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A monitored neutrino beam at the European Spallation Source

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

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

We are no more in the 20th century: systematics do matter!

Next generation long-baseline experiments (DUNE, HyperK, ESSnuSB) conceived for precision ν-oscillation measurements:

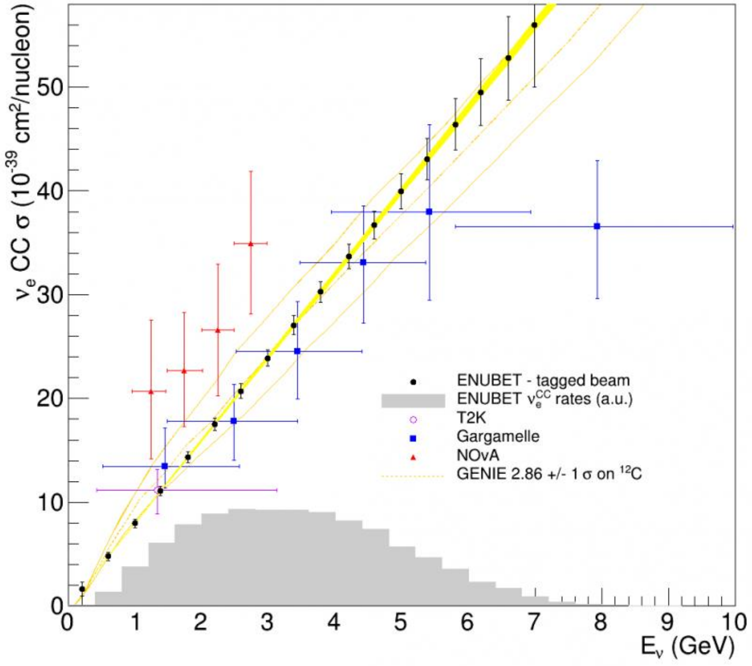
- test the 3-neutrino paradigm;
- determine the mass hierarchy;
- test CP asymmetry in the lepton sector;

$$N_{\nu_e}^{FAR} = P_{\nu_\mu \rightarrow \nu_e} \cdot \sigma_{\nu_e} \cdot \Phi_{\nu_\mu}^{FAR}$$

Very good knowledge needed!

Moreover ν-interaction models would benefit from improved precision on cross-sections measurements

ENUBET impact on σ_{ν_e}



The purpose of ENUBET: design a narrow-band neutrino beam to measure

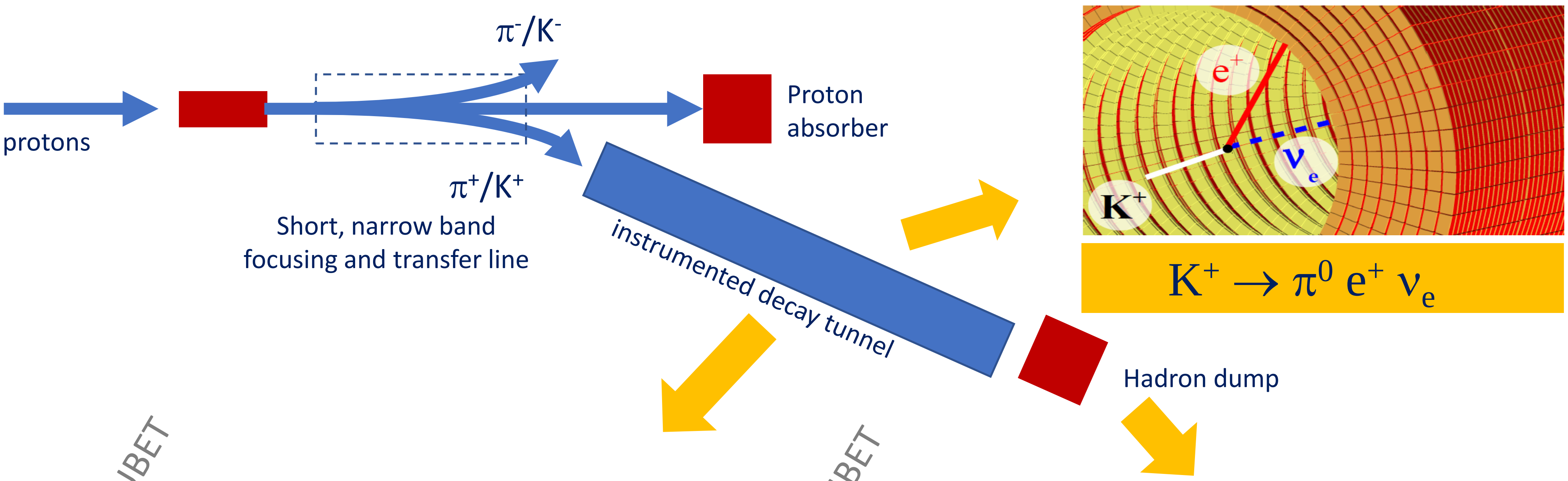
- neutrino cross-section and flavor composition at 1% precision level;
- neutrino energy at 10% precision level;

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.

