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The ENUBET monitored neutrino beam for high precision cross section measurements

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A new generation of cross section experiment: why?

Neutrino physics has entered its precision era with a knowledge of Standard Model processes that has improved enormously (50% -> 10%) in the last 10 years but still **lags behind the standards of quark physics** (1%). This is unfortunate because high-precision cross sections can advance significantly our understanding of nuclear matter and ground on a solid base the physics reach of DUNE and HyperKamiokande.

We may hope to reach such an unprecedented precision if:

- We devise a facility that offers a control of the ν_e and ν_μ neutrino flux and flavor at 1% level [**flux**: main systematics of any cross-section measurement]
- Provide a monochromatic neutrino source with a precision of O(10%) [**ν energy**: main systematics for differential cross sections due to bias in energy reconstruction]
- Provide a ν_e source that can bring the ν_e cross section uncertainty from 30% to a few %. [**ν_e appearance** is the golden channel of neutrino oscillation experiment]

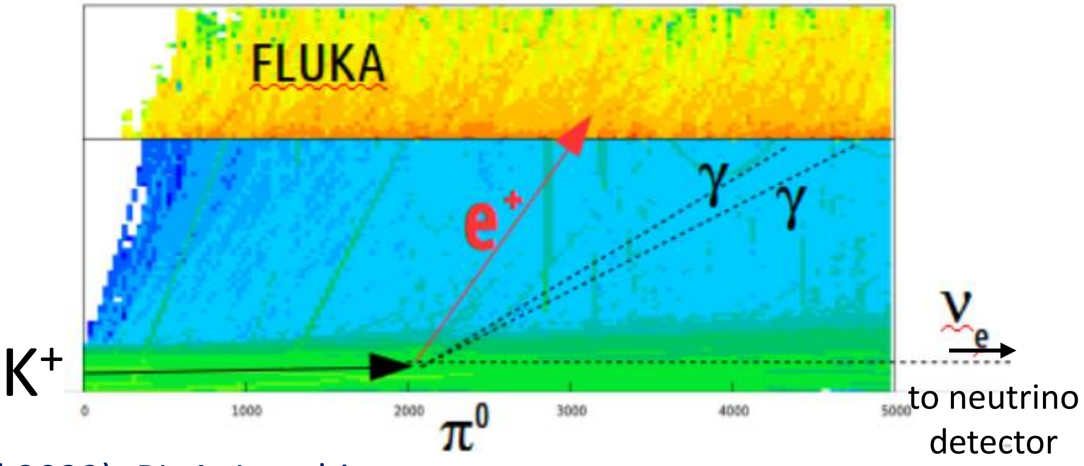
If this facility is available in the next future, we can conceive a new generation of cross section experiments with state-of-the-art detectors to study differential cross sections in the region of interest for neutrino oscillations. We aim at such a generation "up and running" in parallel with DUNE and HyperKamiokande (around 2030)

In 2023 we have shown(*) that ENUBET can do the job ☺

(*) F. Acerbi et al. arXiv:2308.09402 (EPJC - in press)

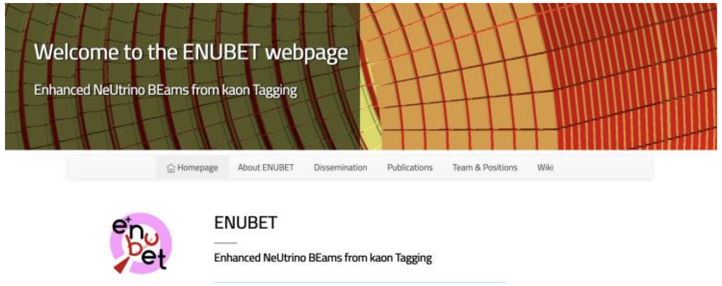
ENUBET is the project for the realization of the first monitored neutrino beam.

"Monitored neutrino beams are beams where diagnostic can directly measure the flux of neutrinos because the experimenters monitor the production of the lepton associated with the neutrino at the single-particle level. " (Wikipedia)



- 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 – and part of Physics Beyond Colliders;
    - Collaboration: 74 physicists & 24 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna;

Visit our webpage for further info and material!
https://www.pd.infn.it/eng/enubet/



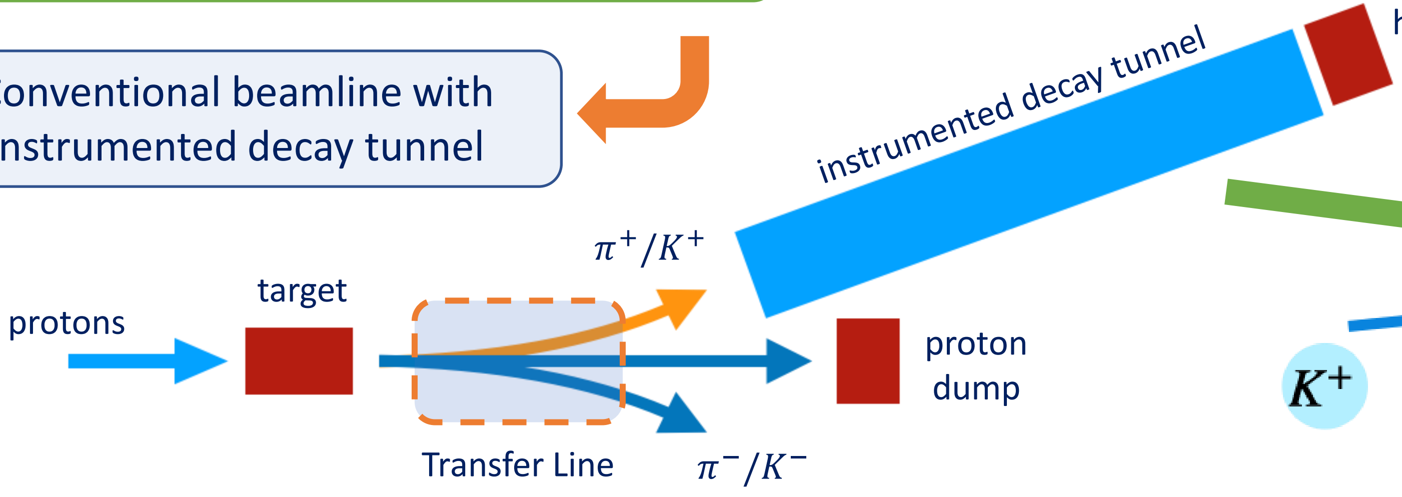
ENUBET: the first monitored neutrino beams

