SBN@PBC
High precision neutrino physics at CERN

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on behalf of the ENUBET and NuTAG Collaborations

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Introduction

Since 2023, PBC - Conventional Beams Working Group and Neutrino Beams subgroup - is investigating the possibility of a high-precision neutrino beam at CERN to perform neutrino cross-section measurements that are one order of magnitude better than state-of-the-art. This activity reaps the results and expertise of a 5-year long R&D performed by **NP06/ENUBET** in the framework of the CERN Neutrino Platform and the opportunities opened up by the **NuTAG** Collaboration.

SBN@PBC is the result of such a common effort

Aims of this talk:

- Ground the physics case of a high-precision neutrino beam at CERN
- Present the main features of a monitored and tagged neutrino beam driven by the SPS
- Outline the impact on neutrino physics when this facility will be running (in the 2030s)
- Introduce the next talk by Marc Jebramcik devoted to the implementation

The key role of neutrino cross-sections

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.

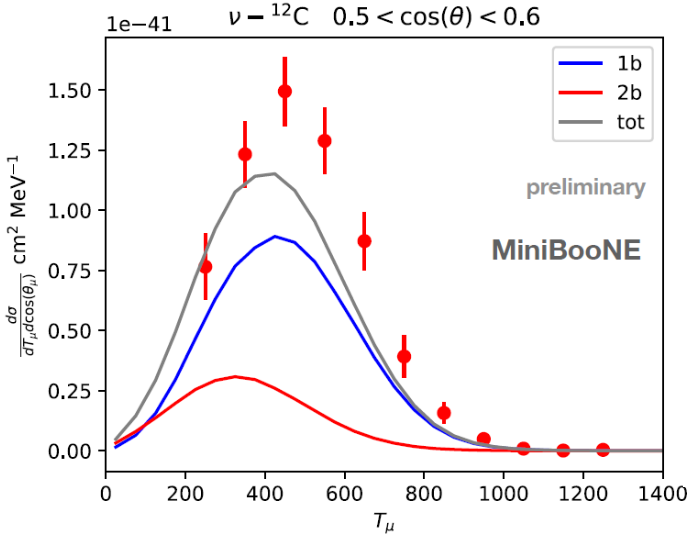
A harmful ignorance

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

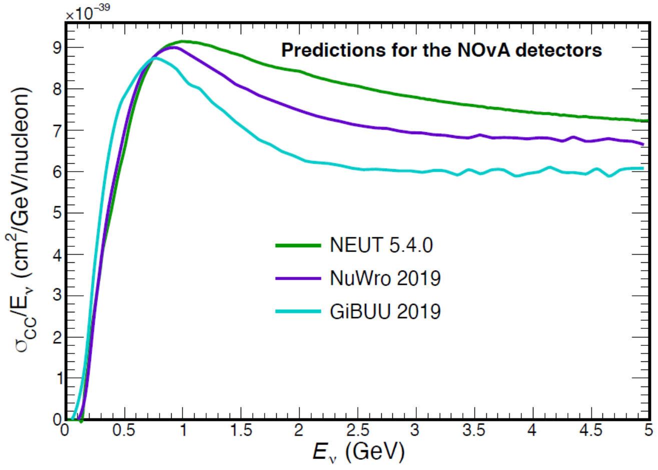
T2K

	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

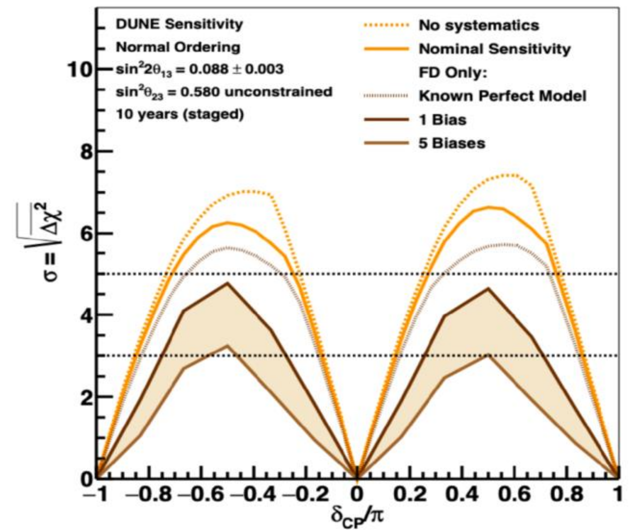


