Experimenal limits on neutrino magnetic moments (Borexino results)

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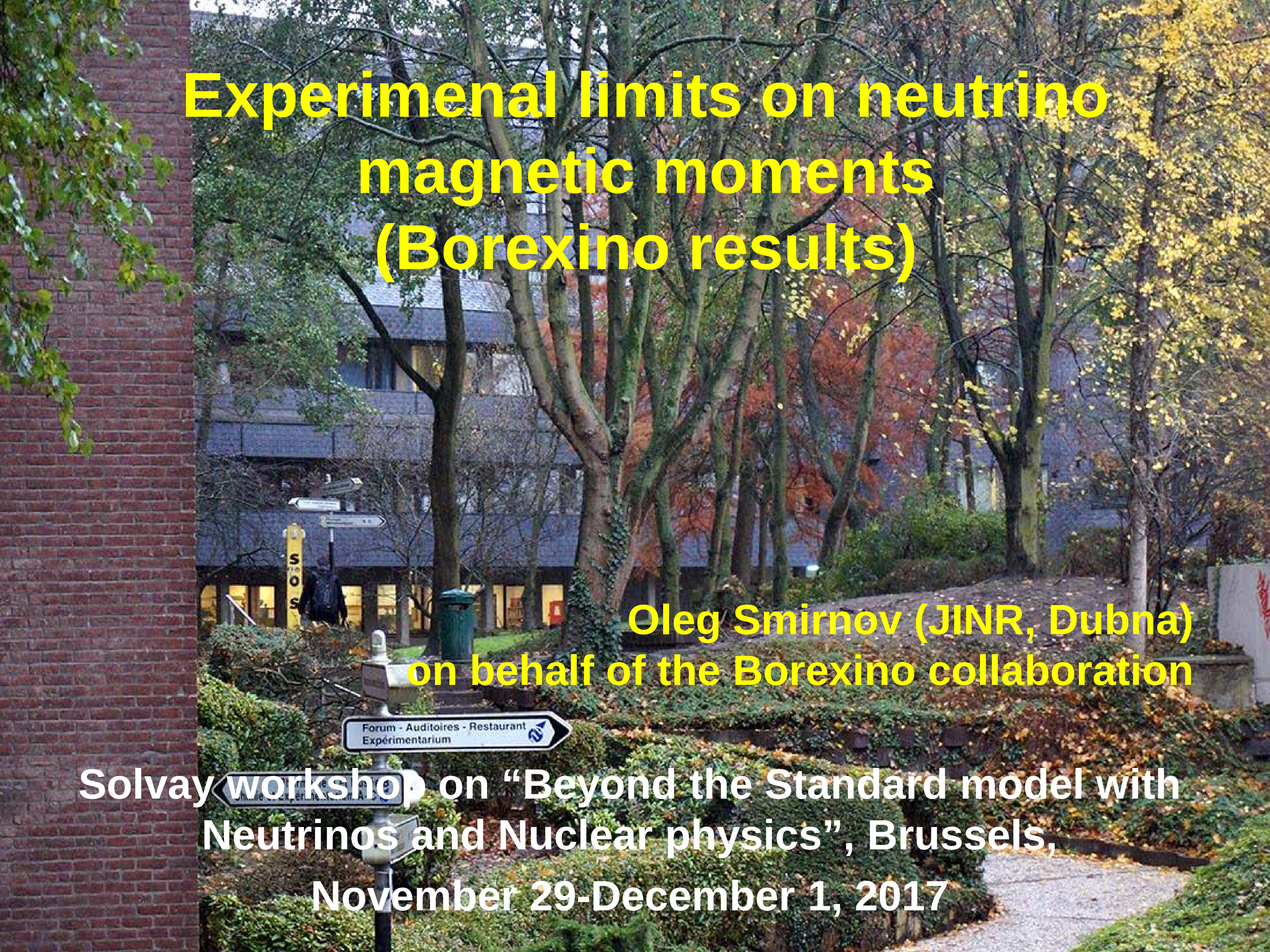
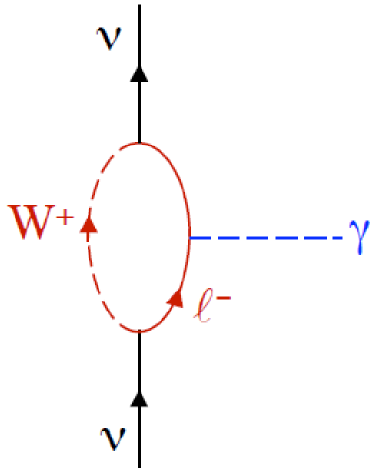
on behalf of the Borexino collaboration

Solvay workshop on “Beyond the Standard model with Neutrinos and Nuclear physics”, Brussels, November 29-December 1, 2017



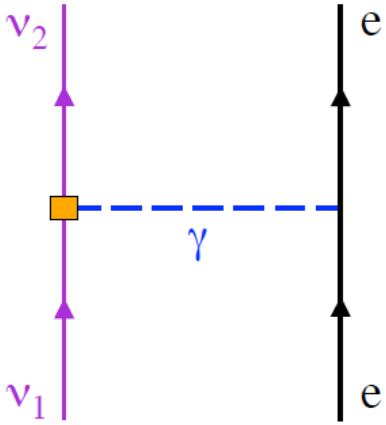
neutrino dipole magnetic moment



For Dirac neutrino loop-diagrams of a kind produce a magnetic dipole moment. Majorana neutrino can't have one

neutrino transition magnetic moment

For **Dirac** neutrino case transition magnetic moments cause transitions between left–handed neutrinos of a given flavour and right–handed (sterile) neutrinos of a different flavour.



For **Majorana** neutrino the spin–flavour precession due to transition magnetic moments induces transitions between left–handed neutrinos of a given flavour and right–handed antineutrinos of a different flavour which are not sterile.

Neutrino Magnetic Moment Upper Limit*

Clyde L. Cowan, Jr., and Frederick Reines
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received April 11, 1957)

A giant liquid scintillation detector was employed in a fission-reactor neutrino flux to set an upper limit of 10^{-9} Bohr magneton for the neutrino magnetic moment. The experiment consisted in searching for a count-rate difference associated with the reactor neutrinos.

