International Conference on Exotic Atoms and Related Topics - EXA2011
Vienna, September 5-9, 2011

g-2 of the muon

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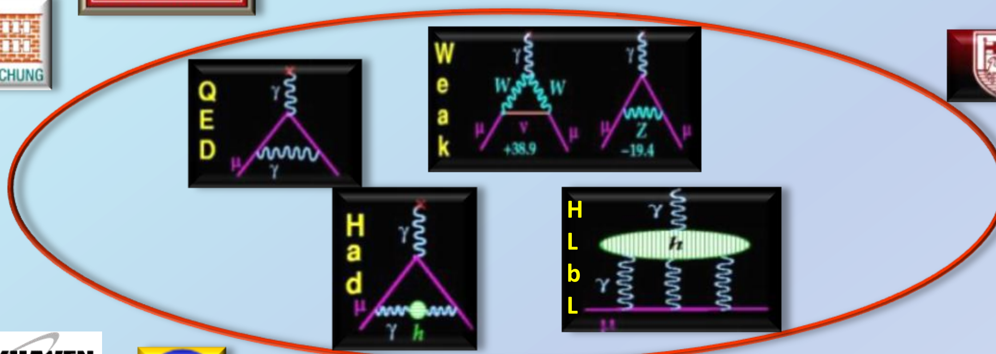
KVI

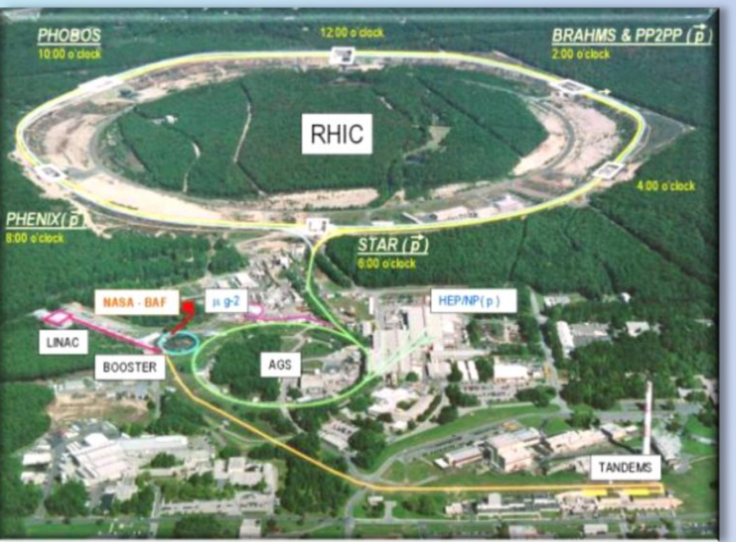
with slides from
B.L. Roberts
Boston University

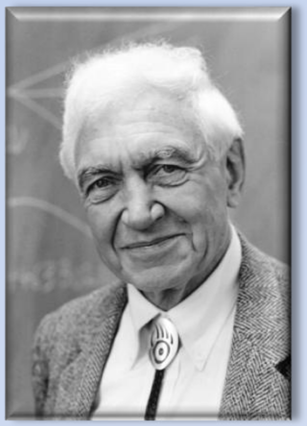
BOSTON UNIVERSITY

Magnetic Anomaly of the Muon

BNL - 821





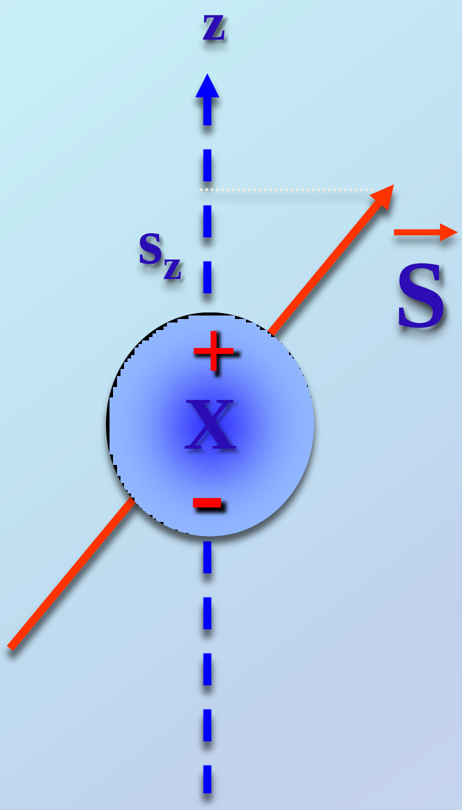


Vernon Hughes
1921-2003

BROOKHAVEN NATIONAL LABORATORY

Fermilab

Spin of Fundamental Particles



$\vec{S}$ is the only vector characterizing a non-degenerate quantum state

magnetic moment:

$$\vec{\mu}_x = 2(1+a_x)\ \mu_{0x}\ c^{-1}\ \vec{S}$$

electric dipole moment:

$$\vec{d}_x = \eta\ \mu_{0x}\ c^{-1}\ \vec{S}$$

magneton:

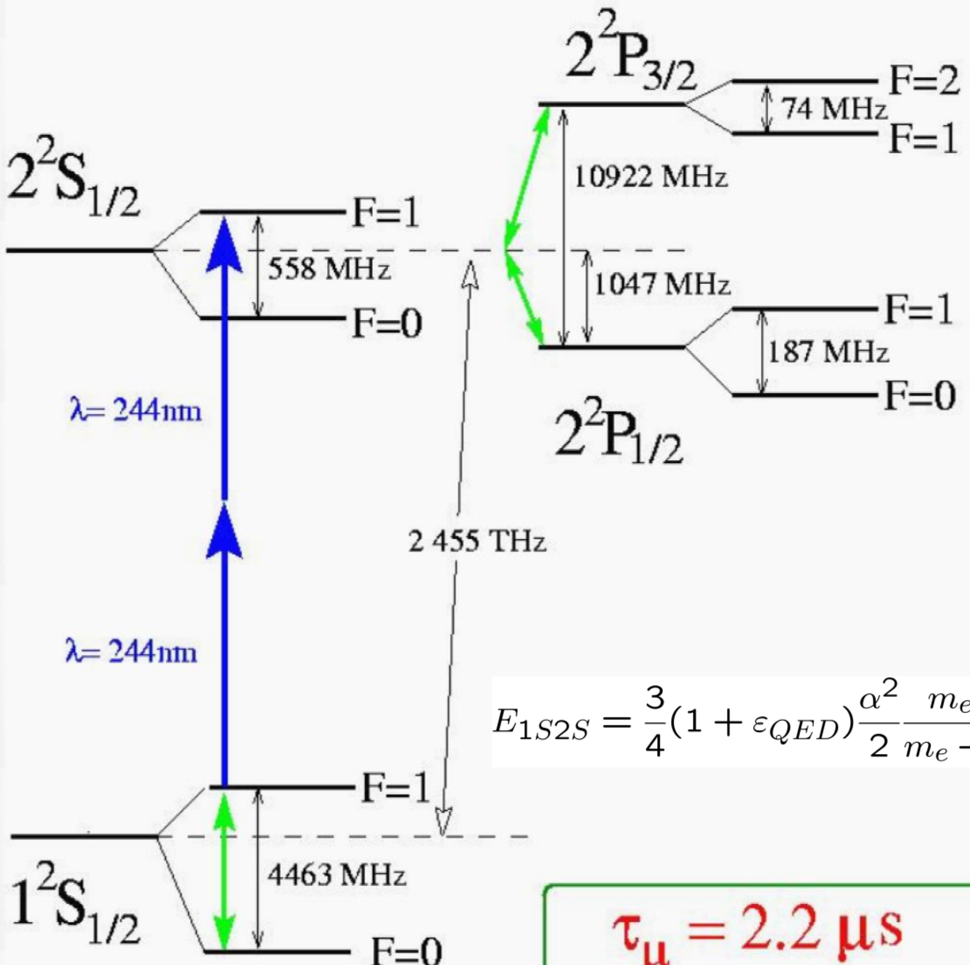
$$\mu_{0x} = e\hbar\ /\ (2m_x)$$

$$\mu_{0x}\ c^{-1}\ S = \begin{cases} 9.7 \cdot 10^{-12}\ \text{e cm} & \text{(electron)} \\ 4.6 \cdot 10^{-14}\ \text{e cm} & \text{(muon)} \\ 5.3 \cdot 10^{-15}\ \text{e cm} & \text{(nucleon)} \end{cases}$$

Muonium I

to verify muon charge

Muonium ($M=\mu^+e^-$) Energy Levels
n=1 and n=2



$$E_{1S2S} = \frac{3}{4}(1+\varepsilon_{QED})\frac{\alpha^2}{2}\frac{m_e m_\mu}{m_e + m_\mu}c^2$$

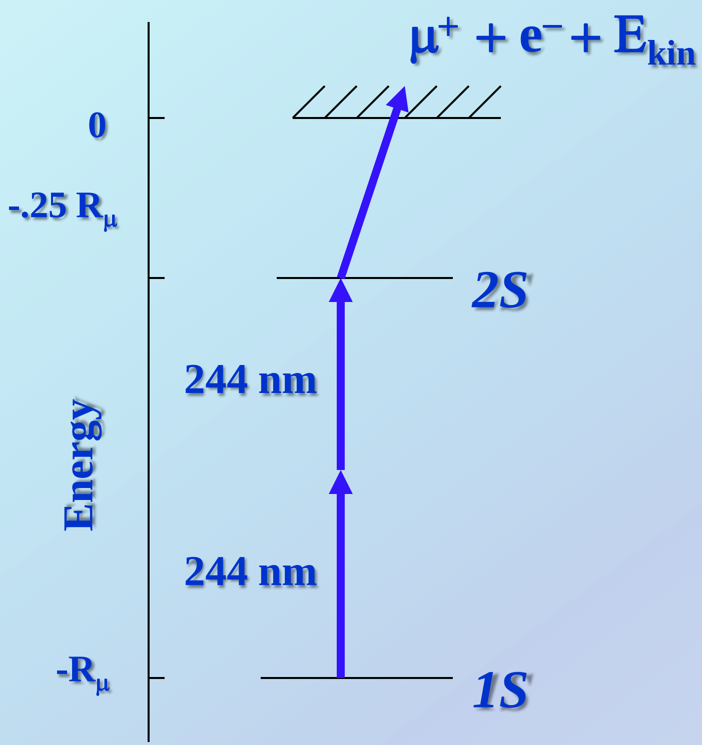
$\tau_\mu = 2.2\ \mu s$

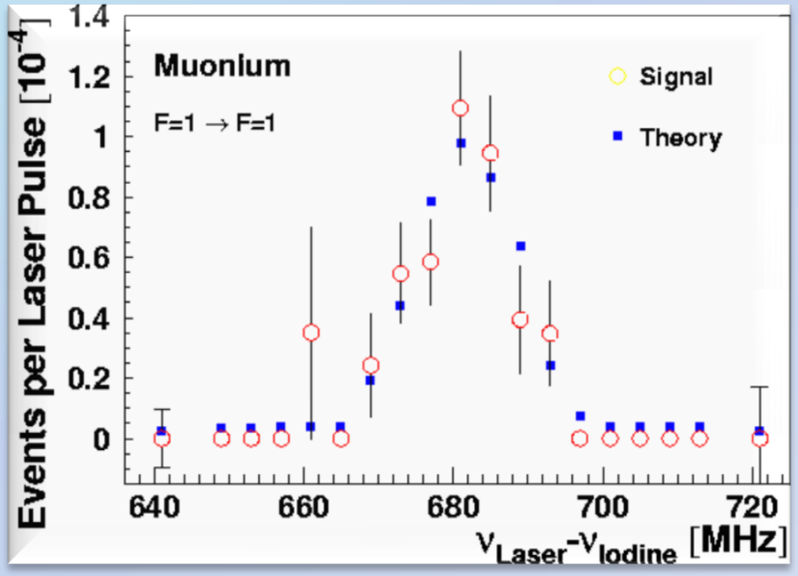
min $\Delta\nu_{nat} = 145$ kHz

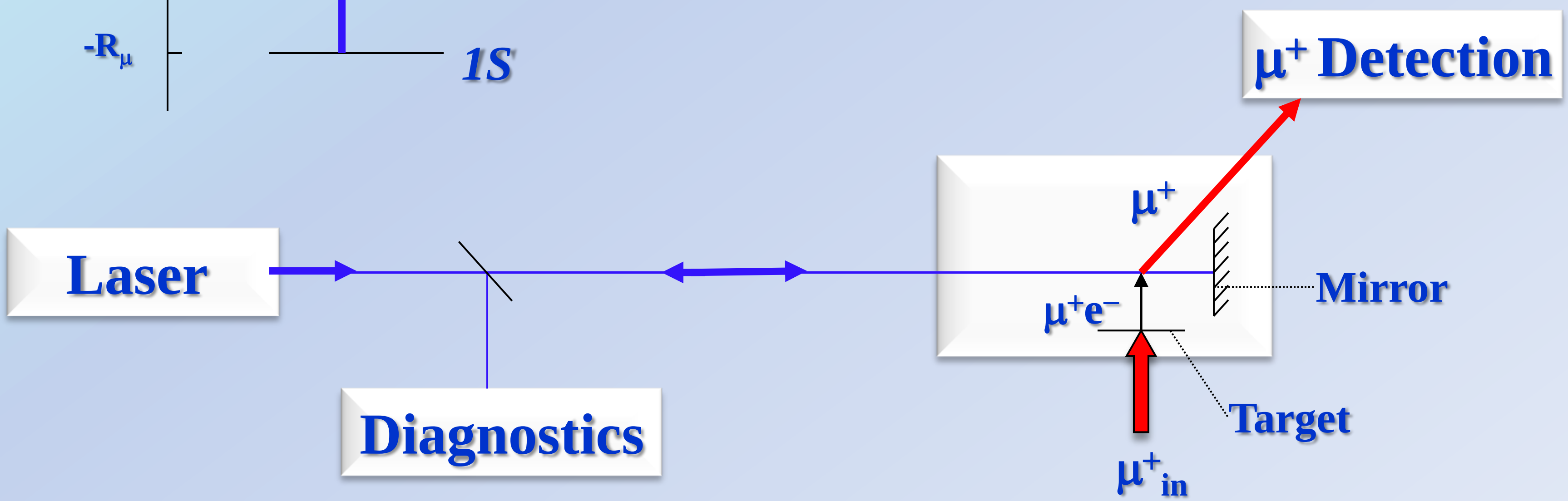
(not to scale)

