Daniele Guffanti
for the **ENUBET Collaboration**
University & INFN Milano-Bicocca

Funded by the European Union
European Research Council
Established by the European Commission

This project has received funding from the European Research Council (ERC) under the European Union's Horizon2020 research and innovation programme (grant agreement No 681647)

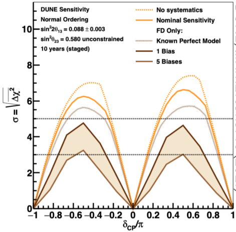
Towards the implementation of the ENUBET neutrino cross section experiment at CERN

XIII International Conference On New Frontiers in Physics
Crete - August 27, 2024

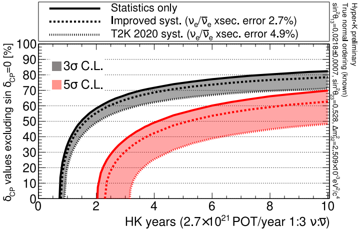
A shadow on the long baseline neutrino program

The knowledge of neutrino cross-section is stuck at 10–30% level → community needs ≈ **1% level**

- **Leading systematics for long-baseline experiment**
  Neutrino Oscillation Physics

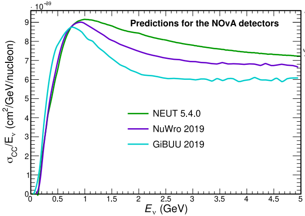


DUNE, arXiv:2103.13910 (2021)



HyperKamiokande, Neutrino2024

- Neutrino generators based on different approaches gives discrepant results
  Nuclear Physics



J. Paley, NuFact 2022

- Neutrino cross section measurements limited by beam systematics

$$N_{\nu_\alpha}(E) = \mathcal{E} \cdot \boxed{\Phi_{\nu_\alpha}(E)\,\sigma_{\nu_\alpha}(E)}$$

Requirements for a new generation cross-section facility

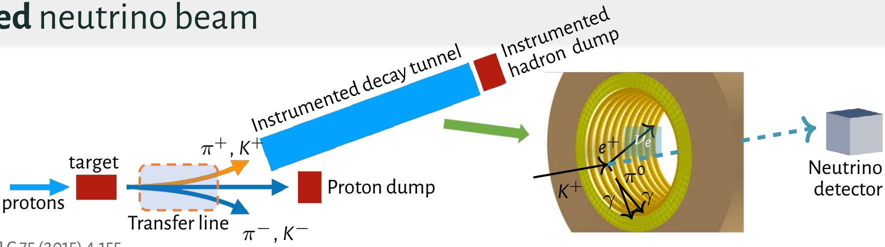
Branca et al., Symmetry 13 (2021) 9

- **Measure the neutrino flux** of a short-baseline beam devoted to cross-section measurements with a precision <1% in ν_e and ν_μ (typical precision $\approx 10\%$). **Flux is the dominant systematics**.
  - Monitored neutrino beams are beams with unprecedented control of the ν flux and can achieve $< 1\%$ precision
- **Measure the neutrino's energy** without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Monitored narrow-band (10% momentum bite) neutrino beams can measure *a priori* the neutrino energy exploiting the correlation between the neutrino energy and the production angle (i.e. the position of the vertex in the neutrino detector). This method ("narrow-band off-axis"), inspired by PRISM, is used by ENUBET and SBND and offers $\mathcal{O}(10\%)$ precision
  - If we can time-tag a fraction of the ENUBET ν_μ we can achieve an energy resolution of $\mathcal{O}(1\%)$ for such a subsample: a golden sample for ν_μ scattering studies.
- Use the **same target as DUNE and HyperKamiokaNDE** + low Z target (existing or new experiments)
  - ENUBET at CERN would enable using the ProtoDUNEs and WCTE as neutrino detectors with ideal targets (water, LAr)

ENUBET: a **monitored** neutrino beam

A neutrino beam with an **instrumented decay tunnel**, where we **identify** and **count** the charged leptons produced together with the neutrinos.