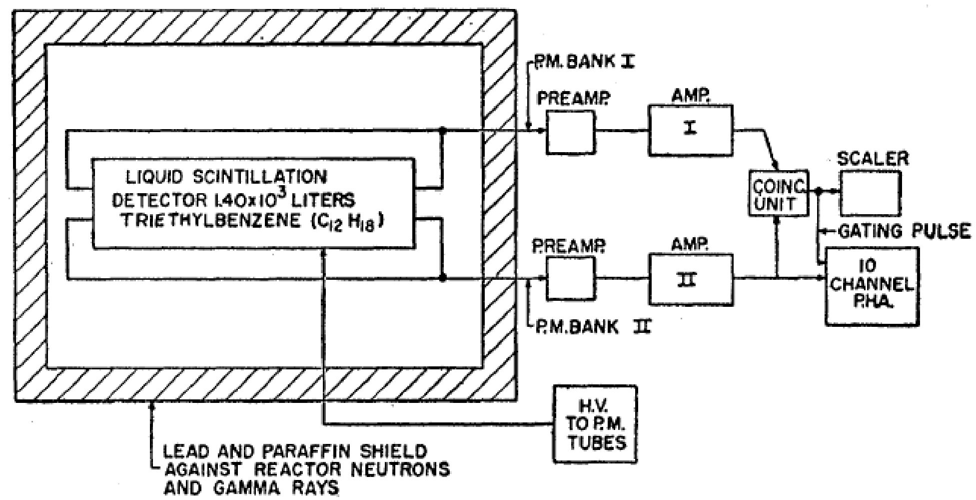


Fig. 2. Schematic diagram of the experimental arrangement.

The interest to neutrino MM was revived as a SFP solution of SNP

The spin flavour precession (SFP), based on the interaction of the neutrino magnetic moment with the solar magnetic field was the second (after the MSW) most attractive scenario for the SNP solution.

In particular it was giving a natural explanation of the "confusing 11 year modulation" of the solar neutrino flux

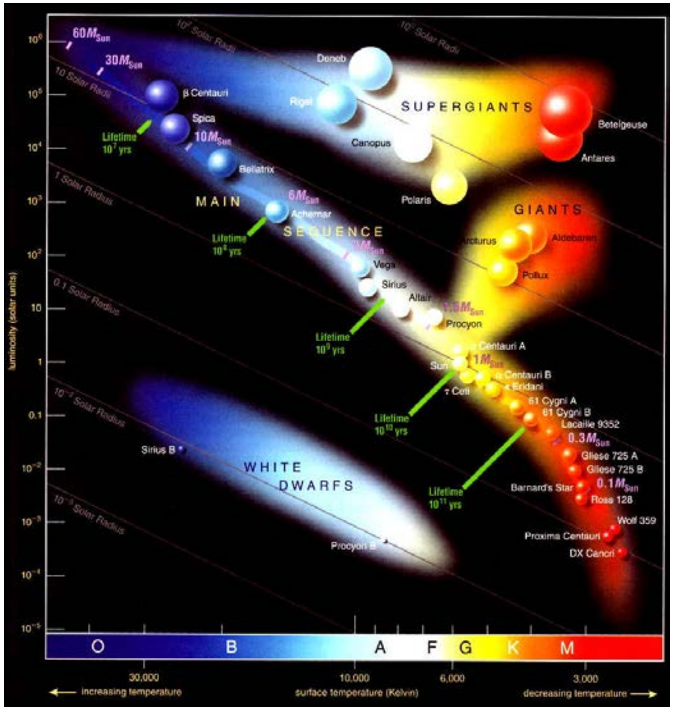
Neutrinos with transition magnetic moments experience a simultaneous rotation of their spin and flavour in a transverse magnetic field (spin–flavour precession). In vacuum, such a precession is suppressed, but in matter a resonant enhancement of the spin–flavour precession is possible. The RSFP of neutrinos is similar to resonant neutrino oscillations (MSW).

- May still be present as a subdominant process, provided neutrinos have a sizeable transition magnetic moment.
- Neutrino magnetic moment provides another mechanism for astrophysical bodies to cool.

Strongest limits come from astrophysical considerations

- G.G. Raffelt, Astrophysical Journal, 365, p.559 (1990), analysis of RG branch:

  $\boldsymbol{\mu_\nu < 3.0 \cdot 10^{-12}\ \mu_B}$ (nominally at 3σ level)
- Similar limits are obtained from analysis of WD
- For a supernova(SN), left-handed (Dirac) neutrinos are trapped and right-handed neutrinos are not, this would mean a very efficient cooling mechanism.
- Similarly, the analysis of big bang nucleosynthesis puts limits on the magnetic moment for Dirac neutrinos.



a Majorana neutrino with a MM could be transformed into an antineutrino of a different flavour in an external electromagnetic field. (The lack of) the observation of the antineutrino flux from the Sun can be used.

SFP+oscillations

- Could lead to appearance of the electron antineutrino in the Solar neutrino flux, schematically:

$$\nu_{eL} \to \nu_{\mu L} \to \bar{\nu}_{eR} \quad \text{(osc+SFP)}$$

$$\nu_{eL} \to \bar{\nu}_{\mu R} \to \bar{\nu}_{eR} \quad \text{(SFP+osc)}$$

- A search for electron antineutrino has been performed by Borexino

(Physics Letters B 696 (2011) 191)