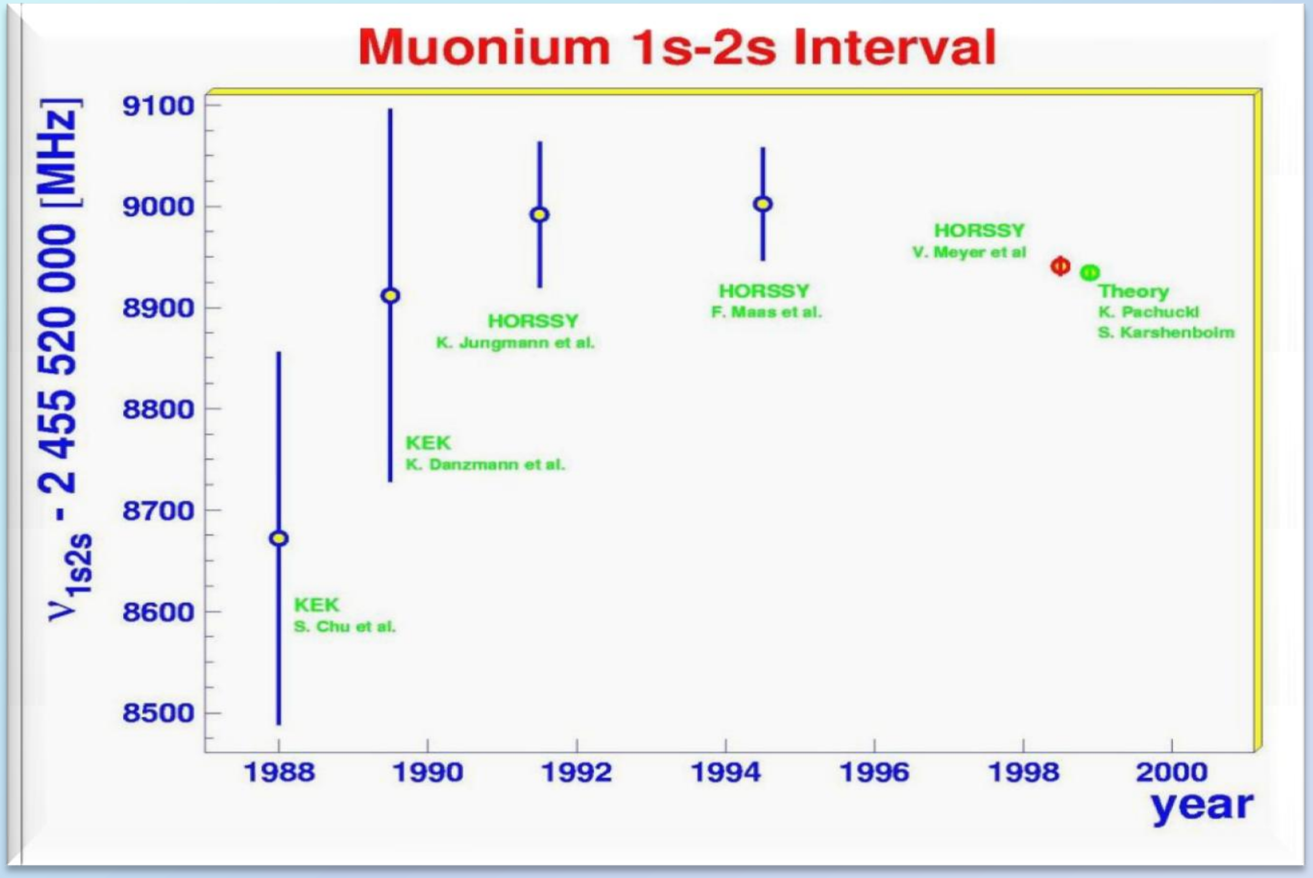
Muonium 1S-2S Experiment

Heidelberg - Oxford - Rutherford - Sussex - Siberia - Yale









$$\Delta\nu^{exp}_{1s\text{-}2s} = 2455\,528\,941.0(9.1)(3.7)\ \text{MHz}$$

$$\Delta\nu^{theo}_{1s\text{-}2s} = 2455\,528\,935.4(1.4)\ \text{MHz}$$

$$m_{\mu+} = 206.768\,38\,(17)\ m_e \quad (0.8\text{ppm})$$

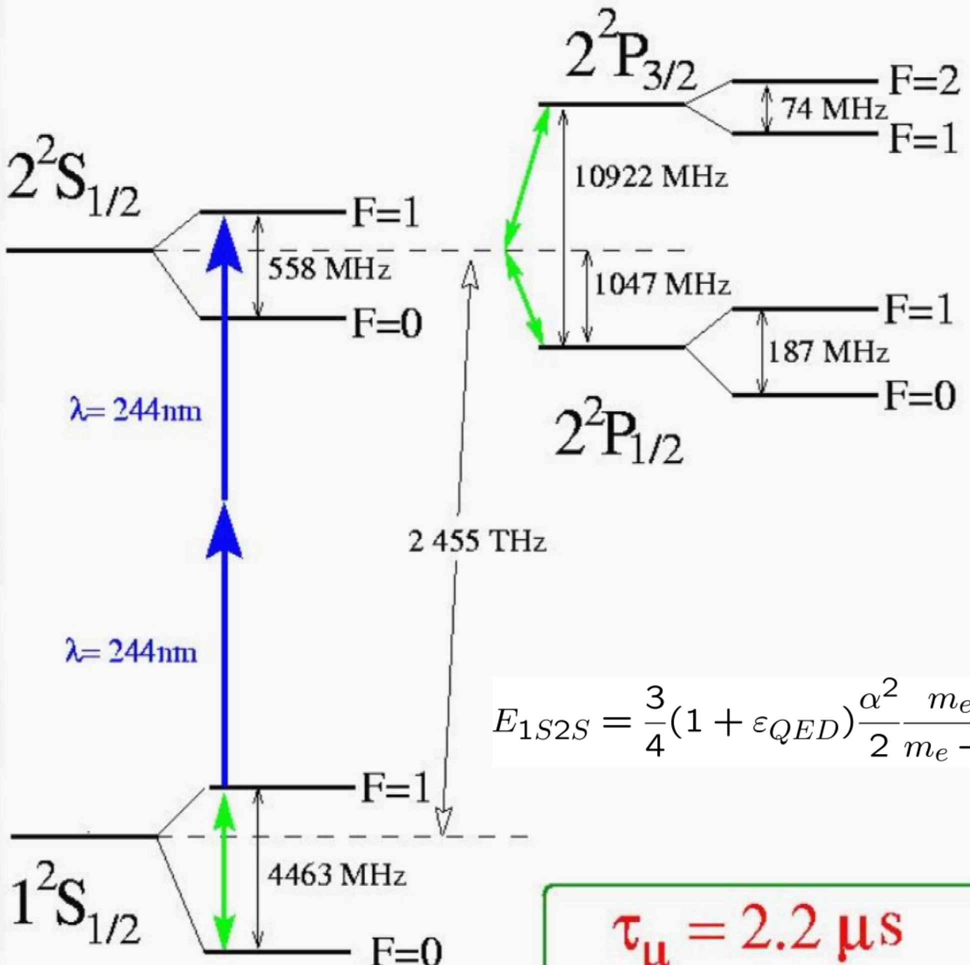
$$q_{\mu+} = [\,-1\ -1.1\,(2.1)\,10^{-9}\,]\ q_{e-} \quad (2.2\text{ ppb})$$

⇒ good enough for foreseeable future

Muonium II

to measure muon magnetic moment

Muonium ($M=\mu^+e^-$) Energy Levels
n=1 and n=2



$$E_{1S2S} = \frac{3}{4}(1+\varepsilon_{QED})\frac{\alpha^2}{2}\frac{m_e m_\mu}{m_e+m_\mu}c^2$$

$\tau_\mu = 2.2\ \mu s$

min $\Delta\nu_{nat} = 145$ kHz

(not to scale)

Muonium Hyperfine Structure – Theory

$$\Delta\nu_{HFS} = \nu_F\,(1+\varepsilon_{QED}) + \Delta\nu_{strong} + \Delta\nu_{weak} + \Delta\nu_{exotic}$$

$$\nu_F = {}^{16}/_3\,(Z\alpha)^2\,R_\infty\,\mu_\mu/\mu_B\,[1 + m_e/m_\mu]^{-3} = 4\,459\,033.4\,(6)\ \text{kHz}$$

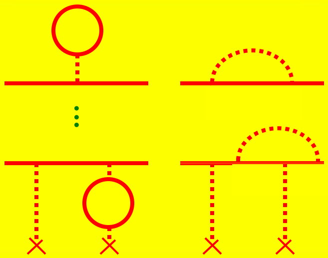
$$\varepsilon_{QED} = \varepsilon_{rad} + \varepsilon_{rec} + \varepsilon_{rad\text{-}rec}$$

$$\varepsilon_{rad} = f_{rad}\,(\alpha, Z\alpha)$$

$$?\ ?\ \alpha(Z\alpha)^3\ ,\ \alpha^2(Z\alpha)^2\ \ ?\ ?$$

$$\varepsilon_{rec} = f_{rec}\,(Z\alpha, m_\mu, m_e)$$

$$\varepsilon_{rad\text{-}rec} = f_{rad\text{-}rec}\,(\alpha, Z\alpha, m_\mu, m_e)$$



$\Delta\nu_{strong} = \nu_F \dfrac{\alpha(Z\alpha)m_e}{\pi^2 m_\mu}(2.15(14))$	$= 250(16)$ Hz	hadronic vacuum polarisation
$\Delta\nu_{weak} = -130 \cdot C_{AA}^{e\mu}$ Hz	$= -65$ Hz	axial – axial vector via Z
$\Delta\nu_{M\overline{M}} = 519 \cdot (G_{M\overline{M}}/G_F)$Hz	< 9.3 Hz	$M-\overline{M}$ oscillation
$\Delta\nu_{NL} < b_3^\mu + d_{30}^\mu m_\mu + H_{12}^\mu$	< 500 Hz	Lorentz non invarianz

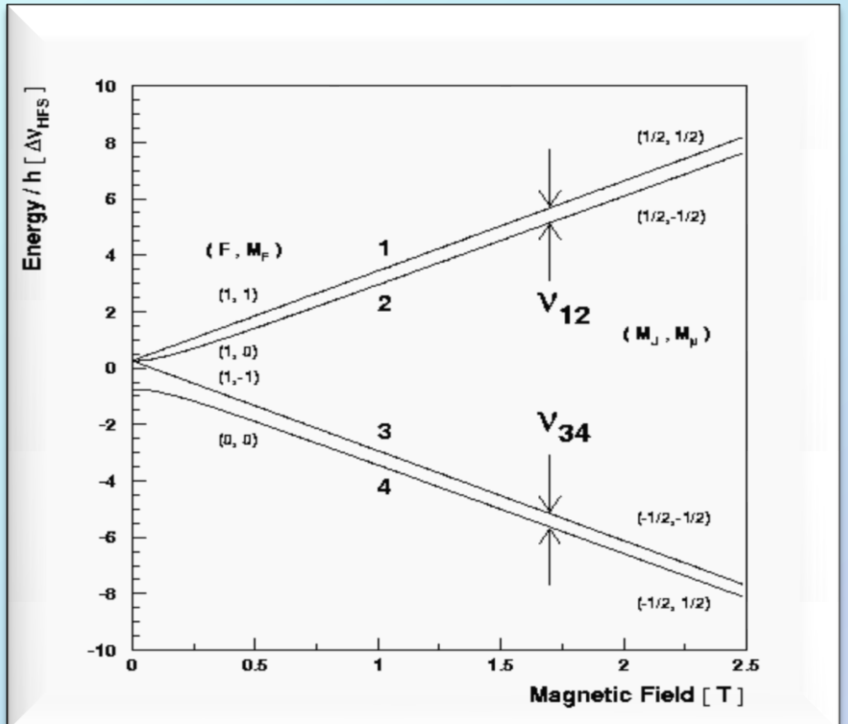
$\Delta\nu_{HFS}$ (theo) = 4 463 302.563 (510) (34) (<100) kHz (120 ppb)

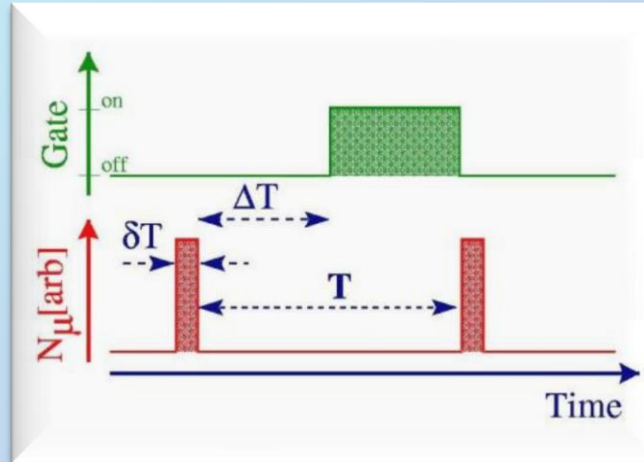
$\Delta\nu_{HFS}$ (expt) = 4 463 302.765 (53) kHz (12 ppb)

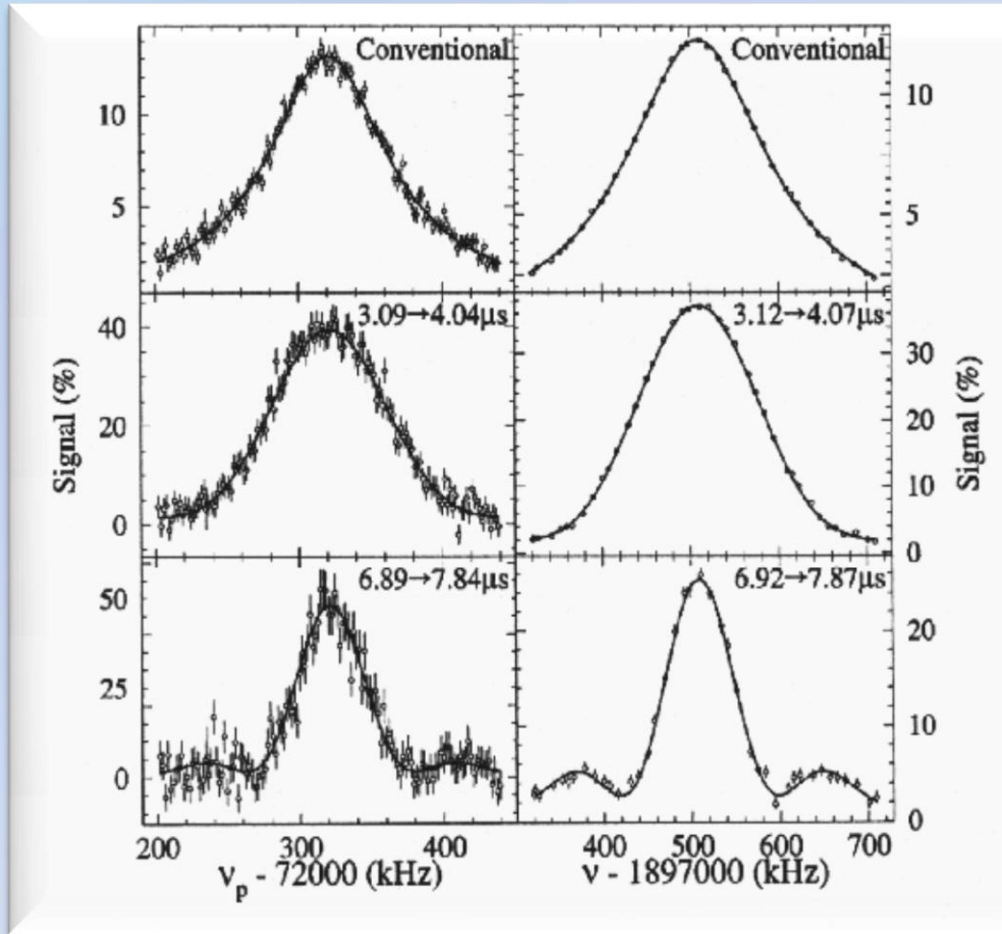
theory: Eides, Shelyuto (95);Karshenboim (96);Kinoshita, Nio (97); Blundell,Cheng, Sapirstein (97);Pachucki (98);Kinoshita (98)

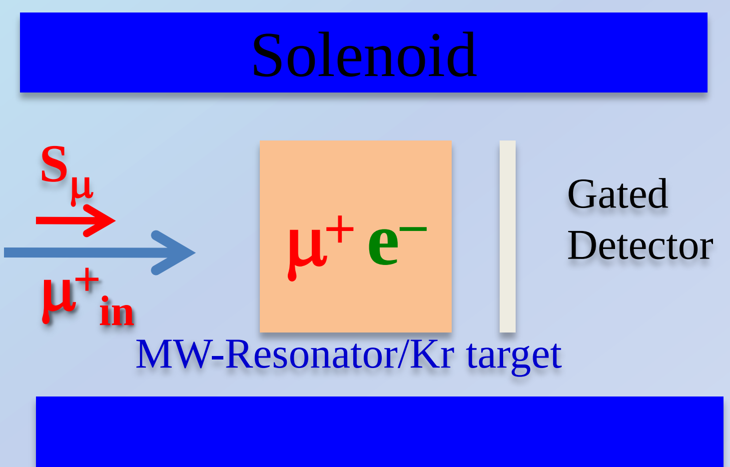
Muonium Hyperfine Structure

Yale - **Heidelberg** - **Los Alamos**









Results from LAMPF Muonium HFS Experiment

measured:

- ν_{12} = 1 897 539 800(35) Hz (18 ppb)
- ν_{34} = 2 565 762 965(43) Hz (17 ppb)

from Breit-Rabi equation:

$\nu_{12} + \nu_{34}$

- $\Delta\nu_{exp}$ = 4 463 302 765(53) Hz (12 ppb)
- $\Delta\nu_{theo}$ = 4 463 302 563(520)(34)(<100) Hz (<120 ppb)

$\nu_{12} - \nu_{34}$

- μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

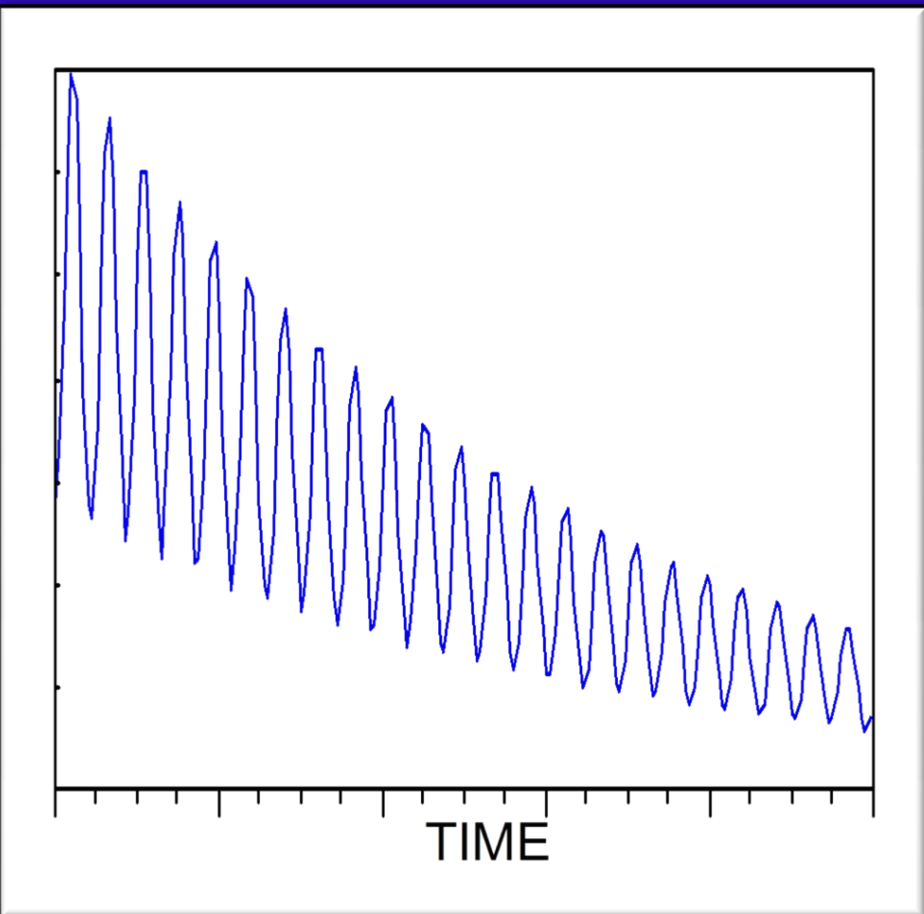
alternatively derived:

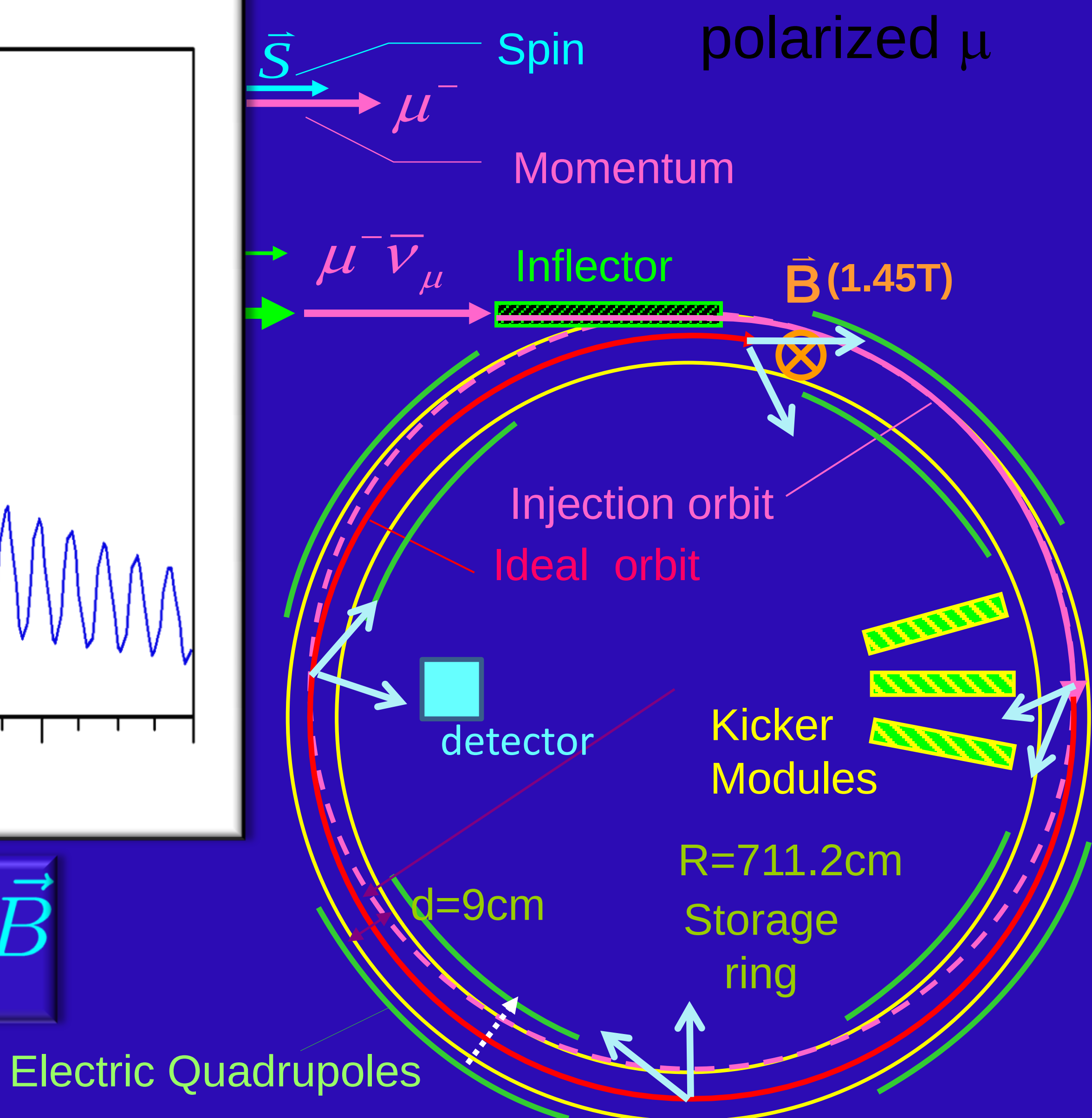
- m_μ/m_e = 206.768 277(24) (120 ppb)
- α^{-1} = 137.036 004 7(4 8) (35 ppb)

muon g-2

Measure muon magnetic anomaly

Muon Magnetic Anomaly (g-2)





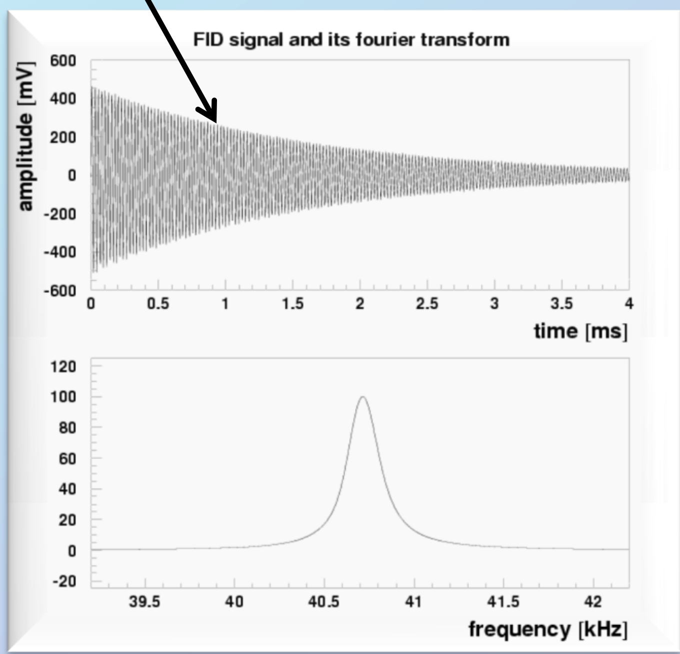
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

From B.L. Roberts

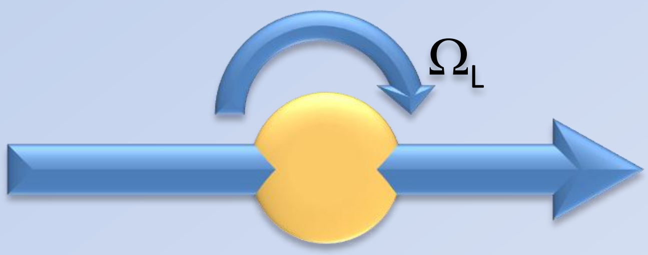
NMR Magnetometer

- coherently excite nuclear spins
- have nuclear spins precess in magnetic field B
- follow spin precession via induced voltage U(t)

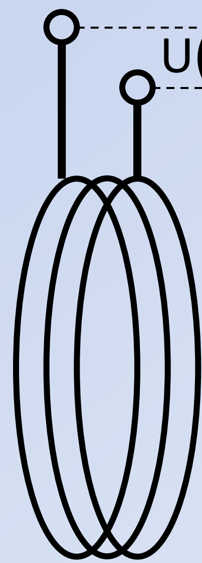
envelope ∝ exp[-t/T_2*] $1/T_2^* = 1/T_1 + 1/T_{2\,\mathrm{field}}$



$$\Omega_L = \gamma|\vec{B}|$$



A rotating spin induces an ac voltage in a coil

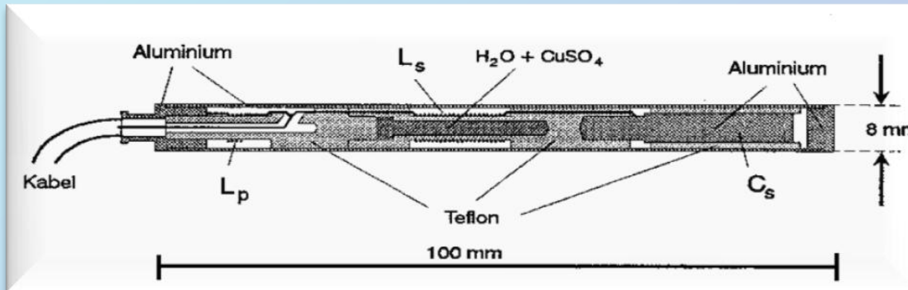


$U(t) = U_0 \cos \Omega_L t$

NMR Magnetometer (I)

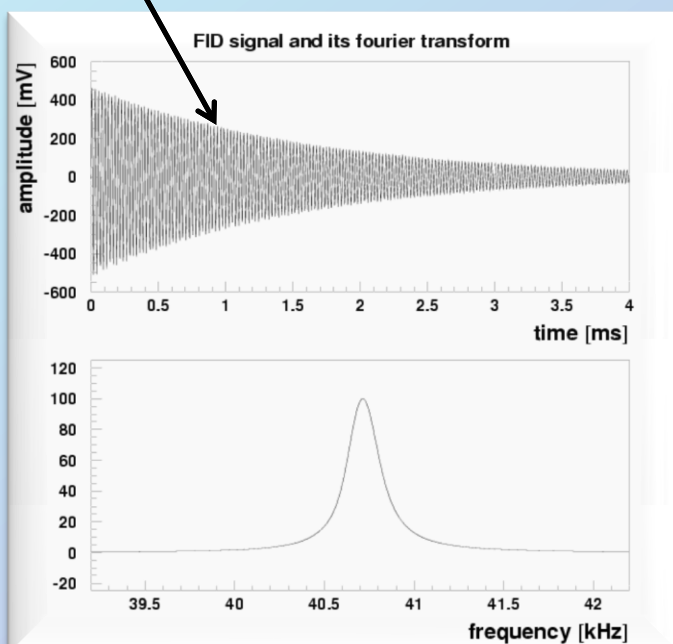
- coherently excite nuclear spins
- have nuclear spins precess in magnetic field B
- follow spin precession via induced voltage U(t)

e.g. proton NMR



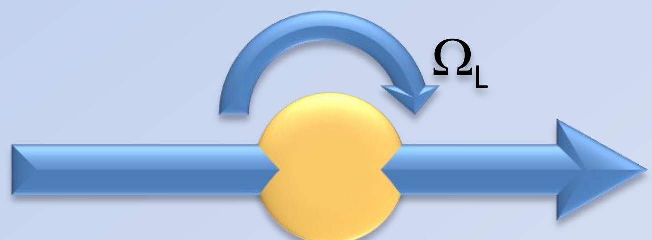
envelope ∝ exp[-t/T_2*]

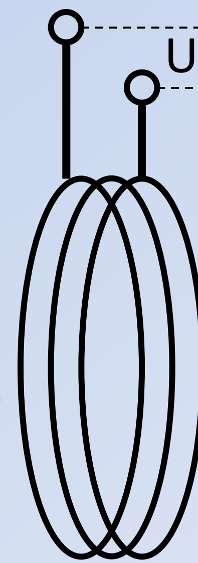
$1/T_2^* = 1/T_1 + 1/T_{2\,\text{field}}$



$$\Omega_L = \gamma|\vec{B}|$$

$U(t) = U_0 \cos \Omega_L t$

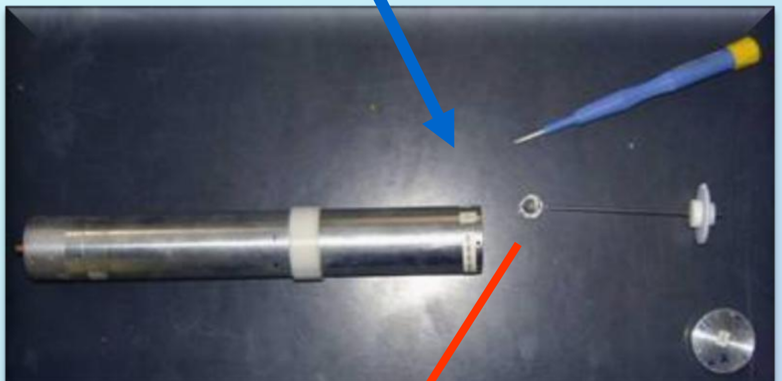




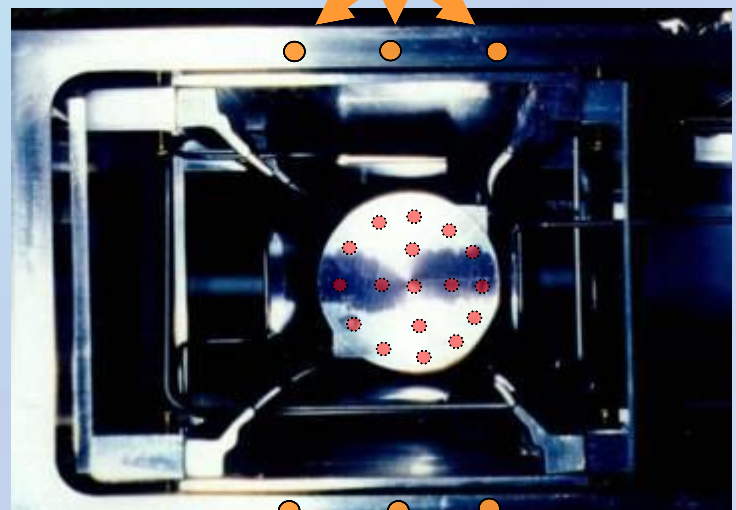
A rotating spin induces an AC voltage in a coil

Key Elements of the Field Measurement System

Absolute Calibration Probe:
a Spherical Water Sample



Fixed Probes in the walls of the vacuum tank

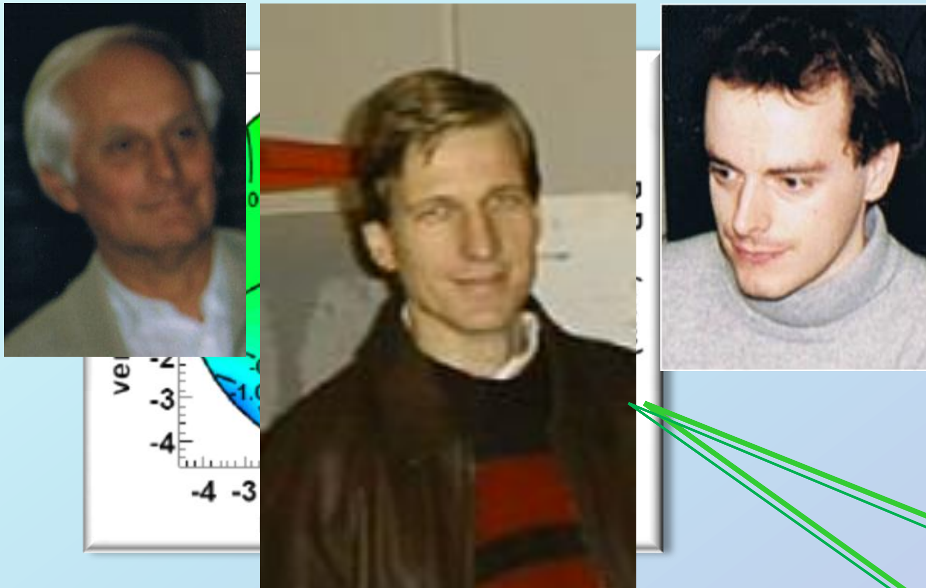


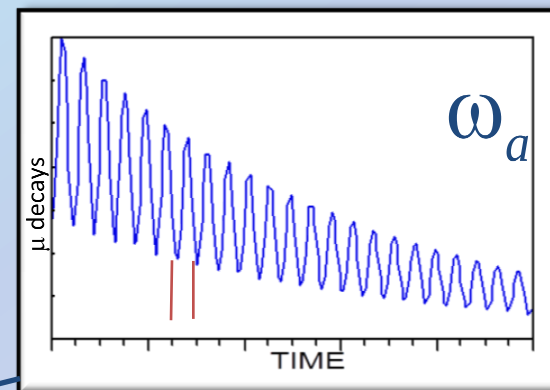
Trolley with matrix of 17 NMR Probes

Electronics, Computer & Communication

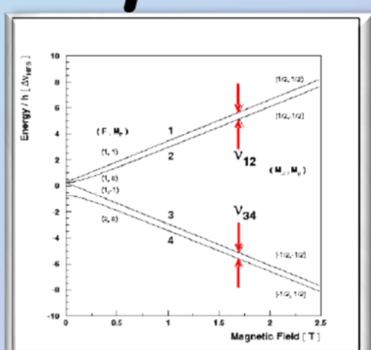
Position of NMR Probes

The Anomaly is Obtained from 3 well-measured Quantities



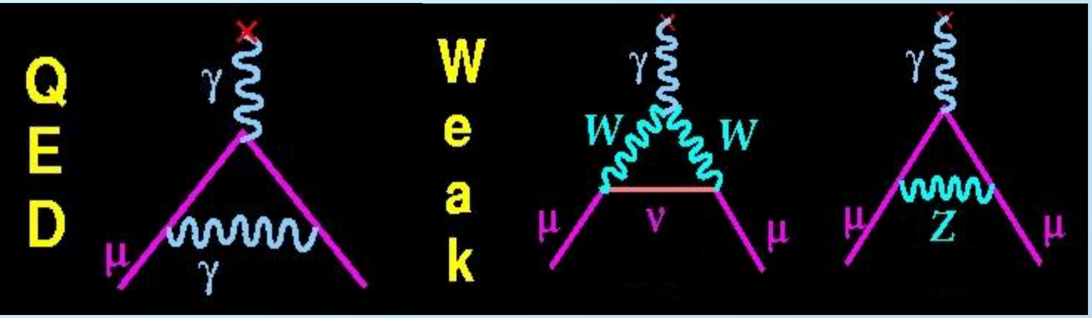


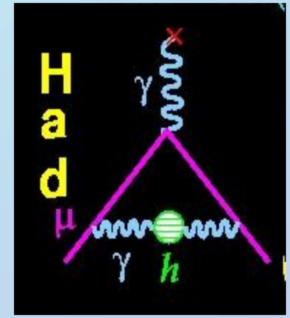
$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

