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# Development of the comprehensive analysis tools for the Supernova neutrino detectors

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**Summary.** — A supernova explosion is a unique astrophysics event that would allow us to learn a lot about the conditions inside massive stars during their evolution and answer many physics questions about their nature. By combining the analysis of the possible explosion in multiple next generation neutrino experiments, one could significantly improve the precision of determining the neutrino spectra parameters such as the mean energy and spectral index. In this contribution it is shown what one could achieve by doing a simultaneous fit of the energy spectra of JUNO and DUNE-like detectors. Preliminary results of the fit framework under development are presented.

## 1. – Introduction

A galactic supernova explosion is a unique neutrino source: detecting the neutrinos from deep inside the star will help us understand both the physics of the core collapse and properties of the neutrino themselves. If a SN neutrino burst arrived at Earth today, it would be detected by a variety of ton to kiloton scale neutrino detectors based on different technologies and target media [1]. A full understanding of the observed signals can only be obtained by a combined analysis of the different interaction channels. The possibility of such a reconstruction of SN neutrino spectra was shown before [2]. This contribution presents an analysis framework which is being developed to combine and fit the neutrino spectra from different detectors assuming a common flavour-dependent neutrino signal. For the moment we do not consider $\nu$ oscillations, because currently the analysis effort concentrates on combining the different signals and detector responses. Multi-detector analysis allows to eliminate degeneracies between physics quantities, such as flux, mean energy and the energy shape parameter. It can provide experiments with limited energy resolution, such as IceCube, with spectral information. As a consequence, rates can be translated into fluxes and profit from experiments with low systematic and excellent energy resolution to improve on the normalisation uncertainties of other experiments. In this work two future next generation neutrino experiments were considered: JUNO and DUNE.

 

## 2. – Supernova neutrino detection channels

**2**·1. *JUNO*. – The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment that is currently under construction in South-East China [3]. Its main goal is to determine neutrino mass hierarchy, but it will also be able to detect Supernova burst neutrinos. JUNO is a liquid scintillator (LS) detector with a 20 kton fiducial mass, deployed in a laboratory 700 meter underground. There are six possible channels of detection. Inverse beta decay (IBD) is the dominant one because there is a large number of free protons available in liquid scintillators.

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Deposition of the energy and positron-electron annihilation gives the prompt signal. In addition, there will be a capture of the neutron on a free proton which will produce 2.2 MeV $\gamma$s.

One advantage of liquid scintillator detectors is that the charge-current (CC) interaction on $^{12}$C takes place for both $\nu_e$ and $\bar{\nu}_e$ via

$$\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + {}^{12}\mathrm{N}$$
$$\bar{\nu}_e + {}^{12}\mathrm{C} \rightarrow e^+ + {}^{12}\mathrm{B}$$

The subsequent beta decay of $^{12}$N and $^{12}$B will lead to a prompt-delayed coincidental signal. These charge-current reactions will hence provide a possibility to detect $\nu_e$ and $\bar{\nu}_e$ separately. The neutral-current interaction on $^{12}$C is very important in order to probe neutrinos of non-electron flavour.

$$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$$

Finally there are $\nu$-electron and $\nu$-proton scattering processes. In elastic scattering of neutrinos on electrons, the scattered electrons carry the directional information of incident neutrinos, and thus can be used to locate the SN.

$$\nu + e^- \rightarrow \nu + e^-$$

The elastic scattering of neutrinos on protons is a promising channel to detect neutrinos of non-electron flavours.

$$\nu + p \rightarrow \nu + p$$

Although the total cross-section is about 4 times smaller than the IBD one, the contribution from all the neutrino-species will compensate for the loss in cross-section.

**2**·2. *DUNE*. – The Deep Underground Neutrino Experiment (DUNE) is hosted by the U.S. Department of Energy's Fermi National Accelerator Laboratory (Fermilab) in Illinois, comprises three central components: a new, high-intensity neutrino source generated from a megawatt-class proton accelerator at Fermilab, a massive far detector (FD) situated 1.5 km underground at the Sanford Underground Research Facility (SURF) in South Dakota, and a composite near detector (ND) installed just downstream of the neutrino source [4]. The DUNE FD will consist of four LArTPC detector modules, each with a LAr mass in the sensitive region of the cryostat (fiducial mass) of at least 10 kt, installed underground. Each LArTPC fits inside a cryostat of internal dimensions 15.1 m (w) $\times$ 14.0 m (h) $\times$ 62.0 m (l) containing a total LAr mass of about 17.5 kt. The design of the four identically sized modules is sufficiently flexible for staging construction and evolving the LArTPC technology. Liquid argon detectors will have excellent sensitivity to $\nu_e$ via the charge-current interaction on $^{40}$Ar.

