Neutrino electromagnetic properties

2nd International Workshop on Particle Physics and Cosmology after Higgs and Planck,

National Centre for Theoretical Sciences
National Tsing Hua University
Hsinchu
09/10/2014

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&

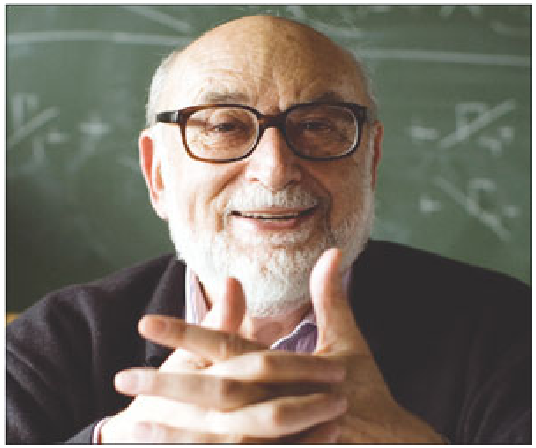
JINR - Dubna

The last two years since

2012

- . . . has been celebrated by spectacular step further in **High Energy Physics** . . .


Robert Brout


François Englert


Peter Higgs

Observation of Higgs boson confirms the symmetry breaking mechanism by Brout-Englert-Higgs (BEH)

- provides final glorious triumph of Standard Model
- … new division in particle physics with special name **BEH Physics**

(as it has been fixed by ICHEP in Valencia, July 2014)

What is next ?

(... after Higgs ...

or after coming instead of Higgs as Harald Fritzsch has proposed) ν unique particle that is precursor of BSM physics

BEH physics ⇒ BSM physics

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 80 years left !

… however … $\Longrightarrow$

… an optimistic view on the present and future of ν

In 1946 Bruno Pontecorvo:

"… observation of neutrinos is not out of question…"

$$\nu + (A, Z) \rightarrow e^- + (A, Z+1)$$

$$^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$$

Бруно Понтекорво

1913-1993

August 22, 2013

Centenary of the birth of Bruno Pontecorvo

ν electromagnetic properties
(up to now nothing has been seen)

is a tool for studying

Beyond
Extended
Standard
Model physics…

BEH physics $\Rightarrow$ BSM physics $\Rightarrow$ BESM physics

ν electromagnetic properties

(short review)

$m_\nu \neq 0$

1. A. Studenikin, Neutrino magnetic moment: a window to new physics, Nucl.Phys.B (Proc.Supl.) 188 (2009) 220

2. C.Giunti, A. Studenikin, Neutrino electromagnetic properties Phys.Atom.Nucl. 73 (2009) 2089

3. C. Giunti, A. Studenikin, Electromagnetic properties of neutrino J.Phys.: Conf.Series. 203 (2010) 012100

4. C.Broggini, C. Giunti, A. Studenikin : "Electromagnetic properties of neutrinos", in: Special issue "Neutrino Physics", Adv. in High Energy Phys. 2012 (2012) 459526

5. C. Giunti, A. Studenikin : "Electromagnetic interactions of neutrinos: a window to new physics", arXiv:1403.6344 submt to Rev.Mod.Phys.

6. K.Kouzakov, A.Studenikin, Theory of neutrino-atom collisions: the history, present status, and BSM physics, in: Special issue "Through Neutrino Eyes: The Search for New Physics", Adv. in High Energy Phys. 2014 (2014) 569409

ν electromagnetic properties (new limits and astrophysical consequences)

1. A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 21001

2. A. Studenikin , I.Tokarev, "Millicharged neutrino with anomalous magnetic moment in rotating magnetized matter" , Nucl. Phys. B 884 (2014) 396

3. I.Balantsev, A.Studenikin, "Spin light of electron in dense neutrino fluxes" , arXiv: 1405.6598

$m_\nu \neq 0$ … a tool for studying physics Beyond Extended Standard Model…

Theory (Standard Model with ν_R)

$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3\cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1\,eV}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee Shrock, 1977; Fujikawa Shrock, 1980

magnetic moment

$$a_e = \frac{\alpha_{QED}}{2\pi} \sim 10^{-3}$$

… much greater values are desired

for astrophysical or cosmology

visualization of μ_ν

… hopes for physics BESM …

- **Astrophysical bounds**

$$\mu_\nu \lesssim 3 \cdot 10^{-12} \mu_B$$

G. Raffelt **(1990)**

- **Theory (Standard Model with ν_R)**

$$\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1\,eV}\right), \quad \mu_B = \frac{e}{2m_e}$$

Lee, Shrock, 1977; Fujikawa, Shrok, 1980

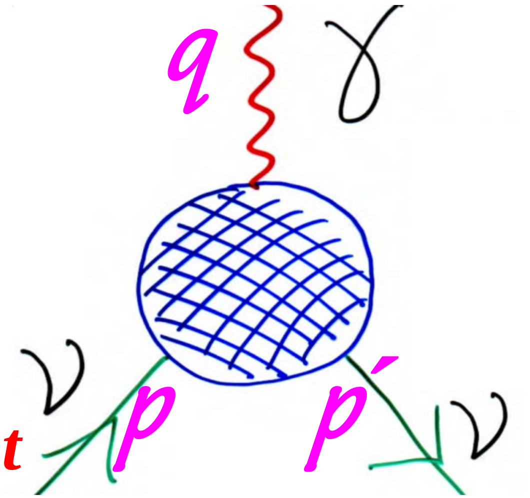
- **Limits from reactor ν-e scattering experiments**

A.Beda et al. (GEMMA Coll.) (2012):

$$\mu_\nu < 2.9 \times 10^{-11} \mu_B$$

… a bit of ν electromagnetic properties theory …

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

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) $\Longrightarrow$

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

dipole

2. magnetic

3. electric

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:* $Im f_Q = Im f_M = Im f_A = 0$

Majoran 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

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

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

and

… beyond SM…

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

form factors are matrices in ν mass eigenstates space.

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

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) .

… quite different EM properties …

1) *CP invariance + hermiticity*

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

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

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 can have nonvanishing values

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

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

ν magnetic moment in experiments

(most easily understood
and accessible for experimental
studies are dipole moments)

Studies of ν-e scattering - most sensitive method for experimental investigation of μ_ν

Cross-section:

- $$\frac{d\sigma}{dT}(\nu + e \to \nu + e) = \left(\frac{d\sigma}{dT}\right)_{\rm SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu}$$

where the Standard Model contribution

- $$\left(\frac{d\sigma}{dT}\right)_{\rm SM} = \frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}\right],$$

T is the electron recoil energy and

- $$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} = \frac{\pi\alpha_{em}^2}{m_e^2}\left[\frac{1 - T/E_\nu}{T}\right]\mu_\nu^2$$

$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left|\sum_i U_{li} e^{-iE_i L}\mu_{ji}\right|^2$$

$$\mu_{ij} \to |\mu_{ij} - \epsilon_{ij}|$$

$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2} & \text{for } \nu_e, \\ 2\sin^2\theta_W - \frac{1}{2} & \text{for } \nu_\mu, \nu_\tau, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2} & \text{for } \nu_e, \\ -\frac{1}{2} & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

for anti-neutrinos $g_A \to -g_A$

to incorporate charge radius: $g_V \to g_V + \frac{2}{3}M_W^2\langle r^2\rangle \sin^2\theta_W$

Effective ν_e magnetic moment measured in ν-e scattering experiments ?

$$\mu_e^2$$

Two steps:

1) consider ν_e as superposition of mass eigenstates ($i=1,2,3$) at some distance L from the source, and then sum up magnetic moment contributions to ν-e scattering amplitude (of each of mass components) induced by their magnetic moments

$$A_j \sim \sum_i U_{ei} e^{-iE_i L} \mu_{ji}$$

J.Beacom, P.Vogel, 1999

2) amplitudes combine incoherently in total cross section

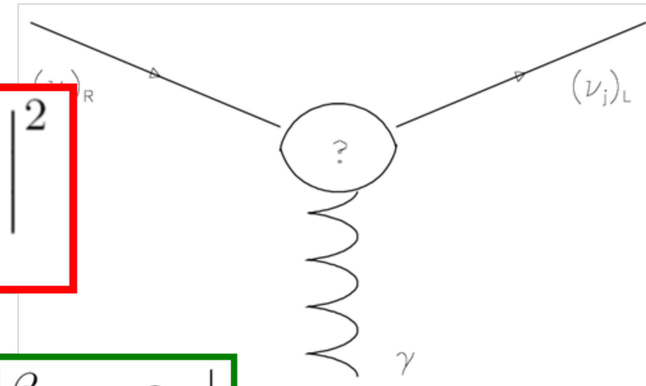
$$\sigma \sim \mu_e^2 = \sum_j \left| \sum_i U_{ei} e^{-iE_i L} \mu_{ji} \right|^2$$

C.Giunti, A.Studenikin, 2009

NB! Summation over ***j=1,2,3*** is outside the square because of **incoherence** of different final mass states contributions to cross section.

Effective ν magnetic moment in experiments

(for neutrino produced as ν_l with energy E_ν and after traveling a distance L)



$$\mu_\nu^2(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-iE_i L} \mu_{ji} \right|^2$$

