Novel neutrino beams

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Outline

- “Monitored” beams
- Muon-based beams
- New ideas (timing)
Accelerator based neutrino beams

Pion based neutrino beams have a ~60 y long history. Lots of physics done at different energies.

Enormous increase in intensity → a leap in technology and complexity

More “brute force” than conceptual innovations. Still OK in the era of “statistical errors-dominance” and “large $\theta_{13}$” but ...

New future challenges ($\delta_{CP}$, searches) require timely changes or at least “adjustments” in this strategy.
Improvements in standard beams (*)

Beam monitoring systems are being enriched

Hadro-production data covering larger phase space with replica targets

Near detectors are evolving towards multi-detector systems with variable off-axis angles, target redundancy, high-granularity.

J-PARC Beam Induced Fluorescence monitor

BabyMIND+WAGASCI running @ ND280

T2K target

Poster 629 M. Tenti
Poster 256 A. Sitraka
Poster 79 P. Weatherly
Directions for novel neutrino beams

Still, due to reinteractions, alignment, degradation of targets etc... flux errors > 5 %

We should aim at doing significantly better!

EU strategy document (19 June 2020):

“To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied”.

How ? →
Directions for novel neutrino beams

How ? →

1) The “brave” way: use “clean” sources (~ easy, “textbook” flux prediction)

- unstable nuclei → β-beams
- stored muons → ν factories
- decays at rest

“LHC neutrinos” are also a very interesting “perturbative QCD-based” novel beam at very high energy → see

Poster 118, M.H. Reno
Poster 249, A. Ariga (FASER)
Directions for novel neutrino beams

How ? →

1) The “brave” way: use “clean” sources (~ easy, “textbook” flux prediction)

- unstable nuclei → β-beams
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Pre-2012: use for long baseline experiments
Evolution: a short baseline setup for cross section measurements with high precision supporting the long baseline program which will be carried on with high intensity “meson based” HK & DUNE SuperBeams → nuSTORM, MICE
nuSTORM

ν\text{e} and ν\text{μ} beams from decay of circulating low-E muons

\[ \mu^+ \rightarrow e^+ \nu_\text{e} \bar{\nu}_\mu \]
\[ \mu^- \rightarrow e^- \bar{\nu}_\text{e} \nu_\mu \]

- 100 GeV/c p from SPS (156 kW). Fast extr. (10.5 us).
- Storage ring (1-6 GeV/c with a 16% acceptance)
- 52% of π → μ before 1\text{st} turn
  - → ν\text{μ} flash @ “injection pass”
- 1 τ\text{μ} ~ 27 orbits:
- For 10^{20} POT (2 × 10^{20} expected in 5 y) @ 50 m
  - 6.3×10^{16} ν\text{μ}/m²
  - 3.0×10^{14} ν\text{e}/m²
nuSTORM

Physics Beyond Colliders study
Costing performed at CERN(*) and FNAL (PDR)
Beside cross section and sterile neutrino program
Test-bed for 6D cooling, muon collider

(*) [Link to CERN feasibility study](https://indico.cern.ch/event/837890/attachments/1921676/3196005/2019-10-21-nuSTORM-at-CERN_Feasibility-study-d1.pdf)

For sterile searches. For cross sections other detector schemes could be more appropriate, with similar small sizes.
MICE ionization cooling results

\[ \frac{d\varepsilon_T}{dz} = -\frac{\varepsilon_T}{E_\mu} \frac{dE_\mu}{dz} + \frac{\beta_p}{2mc^2\beta^3} \left(13.6\text{ MeV}\right)^2 \]

RAL ISIS synchrotron
\( p_\mu = 140-240 \text{ MeV/c.} \)
Input emittance: 4-6-10 mm
Absorbers: Lithium hydride (6.5 cm)  
           Liquid H (35 cm)
MICE ionization cooling results


Amplitude: distance of the particle from beam centroid in normalized phase space. Conserved quantity without cooling.

Results for a 140 MeV/c muons with normalized r.m.s. initial emittance of 10 mm. Significant (but smaller) effect also at lower input emittances (4-6 mm).

With absorbers, # of low amplitude events considerably larger in the downstream sample than in the upstream sample → increase in the number of particles in the beam core → ionization cooling effect

Fractional (9%) emittance z-evolution.

