Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

Tests of the Standard Model III

Contents

Testing the Standard Model

The Standard Model and New Physics can be tested in via quantum fluctuations (in loops)

Running couplings

$$\alpha_{em} = \alpha_{em}(Q^2) \qquad g_V = g_V(Q^2)$$
$$\alpha_S = \alpha_S(Q^2) \qquad g_A = g_A(Q^2)$$

→ prediction of W, Top and Higgs masses

Magnetic dipole moments

$$\vec{\mu} = g\,\mu_B\,\vec{J} = g\,\frac{e\hbar\vec{J}}{2m}$$

CP,T invariant

Electric dipole moments

$$\vec{d} = \eta\left(\frac{q\vec{J}}{2m}\right)$$

η=0 in SM (LO)

not P (CP), T invariant

G-2 Experiments

Magnetic moment of fermions:

$$\mu = g \mu_B J \qquad \mu_B = \frac{e\hbar}{2m} \qquad g = \text{ Landé factor}$$

Anomalous magnetic moment from radiative corrections:

$$a = (g-2)/2$$

Precision experiments for electrons and muons:

$$a(e) = 1.15965218073(28) \times 10^{-3}$$

Hanneke et al.

$$a(e)_{theor} = 1.15965217760(520) \times 10^{-3}$$

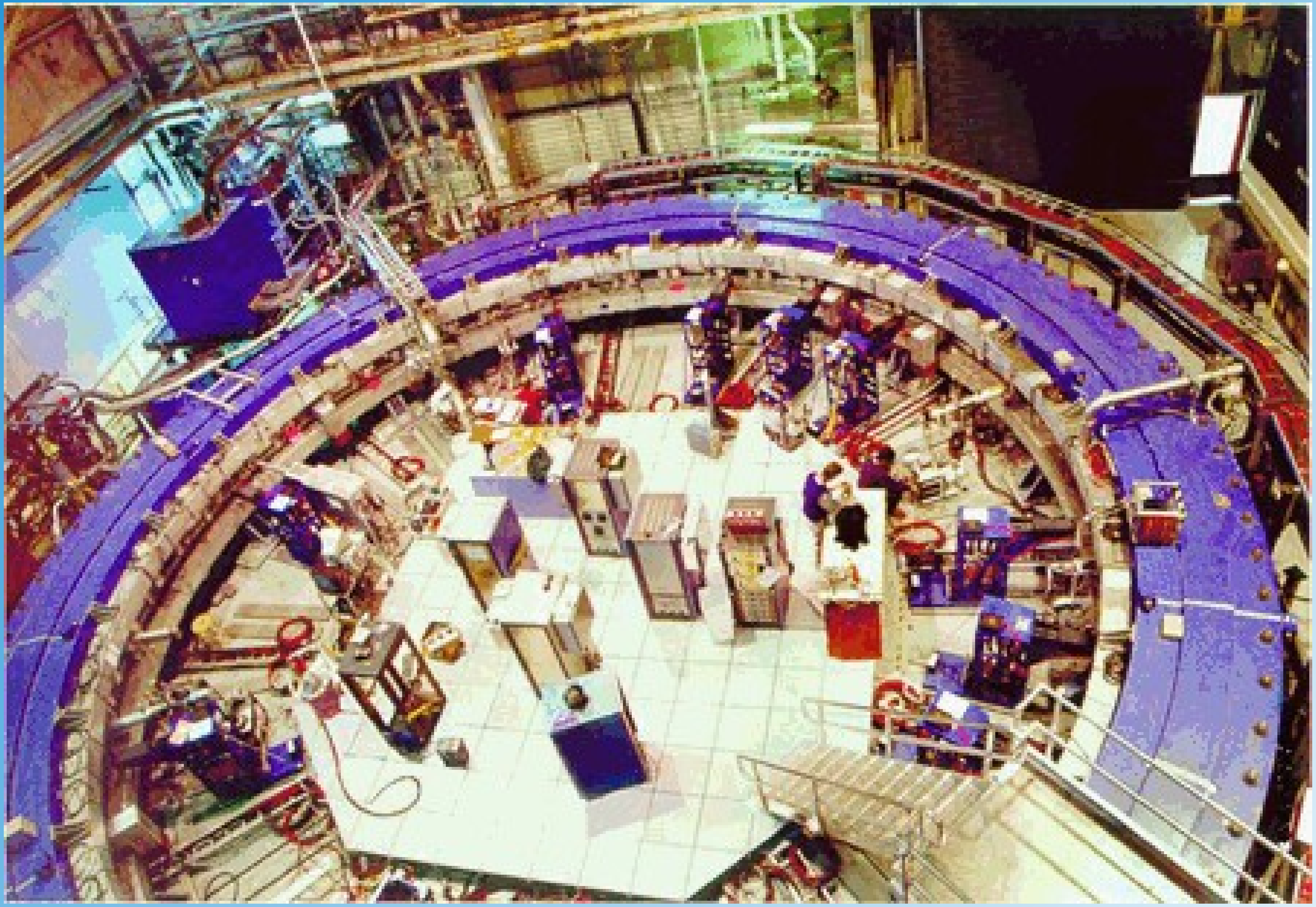
factor 20!

$$a(\mu) = 1.16592080(53) \times 10^{-3}$$

$$a(\mu)_{theor} = 1.16591773(63) \times 10^{-3}$$

3.7 sigma discrepancy

Muon Storage Ring at BNL



Muon Injection Line

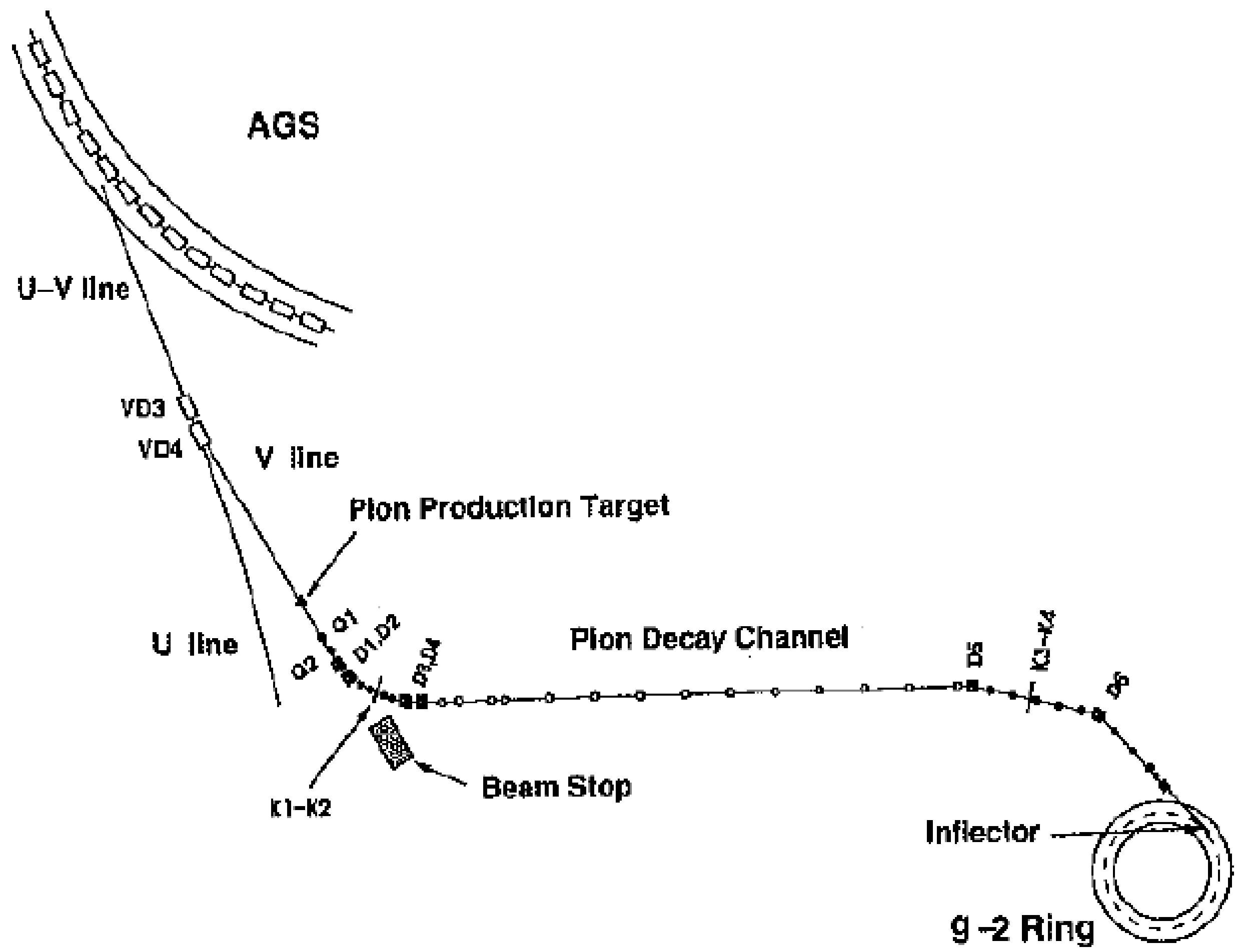


Fig. 11.3. The E821 beamline and storage ring. Pions produced at 0° are collected by the quadrupoles Q1-Q2 and the momentum is selected by the collimators K1-K2. The pion decay channel is 72 m in length. Forward muons at the magic momentum are selected by the collimators K3-K4. (This figure was reprinted with permission from [25]. Copyright 2006 by the American Physical Society.)

Muon Injection

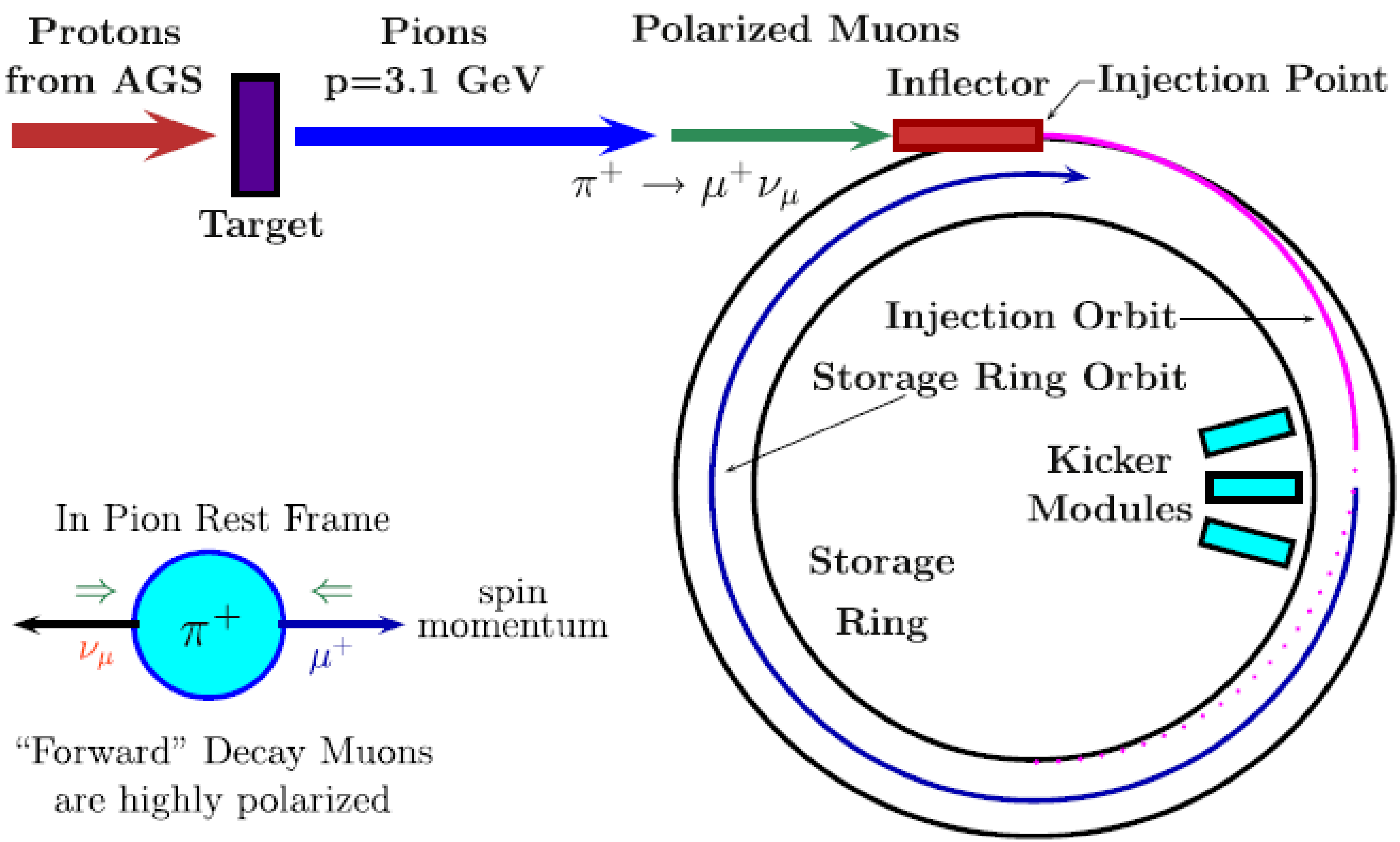


Fig. 4. The schematics of muon injection and storage in the $g-2$ ring.

