Studies of non-standard neutrino properties with Borexino

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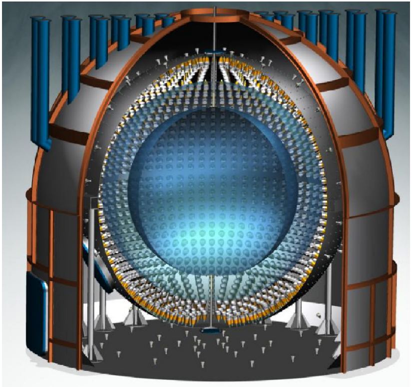
CNNP2020, 23-28/02/2020

Borexino detector

- **Location:** Laboratori Nazionali del Gran Sasso (Italy)
- **Primary goal:** measurements of solar neutrino fluxes at low energies
- **Energy threshold:** ~ 150 keV (recoil electrons)
- **Energy resolution:** $\sim 5\%$ @ 1 MeV
- **^{238}U abundance:** $< 9.4 \times 10^{-20}$ g/g
- **^{232}Th abundance:** $< 5.7 \times 10^{-19}$ g/g
- **Muon flux suppression:** $\approx 10^6$

More about Borexino: talk by A. Caminata on Thursday

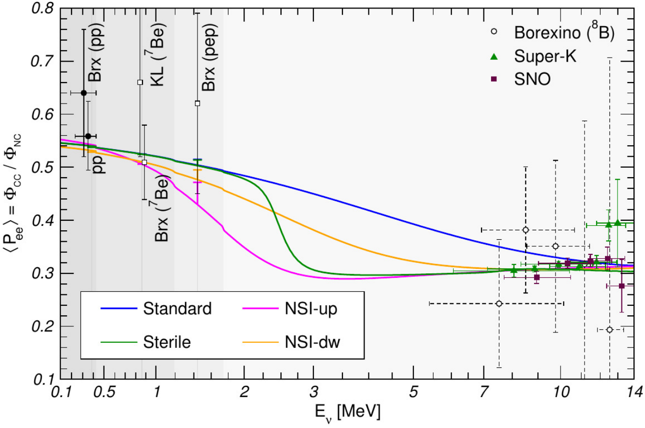


Detection techniques:

- Elastic scattering on e (ν, $\bar{\nu}$)
- inverse β-decay ($\bar{\nu}$)

Non-standard neutrino interactions: motivation

Non-standard interactions can change the observed survival probability curve of solar neutrinos



M. Maltoni, A. Smirnov, Eur. Phys. J. A52 (2016)

Neutral current NSI

$$f + \nu_\alpha \rightarrow f + \nu_\beta$$

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \varepsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha \gamma^\mu \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$\varepsilon^{fP}_{\alpha\beta}$ is the coupling constant

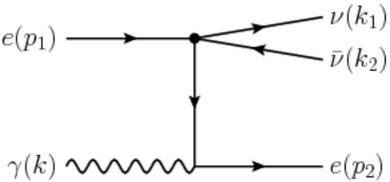
$$g^P_\alpha \rightarrow \tilde{g}^P_\alpha = g^P_\alpha + \varepsilon^P_{\alpha\beta}$$

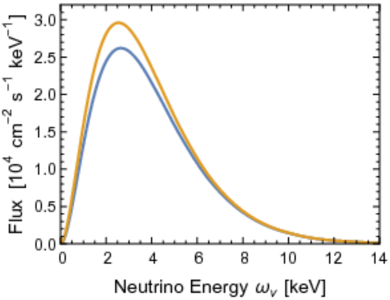
For solar neutrinos, NSI can occur at:

- **production:** bremsstrahlung and photo-production of $\nu\bar{\nu}$ pairs
  - energies below Borexino threshold
- **propagation:** shift of the MSW resonant energy
- **detection:** contribution to $\nu - e$ cross section

