GLoBES AND ITS APPLICATION TO NEUTRINO PHYSICS*

Mark Rolinec

Physik-Department T30d, Technische Universität München
James-Franck-Strasse, 85748 Garching, Germany
e-mail: rolinec@ph.tum.de

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The General Long Baseline Experiment Simulator (GLoBES) is a software package that allows to simulate future neutrino oscillation long baseline experiments and analyze their potential to measure neutrino oscillation parameters. Within GLoBES experiments are described in the Abstract Experiment Definition Language (AEDL) that allows to simulate a variety of different detector technologies and point-like neutrino sources. Thus, besides beam based experiments also neutrino reactor experiments can be simulated. Additionally, very different kinds of systematical uncertainties, *e.g.* normalization and energy calibration errors can be described and the matter profile along the baseline can be treated accurately including uncertainties. GLoBES provides oscillation probability and event rate calculation as well as simple $\Delta\chi^2$ calculation. More sophisticated GLoBES functions allow to treat the full multi-parameter correlations and degeneracies by the projection of the $\Delta\chi^2$ to planes or axes in the parameter space. Up to 32 experiments can be simulated at once so that synergies between different experiments can be examined.

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1. Introduction

The last years have provided a lot of insight to neutrino mixing. The phenomenon of neutrino oscillations was established in the solar [1–5] and in the atmospheric sector [6, 7], and the leading solar and atmospheric oscillation parameters were constrained to small regions in the parameter space. For the near and far future more neutrino oscillations experiments are planned in order to perform precision measurements of the leading parameters or

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solve the remaining puzzles like the determination of the small mixing angle $\sin^2 2\theta_{13}$ and the questions if there is CP violation in neutrino oscillations or if neutrinos are of normal or inverted hierarchy. There exist different concepts of oscillation experiments that can solve those problems, and most make use of a stationary point-like neutrino source. This can be either an accelerator produced neutrino beam (conventional beam experiments, superbeam experiments or even more sophisticated concepts like neutrino factories and β-beams) or the reactor core of power plants for a reactor neutrino experiment. The GLoBES (Global Long Baseline Experiment Simulator) software package introduces flexible software tools to describe accurately the corresponding beam and detector characteristics and allows to analyze and simulate the performance of those different kinds of experiments using a complete three-flavor description and the careful inclusion of the matter effect. GLoBES was introduced in [8] and is available for download from `http://www.ph.tum.de/~globes` together with a detailed user manual.

Especially the meausurement of subleading three-flavor effects suffers from parameter correlations and degenerate solutions in parameter space that are intrinsic to the oscillation probabilities. Future long baseline experiments will have to be planned to optimally resolve the correlations and degeneracies and even synergies between different experiments may be of major importance. GLoBES allows to test the optimization strategies for the experiments and also for synergies in combinations of experiments. GLoBES in the past has already been used to simulate a variety of existing and planned long baseline experiments, *e.g.* the conventional beam experiments MINOS, ICARUS, and OPERA [9–11], superbeam experiments T2K and NOνA [9–15], super beam upgrades like T2HK [11, 13–16], reactor experiments [14, 17] as for instance DoubleChooz [9, 18], and even the neutrino factories [13, 15, 19] and β-beams [16].

2. General features

The GLoBES software package is basically separated into two parts. The first part provides an Abstract Experiment Definition Language (AEDL) which allows to describe a certain experimental setup within one ordinary text file. One or even more of the resulting AEDL files can then be processed together with supporting flux and cross section files. The second part consists of a C-Library, which loads the AEDL file(s) and provides the user interface functions for the intended experiment simulations. These functions allow to extract low-level informations like the calculation of oscillation probabilities in vacuum and matter, the calculation of event rates, the simple calculation of $\Delta\chi^2$ and high-level informations as for instance $\Delta\chi^2$-projections of the six-dimensional parameter space to axes or planes in

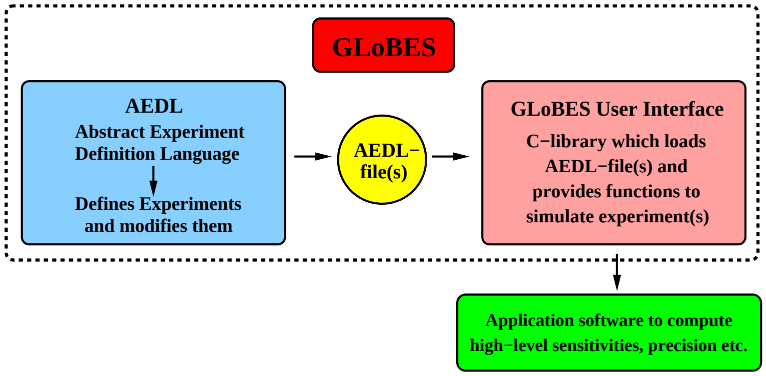

Fig. 1. Basic structure and general concept of the GLoBES package. Basically, GLoBES is divided into two parts, the AEDL part and the GLoBES User Interface. The AEDL (Abstract Experiment Definition Language) allows to describe a neutrino oscillation long baseline experiment, the experiment description is then written to a text file. This file can be read and the GLoBES User Interface provides functions that allow to extract low-level informations like event rates and perform demanding simulations including $\Delta\chi^2$-projections onto axes or planes in the six dimensional oscillation parameter space. This figure is taken from [8].