Muon Storage Ring

Cyclotron frequency:

$$\omega_c = \frac{eB}{m_\mu \gamma}$$

Spin rotation frequency:

$$\omega_s = \frac{eB}{m_\mu \gamma} + a_\mu \frac{eB}{m_\mu}$$

Spin precession frequency:

$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

Extra electric fields (focusing):

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

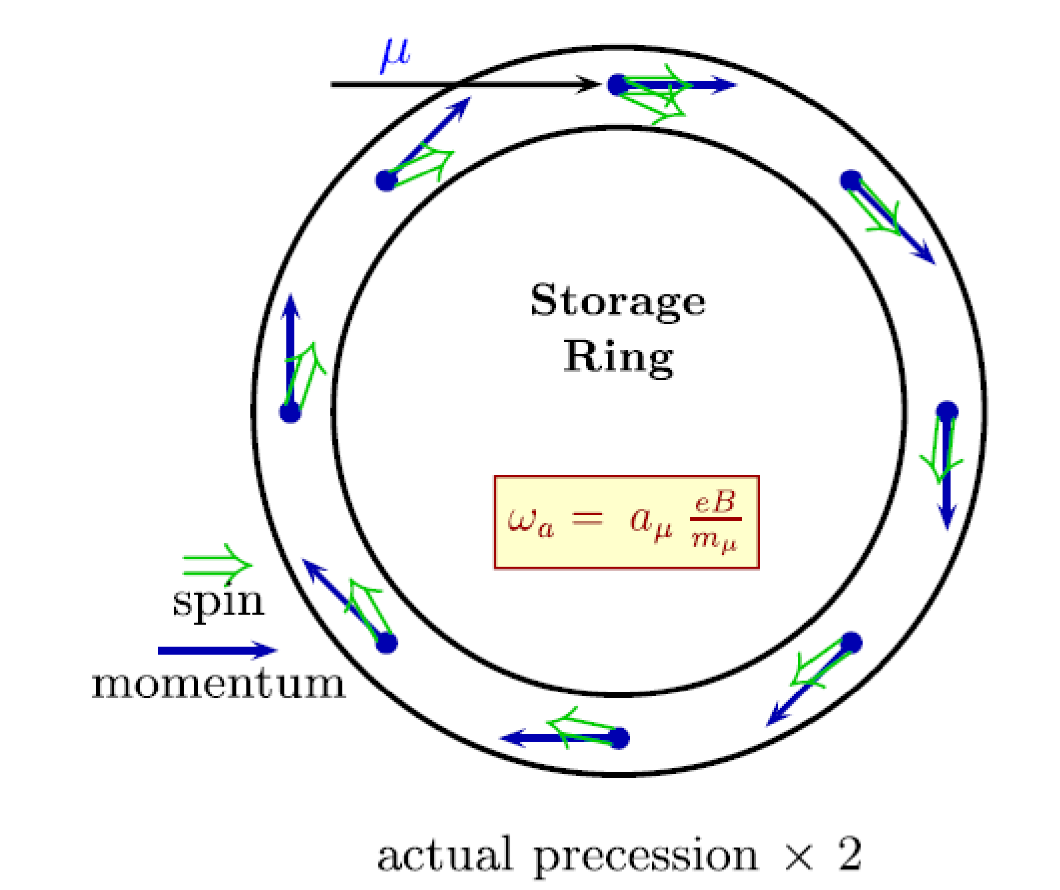


Fig. 3. Spin precession in the $g-2$ ring ($\sim 12°$/circle).

cancellation if: $a_\mu = \frac{1}{\gamma^2 - 1} \quad \rightarrow \quad \gamma = \sqrt{1 + 1/a_\mu} = 29.3 \quad \rightarrow \quad E_{magic} = \gamma m_\mu = 3.098 \ GeV$

Calorimeter

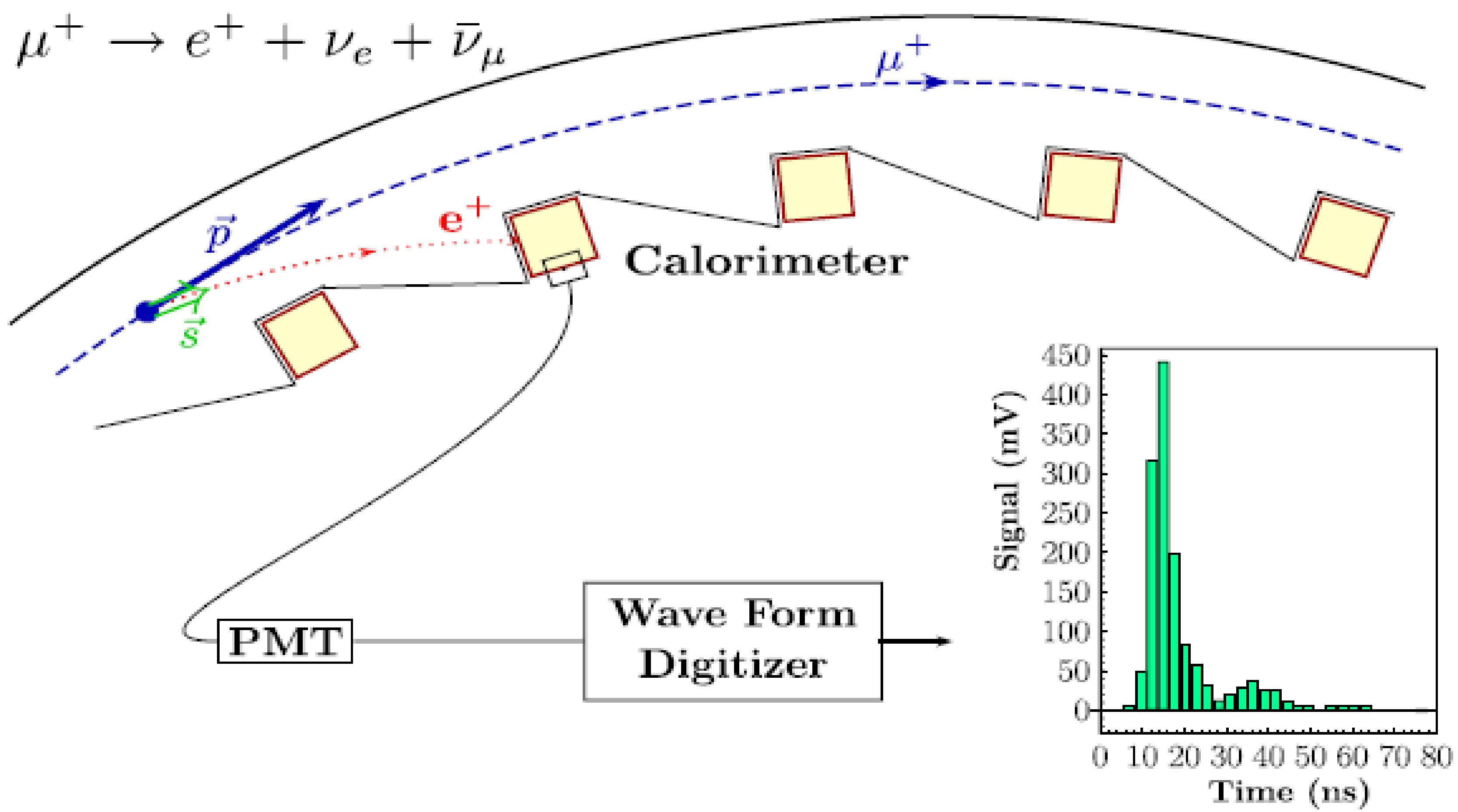
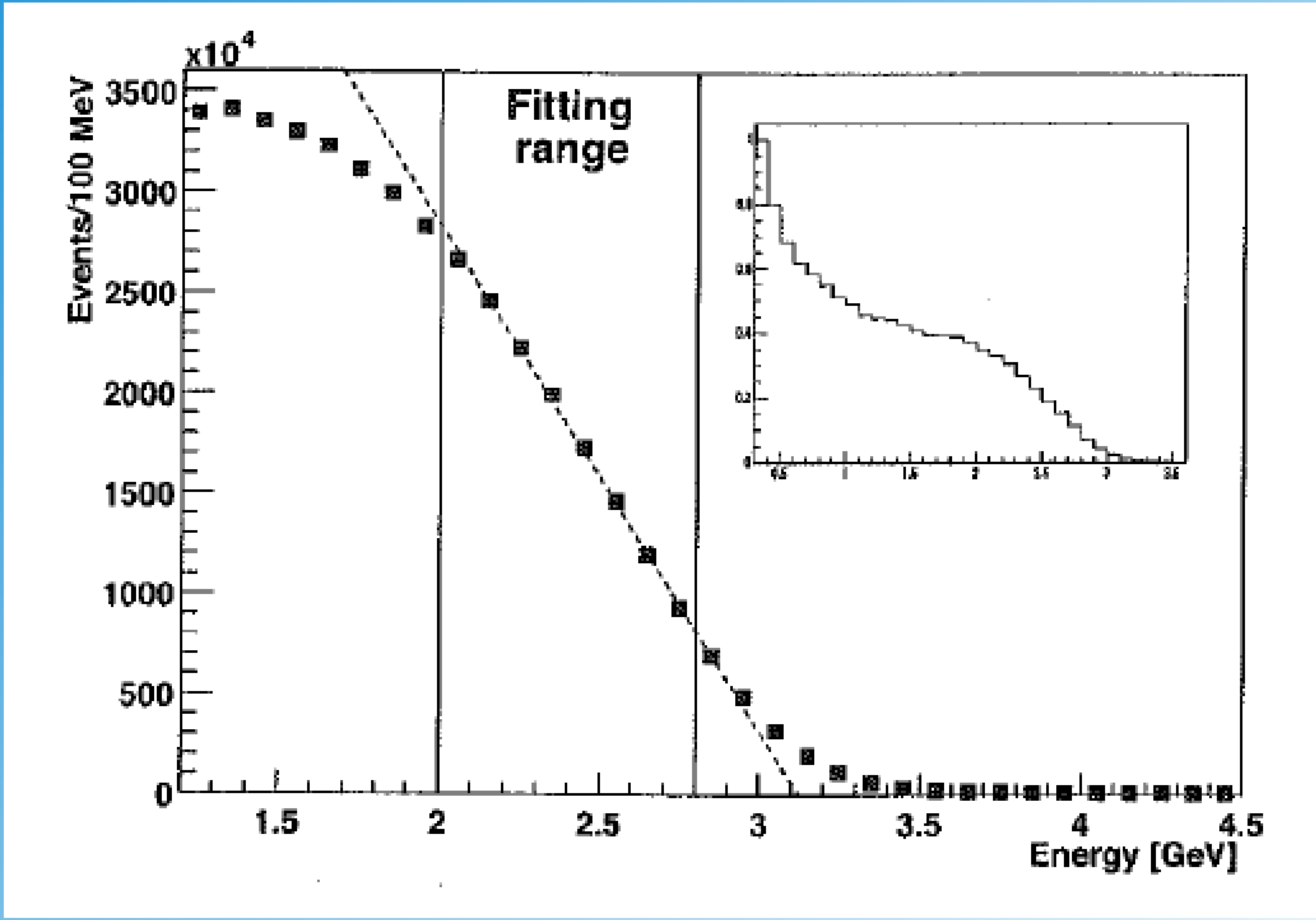