Longhin, Ludovici & Terranova, Eur.Phys.J.C 75 (2015) 4:155



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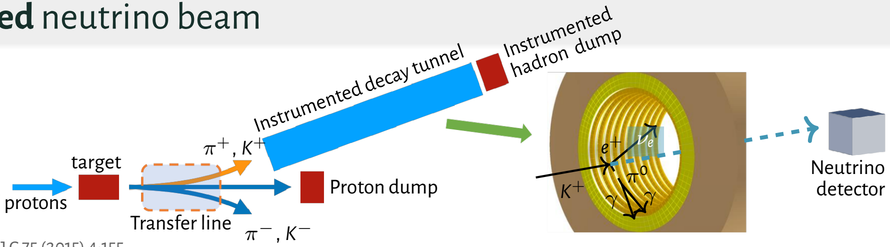

Longhin, Ludovici & Terranova, Eur.Phys.J.C 75 (2015) 4:155

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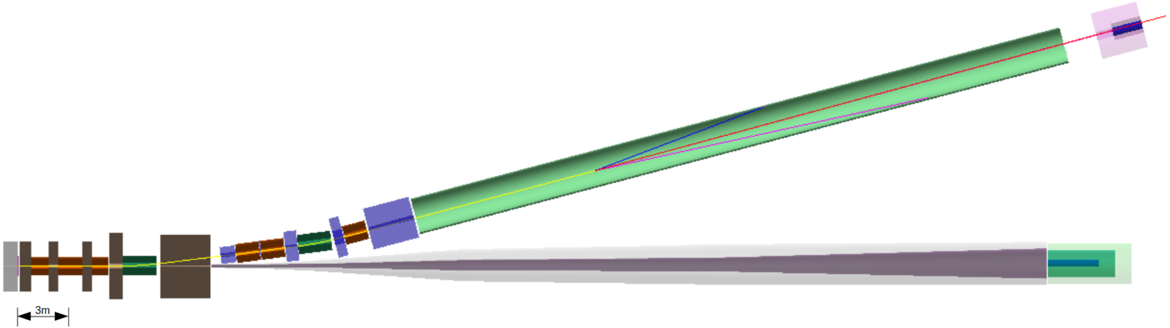
- ENUBET: **ERC Consolidator Grant**, June 2016 – May 2021 (COVID: extended to end 2022). PI: A. Longhin;
- Since April 2019: **CERN Neutrino Platform Experiment – NP06/ENUBET**
- Since 2022 ENUBET is part of the **Physics Beyond Collider** to study possible implementation at CERN
- **ENUBET Collaboration**: 74 physicists from 17 institutions
  More at `www.pd.infn.it/eng/enubet`

Beamline: Challenges (and solutions)

ENUBET, Eur.Phys.J.C 83 (2023) 10:964

- **Particle rate at the tunnel:** below 100 kHz/cm^2 using a **hornless beam** with a slow proton extraction
- **Radiation dose** at the tunnel detector well below 10 Gy and 10^{11} n/cm^2 with appropriate shielding
- **Detector technology:** low-cost sampling calorimeter (iron + plastic scintillator)



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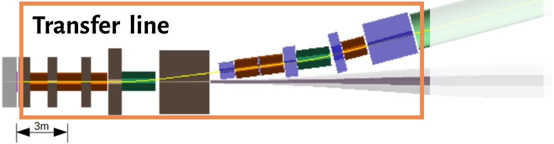
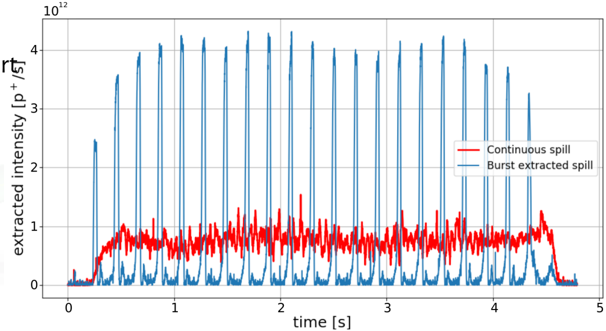
  - 5% momentum bite centered at 8.5 GeV, optimized with TRANSPORT
  - G4Beamline used to simulate particle transport, FLUKA for irradiation studies
  - Short ($<$ 30 m) to minimize early K decays
  - Small beam size





