Solar neutrino experiments and Borexino perspectives

P. Aliani\textsuperscript{a}\textsuperscript{[Milano]}Dip. di Fisica, Università di Milano e I.N.F.N., Sezione di Milano, Via Celoria 16, Milano, Italy, V. Antonelli\textsuperscript{b}*, M. Picariello\textsuperscript{c}, E. Torrente-Luja\textsuperscript{d}\textsuperscript{[Milano]}\textsuperscript{e}MADRID\textsuperscript{[Madrid]}Dept. Fisica Teorica, C-XI, Univ. Aut. de Madrid, Spain and CERN TH-Division, CH-1202 Geneve

\textsuperscript{a}[Milano]\textsuperscript{[Milano]}\textsuperscript{e}[Madrid]\textsuperscript{[Madrid]}

We present an updated analysis of all the data available about solar neutrinos, including the charged current SNO results. The best fit of the data is obtained in the Large Mixing Angle region, but different solutions are still possible. We also study the perspectives of Borexino and conclude that this experiment, with a parallel analysis of total rate and day-night asymmetry, should be able to discriminate between the different possible solutions.

1. INTRODUCTION

Fifty years after neutrino discovery, many of its properties (like its mass) are not completely understood \cite{1}. Many experiments tried to answer these questions using different techniques. Here we focus our attention on solar neutrinos. The SNO experiment \cite{2} measured the \( ^8B \) Solar neutrinos through the two reactions: (1) charged current (CC): \( \nu_e + d \rightarrow 2p + e^- \) and (2) elastic scattering (ES): \( \nu_x + e^- \rightarrow \nu_x + e^- \). The results \cite{2} confirmed the previous evidences \cite{3} that the flux of \( \nu_e \) reaching the Earth is less than the Solar Standard Model (SSM) prediction \cite{4,5}. Comparing the two channels, SNO also gave a strong confirmation of the validity of \( \nu \) oscillation hypothesis and it can be considered the first demonstration of the appearance of muon and tau neutrinos detected at the Earth. In this work we restrict the analysis to the bidimensional case for simplicity, but the extensions to more than two flavours will be treated elsewhere \cite{6}. The interest in neutrino physics is justified not only by the data available, but also by the well founded hope that the forthcoming experiments (like Borexino \cite{7} and the long baseline experiments) will be able to discriminate more clearly between the possible solutions of the solar neutrino problem \cite{8}. The first aim of our work is to produce a phenomenological analysis of all the available solar neutrino data. We determine the values of the mixing parameters compatible with the data and compare the allowed regions with the ones selected from Borexino, depending on the signal it will find. The analysis can be divided in the following steps. We first compute exactly, using an evolution operator formalism \cite{9}, the survival probability that a neutrino produced with a well determined flavour is still of the same kind or has changed flavour when it arrives at the detector. To take into account the interaction with the Earth, we assume a spherical model \cite{10} in which the Earth is divided in eleven radial density zones. The other building block of the analysis is the study of the different aspects of each experiment, as the cross section for the interaction of the neutrino in the detector \cite{11}, the detector resolution and its efficiency. More information about this and other points of analysis are reported in \cite{12}. We obtain a response function for every experiment. From the convolution of survival probability, response function and \( \nu \) flux we obtain the expected signal for every experiment and the ratio between this value and the one predicted by the SSM in absence of oscillations.

2. STATISTICAL ANALYSIS AND RESULTS

For an exhaustive description of the statistical analysis and of our results we refer the interested reader to \cite{12}. Here we just report the salient points. In the most simple case, one includes in
the $\chi^2$ analysis only the values of the global rates 
fors all the experiments. The global $\chi^2$ function is 
simply defined as:

$$\chi_{gl}^2 = (R_{th}^{i} - R_{exp}^{i})^T \sigma^{-2} (R_{th}^{i} - R_{exp}^{i})$$

where the covariance matrix $\sigma$ is made up by

- a diagonal part (theoretical, statistical and un-
correlated errors) and another part (correlated 
 systematic uncertainties). The $R_{th,exp}^{i}$ vectors
 contain the data normalized to the SSM expectations:

$$R_{th,exp}^{i} = S_{th,exp}^{i} / S_{SSM}^{i},$$

where the index $i$ denotes the different Solar experiments: 
Chlorine (Cl), Gallium (Ga), SuperKamiokande (SK)
and charged current SNO (CC-SNO). The correlation 
matrices, both including and excluding 
SNO, are computed using standard techniques 
[13]. We perform a minimization of the $\chi_{gl}^2$ 
as a function of the oscillation parameters. A point 
in parameter space $(\Delta m^2, \tan^2 \theta)$ is allowed if 
the globally subtracted $\chi_{gl}^2$ fulfills the condition:

$$\chi_{gl}^2(\Delta m^2, \theta) - \chi^2_{min} < \chi^2_n (CL).$$

Where $\chi^2_n=2$ are the $n=2$ degrees of freedom quantiles.

![Figure 1](image1.png)

Figure 1. (Left) Global rate analysis from SK, Cl
and Ga experiments. (Right) Same analysis including
CC-SNO. The black dots are the best fit points; the
coloured areas are the allowed regions at 90, 95.99 and
99.7% CL. The region above the solid line is excluded 
by CHOOZ results at 99% CL [14].