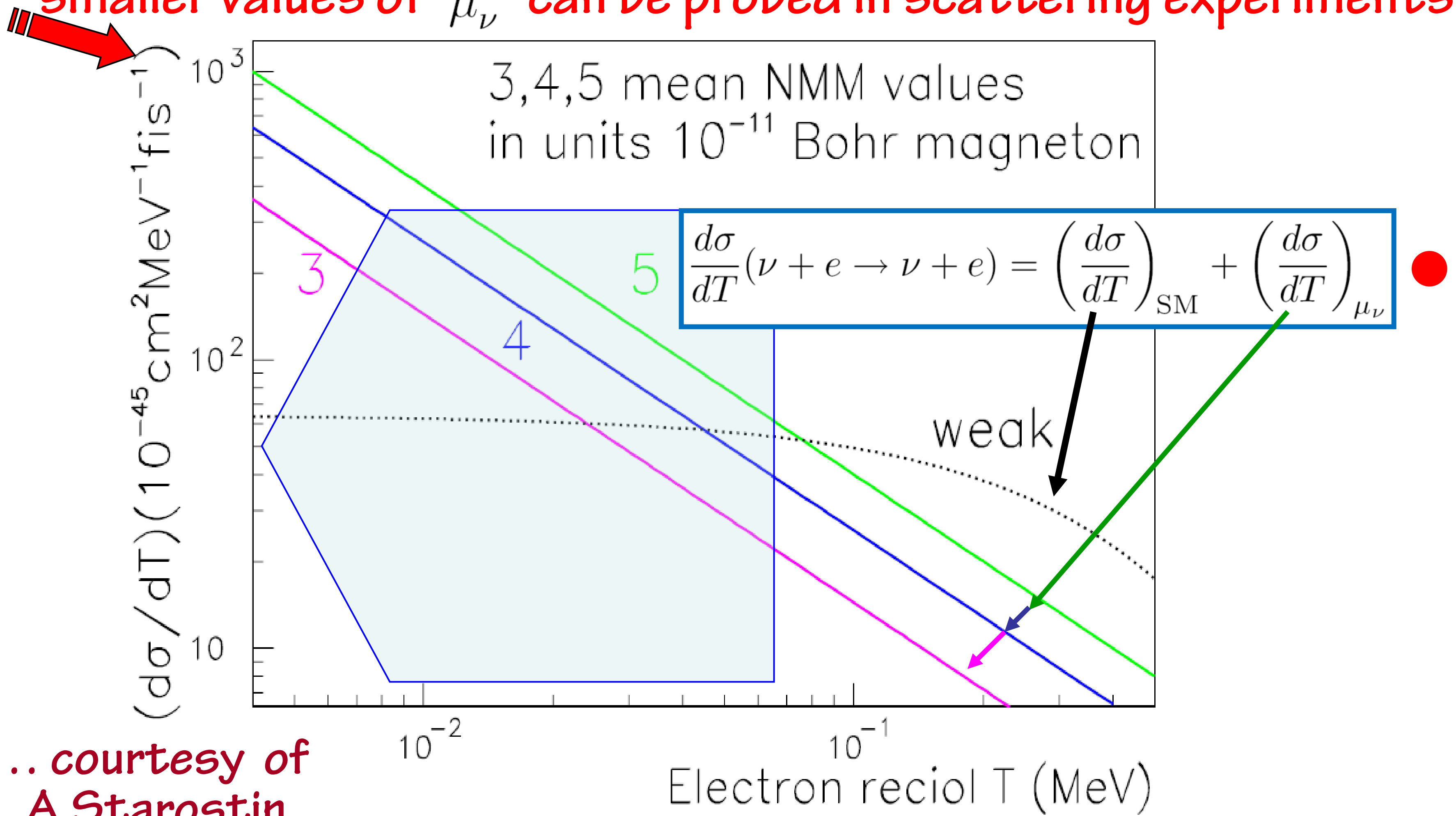
where U_{li} – neutrino mixing matrix, $\mu_{ij} \equiv |\beta_{ij} - \varepsilon_{ij}|$ – magnetic (β_{ij}) and electric (ε_{ij}) moments

- Observable μ_ν is an effective parameter that depends on neutrino flavour composition at the detector.

- Implications of μ_ν limits from different experiments (reactor , solar ^{8}B and ^{7}Be) are different.

Magnetic moment contribution dominates at low electron recoil energies when $\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} > \left(\frac{d\sigma}{dT}\right)_{SM}$ and $\frac{T}{m_e} < \frac{\pi^2\alpha_{em}}{G_F^2 m_e^4}\mu_\nu^2$

… the lower the smallest measurable electron recoil energy is, smaller values of μ_ν^2 can be probed in scattering experiments …



… courtesy of A.Starostin…

MUNU experiment at Bugey reactor (2005)

$$\mu_\nu \leq 9 \times 10^{-11} \mu_B$$

TEXONO collaboration at Kuo-Sheng power plant (2006)

$$\mu_\nu \leq 7 \times 10^{-11} \mu_B$$

GEMMA (2007)

$$\mu_\nu \leq 5.8 \times 10^{-11} \mu_B$$

GEMMA I 2005 - 2007

BOREXINO (2008)

$$\mu_\nu \leq 5.4 \times 10^{-11} \mu_B$$

...was considered as the world best constraint..

$$\mu_\nu \leq 8.5 \times 10^{-11} \mu_B \quad (\nu_\tau,\ \nu_\mu)$$

based on first release of BOREXINO data

Montanino, Picariello, Pulido, PRD 2008

... attempts to improve bounds

GEMMA (2005-2012)

Germanium Experiment for Measurement of Magnetic Moment of Antineutrino

JINR (Dubna) + ITEP (Moscow) at Kalinin Nuclear Power Plant

World best experimental limit

$$\mu_\nu < 2.9 \times 10^{-11} \mu_B$$

June 2012

A. Beda et al, in: Special Issue on "Neutrino Physics", Advances in High Energy Physics (2012) 2012, editors: J.Bernabeu, G. Fogli, A.McDonald, K. Nishikawa

... quite realistic prospects of the near future

$$\mu_\nu \sim 1 \times 10^{-11} \mu_B$$

(V.Brudanin, A.Starostin, priv. comm.)

... quite recent claim that ν-e cross section should be increased by Atomic Ionization Effect:

?

H.Wong et al. (TEXONO Coll.), PRL 105 (2010) 061801

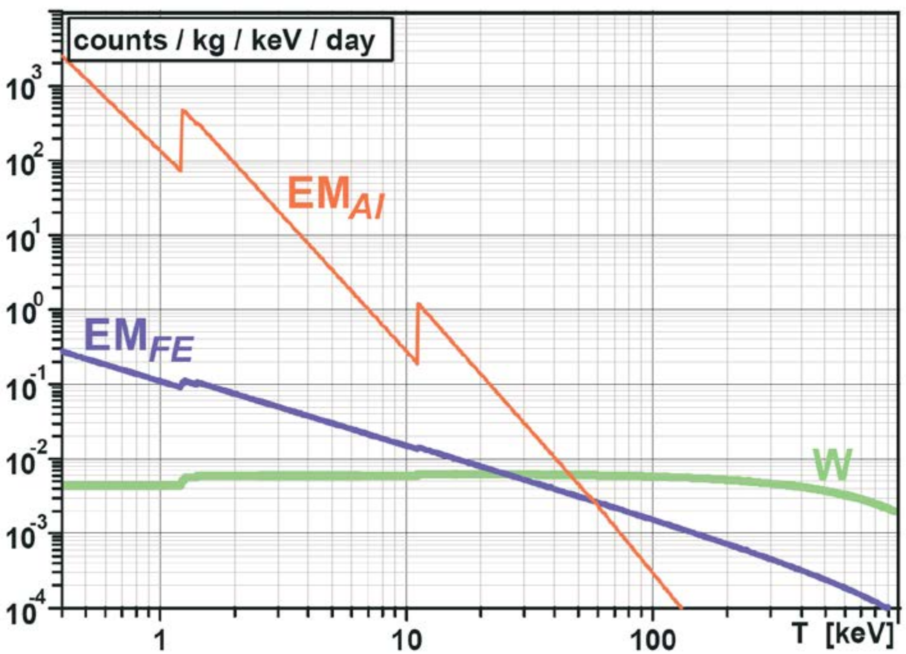
(ν scattering on bound e)

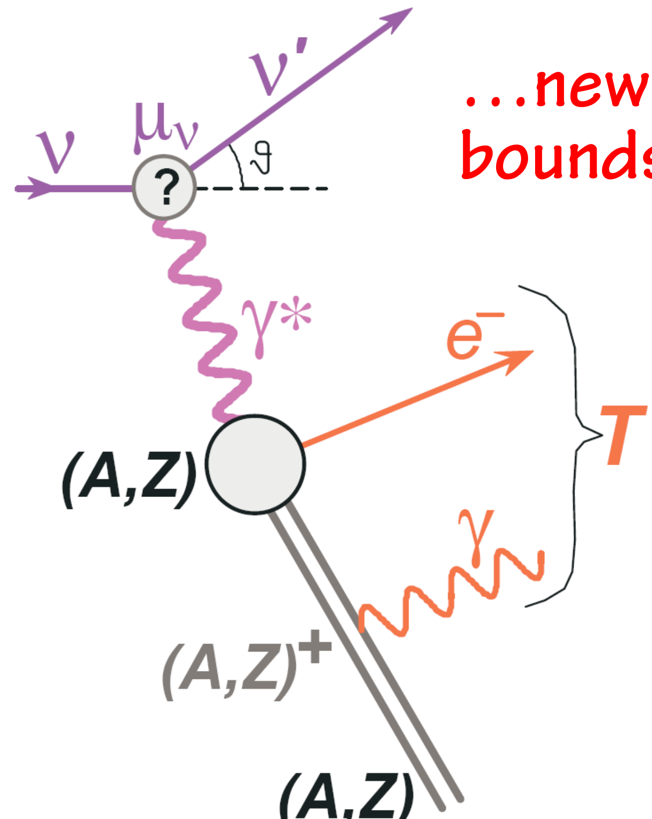
$$\nu + (A,Z) \longrightarrow \nu\,' + (A,Z)^{+} + e^{-}$$

$$\downarrow \text{recombination}$$

$$(A,Z) \quad + \gamma$$

... an interesting hypothetical possibility to improve bounds...





...new bounds ...

K.Kouzakov, A.Studenikin,

- "Magnetic neutrino scattering on atomic electrons revisited" **Phys.Lett. B** 105 (2011) 061801,
- "Electromagnetic neutrino-atom collisions: The role of electron binding" **Nucl.Phys.** (Proc.Suppl.) 217 (2011) 353

K.Kouzakov, A.Studenikin, M.Voloshin,

- "Neutrino electromagnetic properties and new bounds on neutrino magnetic moments" **J.Phys.: Conf.Ser.** 375 (2012) 042045
- "Neutrino-impact ionization of atoms in search for neutrino magnetic moment", **Phys.Rev.D** 83 (2011) 113001
- "On neutrino-atom scattering in searches for neutrino magnetic moments" **Nucl.Phys.B** (Proc.Supp.) 2011 (Proc. of Neutrino 2010 Conf.)
- "Testing neutrino magnetic moment in ionization of atoms by neutrino impact", **JETP Lett.** 93 (2011) 699

M.Voloshin,

- "Neutrino scattering on atomic electrons in search for neutrino magnetic moment" **Phys.Rev.Lett.** 105 (2010) 201801

No important effect of Atomic Ionization on cross section in μ_ν experiments once all possible final electronic states accounted for

...free electron approximation ...