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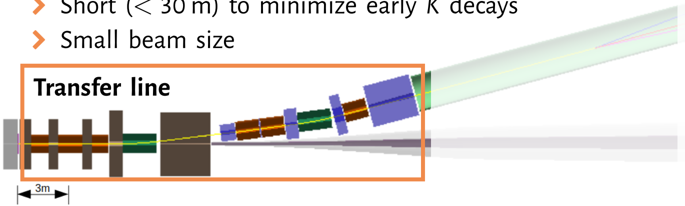

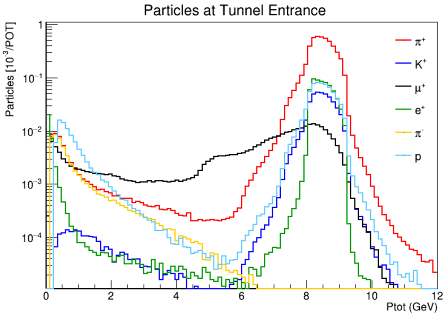

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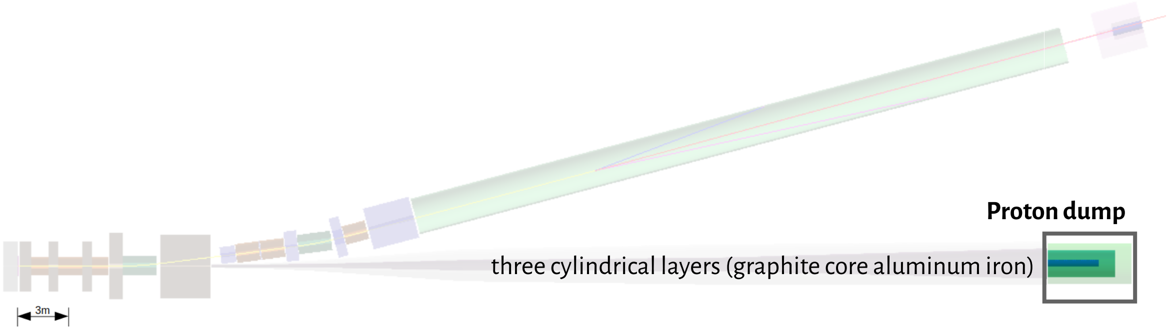

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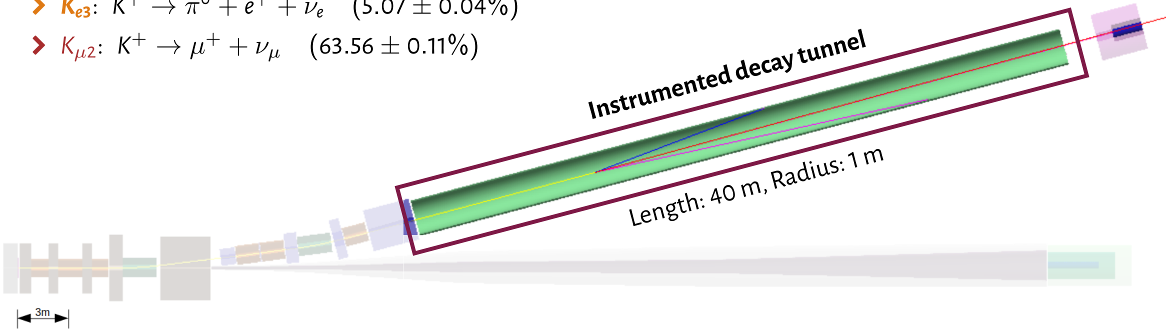
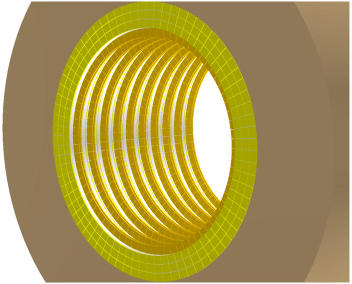
Tunnel acceptance can detect