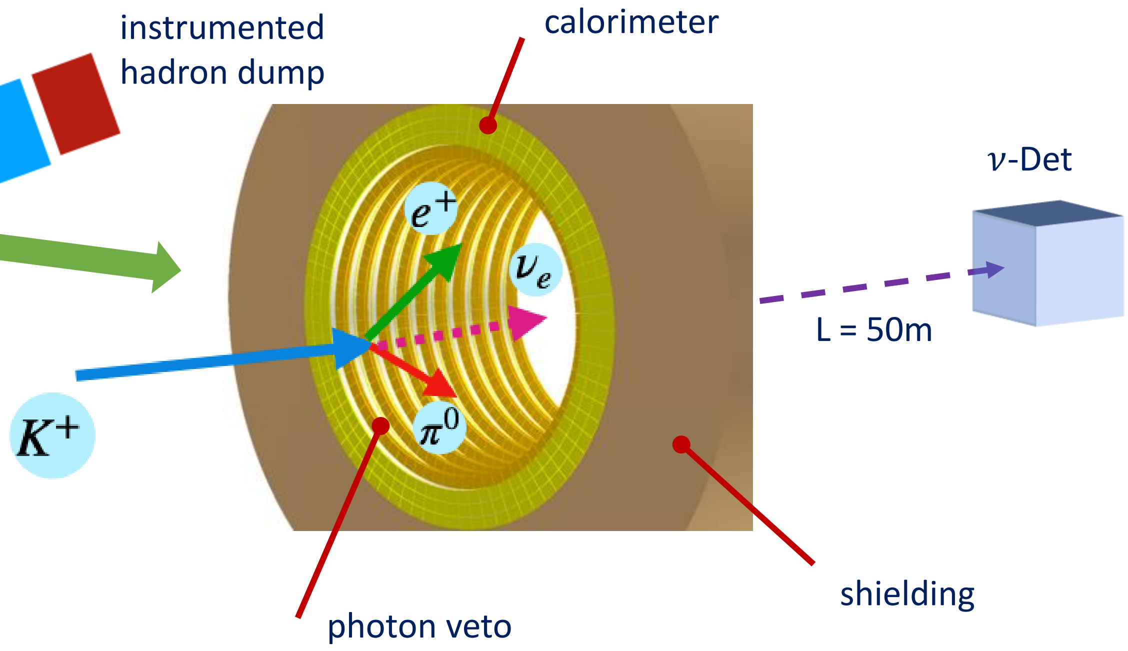
How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam
measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155





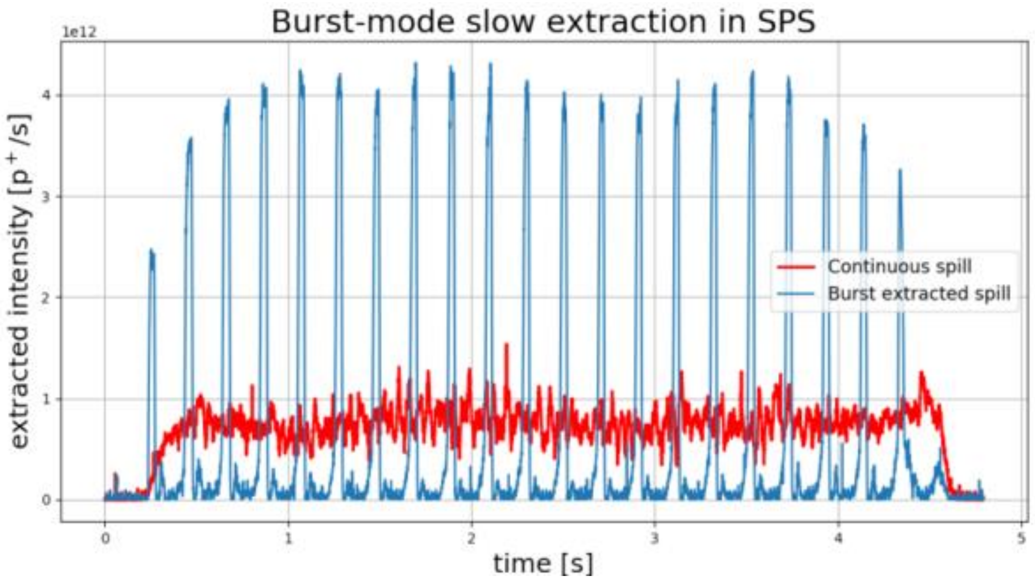
- **ERC project focused on**:
  measure positrons (instrumented decay tunnel) from $K_{e3} \implies$ determination of ν_e flux;
- **As CERN NP06 project**:
  extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu} \implies$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

