PROCEEDINGS OF SCIENCE

Fluxes and systematics reduction with decay monitoring

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The ENUBET collaboration is pursuing an R&D effort to develop and realize the first monitored neutrino beam. This new technique allows to set a tight constraint on the neutrino flux produced in conventional beams, and thus to measure neutrino cross sections with an unprecedented precision of $O(1\%)$. In this contribution the method being developed for the assessment of the systematics on the neutrino flux, before and after the constraint, is discussed. First results from a validation test on a toy-model is also presented.

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1. Introduction

The next generation of long-baseline neutrino experiments, DUNE [1] and HyperKamiokande (HK) [2], are conceived for the precision era of flavour oscillation measurements. In particular, their main goal is to test the 3-neutrino oscillation paradigm, with a possible discovery of CP violation in the lepton sector and the determination of the neutrino mass hierarchy. Nevertheless, the sensitivity of such experiments would be limited by the current knowledge of the neutrino-interaction cross sections, measured with a precision of $O(10-30\%)$. The strategy utilized up to now by long-baseline experiments, exploiting the near-far detector configuration to compare the neutrino interactions in the two locations and cancel out most of the uncertainties, is limited when high precision measurements, such as that of CP violation, are needed.

A new approach can be pursued, by developing a strategy to tackle directly the relatively large uncertainties of neutrino cross sections. The idea is to realize the so called "monitored neutrino beams" [3], to shrink down the main source of systematic uncertainty on neutrino cross sections coming from the knowledge of the initial flux in conventional neutrino beams. The development of a monitored neutrino beam is the goal being pursued by the ENUBET [4, 5] collaboration. With this technique, the neutrino flux is directly monitored by measuring the number of charged leptons from mesons along the decay tunnel [6–10]. An improvement of one order of magnitude in the neutrino cross-section precision is under reach with this strategy, boosting the sensitivity of next generation of long-baseline experiments. Moreover, models of neutrino interaction would benefit from the higher precision in cross section measurements.

The sources of systematic uncertainties with major impact on the neutrino fluxes are those related to the hadroproduction, beamline geometry and focusing. For instance, the hadroproduction systematic is dominant in neutrino fluxes at NuMI and T2K, followed by the beamline related systematics [11, 12]. The hadroproduciton has an impact of ~7% around the flux peak and ~9% at higher energies ($E_\nu \gtrsim 7$ GeV) for NuMi, whereas in T2K the uncertainty is ~10% around the peak and ~15-18% in the high energy tail ($E_\nu \gtrsim 15$ GeV). Beamline and focusing systematics amount to ~6% in the decreasing region of NuMI flux (4-5 GeV), whereas they are comparable to hadroproduction around the flux peak in T2K. A further improvement of the flux precision is achieved in NuMi (~4%) exploiting $\nu_\mu e^-$ scattering and in T2K (~5%) with replica targets.

2. Propagation of systematics to the neutrino flux

A full simulation of the ENUBET facility has been implemented, comprising the proton-target interactions (FLUKA), the transport of produced particles through the beamline (G4beamline, GEANT4), and the evolution of particles in the instrumented decay tunnel (GEANT4). Particles are propagated taking into account kinematics, decay processes and interaction with the facility material and detectors in the instrumented decay tunnel. The G4beamline and GEANT4 simulation of the beamline are redundant, giving the chance to cross-check the resulting performance. Furthermore, the asset of a GEANT4 implementation is to provided information on particle decays and histories. This is essential for the propagation of the systematics, from their sources up to the neutrino fluxes.

The procedure that is adopted to propagate the hadroproduction systematics on the neutrino flux is has follows. Hadroproduction data are used as input to reweight the MC events giving origin to a neutrino. From the reweighted events a nominal neutrino flux at the detector is obtained. The covariance matrix from the hadroproduction data is used to extract new values for the hadroproduction parameters, within their uncertainties, and thus get a set of N reweighted MC events. The adopted method is known as multi-universe. The N realizations of the MC events allow to determine the covariance matrix of the nominal neutrino flux. This covariance matrix encodes the uncertainty on the neutrino flux due to hadroproduction before exploiting the monitoring.

