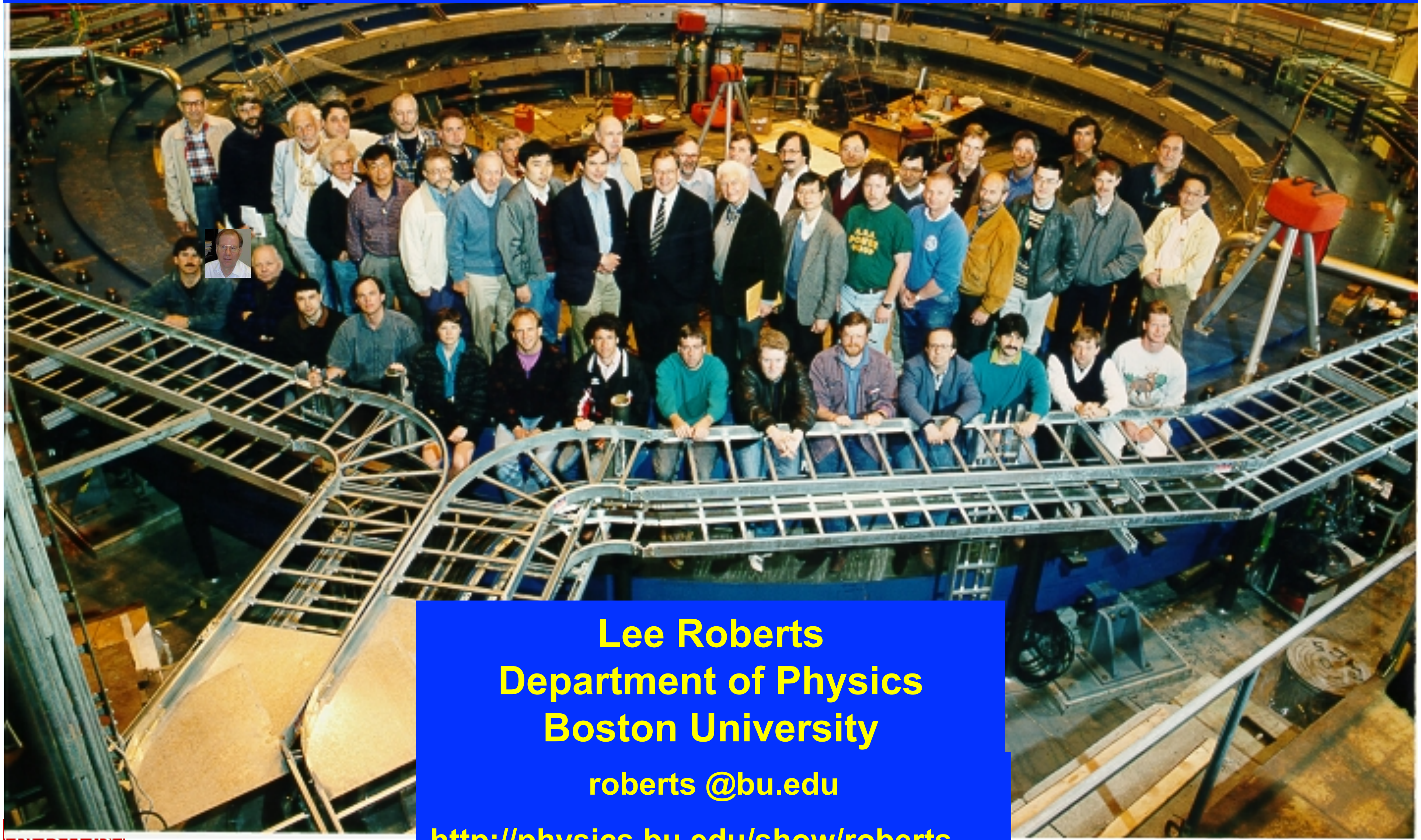
Muon (g-2): Inside or outside of the Standard Model?



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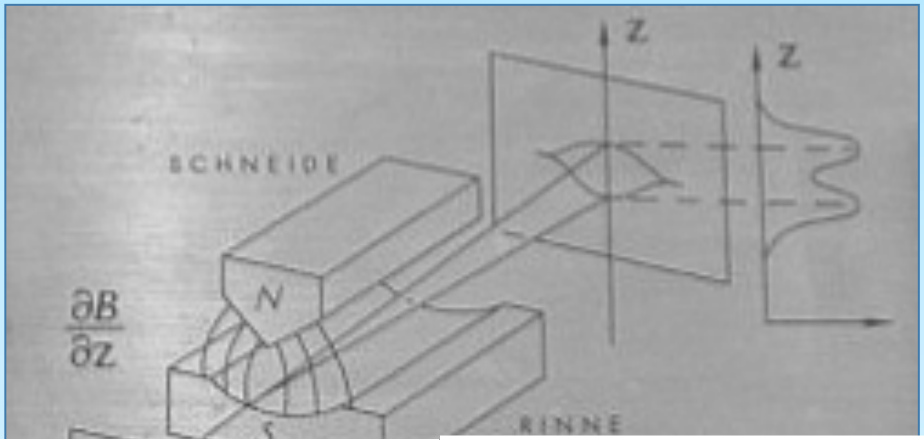
Outline

- Introduction to dipole moments
- The experimental technique and E821 result
- Theory of the muon Magnetic Dipole Moment
- The future at Fermilab

The History



ohne Magnetfeld

Fig. 2.

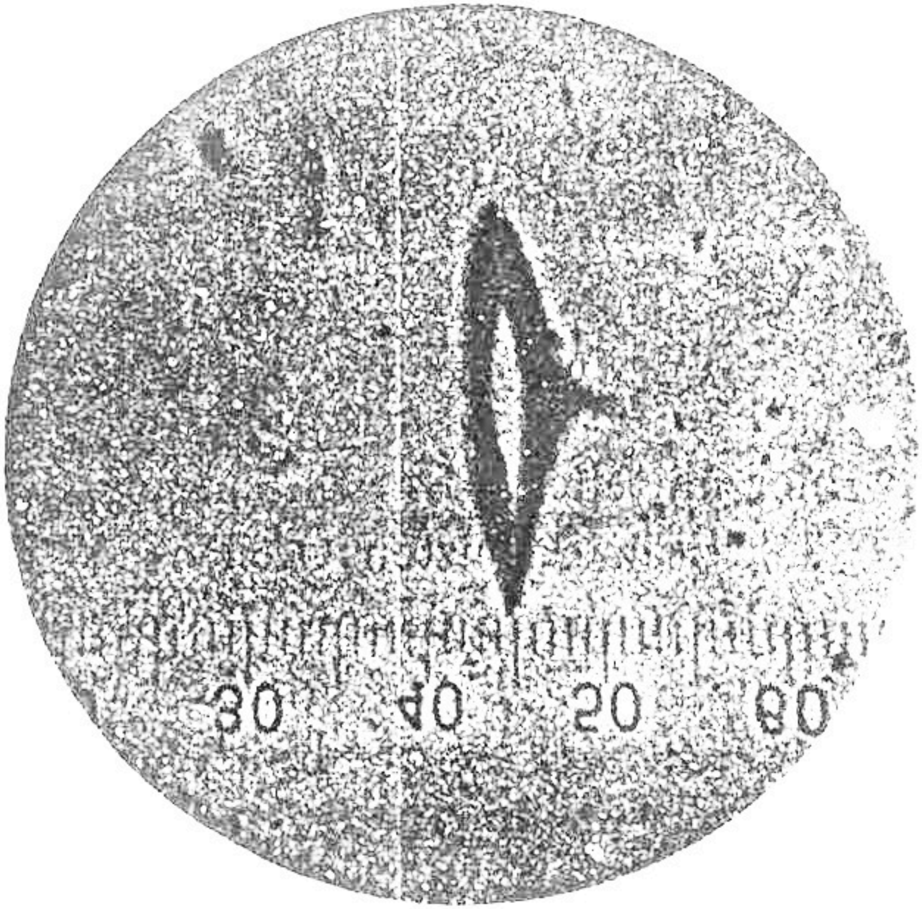
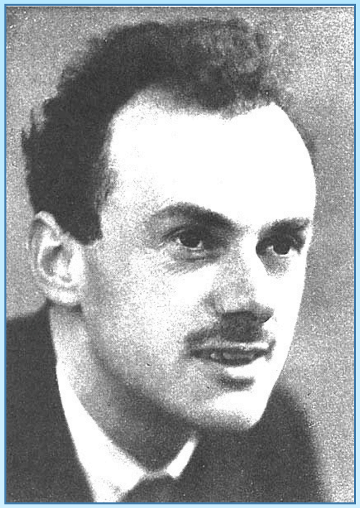


Fig. 3.

mit Magnetfeld

The modern theoretical beginning: Dirac



$$\boxed{i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)}$$

predicted electron magnetic moment

$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}, \quad e > 0$$

$$g \equiv 2$$

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

$$\frac{Qe}{4m} a\bar{\psi}(x)F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x)$$

dimension 5 operator

(only from loops)

where a is the anomaly,

$$g = 2(1 + a) \qquad a = \frac{(g-2)}{2}$$

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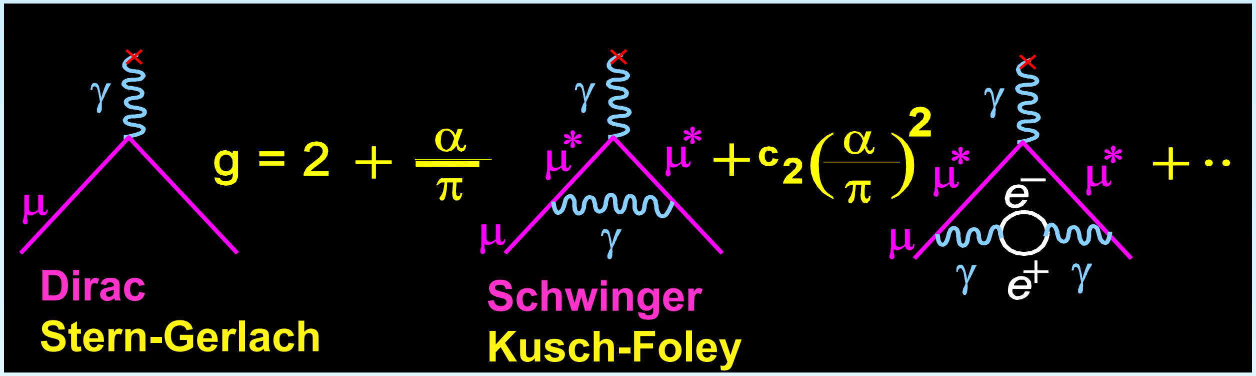
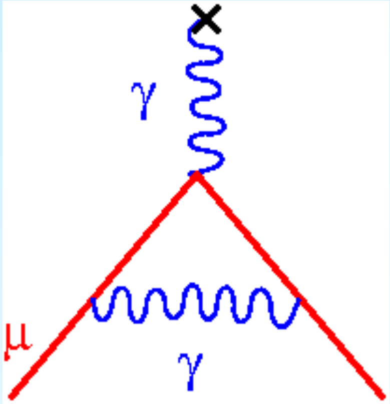
In the QED, a becomes an expansion in (α/π) from loops

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





New Physics contribution to a at some scale Λ

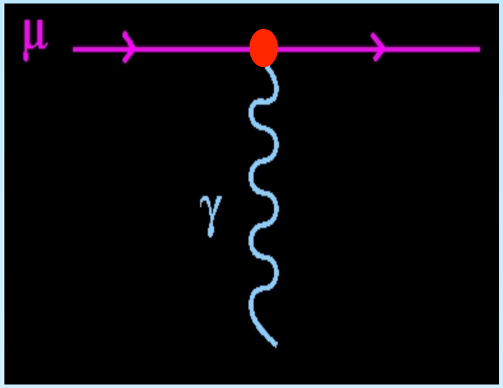
$$a(NewPhysics) = C\left(\frac{m}{\Lambda}\right)^2$$

where C could be $\mathcal{O}(1)$, **or**

$\mathcal{O}(\alpha)$ **in weak coupling loop scenarios**

Magnetic and Electric Dipole Interactions

$$\Gamma_\beta = QeF_1\bar{\psi}_R\gamma_\beta\psi_R + \frac{iQe}{2m}F_2\bar{\psi}_R\sigma_{\beta\delta}q^\delta\psi_L + HC$$



- Magnetic Dipole Momoment a_μ

chiral changing

$$\bar{u}_\mu[QeF_1(q^2)\gamma_\beta \boxed{+\frac{iQe}{2m_\mu}F_2(q^2)\sigma_{\beta\delta}q^\delta]u_\mu}$$

$$F_1(0) = 1 \qquad F_2(0) = a_\mu$$

- Electric Dipole Moment

$$\bar{u}_\mu\left[\frac{iQe}{2m_\mu}F_2(q^2) - F_3(q^2)\gamma_5\right]\sigma_{\beta\delta}q^\delta u_\mu$$

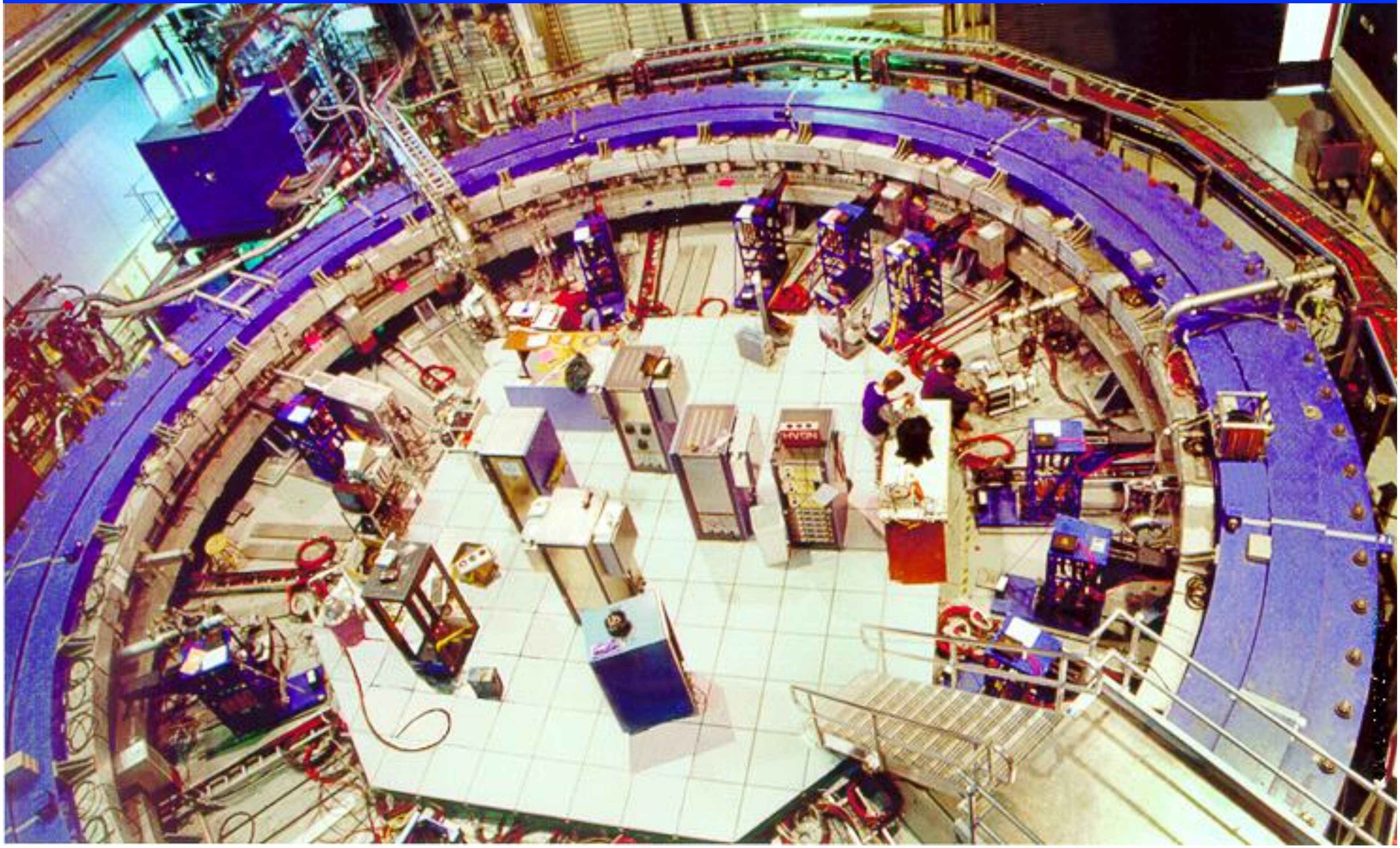
$$F_2(0) = a_\mu \qquad F_3(0) = d_\mu;\ \text{EDM}$$

Magnetic Dipole Moments

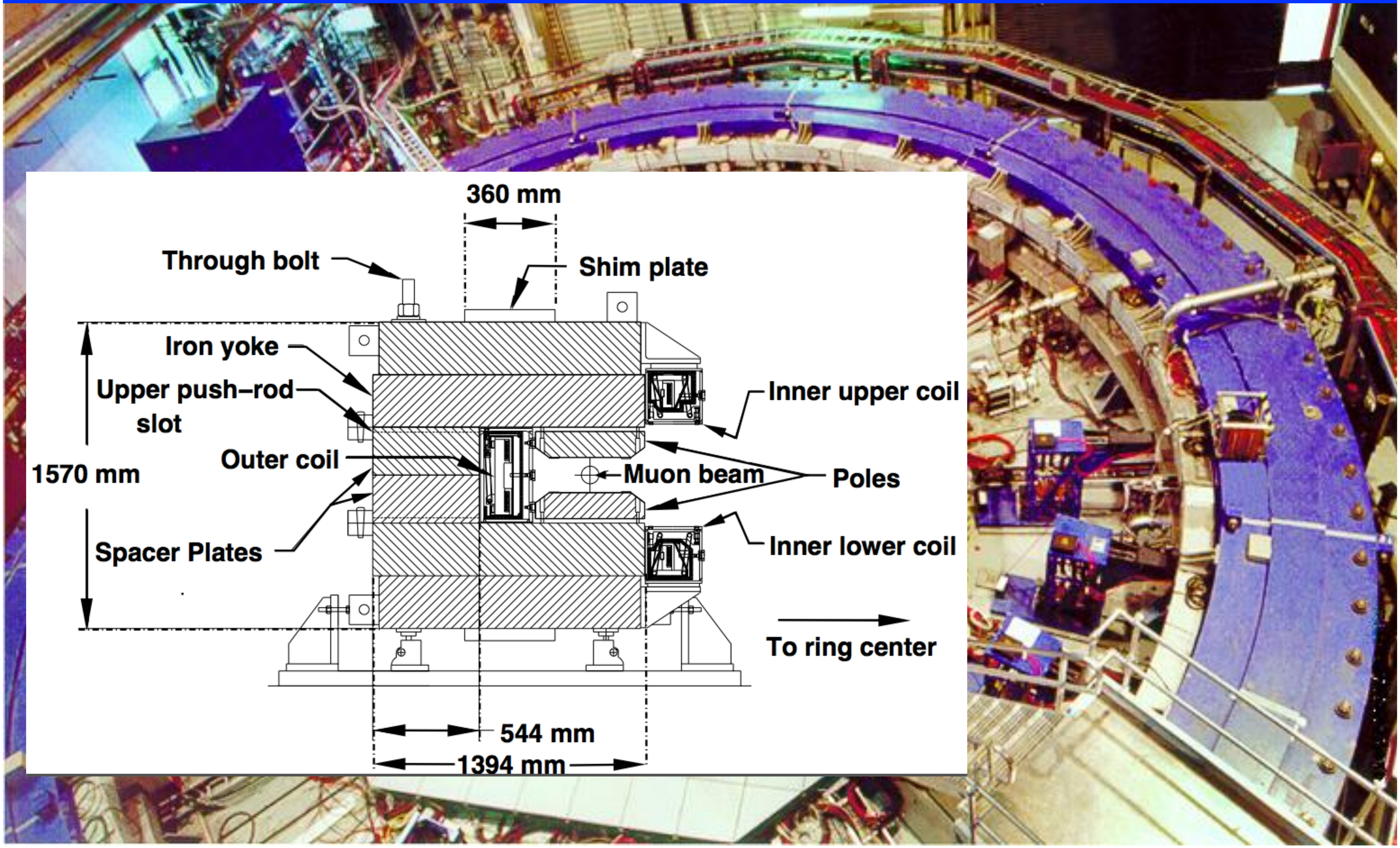
$$\vec{\mu} = g\left(\frac{Qe}{2m}\right)\vec{s}$$

$$g = 2(1+a) \qquad a = \frac{(g-2)}{2}$$

The Experiment



The Experiment



The miracles that make the experiment possible:

- Parity violation
  - produces polarized muons

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$

  - analyzes the spin orientation at the decay time

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

- The 2.2μs lifetime permits precision measurements
- The mass ~107 m_e gives sensitivity to the TeV scale
- The rate at which the spin turns relative to the momentum only depends on the anomaly and B field.