The results of this analysis are represented in 
Fig. 1. One can distinguish four different regions: 
Small Mixing Angle (SMA), Large Mixing Angle 
(LMA), Low mass (LOW) and Vacuum region 
(VAC). After the introduction of SNO data 
the different regions become well separated. The 
best-fit point is no longer the SMA solution, but 
the one in the LMA region and the statistical

significance of the SMA region is drastically reduced. 
When introducing also the data of the SK energy spectrum rates 
the statistical analysis becomes more complex. In this case we have 
41 experimental data inputs: the 2x19 values of the 
Bins in which the day and night spectrums 
are divided, plus the total rates for Cl, Ga and 
CC-SNO. The procedure we adopt to define the $\chi^2$ parameter 
and perform the minimization (see [12]) follows the one used by the SK collaboration. 
In Table 1 we report the results that one gets in 
the case in which the $^8B$ flux is constrained to 
varies around the BPB2001 [5] central value with 
the standard deviation given by SSM. The corresponding 
contour plots are drawn in Fig. 2 to-
gether with the Borexino contour lines. The other possibility (free $^8B$ flux) is discussed in [12].

3. BOREXINO PERSPECTIVES

![Figure 2](image2.png)

Figure 2. (Left) Contour lines (full lines) for 
$S_{Bor}/S_0 = 0.5, 0.6, 0.7$ superimposed to the contour 
plots obtained from all other experiments and to the 
regions from Cl experiment alone (inside the dashed lines).(Right) Borexino day night asymmetry ($A^{DN}$) 
versus normalized signal ($S_{Bor}/S_0$).

We analyze the results from all other experiments 
together with the expectations for Borexino 
day-night averaged signal normalized with 
respects to SSM ($S_{Bor}/S_0 = S^{D-N}/SSM$) and 
day-night asymmetry ($A^{DN} = 2(D-N)/(D + N)$). In Fig. 2 the contour lines corresponding to 
different possible values of $S_{Bor}/S_0$ are superim-
posed on the allowed regions obtained from 
the global analysis of the full set of data for the other 
experiments. The signal discrimination power 
of the experiment [15] should be sufficient to distinguish 
between the different allowed regions in the 
($\Delta m^2, \tan^2 \theta$) plane or at least to strongly favour
Table 1
Best fit oscillation parameters. The analysis includes the global rates for Cl,Ga and CC-SNO, and the SK day and night energy spectra. The flux normalization is constrained to vary with SSM standard error and the number of d.o.f. is $n = 41 - 4$. Also reported are the values of $\chi^2$ minimum per degree of freedom ($\chi^2_{min}/n$) and the statistical significance (goodness of fit g.o.f.)

<table>
<thead>
<tr>
<th>Sol</th>
<th>$\Delta m^2$</th>
<th>$\tan^2(\theta)$</th>
<th>$\chi^2_{min}/n$</th>
<th>g.o.f</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMA</td>
<td>$5.2 \times 10^{-05}$</td>
<td>0.47</td>
<td>0.8</td>
<td>77</td>
</tr>
<tr>
<td>LOW</td>
<td>$9.9 \times 10^{-09}$</td>
<td>1.03</td>
<td>0.9</td>
<td>65</td>
</tr>
<tr>
<td>LOW</td>
<td>$3.6 \times 10^{-08}$</td>
<td>0.97</td>
<td>0.9</td>
<td>60</td>
</tr>
<tr>
<td>VAC</td>
<td>$5.0 \times 10^{-10}$</td>
<td>1.86</td>
<td>1.1</td>
<td>28</td>
</tr>
<tr>
<td>VAC</td>
<td>$5.0 \times 10^{-10}$</td>
<td>0.52</td>
<td>1.1</td>
<td>24</td>
</tr>
<tr>
<td>SMA</td>
<td>$5.6 \times 10^{-06}$</td>
<td>$1.32 \times 10^{-3}$</td>
<td>1.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

one of them. Borexino potentiality becomes even more evident when we look at the day night asymmetry. From the second graph of Fig. 2 we see that the LMA and the SMA regions correspond to two solutions which fit the present data, we studied Borexino expectations. In the most comprehensive case, global rates plus spectrum, the best fit was obtained in the LMA region. Solutions in the LOW and VAC regions are still possible although much less favoured. The best possible solution in the SMA region gets a low statistical significance. From the study of the expected Borexino normalized signal and day night asymmetry we conclude the following. In the near future, after 2-3 years of data taking, the combined Borexino measurements of the total event rate with an error below $\pm 5 - 10\%$ and day-night total rate asymmetry with a precision comparable to that of SK should allow us to discriminate between the Solar neutrino solutions suggested by present data.

4. CONCLUSIONS
We analyzed all the Solar neutrino data available and for the best solutions which fit the present data, we studied Borexino expectations. In the most comprehensive case, global rates plus spectrum, the best fit was obtained in the LMA region. Solutions in the LOW and VAC regions are still possible although much less favoured. The best possible solution in the SMA region gets a low statistical significance. From the study of the expected Borexino normalized signal and day night asymmetry we conclude the following. In the near future, after 2-3 years of data taking, the combined Borexino measurements of the total event rate with an error below $\pm 5 - 10\%$ and day-night total rate asymmetry with a precision comparable to that of SK should allow us to discriminate between the Solar neutrino solutions suggested by present data.

ACKNOWLEDGMENTS
We are really glad to thank R. Ferrari for his continuous scientific and organizative support, that has been essential for this work. We thank the Milano Borexino group, M. Pallavicini and the organizers of TAUP meeting. We acknowledge the financial support of MIUR and CYCIT.

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D62 (2000) 072002