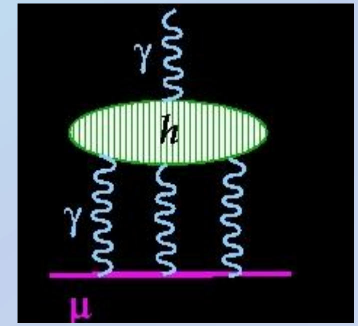


μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

The SM Value for a_μ





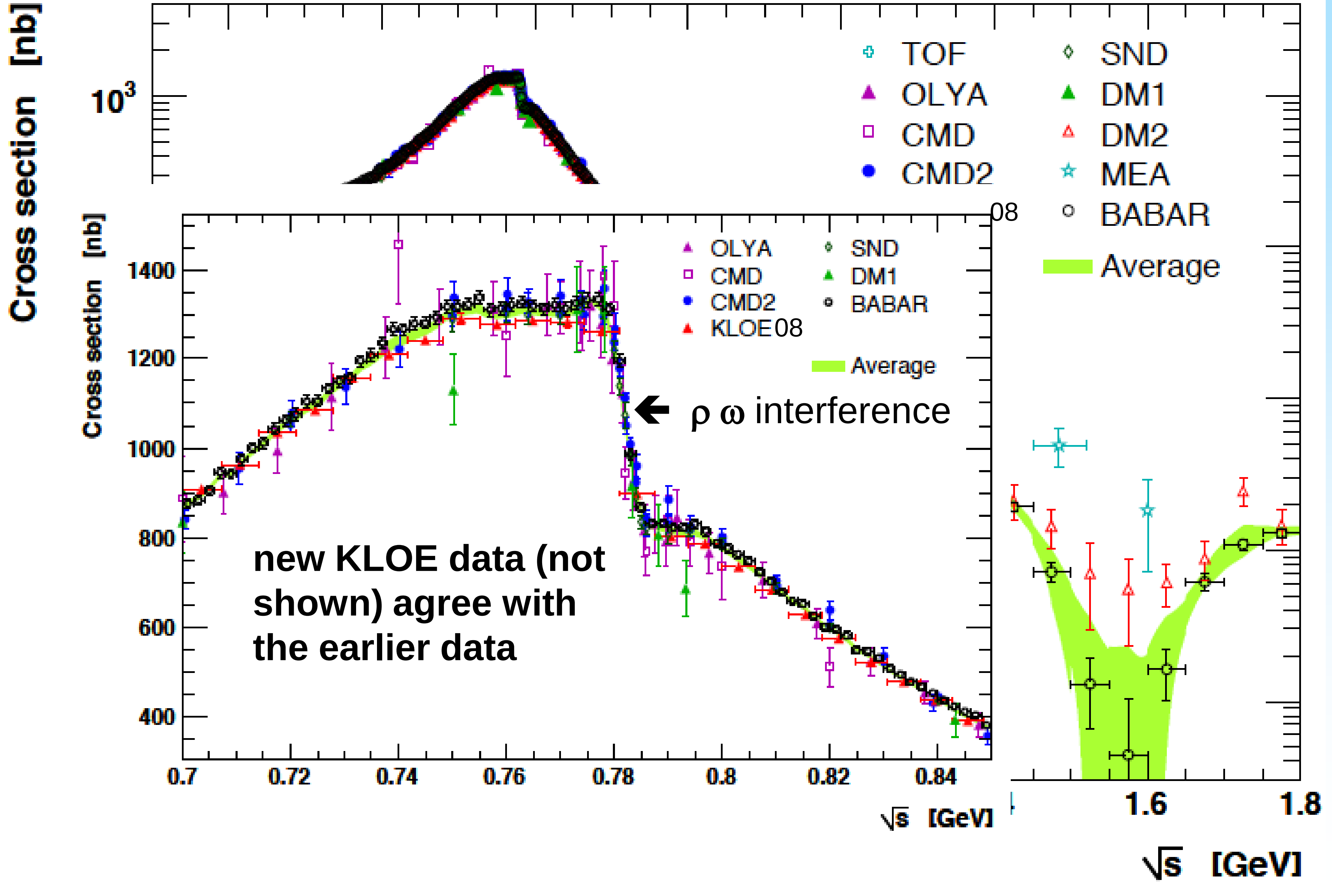


well known

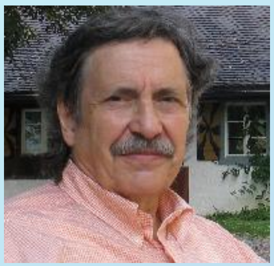
significant work ongoing

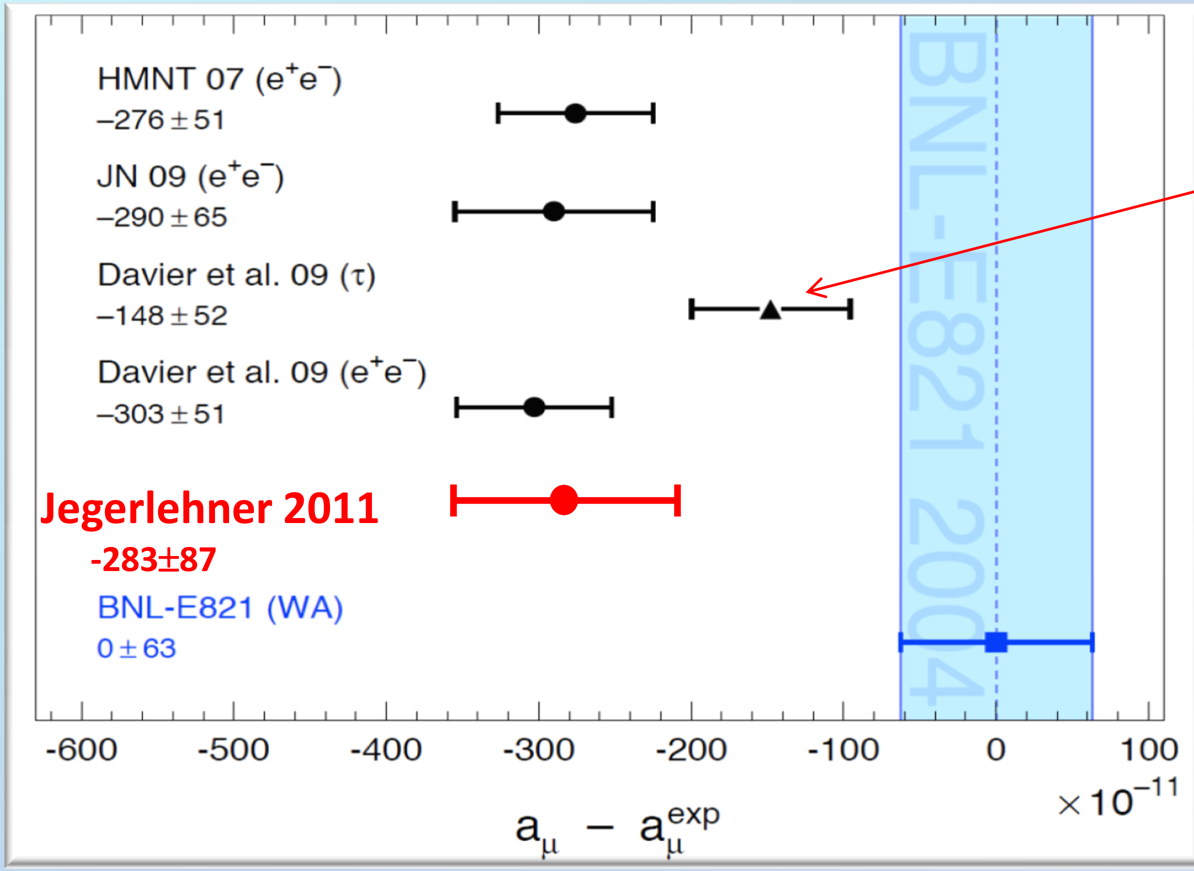
- QED calculated to α^5
- Weak calculated through 2 loops
  - 2-loop contribution reduced the contribution by 20%
  - 3-loop leading logs estimated to be small

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



Muon Magnetic Anomaly



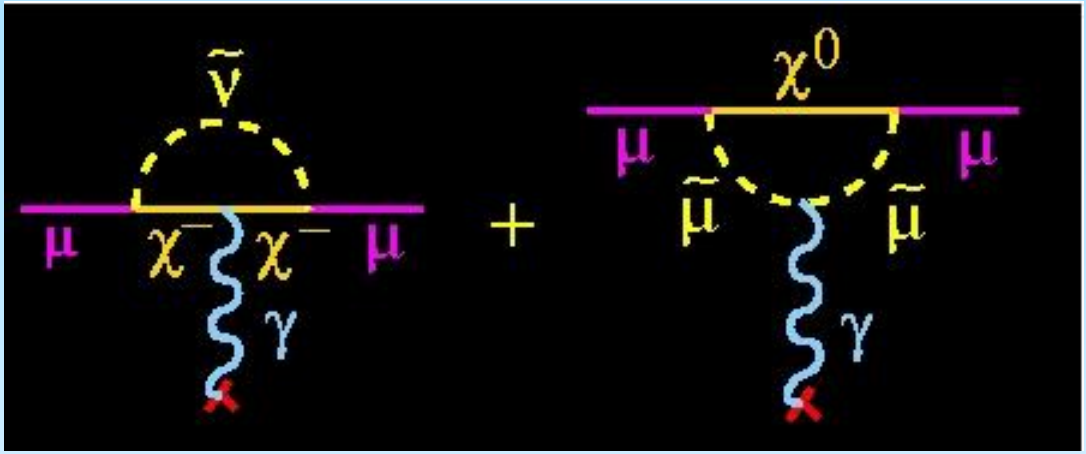


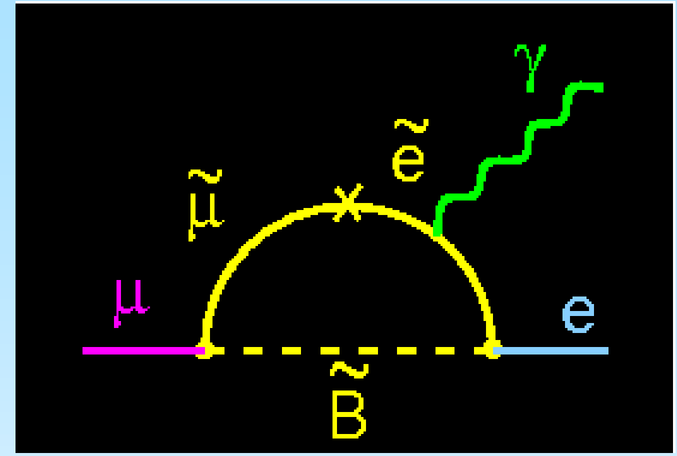
missing term

F. Jegerlehner arXiv:1101.2872 (2011)

- There is a **3.3 σ** difference between Standard Model and Experiment
- Includes forgotten parts relating to isospin breaking

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





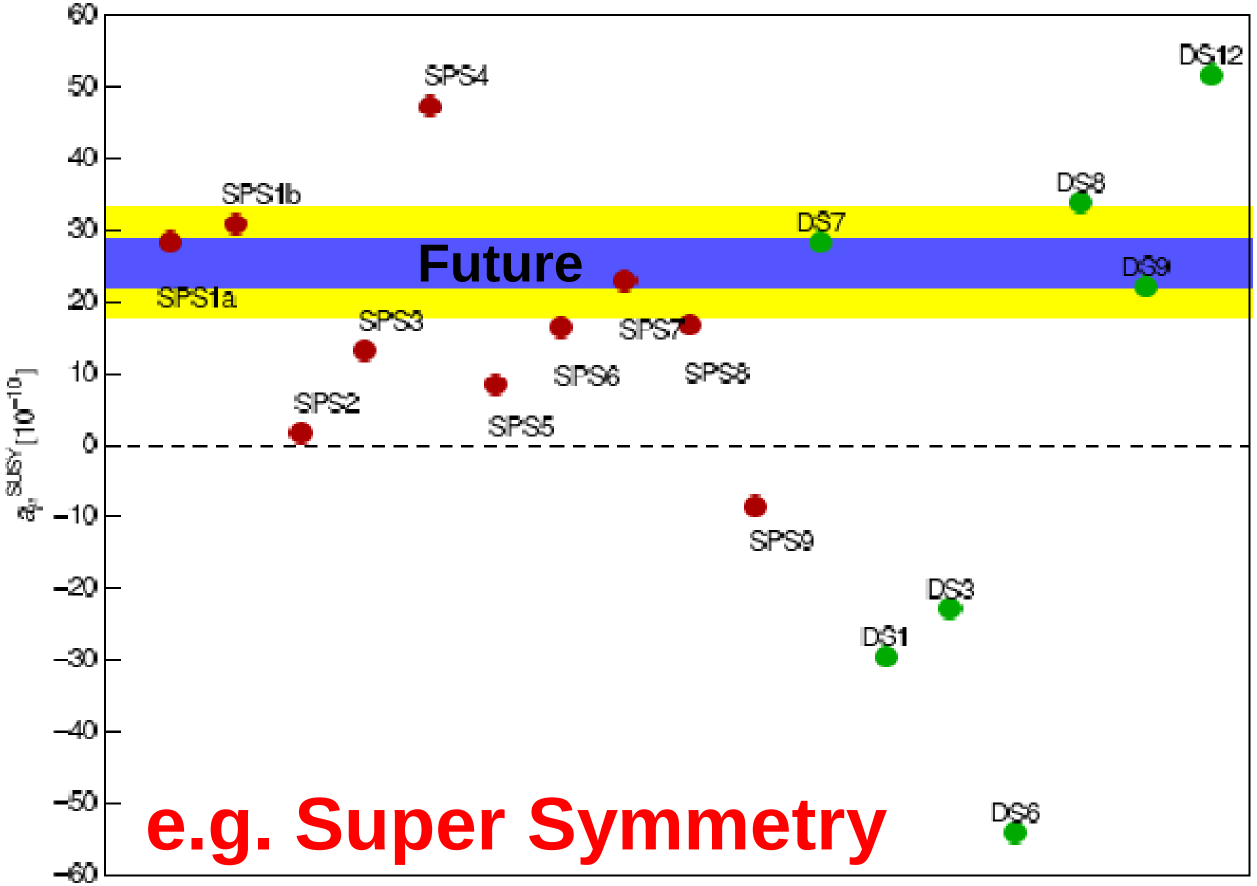
$$a_\mu(\text{SUSY}) \simeq (\text{sgn}\mu)\, 130\times 10^{-11} \tan\beta \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2$$

difficult to measure at LHC

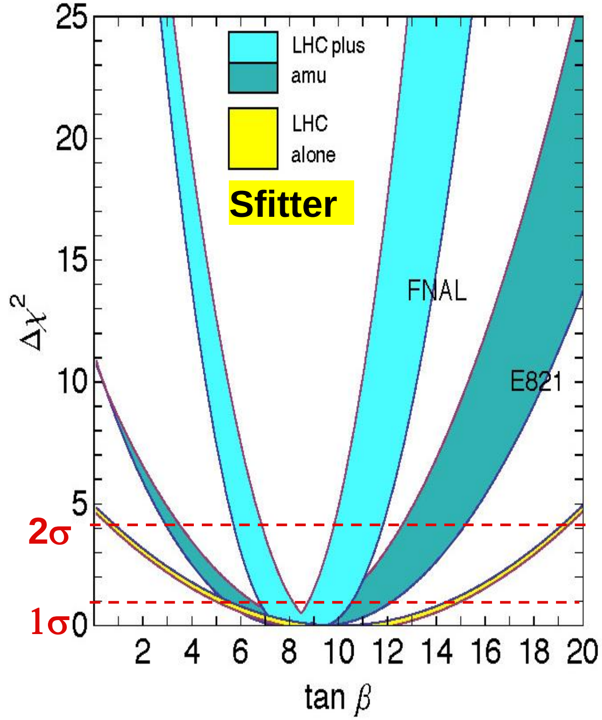
Related processes in SUSY

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

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



tan β sensitivity



Snowmass points and slopes (SUSY)

from D. Stöckinger

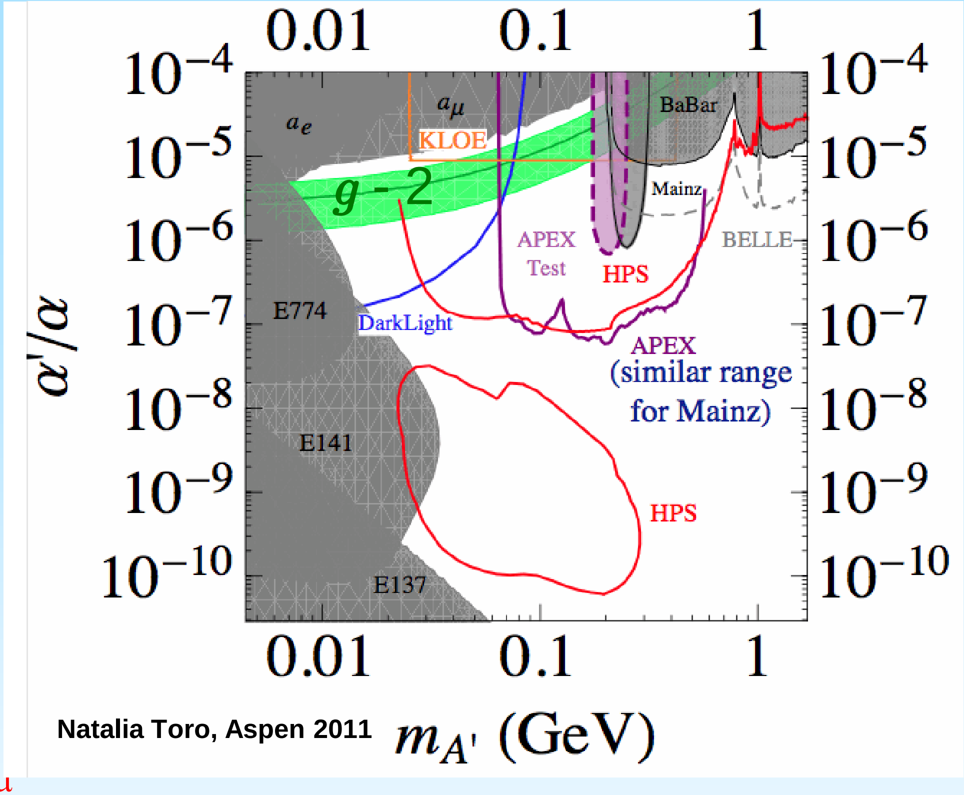
LHC Inverse Problem ($300 fb^{-1}$)

