This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

The ENUBET monitored neutrino beam

F. Terranova(*) on behalf of the NP06/ENUBET Collaboration

(*) University of Milano-Bicocca & INFN Milano-Bicocca

Info: https://greybook.cern.ch/experiment/detail?id=NP06

https://www.pd.infn.it/eng/enubet/

Introduction

The CERN neutrino platform (NP) is aimed at supporting the international neutrino physics programme and foster new ideas to cope with the challenges and opportunities of the precision era of neutrino physics. **The NP06/ENUBET experiment is a prime example that illustrates the NP mission.**

Aims of this Detector Seminar:

- Present the very concept of "Monitored neutrino beam" since its inception from the concept paper (A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155) to full demonstration (F. Acerbi et al. [ENUBET Coll.] EPJ C 83 (2023) 964)
- Discuss the technology breakthroughs that make monitored and tagged beams a technology available for use in the next few years
- Present the physics case of a new generation of cross section experiments based on monitored neutrino beams
- Discuss the possibility of an implementation of this facility at CERN, possibly using the existing ProtoDUNE detectors (400-ton each) and a moderate mass (50 ton) Water Cherenkov detector at the CERN North Area

The rationale of ENUBET

The knowledge of neutrino cross section is stuck at 10-30 % level and the needs of the neutrino community are at 1% level because:

- Leading systematics for long baseline experiments → Neutrino Oscillation Physics
- Limited possibility to validate nuclear electroweak effects ("nucleus and nuclear correction") → Electroweak physics
- Neutrino generators based on different approach still provide results with >50% discrepancies → Nuclear Physics

From the **European Strategy for Particle Physics Deliberation document**:

To extract the most physics fromDUNE 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.

From the Physics Briefbook for the **European Strategy for Particle Physics (arXiv:1910.11775)**

Both NuSTORM and ENUBET are to a large extent site-independent concepts, studies and R&D; however both consider a possible implementation at CERN. For nSTORM, under the auspices of the PBC program, an initial study of implementation at CERN was carried out, and no showstoppers have been identified. For ENUBET the option of using SPS as the proton driver has been considered in greater detail with a possible site in the North Area and the ProtoDUNEs as neutrino detectors.
A dedicated study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or nSTORM) with conclusion in a few years time.

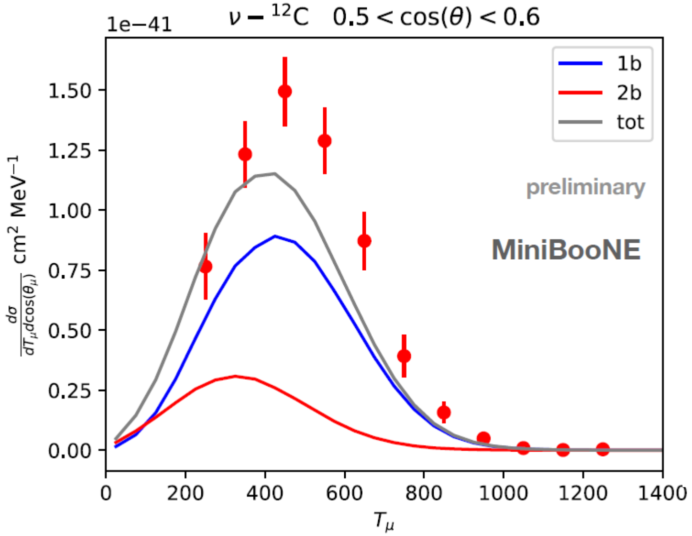
A harmful ignorance

- Major impact on the sensitivity of DUNE and HyperKamiokande (already dominant in T2K…)

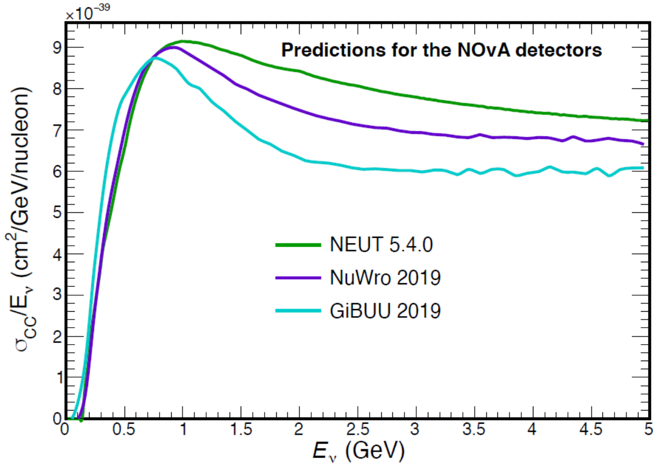
T2K

Systematic uncertainties			
Beam mode	Neutrino		
SK sample	1 Ring μ-like	1 Ring e-like	1 Ring e-like 1de
Flux	5.1%	4.8%	4.9%
Cross-section	10.1%	10.3%	12.0%
SK	2.9%	4.4%	13.4%

- Modeling of nuclear effects in neutrino interactions

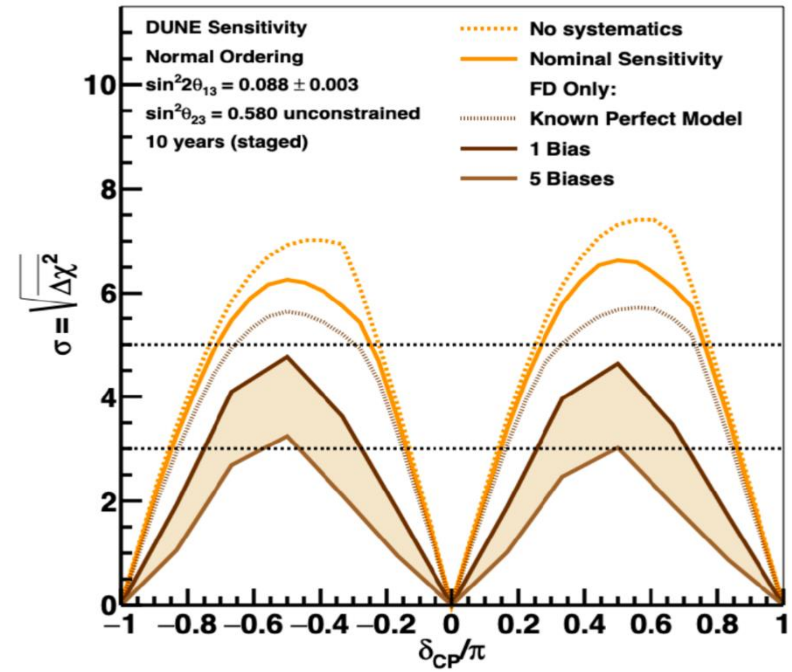


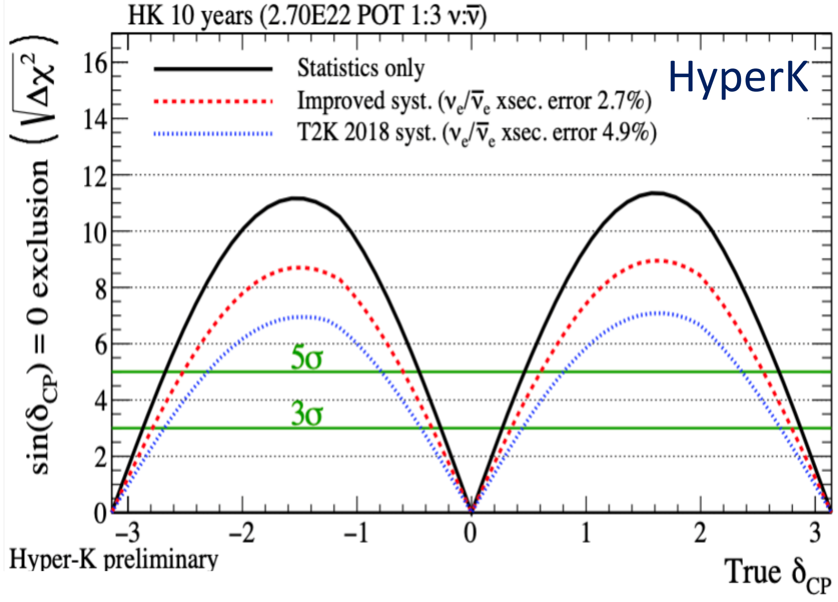
N. Rocco, Nufact2022



J. Paley, Nufact2022

DUNE





For a review see e.g. NuSTEC white paper, arXiv:1706.03621

What is needed for a new generation cross-section facility?