M.Voloshin, 23 Aug 2010;
K.Kouzakov, A.Studenikin, 26 Nov 2010;
H.Wong et al, arXiv: 1001.2074 V3, 28 Nov 2010

K.Kouzakov, A.Studenikin,
"Theory of neutrino-atom collisions:
the history, present status, and BSM physics",

in: Special issue
"Through Neutrino Eyes: The Search for New Physics",
Adv. in High Energy Phys. 2014 (2014) 569409 (37pp)

Experimental limits for different effective μ_ν

Method		Experiment	Limit	CL	Reference
		Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}\,\mu_B$	90%	Vidyakin *et al.* (1992)
		Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}\,\mu_B$	95%	Derbin *et al.* (1993)
Reactor $\bar{\nu}_e$-e^-	●	MUNU	$\mu_{\nu_e} < 0.9 \times 10^{-10}\,\mu_B$	90%	Daraktchieva *et al.* (2005)
	●	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}\,\mu_B$	90%	Wong *et al.* (2007)
	●	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}\,\mu_B$	90%	Beda *et al.* (2012)
Accelerator ν_e-e^-		LAMPF	$\mu_{\nu_e} < 10.8 \times 10^{-10}\,\mu_B$	90%	Allen *et al.* (1993)
Accelerator $(\nu_\mu, \bar{\nu}_\mu)$-e^-		BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}\,\mu_B$	90%	Ahrens *et al.* (1990)
		LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}\,\mu_B$	90%	Allen *et al.* (1993)
		LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}\,\mu_B$	90%	Auerbach *et al.* (2001)
Accelerator $(\nu_\tau, \bar{\nu}_\tau)$-$e^-$		DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}\,\mu_B$	90%	Schwienhorst *et al.* (2001)
Solar ν_e-e^-		Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5\,\mathrm{MeV}) < 1.1 \times 10^{-10}\,\mu_B$	90%	Liu *et al.* (2004)
	●	Borexino	$\mu_S(E_\nu \lesssim 1\,\mathrm{MeV}) < 5.4 \times 10^{-11}\,\mu_B$	90%	Arpesella *et al.* (2008)

C. Giunti, A. Studenikin, arXiv: 1403.6344

… if one trusts ν

to be precursor for

BESM physics …

… 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

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

- *…General proof:*
- *In SM :* $Q = I_3 + \frac{Y}{2}$ ($SU(2)_L \times U(1)_Y$)
- *In SM (without ν_R) triangle anomalies cancellation constraints* → *certain relations among particle hypercharges Y, 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; M.Dvornikov, A.S., 2004 (for extended SM in one-loop calculations)

- *… However, strict requirements for* **Q** *quantization may disappear in extensions of standard $SU(2)_L \times U(1)_Y$ EW model if ν_R with* $\mathbf{Y \neq 0}$ *are included : in the absence of* **Y** *quantization electric charges* **Q** *gets dequantized* → millicharged ν

Experimental limits for different effective q_ν

Limit	Method	Reference
$\lvert q_{\nu_\tau} \rvert \lesssim 3 \times 10^{-4}\, e$	SLAC e^- beam dump	Davidson *et al.* (1991)
$\lvert q_{\nu_\tau} \rvert \lesssim 4 \times 10^{-4}\, e$	BEBC beam dump	Babu *et al.* (1994)
$\lvert q_{\nu} \rvert \lesssim 6 \times 10^{-14}\, e$	Solar cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu} \rvert \lesssim 2 \times 10^{-14}\, e$	Red giant cooling (plasmon decay)	Raffelt (1999a)
$\lvert q_{\nu_e} \rvert \lesssim 3 \times 10^{-21}\, e$	Neutrality of matter	Raffelt (1999a)
$\lvert q_{\nu_e} \rvert \lesssim 3.7 \times 10^{-12}\, e$	Nuclear reactor	Gninenko *et al.* (2007)
$\lvert q_{\nu_e} \rvert \lesssim 1.5 \times 10^{-12}\, e$	Nuclear reactor	Studenikin (2013)

C.Giunti, A.Studenikin, arXiv: 1403.6344

Bounds on millicharge q_ν from μ_ν (GEMMA Coll. data)

ν-e cross-section

$$\left(\frac{d\sigma}{dT}\right)_{\nu-e} = \left(\frac{d\sigma}{dT}\right)_{SM} + \left(\frac{d\sigma}{dT}\right)_{\mu_\nu} + \left(\frac{d\sigma}{dT}\right)_{q_\nu}$$

two not seen contributions:

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a} \approx \pi\alpha^2 \frac{1}{m_e^2 T}\left(\frac{\mu_\nu^a}{\mu_B}\right)^2$$

$$\left(\frac{d\sigma}{dT}\right)_{q_\nu} \approx 2\pi\alpha \frac{1}{m_e T^2} q_\nu^2$$

Bounds on q_ν from

$$R = \frac{\left(\frac{d\sigma}{dT}\right)_{q_\nu}}{\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a}} = \frac{2m_e}{T}\frac{\left(\frac{q_\nu}{e_0}\right)^2}{\left(\frac{\mu_\nu^a}{\mu_B}\right)^2} \lesssim 1$$

... no observable effects of New Physics

Studenikin, arXiv:1302.1168, Eur.Phys.Lett. 107 (2014) 21001

Constraints on μ_ν from GEMMA: Constraints on q_ν

now $\mu_\nu^a < 2.9 \times 10^{-11}\mu_B$ $(T \sim 2.8\ keV)$ $|q_\nu| < 1.5 \times 10^{-12} e_0$

2015 (expected) $\mu_\nu^a \sim 1.5 \times 10^{-11}\mu_B$ $(T = 1.5\ keV)$ $|q_\nu| < 3.7 \times 10^{-13} e_0$

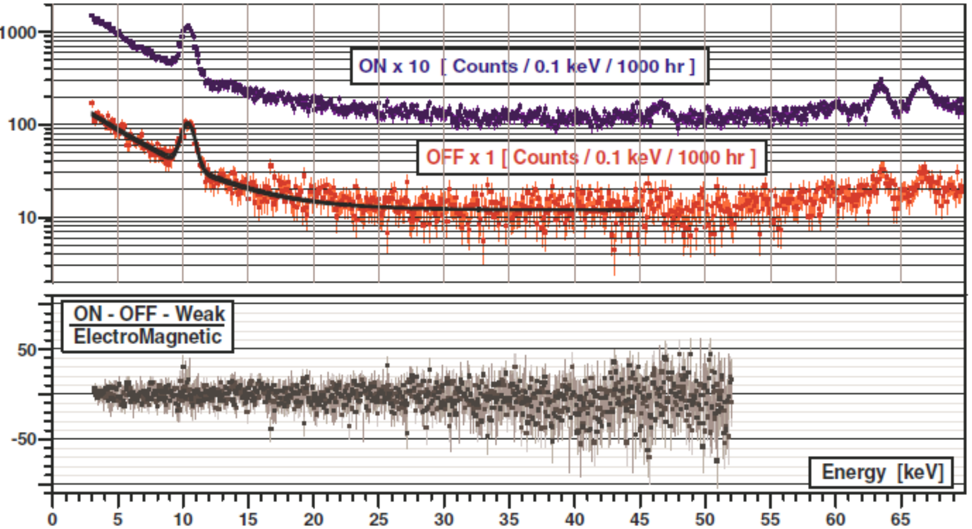
2018 (expected) $\mu_\nu^a \sim 0.9 \times 10^{-12}\mu_B$ $T = 350\ eV$ $|q_\nu| < 1.8 \times 10^{-13} e_0$

... the obtained constraint on neutrino millicharge q_ν

- rough order-of-magnitude estimation,
- exact values should be evaluated using the
- corresponding statistical procedures

this is because limits on neutrino μ_ν are derived from GEMMA experiment data taken over an extended energy range 2.8 keV --- 55 keV, rather than at a single electron energy-bin at threshold

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment",
Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168



Difference between reactor on and off electron recoil energy spectra (with account for weak interaction contribution) normalized by theoretical electromagnetic spectra

A. Beda et al, Adv. High Energy Phys. 2012(2012) 350150

- Limit evaluated using statistical procedures is of the same order as previously discussed

- $$| q_\nu | < 2.7 \times 10^{-12} e_0 \ (90\% \text{ C.L.})$$

A.Studenikin : "New bounds on neutrino electric millicharge from limits on neutrino magnetic moment", Eur.Phys.Lett. 107 (2014) 2100, arXiv:1302.1168