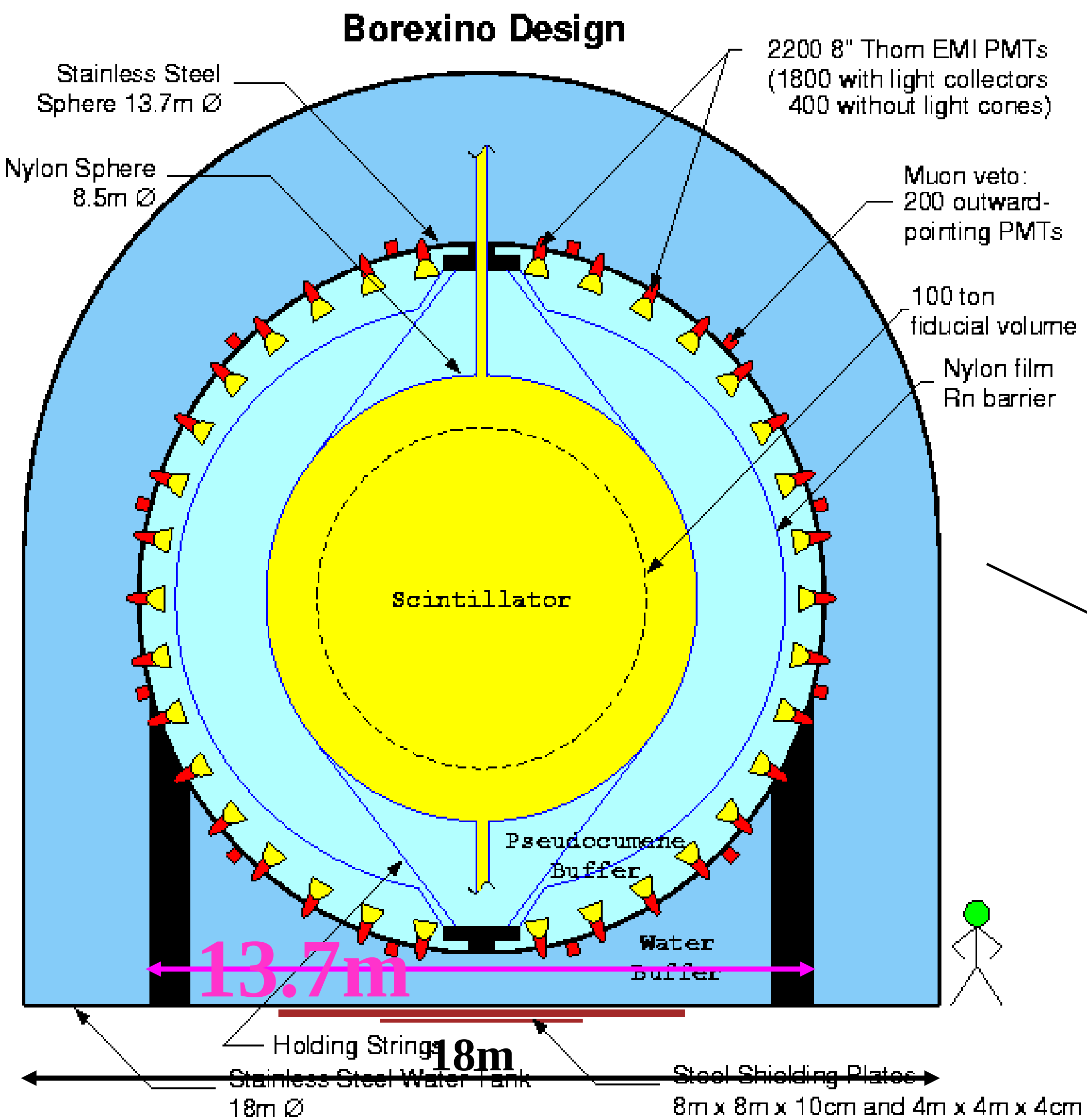
New limits have been set on the possible $\overline{\nu}$ admixture in the ^{8}B solar neutrino flux. In particular:

$p(\nu \to \overline{\nu}) < 1.7 \cdot 10^{-4}$ (90% C.L.) for $E_{\overline{\nu}} > 7.3$ MeV

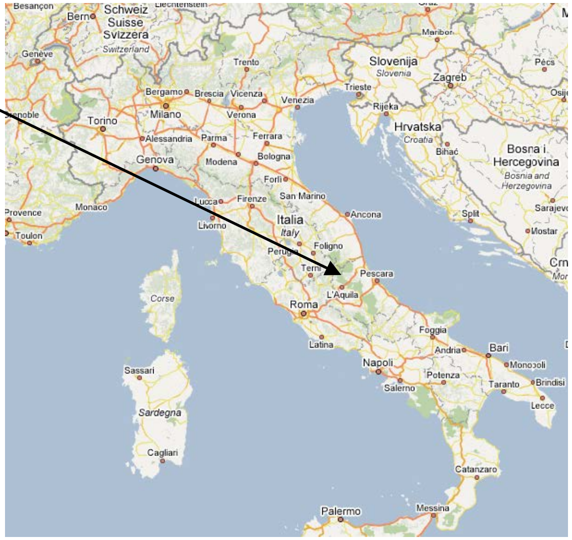
$p(\nu \to \overline{\nu}) < 1.3 \cdot 10^{-4}$ (90% C.L.) for the whole ^{8}B energy region, and

$p(\nu \to \overline{\nu}) < 0.35$ (90% C.L.) for 862 keV ^{7}Be neutrinos.