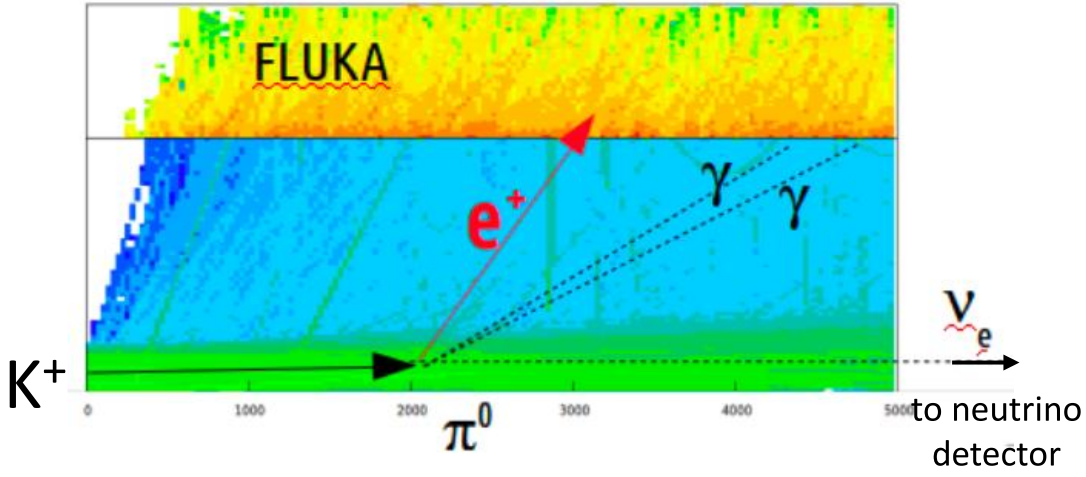
- Measure the neutrino flux of a xsect-dedicated short baseline beam with a precision <1% in ν_e and ν_μ . **Flux** is the dominant systematics. Generally known at 10% level with a few notable exceptions
  - Combine hadroproduction data + ν-e scattering (5-10%). World record: L. Zazueta [Minerva Coll.] PRD 107 (2022) 012001 (3.3-4.7% for ν_μ)
  - Monitored neutrino beam (**this seminar**) 0.5-1 %
  - Muon storage ring (nuSTORM) <1%
- Measure the **energy** of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Narrow band beams combined with movable detectors (rough approximation of a "monocromatic beam")
  - Monitored neutrino beam "Narrow band- off-axis technique" (**this seminar**)
  - Tagged neutrino beams (ENUBET+NuTAG – Physics Beyond Collider)
- Use the same **target** as DUNE and HyperK + low Z target (existing or new experiments)
  - Some information available from near detectors (but, then, issues with flux × cross-section deconvolution)
  - New experiments with existing or novel detectors along a short-baseline beam (following the success of dedicated experiments like Minerva)

For a review see e.g. A. Branca et al., Symmetry 13 (2021) 9, 1625

What is ENUBET?

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;
- Since 2022 ENUBET is part of the Physics Beyond Collider to study possible implementation at CERN

Collaboration: 74 physicists & 17 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna

ENUBET: the first monitored neutrino beam

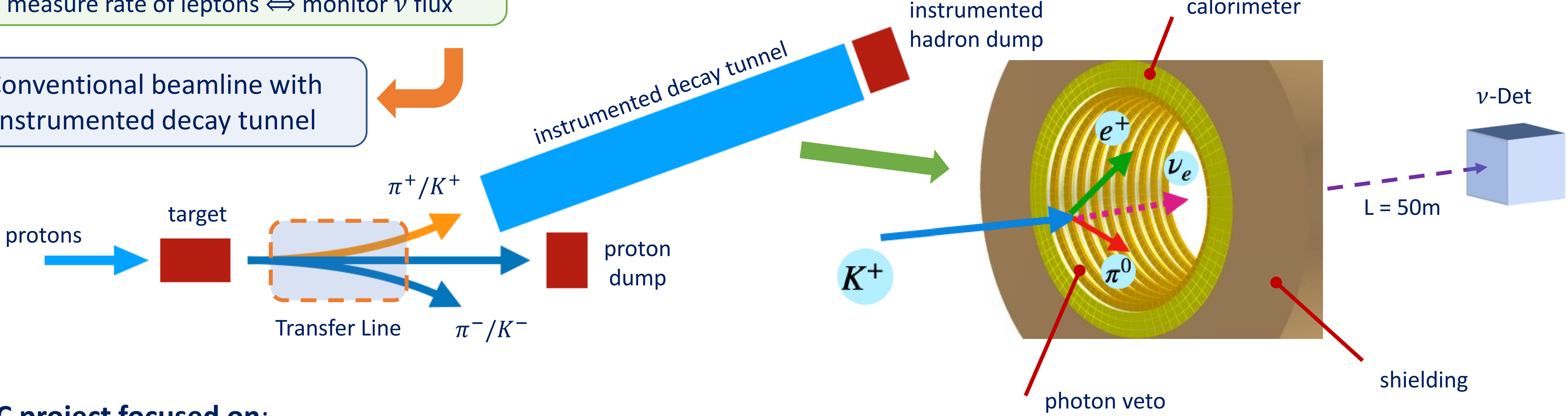
How do we achieve such a precision on the neutrino flux, flavor composition and energy?

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



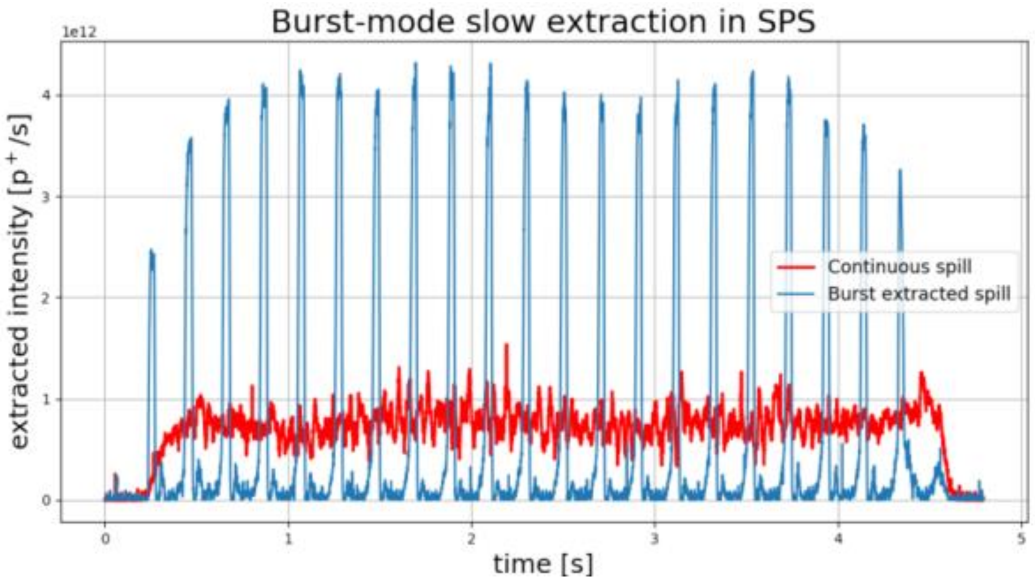
- **ERC project focused on**: measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**: extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$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

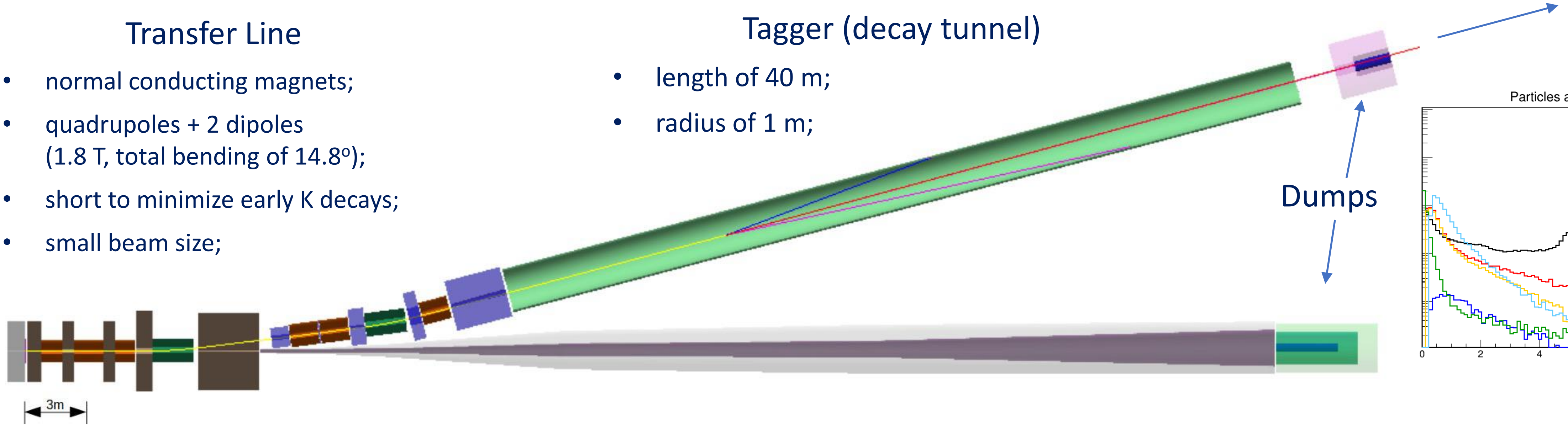
See EPJ C 83 (2023) 964

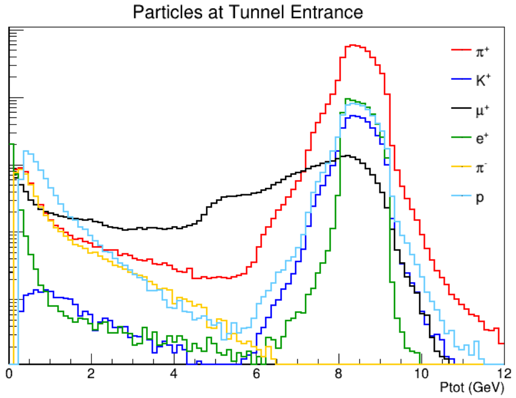
Transfer Line

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

Tagger (decay tunnel)

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





Large bending angle of 14.8°: 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 within the momentum bite (10%)	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.6	0.4

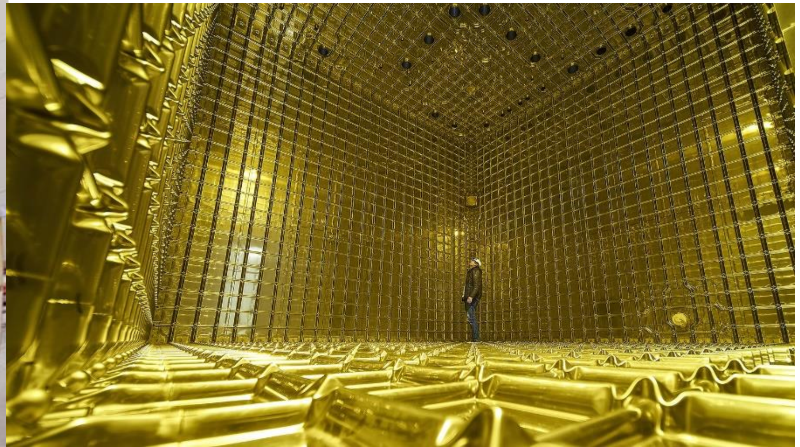
Is this neutrino beam powerful enough? Yes (details in EPJC C 83 (2023) 964)

