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THE BOREXINO IMPACT IN THE GLOBAL ANALYSIS OF NEUTRINO DATA

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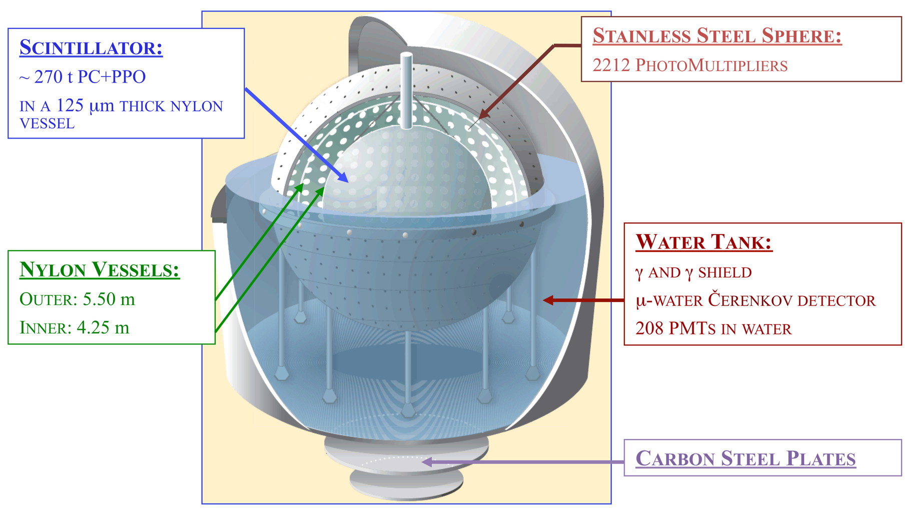
THE BOREXINO DETECTOR



The Borexino detector, designed and constructed for sub-MeV solar neutrino spectroscopy, is taking data at the Gran Sasso Laboratory (Italy) since May 2007.
The detector was designed exploiting the principle of graded shielding: an onion-like structure allows to protect the inner part from external radiation and from radiation produced in the external shielding layers. The requirements on material radiopurity increase when going to the innermost region of the detector[1].

[1] NIM A 600, 568-593 (2009)

THE LATEST OUTSTANDING RESULTS

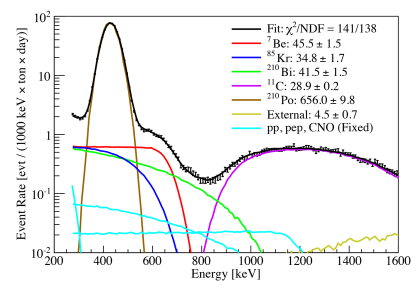
The Borexino collaboration has recently released the most precise, direct measurement of ^{7}Be solar neutrino rate and the exclusion of a significant day-night asymmetry.

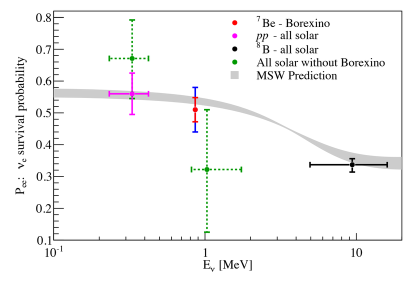
$$^7\mathrm{Be}: 46.0 \pm 1.5(\mathrm{stat})\,^{+1.5}_{-1.6}(\mathrm{syst})\ \mathrm{cpd/100ton} \quad [2]$$

$$A_{dn} = 0.001 \pm 0.012(\mathrm{stat}) \pm 0.007(\mathrm{syst}) \quad [3]$$

These results, combined with the other solar neutrino data, isolate for the first time the Large Mixing Angle solution at $\Delta\chi^2 > 190$ (2 d.o.f.) without relying on the antineutrino results. Moreover, we find $P_{ee} = 0.51 \pm 0.07$ at 862 keV and this yields to an improved constraint on the low energy solar survival probability. Thanks to this achievement, the no flavor change hypothesis is ruled out at 5.0σ.

[2] arXiv: 1104.1816 [hep-ex], 2011
[3] arXiv: 1104.2150 [hep-ex], 2011





THE SURVIVAL PROBABILITY PROPAGATION

All solar neutrinos are electron neutrinos produced in the inner part of the Sun. To perform a proper analysis, we first have to study how the Survival Probability of an electron neutrino propagates in the Sun core, in vacuum (the Sun-Earth walk) and in the Earth.

