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).

ENUBET

A novel neutrino beam for a new generation of cross-section experiments

G. Brunetti(*) on behalf of the NP06/ENUBET Collaboration

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

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

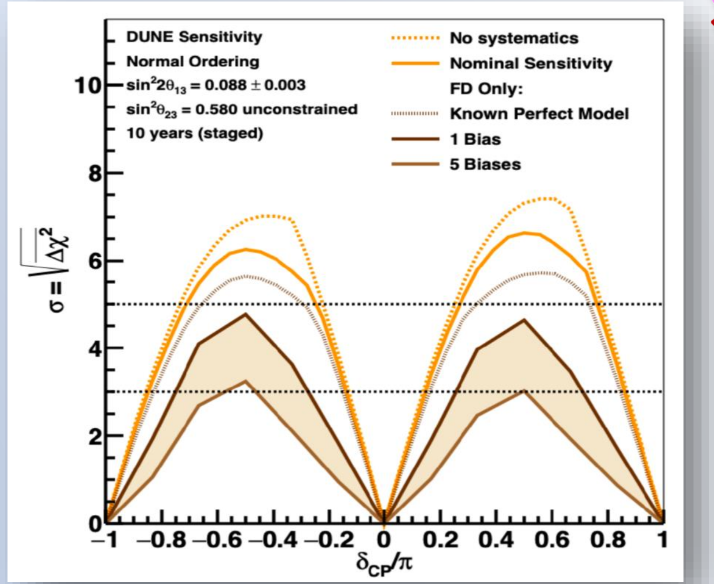
https://www.pd.infn.it/eng/enubet/

The rationale of ENUBET

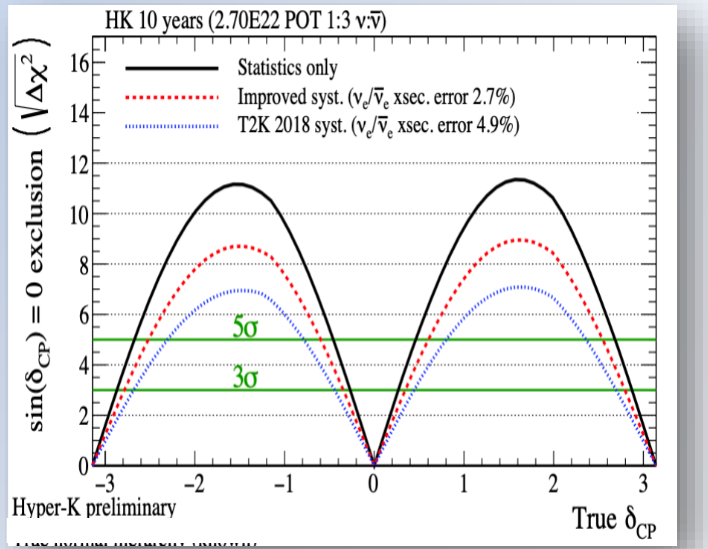
The knowledge of neutrino cross-section is stuck at 10-30 % level and the needs of the neutrino community are at 1% level because:

- 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 approaches still provide results with >50% discrepancies → Nuclear Physics

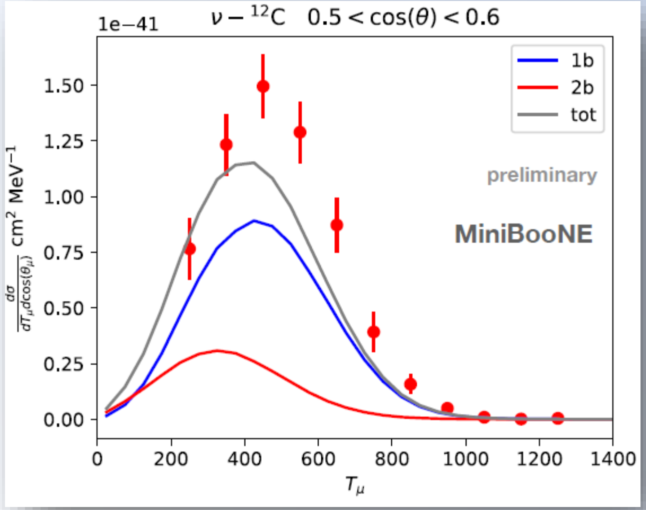
DUNE



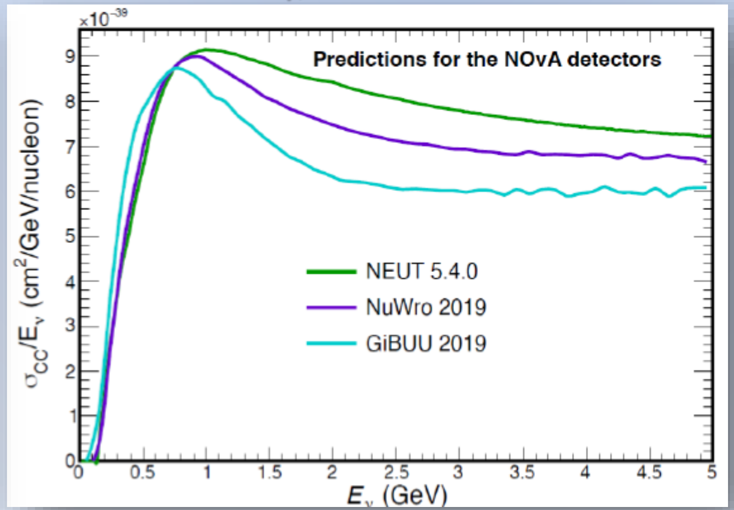
HyperKamiokande



N. Rocco, Nufact2022



J. Paley, Nufact2022



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

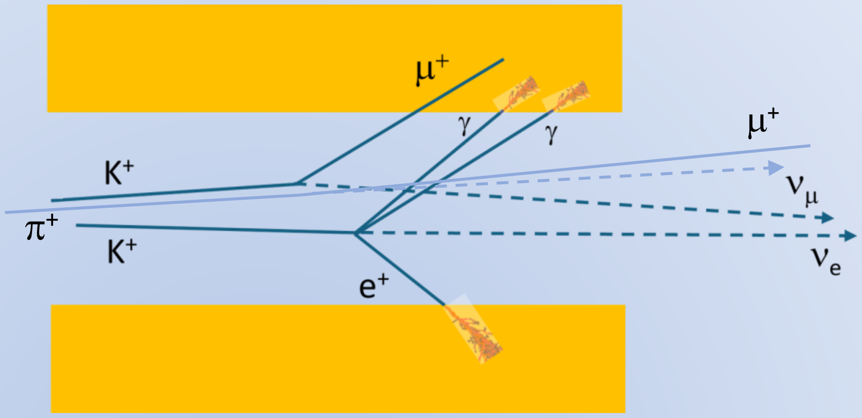
- Measure the neutrino flux of a short-baseline beam devoted to cross-section measurements with a precision <1% in ν_e and ν_μ. **Flux is the dominant systematics. Generally known at 10% level**.
  - Spoiler(*): Monitored neutrino beams are beams with unprecedented control of the neutrino flux and offer precision on the flux of <1%
- Measure the **energy** of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Spoiler(*): 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", NBOA) is used by ENUBET and SBND (inspired by PRISM) and offers O(10%) precision
  - If we can time-tag a fraction of the ENUBET ν_μ we can achieve an energy resolution of O(1%) for such a subsample: a golden sample for ν_μ scattering studies.
- Use the same **target** as DUNE and HyperK + low Z target (existing or new experiments)
  - Spoiler: ENUBET at CERN would enable using the two ProtoDUNEs and WCTE as neutrino detectors with ideal targets (water, liquid argon).

(*) F. Acerbi et al. [ENUBET Coll] Eur. Phys. J C 83 (2023) 964

ENUBET is a "monitored neutrino beam"

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

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



Due to the huge particle flux in the tunnel, ENUBET posed tremendous technical challenges that were solved in 2016 – 2023 by the NP06/ENUBET Collaboration at CERN

Thanks to this success, ENUBET is being investigated in the framework of Physics Beyond Collider for possible implementation at CERN

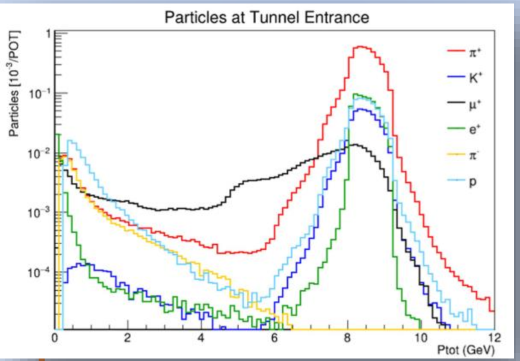
Collaboration: 74 physicists & 17 institutions; Spokespersons: A. Longhin, F. Terranova; Technical Coordinator: V. Mascagna

Technical challenges and their solutions

To measure cross sections with high statistics, we need a **medium-power short-baseline beam**, whose particle rate at the decay tunnel may exceed the capabilities of any (low-cost) detector installed in the tunnel.

- Particle rate at the tunnel: reduced below 100 kHz/cm^2 using a **hornless beam** with a slow proton extraction
- Radiation doses at the tunnel detectors well below 10 Gy and 10^{11} n/cm^2 using appropriate shielding
- Detector technology: low-cost iron-scintillator sampling calorimeters

Proof-of-principle: ENUBET has delivered an end-to-end simulation of the facility optimized for the energy range of DUNE and built a full-scale demonstrator of the decay tunnel instrumentation

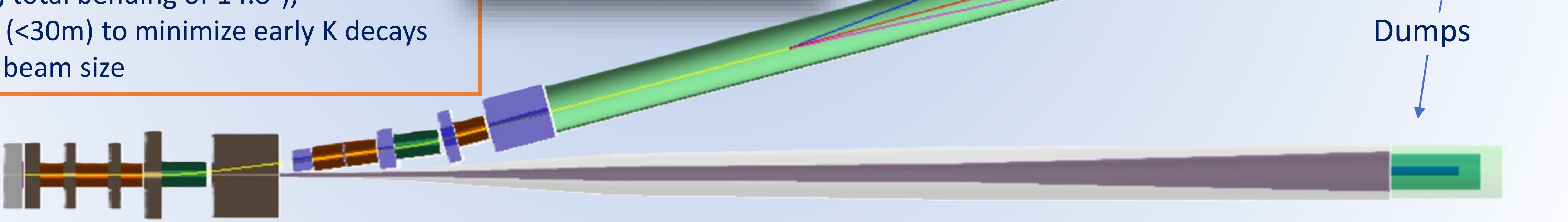


Tagger (decay tunnel)

- Length = 40 m
- Radius = 1 m

Transfer Line

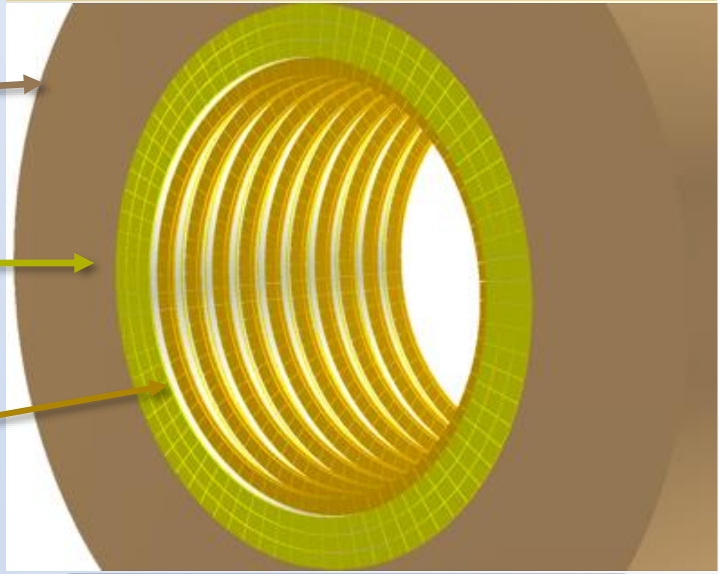
- normal conducting magnets
- quadrupoles + 2 dipoles (1.8 T, total bending of 14.8°);
- Short (<30m) to minimize early K decays
- small beam size