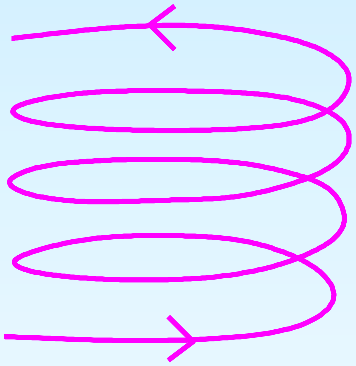
$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{Qe}{m} a_\mu \vec{B}$$

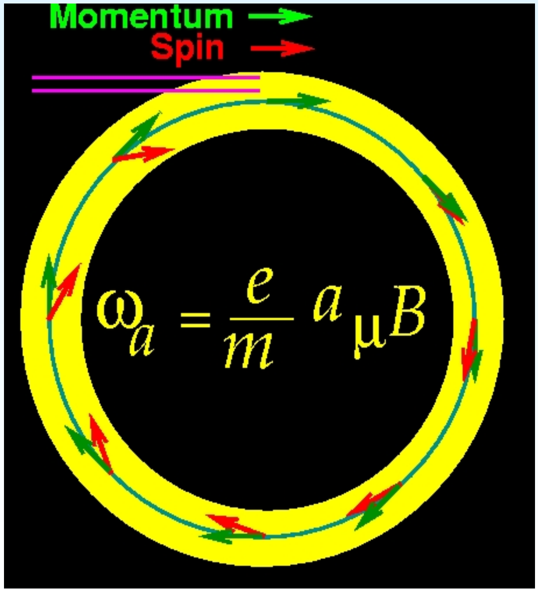
- There is a “magic” value of γ such that an E field doesn’t mess up this dependence

Need vertical focusing:

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{QeB}{m} \qquad B \Rightarrow \langle B \rangle_{\mu\text{-dist}}$$

without vertical focussing



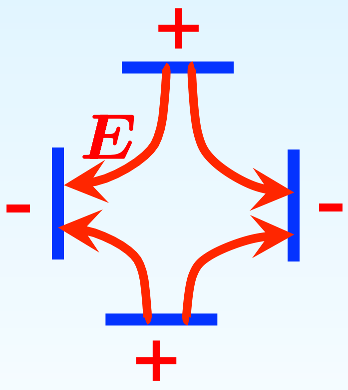


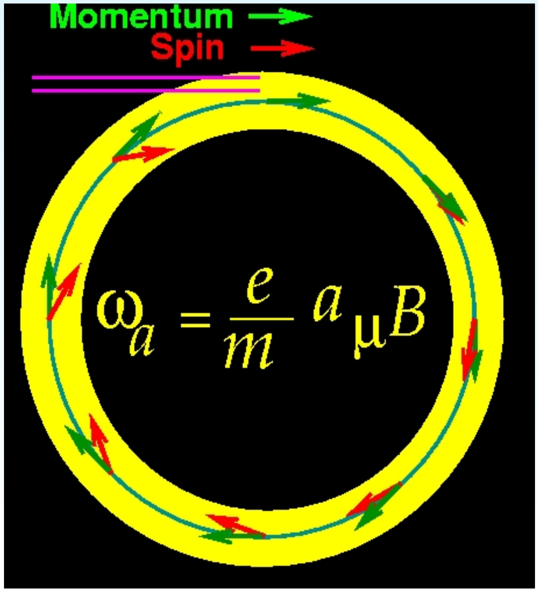
Need vertical focusing:

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{QeB}{m} \qquad B \Rightarrow \langle B \rangle_{\mu-\mathrm{dist}}$$

With an electric quadrupole field for vertical focusing

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





Need vertical focusing:

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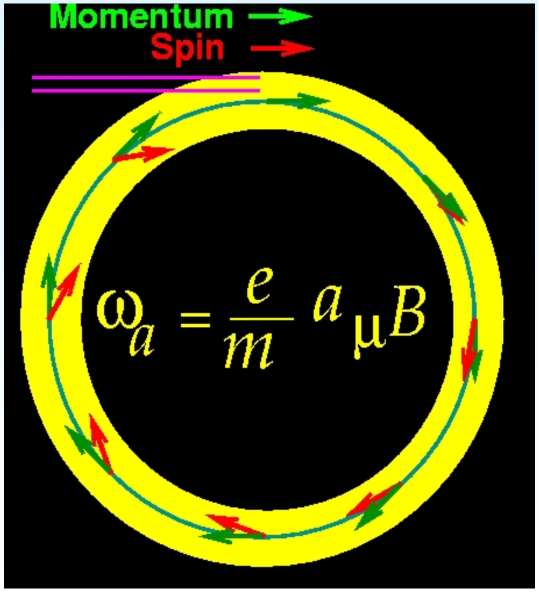
With an electric quadrupole field for vertical focusing

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

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

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



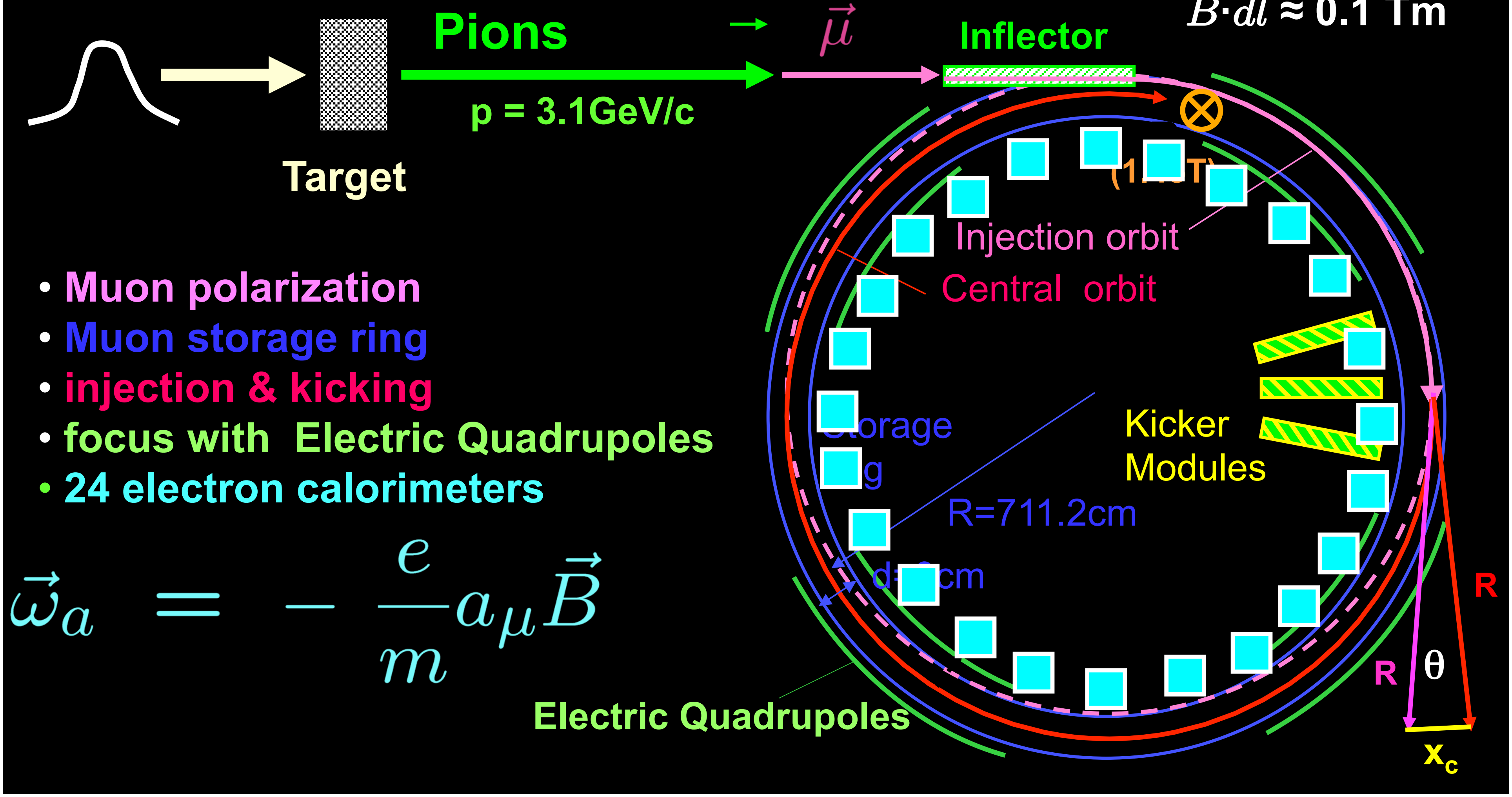
E821 Experimental Technique

25ns bunch of
5 X 10^{12} protons
from AGS

$x_c \approx$ 77 mm

$\theta \approx$ 10 mrad

$B\cdot dl \approx$ 0.1 Tm

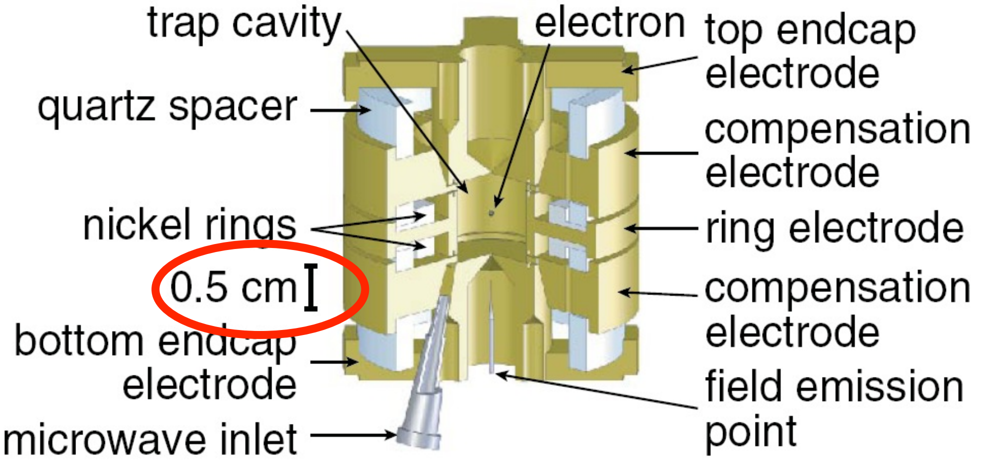


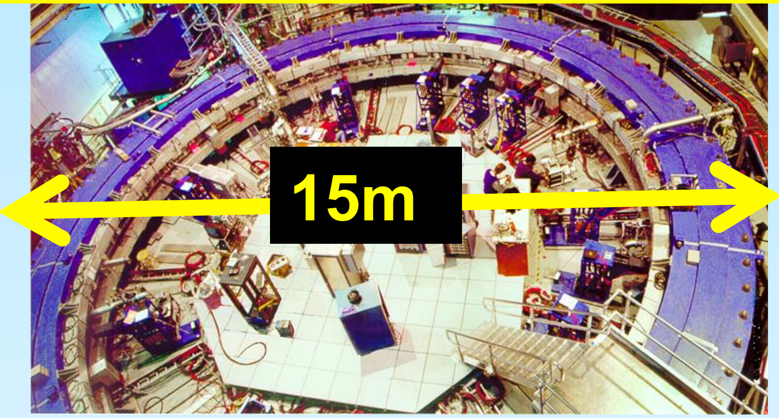
- **Muon polarization**
- **Muon storage ring**
- **injection & kicking**
- **focus with Electric Quadrupoles**
- **24 electron calorimeters**

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

e PRL 100, 120801 (2008)

μ PRL, 92, 161802 (2004)
PR D73, 072003 (2006)





$$a_e = (115\,965\,218\,073 \pm 28) \times 10^{-14} \; (0.24 \text{ ppb})$$

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

muon more sensitive to heavier physics by $\sim \left(\frac{m_\mu}{m_e}\right)^2 \simeq 42,000$

The measurement of a_e tests QED to the precision of the independent measurement of α, ± 0.66 ppb.

To determine a_μ we measure two numbers:

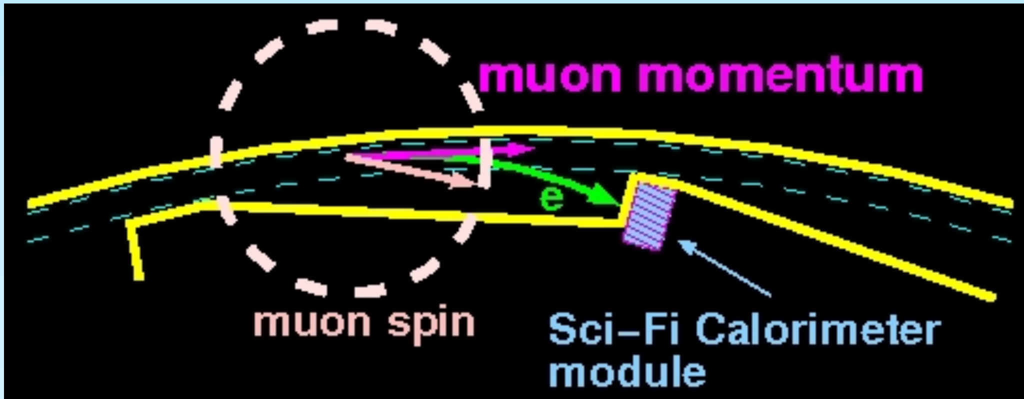
The muon spin frequency: ω_a

$$\boxed{\omega_a} = a\frac{e\boxed{B}}{mc}$$

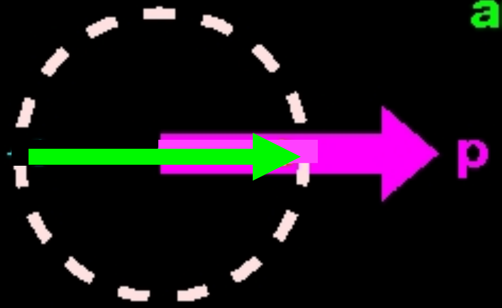
The magnetic field normalized to the Larmor frequency of the free proton: ω_p

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

To measure ω_a, we used Pb-scintillating fiber calorimeters.