The 2020 breakthrough: a high-intensity horn-less neutrino beam

When we first proposed ENUBET, we were aiming at a beam where the leptons in the decay tunnel are produced at **slow rate** because we were afraid of pile-up and saturation of the instrumentation in the tunnel

Original design: a horn pulsed every 100 ms with a 10 ms pulse (“burst proton extraction”)



First demonstration of this proton extraction scheme in 2018 at CERN-SPS

M. Pari, M. A Fraser et al, IPAC2019

2020 design (“static focusing system”): a neutrino beam without a horn where focusing at 8 GeV/c is accomplished by quadrupoles (like e.g. NuTeV but at much lower energy!)

The design was so successful that it achieved a flux that is just 2 times smaller than the corresponding horn-based design but protons are extracted in 2 seconds!! Rates reduced by more than one order of magnitude!

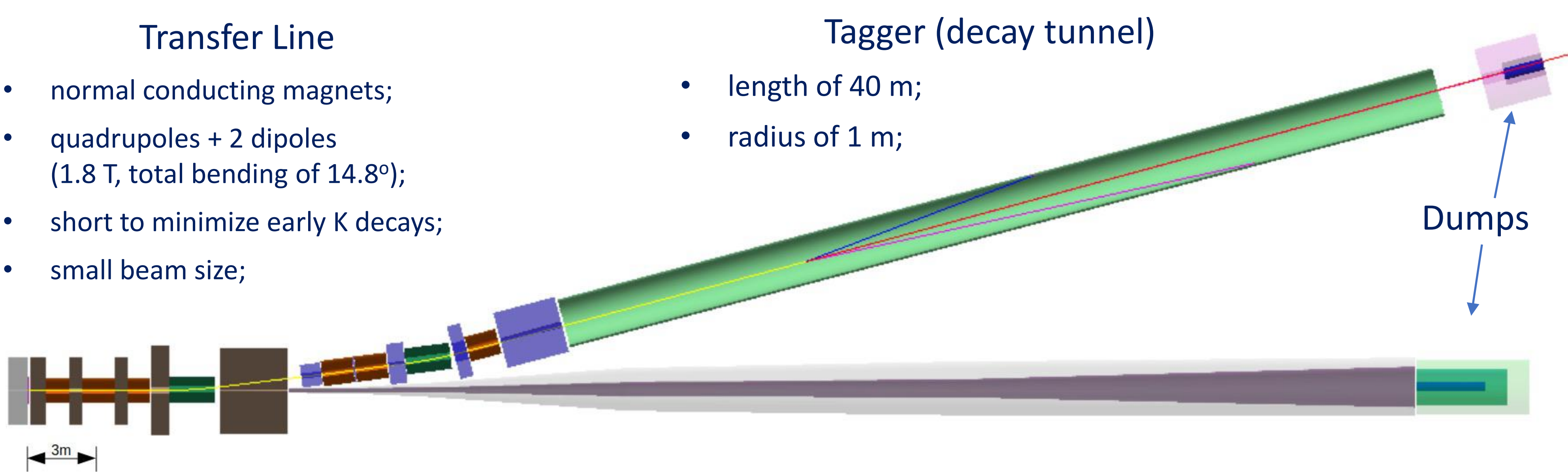
The ENUBET beamline optimized for the DUNE energy range

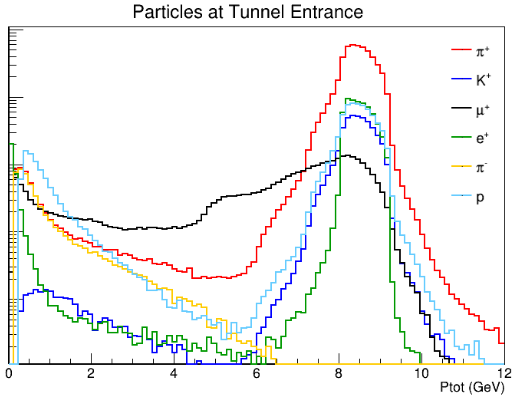
Transfer Line

- normal conducting magnets;
- quadrupoles + 2 dipoles (1.8 T, total bending of 14.8º);
- short to minimize early K decays;
- small beam size;

Tagger (decay tunnel)

- length of 40 m;
- radius of 1 m;





Large bending angle of 14.8º: better collimated beam + reduced muons background + reduced ν_e from early decays;

Transfer Line:

- optics optimization w/ **TRANSPORT** (5% momentum bite centered @ 8.5 GeV) **G4Beamline** for particle transport and interactions;
- **FLUKA** for irradiation studies, **absorbers and rock** volumes included in simulation (not shown above);
- **optimized graphite target** 70 cm long & 3 cm radius (dedicated studies, scan geometry and different materials);
- **tungsten foil downstream target** to suppress positron background;
- tungsten alloy **absorber @ tagger entrance** to suppress backgrounds;

Proton dump: three cylindrical layers (graphite core → aluminum layer → iron layer);