parameter space, pre-defined or manually defined. Furthermore, the inclusion of external input and the treatment of arbitrary matter density profiles along the baseline, including the effect of matter density uncertainties, is easily possible. The basic scheme of GLoBES is visualized in Fig. 1.

2.1. Experiment description in AEDL

The goal of AEDL is to describe a large number of complex and very different experimental setups by a limited number of parameters within one data structure. A point-like neutrino source produces a neutrino flux of different flavors that can be loaded from a different text file (in the case of neutrino factories GLoBES provides a built-in flux) which is then mapped into an energy-binned event rate vector for different channels. The definition of a channel can be seen from the left-hand side of Fig. 2. First, a channel contains the initial and final flavors (appearance or disappearance) and its polarity (neutrinos or anti-neutrinos), the flux of the initial neutrinos from the source, and detection effects as cross sections, energy depending efficiencies and the energy resolution function. As indicated by the right-hand side of Fig. 2 different channels are combined to signal and backgrounds which is then called a rule. GLoBES can handle several numbers of channels in one rule and several rules in one experiment. For each channel the event rates are

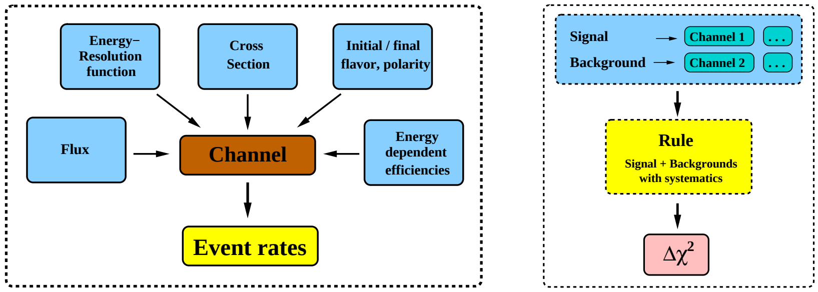

Fig. 2. The most important components of AEDL. The left-hand side shows the definition of a channel, that contains the information of initial flux, energy resolution, cross sections, participating neutrino flavors, and energy dependent efficiencies. Event rates are computed for the different channels and different channels can be combined to rules containing the signal and background channels. For each rule, $\Delta\chi^2$ values can be calculated by GLoBES including systematics. An experiment definition can contain several rules. This figure is taken from [8].

calculated as is described in detail in [8] or the GLoBES user manual. AEDL also gives the opportunity to accurately treat systematical uncertainties.

2.2. The GLoBES user interface

At the beginning of all simulations GLoBES calculates the event rate vector for an assumed set of so-called true oscillation parameter values, which have to be given by the user. This event rate vector then is treated as the simulated data of the simulated experiment(s). The GLoBES User Interface provides functions to fit the simulated data, *i.e.* calculate the $\Delta\chi^2$ values depending on the expected event rate vectors that are calculated the same way as the simulated data within the same AEDL description. More sophisticated functions allow to marginalize over different parameters in the parameter space and build projections from the six-dimensional parameter space to axes or planes in the parameter space, predefined or manually defined. In Fig. 3 this is illustrated for the correlation of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$. The upper left-hand side shows the allowed regions within the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane if the true values would be located at $\sin^2 2\theta_{13} = 10^{-3}$ and $\delta_{\rm CP} = \pi/2$. The upper right-hand plot shows the corresponding projection to the $\delta_{\rm CP}$ axis. For fixed fit values of $\delta_{\rm CP}$ the $\Delta\chi^2$-distribution is marginalized over $\sin^2 2\theta_{13}$ along the vertical gray lines in the upper left-hand side plot and the minima are found along the thick gray line. So, the $\Delta\chi^2$-distribution along the thick gray line is identical with the upper right-hand side plot and in both plots the degenerate solution at higher values of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$