Proton driver: CERN SPS, 400 GeV protons

Tunnel instrumentation

Layout of the instrumented tunnel



Shielding

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

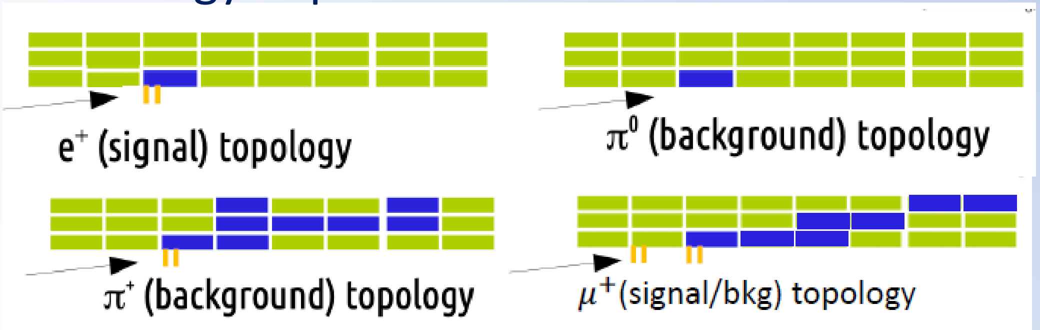
Calorimeter with $e/\pi/\mu$ separation capabilities:

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

Photon-Veto allows π^0 rejection and timing:

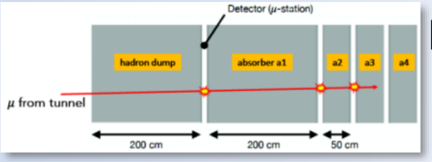
- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of ~400 ps

Particle identification based on the pattern of energy deposit in the calorimeter modules



The ENUBET demonstrator

+ hadron dump instrumentation



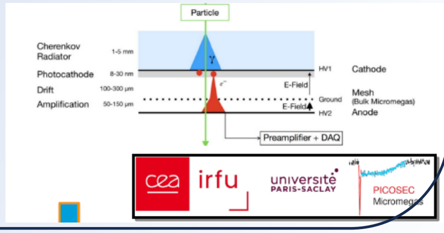
Muon stations

μ from π decays

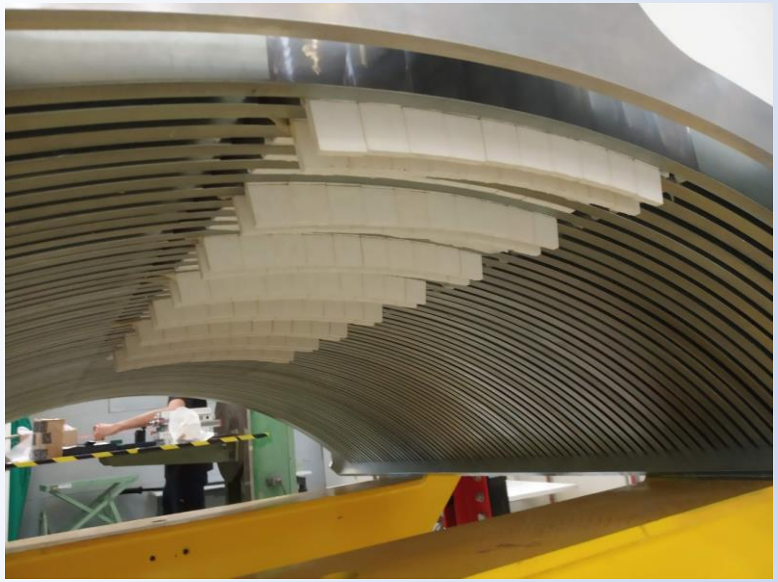
PIMENT

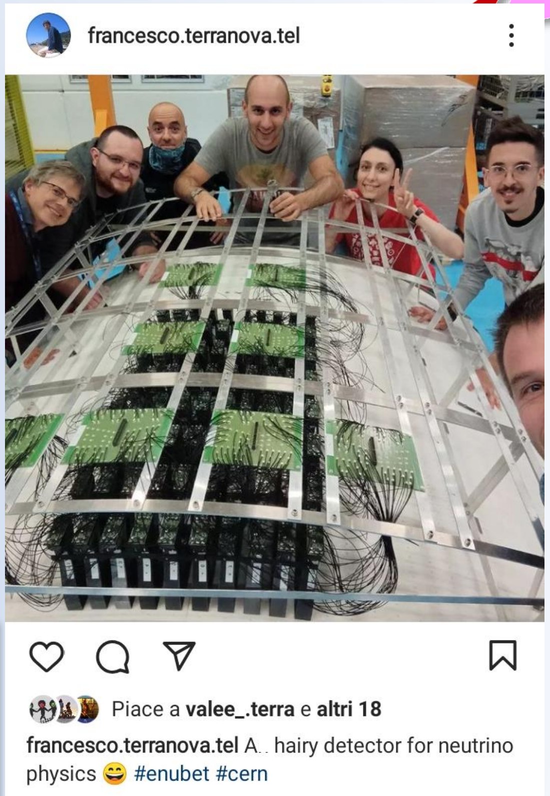
PIcosec Micromegas Detector for ENnubeT

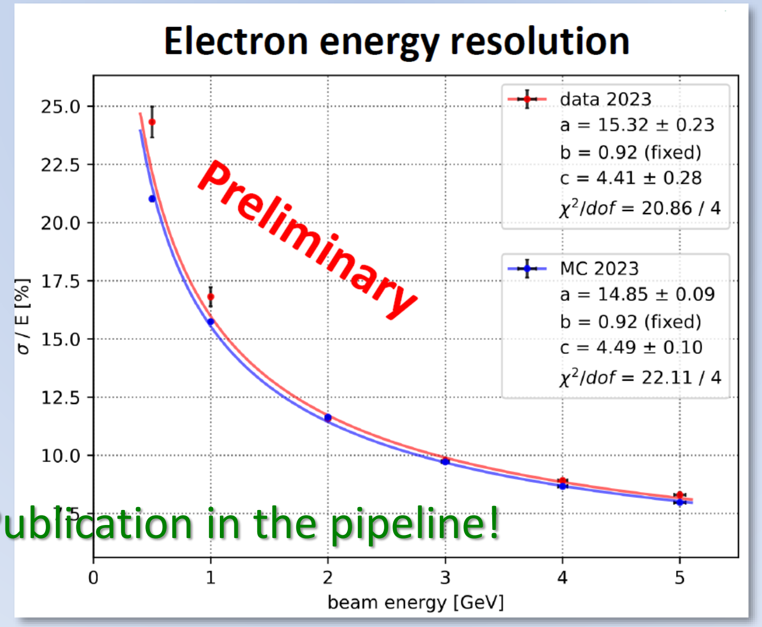
Fast Micromegas detectors employing Cherenkov radiators + thin drift gap with sub-25 ps precision



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







Publication in the pipeline!

See
Poster #61
by L. Halić

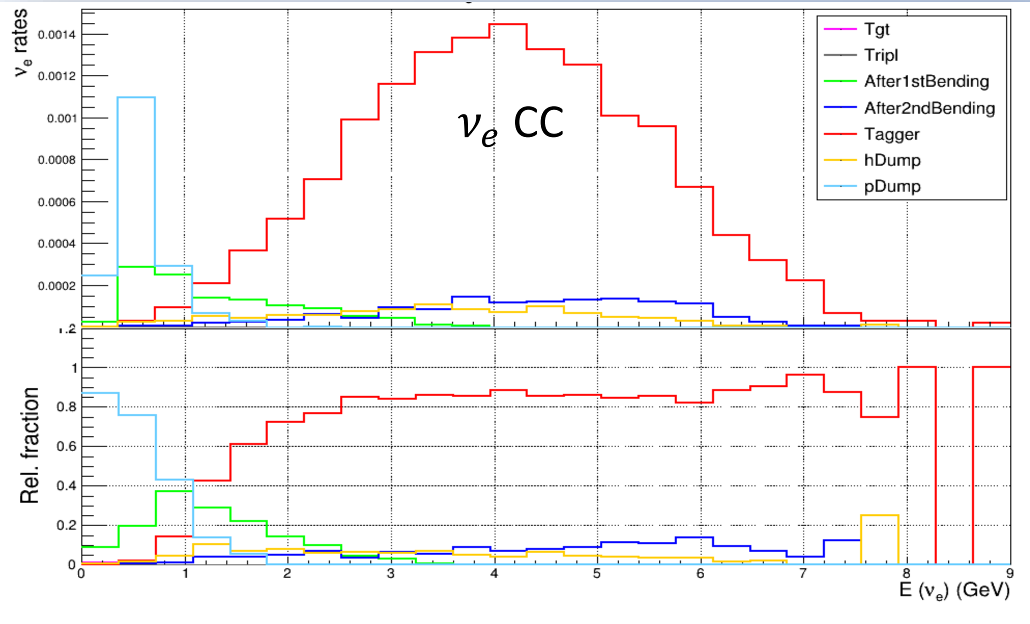
Beam design and performance

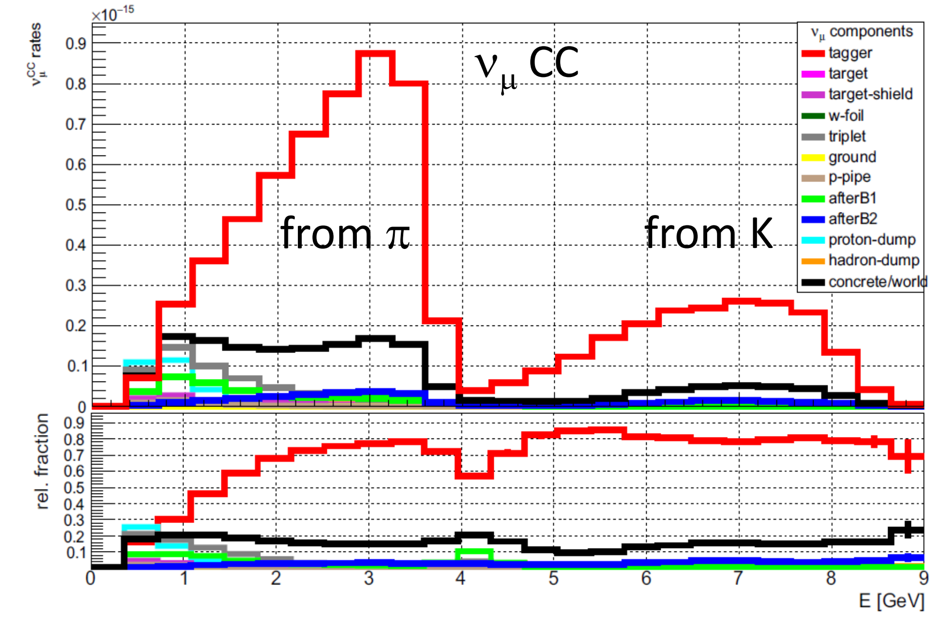
Proton driver: CERN SPS, 400 GeV protons. Up to 4.5 10^{19} pot/y, 2s long extraction