3

. . . a bit of ν electromagnetic properties theory

3.1 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

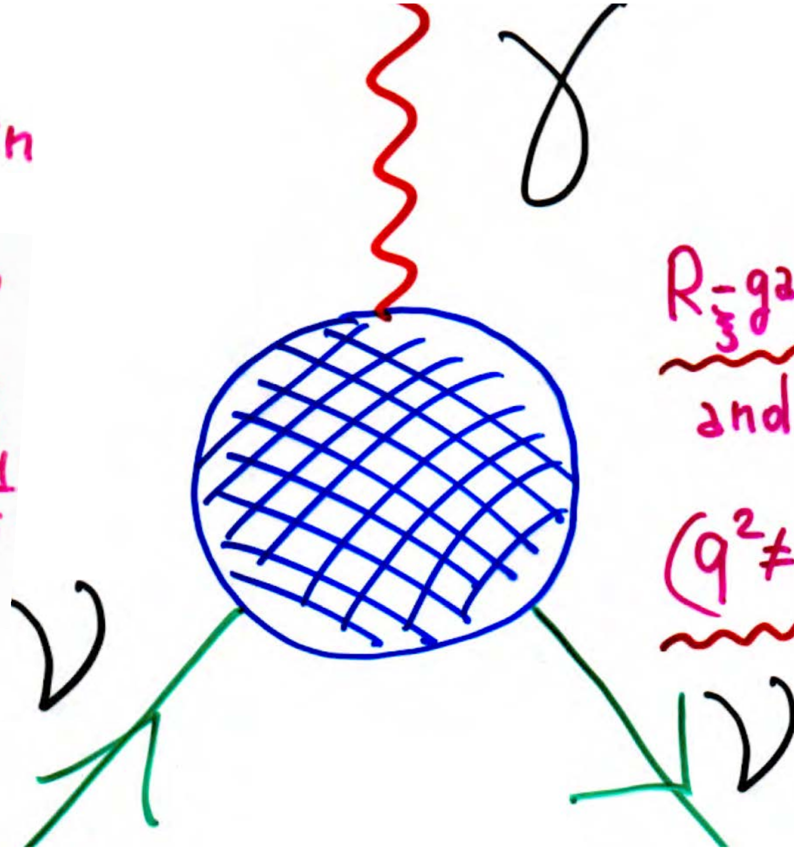
M. Dvornikov, A. Studenikin

⊛ 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

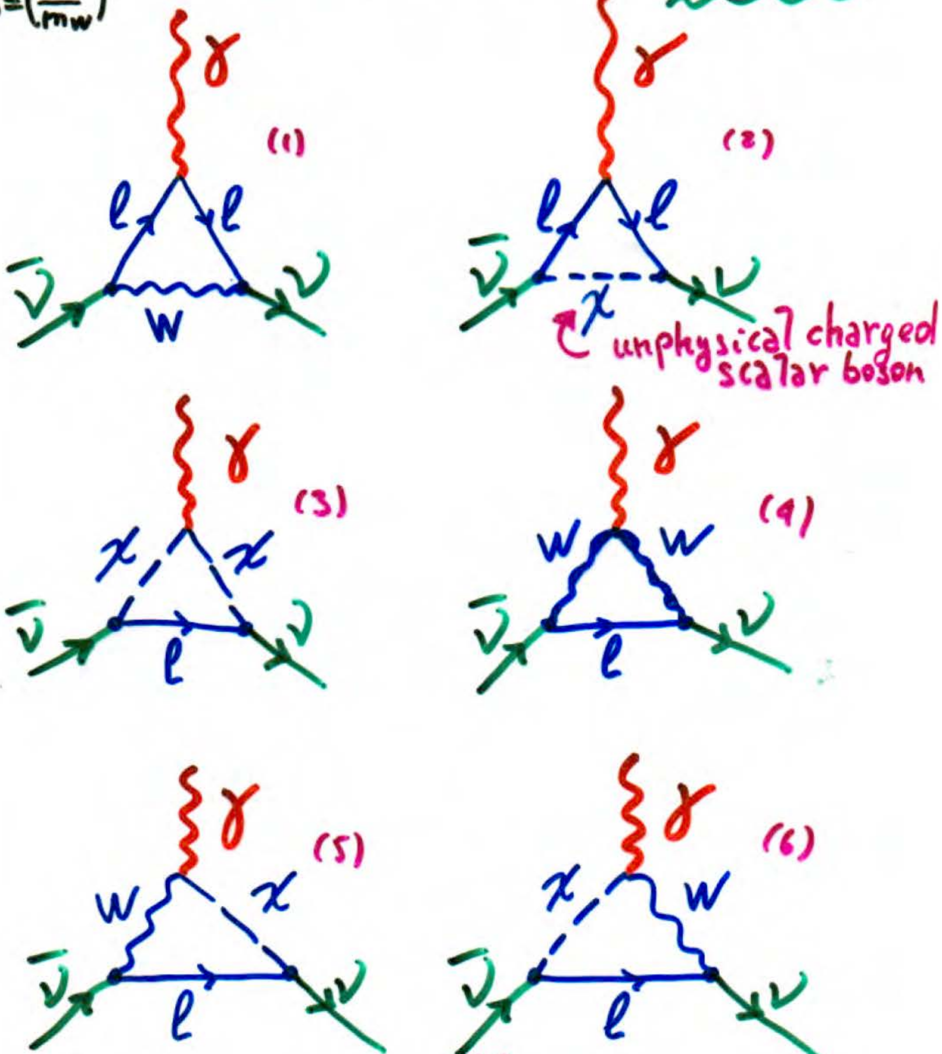
$$\Delta_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2) i\sigma_{\mu\nu} q^\nu - f_E(q^2) i\sigma_{\mu\nu} q^\nu \gamma_5 - f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

electric moment

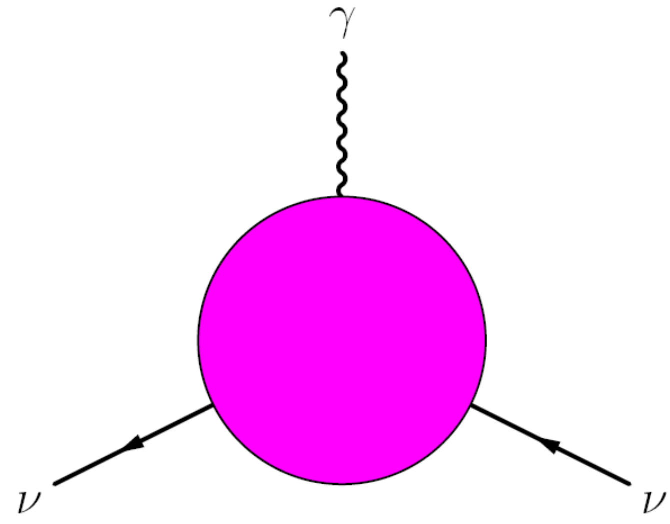
anapole moment

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

Proper vertices — R_ξ-gauge



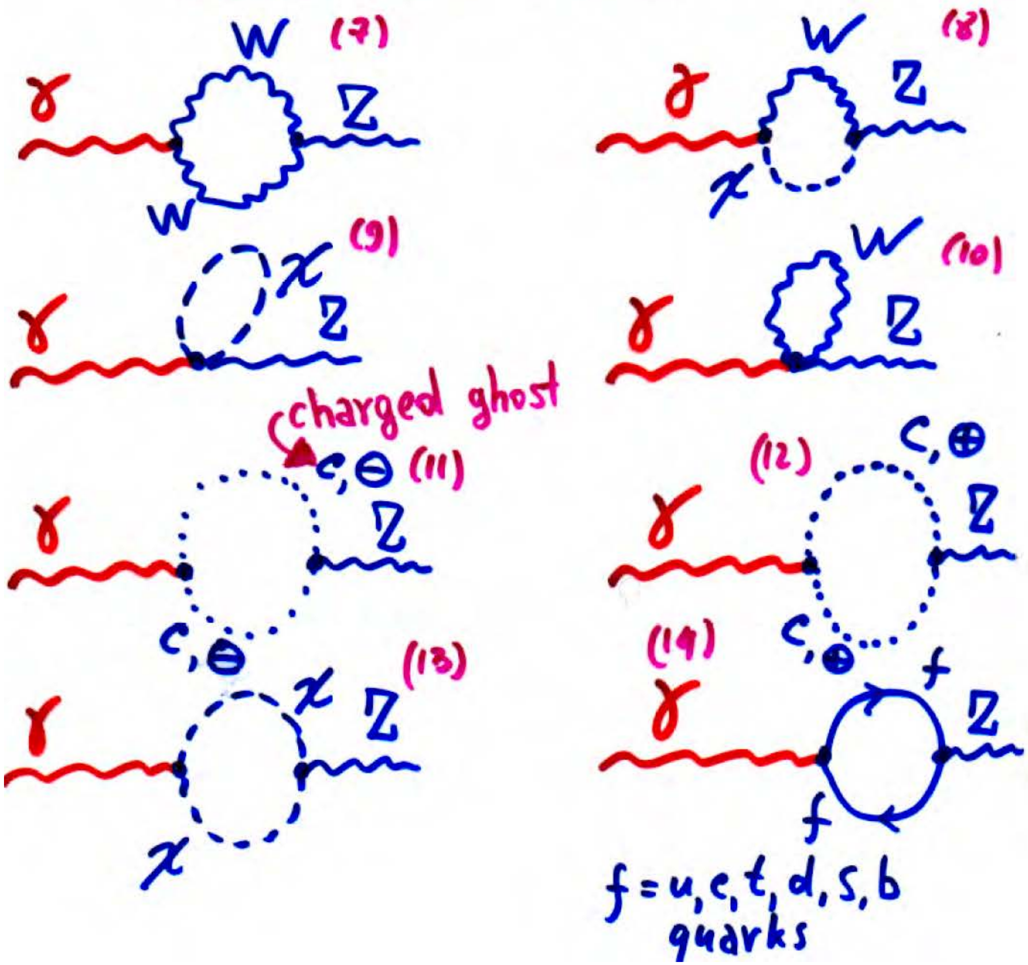
$$\Lambda_\mu(q) = \sum_{i=1}^{14} \Lambda_\mu^i(q)$$

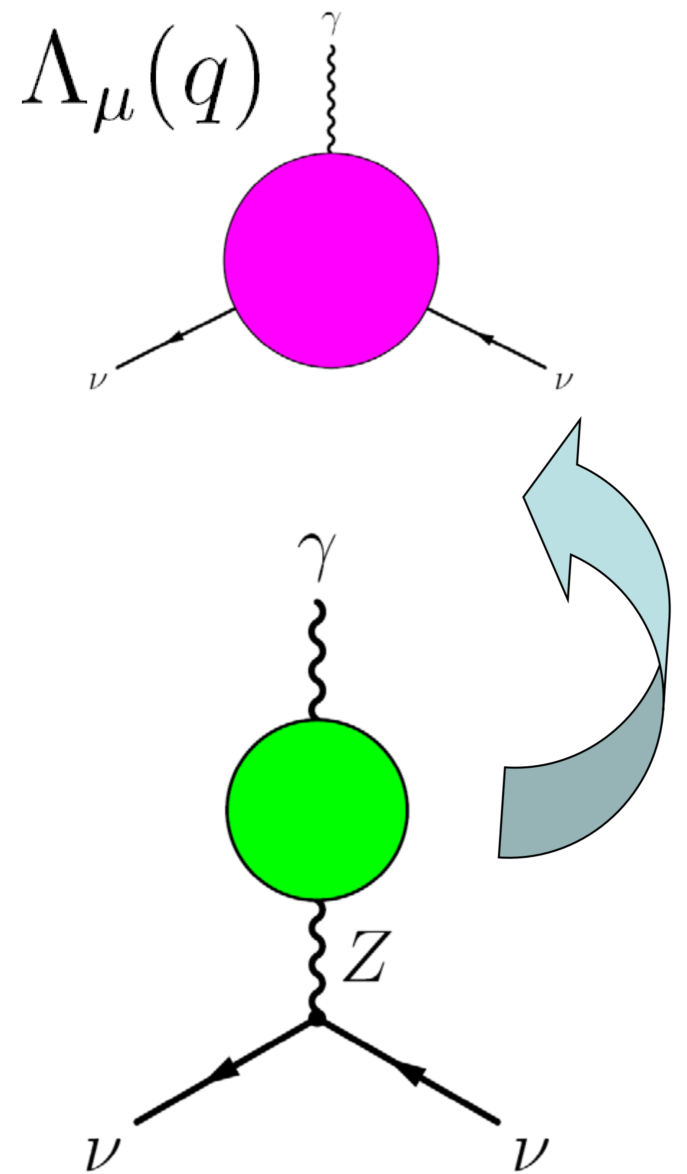


$$\Lambda_\mu(q)$$

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

γ-Z self-energy diagrams





$\gamma - Z$ self-energy diagrams

Magnetic moment dependence

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

on neutrino mass

- $m_\nu \ll m_e \ll M_W$ **light** ν

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

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

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

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

- $m_e \ll M_W \ll m_\nu$ **heavy** ν

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

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

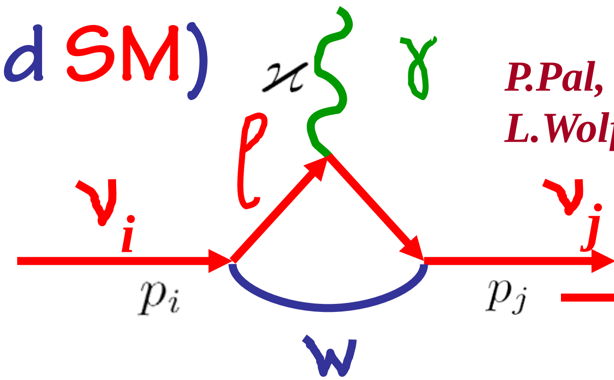
... μ_ν *in case of mixing ...*

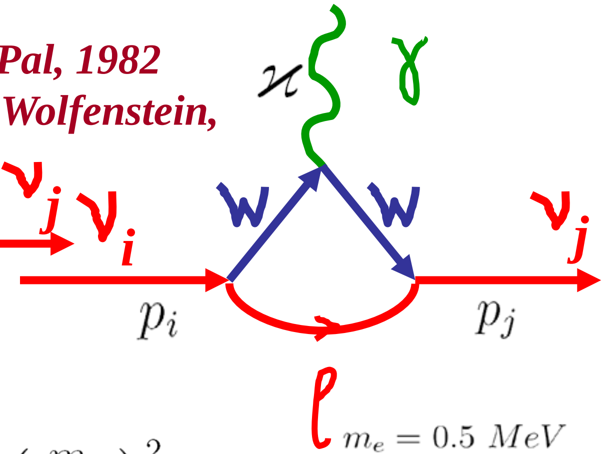
3.5

Neutrino (beyond SM) dipole moments

(+ transition moments)