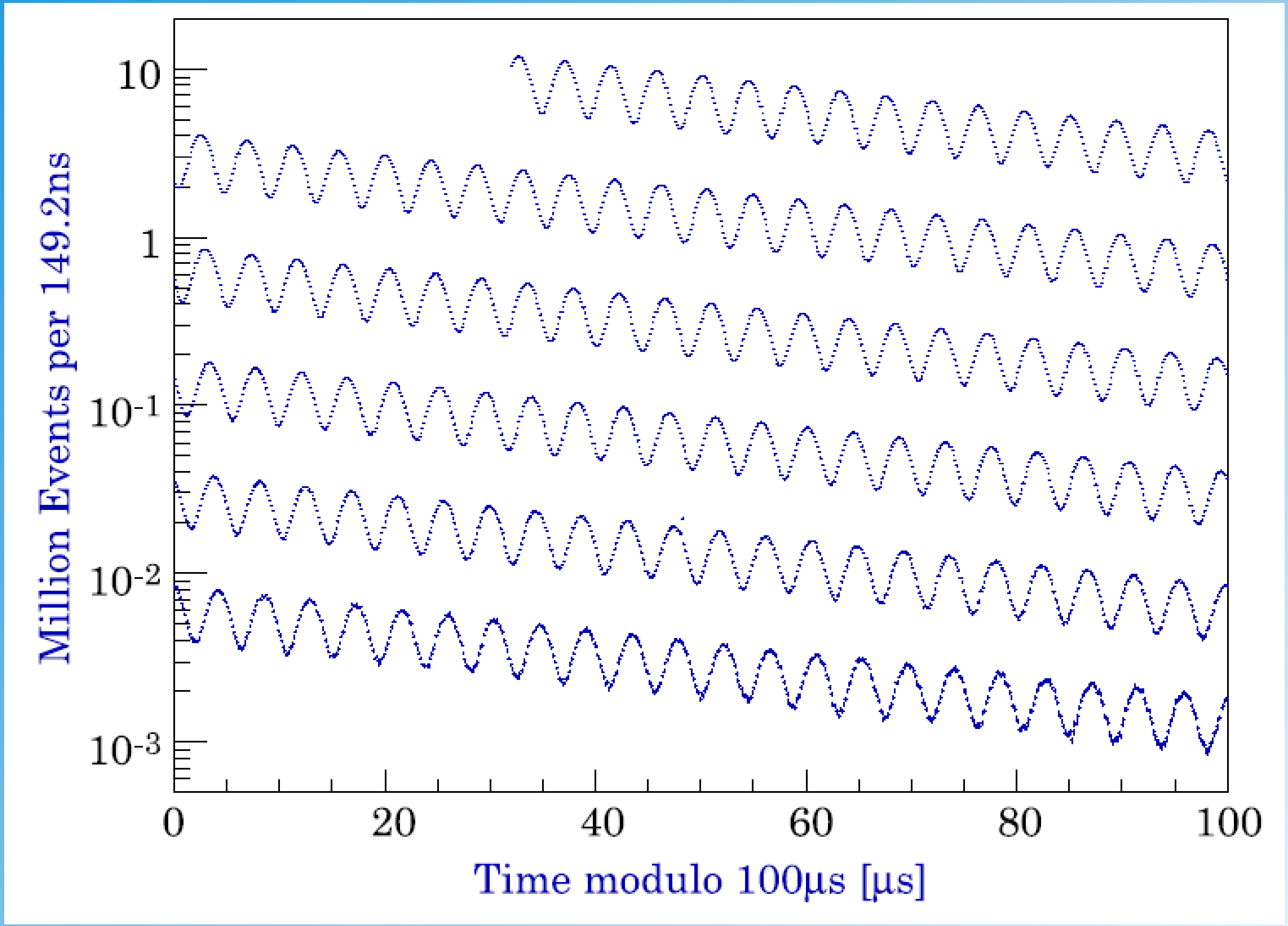
Fig. 5. Decay of μ^+ and detection of the emitted e^+ (PMT = Photomultiplier).

Energy Spectrum

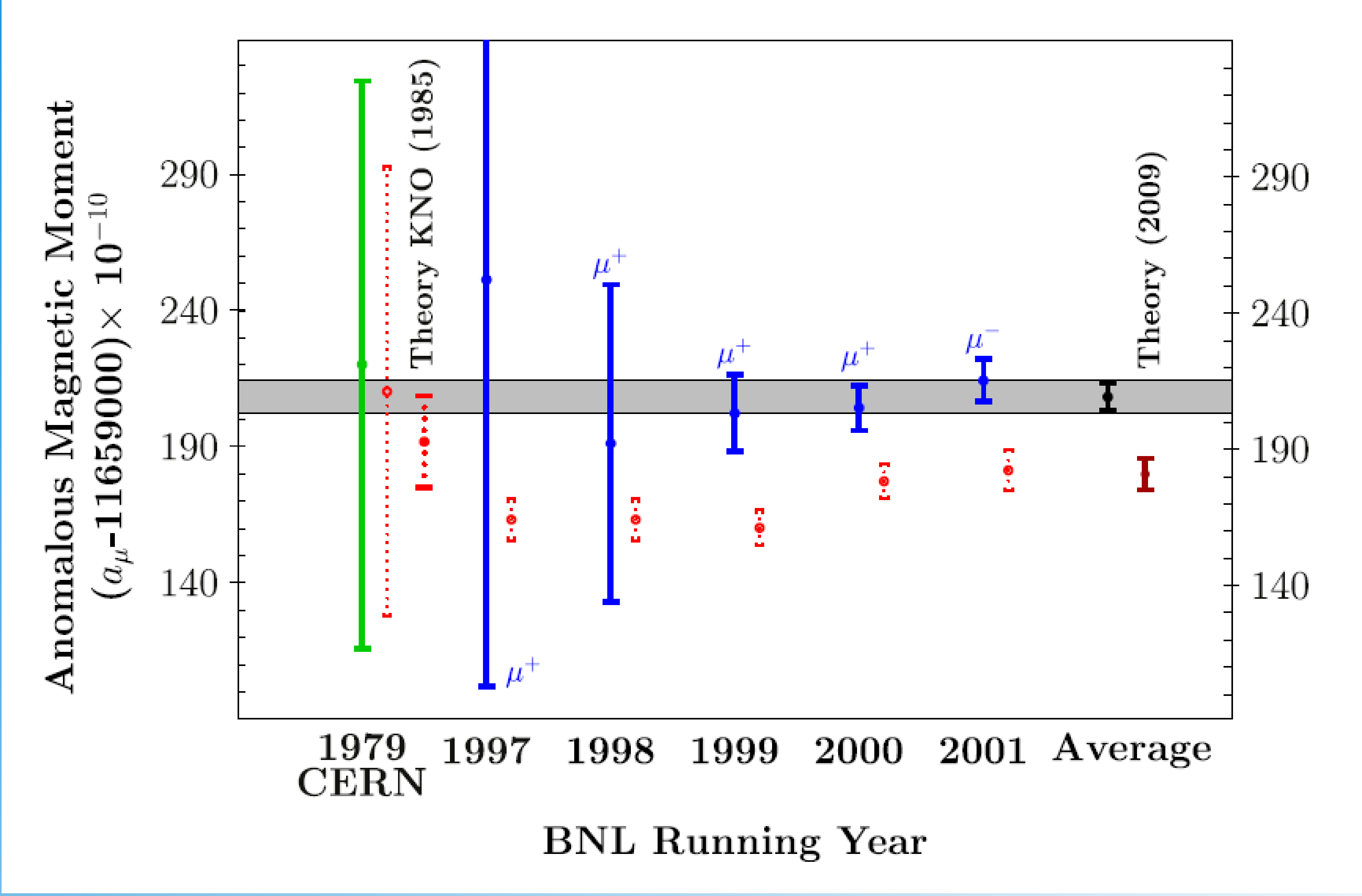
Decay: $\mu \rightarrow e \nu \nu$ (boosted Michel spectrum)



Time Dependent Rate



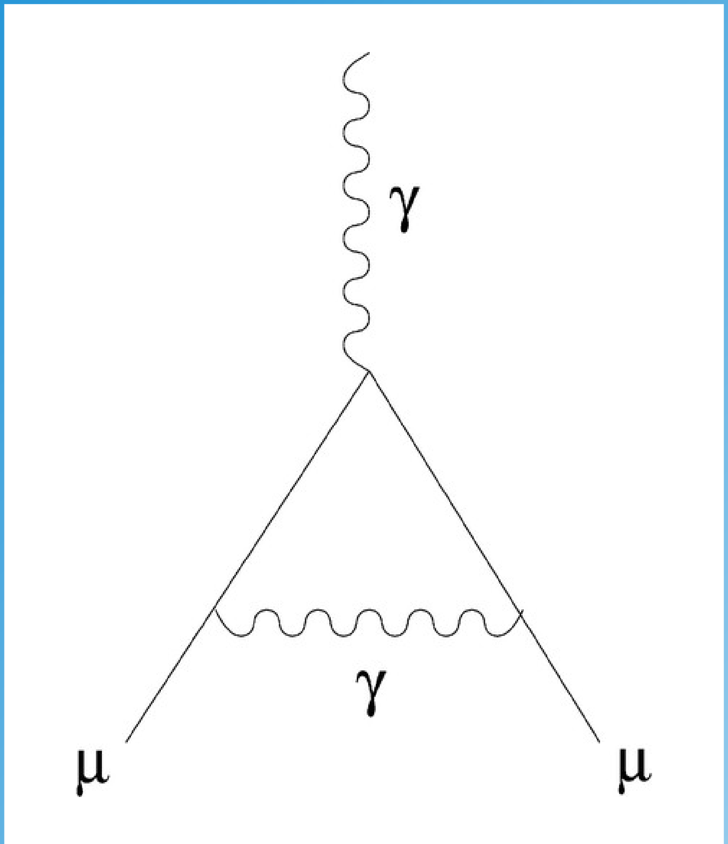
Summary Plot g_μ-2 Experiments



Muon Magnetic Moment

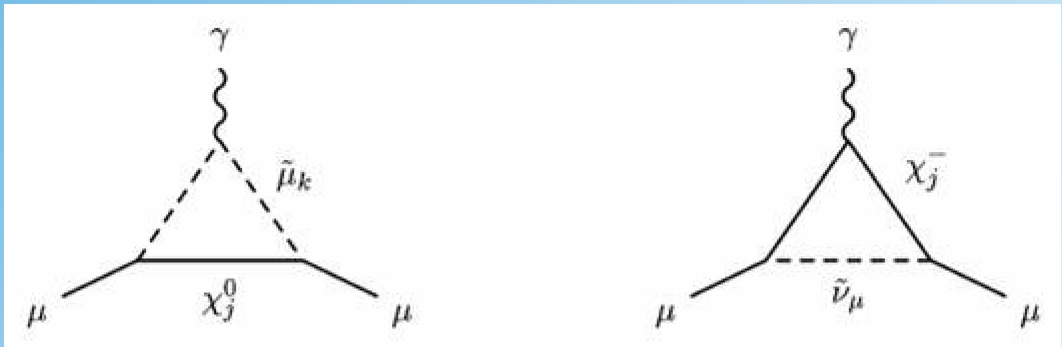
Magnetic moment of a fermion from radiative corrections:

QED first order

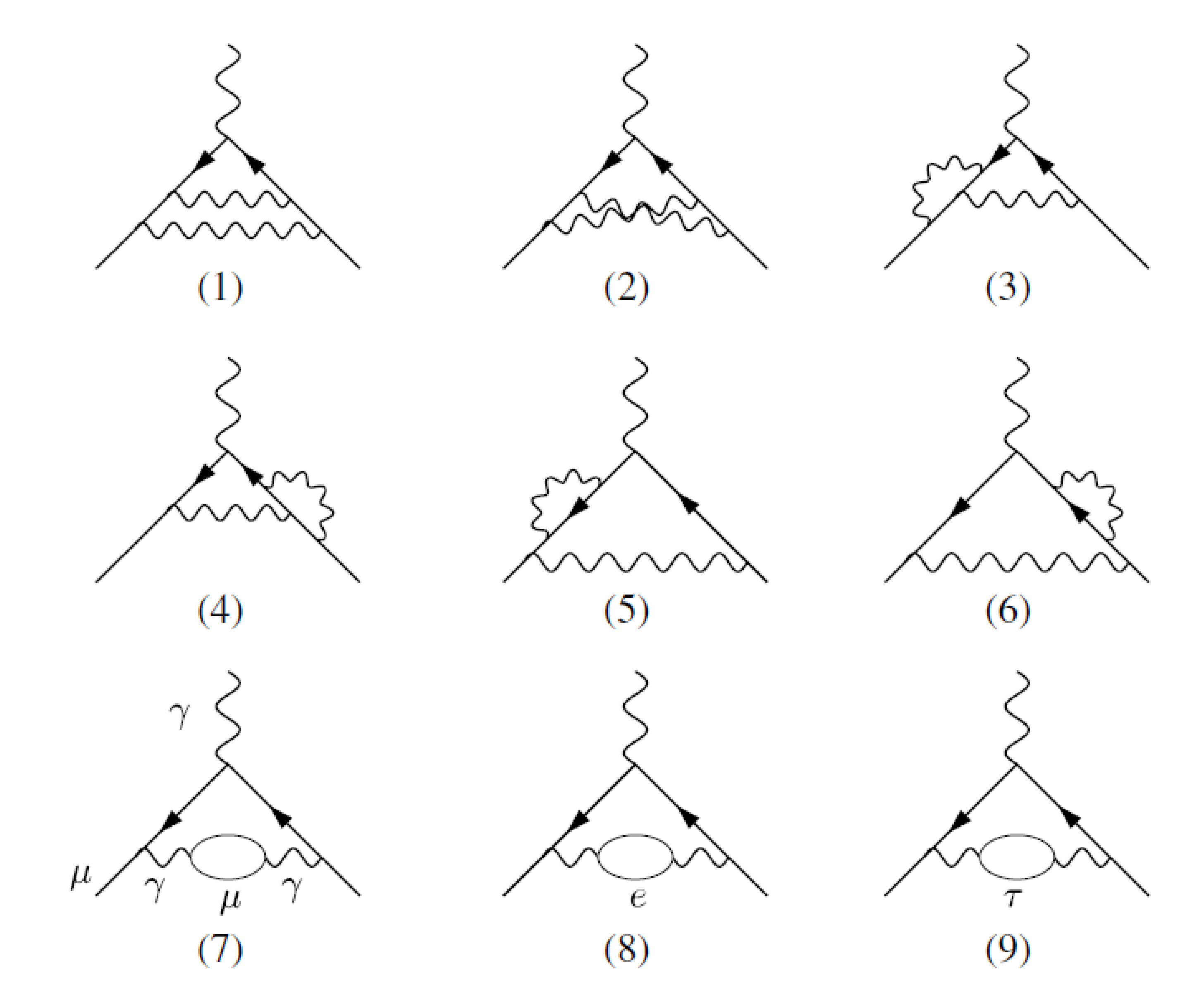


Schwinger diagram

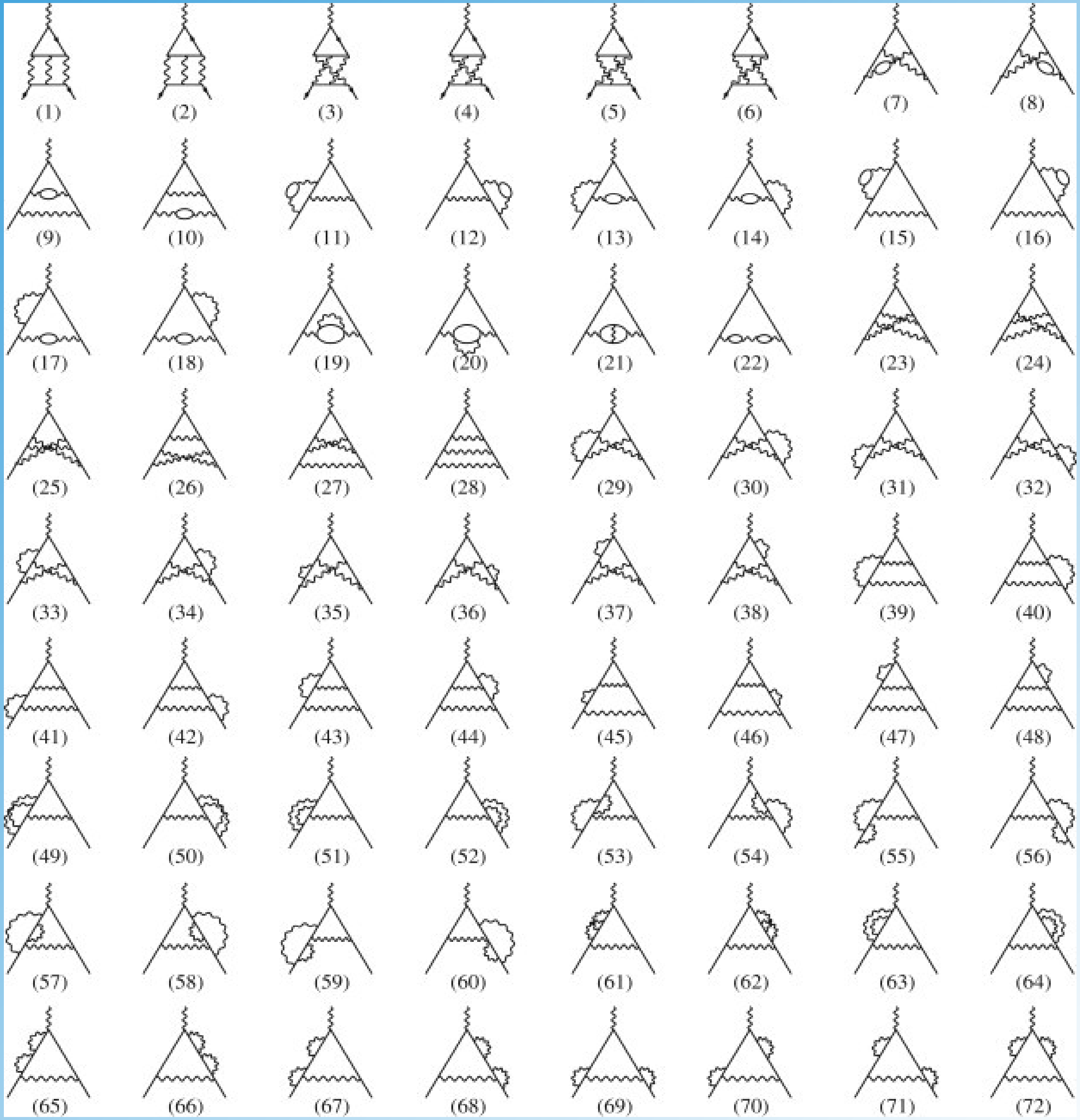
New Physics: Supersymmetry



Second Order Diagrams (QED)

