Technical challenges and physics opportunities of modern tagged neutrino beams

- Accelerator neutrino beams and the Holy Grail of neutrino physics
- Beams with a superior control of the flux at source: the monitored neutrino beams
- Beams where the neutrino observed at the detector is uniquely associated to the particles produced in the beamline: the tagged neutrino beams
Producing neutrinos... shooting in the dark

It has been the workhorse of major discoveries in electroweak and neutrino physics because it is scalable to very high beam power (up to MW, right now)
The holy grail of neutrino physics

\[ \pi^+ \rightarrow \mu^+ \nu_\mu, \ K^+ \rightarrow \mu^+ \nu_\mu, \ K^+ \rightarrow e^+ \nu_e \pi^0 \]

This possibility has been envisaged for the first time in 1969 and strongly supported by B. Pontecorvo in the USSR in the 80s.

In order to observe a neutrino in a moderate mass detector (e.g. Protodune-SP at CERN) we need to produce \(10^{13}\) pions or kaons. Producing, tracing, recording such an amount of data is a tremendous technical challenge although is within reach of contemporary technology.
The need of high precision neutrino beams

To observe the very existence of neutrino oscillation (1998-2005) natural (i.e. poorly known) sources are enough. But if you want to pin down precisely how neutrino flavor mix, you need unprecedented precision in the knowledge of the flux, flavor and energy of the neutrinos at source.

This issue is the main limitation of the «precision era of neutrino physics»
Accelerator neutrino beams... before 2012

Accelerator neutrino beams played a key role in the discovery of neutrino oscillation because they are sources of pure and well controlled (energy, direction and flavor) GeV neutrinos

... but the energy range, flavor and oscillation distance ("baseline") are limited

- Energy: 0.2 – 100 GeV
- Flavor: mostly $\nu_\mu$
- Distance: 10 m – 1000 km
2012: a breakthrough, literally

• The precision era of accelerator neutrino beams commences in 2012 with the discovery of $\theta_{13}$ (Daya-Bay, RENO and T2K)

• The mixing between the first and third family is large ($\theta_{13} \approx 8^0$)

  - Artificial neutrino sources can perform precision measurement of all oscillation parameters in the standard three-family paradigm

  - Accelerator neutrino beams may access CP violation in the leptonic sector, the neutrino mass hierarchy and all angles of relevance at the atmospheric scale (in particular the octant of $\theta_{23}$)

Since 2012 accelerator neutrino physics has grown by a factor ten in participants and investment and is the field that gathers the largest community in neutrino physics
A strategy for the next decade

Use «high intensity (1 MW) conventional beams» with neutrino detector located at >100 km to study neutrino oscillations.

In jargon: «long-baseline superbeams» (e.g. DUNE and HyperKamiokande)

Use «moderate intensity (100 kW) high precision beams» with neutrino detector located at <1 km to study neutrino interactions with matter and substantially reduce the systematic uncertainties of long baseline experiments.
Input document for the European Particle Physics Strategy

A high precision neutrino beam for a new generation of short baseline experiments

arXiv:1901.04768

Future Opportunities in Accelerator-based Neutrino Physics

The Participants of the European Neutrino Town Meeting
22–24 October, 2018
CERN, 1 Esplanade des Particules, 1211 Geneva 23, Switzerland

Editors: Alain Blondel\textsuperscript{a}, Albert De Roeck\textsuperscript{b}, Joachim Kopp\textsuperscript{c}
(full author list in the appendix)

arXiv:1812.06739

Input from the CENF-ND Forum to the 2020 Update of the European Strategy for Particle Physics


arXiv:1901.04346
A high precision narrow band neutrino beam

**Difficulty:** MEDIUM  
**Physics reach:** MEDIUM-HIGH (*)

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**Key component:** a transfer line with a geometrical acceptance of 0.6 mm rad and a momentum bite of 10% in the energy of interest for long baseline experiment (secondary: 1-10 GeV)

- Beam power: 100 kW
- $4 \times 10^{13}$ protons-on-target per spill
- $1$-$2 \times 10^{19}$ integrated protons in a few years
- Horn with fast extraction: 10 μs

(*) depends on final precision on fluxes
Why a narrow band beam?

Rates for $\approx 1 \times 10^{19}$ protons-on-target ($\approx 3$ months of CNGS) and Protodune-SP

$\nu_\mu^{CC}$ in radial bins
The «narrow band off-axis technique»

You just measure the distance of the vertex of the neutrino interaction with respect to the axis of the decay tunnel to get the initial neutrino energy.

