# Goals and Perspectives on the New g-2 Experiment

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**For the new (g-2) Collaboration**

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# The New $g-2$ Experiment:
# A Proposal to Measure the Muon Anomalous Magnetic Moment to $\pm 0.14$ ppm Precision

**Fermilab E989**

**New $g-2$ Collaboration:** R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], W.M. Morse[2], Y.K. Semertzidis[2], V.P. Druzhinin[3], B.I. Khazin[3], I.A. Koop[3], I. Logashenko[3], S.I. Redin[3], Y.M. Shatunov[3], E.P. Solodov[3], Y. Orlov[4], R.M. Talman[4], B. Casey[5], B. Drendel[5], K. Genser[5], J. Johnstone[5], A. Jung[5], D. Harding[5], A. Klebaner[5], A. Leveling[5], J-F. Ostiguy[5], N.V. Mokhov[5], J. P. Morgan[5], V. Nagaslaev[5], D. Neuffer[5], A. Para[5], C.C. Polly[5], M. Popovic[5], M. Rominsky[5], A. Soha[5], P. Spentzouris[5], S.I. Striganov[5], M.J. Syphers[5], G. Velev[5], S. Werkema[5], F. Happacher[6], G. Venanzoni[6], M. Martini[6], D. Moricciani[7], J.D. Crnkovic[8], P.T. Debevec[8], M. Grosse-Perdekamp[8], D.W. Hertzog[8], P. Kammel[8], N. Schroeder[8], P. Winter[8], K.L. Giovanetti[9], K. Jungmann[10], C.J.G. Onderwater[10], N. Saito[11], C. Crawford[12], R. Fatemi[12], T.P. Gorringe[12], W. Korsch[12], B. Plaster[12], V. Tishchenko[12], D. Kawall[13], T. Chupp[14], R. Raymond[14], B. Roe[14], C. Ankenbrandt[15], M.A Cummings[15], R.P. Johnson[15], C. Yoshikawa[15], A. de Gouvêa[16], T. Itahashi[17], Y. Kuno[17], G.D. Alkhazov[18], V.L. Golovtsov[18], P.V. Neustroev[18], L.N. Uvarov[18], A.A. Vasilyev[18], A.A. Vorobyov[18], M.B. Zhalov[18], F. Gray[19], D. Stöckinger[20], S. Baeßler[21], M. Bychkov[21], E. Frlež[21], and D. Počanić[21]

# Outline

- Brief words on the experiments:
  - E821 at BNL
  - E989 at Fermilab
- Summary and Conclusions

# Spin Motion in B field: difference frequency between $\omega_S$ and $\omega_C$ with electrostatic focusing

$$\vec{\omega}_a = \omega_S - \omega_C$$

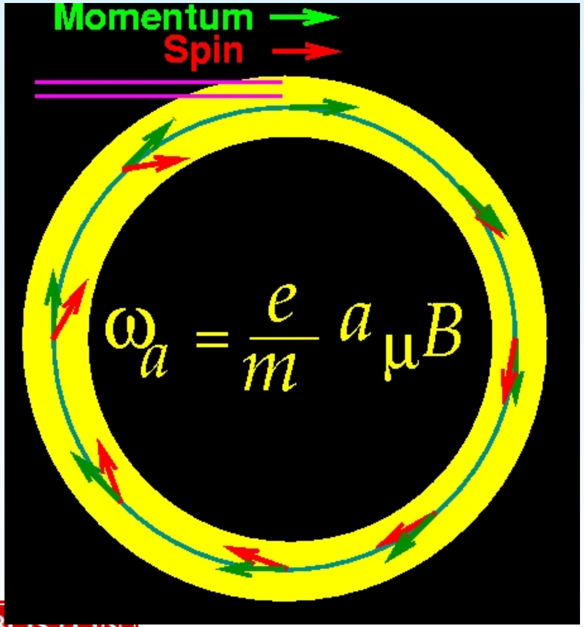
average over muons

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

0

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

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

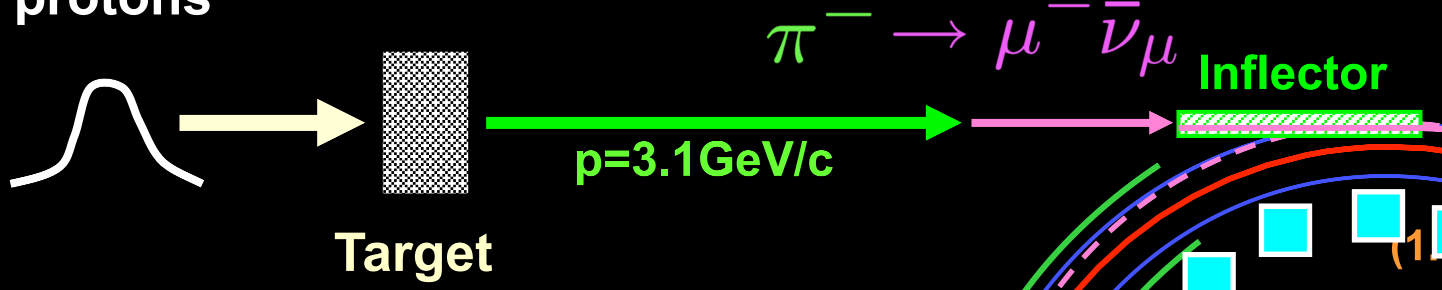



**Since g > 2, the spin gets ahead of the momentum**

**P989:** $$\frac{\delta \langle B \rangle_{\mu \ dist}}{\langle B \rangle_{\mu \ dist}} \leq 2 \times 10^{-8}$$

# Experimental Technique

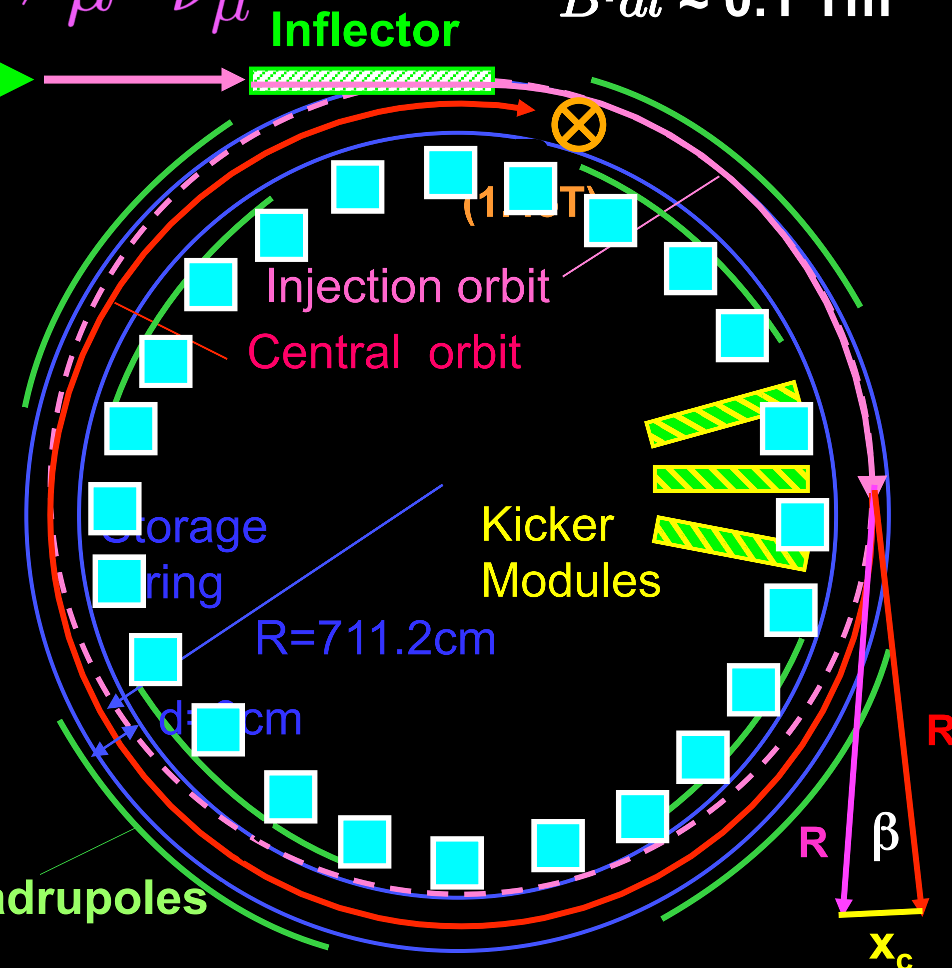
25ns bunch of
$\geqslant$ 1 X $10^{12}$
protons