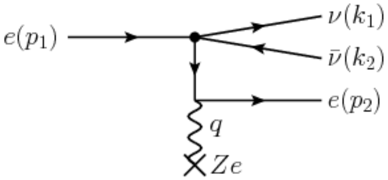
Production

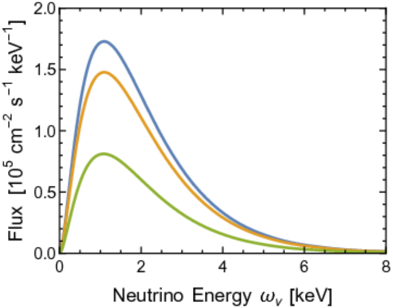
Photo-production





Bremsstrahlung

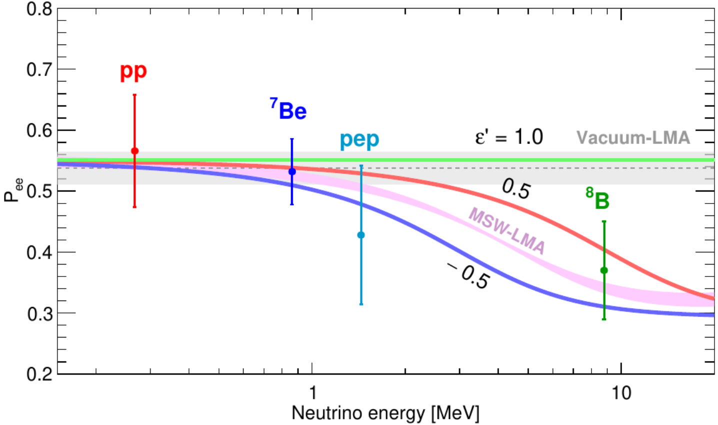




E. Vitagliano, J. Redondo and G. Raffelt, JCAP 1712 (2017) 010

Propagation

$$V_{\alpha\beta} = V_e \delta_{e\alpha}\delta_{e\beta} + \sqrt{2} G_F \sum n_f \varepsilon^f_{\alpha\beta}$$

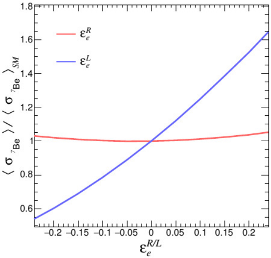


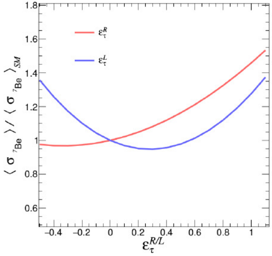
Resonant energy shift $E^{\odot}_{res} \simeq 2 \text{ MeV}/(1-\varepsilon')$,

where $\varepsilon' = \varepsilon^V_\tau \sin^2\theta_{23} - \varepsilon^V_e$, $\varepsilon^V_\alpha = \varepsilon^L_\alpha + \varepsilon^R_\alpha$

Detection

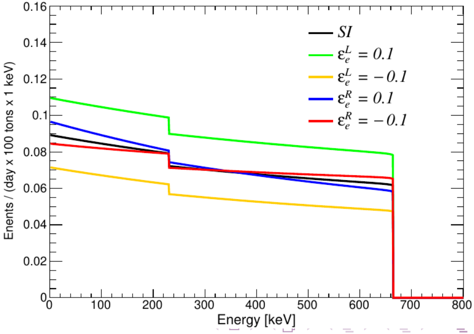
$\nu_e - e$ and $\nu_\tau - e$ cross sections $\Rightarrow$





ν_μ is not considered due to poor sensitivity w.r.t. CHARM-II

Example: electron recoil spectrum of ^7Be solar neutrinos



Elastic scattering data: event selection

Exposure: Phase II (Dec 2011 – May 2016, 1291.51 days)

Muon veto:

- 2 ms after crossing the outer detector
- 300 ms after crossing the inner detector

Fiducial volume:

- $R < 2.8$ m
- $-1.8 < z < 2.2$ m

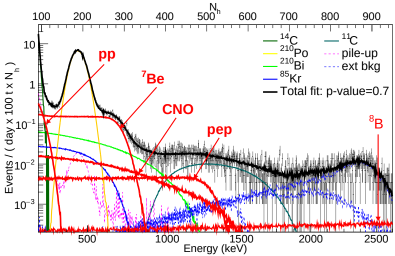
^{11}C **cut: three-fold coincidence (TFC)**

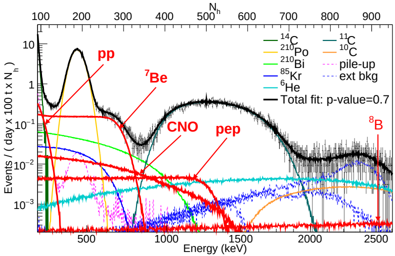
- muon event
- neutron capture
- β^{+} decay of ^{11}C