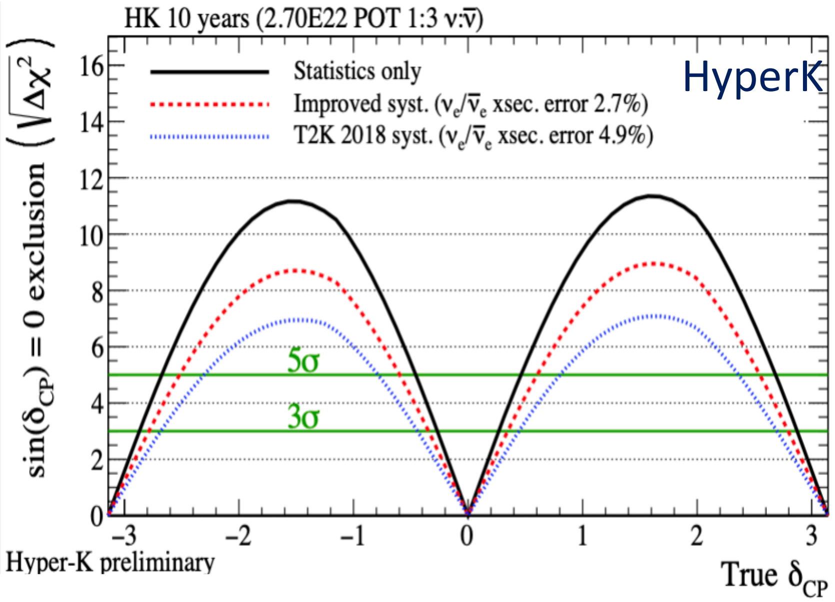
N. Rocco, Nufact2022



J. Paley, Nufact2022

DUNE





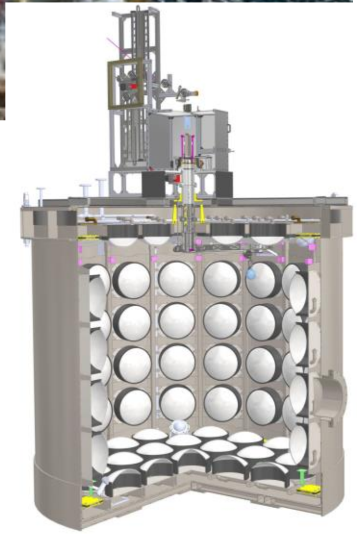
For a review see e.g. NuSTEC white paper, arXiv:1706.03621

In the DUNE-HyperKamiokande era, investing in a new generation of short-baseline cross-section experiments (cost: tens of M€) is equivalent to substantially increasing the mass or exposure of long-baseline experiments (cost: hundreds of M€)

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

- Measure the **energy** of the neutrino without relying on the final state to get rid of all biases coming from nuclear reinteractions
  - Monitored neutrino beam "Narrow band- off-axis technique" ENUBET (10-25 % depending on the energy)
  - Particle tracking in the tunnel: NuTAG (<5%)
- Use the same **target** as DUNE and HyperK + low Z target (existing or new experiments)
  - Ideal detectors: the ProtoDUNEs (fiducial mass: 400+400 tons of liquid argon) and WCTE (fiducial mass: 40 tons). All these detectors are already available at CERN.
  - New, moderate mass detectors based on Carbon and Hydrogenated material are also being considered



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

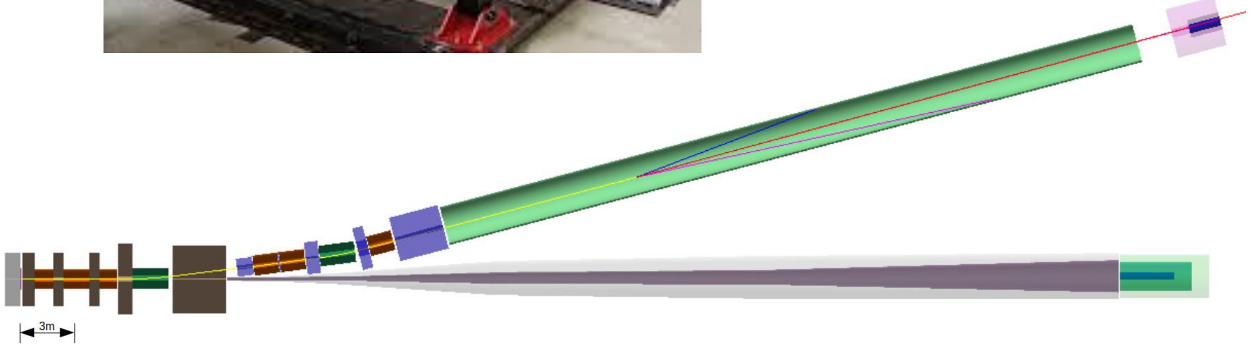
NP06/ENUBET

Monitored neutrino beam

Identify charged leptons in the instrumented decay tunnel

Employ a horn-less beam ("static focusing system") with narrow-band optics.