A total ν_e^{CC} statistics of 10^4 events in ~2 years

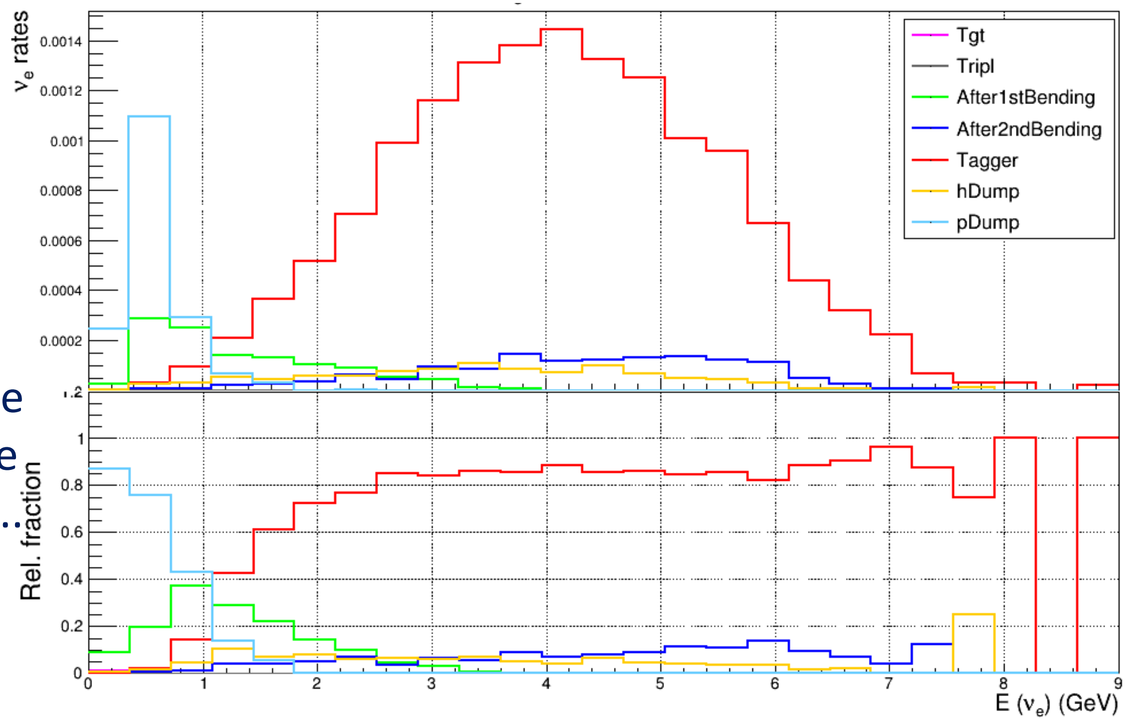
- @ SPS with $4.5 \cdot 10^{19}$ POT/year;
- 500 tonne detector @ 50 m from tunnel end;

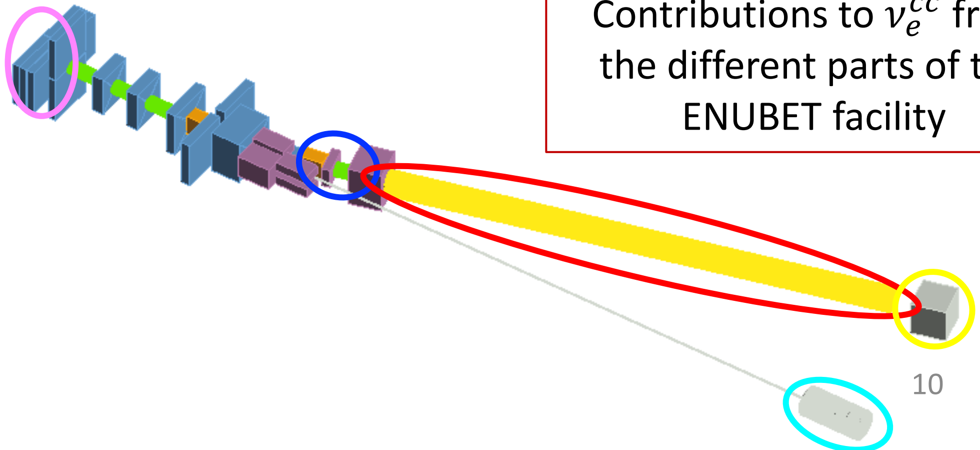
Important: this number is incompatible with the CERN fixed target programme with SHIP or HIKE up and running but... see below

ProtoDUNE-SP (NP04)



ν_e CC spectra





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

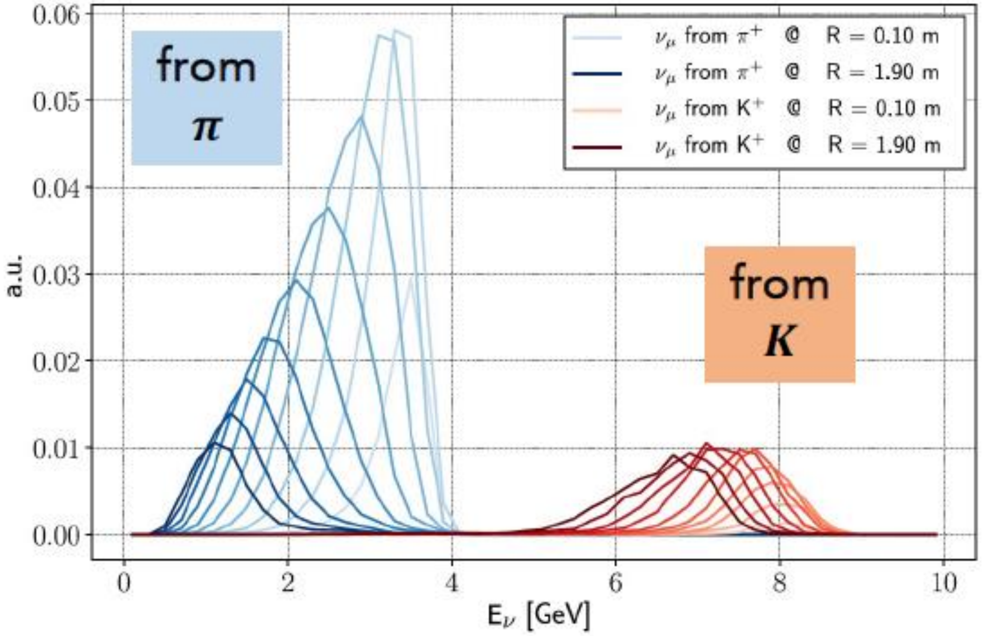
E_ν = neutrino energy;

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

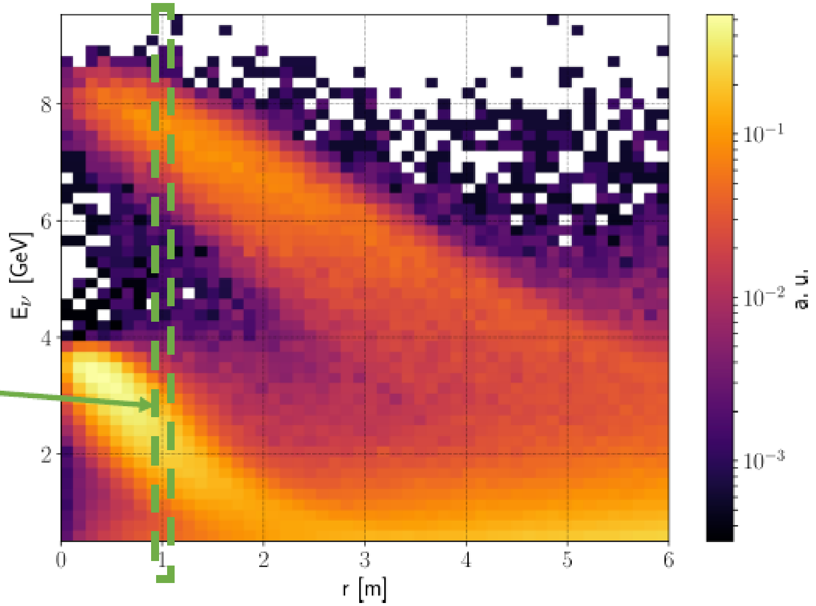
10-25% E_ν resolution from π in the DUNE energy range

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;

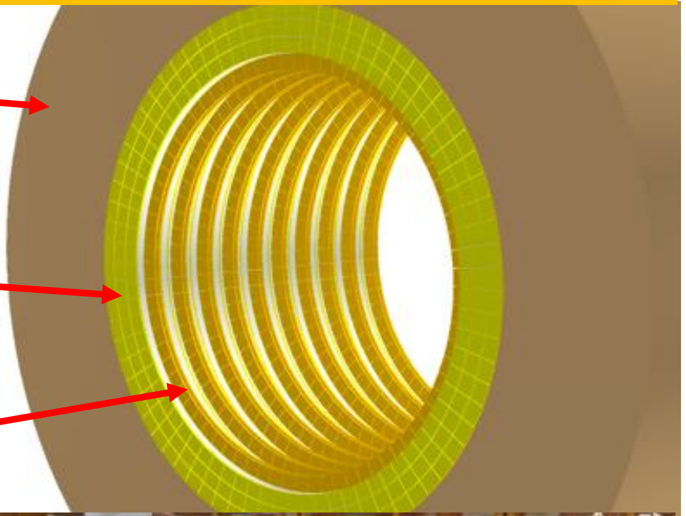
Calorimeter with $e/\pi/\mu$ separation capabilities:

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

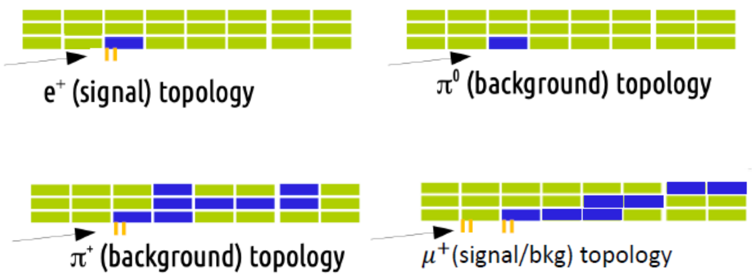
Photon-Veto allows π^0 rejection and timing:

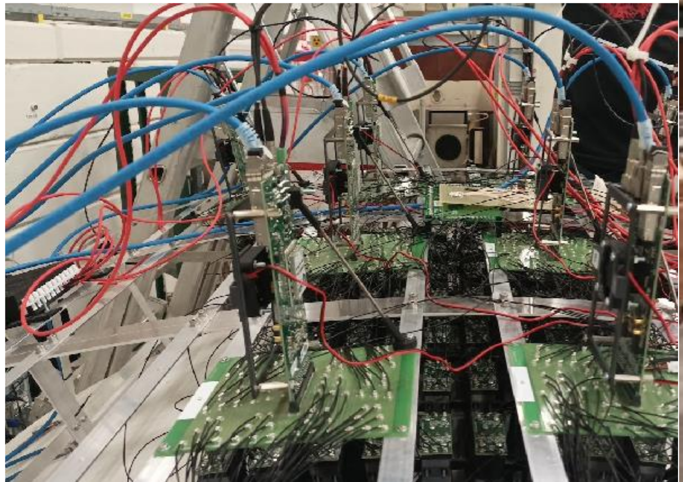
- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of ~ 400 ps;

Layout of the instrumented tunnel



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



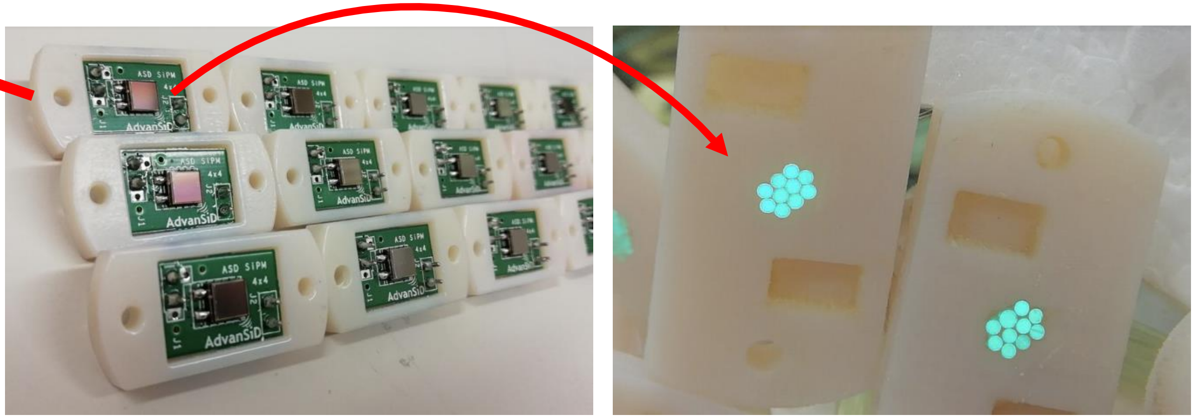


The ENUBET demonstrator

Decay tunnel instrumentation prototype & tests (2017-2020)

Prototype of sampling calorimeter built out of LCM with lateral WLS-fibers for light collection

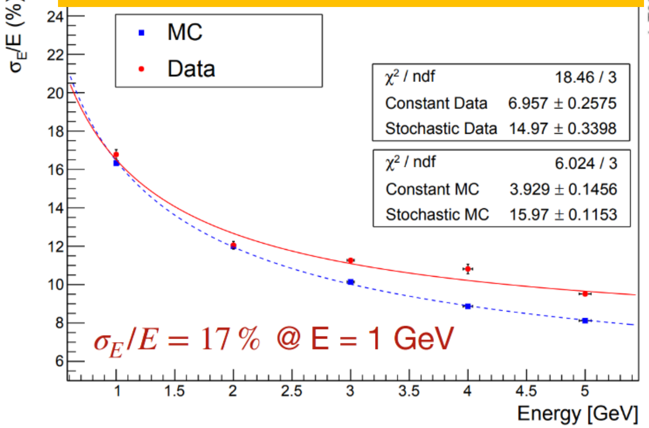
Large SiPM area (4x4 mm^2) for 10 WLS readout (1 LCM)



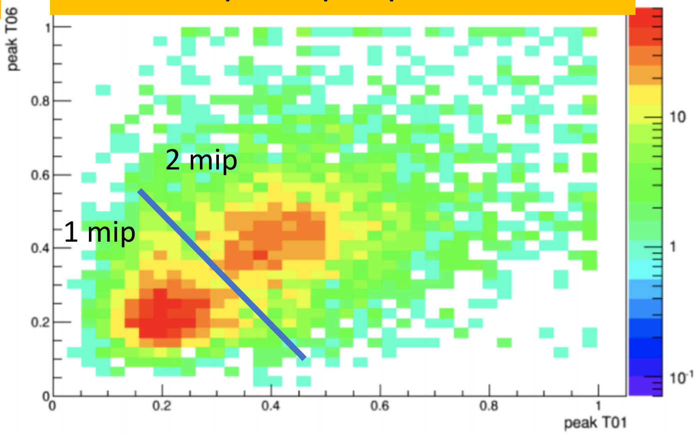
SiPMs installed outside of calorimeter, above shielding: avoid hadronic shower and reduce (factor 18) aging

Tested during 2018 test-beams runs @ CERN TS-P9

Electron energy resolution



1mip/2mip separation



- ✓ longitudinally segmented calorimeter prototype successfully tested;
- ✓ photon veto successfully tested;
- ▪ custom digitizers: in progress;

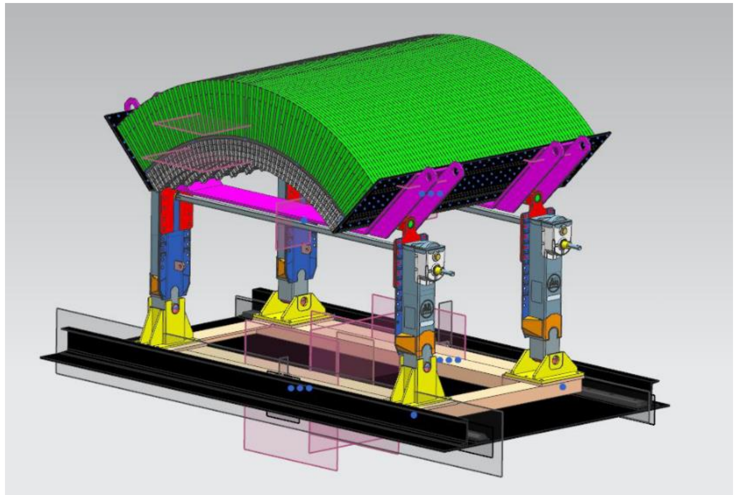
Choise of technology: finalized and cost-effective!

F. Acerbi et al, JINST 15 (2020) P08001

The ENUBET demonstrator

Construction @ LNL-INFN Labs

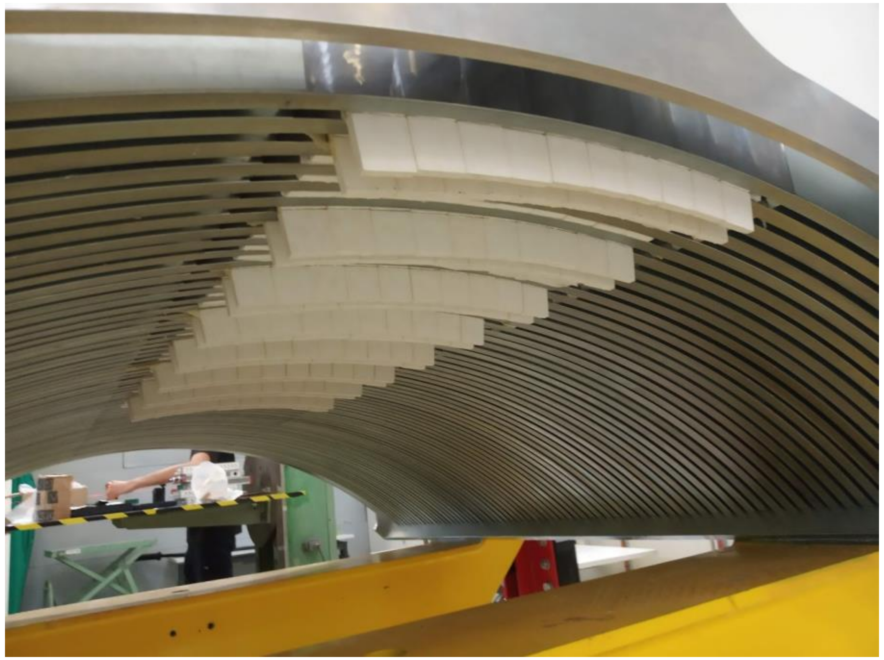
Iron arcs and borated polyethylen shielding



Lifting test of demonstrator

Fiber concentrator (boundling/routing to SiPMs)