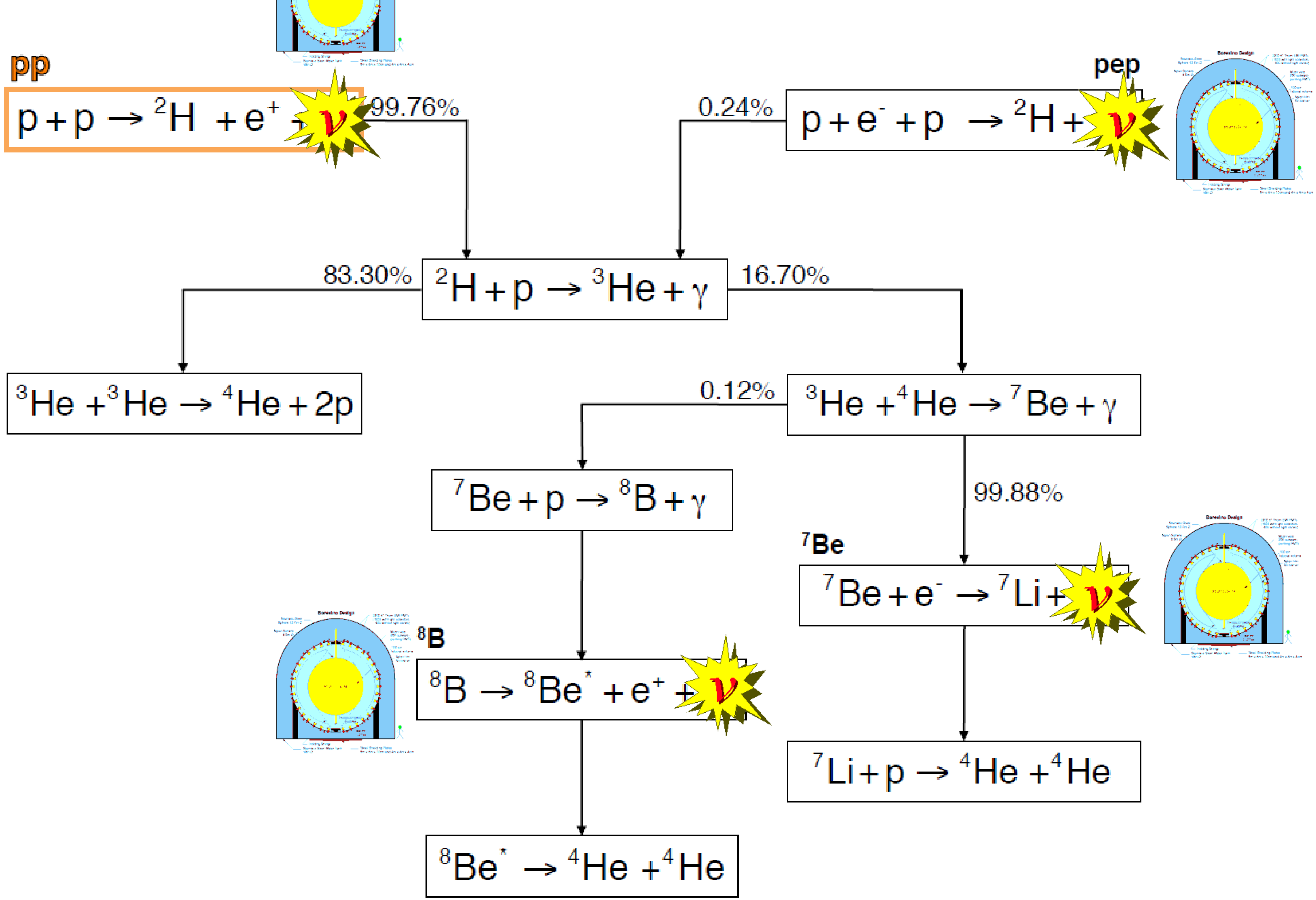
BOREXINO *(in operation from May,2007)*



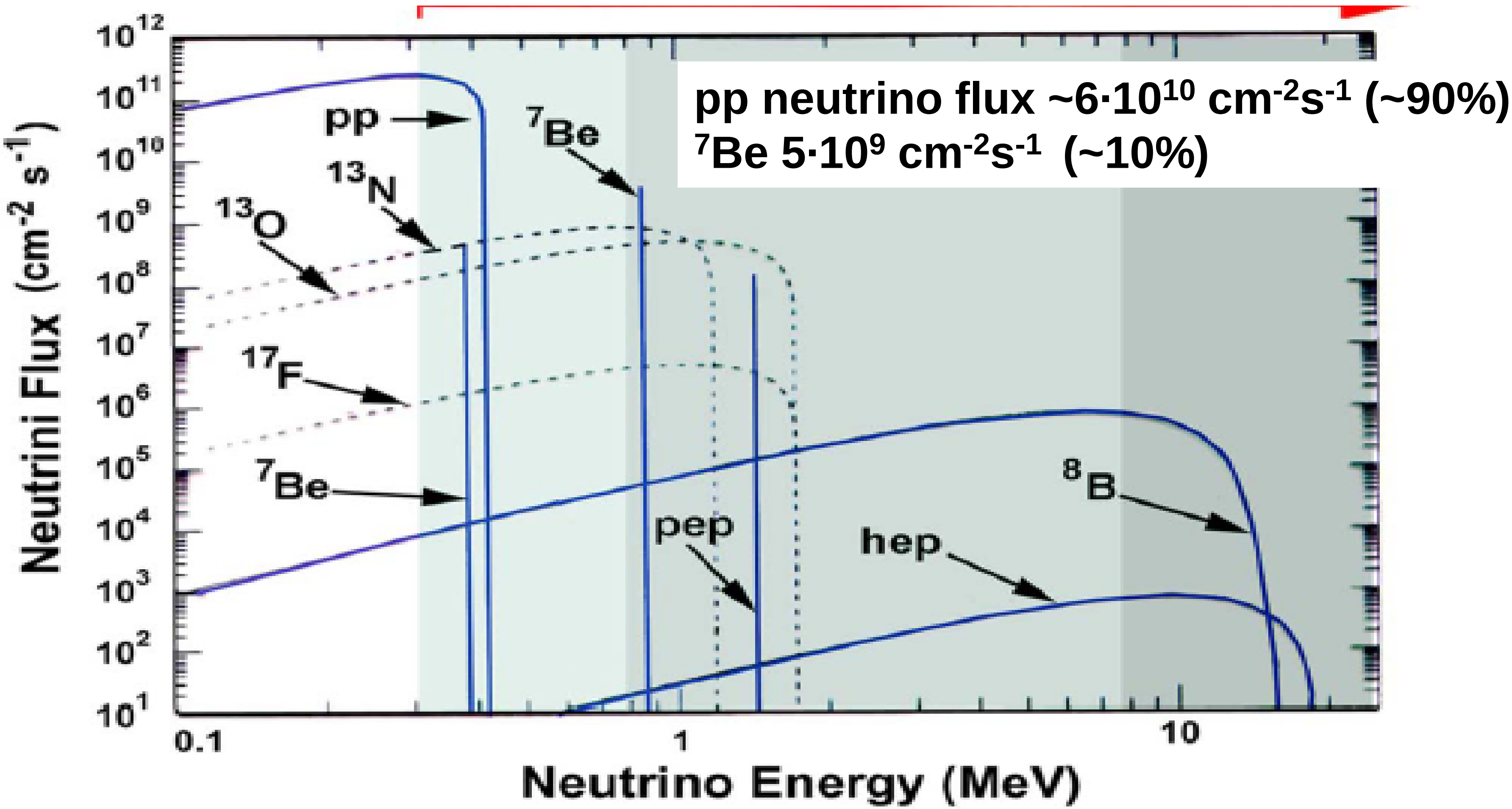
- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with low threshold (~200 keV)
- Outer muon detector



pp-chain



pp
$p + p \rightarrow {}^2H + e^+ + \nu$
99.76%
pep
0.24%
$p + e^- + p \rightarrow {}^2H + \nu$
83.30%
$^2H + p \rightarrow {}^3He + \gamma$
16.70%
$^3He + {}^3He \rightarrow {}^4He + 2p$
0.12%
$^3He + {}^4He \rightarrow {}^7Be + \gamma$
$^7Be + p \rightarrow {}^8B + \gamma$
99.88%
^{7}Be
$^7Be + e^- \rightarrow {}^7Li + \nu$
^{8}B
$^8B \rightarrow {}^8Be^* + e^+ + \nu$
$^7Li + p \rightarrow {}^4He + {}^4He$
$^8Be^* \rightarrow {}^4He + {}^4He$

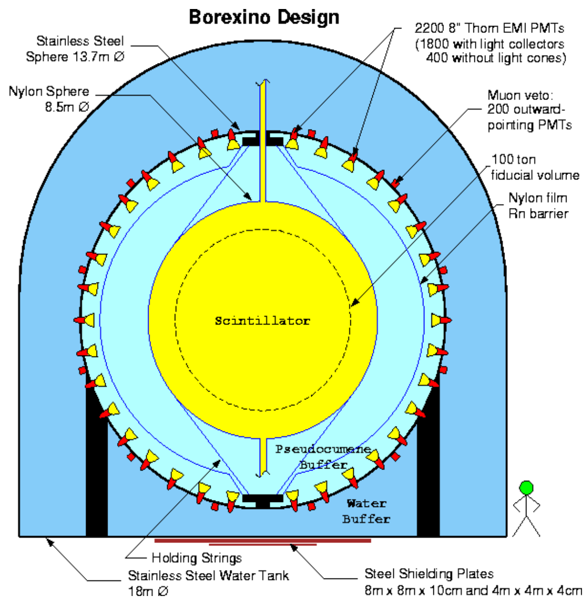


50 events/d/100t expected (ν_e and ν_μ elastic scattering on e^-) or $5 \cdot 10^{-9}$ Bq/kg (typically: drinking water ~10 Bq/kg; human body in ^{40}K: 5 kBq)

