NP06/ENUBET

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).

F. Terranova (Univ. of Milano-Bicocca and INFN) on behalf of the ENUBET Collaboration

ENUBET: ERC Consolidator Grant. Jun 2016 - May ~~2021~~ 2022. PI: A. Longhin.
Since April 2019, ENUBET is also **a CERN Neutrino Platform experiment: NP06/ENUBET**

The ENUBET Collaboration:
60 physicists, 12 institutions
Spokespersons: A. Longhin, F. Terranova
Technical Coordinator: V. Mascagna

High-precision beams in the DUNE/HK era

The aim of my talk:

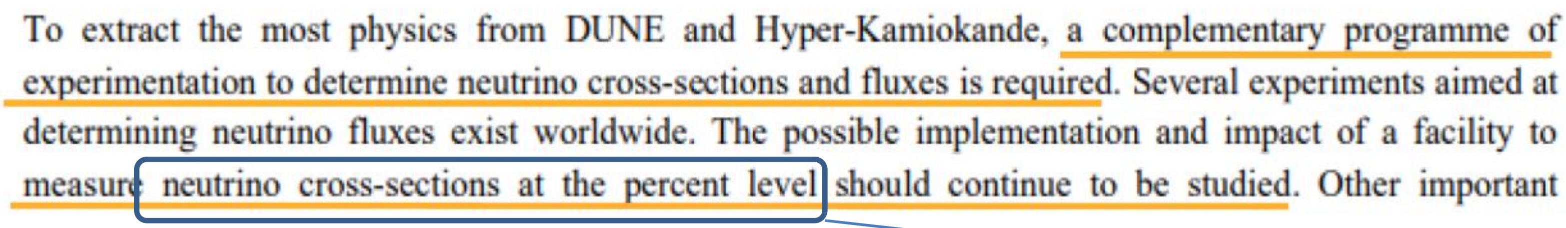
- We have been living with «beams for oscillations» hoping to get precision physics «for free»
- It worked at 10% level! But all good things come to an end.
- There is too large a leap between our knowledge of standard neutrino properties (firstly cross sections) and the needs of the next generation experiments.
- We need appropriate tools to perform precision physics:
  - High power beams and large mass detectors (osc. DUNE, HK + long term proposals)
  - **High precision beams for cross section, neutrino interactions and BSM physics measurements**

Flux at per-cent level measured in a direct manner

Good knowledge of the neutrino energy without using final-state particle reconstruction

Superior control of flavor and contamination at source

The rationale of



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

European Strategy for Particle Physics Deliberation document (pag. 5)

ENUBET and NUSTORM (see also the European Strategy Physics Briefbook, arXiv:1910.11775)