Monitored neutrino beams (*)

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



NP06/ENUBET

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

$$K^+ \to \mu^+ \nu_\mu$$

NP06/ENUBET

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

$$\pi^+ \to \mu^+ \nu_\mu$$

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

“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)

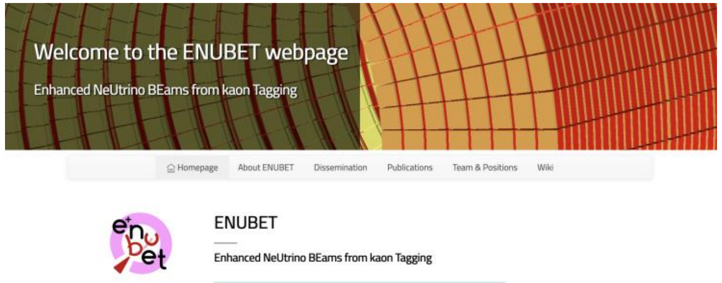
A bit of history

- First idea presented at Nufact2014 (Aug 20-25, 2014, Glasgow, UK)
- 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;

See C. Delogu @ NuFact22

The **ENUBET Collaboration**: 65 physicists & 13 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/



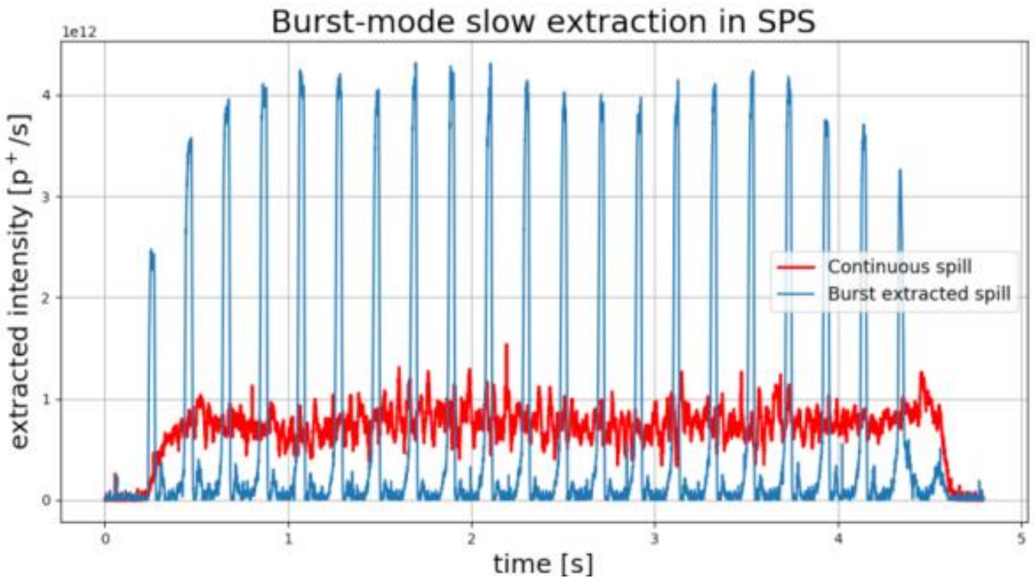
- **ERC project focused on**:
  measure positrons (instrumented decay tunnel) from K_{e3} $\Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**:
  extend measure to muons (instrumented decay tunnel) from $K_{\mu\nu}$ and (replacing hadron dump with range meter) $\pi_{\mu\nu}$ $\Longrightarrow$ determination of ν_μ flux; measure the neutrino energy a priori using the **narrow band off axis technique**

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")



