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FUTURE NEUTRINO BEAM STUDIES UNDER THE FRAMEWORK OF PHYSICS BEYOND COLLIDERS

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Abstract

A Physics Beyond Colliders (PBC) initiative was recently established at CERN to exploit the full scientific potential of its accelerator complex and scientific infrastructure to tackle fundamental open questions in particle physics through experiments complementary to those in current and future colliders. This initiative brings together similar studies to optimize resources globally in order to reach a common goal and promote scientific development more efficiently. In this proceedings, we present the work performed by the Conventional Beam Working Group (CBWG) and specifically from the Neutrino Beams (NB) subgroup. The subgroup currently deals with two novel neutrino-tagged beams projects, ENUBET and NuTAG, as well as with a more conventional, low energy beamline dedicated to hadron cross-sections measurements with the NA61 experiment already installed in the H2 beamline of the CERN North Area. This contribution will detail the advances made with these three projects as well as their status and future plans.

ENUBET

The precision of the measurements of the various neutrino species cross-sections at the GeV scale is mainly limited by the knowledge of the initial flux, which in turn is affected by the uncertainties on hadro-production and particle propagation along the beamline [1]. This limitation leads to a precision of $O(5-10\%)$. Conventional neutrino beams are sources of muon neutrinos originating from pion or kaon decays, mixed with a small fraction of electron neutrinos produced by kaon and muon decays. [2] The ENUBET project (Enhanced NeUtrino BEams from kaon Tagging) aims to develop a facility that produces a beam of electron neutrinos originating from the decays of kaon mesons. The rate of K_{e3} ($K^+ \longrightarrow \pi^0\, e^+\, \nu_e$) decay is tagged and monitored in a specially instrumented decay tunnel that tags all neutrinos on an event-by-event basis, in order to improve the precision of the neutrino cross-section measurements by an order of magnitude, reaching an overall precision of 1% [3]. The designed neutrino beam is a narrow-band beam with a short (~ 30 m) transfer line followed by a ~ 40 m long decay tunnel. Secondary kaons produced by the interaction of protons on target are focused, momentum selected and transported at the entrance of the decay tunnel. The electron neutrino flux is subsequently monitored observing the large-angle positrons produced by the decays with a longitudinally segmented calorimeter instrumenting the decay tunnel [4, 5].

Optics

A careful selection and transport of the secondary beam requires a systematic beamline optimization ([6]). Particle collimation, magnets apertures, and magnetic fields define the beamline phase space acceptance. The first order optics optimization has been performed using TRANSPORT [7] and the results have been validated using G4Beamline [8] and FLUKA [9, 10] to simulate re-interactions of stray particles and background inside the instrumented decay tunnel, called the tagger. ENUBET is currently pursuing two different beamline designs: a baseline layout as seen in Fig. 1 designed to transport kaons with an average momentum of 8.5 GeV and a ±20% momentum bite [1], and a "multi-momentum" beamline shown in Fig. 2 that transports secondary particles of 4, 6, and 8.5 GeV/c, with different layout and design, and the purpose to select more than one momentum, allowing the exploration of a larger phase-space of neutrino cross-section measurements, including the region of interest of T2K/HyperK [11, 12].

Figure 1: Baseline beamline layout in Genat4.

Both transfer lines have undergone systematic optimization processes, the baseline version using a framework based

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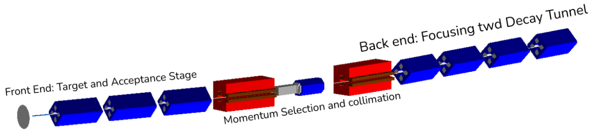

Figure 2: "Multi-Momentum" beamline layout in G4Beamline with the magnetic elements and the collimating structures appearing.

on a genetic algorithm, and the multi momentum line involving computational algorithms python based.

NuTAG

The NuTAG project [13] proposes a new method to refine the measurement of neutrino oscillation properties by exploiting the neutrino production mechanism in the $\pi^{\pm} \rightarrow \mu^{\pm}\overset{(-)}{\nu}_{\mu}$ decay. Instrumenting an intense pion beam with the latest generation trackers would allow reconstructing all the pion decays from the tracks of the incoming $\pi^{\pm}$ and outgoing $\mu^{\pm}$, uniquely tagging each neutrino interacting in the far detector. This method enhances the neutrino energy reconstruction and reduces the systematic uncertainties related to the beam knowledge. The designed neutrino beam is a conventional narrow-band beam starting from a short pion momentum-selecting beam line followed by a 300 m long decay tunnel. Two different approaches are being pursued: (a) the "Double Charge Focusing" (DCF) layout, and (b) the "Single Charge Focusing (SCF) one. The former allows the transport of both π^{+}s and π^{-}s at the same time, momentum selecting the pions of both charges in a momentum range relevant for the phenomena under stud. The latter allows for a higher acceptance but only momentum-selects and transports one of the two charges at a time, either π^{+} or π^{-}.