- K_{e3}: $K^+ \to \pi^0 + e^+ + \nu_e$ $(5.07 \pm 0.04\%)$
- $K_{\mu2}$: $K^+ \to \mu^+ + \nu_\mu$ $(63.56 \pm 0.11\%)$



Decay tunnel instrumentation

ENUBET, Eur.Phys.J.C 83 (2023) 10:964



Shielding

- 30 cm of borated polyethylene installed on top
  ↪ factor 18 reduction in neutron fluence;

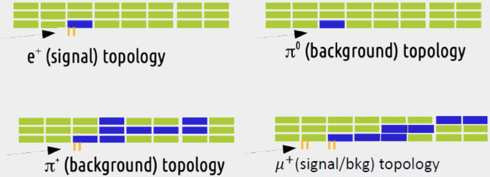
Calorimeter with $e/\pi/\mu$ separation capabilities

- sampling calorimeter: sandwich of plastic scintillators and iron absorbers
- three radial layers of LCM / longitudinal segmentation (11.5 cm, 4.3 X_0)
- WLS-fibers/SiPMs for light collection/readout

Photon-Veto for π^0 rejection and timing

- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of $\approx$ 400 ps

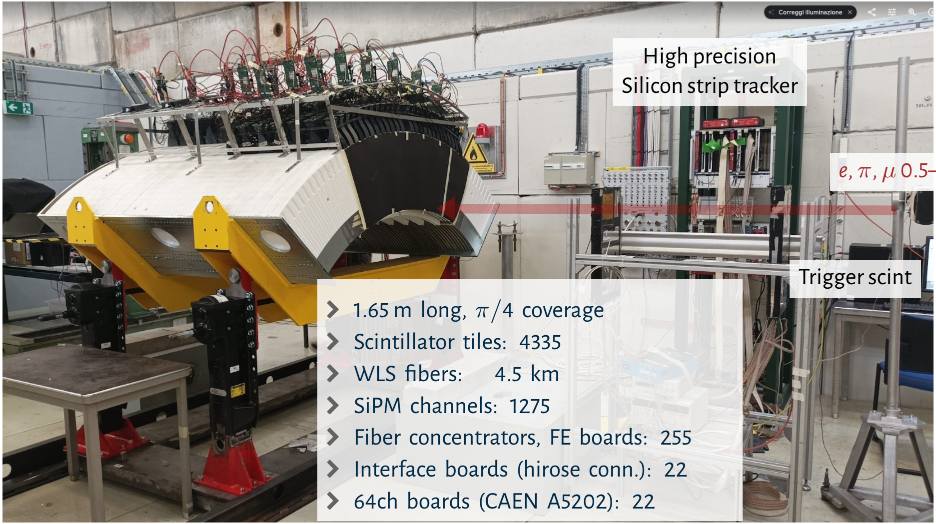
Particle ID based on pattern of energy deposit in calorimeter modules and photon-veto



+ Hadron dump instrumentation

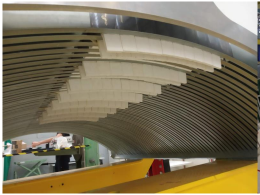
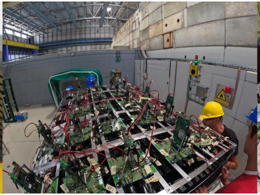
Install muon stations to monitor μ from π decays outside tagger acceptance