The effective Hamiltonian for three-neutrino propagation in matter can be conveniently (assuming stable, non-sterile neutrinos) written as:

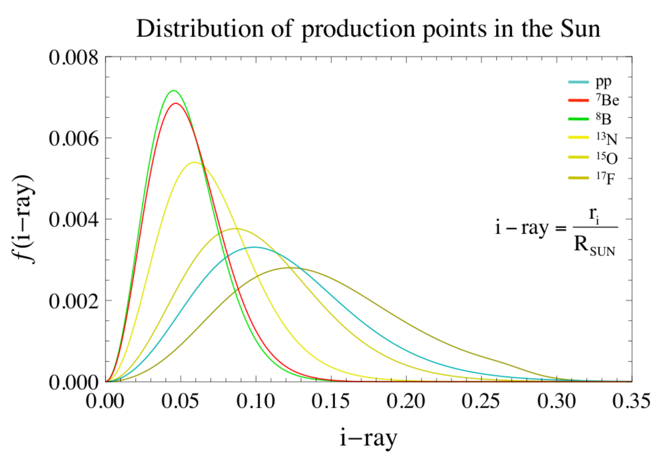
$$\mathcal{H}^{eff} = \begin{pmatrix} -\frac{\Delta^2 m_{21}}{4E}\cos^2\theta_{12} + \sqrt{2}G_F N_e \cos^2\theta_{13} & \frac{\Delta^2 m_{21}}{4E}\sin^2\theta_{12} \\ \frac{\Delta^2 m_{21}}{4E}\sin^2\theta_{12} & \frac{\Delta^2 m_{21}}{4E}\cos^2\theta_{12} - \sqrt{2}G_F N_e \cos^2\theta_{13} \end{pmatrix}$$

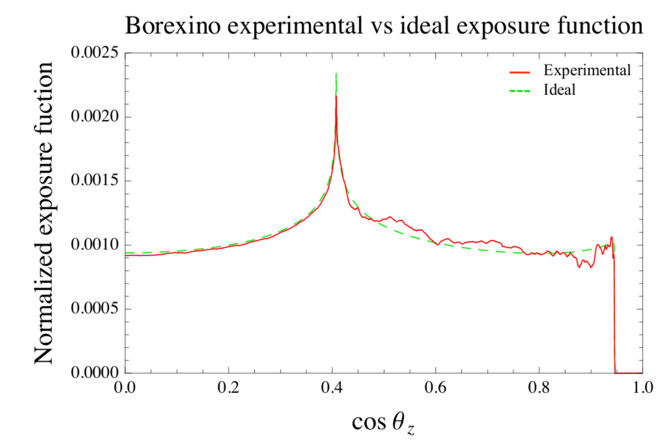
If we assume $P^S_{e1'}$ to be the probability that an electron neutrino produced in the Sun becomes a neutrino mass eigenstate $\nu_{1'}$ and $P^E_{2'e}$ the probability that a neutrino propagating in vacuum as mass eigenstate $\nu_{2'}$ is detected on Earth as an electron neutrino, the Survival Probability for an electron neutrino can be written as:

$$P_{ee} = |\langle\nu_e|\mathcal{H}^{eff}|\nu_e\rangle|^2 = \sin^4\theta_{13} + \cos^4\theta_{13}[P^S_{e1'}(1-P^E_{2'e}) + P^E_{2'e}(1-P^S_{e1'})]$$

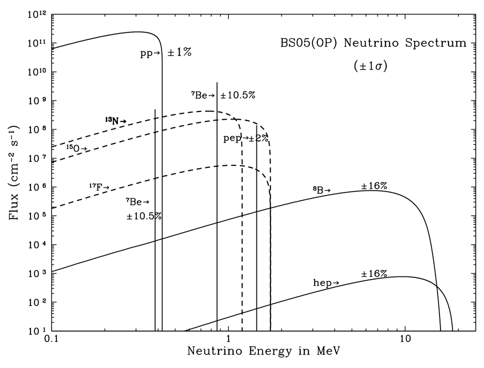
For each neutrino source, the probability $P^S_{e1'}$ is obtained by weighting the P_{ee} of each production point for the corresponding distribution.