Double Charge Focusing Layout

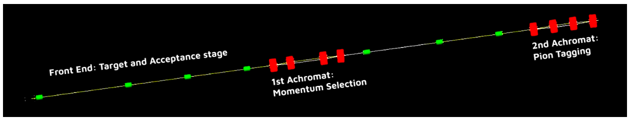

Figure 3: Double charge focusing beamline layout in G4Beamline with standard magnets.

The ambition of this design lies in the idea of focusing both negative and positive pion beams at the same time, therefore minimizing the data-taking time. As such, data taking-time is reduced and rate asymmetries between ν and $\bar{\nu}$ are made insensitive to systematics uncertainties induced by variations of the data-taking conditions. As seen in Fig. 3, the concept of this version employs two achromat sections, both consisting of large aperture bending magnets. The first, in the horizontal plane performs momentum selection of the secondary beam, and a second one placed downstream, acts as a magnetic spectrometer that, with 3 tracking devices, allows for the tagging of the secondary pions before their natural decay. To ensure the momentum selection and reduce the momentum spread to around ~ 10%, a collimator with two equally spaced holes for the π^{+} and π^{-} beams has been designed and placed in the middle of the first achromat. To reduce further the background, this particular design adopts a production angle at the target level of 40 mrad, allowing the primary beam to escape on the side without interfering with the apertures or magnetic elements of the line, thus avoiding the creation of extra background. However, since in this version the target and the decay tunnel lies in a straight line, the background from particles created at the target can still be significant. The overall length of this design is about 80m long, meaning that inside the line the 12% of pions are expected to decay.

Single Charge Focusing Layout

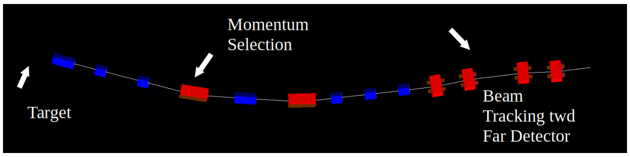

Figure 4: Single charge focusing beamline layout in G4Beamline. The beam has a deflection angle in the horizontal plane allowing the primary beam to escape, while the single-charged pions are tagged downstream.

In parallel, a second layout has been envisioned to counteract the rate drop due to the imposed production angle and at the same time, the background created at the target. This design includes a momentum selection stage using only two dipole magnets, and a single 4-bend achromat for the pion tagging. The advantages of this second "Single Charge Focusing" design, as shown in Fig. 4, are the larger acceptance phase space, along with a reduced overall length of 40 m due to the single achromat section. However, all these advantages come at the cost of the simultaneous study of both secondary beam charges, hence doubling the beam time and potentially increasing the systematic uncertainties. Further studies will investigate which layout is more efficient for the project.

Monte Carlo Simulations

We performed radiation and particle fluence studies using the new version of the FLUKA code available ad CERN. These studies are focused mainly on the double charge focusing layout, to better understand the expected signal-to-noise ratio in the far detector and estimate the number of events expected.

The overall performance of this design has been evaluated with simulated $\pi^{\pm}$ beams of 12 GeV/c. An illustration of the π^{+} fluence along the beamline, projected on the y and x planes respectively, can be seen in Fig. 5. One can also see that the divergence of the pion beam is of the order of $25 mrad/mm$, allowing for the produced neutrino to move mostly in the forward direction towards the far detector.

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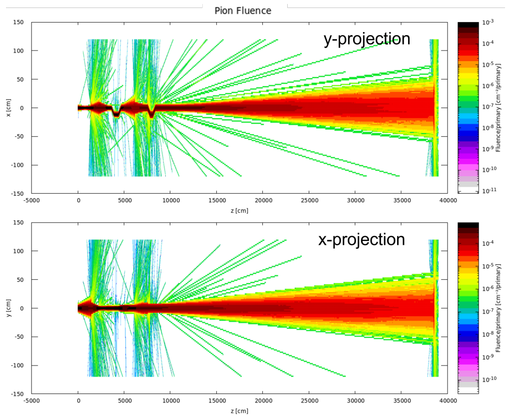

Figure 5: Pion fluence per primary along the beam line projected onto the y (top) and x (bottom) planes.