Low energy->no Cherenkov light->No directionality,

no other tags-> extremely pure scintillator needed

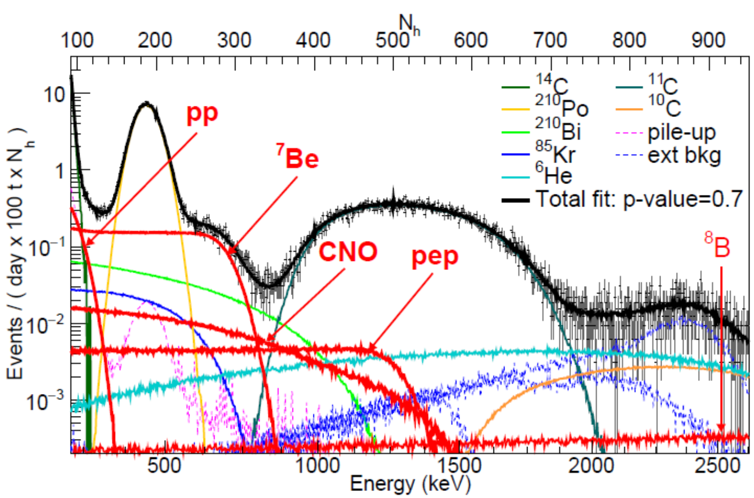
Borexino is spectroscopical detector



detects solar neutrino through **ν-e elastic scattering**

low threshold on recoil electrons;

Solar neutrino analysis (spectral fit) is performed assuming SM cross sections



any non-standard interaction (including EM interaction of neutrino with electrons due to the anomalous magnetic moment) would change cross section and/or shape of the detector’s response

Neutrino interactions due to the magnetic moment

In simple extension of SM Dirac (Fujikawa and Shrock, 1980 PRL 45 963) neutrino gains very small μ_ν (proportional to m_ν):

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

Note: expression holds for diagonal elements of the MM matrix. Non-diagonal elements are even smaller because of the flavour changing

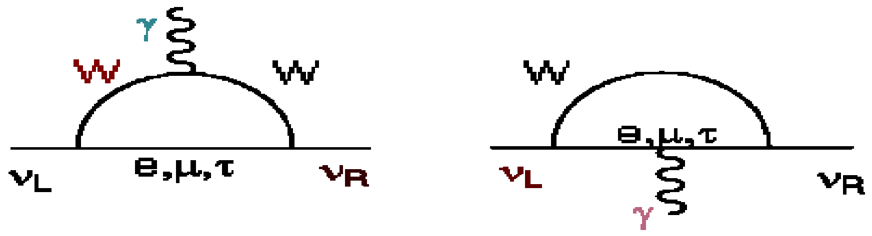
EM diff. cross section is proportional to μ_ν^2 :

$$\frac{d\sigma_{EM}}{dT_e}(T_e, E_\nu) = \pi \, r_0^2 \, \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right)$$

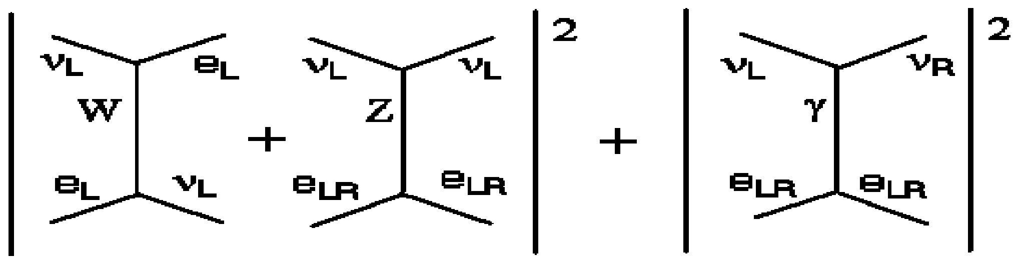
and has $\frac{1}{T_e}$ behaviour (very different from “flat” EW) , which makes possible the search for the EM contribution to the nu-e cross section. Low threshold is an advantage.

Because of the neutrino mixing, the term “effective” is used for the magnetic moment of solar neutrino detected at the Earth.

Neutrino-electron elastic scattering is the most sensitive process in search for the neutrino magnetic moment



a)