The probability $P^E_{2'e}$ is computed taking into account the Sun exposure related to Borexino location (LNGS, Italy) and weighted by its livetime.





THE STANDARD SOLAR MODEL



Direct measurement of sub-MeV solar neutrinos is not only a way through which we can study neutrino oscillations: it is also valuable for solar Physics since it could help in solving the metallicity controversy.
The controversy arises because some recent refined calculations showed new (lower) metallicity values in the Sun and in its core, changing the expected fluxes. However, this low-metallicity values lead to solar models which disagree with different helioseismological measurements.

This analysis was carried out using a new standard solar model[4] (hereafter SHP11) recently published by Serenelli, Haxton & Pena Garay. This solar model uses newly analyzed nuclear fusion cross sections and, according to the high (GS98[5]) or low (AGSS09[6]) metallicity hypothesis, predicts the different solar neutrinos fluxes listed in the table.

Starting from the survival probability P_{ee} and assuming the GS98(SHP11) neutrino fluxes, the theoretical predictions for each Borexino relevant quantity are evaluated as a function of the free parameters of the fit: the oscillation parameters Δm^2_{21}, θ_{12} and θ_{13}.

SOLAR NEUTRINO FLUXES

ν Flux	[5]GS98(SHP11)	[6]AGSS09(SHP11)	Difference %
pp	5.98(1 ± 0.006)	6.03(1 ± 0.006)	0.8
pep	1.44(1 ± 0.012)	1.47(1 ± 0.012)	2.1
hep	8.04(1 ± 0.30)	8.31(1 ± 0.30)	3.4
^{7}Be	5.00(1 ± 0.07)	4.56(1 ± 0.07)	8.8
^{8}B	5.58(1 ± 0.14)	4.59(1 ± 0.14)	17.7
^{13}N	2.96(1 ± 0.14)	2.17(1 ± 0.14)	26.7
^{15}O	2.23(1 ± 0.15)	1.56(1 ± 0.15)	30.0
^{17}F	5.52(1 ± 0.17)	3.40(1 ± 0.16)	38.4

Neutrino fluxes are given in units of 10^{10} (pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6 (^{8}B, ^{17}F) and 10^3 (hep) cm^{-2} s^{-1}. Asymmetric uncertainties have been averaged.

[4] arXiv: 1104.1639 [astro-ph.SR], 2011
[5] Space Sciences Reviews 85-161, 1998
[6] ApJ 705 L123, 2009

THE GLOBAL ANALYSIS ON BOREXINO DATA

The χ^2 is computed by comparing theoretical and experimental results. If R_{exp} is the set of results actually obtained by Borexino and the corresponding set of computed values is $R_{theo}(\Delta m^2_{21}, \theta_{12}, \theta_{13}, \Phi_i)$, then:

$$\chi^2 = [R^i_{exp} - R^i_{theo}(\Delta m^2_{21},\theta_{12},\theta_{13},\Phi_i)]\,\sigma^{-2}_{ij}\,[R^j_{exp} - R^j_{theo}(\Delta m^2_{21},\theta_{12},\theta_{13},\Phi_i)]$$

The error matrix σ_{ij} includes both the theoretical and experimental errors as well as the cross-correlations between errors on the different parameters.

The Borexino measurements included in this global analysis are the ^{7}Be total count rate[2], the day-night asymmetry[3] and the ^{8}B total count rate[7].
The resulting χ^2 is then minimized for Δm^2_{21}, $tg^2\,\theta_{12}$ and $\sin^2\theta_{13}$: in this way we obtain the χ^2 projection for each parameter of the fit.

Fig. 1 and Fig. 2 show in sequence the effect of including ^{7}Be plus ^{8}B count rate and ^{7}Be day-night asymmetry in the fit. The joint analysis of the ^{7}Be and ^{8}B count rate is required since the two neutrino fluxes are strictly correlated.

Finally, the effect of the day-night measurement is very clear in Fig. 3 where all the Borexino results are fitted together: in the MSW solution, Borexino prefers the LMA region while definetely excludes the LOW region of parameter space.