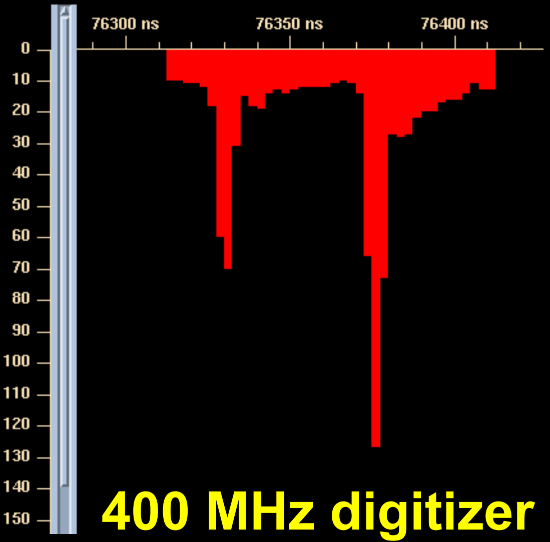


Measures Energy and time

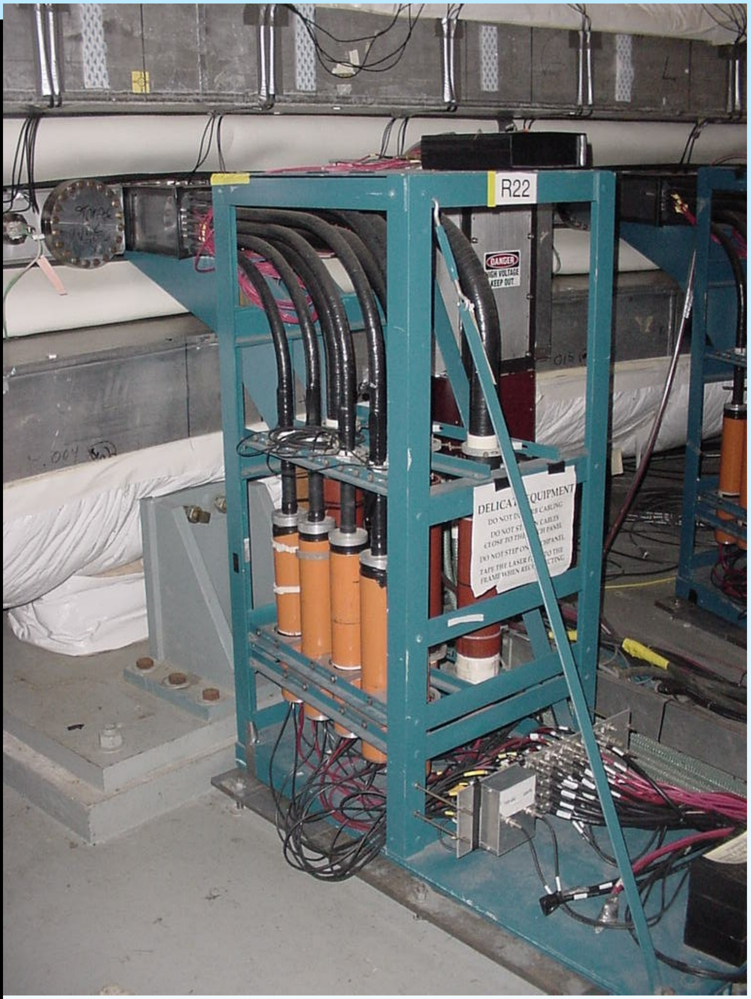


spin forward, more high energy e

spin backward, less high energy e



400 MHz digitizer gives t, E

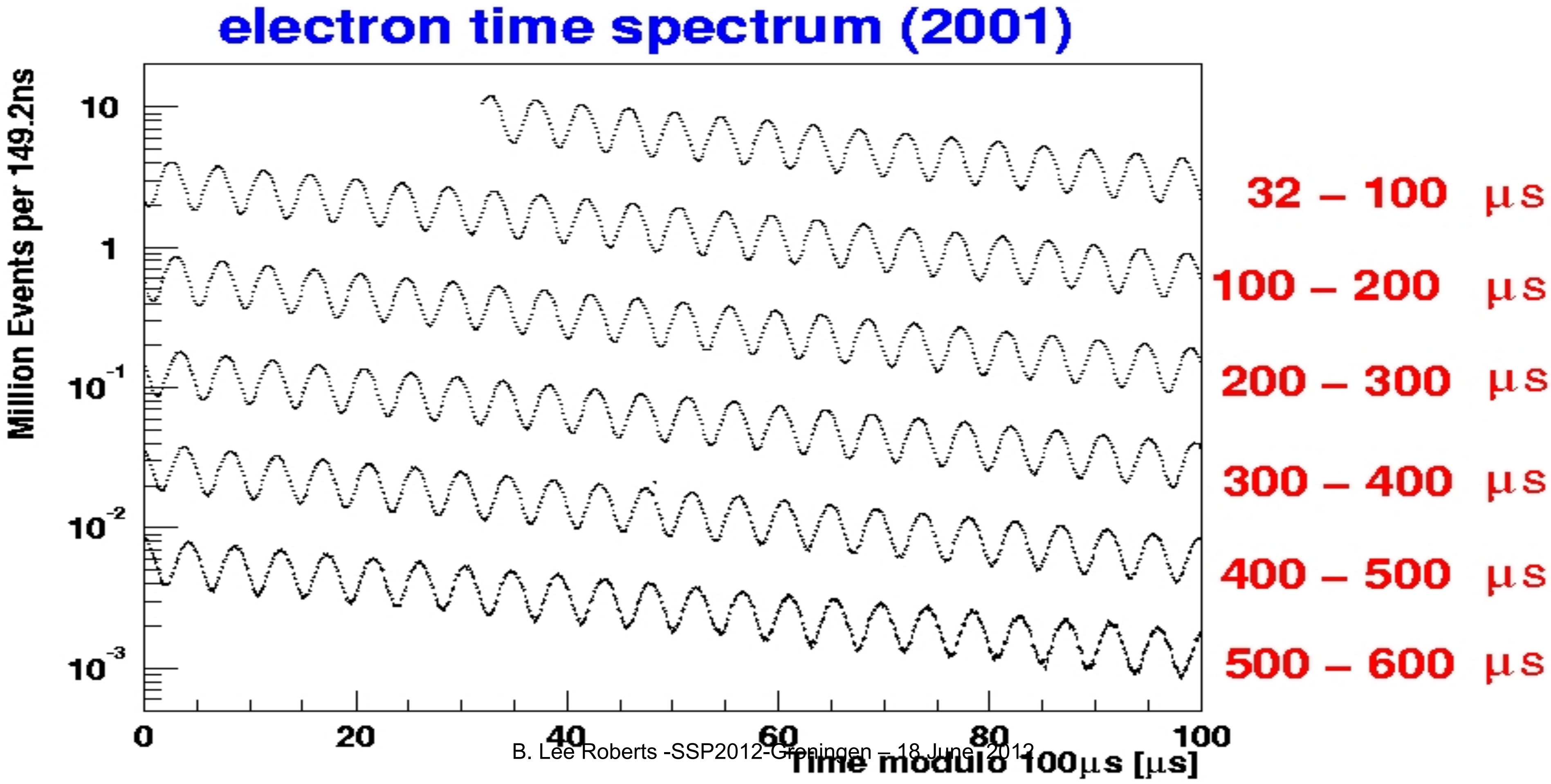


Count number of e^- with $E_e \geq 1.8$ GeV

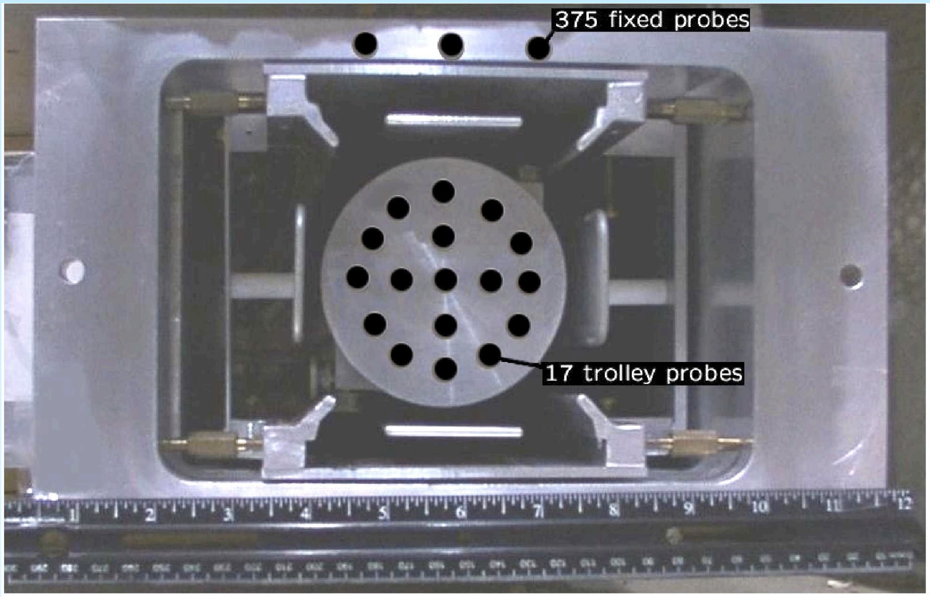
Arrival time spectrum

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

$$4 \times 10^9 \ e^-, \ E_{e^-} \geq 1.8 \ \text{GeV}$$

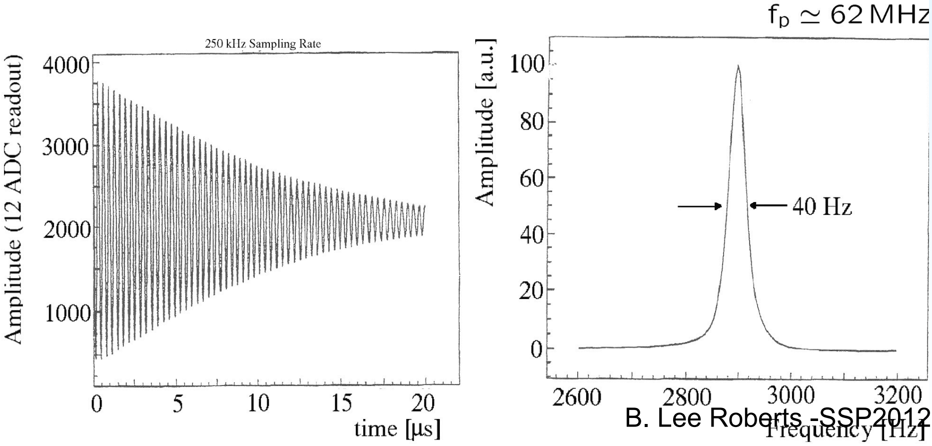


The magnetic field is measured and controlled using pulsed NMR and the free-induction decay.



- **Calibration to a spherical water sample that ties the field to the Larmor frequency of the free proton ω_p.**

Free induction decay signals:

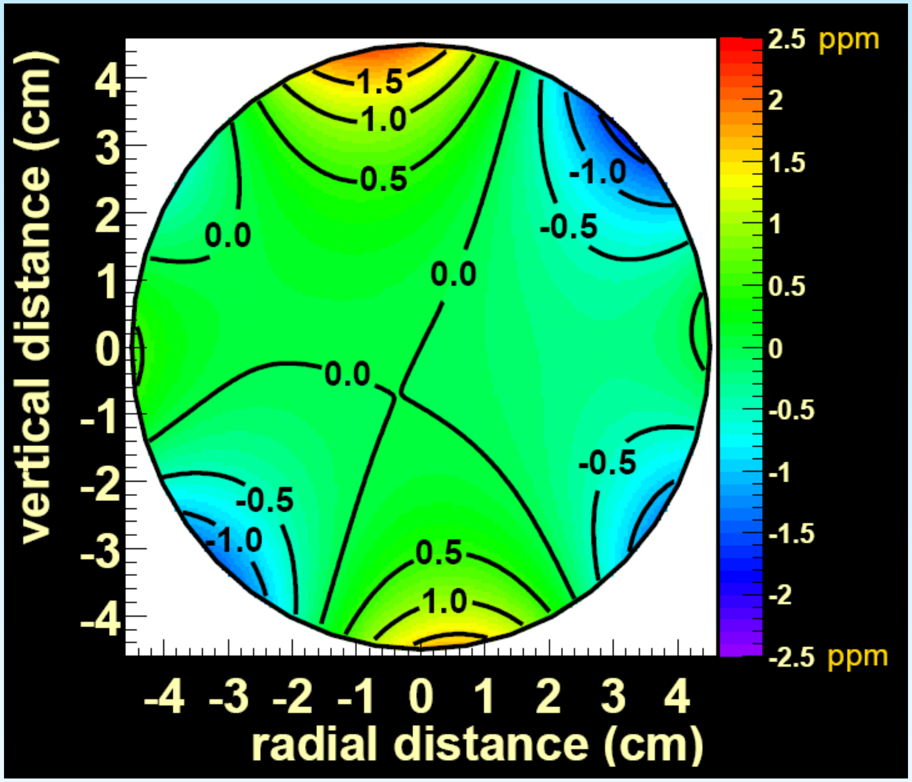


$$\boxed{a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}}$$

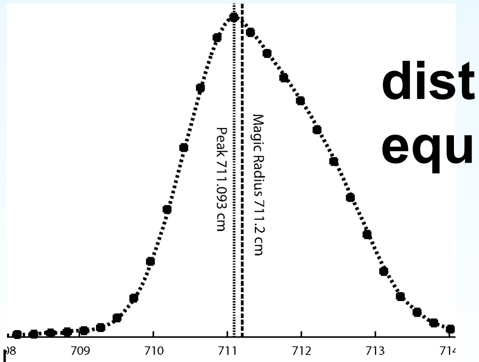
Average field uniformity ± 1 ppm

$\langle B \rangle_{\mathrm{azimuth}}$

0.5 ppm contours



$$\sigma_{\mathrm{syst}} \langle B \rangle_{\mu-\mathrm{dist}} = \pm 0.03 \text{ ppm}$$

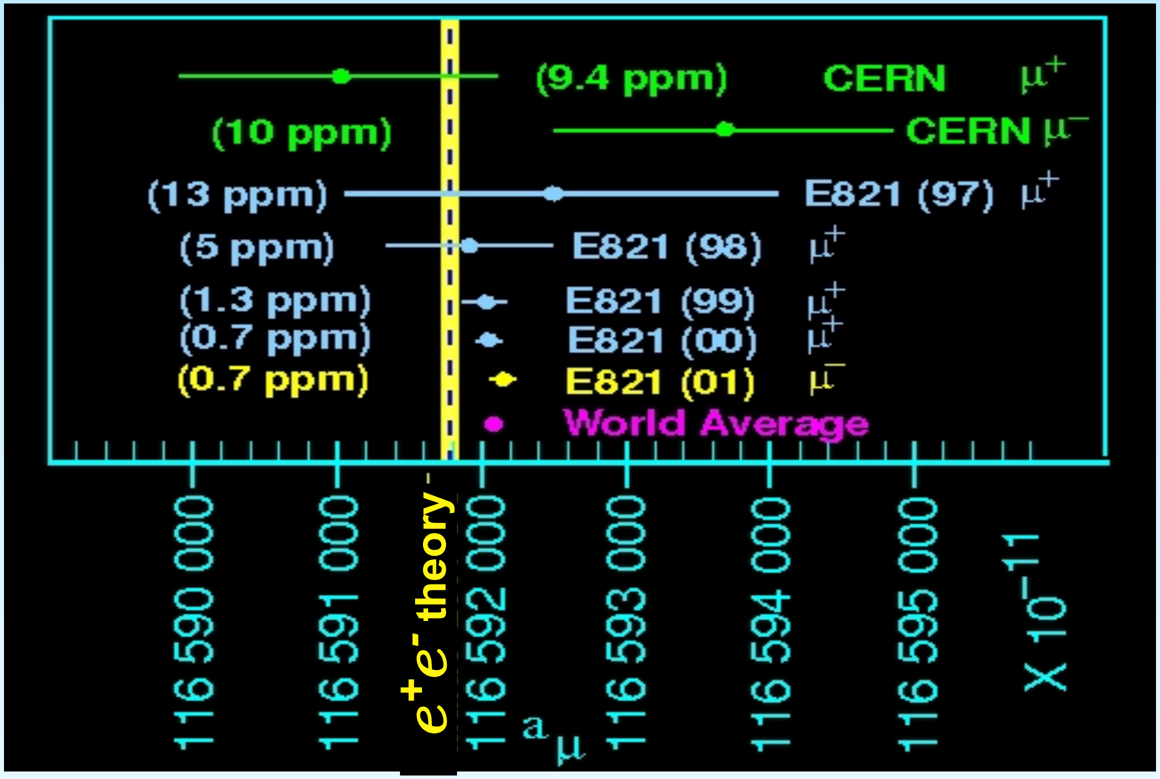


dist. of μ equil. radii

E821 achieved ± 0.54 ppm. The e^+e^- based theory is at the ~0.49 ppm level. Difference is >3σ

SM: Davier et al, , Eur. Phys. J. C (2011) 71:1515

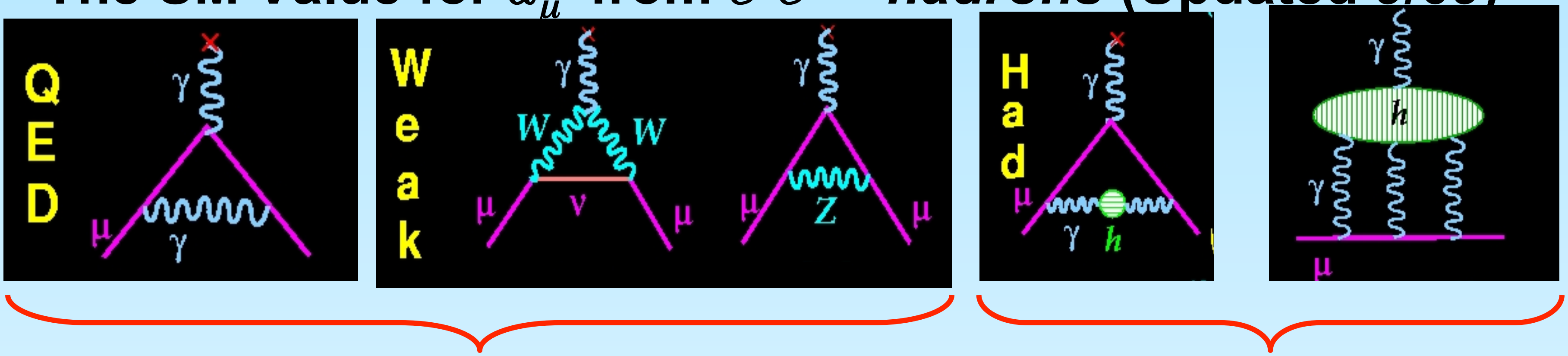
Hagiwara, et al., J.Phys. G **38** (2011) 085003



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

How can the Standard Model digest this result?

The SM Value for a_μ from $e^+e^- \to$ *hadrons* (Updated 9/09)



well known **significant work ongoing**

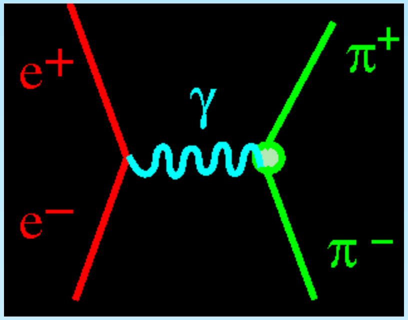
	Value $(\times 10^{-11})$ units
QED $(\gamma + \ell)$	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)	-98.4 ± 0.7
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

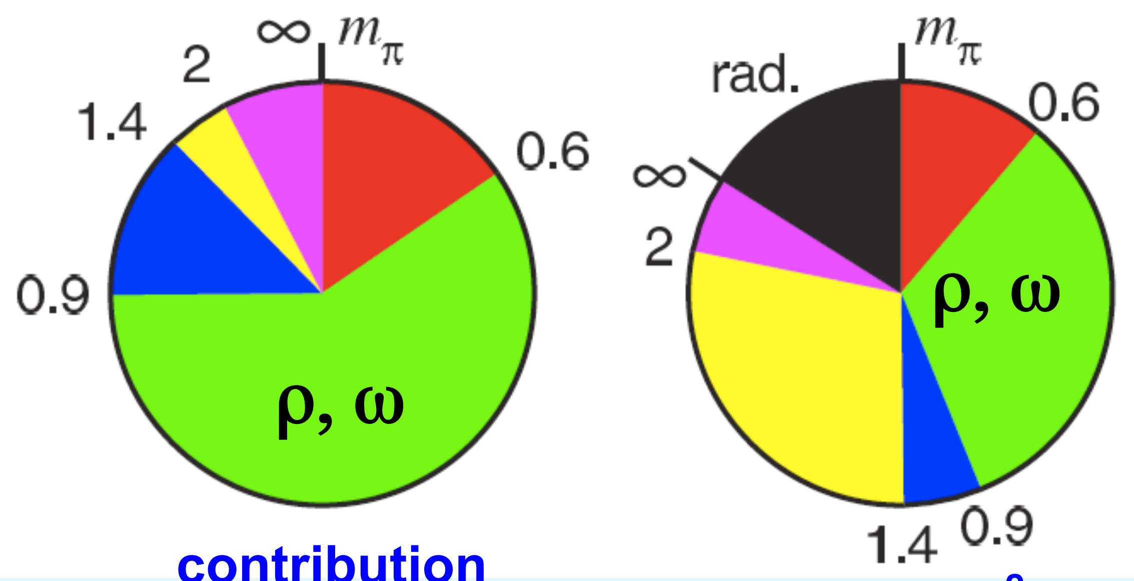
$$\sigma_{\text{exp}} = \pm 63$$

*Davier et al, Eur. Phys. J. C (2011) 71:1515

a_μ^{had}(LO) Analyticity + Optical Theorem

$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$





contribution

error²

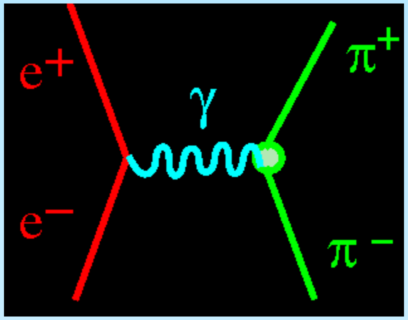
(from T. Teubner)