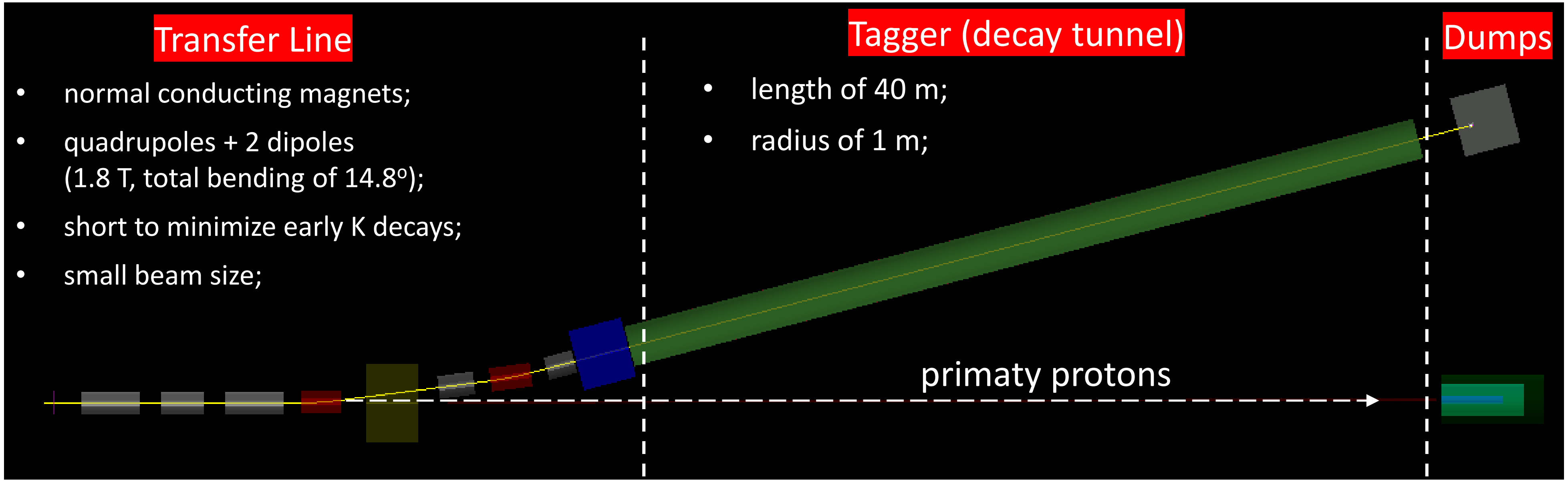
First demonstration of this proton extraction scheme in 2018 at CERN-SPS

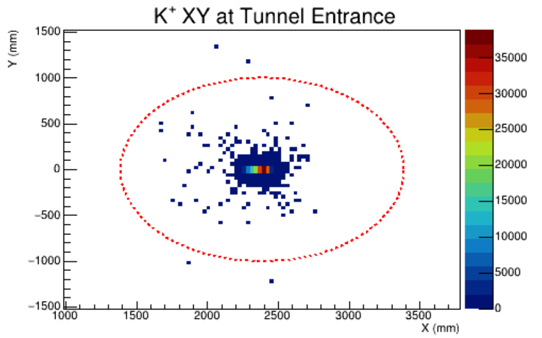
M. Pari, M. A Fraser et al, IPAC2019

2020 design ("static focusing system"): a neutrino beam **without a horn**, where focusing at 8.5 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: (details in E. Parozzi @ NuFact22)





Rates @ Tunnel entrance for 400 GeV POT	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.13	0.34

~1.5X w.r.t. previous results

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;

Dumps:

- **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;

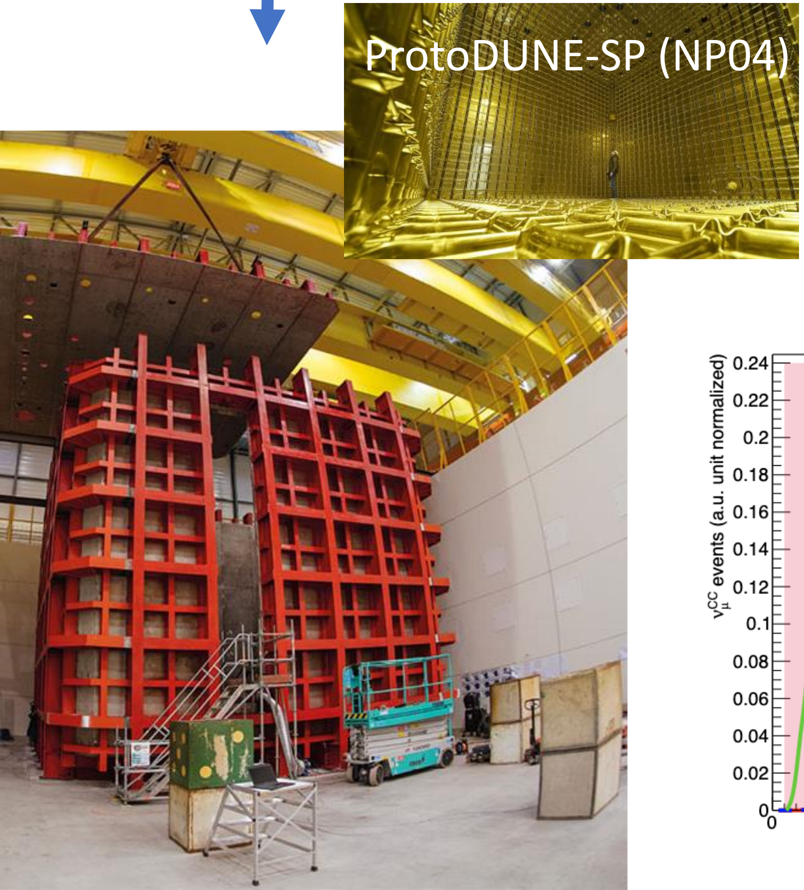
Full facility implemented in GEANT4:
- Controll over all paramaters;
- Access to the paricles histories;