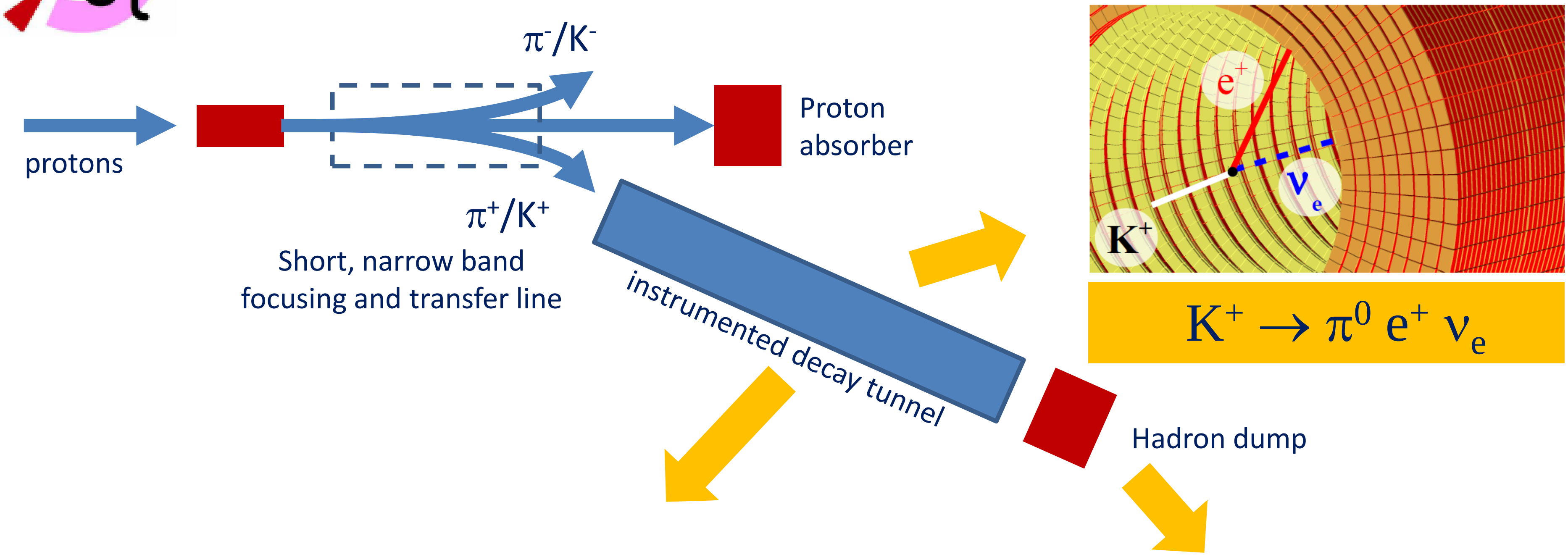
ENUBET is aimed at

- Designing a narrow band neutrino beam at the GeV scale and measure at 1% the **flux, flavor** and (at 10%) the **energy of the neutrinos** produced at source

It is the core technology for

- A new generation of short-baseline experiments to achieve a 1% precision on the **ν_e and ν_μ cross sections** and **remove all the biases** due the ν energy reconstruction
- It is essential to lower <3% the systematic budget of **DUNE and HyperK** and enhance remarkably their discovery reach
- Is the most natural follow-up of the previous generation of x-sect experiments (including the possibility to upgrade **the ProtoDUNE** or **the SBN physics programme**)

Monitored neutrino beams (*)



π^-/K^-

protons

Proton absorber

π^+/K^+

Short, narrow band focusing and transfer line

instrumented decay tunnel

Hadron dump

$K^+ \rightarrow \pi^0\, e^+\, \nu_e$

NEW! (2019-20) muon identification and monitoring for

$K^+ \rightarrow \mu^+\, \nu_\mu$

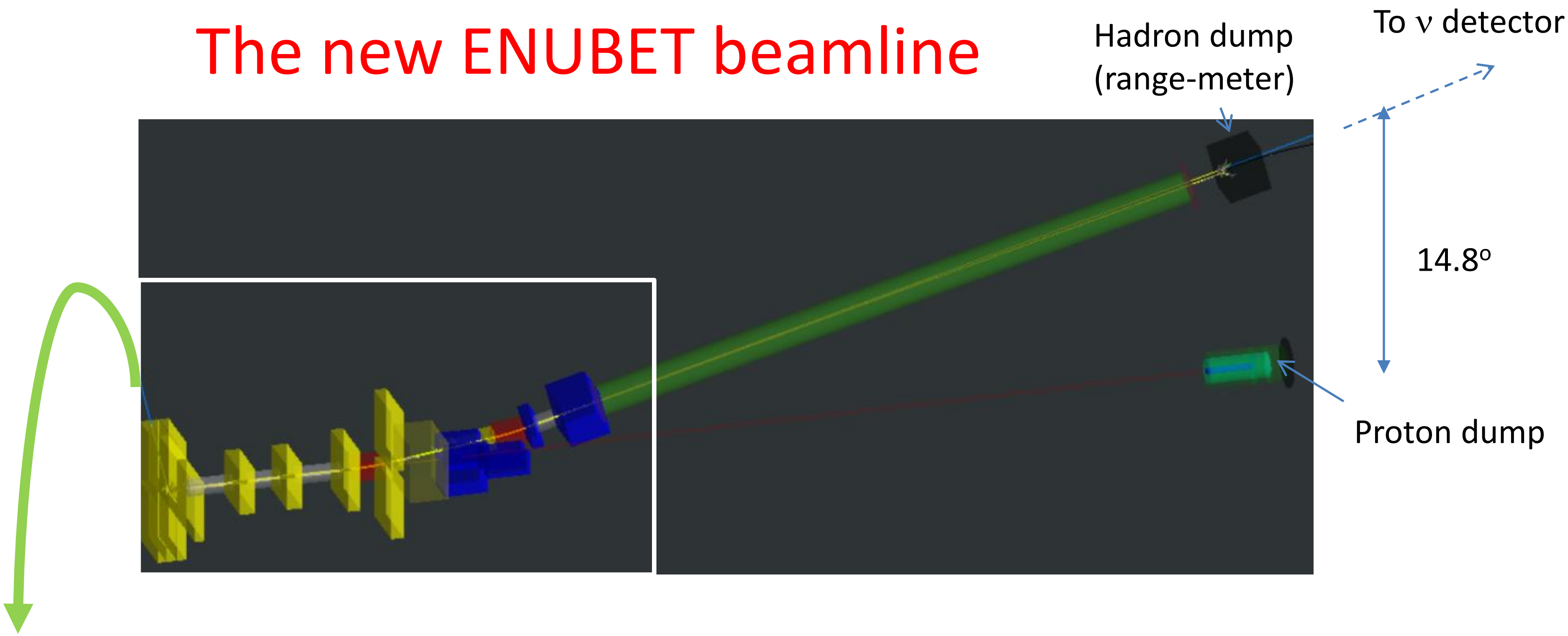
NEW! (2019-20) muon monitoring at single particle level replacing the hadron dump with a real range-meter