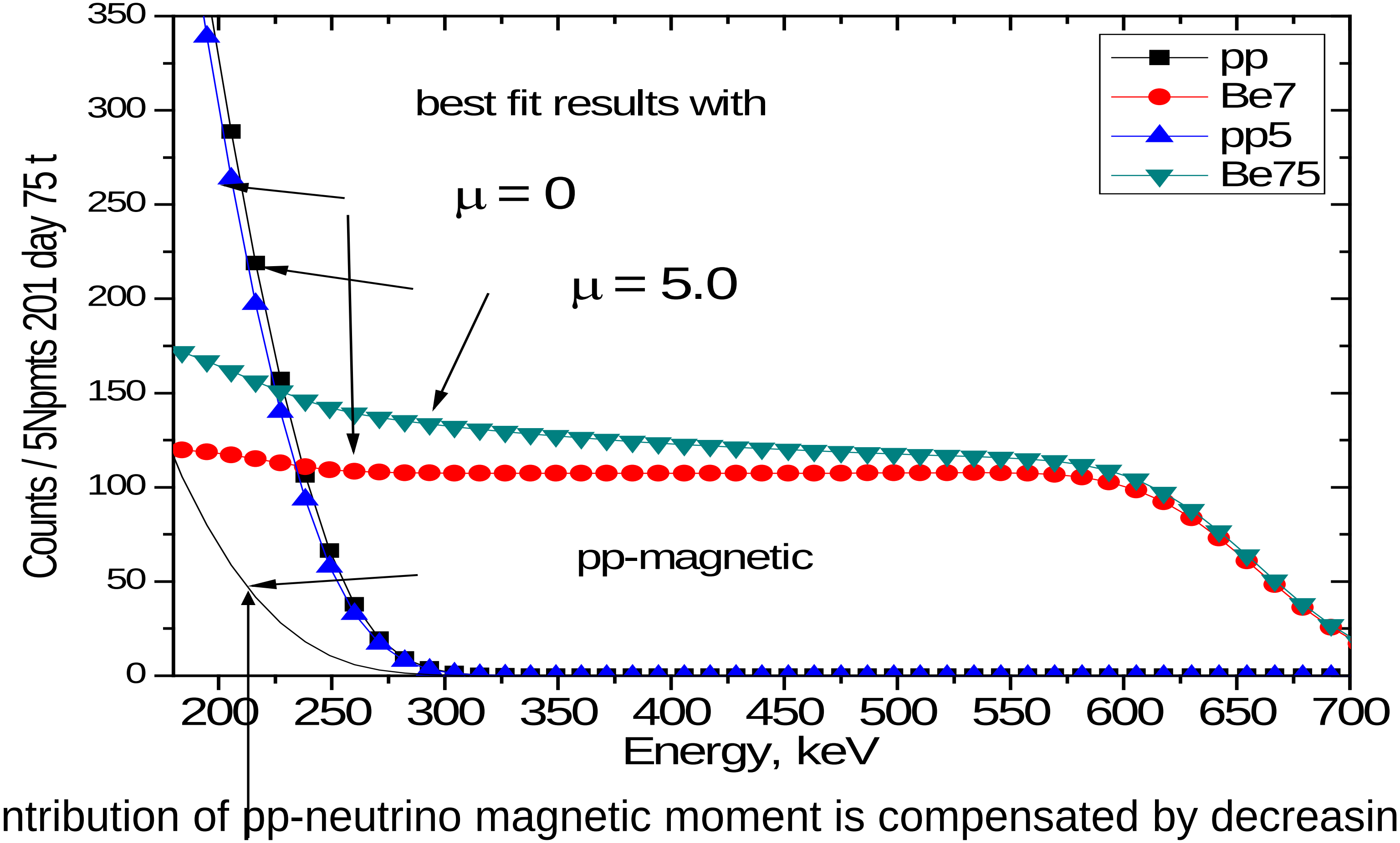


EW

EM

EM scattering is helicity flipping -> no interference with standard EW, so the total c.s. is sum of two contribution.

The Borexino response to pp- and ^{7}Be-neutrino with $\mu = 0$ and $\mu=5.0\text{x}10^{-11}\mu_B$.



Contribution of pp-neutrino magnetic moment is compensated by decreasing of pp-flux. The basic reason of increasing of X^2 is the changes in the shape of ^{7}Be-neutrino spectrum due to magnetic moment. Because pp-flux is measured by independent (radiochemical) experiments not sensitive to the MM we can apply additional constraint in the fit.

Updating neutrino magnetic moment constraints

B.C. Cañas [a], O.G. Miranda [a,*], A. Parada [b], M. Tórtola [c], J.W.F. Valle [c]

Physics Letters B 753 (2016) 191–198

$\mu < 3.1\text{x}10^{-11}\ \mu_B$ using Borexino Phase I data

our estimate for the whole Phase I was even worse than published with 192 days ($\mu < 5.4\text{x}10^{-11}\ \mu_B$ [PRL 101, 091302 (2008)])

Correlations of the spectral components were not taken into account

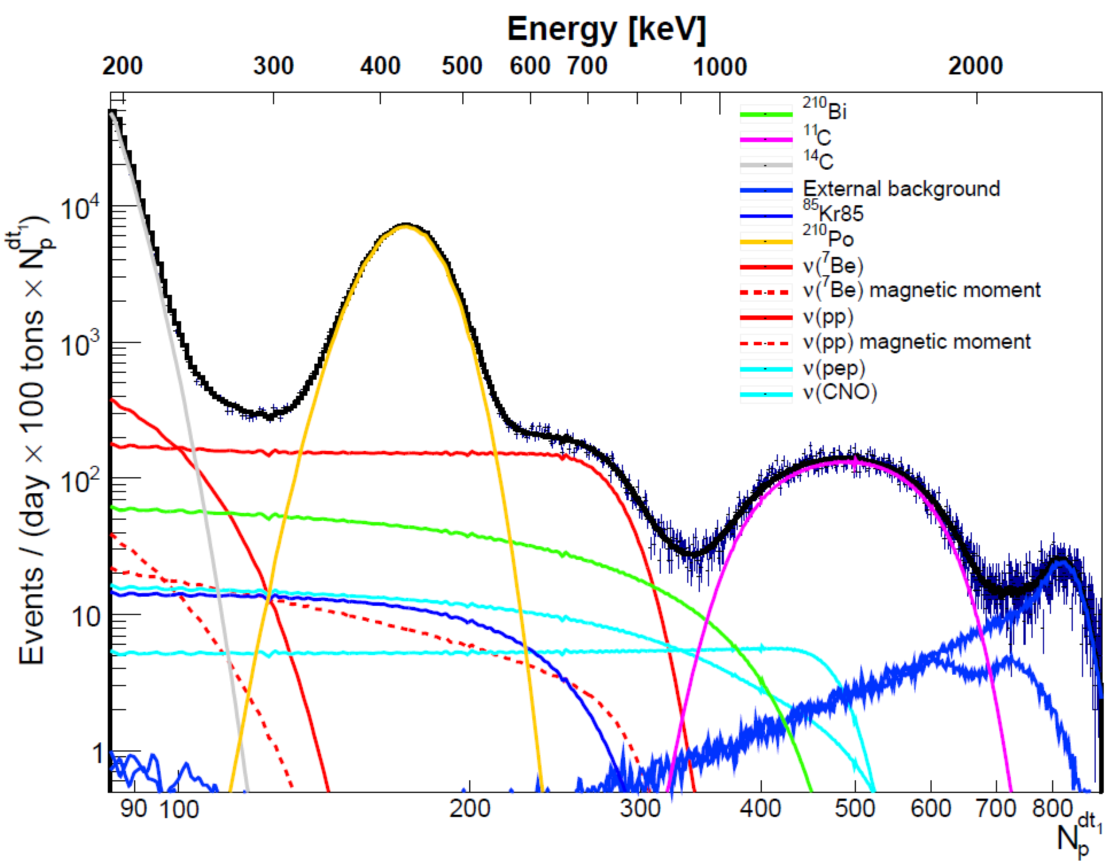
Physics Letters B 757 (2016) 568

Addendum

Addendum to "Updating neutrino magnetic moment constraints" [Phys. Lett. B 753 (2016) 191–198]

B.C. Cañas [a], O.G. Miranda [a,*], A. Parada [b], M. Tórtola [c], J.W.F. Valle [c]

"Standard" fitting procedure has been applied



The analytical model function has in total 15 free parameters. The free parameter describing the energy scale and resolution are the light yield, two free parameters are used for resolution.

Other parameters describe the rates of dominant backgrounds. The pp and ^{7}Be interaction rates represent the solar neutrino parameters. The remaining free parameters describe the position and width of the ^{210}Po α-peak, and the starting point of the ^{11}C β+-spectrum.