In a similar manner, systematics related to beamline parameters are propagated to the neutrino flux. The simulation with the beamline parameters set to their central values provides the nominal neutrino flux distribution, while varied realizations of the flux are obtained by tweaking the parameters within their uncertainties. Again, a covariance matrix for the neutrino flux, encoding the uncertainties on the beamline parameters, is computed from the varied flux.

Thanks to the ENUBET facility, we are able to measure the physics observables related to the leptons produced together with the neutrinos in meson decays and impinging in the calorimeter. Given the correlation between the lepton observables and the produced neutrinos (monitoring technique) a constraint on the neutrino flux can be set. The procedure to propagate the hadroproduction and beamline uncertainties to the neutrino flux is extended to the physics observables. By means of extraction of different possible values for the parameters affected by the uncertainties, using their covariance matrix, and reweighting the MC events, nominal and $\pm 1\sigma$ distributions for the lepton observables are computed. These are the building blocks of the fit model for the ENUBET physics observables.

3. Fit model and procedure

A signal plus background model PDF is built from the nominal and $\pm 1\sigma$ lepton observables (model templates). The variation in the number of observed leptons and in the shape of their distributions, due to hadroproduction and beamline uncertainties, are modeled through corresponding parameters, $\vec{\alpha}$ and $\vec{\beta}$, included in the PDF. An extended maximum likelihood fit approach is adopted, where the parameters $\vec{\alpha}$ and $\vec{\beta}$ are constrained by their pdfs resulted from the uncertainty propagation described above. From the model PDF a set of toy-MC experiments is produced, where each experiment is obtained by extracting the parameters affected by systematics from their covariance matrices. A posteriori values for the parameters are obtained by a fit to each toy-MC: these constrained parameters, with reduced errors, are used to reweight the MC. In turn, a post-fit reweighted neutrino flux (constrained neutrino flux) and corresponding covariance matrix are computed.

4. Validation of the procedure

A validation of the fit and flux constraint procedure has been performed using a hadroproduction toy-model as a test-bed. A sample of events is drawn from the toy-model, for which mock kinematic variables are assigned in order to simulate $K \to \mu\nu$ signals. A reweighting is applied by extracting the values of the hadroproduction parameters taking into account the corresponding covariance matrix. Basically, the procedure described in previous sections is applied to get the nominal neutrino flux and the physics observables, together with the corresponding covariance matrices. As an example, the distribution of the muons impact point along the decay tunnel walls in $K \to \mu\nu$

PoS(NuFact2021)030

decays, used as template for the fit model, is shown in fig. 1-left. Also, the distribution of the simulated muon neutrino flux is shown in fig. 1-right, with corresponding pre-fit error of 15%.

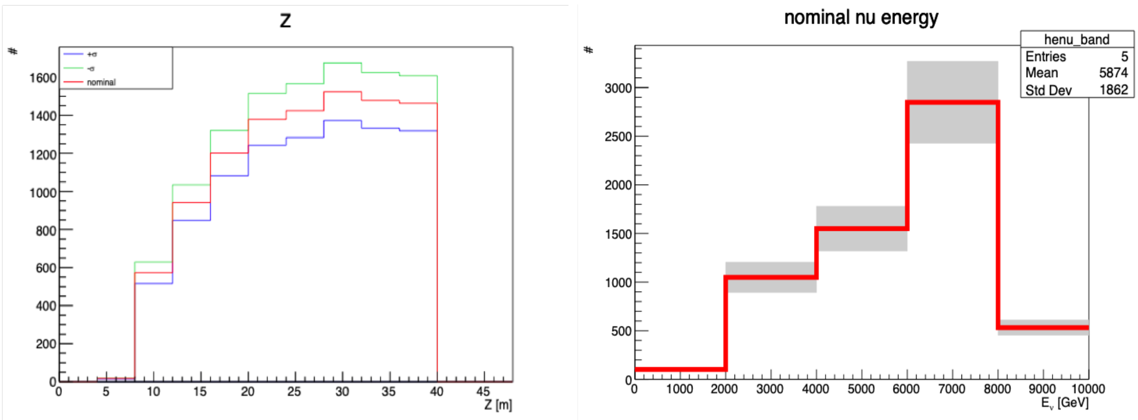

Figure 1: Left: signal template corresponding to the distribution of the muon impact point along the calorimeter of $K \to \mu\nu$ events simulated from the toy-model. The red line is the nominal distribution, green and blue lines are the $\pm 1\sigma$ deviations induced by hadroproduction uncertainties. Right: muon neutrino flux computed from the toy-model. Red line shows the nominal flux and grey band the 1σ error induced by hadroproduction uncertainties, corresponding to a 15% pre-fit error.