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

SPS1a; LHC $100\ fb^{-1}$ at 14 TeV

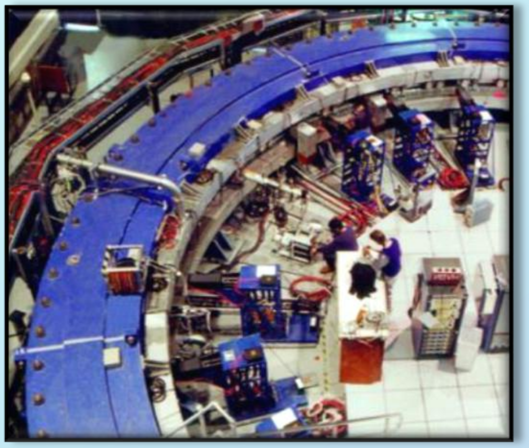
Other Models

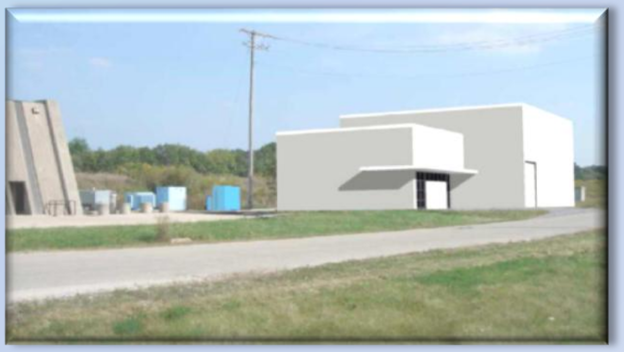
- Technicolor
  - small Δa_μ
- Littlest Higgs with T-parity
  - small Δa_μ
- Universal Extra Dimensions
  - small Δa_μ
- Randall Sundrum
  - could accommodate large Δa_μ
- Two Higgs doublets, shadow Higgs
  - small Δa_μ
- Additional light bosons that can affect EM interactions (difficult to study at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



Natalia Toro, Aspen 2011

The Possible Future

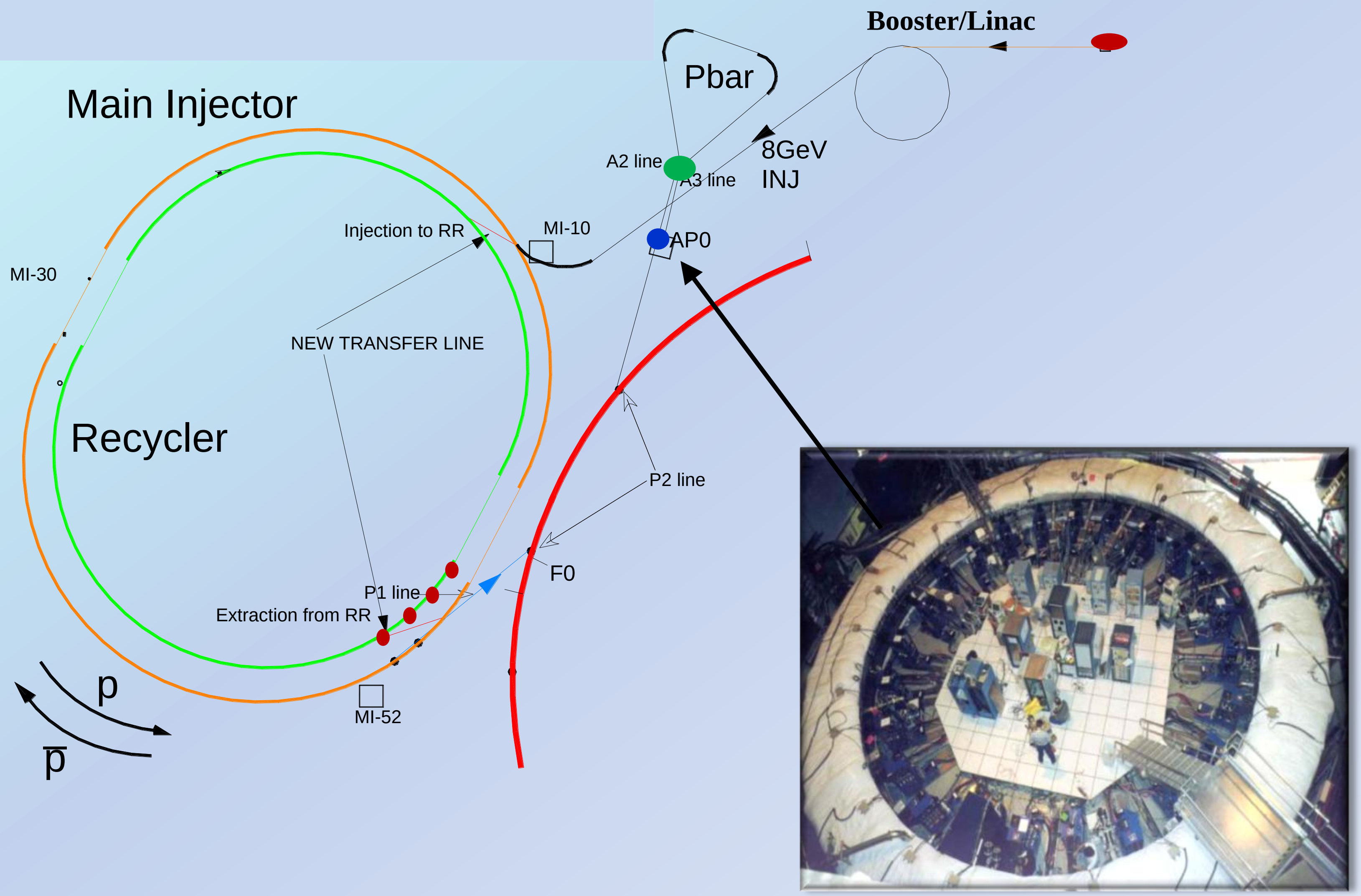




Brookhaven → FERMILAB

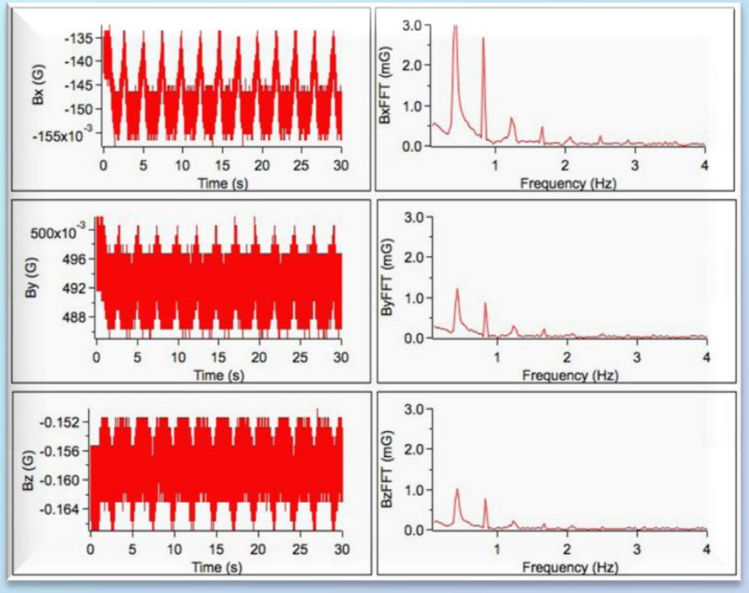
for 5 times improvement

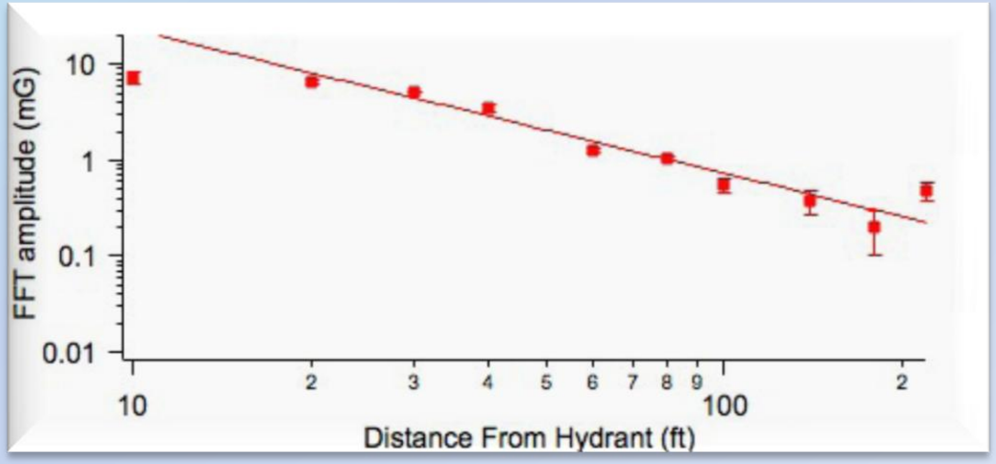
Muon g-2 @ FERMILAB



Muon Magnetic Anomaly – Field Survey @ FNAL

work by T. Chupp & B. Casey & Ch. Poly, April 2011





1 mG corresponds to $7 \bullet 10^{-8}$ of storage field

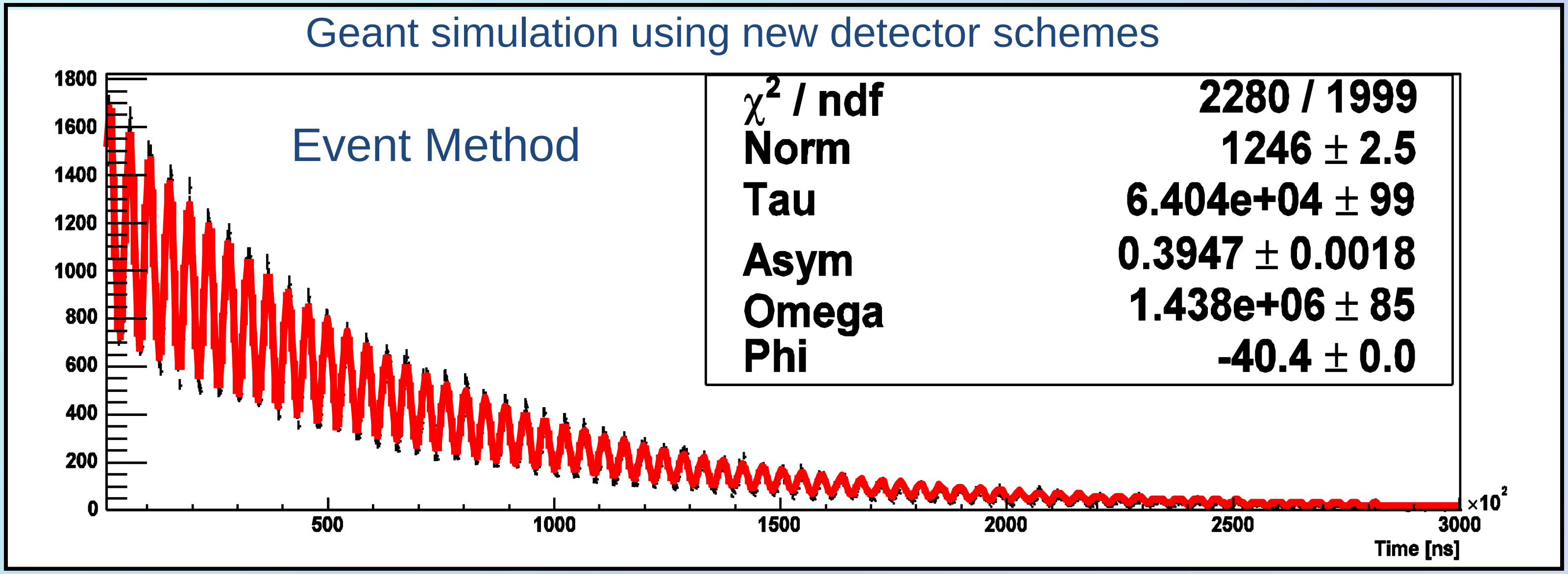
$\Rightarrow$ watch out, but no show stopper

Upgrades at Fermilab

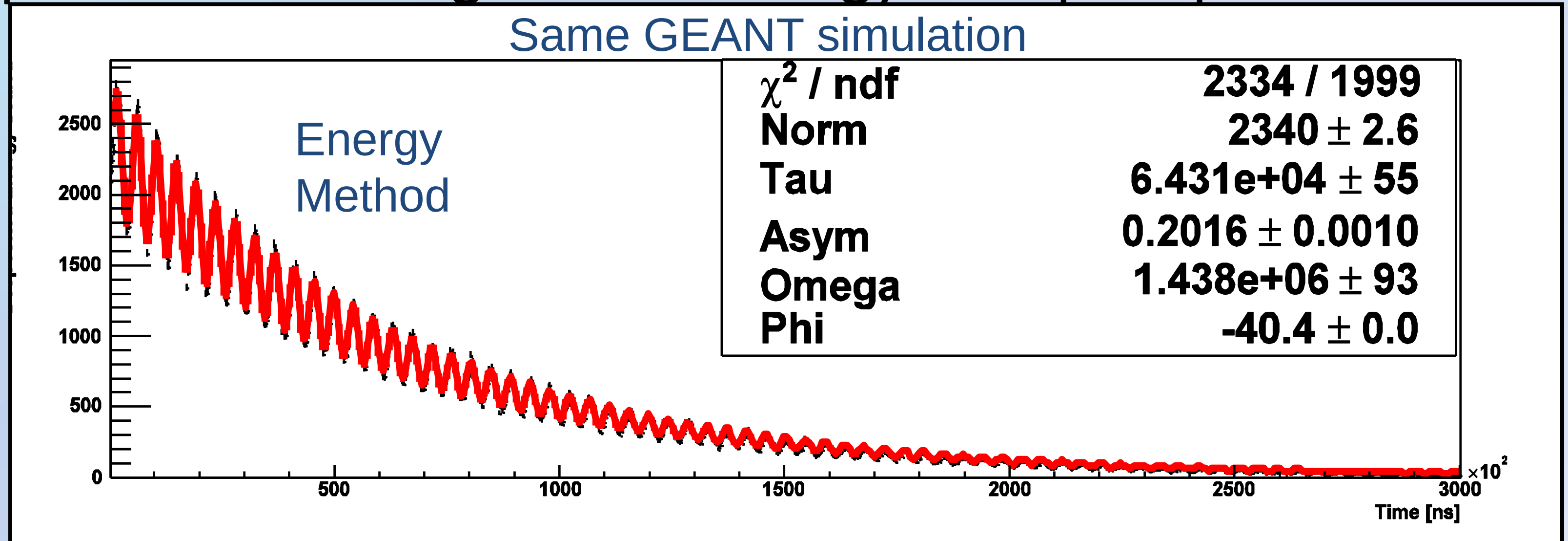
- New segmented detectors to reduce pileup
  - W-scifi prototype under study X_0 = 0.7 cm
  - NIM A602 :396-402 (2009).
- New electronics
  - 500 MHz 12-bit WFDs, with deep memories
- Improvements in the magnetic field calibration, measurement and monitoring.