Radiochemical (Ga) constraints

Measured in Ga experiments (SAGE+Gallex/GNO)

$$R = \sum_i R_i = \sum_i \Phi_i \int_{E_{th}}^{\infty} s_i^{\odot}(E) P_{ee}(E)\sigma(E)dE = \sum_i \Phi_i \langle \sigma^{\odot}{}_i \rangle = 66.1 \pm 3.1 \text{ SNU}$$

Applied to Borexino and taking into account the new estimates of <σ>$_i$:

$$\sum_i \frac{R_i{}^{Brx}}{R_i{}^{Expected}} R_i{}^{Ga} \frac{\langle \sigma^{\odot}{}_i \rangle_{new}}{\langle \sigma^{\odot}{}_i \rangle_{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}$$

Where $R_i{}^{Ga}$ is corresponding estimate of the rate from Ga paper, and $\delta_R = \sum_i \left(\Delta R_i{}^{Ga}\right)^2 \approx 4\%$ is total error coming from the errors in estimate of single rates contributing to Ga experiments (including error on $\langle \sigma^{\odot}{}_i \rangle_{new}$, but excluding error on $\langle \sigma^{\odot}{}_i \rangle_{old}$). The expected rates should be calculated for the same SSM choice. $\delta_{FV} \approx 1\%$ is uncertainty of the FV selection

Borexino results with 1291 days of Phase-II data

Without Ga constraint: $\mathbf{\mu_\nu < 4.0 \cdot 10^{-11}\ \mu_B}$**,** 90% C.L.

With Ga constraint: $\mathbf{\mu_\nu < 2.6 \cdot 10^{-11}\ \mu_B}$**,** 90% C.L.

Obtained studying the likelihood profile

Systematics study

Two types of fixed initial conditions/parameters: discrete and bounded at their central values.

Discrete parameters:

- energy estimator (50/50)
- pile-up model (50/50)
- Solar metallicity (50/50)

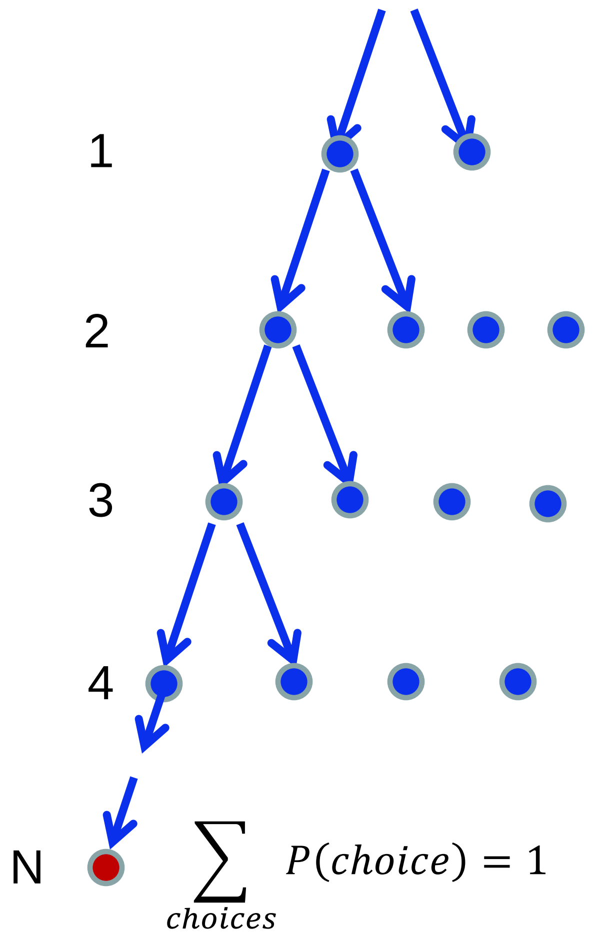
Bounded parameters:

k_B, f_{Ch} etc (see devoted posters for details)

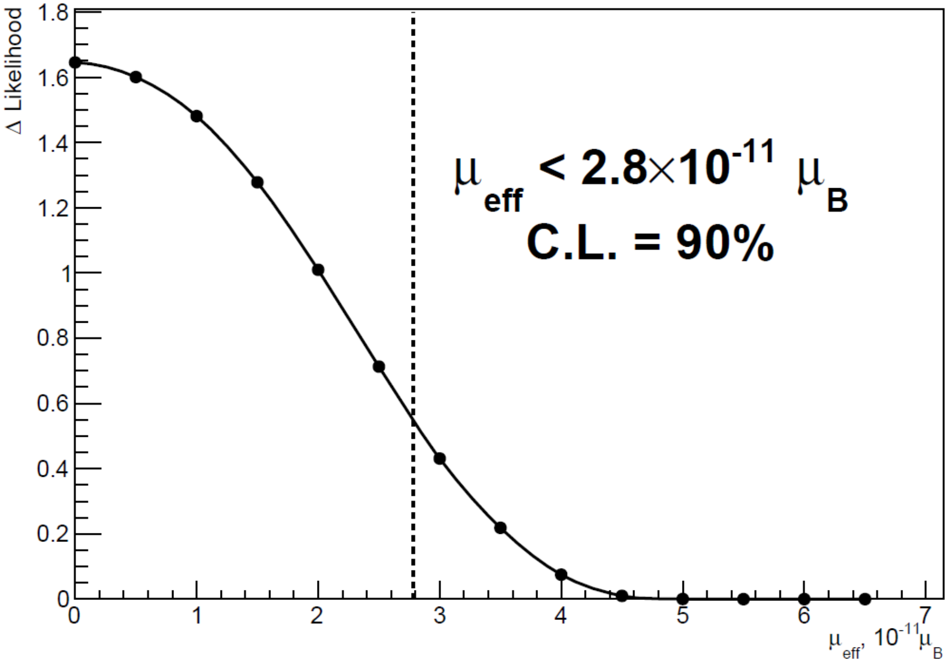
The final profile is a weighted sum of individual profiles

$$P(\mu) = \sum_{choices} w(choice)\, Lkl_{fit}(choice, \mu)$$

Where $\mathrm{w(choice)} = P(choice) Lkl_{fit}(choice, \mu_\nu = 0)$



Including the systematics



main contributions comes from the difference in results depending on the choice of energy estimator (npmt, 230 and 400 ns) and the approach used for the pile-up modelling (convolution vs synthetic).
Since pep- and CNO- neutrino rates are fixed to the SSM predictions, the different rates corresponding to high/low metallicity models are also accounted for in the systematics.

The resulting likelihood profile is the weighted sum of the individual profiles of each fit configuration. Initially, the same weights are used for the pile-up, energy estimator, and SSM choice, assuming equal probabilities for all 8 possibilities. Further weights are assigned proportionally to the maximum likelihood of each profile, therefore taking into account the quality of the realization of the model with a given set of parameters.

Neutrino mixing leads to effective magnetic moment which can depends on energy of neutrino (and source-detector distance)

$$\frac{d\sigma}{dT_e} = \pi r_0^2 \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right)$$

Since neutrinos are a mixture of mass eigenstates the effective magnetic moment for neutrino-electron scattering is

$$\mu_{eff}^2 = \sum_j \left| \sum_k \mu_{jk} A_k (E_\nu, L) \right|^2$$

μ_{ij} is an element of the neutrino electromagnetic moments matrix
A_k is the amplitude of the k-mass state at the point of scattering.