Finally, Fig. 6 shows the ν_μ spectrum at different points along the beam line obtained in this version: the blue line represents the spectrum of neutrinos before the second achromat ("tagger"), and is, therefore, a measure of the neutrino background from early decaying pions, while the yellow line represents the spectrum of neutrinos at the end of the decay tunnel. The ν_μ signal from tagged pion decays is visible between 2 and 5 GeV, as expected, with a signal to noise ratio of about 2 compared to background.

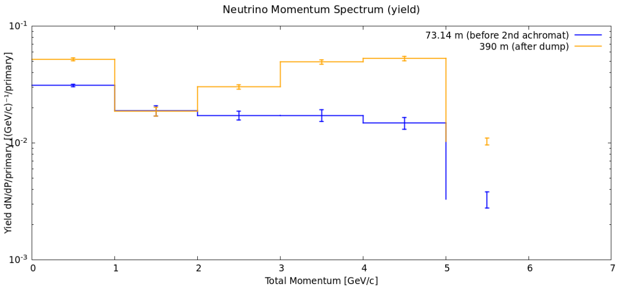

Figure 6: Neutrino spectrum at two different point along the beam line: before the second achromat (blue line) and after the dump (yellow line) at the end of the decay tunnel.

In conclusion, the preliminary studies on both versions of the NuTAG beamlines have given promising results. Further studies are ongoing to optimize the performance of this beamline, especially pointing towards the reduction of the background and to the calculation of a first number of possible neutrino events at the far detector.

NA61 - LOW ENERGY BEAM

As already mentioned, many long-baseline neutrino experiments start from the production, momentum selection, and transport of low-energy hadron beams (typically < 10 GeV/c). NA61/SHINE [14] is an experiment installed at the CERN's North Area that focuses on hadron production cross-sections. T2K has already successfully benefited from the current NA61/SHINE measurements, reducing the flux uncertainty to about 5% in the 31 at T2K flux peak [15]. Currently, the NA61/SHINE collaboration along with the CERN BE-EA group has proposed the design of a new tertiary low energy beamline to be implemented in the present H2 line at CERN that can supply low-energy hadron beams down to 2 GeV/c, thus opening new possibilities for hadron production measurements in this neutrino-interesting regime, that today are not possible with the current infrastructure available at CERN.

The new line needs to satisfy strict requirements. In particular, it needs to provide flexible pions, kaons, and protons in a desirable range of momentum between 2 and 13 GeV/c with a momentum spread better than 5 %, and with variable purities and rates, depending on the purpose of each measurement.

Layout

Figure 7 shows the layout of this proposed new branch, that will be installed in the H2 beam line just upstream of the NA61 main TPC. The first doublet of existing QPL magnets as front-end is chosen to maximize particle acceptance. Next, a four-bend achromat is placed downstream to allow for momentum selection and dispersion recombination while finally, a quadruplet focuses the beam onto the NA61/SHINE target, allowing for sufficient flexibility in the position of the focal point for different experimental configurations. Optimization of the line layout has been performed using a python-based computational algorithm and then validated via MAD-X/PTC studies as mentioned in [16].

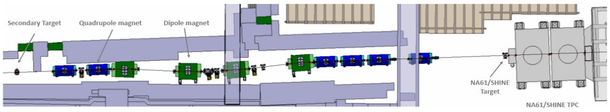

Figure 7: A CAD drawing of the low-energy branch of the H2 line, starting at the secondary target and ending at the NA61/SHINE TPC.

Beam Instrumentation

Beam Instrumentation is currently under study and the following detectors are being considered for a successful design : (a) Three gas threshold Cherenkov detectors together with two plastic scintillator-type counters will be installed to perform particle identification. (b) Four scintillating fiber counters will define a beam trigger signal. Finally, (c) multiple fiber beam profile detectors will be installed at various points of the beamline to measure the beam profiles at various locations and possibly provide a trigger for the experiment.

CONCLUSIONS

We have highlighted in this paper three very promising projects with common physics goals and techniques. Thanks to the Physics Beyond Colliders, Conventional Beams Working Group - Neutrino Subgroup (PBC-CBWG-NB), synergies between these collaborations have been developed and these novel projects have significantly advanced.

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