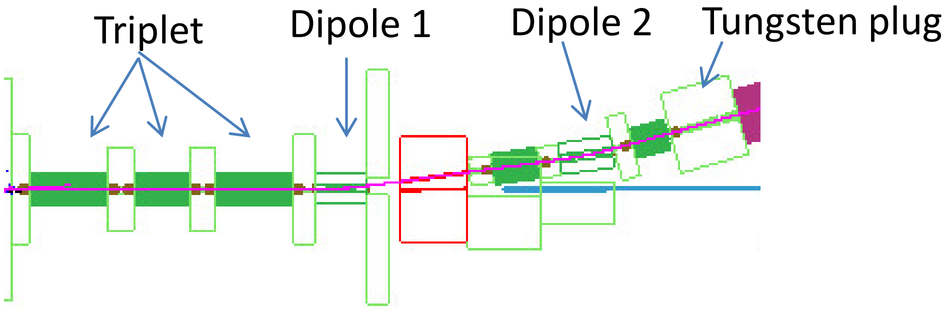
$\pi^+ \rightarrow \mu^+\, \nu_\mu$

ENUBET will be the first “**monitored neutrino beam**” where nearly all systematics are bypassed monitoring the leptons in the decay tunnel at single particle level

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

The new ENUBET beamline





Target simulation: **OK**

Transfer line:

- TRANSPORT/G4Beamline (optics and background shielding **OK**)
- FLUKA (doses and neutron shieldings **~OK**)
- GEANT4 (systematics, **in progress**)

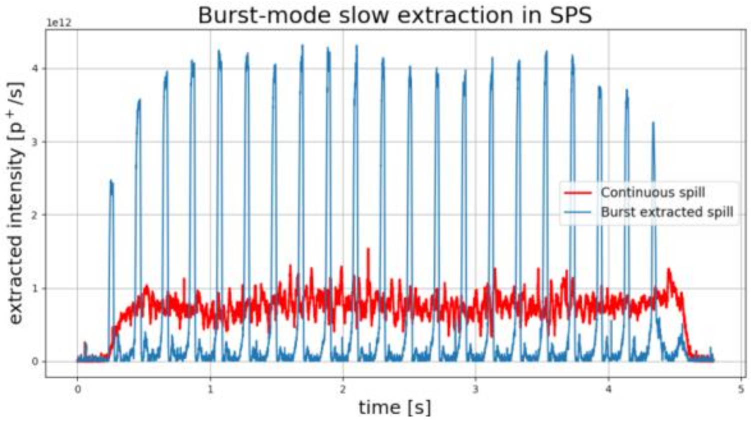
Proton dump: **OK** but engineering studies needed

Hadron dump: **OK** (with neutron shieldings NEW!)

See also: **A. Longhin, Talk @ Neutrino 2020**

Beam design

We are performing this R&D using the CERN-SPS as a benchmark, in collaboration with CERN A&T Division (p=400 GeV/c, 4.5 10^{19} pot/spill)



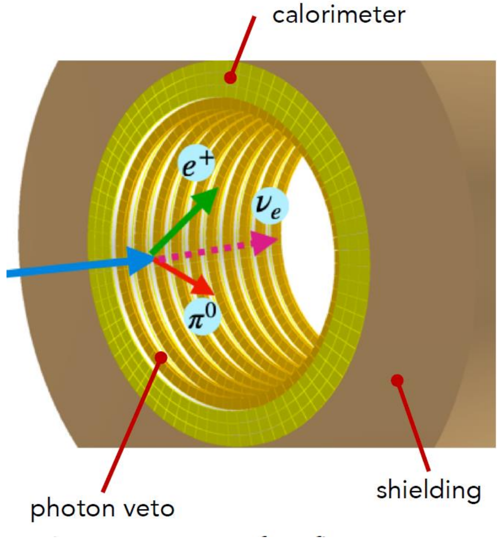
M. Pari, M. A Fraser et al, IPAC2019

Focusing:

We need a "slow" extraction to mitigate the rate of leptons in the decay tunnel

Horn: 2-5 ms extractions in the flat top

Purely static focusing: 2 s extraction



Tunnel instrumentation:

We need cost-effective detectors to identify muons and positrons

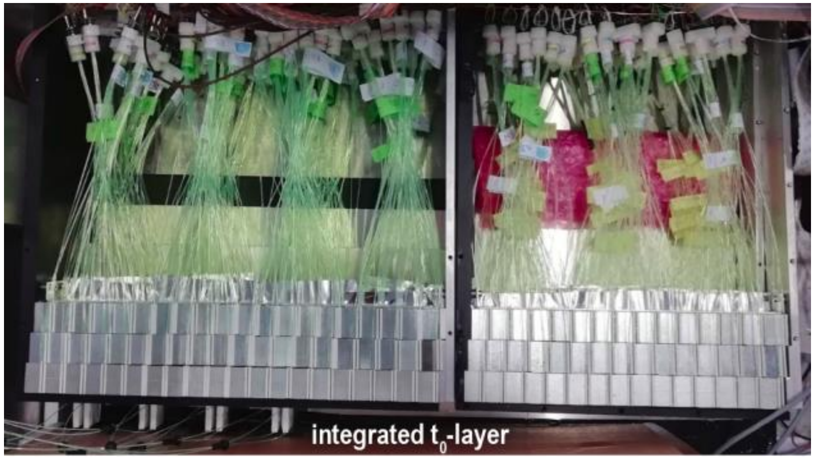
Modular sampling calorimeters (4.3 X0) with a photon veto

Typical rate per channel: 500 kHz/ch

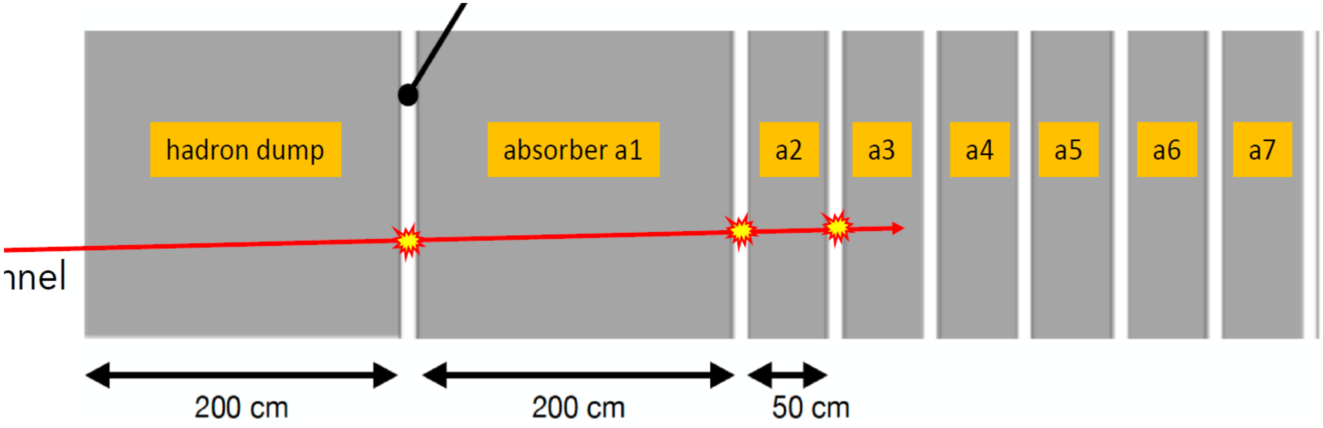
Doses: <10^{10} n/cm^2 at the SiPMs, 0.1 Gy at the scintillator

Instrumentation in the decay tunnel

All instrumentation to monitor positrons and muons have been prototyped, tested in beams of charged particles and **used to validate the MC**



- Longitudinally segmented calorimeter (**OK**)
- SiPMs on top of the calo above a PE borated shield to reduce (x18) radiation damage **OK**
- Test of the photon veto (t0-layer) **OK**
- Custom digitizer: **in progress**



Muon range-meter in the hadron dump: **in progress**

Max rate 1 MHz/cm^2

F. Acerbi et al., JINST 15 (2020) 08, P08001

F. Acerbi et al. JINST 14 (2019) 02, P02029

F. Acerbi et al., Nucl. Instrum. Meth.A 956 (2020) 163379

Particle identification

The PID is performed by the energy pattern in the modules and the photon veto. The event selection is based on 12 variables employed by a Neural Network.