For the Majorana neutrino only the transition moments are non-zero, while the diagonal elements of the matrix are equal to zero due to CPT-conservation.
For the Dirac neutrino, all matrix elements may have non-zero values.

The effective magnetic moment can be expanded both in terms of the mass eigenstates (this is more natural) or the flavour eigenstates.

Effective moments

- In reactor (short base) experiments:

$$(\mu_\nu)_e{}^2 = \sum_\alpha |\mu_\nu{}^{e\alpha}|^2$$

- In solar neutrino experiments we measure:

$$(\mu_\nu)_{eff}{}^2 = \sum_\alpha P_{e\alpha} (\mu_\nu)_\alpha{}^2$$

- Astrophysical models (energy loss in stars):

$$\mu_\nu{}^2 = \sum_{\alpha,\beta} \left|\mu_\nu{}^{\alpha\beta}\right|^2$$

MM of mass eigenstates

the solar neutrinos arriving at the Earth can be considered as an incoherent mixture of mass eigenstates (otherwise the interference terms should be considered). In the case of Dirac neutrinos assuming that only diagonal magnetic moments are non-vanishing:

$$\mu^2{}_{eff} = P^{3\nu}{}_{e1}\mu^2{}_{11} + P^{3\nu}{}_{e2}\mu^2{}_{22} + P^{3\nu}{}_{e3}\mu^2{}_{33}$$

${P_{e_i}}^{3v}$ is the probability of observing the i-mass state at the scattering point for an initial electron flavour.

In the case of Majorana transition magnetic moments the effective moment is:

$$\mu^2{}_{eff} = P^{3\nu}{}_{e1}(\mu^2{}_{12} + \mu^2{}_{13}) + P^{3\nu}{}_{e2}(\mu^2{}_{21} + \mu^2{}_{23}) + P^{3\nu}{}_{e3}(\mu^2{}_{31} + \mu^2{}_{32})$$

Limits on MM in mass eigenstates basis

Using

$P^{3\nu}{}_{e1} = \cos^2\theta_{13} P^{2\nu}{}_{e1}$, $P^{3\nu}{}_{e2} = \cos^2\theta_{13} P^{2\nu}{}_{e2}$ and $P^{3\nu}{}_{e3} = \sin^2\theta_{13} P^{2\nu}{}_{e3}$

and P_{ee} and data for θ_{12} and θ_{13} from the PDG-16 compilation (assuming the independence of probabilities on energy) we obtain:

$$|\mu_{11}| \leq 3.4 \quad |\mu_{22}| \leq 5.1 \quad |\mu_{33}| \leq 18.7$$

$$|\mu_{12}| \leq 2.8 \quad |\mu_{13}| \leq 3.4 \quad |\mu_{23}| \leq 5.0$$

All measured in units of $10^{-11}\mu_B$ and for 90% C.L.

MM of flavour states

In frames of the MSW/LMA solution:

$$\mu^2{}_{eff} = P^{3\nu}\mu^2{}_e + (1 - P^{3\nu})(\cos^2\theta_{23}\,\mu^2{}_\mu + \sin^2\theta_{23}\mu^2{}_\tau)$$

Where $P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13}P^{2\nu}$ is the electron neutrino survival probability. Though P_{ee} depends on energy, the difference between P(400)=0.57 and P(862)=0.55 is negligible. We use P(862) since it provides bigger contribution to the sensitivity.
Using PDG-16 values we obtain:

$$\mu_{\nu_{\boldsymbol{e}}} < 3.9 \cdot 10^{-11}\mu_B$$
$$\mu_{\nu_{\boldsymbol{\mu}}} < 5.8 \cdot 10^{-11}\mu_B$$
$$\mu_{\nu_{\boldsymbol{\tau}}} < 5.8 \cdot 10^{-11}\mu_B$$

all at 90% C.L.

Conservative “unfortunate” choice of mass hierarchy applied

Comparison with other experiments:

Reactor experiments:

- TEXONO:

$$\mu_\nu < 7.4 \cdot 10^{-11} \mu_B, \text{ 90\% C.L.}$$

H. T. Wong et al., *Phys. Rev.D* ***75,*** *012001 (2007)*

- GEMMA:

$$\mu_\nu < 2.9 \cdot 10^{-11} \mu_B, \text{ 90\% C.L.}$$

A.G. Beda et al., Phys. of Part. and Nuclei Lett, Vol. 10, p.139 (2013)

Solar experiments (different neutrino mixtures):

- SuperK: $\mu_\nu{}^{eff} < 11 \cdot 10^{-11} \mu_B$, 90% C.L.

D.W. Liu *et al., Phys. Rev. Lett. 93, 021802 (2004)*

- Borexino: $\mu_\nu{}^{eff} < 2.8 \cdot 10^{-11} \mu_B$, 90% C.L.
  - with $\mu_{\nu_e} < 3.9 \cdot 10^{-11} \mu_B$

Comparison with other experiments:

Accelerator experiments:

- LSND:

$$\mu_{\nu_\mu} < 68 \cdot 10^{-11} \mu_B \textbf{,} \text{ 90\% C.L.}$$

Auerbach, L. B., *et al.*(2001), Phys. Rev. D63,112001.

- DONUT:

$$\mu_{\nu_\tau} < 3900 \cdot 10^{-11} \mu_B \textbf{,} \text{ 90\% C.L.}$$

Schwienhorst, R., et al. (2001), Phys. Lett. B513, 23

Compared to Borexino's:

$$\mu_{\nu_{\boldsymbol{\mu}}} < 5.8 \cdot 10^{-11} \mu_B, \text{ 90\% C.L.}$$

$$\mu_{\nu_{\boldsymbol{\tau}}} < 5.8 \cdot 10^{-11} \mu_B, \text{ 90\% C.L.}$$

Conclusions

New upper limits for the neutrino magnetic moments have been obtained using 1291.5 days of data from the Borexino Phase-II campaign by looking for distortions in the shape of the electron recoil spectrum.

A new model independent limit on effective magnetic moment of solar neutrino $\boldsymbol{\mu_\nu < 2.8 \cdot 10^{-11}\ \mu_B}$**,** 90% C.L.. is obtained using gallium constraints.

The limit is free from uncertainties associated with predictions from the SSM neutrino flux and systematics from the detector's FV.

The limit on the effective neutrino moment for solar neutrinos was used to set new limits on the magnetic moments for the neutrino flavour states and for the elements of the neutrino magnetic moments matrix for Dirac and Majorana neutrinos.