The ENUBET demonstrator at CERN PS-EA in 2022 and 2023



francesco.terranova.tel

Piace a **valee_.terra** e **altri 18**

francesco.terranova.tel An hairy detector for neutrino physics 😄 #enubet #cern

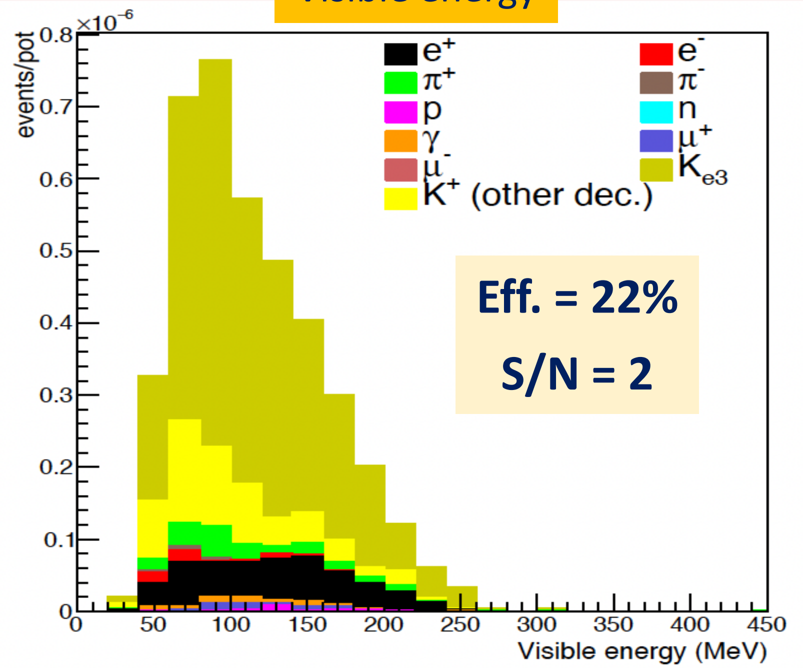
Lepton reconstruction and identification performance

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

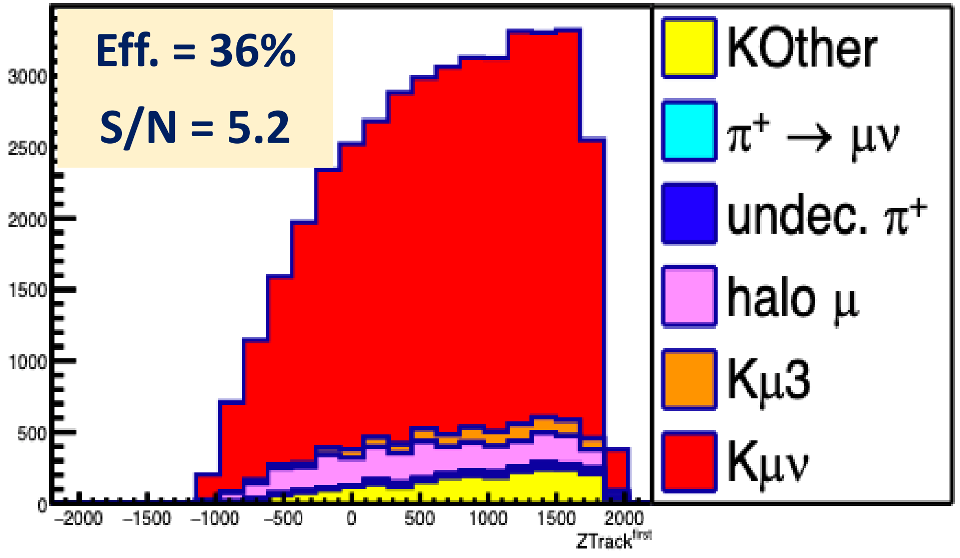
Visible energy



Efficiency ~half geometrical

$K_{\mu 2}$ muons → constrain ν_μ

Tagger impact point

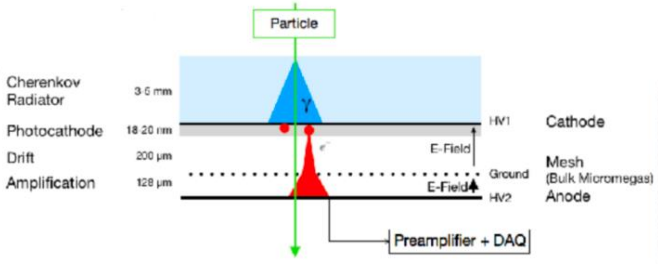


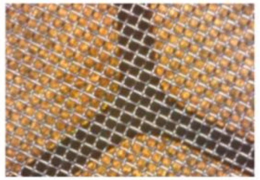
Efficiency ~half geometrical

Forward lepton reconstruction ($\pi \rightarrow \mu\, \nu_\mu$)

$\pi_{\mu 2}$ muon reconstruction to constrain low-energy ν_μ

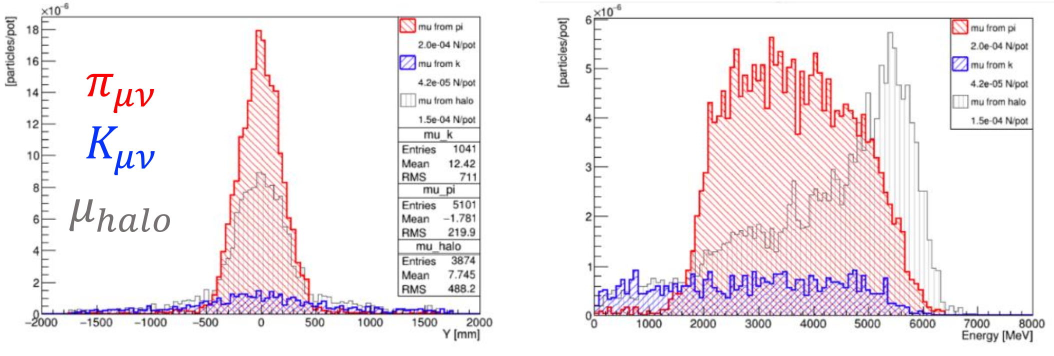
Low angle muons: out of tagger acceptance, need muon stations after hadron dump

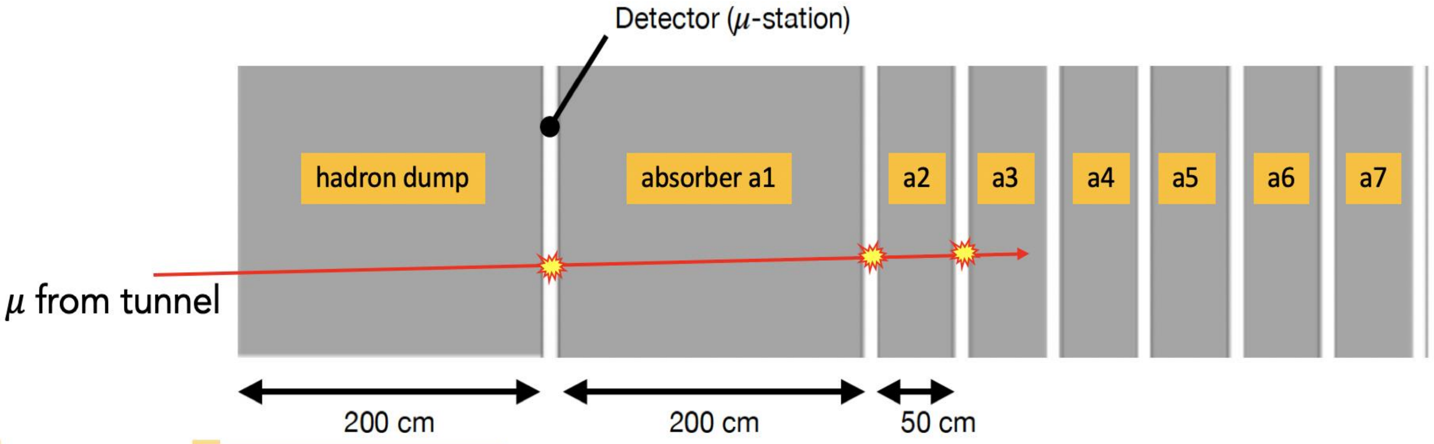




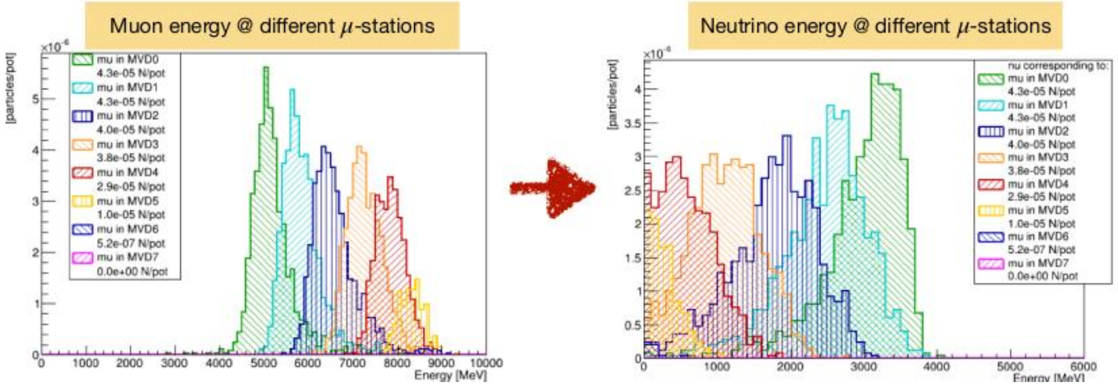
Possible candidates: fast Micromega detectors with Cherenkov radiators (PIMENT)

Exploit differences in distributions to disentangle components





Hottest detector (upstream station): cope with ~2 MHz/cm^2 muon rate and ~10^{12} 1 MeV-n_{eq}/cm^2



Exploit:

- correlation between number of traversed stations (muon energy from range-out) and neutrino energy;
- difference in distribution to disentangle signal from halo-muons;

Detector technology: constrained by muon and neutron rates;

Systematics: punch through, non uniformity, efficiency, halo-μ;