6 mm/140 MeV/LiH

P. Soler
CERN, 11 April 2019
Directions for novel neutrino beams

How ? →

2) "lateral thinking": bring the usual "meson-based" beam to a new standard → use a narrow band beam and shift the monitoring at the level of decays by instrumenting the decay tunnel

Again an ancillary facility providing physics input to the long-baseline program

"By-pass" hadro-production, protons on target, beam-line efficiency uncertainties

→ ENUBET / NP06

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A. 681647, PI A. Longhin, Padova University, INFN

CERN Neutrino Platform: NP06

ENUBET: 60 physicists, 12 institutions
Aims at demonstrating the feasibility and physics performance of a neutrino beam where lepton production is monitored at single particle level.

- Instrumented decay region:
  \[ K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow (\text{large angle}) \, e^+ \]
  \[ K^+ \rightarrow \mu^+ \nu_\mu \pi^0 \text{ or } \mu^+ \nu_\mu \rightarrow (\text{large angle}) \, \mu^+ \]

- \( \nu_e \) and \( \nu_\mu \) flux prediction from \( e^+/\mu^+ \) rates

\[ \rightarrow \text{collimated } p\text{-selected hadron beam} \rightarrow \text{only decay products in the tagger} \rightarrow \text{manageable rates} \]

\[ \rightarrow \text{narrow band beam: } E_\nu \text{-interaction radius correlations} \rightarrow \text{an a priori knowledge of the } \nu_\mu \text{ spectra} \]

**pillars**
1) Build/test a demonstrator of the instrumented decay tunnel
2) Design/simulate the layout of the hadronic beamline (\( p_{\text{protons}} = 30, 120, 400 \text{ GeV} \))
ENUBET: instrumented decay region

Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ \( e^+/\pi^+/\mu \) separation

Integrated photon veto
Plastic scintillators
Rings of \( 3\times3 \) cm\(^2\) pads
→ \( \pi^0 \) rejection

Ultra Compact Module
\( 3\times3\times10 \) cm\(^3\) – 4.3 \( X_0 \)

\( e^+ \) (signal) topology
\( \pi^0 \) (background) topology
\( \pi^+ \) (background) topology
ENUBET: $\nu_e$ constraint with $K_{e3}$ positrons reconstruction

The $K_{e3}$ branching ratio is $\sim 5\%$ and kaons are about 5-10\% of the incoming hadron beam.

**Full GEANT4 simulation** of the detector, validated by prototype tests at CERN in 2016-2018. Clustering of cells in space and time. Treat pile-up with waveform analysis. Multivariate analysis.

Hit map for $e^+$

Selection quality

With a cut on the discriminating variable $> 0.93$:

$S/N = 2.1$ with and efficiency (*) of 24\% (\*) about half geometrical

ENUBET: $\nu_\mu$ constraints

Constrain high-E $\nu_\mu$ from $(K^+ \rightarrow \mu^+ \nu_\mu$ and $K^+ \rightarrow n^0 \mu^+ \nu_\mu$).

The main background from beam halo muons can be effectively selected out and/or used as a control sample.

Efficiency 34% ($K_\mu^2$) and 21% ($K_\mu^3$) S/B ~ 6.1

Constrain low-E $\nu_\mu$ from $\pi^+ \rightarrow \mu^+ \nu_\mu$?

In progress. Measure momentum by range with muon stations → disentangle ($\pi^+ \rightarrow \mu^+ \nu_\mu$) from halo $\mu$. 
ENUBET: flux components

Not directly taggable components:
1) $\nu_e$ from $K^{0+/−}$ in the target region
   → Removable with E cut + larger bending angles
2) $\nu_e$ from $K^+$ in front of the tagger (pointing to the detector) 10-15% contamination → accounted for with simulation (geometry).

Uncertainty reduction for the tagged flux component

Constrain the flux model by exploiting correlations between the measured lepton distributions and the flux → Fit the model with data and get energy dependent corrections.

An example:
Each histogram component corresponds to a bin in neutrino energy
ENUBET: proton extraction, rates, pile-up

**quad focusing:** 2s slow extraction

Rates in the tagger vs z

<table>
<thead>
<tr>
<th>Particle</th>
<th>Graph</th>
<th>Solid: calorimeter inner layer</th>
<th>Dashed: 2\textsuperscript{nd} and 3\textsuperscript{rd} layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>e\textsuperscript{+}</td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>π\textsuperscript{+}</td>
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</table>

Hottest channels ~ 0.5-0.6 MHz

Waveform analysis algorithms developed.