The ENUBET demonstrator

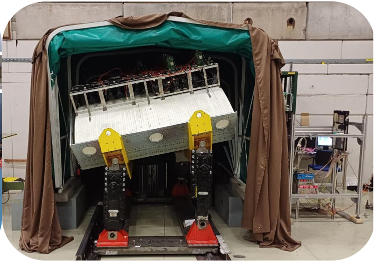


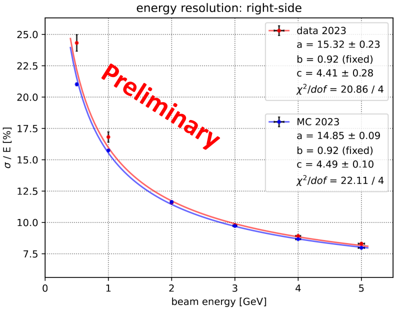
- 1.65 m long, $\pi/4$ coverage
- Scintillator tiles: 4335
- WLS fibers: 4.5 km
- SiPM channels: 1275
- Fiber concentrators, FE boards: 255
- Interface boards (hirose conn.): 22
- 64ch boards (CAEN A5202): 22

The ENUBET demonstrator


Detector prototype tested at CERN in 2022-23-**24**



L. Halić, Neutrino2024

Beam design and performance

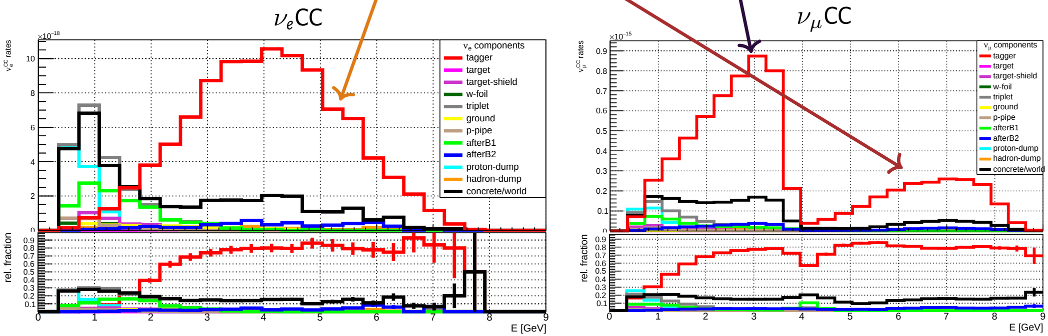
ENUBET, Eur.Phys.J.C 83 (2023) 10:964

- **Proton driver:** 400 GeV protons from CERN SPS. Up tp 4.5×10^{19} pot/yr, 2 s spill
- **Detector baseline:** 500 ton detector 50 m downstream of the tunnel
- **Statistics** @ 4.5×10^{19} pot/yr:

ν_eCC/yr (K_{e3})	ν_μCC/yr ($K_{\mu 2}$)	ν_μCC/yr ($\pi_{\mu\nu}$)
4350	9.1×10^4	22.5×10^4

Rates at tunnel entrance for 400 GeV p within 10% momentum bite

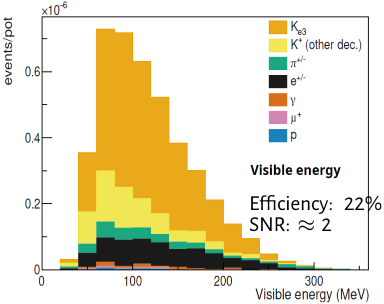
π^+/pot	K^+/pot
4.6×10^{-3}	0.4×10^{-3}



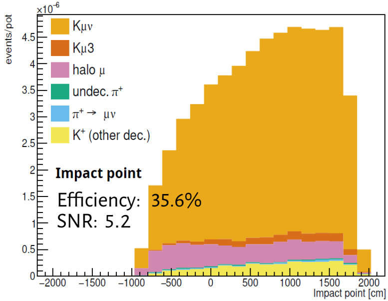
Lepton reconstruction

- **Full GEANT4 simulation of the detector**: validated by prototype tests at CERN in 2016-2018
  - hit-level detector response, pile-up effects included (waveform treatment in progress)
  - event building and PID algorithms
- Large angle positrons and muons from kaon decays reconstructed searching for patterns in E_{dep} in tagger
- Signal identification done using a Neural Network trained on a set of discriminating variables