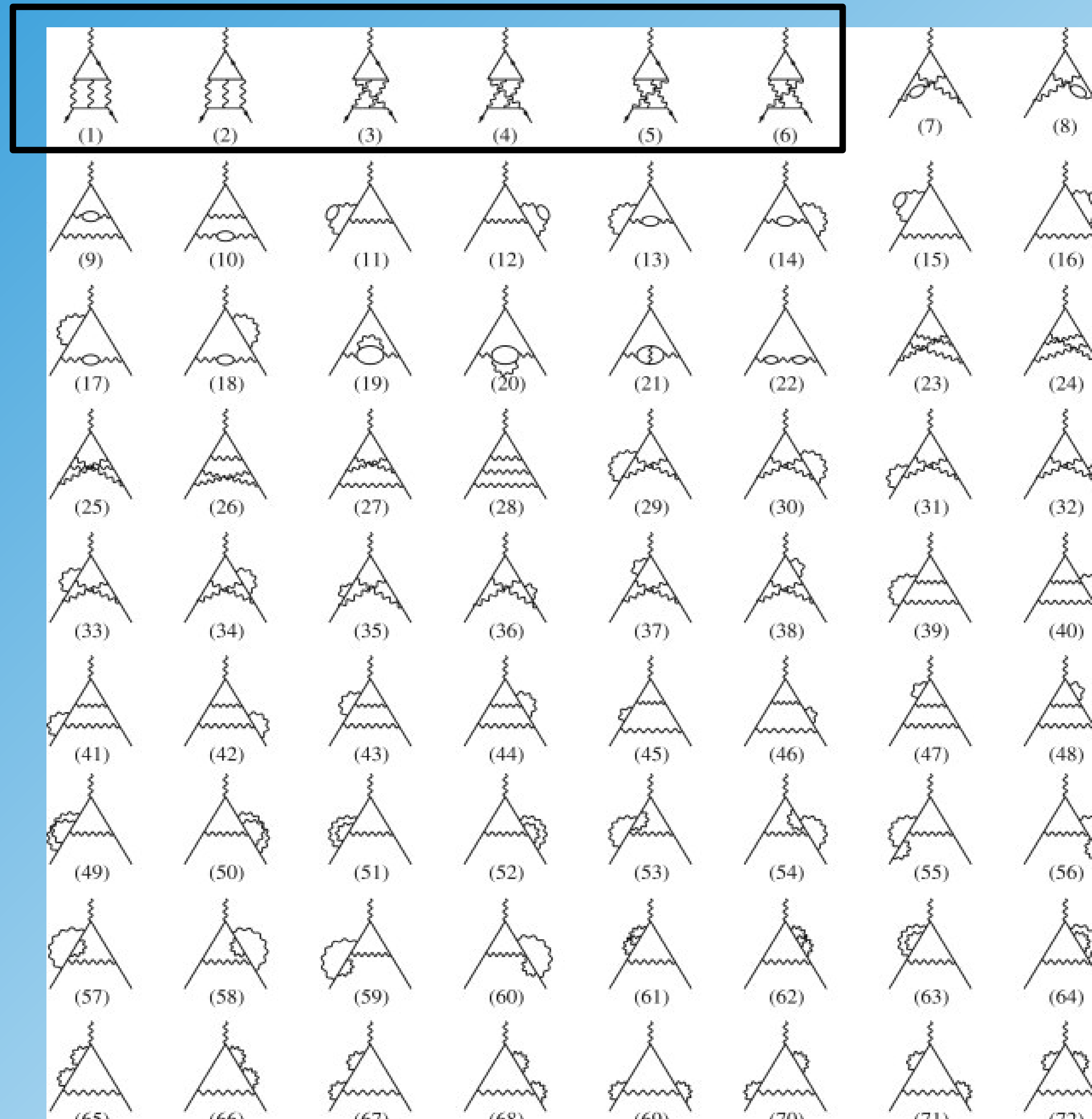


Higher Order Diagrams

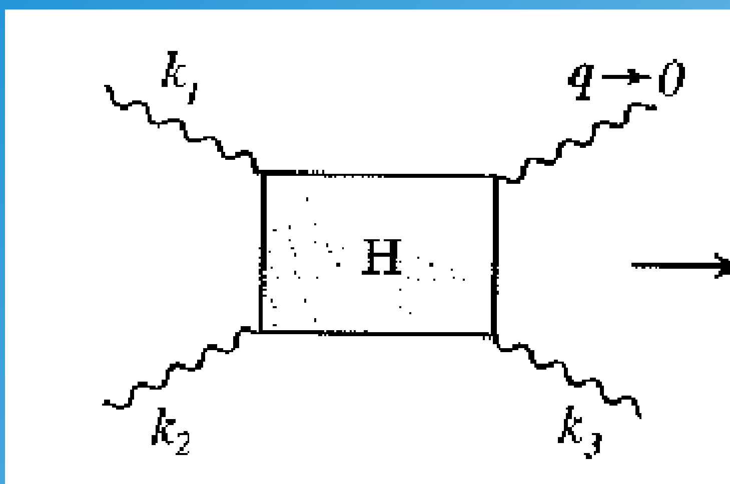


Higher Order Diagrams

light by light diagrams



light by light scattering:



difficulty:
- hadronic structure

Hadronic Corrections

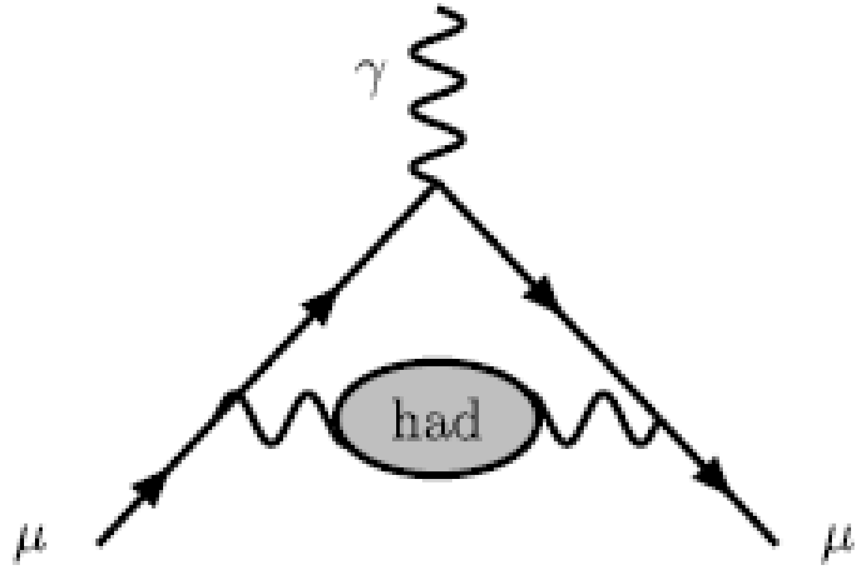


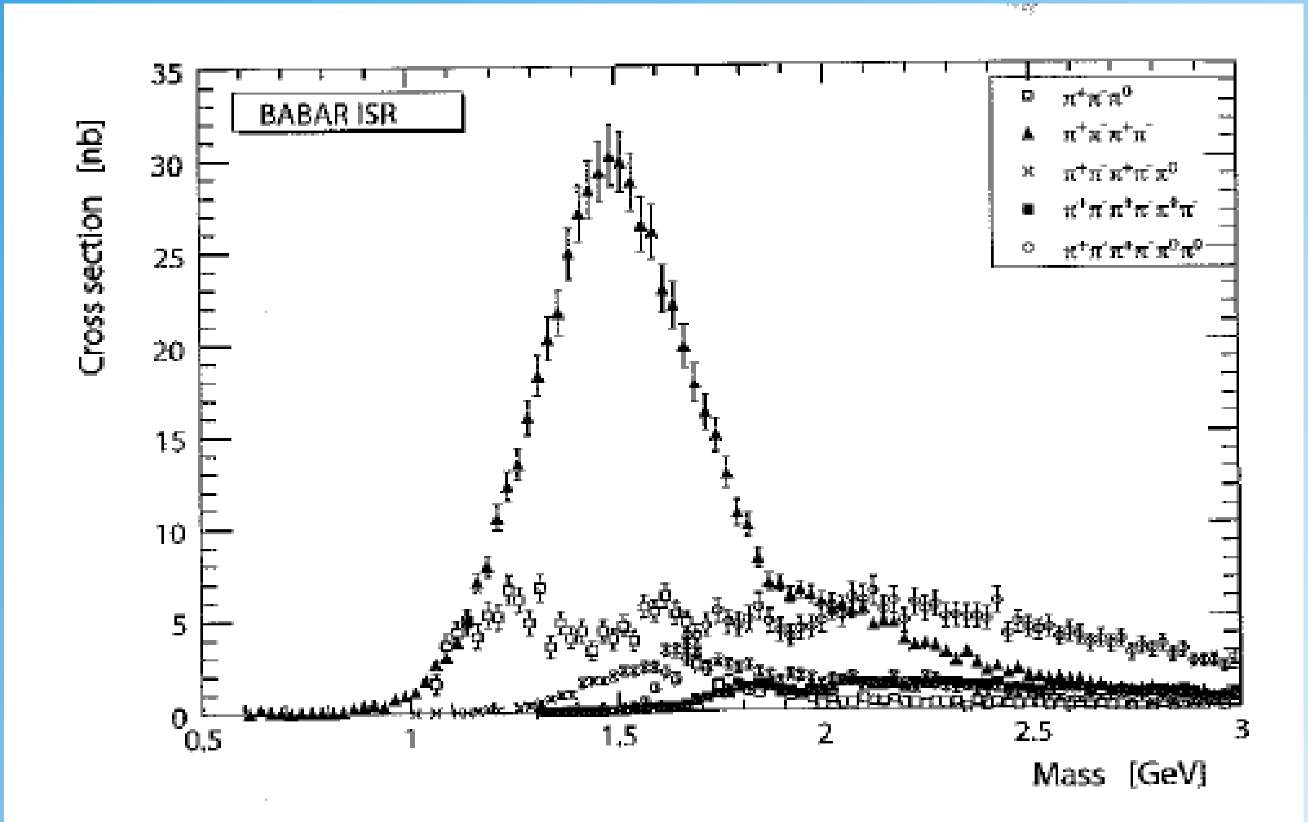
Fig. 19. Leading hadronic contribution to g − 2.

Vacuum polarisation contribution (third order)

can not be precisely calculated:

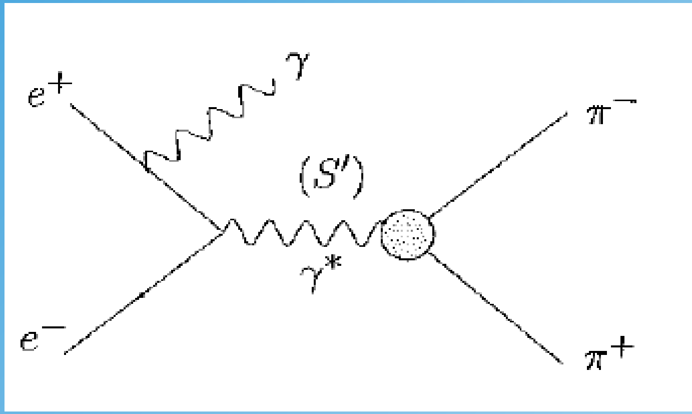
- can be taken from g_e (corrections are identical)
- or can be taken from $e^+ e^-$ scattering !

Hadronic Structure of the Photon



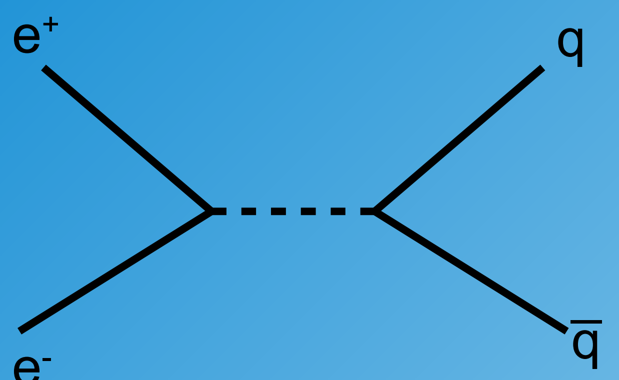
Measurements at Babar:

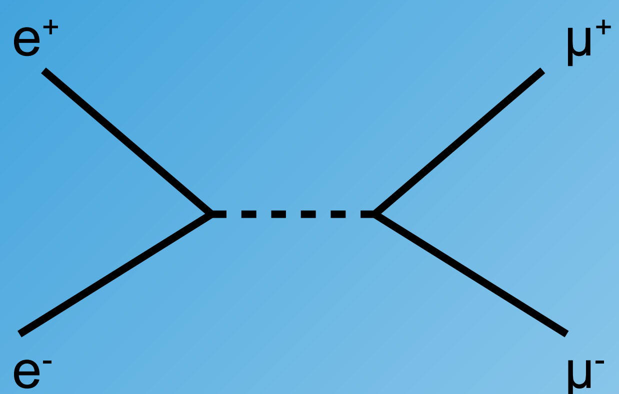
Radiative Return in Initial State Radiation (ISR) eventS