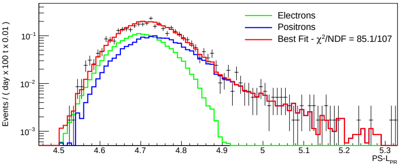
Energy estimator: number of PMTs triggered within

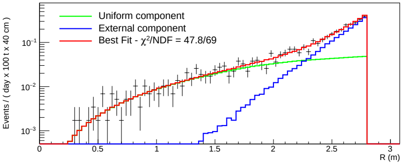
- 230 ns
- 400 ns

Elastic scattering data analysis: multivariate fit







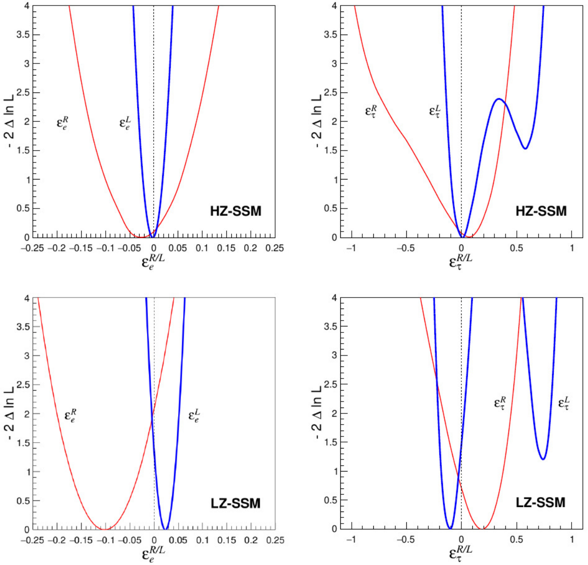


plots from:

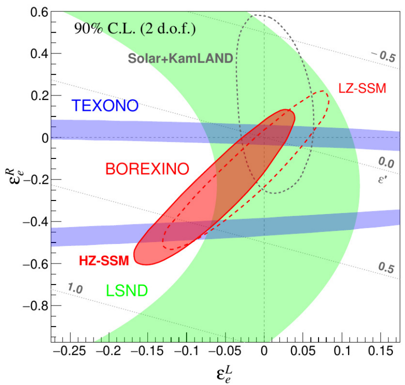
Agostini et al. (Borexino collaboration) Phys. Rev. D **100**, *082004 (2019)*

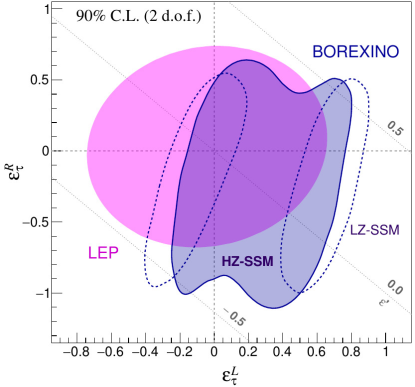
NSI parameters: single profiles

- solar neutrino fluxes from the Standard Solar Model
  N. Vinyoles et al. Astrophys. J ***835****, 202 (2017)*
  - high metallicity (HZ)
  - low metallicity (LZ)
- neutrino oscillation parameters from
  I. Esteban et al. JHEP ***01*** *087 (2017)*



Final results: ε_e, ε_τ and θ_W





$$g_e^L = \frac{1}{2} + \sin^2\theta_W$$

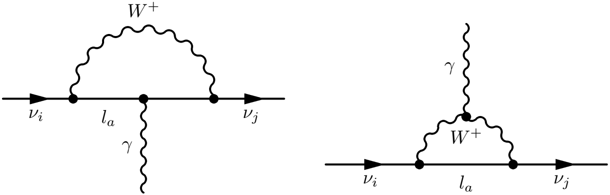
$$g_{\mu,\tau}^L = \frac{1}{2} - \sin^2\theta_W$$

$$g_\alpha^R = \sin^2\theta_W$$

- vary θ_W in coupling constants of $\nu - e$ cross section
- apply the same analysis procedure