Baseline: a 500 ton detector located 50 m after the end of the tunnel (6x6 m^2 detector surface)

Statistics: 4350 ν_e CC/year, 9.1 10^4 ν_μ CC/year ($K_{\mu2}$) and **22.5 10^4 ν_μ CC/year ($\pi_{\mu\nu}$)** @ 4.5 10^{19} pot/y

Rates @ Tunnel entrance for 400 GeV POT within the momentum bite (10%)	
π^+ $[10^{-3}]$/POT	K^+ $[10^{-3}]$/POT
4.6	0.4





Achieving such performance with a horn-less beam has been the breakthrough that made monitored neutrino beams a mature technology

See EPJ C 83 (2023) 964

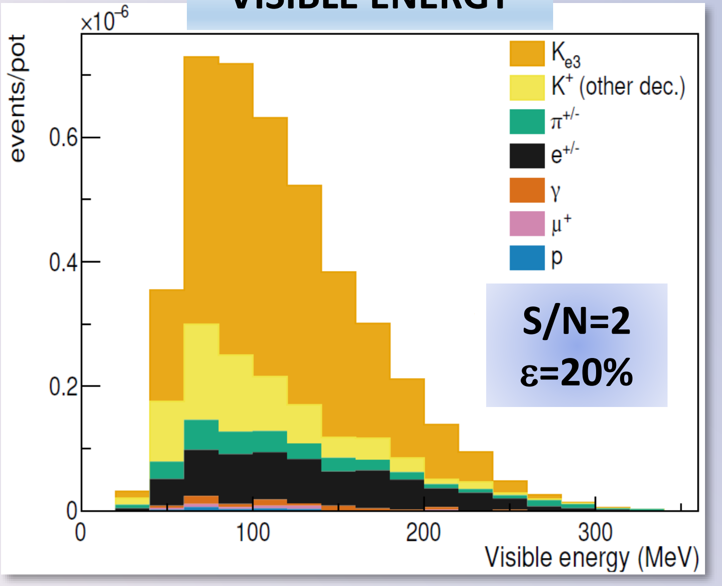
Lepton reconstruction in the decay tunnel

Full GEANT4 simulation of the detector: validated by prototype tests at CERN in 2016-2018; hit-level detector response; pile-up effects (waveform treatment in progress) included; event building and PID algorithms;

- 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

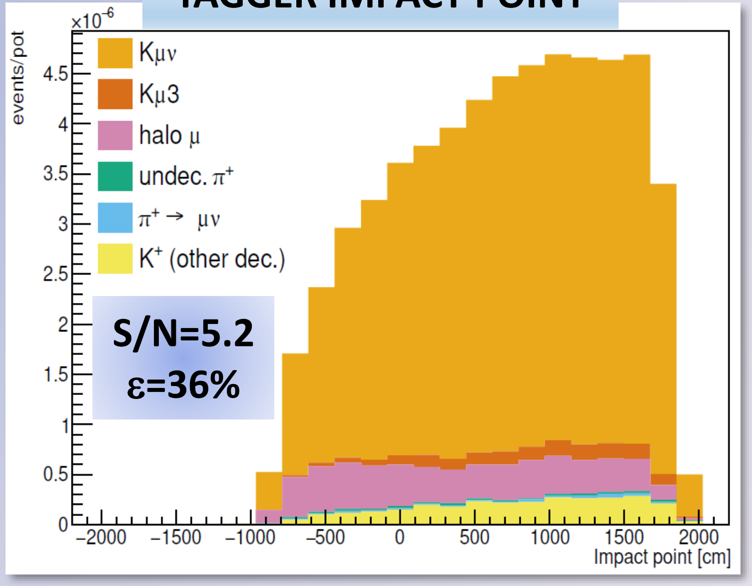
VISIBLE ENERGY



Efficiency ~half geometrical

$K_{\mu 2}$ muons → constrain ν_μ

TAGGER IMPACT POINT



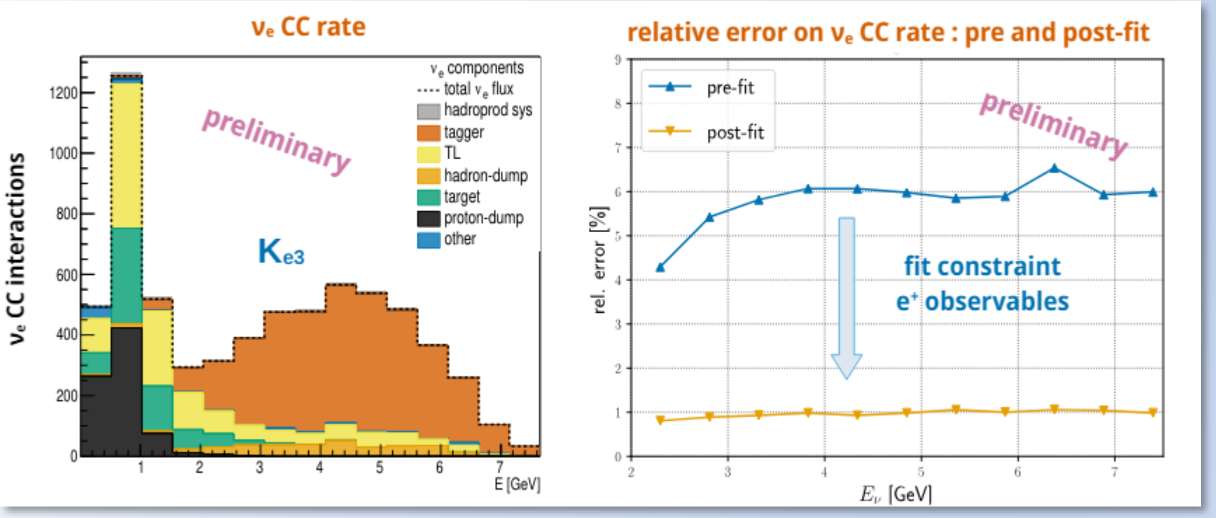
Efficiency ~half geometrical

See EPJ C 83 (2023) 964

Precision on the neutrino flux determination

To establish the flux precision, we performed the same systematic assessment analysis performed by experiments like Minerva or T2K. In particular:

- We considered the **dominant systematics** (hadroproduction) extracted from hadroproduction experiments at the SPS (NA56/SPY), which gives a 6% uncertainty on flux
- We added as an additional prior the rate, position and energy distributions of **positrons from kaon decay reconstructed in the tunnel**



The flux uncertainty for ν_μ and ν_e **drops from 6% to 1%** using positrons only

Further improvements are expected by adding the reconstructed muons

See **Poster #13** by F. Bramati

- In progress: add subdominant systematics (detector effects, magnet current, beam component material budget uncertainty, and exploit the additional constraints from reconstructed muons (paper in preparation)

Neutrino energy measured “a priori” for ν_μ^{CC}

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

(E_ν,R) are strongly correlated

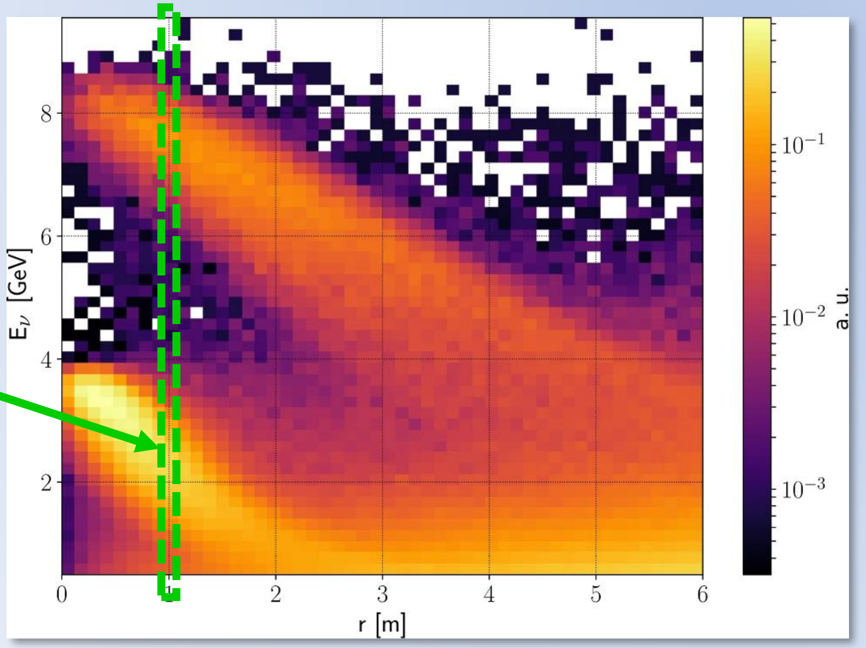
E_ν = neutrino energy;

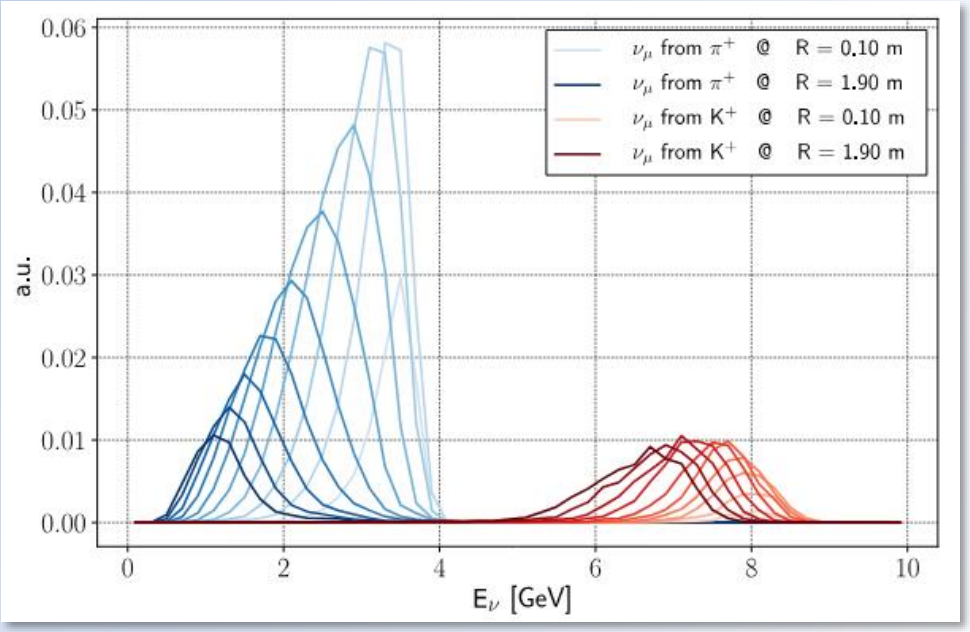
R = radial distance of interaction vertex from beam axis;