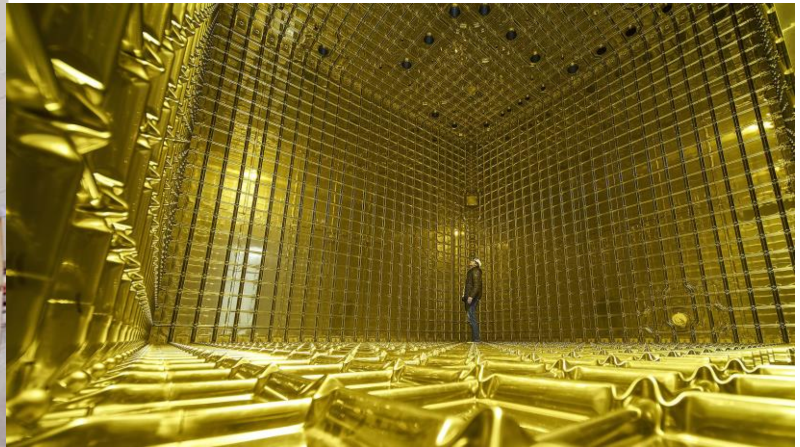
Hadron dump: same structure of the proton dump → allows to reduce backscattering flux in tunnel;

Rates @ Tunnel entrance for 400 GeV POT	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.6	0.4

Is this neutrino beam powerful enough? Yes (details in arXiv:2308.09402)

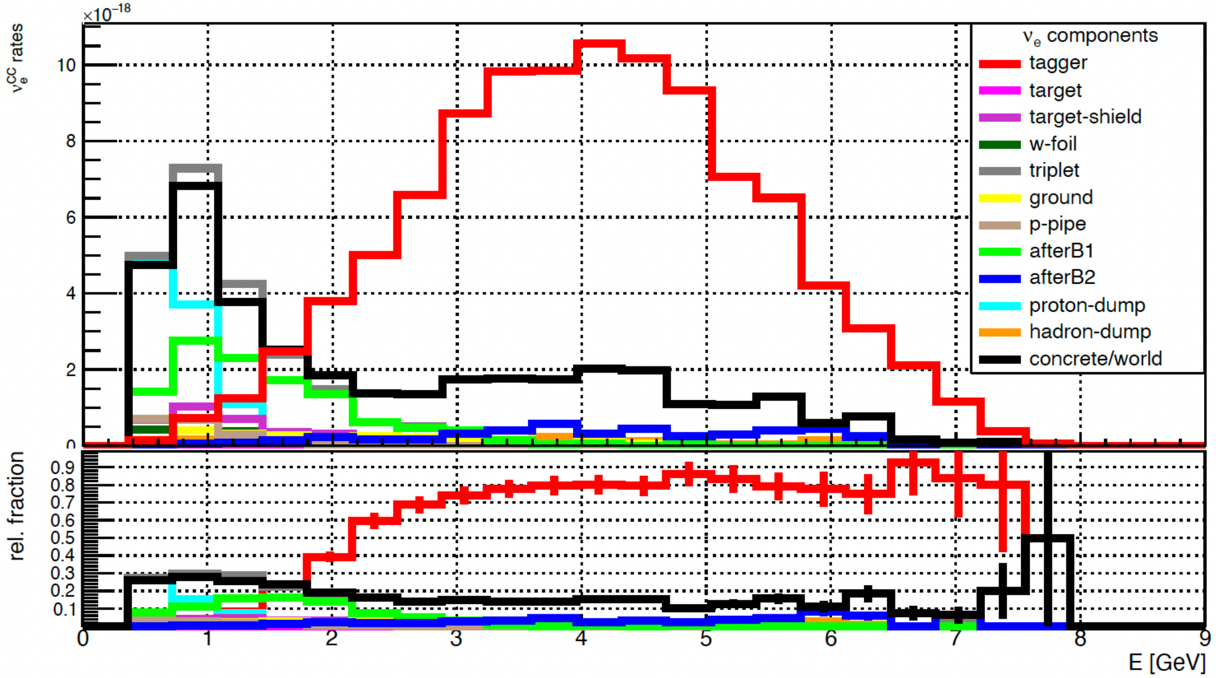
A total ν_e^{CC} (ν_μ) statistics of 10^4 (10^6) events in $\sim$2.3 years

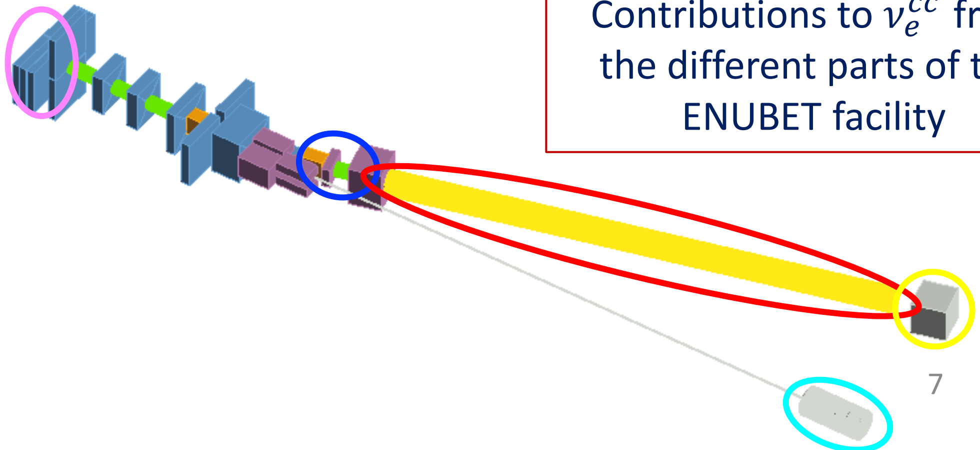
- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;



