Electromagnetic neutrino

theory

laboratory experiments

astrophysical probes

The European Consortium for Astroparticle Theory

Astroneutrino Theory Workshop 2021
Czech Technical University
Prague
20-22/09/2020

Alexander Studenikin

Moscow State University
&
JINR –Dubna

Lecture # 1 (20.09.2021)
Introduction to ν electromagnetic properties

- AS, ν flavor and spin oscillations
- Alexey Lichkunov,
  The interplay of ν flavor and spin oscillations in a magnetic field

Lecture # 2 (21.09.2021)
Electromagnetic ν properties In laboratory experiments and constraints on μ_ν, d_ν, q_ν and $<r^2_\nu>$

- Fyedor Lazarev, Electromagnetic effects in elastic ν scattering on nucleons and nuclei
- Georgy Donchenko, ν magnetic moments in low-energy ν scattering on atomic and condensed matter systems

Lecture # 3 (22.09.2021)
Electromagnetic ν: New effects in magnetic fields and matter

- Vadim Shakhov, ν spin and flavor oscillations in transversal matter currents
- Artem Popov, Majorana ν oscillations in a magnetic field and CP violation
- Konstantin Stankevich, The effect of quantum decoherence in astrophysical ν oscillations

9 presentations at TAUP 2021 dedicated to ν electromagnetic properties and related issues

- 1) A. Studenikin, Electromagnetic neutrino: The theory, laboratory experiments and astrophysical probes, oral presentation # 230
- 2) A.Popov, A.Studenikin, Effects of nonzero Majorana CP phases on oscillations of supernova neutrinos, poster # 231
- 3) K.Stankevich, V.Shakhov, A.Studenikin, Spin and spin-flavor oscillations due to neutrino charge radii interaction with an external environment, poster # 241
- 4) A.Lichkunov, R.Stankevich, A.Studenikin, M.Vialkov, Neutrino quantum decoherence engendered by neutrino decay to photons, familons and gravitons, poster # 242
- 5) V.Shakhov, U.Abdullaeva, A.Studenikin, A.Tsvirov, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 245
- 6) Y.F.Li, Z.Chen, A.Kouzakov, V.Shakhov, K.Stankevich, A.Studenikin, Collective neutrino oscillations in moving and polarized matter, poster # 249
- 7) A.Kouzakov, D.Abeyadira, A.Studenikin, Dirac and Majorana neutrino oscillations in magnetized moving and polarized matter, poster # 266
- 8) G.Donchenko, K.Kouzakov, A.Studenikin, Neutrino magnetic moments in low-energy neutrino scattering on condensed matter systems, poster # 268
- 9) F.Lazarev, K.Kouzakov, A.Studenikin, Electromagnetic effects in elastic neutrino scattering on nucleons and nuclei, poster # 289

Contents

1. introduction to ν electromagnetic properties
2. constraints on μ_ν, d_ν, q_ν and $<r_\nu^2>$ from laboratory experiments
3. effects of electromagnetic ν interactions and astrophysical applications
4. astrophysical probes of electromagnetic ν
5. new effects in ν oscillations related to electromagnetic ν interactions

... two interesting new phenomena in ν spin (flavor) oscillations in moving and polarized mater and magnetic field

Lecture # 1:
Introduction to neutrino electromagnetic properties

The European Consortium for Astroparticle Theory,

Astroneutrino Theory Workshop 2021,
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REVIEWS OF MODERN PHYSICS, VOLUME 87, APRIL–JUNE 2015

Neutrino electromagnetic interactions: A window to new physics

+ upgrade:

Studenikin,
Electromagnetic neutrinos: New constraints and new effects in oscillations,
arXiv: 2102.05468

Electromagnetic interactions: A window to new physics – II,
PoS EPS-HEP2017 (2017) 137

Detailed review and discussion of electromagnetic properties

Carlo Giunti*

INFN, Torino Section, Via P. Giuria 1, I-10125 Torino, Italy

Alexander Studenikin†

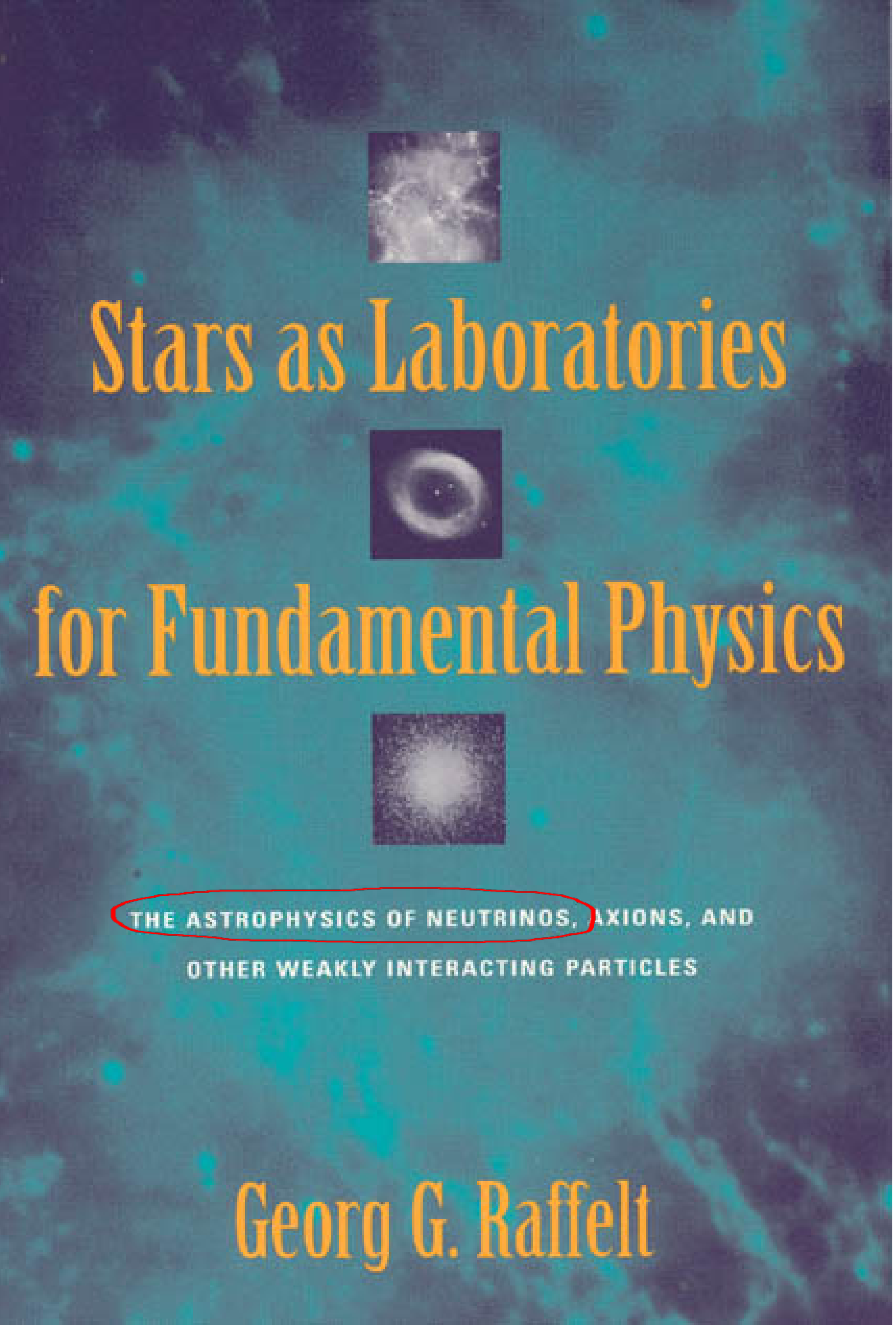
Department of Theoretical Physics, Faculty of Physics, Moscow State University and Joint Institute for Nuclear Research, Dubna, Russia

(published 16 June 2015)

A review is given of the theory and phenomenology of neutrino electromagnetic interactions, which provide powerful tools to probe the physics beyond the standard model. After a derivation of the general structure of the electromagnetic interactions of Dirac and Majorana neutrinos in the one-photon approximation, the effects of neutrino electromagnetic interactions in terrestrial experiments and in astrophysical environments are discussed. The experimental bounds on neutrino electromagnetic properties are presented and the predictions of theories beyond the standard model are confronted.

DOI: 10.1103/RevModPhys.87.531 PACS numbers: 14.60.St, 13.15.+g, 13.35.Hb, 14.60.Lm

CONTENTS



•CONTENTS

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q_ν two very useful papers of the year μ_ν

Hindawi
Advances in High Energy Physics
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Hindawi

Research Article

Constraints on Neutrino Electric Millicharge from Experiments of Elastic Neutrino-Electron Interaction and Future Experimental Proposals Involving Coherent Elastic Neutrino-Nucleus Scattering

A. Parada

Facultad de Ciencias Básicas, Universidad Santiago de Cali, Campus Pampalinda, Calle 5 No. 62-00, 760035 Santiago de Cali, Colombia

Correspondence should be addressed to A. Parada; alexander.parada00@usc.edu.co

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In several extensions of the Standard Model of Particle Physics (SMPP), the neutrinos acquire electromagnetic properties such as the electric millicharge. Theoretical and experimental bounds have been reported in the literature for this parameter. In this work, we first carried out a statistical analysis by using data from reactor neutrino experiments, which include elastic neutrino-electron scattering (ENES) processes, in order to obtain both individual and combined limits on the neutrino electric millicharge (NEM). Then, we performed a similar calculation to show an estimate of the sensitivity of future experiments of reactor neutrinos to the NEM, by involving coherent elastic neutrino-nucleus scattering (CENNS). In the first case, the constraints achieved from the combination of several experiments are $-1.1 \times 10^{-12}e < q_\nu < 9.3 \times 10^{-13}e$ (90% C.L.), and in the second scenario, we obtained the bounds $-1.8 \times 10^{-14}e < q_\nu < 1.8 \times 10^{-14}e$ (90% C.L.). As we will show here, these combined analyses of different experimental data can lead to stronger constraints than those based on individual analysis, where CENNS interactions would stand out as an important alternative to improve the current limits on NEM.

