Lecture:

Standard Model of Particle Physics

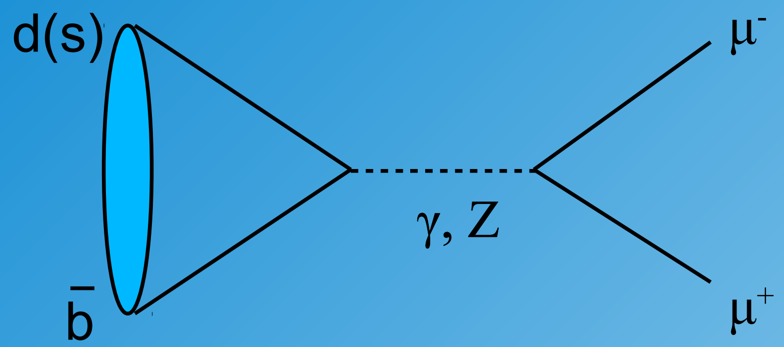
Heidelberg SS 2016

Searches Beyond the SM at Low Energy

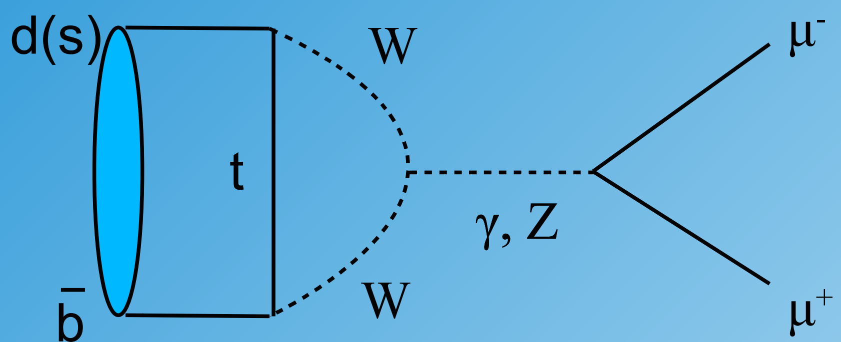
Contents

Flavour Changing Neutral Currents

...are forbidden in the SM at tree level (GIM mechanism)



branching ratio=0



penguin diagram

$$\begin{aligned}\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} &= (3.2 \pm 0.2) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} &= (1.0 \pm 0.1) \times 10^{-10}.\end{aligned}$$

branching ratio enhanced by new physics!

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm CMSSM}}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM}} \approx 1.2^{+0.8}_{-0.2}$$

arXiv:1112.3564

Results from LHCB

PRL **110**, 021801 (2013)

Search for

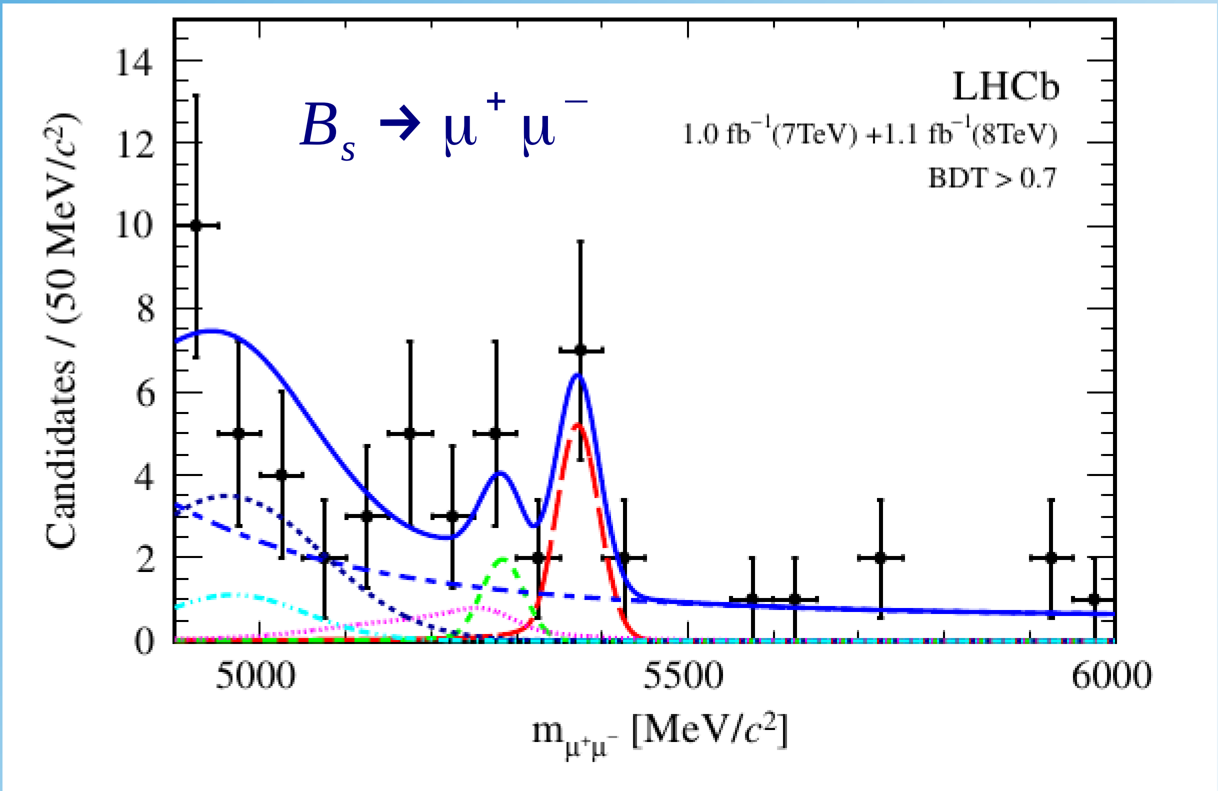
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$$ (95% CL)

SM expected 1.1 x 10^{-10}

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

SM expected 3.2 x 10^{-9}

- well compatible with SM expectation
- not much room for new physics beyond the SM

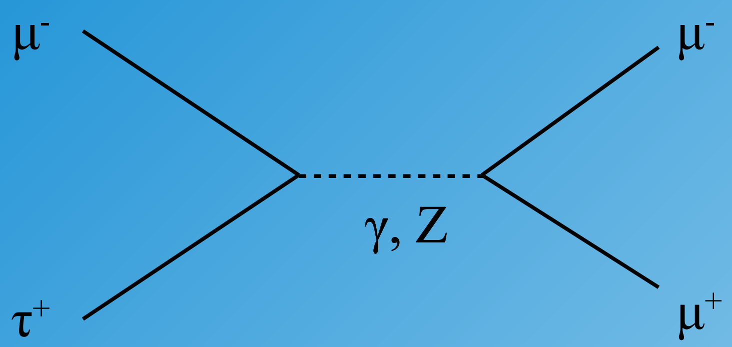


ATLAS and CMS also looking into this channel

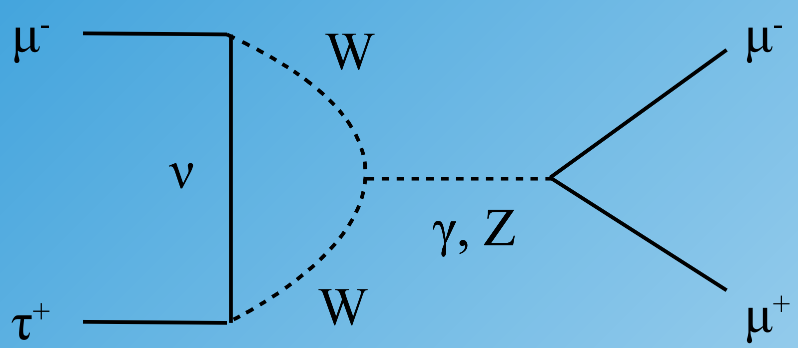
Lepton Flavor Violation (LFV)

...also forbidden in the SM at tree level (GIM mechanism)

Decay: $\tau^+ \rightarrow \mu^+ \mu^+ \mu^-$



branching ratio=0

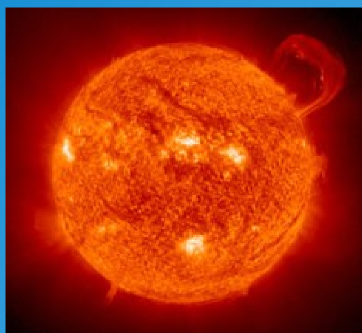


penguin diagram

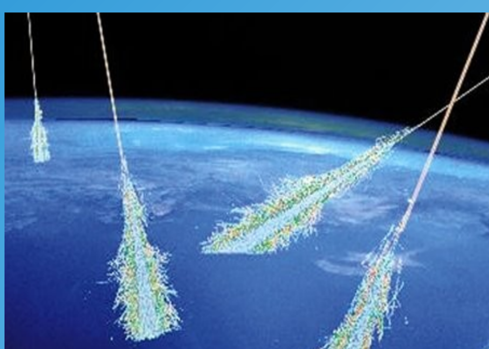
suppressed $\frac{(\Delta m_\nu^2)^2}{m_W^4} \approx 10^{-50}$

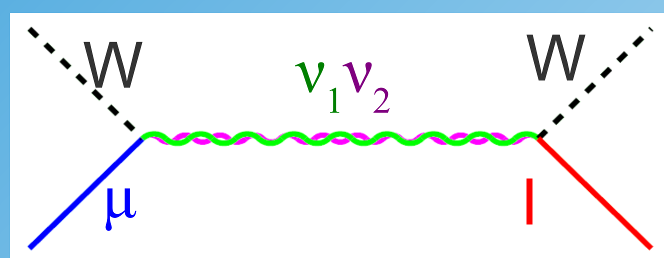
branching ratio largely enhanced by new physics (40 orders of magnitude)!

Discovery of Neutrino Oscillations

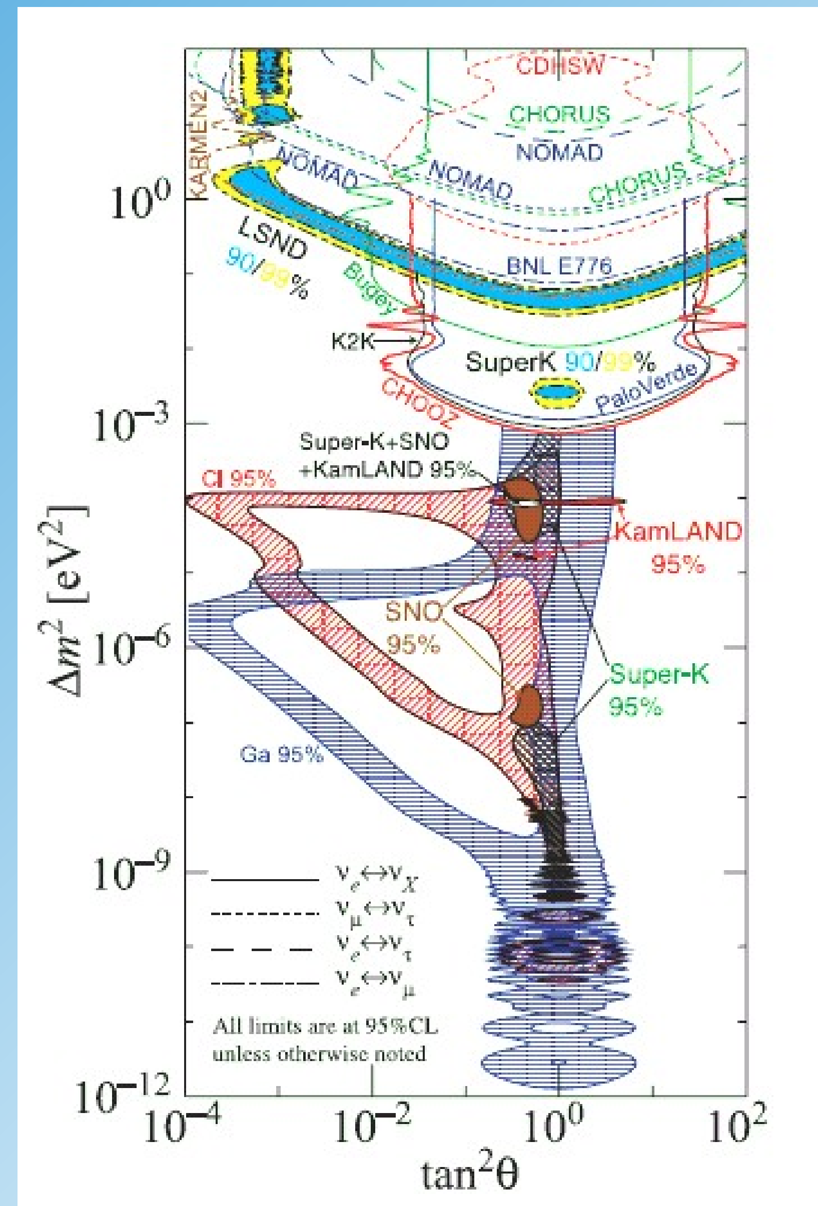


- Neutrino Oscillations:
  - solar neutrinos
  - reactor neutrinos
  - atmospheric neutrinos
  - neutrino beams





$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2_{\alpha\beta}\frac{L}{E}\right)$$

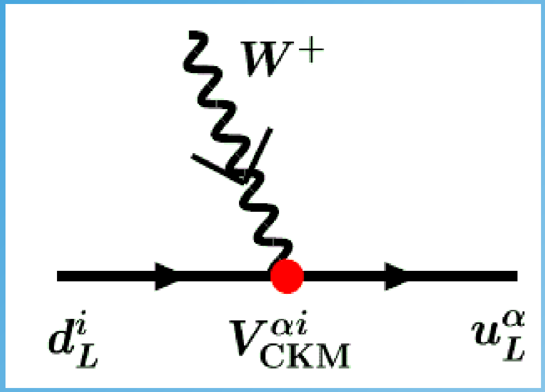


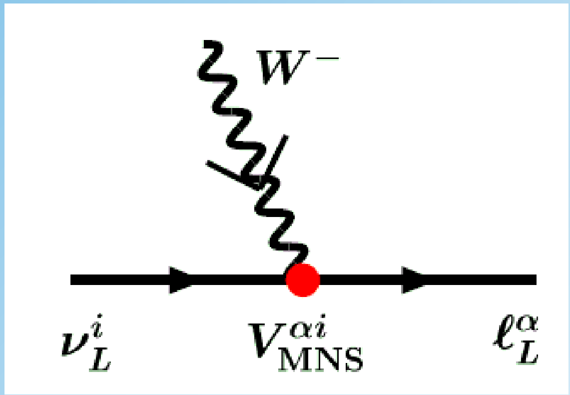
Fermion Mixing

Quarks	Leptons
Cabibbo Kobayashi Maskawa (CKM)	Pontecorvo Maki Nakagawa Sakata (PMNS)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





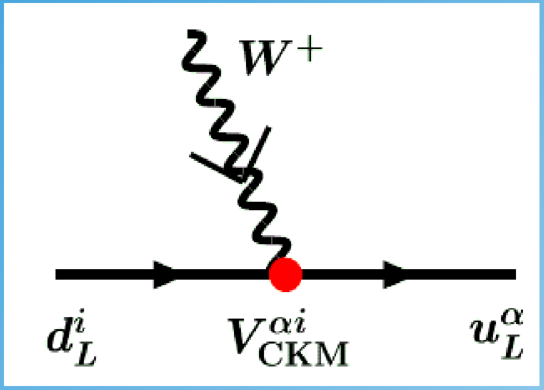
- **W bosons smell different flavors!**
- **other gauge bosons (γ, Z, g) do not (→ no FCNC)**