$x_c \approx$ 77 mm

$\beta \approx$ 10 mrad

$B{\cdot}dl \approx$ 0.1 Tm

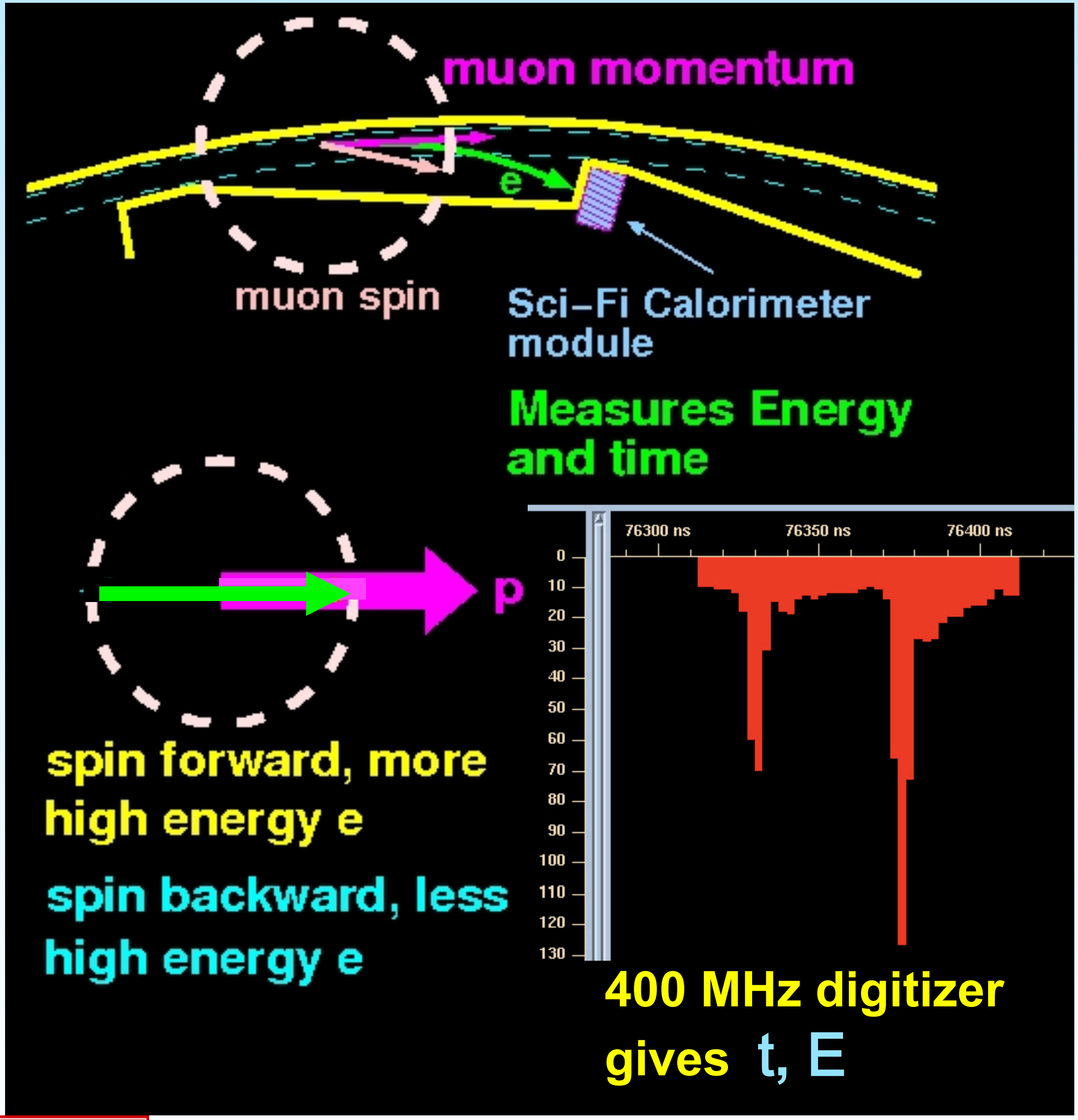


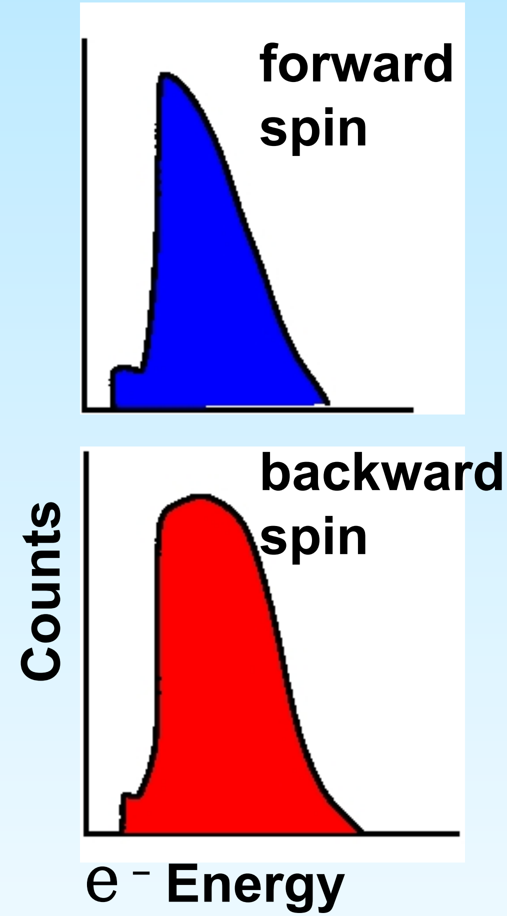

- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

# muon ($g$ - 2) storage ring

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




**measure energy and arrival time of decay $e^-$**

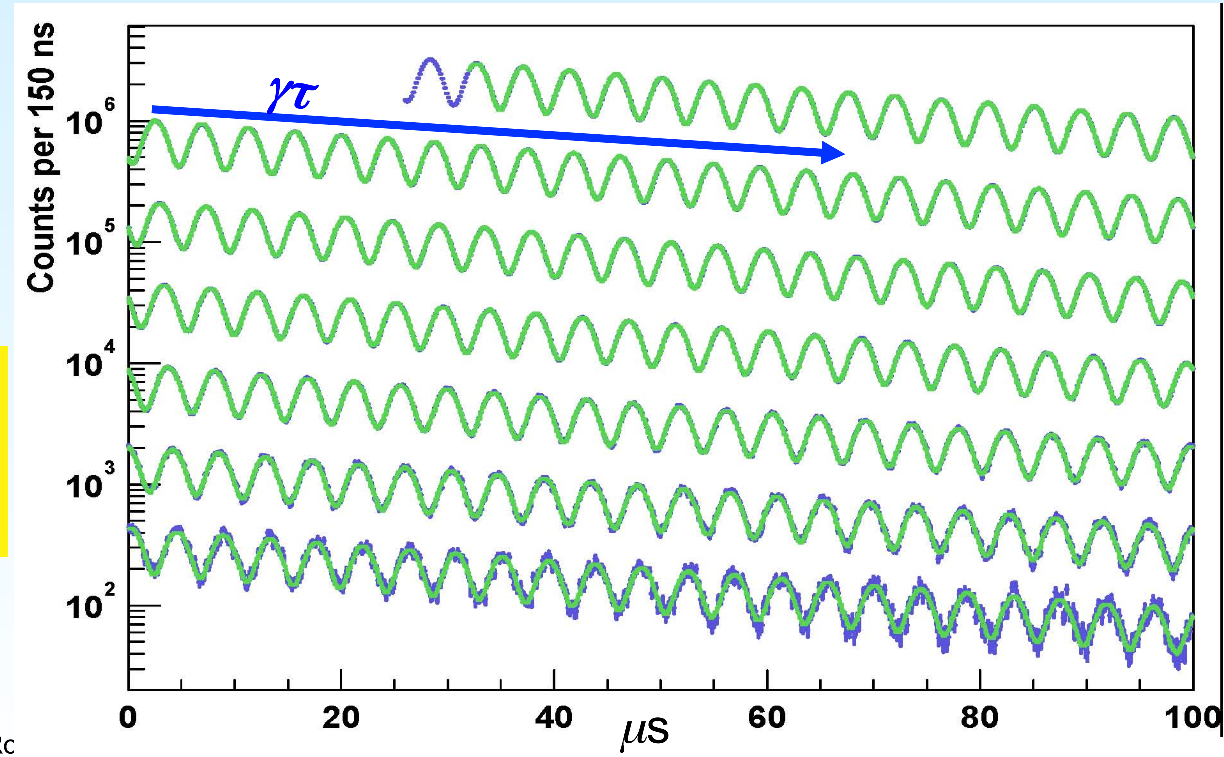
**Histogram N(t) for $E_e \geq 1.8$ GeV**

# E821 $a_{\mu^-}$ Data

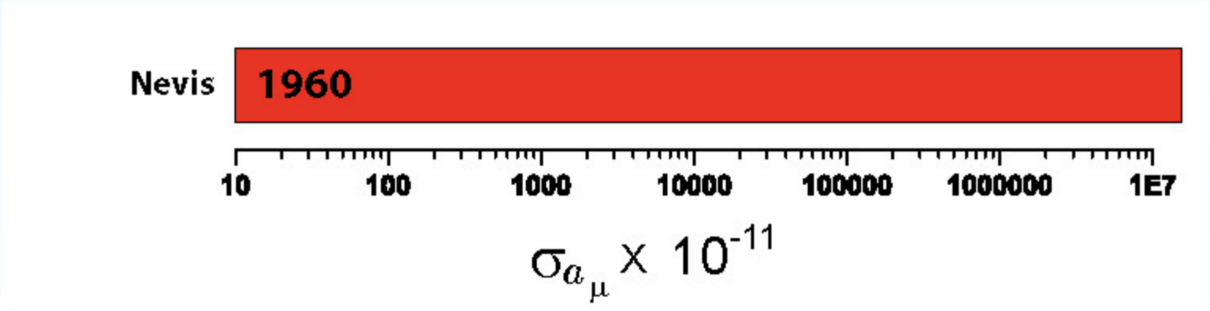
- E821 at Brookhaven
  - superferric storage ring, magic γ, <$B$>$_\theta$ ± 1 ppm