1. Introduction

In the SMPP, the neutrinos are massless, electrically neutral, and only interact weakly with leptons and quarks. Nevertheless, the neutrino oscillation experiments show that neutrinos have mass and are also mixed [1–4]. Hence, the idea of extending the SMPP so as to explain the origin of neutrino mass. Different extensions of SMPP allow the neutrino to have properties such as magnetic and electric dipole moments as well as anapole moment and electric millicharge [5–7]. Even in the Standard Model, it is well-known that the neutrinos also can have nonzero charge radius, as shown in reference [8, 9]. Among these properties, the neutrino magnetic moment (NMM) has been quite studied in several research works, where different experimental constraints to this parameter were obtained, for instance, from reactor neutrino experiments [10–14], solar neutrinos [15, 16], and astrophysical measurements [17, 18]. The limits achieved for the NMM are around $10^{-11}\mu_B$, while the prediction of the simplest extension of the Standard Model, by including right-handed neutrinos, is $3.2 \times 10^{-19}\mu_B$ [19]. Furthermore, considering the representation of three active neutrinos, the magnetic moment is described by a 3×3 matrix whose components are the diagonal and transition magnetic moments. A complete analysis by considering the NMM matrix and using data from solar, reactor, and accelerator experiments was presented in reference [20, 21]. In addition to NMM, the study of the remainder form factors is also important as they are a tool to probe new physics. Among them, the NEM has also been under consideration in the literature, and several constraints have been found mainly from reactor experiments and astrophysical measurements. The most restrictive bound on NEM so far, $q_\nu \lesssim 3.0 \times 10^{-21}e$, was obtained in [18] based on the neutrality of matter. A limit

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The neutrino magnetic moment portal: cosmology, astrophysics, and direct detection

Vedran Brdar,[a] Admir Greljo,[b] Joachim Kopp[b,c] and Toby Opferkuch[b]

[a]Max Planck-Institut für Kernphysik,
Saupfercheckweg 1, 69117 Heidelberg, Germany
[b]Theoretical Physics Department, CERN,
1 Esplanade des Particules, 1211 Geneva 23, Switzerland
[c]PRISMA Cluster of Excellence & Mainz Institute for Theoretical Physics,
Johannes Gutenberg University,
Staudingerweg 7, 55099 Mainz, Germany
E-mail: vbrdar@mpi-hd.mpg.de, admir.greljo@cern.ch, jkopp@cern.ch, toby.opferkuch@cern.ch

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Abstract. We revisit the physics of neutrino magnetic moments, focusing in particular on the case where the right-handed, or sterile, neutrinos are heavier (up to several MeV) than the left-handed Standard Model neutrinos. The discussion is centered around the idea of detecting an upscattering event mediated by a transition magnetic moment in a neutrino or dark matter experiment. Considering neutrinos from all known sources, as well as including all available data from XENON1T and Borexino, we derive the strongest up-to-date exclusion limits on the active-to-sterile neutrino transition magnetic moment. We then study complementary constraints from astrophysics and cosmology, performing, in particular, a thorough analysis of BBN. We find that these data sets scrutinize most of the relevant parameter space. Explaining the XENON1T excess with transition magnetic moments is marginally possible if very conservative assumptions are adopted regarding the supernova 1987 A and CMB constraints. Finally, we discuss model-building challenges that arise in scenarios that feature large magnetic moments while keeping neutrino masses well below 1 eV. We present a successful ultraviolet-complete model of this type based on TeV-scale leptoquarks, establishing links with muon magnetic moment, B physics anomalies, and collider searches at the LHC.

Keywords: cosmology of theories beyond the SM, dark matter detectors, neutrino experiments, particle physics - cosmology connection

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https://doi.org/10.1088/1475-7516/2021/01/039

ν exhibits unexpected properties (puzzles)

W. Pauli, 1930

- neutral "neutron" $\Rightarrow$ ν E.Fermi, 1933
- probably $\mu_\nu \neq 0$!?

Pauli himself wrote to Baade:

"Today I did something a physicist should never do. I predicted something which will never be observed experimentally..."

H.Bethe, R.Peierls,
«The 'neutrino'»
Nature 133 (1934) 532

- «There is no practically possible way of observing the neutrino»

... puzzles ...

- ...up to now absolute value ?

$m_\nu \neq 0$ after 90 years left !

... however ... ⟹

Crucial role of neutrino

ν is a "tiny" particle :

- very light $m_{\nu_f} \ll m_f, \quad f = e, \mu, \tau$
- electrically neutral $q_\nu = 0$? $q_\nu < 4 \times 10^{-17} e$
- with very small magnetic moment μ_ν ?

$\sigma_{\nu_e N} \sim 10^{-39}\ cm^2$ ν-N scattering

$\sigma_{\bar{\nu}_e p} \sim 10^{-40}\ cm^2$ inverse β-decay

$\sigma_{\nu_e e} \sim 10^{-43}\ cm^2$ ν-e scattering

- weak interactions are indeed weak $\bar{\nu} + p \to e^+ + n$ $\sigma \sim 10^{-43}\ cm^2$ $L \sim 10^{15} km$

$E_\nu \sim 3 MeV$ ... free path in water...

at the final stages of development of particular elementary particle physics framework

horizons of new physics

weak interactions are indeed weak … free path in water… $L \sim 10^{15} km$

$$\bar{\nu} + p \to e^{+} + n$$
$$E_{\nu} \sim 3 MeV$$
$$\sigma \sim 10^{-43} \ cm^{2}$$

ν manifests itself most clearly under the influence of

extreme external conditions:

- strong external electromagnetic fields

and

- dense background matter

... problem and puzzle ...

ν electromagnetic properties

up to now nothing has been seen

... in spite of reasonable efforts ...

- results of terrestrial lab experiments on μ_ν (and ν EM properties in general)
- as well as data from astrophysics and cosmology

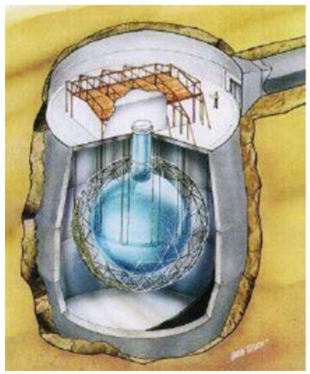
are in agreement with "ZERO" ν EM properties

... However, in course of recent development of knowledge on ν mixing and oscillations,

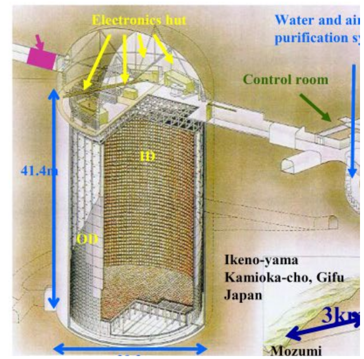
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



$$m_\nu \neq 0$$

ν electromagnetic properties (flash on theory)

... Why ν electromagnetic properties are important ?

...Why ν em properties

to new physics ?

... How does it all relate to ν oscillations ?

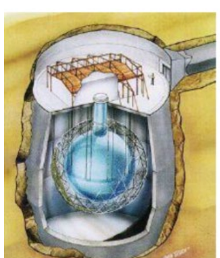
$\Longrightarrow$ $m_\nu \neq 0$ •

magnetic moment $\mu_\nu \neq 0$ •

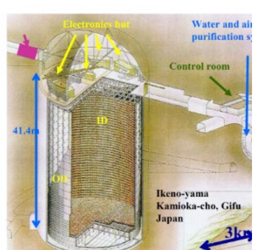
Arthur McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita



«for the discovery of neutrino oscillations, which shows that neutrinos have mass»



in Standard Model

• $m_\nu = 0$!!!

In the easiest generalization of SM

$$\mu_{ii}^{D} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\left(\frac{m_i}{1\ \mathrm{eV}}\right)\mu_B$$

if $m_i \sim 1\ eV$ ⟸ KATRIN limit

then $\mu_{ii}^{D} \sim 3.2\times 10^{-19}\mu_B$!

K.Fujikawa, R.Shrock, Phys.Rev.Lett. 45 (1980) 963

many orders of magnitude smaller than present experimental limits:

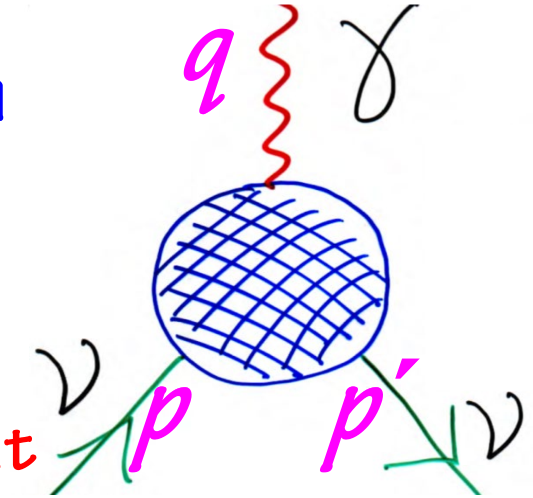
- $\mu_\nu \sim 10^{-11}\mu_B$ reactor ν limits GEMMA 2012
- $\mu_\nu \sim 10^{-11} \div 10^{-12}\mu_B$ astrophysical (ν_{solar} and ν_{SN}) limits
  Borexino 2017

μ_ν is no less extravagant than possibility of $q_\nu \neq 0$

- limitations imposed by general principles of any theory are very strict
- $q_\nu \leq 3\times 10^{-21} e$ from neutrality of hydrogen atom
- much weaker constraints are imposed by astrophysics

... a bit of ν electromagnetic properties theory ...