Fermion Mixing

<u>Quarks</u>

Cabibbo Kobayashi Maskawa (CKM)

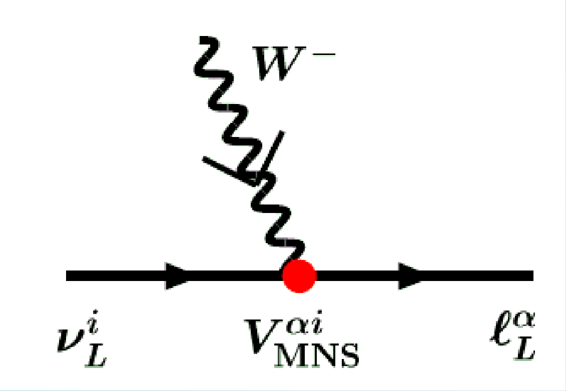
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



<u>Leptons</u>

Pontecorvo Maki Nakagawa Sakata (PMNS)

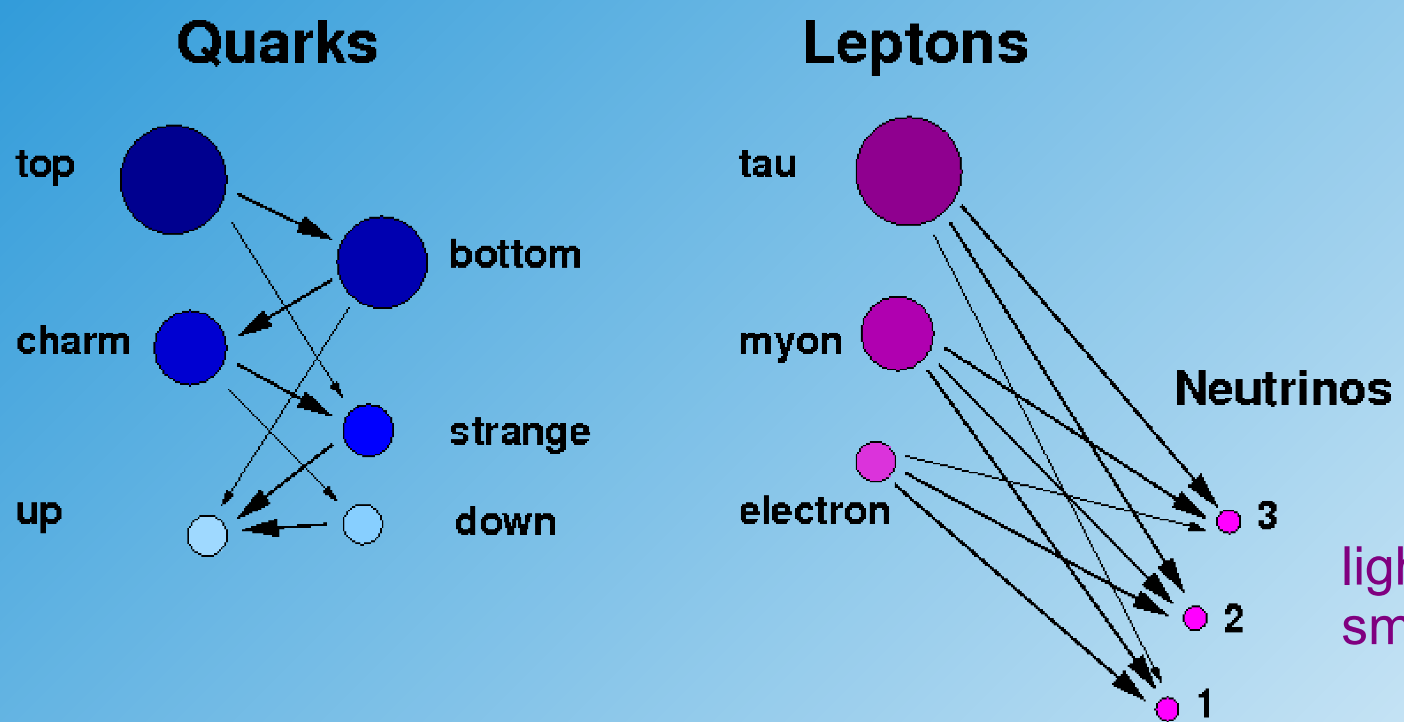
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \approx \begin{pmatrix} 0.816 & 0.577 & <0.2 \\ 0.408 & 0.577 & 0.707 \\ 0.408 & 0.577 & 0.707 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- **W bosons smell different flavors!**
- **other gauge bosons (γ, Z, g) do not (→ no FCNC)**

Family Number Violation

- **Flavor Changing neutral currents are forbidden!**
- **Lepton Flavor Number in Charged Currents is an “adhoc” concept**



light and
small mass splitting

quark flavor not conserved
(family number changes)

lepton flavor not conserved
but difficult to observe!

(concept of families right?)

Overview LFV Experiments

Lepton Decays:

- $\mu \rightarrow e\,\gamma$
- $\mu \rightarrow eee$
- $\tau \rightarrow e(\mu)\,\gamma$
- $\tau \rightarrow l\,l\,l$ $(l = e, \mu)$
- $\tau \rightarrow l\,h$

Meson Decays:

- Φ, K $\rightarrow ll'$
- D, $J/\psi \rightarrow ll'$
- B, $\Upsilon \rightarrow ll'$

LFV

Conversion (μ-Capture):

- $\mu\,N \rightarrow e\,N$

Collider Experiments:

- $e\,p \rightarrow \mu(\tau)\,X$ HERA
- $H \rightarrow l\,l'$ LHC
- $Z' \rightarrow l\,l'$
- $\chi^{0,\pm} \rightarrow l\,l'\,X$

Fixed Target Experiments:

- $\mu\,N \rightarrow \tau\,N$ proposed
- $e\,N \rightarrow \mu(\tau)\,N$ proposed

Charged Lepton Flavour Violation

- Leptons mix in a similar way as quarks (→ PMNS matrix, W.R next week)
- Lepton mixing discovered in neutrino oscillations

<u>But (Charged) Lepton Flavor Violation not seen:</u>

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]

now 4.2×10^{-13} (MEG)

recent updates from LHC

The SM prediction for Lepton Flavor Violating (LFV) Processes is negligible (GIM-like suppression)

Any sign of LFV would manifest New Physics

muon to electron conversion experiments

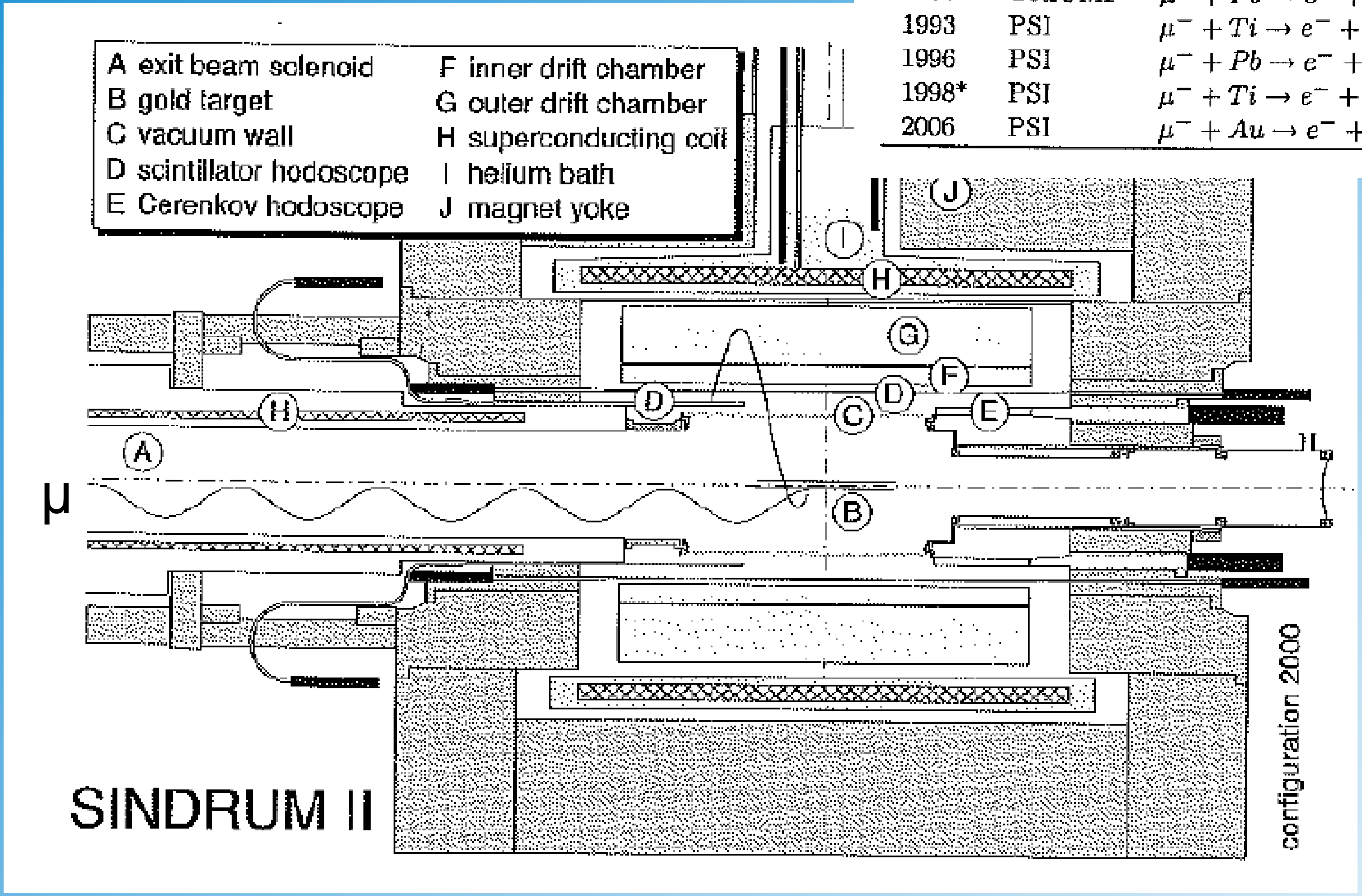
Muon-Electron Conversion

$\mu N \rightarrow e N$ conversion

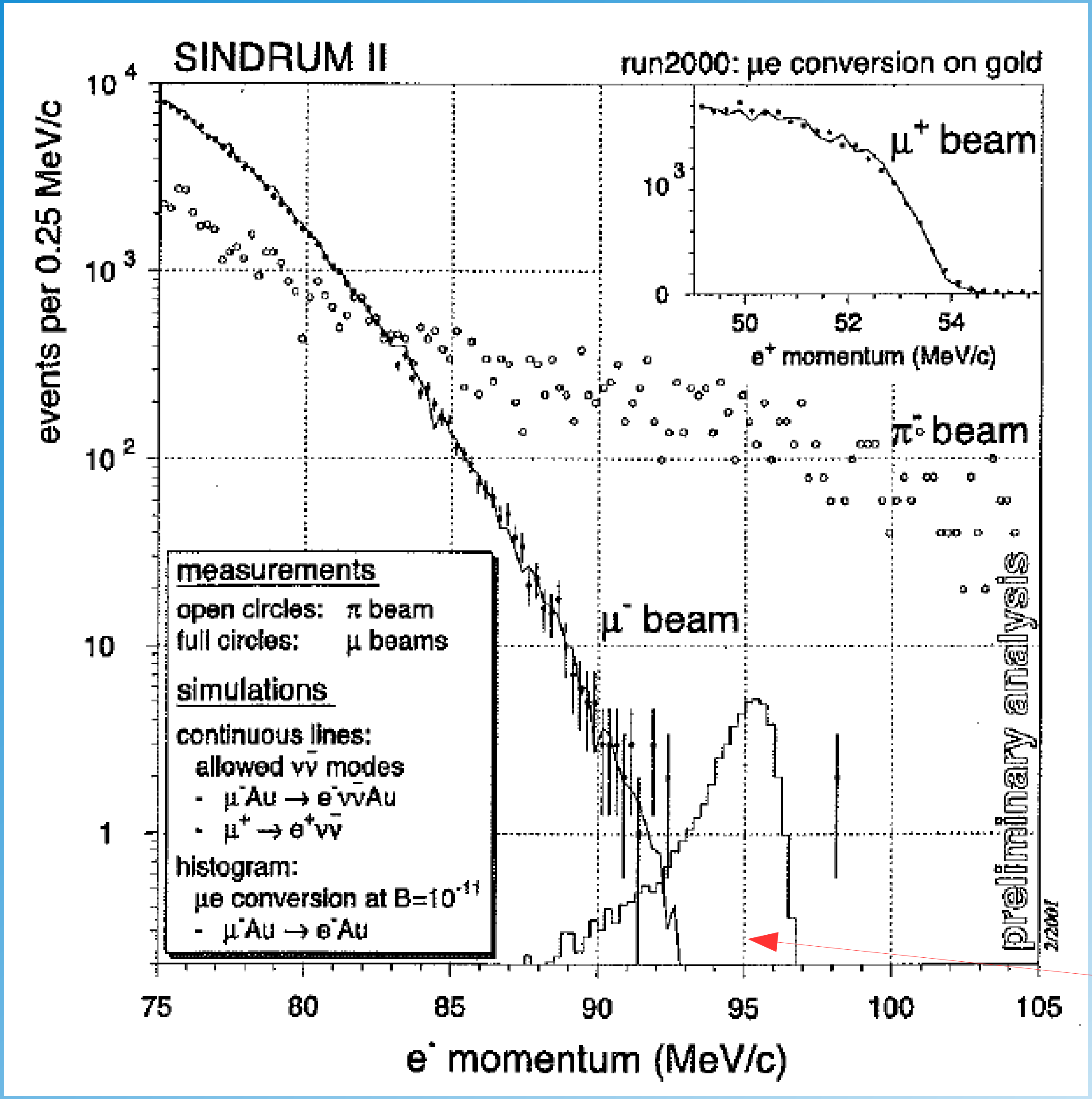
- muon capture in nucleons
- muon decays in orbit

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

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

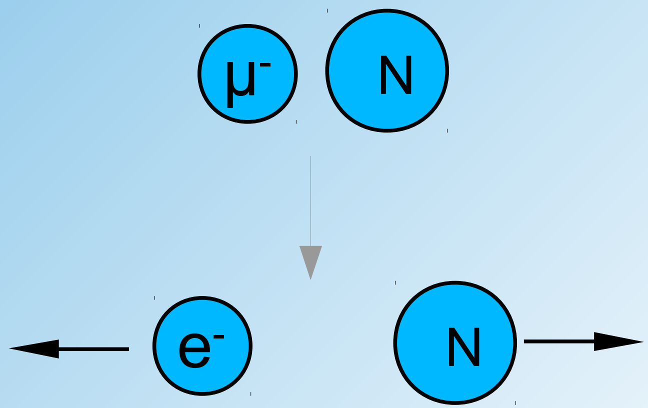


SINDRUM II Result



$\mu^- N \rightarrow e^- N$ conversion

electron receives kinetic energy from muon mass minus nuclear recoil energy



no sign of a signal!