Get rid of the most important shortcut in cross section measurement: the bias due to using final state particles to measure the initial energy of ν.
Where CERN-EN can make the difference

Flux: we want to equip the transfer line with a Beam Current Transformer to estimate the number of charged particles with a precision of <1% (beam transverse area: 10 cm, $10^{10}$ part in a few µs or (see below) a few ms.

First quadrupole at entrance: we want to develop a rad-hard (few MGy/y) quad capture magnet just after the target.

We want to investigate whether this line can be implemented at CERN without changing the position of the two ProtoDUNE detectors.

Proposed for nuSTORM but never implemented in a secondary neutrino beam line.

Conventional (preferred option) Superconducting: cost/benefit unclear.

Beamline for $1-2 \times 10^{19}$ pot/y from SPS.
Counts the lepton produced in the decay tunnel on an event by event basis.

Bypass the entire simulation of the beamline needed to evaluate the neutrino flux. Shortcut the most important systematics in the measurement of the neutrino cross section: the neutrino flux.
A narrow-band beam for the precision era of $\nu$ physics

**Absolute flux** of $\nu_e$ and $\nu_\mu$ at the 1% level
- Remove the leading source of uncertainty in **neutrino cross section measurement**

**Energy of the neutrino** known at the 10% level
- The ideal tool to study neutrino interactions in nuclei

**Flavor composition** known at the 1% level
- The ideal tool to study NSI and sterile neutrinos at the GeV scale
Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angles is monitored at single particle level $\Rightarrow$ direct measurement of the flux

ERC Consolidator Grant. From Jun 2016 to May 2021. PI: A. Longhin
The ENUBET Collaboration: 54 physicists, 12 institutions
The ENUBET 2-triplet beamline

- **Proton driver**: CERN (400 GeV), FNAL (120 GeV), J-PARC (30 GeV)
- **Target**: 1 m Be, graphite target. FLUKA.
- **Focusing**
  - **Horn**: 2-10 ms pulse, 180 kA, 10 Hz during the flat top [not shown in fig.]
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **Transfer line**
  - Kept short to: minimize early K the decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino flux component)
  - **Optics**: optimized with TRANSPORT to a 10% momentum bite centered at 8.5 GeV/c
  - **Particle transport and interaction**: full simulation with G4Beamline
  - **Normal-conducting magnets**: 2 quad triplets (15 cm wide, L < 2 m, B = 4 to 7 T/m)
  - 1 bending dipole (15 cm wide, L = 2 m, B = 1.8 T)
- **Decay tunnel**: r = 1 m. L=40 m, low power hadron dump at the end
- **Proton dump**: position and size under optimization
A design optimized for monitored beams

2 dipoles with an intermediate quadrupole. Increased length of beamline but ...

- Better quality of the beam in the tagger
- Larger bending angle (15.2°) reducing backgrounds from muons and probability for neutrinos produced in the straight section to reach the neutrino detector
## Where CERN-EN can make the difference

<table>
<thead>
<tr>
<th>The <strong>proton extraction scheme</strong>: we need to dilute the proton spill in 10 ms bunches to reduce the particle rate in the walls of the tunnel</th>
<th>In collaboration with CERN-BE-OP</th>
</tr>
</thead>
<tbody>
<tr>
<td>A more sophisticated <strong>transfer line</strong> to reduce secondaries at the entrance of the tunnel</td>
<td>Conventional (preferred option) Superconducting: cost/benefit unclear</td>
</tr>
<tr>
<td>A careful designed <strong>shielding</strong> along the line to reduce tertiaries in the tunnel walls</td>
<td>Material choice, cost</td>
</tr>
<tr>
<td><strong>Doses and irradiation</strong> to quadrupoles and tunnel instrumentation</td>
<td></td>
</tr>
<tr>
<td>Beam dump and target at $5 \times 10^{19}$ pot</td>
<td>Material choice, cost</td>
</tr>
<tr>
<td>Thermal and mechanical behaviour of the horn</td>
<td>2-10 ms at about 10 Hz in 4 s flat top</td>
</tr>
</tbody>
</table>
Machine studies for the horn-based option

- Performed Jul/Aug/Nov 2018 at the SPS

CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

- Idea: synchronize proton beam and horn current pulses
- + keep rates compatible with tagger (10 ms pulses “slow extr.”)