ν electromagnetic vertex function



$$< \psi(p')|J_{\mu}^{EM}|\psi(p) >= \bar{u}(p')\Lambda_{\mu}(q,l)u(p)$$

Matrix element of electromagnetic current is a Lorentz vector

$\Lambda_{\mu}(q,l)$ should be constructed using

matrices $\hat{\mathbf{1}}, \quad \gamma_5, \quad \gamma_{\mu}, \quad \gamma_5\gamma_{\mu}, \quad \sigma_{\mu\nu},$

tensors $g_{\mu\nu}, \quad \epsilon_{\mu\nu\sigma\gamma}$

vectors q_{μ} and l_{μ}

$$q_{\mu} = p'_{\mu} - p_{\mu}, \; l_{\mu} = p'_{\mu} + p_{\mu}$$

Lorentz covariance (1)
and electromagnetic
gauge invariance (2) $\Longrightarrow$

Vertex function $\Lambda_\mu(q,l)$ $\Longrightarrow$ there are three sets of operators:

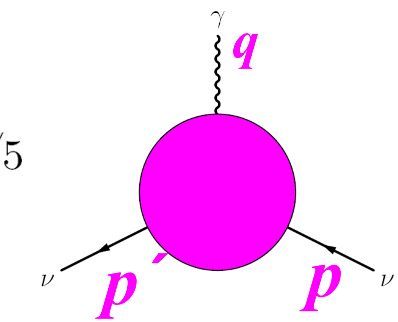
- $\hat{\mathbf{1}} q_\mu, \quad \hat{\mathbf{1}} l_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 l_\mu$

  $\not{q} q_\mu, \quad \not{l} q_\mu, \quad \gamma_5 q_\mu, \quad \gamma_5 \not{q} q_\mu, \quad \gamma_5 \not{l} q_\mu, \quad \sigma_{\alpha\beta} q^\alpha l^\beta q_\mu, \quad \{q_\mu \leftrightarrow l_\mu\}$

- $\gamma_\mu, \quad \gamma_5 \gamma_\mu, \quad \sigma_{\mu\nu} q^\nu, \quad \sigma_{\mu\nu} l^\nu .$

- $\epsilon_{\mu\nu\sigma\gamma} \sigma^{\alpha\beta} q^\nu, \quad \epsilon_{\mu\nu\sigma\gamma} \sigma^{\alpha\beta} l^\nu, \quad \epsilon_{\mu\nu\sigma\gamma} \sigma^{\nu\beta} q_\beta q^\sigma l^\gamma,$

  $\epsilon_{\mu\nu\sigma\gamma} \sigma^{\nu\beta} l_\beta q^\sigma l^\gamma, \quad \epsilon_{\mu\nu\sigma\gamma} \gamma^\nu q^\sigma l^\gamma \hat{\mathbf{1}}, \quad \epsilon_{\mu\nu\sigma\gamma} \gamma^\nu q^\sigma l^\gamma \gamma_5$



✓ vertex function (using Gordon-like identities)

$$\Lambda_\mu(q,l) = f_1(q^2) q_\mu + f_2(q^2) q_\mu \gamma_5 + f_3(q^2) \gamma_\mu + f_4(q^2) \gamma_\mu \gamma_5 + f_5(q^2) \sigma_{\mu\nu} q^\nu + f_6(q^2) \epsilon_{\mu\nu\rho\gamma} \sigma^{\rho\gamma} q^\nu ,$$

the only dependence on q^2 remains because $p^2 = p'^2 = m^2$, $l^2 = 4m^2 - q^2$

Gordon-like identities

$$\bar{u}(\mathbf{p}_1)\gamma^\mu u(\mathbf{p}_2) = \frac{1}{2m}\bar{u}(\mathbf{p}_1)[l^\mu + i\sigma^{\mu\nu}q_\nu]u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)\gamma^\mu\gamma_5 u(\mathbf{p}_2) = \frac{1}{2m}\bar{u}(\mathbf{p}_1)[\gamma_5 q^\mu + i\gamma_5\sigma^{\mu\nu}l_\nu]u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}l_\nu u(\mathbf{p}_2) = -\bar{u}(\mathbf{p}_1)q^\nu u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}q_\nu u(\mathbf{p}_2) = \bar{u}(\mathbf{p}_1)[2m\gamma^\mu l^\mu]u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)i\sigma^{\mu\nu}\gamma_5 q_\nu u(\mathbf{p}_2) = -\bar{u}(\mathbf{p}_1)l^\mu\gamma_5 u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)[\epsilon^{\alpha\mu\nu\beta}\gamma_5\gamma_\beta q_\mu l_\nu]u(\mathbf{p}_2) = \bar{u}(\mathbf{p}_1)\{-i[q^\alpha \not{l} - l^\alpha \not{q}] + i(q^2 - 4m^2)\gamma^\alpha + 2im(l^\alpha + q^\alpha)\}u(\mathbf{p}_2)$$

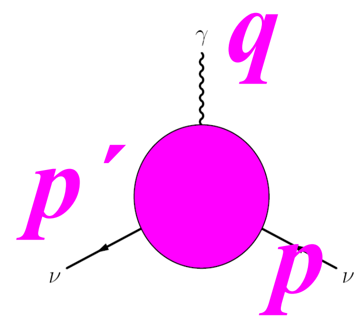
$$\bar{u}(\mathbf{p}_1)[\epsilon^{\alpha\mu\nu\beta}\gamma_\beta q_\mu l_\nu]u(\mathbf{p}_2) = \bar{u}(\mathbf{p}_1)\{i[q^\alpha \not{l} - l^\alpha \not{q}]\gamma_5 + iq^2\gamma_5\gamma^\alpha - 2im(l^\alpha + q^\alpha)\gamma_5\}u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\gamma_\nu\gamma_5]u(\mathbf{p}_2) = \frac{i}{2m}\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\sigma_{\nu\rho}q^\rho]u(\mathbf{p}_2)$$

$$\bar{u}(\mathbf{p}_1)[\epsilon^{\mu\nu\alpha\beta}q_\alpha l_\beta\sigma_{\nu\rho}l^\rho]u(\mathbf{p}_2) = 0$$

Electromagnetic gauge invariance (2)

(requirement of current conservation)



$$\partial_\mu j^\mu = 0$$

$$f_1(q^2)q^2 + f_2(q^2)q^2\gamma_5 + 2m f_4(q^2)\gamma_5 = 0,$$

$$f_1(q^2) = 0, \qquad f_2(q^2)q^2 + 2m f_4(q^2) = 0$$

vertex function

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

charge

dipole electric and magnetic

anapole

4 Form Factors

... consistent with
Lorentz-covariance (1)
+
electromagnetic gauge invariance (2)

Matrix element of electromagnetic current between neutrino states

$$\langle \nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)$$

where vertex function generally contains 4 form factors

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu - f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

1. electric
2. magnetic dipole
3. electric dipole
4. anapole

- Hermiticity and discrete symmetries of EM current J_μ^{EM} put constraints on form factors

Dirac ν

1) CP invariance + Hermiticity ⟹ $f_E = 0$,
2) at zero momentum transfer only electric Charge $f_Q(0)$ and magnetic moment $f_M(0)$ contribute to $H_{int} \sim J_\mu^{EM} A^\mu$
3) Hermiticity itself ⟹ three form factors are real: $Im f_Q = Im f_M = Im f_A = 0$

!

Majorana ν

1) from CPT invariance (regardless CP or ~~CP~~).

$$f_Q = f_M = f_E = 0$$

…as early as 1939, W.Pauli …

- EM properties ⟹ a way to distinguish Dirac and Majorana ν

In general case matrix element of $J_\mu^{\rm EM}$ can be considered between different initial $\psi_i(p)$ and final $\psi_j(p')$ states of different masses

$$< \psi_j(p')|J_\mu^{EM}|\psi_i(p) >= \bar{u}_j(p')\Lambda_\mu(q)u_i(p)$$

$p^2 = m_i^2, \; p'^2 = m_j^2$:

… beyond SM…

and

$$\Lambda_\mu(q) = \Big(f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5\Big)(q^2\gamma_\mu - q_\mu \not{q}) + f_M(q^2)_{ij} i\sigma_{\mu\nu}q^\nu + f_E(q^2)_{ij}\sigma_{\mu\nu}q^\nu\gamma_5$$

form factors are matrices in ν mass eigenstates space

Dirac ν (off-diagonal case $i \neq j$) Majorana ν

Dirac ν

1) Hermiticity itself does not apply restrictions on form factors

2) CP invariance + Hermiticity

$f_Q(q^2), \; f_M(q^2), \; f_E(q^2), \; f_A(q^2)$

are relatively real (no relative phases)

Majorana ν

1) CP invariance + hermiticity

$\mu_{ij}^M = 2\mu_{ij}^D$ and $\epsilon_{ij}^M = 0$ or

$\mu_{ij}^M = 0$ and $\epsilon_{ij}^M = 2\epsilon_{ij}^D$

… quite different EM properties …

Effective Lagrangian for the spin component of ν vertex

$$L = \frac{1}{2}\bar{\nu}_j \sigma_{\eta\xi}(\beta_{ij} + \varepsilon_{ij}\gamma_5)\nu_i F^{\eta\xi} + \text{h.c.}\,,$$

… beyond beyond SM…

em field tensor

magnetic and electric moments which couple together mass eigenstates $(\nu_i)_L$ and $(\nu_j)_R$ ⇒ change of the helicity states

- $\nu_i = \nu_j$ ➡ diagonal moments
- $\nu_i \neq \nu_j$ ➡ transitional moments
- $\varepsilon_{ii} = \beta_{ii} = 0$ for Majorana ν

EM properties
a way to distinguish Dirac and Majorana ν

... importance of μ_ν studies...

If diagonal $\mu_\nu \neq 0$ were confirmed then ν^{Dirac}

... for $\nu^{Majorana}$ non-diagonal = transitional $\mu_\nu \neq 0$

... progress in experimental studies of μ_ν $\Longrightarrow$

... two remarks ...

Difference between electromagnetic vertex function of massive and massless

For $m_\nu = 0$ left-handed ν

$$\bar{u}(p')\Lambda_\mu(q)u(p) = f_D(q^2)\bar{u}(p')\gamma_\mu(1+\gamma_5)u(p)$$

- electric charge $f_Q(q^2)$ and anapole $f_A(q^2)$ form factors are related to Dirac form factor (and to each other):

$$f_Q(q^2) = f_D(q^2), \quad f_A(q^2) = f_D(q^2)/q^2$$

- In case $m_\nu \neq 0$ there is no such simple relation (because term $q_\mu \not{q}\gamma_5$ in anapole FF cannot be neglected)

ν form factors in gauge models

$$< \psi_j(p')|J_\mu^{EM}|\psi_i(p) >= \bar{u}_j(p')\Lambda_\mu(q)u_i(p)$$

- Form Factors at zero momentum transfer $q^2 = 0$ are elements of scattering matrix → in any consistent theoretical model FF in matrix element → gauge independent and finite

...therefore...

FF at $q^2 = 0$ determine static properties of ν that can be probed (measured) in direct interaction with external em fields

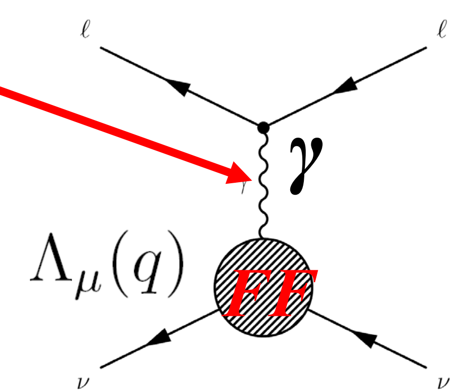
This is the case for $f_Q(q^2),\ f_M(q^2),\ f_E(q^2)$ in minimally extended SM ($f_A(q^2)$ is an exceptional case)

- In non-Abelian gauge models, FF at $q^2 \neq 0$ can be not invariant under gauge transformation because (in general) off-shell photon propagator is gauge dependent !