assessment of the nu flux systematics

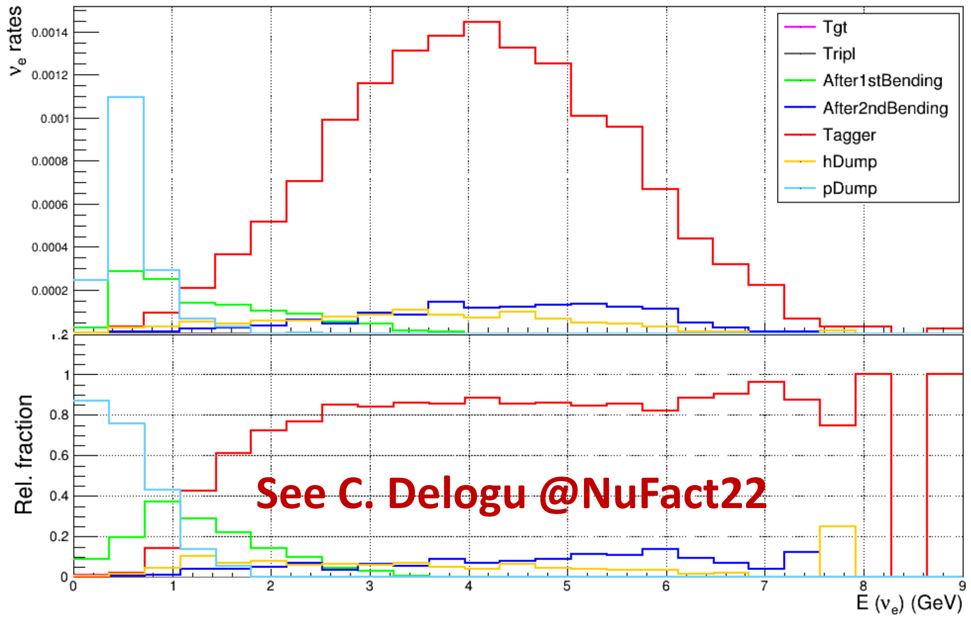
ENUBET as a “high-energy” (1-3 GeV) monitored neutrino beam