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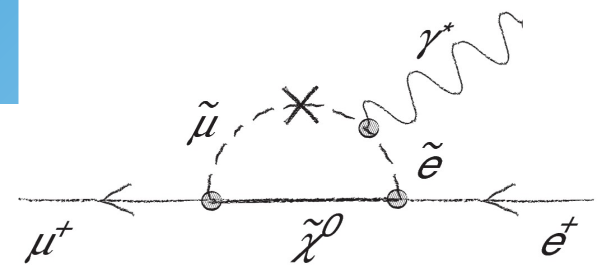
Any sign of LFV would manifest New Physics

muon to electron conversion experiments

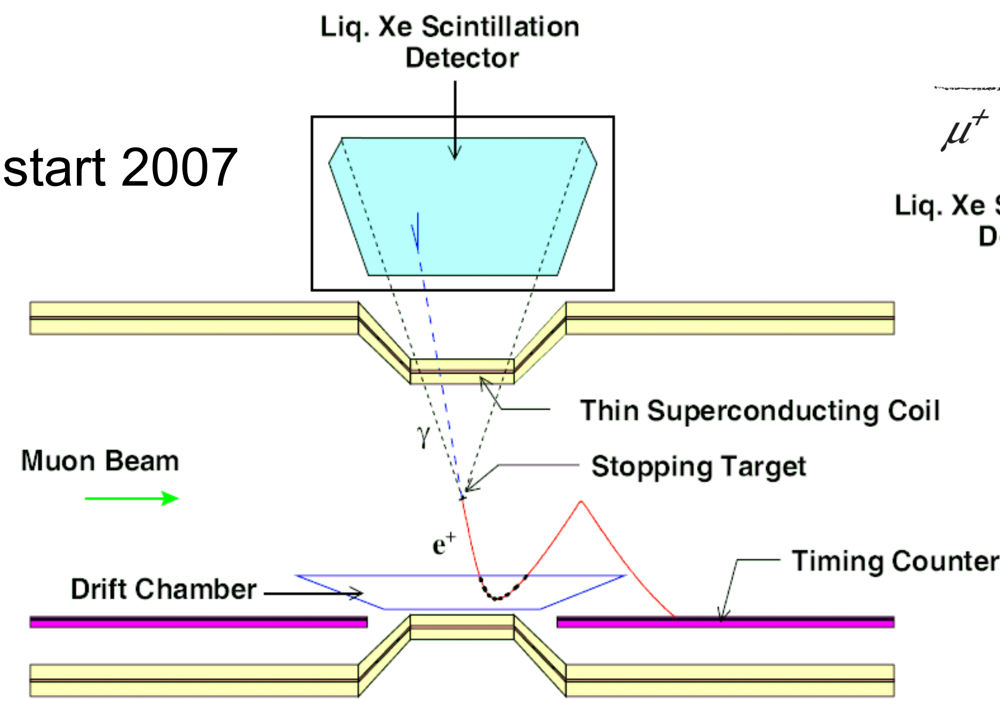
The MEG Experiment

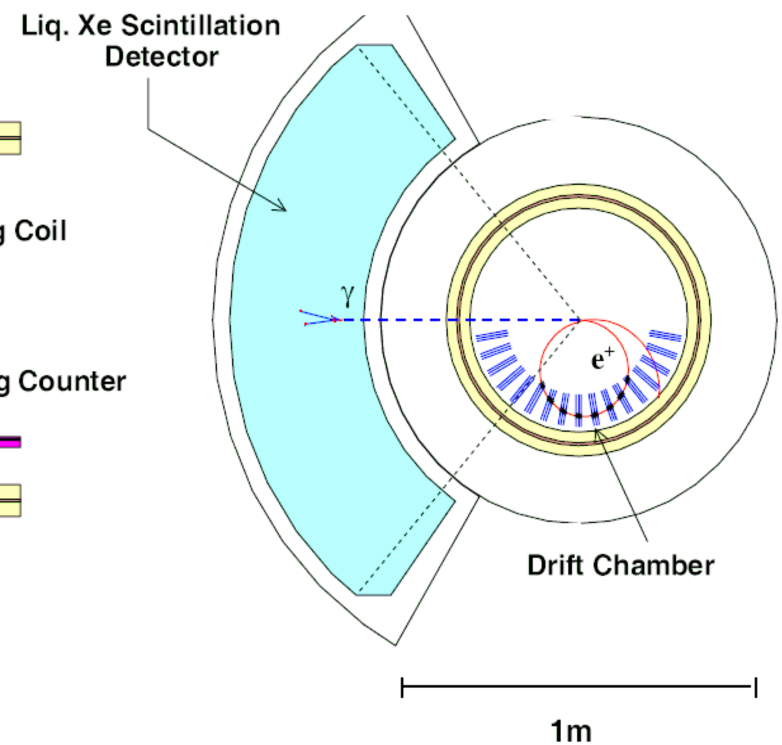
current limit:
BR($\mu^+ \rightarrow e^+ \gamma$) < 4.2 x 10^{-13} (2016)

LFV decay: $\mu^+ \rightarrow e^+ \gamma$



start 2007





Limitation:
- accidental background
  - better space resolution
  - improve tracking

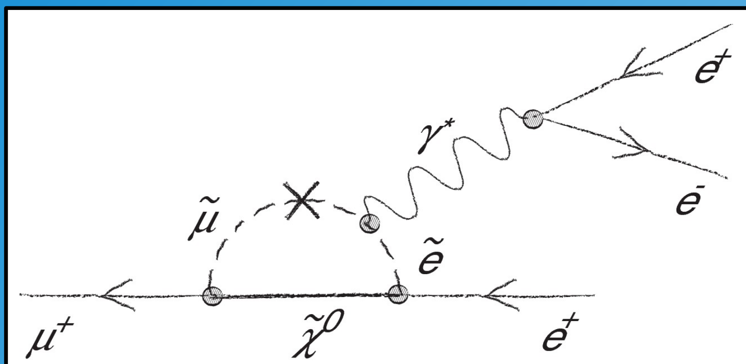
- still taking data
- upgrade planned starting next year

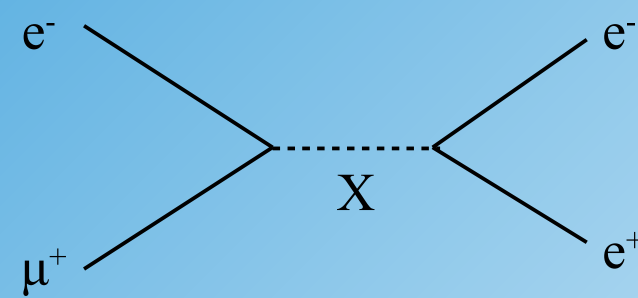
Mu3e Experiment

Search for the decay: $\mu \to eee$

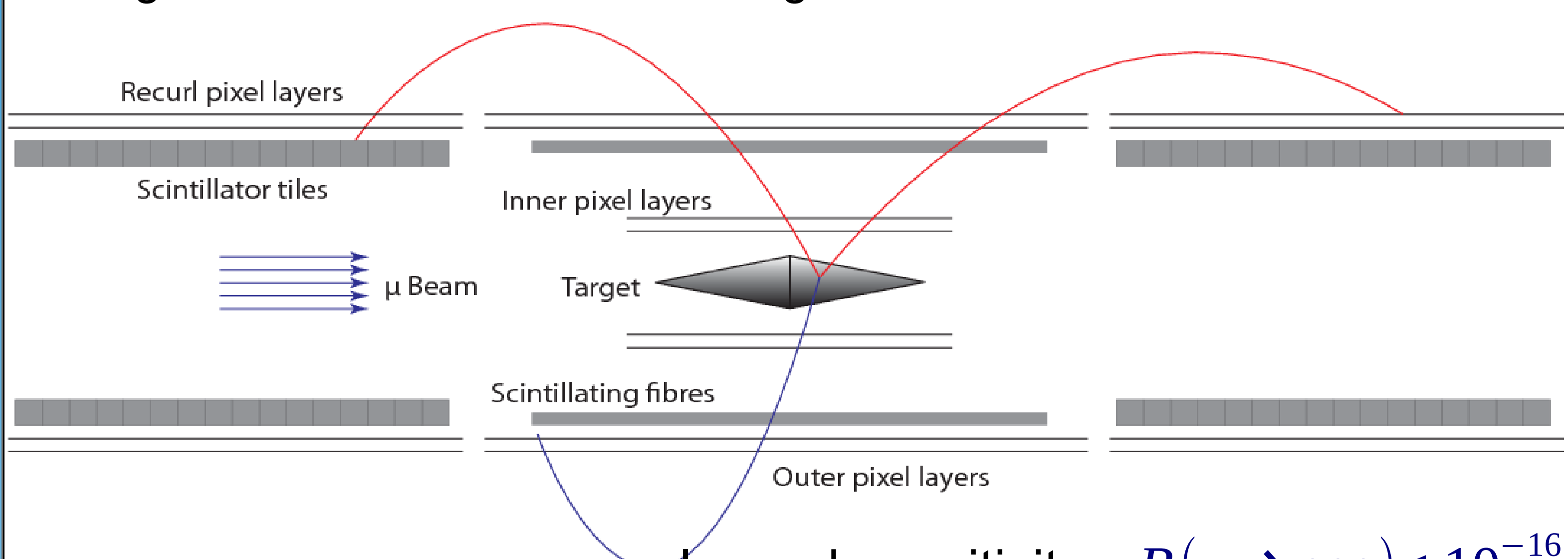
SM prediction: $B(\mu \to eee) \ll 10^{-50}$

current limit $B(\mu \to eee) < 10^{-12}$





Design and construction: Heidelberg



planned sensitivity: $B(\mu \to eee) < 10^{-16}$

will be performed at the Paul Scherrer Institute (PSI) in 2018

Baryon and Lepton Number Violation

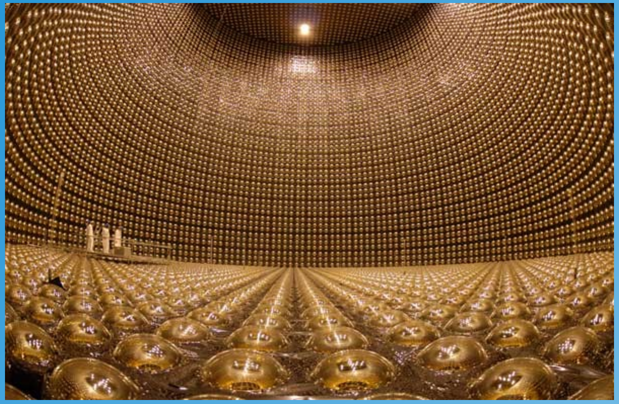
Proton is stable: $\tau > 10^{31} - 10^{33}$ *years*

Not seen:

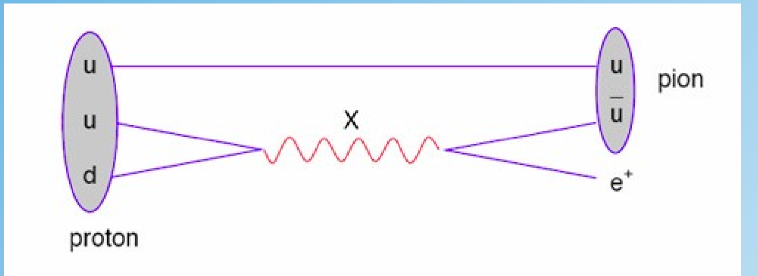
$p \not\to \pi^0 e^+$

$p \not\to \pi^+ \gamma$

$\pi^+ \not\to e^+ \gamma$



Super Kamiokande



No observation of Baryon or Lepton Number Violation!

The fact the humans and life exists on earth (no radiation damage) excludes already BSM scenarios!

However, baryon or lepton number violating processes are required to explain matter antimatter asymmetry in universe

New BSM Physics is required!

Dipole Moments and Test of the Standard Model

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

<u>Running couplings</u>

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

$\longrightarrow$ prediction of W, Top and Higgs masses

<u>Magnetic dipole moments</u>

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

CP,T invariant

<u>Electric dipole moments</u>

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

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.

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

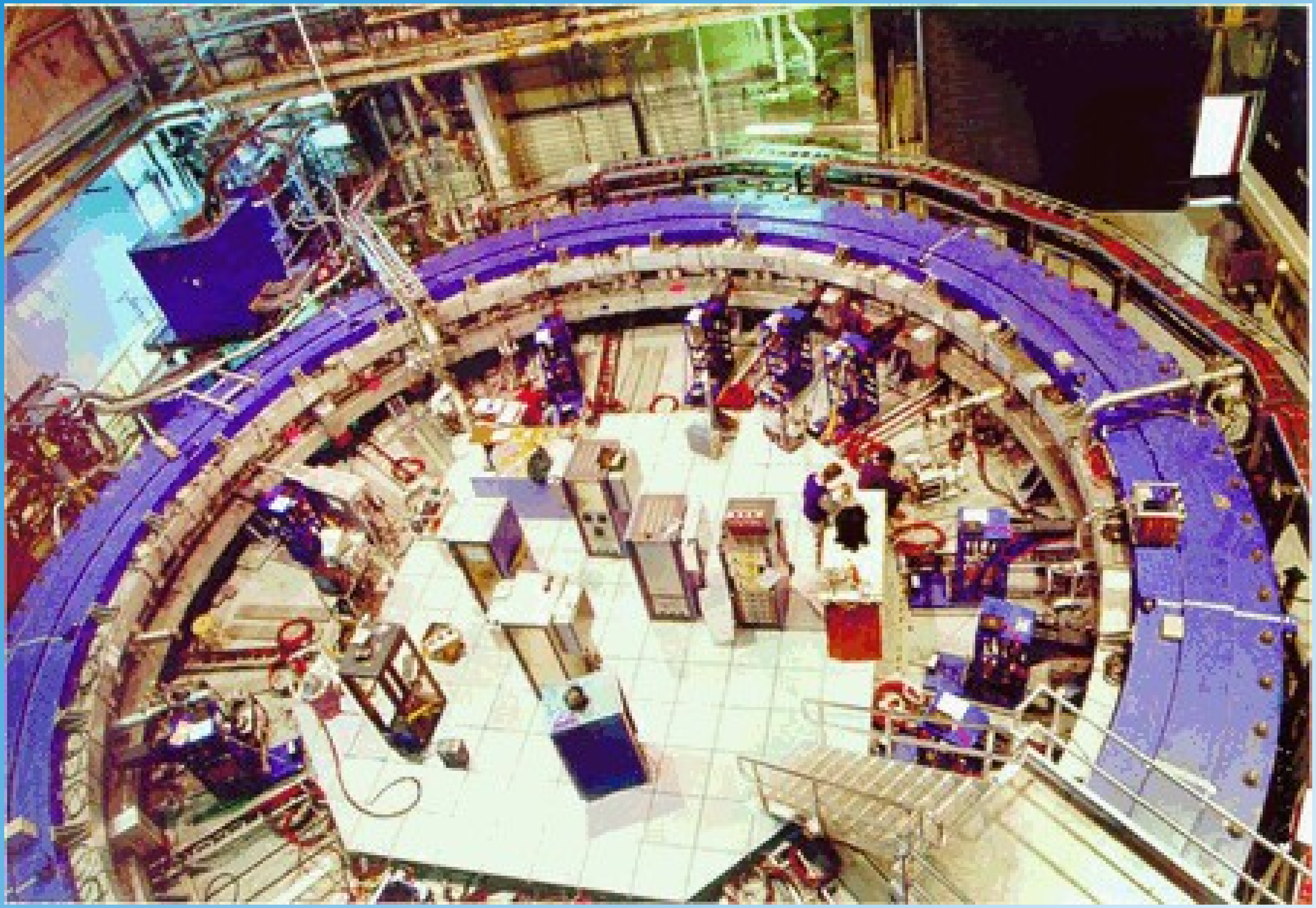
factor 20!