... One-photon approximation is not enough to get physical quantity...

... FF in matrix element cannot be directly measured in experiment with em field ...

... FF can contribute to higher order processes accessible for experimental observation



Dipole magnetic $f_M(q^2)$ and electric $f_E(q^2)$

are most well studied and theoretically understood among form factors

...because in the limit $q^2 \to 0$ they have nonvanishing values

$$\mu_\nu = f_M(0)$$ ← ν magnetic moment

$$\epsilon_\nu = f_E(0)$$ ← ν electric moment ???

. . . a bit more on ν electromagnetic properties theory

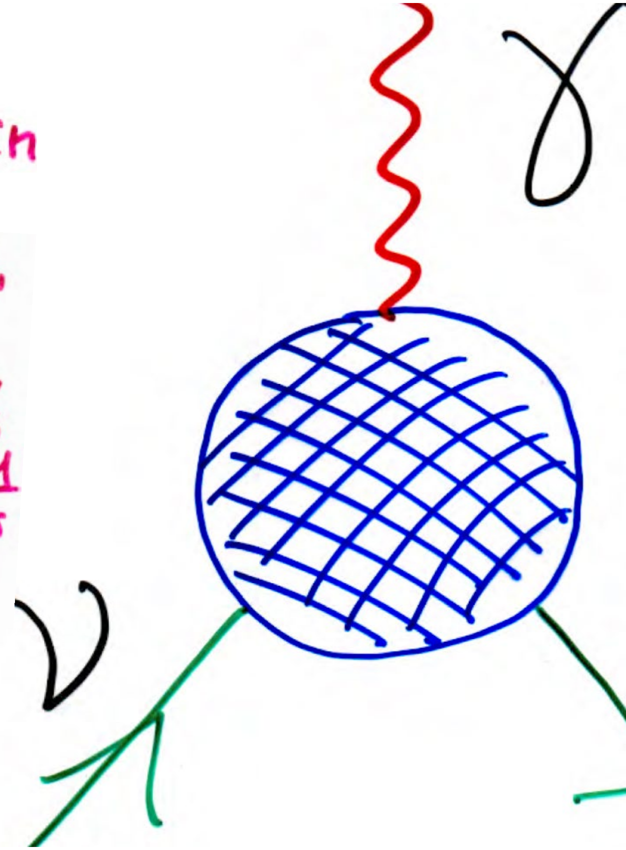
(em properties in gauge models)

ν vertex function

The most general study of the **massive neutrino** vertex function (including electric and magnetic form factors) in arbitrary R_ξ gauge in the context of the SM + SU(2)-singlet ν_R accounting for masses of particles in polarization loops

M. Dvornikov, A. Studenikin

* Phys. Rev. D 63, 073001, 2004, "Electric charge and magnetic moment of massive neutrino";
JETP 126 (2004), N8, 1
* "Electromagnetic form factors of a massiv neutrino."



R_ξ-gauge and $(q^2 \neq 0)$

charge — magnetic moment

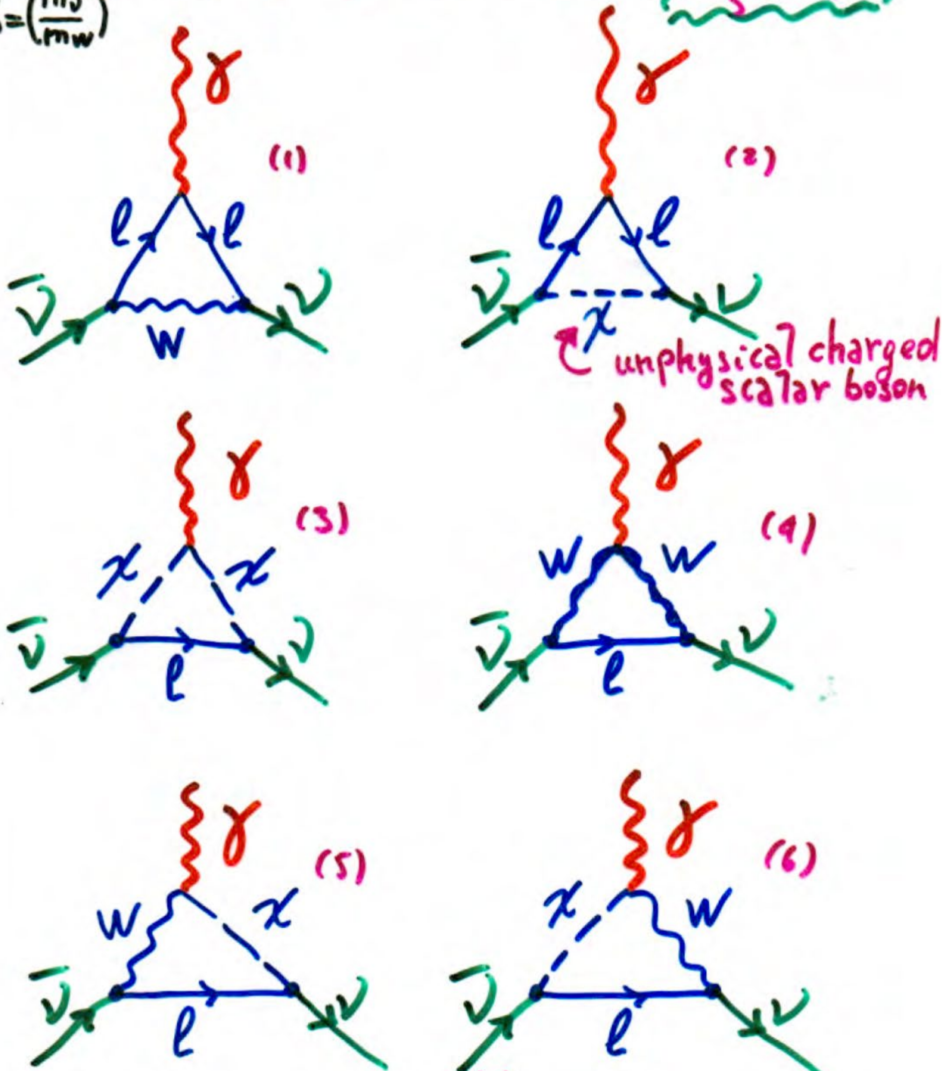
$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)\, i\sigma_{\mu\nu} q^\nu - f_E(q^2)\, i\sigma_{\mu\nu} q^\nu \gamma_5 - f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

electric moment — anapole moment

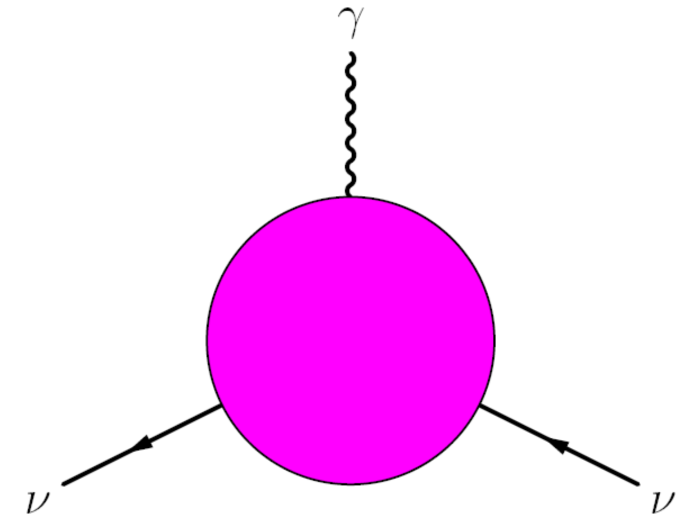
$a=\left(\frac{m_\ell}{m_W}\right)^2,$

$b=\left(\frac{m_\nu}{m_W}\right)^2$

Proper vertices R_ξ-gauge



$$\Lambda_\mu(q)=\sum_{i=1}^{14}\Lambda_\mu^i(q)$$



$$\Lambda_\mu(q)$$

Contributions of proper vertices diagrams

(dimensional-regularization scheme)

- $$\Lambda_\mu^{(1)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\left[g^{\kappa\lambda}-(1-\alpha)\frac{k^\kappa k^\lambda}{k^2-\alpha M_W^2}\right]\times\frac{\gamma_\kappa^L(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)\gamma_\lambda^L}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-M_W^2]},$$

- $$\Lambda_\mu^{(2)} = i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}\frac{(m_\nu P_L-m_\ell P_R)(\not{p}\,'-\not{k}+m_\ell)\gamma_\mu(\not{p}-\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-m_\ell^2][(p-k)^2-m_\ell^2][k^2-\alpha M_W^2]},$$

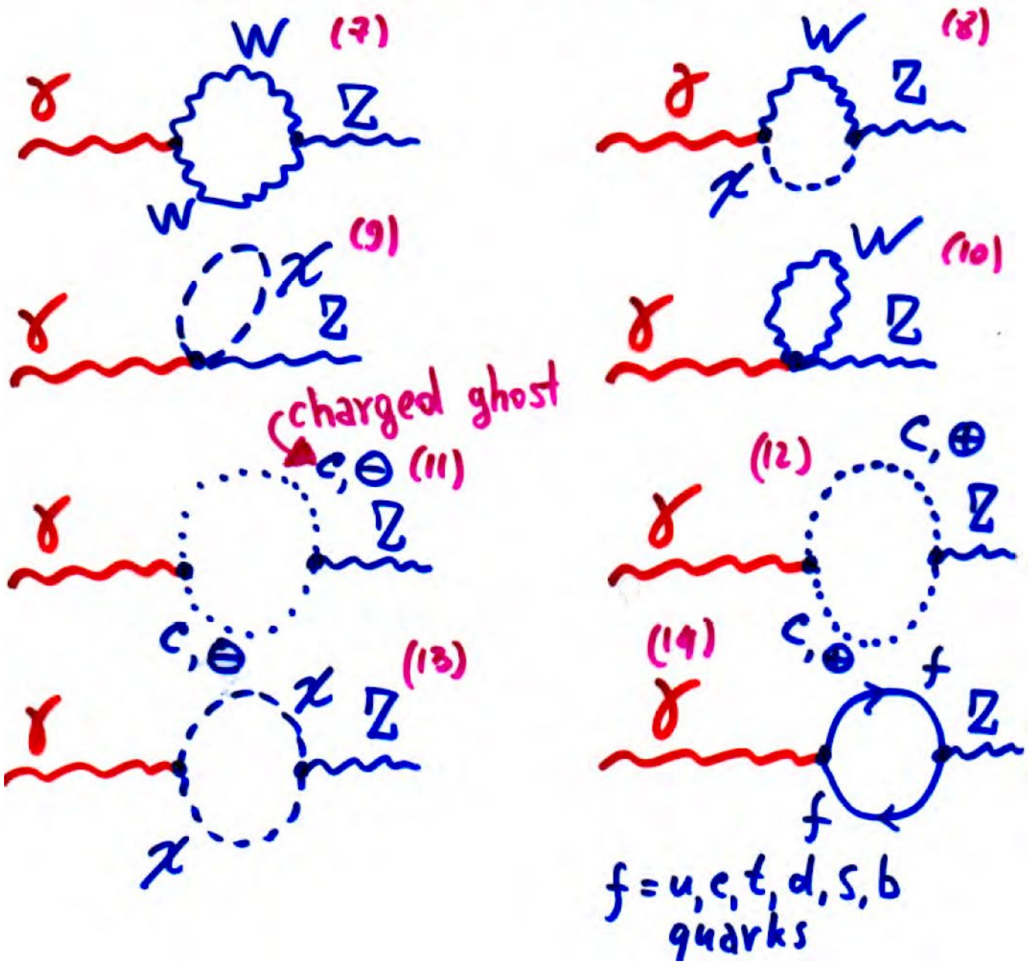
- $$\Lambda_\mu^{(3)} = i\frac{eg^2}{2M_W^2}\int\frac{d^Nk}{(2\pi)^N}(2k-p-p')_\mu\frac{(m_\nu P_L-m_\ell P_R)(\not{k}+m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-\alpha M_W^2][k^2-m_\ell^2]},$$