P.Pal, 1982
L.Wolfenstein,





- **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

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

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

or

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

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

… 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

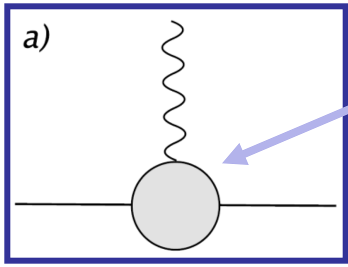
$\mu_{ii}^D = 0$ for massless ν (in the absence of right-handed charged currents)

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

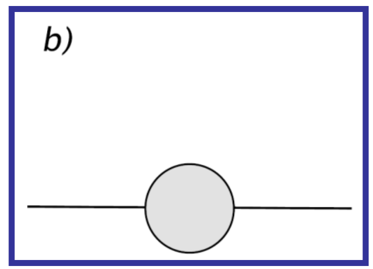


then

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

…combination of constants and loop factors…

contribution to m_ν given by



, then

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

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

Voloshin, 1988;
Barr, Freire, Zee, 1990

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

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

considerable enhancement of μ_ν to experimentally relevant range

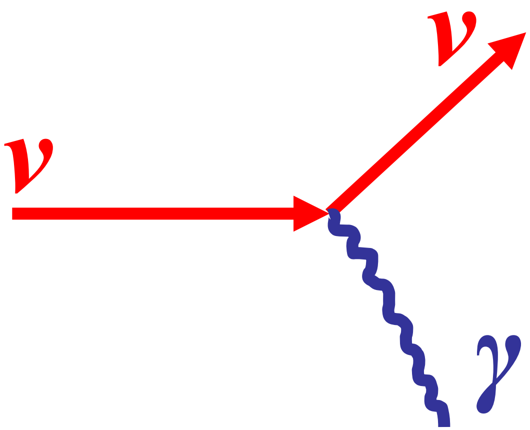
$\mu_\nu^D \leq 10^{-15} \mu_B$

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

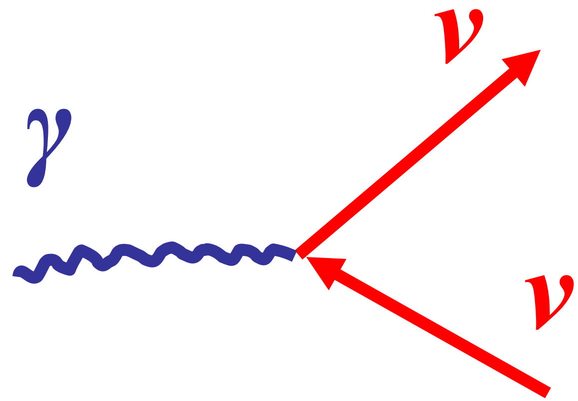
for BSM ($\Lambda \sim 1$ TeV) *without fine tuning and under the assumption that* $\delta m_\nu \leq 1$ eV

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

ν electromagnetic interactions

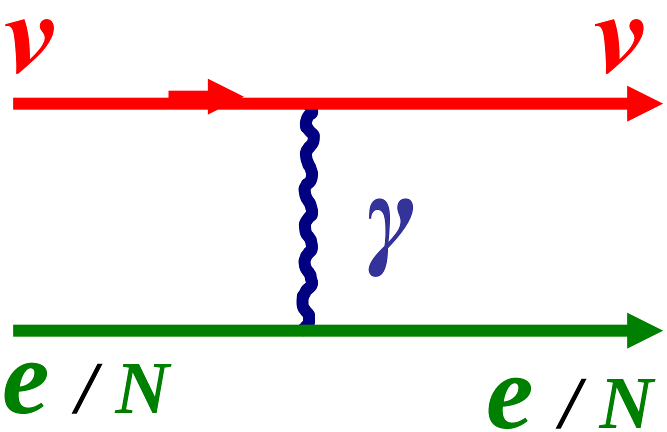


ν decay, Cherenkov radiation

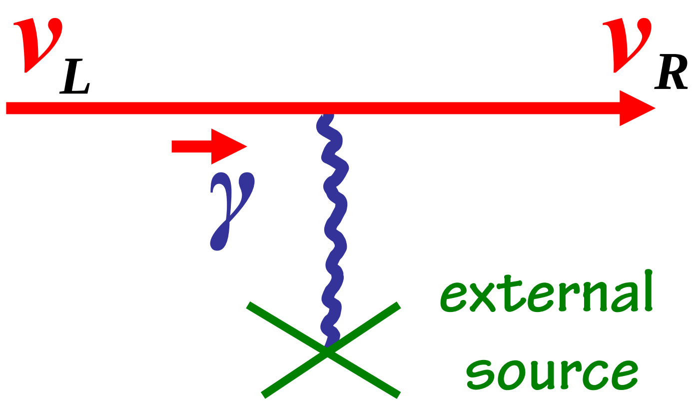


γ decay in plasma

!!!



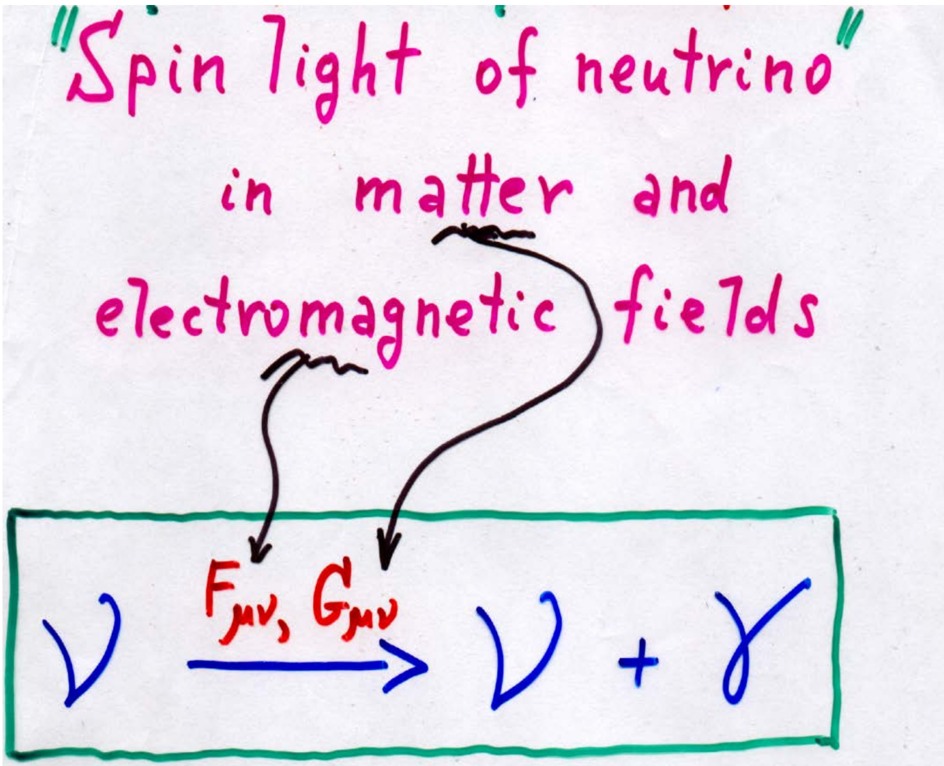
Scattering



Spin precession

• New mechanism of electromagnetic radiation

SLν



A.Lobanov, A.Studenikin,
Phys.Lett. B 564 (2003) 27
Phys.Lett. B 601 (2004) 171

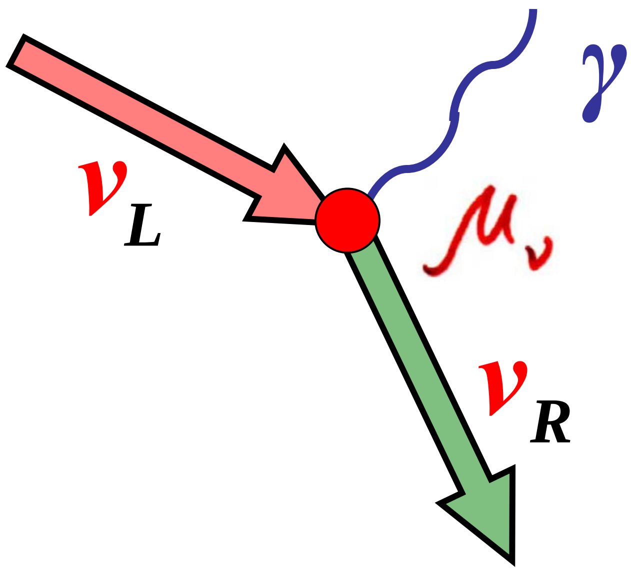
Studenikin, A.Ternov,
Phys.Lett. B 608 (2005) 107

A.Grigoriev, A.S., Ternov,
Phys.Lett. B 622 (2005) 199

Studenikin,
J.Phys.A: Math.Gen. 39 (2006) 6769
J.Phys.A: Math.Theor. 41 (2008) 16402

A.Grigoriev, A.Lokhov,
A.Studenikin, A.Ternov,
Nuovo Cim. 35 C (2012) 57
Phys.Lett.B 718 (2012) 512

Neutrino – photon coupling



broad neutrino lines account for interaction with environment

"Spin light of neutrino in matter"

$SL\nu$

- … within the quantum treatment based on method of exact solutions …

A.Grigoriev, A.Lokhov,
A.Ternov, A.Studenikin

The effect of plasmon mass on Spin Light of Neutrino in dense matter

Phys.Lett. B 718 (2012) 512

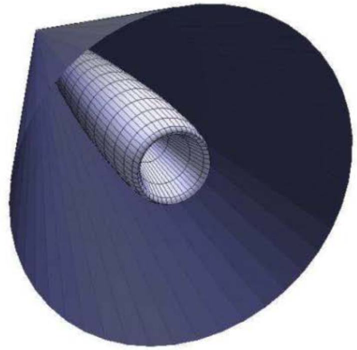


Figure 1: 3D representation of the radiation power distribution.

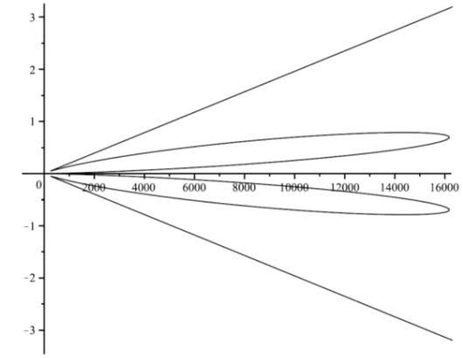


Figure 2: The two-dimensional cut along the symmetry axis. Relative units are used.

