PROCEEDINGS OF SCIENCE

Combined directional and spectral analysis of solar neutrinos from Carbon-Nitrogen-Oxygen fusion cycle with Borexino Experiment

PoS(EPS-HEP2023)163

A. Singhal,[1,2,*] **D. Basilico,**[3] **G. Bellini,**[3] **J. Benziger,**[4] **R. Biondi,**[5,32] **B. Caccianiga,**[3] **F. Calaprice,**[6] **A. Caminata,**[7] **A. Chepurnov,**[8] **D. D'Angelo,**[3] **A. Derbin,**[9] **A. Di Giacinto,**[5] **V. Di Marcello,**[5] **X.F. Ding,**[6,29] **A. Di Ludovico,**[6,26] **L. Di Noto,**[7] **I. Drachnev,**[9] **D. Franco,**[10] **C. Galbiati,**[6,11] **C. Ghiano,**[5] **M. Giammarchi,**[3] **A. Goretti,**[6,26] **M. Gromov,**[8,12] **D. Guffanti,**[13,28] **Aldo Ianni,**[5] **Andrea Ianni,**[6] **A. Jany,**[14] **V. Kobychev,**[15] **G. Korga,**[16,17] **S. Kumaran,**[1,2,31] **M. Laubenstein,**[5] **E. Litvinovich,**[18,19] **P. Lombardi,**[3] **I. Lomskaya,**[9] **L. Ludhova,**[1,2] **I. Machulin,**[18,19] **J. Martyn,**[13] **E. Meroni,**[3] **L. Miramonti,**[3] **M. Misiaszek,**[14] **V. Muratova,**[9] **R. Nugmanov,**[18] **L. Oberauer,**[20] **V. Orekhov,**[13] **F. Ortica,**[21] **M. Pallavicini,**[7] **L. Pelicci,**[1,2] **Ö. Penek,**[1,30] **L. Pietrofaccia,**[6,26] **N. Pilipenko,**[9] **A. Pocar,**[22] **G. Raikov,**[18] **M.T. Ranalli,**[5] **G. Ranucci,**[3] **A. Razeto,**[5] **A. Re,**[3] **N. Rossi,**[5] **S. Schönert,**[20] **D. Semenov,**[9] **G. Settanta,**[1,27] **M. Skorokhvatov,**[18,19] **O. Smirnov,**[12] **A. Sotnikov,**[12] **R. Tartaglia,**[5] **G. Testera,**[7] **E. Unzhakov,**[9] **F. Villante,**[5,25] **A. Vishneva,**[12] **R.B. Vogelaar,**[23] **F. von Feilitzsch,**[20] **M. Wojcik,**[14] **M. Wurm,**[13] **S. Zavatarelli,**[7] **K. Zuber**[24] **and G. Zuzel**[14]

The Borexino Collaboration

[1]*Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*

[2]*III. Physikalisches Institut B, RWTH Aachen University, 52062 Aachen, Germany*

[3]*Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy*

[4]*Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA*

[5]*INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy*

[6]*Physics Department, Princeton University, Princeton, NJ 08544, USA*

[7]*Dipartimento di Fisica, Università degli Studi e INFN, 16146 Genova, Italy*

[8]*Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia*

[9]*St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia*

[10]*AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France*

[11]*Gran Sasso Science Institute, 67100 L'Aquila, Italy*

[12]*Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[*]Speaker

https://pos.sissa.it/

[13]*Institute of Physics and Excellence Cluster PRISMA+, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*
[14]*M. Smoluchowski Institute of Physics, Jagiellonian University, 30348 Krakow, Poland*
[15]*Institute for Nuclear Research of NASU, 03028 Kyiv, Ukraine*
[16]*Department of Physics, Royal Holloway University of London, Egham, Surrey,TW20 0EX, UK*
[17]*Institute of Nuclear Research (Atomki), Debrecen, Hungary*
[18]*National Research Centre Kurchatov Institute, 123182 Moscow, Russia*
[19]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia*
[20]*Physik-Department, Technische Universität München, 85748 Garching, Germany*
[21]*Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi e INFN, 06123 Perugia, Italy*
[22]*Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA*
[23]*Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA*
[24]*Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany*
[25]*Dipartimento di Scienze Fisiche e Chimiche, Università dell'Aquila, 67100 L'Aquila, Italy*
[26]*Present address: INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy*
[27]*Present address: Istituto Superiore per la Protezione e la Ricerca Ambientale, 00144 Roma, Italy*
[28]*Present address: Dipartimento di Fisica, Università degli Studi e INFN Milano-Bicocca, 20126 Milano, Italy*
[29]*Present address: IHEP Institute of High Energy Physics, 100049 Beijing, China*
[30]*Present address: GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[31]*Present address: Department of Physics and Astronomy, University of California, Irvine, California, USA*
[32]*Present address: Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany*