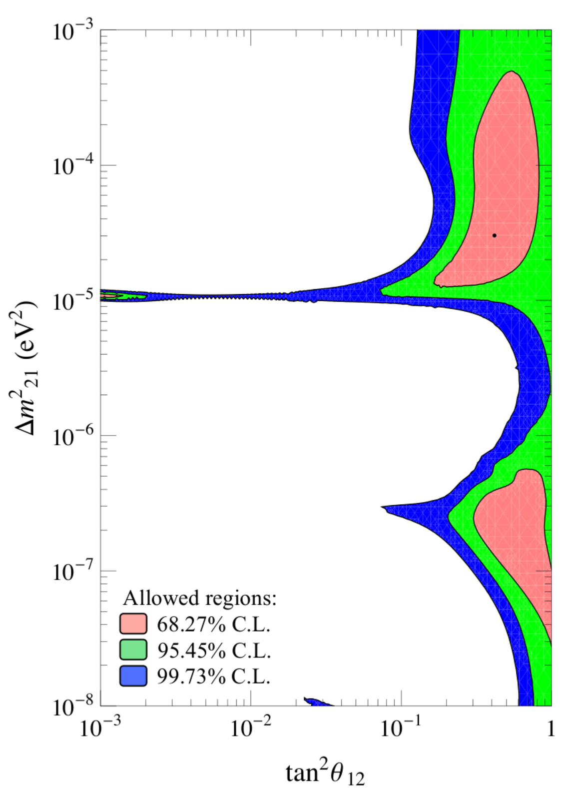


FIG. 1 - 68.27%, 95.45% and 99.73% C.L. allowed region by Borexino ^{7}Be rate and ^{8}B total rate.

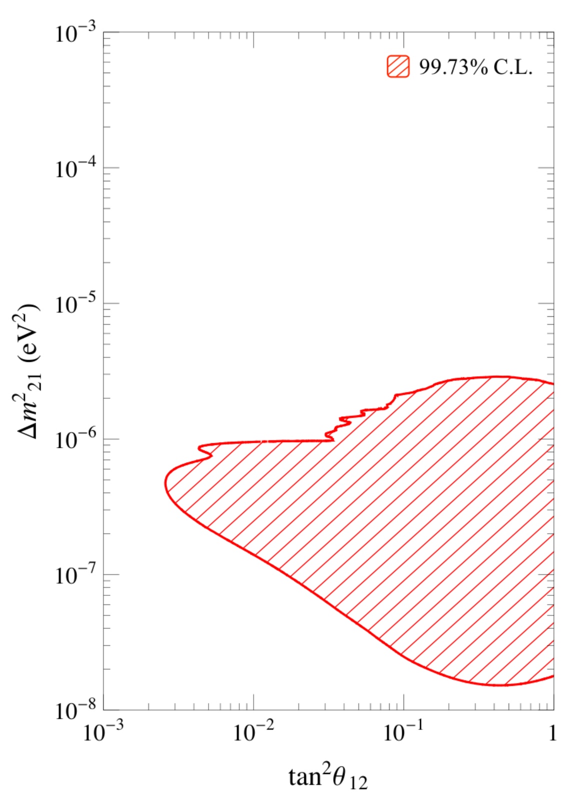


FIG. 2 - 99.73% C.L. excluded region by the absence of day-night asymmetry in the Borexino ^{7}Be rate.

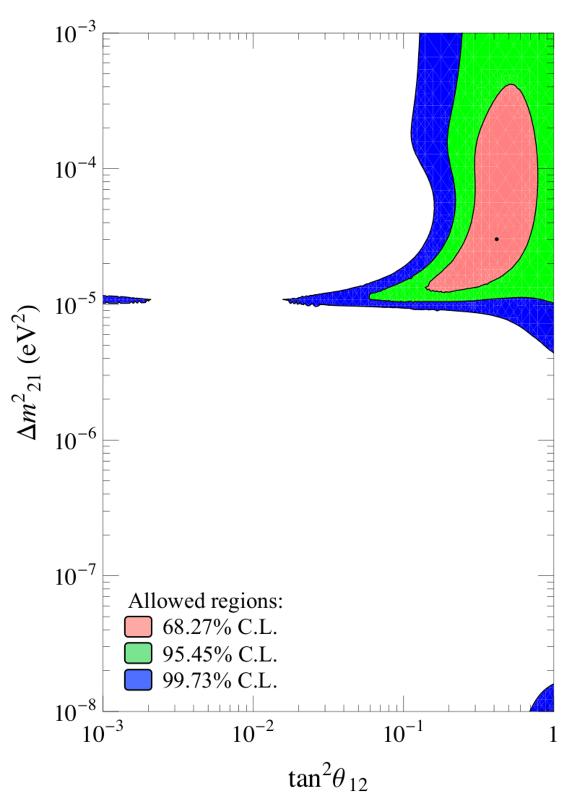


FIG. 3 - 68.27%, 95.45% and 99.73% C.L. allowed region by Borexino ^{7}Be rate, day-night asymmetry and ^{8}B total rate