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

Select ν with given energy with a cut on R





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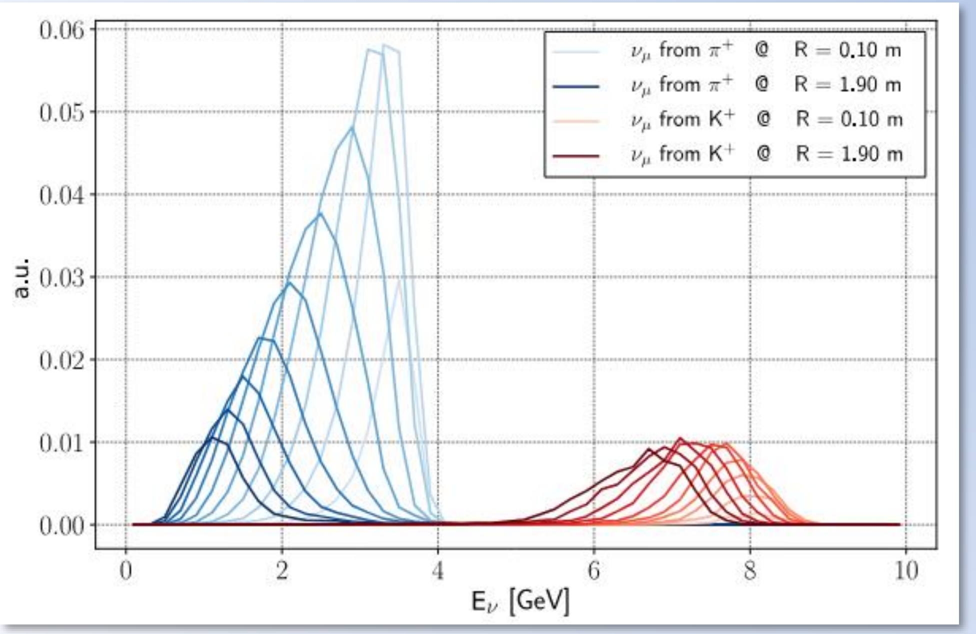
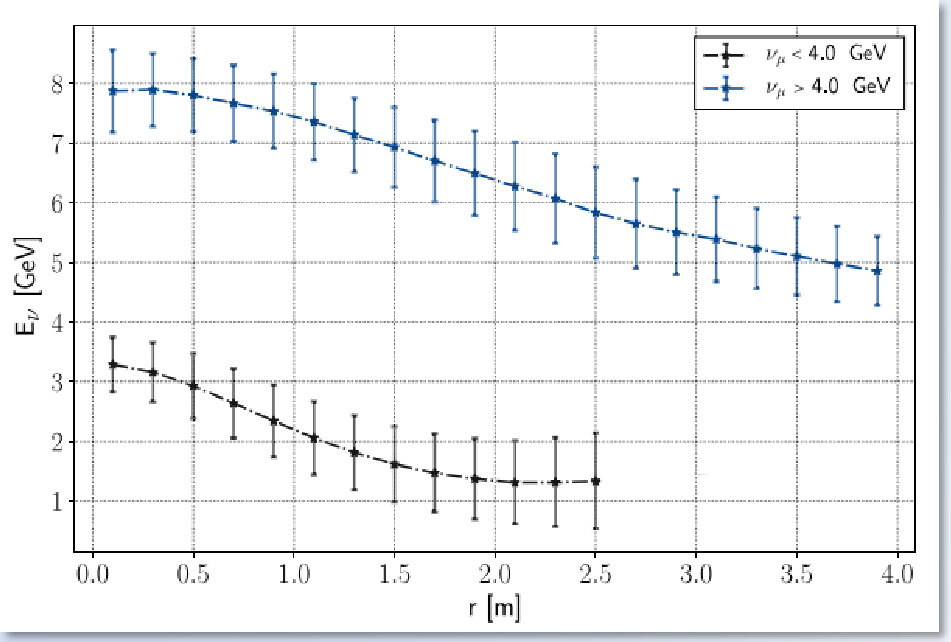




Toward an experiment proposal: the way beyond ENUBET

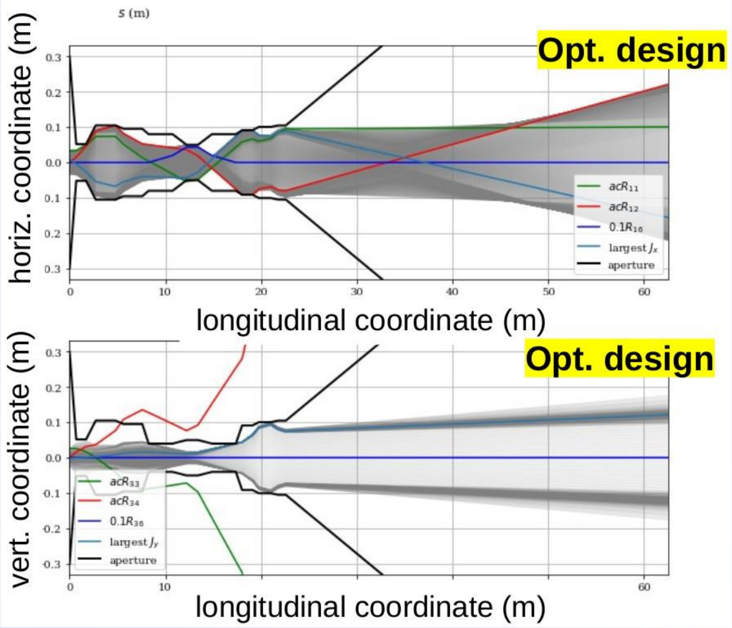
The current ENUBET design has three limitations:

- The facility is optimized for DUNE but we want to cover the energy range of HyperKamiokande, as well
- The number of protons-on-target (pot) is too large if we want to run ENUBET at CERN in parallel with SHiP
- We want to further improve the energy resolution, especially below 2 GeV (HyperKamiokande)

This proposal – called **"short-baseline neutrinos @ Physics Beyond Collider" (SBN@PBC)** is currently under study by CERN, ENUBET, NuTAG, and the CERN Neutrino Platform to address these limitations and provide a solid foundation for the next generation of cross-section experiments.

First results from SBN@PBC have been presented at the PBC Annual Meeting in March 2024 and demonstrate that an optimized ENUBET beamline that runs also at lower secondary momenta, (8.5-4 GeV):

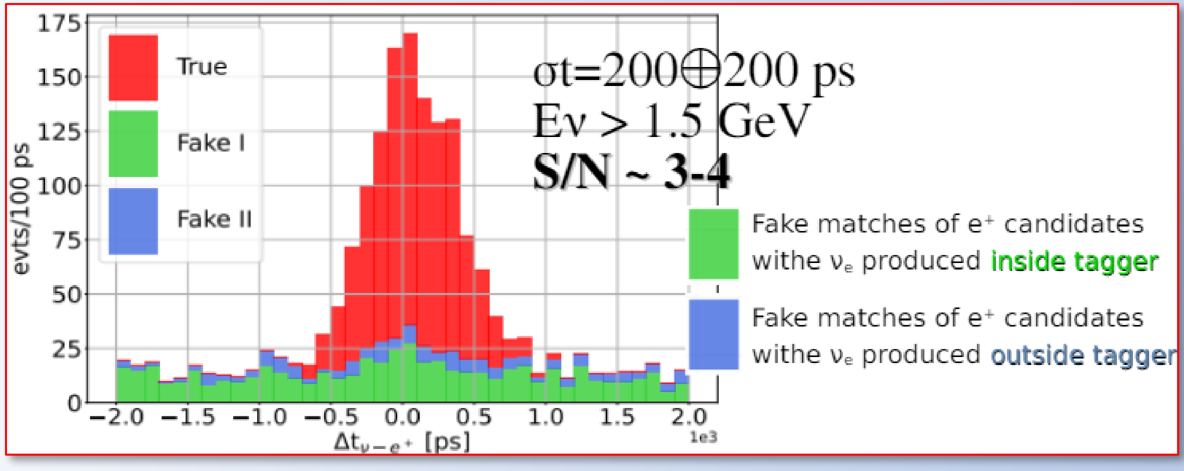
- can achieve the ENUBET performance with 1/3 of the protons-on-target (pot) needed in the original design
- can collect large statistics in the 1-2 GeV energy range for ν_μ CC events
- has the potential to exploit time-tagging to enhance the neutrino energy resolution of ENUBET (see below)

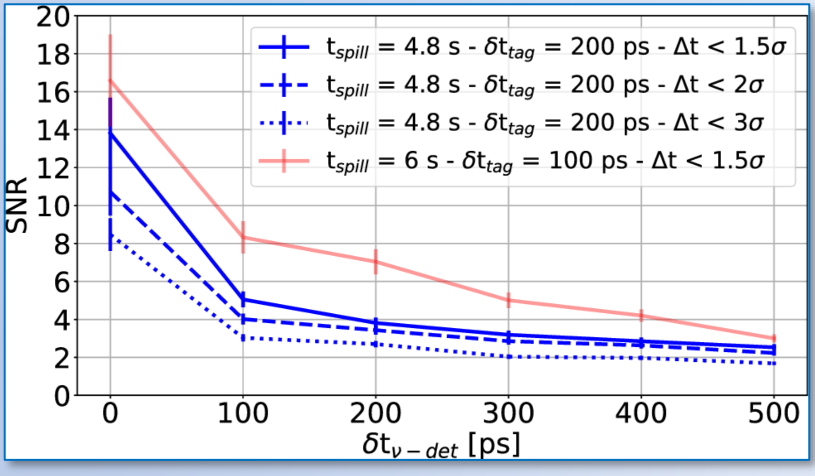


See **Poster #423** by M. A. Jebramcik

Time tagging

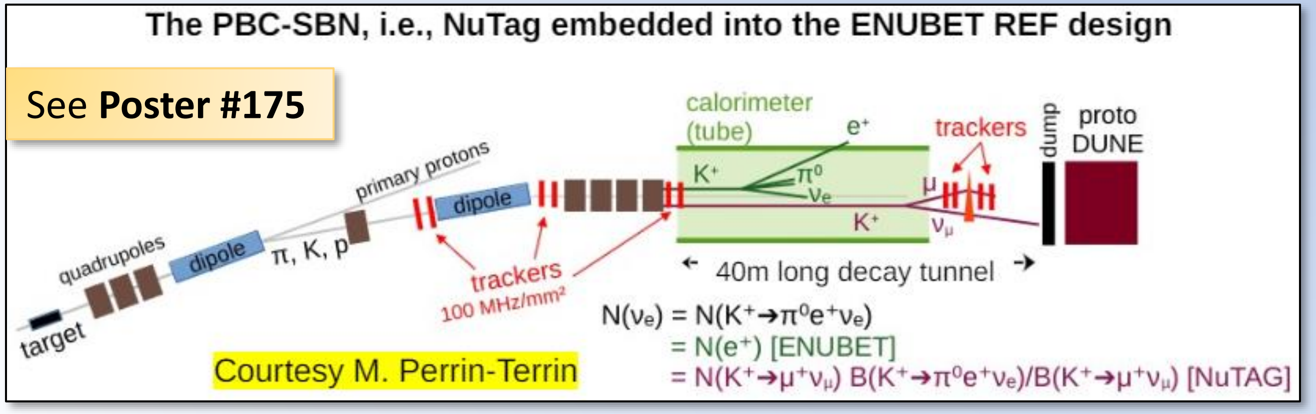
A monitored neutrino beam "counts" the charged leptons in the tunnel. In principle, we can also exploit the **time coincidence between the neutrino observed in the neutrino detector (e.g. ProtoDUNE or WCTE) and the charged lepton observed in the tunnel**. It transforms ENUBET into a **tagged neutrino beam**.