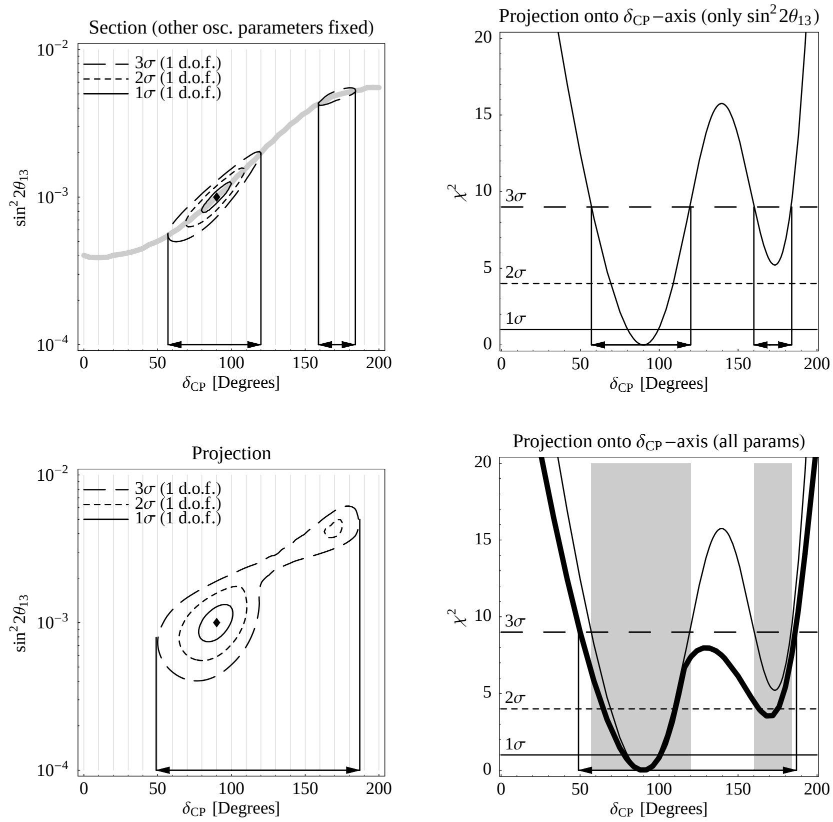

Fig. 3. Upper left plot: Example for a correlation between the parameters $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ (for 1 d.o.f., un-shown oscillation parameters are kept fixed). Besides the allowed region around the input values (true values) $\sin^2 2\theta_{13} = 10^{-3}$ and $\delta_{\rm CP} = \pi/2$ indicated by the black diamond a second allowed solution appears at the 3σ for higher values of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ due to the intrinsic degeneracy. Upper right plot: The $\Delta\chi^2$-values of the projection onto the $\delta_{\rm CP}$-axis as function of $\delta_{\rm CP}$. The projection onto the $\delta_{\rm CP}$-axis is obtained by finding the minimum $\Delta\chi^2$-value for each fixed value of $\delta_{\rm CP}$ in the upper left-hand plot, *i.e.* along the vertical gray lines. The thick gray curve marks the position of these minima in the left-hand plot. Lower left plot: Example for a correlation between the parameters $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ where all other parameters are marginalized over, *i.e.* a $\Delta\chi^2$-projection from the six-dimensional parameter space onto the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane. The degenerate solution now appears also at the 2σ C.L. Lower right plot: The $\Delta\chi^2$-value of the projection onto the $\delta_{\rm CP}$-axis as function of $\delta_{\rm CP}$. The thick black line shows the effect of a marginalization over all parameters. The figures were taken from [8].

appears at the 3σ. In the lower plots of Fig. 3 the same procedure is applied to the six-dimensional parameter space. The plot on the lower left-hand side shows a projection to the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$ plane where GLoBES marginalized over all other oscillation parameters $\sin^2 2\theta_{12}$, Δm^2_{21}, $\sin^2 2\theta_{23}$, and Δm^2_{31} for the same assumption on the true values. In this plot, one has to run the minimization processes along a two dimensional grid, which results in several hours of computation time. In the lower right-hand side the projection to the $\delta_{\rm CP}$-axis is shown and in contrary to the upper right-hand side now the marginalization is performed over all parameters besides $\delta_{\rm CP}$. This plot is calculated in 1–2 hours and the computation time is drastically decreased, featuring the same information for $\delta_{\rm CP}$ as the plot on the lower left-hand side.

3. GLoBES applications to neutrino physics

The ability of GLoBES to build projections in the parameter space allows a variety of applications to the analysis of the performance of neutrino oscillation long baseline experiments. Within this section we specify the different kinds of applications and give examples to show the powerful tools that are provided by the GLoBES software package. Detailed informations on the simulation techniques and experimental setup descriptions can be found in the original publications.

GLoBES has been used to:

- Simulate the achievable precision on the leading atmospheric parameters $\sin^2 2\theta_{23}$ and $|\Delta m^2_{31}|$ for the conventional beam experiments MINOS, ICARUS, and OPERA, and the future superbeam experiments T2K and NOνA [9, 10]. This precision also depends on the chosen true values of the atmospheric parameters as can be read off Fig. 4.