A total ν_e^{CC} statistics of 10^4 events in ~3 years

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

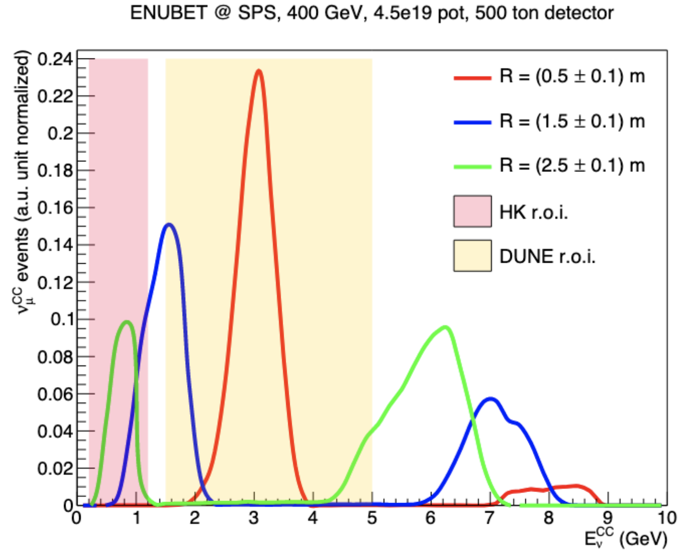


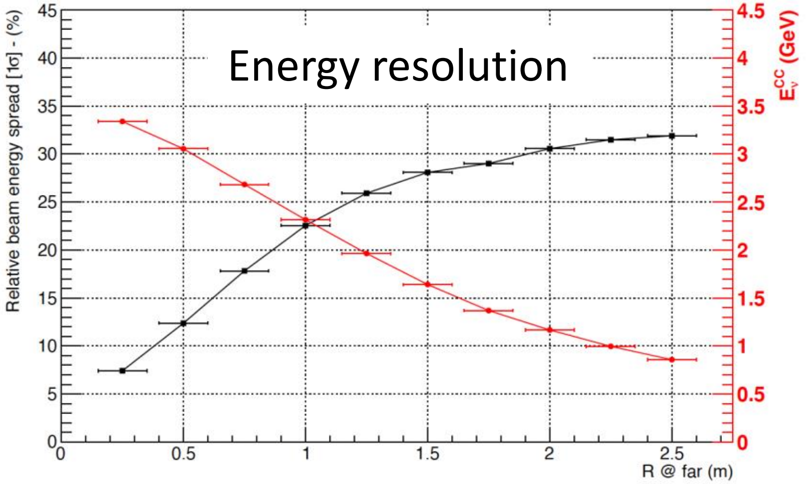
ν_e CC spectra



See C. Delogu @NuFact22

ν_μ CC spectra



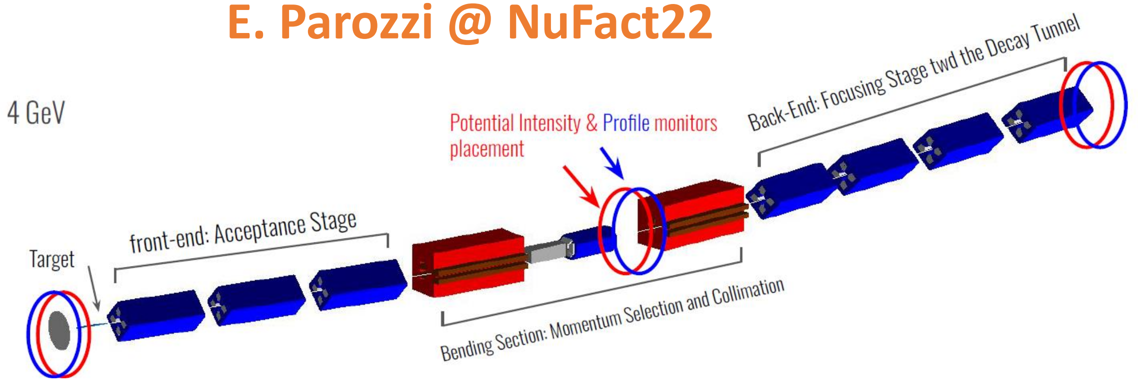


A "low-energy" (<1 GeV) monitored neutrino beam

Multi-momentum beamline @ CERN

A CERN-based beamline with multiple runs at 4,6,8 GeV/c secondary momenta: increase the statistics in the region of interest of HyperK. ν_μ from pion decay (high statistics), ne from kaon decay (low statistics)

E. Parozzi @ NuFact22

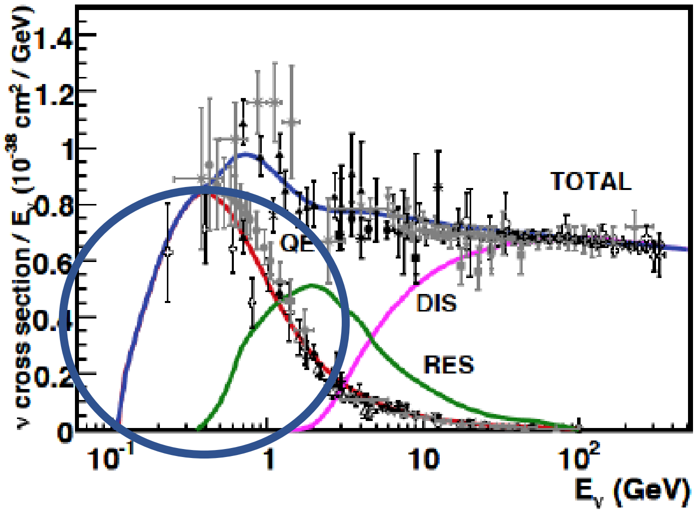


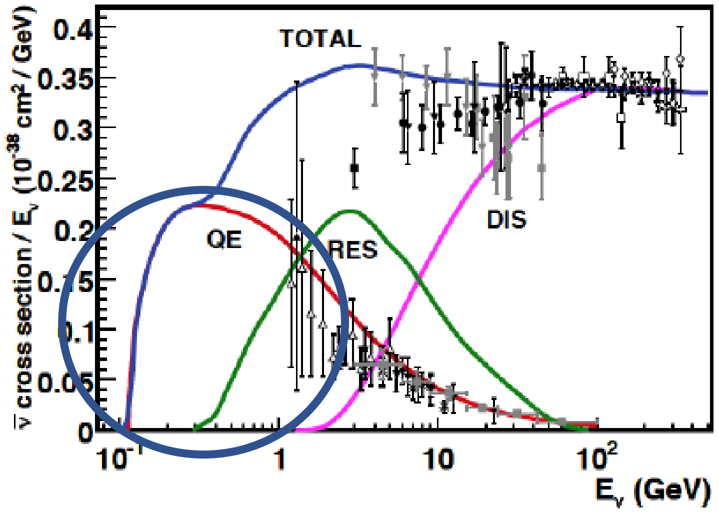
A monitored neutrino beam at ESS (ESSnuSB+)

Address specifically the region below 1 GeV

- ν_μ from pion decay ($\pi \rightarrow \mu\ \nu_\mu$)
- ν_e from decay in flight of muons

$$\pi \rightarrow \mu\ \nu_\mu \rightarrow\ e\ \nu_\mu\ \nu_e\ \overline{\nu}_\mu$$





Can we build a monitored neutrino beam (without relying on kaons) at the European Spallation Source?
Let's call it **MNB@ESS** (but we have to find a cooler name ☺)

Opportunities at the ESS

Construction phase of ESSnuSB

- A high power linac with 3 ms proton pulses at 2 GeV. Max intensity 4 MW; needed intensity for cross section measurements O(500 kW)
- The ESSnuSB near detector and/or dedicated moderate mass (500 t) detectors. **Top priority: water target**. Additional opportunity: the NUSTORM detector. More aggressive option: liquid deuteron or hydrogen (!)
- A transfer line that operates when the accumulator is under construction

In ESSnuSB+ we want to focus on the construction phase!