$$\sin^2\theta_W = 0.229 \pm 0.026 \text{ stat + syst}$$

Magnetic moment of massive neutrinos



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

proportional to the neutrino mass

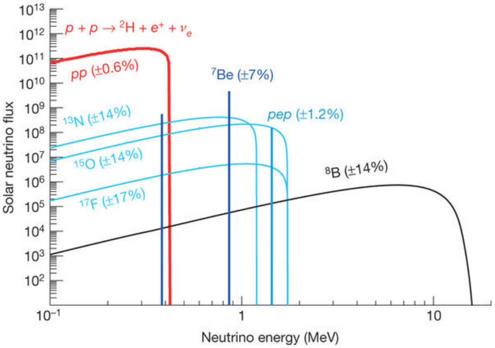
$$\mu = \frac{3 m_e G_\mathrm{F}}{4\pi^2\sqrt{2}} m_\nu \mu_\mathrm{B} \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1\ \mathrm{eV}}\right) \mu_\mathrm{B}$$

Observable effects at:

- **propagation:** spin-flavor precession in the solar magnetic field
- **detection:** contribution to $\nu - e$ cross section

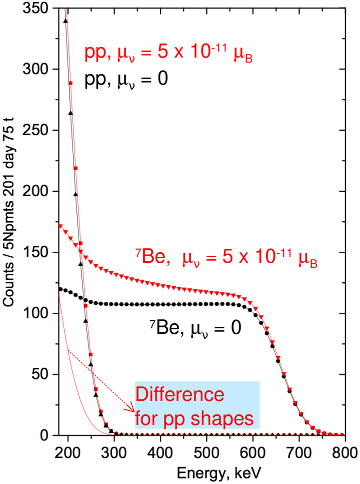
Detection

Neutrino spectra



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

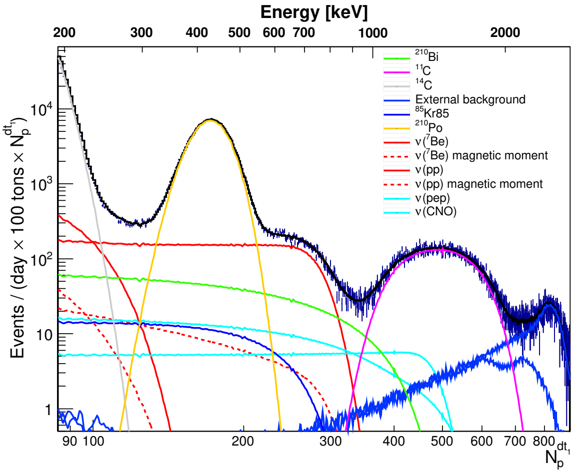
Electron recoil spectra



Elastic scattering data analysis

Constraint on the total solar neutrino rate from:

J. N. Abdurashitov et al., Phys. Rev. C **80**, *015807 (2009)*



$$\mu_{eff} < 2.8 \cdot 10^{-11} \mu_B \text{ (90\% CL)}$$

Propagation

Spin-flavor precession

$$\nu_\alpha^L \gamma \xrightarrow{\mu_\nu^{\alpha\beta}} \nu_\beta^R \gamma$$

Dirac neutrinos

- $\mu_{\alpha\alpha} \gg \mu_{\alpha\beta}$
- neutrino flux deficit
- not enough sensitivity

Majorana neutrinos

- $\mu_{\alpha\alpha} = 0$ (CPT conservation)
- appearance of $\bar{\nu}$
- can be detected via IBD or ES

Electron antineutrino appearance:

$$\nu_e \xrightarrow{\text{SFP}} \bar{\nu}_\mu \xrightarrow{\text{MSW}} \bar{\nu}_e$$

$$\nu_e \xrightarrow{\text{MSW}} \nu_\mu \xrightarrow{\text{SFP}} \bar{\nu}_e$$

Inverse beta decay data: event selection

Exposure: Dec 2007 – Oct 2017, 2485 days

Delayed coincidence of e^+ annihilation (prompt) and neutron capture (delayed):

- $\Delta t \in [20 - 1280]$ μs
- $\Delta r < 1$ m
- $N_{pe}^{prompt} < 408$ p.e.
- $N_{pe}^{delayed} \in [860 - 1300]$ p.e.