Signal to noise ratio of tagged ν_e-e^+ pairs **as a function of the neutrino detector time resolution**

F. Acerbi et al. [ENUBET Coll] Eur. Phys. J C 83 (2023) 964



We can do much better exploiting the NuTAG concept, i.e. adding silicon trackers in the beamline to tag the neutrino parent. **Expected neutrino energy resolution: 1%**

A. Baratto-Roldan et al. arXiv: 2401.17068 (in press)

Conclusions and steps forward

The concept of "monitored neutrino beam" is no longer an "interesting idea". It is a mature technology, which has been demonstrated by NP06/ENUBET in a six-year R&D. In particular:

- **We can measure the charged leptons in a decay tunnel using a horn-less beam** optimized for the energy range of DUNE (ENUBET), DUNE+HyperKamiokande (SBN@PBC)
  - A monitored neutrino beam @ the ESS: ESSnuSB (see talk by T. Tolba, 18/06)
- The ENUBET design is complete and fulfills all requirements for a new generation of cross-section experiments
  - **Statistical error <1% with a 500-ton detector**
  - **Systematic uncertainty on the flux <1%**
  - **A priori measurement of the neutrino energy with a precision of 10-25%**
- **We are moving toward an experiment proposal and studying the implementation at CERN** using existing detectors (the **ProtoDUNEs and WCTE**) and existing beam components to reduce the project cost
- **SBN@PBC** is a common effort of ENUBET, NuTAG, CERN Physics Beyond Collider, and the CERN Neutrino Platform, whose aims are to overcome current limitations (protons, energy range), exploit time tagging to achieve superior energy resolution and **study the concrete implementation at the CERN SPS**

We plan to submit a document at the European Strategy for Particle Physics (March 2025) and a White Paper that describes the physics performance with ProtoDUNE and WCTE (inclusive, double differential, exclusive cross sections for ν_μ and ν_e, non-standard-interactions, sterile neutrinos, and BSM physics)

Thank You!

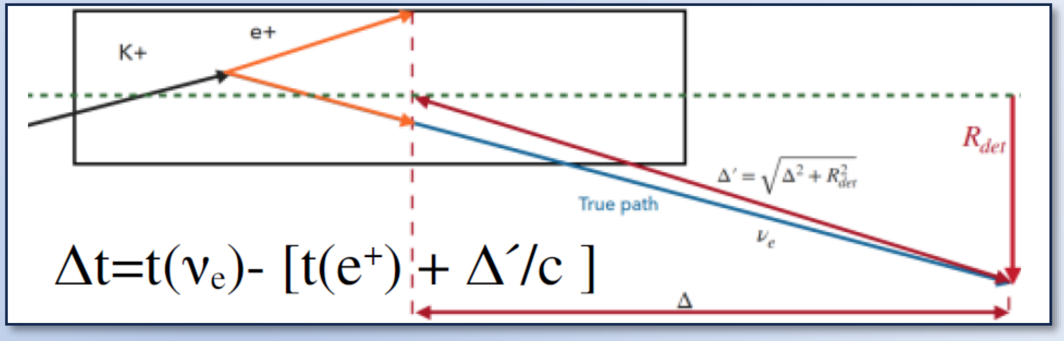
BACK-UPS

Time-Tagged Beam

Beyond the monitored beam: Time coincidence between e^+ and ν_e → Sub-ns sampling would allow:

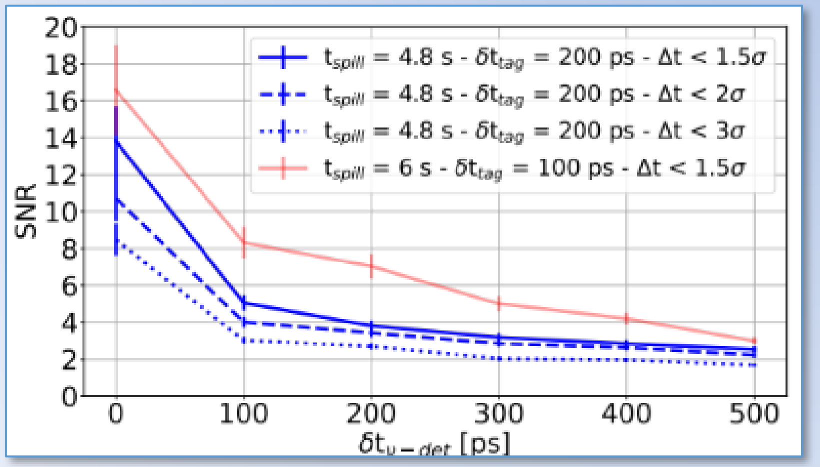
- Correlation event-by-event
- Determine the neutrino flavor

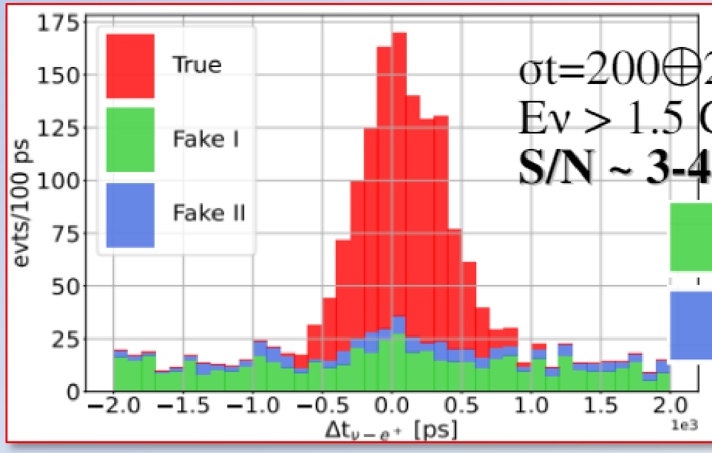
Path difference between the e^+ and ν_e → "irreducible" time spread: σΔt = 74 ps



Assuming a time resolution δt = 200 ps for both the ν detector and the tunnel instrumentation (ENUBET t0-layer with PICOSEC Micromegas)

Signal to noise ratio of tagged ν_e-e^+ pairs **as a function of the neutrino detector time resolution**





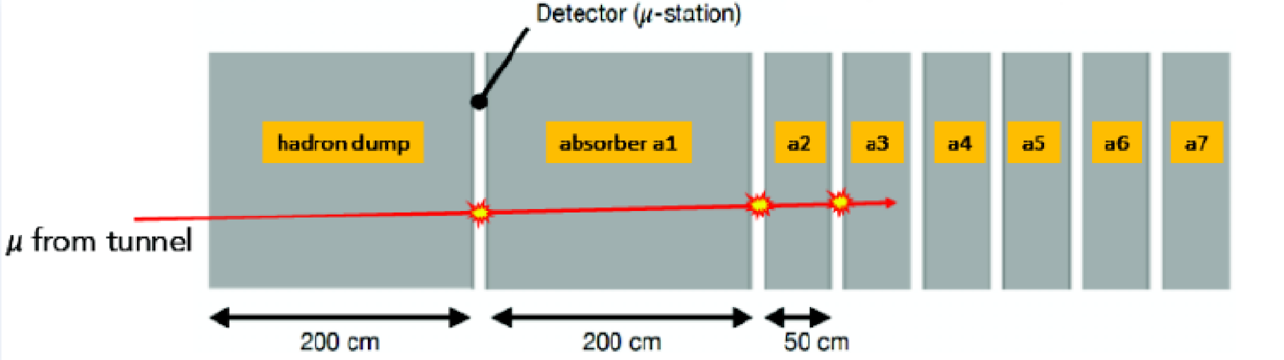
Fake matches of e^+ candidates withe ν_e produced inside tagger

Fake matches of e^+ candidates withe ν_e produced outside tagger

ν_μ from π - Monitoring

Forward Leptons: Measuring muons from pion decays to **constrain low-energy ν_μ**

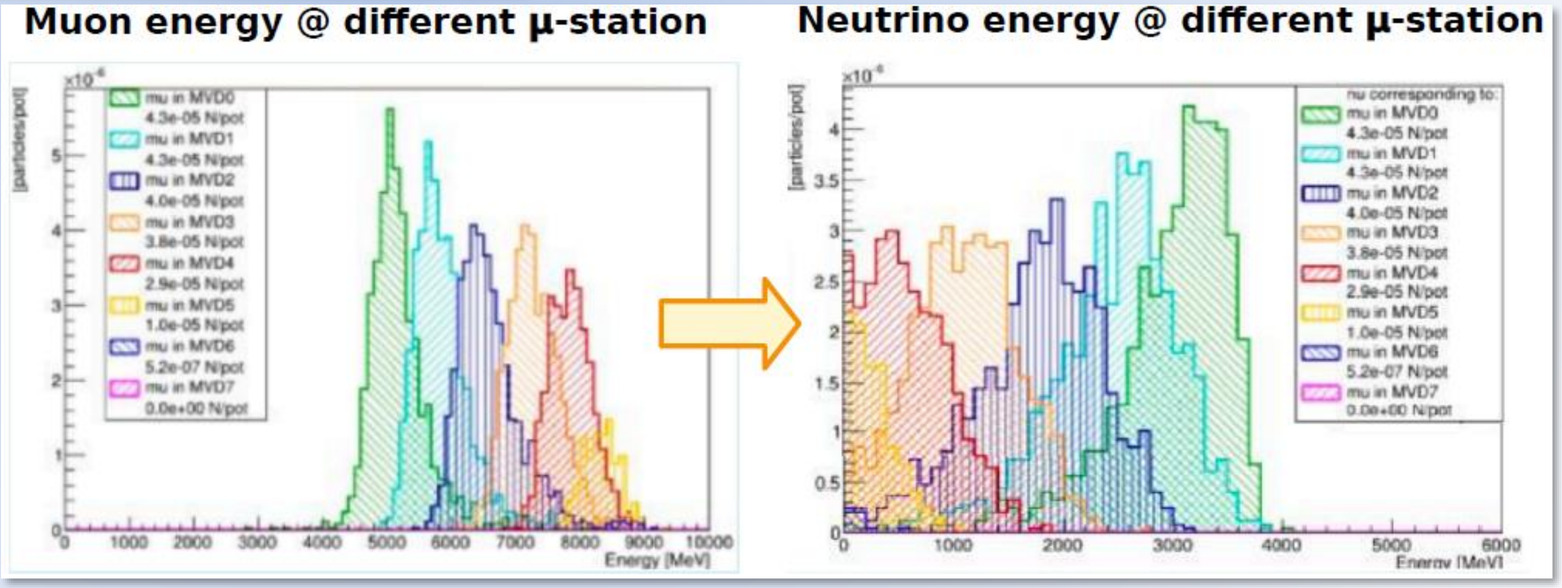
- Low angle muons out of tagger acceptance → <u>Muon stations post hadron-dump</u>



Upstream station constraints the detectors:

- Muon rate (~2 MHz/cm^2)
- Radiation hardness (~10^{12} MeV-neq/cm^2)