Project Collaboration

- Partners:
  - Thomas Papaevangelou (CEA/DRF/IRFU)
  - Anselmo Meregaglia(CNRS/IP2I Bordeaux)
  - Dominique Breton (IN2P3/IJCLab)
  - Michal Pomorski (CEA/DRT/LIST)
- Duration: 36 months started from Jan 2022

- External Partners:
  - CERN (L. Ropelewski, E. Oliveri, F. Brunbauer, Rui d'Oliveira, A. Utrobičić, M.Lisowska)
  - University of Thessaloniki(S.Tzamarias, I.Angelis, D.Sampsonidis, K.Kordas, Ch.Lampoudis, A.Tsiamis)
  - USTC Hefei China (Zhou Yi)
  - ENUBET Collaboration (A.Longhin)

Funded by :

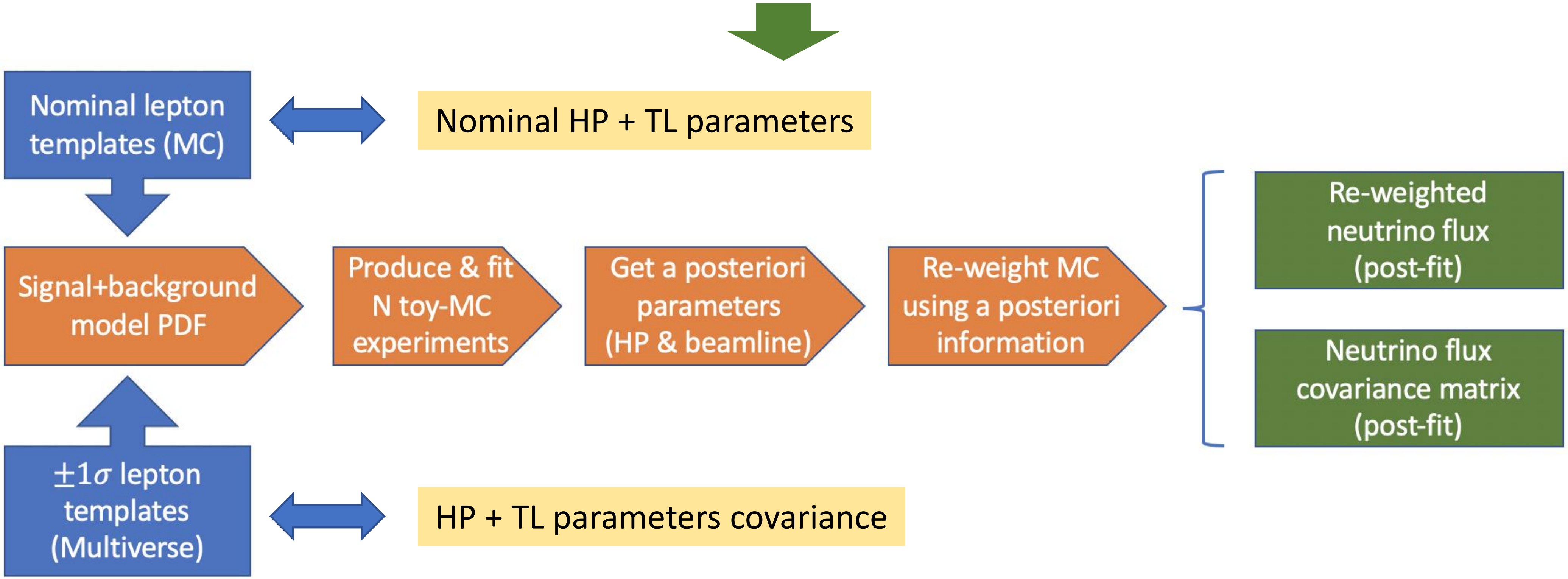
RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

anr agence nationale de la recherche
AU SERVICE DE LA SCIENCE

ν-Flux: assessment of systematics

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

- build a Signal + Background model to fit lepton observables;
- include hadro-production (HP) & transfer line (TL) systematics as nuisances;



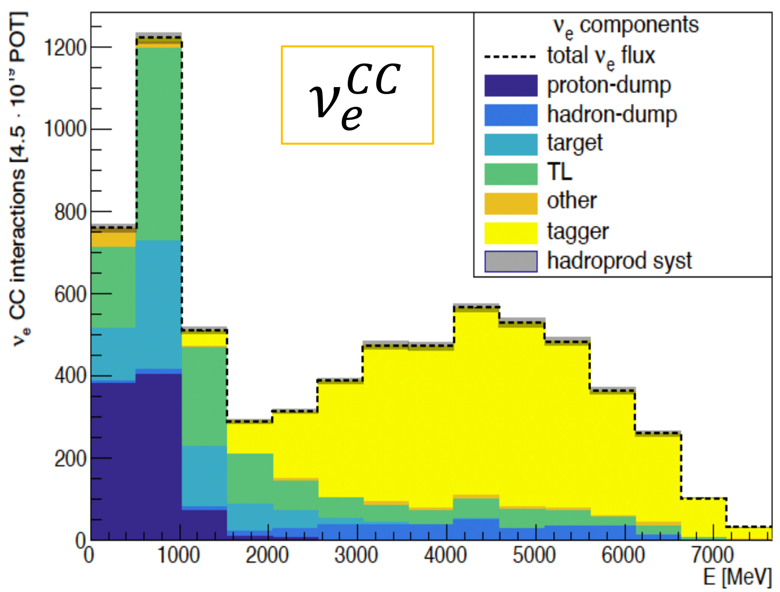
Used hadro-production data from NA56/SPY experiment to:

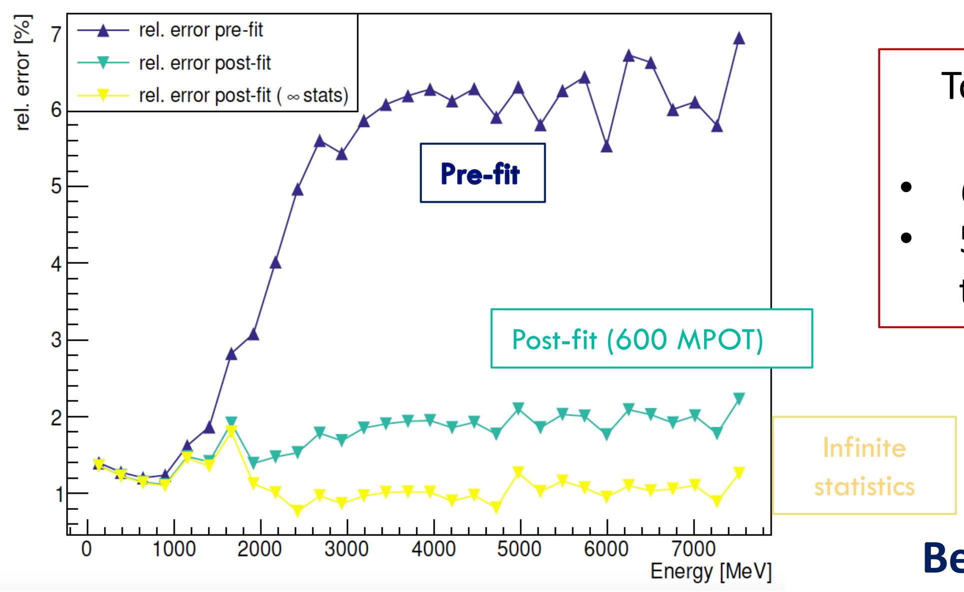
- Reweight MC lepton templates and get their nominal distribution;
- Compute lepton templates variations using multi-universe method;

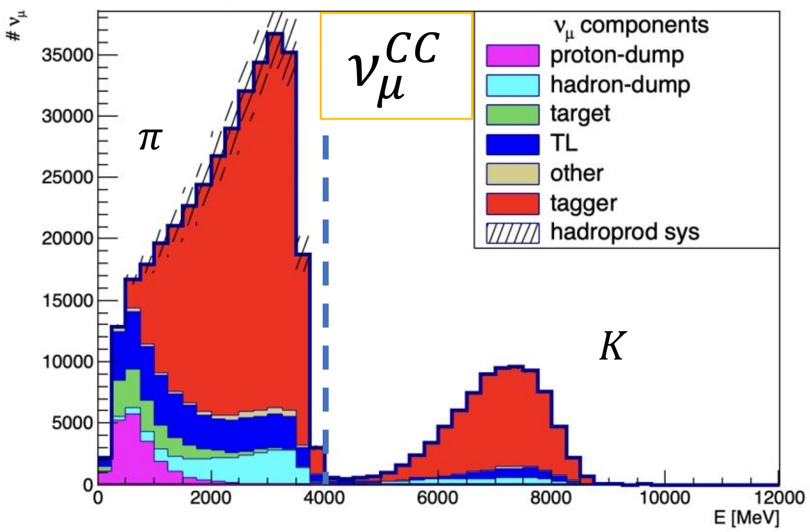
Can we really reduce the flux systematics at <1%? Yes

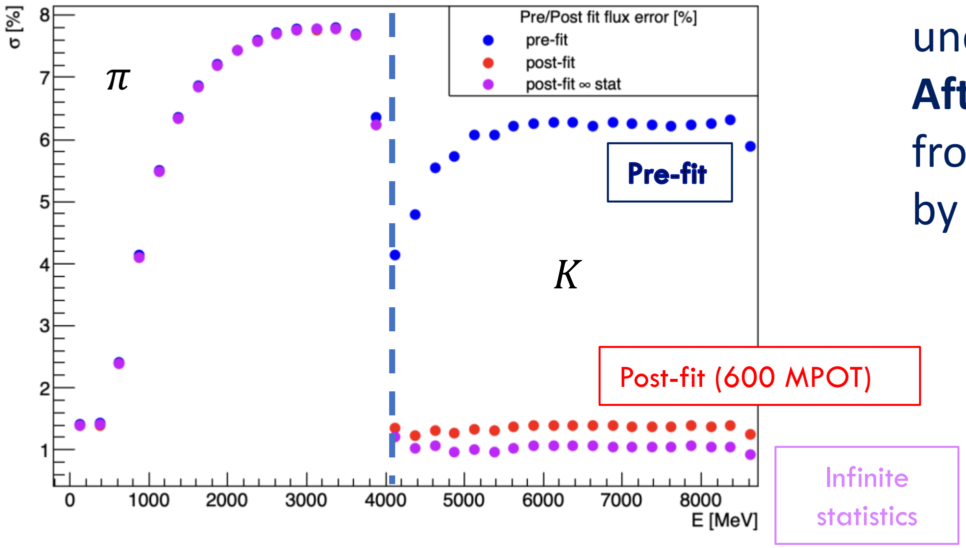
Neutrino interaction rates @ detector

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

Monitored neutrino beams are viable candidates.. with some limitations that we are addressing in Physics Beyond Collider!