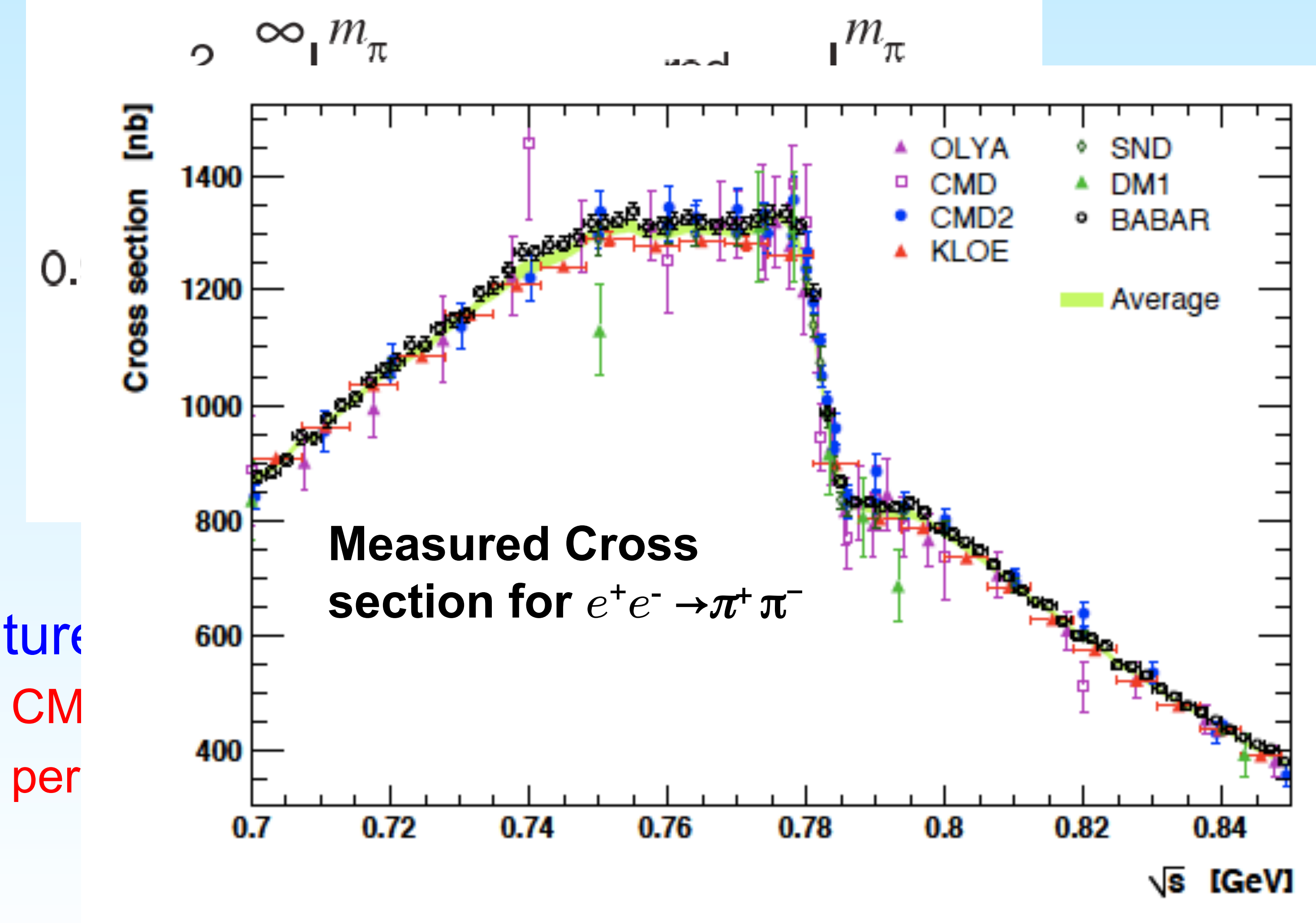
(w/o BaBar)

- Future efforts will reduce errors
  - CMD3 at VEPP2000, up to 2.0 GeV (next 5 years)
  - perhaps Belle

a_μ^{had}(LO) Analyticity + Optical Theorem

$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \quad \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$



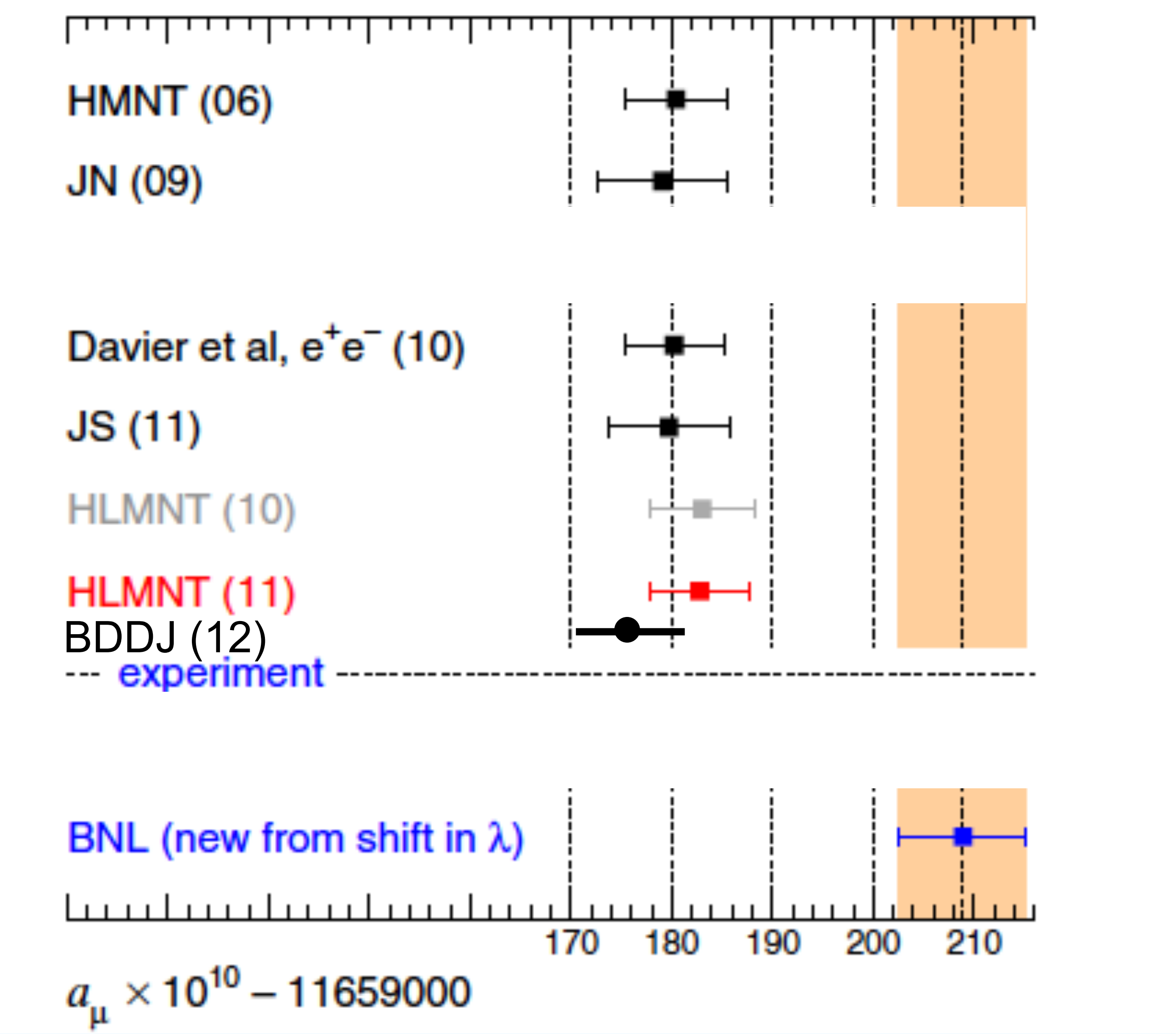


Measured Cross section for $e^+e^- \to \pi^+\pi^-$

Bar)

- Future
  - CM
  - per

Summary of recent e^+e^- based theory evaluations*

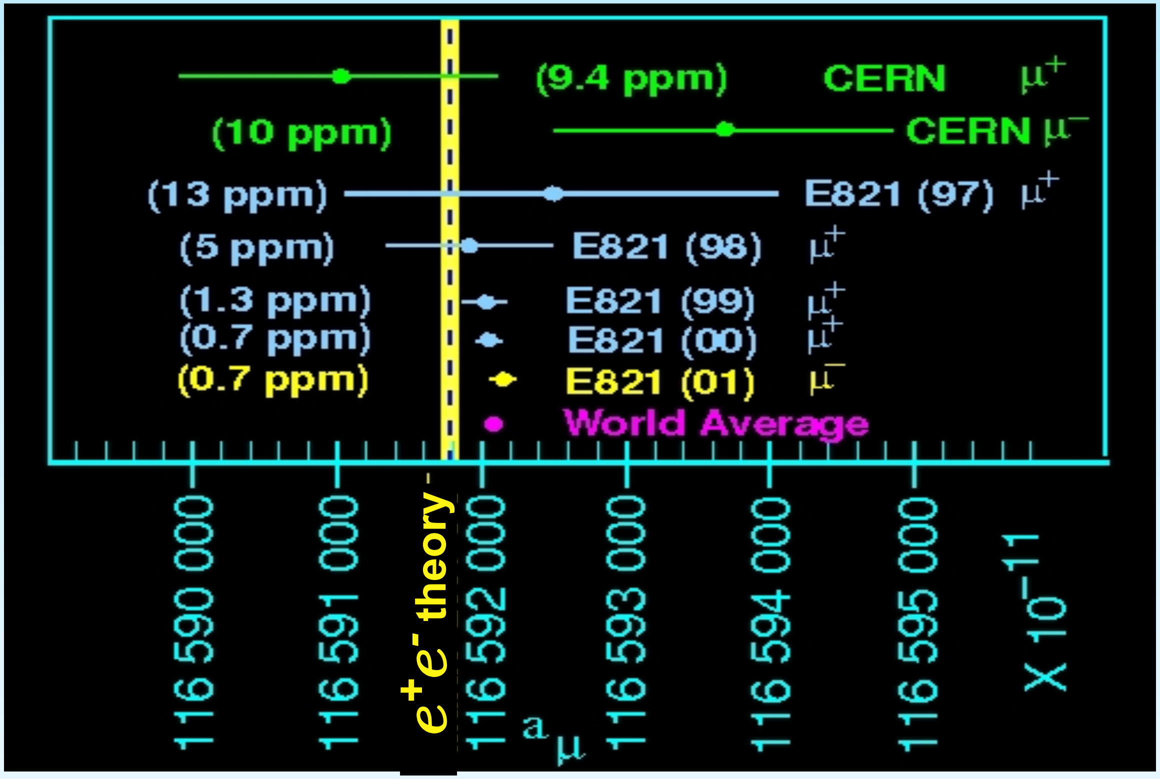


*from Hagiwara et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 085003

E821 achieved ± 0.54 ppm. The $e^{+}e^{-}$ based theory is at the ~0.49 ppm level. Difference is >3σ

SM: Davier et al, , Eur. Phys. J. C (2011) 71:1515

Hagiwara, et al., J.Phys. G **38** (2011) 085003

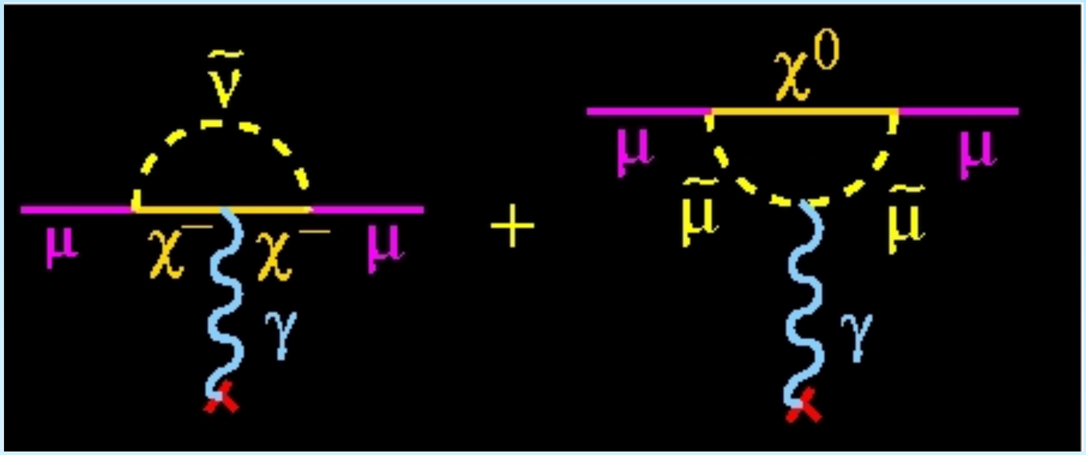


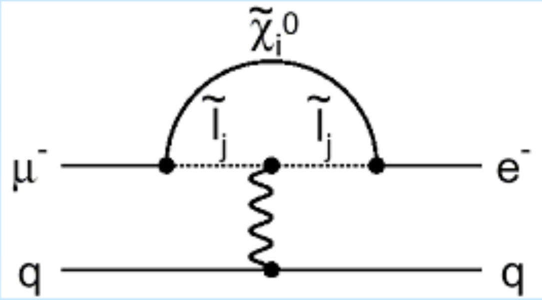
$$a_{\mu}^{exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\,\mathrm{ppm})$$

$$\Delta a_{\mu}^{(\mathrm{today})} = (288 \pm 80) \times 10^{-11}$$

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

a_μ is sensitive to a wide range of new physics, e.g.SUSY





$$a_\mu(\text{SUSY}) \simeq \boxed{(\text{sgn}\mu)}\,130\times10^{-11}\,\boxed{\tan\beta}\left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

Related processes in SUSY

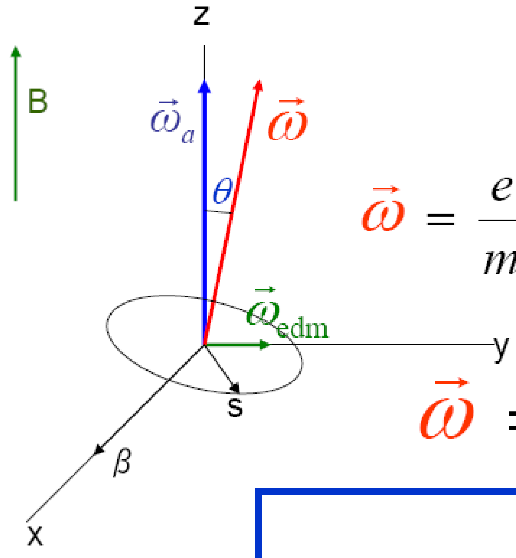
$$\mu^+ \rightarrow e^+\gamma;\ \ \mu^- + \mathcal{N} \rightarrow e^- + \mathcal{N}$$

Intermezzo: EDMs in Storage Rings:

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

$$+ \frac{Qe}{2m}\left[\eta\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\vec{d} = \eta\left(\frac{Qe}{2mc}\right)\vec{s}$$



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

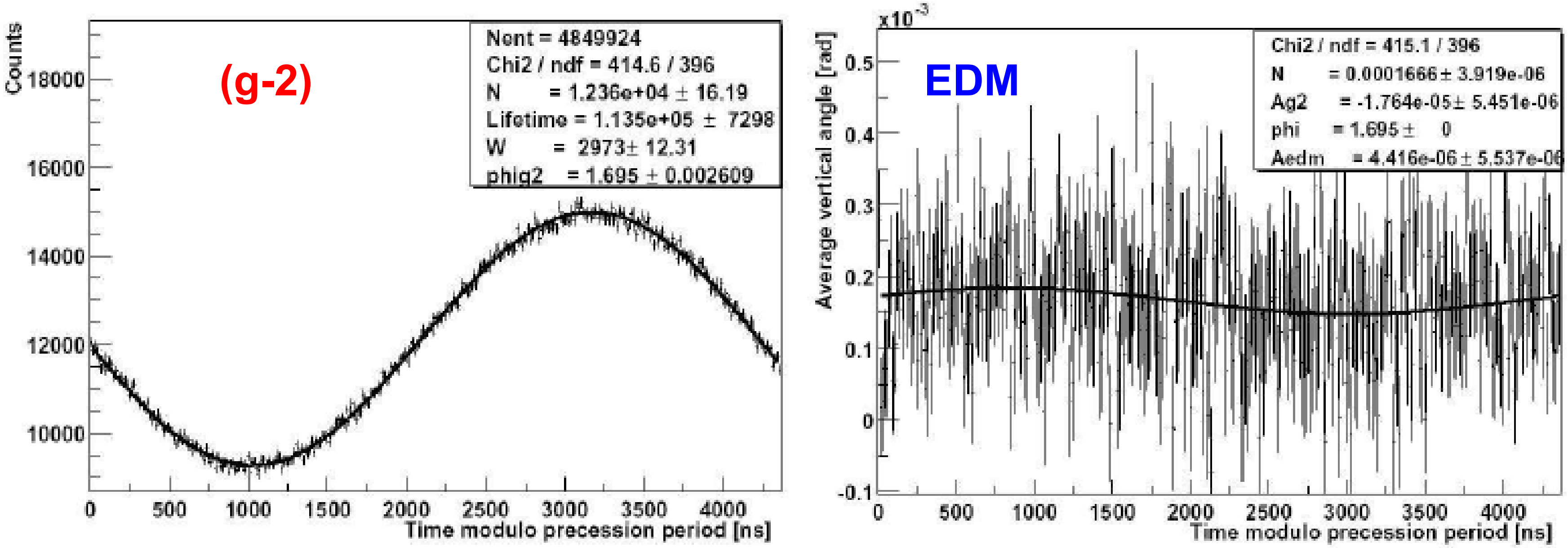
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\rm edm}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

$$\omega_{\rm edm} <<<<<< \omega_a$$

Signal: up-down oscillation π/2 out of phase with ω_a using upward-going and downward-going tracks

E821 Data



Vertical Oscillation out of phase with ω_a

$$N^{\pm}(t) \propto 1 + A_{\mu} \cos(\omega t + \phi) \mp A_{EDM} \sin(\omega t + \phi)$$

$$d_{\mu} < 1.8 \times 10^{-19} \text{ (95\% CL)}$$

This EDM would shift a_μ by $(0.0 \pm 42) \times 10^{-11}$

3.3 – 3.6 σ: Theory & Experiment must do better

The New $g-2$ Experiment:

An experiment to Measure the Muon Anomalous Magnetic Moment

to ±0.14 ppm Precision

- Experiment: E989 at Fermilab ≥ X4 better
  - relocate the storage ring to Fermilab (operations $)
  - use the p-bar debuncher (now called the delivery ring) as a long decay line.
- CD0 expected very soon.
- Building construction will begin in November 2012

The error budget for a new experiment represents a continuation of improvements already made during E821

Systematic uncertainty (ppm)	1998	1999	2000	2001	E821 final	P989 Goal
Magnetic field – ω_p	0.5	0.4	0.24	0.17		0.07
Anomalous precession – ω_a	0.8	0.3	0.31	0.21		0.07
Statistical uncertainty (ppm)	4.9	1.3	0.62	0.66	0.46	0.1
Systematic uncertainty (ppm)	0.9	0.5	0.39	0.28	0.28	0.1
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	0.54	0.14

Sikorsky S64F 12.5 T hook weight (Outer coil 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.