Full simulation: particle transported in the beamline (including beam halo and tertiary interaction), detector response, pile-up, event building, PID algorithms

Doses at the detector and transfer line

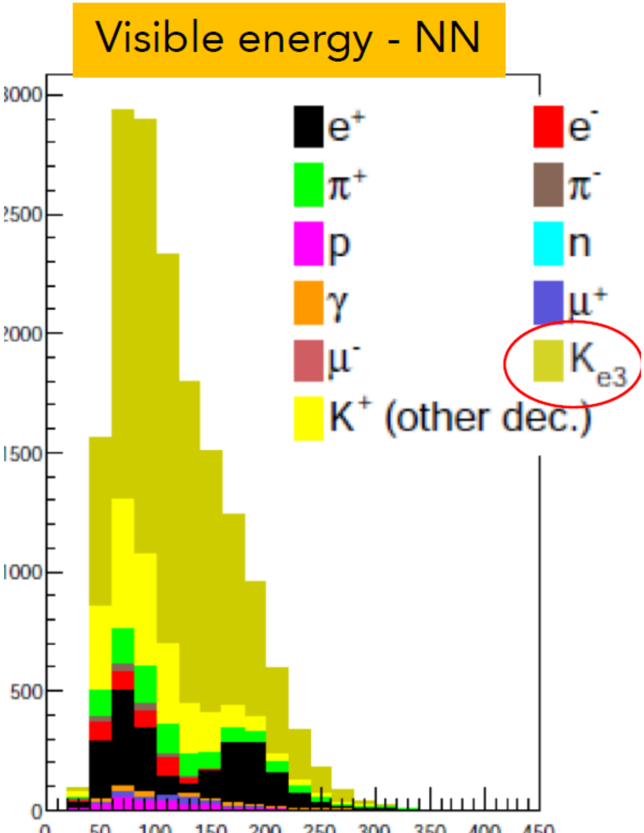
Data-driven simulation of detector response

Codes: FLUKA (target and doses), **G4Beamline** (beamline), **GEANT4** (neutrinos and systematics)

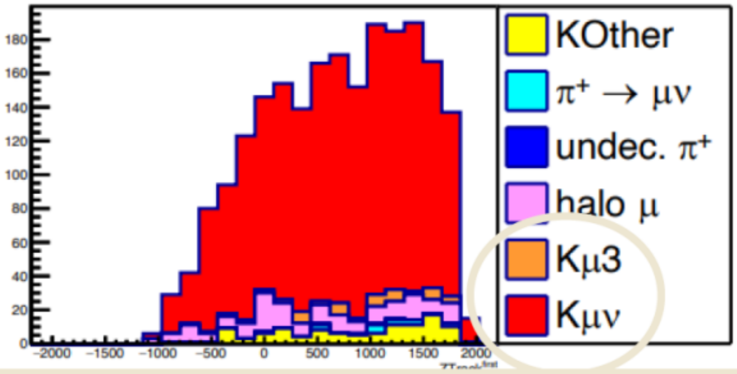
Positrons from K (~ν_e)

S/N = 2.1 Efficiency: 24%

(dominated by geometrical eff.)



Muons from $K_{\mu 2}$ (~ν_μ)



Position along the tunnel

S/N = 6.1

Efficiency: 34%

(dominated by geometrical eff.)

Physics performance: ν_e

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction length	π/cycle (10^{10})	K/cycle (10^{10})	Proposal [(c)]
Horn	**97**	7.9	2 ms [(a)]	438	36	x 2
"static"	**19**	1.4	2 s	85	6.2	**x 4**

To be updated with the new beamline **In progress**

The following results are given under the assumption of a **500 ton neutrino detector** located 100 m from the target

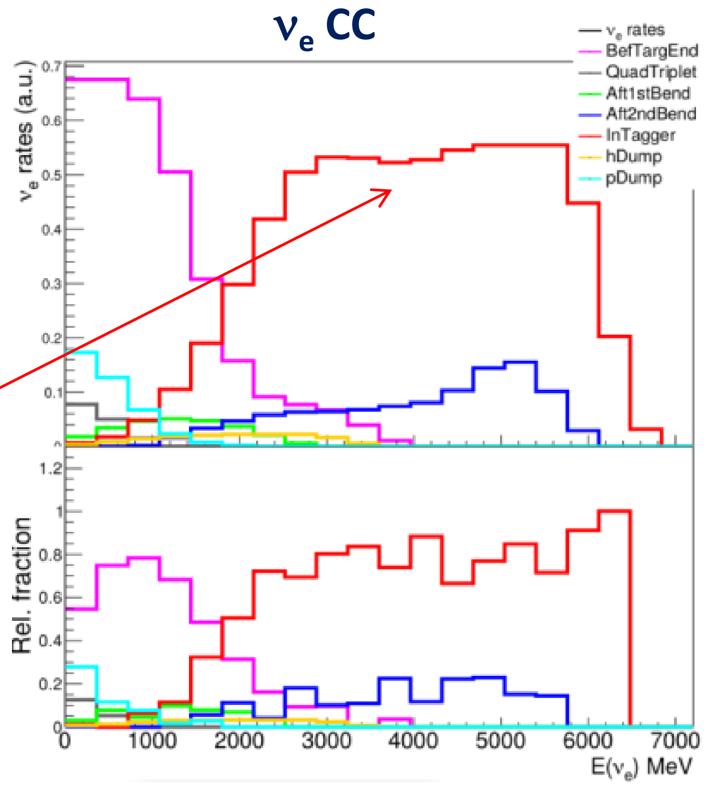
10^4 fully reconstructed ν_e CC in about 1.5 y of data taking (preliminary)