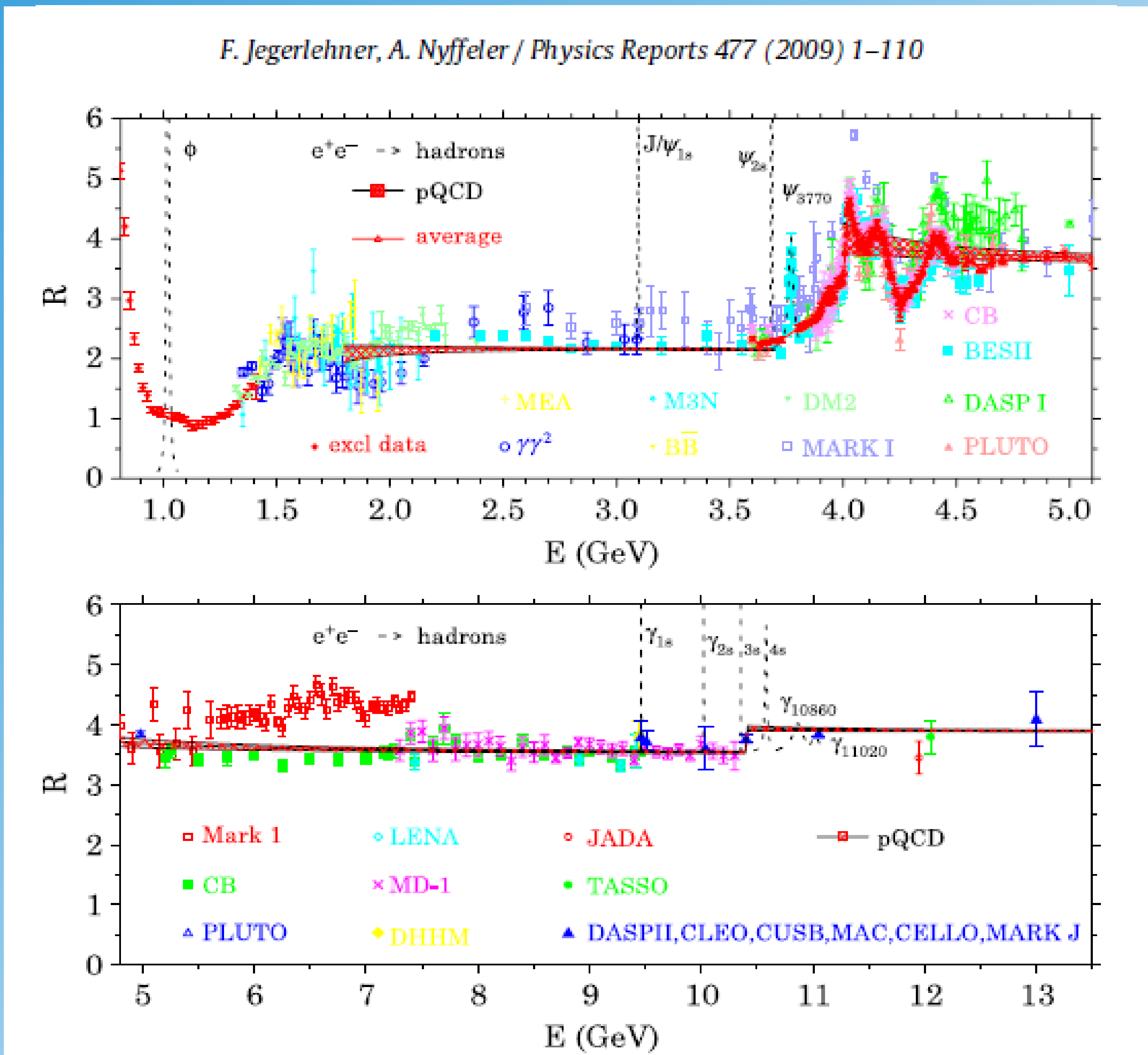
Hadronic Structure of the Photon

from e^+e^- collisions:





measurement of R_{hadr}



Higher Order QED Corrections

E.g. electron magnetic moment:

$$a_e(QED) = A_1 + A_2(m_e/m_\mu) + A_3(m_e/m_\tau) + \ldots$$

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_i^{(6)}\left(\frac{\alpha}{\pi}\right)^3 +$$

$$
\begin{aligned}
A_1^{(2)} &= 0.5 && \text{1 diagram (analytic)} \\
A_1^{(4)} &= -0.328\,478\,965\ \ldots && \text{7 diagrams (analytic)} \\
A_1^{(6)} &= 1.181\,241\,456\ \ldots && \text{72 diagrams (numerical, analytic)} \\
A_1^{(8)} &= -1.914\,4\,(35) && \text{891 diagrams (numerical).} \qquad (3.49)
\end{aligned}
$$

g_μ -2 Corrections

Muon magnetic moment:

QED corrections:

$$a_\mu^{QED} = 1.165847181(2) \times 10^{-3}$$

most precise

Hadronic corrections:

$$a_\mu^{had} = 0.00006901(53) \times 10^{-3}$$

largest uncertainty

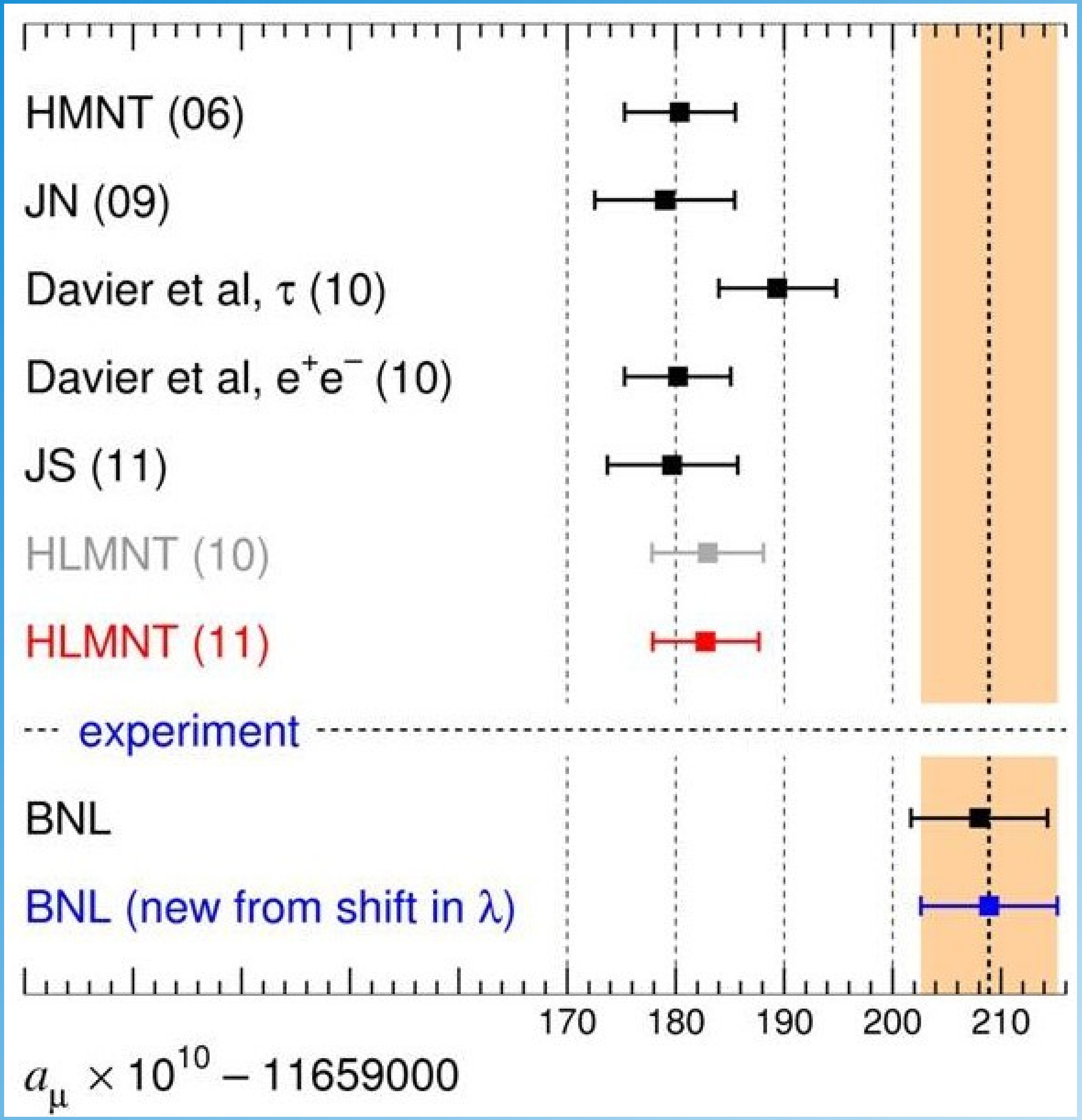
Electroweak corrections:

$$a_\mu^{EW} = 0.00000154(2) \times 10^{-3}$$

Sum:

$$a(\mu)_{theor} = 1.16591773(63) \times 10^{-3}$$

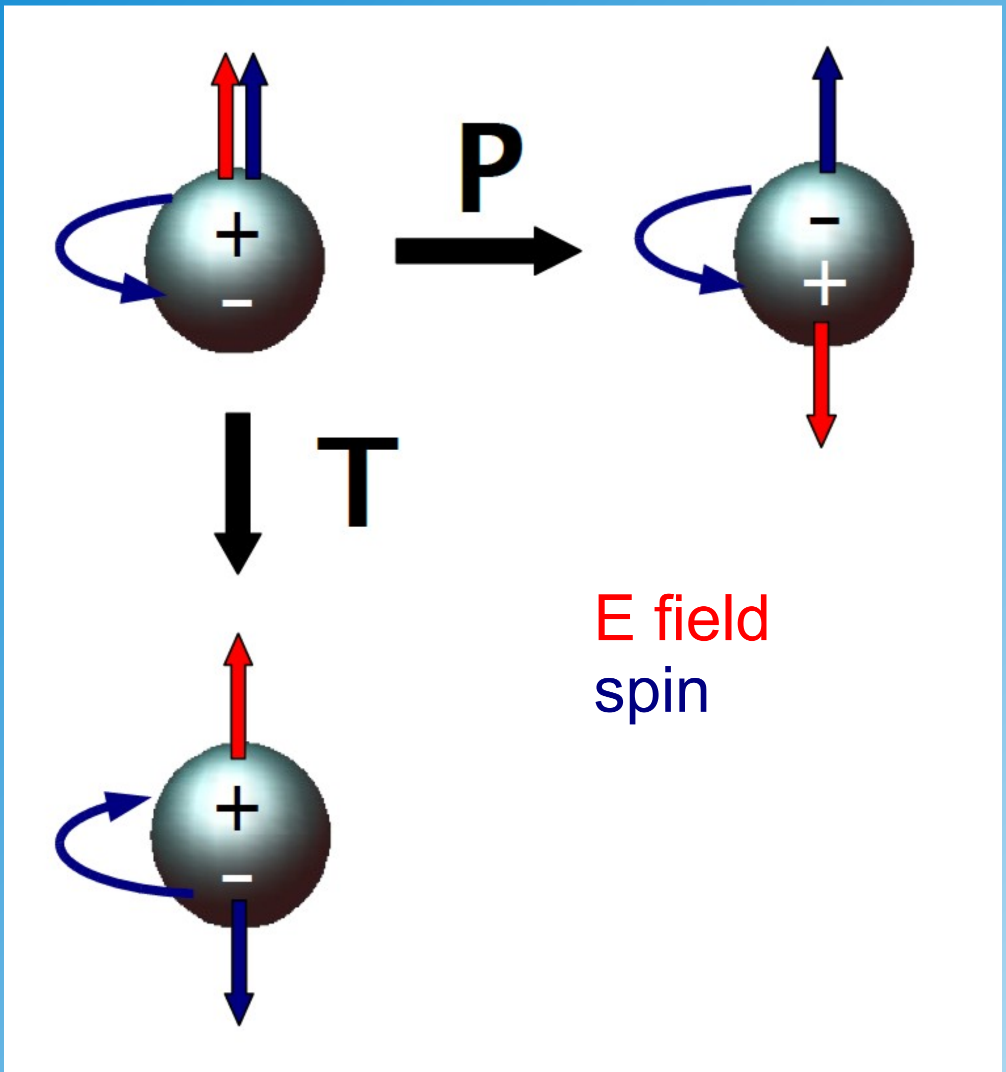
Data-Theory Comparison



3.7 sigma difference

Electric Dipole Moment (EDM)

$$\vec{d} = \eta \left(\frac{q \vec{J}}{2m} \right)$$



Transformation Properties:

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

	E	B	μ or d
P	-	+	+
C	-	-	-
T	+	-	-

EDM violates P and T invariance

Scales of CP Violation

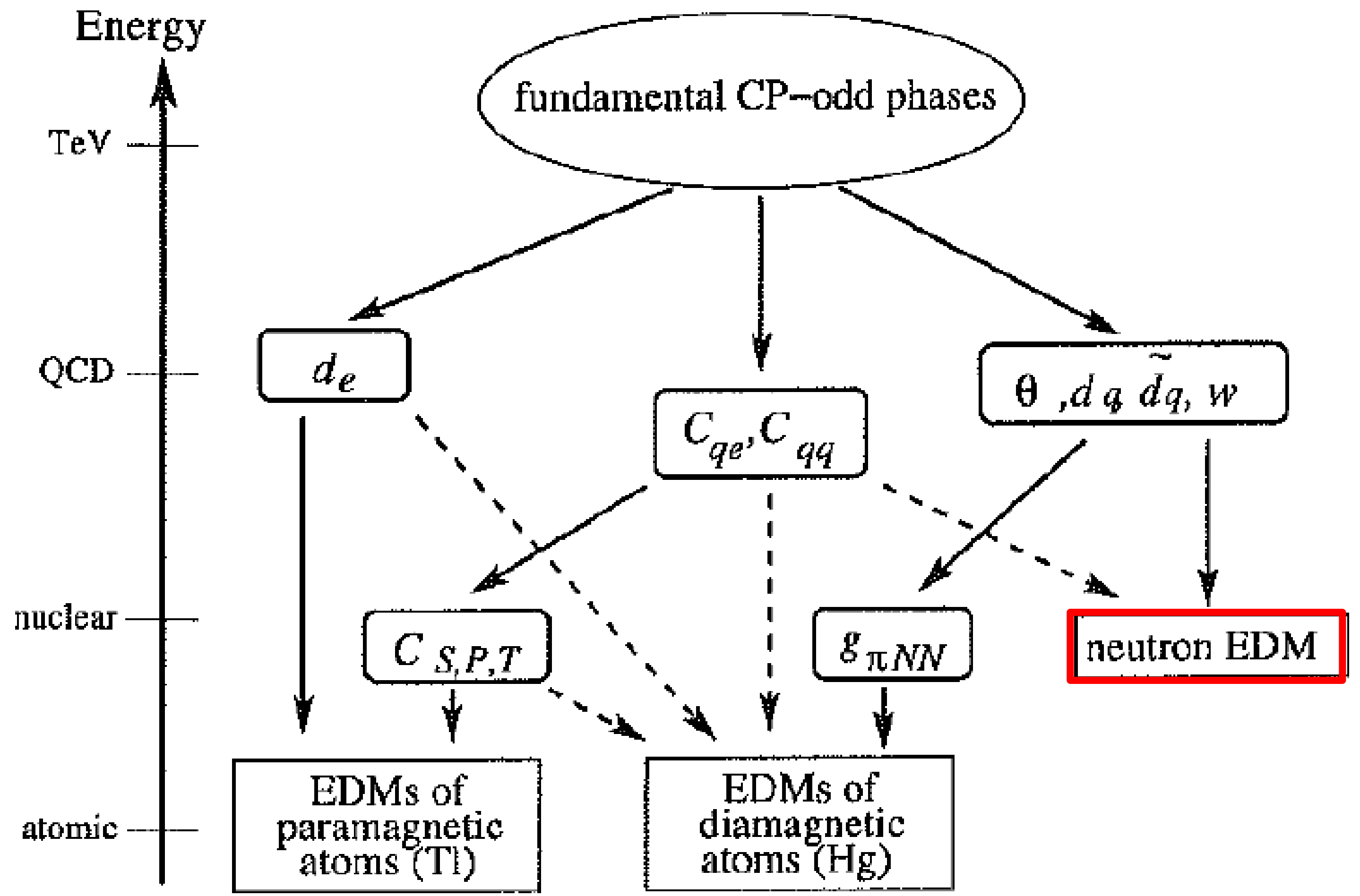
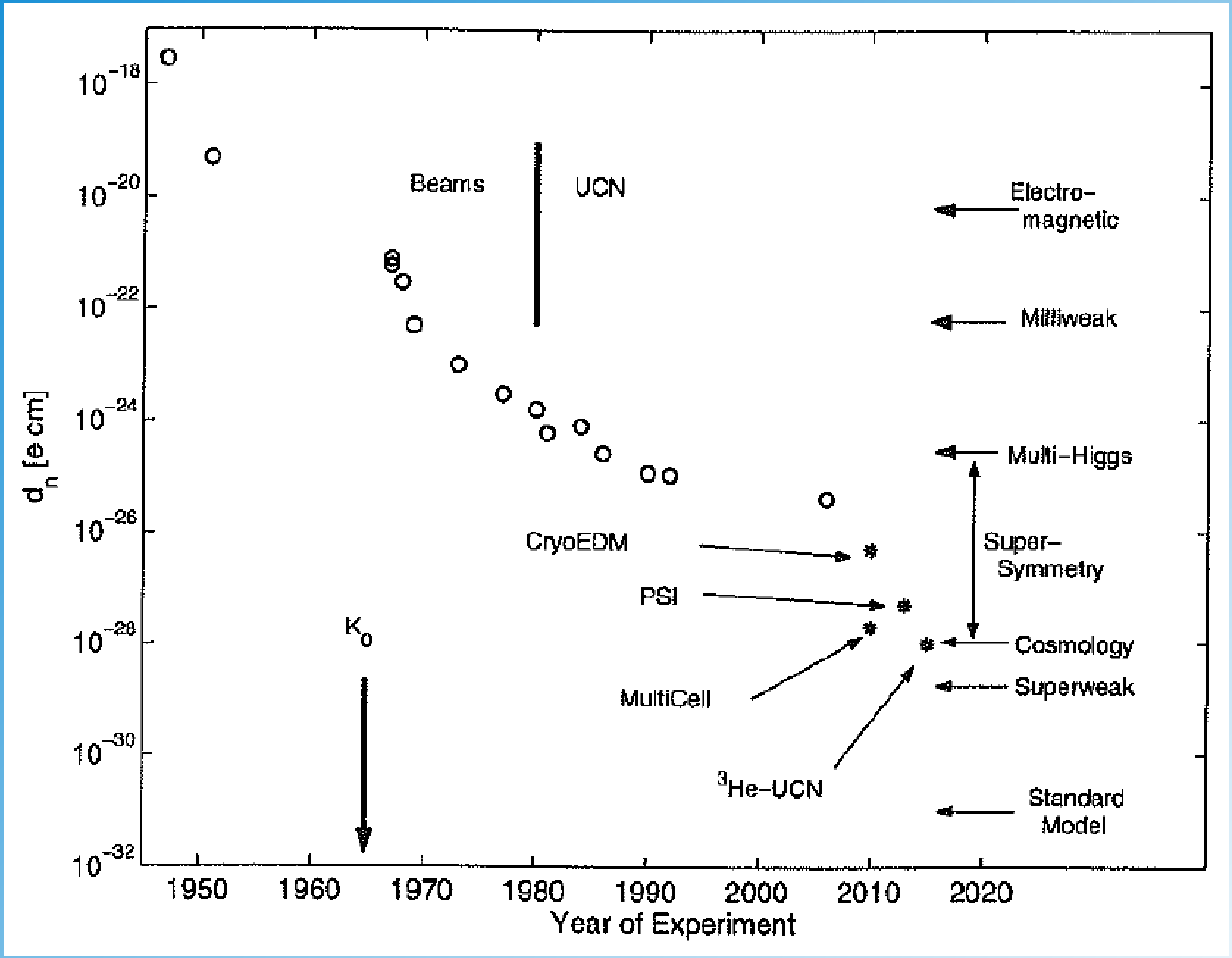
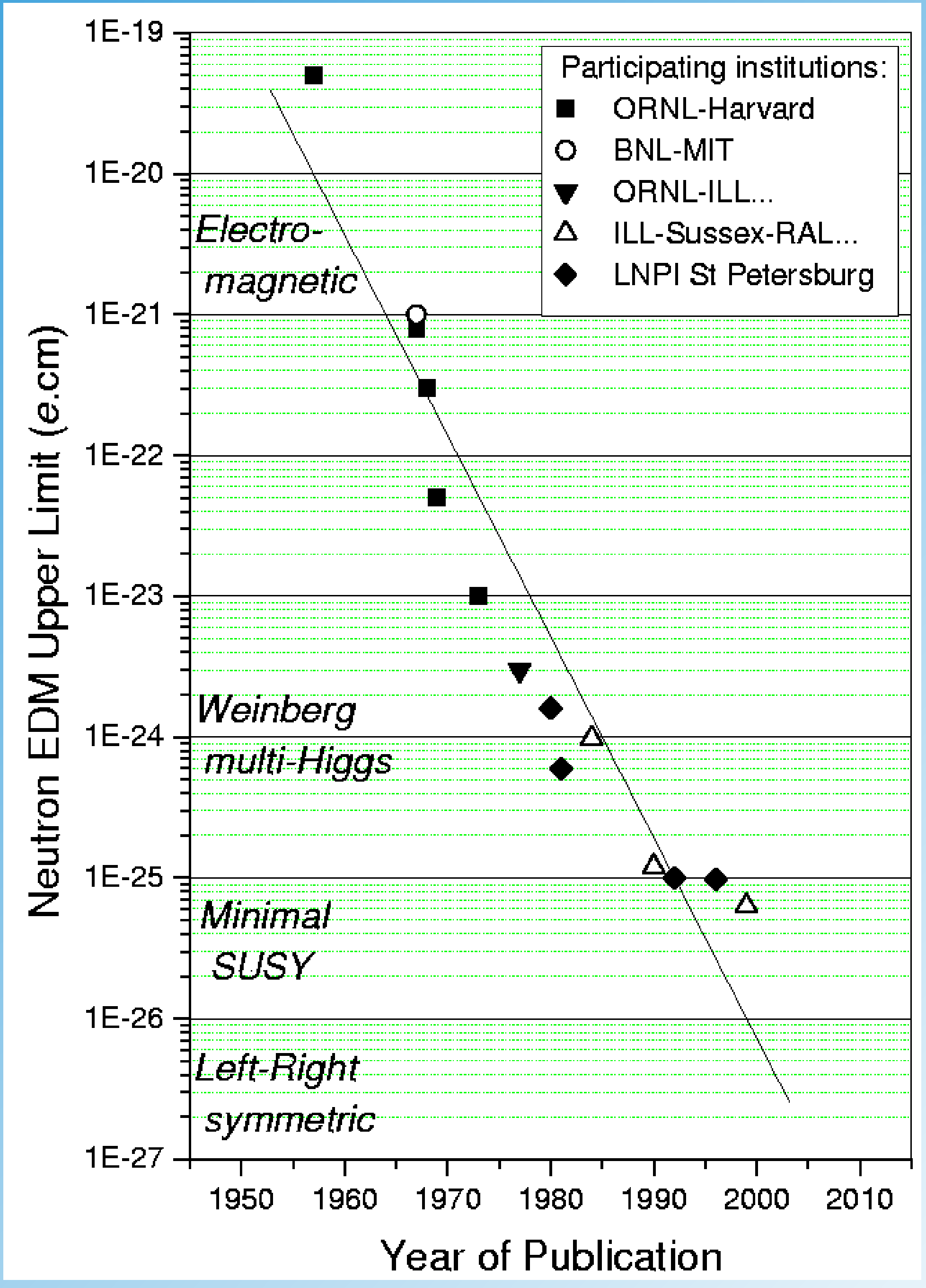


Fig. 13.1. A schematic plot of the hierarchy of scales between the CP-odd sources and three generic classes of observable EDMs. The dashed lines indicate generically weaker dependencies.

Neutron Electric Dipole Moment



Electric Dipole Moment (EDM)



high sensitivity to New Physics!

New experiments are currently in preparation (.e.g Munich, PSI, ...)

Baryon and Lepton Number Violation

Proton is stable: $\tau > 10^{31} - 10^{33}$ *years*

Not seen: $p \not\to \pi^0 e^+$ $p \not\to \pi^+ \gamma$ $\pi^+ \not\to e^+ \gamma$

No observation of Baryon or Lepton Number Violation!