Muon veto:

- 200 ms after crossing the outer detector
- 2 s after crossing the inner detector

Fiducial volume:

- 25 cm offset from the Inner Vessel (prompt)

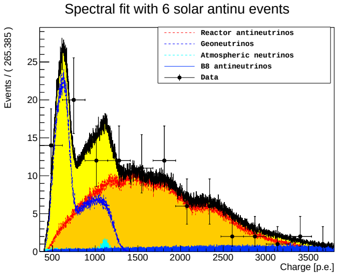
IBD data analysis

1.8–7.8 MeV Spectral fit developed for geoneutrino analysis

Agostini et al. (Borexino collaboration) Phys.Rev. D101 (2020) no.1, 012009

^{8}B solar anti-neutrinos are added to the model

$$N_{\bar{\nu}} < 13.3 \text{ (90\% CL)}$$



7.8–16.8 MeV

Total background: 0.3 events

Observed: 0 events

Limit obtained with the Feldman-Cousins procedure:

$$N_{\bar{\nu}} < 2.15 \text{ (90\% CL)}$$

$\bar{\nu}$ final results

Combined analysis in 1.8–16.8 MeV energy region: $N_{\bar{\nu}} < 2.19$ (90% CL)

$$\phi_{\lim} = \frac{N_{\bar{\nu}}}{< \sigma > \cdot \epsilon \cdot N_p \cdot T}$$

$$\phi_{\bar{\nu}} < 390.8 \text{ cm}^{-2}\text{s}^{-1}.$$

- $< \sigma >$: average cross section
- $\varepsilon = 0.850 \pm 0.015$: cut efficiency
- $N_p = (1.32 \pm 0.06) \times 10^{31}$: number of protons
- $T = 2485$ days: exposure time

$\nu - \bar{\nu}$ conversion probability

$$p^{\mathrm{HZ}}(\nu_e - \bar{\nu}_e) < 7.2 \cdot 10^{-5} \quad (90\%\ \mathrm{CL}),$$
$$p^{\mathrm{LZ}}(\nu_e - \bar{\nu}_e) < 8.7 \cdot 10^{-5} \quad (90\%\ \mathrm{CL}).$$

$\bar{\nu}$ contribution to the ES data

$$p^{\mathrm{HZ}}(\nu_e - \bar{\nu}_e) < 0.14 \quad (90\%\ \mathrm{CL}),$$
$$p^{\mathrm{LZ}}(\nu_e - \bar{\nu}_e) < 0.08 \quad (90\%\ \mathrm{CL}).$$

μ_ν from solar anti-neutrino data

In the solar core:

$$\mu_\nu \leq 7.4 \times 10^{-7} \cdot \left(\frac{p(\nu_e - \bar{\nu}_e)}{\sin^2 2\theta_{12}} \right)^{1/2} \cdot \frac{\mu_B}{B_\perp[\mathrm{kG}]}$$

Taking $p(\nu_e - \bar{\nu}_e) < 7.2 \cdot 10^{-5}$ (HZ)

$$\mu_\nu \leq 6.9 \cdot 10^{-9} B_\perp^{-1}[\mathrm{kG}] \cdot \mu_B \ (90\% \ \mathrm{CL})$$

Magnetic fields in the core:

- observational limit from the solar oblateness: $B < 7$ MG

  A. Friedland, A. Gruzinov, Astroph. J **601**, *570 (2004)*

- theoretical limit from the stability of toroidal magnetic field: $B < 600$ G

  L. Kitchatinov, Astron. Reports **52**, *247 (2008)*

No reliable **B** measurements $\to$ no μ_ν limit

μ_ν from solar anti-neutrino data (2)

In the convection zone:

$$\mu_\nu \leq 8.0 \times 10^{-8} \cdot (p(\nu_e - \bar{\nu}_e))^{1/2} \cdot B^{-1}[\mathrm{kG}] \cdot \mu_B$$

Magnetic field:

- $B \sim 10^4$ G

  Y. Fan, Living Rev. Sol. Phys. **1**, *1 (2009)*

$$\mu < 2.9 \cdot 10^{-11} \mu_B \text{ (90\% CL)}$$

Summary

Non-standard interactions:

- considered both at propagation and detection
- new limits on interaction parameters are obtained
- all parameters are compatible with 0 at 90% C.L.

S. K. Agarwalla et al. JHEP 2002 (2020) 038

Neutrino magnetic moment:

- limited using both neutrino and antineutrino data
- new limits on solar antineutrino flux and $\nu \to \bar{\nu}$ conversion probability

M. Agostini et al. Phys.Rev. D96 (2017) no.9, 091103
M. Agostini et al. arXiv:1909.02422 [hep-ex]