- Measure the neutrino flux with a precision <1% in in ν_e and ν_μ

  OK. ENUBET has achieved a precision of 1% considering the leading systematics and only positron monitoring. We will publish the final results including the muon constraints and the subdominant contributions in 2024

  Room for improvement: reduce the need of protons-on-target to ease implementation at CERN. Enhance statistics in the region of interest for HyperK

- Measure the energy of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions

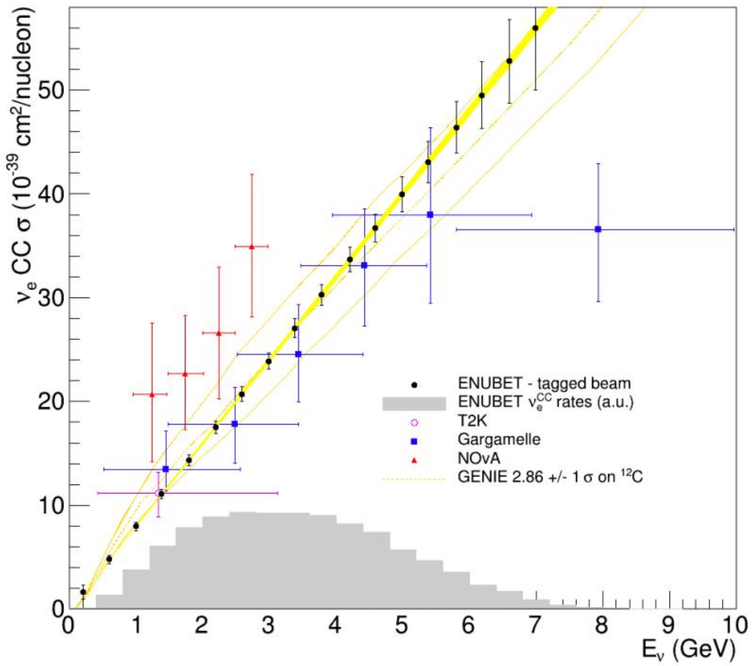
  OK. Using the fact that the ENUBET beam is narrow band we achieve an event-to-event resolution of 8% at 3 GeV and 25% at 1 GeV ("NBOA" technique)

  Room for improvement: a direct muon energy measurement can improve substantially this precision, especially at low E (tracking at the last dipole) [Nutech, **NuTAG**, PIMENT]

- Use the same target as DUNE and HyperK (existing or new experiments)

  YES. All results above work with a 400 ton detector. ProtoDUNE-SP at CERN is a major asset **but** a full site-dependent (SPS@CERN) study is not available yet.

ENUBET impact on σ_{ν_e}

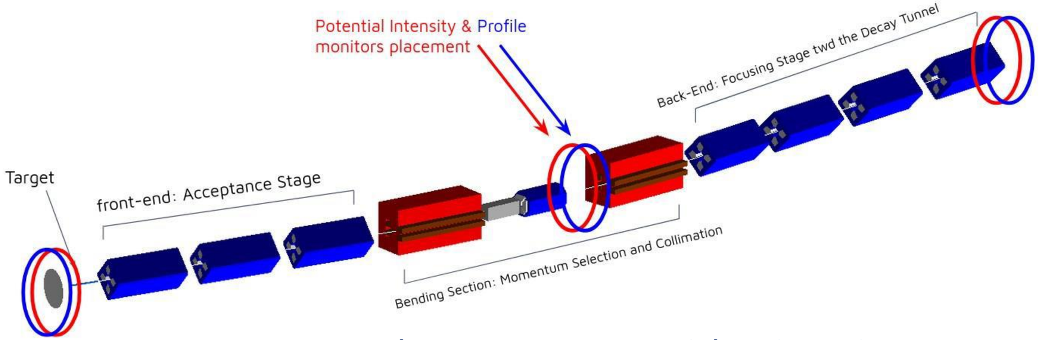


SBL@PBC: a great starting point (I)

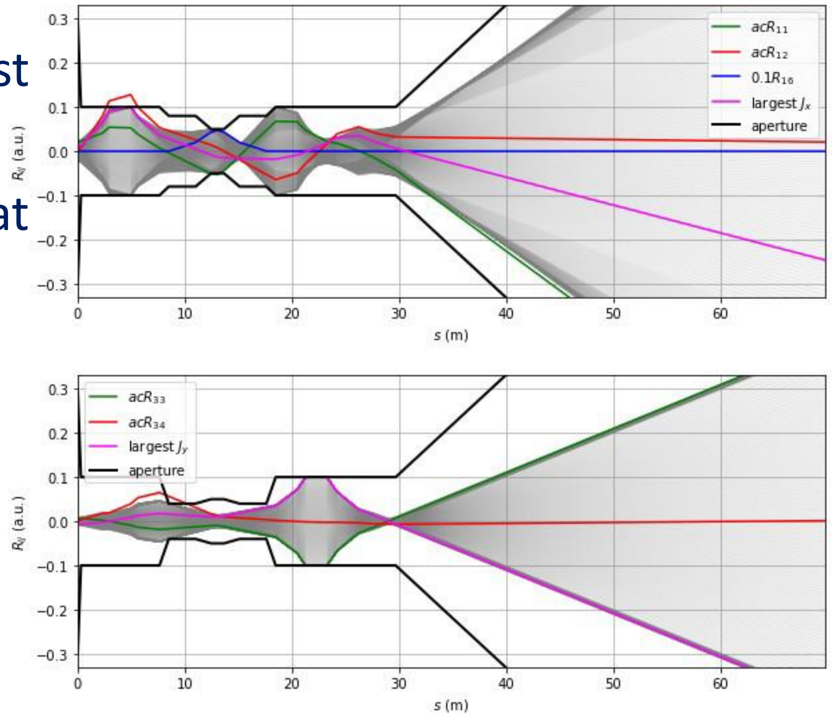
In 2021-23 ENUBET and CERN addressed the most important limitation of the ENUBET monitored neutrino beam: the large number of protons needed to achieve high precision measurements and the limited statistics in the region of interest for HyperKamiokande. This study culminated with the ENUBET "Multi-momentum beamline", which is currently **the starting point for a short baseline experiment at CERN** (SBL@PBC)

The multi-momentum beamline is designed:

- To operate with secondary momenta from 4 to 8.5 GeV and covers both the DUNE and HyperKamiokande region of interest
- To exploit **only existing magnets** at CERN, which are the main cost driver for the facility
- To minimize the requested number of protons using an optics that benefit of multiple runs at different secondary momenta



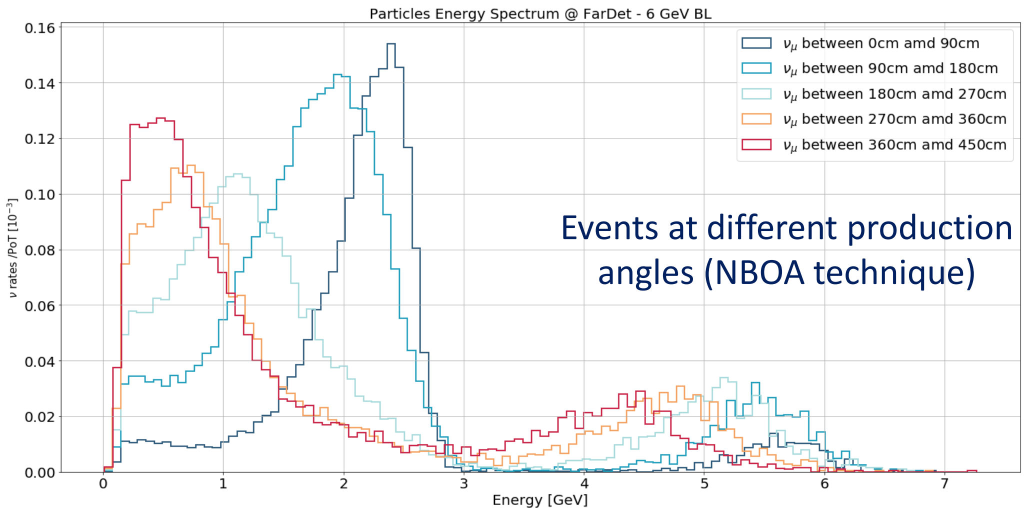
E. Parozzi (CERN & UniMib), PhD thesis

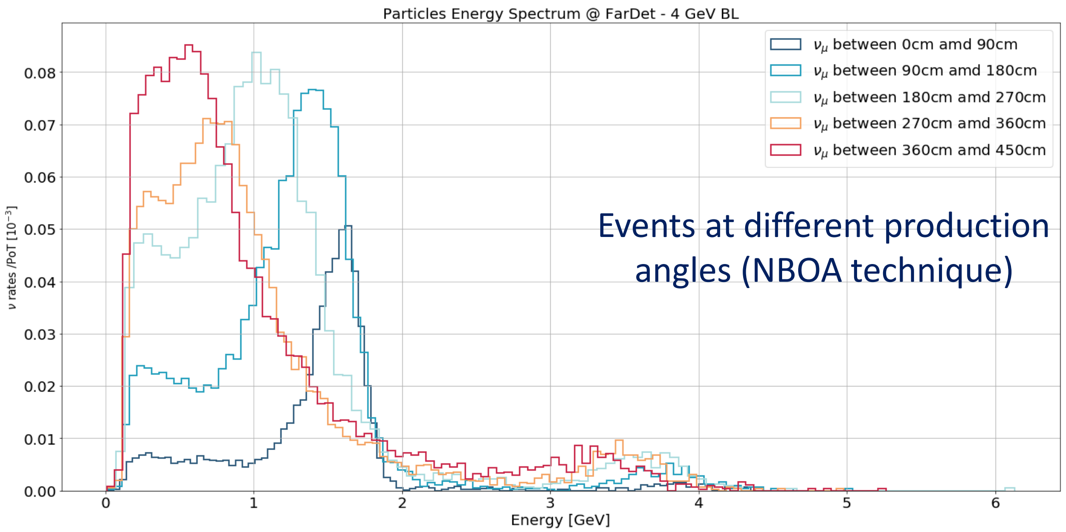


Courtesy of E. Parozzi and M. Jebramcik

SBL@PBC: a great starting point (II)

The multi-momentum beamline provided two important advances:





The low energy runs enhances the exploration of cross-section in the 1 GeV range, i.e. where most of HyperKamiokande events are located.