$$a(\mu) = 1.1659\boxed{2080}(53) \times 10^{-3}$$

$$a(\mu)_{theor} = 1.1659\boxed{1773}(63) \times 10^{-3}$$

3.7 sigma discrepancy

Muon Storage Ring at BNL



after transportation currently re-commissioned at Fermilab

Muon Injection Line

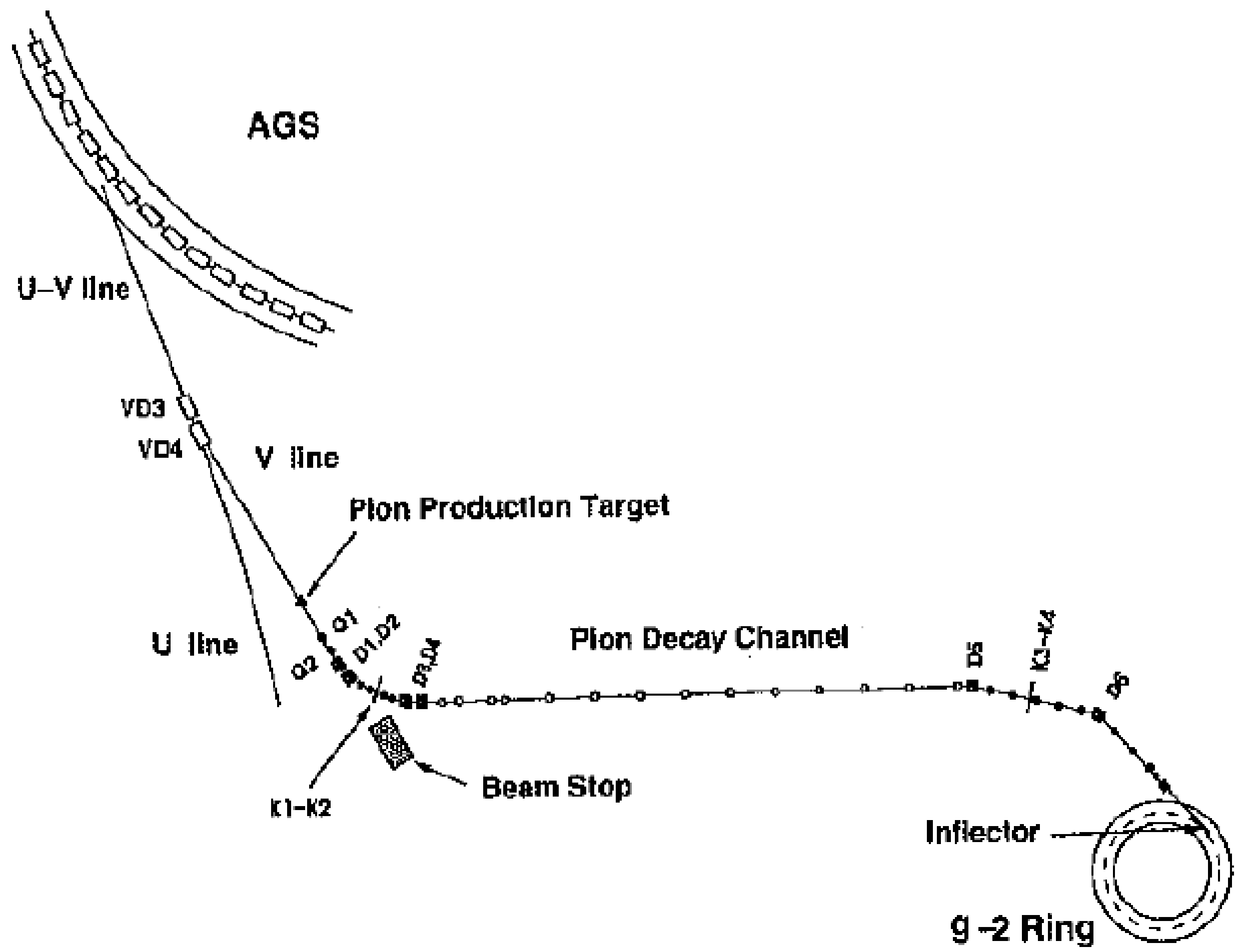


Fig. 11.3. The E821 beamline and storage ring. Pions produced at 0° are collected by the quadrupoles Q1-Q2 and the momentum is selected by the collimators K1-K2. The pion decay channel is 72 m in length. Forward muons at the magic momentum are selected by the collimators K3-K4. (This figure was reprinted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

Muon Injection

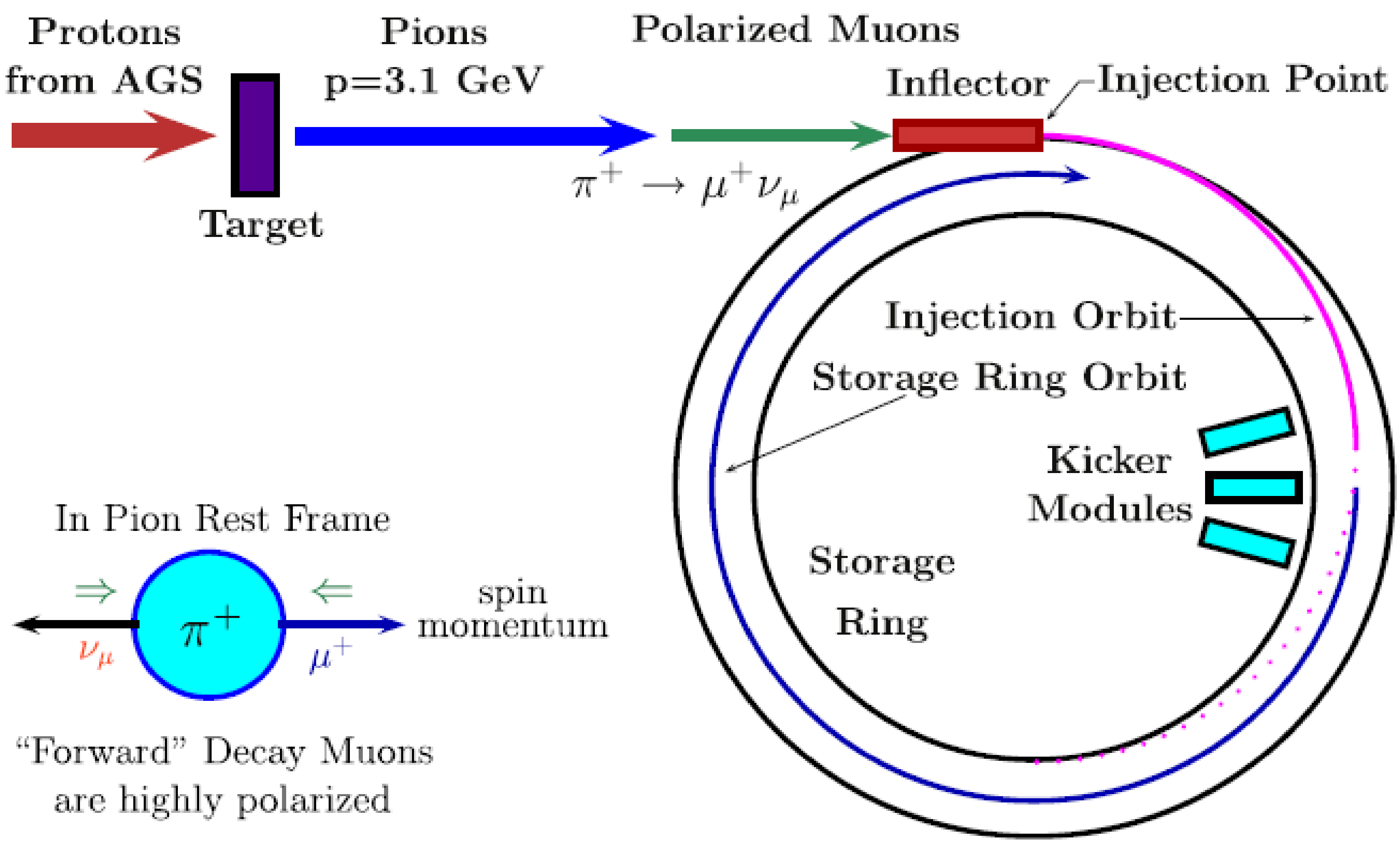


Fig. 4. The schematics of muon injection and storage in the $g-2$ ring.

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):

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

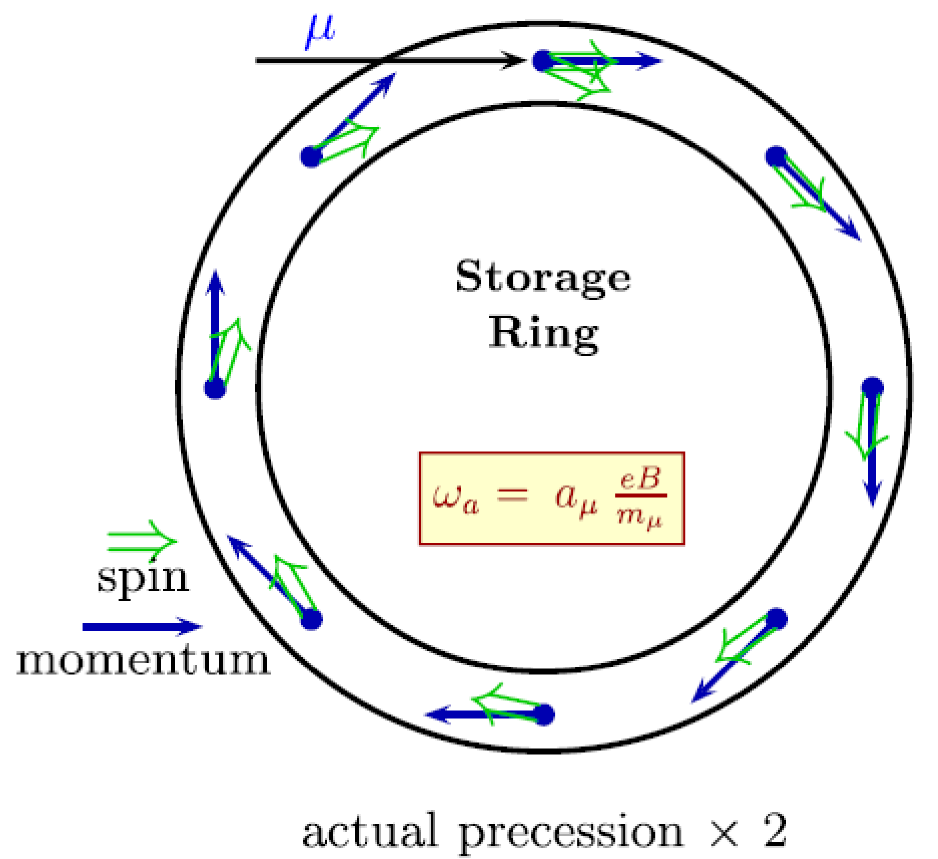


Fig. 3. Spin precession in the $g-2$ ring ($\sim 12°$/circle).

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

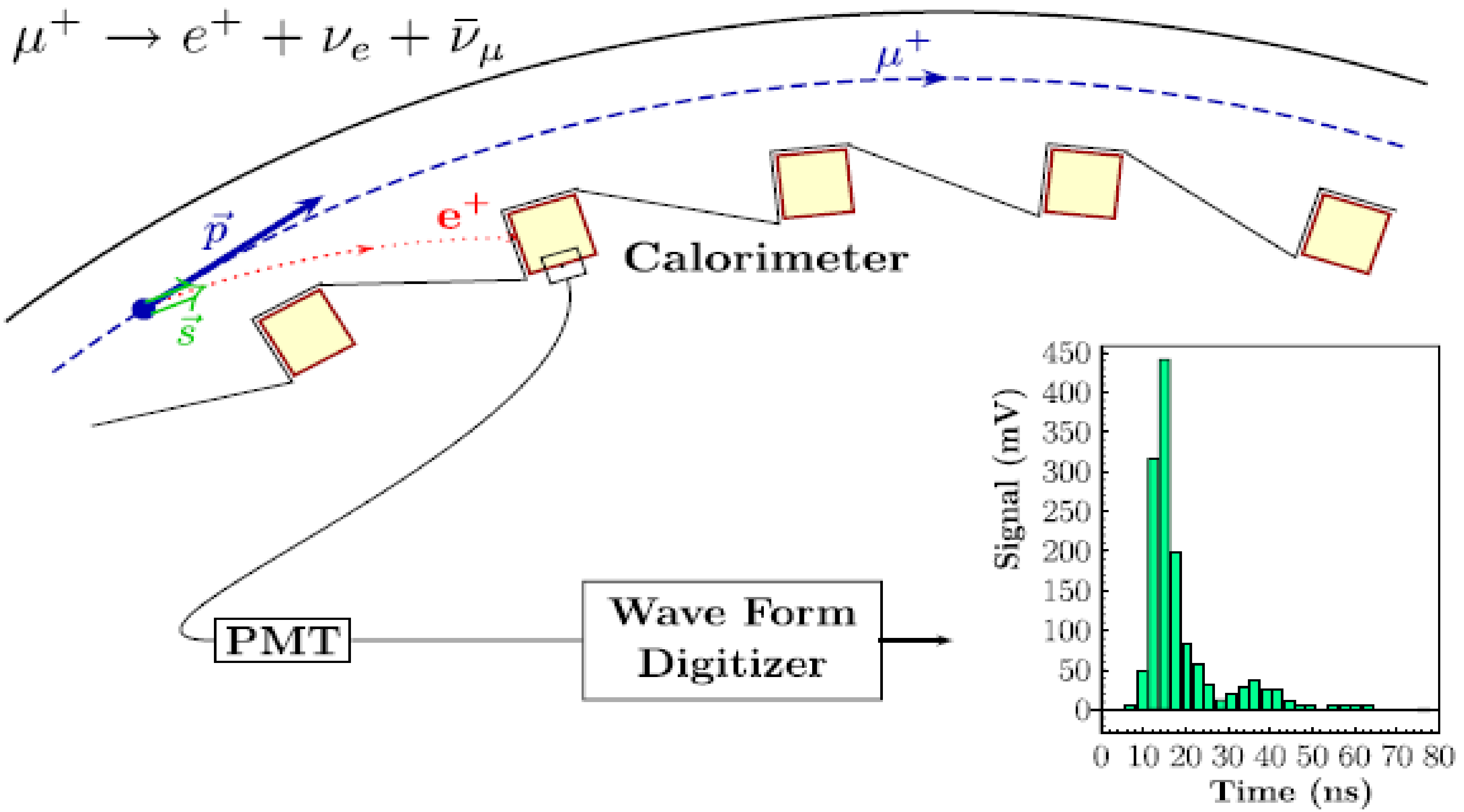
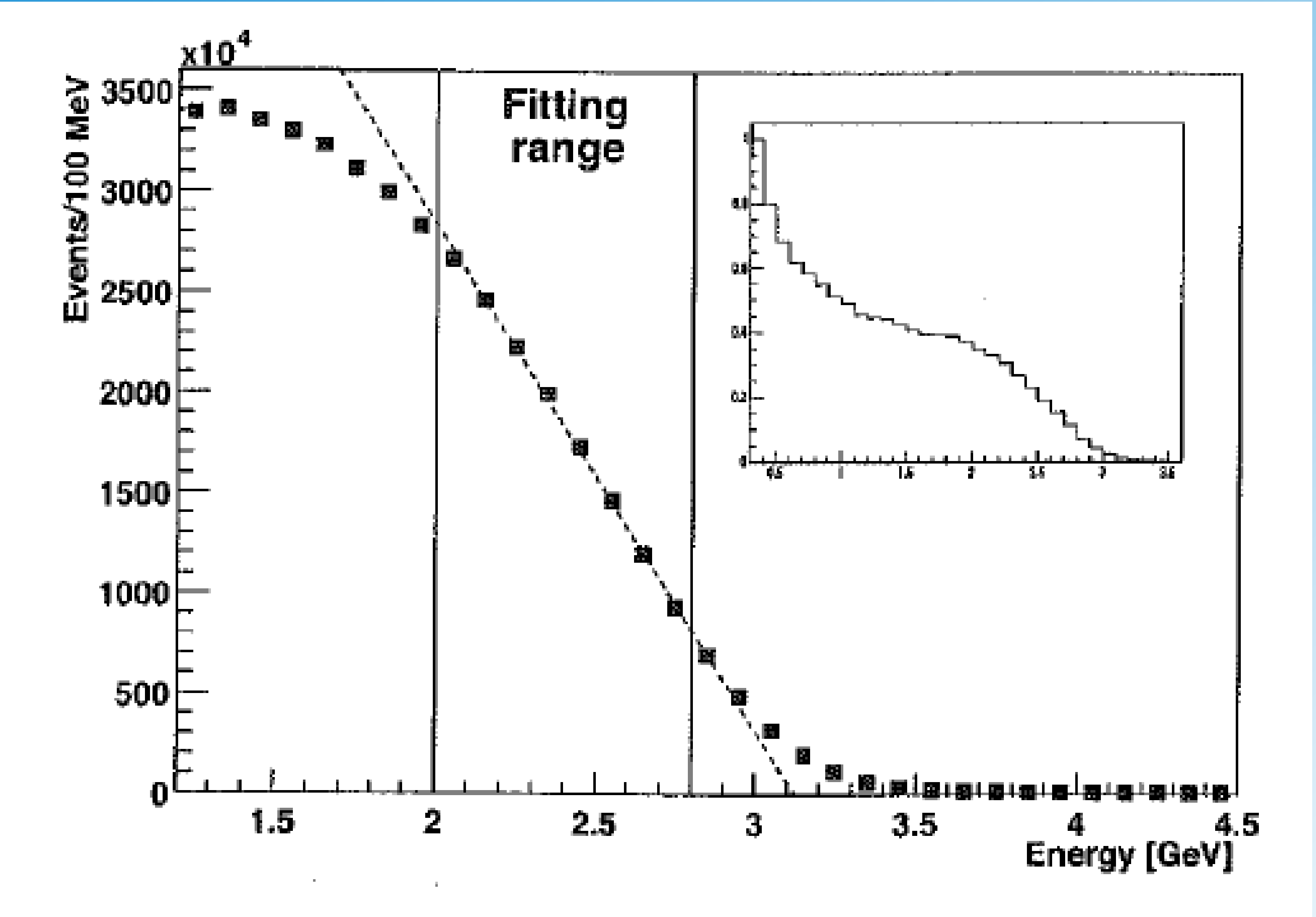