80% of the detected events produce a positron in the decay tunnel

10% from decay in the transfer line

10% from the target

(mostly low energy events from K^0_L)



Beamline optimized for DUNE

Physics performance: ν_μ

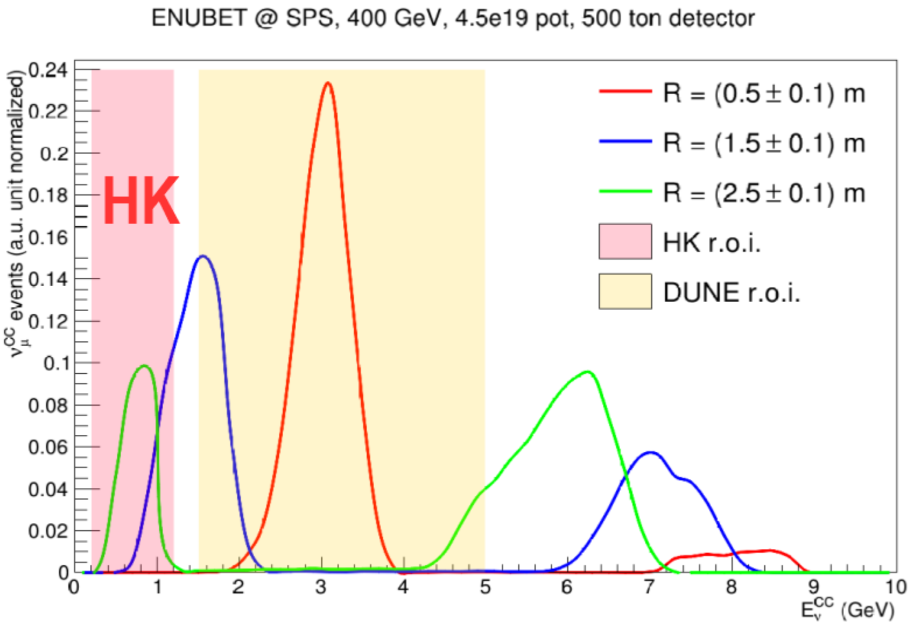
Flux:

- Muons from π monitored by the range-meter
- High energy muons monitored by $K_{2\mu}$

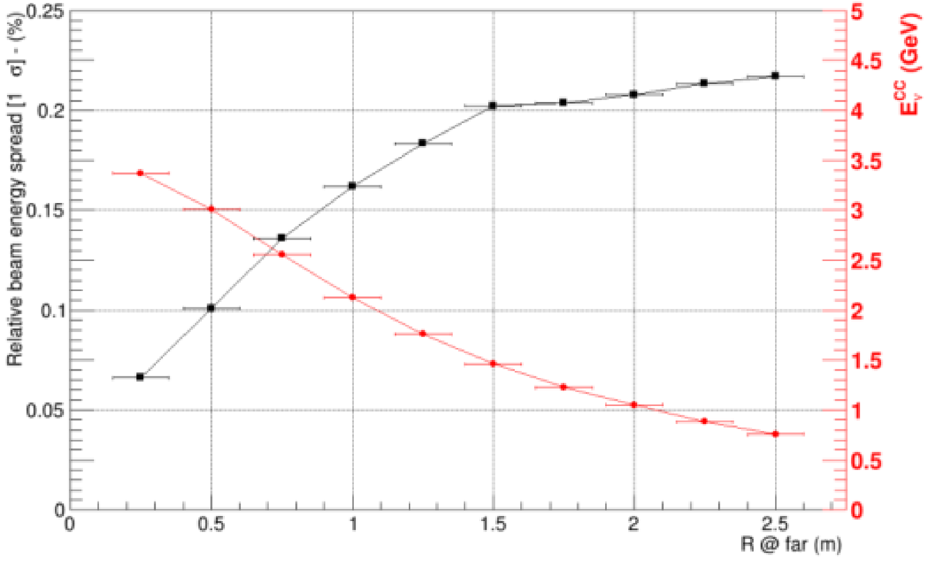
Energy:

- Since the momentum bite is <10% and the detector distance is small, strong correlation between the position of the neutrino vertex and its energy.
- We dubbed this technique "narrow-band off-axis technique" (*)
- **We provide the ν energy on a event-by-event basis without relying on final state particles in ν_μ CC**

About **O(10^6)** fully reconstructed ν_μ CC per year (preliminary)



(*) F. Acerbi et al., CERN-SPSC-2018-034



WORK IN PROGRESS

Systematics

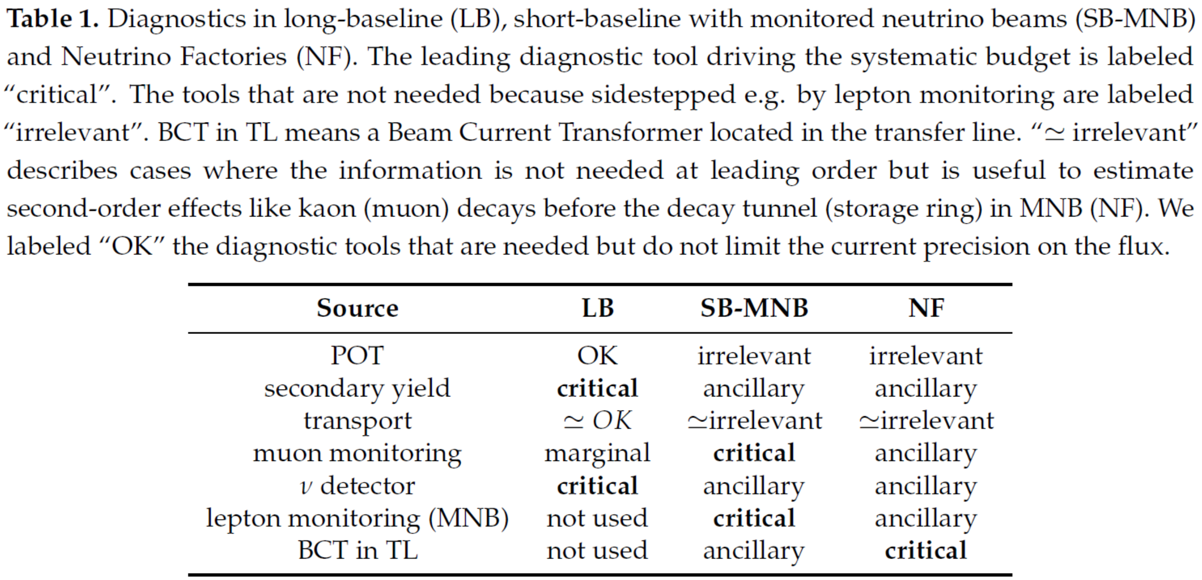


Table 1. Diagnostics in long-baseline (LB), short-baseline with monitored neutrino beams (SB-MNB) and Neutrino Factories (NF). The leading diagnostic tool driving the systematic budget is labeled "critical". The tools that are not needed because sidestepped e.g. by lepton monitoring are labeled "irrelevant". BCT in TL means a Beam Current Transformer located in the transfer line. "$\simeq$ irrelevant" describes cases where the information is not needed at leading order but is useful to estimate second-order effects like kaon (muon) decays before the decay tunnel (storage ring) in MNB (NF). We labeled "OK" the diagnostic tools that are needed but do not limit the current precision on the flux.

Source	LB	SB-MNB	NF
POT	OK	irrelevant	irrelevant
secondary yield	**critical**	ancillary	ancillary
transport	$\simeq$ *OK*	$\simeq$irrelevant	$\simeq$irrelevant
muon monitoring	marginal	**critical**	ancillary
ν detector	**critical**	ancillary	ancillary
lepton monitoring (MNB)	not used	**critical**	ancillary
BCT in TL	not used	ancillary	**critical**

N. Charitonidis , A. Longhin, M. Pari, E.G. Parozzi, F. Terranova submitted to Appl. Phys.

Input:

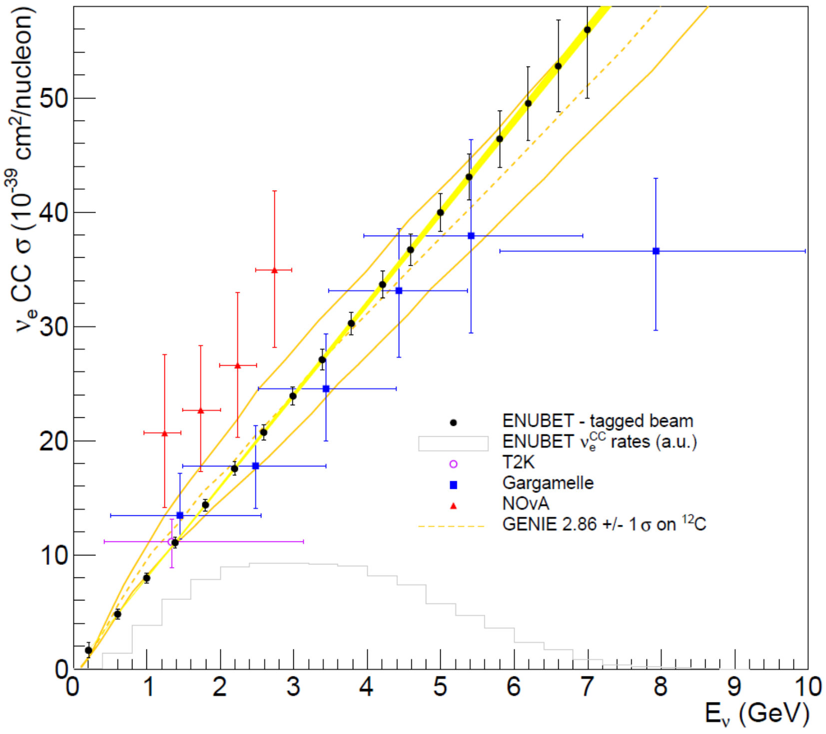
- GEANT4 simulation of beamline
- Hadroproduction data
- Beamline geometry and magnet currents
- Rate and kinematics of positrons
- Rate and kinematics of muons
- ν-e and low-ν events at the detector

Implementation:

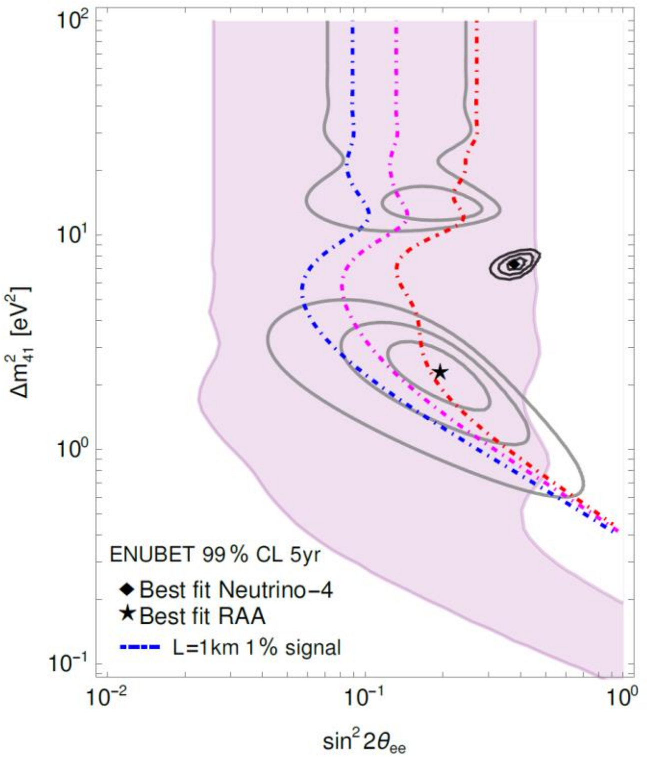
- The rates in the tunnel are used as constraints on the flux
- The vertex position in the detector is used to estimate E_ν
- Flux from minimization of the binned extended likelihood (see also M. Kordowsky, MINERvA-doc-7433)

WORK IN PROGRESS

Impact



Electron neutrino cross section



Sterile neutrinos

L. Delgadillo, P. Huber, arXiv:2010.10268

Others to be investigated in detail, yet

- Differential distributions in the 1-4 GeV range for ν_μ and ν_e with reduced bias from the knowledge of Eν
- DAR at the proton dump (beam dump physics at 400 GeV)
- **Tagged neutrino beams**

Conclusions and next steps

- **ENUBET is on schedule**: the design phase is over, the simulation are nearly completed, and we are going to build the final demonstrator
- The physics performance are extremely appealing, but we have to go through the complete study:
  - Update of flux and spectra with the final beamline
  - Establish the final systematic budget for ν_e and ν_μ: **in progress** using the same techniques currently employed by T2K/MINERvA. We **add the ENUBET observables as additional priors** to defeat the flux systematics. We use the information on the **initial energy** to reduce the systematics on cross section measurements
- The main tasks for 2021 are the construction of the **demonstrator** and the **full assessment of systematics**
- Beam-tests and machine studies are postponed to 2022 due to the COVID pandemics (the ERC Project will be extended by one year, too)
- We aim at the final **Conceptual Design Report** by 2022

We look forward to seeing ENUBET up and running
in the DUNE/HyperK era!