Complementary ways to collect data

- "t" method – time and energy of each event - pileup



- "q" method – integrate the energy - no pileup



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

Systematic errors on ω_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

(circled) better with Fermilab beam structure and improved detectors/electronics

$\Sigma^* = 0.11$

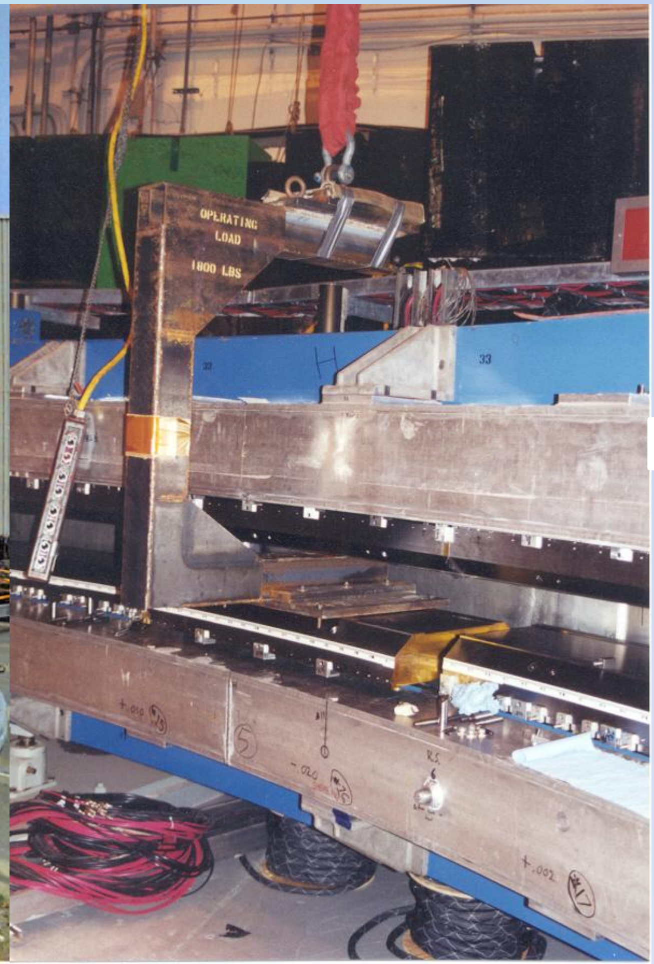
The Precision Field: Systematic errors

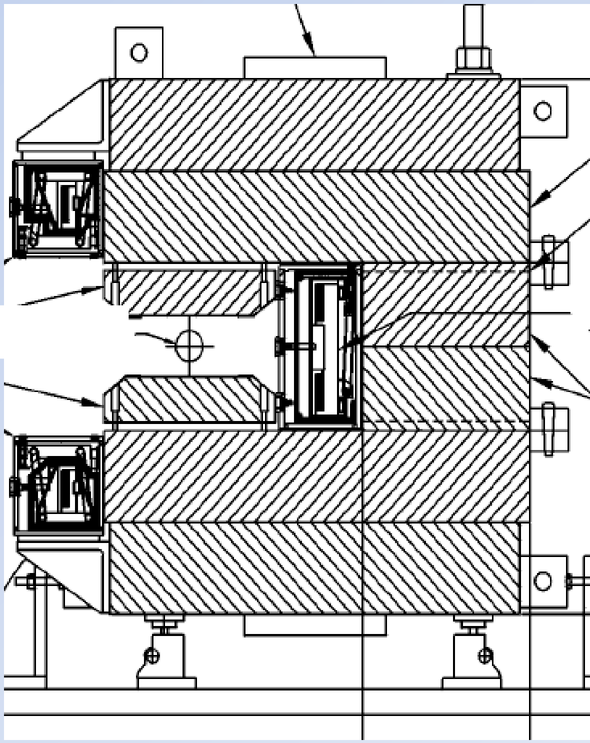
- Why is the error 0.11 ppm?
  - That's with *existing* knowledge and experience
    - with R&D defined in proposal, it will get better

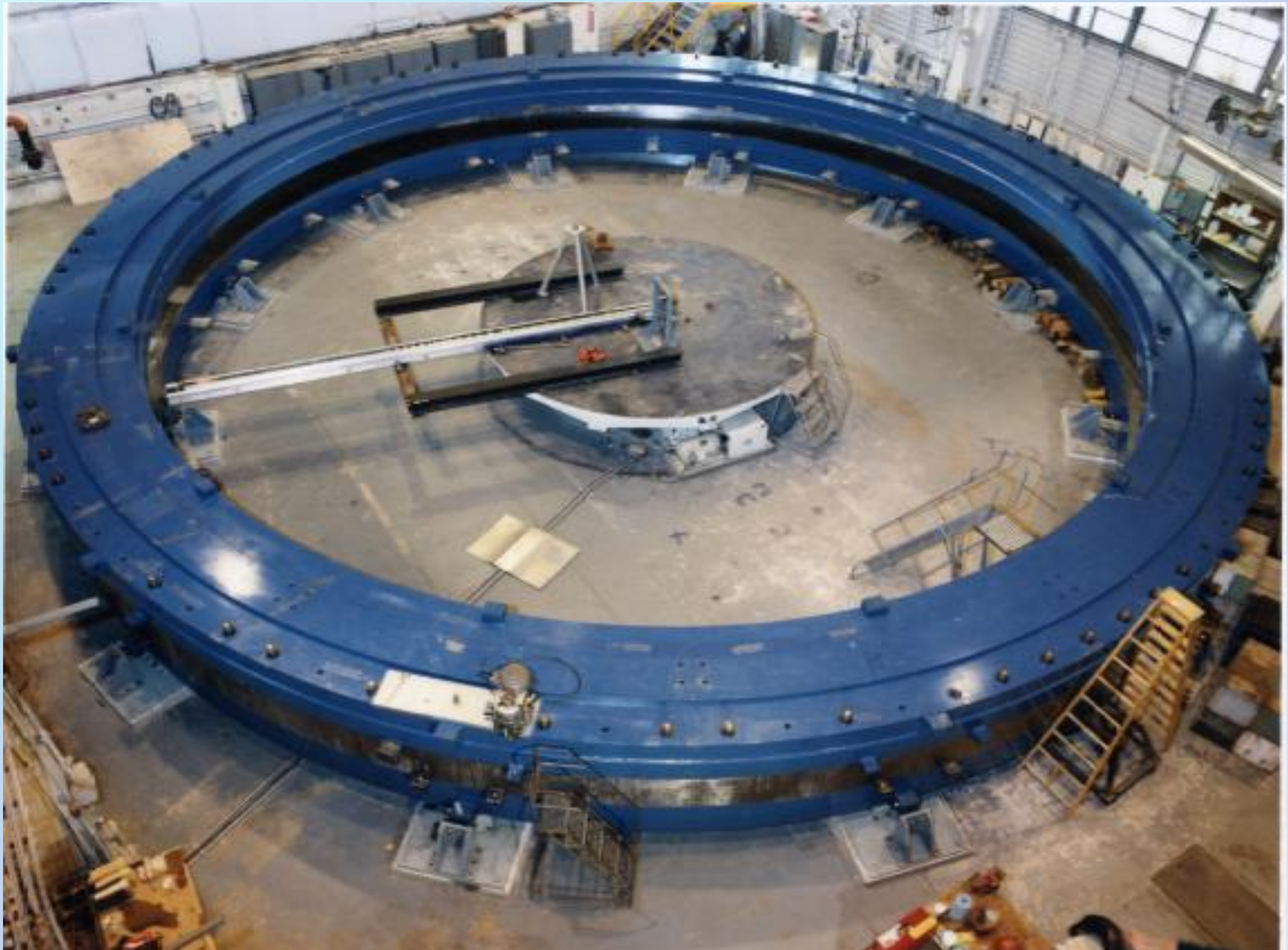
Source of Uncertainty	1998	1999	2000	2001	Next (g-2)
Absolute Calibration	0.05	0.05	0.05	0.05	0.05
Calibration of Trolley	0.3	0.20	0.15	0.09	0.06
Trolley Measurements of B0	0.1	0.10	0.10	0.05	0.02
Interpolation with the fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	
uncertainty 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

Ring relocation to Fermilab

- Heavy-lift helicopters bring coils to a barge
- Rest of magnet is a “kit” that can be trucked to and from the barge



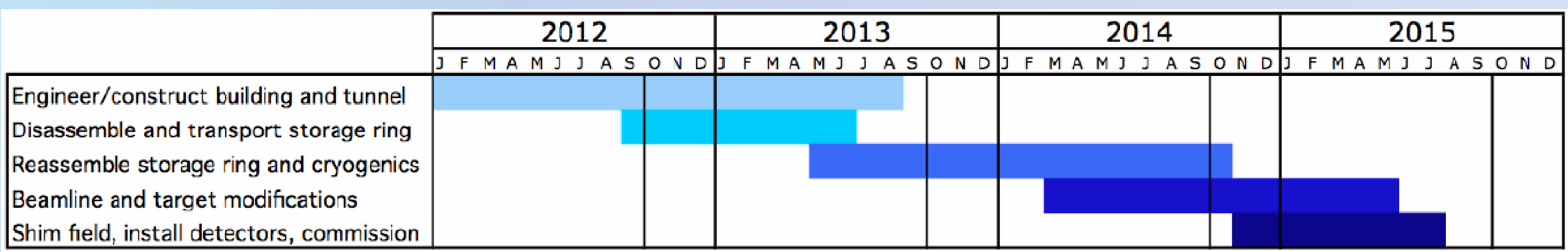




- Transport coils to and from barge via Sikorsky aircrane
- Ship through St Lawrence -> Great Lakes -> Calumet SAG
- Subsystems can be transported overland, but probably more cost effective to ship steel on barge as well.

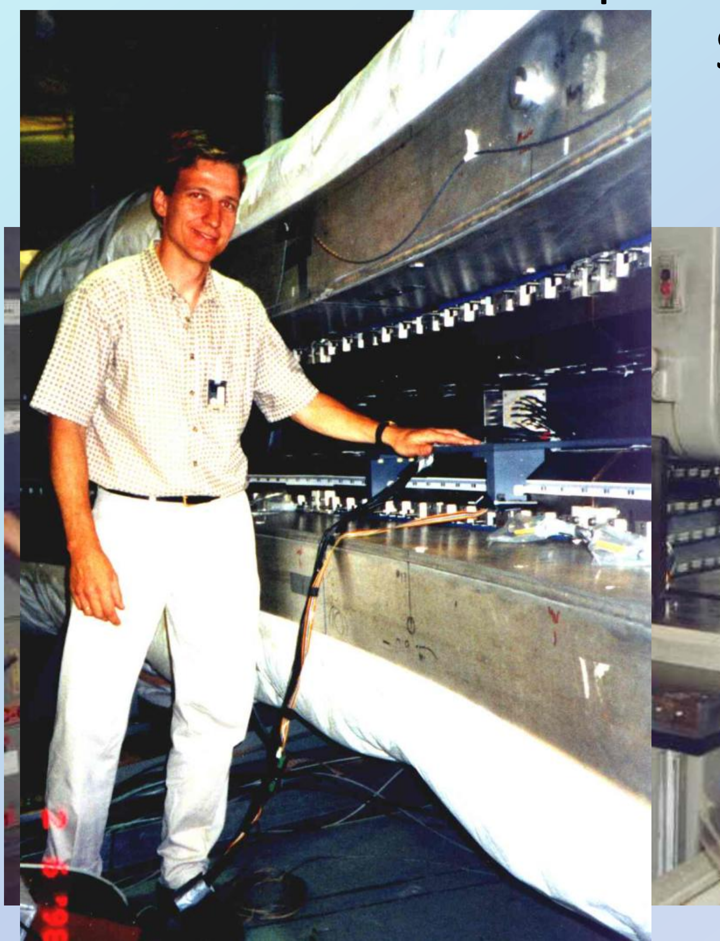
Goal is to be ready for data in 2015 - Subject to funding availability

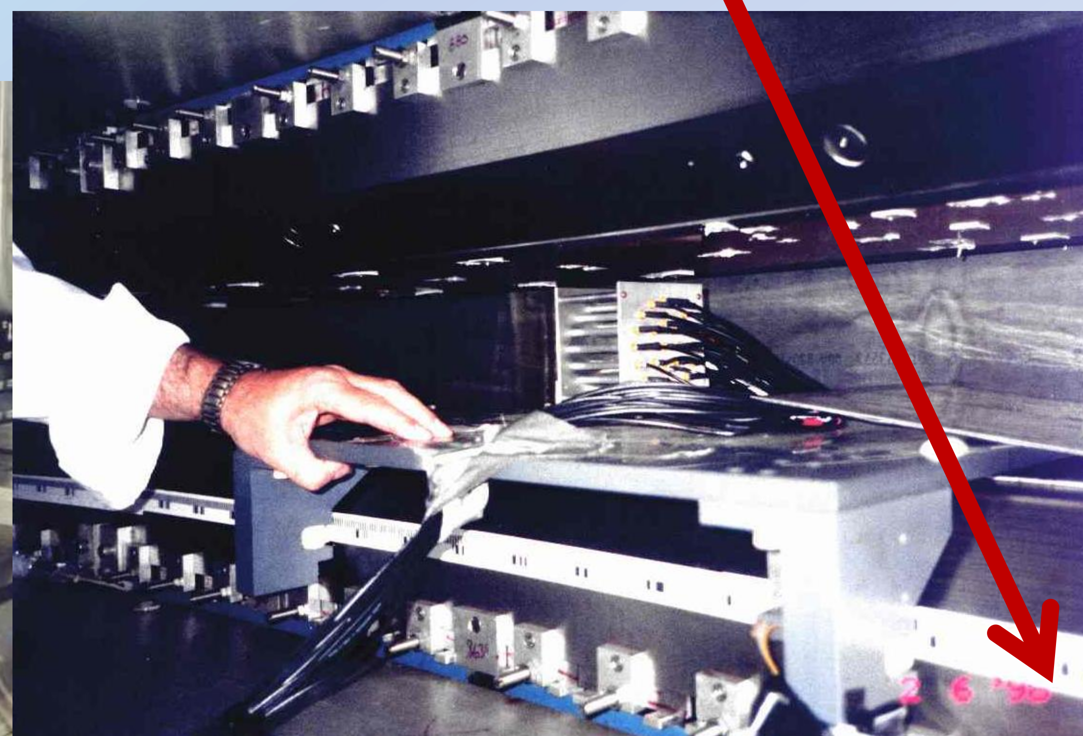
- Total project cost ~$42M
  - CD0 expected this fall
  - Conceptual Design Report being prepared
- FY2011 Funding began this June
- FY12 and beyond is being discussed between DOE and Fermilab



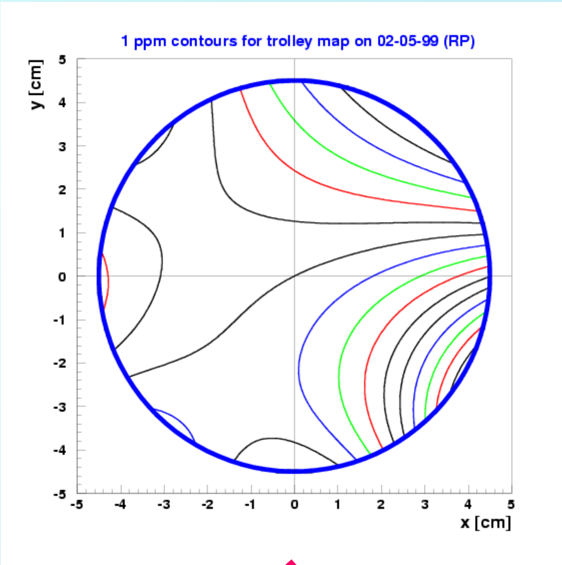
Shimming

- mechanical: Wedges in gap underneath pole pieces
  Do something about pole gaps
- electrical: Surface ring coils (80) , dipole coils
  Do something about PS ringing: Thick cables
- iterative procedure: Allow for months
  Shimming trolley (bar code)





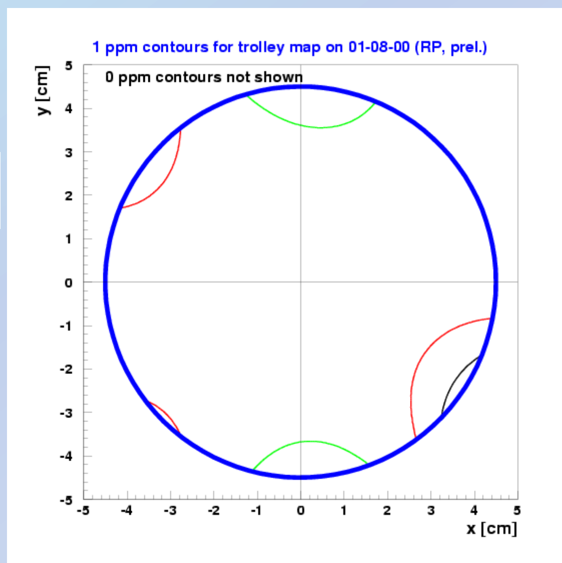
Improvement of Field



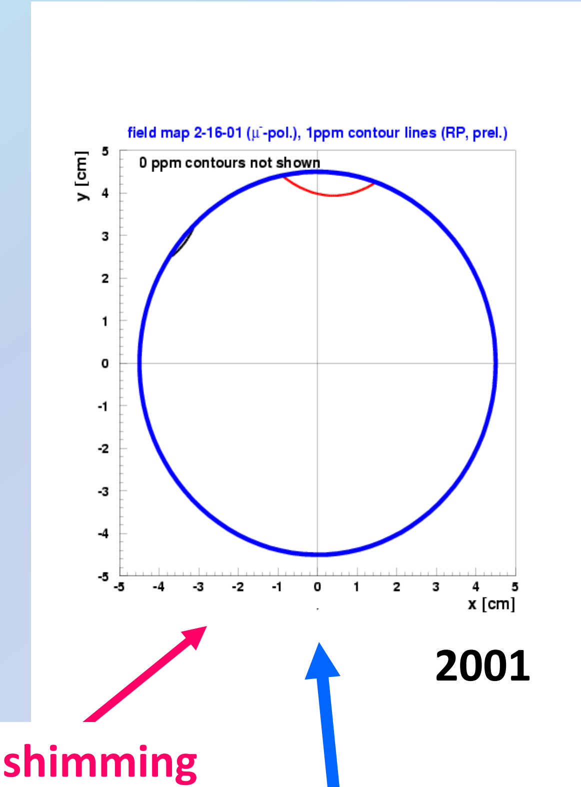
1999

shimming

2000



shimming



2001

At this level, one hardly needs to know the muon distribution

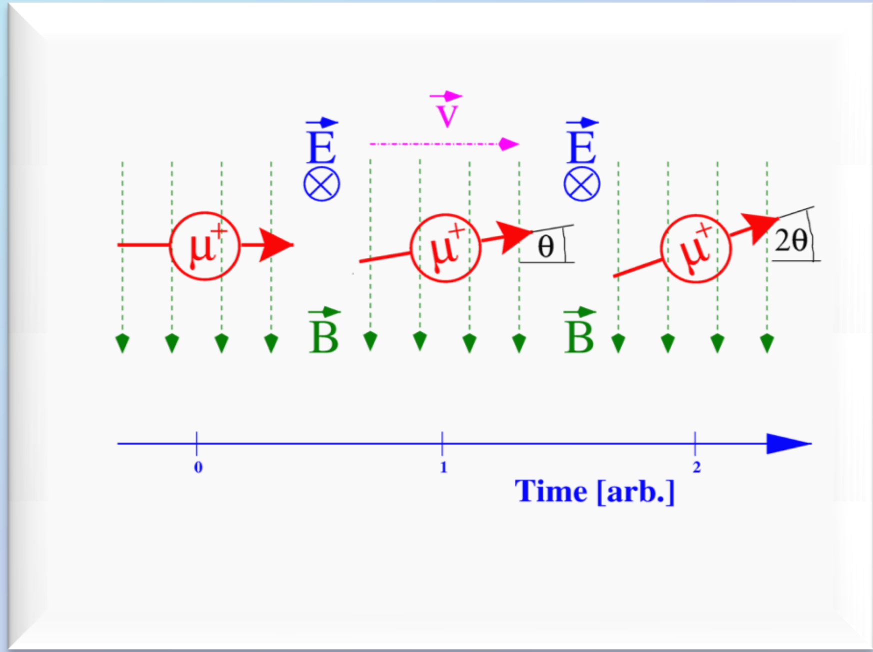
Susceptibility ‘Police’

