A

Appendix

A.1 Calculation of neutrino oscillation probabilities

In this section, we provide a simple derivation to obtain neutrino oscillation probabilities. In experiments studying neutrino oscillations, flavor neutrinos originate at the source through processes such as pion, kaon, or µ decays, or through nuclear reactions. These neutrinos are then detected through weak interactions at the detector, either through charged current (CC) or neutral current (NC) interactions. The flavor states are combinations of mass eigenstates. While propagating, distinct mass eigenstates accumulate varying phases, leading to a nonzero probability of transitioning between different flavor states.

A neutrino characterized by its flavor ν_α is represented as the flavor state below,

$$|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle, \tag{A.1}$$

with $\alpha = e, \mu, \tau$ and $i = 1,\ 2,\ 3$. Here U is the unitary mixing matrix known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. Also as the PMNS matrix is unitary we can write,

$$\sum_{\alpha} U^*_{\alpha i} U_{\alpha j} = \delta_{ij} \tag{A.2}$$

The mass states of neutrinos $|\nu_i >$ are eigenstates of the neutrino Hamiltonian and hence it can be written as,

$$\mathcal{H}|\nu_i\rangle = E_i|\nu_i\rangle, \tag{A.3}$$

where energy $E_i = \sqrt{p^2 + m_i^2}$. For ultrarelativistic neutrinos, we can write $p \sim E$ and

$$E_i = E + \frac{m_i^2}{2E} \tag{A.4}$$

Hence the corresponding Schrödinger equation can be written as,

$$i\frac{d}{dt}|\nu_i\rangle = \mathcal{H}|\nu_i\rangle \tag{A.5}$$

Therefore, we can write the mass states after some time t as follows,

$$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i(0)\rangle, \tag{A.6}$$

here $|\nu_i(0)\rangle$ is the mass eigenstate at time t=0. Now the neutrino flavour state at time t can be written as,

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle, \tag{A.7}$$

Also, the neutrino mass states can be written as,

$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i}|\nu_\alpha\rangle, \tag{A.8}$$

Therefore the equation A.7 can be written as,

$$|\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} (\sum_{i=1}^{3} U^*_{\alpha i} U^*_{\beta i})|\nu_i\rangle, \tag{A.9}$$

Hence the amplitude for the transition from one flavour $|\nu_\alpha\rangle$ to $|\nu_\beta\rangle$ can be written as,

$$A_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta|\nu_\alpha(t)\rangle \sum_{i=1}^{3} U^*_{\alpha i} U^*_{\beta i} \tag{A.10}$$

Hence transition probability from $\nu_\alpha \rightarrow \nu_\beta$ can be obtained as,

$$P_{nu_\alpha \rightarrow \nu_\beta} = |A_{\nu_\alpha \rightarrow \nu_\beta}(t)|^2 = \sum_{i,j}^{3} U^*_{\alpha i} U_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-(E_i - E_j)t} \tag{A.11}$$

using equation A.4 the energy difference can be written as,

$$E_i - E_j = \frac{\Delta m^2_{ij}}{2E} \tag{A.12}$$

There the final probability expression becomes,

$$P_{nu_\alpha \rightarrow \nu_\beta} = \sum_{i,j}^{3} U^*_{\alpha i} U_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i \frac{\Delta m^2_{ij}}{2E} L} \tag{A.13}$$

Using the unitarity of the PMNS matrix, U we can show that,

$$\sum_{i}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 = \delta_{\alpha\beta} - 2sum^3_{i>j} U^*_{\alpha i} U_{\beta i} U^*_{\alpha j} U_{\beta j} \tag{A.14}$$

Hence the final expression for the probability can be written as,

$$\begin{aligned} P_{\alpha\beta} = \delta_{\alpha\beta} \quad & - \quad 4 \sum_{i<j} \mathrm{Re}\big(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i}\big) \sin^2\{\Delta_{ij} L/4E\} \\ & + \quad 2 \sum_{i>j} \mathrm{Im}\big(U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i}\big) \sin\{2\Delta_{ij} L/4E\}, \end{aligned} \tag{A.15}$$

where $\Delta_{ij} = m_i^2 - m_j^2$ and i, j runs from 1 to 3.