Lepton Flavor Violation also not seen:

Reaction	Present limit	Reference
$\mu^+ \to e^+\gamma$	$< 1.2 \times 10^{-11}$	Brooks *et al.* [49]
$\mu^+ \to e^+e^+e^-$	$< 1.0 \times 10^{-12}$	Bellgardt *et al.* [55]
$\mu^- Ti \to e^- Ti$	$< 4.3 \times 10^{-12}$	C. Dohmen *et al.* [70]
$\mu^- Ti \to e^- Ti$	$< 6.1 \times 10^{-13}$	Wintz [72] *
$\mu^- Au \to e^- Au$	$< 7 \times 10^{-13}$	Bert *et al.* [73]
$\mu^- Pb \to e^- Pb$	$< 4.6 \times 10^{-11}$	Honecker *et al.* [71]
$\mu^+ e^- \to \mu^- e^+$	$< 8.3 \times 10^{-11}$	Willmann *et al.* [23]
$\tau \to e\gamma$	$< 1.1 \times 10^{-7}$	Aubert *et al.* [24]
$\tau \to \mu\gamma$	$< 4.5 \times 10^{-8}$	Hayasaka *et al.* [25]
$\tau \to \mu\mu\mu$	$< 3.2 \times 10^{-8}$	Miyazaki *et al.* [26]
$\tau \to eee$	$< 3.6 \times 10^{-8}$	Miyazaki *et al.* [26]
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$	Edwards *et al.* [27]
$K_L^0 \to \mu e$	$< 4.7 \times 10^{-12}$	Ambrose *et al.* [28]
$K^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$	Lee *et al.* [29]
$K_L^0 \to \pi^0\mu^+e^-$	$< 3.1 \times 10^{-9}$	Arisaka *et al.* [30]
$Z^0 \to \mu e$	$< 1.7 \times 10^{-6}$	Akers *et al.* [31]
$Z^0 \to \tau e$	$< 9.8 \times 10^{-6}$	Akers *et al.* [31]
$Z^0 \to \tau\mu$	$< 1.2 \times 10^{-5}$	Abreu *et al.* [32]

The SM prediction for Lepton Flavor Violating (LFV) Processes is negligible.

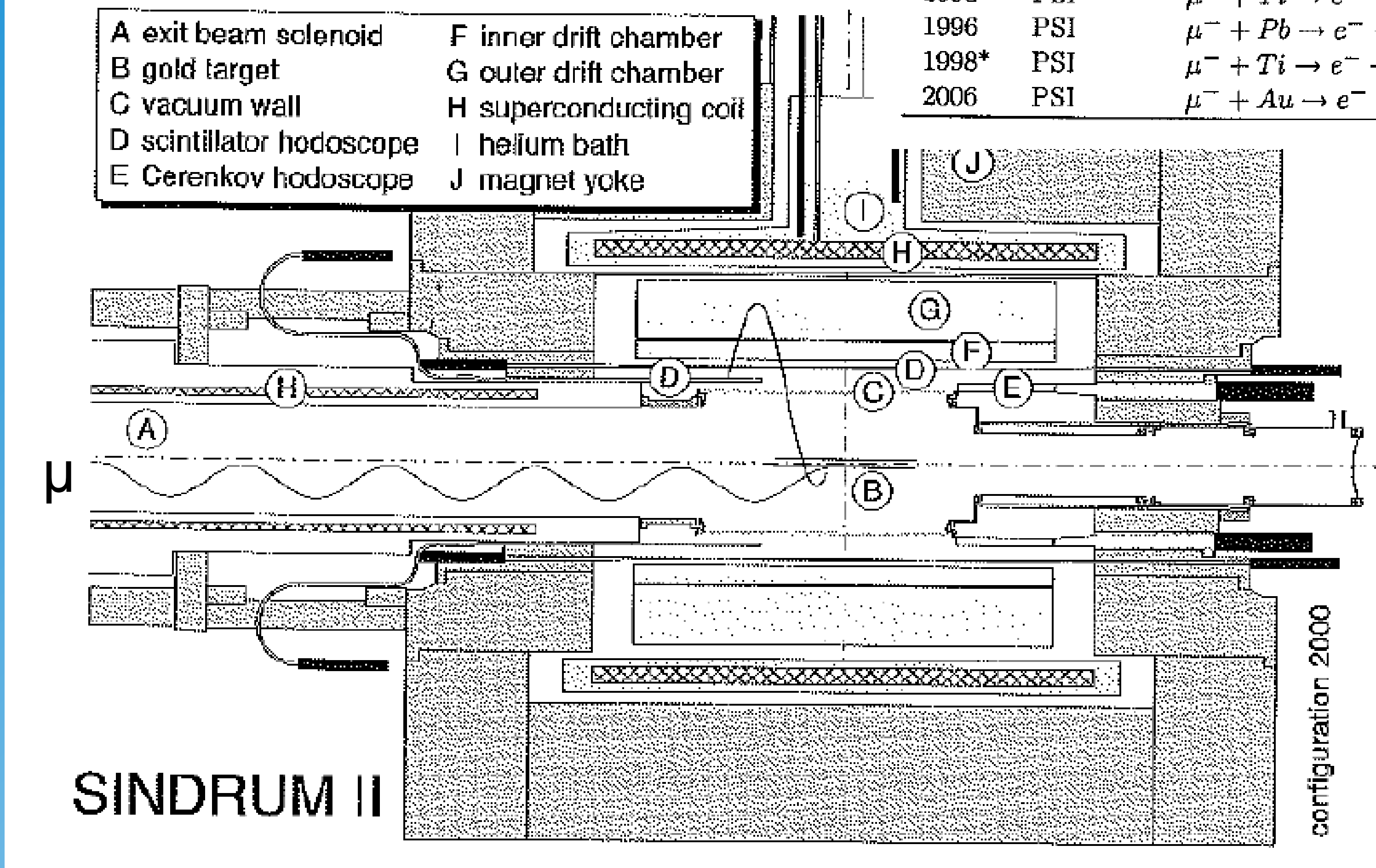
Any sign of LFV would manifest New Physics

Muon-Electron Conversion

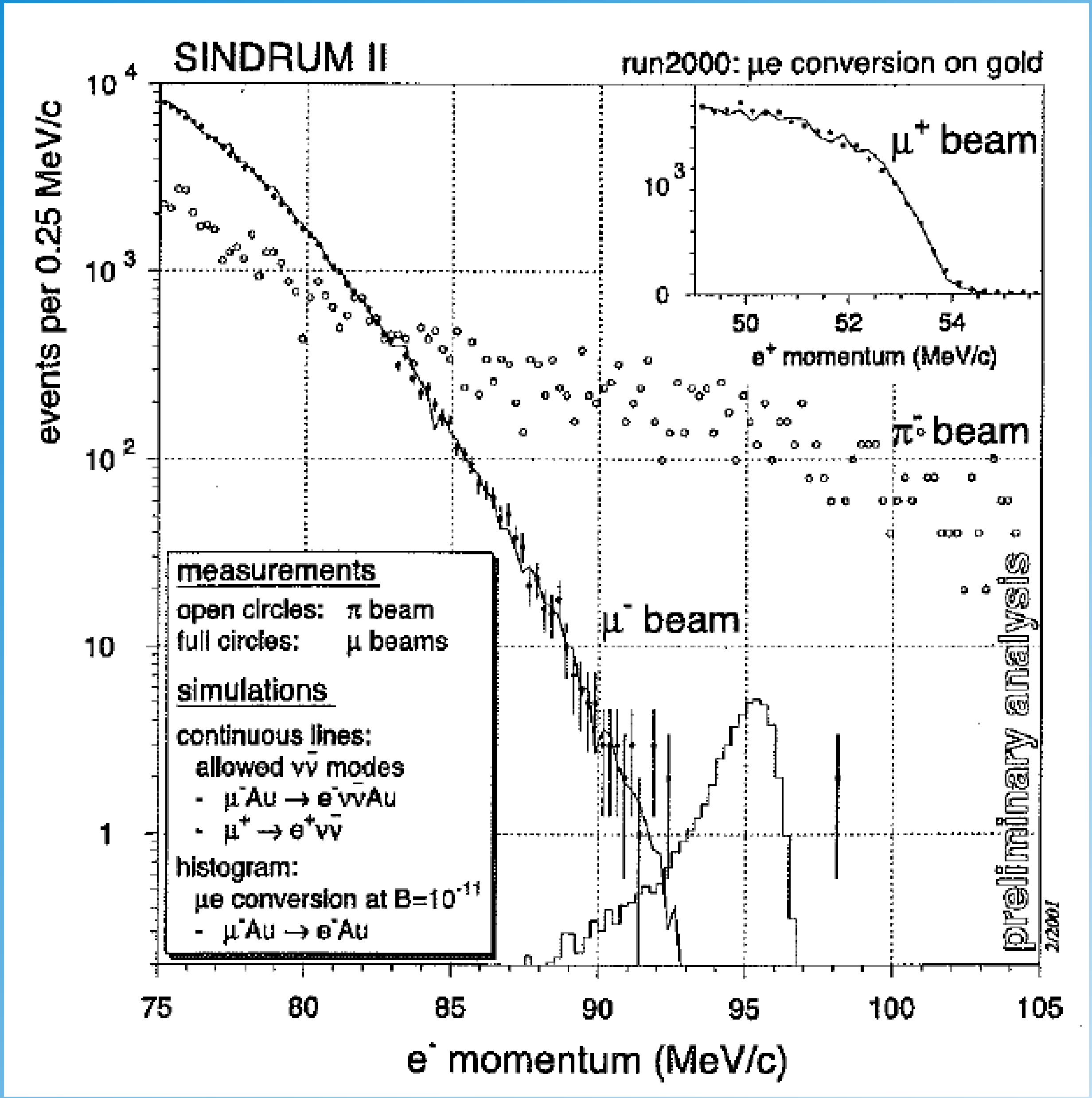
μ N → e N conversion

Table 19.6. Past experiments on $\mu^- - e^-$ conversion. (*Reported only in conference proceedings.)

Year	Location	Process	Upper Limit	Reference
1972	SREL	$\mu^- + Cu \to e^- + Cu$	$< 1.6 \times 10^{-8}$	[66]
1982	SIN	$\mu^- + {}^{32}S \to e^- + {}^{32}S$	$< 7 \times 10^{-11}$	[67]
1985	TRIUMF	$\mu^- + Ti \to e^- + Ti$	$< 1.6 \times 10^{-11}$	[68]
1988	TRIUMF	$\mu^- + Ti \to e^- + Ti$	$< 4.6 \times 10^{-12}$	[69]
1988	TRIUMF	$\mu^- + Pb \to e^- + Pb$	$< 4.9 \times 10^{-10}$	[69]
1993	PSI	$\mu^- + Ti \to e^- + Ti$	$< 4.3 \times 10^{-12}$	[70]
1996	PSI	$\mu^- + Pb \to e^- + Pb$	$< 4.6 \times 10^{-11}$	[71]
1998*	PSI	$\mu^- + Ti \to e^- + Ti$	$< 6.1 \times 10^{-13}$	[72]
2006	PSI	$\mu^- + Au \to e^- + Au$	$< 7 \times 10^{-13}$	[73]



SINDRUM II Result



μ N → e N conversion

electron receives kinetic energy from muon mass minus nuclear recoil energy

no sign of a signal!

Summary

- **The Standard Model is tested with high precision by**
  - **measuring precisely anomalous magnetic moments**
  - **searching for electric dipole moments**
  - **searching for baryon or lepton number violation**
  - **searching for charged lepton flavor violating processes**
- **These measurements and searches are model killers!**
- **Largest discrepancy seen in g_μ-2**
- **There is no evidence for new physics**