- Not only to avoid flying Soldering stations and scissors
- No ferromagnetic material inside ring
- Common sense & Luck helped at BNL

muon EDM

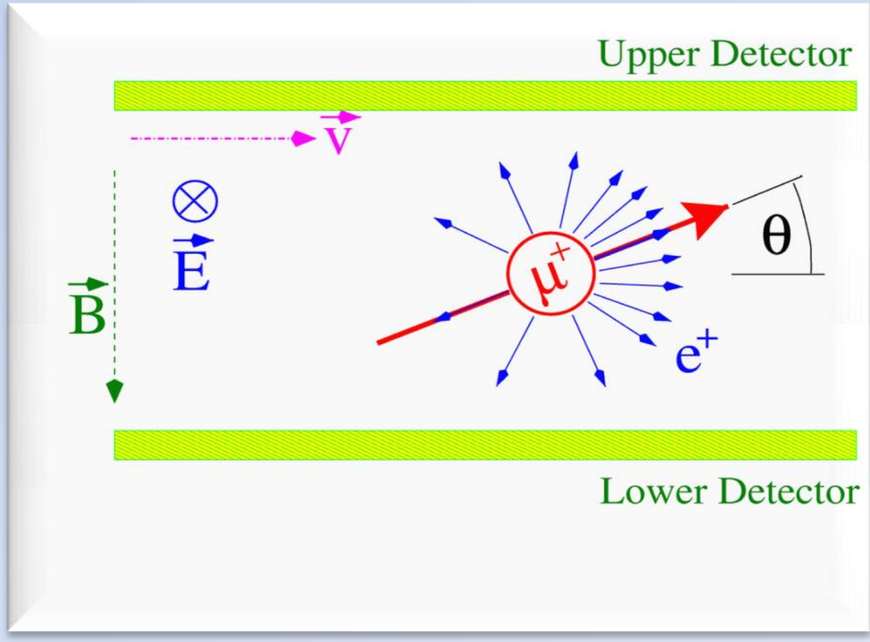
method for charged particles

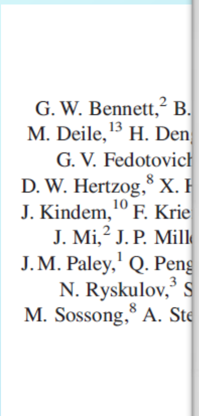
Permanent Electric Dipole Moment in a Ring



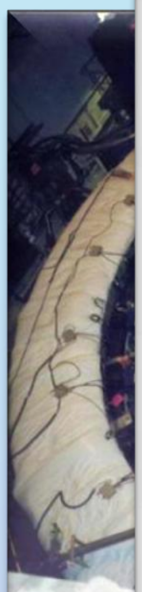
Spin precession in (electro-) magnetic field

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

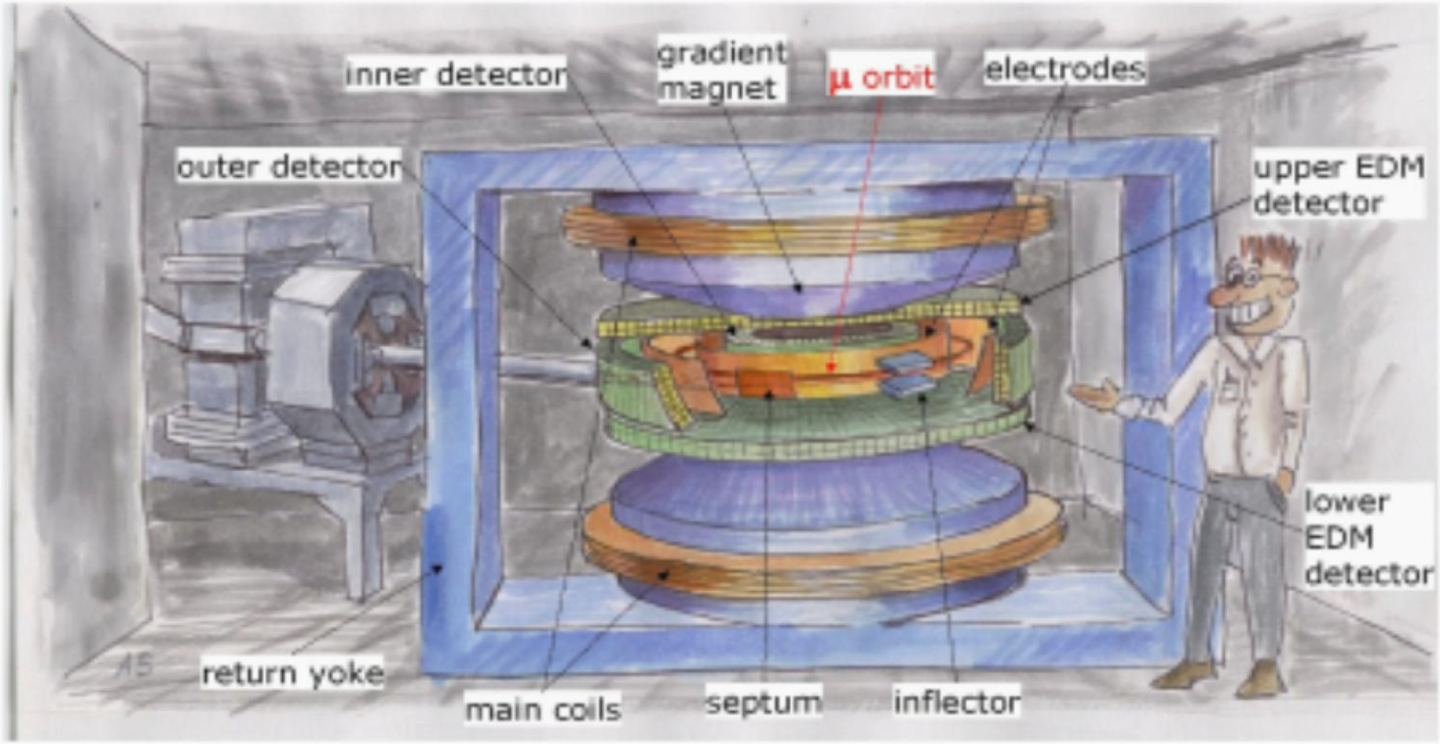




G. W. Bennett,[2] B.
M. Deile,[13] H. Den
G. V. Fedotovich
D. W. Hertzog,[8] X. H
J. Kindem,[10] F. Krie
J. Mi,[2] J. P. Mill
J. M. Paley,[1] Q. Peng
N. Ryskulov,[3] S
M. Sossong,[8] A. Ste



Concept for a μEDM experiment at PSI



- Trade off high intensity of muon beam for beam quality selecting the muons to be injected into the ring
- Use one muon at a time from the PSI μE1 beam with p_μ=125 MeV/c (β=0.77, γ=1.55, P_μ~0.9)
- possible layout: 1 T B-field ⇒ 42 cm orbit radius and 64 kV/10 cm E-field
- Clockwise and counter-clockwise operation (systematics)

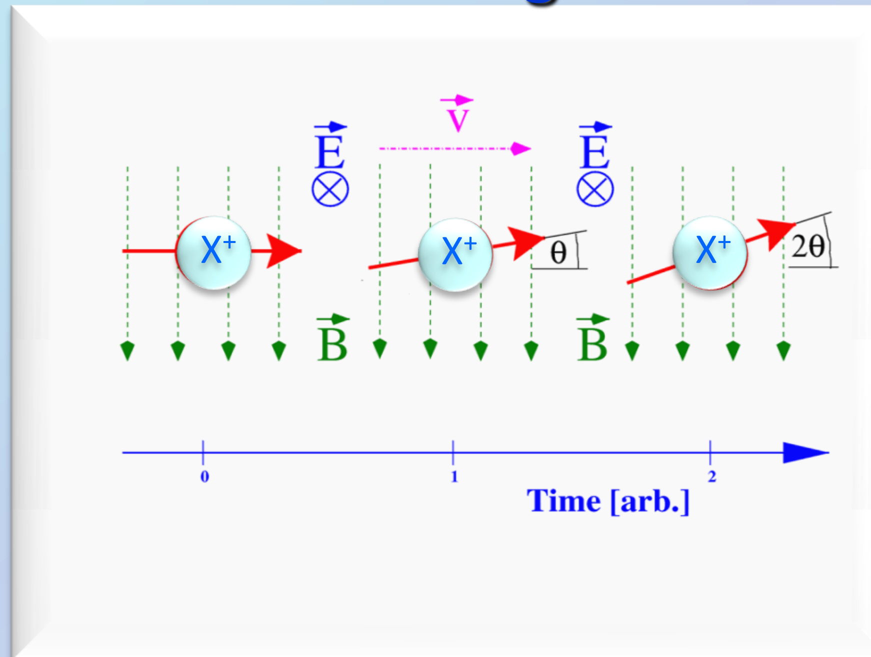
Sensitivity estimate:

- Detect $N = 5.8 \times 10^{12}$ muon decays per year
- Statistical sensitivity is 10^{-16} e cm $/\sqrt{N}$
- Sensitivity after one year:

5×10^{-23} e cm

Adelmann, Kirch, Onderwater, J. Phys. G: Nucl. Part. Phys. 37 085001 (2010)

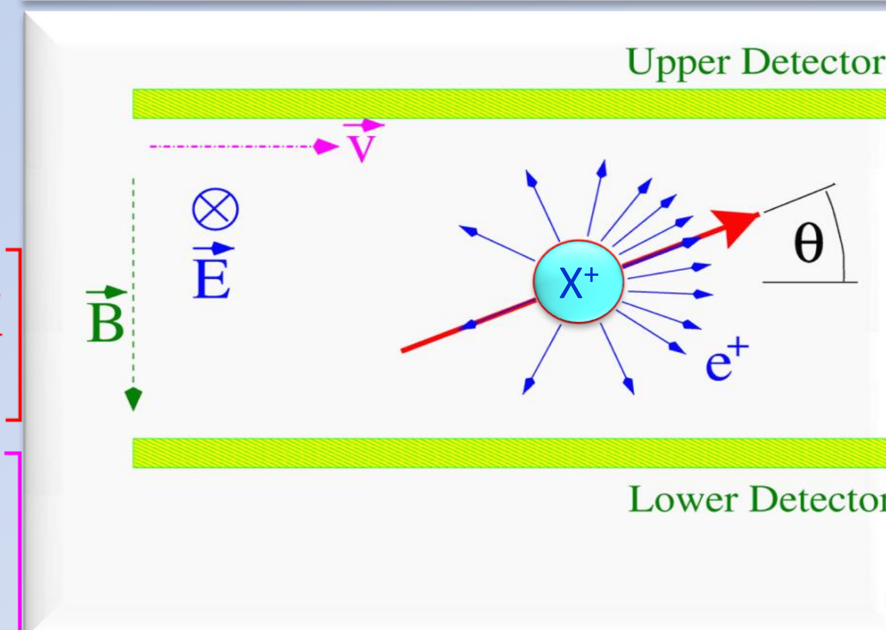
Permanent Electric Dipole Moment in a Ring



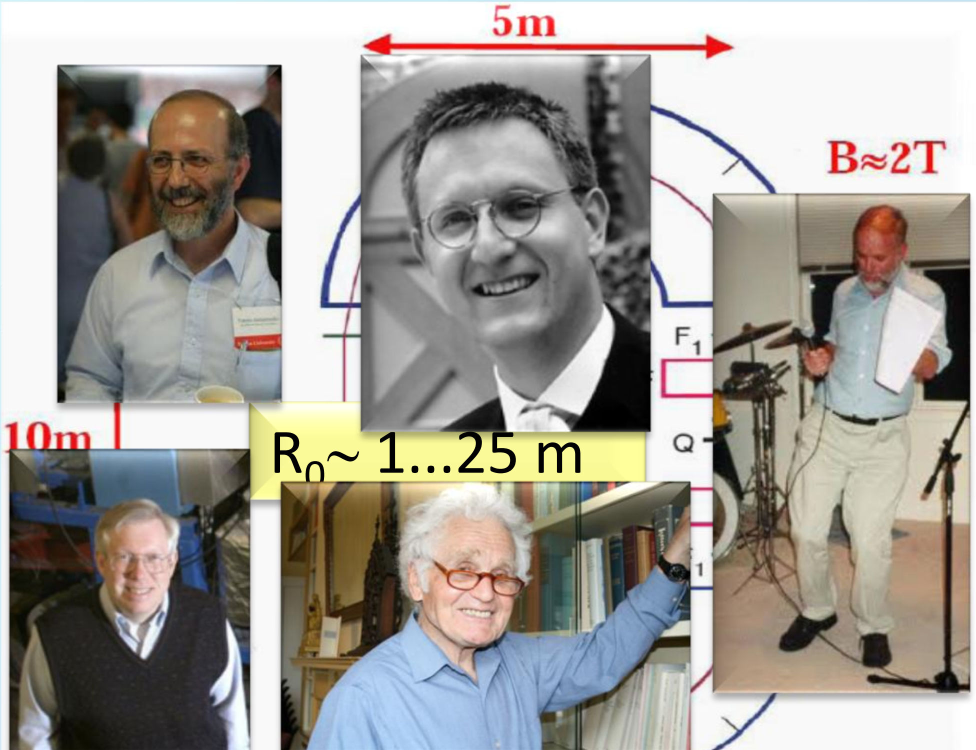
Spin precession
in (electro-)
magnetic field

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

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



Searches for EDMs in charged particles:
Novel Method invented Motional Electric Fields exploited



edm collaboration
(Y. Semerzidis et al.,arXiv:hep-ex/0308063)

International Collaboration

- possible sites discussed: BNL, **COSY**, …
- d, p, ^{3}He
- Limit $d_{d,p,3He} < 10^{-27} \ldots 10^{-29}$ e cm
- Can be >10 times more sensitive than neutron d_n, best test for Θ_{QCD}, …

Phys.Rev.C 70, 055501 (2004)

Other EDMs

Lines of attack towards an EDM

Free Particles

neutron
muon
deuteron
bare nuclei ?
…

→ particle EDM
→ unique information
→ new insights
→ new techniques
→ challenging technology

Atoms

Hg Xe
Tl
Cs Rb
Ra Rn
…

→ electron EDM
→ nuclear EDM
→ enhancements
→ challenging technology

Electric Dipole Moment

goal:
new source of ~~CP~~

Molecules

→ electron EDM
→ strong enhancements
→ new techniques
→ poor spectroscopic data

YbF
PbO
PbF ,ThO
HfF^+,ThF^+
…

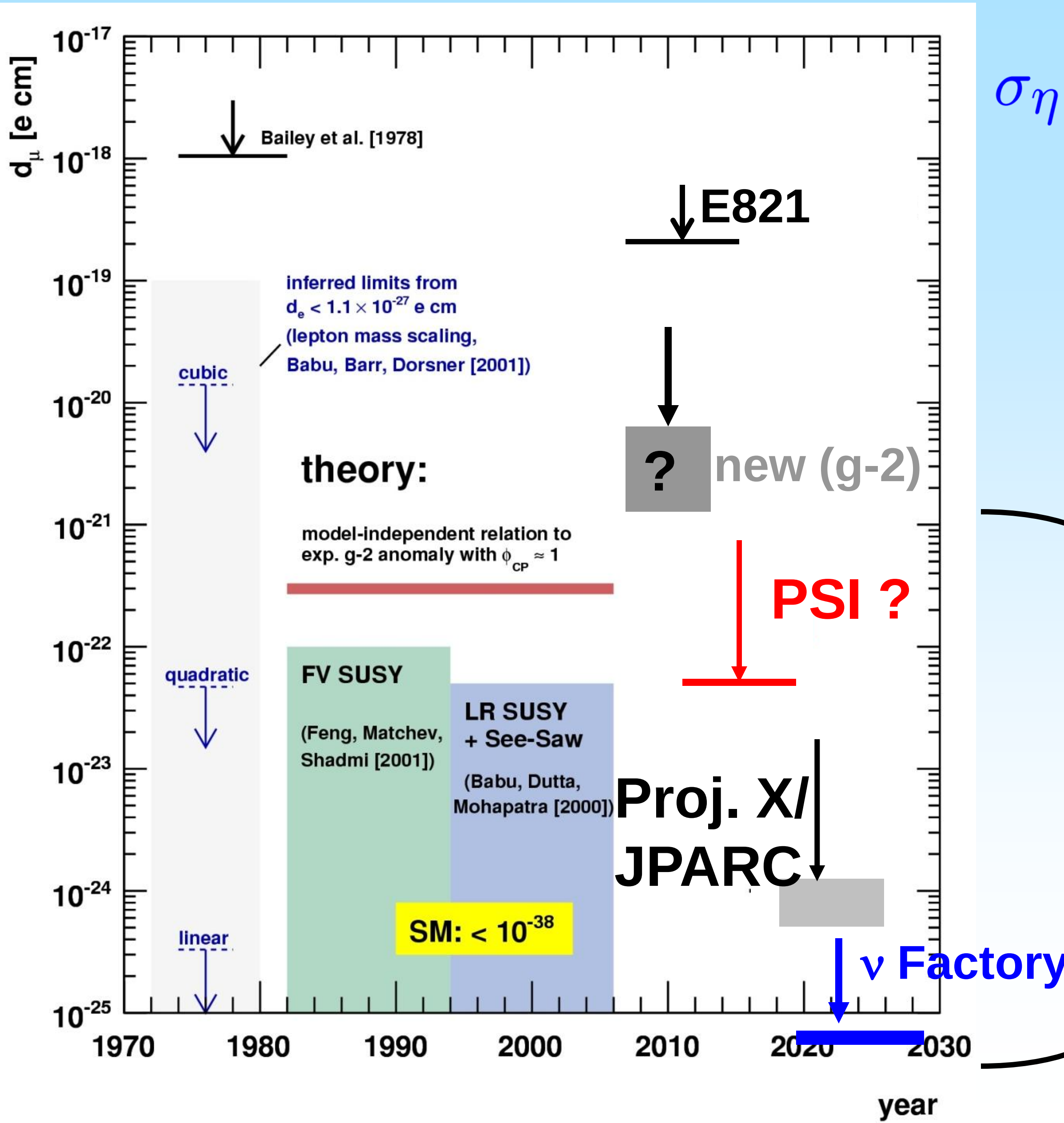
Condensed State

→ electron EDM
→ strong enhancements
→ systematics ??