B

Appendix

B.1 Details of GLoBES simulation package

GLoBES (General Long Baseline Experiment Simulator) is a versatile software package designed for simulating both long and short baseline neutrino experiments. It provides the capability to simulate experiments under the assumption of a point neutrino source. GLoBES facilitates the calculation of neutrino oscillation probabilities, event rates at experiments, and χ^2 values comparing event spectra, among other functionalities. In this thesis, GLoBES was employed to compute χ^2 values for various oscillation channels in an experiment or any combination of experiments. While the built-in functions can yield the total χ^2 by keeping all oscillation parameters and matter density scaling factors constant, they may be insufficient for certain experimental setups. This is particularly true for setups with systematics involving correlated errors across different components of a multi-detector configuration. To address this limitation, GLoBES (version 3.0 or higher) permits users to override the default χ^2 using custom-defined systematic functions.

As shown in figure B.1, GLoBES consists of various modules. To define an experiment GLoBES uses AEDL ("Abstract Experiment Definition Language"). There are

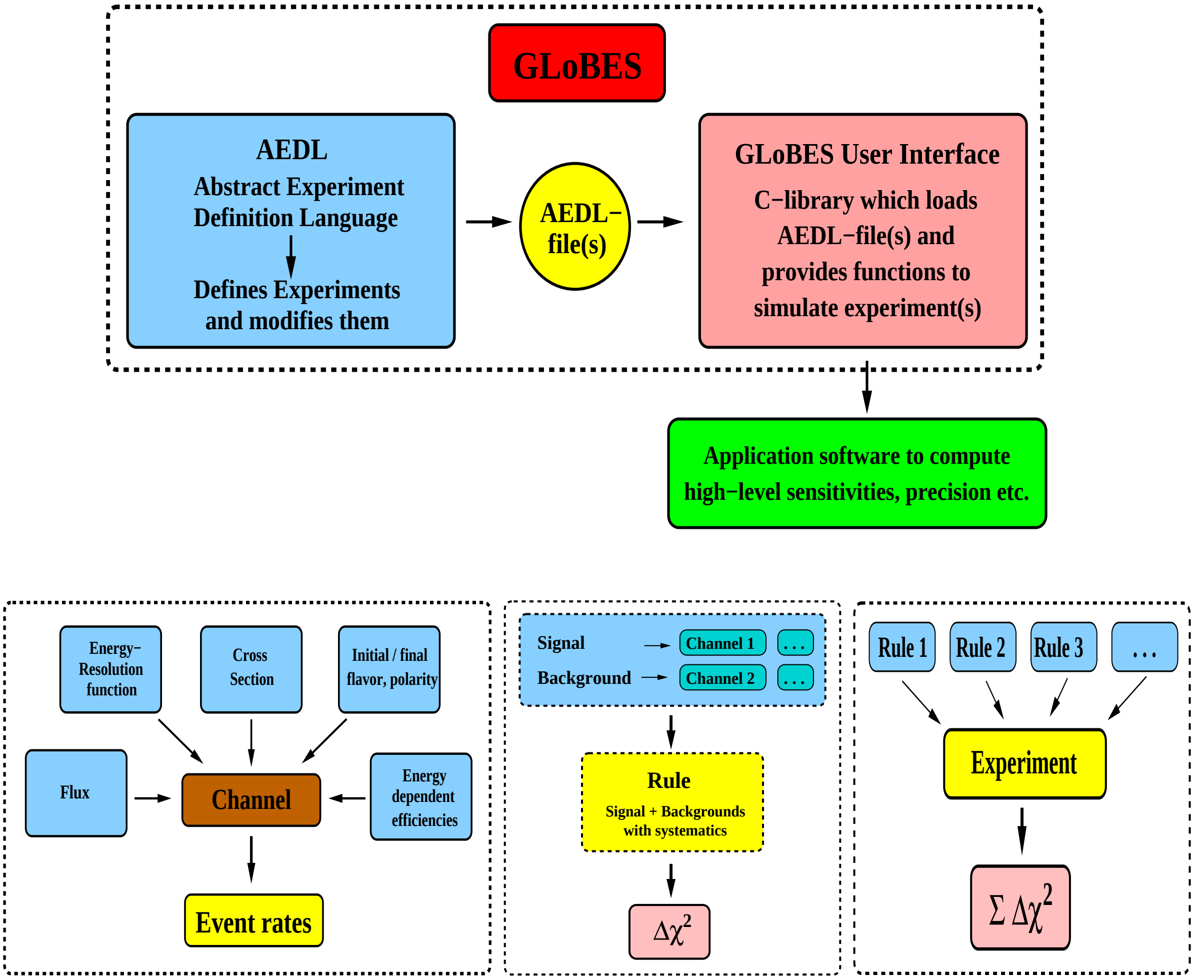

FIGURE B.1: *Top:* Different modules in GLoBES. *Bottom:* The most important components of AEDL: Channels, rules, and experiments.