$$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$$

This is a taggable interaction and $\gamma$s from ${}^{40}\mathrm{K}^*$ can be observed. The $\bar{\nu_e}$ interaction,

$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$$

will also occur and can be tagged. Neutral current excitations are also possible, although little information is currently available in the literature about cross sections and observables.

$$\nu + {}^{40}\mathrm{Ar} \to \nu + {}^{40}\mathrm{Ar}^*$$

Finally, there will be elastic scattering of neutrinos on electrons.

$$\nu + e^- \to \nu + e^-$$

## 3. – Fit procedure

**3**·1. *SNOwGLoBES*. – SNOwGLoBES is a public software for computing interaction rates and distributions of observed quantities for supernova burst neutrinos in common detector materials [5]. Since the ultimate goal is to create a multi-detector analysis tool, SNOwGLoBES was the choice in order to simulate data for various experiments. It is not intended to replace full detector simulations; however, output should be useful for many types of studies. Inside there are many interaction channels and cross-sections that are already included, but in order to perform simulations for a JUNO-like detector the neutrino-proton elastic scattering had also to be included. The cross-section was taken from the work of John F. Beacom [6] and ported into the SNOwGLoBES simulation procedure.

**3**·2. *Common fit of all neutrino spectra*. – As a fit function a common parametrization of the SN neutrino spectra, following Keil, Raffelt, Janka [7] was used. It is being forward-folded with the cross-section and energy response of the detectors in order to do the fit of the observed event spectra in the detectors.

$$\frac{\mathrm{d}F_\alpha}{\mathrm{d}E_\alpha} = \frac{3.5\times 10^{13}}{\mathrm{cm}^2\mathrm{MeV}} \cdot \frac{1}{4\pi D^2}\frac{\epsilon_\alpha}{\langle E_\alpha\rangle}\frac{E_\alpha^{\gamma_\alpha}}{\Gamma(1+\gamma_\alpha)}\left(\frac{1+\gamma_\alpha}{\langle E_\alpha\rangle}\right)^{1+\gamma_\alpha} \exp\left[-(1+\gamma_\alpha)\frac{E_\alpha}{\langle E_\alpha\rangle}\right], \tag{1}$$

where $\alpha$ denotes the neutrino flavour, $E_\alpha$ the energy of the neutrino, $\epsilon_\alpha$ flavour-dependent total neutrino energy is given in units of $5\cdot 10^{52}$ erg, $\langle \mathrm{E}\rangle$ - mean energy of the neutrino flux and $\gamma$ is a spectral index. Normalisation, the mean energy and the spectral index were free parameters in the fit. A set of values for the mean energy was chosen in the range [10, 15] MeV with a step size of 0.5 MeV. The spectral index was varied in the range [2.2, 3] with a step size of 0.05. A histogram array of data, containing the visible energy spectra was simulated and pre-stored. In order to make the fit better for the cases when the parameters were not on the grid of values, the interpolation method was applied. It means that the fit looks for the four closest histograms in the array and builds the result histogram using these four with the corresponding weights.

$$\begin{aligned}\mathrm{FIT} = {} & w_e w_\gamma \mathrm{Hist}(\langle E\rangle_{j+1}, \gamma_{i+1}) + (1-w_e)w_\gamma \mathrm{Hist}(\langle E\rangle_{j+2}, \gamma_{i+1}) \\ & + w_e(1-w_\gamma)\mathrm{Hist}(\langle E\rangle_{j+1}, \gamma_{i+2}) + (1-w_e)(1-w_\gamma)\mathrm{Hist}(\langle E\rangle_{j+2}, \gamma_{i+2}).\end{aligned} \tag{2}$$

Therefore, a global fit was performed to the Asimov data sets returning median sensitivity and uncertainties.