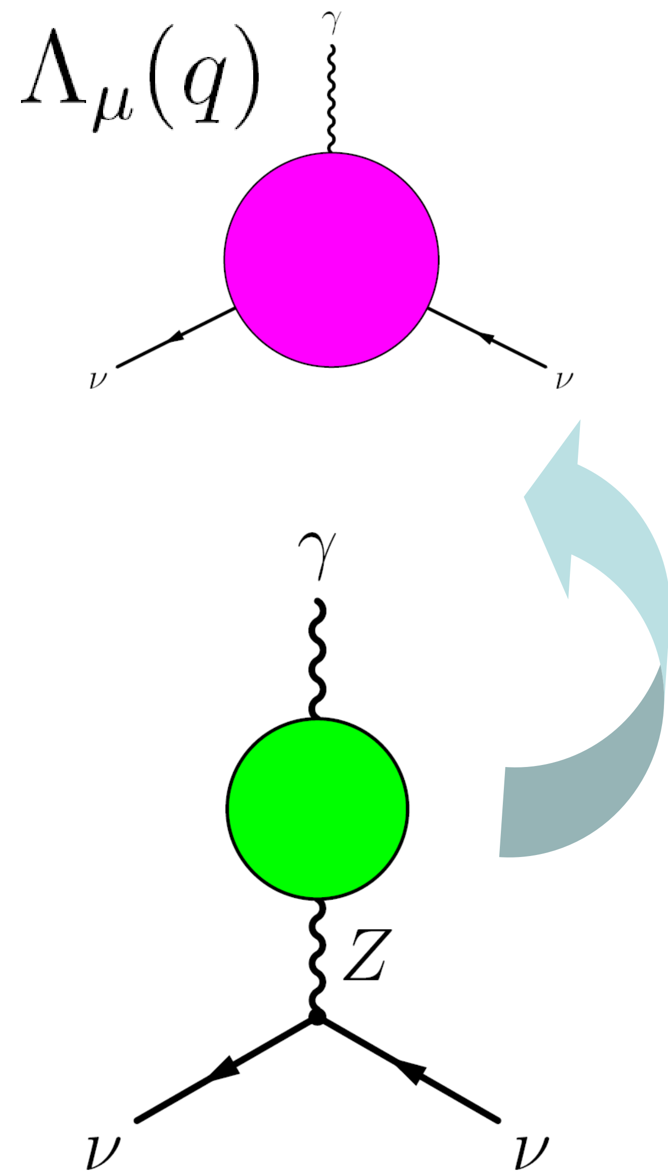
- $$\Lambda_\mu^{(4)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}\gamma_\kappa^L(\not{k}+m_\ell)\gamma_\lambda^L\left[\delta_\beta^\kappa-(1-\alpha)\frac{(p'-k)^\kappa(p'-k)_\beta}{(p'-k)^2-\alpha M_W^2}\right]\left[\delta_\gamma^\lambda-(1-\alpha)\frac{(p-k)^\lambda(p-k)_\gamma}{(p-k)^2-\alpha M_W^2}\right]$$
$$\times\frac{\delta_\mu^\beta(2p'-p-k)^\gamma+g^{\beta\gamma}(2k-p-p')_\mu+\delta_\mu^\gamma(2p-p'-k)^\beta}{[(p'-k)^2-M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]},$$

- $$\Lambda_\mu^{(5)+(6)} = i\frac{eg^2}{2}\int\frac{d^Nk}{(2\pi)^N}$$
$$\times\left\{\frac{\gamma_\beta^L(\not{k}-m_\ell)(m_\ell P_L-m_\nu P_R)}{[(p'-k)^2-M_W^2][(p-k)^2-\alpha M_W^2][k^2m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p'-k)^\beta(p'-k)_\mu}{(p'-k)^2-\alpha M_W^2}\right]\right.$$
$$\left.-\frac{(m_\nu P_L-m_\ell P_R)(\not{k}-m_\ell)\gamma_\beta^L}{[(p'-k)^2-\alpha M_W^2][(p-k)^2-M_W^2][k^2-m_\ell^2]}\left[\delta_\mu^\beta-(1-\alpha)\frac{(p-k)^\beta(p-k)_\mu}{(p-k)^2-\alpha M_W^2}\right]\right\}$$

$$\Lambda^{j}_{\mu}(q) = \frac{g}{2\cos\theta_W}\,\Pi^{(j)}_{\mu\nu}(q)\,\frac{1}{q^2 - M_Z^2} \times \left\{ g^{\nu\alpha} - (1-\alpha_Z)\frac{q^\nu q^\alpha}{q^2 - \alpha_Z M_Z^2} \right\} \gamma^4_\alpha, \; j=7,\dots,14$$

γ-Z self-energy diagrams





γ − Z self-energy diagrams

Direct calculations of complete set of one-loop contributions to ν vertex function in minimally extended SM

(for a massive Dirac neutrino)

M.Dvornikov, A.Studenikin
PRD, 2004

… in case CP conservation

- $\Lambda_\mu(q) \Longrightarrow f_Q(q^2),\ f_M(q^2),\ f_E(q^2),\ f_A(q^2)$

- Electric charge $f_Q(0) = 0$ and is gauge-independent

- Magnetic moment $f_M(0)$ finite and gauge-independent

- Gauge and q×q dependence … $\Longrightarrow$

ν

Magnetic moment dependence

$$\mu_\nu = \mu_\nu(m_\nu)$$

on neutrino mass

3.2

Calculation of ν magnetic moment (massive ν , arbitrary R_ξ - gauge)

Dvornikov, Studenikin
PRD 2004

$$\Lambda_\mu(q)=f_Q(q^2)\gamma_\mu+f_M(q^2)i\sigma_{\mu\nu}q^\nu-f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5+f_A(q^2)(q^2\gamma_\mu-q_\mu \not{q})\gamma_5$$

magnetic moment

$$\mu(a,b,\alpha)=f_M(q^2=0)$$

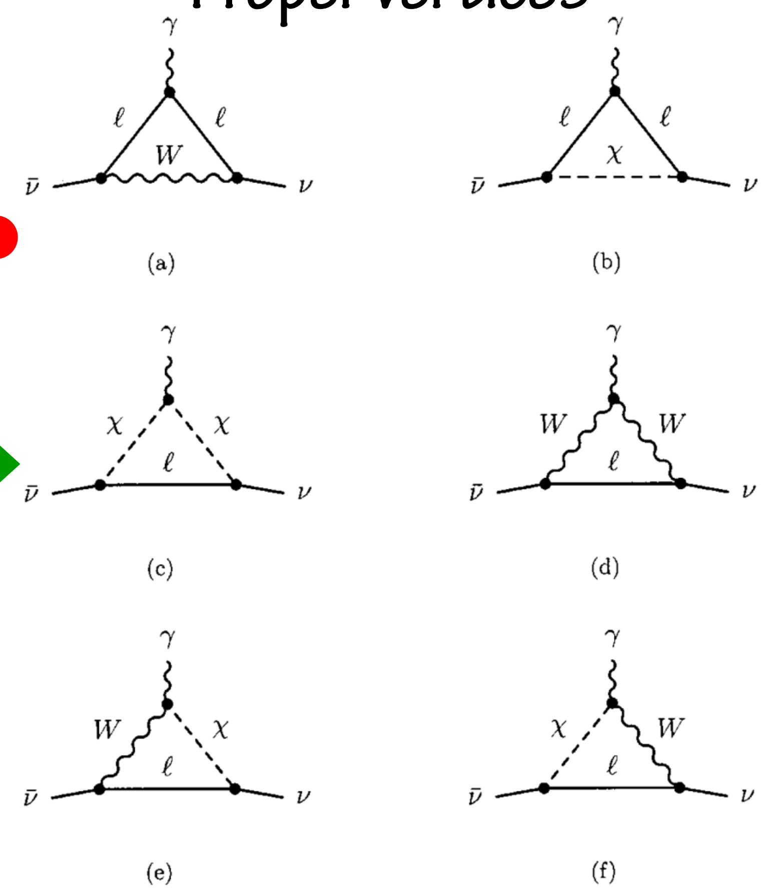
two mass parameters $a=\left(\frac{m_\ell}{M_W}\right)^2$ $b=\left(\frac{m_\nu}{M_W}\right)^2$