garnets
($Gd_3Ga_5O_{12}$)
($Gd_3Fe_2Fe_3O_{12}$)
solid He ?
liquid Xe

Muon EDM Limits: Present and Future

Back



$$\sigma_\eta = \frac{\sqrt{2}}{\gamma\tau(e/m)\beta B A\sqrt{N}}$$

Need:

$NA^2 = 10^{16}$ **for**

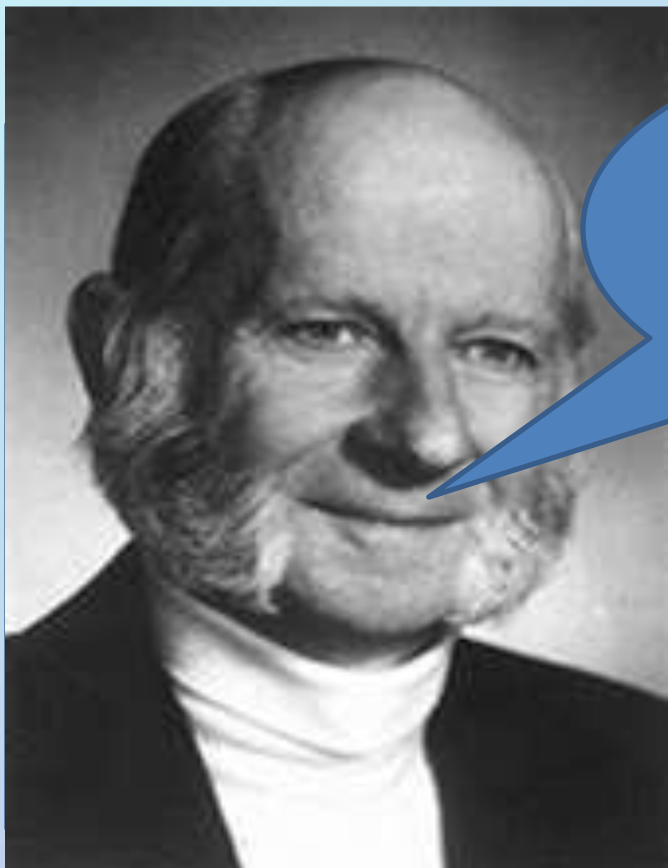
$d_\mu \simeq 10^{-23}\ e{\cdot}\mathrm{cm}$

Dedicated storage rings

Search for violation of Lorentz /CPT violation

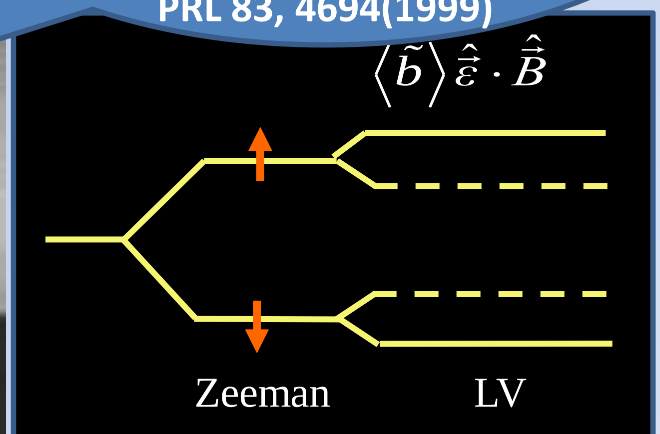
Modified Dirac equation for a free spin ½ particle (w=e,p,n)

$$\left(\underbrace{i\gamma^{\mu}\partial_{\mu} - m_w}_{\text{standard DE}} \underbrace{- a^{w}_{\mu}\gamma^{\mu} - b^{w}_{\mu}\gamma_5\gamma^{\mu} + ie^{w}_{\nu}\partial^{\nu} - f^{w}_{\nu}\gamma_5\partial^{\nu} + i\frac{1}{2}g^{w}_{\lambda\mu\upsilon}\sigma^{\lambda\mu}\partial^{\nu}}_{\text{CPT violating}} \underbrace{- \frac{1}{2}H^{w}_{\mu\nu}\sigma^{\mu\nu} + ic^{w}_{\mu\nu}\gamma^{\mu}\partial^{\nu} + id^{w}_{\mu\nu}\gamma_5\gamma^{\mu}\partial^{\nu}}_{\text{CPT preserving terms}} \right)\Psi = 0$$



1999 :
during Lepton Moments 1
Works with single electron
PRL 83, 4694(1999)

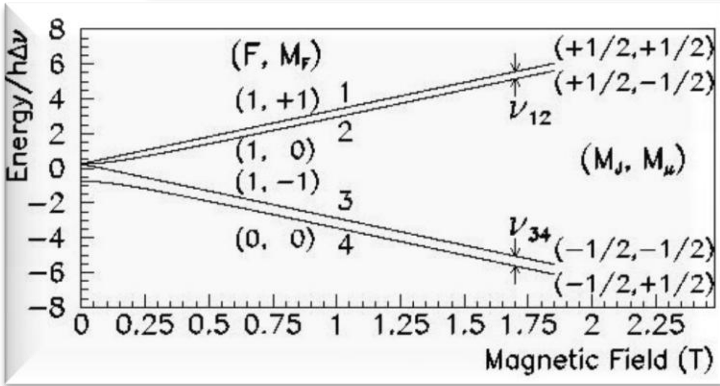
$$b^{w}_{\mu}, \ldots \approx \eta_w \cdot \left(\frac{m_w}{M_{Planck}} \right)^{n}$$

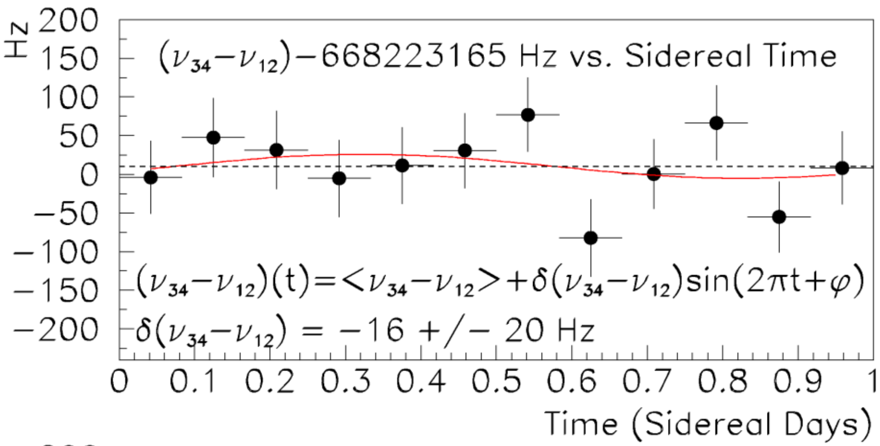


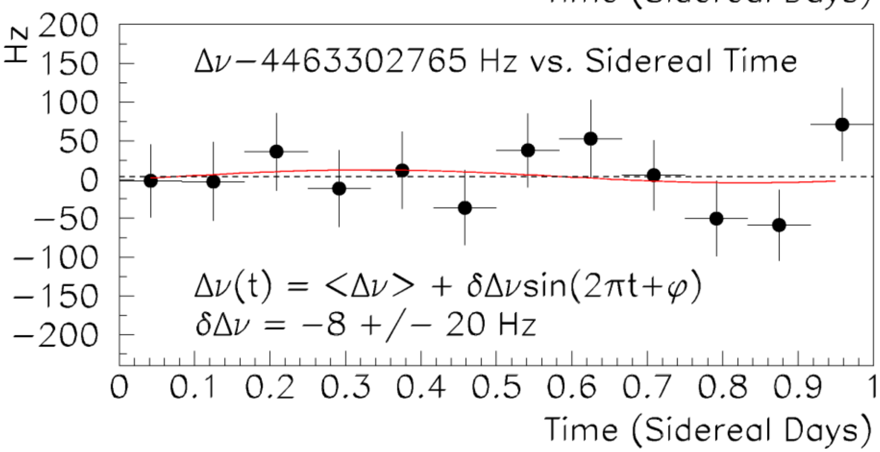
$$\tilde{b}_e \approx 10^{-25}\ \text{GeV}$$

see e.g.
A. Kostelecky and C. Lane
Phys. Rev. D 60, 116010 (1999)

CPT and Lorentz Invariance from Muon Experiments







Muonium:

new interaction below

$2 * 10^{-23}$ GeV

V.W. Hughes et al. PRL 87, 111804 (2001)

Muon g-2:

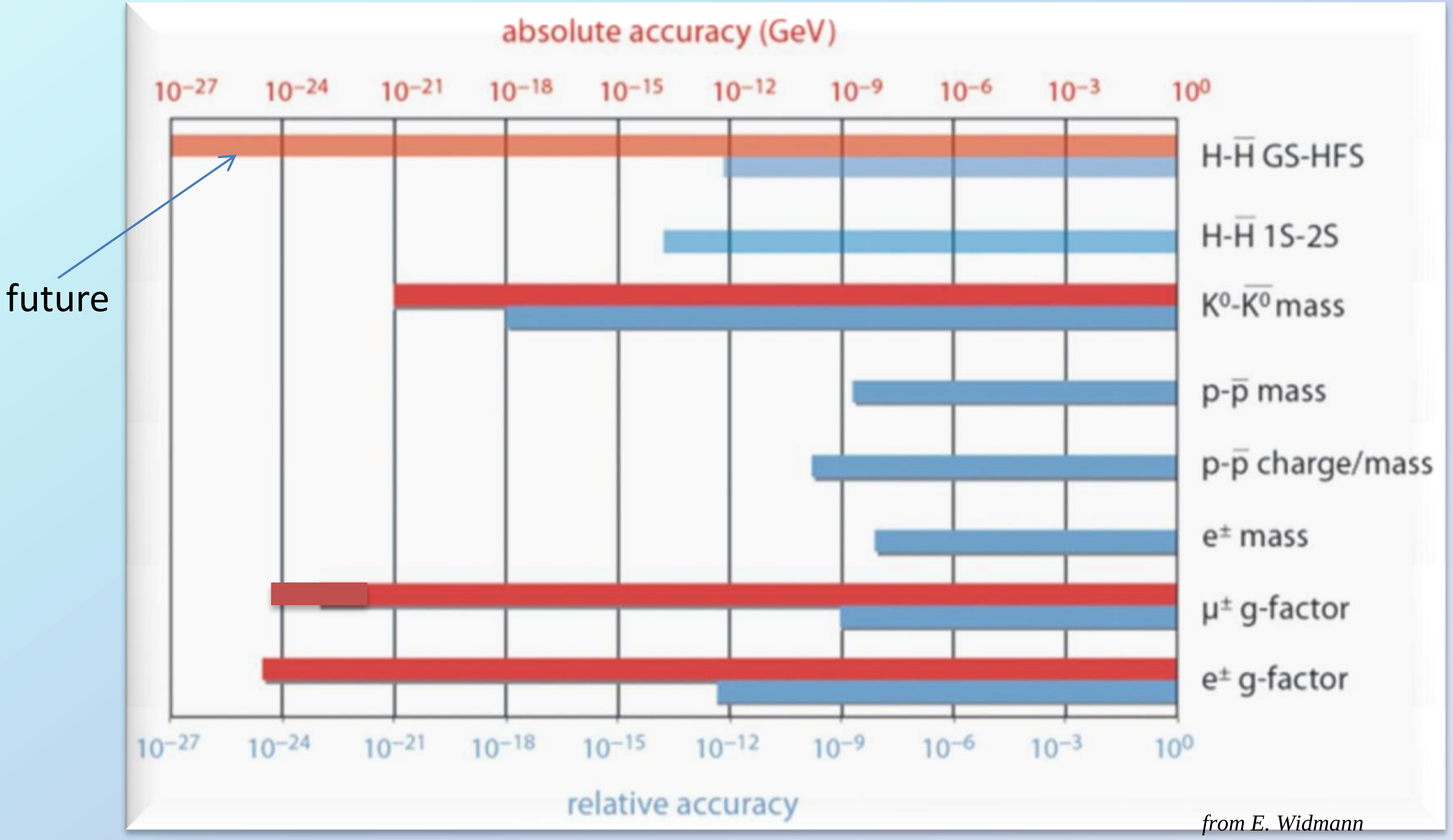
new interaction below

10^{-24} GeV

G.W. Bennett et al. PRL 100, 91602 (2008)

V.W. Hughes et al., Phys.Rev. Lett. 87, 111804 (2001)

Some CPT Tests



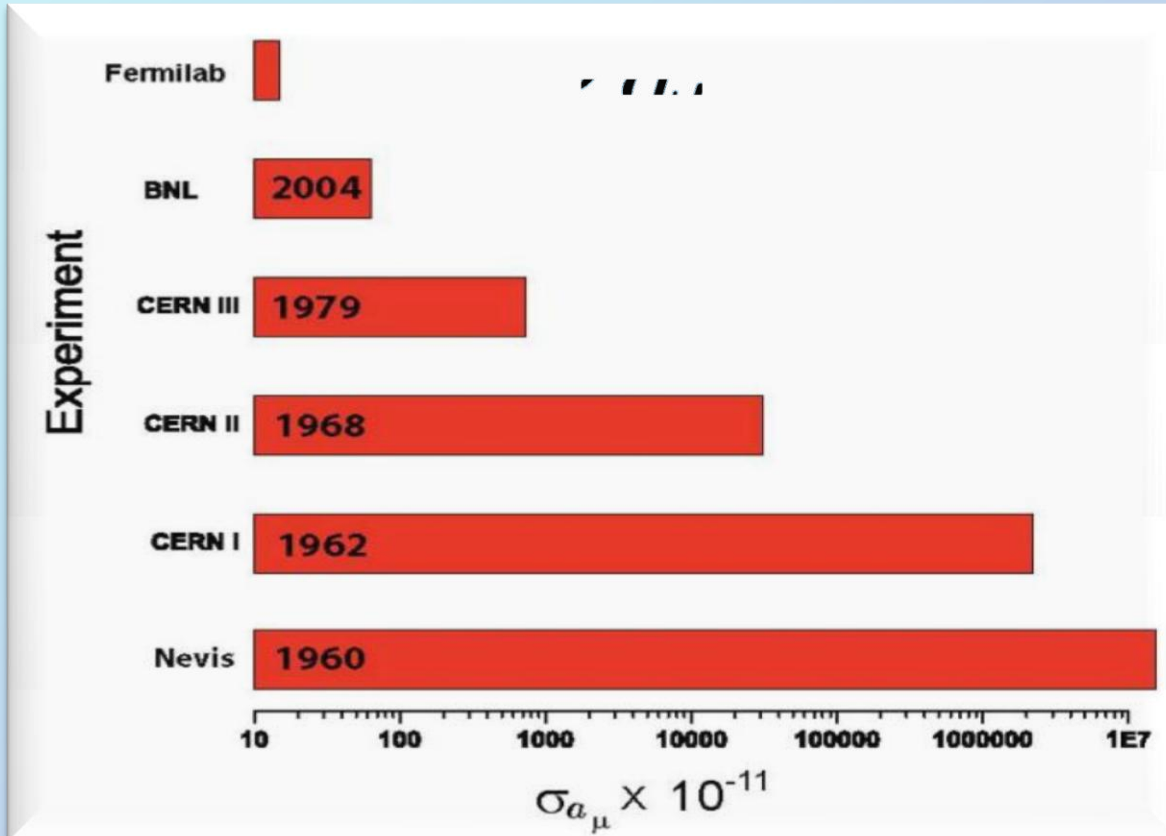
from E. Widmann

Summary (g-2)

- The measurements of $e^{\pm}$ and $\mu^{\pm}$ magnetic dipole moments have been important benchmarks for the development of QED and the Standard Model.
- At present there appears to be a > 3.3 σ difference between $\boldsymbol{a}_{\mu}$ and the SM prediction.

  if confirmed this would fit well with SUSY expectations, but LHC data will play a role in the interpretation.
- A worldwide effort continues to improve the SM value.
- a_{μ} has been particularly valuable in restricting physics beyond the standard model.
- It will continue that role in guiding the interpretation of the LHC data.

Muon Magnetic Anomaly - Future



Different types of new physics lead to very different δa_μ(N.P.)

- SUSY, RS, ADD, . . . : strong parameter constraints
- Z', UED, LHT, . . . : ruled out if deviation confirmed