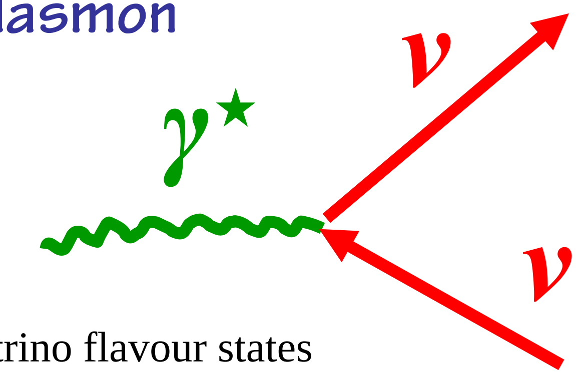
4. Conclusions

We developed a detailed evaluation of the spin light of neutrino in matter accounting for effects of the emitted plasmon mass. On the base of the exact solution of the modified Dirac equation for the neutrino wave function in the presence of the background matter the appearance of the threshold for the considered process is confirmed. The obtained exact and explicit threshold condition relation exhibit a rather complicated dependance on the matter density and neutrino mass. The dependance of the rate and power on the neutrino energy, matter density and the angular distribution of the $SL\nu$ is investigated in details. It is shown how the rate and power wash out when the threshold parameter $a = m_\gamma^2/4\tilde{n}p$ approaching unity. From the performed detailed analysis it is shown that the $SL\nu$ mechanism is practically insensitive to the emitted plasmon mass for very high densities of matter (even up to $n = 10^{41} cm^{-3}$) for ultra-high energy neutrinos for a wide range of energies starting from $E = 1$ TeV. This conclusion is of interest for astrophysical applications of $SL\nu$ radiation mechanism in light of the recently reported hints of $1 \div 10$ PeV neutrinos observed by IceCube [17].

Astrophysical bound on μ_ν

G.Raffelt, PRL 1990

comes from cooling of red gaint stars by plasmon decay $\gamma^\star \longrightarrow \nu\nu$



$$L_{int} = \frac{1}{2}\sum_{a,b}\left(\mu_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\psi_b + \epsilon_{a,b}\bar{\psi}_a\sigma_{\mu\nu}\gamma_5\psi_b\right)$$

neutrino flavour states

Matrix element $\epsilon_\alpha k^\alpha = 0$

$$|M|^2 = M_{\alpha\beta}p^\alpha p^\beta, \quad M_{\alpha\beta} = 4\mu^2(2k_\alpha k_\beta - 2k^2\epsilon^*_\alpha\epsilon_\beta - k^2 g_{\alpha,\beta}),$$

Decay rate

$$\Gamma_{\gamma\to\nu\bar{\nu}} = \frac{\mu^2}{24\pi}\frac{(\omega^2 - k^2)^2}{\omega}$$

= 0 in vacuum $\omega = k$

In the classical limit $\gamma^\star$ - like a massive particle with $\omega^2 - k^2 = \omega_{pl}^2$

Energy-loss rate per unit volume

$$Q_\mu = g\int \frac{d^3k}{(2\pi)^3}\omega f_{BE}\Gamma_{\gamma\to\nu\bar{\nu}}$$

$$\mu^2 \to \sum_{a,b}\left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2\right)$$

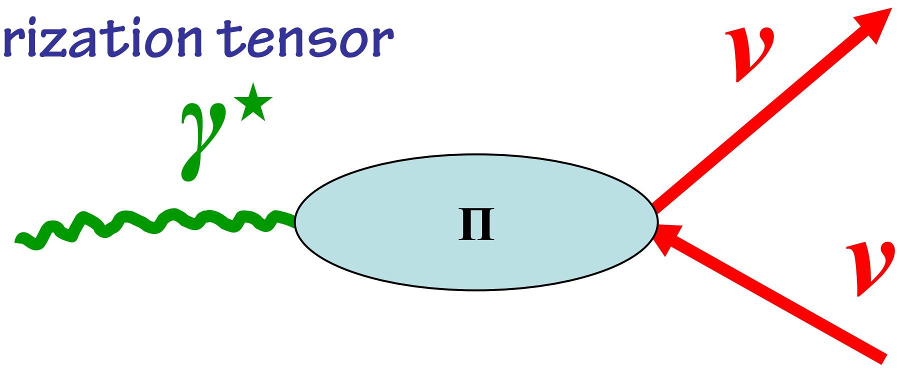
distribution function of plasmons

Astrophysical bound on μ_ν

$$Q_\mu = g \int \frac{d^3k}{(2\pi)^3} \omega f_{BE} \Gamma_{\gamma \to \nu\bar{\nu}}$$

Energy-loss rate per unit volume

Magnetic moment plasmon decay enhances the Standard Model photo-neutrino cooling by photon polarization tensor



more fast star cooling

In order not to delay helium ignition ($\lesssim$5% in Q)

$$\mu \leq 3 \times 10^{-12} \mu_B$$

$$\mu^2 \to \sum_{a,b} \left(|\mu_{a,b}|^2 + |\epsilon_{a,b}|^2 \right)$$

… best astrophysical limit on ν magnetic moment…

G.Raffelt, PRL 1990

ν energy quantization in rotating magnetized media

Grigoriev, Savochkin, Studenikin, Russ.Phys.J. 50 (2007) 845
Studenikin, J.Phys. A: Math.Theor. 41 (2008) 164047
Balantsev, Popov, Studenikin,
J.Phys. A:Math.Theor. 44 (2011) 255301
Balantsev, Studenikin, Tokarev, Phys.Part.Nucl. 43 (2012), 727
Phys.Atom.Nucl. 76 (2013) 489

Studenikin, Tokarev, Nucl.Phys. B 884 (2014) 396

Millicharged ν in rotating magnetized matter

Balatsev, Tokarev, Studenikin,
Phys.Part.Nucl., 2012,
Phys.Atom.Nucl., Nucl.Phys. B, 2013,
Studenikin, Tokarev, Nucl.Phys.B (2014)

Modified Dirac equation for ν wave function

$$\left(\gamma_\mu(p^\mu + q_0 A^\mu) - \frac{1}{2}\gamma_\mu(c_l + \gamma_5)f^\mu - \frac{i}{2}\mu\sigma_{\mu\nu}F^{\mu\nu} - m\right)\Psi(x) = 0$$

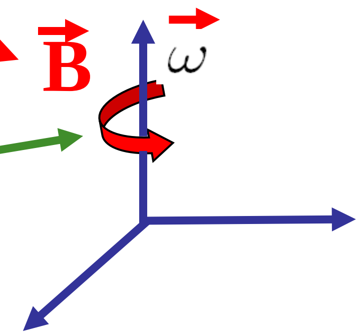
external magnetic field

$$V_m = \tfrac{1}{2}\gamma_\mu(c_l + \gamma_5)f^\mu \qquad c_l = 1$$

matter potential

rotating matter

$$f^\mu = -Gn_n(1, -\epsilon y\omega, \epsilon x\omega, 0)$$



rotation angular frequency

✓ energy is quantized in rotating matter

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

$G = \frac{G_F}{\sqrt{2}}$

$$p_0 = \sqrt{p_3^2 + 2N|2Gn_n\omega - \epsilon q_\nu B| + m^2} - Gn_n - q\phi$$

$N = 0, 1, 2, ...$

integer number

matter rotation frequency

scalar potential of electric field

✓ energy is quantized in rotating matter like electron energy in magnetic field (Landau energy levels):

$$p_0^{(e)} = \sqrt{m_e^2 + p_3^2 + 2\gamma N}, \quad \gamma = eB, \quad N = 0, 1, 2, ...$$

- In quasi-classical approach
  - ν quantum states in rotating matter
- ν motion in circular orbits

$$R = \int_0^\infty \Psi_L^\dagger \, \mathrm{r} \, \Psi_L \, d\mathbf{r} = \sqrt{\frac{2N}{|2Gn_n\omega - \epsilon q_0 B|}}$$

- due to effective Lorentz force

Studenikin, J.Phys. A (2008)

$$\mathbf{F}_{eff} = q_{eff}\mathbf{E}_{eff} + q_{eff}\left[\boldsymbol{\beta} \times \mathbf{B}_{eff}\right]$$

$$q_{eff}\mathbf{E}_{eff} = q_m\mathbf{E}_m + q_0\mathbf{E} \qquad q_{eff}\mathbf{B}_{eff} = |q_m B_m + q_0 B|\mathbf{e}_z$$

where $q_m = -G, \quad \mathbf{E}_m = -\boldsymbol{\nabla} n_n, \quad \mathbf{B}_m = 2n_n\boldsymbol{\omega}$

- matter induced "charge", "electric" and "magnetic" fields

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

. . . we predict :

$E \sim 1\ eV$

1) low-energy ν are trapped in circular orbits inside rotating neutron stars

$$R = \sqrt{\frac{2N}{Gn\omega}} < R_{NS} = 10\ km$$

$R_{NS} = 10\ km$
$n = 10^{37} cm^{-3}$
$\omega = 2\pi \times 10^3\ s^{-1}$

2) rotating neutron stars as filters for low-energy relic ν ?

$$T_\nu \sim 10^{-4}\ \mathrm{eV}$$

. . . we predict :

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

3) high-energy ν are deflected inside a rotating astrophysical transient sources (GRBs, SNe, AGNs)

absence of light in correlation with ν signal reported by ANTARES Coll.