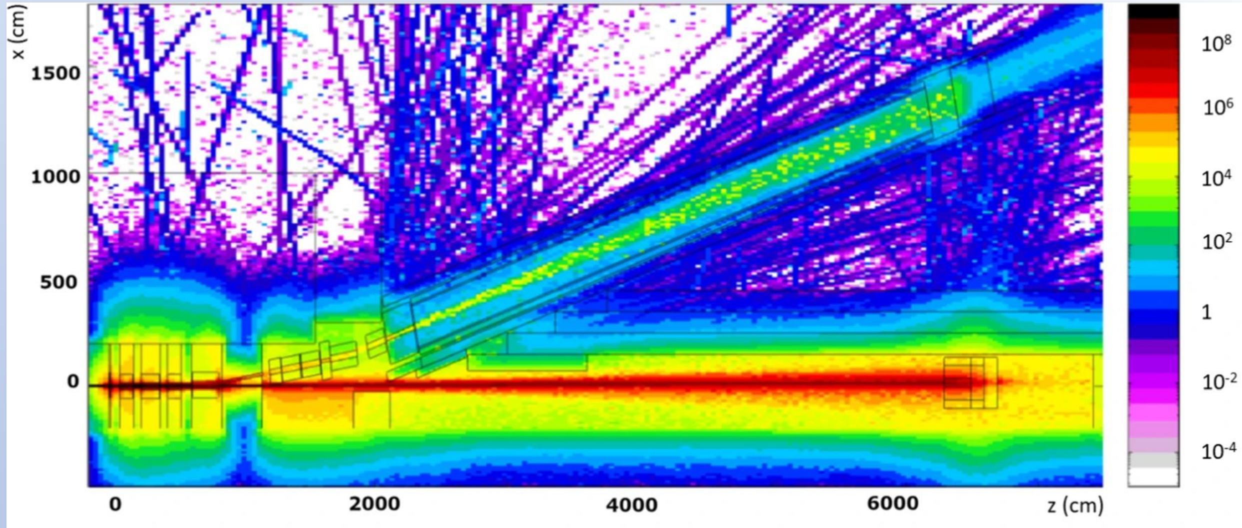
- Exploit the Correlation between traversed stations and neutrino energy:



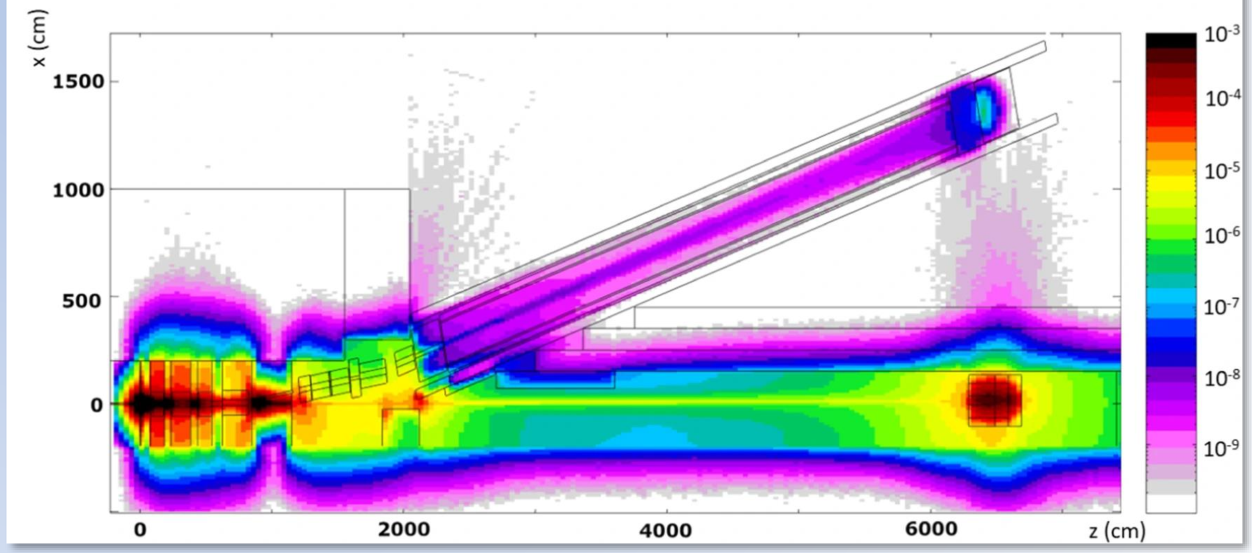
Doses

Dose map in Gy for 10^{20} pot

- The first quadrupole in the map is located between z=200 and 500 cm



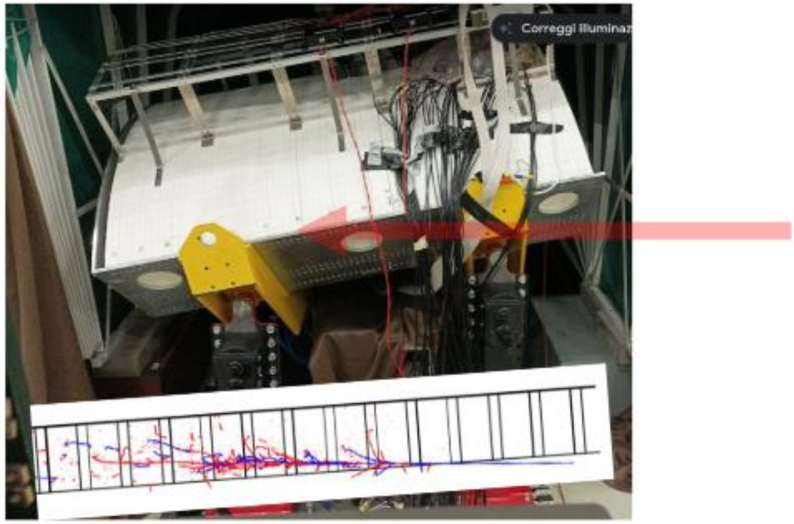
1-MeV-eq neutron fluences

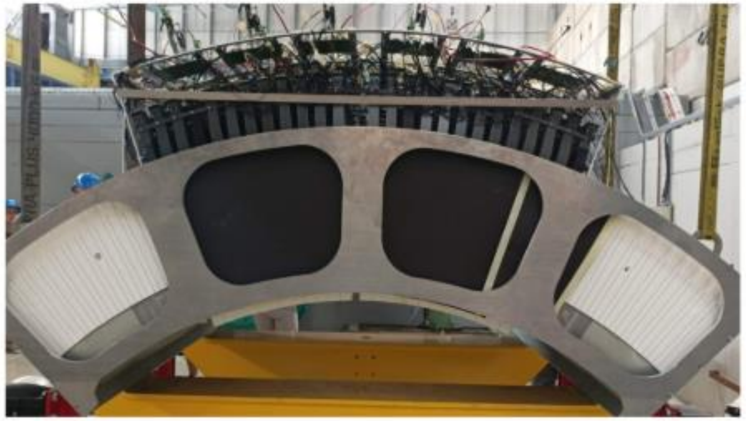


ENUBET Demonstrator - Test Beams

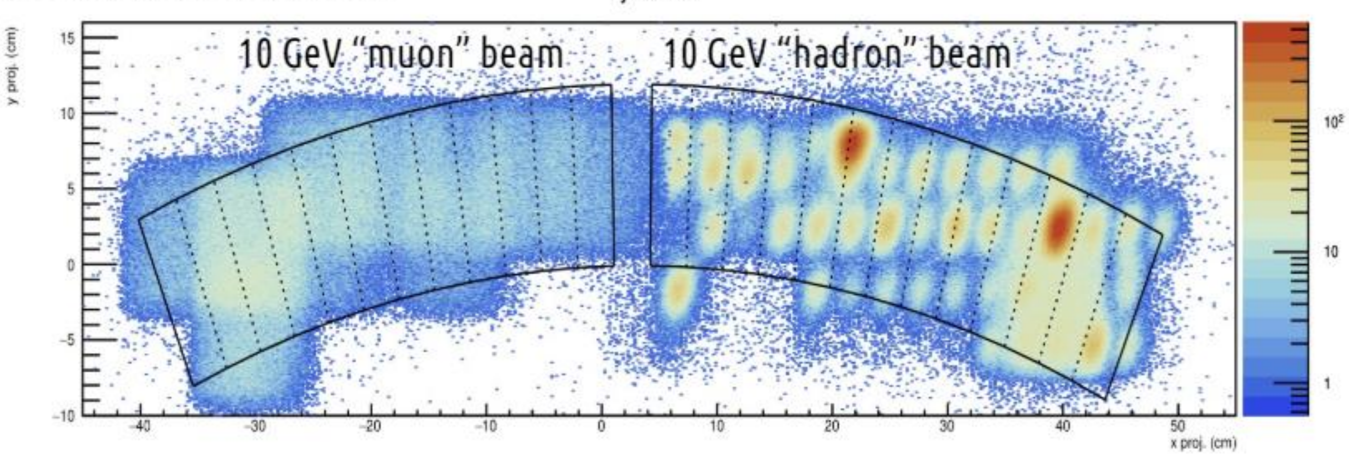
Inclined and Calibration Runs

200 mrad tilt run

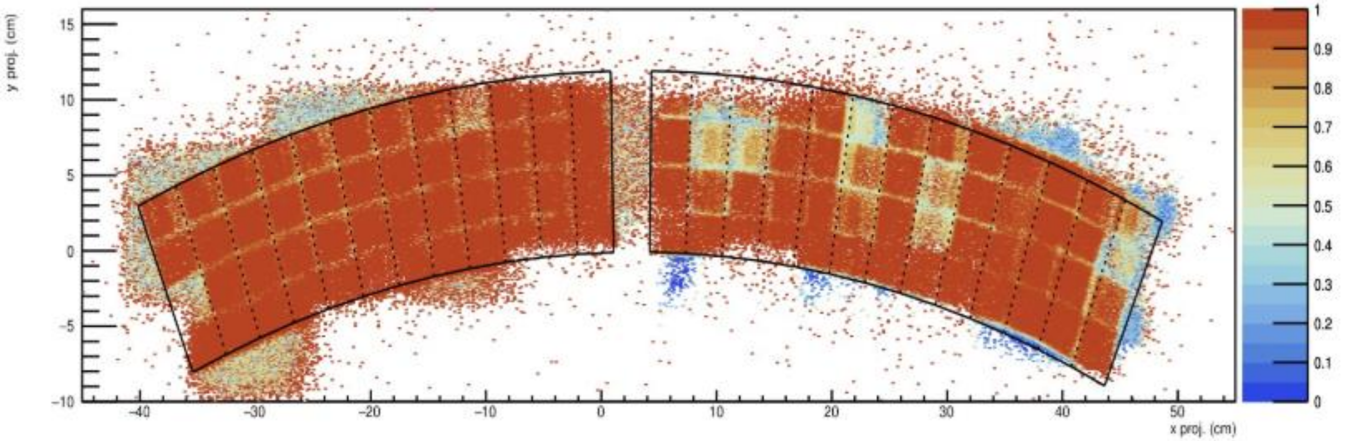




Hit map (silicon trackers)