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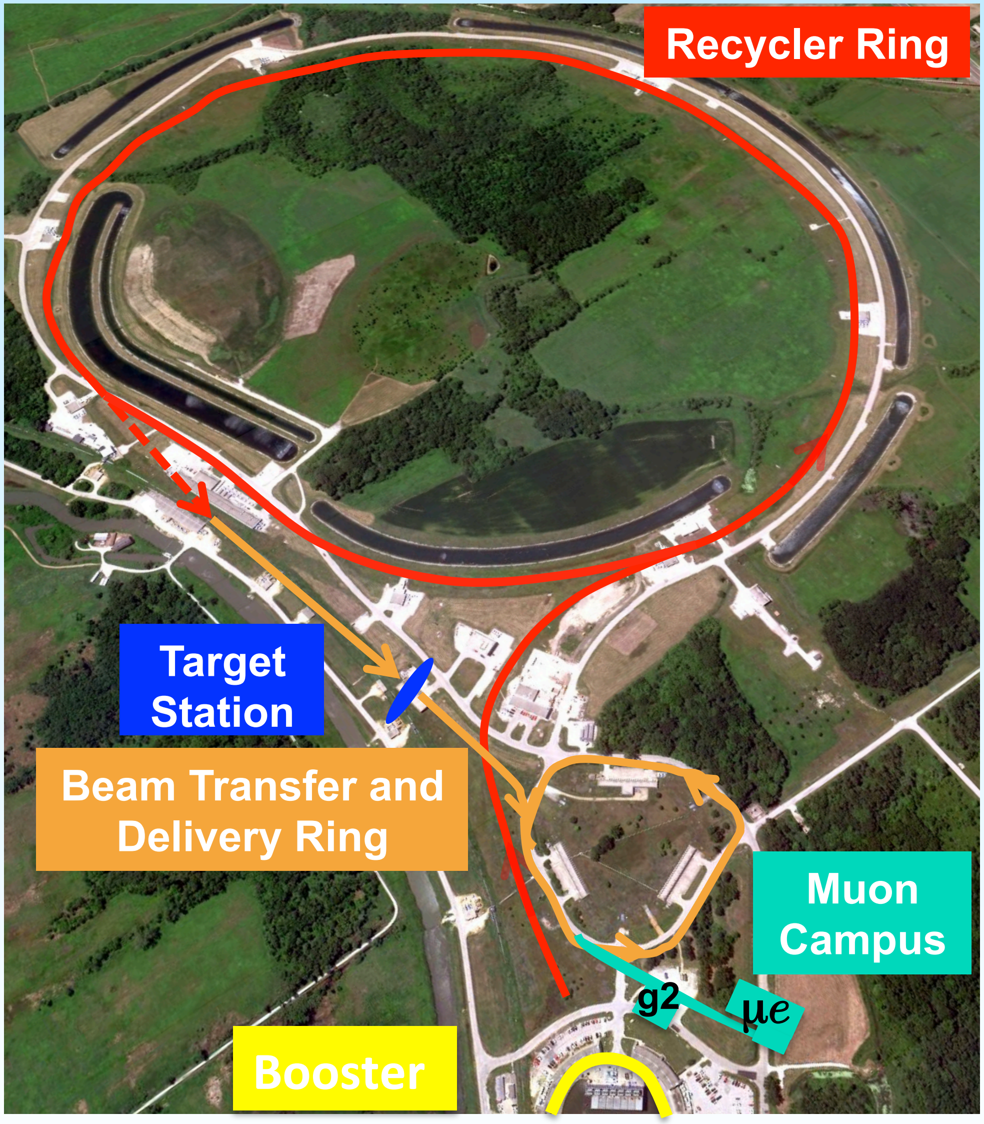
Fermilab Muon Campus

Multipurpose Building designed for future experiments as well

Fermilab Muon Campus

Multipurpose Building designed for future experiments as well

Fermilab Muon Beam



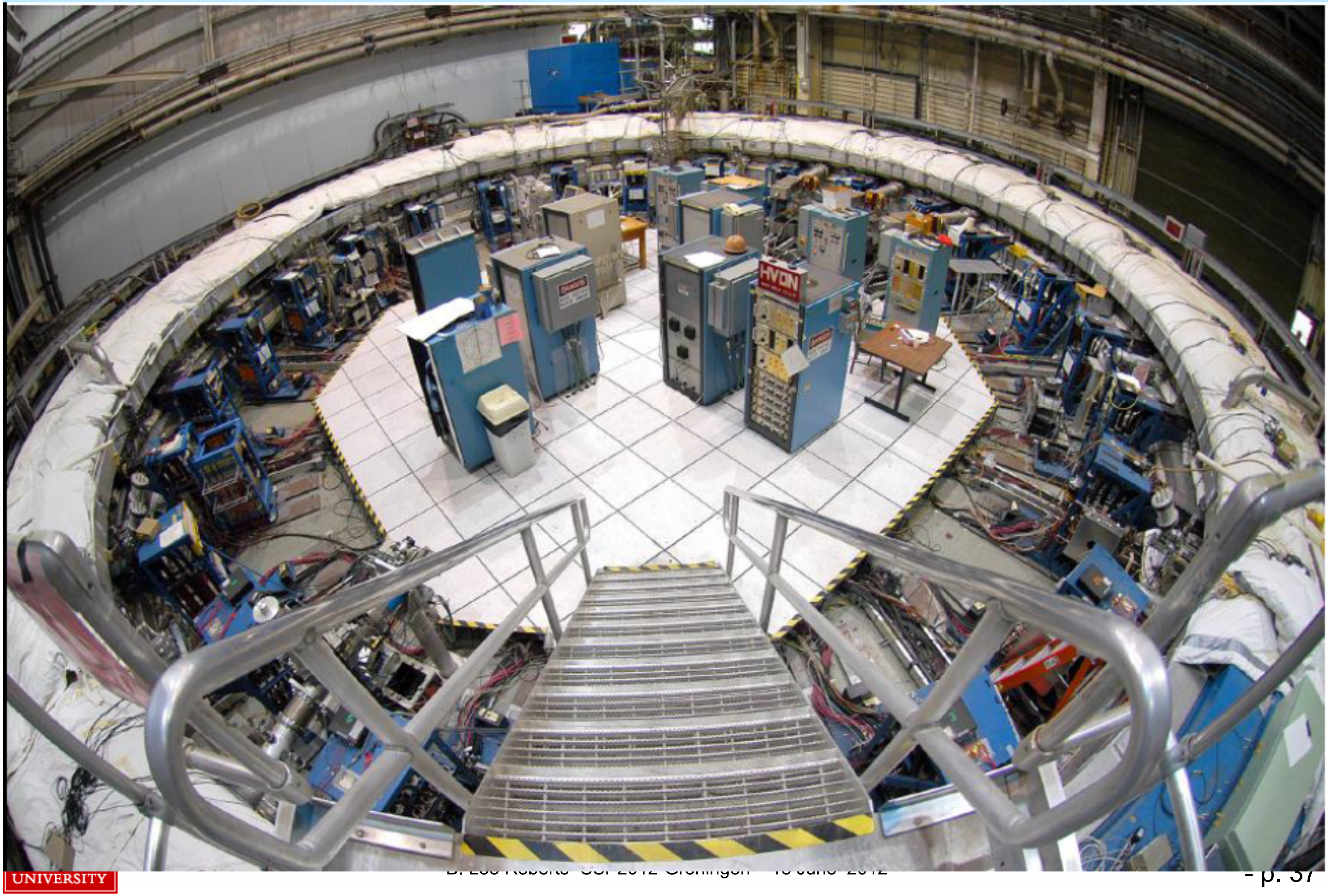
One 4×10^{12} p bunch to recycler

Re-bunch to 4 bunches

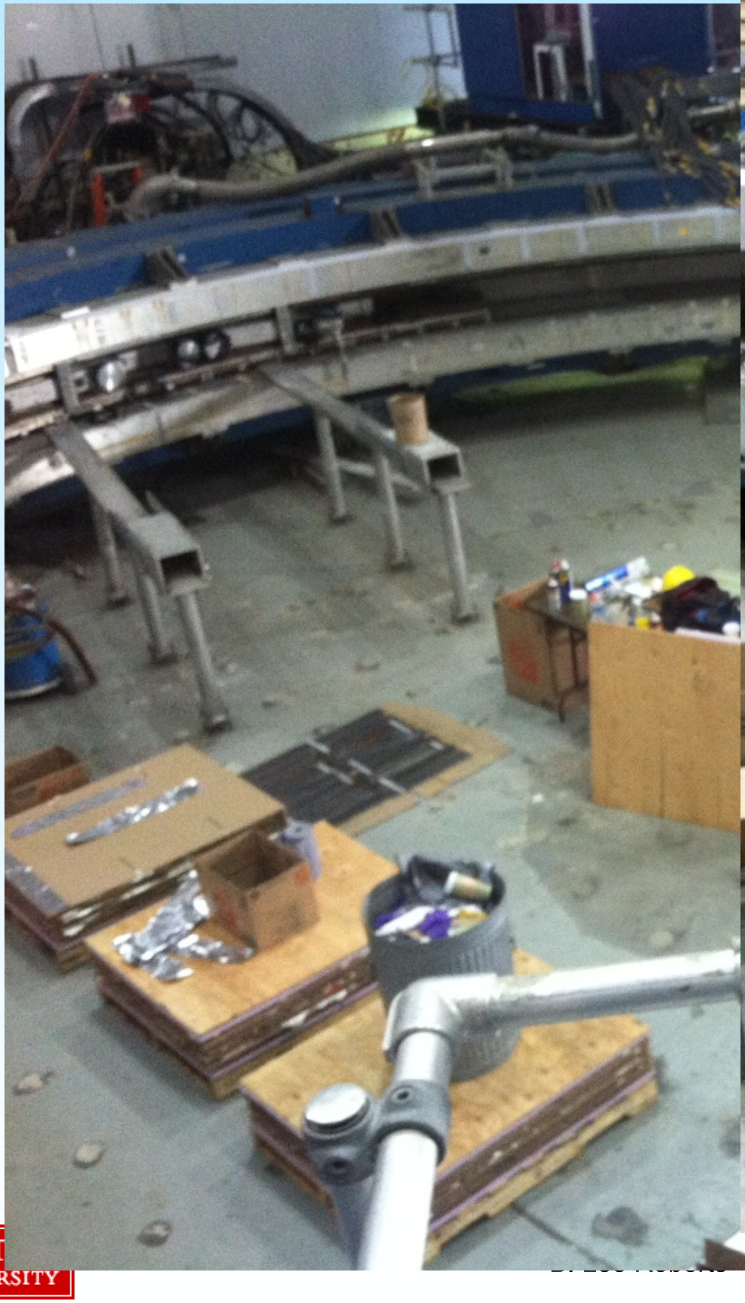
Extract one bunch at a time to target

Use the delivery ring as a 1,900 m decay line

Storage Ring at BNL in 2011

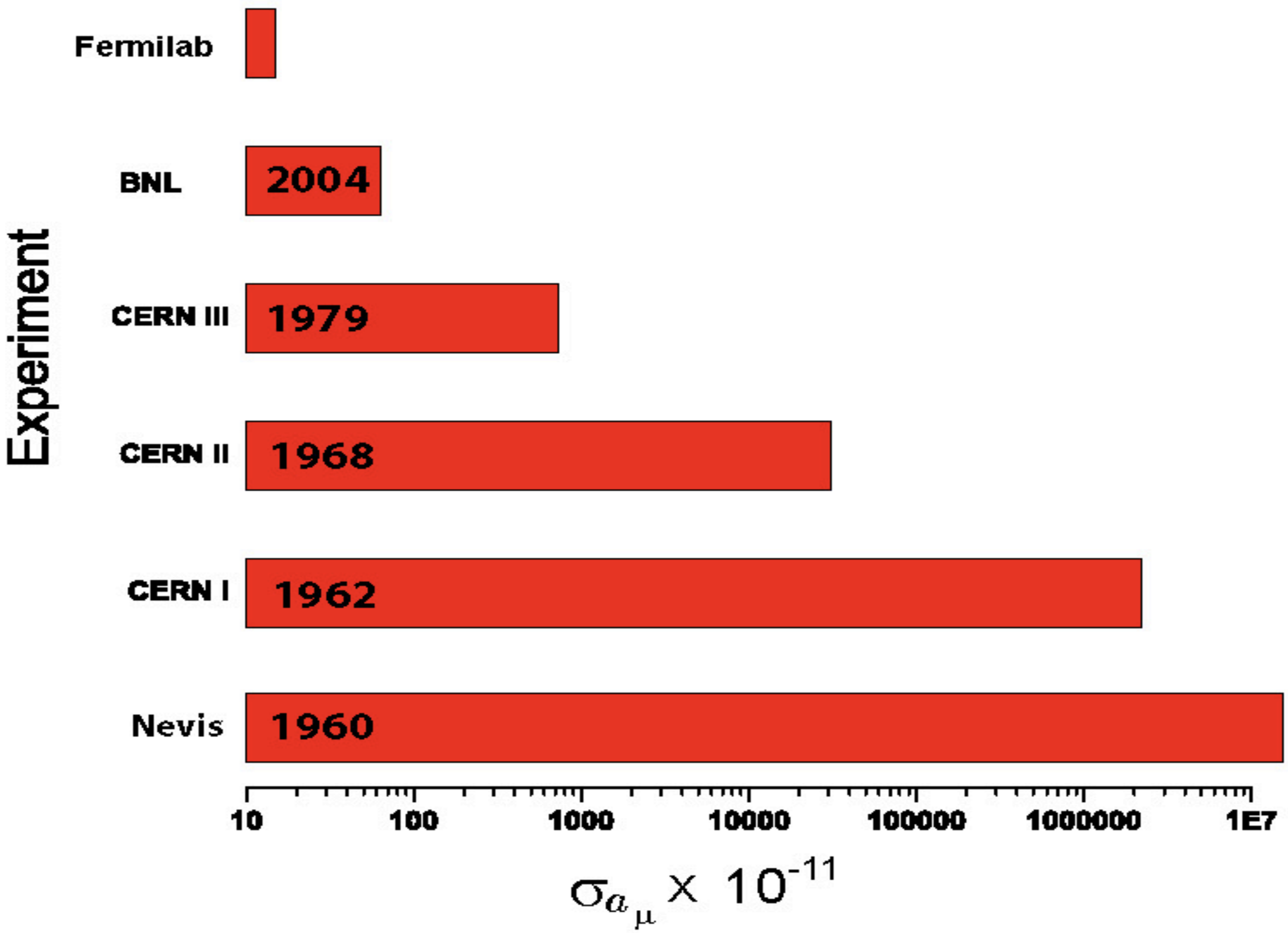


May 2012



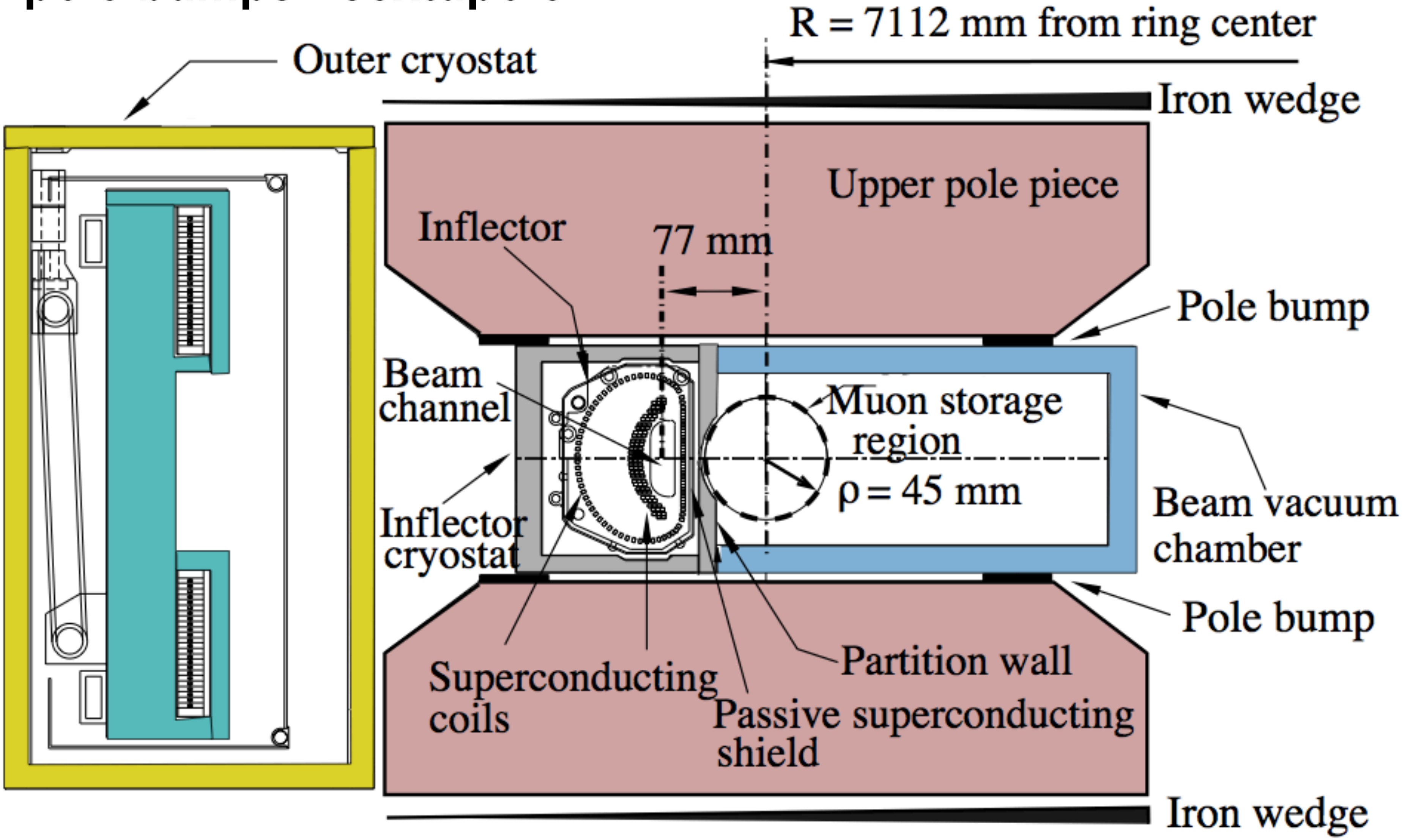
Final words:

- There appears to be a ≥ 3.2 s difference between experiment and theory
- E989 is at an exciting point
  - will improve on E821 by at least X4
  - CD0 soon, building construction starting November 2012
  - plan to relocate the storage ring in 2013
- Worldwide effort on all aspects of the theory continues
  - more e^+e^- data from BES, KLOE, Mainz, Novosibirsk
  - H-LBL work continues on several fronts (including KLOE)
  - The lattice is becoming relevant, both for H-LO and H-LBL
- It’s an opportunity to make a huge impact in the search for physics beyond the standard model.


