ENUBET
Enhanced NeUtrino BEams from kaon Tagging

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On behalf of the ENUBET Collaboration

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High Precision Neutrino Flux Measurements in Conventional Neutrino Beams
The Idea and The Conceptual Design

- Neutrino cross sections have crucial role in the oscillation physics
  \( \nu_\mu \rightarrow \nu_e \) experiments in appearance mode need direct \( \nu_e \) cross section measurements
- Exact knowledge of initial flux is the main limiting factor for neutrino oscillation experiments
  - Flux estimate is an indirect procedure in conventional beams
  - Remarkable progress on neutrino cross-section measurements and hadro-production in targets but still uncertainties are at the order of \( \sim 7\text{-}10\% \)

**idea**

Monitor the neutrino beam with a direct measurement of neutrino fluxes with conventional technologies by **tagging the \( \text{Ke}_3 \) decays**

Protons \( \rightarrow \) Target \( (K^+,\pi^+) \) \( \rightarrow \) \( \text{Ke}_3 \) decays
\( K^+ \rightarrow e^+\pi^0\nu_e \)

- Measure positrons in a FULLY INSTRUMENTED decay region
- \( \nu_e \) flux prediction = \( e^+ \) counting
- "By-pass" uncertainties from POT, hadro-production, beamline efficiency
- **ve flux prediction = e+ counting**

\[ \rightarrow \text{Improvement of one order of magnitude cross-section measurement @GeV scale} = \]

\[ \text{Determine absolute } \nu_e \text{ flux at neutrino detector with } O(1\%) \text{ precision} \]
High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

The Idea and The Conceptual Design

Reference Parameters
- $P_{\pi/K} = 8.5$ GeV/c (±10%)
- Tagger L=40m, r=1m
- $\langle \theta e^+ \rangle = 88$ mrad

- Short tunnel: contribution to $\nu e$ flux from $\mu$ decays negligible
- $\rightarrow \nu e$ flux dominated (~98%) by neutrinos from $K_e3$ decays
  Complete control on $\nu e$ flux with tolerable rates (<500kHz/cm²) and low irradiation (<1kGy)

- Requirements:
  - Transfer Line: as short as possible, keep contaminations low
  - Tagger:
    - $e^+$: Longitudinal sampling + integrated light readout
    - Photon veto: photon ID + precise timing + exploit 1mip/2mip separation
The Transfer Line

2 possibilities:

- **HORN-BASED** beamline  
  → PRO: focusing more $\pi$ & $K$ in the wanted $P$ range before the transfer part to the decay tunnel  
  → Higher yields @ decay tunnel

- **CONS:**
  - Horn pulse limit < $O(1-10)$ ms
  - Tagger rate limit reached with $\sim10^{12}$ POT/spill
  - We need $10^4$ ve-CC in a 500-ton detector → $\sim10^{20}$ POT = fraction of a year at present proton drivers  
  $\sim10^8$ spills → challenging/unconventional

  → **Multi-Hz extractions + Horn Pulsing (2ms)** → machine studies @ SPS

- **STATIC-FOCUSING** beamline  
  → PROS: Lower rates @ decay tunnel (1e+/30ns) + Possibility of event-by-event tagging by coincidences between $\nu_e$ at the detector and $e^+$ at the tagger

- **CONS:**
  - Less efficient focusing: lower yields, more POT needed

  → **Single slow extraction**
The Transfer Line

- Preliminary study for the Horn-based beamline completed → best configuration: Target + Horn + quad triplet + dipole + quad triplet (background studies not yet completed)
- Concentrating now on the Static beamline → looks very promising despite lower yields

Latest layout of the static transfer line option
- FLUKA for protons interactions in the target
- TRANSPORT for optic optimization + G4Beamline for complete TL simulation

Hadronic rates @ Tunnel Entrance (with G4beamline). In parenthesis (EPJ initial estimate)