Operation phase of ESSnuSB

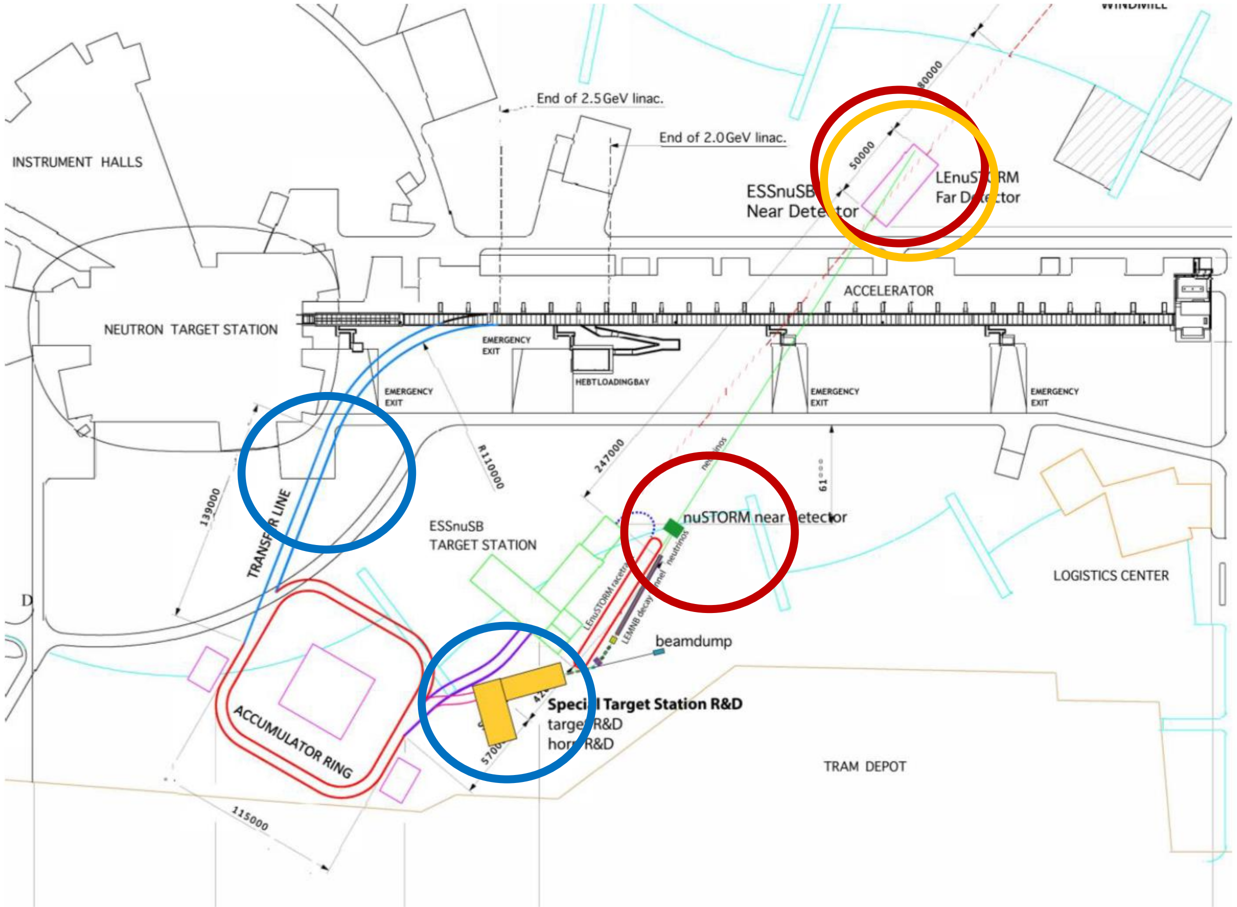
A high power linac with 3 ms proton pulses at 2 GeV + the accumulator. MNB@ESS cannot operate with a μs beam and we do not want to employ the accumulator:

- The accumulator can be used as a transfer line for the linac bunches devoted to MNB@ESS
- More aggressive: we can use the accumulator as a debuncher to have a long (enubet-like) extraction and further reduce pile up (at the expenses of cosmic background)