M.Ageron et al, Nucl.Instrum.Meth. A692 (2012) 184

• Millicharged ν as star rotation engine

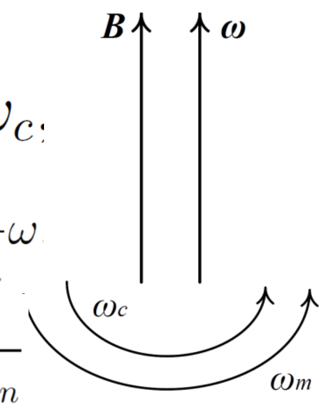
- Single ν generates feedback force with projection on rotation plane

- $F = (q_0 B + 2Gn_n\omega)\sin\theta$

$$\Omega = \omega_m + \omega_c;$$

$$\omega_m = \frac{2Gn_n}{p_0 + Gn_n}\omega,$$

$$\omega_c = \frac{q_0 B}{p_0 + Gn_n}$$

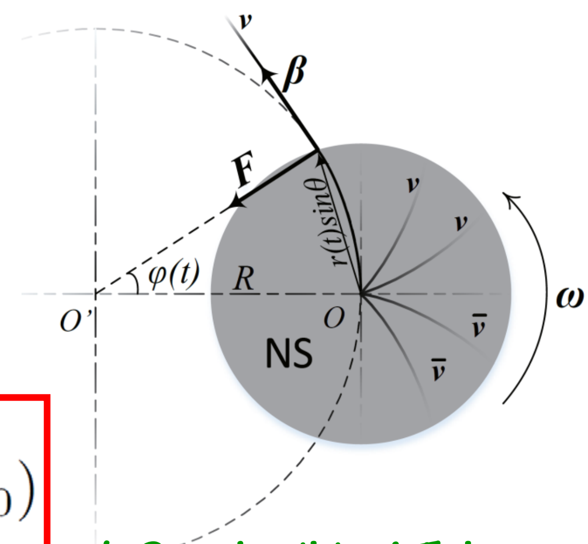


single ν torque

- $$M_0(t) = \sqrt{1 - \frac{r^2(t)\Omega^2\sin^2\theta}{4}}\,F r(t)\sin\theta$$

total N_ν torque

$$M(t) = \frac{N_\nu}{4\pi}\int M_0(t)\sin\theta d\theta d\varphi$$



- Shift of star angular velocity

$$|\Delta\omega| = \frac{5N_\nu}{6M_S}(q_0 B + 2Gn_n\omega_0)$$

$$\Delta\omega = \omega - \omega_0$$

A.Studenikin, I.Tokarev, Nucl.Phys.B (2014)

• ν Star Turning mechanism (νST)

A.Studenikin, I.Tokarev, Nucl.Phys.B 884 (2014) 396

Escaping ν s move on curved orbits inside magnetized rotating star and feedback of effective Lorentz force should effect initial star rotation

• New astrophysical constraint on ν millicharge

$$\frac{|\Delta\omega|}{\omega_0} = 7.6\varepsilon \times 10^{18} \left(\frac{P_0}{10\ \mathrm{s}}\right) \left(\frac{N_\nu}{10^{58}}\right) \left(\frac{1.4M_\odot}{M_S}\right) \left(\frac{B}{10^{14}G}\right)$$

• $|\Delta\omega| < \omega_0$! ...to avoid contradiction of νST impact with observational data on pulsars ...

$$q_0 < 1.3 \times 10^{-19} e_0$$

• ... best astrophysical bound ...

Conclusions

Spin light of electron in dense neutrino fluxes SLe_ν

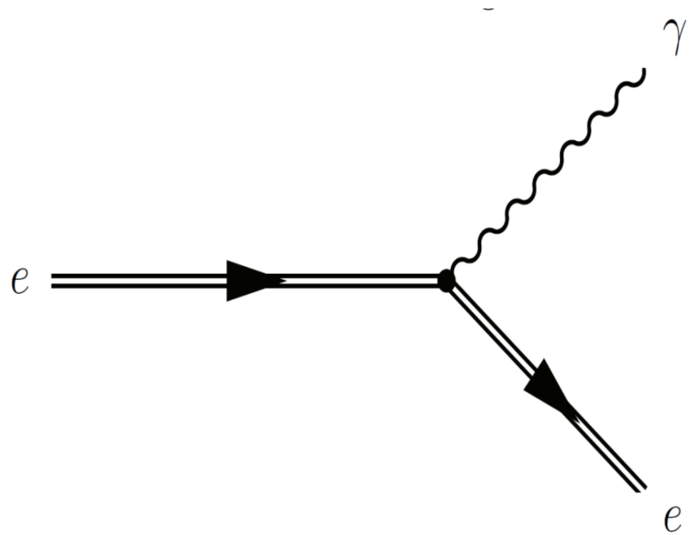
I.Balantsev, A.Studenikin, arXiv: 1405.6598

Dirac eq for e in dense relativistic flux of ν

- $$\left(\gamma_\mu p^\mu + \gamma_\mu \frac{c + \delta_e \gamma^5}{2} f^\mu - m\right)\Psi(x) = 0$$

$$c = \delta_e - 12\sin^2\theta_W$$

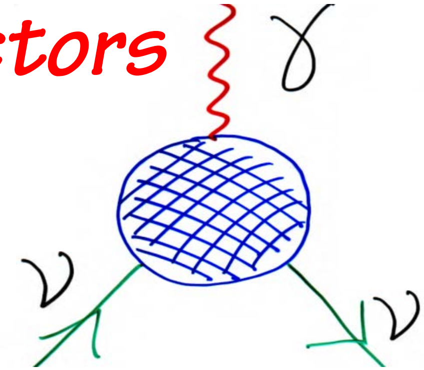
$$\delta_e = \frac{n_\mu + n_\tau - n_e}{n}$$



$$f^\mu = G(n, 0, 0, n)$$

background matter (ν flux) potential

ν e.m. vertex function ⟹ 4 form factors



charge dipole magnetic and electric

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

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

- Standard Model with ν_R $(m_\nu \neq 0)$: $\mu_e = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \sim 3 \cdot 10^{-19} \mu_B \left(\frac{m_{\nu_e}}{1\,eV}\right)$

- In extensions of SM → enhancement of ν magnetic moment, even electrically millicharged ν

- Limits from reactor ν-e scattering experiments (2012):

$$\mu_\nu < 2.9 \times 10^{-11} \mu_B$$

A.Beda et al. (GEMMA Coll.)

$$|\, q_\nu \,| < 1.5 \times 10^{-12} e_0$$

- Limits from astrophysics, star cooling (1990):

$$\mu_\nu < 3 \times 10^{-12} \mu_B$$

G.Raffelt

$$q_0 < 1.3 \times 10^{-19} e_0$$

ν ST mechanism

μ_ν is "presently known" to be in the range

$$10^{-20}\mu_B \leq \mu_\nu \leq 10^{-\mathbf{11}}\mu_B$$

μ_ν provides a tool for exploration possible physics beyond the Standard Model

- Due to smallness of neutrino-mass-induced magnetic moments,

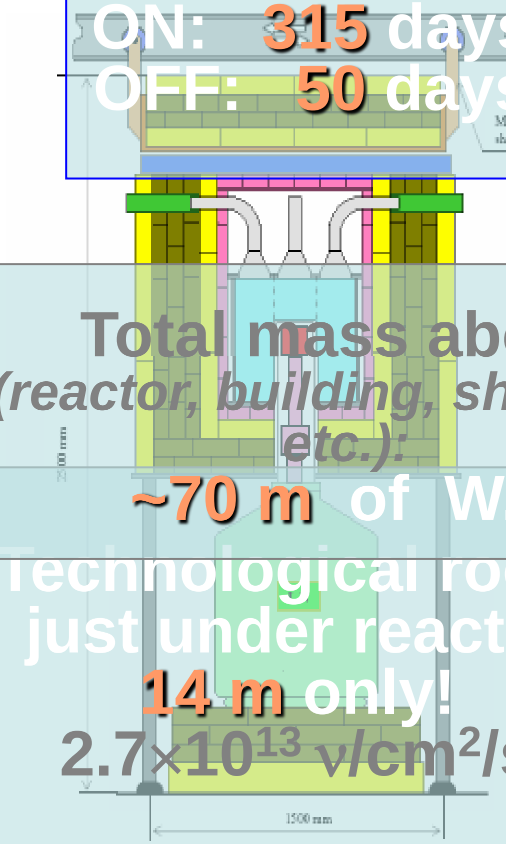
$$\mu_{ii} \approx 3.2 \times 10^{-19}\left(\frac{m_i}{1\ eV}\right)\mu_B$$

any indication for non-trivial electromagnetic properties of ν, that could be obtained within reasonable time in the future, would give evidence for BESM physics

Beyond Extended Standard Model

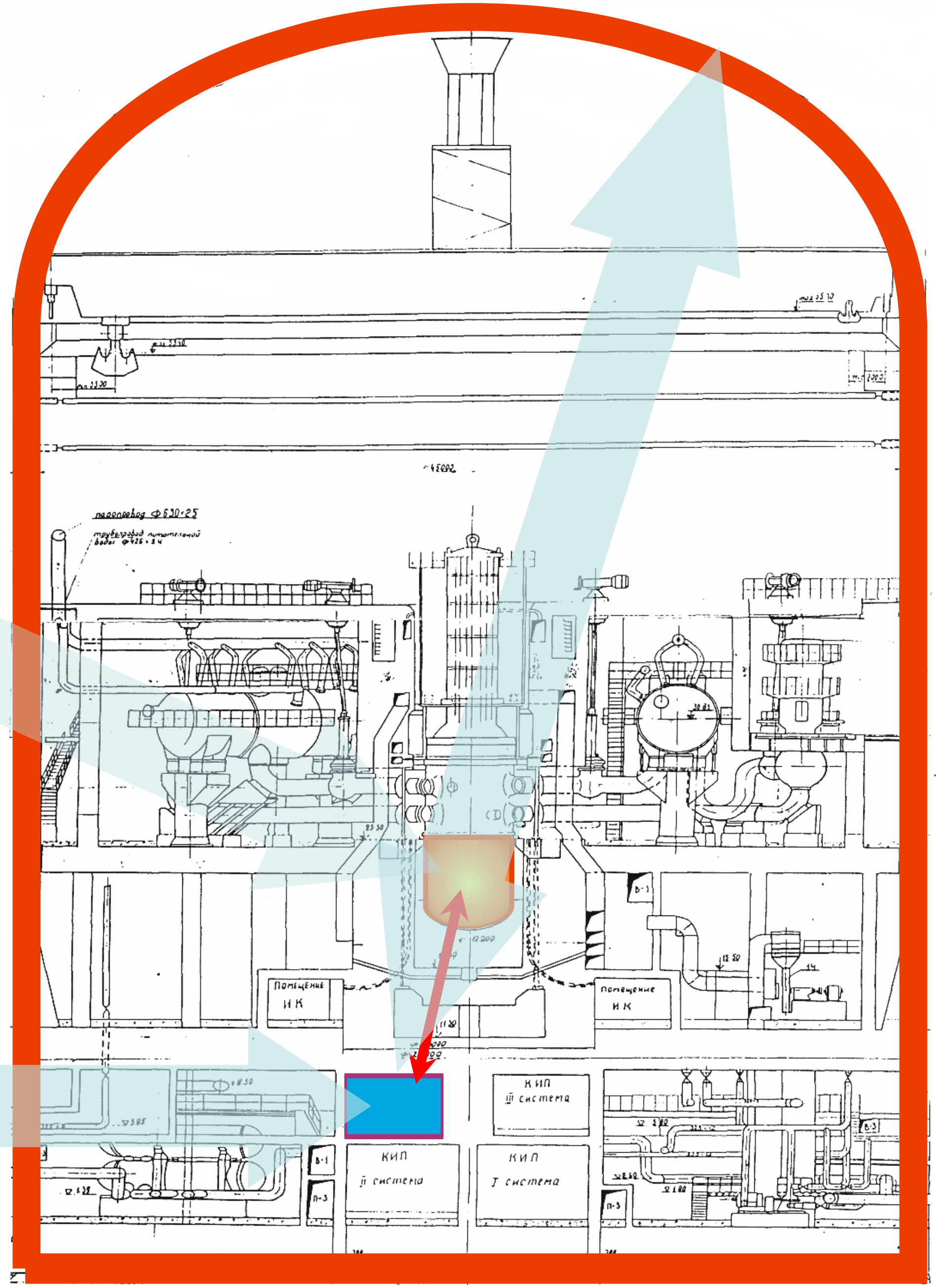
Reactor unit #2 of the "Kalinin" Nuclear Power Plant (400 km North from Moscow)

Power: 3 GW
ON: 315 days/y
OFF: 50 days/y



Total mass above
(reactor, building, shielding, etc.):
~70 m of W.E.