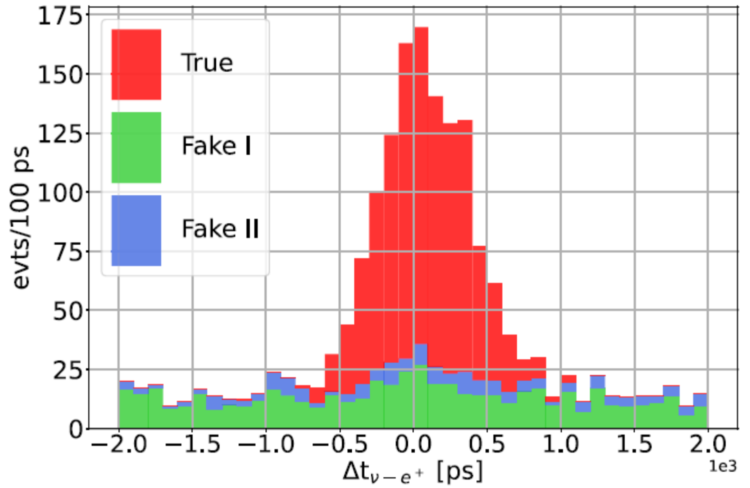
Even more, **it halves the proton needs of ENUBET without compromising monitoring.**

Configuration	Pot needed	detector mass	pot/y (5y run)
ENUBET + ProtoDUNE-SP	10^{20}	400 t (liquid argon)	$2\ 10^{19}$
ENUBET ProtoDUNE SP+DP	$5\ 10^{19}$	800 t (liquid argon)	$1\ 10^{19}$
ENUBET-multi ProtoDUNEs	$2.5\ 10^{19}$	800 t (liquid argon)	$5\ 10^{18}$
SBL@PBC	$2.5\ 10^{19}$	800 t (LAr) + 40 t (w.Ch.)	$<5\ 10^{18}$

SBL@PBC: can we do better?

The multi-momentum beamline is a good starting point, but a lot of work is still ahead of us:

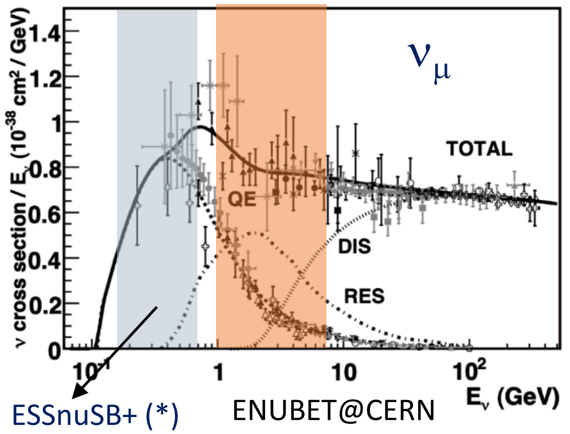
- We can improve the neutrino yield by further optimizing the beamline and, in particular, the momentum acceptance – new results will be presented in early 2024
- We can have some of the beamline component specifically built for SBS@PBC (cost/benefit TBD)
- We can exploit the slow extraction to trace mesons inside the beamline and gain additional energy resolution for ν_μ → NUTAG
- We can rely on a golden subsample where the lepton is correlated in time with the interacting neutrino in the neutrino detector operating ENUBET as a real tagged neutrino beam. This would be a breakthrough in particle physics but comes with additional challenge:
  - install a fast tracker in the beamline where meson fluxes are tolerable → NUTAG
  - Reduce the timing resolution of ProtoDUNE and WCTE to 100 ps (easy for WCTE, difficult for ProtoDUNE !)
- We need to address site-specific constraints: radioprotection in the compatibility with the CERN Fixed Target programme

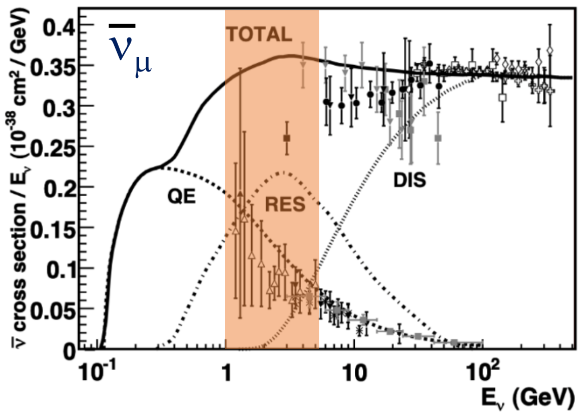


These goals will be the core activities of ENUBET+NUTAG at Physics Beyond Collider and we aim at a Proposal to the SPSC in early 2026

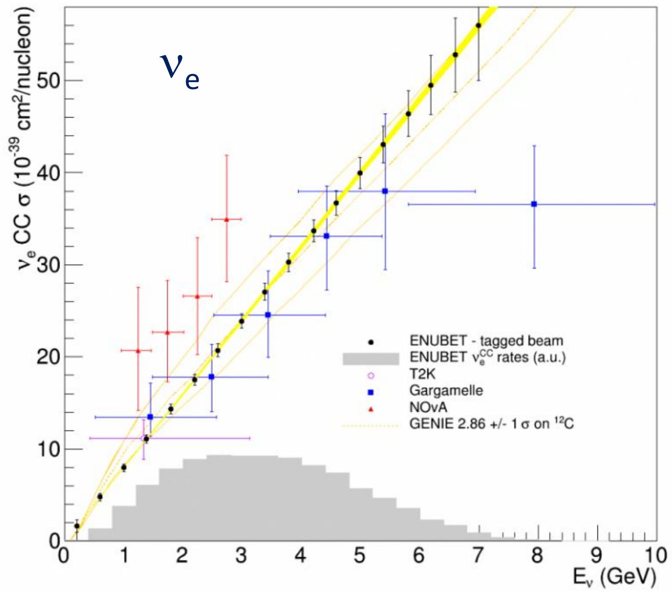
Impact

Inclusive neutrino cross section: solid results available at 10-30% level

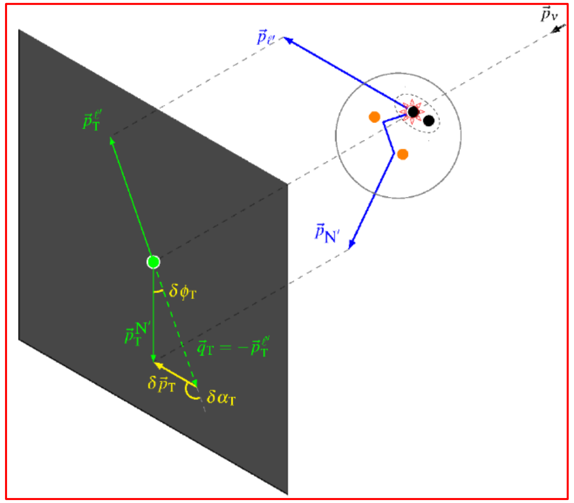




(*) monitored neutrino beam @ESS Design studied approved by EU (lead CNRS) in July 2022



Differential cross sections:



Exploit the knowledge of the neutrino energy without relying on final states: ENUBET NBOA + transverse kinematic imbalance (*)

(*) X.G. Lu et al. PRC 94 (2016) 105503

Nuclear effects in argon and water:

- 1% cross section in argon for all flavors with the ProtoDUNEs
- 1% cross section in water for ν_μ

BSM: High precision studies of non-standard interactions and sterile neutrinos at L= O(100 m). See e.g. L.A. Delgadillo, P. Huber, PRD 103 (2021) 035018

BSM: Exotic neutral particles produced at the hadron dump (beam dump physics with the ProtoDUNEs)

Conclusions

- Monitored neutrino beams are no more an “interesting idea”: the proof-of-concept is nearly complete and NP06/ENUBET has proven it both by simulations and a full experimental validation
- A monitored neutrino beam has all features needed for a new generation of cross section experiments
- The final ENUBET results (baseline beamline, multi-momentum beamline, systematic assessment, and performance of the demonstrator) are available here and in three ancillary papers that will appear in 2024
- We have started the process of addressing the real implementation at CERN and aim at a proposal in 2026
- **We wish to express our gratitude to CERN** and, in particular, to the CERN Neutrino Platform for the support and commitment that brought to the demonstration of the monitored neutrino beam concept, and we look forward to continue this collaboration in the framework of Physics Beyond Collider

We look forward to your suggestions for a design that fulfill the needs of the neutrino and nuclear physicists to have these experiment up and running in parallel with DUNE and HyperK