E-mail: a.singhal@fz-juelich.de

Borexino, placed at LNGS in Italy, was a 280-ton liquid scintillator detector that took data from May 2007 to October 2021. Thanks to its unprecedented radio-purity, the real time spectroscopic measurement of solar neutrinos from both the *pp*-chain and Carbon-Nitrogen-Oxygen (CNO) fusion cycle of the Sun has been performed. Borexino also reported the first directional measurement of sub-MeV ^{7}Be solar neutrinos with the Phase-I period (May 2007-May 2010) using a novel technique called Correlated and Integrated Directionality (CID), exploiting the sub-dominant and directional Cherenkov photons detected at early times. For the first time, we provide the CNO solar neutrinos measurement without using an independent constraint on ^{210}Bi background rate by exploiting the CID technique on the complete Borexino detector live time dataset. This article presents the complete analysis strategy and the latest results on CNO solar neutrinos obtained by using the CID technique in Borexino. In addition, we also present the most precise CNO measurement obtained by Borexino using a spectral fit on the Phase-III dataset as used in 2022 analysis, where the novel CID result is now applied as an additional constraint.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

1. Introduction

The Sun is powered by the two distinct sets of nuclear reactions occurring in its core, in which hydrogen is fused to form helium, classified as proton-proton (*pp*) chain and Carbon-Nitrogen-Oxygen (CNO) cycle. While only ~1% of solar energy is produced by the CNO cycle, where the fusion is catalyzed by the presence of C, N, and O, it is expected to be a principal fusion mechanism in more massive and hotter stars. Several neutrino types are emitted: *pp*-ν, ^{7}Be-ν, *pep*-ν, ^{8}B-ν, and *hep*-ν in the *pp*-chain, while ^{13}N, ^{15}O, and ^{17}F neutrinos (collectively known as the CNO-ν) in the CNO cycle. The motivation to study CNO solar neutrinos is to address the *solar metallicity puzzle*. Metallicity refers to the abundance of elements with $Z > 2$. The Standard Solar Model (SSM) predictions on the flux of CNO-ν depend both directly and indirectly on solar metallicity inputs, grouped as: high metallicity (HZ) [1] or low metallicity (LZ) [2], based on different analyses of solar spectroscopic data. The LZ-SSM and HZ-SSM predictions on CNO flux differ at ~30% level [3] and the precise measurement of the CNO-ν flux would provide an input in solving a key question of solar physics.

The Borexino detector [4], located at the Laboratori Nazionali del Gran Sasso in Italy, was the world's purest liquid scintillator (LS) detector. It started data taking in May 2007 and stopped in October 2021. It provided the direct experimental evidence of CNO-ν from the Sun at ~7σ significance using January 2017 - October 2021 (*Phase-III*) dataset [5, 6]. For this, a multivariate (MV) spectral fit is used,where the ^{210}Bi background rate is constrained by analyzing its daughter ^{210}Po (α-decay). This was possible due to the thermal insulation of the detector before Phase-III. Borexino also developed "Correlated and Integrated Directionality" (CID) method, exploiting sub-dominant Cherenkov light to disentangle solar neutrinos from backgrounds and provided its proof of concept using ^{7}Be-ν [7].