**4 x 10$^9$ High-energy $e^-$**

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

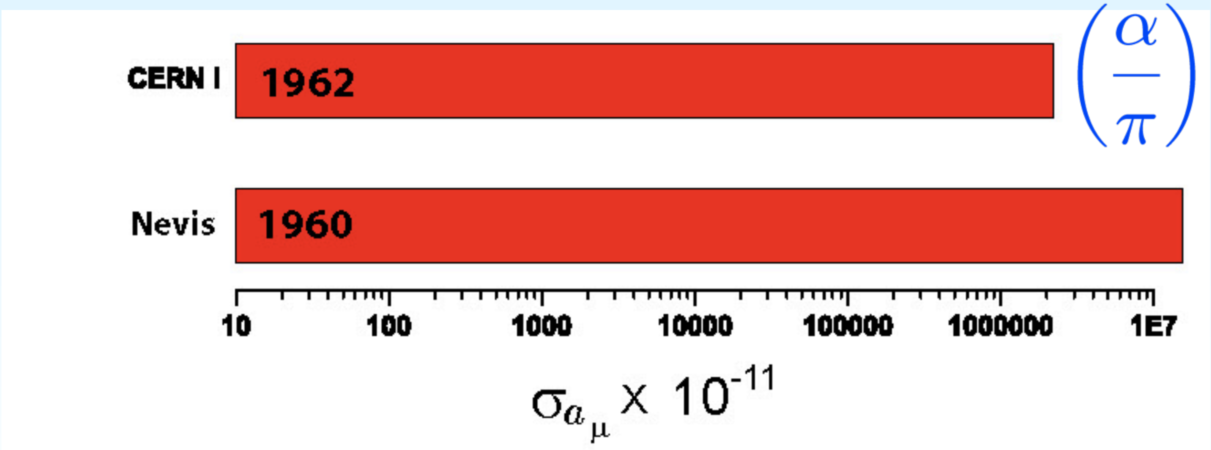


# Experimental History




$$\frac{\alpha}{2\pi}$$

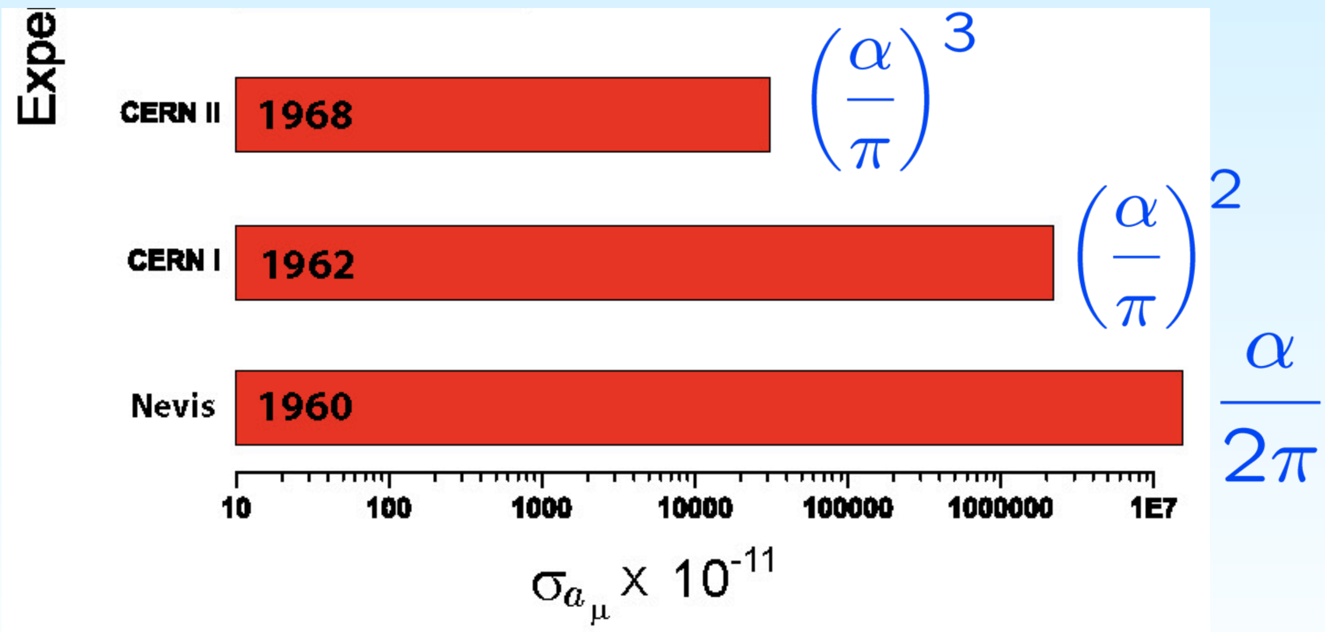
# Experimental History



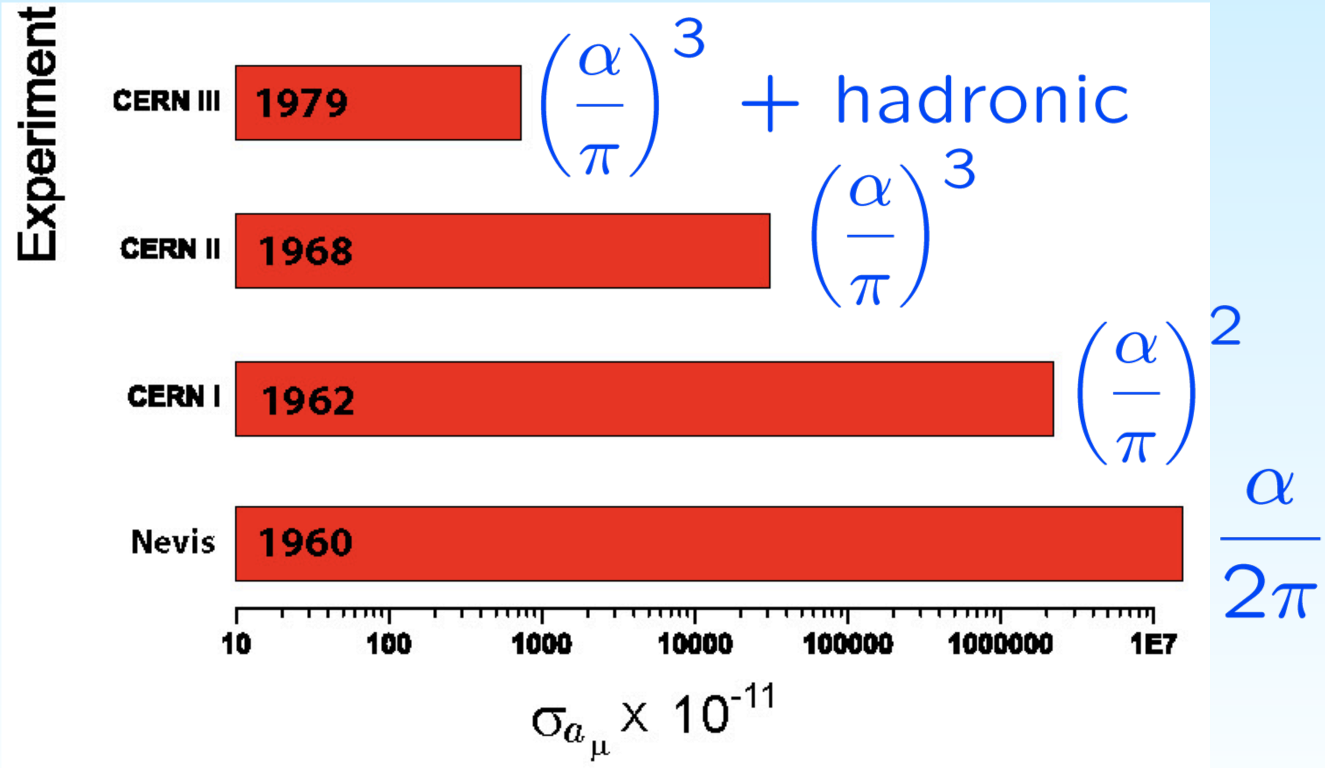

$$\left(\frac{\alpha}{\pi}\right)^2$$

$$\frac{\alpha}{2\pi}$$

# Experimental History



# Experimental History



# First major result from E821

- Feb. 2001: first E821 1.3 ppm major result, 2.6 $\sigma$ difference with SM

VOLUME 86, NUMBER 11 PHYSICAL REVIEW LETTERS 12 MARCH 2001

## Precise Measurement of the Positive Muon Anomalous Magnetic Moment

H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[9] G. T. Danby,[2] P. T. Debevec,[7] M. Deile,[11] H. Deng,[11] W. Deninger,[7] S. K. Dhawan,[11] V. P. Druzhinin,[3] L. Duong,[9] E. Efstathiadis,[1] F. J. M. Farley,[11] G. V. Fedotovich