three main components of AEDL: Channels, rules and experiment. A channel corresponds to a neutrino oscillation channel including flux, cross-section (for one specific interaction type), energy resolution function, initial and final neutrino flavours, their polarity (neutrinos or antineutrinos), and efficiencies. Each channel leads to the raw event rates for a specific interaction type. The raw event rates of one or more signal channels and one or more background channels are added to the rule. The event rates of all signal and background components add up to the total event rate of the rule, which leads to a $(\Delta\chi^2)_r$. The signal or background within each rule allows the specification of signal and background normalization errors and energy tilt or calibration errors. These systematics errors are evaluated with the "pull method". In addition to these systematics errors, an overall evaluation strategy is assigned to each rule, which specifies the type of systematics (tilt or calibration error), and the use of spectral information or total event rates. Finally, one or more rules add up to an experiment, where the total $\Delta\chi^2$

is obtained as the sum of the $(\Delta\chi^2)_r$ of all rules. This approach allows the definition of appearance and disappearance channels, neutrino and antineutrino running, or interaction types with different systematics (spectral information versus counting rate) within one experiment. Also, the GLoBES user interface allows the simulation of one or more experiments simultaneously, which means that one could also use different experiments for different oscillation channels.

C

Appendix

C.1 Working principle of RPC

The generation of the electric signal within the RPC detectors relies on the phenomenon of electron multiplication. As a charged particle traverses the detector, a specific quantity of primary electrons is generated. These electrons have the potential to aggregate into clusters. Subsequently, an electric field propels the electrons within each cluster, initiating a process of multiplication. This phenomenon is governed by two key factors: α, representing the rate of ionization per unit length (first Townsend coefficient), and β, signifying the rate of electron capture by the gas per [224] unit length (attachment coefficient). The mathematical expression below can be employed to represent the number of electrons, denoted as 'n', that ultimately reaches the anode:

$$n = n_0 exp[(\alpha - \beta)x] \tag{C.1}$$

Here, 'n_0' represents the initial count of primary electrons within the cluster, and 'x' signifies the separation between the origin of the cluster and the anode. The amplification of the detector's signal is determined by the following equation:

$$M = \frac{n}{n_0} \tag{C.2}$$

The categorization of RPC operation modes into two types, streamer and avalanche mode based on the gain value. When the gain, represented by 'M', surpasses 10^8, there is a high likelihood of primary ionizations resulting in the formation of streamers. Conversely, when the gain is around 10^6 or less, a lesser amount of charge is generated through basic charge multiplication, signifying operation in the avalanche mode. The governing factors for this operational classification, as indicated in Equation C.1, are the parameters α and β, both of which reflect the characteristics of the gas employed. In the context of the ICAL detector, a gas mixture comprising R134a, Isobutane, and SF6 has been utilized to operate RPCs in the avalanche mode [225, 226].

When a charged particle traverses the gas, its ionization leads to the initiation of electron avalanches, triggering a discharge process. The electrodes' high resistivity prevents this discharge from propagating throughout the entire gas volume. Instead, it is confined to a small region around the point of initiation, causing a localized drop in the electric field. The recharging of this discharged region takes place gradually through the highly resistive glass plates, and the recovery process lasts approximately 2 seconds. The movement of the electron avalanche results in the induction of a current on external electrodes. These external copper pickup strips, with a width of 2.8 cm, are positioned perpendicular to each other on the two electrodes, as illustrated in Figure 6.10. This arrangement allows for the identification of the particle's passage location in units of 2.8 cm × 2.8 cm pixels. Throughout the remainder of this thesis, the recorded position of a charged particle within the RPCs will be referred to as "hits". For an in-depth understanding of the operational principles and design specifics of the RPC detectors, refer to [226].

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