**PANEL 4 Exploration of systematics**
**Ancillary measurements and developments: models and experiments**

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## Modelling neutrino-nucleus interactions

Facing a lack of monochromatic neutrino beams, a good understanding and detailed theoretical modeling of neutrino-nucleus responses over a broad energy range is pivotal for **energy reconstruction** in oscillation experiments. During the last decades, theoretical developments managed to establish detailed knowledge of the role of different reaction mechanisms in neutrino-nucleus interaction, thereby allowing one to recognize the right event type in data. This way, theory strongly contributed to reducing systematic errors in reconstruction analyses. Currently, **theoretical progress is slowed down by a lack of manpower.** The effect of the interplay between different interaction mechanisms, **nuclear correlations, meson exchange currents and of binding and excitation energies** on cross sections, also at low energy transfer and for forward lepton scattering is in great need of more detailed investigations. The same is true for **electron- and muon neutrino- cross section differences**. At low energy transfers, predictions for differential cross sections are critically different for different calculations. As important aspects of the model dependence of the reconstruction procedure are not sufficiently understood, it has to be established how theoretical and generator uncertainties propagate in the oscillation analyses. Pion production is an increasingly important channel for current and future experiments and additionally constitutes an important background (after pion absorption) to quasi-elastic processes. The description **above the delta-region (W > 1.4 - 2.0 GeV)** where numerous channels are opening up, is subject to major uncertainties and theoretical problems, where only a few models specifically focusing on neutrino-induced interactions have been developed so far. The role of the non-resonant background, unitarity, multiple pion production, nuclear effects, etc are issues that need further attention. From a purely theoretical point of view, the **Shallow Inelastic Scattering (SIS) and Deep Inelastic Scattering (DIS) region** in neutrino interactions is a largely unexplored wilderness and it will be relevant for wide band beam neutrino oscillation experiments (i.e. DUNE) and atmospheric neutrino experiments. The influence of final state-interactions and of hadronization in the DIS region is provided by generators. Progress in this field requires that new and more refined theoretical models should be embedded in generators. A flexible and universal interface for generators should be developed to encourage a fast transfer of theoretical progress to Monte Carlo simulations. Theoretical models need to be **benchmarked against electron scattering** data and where available against axial vector constraints in a systematic way. To improve on the understanding of neutrino interactions, events must be measured for all possible momentum transfer and addressing low energy particle detection emitted during the interactions. Neutrino-nucleus physics is no stranger to the classical synergy between theoretical and experimental physics. On the one hand, models need to be constrained by data, on the other hand, a strong theory community will be able to provide models with the power to offer guidance for efficient experimental design.

**Cross-section experiments.**

This theoretical development should be complemented with measurements performed either at the Near Detectors of the long baseline experiments or at dedicated experiments. This will require optimized **neutrino flux predictions** in conventional accelerator experiments provided by dedicated hadroproduction experiments or dedicated facilities such as **ENUBET** and **NUSTORM**. The other experimental frontier is the understanding of low energy particle production in neutrino nucleus interactions as well as improving the final state particle measurements in the full kinematical range. High resolution fully active-target detectors such as **SuperFGD (Fine-Grain Detector), LiqAr TPC or High Pressure TPC (HPTPC)** will be key technologies for this purpose. Low energy tracking devices and 4π acceptance detectors are key element to improve the theoretical models. This experimental program needs to be complemented with a program that allows to measure interactions in different nuclei. So far, theoretical models did not manage to keep pace with these developments. More exclusive measurements containing more **precise information on the outgoing nucleons** need specific theoretical modeling. An active **R&D** in Europe under the umbrella of the **CERN neutrino platform** and the **CENF-ND** will place European groups in an optimal position to make critical contributions in this field of research. The combination of **strong theoretical and experimental groups in Europe** will enhance further the impact of these developments.

NUPRISM aims at fixing the problem using the knowledge of the flux dependency with the beam off-axis angle. NUPRISM allows to have an almost quasi monochromatics beam and providing a direct measurement of the response function. This technique, complementary to that of conventional cross-section measurements will help to reduce uncertainties in the neutrino energy reconstruction.

**Secondary hadron-nucleus interactions**

One of the largest systematic errors in current experiments are due to the poor knowledge of the **cross section of pions and protons** emitted during the neutrino interaction with the detector material. The accurate measurement of this cross section will also reduce the uncertainties on the final state interaction models describing the interaction of hadrons inside the nuclei. The uncertainty in the oscillation results has been estimated to be around **6%** by the T2K experiment. A consistent set of measurements at relatively **low energy (i.e. ~250 MeV/c pions)** will improve future oscillation physics results. These measurements are part of the physics program of the Proton-DUNE experiments at CERN. Measurements using lighter nuclei than argon need to be performed. These experiments are normally small and can be carried out in Test Beam facilities around Europe with a large impact on the precision of oscillation results.