,[3] S. Giron,[9] F. Gray,[7] D. Grigoriev,[3] M. Grosse-Perdekamp,[11] A. Grossmann,[6] M. F. Hare,[1] D. W. Hertzog,[7] V. W. Hughes,[11] M. Iwasaki,[10] K. Jungmann,[6] D. Kawall,[11] M. Kawamura,[10] B. I. Khazin,[3] J. Kindem,[9] F. Krienen,[1] I. Kronkvist,[9] R. Larsen,[2] Y. Y. Lee,[2] I. Logashenko,[1,3] R. McNabb,[9] W. Meng,[2] J. Mi,[2] J. P. Miller,[1] W. M. Morse,[2] D. Nikas,[2] C. J. G. Onderwater,[7] Y. Orlov,[4] C. S. Özben,[2] J. M. Paley,[1] C. Polly,[7] J. Pretz,[11] R. Prigl,[2] G. zu Putlitz,[6] S. I. Redin,[11] O. Rind,[1] B. L. Roberts,[1] N. Ryskulov,[3] S. Sedykh,[7] Y. K. Semertzidis,[2] Yu. M. Shatunov,[3] E. P. Sichtermann,[11] E. Solodov,[3] M. Sossong,[7] A. Steinmetz,[11] L. R. Sulak,[1] C. Timmermans,[9] A. Trofimov,[1] D. Urner,[7] P. von Walter,[6] D. Warburton,[2] D. Winn,[5] A. Yamamoto,[8] and D. Zimmerman[9]
(Muon ($g-2$) Collaboration)