With 250 MS/s sampling:
pile-up efficiency loss stays sub-% up to ~ 1 MHz/ch

**horn focusing:** “burst mode” slow extraction tested during machine studies at the CERN-SPS ~x10 rates increase

Burst-mode slow extraction in SPS

With the increased rates implied in the horn focusing scheme → ~ few % loss
**ENUBET: prototypes at the CERN-PS**

- **Trigger:** PM1 and VETO and PM2

- **Charge exchange:** \( \pi^- \text{p} \rightarrow n \pi^0 (\rightarrow \gamma \gamma) \)

- **\( \sigma_t \sim 400 \text{ ps} \)**
**ENUBET: demonstrator**

- Large prototype to demonstrate **performance**, **scalability** and **cost-effectiveness**
- Will be tested after the LS2 at the renovated East-Area at the CERN-PS (2021-2022)

~ 30 cm of **borated polyethylene** → **factor ~ x 18** neutron reduction. Add safety margin for SiPM.  

Custom developed digitizers

- 8 ch, 14-bit ADC, 500 MS/s
- Triggerless over ~10 ms.
- ~40 MB/spill/ch

Full beamline FLUKA sim

**n longitudinal position along the tunnel**
### nuSTORM & ENUBET

<table>
<thead>
<tr>
<th></th>
<th>Decay region</th>
<th>Hadron dump</th>
<th>Proton extraction</th>
<th>Target, sec. transfer line, p-dump</th>
<th>Neutrino detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ENUBET</strong></td>
<td>~40 m. Instrumented.</td>
<td>Yes. Dumps muons in addition → preventing a (small) $\nu_{e}$ pollution to $K_{e3} - \nu_{e}$</td>
<td>Slow, 400 GeV (flexible)</td>
<td>Yes, similar</td>
<td>~100 m (some flexibility)</td>
</tr>
<tr>
<td><strong>nuSTORM</strong></td>
<td>Replaced by straight section of the ring (180 m).</td>
<td>No. Muons are kept: the most interesting flux parents.</td>
<td>Fast, 100 GeV</td>
<td>Yes, similar</td>
<td>&gt; 300 m from target (ring straight section)</td>
</tr>
</tbody>
</table>

- Different concepts, budget, geometry.
- Main synergy: target facility, 1\textsuperscript{st} stage of meson focusing, proton dump.
Directions for novel neutrino beams

How ? →

3) “technology driven”

Profit of advances/affordability of excellent timing capabilities over large areas →

• neutrino “time tagging” (ENUBET)
Directions for novel neutrino beams

How? →

3) “technology driven”

Profit of advances/affordability of excellent **timing capabilities over large areas** →

- neutrino “time tagging” (**ENUBET**). R&D on detector technologies other than scintillators in progress.

→ time coincidences of ν<sub>e</sub> and e<sup>+</sup>

Flavour and energy determination at **interaction level** are enriched by information at the **decay level**.

2.5×10<sup>13</sup> pot / 2s with 20% eff. S/N 1.6

genuine K<sub>e3</sub> cand. : → 1 every ~ 77 ns

background K<sub>e3</sub> cand. ~ 0.6 x → 1 cand / ~ 130 ns

δ=0.4±0.4 ns resolutions
Directions for novel neutrino beams

How ? →

3) “technology driven”

Profit of advances/affordability of excellent **timing capabilities over large areas** →

- neutrino “time tagging” ([ENUBET](#))
- Correlations btw proton RF fine time structure ↔ neutrino E-flavour ([FNAL study 1904.01611](#))
Proton RF bunching for energy-flavour discrimination

- Use relative arrival times of the $\nu$ with respect to the RF bunch structure in a WBB.
- $\nu$ from lower-E hadron parents tend to arrive later
- Need p-bunch $O(100\text{ ps}) +$ commensurate $\sigma_t$ in the detector.
- Works at near and far site.
- Past attempts in MiniBooNE. A SC RF cavity to rebunch the present FNAL MI 53.1 MHz RF bunch structure by x 10 is proposed.

bunch width=$250\text{ ps} + \sigma_t = 100\text{ ps}$

Late neutrinos enriched in $\nu_e$
Looking ahead

In the next year **ENUBET** will release a full assessment of **systematics** on the neutrino fluxes, build a **demonstrator prototype** of the tagger and provide a **Conceptual Design Report** with physics and costing.

**nuSTORM** has provided last year feasibility studies at FNAL, CERN.

Getting better tools to study cross sections and second order effects seems a **worthy investment** for our community to be **capitalized by the long-baseline projects**.

To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important