ProtoDUNE-SP (NP04)

ν_e^{CC} energy distribution at the detector





Contributions to ν_e^{cc} from the different parts of the ENUBET facility

Can we measure the neutrino energy “a priori”? yes for ν_μ^{CC}

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

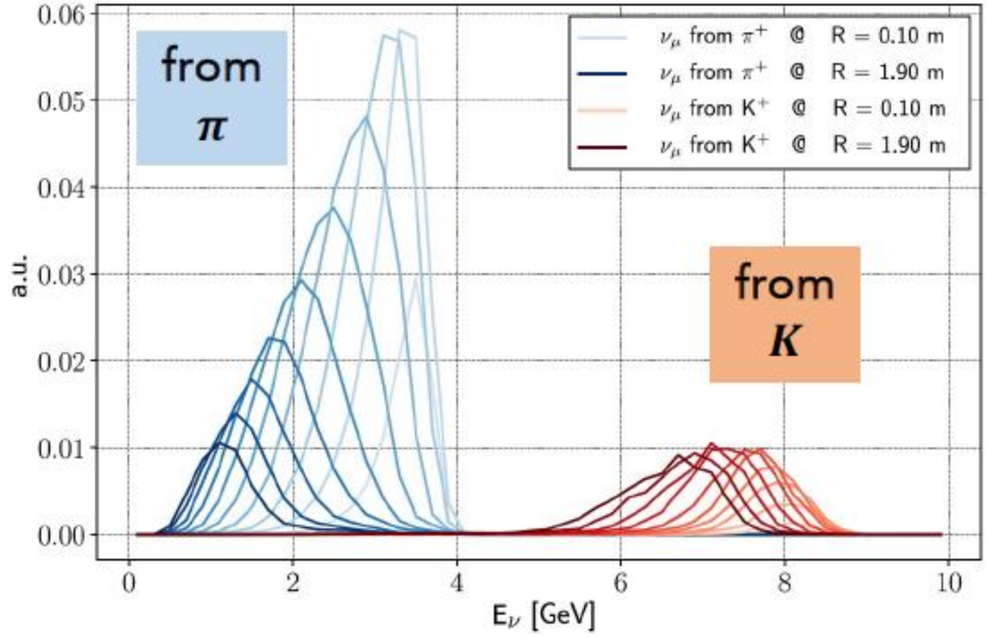
E_ν = neutrino energy;

R = radial distance of interaction vertex from beam axis;

Precise determination of E_ν :
no need to rely on final state particles from ν_μ^{CC} interaction

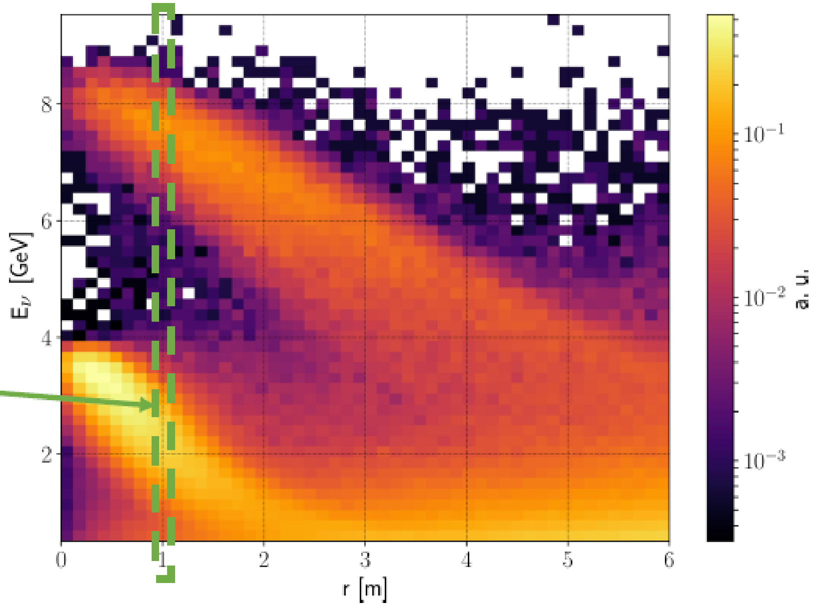
10-25% E_ν resolution from π in the DUNE energy range

ongoing R&D: Multi-Momentum Beamline (4.5, 6 and 8.5 GeV) => HyperK & DUNE optimized [will be published in early 2024]



π/K populations well separated

All ν_μ^{CC}: backgroun @ low E and high R



Select ν_μ with given energy by performing cut on R

Can we identify the leptons in the tunnel at single particle level? Yes

Shielding

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

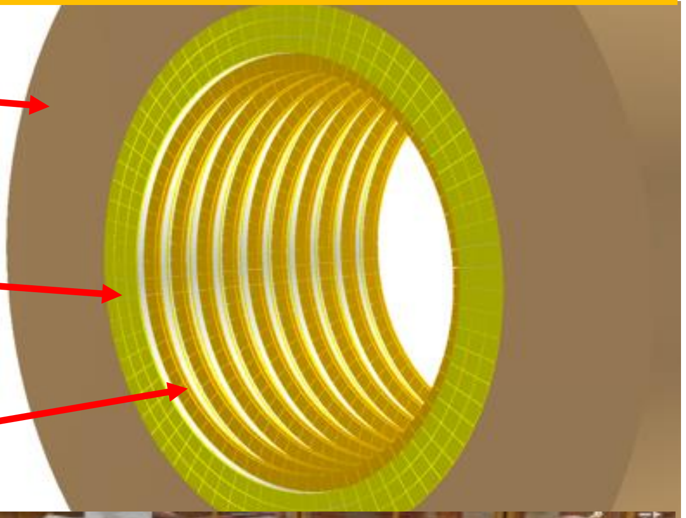
Calorimeter with $e/\pi/\mu$ separation capabilities:

- sampling calorimeter: sandwich of plastic scintillators and iron absorbers;
- three radial layers of LCM / longitudinal segmentation;
- WLS-fibers/SiPMs for light collection/readout;

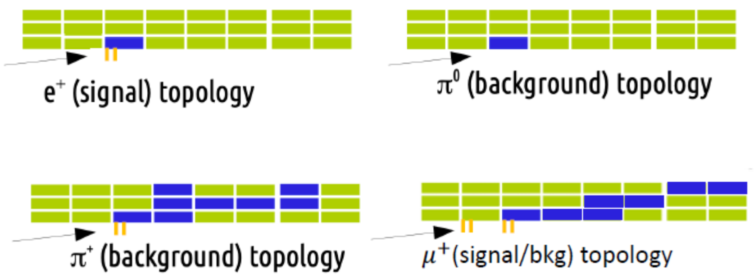
Photon-Veto allows π^0 rejection and timing:

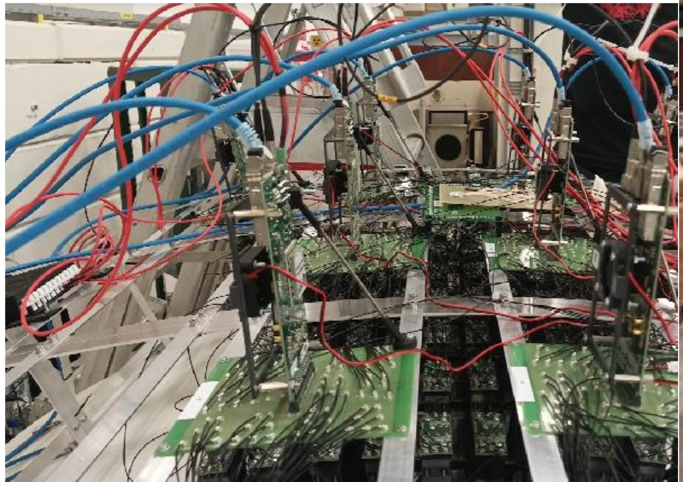
- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of ~ 400 ps;

Layout of the instrumented tunnel



PID based on the pattern of energy deposit in the calorimeter modules






The ENUBET demonstrator

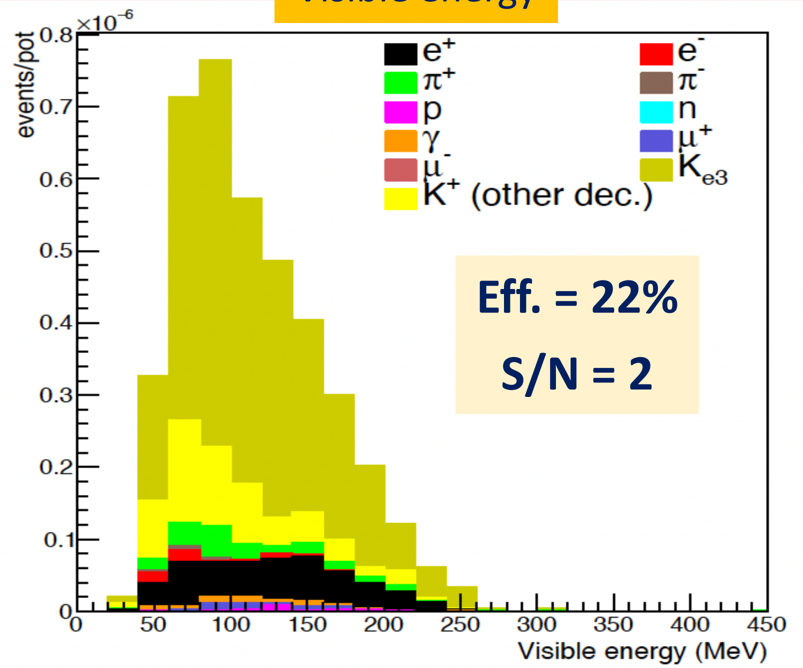
Lepton reconstruction and identification performance

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 (2016-2020);

- Large angle positrons and muons from kaon decays reconstructed searching for patterns in energy depositions in tagger;
- Signal identification done using a Neural Network trained on a set of discriminating variables;