In ESSnuSB+ we can assess this option only once the previous job is done

The Work Package 6 of ESSnuSB+

Participants: Unimib (Milano, Italy), INFN (Padova, Italy), RBI (Zagreb, Croatia), NCSRD (Athens, Greece), AUTH (Thessaloniki, Greece)
External support: from the ENUBET Collaboration on the re-optimization of the horn-less beamline



Synergy with other WPs

- WP3: Target station [target, transfer line]
- WP4: Low energy nustorm [target area, detector]
- WP5: Detector and physics performance [use of cross section, near detector]

Goals of WP6 (I)

What is the intensity needed to achieve a 1% precision in the 200-600 MeV range?
The pion yield is only approximately constant with power as a function of energy. At 2 GeV the flux losses is large (factor of 2 compared with ENUBET) and the focusing efficiency of the horn-less beam further reduces the number of neutrinos. Similarly, the nu CC rate decreases due to the energy of the incoming neutrino

Starting expectation:
We expect a needed power of the order of 500 kW – 1 MW (10-20% of the available power) to reach this precision for ν_e CC in 5 years of data taking with the ESSnuSB near detector. On the contrary, we can achieve the same precision on ν_μ in 1 year with 100 kW. But there are large uncertainties there to be settled during ESSnuSB+

What is the optimal beamline design
The muon production angle is large and we can instrument a relatively short tunnel: cheaper than ENUBET@CERN. However, we need to optimize the instrumentation and tunnel geometry to reap the decays in flight of muons, which has not been addressed in ENUBET

Starting expectation:
For secondaries in the 1-2 GeV range, a 30 m instrumented tunnel plus an instrumented beam dump is likely the optimal choice.

Goals of WP6 (II)

Do we need a dedicated target station?
MNB@ESS is a horn-less beam while NUSTORM requires a horn partially embedding the target. The ESSnuSB target station is even more complex (4 targets fully embedded in horns).

Starting expectation:
MNB@ESS requires a <1 MW target station but we don’t know yet if it deserves a dedicated station.

Can we operate with a 3 ms proton extraction?
ENUBET@CERN uses a 2s long extraction but has been designed also for a 2-10 ms pulsed horn.

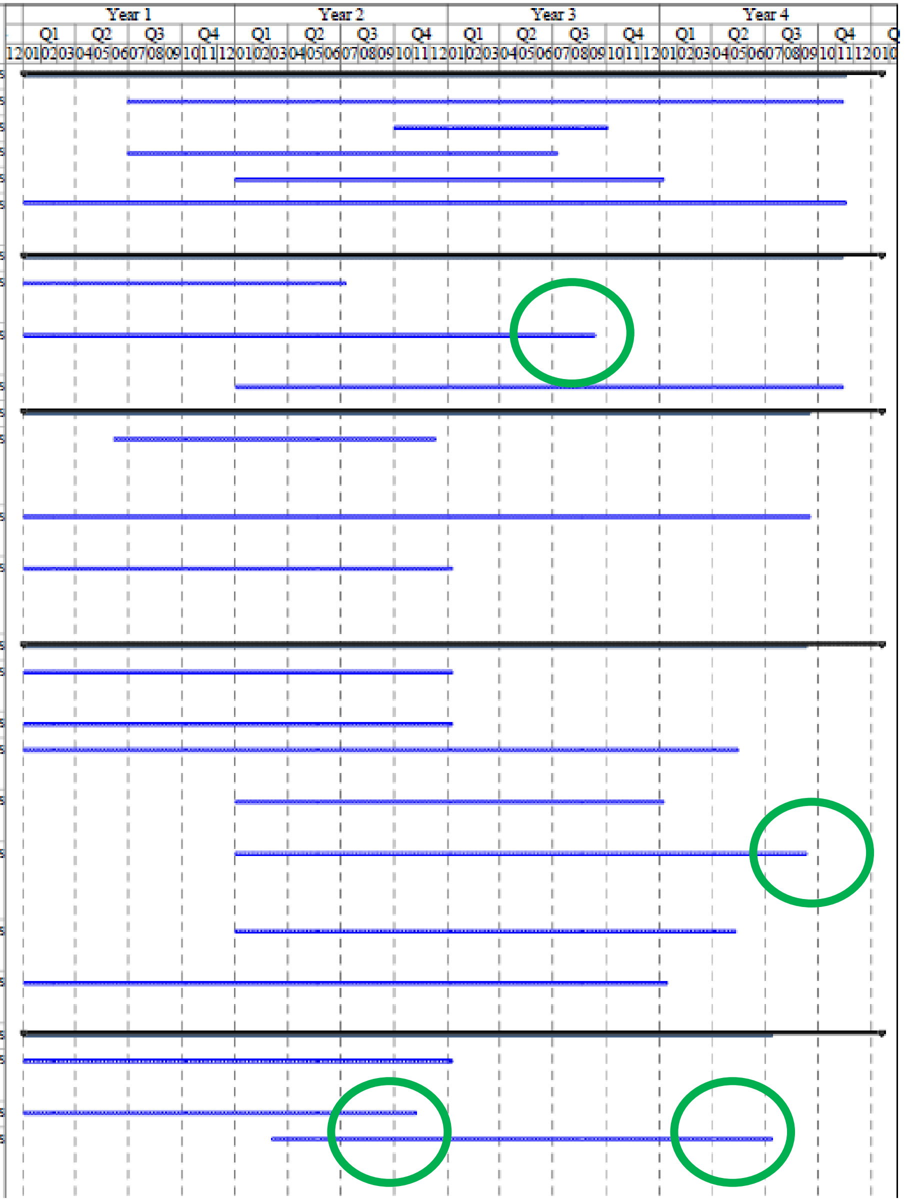
Starting expectation:
Pile up is not an issue for muons. It deserves a dedicated study for positrons, which depends on the beamline background