# Final result: April 2004; Final report April 2006

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

VOLUME 92, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 23 APRIL 2004

**Measurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm**

G.W. Bennett,[2] B. Bousquet,[9] H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[9] G. T. Danby,[2] P.T. Debevec,[7]

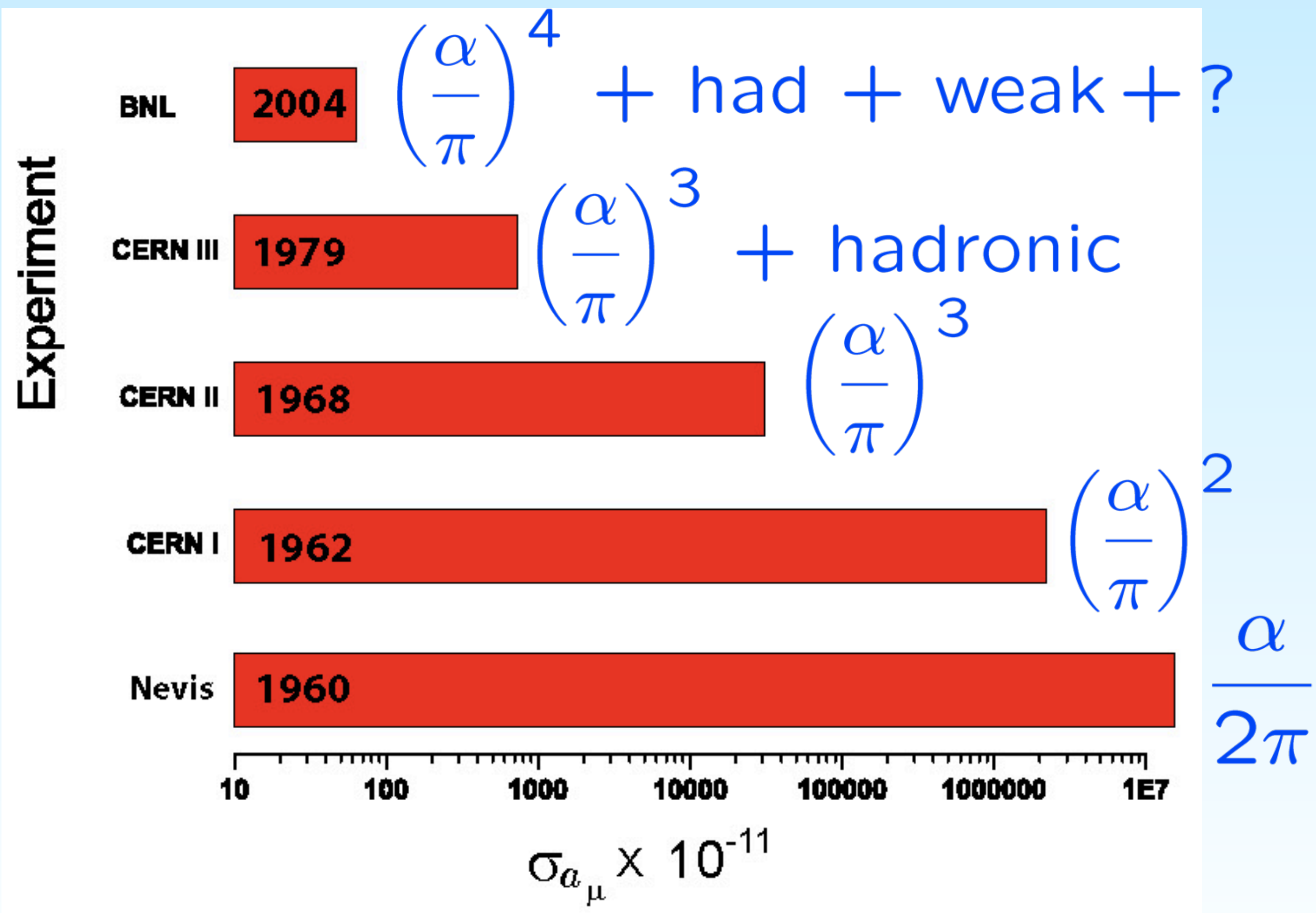
PHYSICAL REVIEW D 73, 072003 (2006)

**Final report of the E821 muon anomalous magnetic moment measurement at BNL**

G. W. Bennett,[2] B. Bousquet,[10] H. N. Brown,[2] G. Bunce,[2] R. M. Carey,[1] P. Cushman,[10] G. T. Danby,[2] P. T. Debevec,[8] M. Deile,[13] H. Deng,[13] W. Deninger,[8] S. K. Dhawan,[13] V. P. Druzhinin,[3] L. Duong,[10] E. Efstathiadis,[1] F. J. M. Farley,[13] G. V. Fedotovich,[3] S. Giron,[10] F. E. Gray,[8] D. Grigoriev,[3] M. Grosse-Perdekamp,[13] A. Grossmann,[7] M. F. Hare,[1] D. W. Hertzog,[8] X. Huang,[1] V. W. Hughes,[13,*] M. Iwasaki,[12] K. Jungmann,[6,7] D. Kawall,[13] M. Kawamura,[12] B. I. Khazin,[3] J. Kindem,[10] F. Krienen,[1] I. Kronkvist,[10] A. Lam,[1] R. Larsen,[2] Y. Y. Lee,[2] I. Logashenko,[1,3] R. McNabb,[10,8] W. Meng,[2] J. Mi,[2] J. P. Miller,[1] Y. Mizumachi,[11] W. M. Morse,[2] D. Nikas,[2] C. J. G. Onderwater,[8,6] Y. Orlov,[4] C. S. Özben,[2,8] J. M. Paley,[1] Q. Peng,[1] C. C. Polly,[8] J. Pretz,[13] R. Prigl,[2] G. zu Putlitz,[7] T. Qian,[10] S. I. Redin,[3,13] O. Rind,[1] B. L. Roberts,[1] N. Ryskulov,[3] S. Sedykh,[8] Y. K. Semertzidis,[2] P. Shagin,[10] Yu. M. Shatunov,[3] E. P. Sichtermann,[13] E. Solodov,[3] M. Sossong,[8] A. Steinmetz,[13] L. R. Sulak,[1] C. Timmermans,[10] A. Trofimov,[1] D. Urner,[8] P. von Walter,[7] D. Warburton,[2] D. Winn,[5] A. Yamamoto,[9] and D. Zimmerman[10]

(Muon ($g-2$) Collaboration)

