Tagged Neutrino Beams

Mathieu Perrin-Terrin

Transcendental Preprint
18th March 2022

Tagged Neutrino Beams

M. Perrin-Terrin

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

ABSTRACT

This article describes a new experimental method for accelerator based neutrino experiments called neutrino *tagging*. The method consists in exploiting the neutrino production mechanism, the $\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu}$ decay, to kinematically reconstruct the neutrino properties from the decay incoming and outgoing charged particles. The reconstruction of these particles relies on the recent progress and on-going developments in silicon particle detector technology. A description of the method is presented, together with its potential benefits for short and long baseline experiments. Then, a novel configuration for long baseline experiments is discussed in which a *tagged* beam would be employed together with mega-ton scale natural deep water Cherenkov detectors. The coarseness of this type of detectors is overcome by the precision of the *tagging* and, conversely, the rate limitation imposed by the *tagging* is outweighed by the size of the detector. These mutual benefits result in an affordable design for next generations of long based line experiments.

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

This contributed paper is conceived as an executive summary of the following paper:

- M. Perrin-Terrin, *Neutrino Tagging: a new tool for accelerator based neutrino experiments*, 2112.12848,

to which the reader is reported for a full description of the *tagging* technique.

1 Neutrino tagging concept

The neutrino beams produced at accelerators are primarily obtained by generating intense beams of $\pi^{\pm}$'s that decay in flight as $\pi^{\pm} \rightarrow \mu^{\pm}\overset{(-)}{\nu}_{\mu}$. Trackers installed in such beams would allow to reconstruct all $\pi^{\pm} \rightarrow \mu^{\pm}\overset{(-)}{\nu}_{\mu}$ decays. Each decay would be associated to a *tagged* neutrino of known chirality, flavour and with momentum and direction derived from the decay kinematics. Based on time and angular coincidence, each neutrino *interacting* in the detector could be associated with a single *tagged* neutrino.

2 Benefits over conventional beams

In conventional setups, neutrinos are reconstructed from their interaction. The variety of final states and the limited precision of the models describing them strongly impact these reconstructions. Moreover, accessing the neutrino flux requires extrapolations based on cross-section and hadron production models which also suffer from large uncertainties.

By contrast, in a *tagged* experiment, neutrinos are reconstructed from a single and simple process, the $\pi^{\pm} \rightarrow \mu^{\pm}\overset{(-)}{\nu}_{\mu}$ decay. Their properties are precisely deduced based on simple kinematics. As a result, ν and $\bar{\nu}$ can be collected at the same time and the requirements on the neutrino detectors are relaxed. Indeed, they only needs to measure the time, the position and identify the flavour of the interacting neutrinos. Moreover, the method allows to reconstruct all the neutrinos from $\pi^{\pm} \rightarrow \mu^{\pm}\overset{(-)}{\nu}_{\mu}$ decays and thus provides a solid input to estimate the neutrino flux which removes the need for near detectors.

3 Implementing neutrino *tagging*

The main challenges for the *tagging* method are the ability to operate trackers in a high particle rate environment, and to associate the *interacting* neutrino to a unique *tagged* neutrino. Both challenges can be met using the tracker technology being developed for the HL-LHC and a specific beam line designed to operate in slow extraction mode. An early version of the line, under study by the CERN PBC study group, is shown in Fig. 1.

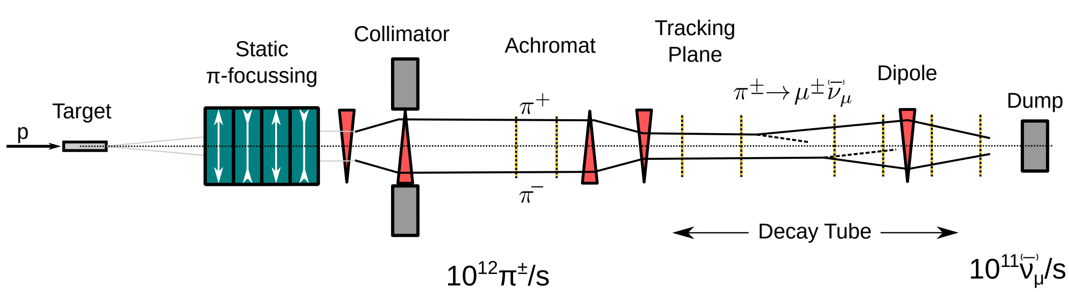

Figure 1: Schematic of a *tagged* beam line. Blue rectangles represent quadrupoles, red triangles dipoles and vertical dotted lines correspond to tracking planes. Assuming a beam size of $\mathcal{O}(0.1)\,\mathrm{m}^2$, trackers can operate up to $10^{12}\,\pi^{\mathrm{pm}}$/s. More details can be found in [1].

4 Applications to neutrino experiments

Short base line experiments would benefit from the precise knowledge of the flux to measure cross-sections. Moreover, *tagged* neutrinos could be employed as probes to refine the models used to infer neutrino properties from the final states. Finally, searches for sterile neutrinos would benefit from background suppression, improved reconstruction and reduced systematic uncertainties.

Long base line experiments (LBE's) would benefit from the same improvements to study the neutrino oscillation. However, they would need large detectors to collect enough neutrinos with beam intensities compatible with the *tagging*. Megaton scale water Cherenkov detectors could be employed. Their coarseness would be overcome by the precision of the *tagging*. Implementations could be envisaged with *tagged* beams from U70 (Russia) or FNAL (USA) using the existing infrastructures in the Mediterranean sea (KM3NeT), the lake Baikal (GVD) and the Pacific ocean (Neptune).

The P2O experiment between U70 in Protvino, Russia and the KM3NeT/ORCA detector off-shore Toulon, France, was used as a case study for a *tagged* LBE. A beam power of 450 kW was assumed and four scenarios were considered: P2O without tagging, *tagged* P2O, *tagged* P2O with a detector twice as dense as KM3NeT/ORCA, and with perfect neutrino flavour identification. At this intensity, about 90% of the interacting neutrinos can be unambiguously associated to a *tagged* neutrino. As reported in Fig. 2, the *tagging* stongly improves the sensitivity to the leptonic CP violating phase, δ_{CP}. With 10 years of operation and a dense detector (blue line), the precision on δ_{CP} ranges between 4° and 5° which opens new horizons beyond the next generation of LBE's (DUNE and HK).

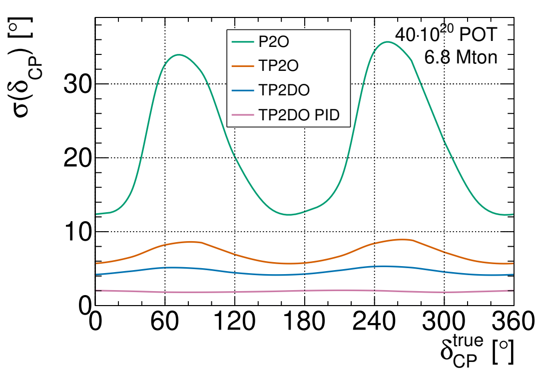

Figure 2: Precision on δ_{CP} as a function of the true δ_{CP} value for P2O (green), *tagged* P2O (red), *tagged* P2O with a far detector with a photocathode density twice as large as KM3NeT/ORCA (blue), and, with a perfect neutrino flavour identification (purple).

References

A full list of references is available in [1].

[1] M. Perrin-Terrin, *Neutrino Tagging: a new tool for accelerator based neutrino experiments*, 2112.12848.