Design of the beamline and instrumentation
We have a large experience thanks to ENUBET, including tools for optics, tertiary interactions, doses and irradiation, particle identification, and reconstructed algorithm

Starting expectation:
We do not envision major issues except for the aforementioned focusing efficiency (which impact on integrated power and, hence, doses)

Planning our activities

ID	Task Name	Resource Names	Duration
1	**Engineering/Infrastructures**		48 mons
2	Mechanical conceptual design	ESS	40 mons
3	Machine conceptual design	ESS	12 mons
4	ESS site conceptual design in CAD	ESS	24 mons
5	Time estimation for ESS site	ESS	24 mons
6	Civil engineering study for far detector site	LTU	46 mons
7	**Target Station**		48 mons
8	Adapt the ESSnuSB target station to pion production requirements	CNRS;UHH;UNISTRA	18 mons
9	Investigate pion extraction and initial focusing system	UHH;UNISTRA;CNRS;CERN	32 mons
10	Target station facility	CNRS;UHH;UNISTRA;ESSB	34 mons
11	**LEnuSTORM**		48 mons
12	Design an extraction line from the ring-to-target transfer line and a transfer line up to the fifth target station	CNRS;ESS	18 mons
13	Conceptual design of the racetrack ring for LEnuSTORM	ESSB;CERN;ESS;UU	44 mons
14	Study the compatibility of LEnuSTORM and ESSnuSB and modify the original design accordingly	CERN;ESS;UU;ESSB	24 mons
15	**Detectors and physics reach**		48 mons
16	Set up full MC simulation chain for far detector	AUTH;NCSRD;RBI;CU	24 mons
17	Near detector MC simulation chain	UniSofia;CU;RBI;NU	24 mons
18	Design and optimisation of the near detector for LEnuSTORM and LEMNB	RBI;AUTH;NCSRD;UniSofia	40 mons
19	Sensitivity of the far detector to non-beam physics	UNIROMA3;RBI;KTH	24 mons
20	Sensitivity study of LEnuSTORM and LEMNB to sterile neutrinos and other new physics	KTH;RBI;UNIROMA3	32 mons
21	Determination of expected precision of neutrino cross-section measurement	AUTH;NCSRD;RBI;UniSofia;NU	28 mons
22	Event analysis for the Water Cherenkov detector using machine learning methods	ULUND;UU	36 mons
23	**Monitored neutrino beam**		48 mons
24	Design of the transfer line and focusing system	INFN;UNIMIB	24 mons
25	Optimization of the physics performance	RBI;AUTH;INFN;UNIMIB	22 mons
26	Flux systematics benefiting from the reconstructed lepton rate in the decay tunnel	UNIMIB;RBI;INFN;AUTH	28 mons



Assessing showstoppers:
Mid 2024 [fluxes and rates]

Design of infrastructures and running mode compatible with ESSnuSB:
Mid 2025 [transfer line, target station, beam economics]

Physics performance:
Fall 2026 [cross section precision, near detector optimization]

Is a Monitored Neutrino beam an asset for ESS?

- Provides a strong physics programme in the construction phase of ESSnuSB
- It offers an unprecedented opportunity to study electroweak nuclear physics in the region of interest of ESSnuSB and HyperKamiokande, including long-baseline systematic reduction
- It is a smart way to use the most powerful linac in Europe for particle physics during the running of DUNE and HyperKamiokande
- It sets on a solid ground the systematic reduction programme of ESSnuSB

But we still need to address prominent items like:

- Flux and rates with a 2 GeV primary beam
- Energy reconstruction with the ENUBET narrow-band off-axis technique (not studied yet)
- Compatibility with the run of ESSnuSB
- Pros and cons with respect to LENUSTORM: we don't know yet if we will have to downselect or if we can envisage MNB@ESS for the construction phase and LEnuSTORM for the running phase

As usual, new opportunities requires new studies and ESSnuSB+ is the best environment to carry them out