Due to the dominance of scintillation light (>99% of all PMT hits) in Borexino, an event by event directional reconstruction is not possible. Here, we adopt the CID technique, where we calculate angle α between the direction of early photons detected by PMTs of an event and the incoming solar-νdirection. The photon direction is reconstructed using the reconstructed event vertex and the hit PMT position. The resulting $\cos\alpha$ distribution has a signature peak at $\cos\alpha > 0$ for all solar-ν events, while the distribution is expected to be flat for background events. Cherenkov photons are detected earlier in time than the scintillation light and they are emitted in a cone towards direction of recoiled electron. These early photons preserve the directional information of the incident solar-ν as the electron is mostly forward scattered by solar-ν. However, Cherenkov photons from backgrounds are uncorrelated with the solar direction. Scintillation photons from both solar-ν and background events are emitted isotropically and result in a flat angular distribution.

2. Directional analysis strategy

The CID analysis for CNO-ν is performed on the entire Borexino dataset: Phase-I (May 2007-May 2010, 740.7 days) and Phase-II+III (December 2011- October 2021, 2888.0 days) separately. A spherical fiducial volume of radius R < 3.05(2.95) m and mass 104.3(94.4) t and a region of interest (RoI$_{\mathrm{CNO}}$) of 0.85(0.85) - 1.3(1.29) MeV for Phase-I(Phase-II+III) are chosen. The Three-Fold-Coincidence algorithm [8] is also utilized to suppress cosmogenic ^{11}C background. RoI$_{\mathrm{CNO}}$

is expected to consist of mainly *pep*-ν (~64%), CNO-ν (~33%), and ^{8}B-ν (~3%) as signals, as well as residual ^{11}C, β-decaying, and external γ backgrounds.

Then, the detected PMT hits of each event are ordered relatively in time after subtracting their time of flight (ToF) and are classified as N$^{\text{th}}$ hit with order: 1$^{\text{st}}$ hit, 2$^{\text{nd}}$ hit .. and up to total number of hits. The cos α distributions are constructed for each N$^{\text{th}}$ hit for all events. Using Monte Carlo (MC) studies, early hits up to N$^{\text{th}}$-Hit(max) = 15(17) for Phase-I(Phase-II+III) are selected to maximize the use of direct and indirect directional information from the Cherenkov photons. Note that the scintillation photons also contribute significantly in the early hits. The cos α distributions for each N$^{\text{th}}$ hit of all selected data events is fitted with the corresponding N$^{\text{th}}$ hit distributions of the MC probability density functions (PDFs) of signal and background events using a χ^2-fit. From the fit, the total number of solar neutrinos events (N$_\nu$) is extracted, since the CID distributions of different signal types are indistinguishable within the data statistics. The fit includes two nuisance parameters to take into account following major systematics of CID:

Position reconstruction bias in true electron direction ($\Delta r_{\mathbf{dir}}$): In Borexino, the reconstructed position of the event is slightly biased towards the early hit PMTs of the corresponding event, which has most of the Cherenkov photons and hence, the true direction of recoiled electron. Since the direction of all hits is calculated using the reconstructed event position, the reconstructed photon direction is also biased. It influences the shape of cos α distributions of signal by inducing a negative slope for cos $\alpha < 0$, while it has no effect on backgrounds' cos α distributions. Its value is unknown in data and is treated as a free nuisance parameter in the fit.

Effective correction of the group velocity for Cherenkov photons ($\mathbf{gv_{ch}}$): As Borexino is a high light yield LS detector, it never had a calibration dedicated for small amount of Cherenkov photons. Since the effective wavelength distribution of detected Cherenkov photons has not been measured and the refractive index in MC has a finite accuracy, the relative group velocity of Cherenkov light and scintillation photons can be different in data and MC. Therefore, an effective correction on Cherenkov photons' group velocity in MC is determined, that calibrates the relative time differences between the scintillation and Cherenkov light in data and MC. This parameter influences the shape of signal PDFs by changing the ratio of Cherenkov photons arriving at early hits.

To estimate gv$_{\text{ch}}$, CID analysis is performed for the first time in the ^{7}Be-edge region using each dataset, where the number of solar neutrinos is constrained to the SSM predictions while leaving the CNO-ν rate free. This paves the way to perform CID analysis for CNO-ν on all phases, unlike the previous measurement on gv$_{\text{ch}}$ using γ calibration sources deployed during the Phase-I (in mid 2009) and restricting CID analysis to be performed only in Phase-I. The new measured values are $0.140 \pm 0.029(\text{stat.} + \text{syst.})\,\text{ns}\,\text{m}^{-1}$ (Phase-I) and $0.089 \pm 0.019(\text{stat.} + \text{syst.})\,\text{ns}\,\text{m}^{-1}$ (Phase-II+III) and are compatible with the measurement using γ-source calibration. Since the gv$_{\text{ch}}$ parameter can be determined independently, this nuisance parameter is constrained using a Gaussian pull term.