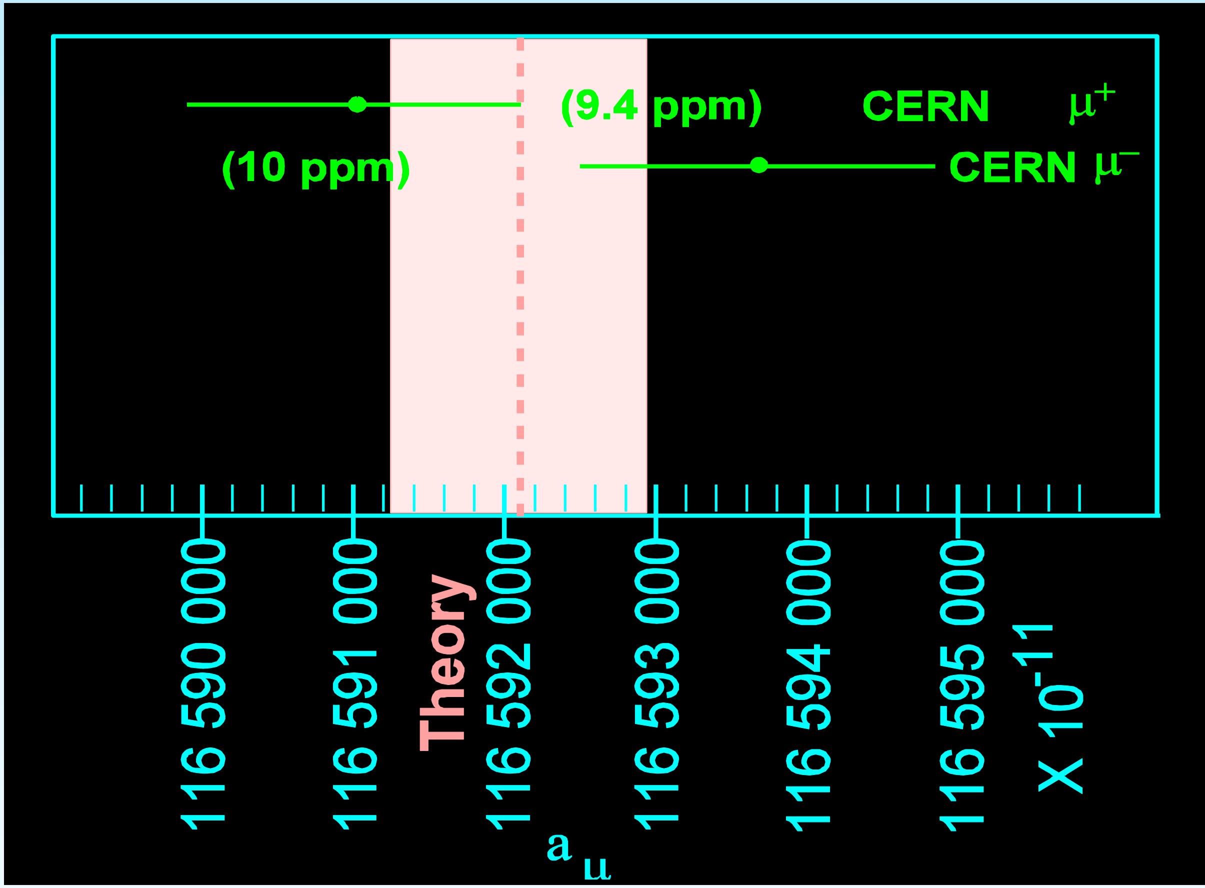
# Experimental History



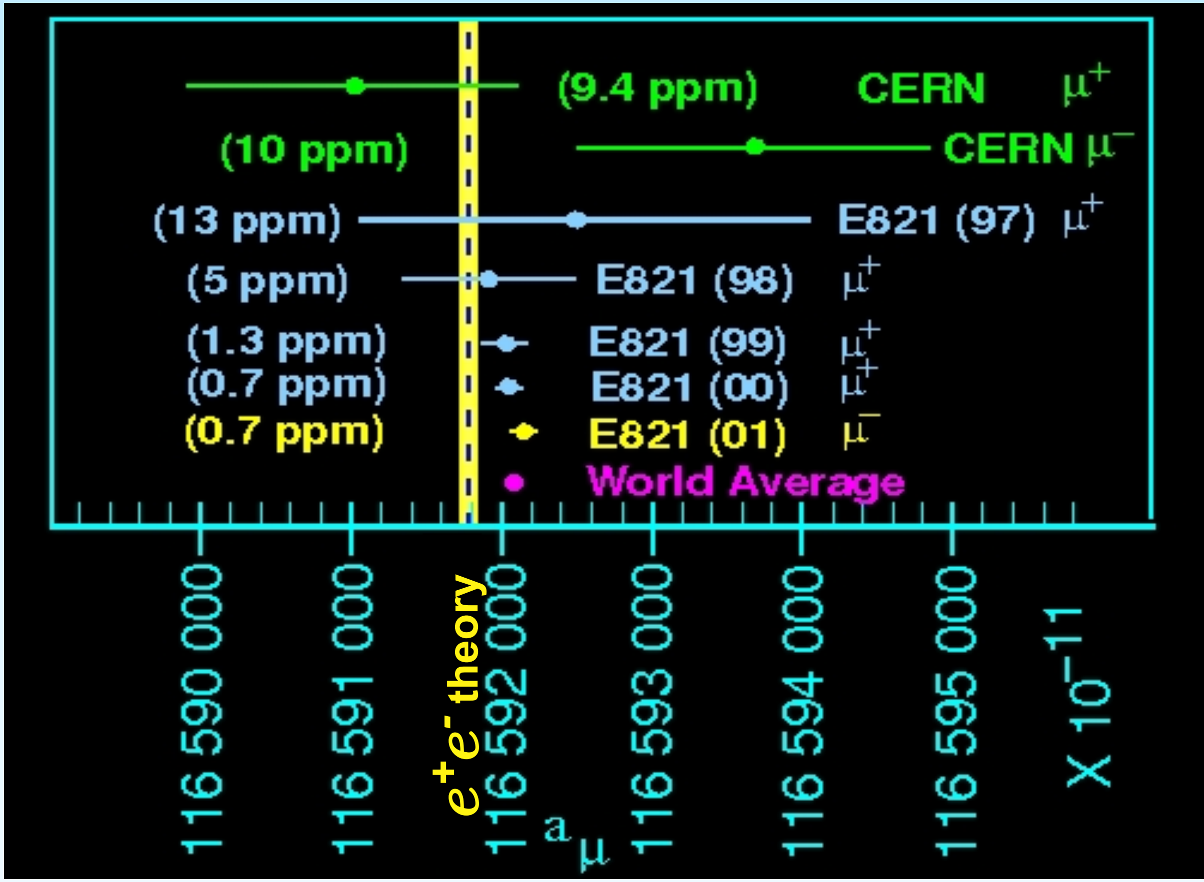
# When E821 group started in 1983, theory and experiment were known to about 10 ppm.