K_{e3} positrons $\rightarrow \nu_e$ constraint



$K_{\mu 2}$ muons $\rightarrow \nu_\mu$ constraint

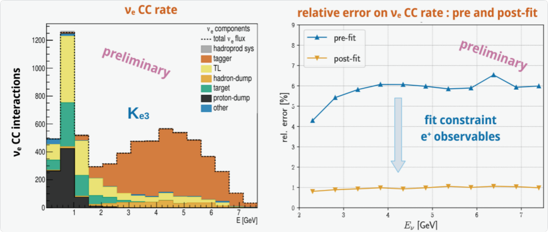


F. Bramati, Neutrino2024

Neutrino flux precision determination

Same systematics approach as **Minerva** and **T2K**

- Dominant systematic (**hadroproduction**) extracted from experimental data (NA56/SPY)
  $\hookrightarrow$ 6% uncertainty on neutrino flux
- **Rate, position and energy distribution** of **positrons** from K decay measured in the tunnel used as **prior** (Γ_{e3} know at sub-percent level)
- Flux uncertainty drop **6%** $\rightarrow$ **1%** for ν_e and ν_μ above 4 GeV



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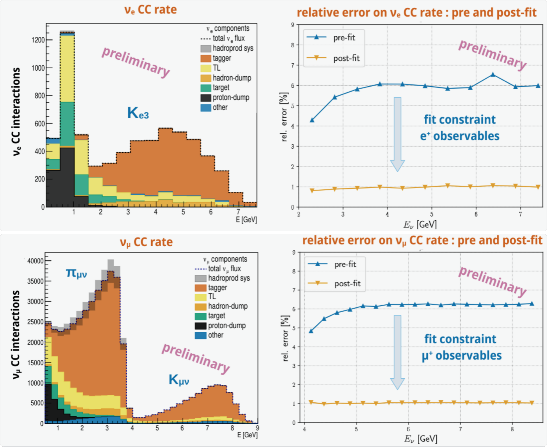
- Further improvement on ν_μ flux systematics above 4 GeV combining measured μ from $K_{\mu 2}$
- In progress: add subdominant systematics (detector effects, magnet current, beam component material budget uncertainty preparation)



F. Bramati, Neutrino2024

Muon neutrino “a priori” energy estimate

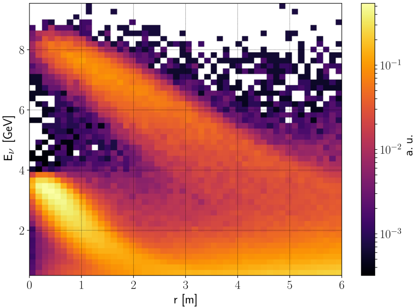
ENUBET, Eur.Phys.J.C 83 (2023) 10:964

Narrow-band off-axis technique

(E_ν, R) are strongly correlated

E_ν Neutrino energy

R radial distance of interaction vtx from beam axis



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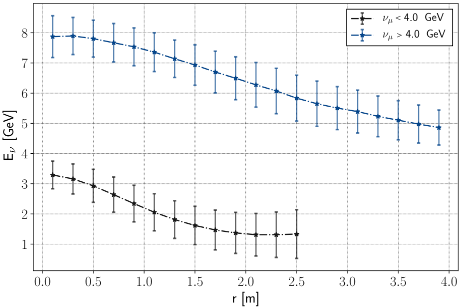
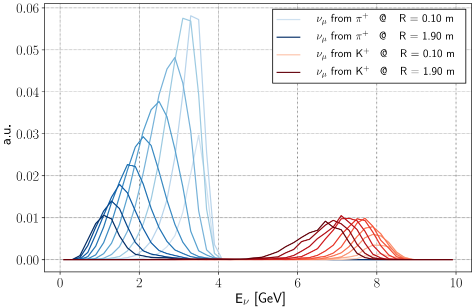
E_ν Neutrino energy