<table>
<thead>
<tr>
<th></th>
<th>(\pi^+)/pot ((10^{-3}))</th>
<th>(K^+)/pot ((10^{-3}))</th>
<th>Increase factor wrt initial estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn-based transfer line</td>
<td>77.3 (33.5)</td>
<td>7.9 (3.7)</td>
<td>(~2.2)</td>
</tr>
<tr>
<td>Static transfer line</td>
<td>26.7 (3.6)</td>
<td>2.05 (0.43)</td>
<td>(5-7)</td>
</tr>
</tbody>
</table>

- Very promising!
- Detailed study on beam contaminations in progress
1) Shashlik Calorimeter
   - Ultra Compact Module (UCM) (Fe absorber+Plastic scint)
   - Light Readout with SiPM
   \[\rightarrow 4X_0\] Longitudinal sampling: \(e^+ / \pi^\pm\) separation

2) Integrated Photon-veto
   3) 3x3 cm² plastic scintillator pads
   \[\rightarrow e^+ / \pi^0\] separation (\(\pi^0\) rejection)

\[\begin{array}{c}
\text{hadronic} \\
\text{em} \\
10 \text{ cm }= 5X_0 \\
60 \text{ cm}
\end{array}\]
The Tagger

Shashlik Calorimeter

Calorimeter prototype performance with test-beam data

Calorimeter Prototype
The Tagger

Calorimeter prototype performance with test-beam data

- Test Beam @ CERN-PS T9 beamline in Nov 2017
- 56 UCM arranged in 7 longitudinal block (~30X₀) + hadr. Layer (coarse sampling)
- e/µ tagged with Cherenkov counters and muon catcher
- Beam Composition @ 3GeV: 9% e-, 14% µ, 77% hadrons
- Tested response to MIP, electrons and charge pions

Ballerini et al., JINST 13 (2018) P01028

- em energy res 17%/√E(GeV)
- Linearity <3% in 1-5 GeV
- From 0 to 200mrad tilts tested → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities (effect corrected equilizing UCM response to mip)
- MC/data already in good agreement, longitudinal profiles of partially contained π reproduced by MC @ 10% precision
Detectors R&D

- $\gamma/e^+$ discrimination (Photon-Veto)
  - **t0 layer** scintillator ($3\times3\times0.5$ cm$^3$) + WLS Fiber + SiPM
  - Tested @ CERN T9 in July + October
  - Goal: Study light collection efficiency $\rightarrow >95$
  - First measure of time res $\rightarrow \sigma \sim 400$ps
  - First 1mip/2mip separation using photon conversion from $\pi^0$ gammas. ($\pi^0$ by charge exchange of $\pi^+$ with low density target after silicon chambers)

  We are able to discriminate $\gamma$ from Ke3 e+

- **Irradiation Studies**
  - **SiPM** were irradiated at LNL-INFN with 1-3 MeV neutrons in June 2017
  - Characterization of 12, 15 and 20 $\mu$m SiPM cells up to $1.2 \times 10^{11}$ n/cm$^2$ 1 Mev-eq (i.e. max non ionizing dose accumulated for $10^4$ $\nu$eCC at neutrino detector)

  **irradiated SiPM** tested at CERN in October 2017

  Detectors are radiation hard, we see mip & electrons

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ENUBET, G. Brunetti

IFAE2018 – 6 April 2018
Conclusions

- Results of ENUBET studies coming faster than expected and very promising
- Many R&D activities currently on-going and another year of test-beams @ CERN ahead →
  - Achieve recovery time <10ns (to cope with pile-up)
  - Test of custom digitizer electronics
  - Photon veto prototypes with plastic scintillators
  - Scalable/reproducible technological solutions (water-jet holes machining for absorbers, molded scintillators, polysiloxane scintillators → First application in HEP! No drilling & high rad. hard)
- Static beam line looks very promising, would avoid the problem of pulsing a horn + event-by-event tagged beam!
  Work in progress to have precise estimation of expected beam backgrounds