Theory uncertainty was ~ 9 ppm

Experimental uncertainty was 7.3 ppm



# E821 achieved ± 0.54 ppm. The $e^+e^-$ based theory is at the ~0.4 ppm level. Difference is ~3.6 $\sigma$

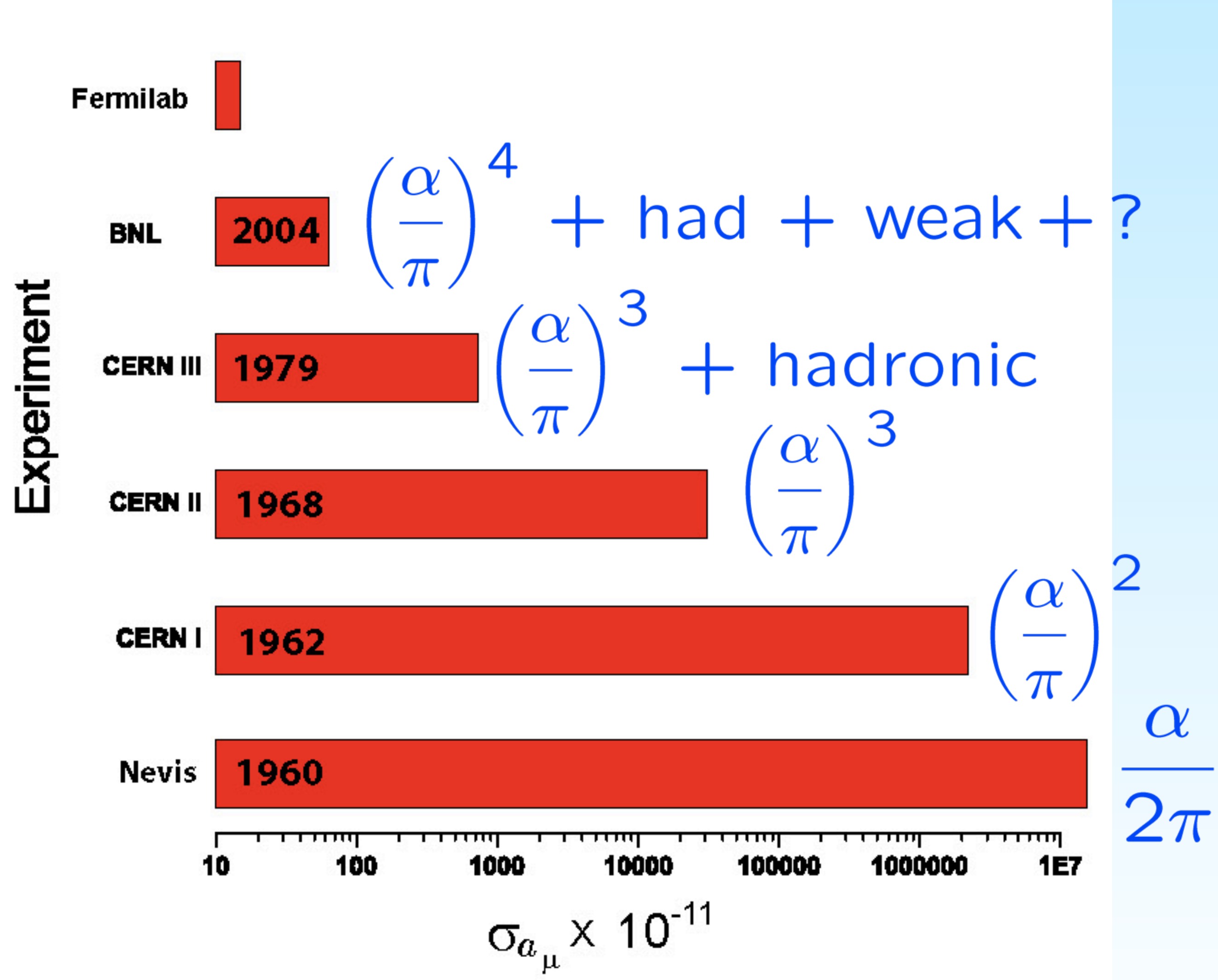



$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11} \;\; (0.54\,\text{ppm})$$

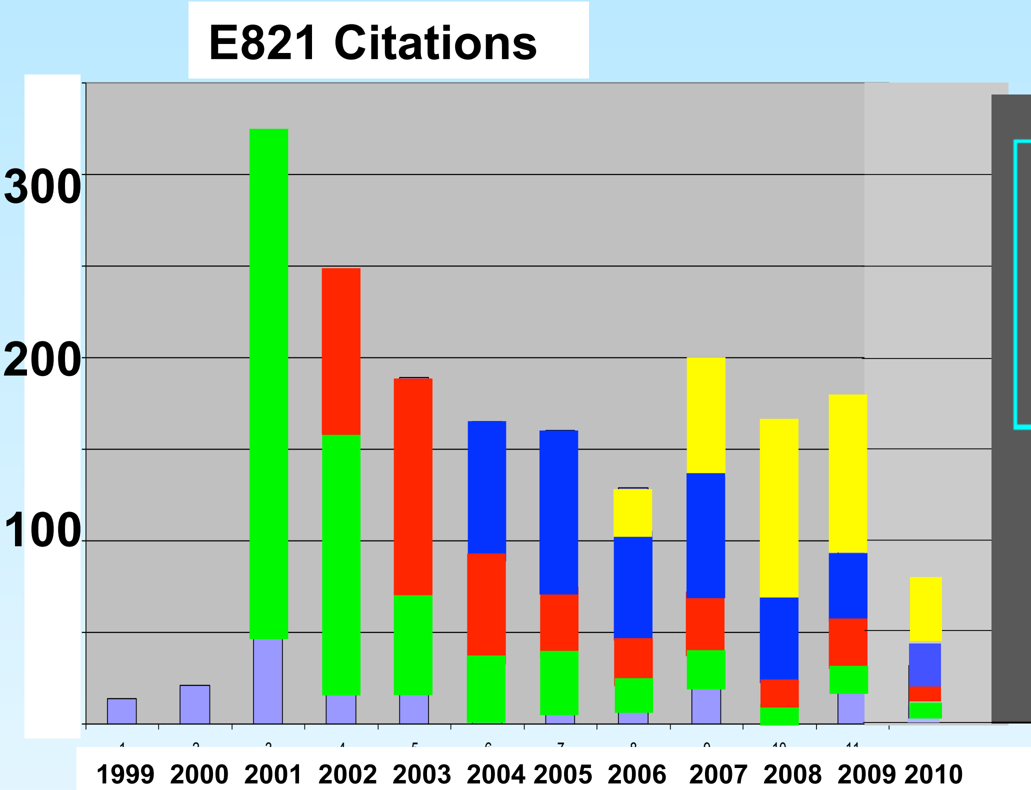
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11}$$

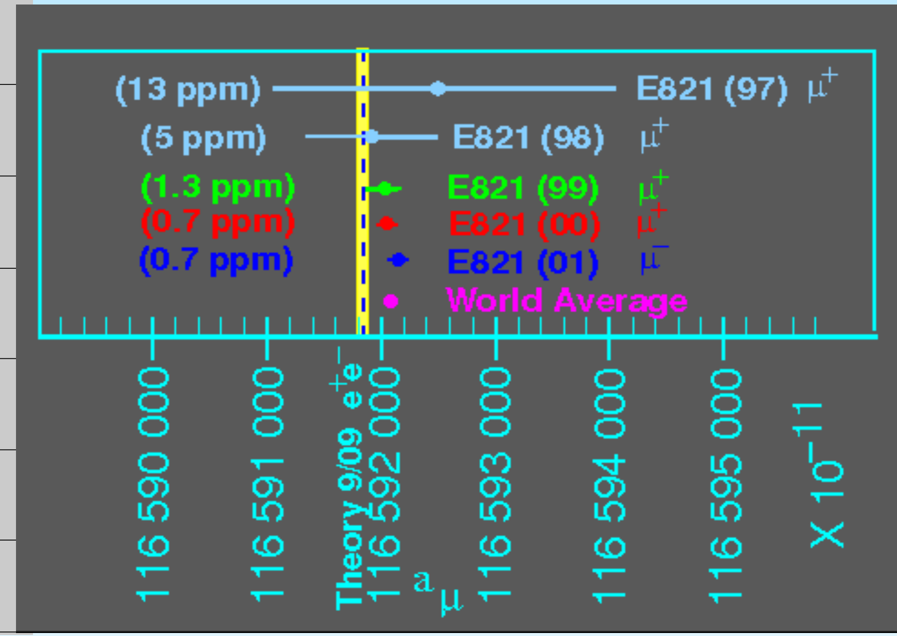
Theory: arXiv:1010.4180v1 [hep-ph] Davier, Hoecker, Malaescu, and Zhang, Tau2010