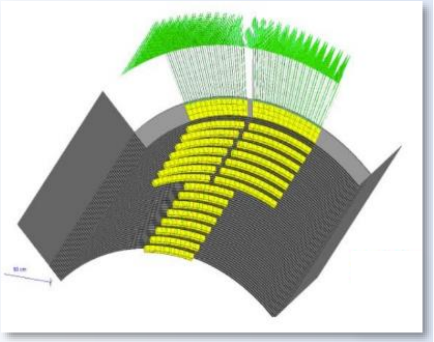


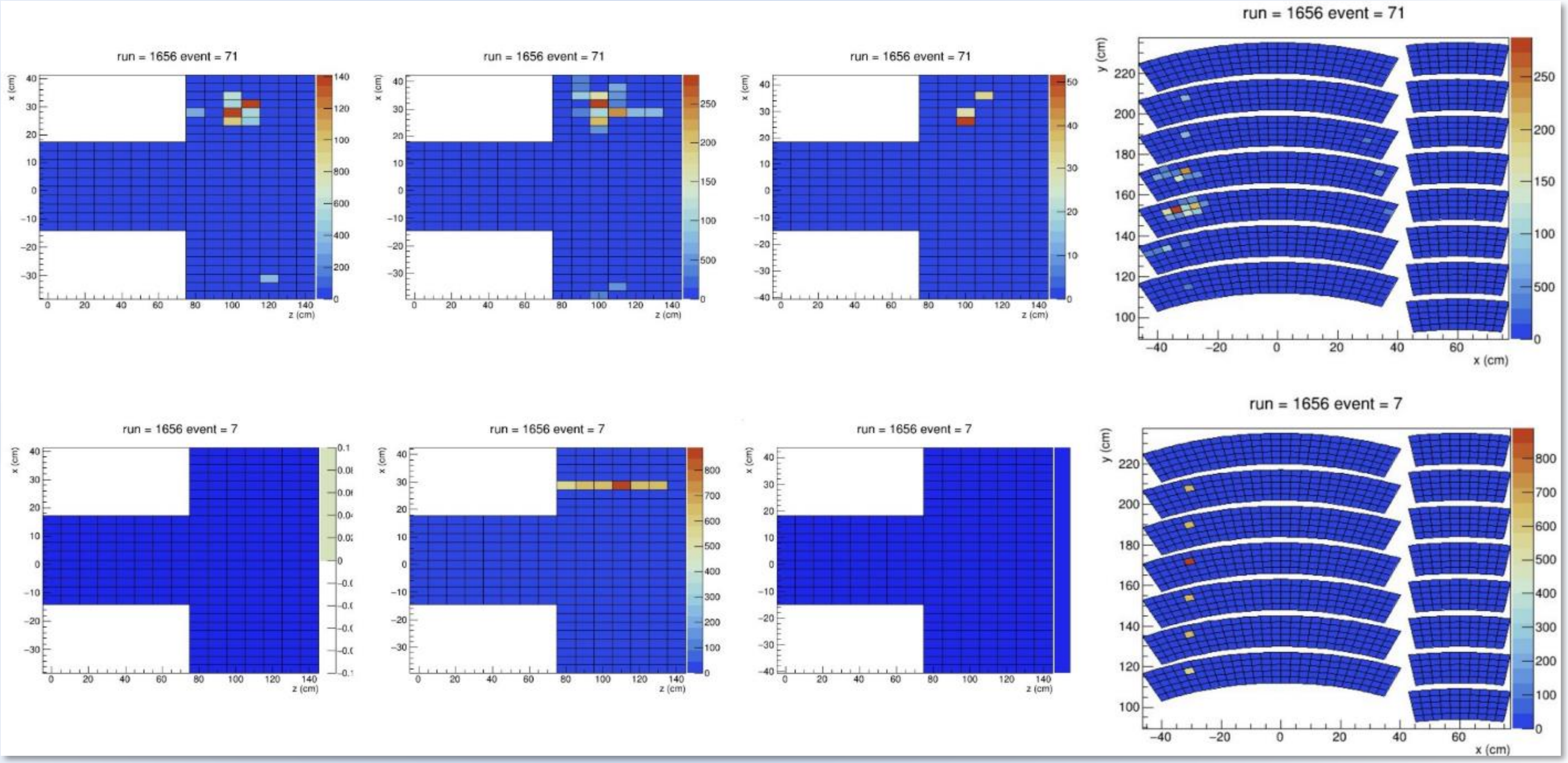
Efficiency map



ENUBET Demonstrator - Test Beams

Event Displays (10 GeV hadrons and muons)



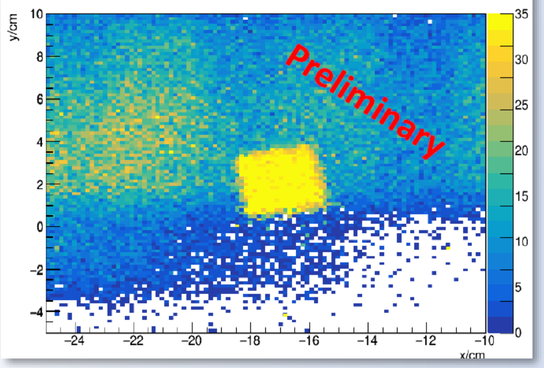


ENUBET Demonstrator - Test Beams

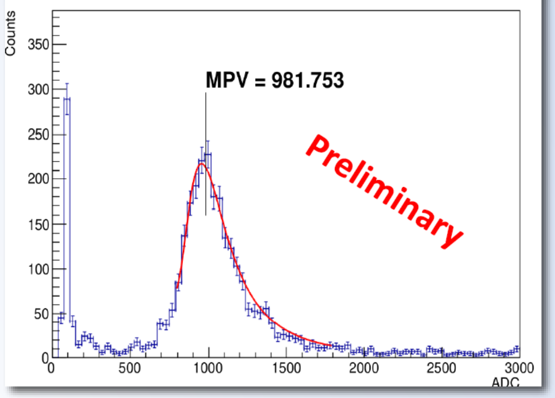
Poster #61 by L. Halić

Channel equalization

Energy deposit of MIPs



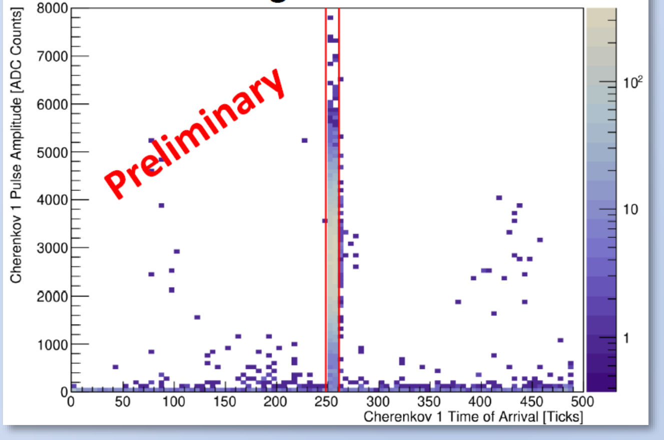
Landau Fit of MIP Peak



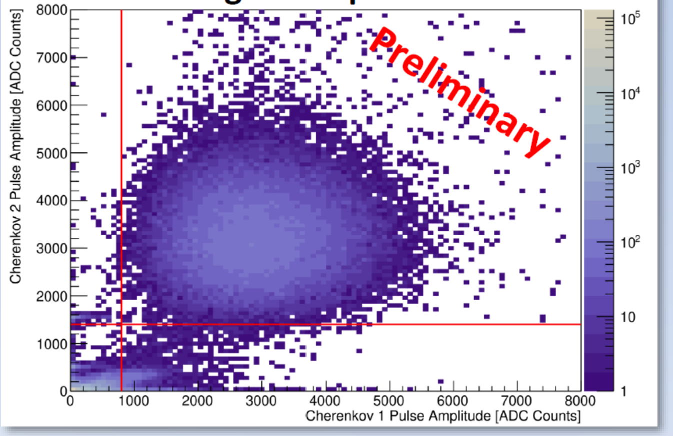
Energy resolution for electrons

Considering only electron whose electromagnetic showers are fully contained within the calorimeter