Fermilab
BNL
2004
CERN III
1979
CERN II
1968
CERN I
1962
Nevis
1960
Experiment
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$

Magnet shimming tools (Gordon Danby's design):

wedges – radial motion dipole;
wedge angle – quadrupole
pole bumps - sextupole



The absolute B - field calibration

- The Larmor frequency of a proton in a spherical water sample is related to the free proton by:

$$f_{\mathrm{L}}(\mathrm{sph}-\mathrm{H_2O},T) = [1-\sigma(\mathrm{H_2O},T)]\, f_{\mathrm{L}}(\mathrm{free})$$

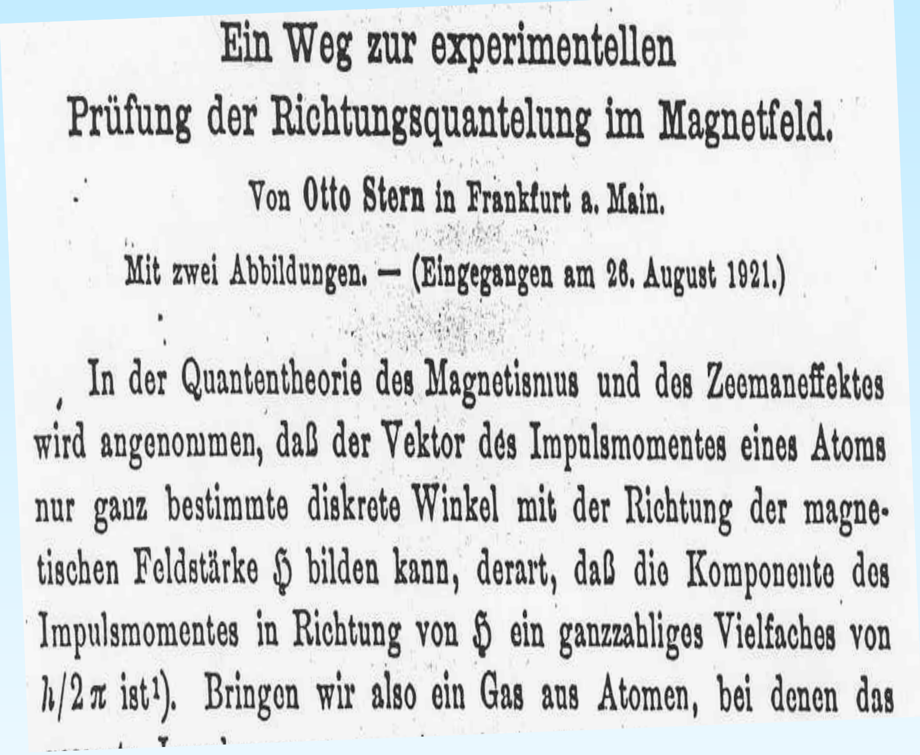
where is from the internal diamagnetic shielding of the proton in a water molecule

$$\sigma(\mathrm{H_2O}, 34.7^\circ C) = 1 - \frac{g_p(\mathrm{H_2O}, 34.7^\circ C)}{g_J(H)} \frac{g_J(H)}{g_p(H)} \frac{g_p(H)}{g_p(\mathrm{free})}$$

- We have thought about a 3He absolute calibration probe, which would provide an independent absolute calibration.
  - This is an opportunity for new collaborator(s) to make a significant contribution to E989

Measurements of MDMs began with a proposal by Otto Stern to study space quantization:

Z. Phys. 7, 249 (1921)

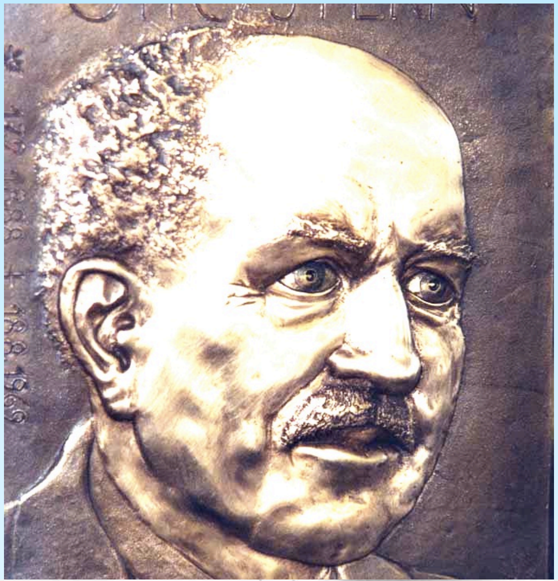


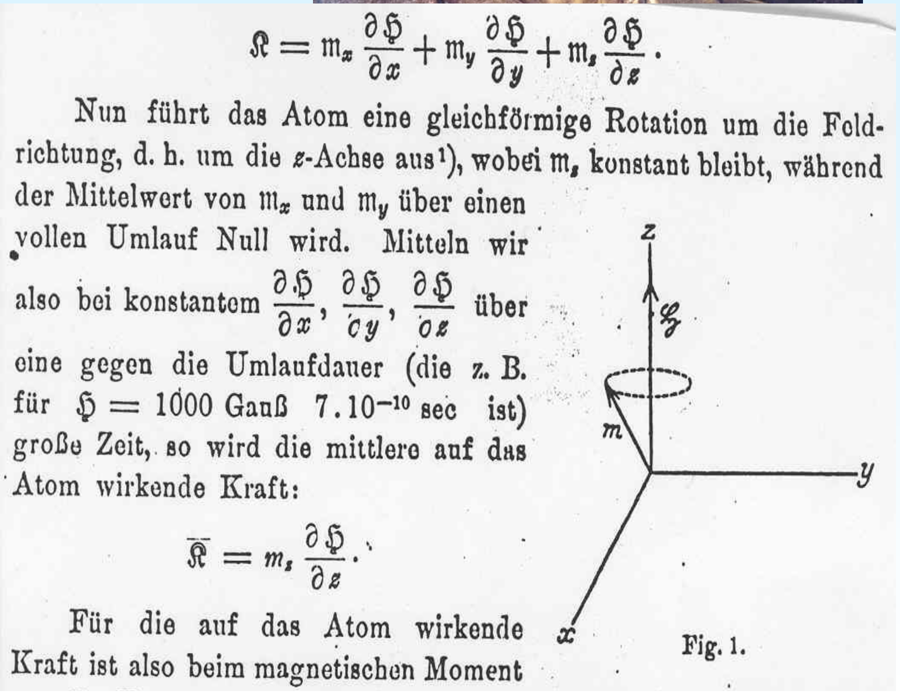
Ein Weg zur experimentellen Prüfung der Richtungsquantelung im Magnetfeld.

Von Otto Stern in Frankfurt a. Main.

Mit zwei Abbildungen. — (Eingegangen am 26. August 1921.)

In der Quantentheorie des Magnetismus und des Zeemaneffektes wird angenommen, daß der Vektor des Impulsmomentes eines Atoms nur ganz bestimmte diskrete Winkel mit der Richtung der magnetischen Feldstärke $\mathfrak{H}$ bilden kann, derart, daß die Komponente des Impulsmomentes in Richtung von $\mathfrak{H}$ ein ganzzahliges Vielfaches von $h/2\pi$ ist[1]). Bringen wir also ein Gas aus Atomen, bei denen das





$$\mathfrak{K} = \mathfrak{m}_x \frac{\partial \mathfrak{H}}{\partial x} + \mathfrak{m}_y \frac{\partial \mathfrak{H}}{\partial y} + \mathfrak{m}_z \frac{\partial \mathfrak{H}}{\partial z}.$$

Nun führt das Atom eine gleichförmige Rotation um die Feldrichtung, d. h. um die z-Achse aus[1]), wobei $\mathfrak{m}_z$ konstant bleibt, während der Mittelwert von $\mathfrak{m}_x$ und $\mathfrak{m}_y$ über einen vollen Umlauf Null wird. Mitteln wir also bei konstantem $\frac{\partial \mathfrak{H}}{\partial x}, \frac{\partial \mathfrak{H}}{\partial y}, \frac{\partial \mathfrak{H}}{\partial z}$ über eine gegen die Umlaufdauer (die z. B. für $\mathfrak{H} = 1000$ Gauß 7.10^{-10} sec ist) große Zeit, so wird die mittlere auf das Atom wirkende Kraft:

$$\overline{\mathfrak{K}} = m_z \frac{\partial \mathfrak{H}}{\partial z}.$$

Für die auf das Atom wirkende Kraft ist also beim magnetischen Moment

Fig. 1.

By 1924: they published 3 papers plus this review article.

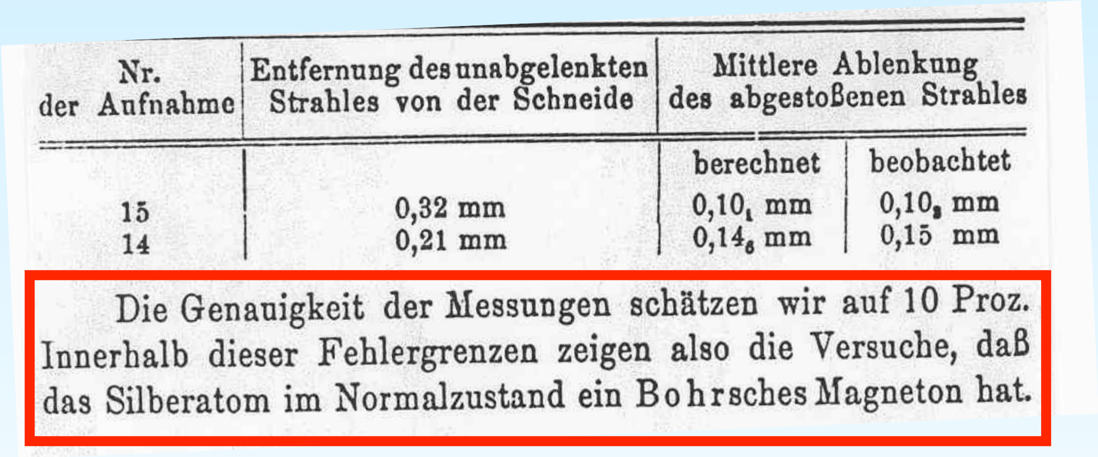
1924. № 10.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 74.

1. *Über die Richtungsquantelung im Magnetfeld*[1]);
von Walther Gerlach und Otto Stern.

(Hierzu Tafel III.)



Nr. der Aufnahme	Entfernung des unabgelenkten Strahles von der Schneide	Mittlere Ablenkung des abgestoßenen Strahles	
		berechnet	beobachtet
15	0,32 mm	$0{,}10_1$ mm	$0{,}10_3$ mm
14	0,21 mm	$0{,}14_6$ mm	0,15 mm

Die Genauigkeit der Messungen schätzen wir auf 10 Proz. Innerhalb dieser Fehlergrenzen zeigen also die Versuche, daß das Silberatom im Normalzustand ein Bohrsches Magneton hat.

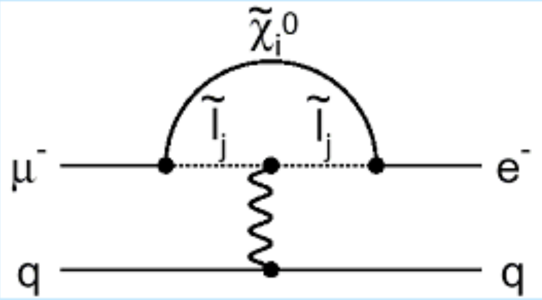
in modern language

$$\vec{\mu}_s = g_s \left(\frac{Qe}{2m} \right) \vec{s}$$

$$\Rightarrow g = 2$$

Connection to other muon physics: Transition Moments and Form Factors $f_i \rightarrow f_j$

$$\left\langle f_j\left(p'\right)\left|J_\mu^{\mathrm{em}}\right| f_i(p)\right\rangle = \bar{u}_j\left(p\right.$$



$$\Gamma_\mu^{ij} = \underbrace{\left(q^2 g_{\mu\nu} - q_\mu q_\nu\right)\gamma^\nu \left[F_{E0}^{ij}\left(q^2\right) + \gamma_5\right.}$$

chiral-conserving, flavor-changing amplitudes at $q^2 \neq 0$

$$\text{e.g. } K^+ \longrightarrow \pi^+ e^+ e^-; \quad \mu^+ \longrightarrow e^+ e^+ e^-$$

$$\underbrace{+ i\sigma_{\mu\nu} q^\nu \left[F_{M1}^{ij}\left(q^2\right) + \gamma_5 F_{E1}^{ij}\left(q^2\right)\right]}.$$

chiral-changing, flavor-changing amplitudes at $q^2 \neq 0$

$$\text{e.g. } b \longrightarrow s\gamma; \quad \mu \longrightarrow e\gamma; \quad \tau \longrightarrow \mu\gamma$$

I wish to acknowledge up front that I have borrowed heavily from articles in the new World Scientific book

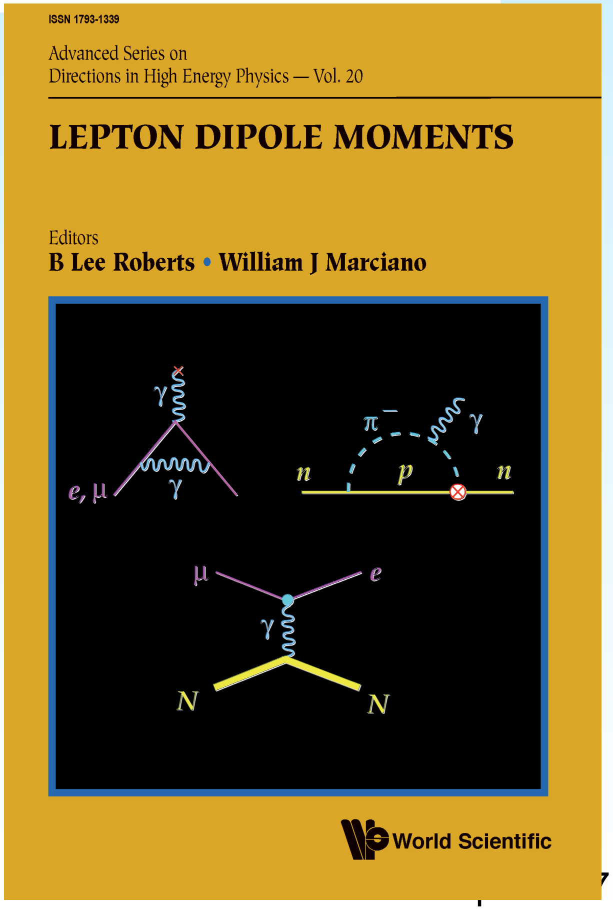
Advanced Series on Directions in High Energy Physics - Vol. 20

LEPTON DIPOLE MOMENTS

edited by **B Lee Roberts** *(Boston University, USA)* **& William J Marciano** *(Brookhaven National Laboratory, USA)*

http://www.worldscibooks.com/physics/7273.html

Especially the article by Czarnecki and Marciano for the introduction



ISSN 1793-1339

Advanced Series on
Directions in High Energy Physics — Vol. 20

LEPTON DIPOLE MOMENTS

Editors
B Lee Roberts • William J Marciano

Electric Dipole Moment: $\cancel{P}$ $\cancel{T}$

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s} \qquad \vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \boxed{\vec{d}\cdot\vec{E}}$$

$\vec{\mu},\ \vec{d} \parallel$ to $\vec{\sigma}$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

Transformation Properties

If *CPT* is valid, an EDM would imply non-standard model $\cancel{CP}$. Of course, we need new sources of $\cancel{CP}$ to explain why we' re here.

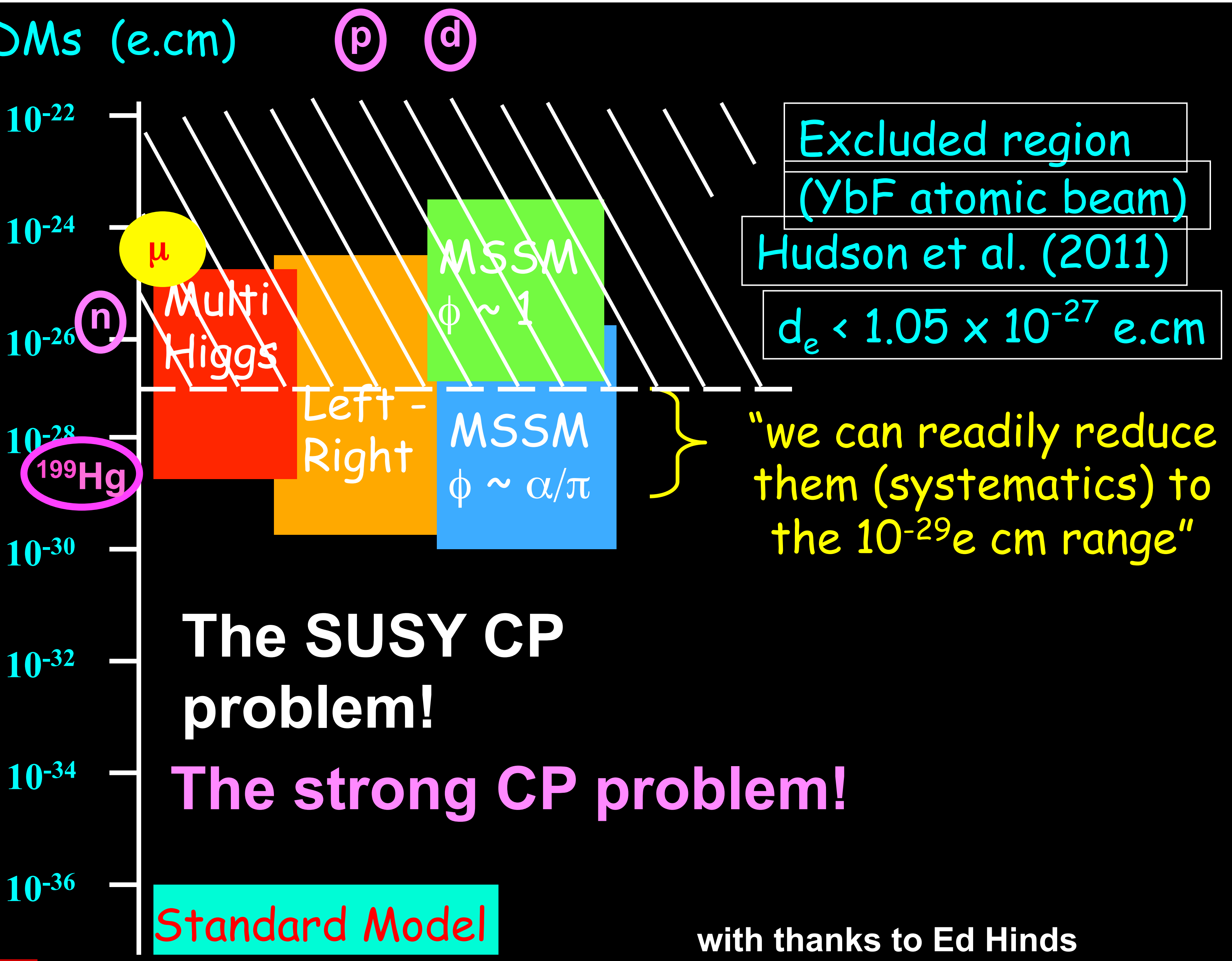
The present EDM limits are orders of magnitude from the standard-model value

Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
p	7.9×10^{-25}	
n	2.9×10^{-26}	$\simeq 10^{-32}$
^{199}Hg	3.1×10^{-29}	$\simeq 10^{-33}$
e^{-}	$\sim 1.05 \times 10^{-27}$	$< 10^{-41}$
μ	1.8×10^{-19} (E821)	$< 10^{-38}$

References: n PRL **97**, 131801 (2006)
p, **^{199}Hg** PRL **102**, 101601 (2009)
e^- Nature 473, 493 (2011)
μ PR D **80**, 052008 (20019)

At the moment, the Imperial College group leads the e^- pack

EDMs (e.cm)



Excluded region
(YbF atomic beam)
Hudson et al. (2011)
$d_e < 1.05 \times 10^{-27}$ e.cm

"we can readily reduce them (systematics) to the 10^{-29}e cm range"

The SUSY CP problem!