THE BOREXINO IMPACT IN THE GLOBAL ANALYSIS OF NEUTRINO DATA

The impact of the latest Borexino results can be better understood through a global analysis of all solar neutrino data. This exercise has been carried out adding to the previous Borexino-only analysis the radiochemical data (Homestake[8], SAGE[9], GALLEX/GNO[10]), the Super-KamiokaNDE[11] and the SNO[12] data. In this part of the analysis, we reasonably assumed $\theta_{13} = 0$.

For what concerns solar Physics, the best way to approach to the study of the Standard Solar Model parameters and to look deeper into the low/high metallicity controversy is to let data decide by leaving $\Phi(^7\mathrm{Be})$ and $\Phi(^8\mathrm{B})$ as free parameters of the fit.

Reduced fluxes:

$$fBe = \frac{\Phi(^7\mathrm{Be})}{\Phi^{SHP11}_{GS98}(^7\mathrm{Be})}$$

$$fBo = \frac{\Phi(^8\mathrm{B})}{\Phi^{SHP11}_{GS98}(^8\mathrm{B})}$$

HIGH-Met: GS98(SHP11)

$fBe = 1.00 \pm 0.07$

$fBo = 1.00 \pm 0.14$

LOW-Met: AGSS09(SHP11)

$fBe = 0.91 \pm 0.06$

$fBo = 0.82 \pm 0.11$

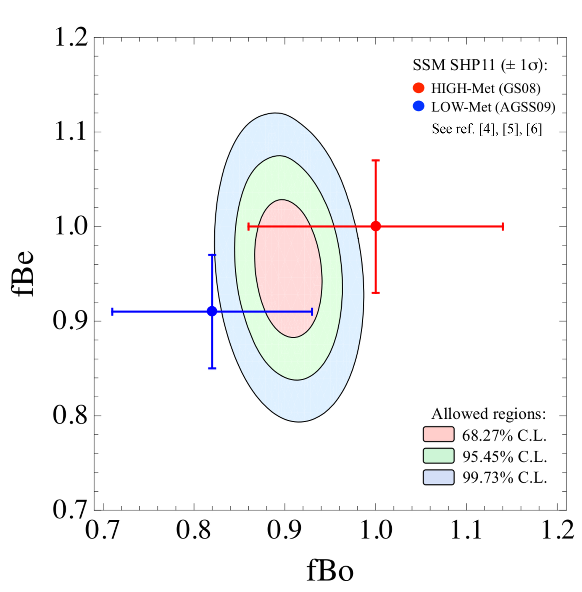


FIG. 4 - 1σ theoretical range of high (red) and low (blue) metallicity model compared to the 68.27%, 95.45% and 99.73% C.L. allowed region predicted by all solar neutrino data.

We studied the reduced fluxes (i.e. the fluxes normalized to the high metallicity GS98(SHP11) predictions) under the light form of the luminosity constraint[13]. Fig. 4 shows the allowed region for fBe and fBo after marginalization over Δm^2_{21} and $tg^2\,\theta_{12}$. Unluckily, at present, solar neutrino data cannot discriminate between the low/high metallicity hypothesis in the solar model.