**Electron neutrino cross-sections**

Conventional neutrino beams are powerful sources of muon neutrinos. The $\nu_e$ flux in these facilities is at least two orders of magnitude smaller than $\nu_\mu$ since accelerator neutrino beams are optimized to reduce the $\nu_e$ contamination at the far detector. As a consequence, the **$\nu_e$ and anti $\nu_e$ cross sections are poorly known** (relative uncertainty >20%) due to limited statistics, large uncertainties in the initial flux and detector response systematics. Their values are mostly inferred from $\nu_\mu$ cross sections. These difficulties are exacerbated in electron antineutrino measurements because of the lower production yield and cross sections. On the other hand, oscillation physics at long baseline experiments is based on $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-$\nu_e$ transitions so a direct measurement of $\nu_e$ (anti-$\nu_e$) cross sections is unique for the physics of neutrino interactions and impacts on the physics of neutrino oscillations**.** The **next generation of near detectors** for T2K-II, DUNE and Hyper-K is being optimized to exploit the large $\nu_e$ CC statistics that will be available from MW power beams. These data will be of paramount importance to reach systematic-limited (<10%) measurements of $\nu_e$ and anti-$\nu_e$ cross sections and to pin down detector response systematics in the $\nu_e$ appearance channel. $\nu_e$ cross section measurements at the per cent level can be achieved by dedicated facilities. **ENUBET** is a proposed narrow band beam based on a static focusing system where $\nu_e$ are produced by the three-body semileptonic decay of the kaons and the $\nu_e$ flux at the source is measured at 1% level monitoring large angle positrons in the decay tunnel. This facility is optimized for a superior control of the neutrino source with regards to flux and energy in order to reach percent level precisions for $\nu_e$, $\nu_\mu$ and anti-$\nu_\mu$ cross sections. Replacing the instrumented decay tunnel of ENUBET with a **muon storage ring** would represent the next major technology leap in this field and a remarkable step forward in accelerator science. **NUSTORM** is the first accelerator neutrino beam where the flux of $\nu_e$ at source is comparable with the flux of $\nu_\mu$ since neutrinos are produced by muon decays. The design of the capture and storage components relies on decade-long developments performed world-wide in the framework of R&D for future Neutrino Factories. NUSTORM produces O($10^6$) $\nu_e$ and anti-$\nu_e$ CC events at the detector with a precision in the flux determination comparable to ENUBET. In addition, the muon capture and storage techniques developed by NUSTORM contribute in a decisive manner to the **R&D toward a muon collider** and grounds on a solid base the **Neutrino Factory** proposals.

**Atmospheric neutrino oscillations requirements**

Next generation of atmospheric neutrino experiments will increase the statistical samples and the precision of the measurements. Some of these experiments will be instrumental in the determination of the neutrino hierarchy and the improvement of the atmospheric oscillation parameters. The experimental program covers from very large **ORCA(Km3Net)** and **Deep Core(IceCube)** observatories to more precise but still large mass long baseline detectors such as **DUNE** and **HyperKamiokande**. The increase of the experiment statistics will require an equivalent development on the systematic errors, including the improvement on the understanding of the neutrino flux and neutrino-nucleus cross-sections in the **medium and high energy region corresponding to the so-called shallow to deep inelastic interaction regions**. Oscillations into $\nu_\tau$ can be studied using atmospheric neutrinos in these experiments. These needs have to be covered by ancillary activities related to theory development and experiments (SHiP). The understanding of very high energy neutrinos interaction with matter should be part of the theoretical developments. Atmospheric neutrino experiments also require a program of measurements of proton nucleon interactions at a variety of energies and detector acceptances. A consistent program covering the different long baseline and atmospheric flux prediction requirements will enlarge the impact of those experiments.

**Hadroproduction experiments**

To profit fully from the running and future accelerator neutrino experiments, a better understanding of the systematic uncertainties on the (anti-)neutrino fluxes and cross sections is required. To this end, it is crucial to support the on-going **NA61/SHINE** experiment at the CERN SPS focused on the **precise measurements of hadron production** for (anti-)neutrino flux predictions in T2K and Fermilab-based experiments. Two targets have so far been measured for T2K: a thin carbon target and a T2K replica target. Including the NA61/SHINE results from the thin carbon target, has brought the (anti-)neutrino flux systematic uncertainty at the near (ND280) and far (SuperKamiokande) detector down from ~25% to 10%. Recent work, using results from the T2K replica target, reduces further this systematic uncertainty down to 5%. Even a better knowledge is needed for future experiments such as T2K-II, and new hadron production measurements are planned for future Hyper-K and DUNE projects. Dedicated hadroproduction measurements at lower incoming proton momentum (< 15 GeV/c) could also help reducing systematic uncertainties in atmospheric neutrino fluxes. Thus, **NA61/SHINE is a major European contribution to the current and future world-wide neutrino program**. Based on the Fermilab Test Beam Facility, the **EMPHATIC** experiment also aims to measure complementary hadron production observables using a variety of beam particle species on different nuclear targets.

These developments are critical to improve the systematic errors in neutrino oscillation experiments and they can be carried out mostly in Europe. These research topics are an excellent opportunity to contribute to the global neutrino oscillation program in Europe under European leadership.