Technological room just under reactor
14 m only!
$2.7\times10^{13}\ \nu/cm^2/s$

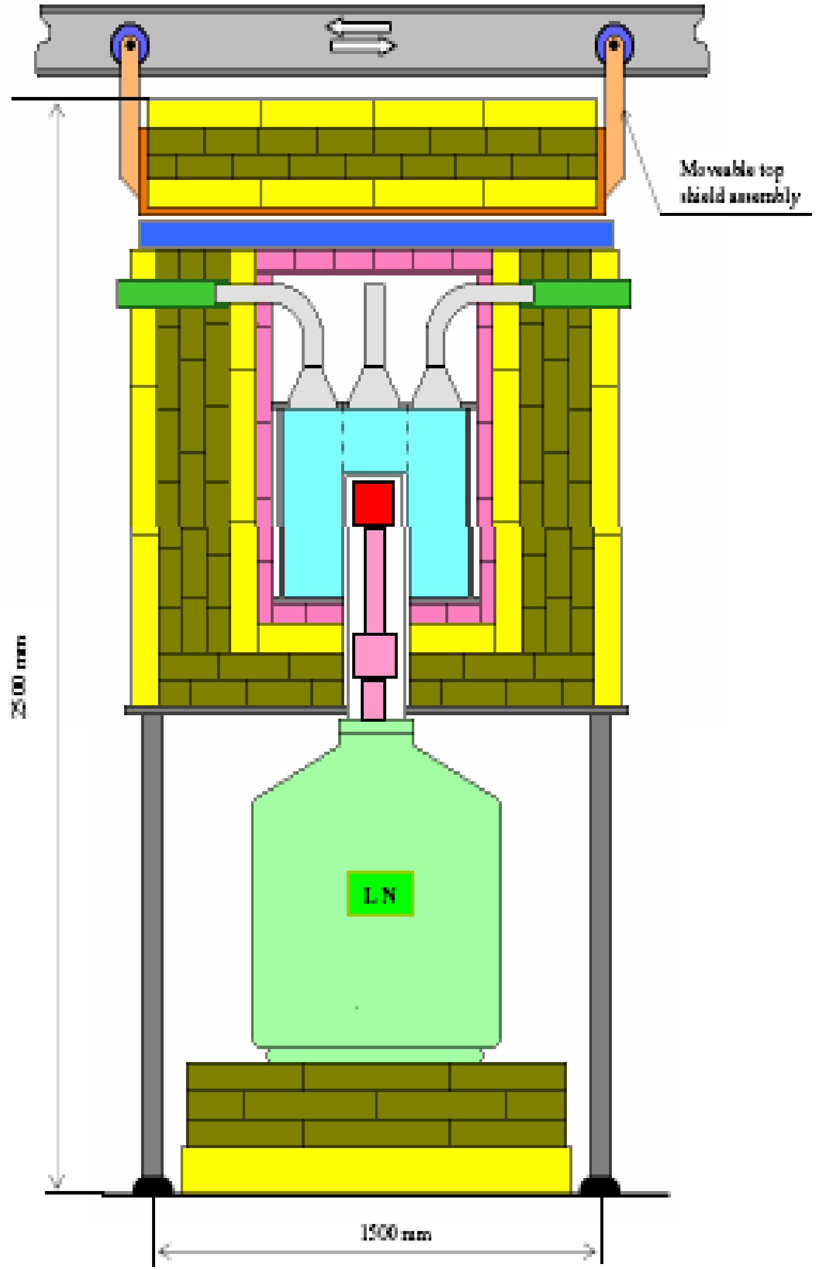


Experiment GEMMA

(Germanium Experiment for measurement of Magnetic Moment of Antineutrino)

*[Phys. of At. Nucl.,**67**(2004)1948]*

- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding : electrolytic copper, borated polyethylene and lead.



Experimental sensitivity

$$\mu_\nu \propto \frac{1}{\sqrt{N_\nu}} \left(\frac{B}{mt} \right)^{\frac{1}{4}}$$

- N_ν : number of signal events expected
- B : background level in the ROI
- m : target (=detector) mass
- t : measurement time

$N_\nu \sim \varphi_\nu$ (~ Power / r^2)
~ (T_{max} - T_{min} / T_{max} * T_{min})$^{1/2}$

GEMMA I

- φ_ν ~ 2.7×10^{13} ν / cm² / s
- t ~ 4 years
- B ~ 2.5 keV^{-1} kg^{-1} day^{-1}
- m ~ 1.5 kg
- T_{th} ~ 2.8 keV

$$\mu_\nu \le 2.9 \times 10^{-11} \mu_B$$

Data Set

- I phase – 5184 h ON, 1853 h OFF

[redacted]

- II phase – 6798 h ON, 1021 h OFF
- I+II – 11982 h ON, 2874 h OFF

[redacted]

- III phase – 6152 h ON, 1613 h OFF
- I+II+III – 18134 h ON, 4487 h OFF

[redacted]

Beda A.G. et al. **// Advances in High Energy Physics. 2012. V. 2012, Article ID 350150.**
Beda A.G. et al. **// Physics of Particles and Nuclei Letters, 2013, V. 10, №2, pp. 139–143.**

GEMMA II

- φ_ν ~ 5×10^{13} ν / cm^2 / s
- t ~ 2 years
- B ~ 0.5–1.0 $keV^{-1}kg^{-1}day^{-1}$
- m ~ 6 kg (two detectors)
- T_{th} ~ 1.5 keV

$$\mu_\nu \le 1.0 \times 10^{-11} \mu_B$$

Бруно Понтекорво

1913-1993

August 22, 2013
was the birth centenary of Bruno Pontecorvo

- Since 1950,
 Bruno Pontecorvo
 lived in Russia and
 was staff member of
 Joint Institute for Nuclear Research, Dubna

- During 1966 - 1986 Bruno Pontecorvo was Head of Department of Particle Physics and member of Scientific Council at Faculty of Physics of Moscow State University

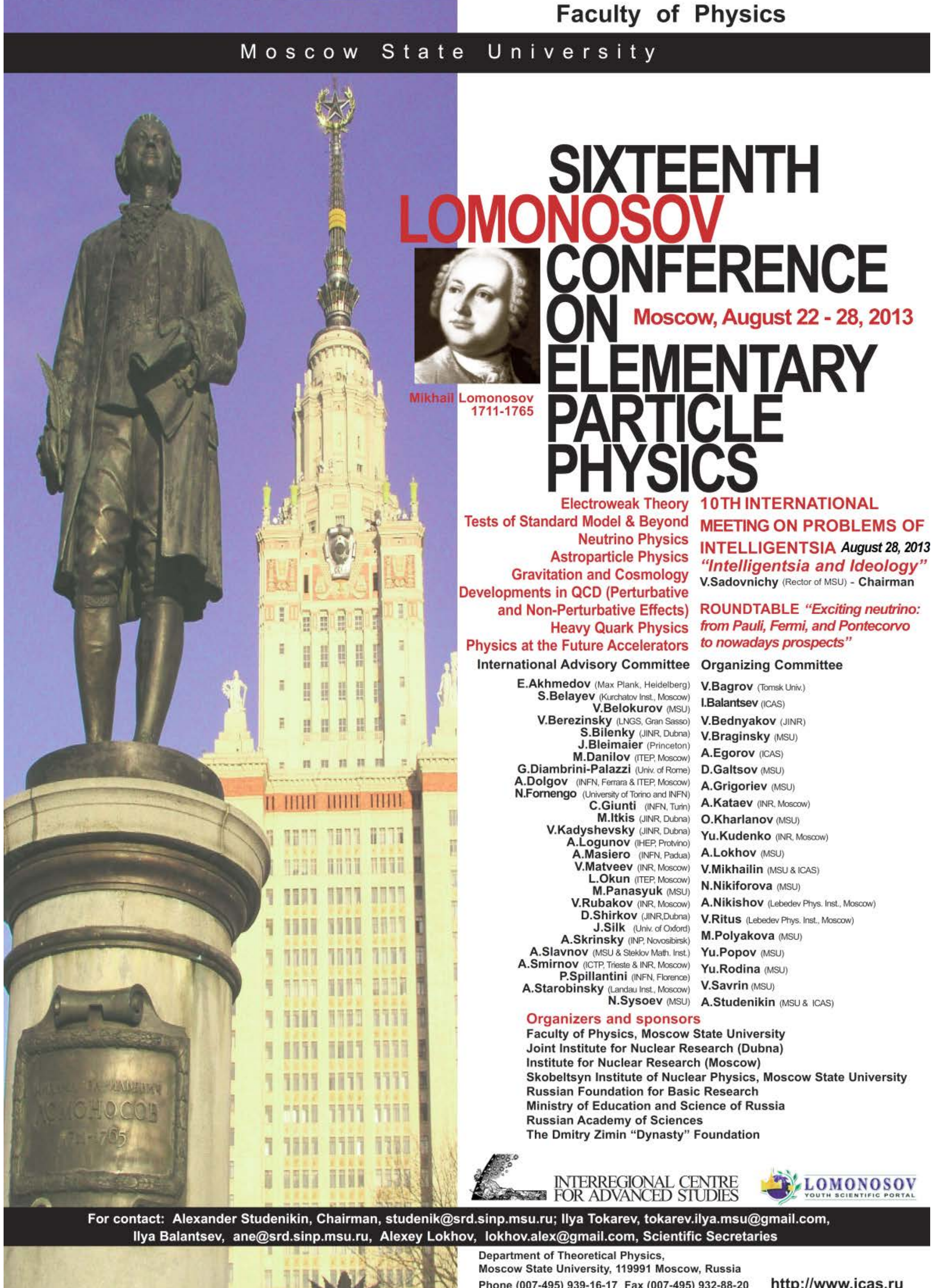
16th Lomonosov Conference on Elementary Particle Physics,

www.icas.ru

Moscow State University,

August 22-28, 2013

Dedicated to the birth centenary of Bruno Pontecorvo



17th Lomonosov Conference on Elementary Particle Physics,

www.icas.ru

Moscow State University,

August 20-26, 2015

Dedicated to

The Year of Light

(United Nations)

Maxwell (1865)

Einstein (1905, 1915)

Penzias & Wilson (1965)