# Experimental Future



# The E821 (g-2) papers are highly cited.




Carey, et al., PRL 82, 1632 (1999)
Brown, et al. PRD 62, 091101 (2000)
Brown, et al. PRL 86, 2227 (2001)
Bennett, et al. PRL 89, 101804 (2002)
Bennett, et al. PRL 92, 161802 (2004)
Bennett, et al, PRD 73, 072003 (2006)

**>1850 total citations to our results**

"g-2 is the most important constraint (for SUSY), even more important than dark matter" **Fittino-collaboration, arXiv:0907.2589**

## E821

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

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}$$

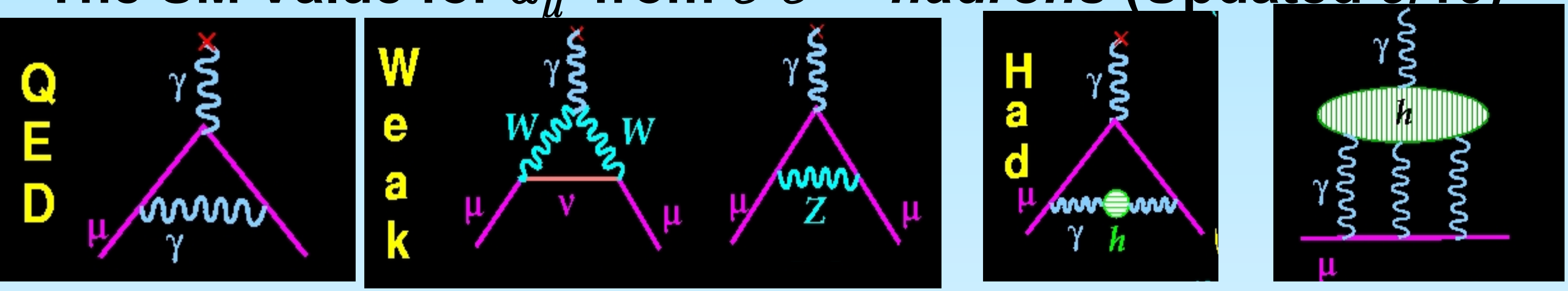
$$a_\mu^{SM} = 116\ 591\ 793 \pm 51$$

## E989

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

$$a_\mu^{exp} = 116\,59x\,xxx(16) \times 10^{-11}$$

# The SM Value for $a_\mu$ from $e^+e^- \rightarrow$ *hadrons* (Updated 9/10)




**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) | $6\ 914 \pm 42_{\rm exp} \pm 14_{\rm rad} \pm 7_{\rm pQCD}$ |
| HVP(ho) | $-98 \pm 1_{\rm exp} \pm 0.3_{\rm rad}$ |
| HLxL | $105 \pm 26$ |
| EW | $152 \pm 2 \pm 1$ |
| Total SM | $116\ 591\ 793 \pm 51$ |

# A. Höcker Tau 2010, U. Manchester September 2010

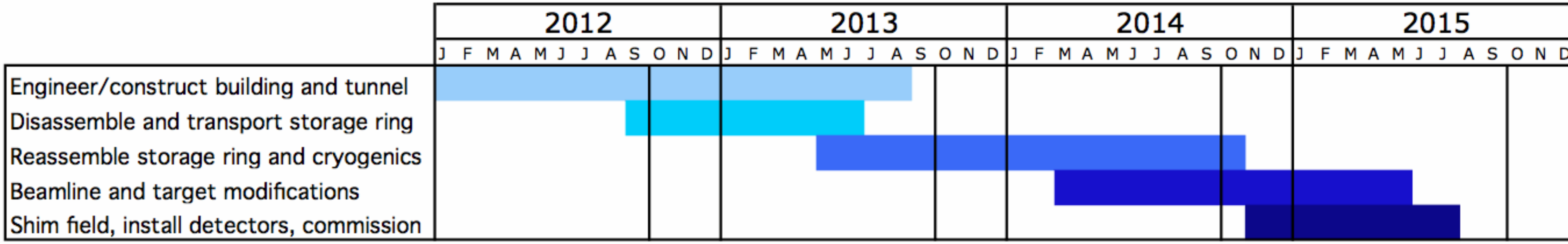
# Fermilab E989: Approved January 2011

- Re-locate the ($g$ - $2$) storage ring to Fermilab
- Use the many proton storage rings to form the ideal proton beam
- Use one of the antiproton rings as a 900 m decay line to produce a pure muon beam
- Accumulate 21 times the statistics
- Improve the systematic errors
- Final goal: At least a factor of 4 more precise over E821

# Sikorsky S64F  12.5 T hook weight (Outer coil/cryostat 8T)

- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

# Timeline presented to DOE this week



# On this timescale it's essential that the theory improve

- Lowest-order hadronic
  - BaBar and Belled have additional unanalyzed data
    - especially important for multihadron channels
  - VEPP2000 at Novosibirsk
    - CMD3
    - SND
- HLBL
  - Agreement among theorists and additional work
  - KLOE 2 photon physics
  - BES, Mainz

**We look forward to working with the theory community to improve the confrontation between $a_\mu$ and the Standard Model**

Thanks to each of you for coming to this workshop.

# Extra Slides

# Systematic errors on $\omega_a$ (ppm)

| $\sigma_{systematic}$ | 1999 | 2000 | 2001 | Future |
|---|---|---|---|---|
| Pile-up | 0.13 | 0.13 | 0.08 | 0.04 |
| AGS Background | 0.10 | 0.10 | 0.015* | |
| Lost Muons | 0.10 | 0.10 | 0.09 | 0.02 |
| Timing Shifts | 0.10 | 0.02 | 0.02 | |
| E-Field, Pitch | 0.08 | 0.03 | 0.06* | 0.03 |
| Fitting/Binning | 0.07 | 0.06 | 0.06* | |
| CBO | 0.05 | 0.21 | 0.07 | 0.04 |
| Beam Debunching | 0.04 | 0.04 | 0.04* | |
| Gain Change | 0.02 | 0.13 | 0.13 | 0.02 |
| total | 0.3 | 0.31 | 0.21 | ~0.07 |

**Σ* = 0.11**

# The Precision Field: Systematic errors

- Why is the error 0.11 ppm?
  - That's with *existing* knowledge and experience
    - with R&D defined in proposal, it will get better

| Source of Uncertainty | 1998 | 1999 | 2000 | 2001 | Next (g-2) |
|---|---|---|---|---|---|
| Absolute Calibration | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Calibration of Trolley | 0.3 | 0.20 | 0.15 | 0.09 | 0.06 |
| Trolley Measurements of B0 | 0.1 | 0.10 | 0.10 | 0.05 | 0.02 |
| Interpolation with the 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 |
| Other* | | 0.15 | 0.10 | 0.10 | 0.05 |
| Total | 0.5 | 0.4 | 0.24 | 0.17 | 0.11 |

BO UNI