K_{e3} positrons → constrain ν_e

Visible energy



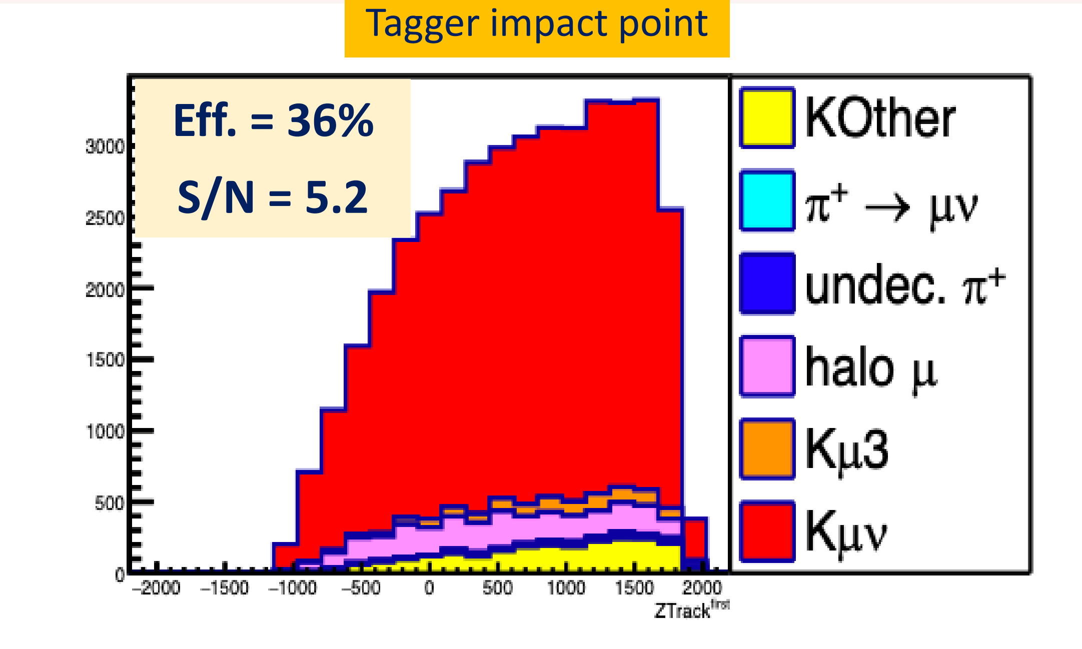
Eff. = 22%

S/N = 2

Efficiency ~half geometrical

$K_{\mu 2}$ muons → constrain ν_μ

Tagger impact point



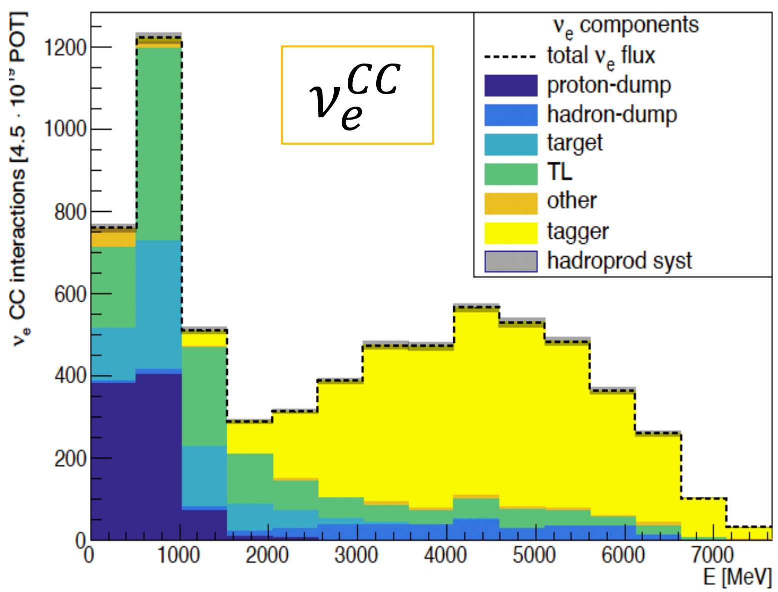
Eff. = 36%

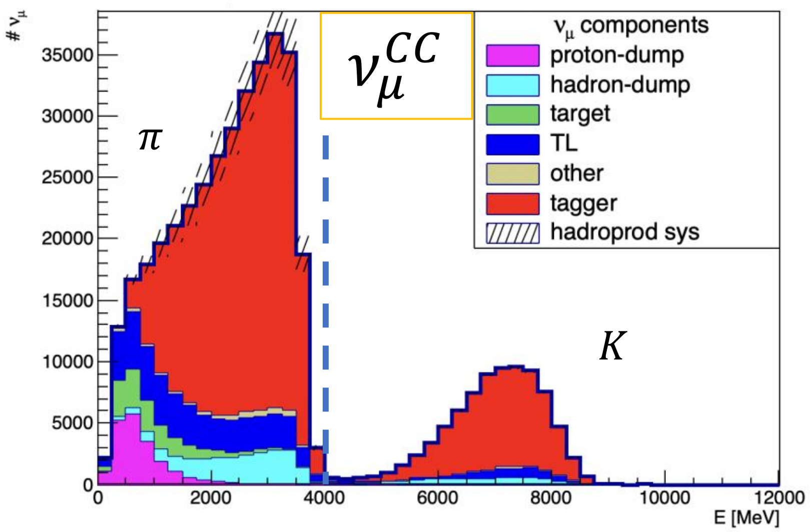
S/N = 5.2

Efficiency ~half geometrical

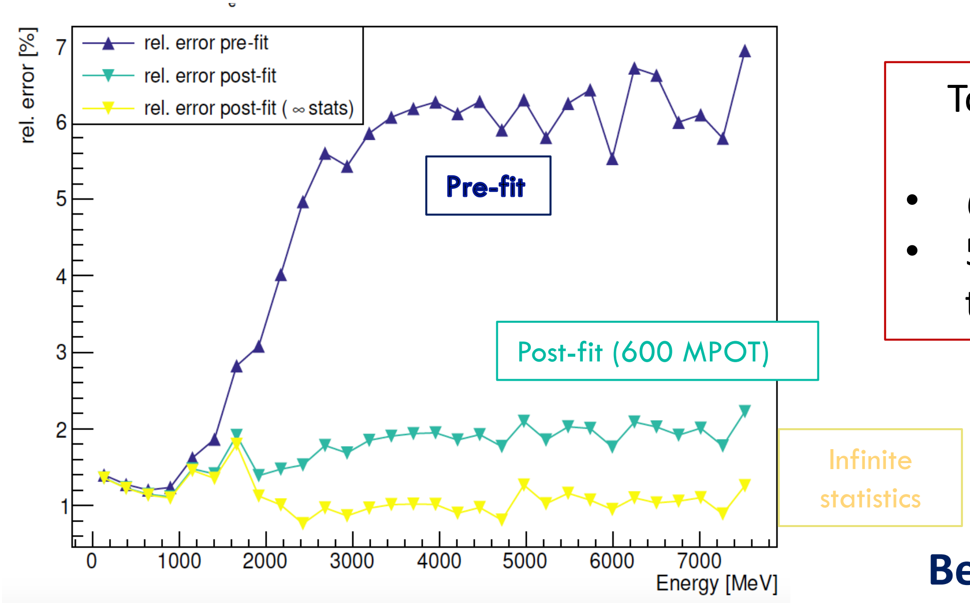
Can we really reduce the flux systematics at <1%? Yes

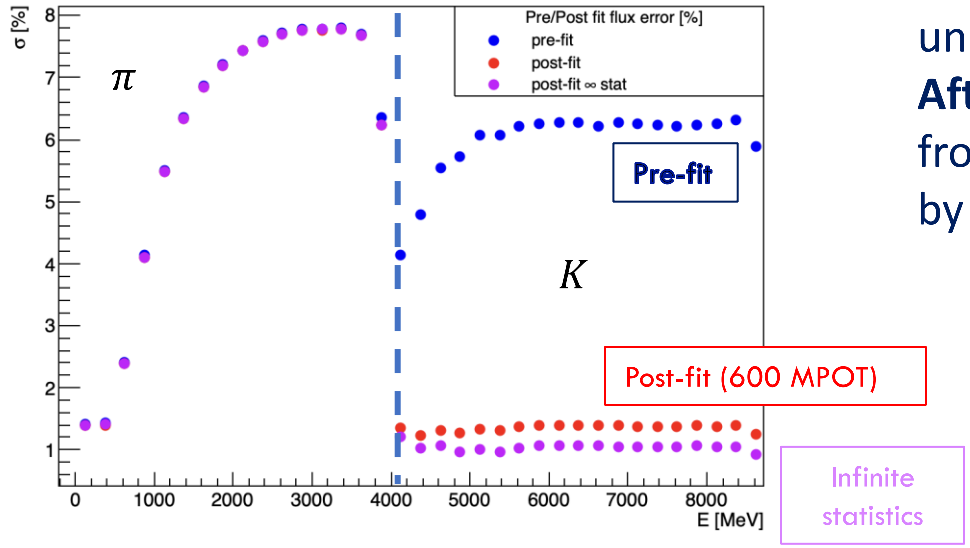
Neutrino interaction rates @ detector





Pre & Post fit relative errors on rates





Total rates in 1 year of data taking

- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 ton detector @ 50 m from tunnel end;

Before constraint: 6% systematics due to hadro-production uncertainties;
After constraint: 1% systematics from fit to lepton rates measured by tagger;

Achieved ENUBET goal of 1% systematics from monitoring lepton rates

From a successful R&D to a real experiment

The monitored neutrino beam technique has been demonstrated in the sense that all technical challenges were successfully address. We need to complete the work by addressing even the subdominant systematics, complete the analysis of the Demonstrator, devise a beamline that attains the energy range of interest of HyperKamiokande and quantify the overall improvement on cross-sections using e.g ProtoDUNE as the neutrino detector.

The most challenging task we need to address, however, **is whether this facility can be built at CERN at a moderate cost without interfering with the rest of the CERN programme**. We are tacking this task in the framework of the CERN Physics Beyond Collider group and hope to be ready for a proposal in 2025.