$$\mu(a,b,\alpha)=\sum_{i=1}^{6}\mu^{(i)}(a,b,\alpha)$$

and gauge-fixing parameter $\alpha=\frac{1}{\xi}$

$\xi=0$ - unitary gauge, $\xi=1$ - 't Hooft-Feynman gauge

Proper vertices

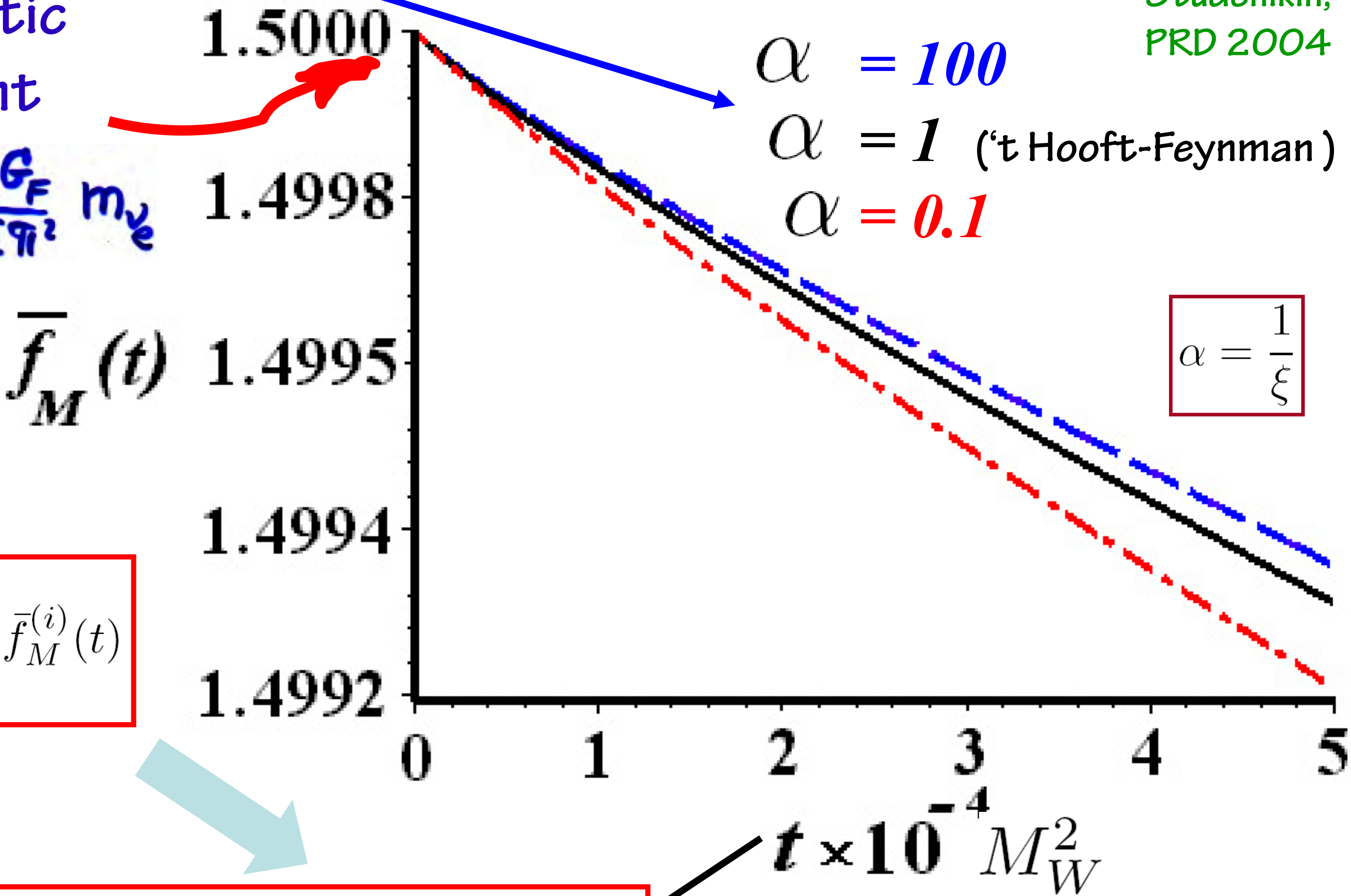


⟹ Gauge and q×q dependence …

Dvornikov, Studenikin, PRD 2004

ν magnetic moment

● $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$



$$\alpha = \frac{1}{\xi}$$

$$\bar{f}_M(t) = \sum_{i=1}^{6} \bar{f}_M^{(i)}(t)$$

$$f_M(q^2) = \frac{eG_F}{4\pi^2\sqrt{2}} m_\nu \sum_{i=1}^{6} \bar{f}_M^{(i)}(q^2)$$

ν dipole magnetic form factor

$m_\nu \ll m_e \ll M_W$ **light** ν

$\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e}$

$$\mu_\nu = \frac{eG_F m_\nu}{4\pi^2\sqrt{2}} \frac{3}{4(1-a)^3}(2 - 7a + 6a^2 - 2a^2 \ln a - a^3) \qquad a = \left(\frac{m_e}{M_W}\right)^2$$

Dvornikov, Studenikin, Phys.Rev.D 69 (2004) 073001; JETP 99 (2004) 254

Gabral-Rosetti, Bernabeu, Vidal, Zepeda, Eur.Phys.J C 12 (2000) 633

$m_e \ll m_\nu \ll M_W$ **intermediate** ν

$$\mu_\nu = \frac{3eG_F m_\nu}{8\pi^2\sqrt{2}} \left\{1 + \frac{5}{18} b\right\} \qquad b = \left(\frac{m_\nu}{M_W}\right)^2$$

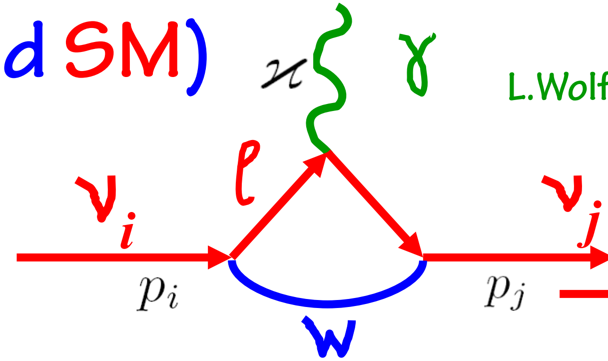
$m_e \ll M_W \ll m_\nu$ **heavy** ν

$$\mu_\nu = \frac{eG_F m_\nu}{8\pi^2\sqrt{2}}$$

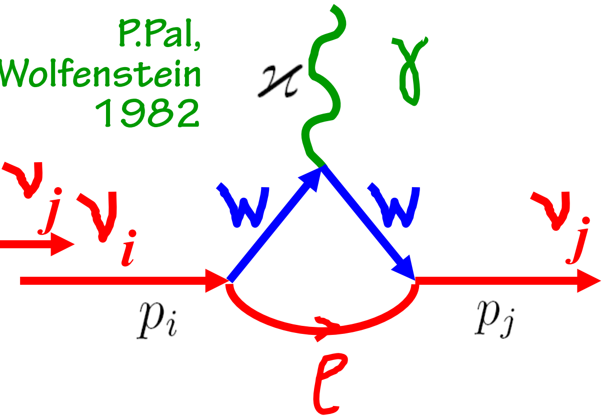
$\sim 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1\,eV}\right)$

. . . μ_ν in case of mixing . . . $\Longrightarrow$

Neutrino (beyond SM) dipole moments (+ transition moments)



P.Pal, L.Wolfenstein 1982



- **Dirac neutrino**

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\sum_{l=\,e,\,\mu,\,\tau} f(r_l)U_{lj}U^*_{li}$$

$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

$m_e = 0.5\ MeV$
$m_\mu = 105.7\ MeV$
$m_\tau = 1.78\ GeV$
$m_W = 80.2\ GeV$

- $m_i, m_j \ll m_l, m_W$

$$f(r_l) \approx \frac{3}{2}\left(1 - \frac{1}{2}r_l\right), \quad r_l \ll 1$$

transition moments vanish because unitarity of U implies that its rows or columns represent orthogonal vectors

- **transition moments are suppressed, Glashow – Iliopoulos - Maiani cancellation,**
- **for diagonal moments there is no GIM cancellation**

- **Majorana neutrino only for** $i \neq j$

$$\mu^M_{ij} = 2\mu^D_{ij} \quad and \quad \epsilon^M_{ij} = 0$$

or

$$\mu^M_{ij} = 0 \quad and \quad \epsilon^M_{ij} = 2\epsilon^D_{ij}$$

… depending on relative CP phase of ν_i and ν_j

The first nonzero contribution from neutrino transition moments

$$f_{r_l} \to -\frac{3}{2} + \frac{3}{4}\left(\frac{m_l}{m_W}\right)^2 \ll 1$$

GIM cancellation

$$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = \frac{3eG_F m_i}{32\sqrt{2}\pi^2}\left(1 \pm \frac{m_j}{m_i}\right)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{l=e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

$$\mu_B = \frac{e}{2m_e}$$

- $$\left.\begin{matrix}\mu_{ij}\\ \epsilon_{ij}\end{matrix}\right\} = 4\times 10^{-23}\mu_B\left(\frac{m_i \pm m_j}{1\ eV}\right)\sum_{l=e,\ \mu,\ \tau}\left(\frac{m_l}{m_\tau}\right)^2 U_{lj}U_{li}^*$$

… neutrino radiative decay is very slow

- Dirac ν diagonal (i=j) magnetic moment

$\epsilon_{ii}^D = 0$ for CP-invariant interactions

$\mu_{ii}^M = \epsilon_{ii}^M = 0$

$$\mu_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2}\left(1 - \frac{1}{2}\sum_{l=e,\mu,\tau} r_l \mid U_{li}\mid^2\right) \approx 3.2\times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

$$r_l = \left(\frac{m_l}{m_W}\right)^2$$

Lee, Shrock, Fujikawa, 1977

- no GIM cancellation
- μ_{ii}^D - to leading order - independent on U_{li} and $m_{l=e,\ \mu,\ \tau}$
- $$\mu_e^2 = \sum_{i=1,2,3} \mid U_{ie}\mid^2 \mu_{ii}^2$$

…possibility to measure fundamental μ_{ii}^D

$\mu_{ii}^D = 0$ for massless ν (in the absence of right-handed charged currents)

...the present status...

to have visible $m_\nu \neq 0$

is not an easy task for

theoreticians

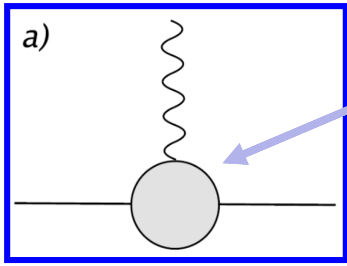
and experimentalists

3.3 Naïve relationship between m_ν and μ_ν

... problem to get large μ_ν and still acceptable m_ν

If μ_ν is generated by physics beyond the SM at energy scale Λ,

P. Vogel e.a., 2006

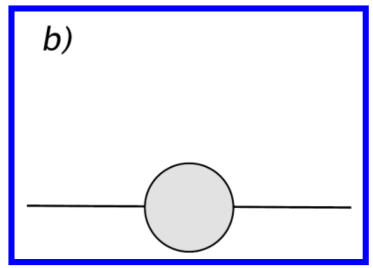


then

$$\mu_\nu \sim \frac{eG}{\Lambda},$$

...combination of constants and loop factors...