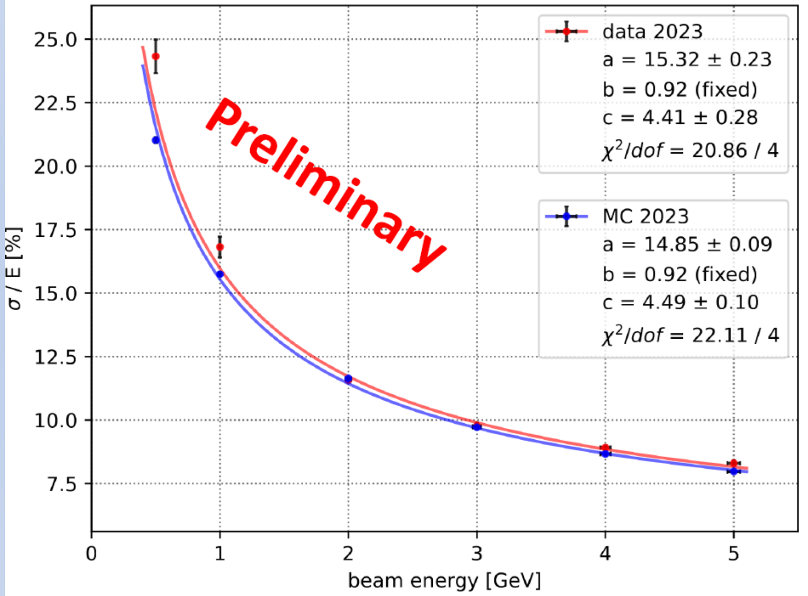
Timing information

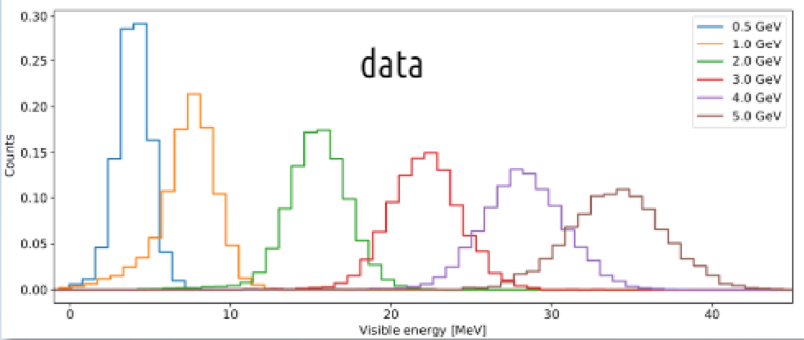


Signal amplitude



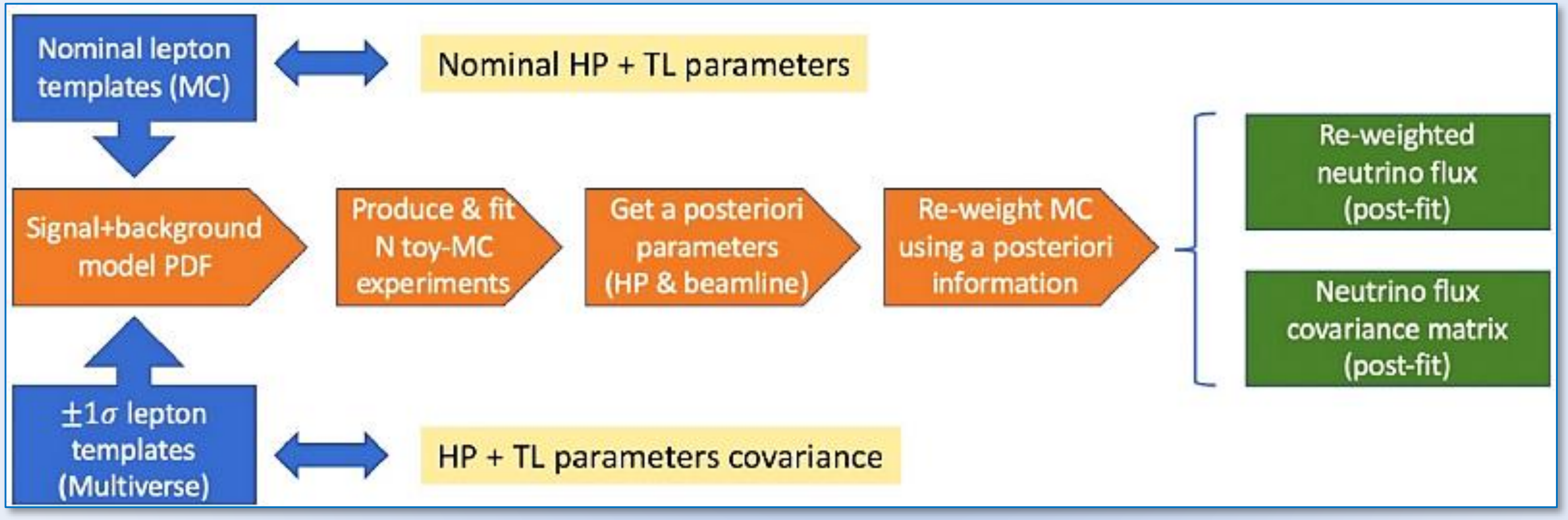
Electron energy resolution





Assessment of Systematics

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

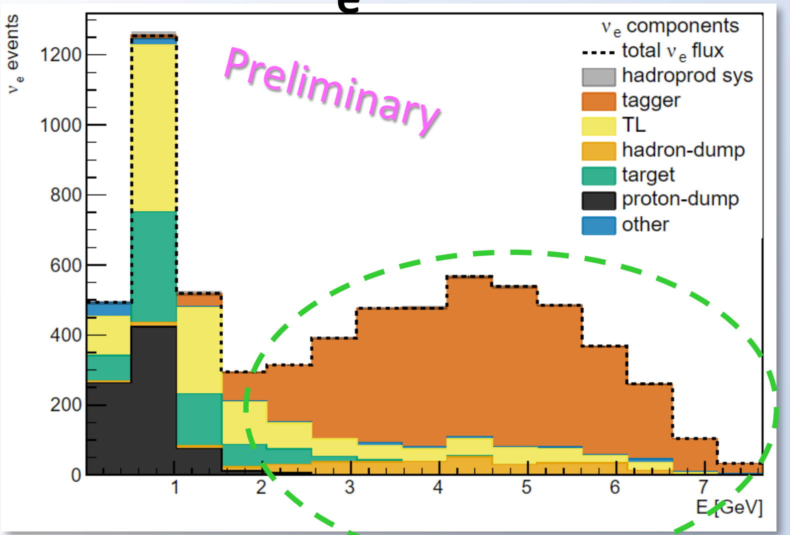


Used hadro-production data from NA56/SPY experiment to:

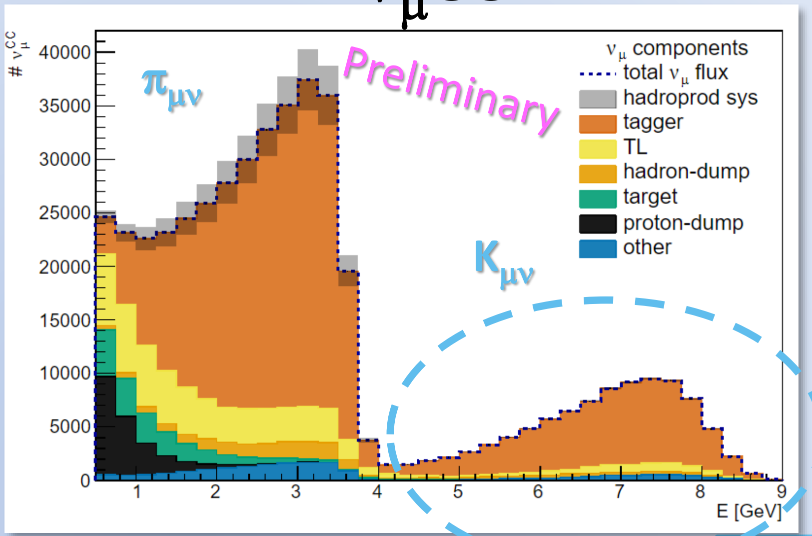
- Reweight MC lepton templates and get their nominal distributions
- Compute lepton templates variations using multi-universe method

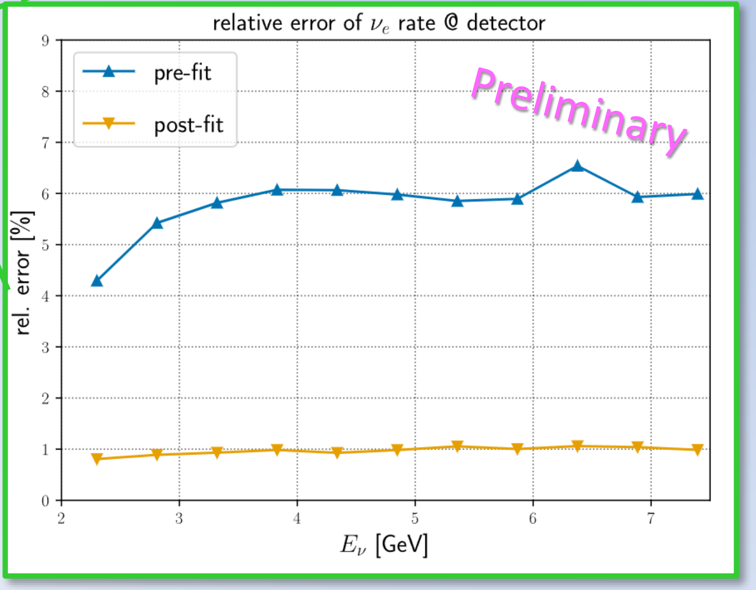
Precision on the neutrino flux from lepton monitoring

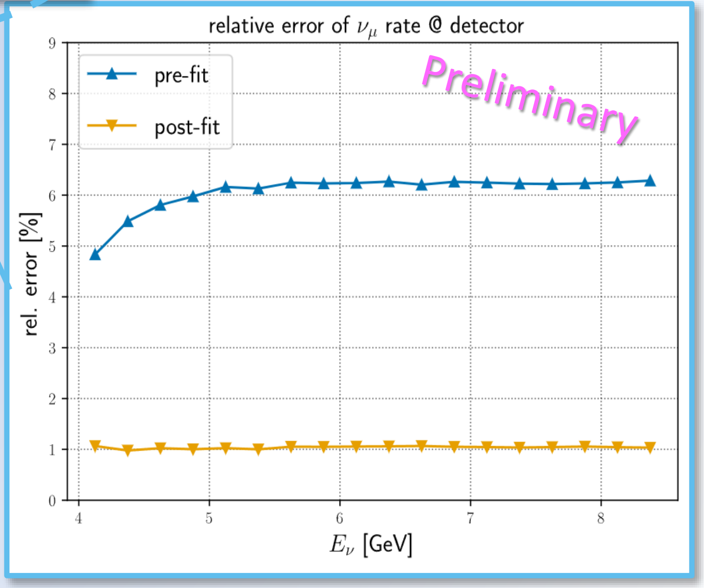
ν_eCC



ν_μCC

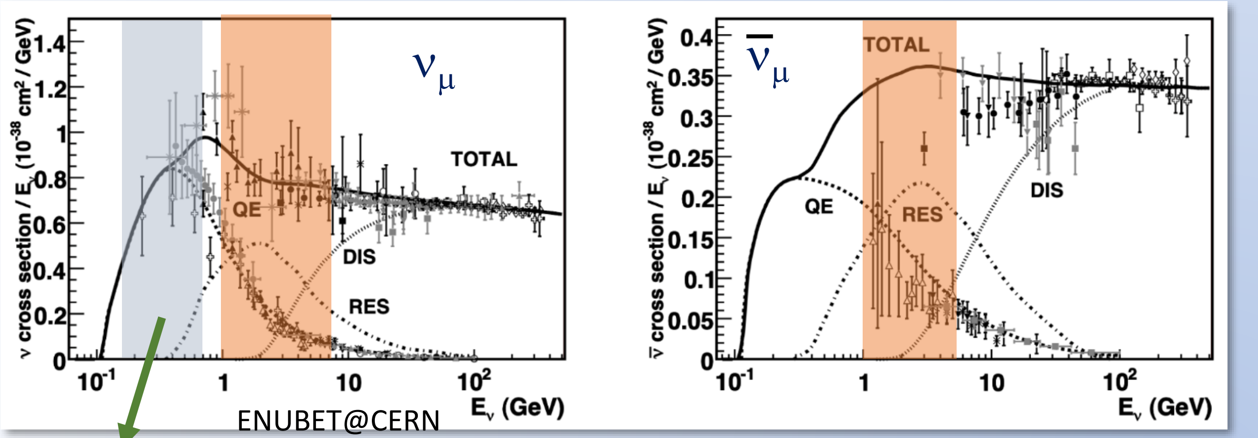






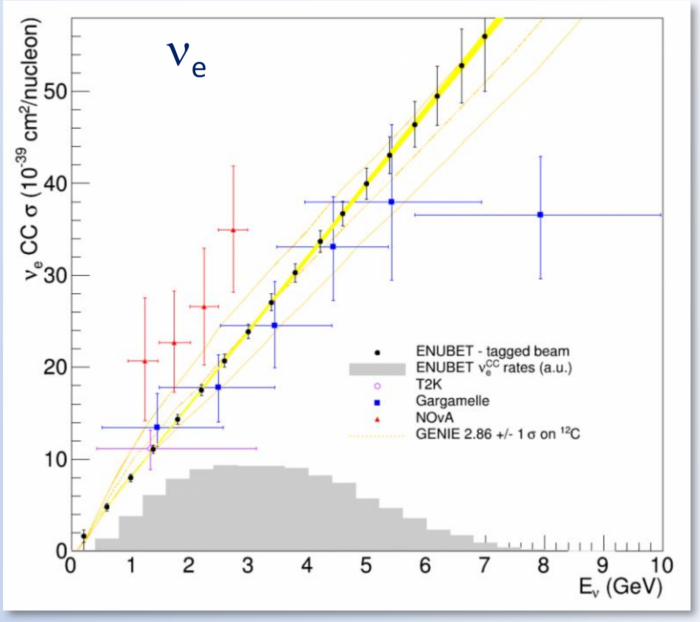
A glimpse to the physics reach of ENUBET

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

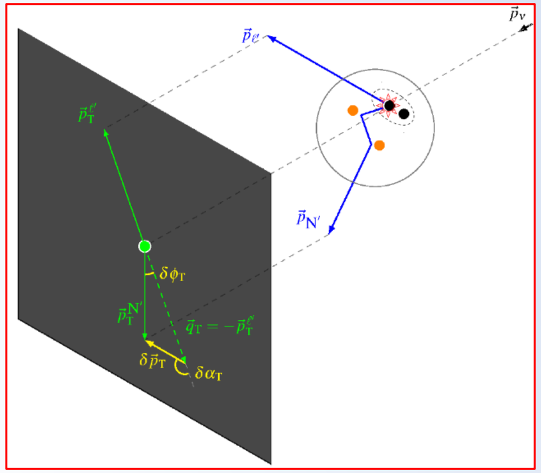


ESSnuSB+ (*)

(*) 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)