- By The end of the year we expect to complete the Reference Design:
  Complete simulation end-to-end of the beamline +
  Final configuration of the calorimeter +
  (will test a non-shaslik configuration as well)
  Updated physics performance
  (monitor of major BR of K+, neutrinos flux determination at 1%, possibility of a tagged beam)
Thank you!
Back-ups
High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

**Constraining \( \nu \) Fluxes**

**IDEAL SOLUTION FOR NEW GENERATION SHORT-BASELINES**
- 1% precision on \( \nu_e \) fluxes for x-section measurements ("monitored neutrino beams")
- Comparable precision on \( \nu_\mu \) fluxes from K for x-section measurements
- Narrow-band facility where neutrino energy is well-known thanks to small momentum bite
- With static-focusing transfer line option (next slide) possibility of complete K-decay kinematic reconstruction \( \rightarrow \) \( \nu_e \) energy event-by-event ("tagged neutrino beam")

**\( \nu_e \) Flux**
- **Ke3 golden sample**
  - \( \pi^+/\pi^0 \) from K+ can mimic an \( e^+ \)
    e/\( \pi \) discrimination through
    I. Shower Longitudinal profile
    II. Vertex reconstruction by timing
  - Non Ke3 (silver sample) exploitable

**\( \nu_\mu \) Flux**
- K well constrained by tagger (from Ke3 and hadronic decays)
- \( \nu_\mu \) from K can be selected at the neutrino detector using radius-energy correlations
  \( \rightarrow \) high precision \( \sigma(\nu_\mu) \)
Neutrino Samples

- Need good e-tagging capabilities, like:
  - ICARUS/μBOONE @ FNAL
  - Proto-DUNE SP/DP @ CERN
  - Water Cerenkov (e.g. E61 @ JPARC)

- Assumed a 500 t LAr det ($6 \times 6 \times 10$ m$^3$) @ 100 m

<table>
<thead>
<tr>
<th>$E_p$ (GeV)</th>
<th>PoT ($10^{20}$) for $10^4 \nu_e^{\text{CC}}$ (on-axis)</th>
<th>Run duration (w/ nominal int)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.03</td>
<td>$\sim 0.2$ JPARC y</td>
</tr>
<tr>
<td>120</td>
<td>0.24</td>
<td>$\sim 0.4$ NUMI y</td>
</tr>
<tr>
<td>400</td>
<td>0.11</td>
<td>$\sim 0.25$ CNGS y</td>
</tr>
</tbody>
</table>

- Reference design better suited for multi-GeV (e.g. DUNE)
- Hyper-K r.o.i accessible in off-axis configuration, but larger exposures needed
- Studying the possibility to reduce the initial hadron momentum
- Can exploit also $\nu_\mu$ from $\pi$ ($\sim 10^5$ @ low $E$), estimating the initial $\pi$ flux with BCT and $K$ constraint from the tagger → to be investigated
Systematics on $\nu_e$ Flux

Positron tagging eliminates the most important contributions. Assessing in detail the viability of the 1% systematics on the flux is one of the final goals of ENUBET. Full analysis is being setup profiting from a detailed simulation of the beamline, the tagger and inputs from test beams.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical error</td>
<td>$&lt;1% \ (10^4 \nu_e^{cc})$</td>
</tr>
<tr>
<td>kaon production yield</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>number of integrated PoT</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>secondary transport efficiency</td>
<td>irrelevant (positron tag)</td>
</tr>
<tr>
<td>branching ratios</td>
<td>negligible + only enter in bkg estimation</td>
</tr>
<tr>
<td>3-body kinematics and mass</td>
<td>$&lt;0.1%$</td>
</tr>
<tr>
<td>phase space at the entrance</td>
<td>to be checked with low intensity pion runs</td>
</tr>
<tr>
<td>$\nu_e$ from $\mu$-decay</td>
<td>constrain $\mu$ from $K$ by the tagger and $\mu$ from $\pi$ by low intensity runs</td>
</tr>
<tr>
<td>$e/\pi$ separation</td>
<td>being checked directly at test beams</td>
</tr>
</tbody>
</table>