“burst ” slow extraction: trigger the third integer betatron resonance with a periodic pattern

M. Pari (CERN doctoral student, Univ. of Padova) @ SLAWG meeting of 5/12/2019
https://indico.cern.ch/event/777458/

New proposed tune functions

- Original Tune
- Burst SE - Manual
- Burst SE - Optimized
- Burst SE - Parabolic
- Burst SE - Parabolic2

New proposed tune functions
Machine studies for the horn-based option

from powerpoint to implementation 😊

Real data

Same integrated pot extracted.
Protons squeezed into intervals when horn is pulsed

CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard
The ENUBET beam line – particle yields

<table>
<thead>
<tr>
<th>Focusing system</th>
<th>$\pi$/pot $(10^{-3})$</th>
<th>K/pot $(10^{-3})$</th>
<th>Extraction length</th>
<th>$\pi$/cycle $(10^{10})$</th>
<th>K/cycle $(10^{10})$</th>
<th>Proposal (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn</td>
<td>97</td>
<td>7.9</td>
<td>2 ms (a)</td>
<td>438</td>
<td>36</td>
<td>x 2</td>
</tr>
<tr>
<td>“static”</td>
<td>19</td>
<td>1.4</td>
<td>2 s</td>
<td>85</td>
<td>6.2</td>
<td>x 5</td>
</tr>
</tbody>
</table>

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

The horn-based option still allows ~x5 faster statistics but the static option gained
momentum since initial estimates were ~ x 5 too conservative wrt to present simulations!

Furthermore ... advantages of the static extraction:
• No need for fast-cycling horn
• Strong reduction of the rate (pile-up) in the instrumented decay tunnel
• Monitor the $\mu$ after the dump at % level (flux of $v_\mu$ from $\pi$) [under evaluation]
• Pave the way to a “tagged neutrino beam”, namely a beam where the neutrino interaction at the detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel
The ENUBET static beamline

Divergence of the kaon beam

$K^+ @$ tagger entrance  exit

1 m radius

Particle budget @ tagger entrance

$\pi^+, p, e^+, \mu^+$

Momentum bite

$(8.5 \pm 10\%) \text{ GeV/c}$

Spectra @

tagger entrance  tagger exit

Low energy high angle $\pi$

Loss driven by decays

$K^+$
Beamline shielding tuning studies

- Studies in progress to optimize the shielding to shield muons and other backgrounds.

**G4Beamline**

**FLUKA (muon energy deposition map)**

Particle budget @ tagger entrance

Factor >3 reduction in muons at ~ constant background from other sources (e⁺, π⁻)

Azimuthal angle
Particle rates in the tunnel

Static focusing system
4.5 x 10^{13} pot in 2 s (400 GeV)

Radius = 1 m from the axis of the tunnel

Rates vs longitudinal position in the tunnel (before any reconstruction)

- Primary particles background largely reduced with tuning in the shielding
- The second part of the tunnel is significantly favored in terms of signal-to-background
- With static focusing scheme rates in the second half are below 10 kHz/cm^2
$K^+ \rightarrow \pi^0 e^+ \nu_e$ positrons reconstruction

Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. Includes particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain

- **Event Builder**: Identify the seed of the event (module with largest energy deposit in inner layer and > 20 MeV). Cluster neighboring modules close in time. Iterate on not-yet-clustered cells.
- **e/$\pi$/\(\mu\) separation**: Multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter) with TMVA
- **e/$\gamma$ separation**: Signal on the tiles of the photon veto (0-1-2 mip)

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Before tuning of shielding

Reco level full sim.

<table>
<thead>
<tr>
<th></th>
<th>(\varepsilon_{\text{geom}})</th>
<th>0.36</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\varepsilon_{\text{sel}})</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>(\varepsilon_{\text{tot}})</td>
<td>0.20</td>
</tr>
<tr>
<td>Purity</td>
<td></td>
<td>0.26</td>
</tr>
<tr>
<td>S/N</td>
<td></td>
<td>0.36</td>
</tr>
</tbody>
</table>

Instrumenting half of the decay tunnel: $e^+$ from $K$ at single particle level with a $S/N = 0.46$
The Holy Grail of neutrino physics

Since in the static focusing system, particles in the decay tunnel are very diluted, it becomes realistic to associate the neutrino observed at the detector with the particles in the decay tunnel event-by-event.