- Simulate the ability of conventional beam experiments, superbeam experiments, and neutrino factories to exclude maximal mixing for a true $\sin^2\theta_{23}$ deviating from maximal mixing. This also depends on the true values of the leading atmospheric parameters, since a value of $\sin^2\theta_{23}$ very close to maximal mixing cannot be distinguished from $\sin^2\theta_{23} = 0.5$ [11].

- Simulate the sensitivity limit to the small mixing angle $\sin\theta_{13}$ at conventional beam experiments [9], superbeam experiments (*e.g.* [12]), reactor experiments [14, 18], neutrino factories (*e.g.* [13]), and β-beams [16]. The sensitivity limit to $\sin^2 2\theta_{13}$ is calculated with the hypothesis of a true $\sin^2 2\theta_{13} = 0$, considering all possible correlations and degeneracies (see Fig. 5).

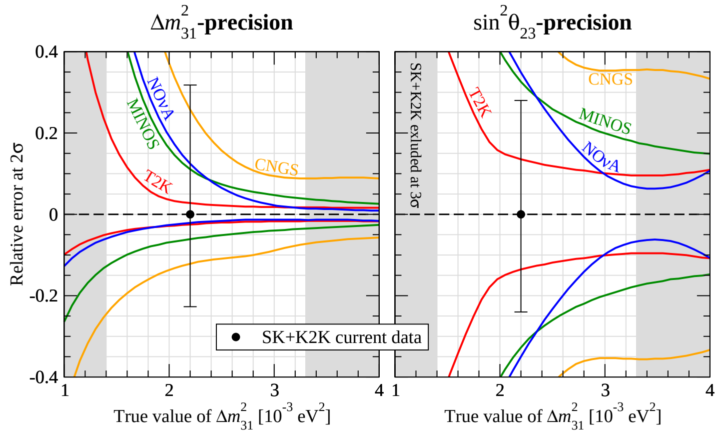

Fig. 4. The obtainable 2σ precision of the leading atmospheric parameters $|\Delta m^2_{31}|$ (left) and $\sin^2\theta_{23}$ (right) at the MINOS experiment, the CNGS experiments, and the superbeam experiments NOνA and T2K as function of the true value of Δm^2_{31}. This figure is taken from [10].

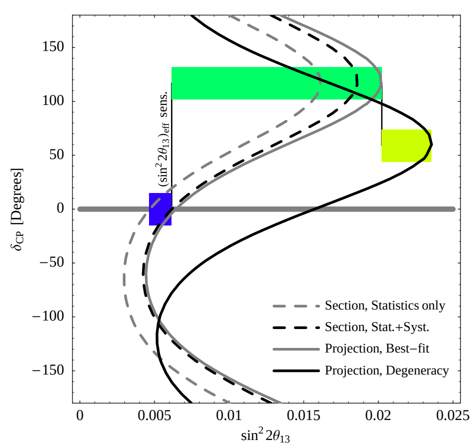

Fig. 5. The 90% C.L. fit manifold (1 d.o.f.) in the $\sin^2 2\theta_{13}$-$\delta_{\rm CP}$-plane for T2K to illustrate the effect of correlations (mainly with $\delta_{\rm CP}$) and degeneracies on the sensitivity limit to $\sin^2 2\theta_{13}$. The different curves correspond to various sections (un-displayed oscillation parameters fixed) and projections (minimized over un-displayed oscillation parameters) as described in the plot legend. The bars demonstrate the individual contributions to the final $\sin^2 2\theta_{13}$ sensitivity limit. This figure is taken from [9].

- Simulate the sensitivity to CP violation and the ability of precision measurements of the CP phase δ_{CP} at superbeam experiments [13,15], neutrino factories [13,15], and β-beams [16] including correlations and degeneracies.

- Simulate the sensitivity to the sign of Δm^2_{31} at superbeam experiments [13,15], neutrino factories [13,15], and β-beams [16], *i.e.* if and under which circumstances the neutrino mass hierarchy can be determined at the corresponding experiments.

4. Conclusion

The GLoBES software package provides powerful tools for analyzing the performance of neutrino oscillation long baseline experiments and reactor experiments including systematics. Furthermore, GLoBES allows to include all parameter correlations and degeneracies in order to examine the potential of special experimental setups to resolve the correlations and degeneracies, find optimization strategies for the simulated experiments and search for synergy effects in the combination of different experiments. Therefore the Abstract Experiment Definition Language allows to describe very different types of experiments on an abstract level. The C-functions from the library of the GLoBES User Interface make it possible to take into account the full multi-parameter correlations by building projections onto predefined or user-defined axes or planes in the parameter space. External input and matter density uncertainties can be easily included.

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