The strong CP problem!

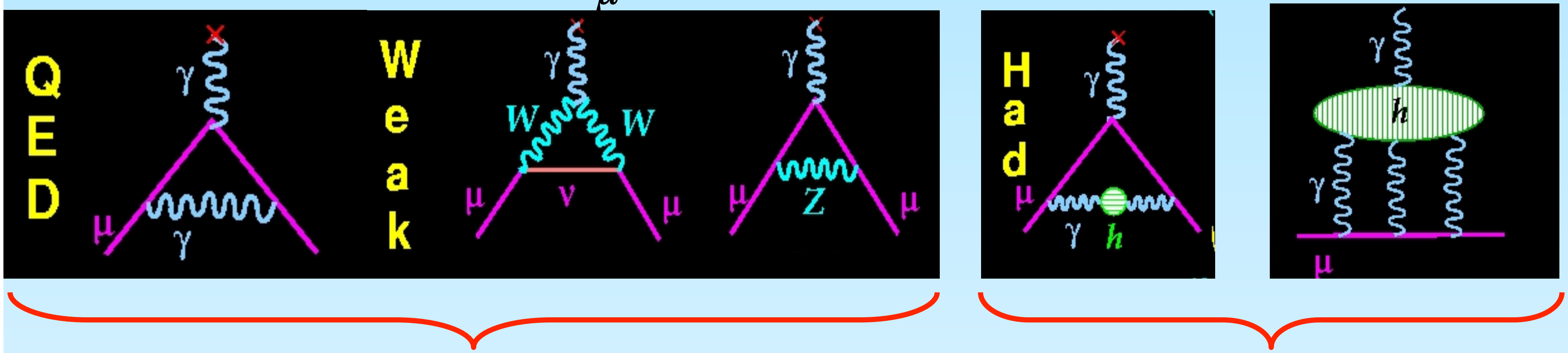
with thanks to Ed Hinds

How to clarify the 3 – 4 σ situation?

Good question!

B.

The SM Value for a_μ from $e^+e^- \to$ *hadrons*

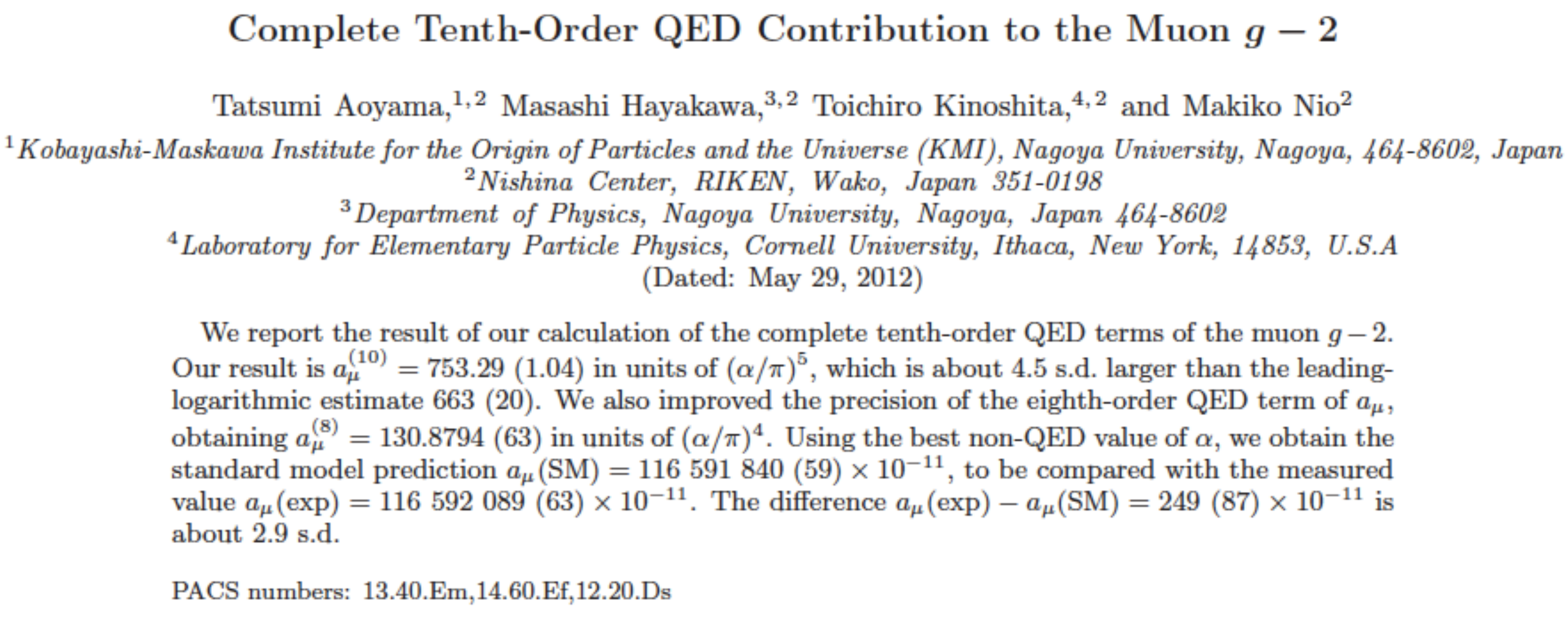


well known

significant work ongoing

- Lowest order hadronic from data and a dispersion relation
  - More data to come
- KLOE setting up to measure $\gamma^*\gamma^* \to \pi\,\pi$ to determine the amplitudes and remove some of the theoretical uncertainty on the HLBL

QED now calculated to 5-loops!



Complete Tenth-Order QED Contribution to the Muon $g-2$

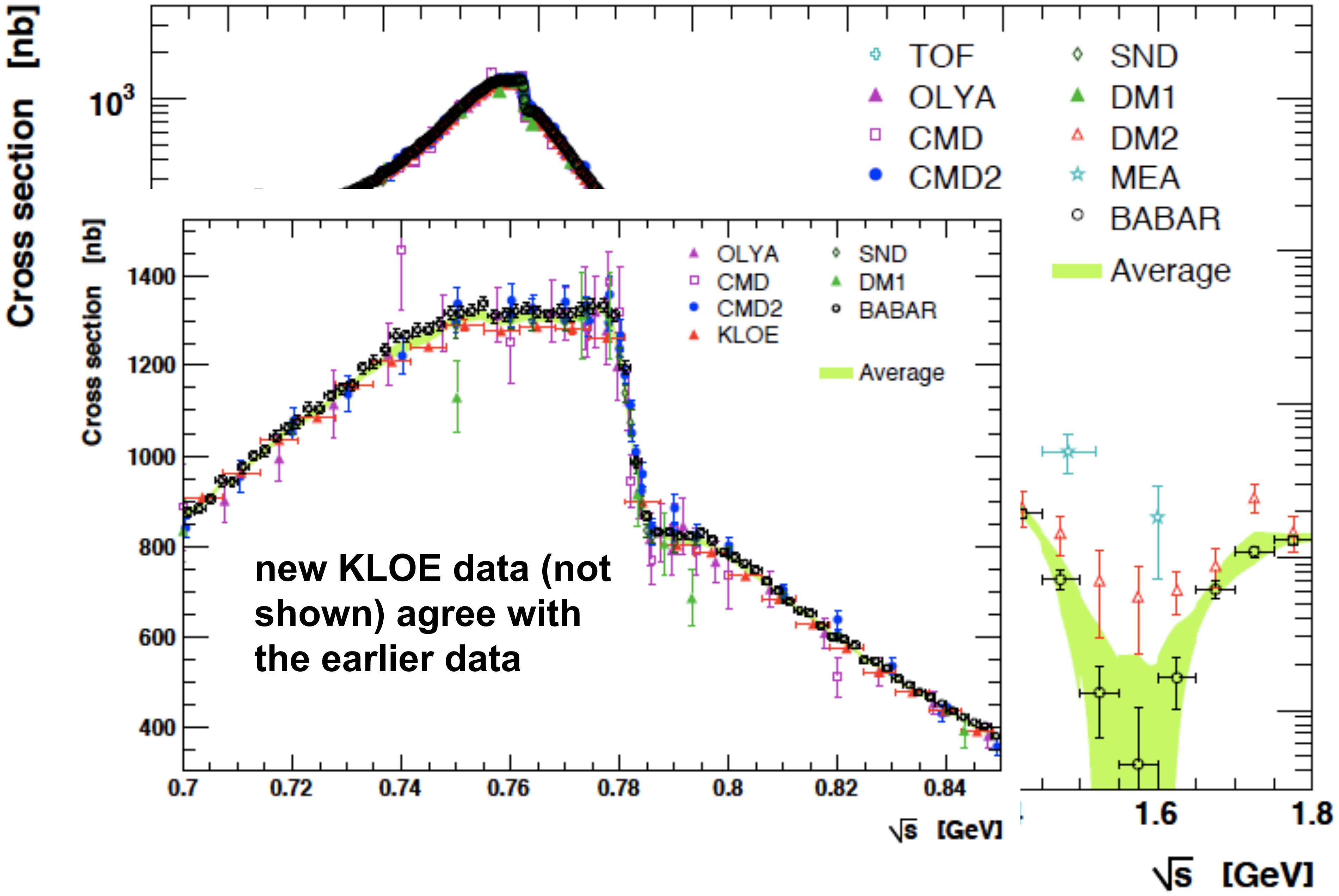
Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]
[1] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*
[2] *Nishina Center, RIKEN, Wako, Japan 351-0198*
[3] *Department of Physics, Nagoya University, Nagoya, Japan 464-8602*
[4] *Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York, 14853, U.S.A*
(Dated: May 29, 2012)

We report the result of our calculation of the complete tenth-order QED terms of the muon $g-2$. Our result is $a_\mu^{(10)} = 753.29\ (1.04)$ in units of $(\alpha/\pi)^5$, which is about 4.5 s.d. larger than the leading-logarithmic estimate 663 (20). We also improved the precision of the eighth-order QED term of a_μ, obtaining $a_\mu^{(8)} = 130.8794\ (63)$ in units of $(\alpha/\pi)^4$. Using the best non-QED value of α, we obtain the standard model prediction $a_\mu(\mathrm{SM}) = 116\ 591\ 840\ (59) \times 10^{-11}$, to be compared with the measured value $a_\mu(\mathrm{exp}) = 116\ 592\ 089\ (63) \times 10^{-11}$. The difference $a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = 249\ (87) \times 10^{-11}$ is about 2.9 s.d.

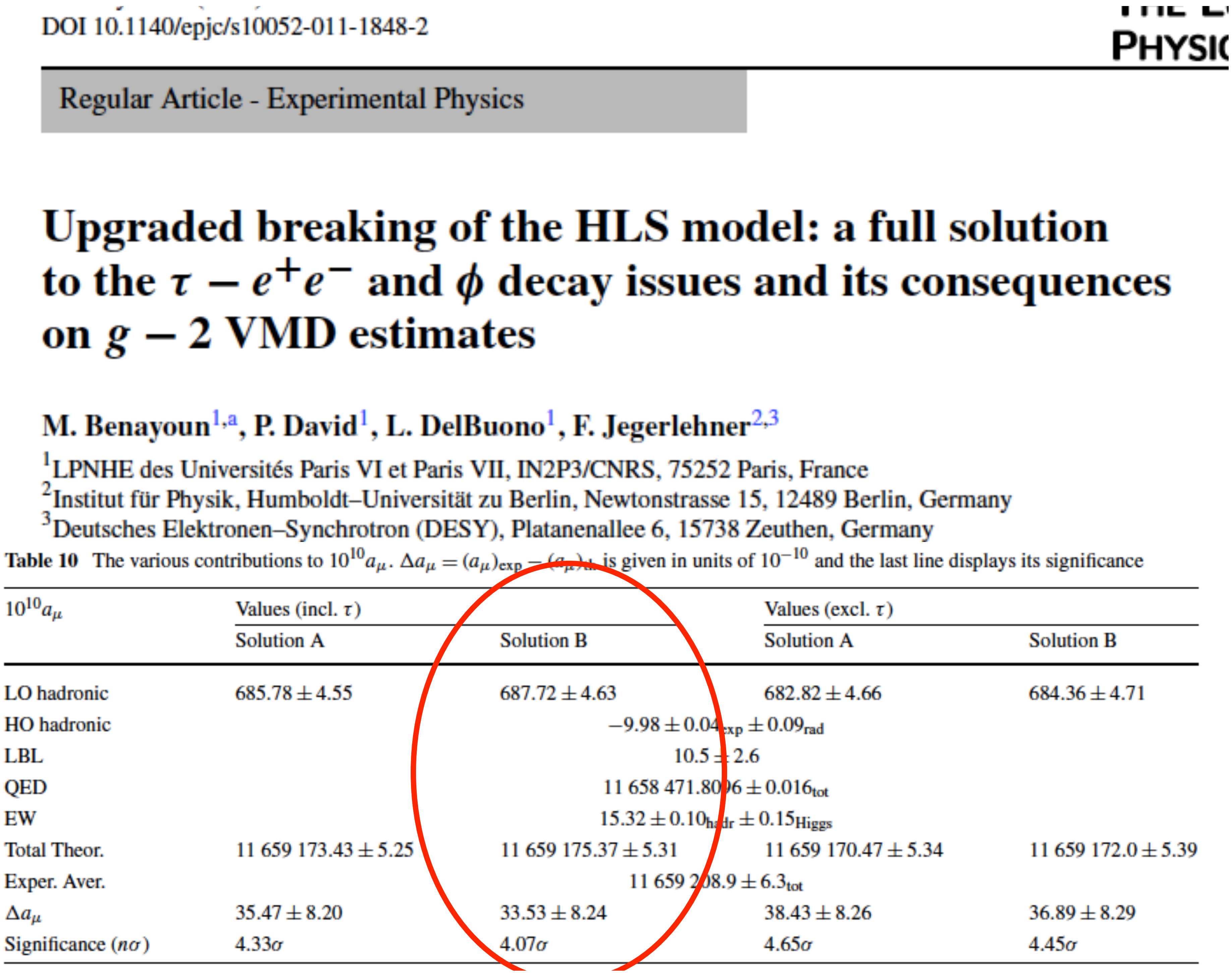
PACS numbers: 13.40.Em,14.60.Ef,12.20.Ds

- arXiv:1205.5370v2 [hep-ph] 27 May 2012
- 12,672 diagrams

Measured Cross section for $e^+e^- \rightarrow \pi^+\pi^-$



new KLOE data (not shown) agree with the earlier data



DOI 10.1140/epjc/s10052-011-1848-2

PHYSIC

Regular Article - Experimental Physics

Upgraded breaking of the HLS model: a full solution to the $\tau - e^+e^-$ and ϕ decay issues and its consequences on $g-2$ VMD estimates

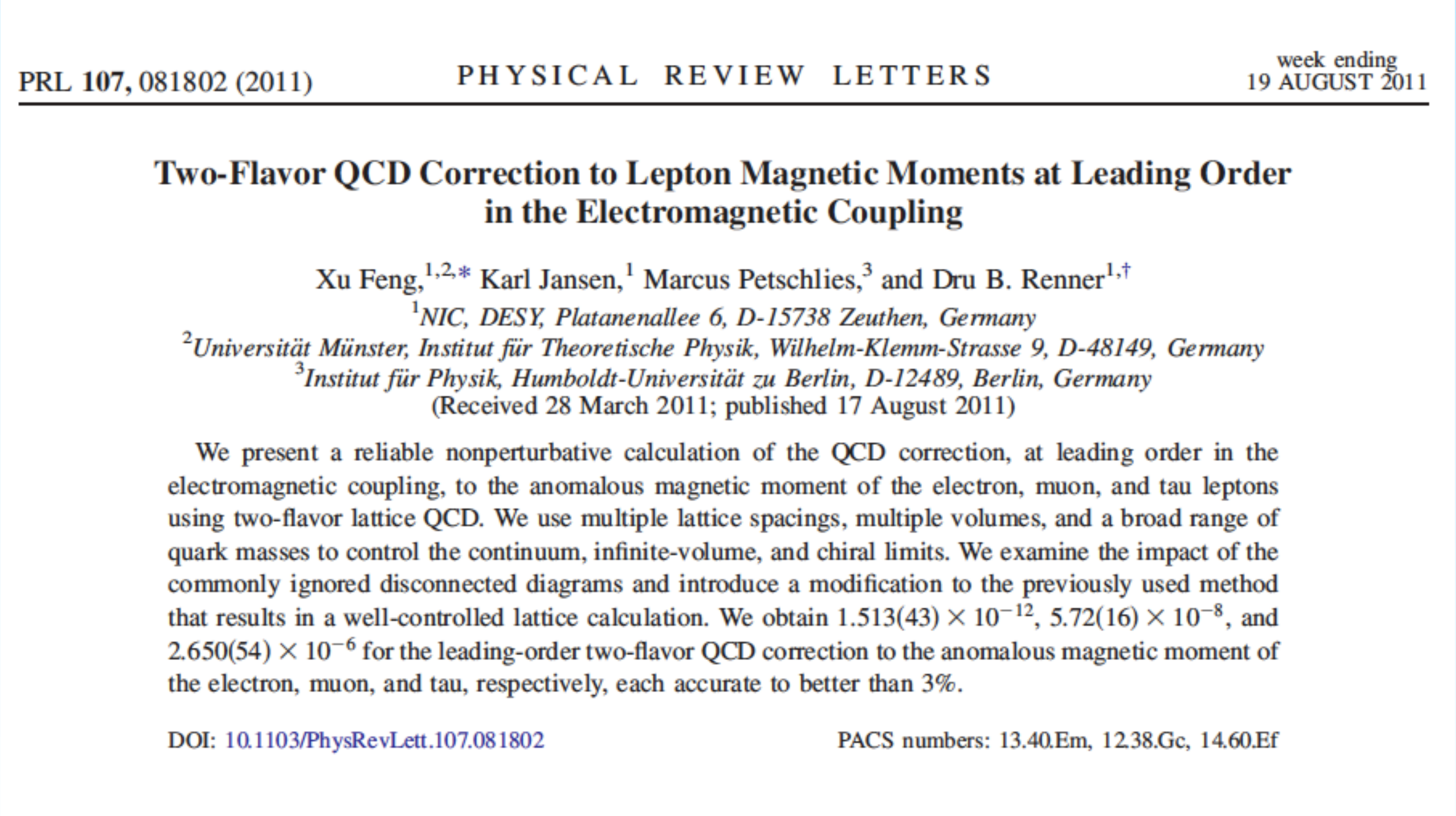
M. Benayoun[1,a], **P. David**[1], **L. DelBuono**[1], **F. Jegerlehner**[2,3]

[1] LPNHE des Universités Paris VI et Paris VII, IN2P3/CNRS, 75252 Paris, France
[2] Institut für Physik, Humboldt–Universität zu Berlin, Newtonstrasse 15, 12489 Berlin, Germany
[3] Deutsches Elektronen–Synchrotron (DESY), Platanenallee 6, 15738 Zeuthen, Germany

Table 10 The various contributions to $10^{10}a_\mu$. $\Delta a_\mu = (a_\mu)_{\text{exp}} - (a_\mu)_{\text{th}}$ is given in units of 10^{-10} and the last line displays its significance

$10^{10}a_\mu$	Values (incl. τ)		Values (excl. τ)	
	Solution A	Solution B	Solution A	Solution B
LO hadronic	685.78 ± 4.55	687.72 ± 4.63	682.82 ± 4.66	684.36 ± 4.71
HO hadronic	$-9.98 \pm 0.04_{\text{exp}} \pm 0.09_{\text{rad}}$			
LBL	10.5 ± 2.6			
QED	$11\,658\,471.8096 \pm 0.016_{\text{tot}}$			
EW	$15.32 \pm 0.10_{\text{hadr}} \pm 0.15_{\text{Higgs}}$			
Total Theor.	$11\,659\,173.43 \pm 5.25$	$11\,659\,175.37 \pm 5.31$	$11\,659\,170.47 \pm 5.34$	$11\,659\,172.0 \pm 5.39$
Exper. Aver.	$11\,659\,208.9 \pm 6.3_{\text{tot}}$			
Δa_μ	35.47 ± 8.20	33.53 ± 8.24	38.43 ± 8.26	36.89 ± 8.29
Significance ($n\sigma$)	4.33σ	4.07σ	4.65σ	4.45σ

The lattice can can also do it!