In this test, one signal template for each bin in the neutrino energy is considered, where the hadroproduction induces a 15% variation in normalization and negligible change in shape. The effect is ~100% correlated between templates, implying only a normalization variation in the neutrino flux. A background template is also simulated, with a 14% variation in normalization and a change also in shape. The variation due to hadroproduction is modeled by one parameter for the signal and one for the background (assuming signal and background variation are not correlated). A sample of toy-MC experiments was used to study the fit bias and stability, and the precision induced by the constraint on the neutrino flux. An example of a toy-MC experiment fit is shown in fig. 2-left. No bias in the fit procedure has been observed, and a post-fit error of ~1.8% on the neutrino flux is obtained (see fig. 2-right).

5. Conclusion and future steps

A procedure for the assessment of systematics on the neutrino flux with lepton monitoring has been developed and discussed above. The RooFit package from ROOT is exploited to build the signal plus background model from lepton observable templates. The propagation of the uncertainties to the observables and the neutrino flux is performed by means of the multi-universes approach. A hadroproduction toy-model has been used as test-bed for testing and validating the procedure. Work is in progress to build a real model utilizing the observable templates of the ENUBET facility from its GEANT4 simulation. Furthermore, real hadroproduction data are being considered for the MC reweighting and systematics propagation. NA56/SPY data [13] are those that suit better the needs, since the primary proton beam is close to the one considered for ENUBET. A model for the constraint of both electron and muon neutrino will be built.

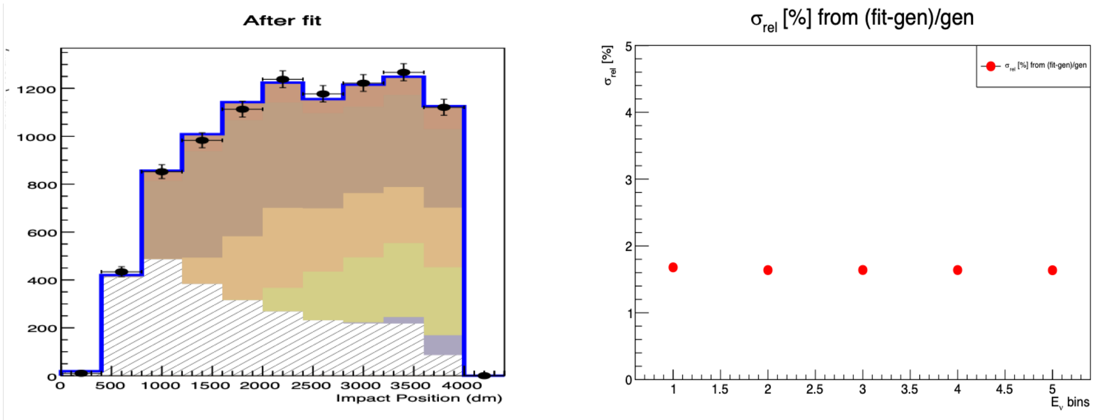

Figure 2: Left: example of a fit to a dataset (black dots) from a toy-MC experiment. Color filled histograms are signal templates corresponding to the different neutrino energy bins. The dashed histogram models the background contribution. The overall model is shown by the blue line. Right: byn-by-bin post-fit relative error on the neutrino energy bins, showing a ~1.8% error after the constraint from monitoring the leptons.

The impact of the beamline systematics will be assessed following the same procedure described in this contribution. Preliminary tests have already been performed, studying the impact of the dipole magnetic field error on the lepton observables.

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