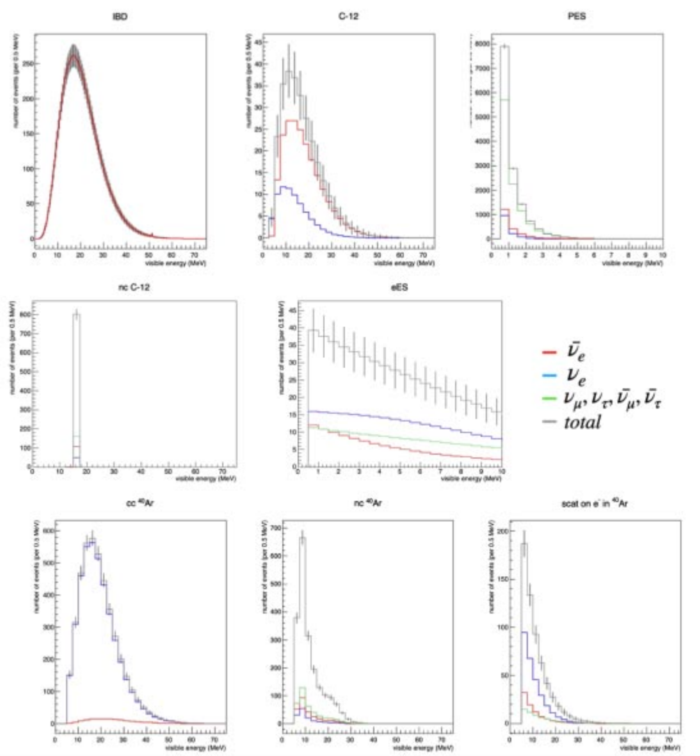


Fig. 1. – Result of the simultaneous fit of different channels of interaction.

## 4. – Results

As was mentioned in sect. 2, there are a lot of channels of interaction and all of them were fitted simultaneously. In the JUNO-like detector, charged-current interactions on $^{12}$C electron neutrinos and antineutrinos were considered indistinguishable, elastic scattering processes were fitted together with neutral current interaction events on $^{12}$C as a sum of all neutrino spectra and finally for the DUNE-like detector data each channel of interaction was fitted as a sum of all involved neutrino species. The results are presented in fig. 1. The basic framework works and fits all the spectra well. In order to estimate the goodness of the fit, the $\chi^2$ profiles in mean energy - spectral index space were plotted. First it was done only for JUNO simulated data (fig. 2). The fit gives good precision of the order of 1–3% on $\bar{\nu}_e$ and $\nu_x$ ($\nu_\mu, \nu_\tau, \bar{\nu_\mu}, \bar{\nu_\tau}$) neutrino spectra parameters ($\langle \mathrm{E} \rangle$ and $\gamma$). This can be explained by the large number of electron antineutrino events in IBD and $\nu_x$ events in elastic scattering and neutral current processes. However, a large ambiguity remains in $\nu_e$ spectrum parameters.

In the case of a combined fit for JUNO-like and DUNE-like data, the $\nu_e$ parameter determination could be significantly improved (see fig. 3). Many electron neutrino events from $\nu_e$ $^{40}$Ar charge-current interactions and neutral current interactions on $^{40}$Ar allow to better constrain mean energy and spectral index values. The parameters of $\bar{\nu}_e$ and $\nu_x$ spectra in the combined fit only slightly improve, since compared to JUNO, DUNE has much fewer electron antineutrino and $\nu_x$ events.

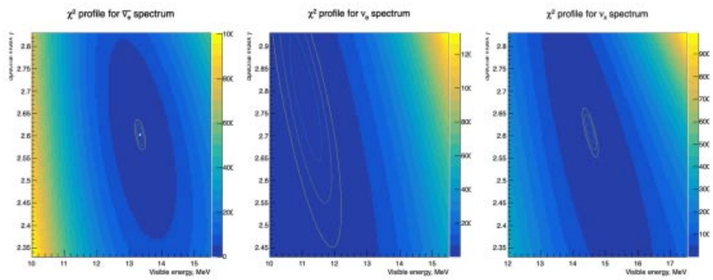


Fig. 2. – $\chi^2$ profiles for the neutrino spectra in mean energy - spectral index space for a JUNO-like detector. Contours show 1-3 $\sigma$ deviation.

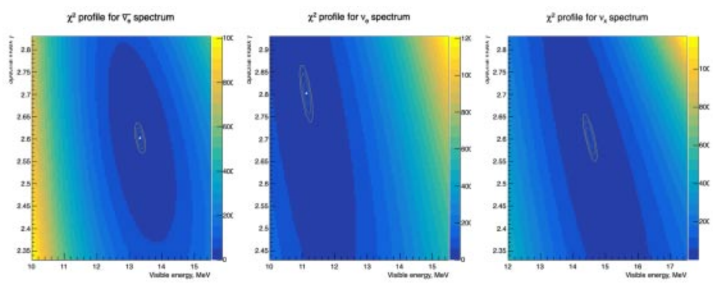


Fig. 3. – $\chi^2$ profiles for the neutrino spectra in mean energy - spectral index space for combined fit of JUNO and DUNE-like detectors. Contours show 1-3 $\sigma$ deviation.

The work is not yet finished and needs some improvement. Currently, the framework includes an energy range of [10,15] MeV. Since the mean energies of the neutrino spectra (especially $\nu_x$) could be potentially higher than that, the energy range will be increased up to 20 MeV. Proton quenching in the JUNO-like detector configuration was not yet taken into account. This will affect the number of events in neutrino proton elastic scattering process histogram and hence the error on $\nu_x$ energy spectra parameters, but not the whole fit procedure. For the same reason oscillations were also not considered. In addition, the uncertainty of the energy of the supernova explosion will be estimated as well in the future.

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