contribution to m_ν given by



, then

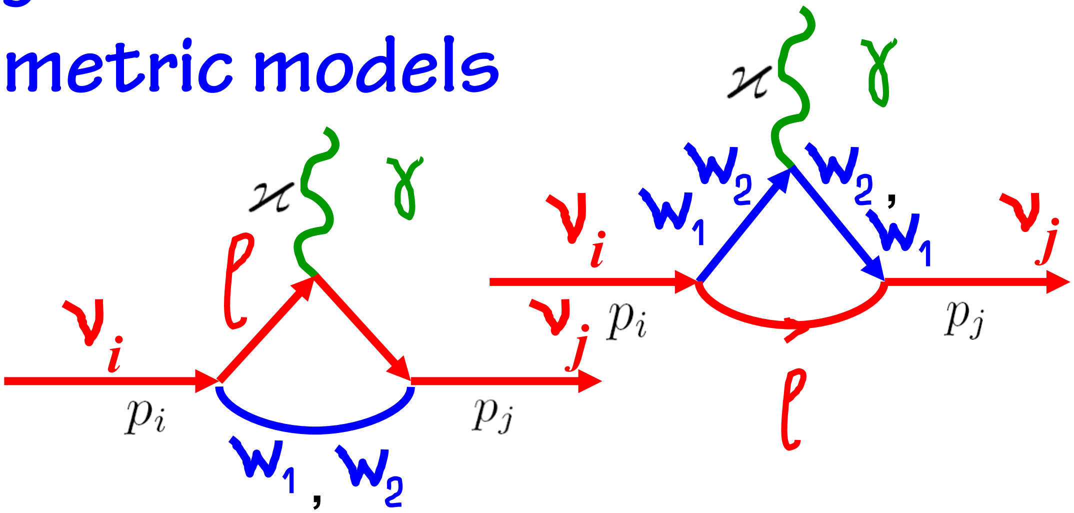
$$m_\nu \sim G\Lambda$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}[\Lambda(\mathrm{TeV})]^2 \quad \mathrm{eV}$$

Voloshin, 1988;
Barr, Freire,
Zee, 1990

3.6 Neutrino magnetic moment in left-right symmetric models

$SU_L(2) \times SU_R(2) \times U(1)$



Gauge bosons mass states $W_1 = W_L \cos\xi - W_R \sin\xi$

$W_2 = W_L \sin\xi + W_R \cos\xi$

with mixing angle ξ **of gauge bosons** $W_{L,R}$ **with pure** $(V \pm A)$ **couplings**

Kim, 1976; Marciano, Sanda, 1977
Beg, Marciano, Ruderman, 1978

$$\mu_{\nu_l} = \frac{eG_F}{2\sqrt{2}\pi^2}\left[m_l\left(1 - \frac{m^2_{W_1}}{m^2_{W_2}}\right)\sin 2\xi + \frac{3}{4}m_{\nu_l}\left(1 + \frac{m^2_{W_1}}{m^2_{W_2}}\right)\right]$$

… charged lepton mass … … neutrino mass …

Large magnetic moment $\mu_\nu = \mu_\nu(m_\nu, m_{B^+}, m_{e^-})$

- In the L-R symmetric models $(SU(2)_L \times SU(2)_R \times U(1))$ — Kim, 1976; Beg, Marciano, Ruderman, 1978
- Voloshin, 1988
  "On compatibility of small m_ν with large μ_ν of neutrino",
  Sov.J.Nucl.Phys. 48 (1988) 512
  … there may be $SU(2)_\nu$ symmetry that forbids m_ν but not μ_ν

Z.Z.Xing, Y.L.Zhou,
"Enhanced electromagnetic transition dipole moments and radiative decays of massive neutrinos due to the seesaw-induced non-unitary effects"
Phys.Lett.B 715 (2012) 178

- Bar, Freire, Zee, 1990
- supersymmetry
- extra dimensions
- model-independent constraint μ_ν

considerable enhancement of μ_ν to experimentally relevant range

$\mu_\nu^D \leq 10^{-15}\mu_B$

$\mu_\nu^M \leq 10^{-14}\mu_B$

for BSM ($\Lambda \sim 1\ \mathrm{TeV}$) without fine tuning and under the assumption that $\delta m_\nu \leq 1\ \mathrm{eV}$

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise, 2005

... A remark on electric charge of ν ...

Beyond Standard Model

ν neutrality $Q=0$ is attributed to

gauge invariance
+
anomaly cancellation constraints

imposed in SM of electroweak interactions

- ...General proof:

In SM : $SU(2)_L \times U(1)_Y$

$$Q = I_3 + \frac{Y}{2}$$

Foot, Joshi, Lew, Volkas, 1990;
Foot, Lew, Volkas, 1993;
Babu, Mohapatra, 1989, 1990
Foot , He (1991)

In SM (without ν_R) triangle anomalies cancellation constraints → certain relations among particle hypercharges that is enough to fix all Y so that they, and consequently Q, are quantized → $Q=0$

- $Q=0$ is proven also by direct calculation in SM within different gauges and methods

Bardeen, Gastmans, Lautrup, 1972;
Cabral-Rosetti, Bernabeu, Vidal, Zepeda, 2000;
Beg, Marciano, Ruderman, 1978;
Marciano, Sirlin, 1980; Sakakibara, 1981;
- Dvornikov, Studenikin, 2004 (for SM in one-loop calculations)

- ... Strict requirements for Q quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with Y = 0 are included : in the absence of Y quantization electric charges Q gets dequantized → **millicharged ν**

ν charge radius and anapole moment

$$\Lambda_\mu(q)=f_Q(q^2)\gamma_\mu+f_M(q^2)i\sigma_{\mu\nu}q^\nu-f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5+f_A(q^2)(q^2\gamma_\mu-q_\mu\not{q})\gamma_5$$

electric — magnetic — dipole electric — anapole

Although it is usually assumed that ν are electrically neutral (charge quant. Implies $Q\sim\frac{1}{3}e$), ν can be characterized by two ± charge distributions

$$f_Q(q^2)=f_Q(0)+q^2\frac{df_Q}{dq^2}(0)+\cdots,$$ and $f_Q(q^2)\neq 0\ for\ q^2\neq 0$ even for electric charge $f_Q(0)=0$

ν charge radius is introduced as $\langle r_\nu^2\rangle=+6\frac{df_Q}{dq^2}(0)$

- … it is often claimed for SM massless ν anapole moment $a_\nu=f_A(q^2)=\frac{1}{6}\langle r_\nu^2\rangle$? ? ?

to be correct ⟹

- for two-component massless left-handed Weyl spinors of SM

$$\Lambda^{Q,A}_{\mathrm{SM}\mu}(q)=(\gamma_\mu q^2-q_\mu\not{q})\mathfrak{f}^{\mathrm{SM}}(q^2)$$

$$\mathfrak{f}^{\mathrm{SM}}(q^2)=\tilde{\mathfrak{f}}_Q(q^2)-\mathfrak{f}_A(q^2)\underset{q^2\to 0}{\longrightarrow}\frac{\langle r^2\rangle}{6}-\mathfrak{a}$$

Giunti, Studenikin Rev.Mod.Phys.2015

… in SM charge radius and anapole moment are not defined separately …

Interpretation of charge radius as an observable is rather delicate issue: $\langle r_\nu^2\rangle$ represents a correction to tree-level electroweak scattering amplitude between ν and charged particles, which receives radiative corrections from several diagrams (including γ exchange) to be considered simultaneously ⟶ calculated CR is infinite and gauge dependent quantity. For ν with m=0, $\langle r_\nu^2\rangle$ and a_ν can be defined (finite and gauge independent) from scattering cross section.

Bernabeu, Papavassiliou, Vidal, Nucl.Phys. B 680 (2004) 450

? ? ? For massive ν ? ? ?

The definition of the neutrino charge radius follows an analogy with the elastic electron scattering off a static spherically symmetric charged distribution of density $\rho(r)$ ($r = |\mathbf{x}|$), for which the differential cross section is determined [79–81] by the point particle cross section $\frac{d\sigma}{d\Omega}|_{point}$,

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{|point} |f(q^2)|^2, \tag{90}$$

where the correspondent form factor $f(q^2)$ in the so-called *Breit frame*, in which $q_0 = 0$, can be expressed as

$$f(q^2) = \int \rho(r) e^{i\mathbf{qx}} d^3x = 4\pi \int dr r^2 \rho(r) \frac{\sin(qr)}{qr}, \tag{91}$$

here $q = |\mathbf{q}|$. Thus, one has

$$\frac{df_Q}{dq^2} = \int \rho(r) \frac{qr\cos(qr) - \sin(qr)}{2q^{3/2}r} d^3x. \tag{92}$$

In the case of small q, we have $\lim_{q^2 \to 0} \frac{qr\cos(qr)-\sin(qr)}{2q^{3/2}r} = -\frac{r^2}{6}$ and

$$f(q^2) = 1 - |\mathbf{q}|^2 \frac{\langle r^2 \rangle}{6} + \ \dots \ . \tag{93}$$

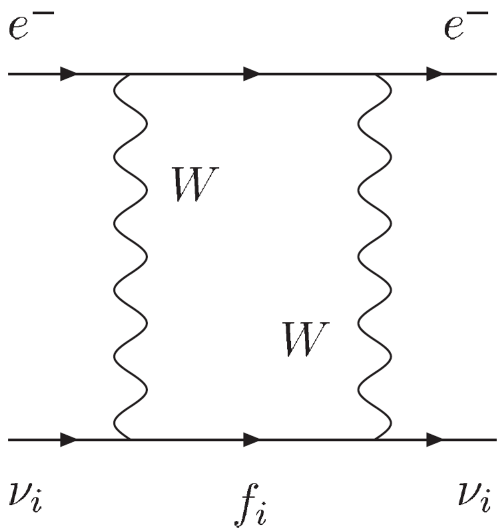
Therefore, the neutrino charge radius (in fact, it is the charge radius squared) is usually defined by

$$\boxed{\langle r_\nu^2 \rangle = -6 \frac{df_Q(q^2)}{dq^2}|_{q^2=0}.} \tag{94}$$

Since the neutrino charge density is not a positively defined quantity, $\langle r_\nu^2 \rangle$ can be negative.

