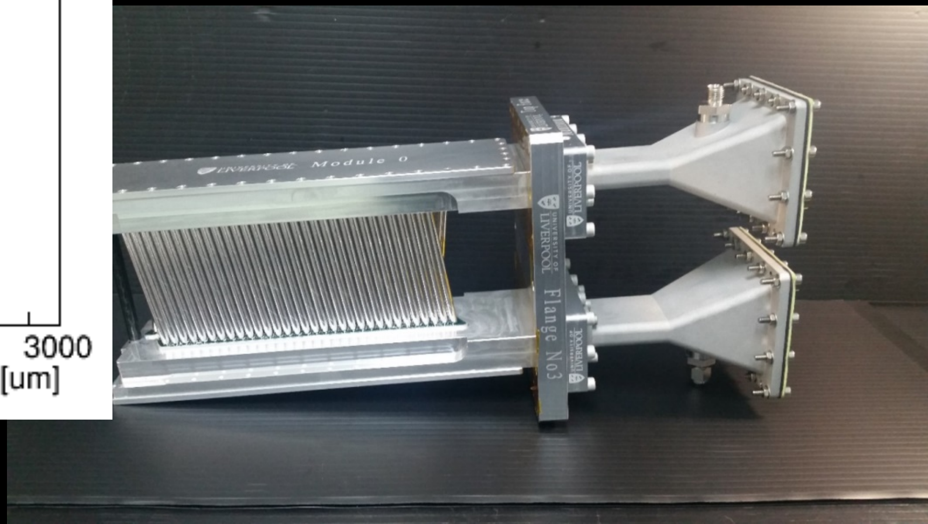


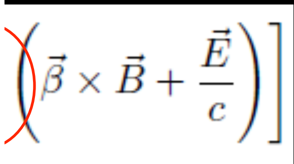
Tracking system

ubes in stereo arrangement

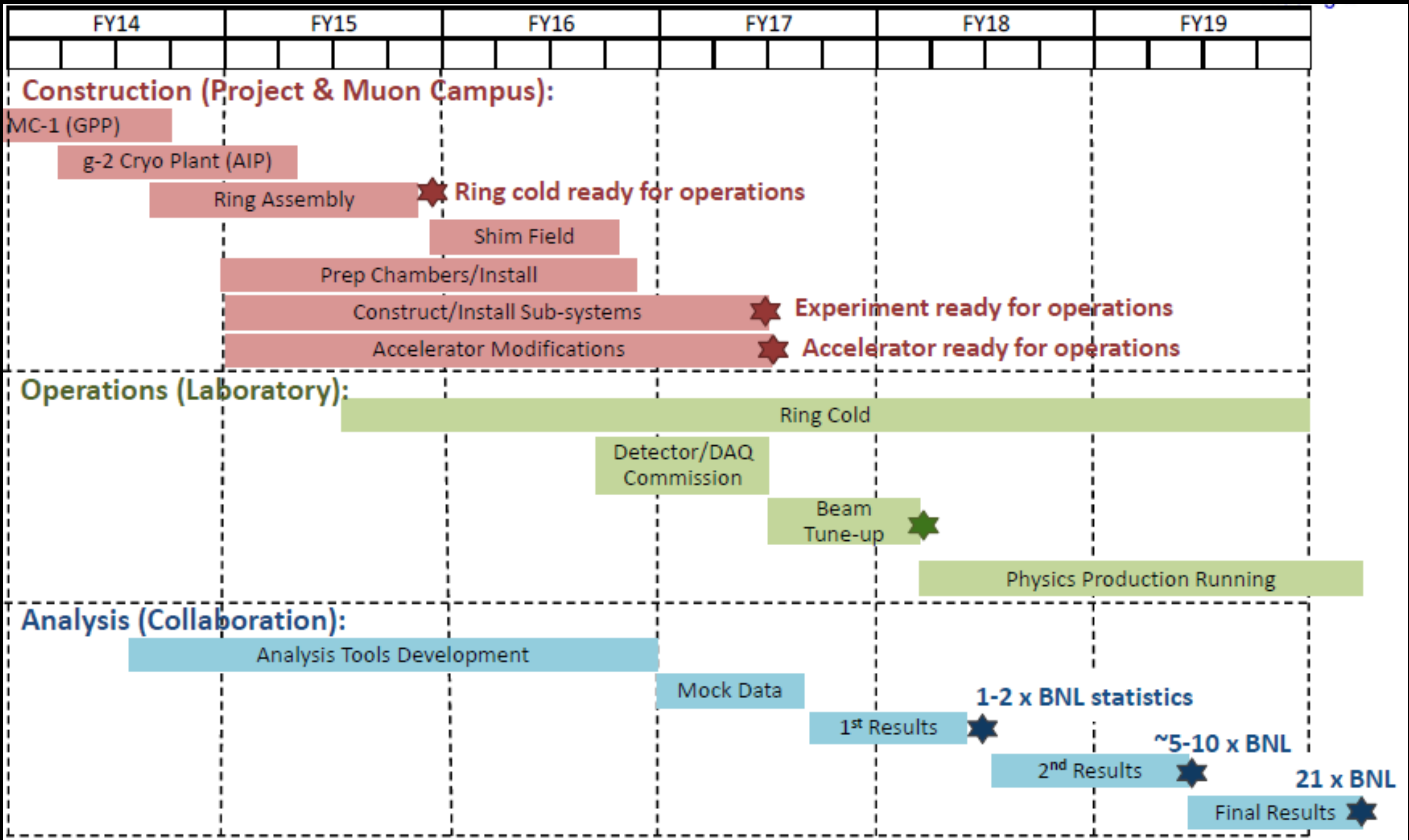


$$\left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c}\right)\Big]$$





Status and plan



Conclusions

hysics

e projects

riment

s and

d

!!

- ..but cross your fingers

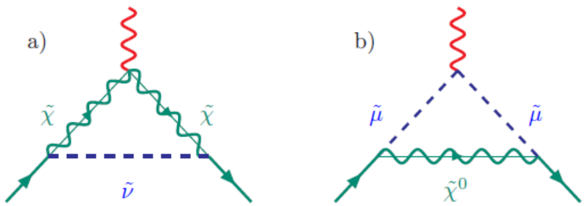
Backup slides

MORE SLIDES

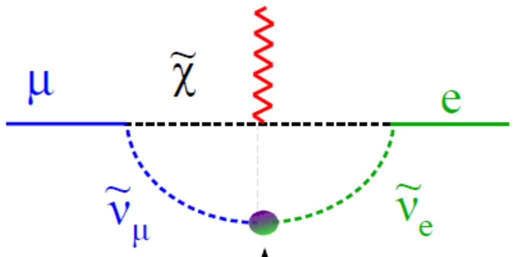
Correlation with μ→eγ

→back

g-2

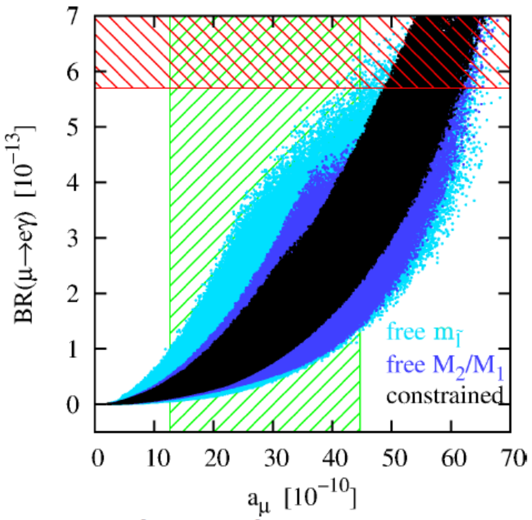


μ→eγ

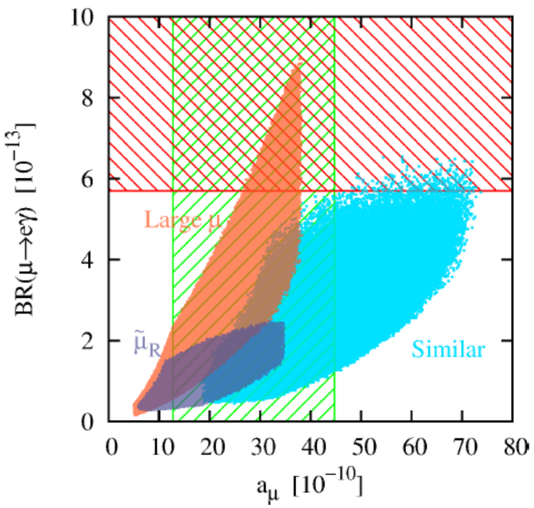


- study correlation for fixed $\delta_{LL} = 2 \times 10^{-5}$
- However: strong correlation of individual diagrams does not imply strong correlation of the sum! Strong correlations for strong parameter constraints or domination of certain diagrams

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



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



parameter regions where single diagrams dominate

Misure di α_{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)

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

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

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

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

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

Theory of g-2

Back

- a_μ 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_μ (QED)

Back

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

  $a_\mu^{(2)}(QED) = 0.5$

  $a_\mu^{(4)}(QED) = 0.765\,857\,425\,(17)$

  $a_\mu^{(6)}(QED) = 24.050\,509\,96\,(32)$

  $a_\mu^{(8)}(QED) = 130.877\,4\,(61) \quad (A_1^{(8)}$ is updated)

  $a_\mu^{(10)}(QED) = 751.77\,(93) \quad (A_1^{(10)}$ is updated)

- τ-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_μ (had) & a_μ (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).