3. Directional analysis results on the CNO solar neutrinos

Figure 1a shows the best fit results illustration for all phases compared to a pure background hypothesis for the first 4 N$^{\text{th}}$ hits. It can be seen that the direct Cherenkov light causes signature peak at cos α>0, especially for early hits and the influence of Δr_{dir} inducing a slope at cos α<0. The background distribution is also non-flat due to non-isotropic distribution of live PMTs relative to Sun's position distribution as seen by Borexino. The best fit results in RoI_{CNO} are $N_\nu = 643^{+235}_{-224}$ (stat)$^{+37}_{-30}$ (syst.) for the Phase-I and $N_\nu = 2719^{+518}_{-494}$ (stat)$^{+85}_{-83}$ (syst.) for the Phase-II+III with 68% equal-tailed credible interval (CI). These results are estimated using Bayesian posterior distribution of N_ν and include the correction on the fit response bias. All additional systematic errors arising from deselection of mis-behaving PMTs, relative PMT time offset correction and MC production of signal events are also included. The one-sided zero neutrino hypothesis can be excluded with $P(N_\nu = 0) = 2.8\times10^{-5}$ ($\sim4.2\sigma$) for Phase-I and $P(N_\nu = 0) = 6.4 \times 10^{-11}$ ($\sim6.5\sigma$) for Phase-II+III. After constraining non-CNO solar neutrinos and combining all phases together, the CNO-ν rate is extracted. The final CID result for the CNO-ν rate is $R^{\text{CID}}_{\text{CNO}} = 7.2^{+2.8}_{-2.7}(\text{stat.} + \text{syst.})$ cpd/100 t. The probability that exactly zero CNO-ν events contribute to the measured data CID cos α distribution is 7.93×10^{-8} and this corresponds to a one-sided exclusion of the zero-CNO hypothesis at about 5.3σ credible level for combined Phase-I and Phase-II+III.

4. Combined directional and spectral analysis

Analysis strategy

Now, the results obtained from the CID analysis using the entire Borexino dataset is combined with the standard MV fit to improve the results on the CNO-ν rate measurement using Phase-III. The MV fit is based on the likelihood maximisation approach using information from energy and radial distributions of events, including the independently determined constraint on *pep*-ν rate (2.74 ± 0.04 cpd/100 t) as a pull term and the ^{210}Bi rate (10.8 ± 1.0 cpd/100 t) as an upper limit. Now, we use two N_ν posterior distributions from the CID analysis on Phase-I and Phase-II+III as external likelihood terms in the minimization routine after the statistical subtraction of ^{8}B-ν. The exposure used for MV fit is 1431.6 days $\times$ 71.3 t. The region of interest for MV analysis is (0.32 - 2.64) MeV. The free parameters of the fit are rates of all neutrino and background species in the region of interest, except for *pep*-ν and ^{210}Bi.