To obtain ν electroweak radius as physical (finite, not divergent) quantity

Bernabeu, Papavassiliou, Vidal, 2004



$$\langle r^2_{\nu_i} \rangle = \frac{G_F}{4\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m_i^2}{m_W^2}\right)\right] \qquad i = e, \mu, \tau$$

$$\langle r^2_{\nu_e} \rangle = 4 \times 10^{-33}\,\mathrm{cm}^2$$

Contribution of box diagram to

$$\nu_l + l' \to \nu_l + l'.$$

…contribution to ν - e scattering experiments through

$$g_V \to \frac{1}{2} + 2\sin^2\theta_W + \frac{2}{3} m_W^2 \langle r^2_{\nu_e} \rangle \sin^2\theta_W$$

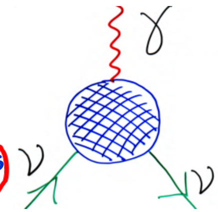
… theoretical predictions and present experimental limits are in agreement within one order of magnitude…

(1) Electromagnetic Properties of ν

MSU Alexander Studenikin JINR

Giunti, Studenikin, " ν electromagnetic interactions: A window to new physics", Rev.Mod.Phys, 2015

Studenikin, "Electromagnetic ν properties: New constraints and new effects", arXiv: 2102.05468



(1) νEP theory - ν vertex function

matrices in ν mass eigenstates space

$$\Lambda_\mu^{if}(q) = f_Q^{if}(q^2)\gamma_\mu + f_M^{if}(q^2) i\sigma_{\mu\nu}q^\nu + f_E^{if}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A^{if}(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5,$$

form factors $f_X^{if}(q^2)$ at $q^2 = 0$ static EP of ν ⇒

electric charge
magnetic moment
electric moment
anapole moment

⇐

Dirac	ν	Majorana	
q_{if}, μ_{if}, ε_{if}, a_{if}	≠ 0	$q_{if} = 0$, μ_{if} $(i \neq f)$, ε_{if} $(i \neq f)$, a_{if}	CPT + charge concervation

Hermiticity and discrete symmetries of EM current $\langle\nu(p')|J_\mu^{EM}|\nu(p)\rangle = \bar{u}(p')\Lambda_\mu(q)u(p)$ put constraints on form factors

(2) $$\mu_{jj}^D = \frac{3e_0 G_F m_j}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\mu_B \left(\frac{m_j}{1\ \mathrm{eV}}\right)$$

Fujikawa & Shrock, 1980

- much greater values are Beyond Minimally Extended SM
- transition moments $\mu_{i\neq f}$, $\varepsilon_{i\neq f}$ are GIM suppressed

(3) ν EMP experimental bounds

$$\mu_\nu^{eff} < 2.8 \times 10^{-11} \mu_B$$
(2.9, ~0.1)

GEMMA 2012
Borexino 2017 ~ XENON1T 2020
astrophys., Raffelt ea 1988, 2020
Arcoa Dias ea 2015

$q_{\nu_e} <$ ~ 10^{-12}, ~ 10^{-19}, ~ 10^{-21} e_0

reactor ν scattering: AS '14, Chen ea '14
AS '14 (astrophysics)
neutrality of matter

- charge rad. $\langle r_\nu^2 \rangle$ is most accessible for exp. observations

The end of Lecture # 1

Participants discussion # 1.2: Neutrino oscillations in vacuum, matter and spin oscillations in magnetic field

Alexander Studenikin

Moscow State University

&

JINR -Dubna

The European Consortium for Astroparticle Theory

Astroneutrino Theory Workshop 2021

Czech Technical University

Prague, 20/09/2020

Бруно Понтекорво

if $m_\nu \neq 0$

then

$\nu \leftrightarrow \bar{\nu}$

In vacuum

Bruno Pontecorvo,

«Mesonium and anti-mesonium»,

Sov.Phys.JETP 6 (1957) 429

Zh.Eksp.Teor.Fiz. 33 (1957) 549-551:

«It was assumed above that there exists a conservation law for the neutrino charge, according to which a neutrino cannot change into an antineutrino in any approximation. This law has not yet been established; evidently it has been merely shown that the neutrino and antineutrino are not identical particles.

If the two-component neutrino theory should turn out to be incorrect ... and if the conservation law of neutrino charge would not apply, then in principle neutrino – antineutrino transitions could take place in vacuo»

Бруно Понтекорво

Staff member at
Faculty of Physics of
Moscow State University,
1966 - 1986

if $m_\nu \neq 0$

then $\nu \leftrightarrow \bar{\nu}$

in vacuum

Bruno Pontecorvo,
«Inverse β processes and nonconcervation of leptonic charge»,
JINR Preprint P-95, Dubna, 1957,
3 pages :

64 years of mixing and oscillations !

«Neutrinos in vacuum can transform themselves into antineutrino and vice versa. This means that neutrino and antineutrino are particle mixtures...
So, for example, a beam of neutral leptons from a reactor which at first consists mainly of antineutrinos will change its composition and at a certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities».

Main steps in ν oscillations

1. $\nu_e \overset{vac}{\longleftrightarrow} \bar{\nu}_e$, B. Pontecorvo, 1957
2. $\nu_e \overset{vac}{\longleftrightarrow} \nu_\mu$, Z. Maki, M. Nakagava, S. Sakata, 1962
3. $\nu_e \overset{matter,\ \rho = const}{\longleftrightarrow} \nu_\mu$, L. Wolfenstein, 1978
4. $\nu_e \overset{matter,\ \rho \neq const}{\longleftrightarrow} \nu_\mu$, S. Mikheev, A. Smirnov, 1985

- resonances in ν flavour oscillations $\Rightarrow$ MSW-effect, solution for $\nu_\odot$ - problem

5. $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}$, A. Cisneros, 1971; M. Voloshin, M. Vysotsky, L. Okun, 1986, $\nu_\odot$
6. $\nu_{e_L} \overset{B_\perp}{\longleftrightarrow} \nu_{e_R}, \nu_{\mu_R}$, E. Akhmedov, 1988; C.-S. Lim & W. Marciano, 1988

- resonances in ν spin (spin-flavour) oscillations in matter

64 years!

Bruno Pontecorvo
1913-1993

only in $B_\perp$ and matter at rest

* Neutrino oscillations in vacuum

B. Pontecorvo (1957)

(1) Flavour states, ν_e, ν_μ, are linear combinations of the mass states, ν_1, ν_2

Z. Maki
M. Nakagawa
S. Sakata
(1962)

$$\nu_e = \nu_1 \cos\theta_V + \nu_2 \sin\theta_V$$

$$\nu_\mu = -\nu_1 \cos\theta_V + \nu_2 \sin\theta_V ,$$

flavour states → $\nu^{(f)}$; physical states → $\nu^{(p)}$

$$\nu^{(f)} = U \nu^{(p)} , \quad \nu^{(f)} = \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \quad \nu^{(p)} = \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_V & \sin\theta_V \\ -\sin\theta_V & \cos\theta_V \end{pmatrix}$$

PMNS matrix

* Time evolution of ν beam

(vacuum mixing angle

V. Gribov, B. Pontecorvo (1969)

S. Bilenky, B. Pontecorvo (1976)

Probability of finding ν_μ in an initial ν_e beam

$$* \quad P_{\nu_e \nu_\mu}(x) = |\langle \nu_\mu | \nu_e \rangle_t|^2 = \sin^2 2\theta_\nu \sin^2\left(\frac{\pi x}{L_\nu}\right),$$

$$L_\nu = \frac{4\pi E}{|m_1^2 - m_2^2|}, \quad (E \simeq |\vec{p}|),$$

4 ν spin and spin-flavour oscillations in $B_\perp$

Consider two different neutrinos: $\nu_{e_L}, \quad \nu_{\mu_R}, \quad m_L \neq m_R$

with magnetic moment interaction

$$L \sim \bar{\nu}\sigma_{\lambda\rho}F^{\lambda\rho}\nu\ ' = \bar{\nu}_L\sigma_{\lambda\rho}F^{\lambda\rho}\nu_R\ ' + \bar{\nu}_R\sigma_{\lambda\rho}F^{\lambda\rho}\nu_L\ '.$$

Twisting magnetic field $B = |\mathbf{B}_\perp|e^{i\phi(t)}$ (for solar ν etc ...)

ν evolution equation

$$i\frac{d}{dt}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix} = H\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}$$

$$H = \begin{pmatrix} E_L & \mu_{e\mu}Be^{-i\phi} \\ \mu_{e\mu}Be^{+i\phi} & E_R \end{pmatrix} = \ldots \begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \tilde{H}$$

$$\tilde{H} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \frac{V_{\nu_e}}{2} & \mu_{e\mu}Be^{-i\phi} \\ \mu_{e\mu}Be^{+i\phi} & \frac{\Delta m^2}{4E} - \frac{V_{\nu_e}}{2} \end{pmatrix}$$

ν spin and spin-flavour oscillations in $B_\perp$

$$\nu_{e_L} \leftrightarrow \nu_{\mu_R}$$

$$B = |\mathbf{B}_\perp| e^{i\phi(t)}$$

- $$P_{\nu_L \nu_R} = \sin^2\beta \, \sin^2\Omega z \qquad \sin^2\beta = \frac{(\mu_{e\mu}B)^2}{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2}$$

$$\Omega^2 = (\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2$$

$$\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$$

- Resonance amplification of oscillations in matter:

Akhmedov, Lim
Marciano, 1988

$$\Delta_{LR} \to 0 \implies \sin^2\beta \to 1$$

… similar to MSW effect

… flavour oscillations ⟷ spin oscillations …

$$P_{\nu_e\nu_\mu} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} z \quad \Longleftrightarrow \quad P_{\nu_L\nu_R} = \sin^2\beta \; \sin^2\Omega z$$

$$\Omega^2 = (\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2$$

$$\sin^2 2\theta \quad \Longleftrightarrow \quad \frac{(\mu_{e\mu}B)^2}{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2} = \sin^2\beta$$

$$\frac{\Delta m^2}{4E} \quad \Longleftrightarrow \quad \sqrt{(\mu_{e\mu}B)^2 + \left(\frac{\Delta_{LR}}{4E}\right)^2} = \mathbf{\Omega}$$

$$B = |\mathbf{B}_\perp| e^{i\phi(t)}$$

$$\Delta_{LR} = \frac{\Delta m^2}{2}(\cos 2\theta + 1) - 2EV_{\nu_e} + 2E\dot{\phi}$$

The end of Presentation # 1.1

The end of Lecture # 1