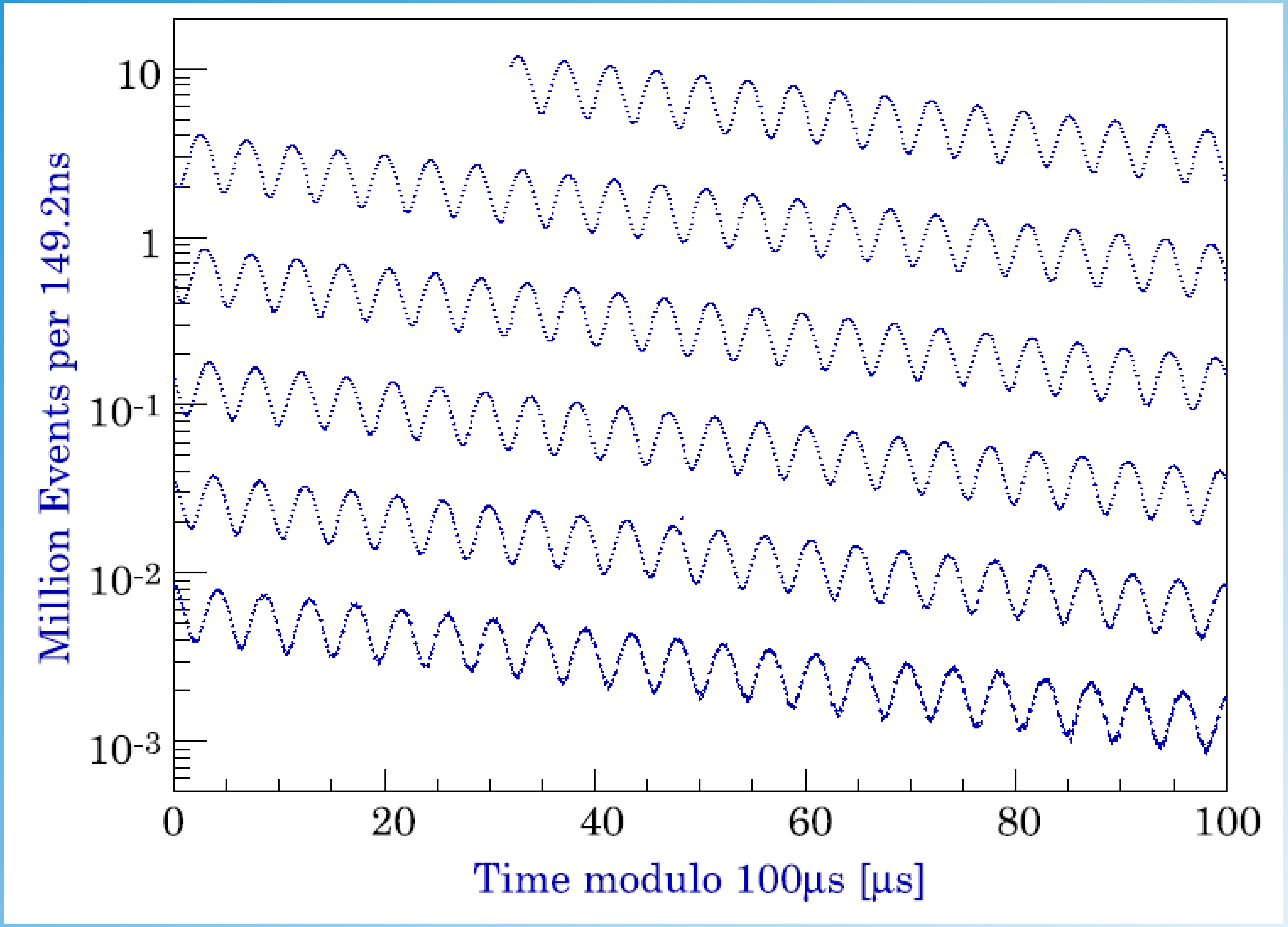
Fig. 5. Decay of μ^+ and detection of the emitted e^+ (PMT = Photomultiplier).

Energy Spectrum

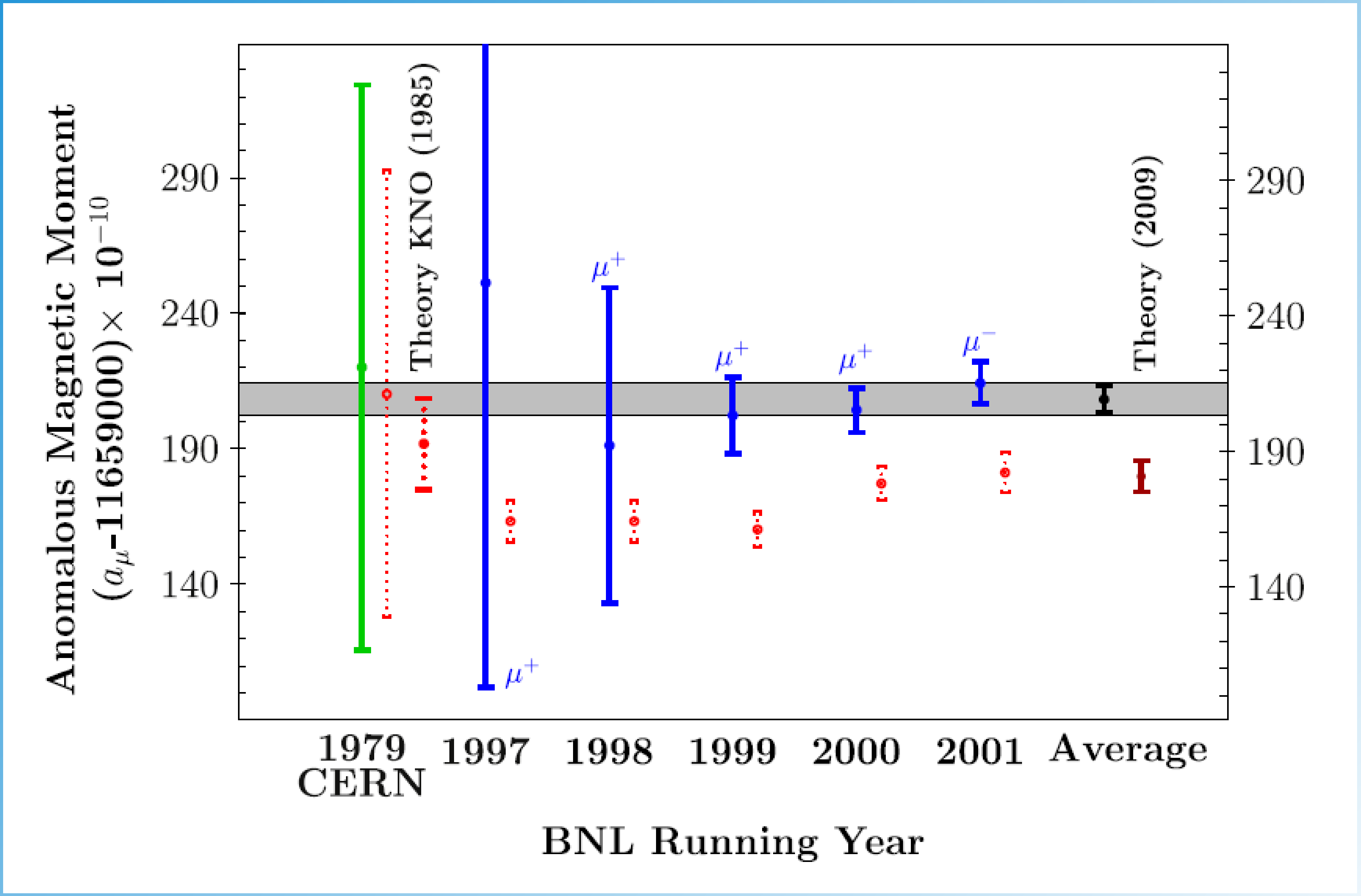
Decay: $\mu \rightarrow e \nu \nu$ (boosted Michel spectrum)



Time Dependent Rate



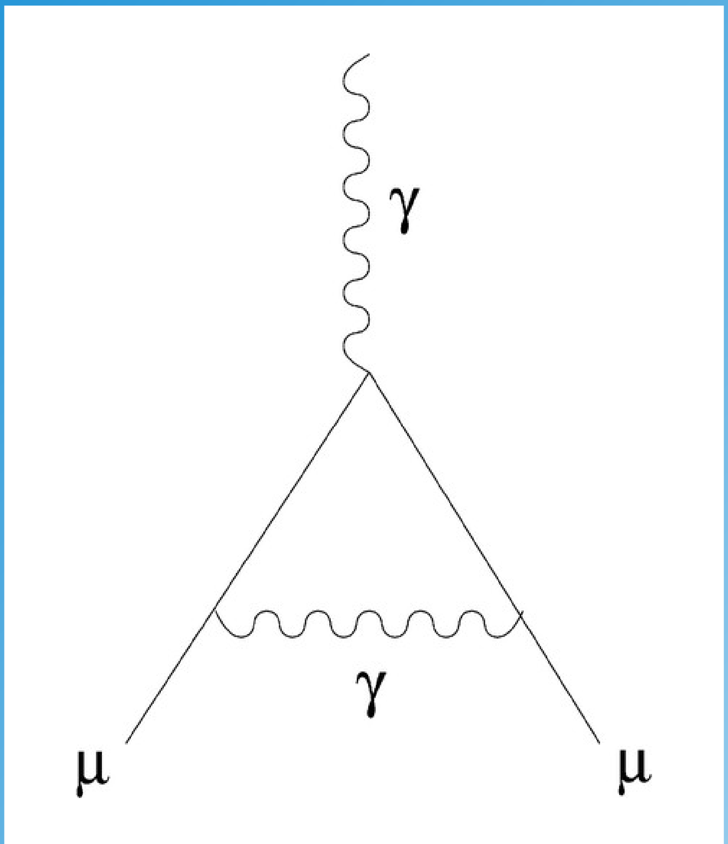
Summary Plot g_μ-2 Experiments



Muon Magnetic Moment

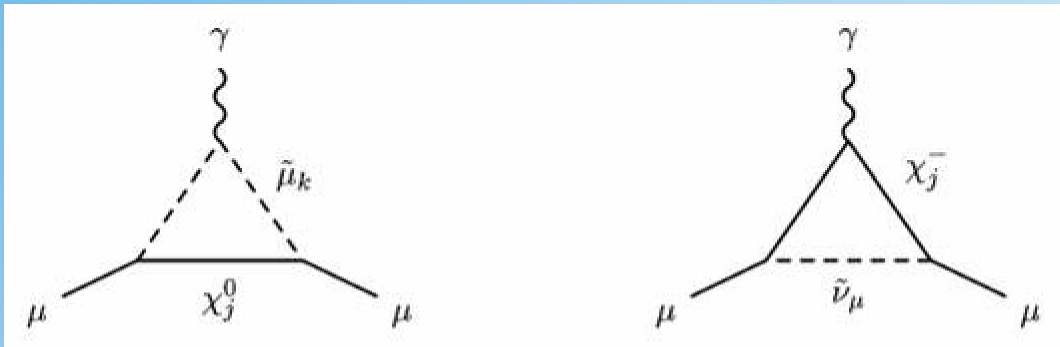
Magnetic moment of a fermion from radiative corrections:

QED first order

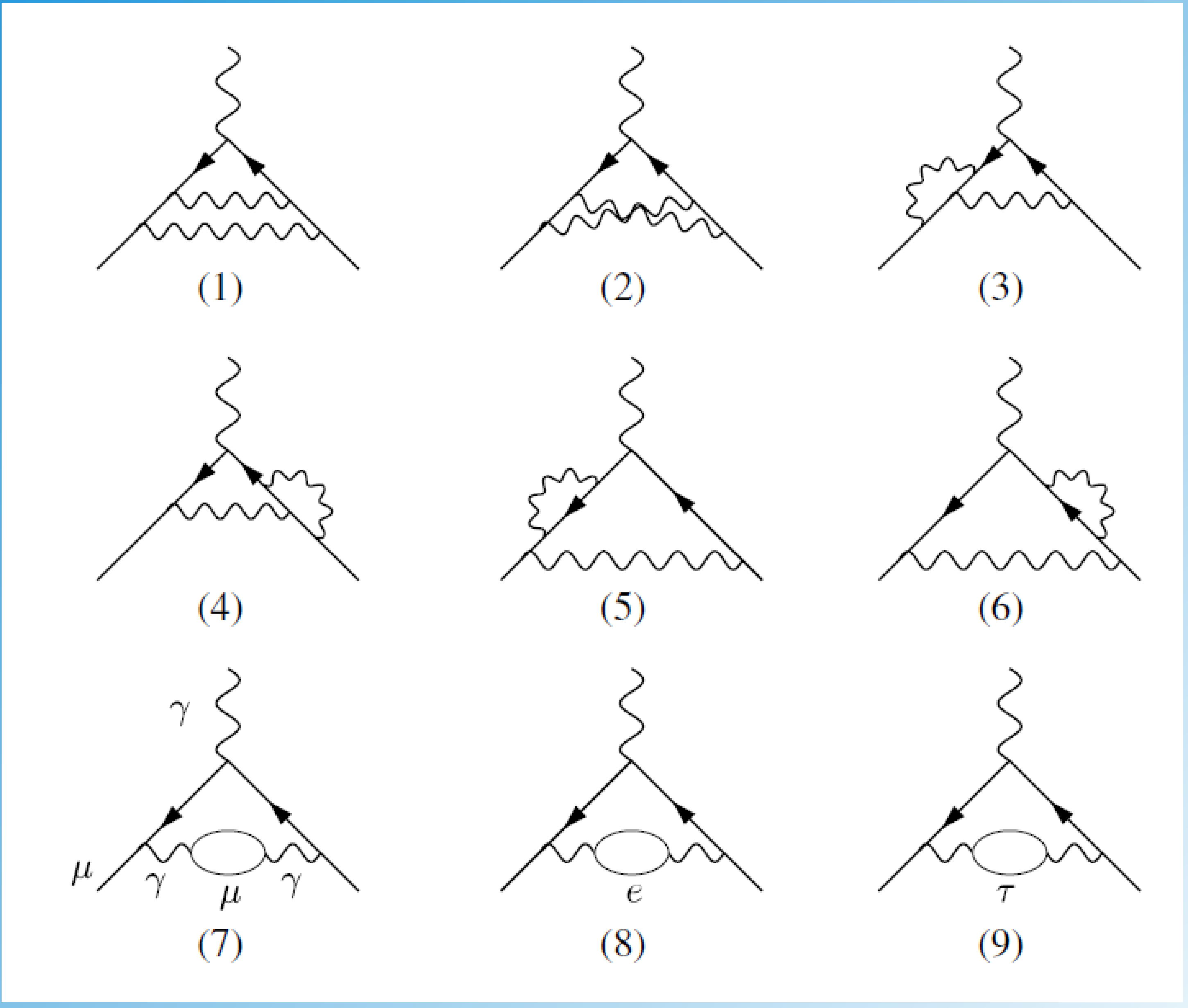


Schwinger diagram

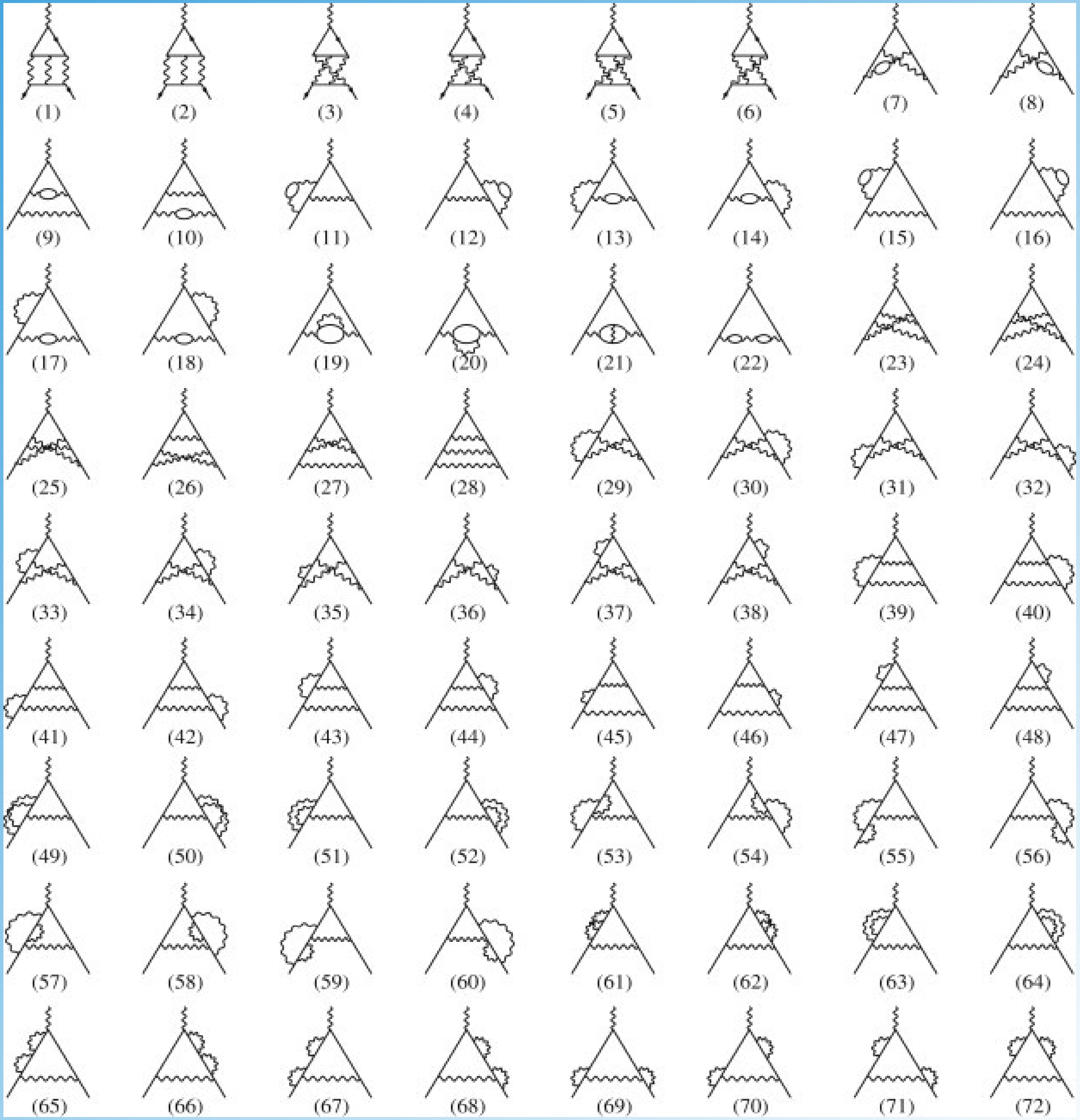
New Physics: Supersymmetry



Second Order Diagrams (QED)



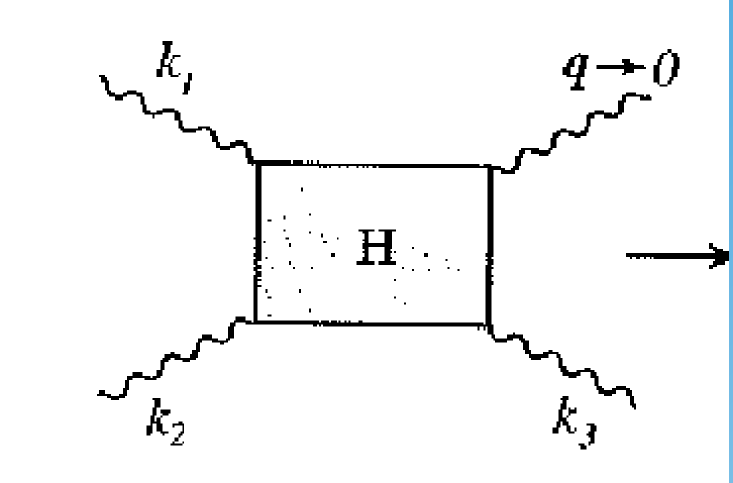
Higher Order Diagrams

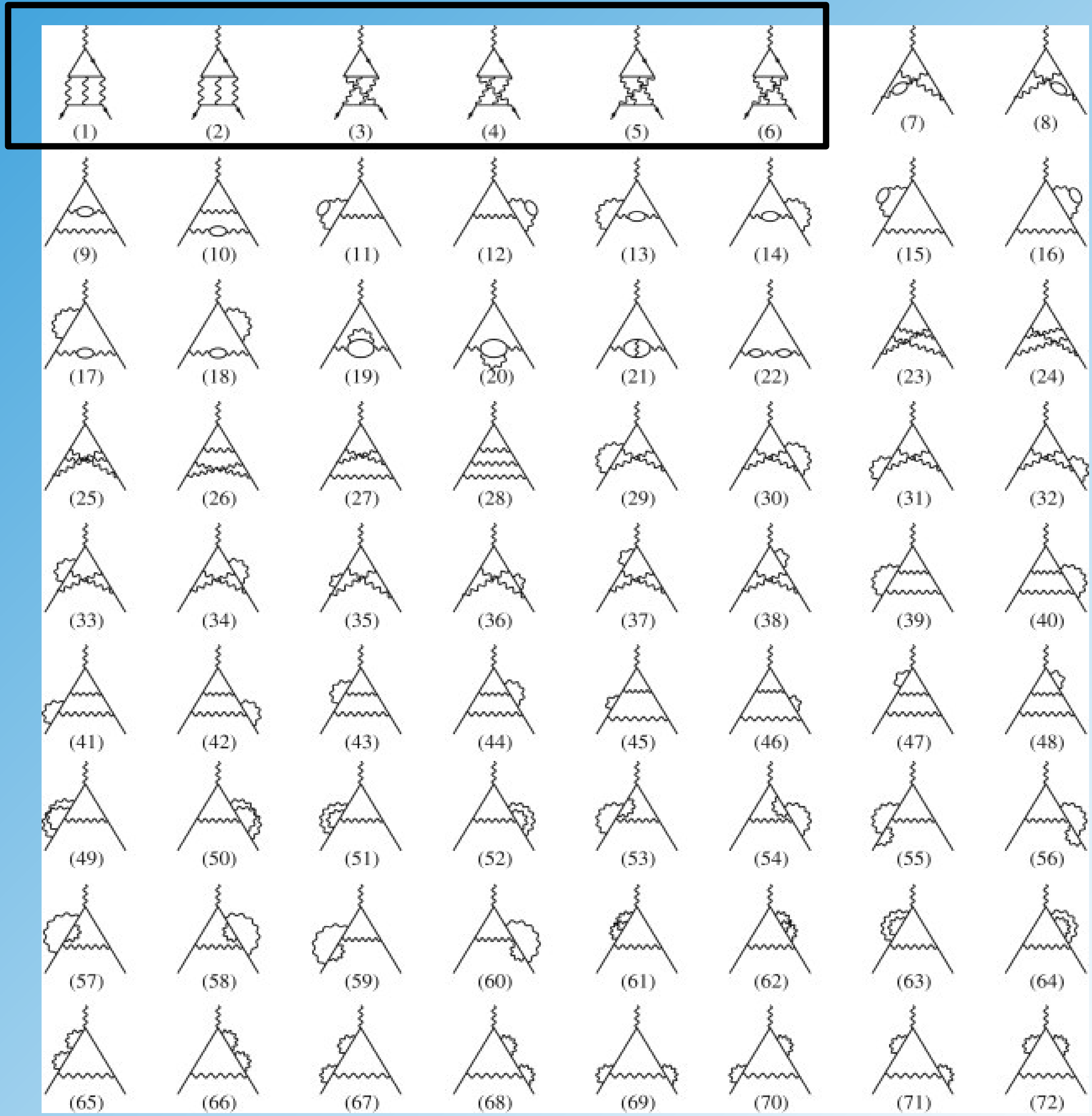


Higher Order Diagrams

light by light diagrams

light by light scattering:





difficulty:
- hadronic structure

Hadronic Corrections

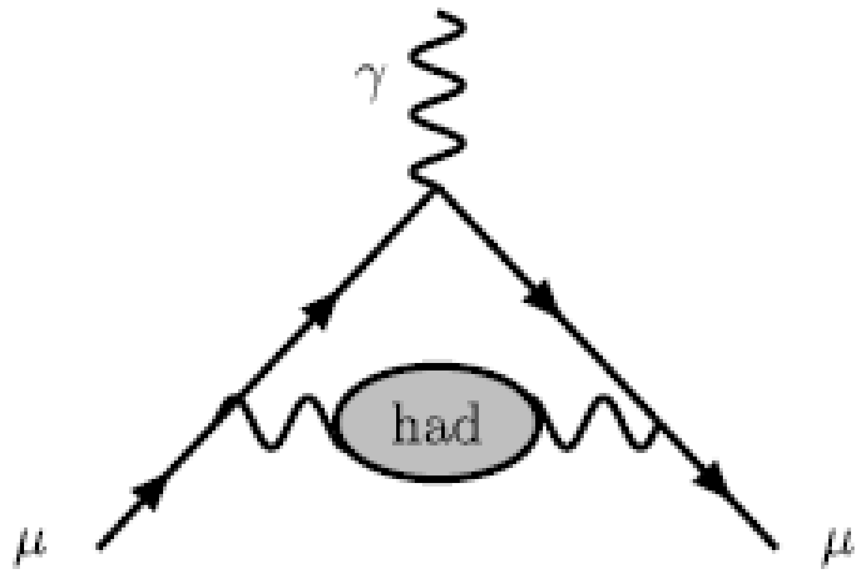


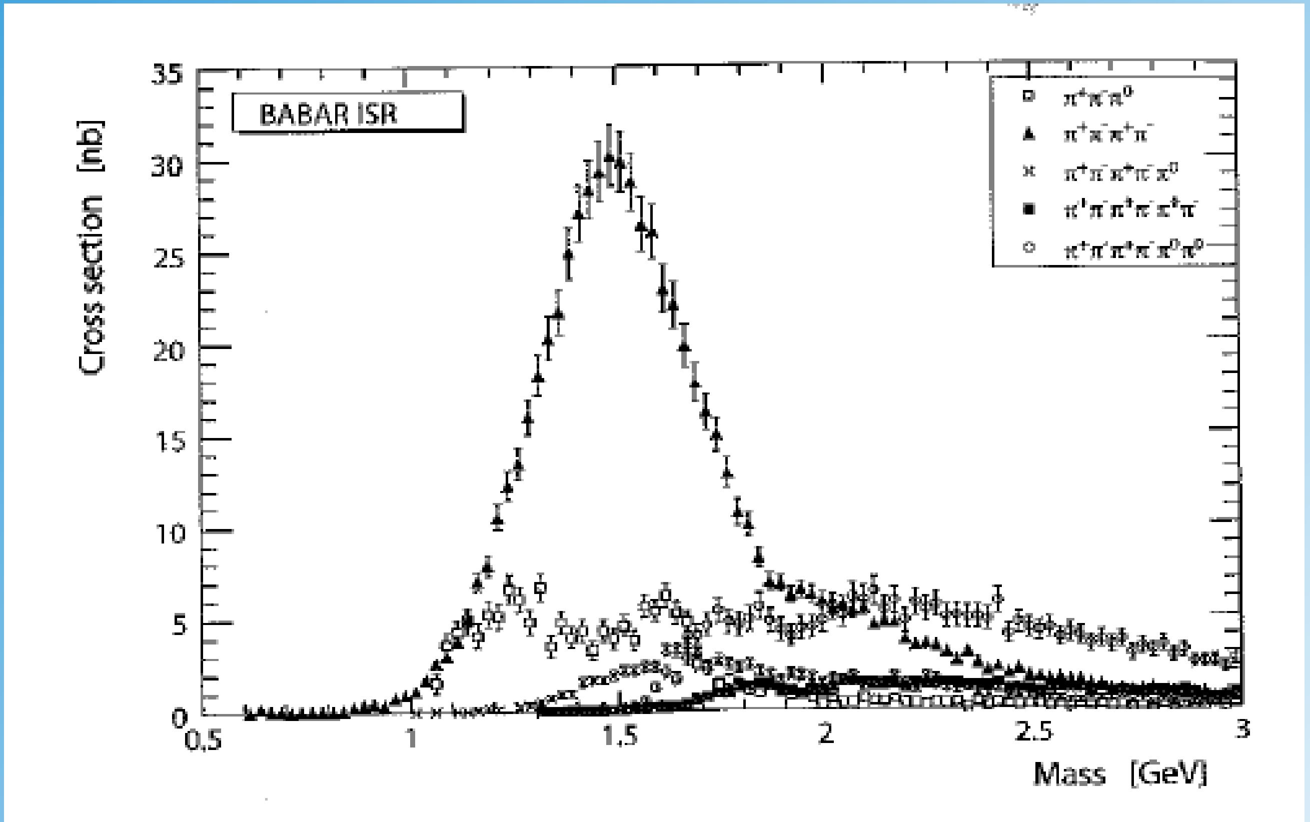
Fig. 19. Leading hadronic contribution to $g - 2$.