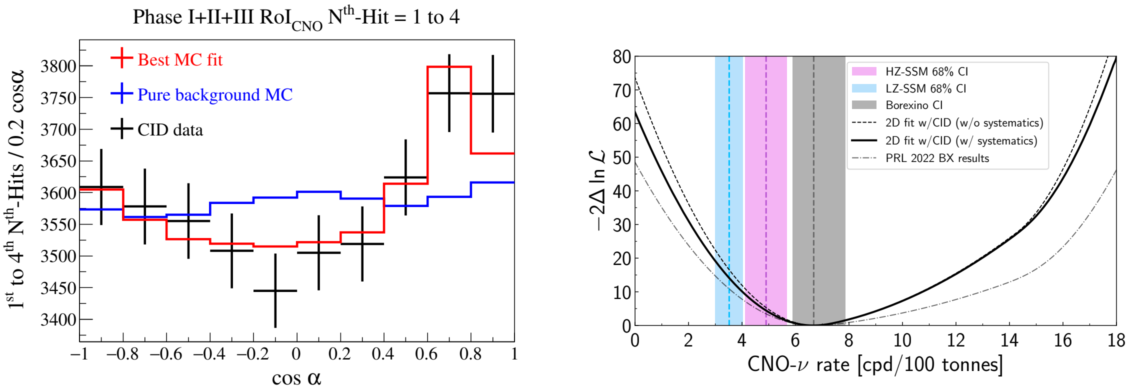
Final results on CNO solar neutrinos

The extracted CNO-ν rate is $6.7^{+1.2}_{-0.7}$ (stat.) cpd/100 t with a p-value of 0.2, obtained by performing the MV fit using CID posterior distributions. After taking into account various systematic contributions, the resulting CNO-ν rate is $6.7^{+1.2}_{-0.8}$ (stat. + syst.) cpd/100 t. This is extracted from 68% quantile of the likelihood shown in Figure 1b (in black solid). We disfavor no-CNO hypothesis at $\sim8\sigma$ C.L. and the CNO flux at Earth is calculated to be $6.7^{+1.2}_{-0.8} \times 10^{8}$ cm^{-2}s^{-1}. This result is used with the ^{8}B flux obtained from the global analysis of all solar data to estimate the solar abundance of C + N with respect to H with an improved precision, $\text{N}_{\text{CN}} = 5.81^{+1.22}_{-0.94}\times 10^{-4}$. This error includes both the statistical error from the CNO measurement and the systematic errors due to the additional contribution of the SSM inputs, ^{8}B flux measurement, and ^{13}N/^{15}O fluxes ratio. This result is in agreement with HZ measurements and has a $\sim2\sigma$ tension with LZ ones.

5. Conclusions

It has been shown that the CID method can be applied to extract the CNO signal, without any constraint on the backgrounds (especially ^{210}Bi). Here, for the first time, we performed a calibration

PoS(EPS-HEP2023)163



(a) **(b)**

Figure 1: (a) CID best fit illustration (red) and a pure background hypothesis (blue) for the first 4 hits in all phases. (b) Likelihood profile of the CNO-ν rate from spectral fit using the CID constraint without (black dotted) and with (black solid) systematic errors. Grey dashed line shows the profile without the CID constraint [5, 9].

for Cherenkov light using ^{7}Be-ν. Using Bayesian statistics, the CNO rate with CID only is $7.2^{+2.8}_{-2.7}$(stat. + syst.) cpd/100 t and the no-CNO hypothesis is rejected at the 5.3σ level. At the end, we demonstrate that the directional information coming from Cherenkov radiation (Phase-I+II+III) can be effectively combined with the spectral information (Phase-III) coming from scintillation, to obtain the final and best result of Borexino on CNO-ν: $6.7^{+1.2}_{-0.8}$ (stat. + syst.) cpd/100 t [9].

References

[1] N. Grevesse and A. Sauval, Space Sci. Rev. 85, 161 (1998). E. Magg et. al., Astron. Astrophys. 661, A140 (2022).

[2] M. Asplund et. al., Annu. Rev. Astron. Astrophys. 47, 481 (2009). E. Caffau et. al., Sol. Phys. 268, 255 (2011). M. Asplund et. al., Astron. Astrophys. 653, A141 (2021).

[3] N. Vinyoles et. al., 2017 ApJ 835 202.

[4] G. Alimonti et al. (Borexino Collaboration), Nucl. Instrum. Methods A 600, 568 (2009).

[5] S. Appel et al. (Borexino Collaboration), Phys. Rev. Lett. 129, 252701 (2022).

[6] M. Agostini et al. (Borexino Collaboration), Nature volume 587, pages 577–582 (2020).

[7] M. Agostini et al. (Borexino Collaboration), Phys. Rev. Lett. 128, 091803 (2022), Phys. Rev. D 105, 052002 (2022).

[8] M. Agostini et al. (Borexino Collaboration), Eur. Phys. J. C 81, 1075 (2021).

[9] D. Basilico et al. (Borexino Collaboration), arXiv:2307.14636 [hep-ex] (2023).