R radial distance of interaction vtx from beam axis

E_ν estimate based on interaction vertex in the detector
no need to rely on final state particles from ν_μCC interactions

10–25% E_ν resolution from π in the DUNE energy range





Beyond ENUBET: towards a new experiment

Limitations of the current ENUBET design:

- Facility optimized for DUNE, but we want to cover also Hyper-Kamiokande energy range
- Number of pot is too high to run ENUBET at CERN in parallel with SHiP
- Low energy resolution, especially below 2 GeV

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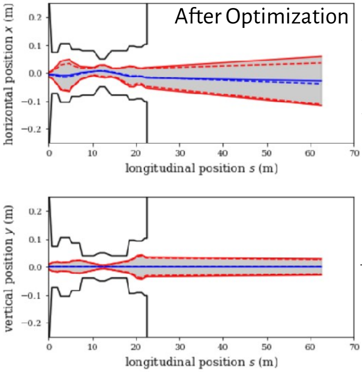
Short-Baseline Neutrinos @ Physics Beyond Colliders - SBN@PBC

Proposal under study by **CERN**, **ENUBET**, **NuTAG** and the **CERN Neutrino Platform** to address such limitations and set the ground for the next generation of cross-section experiment

First preliminary results of beamline from SBN@PBC indicate that an optimized ENUBET beamline

- Can also run at lower secondary momenta (4–8.5 GeV/c)
- Can achieve ENUBET performance with 33% of the pot needed in the original design
- Can collect large ν_μCC statistics in the 1–2 GeV range
- Can further improve E_ν resolution by measuring parent meson momentum and exploiting **time-tagging**



M.A. Jebramcik, Neutrino2024
M.A. Jebramcik, PBC Ann. Workshop 2024

Time-tagging

ENUBET, Eur.Phys.J.C 83 (2023) 10:964

Monitored Neutrino Beam
Counting charged leptons
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Tagged Neutrino Beam
Matching detected neutrinos w/ corresponding charged leptons in the decay tunnel

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ENUBET, Eur.Phys.J.C 83 (2023) 10:964

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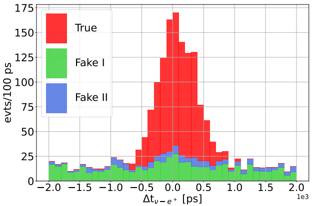
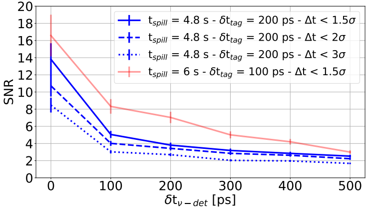
Time coincidence between neutrino event in the detector and lepton event in the tagger
ENUBET $\rightarrow$ Tagged neutrino beam



$\sigma_t = 200 \oplus 200$ ps
$E_\nu > 1.5$ GeV
SNR $\sim$3/4

- Fake matches of e^+ candidates with ν_e produced **inside tagger**
- Fake matches of e^+ candidates with ν_e produced **outside tagger**



Even better tagging introducing the **NuTAG** concept:
silicon trackers in the beamline to monitor the neutrino parent
Expected E_ν resolution: 1%

Conclusions and Outlooks

Monitored neutrino beam: interesting idea —6 years R&D, ENUBET/NP06→ **mature technology**

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  - DUNE energy range (ENUBET ✔)
  - DUNE + Hyper-Kamiokande energy range (SBN@PBC 🔧)

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  - Estimate of the neutrino energy with 10–25% precision

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- **SBN@PBC**: common effort of ENUBET, NuTAG, CERN Physics Beyond Collider and CERN Neutrino Platform to overcome current limitations (protons, energy range) and exploit advanced time tagging to achieve percent-level E_ν resolution