Vacuum polarisation contribution (third order)

can not be precisely calculated:

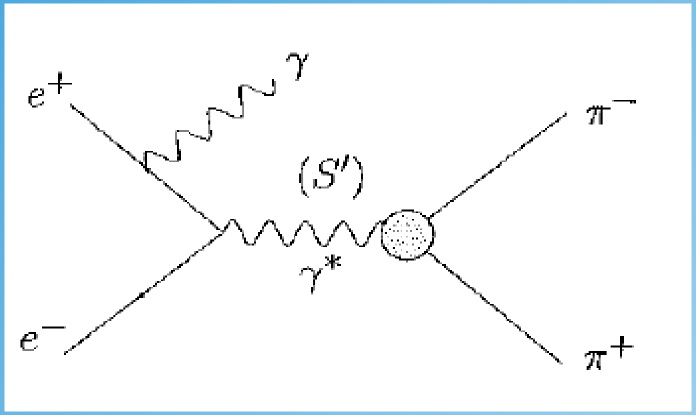
- but can be taken from g_e (corrections are identical)
- or can be taken from $e^+ e^-$ scattering !

Hadronic Structure of the Photon



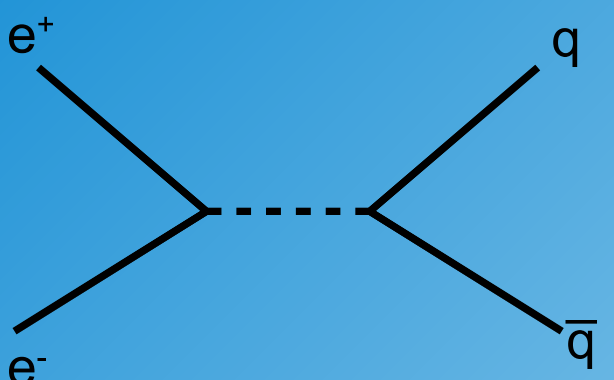
Measurements at Babar:

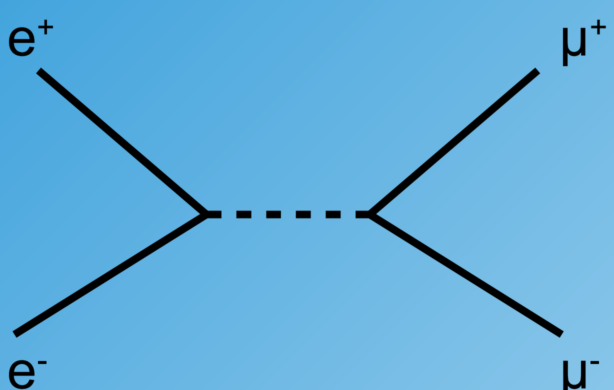
Radiative Return in Initial State Radiation (ISR) events

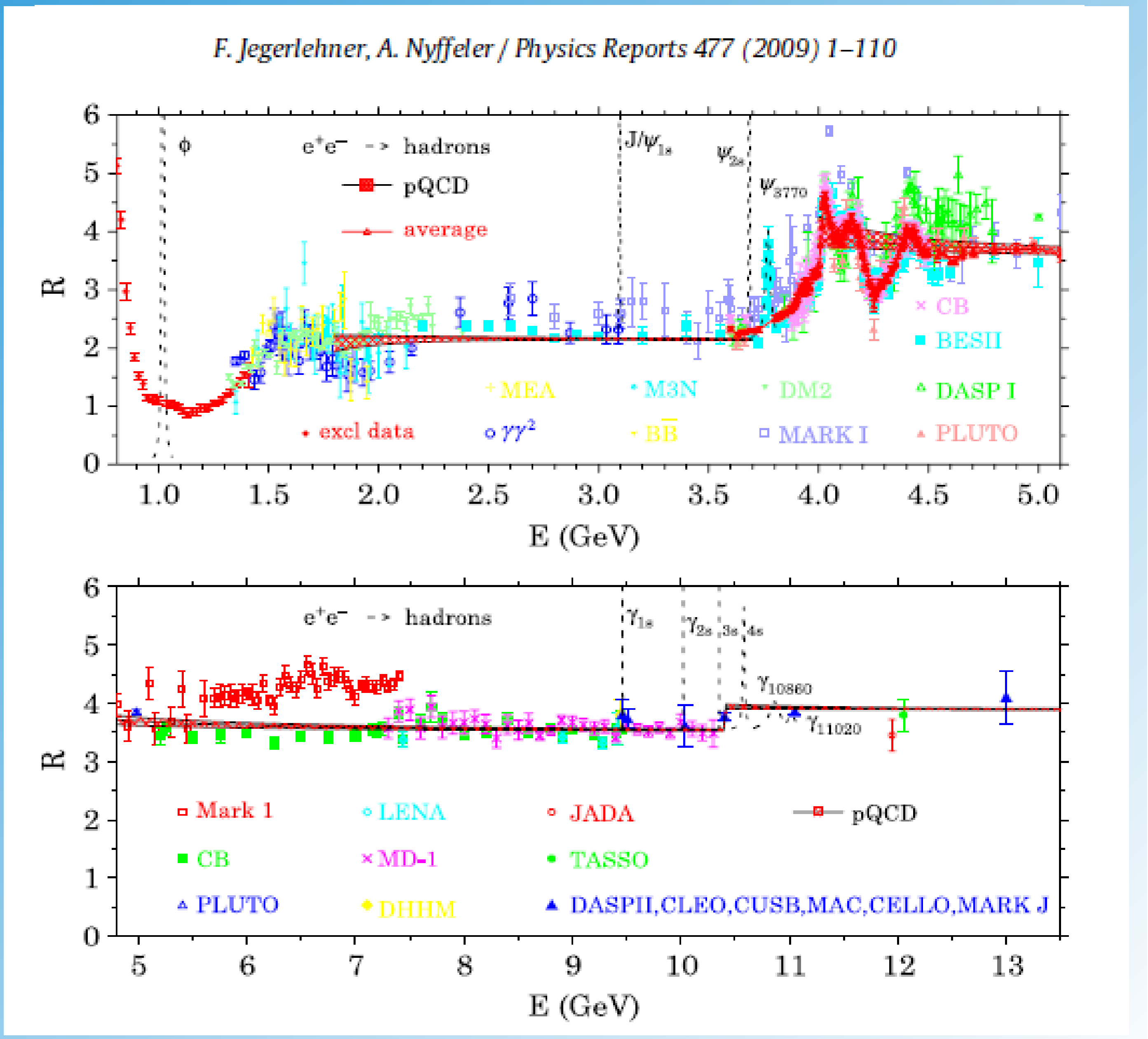


Hadronic Structure of the Photon

from e^+e^- collisions:







measurement of R_{hadr}

Higher Order QED Corrections

E.g. electron magnetic moment:

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

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

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

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

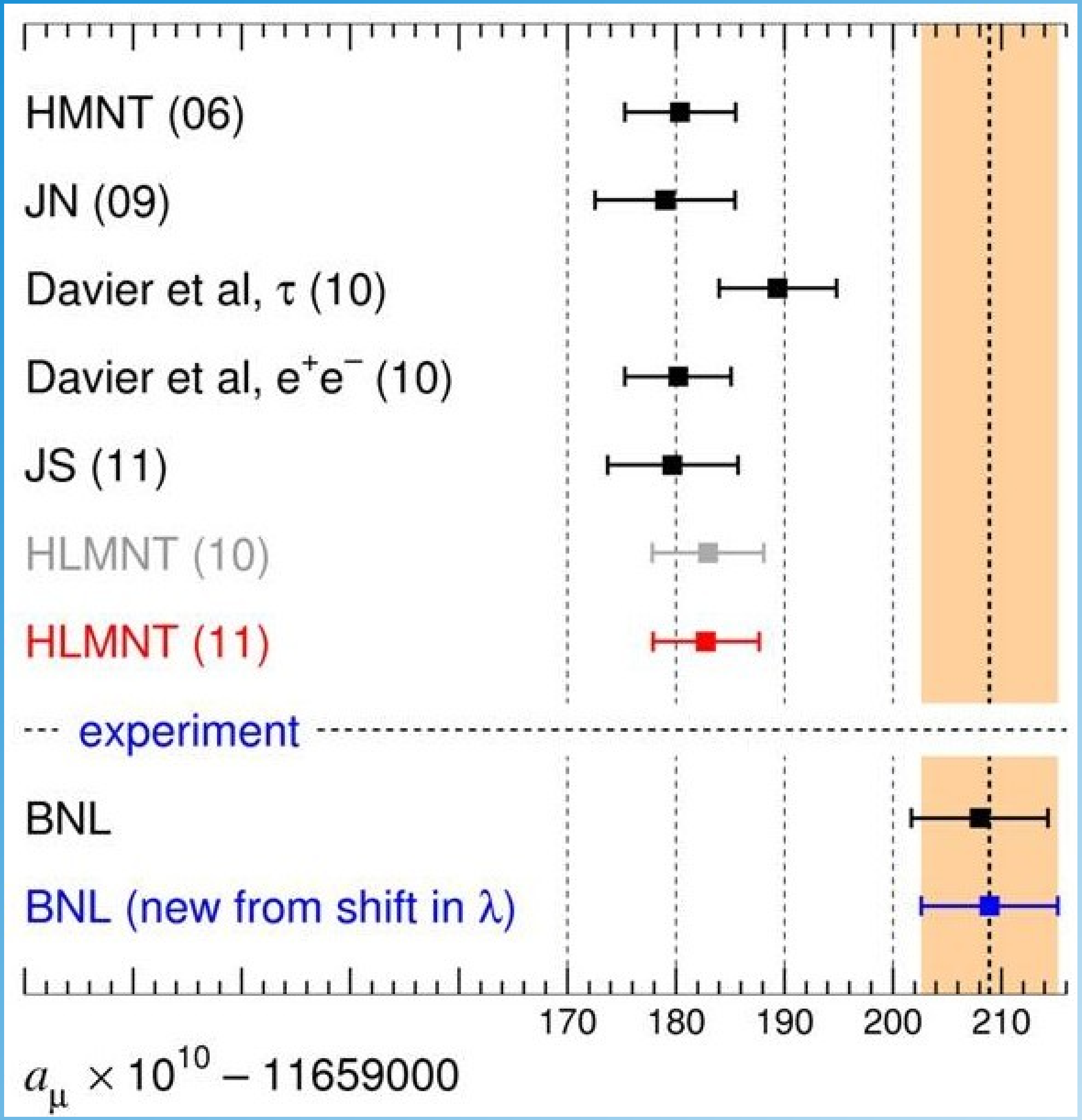
Electroweak corrections:

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

Sum:

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

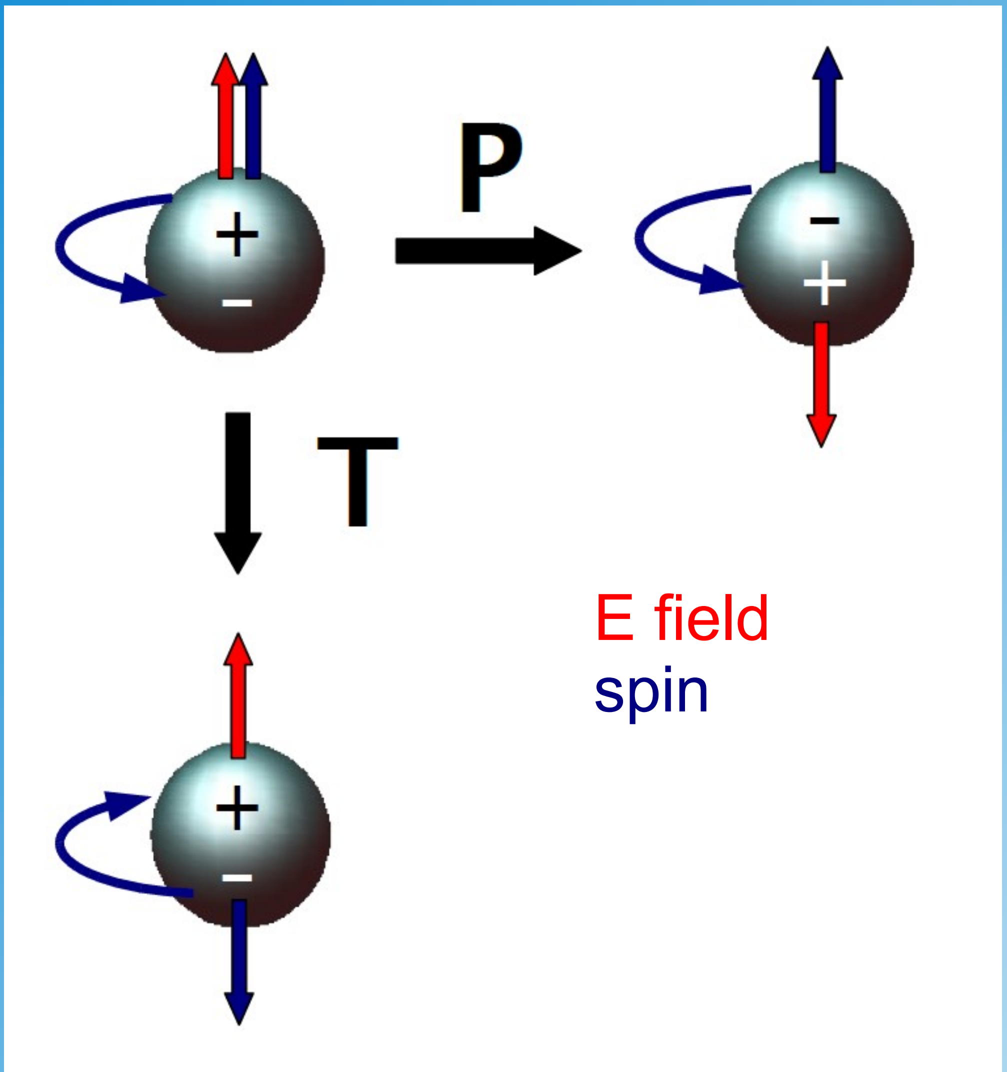
Data-Theory Comparison



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

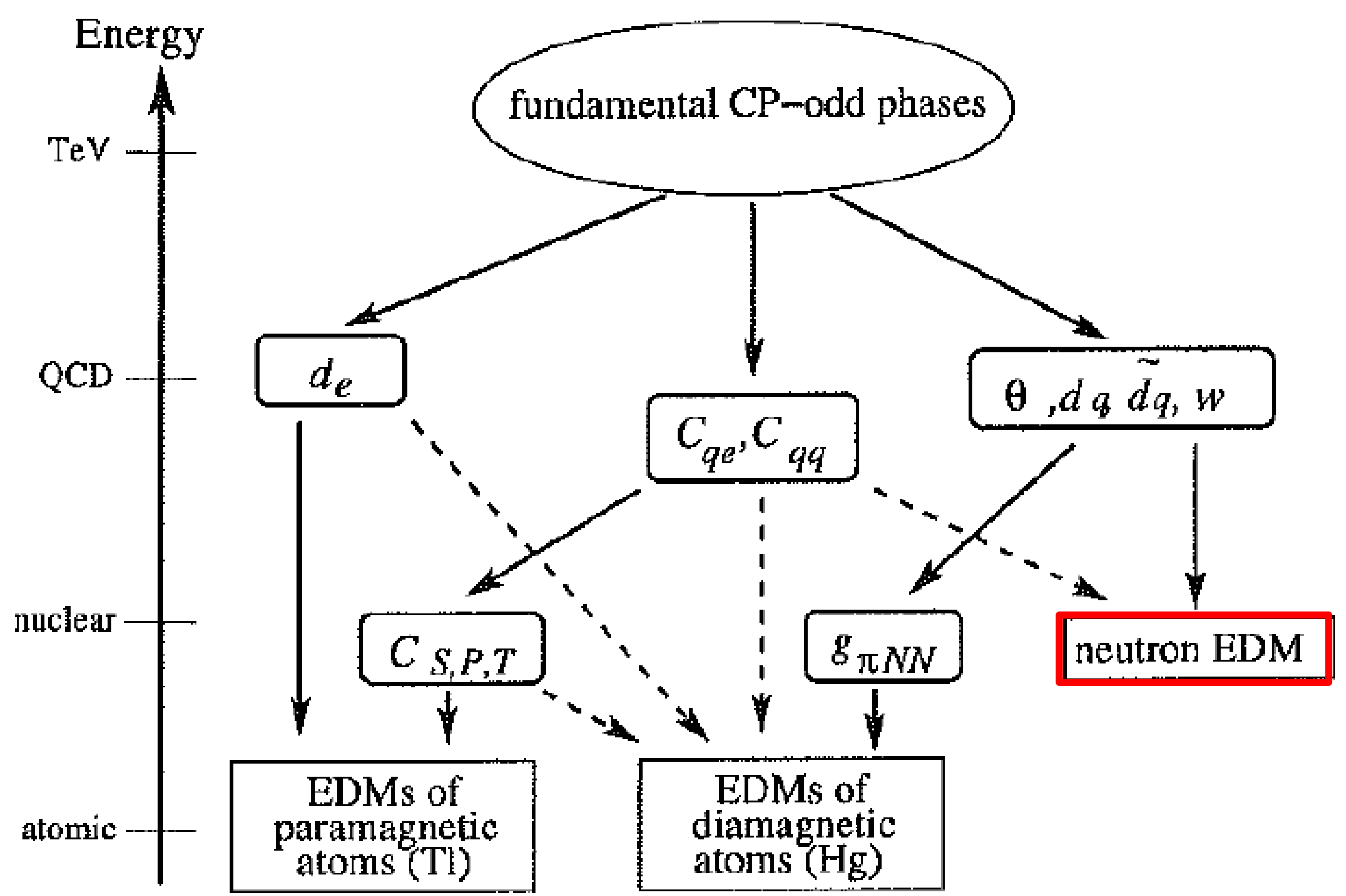
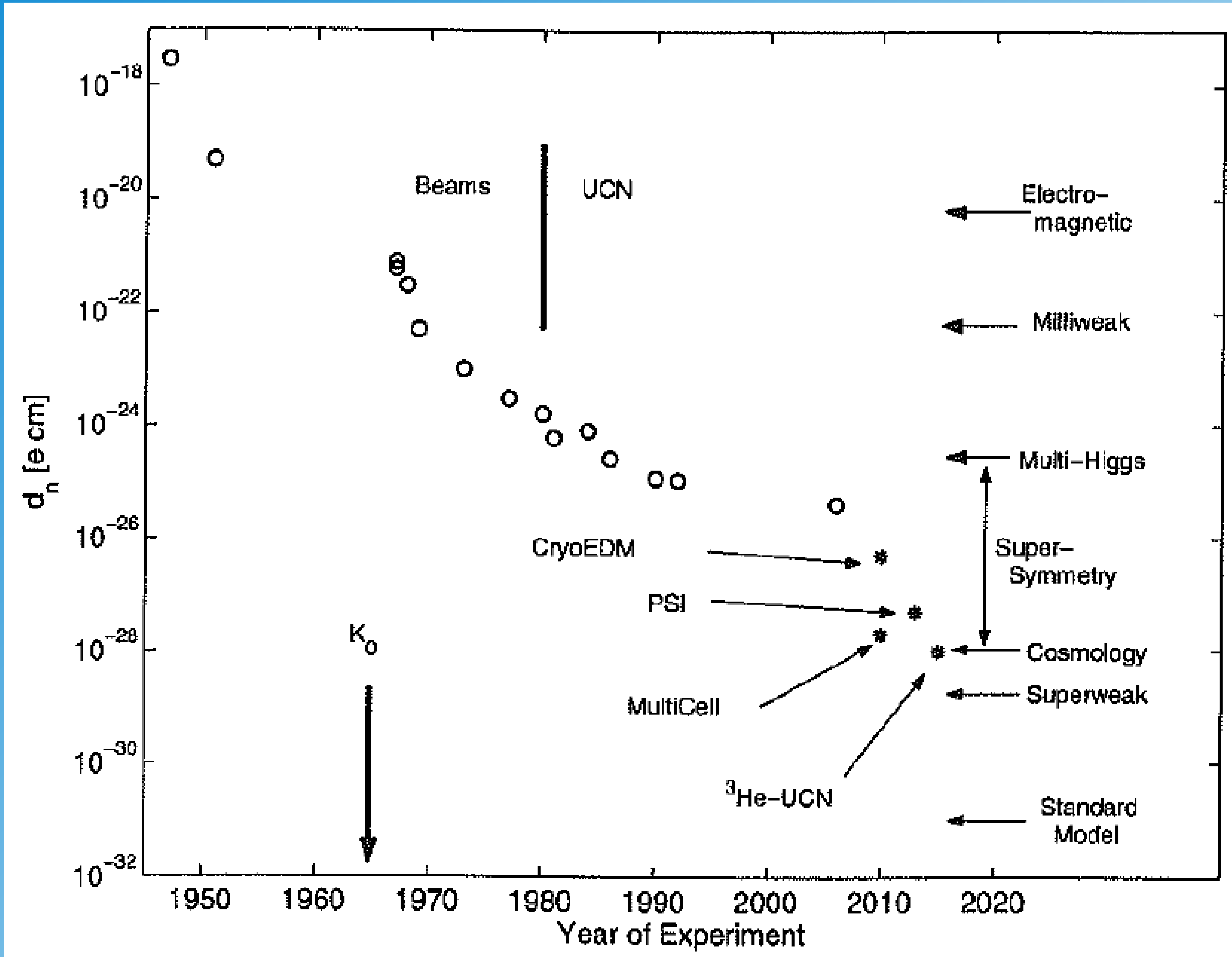


Fig. 13.1. A schematic plot of the hierarchy of scales between the CP-odd sources and three generic classes of observable EDMs. The dashed lines indicate generically weaker dependencies.

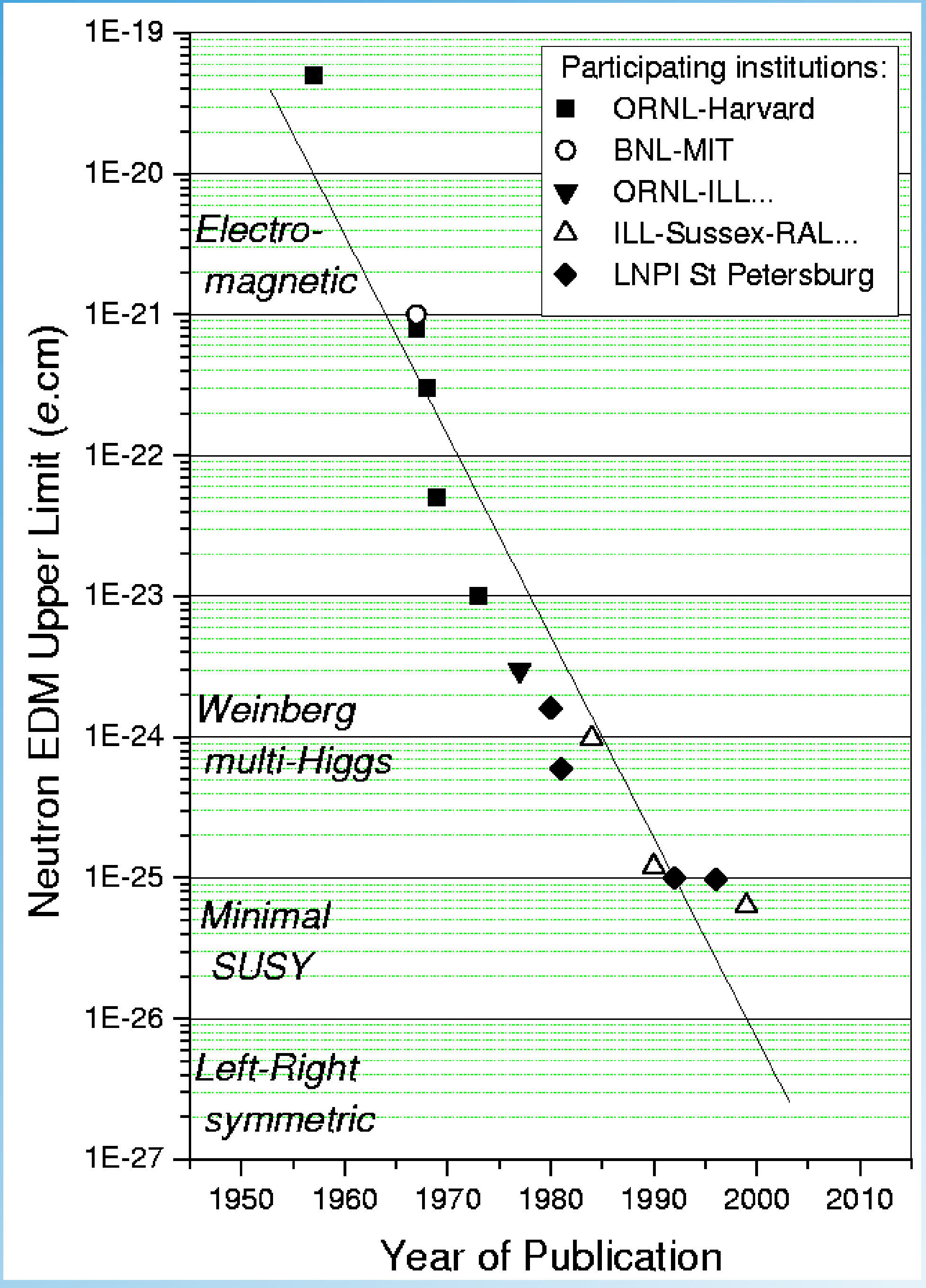
Neutron Electric Dipole Moment



Electric Dipole Moment (EDM)

high sensitivity to New Physics!

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



Summary

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

WS 2016/17

Particle tracking and identification at high rates

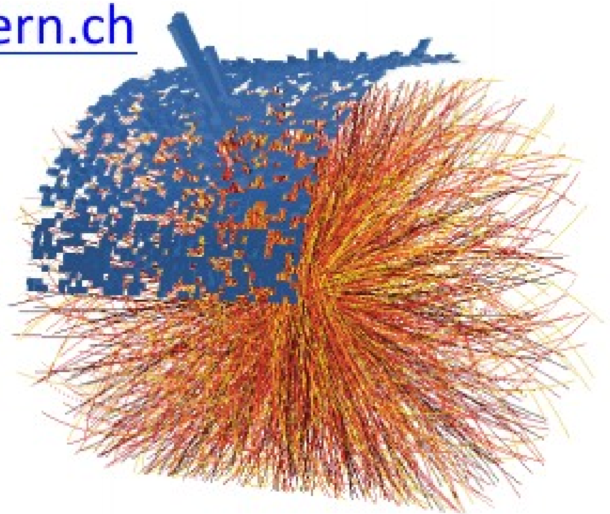
Master Seminar

PD Dr. Silvia Masciocchi, PD Dr. Kai Schweda
Email: s.masciocchi@gsi.de, kschweda@cern.ch

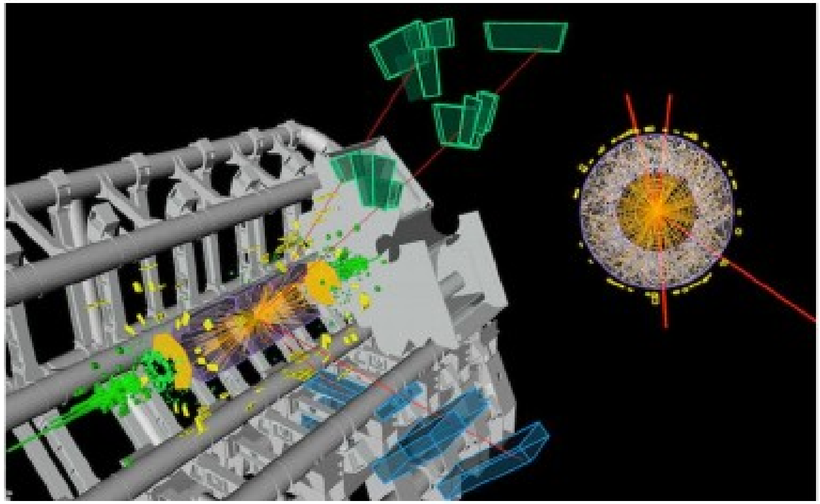
Friday 13:00, INF 226, SR 01.106
21-Oct-2016: assignment of topics

Focus on high rate detectors for applications in the near and the further future, in nuclear and particle physics:

- Monolithic active pixel sensors
- High-rate gaseous detectors
- Ring Imaging Cherenkov detectors
- Electromagnetic and hadronic calorimeters
- Fast readout electronics
- Wireless data and power transfer
- Track and vertex reconstruction



High-multiplicity Pb-Pb collision in ALICE



Higgs boson to 4 muons in ATLAS