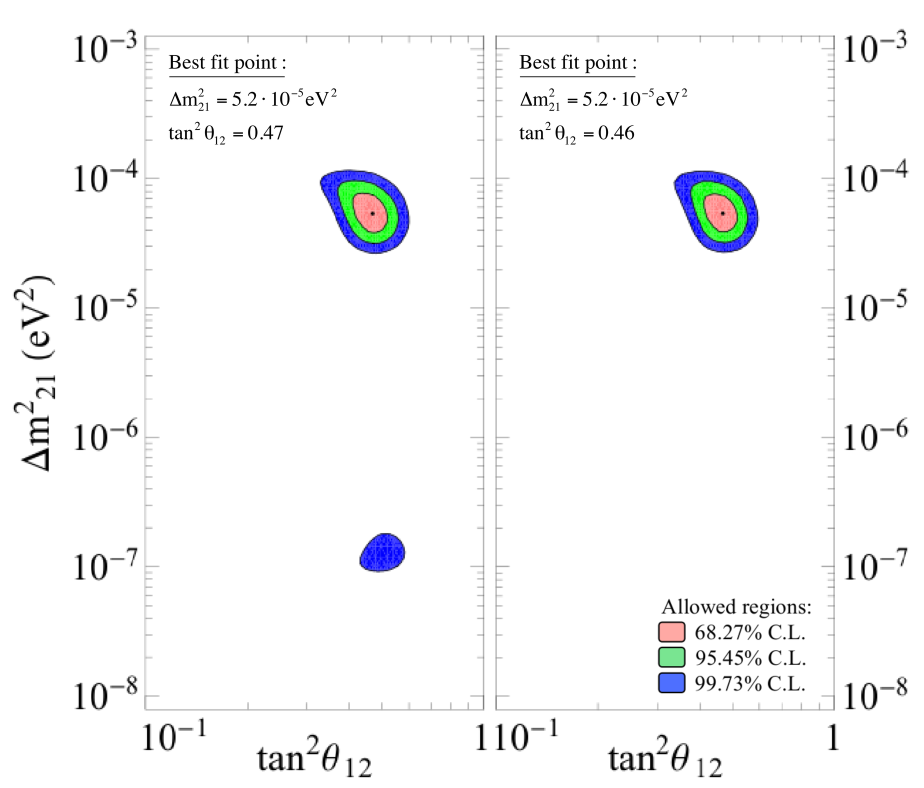


FIG. 5 - 68.27%, 95.45% and 99.73% C.L. allowed region by the solar neutrino data without (left panel) and including (right panel) the Borexino[2, 3, 7] data.

For what concerns neutrino Physics, in particular the neutrino oscillations parameter estimation, the left panel of Fig. 5 shows the 1, 2, 3σ allowed region for the mixing parameters Δm^2_{21} and $tg^2\theta_{12}$ by all solar neutrino data without Borexino. The best fit point is in the LMA region and a small portion of LOW region is still allowed at $\Delta\chi^2 = 11.83$. The right panel shows the same allowed region once the Borexino[2, 3, 7] data are included in the analysis.
The LMA region is only slightly modified but the LOW region is now strongly excluded at $\Delta\chi^2 > 190$. Therefore, after the inclusion of the Borexino data, solar neutrino data alone can single out the LMA solution with very high confidence (see Fig. 6).

The origin of this powerful result, as already shown in Fig. 2, is mainly ascribable to the goodness of Borexino day-night asymmetry measurement[3].
In fact, the measured asymmetry, in agreement with the prediction of MSW-LMA neutrino oscillations, disfavours at more the 8.5σ MSW oscillations with mixing parameters in the LOW region: for the first time, this region is strongly disfavoured without using Kamland data that is without assuming of CPT symmetry.

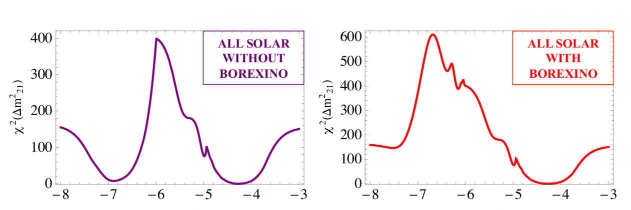


FIG. 6 - Results of the global fit: χ^2 profile for Δm^2_{21} for all solar data without Borexino (left) and after the inclusion of the Borexino results (right).

[7] Phys.Rev.D 82:033006 (2010)
[8] ApJ 496:505 (1998)
[9] Phys.Rev.C 80:015807 (2009)
[10] Phys.Lett.B 685:1 (2010)
[11] Phys.Lett.B 539:3-4 (2002)
Phys.Rev.C 73:025503 (2006)
Phys.Rev.D 83:052010 (2011)
[12] Phys.Rev.Lett. 101:111301 (2008)
Phys.Rev.C 81:055504 (2010)
[13] Phys.Rev.D 65:025801 (2002)