Difficulty: VERY HIGH
Physics reach: VERY HIGH

Presently with \(2.5 \times 10^{13}\) pot / 2s slow extraction:
- genuine \(K_{e3}\) cand. : 80 MHz \(\rightarrow\) 1 every \(\sim 12\) ns
- background \(K_{e3}\) cand. \(\sim 2\) \(\rightarrow\) 1 cand. every \(\sim 4\) ns

With \(\delta=0.5 + 0.5\) ns resolutions already interesting!
S/N ratio will likely improve with further tuning.
Tagged neutrino beams

- Know the flavor of the observed neutrino before it changes due to oscillation
- Reconstruct the energy of every single neutrino by the kinematics reconstruction in the decay tunnel

The proton extraction time must be \( \sim 1 \text{s} \)

The time resolution of the tag must be \( \text{O}(100 \text{ ps}) \)

The time resolution of the neutrino detector must be \( \sim 1 \text{ ns} \)

The cosmic background increases by \( x10 \) [i.e. by \( A \times (1 \text{s})/(2 \text{ ms}) \) ]

The momentum bite of the \( K^+ \) must be small enough not to limit the \( \nu_e \) energy reconstruction

Time synchronization between the tagger and the detector \( \ll 1 \text{ ns} \)

Cannot use any more the horns. Must rely on static systems \( \rightarrow \) reduction of acceptance

Feasible with technology developed for LHC

Feasible and strongly synergic with current R&D’s

Comparable to what have to be dealt by ICARUS@Fermilab

Narrow band neutrino beam

OK [direct optical link at short baselines]
The ENUBET tagger

Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
\[ \rightarrow e^+/\pi^+/\mu \text{ separation} \]

Integrated photon veto
Plastic scintillators
Rings of 3×3 cm² pads
\[ \rightarrow \pi^0 \text{ rejection} \]
Enabling time tagging in ENUBET

@ CERN-PS T9 line 2016-2018

- $\gamma$ / e$^+$ discrimination + timing
  scintillator (3×3×0.5 cm$^3$) + WLS Fiber (40 cm) + SiPM
- light collection efficiency $\rightarrow$ >95%
- time resolution $\rightarrow$ $\sigma_t \sim$ 400 ps
- 1mip/2mip separation

Decay tunnel instrumentation
500 $\mu$s running window in the 4 s proton extraction

35 ps resolution demonstrated in CMS

NUTECH Project (funded by MIUR)

$\nu$ detector: trigger formation (< 500 $\mu$s)

trigger
Where CERN-EN can make the difference

A tagged neutrino beam change the paradigm of accelerator neutrino physics because the data acquisition of the entire beam instrumentation from the SPS to the beam dump is triggered by the neutrino detector.

Time synchronization of kicker, BCT, particle detectors in the tunnel ($10^5$-$10^6$ channel!) at 100 ps level

Data persistency only for events with a candidate neutrino at the neutrino detector. The trigger for the detector waveform is given by a system located outside the beamline.

Zero suppression must be performed online even if the particles belonging to the same parent are located tens of meters away.

Radiation tolerance and cost of the tunnel instrumentation.
Is a tagged neutrino beam worth the effort?


Sure!

- Complete reconstruction of the kinematics of the initial state neutrinos cross section
- Knowledge of the flavor for each single events: physics beyond the standard model (sterile neutrinos, non standard interaction, neutrino portal)
- Test of quantum decoherence in neutrino oscillation: the entangled neutrino - lepton state has never been observed
- [Far future] Neutrino telecommunications at 100 km distance by modulation of four-momentum of secondary particles
Conclusions

- High precision – moderate intensity neutrino beams are desperately needed for the next generation of neutrino experiments
- Several technology breakthrough from neutrino (ENUBET) and collider (LHC) physics give us the opportunity to design ambitious facilities:
  - High precision narrow band beam $\rightarrow$ Energy of the incoming neutrino on event by event basis. Knowledge of the flux at few % level on $\nu_\mu$
  - Monitored neutrino beam (ENUBET) $\rightarrow$ Energy of the incoming neutrino on event by event basis. Knowledge of the flux at O(1%) level on all flavors
  - Tagged neutrino beam $\rightarrow$ Full momentum reconstruction of the energy and flavor of each neutrino. Simultaneous observation of neutrino and associated lepton at source

This facility is now (2018!) within reach of modern technology but several technical challenges remain at the frontier of accelerator physics.