PRL **107,** 081802 (2011) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2011

Two-Flavor QCD Correction to Lepton Magnetic Moments at Leading Order in the Electromagnetic Coupling

Xu Feng,[1,2,*] Karl Jansen,[1] Marcus Petschlies,[3] and Dru B. Renner[1,†]
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[2] *Universität Münster, Institut für Theoretische Physik, Wilhelm-Klemm-Strasse 9, D-48149, Germany*
[3] *Institut für Physik, Humboldt-Universität zu Berlin, D-12489, Berlin, Germany*

(Received 28 March 2011; published 17 August 2011)

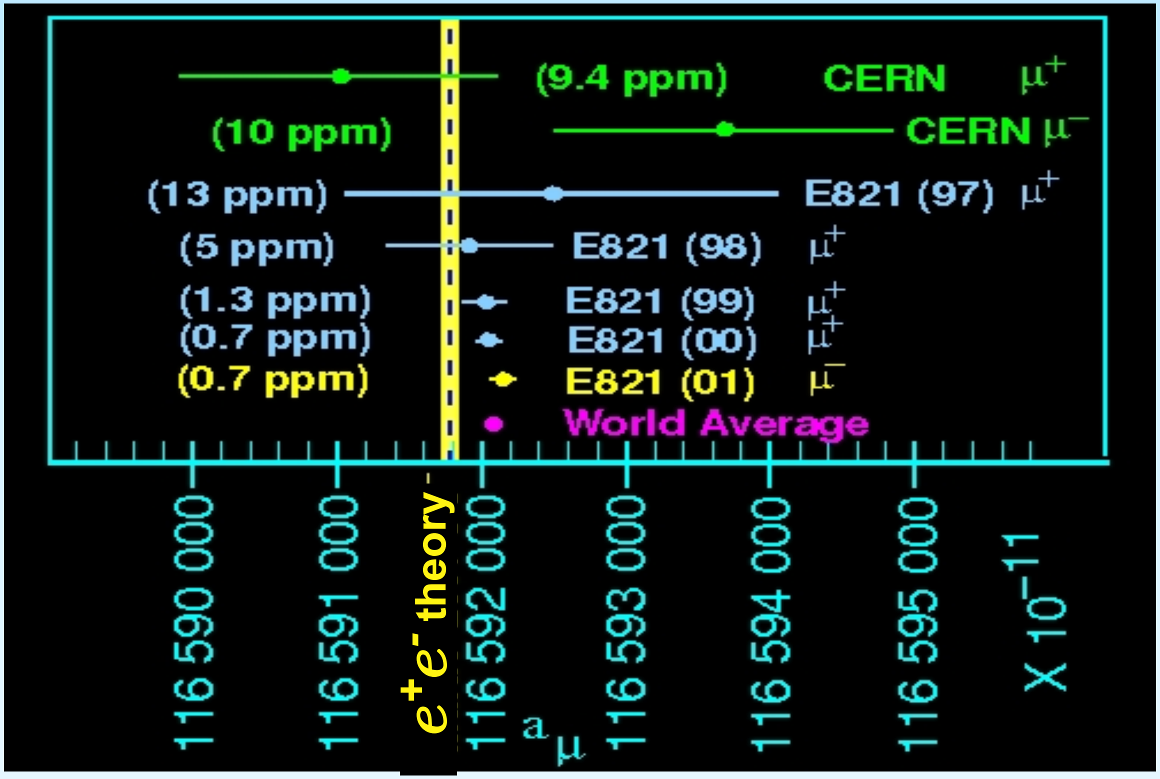
We present a reliable nonperturbative calculation of the QCD correction, at leading order in the electromagnetic coupling, to the anomalous magnetic moment of the electron, muon, and tau leptons using two-flavor lattice QCD. We use multiple lattice spacings, multiple volumes, and a broad range of quark masses to control the continuum, infinite-volume, and chiral limits. We examine the impact of the commonly ignored disconnected diagrams and introduce a modification to the previously used method that results in a well-controlled lattice calculation. We obtain $1.513(43) \times 10^{-12}$, $5.72(16) \times 10^{-8}$, and $2.650(54) \times 10^{-6}$ for the leading-order two-flavor QCD correction to the anomalous magnetic moment of the electron, muon, and tau, respectively, each accurate to better than 3%.

DOI: 10.1103/PhysRevLett.107.081802 PACS numbers: 13.40.Em, 12.38.Gc, 14.60.Ef

E821 achieved ± 0.54 ppm. The e^+e^- based theory is at the ~0.49 ppm level. Difference is >3σ

SM: Davier et al, , Eur. Phys. J. C (2011) 71:1515

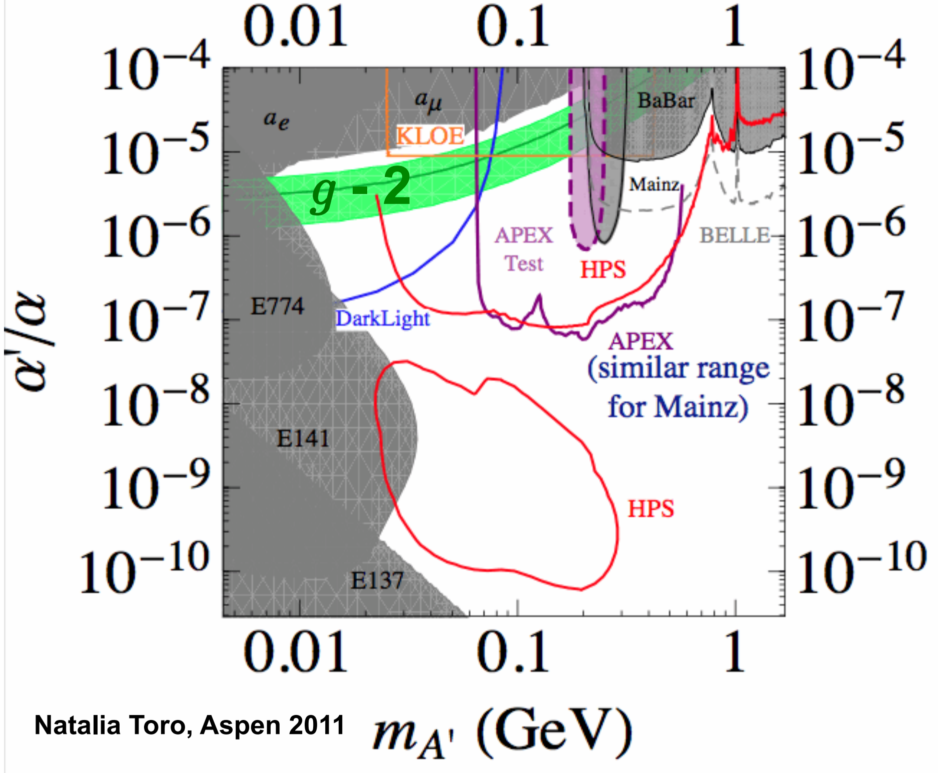
Hagiwara, et al., J.Phys. G **38** (2011) 085003



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

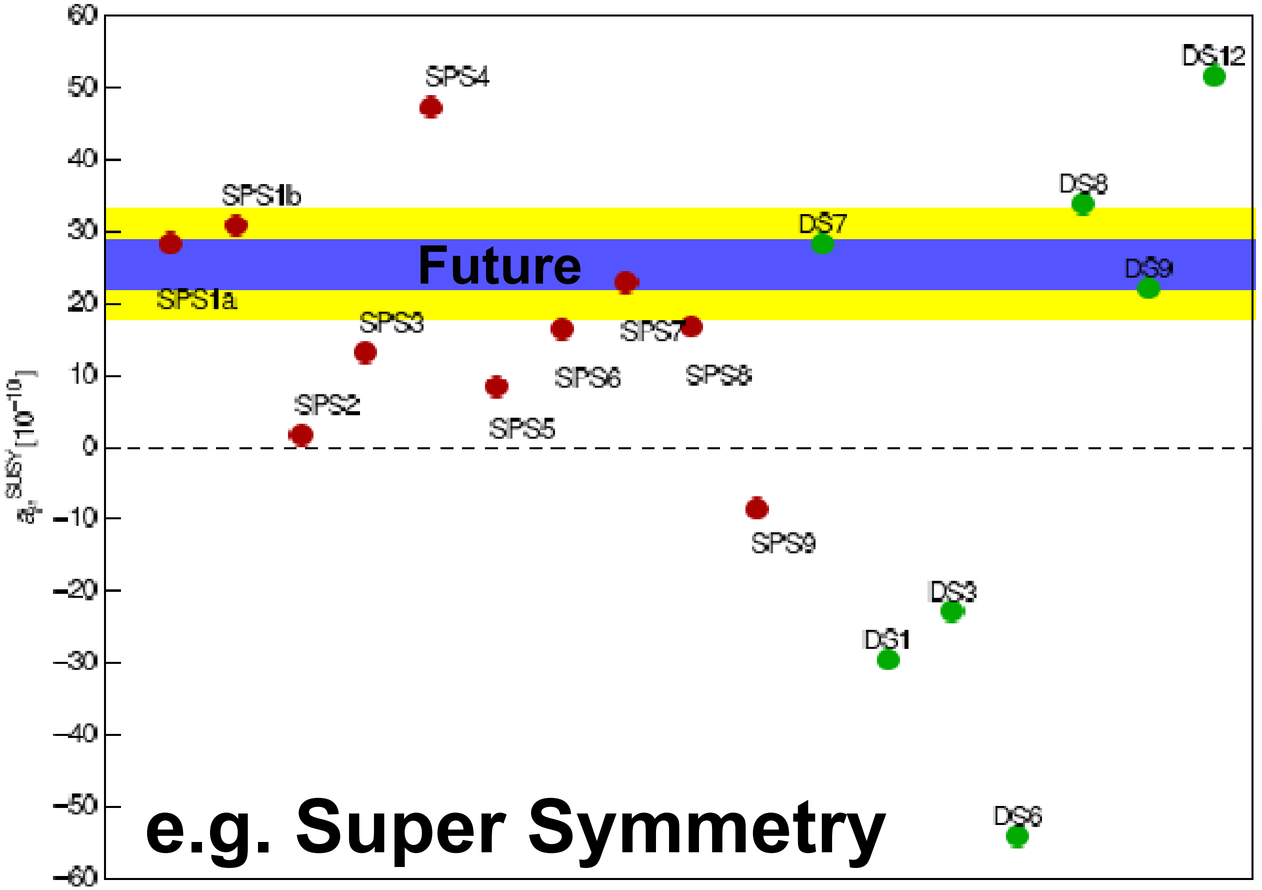
Other Models

- Technicolor
  - small Δa_μ
- Littlest Higgs with T-parity
  - small Δa_μ
- Universal Extra Dimensions
  - small Δa_μ
- Randall Sundrum
  - could accommodate large Δa_μ
- Two Higgs doublets, shadow Higgs
  - small Δa_μ
- Additional light bosons that can affect EM interactions (difficult to study at LHC)
  - secluded U(1),etc., could have significant Δa_μ



Natalia Toro, Aspen 2011

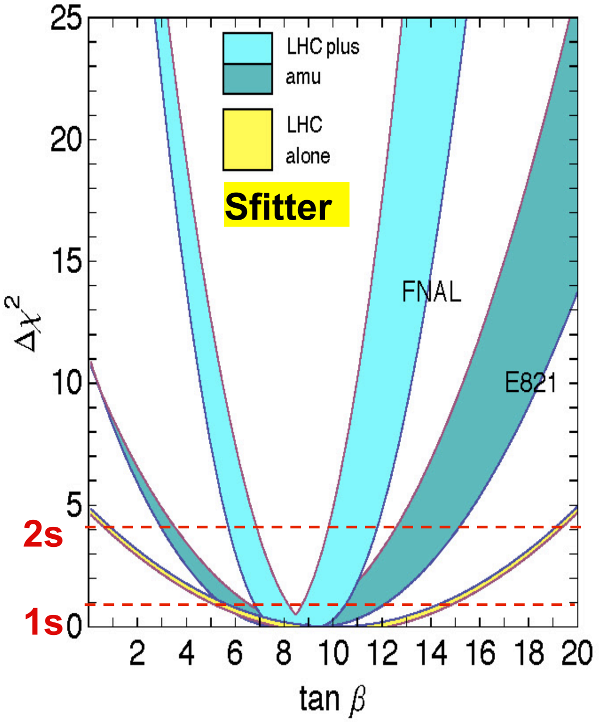
Muon g-2 is a powerful discriminator between models; chiral-changing, flavor and CP conserving interaction.



Future

e.g. Super Symmetry

tan β sensitivity



Snowmass points and slopes (SUSY)

from D. Stöckinger

LHC Inverse Problem (300fb^{-1})

can't be distinguished at LHC [Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]

SPS1a; LHC 100 fb-1 at 14 TeV

Improvements

- New segmented detectors
- New electronics
- Straw tube system at many detector systems for beam profile and EDM measurements
- Improved magnetic field measurement and control
- Improved magnetic field absolute calibration

Systematic errors on ω_a (ppm)

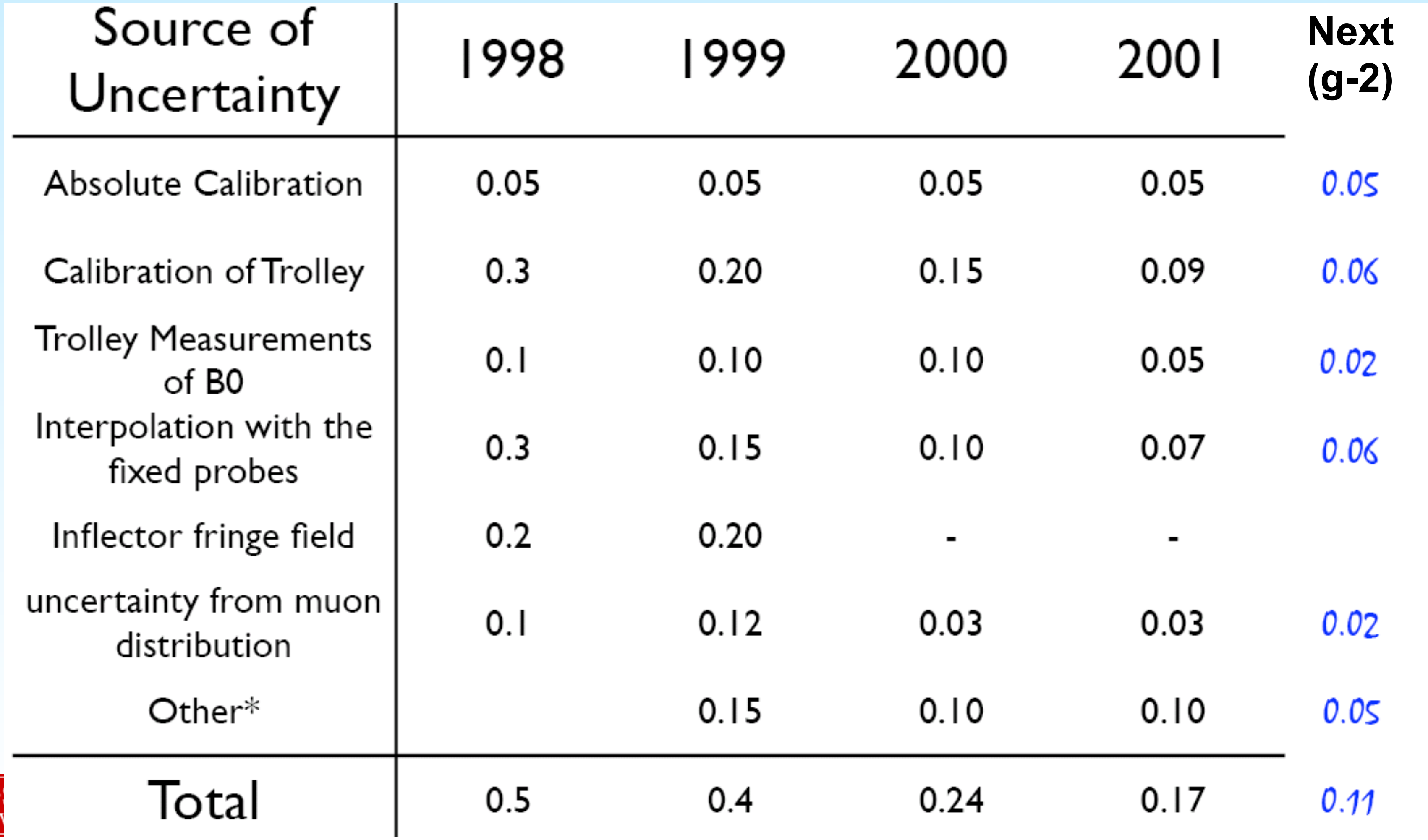
$\sigma_{\text{systematic}}$	1999	2000	2001	Future
Pile-up	0.13	0.13	0.08	0.04
AGS Background	0.10	0.10	0.015*	
Lost Muons	0.10	0.10	0.09	0.02
Timing Shifts	0.10	0.02	0.02	
E-Field, Pitch	0.08	0.03	0.06*	0.03
Fitting/Binning	0.07	0.06	0.06*	
CBO	0.05	0.21	0.07	0.04
Beam Debunching	0.04	0.04	0.04*	
Gain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

◯ **better with Fermilab beam structure and improved detectors/electronics**

$\Sigma^* = 0.11$

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