Options under consideration			
A dedicated neutrino beamline extracted from the CERN North Area pointing toward ProtoDUNE (cheapest option)			
Maximize use of existing facilities ☺	Slow extraction already implemented ☺	Potential radiation issues To be checked	Interference with other experiments To be checked
A dedicated extraction line near the North Area toward ProtoDUNE (cleanest option)			
No interference with any other experiment ☺	Minor radiation issues ☺	Higher cost	Potential issues with slow extraction To be checked

Conclusions

The ENUBET R&D phase is nearly over and the outcome is very positive. The "monitored neutrino beam" technique works because:

- The static focusing system allows for lepton monitoring at single particle level without jeopardizing the beam intensity
- Particle identification in the tunnel can be done with S/N>2, well above what is needed for monitoring ν_e from kaon decays and ν_μ from pion and K decays.
- The monitored beam provides enough statistics for a <1% measurements of the cross-sections in the energy range of DUNE. We are extending the ENUBET energy range to cover the region of interest of HyperKamiokande, too.
- We demonstrated that the distribution of charged leptons in the decay tunnel lowers the dominant systematics on flux down to <1% using only the positrons (and even better when we will include muons!)
- The technology for the tunnel instrumentation was validated in 2022-23 by the ENUBET Demonstrator

We have started the work to investigate the actual implementation of ENUBET at CERN employing the ProtoDUNE detectors and we aim at a Proposal in 2025.