See F.. Acerbi et al. [ENUBET Coll.] EPJ C 83 (2023) 964

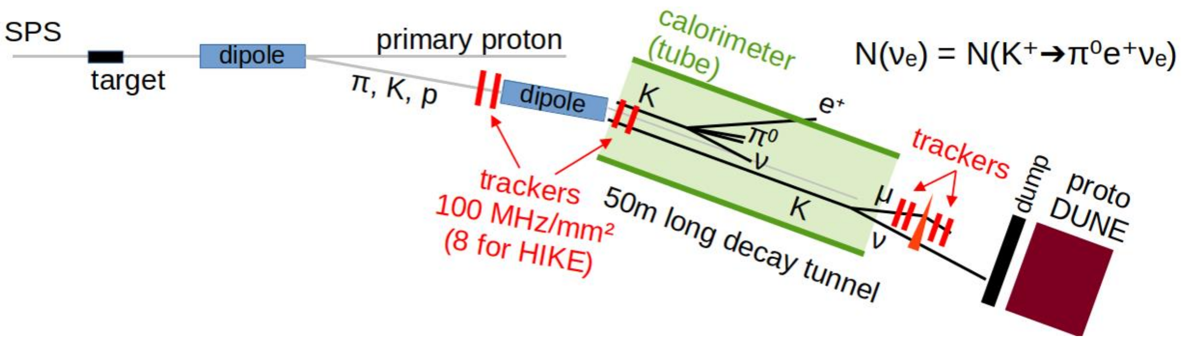


NuTAG

Tagged neutrino beam

Uniquely associate the neutrino with the parent meson and the accompanying muon

See A. Baratto-Roldan et al. [NuTAG] arXiv: 2401.17068

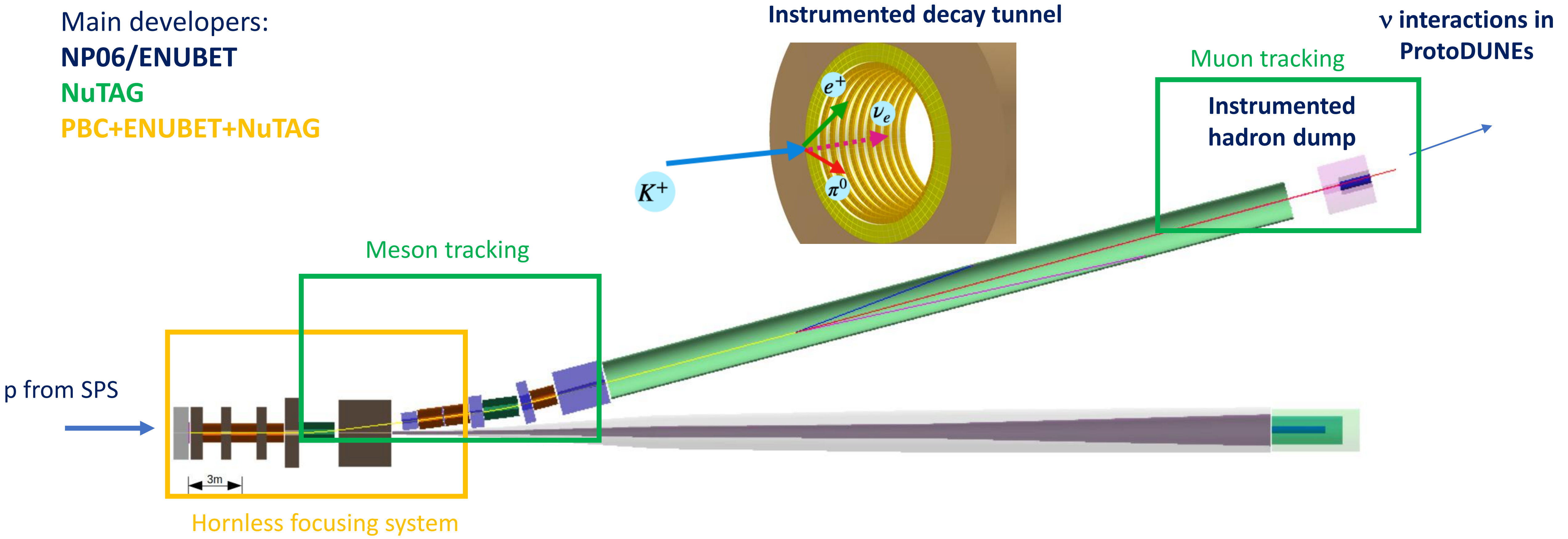


The SBN@PBC layout

The project layout is inspired by the achievement of NP06/ENUBET but enhances its physics reach by:

- Extending the energy range down to 1 GeV
- Devising a beamline that is compatible with the CERN fixed target programme
- Performing high-precision measurements of the neutrino energy through meson tracking inside the beamline: NuTAG!

Main developers:
NP06/ENUBET
NuTAG
PBC+ENUBET+NuTAG



Expected performance

SBN@PBC is a high-precision source of electron and muon neutrinos. It can also be operated in anti-neutrino mode. The current design

- collects about 10^4 ν_e CC events and 5 10^5 ν_μ CC events in the ProtoDUNEs (800 t fiducial mass) in 5 (7) years of data taking assuming 2 (1.4) 10^{18} pot/y
- spans an energy range from 1 to 8 GeV
- can measure the ν_μ neutrino energy «a priori» from the measurement of the interaction vertex in ProtoDUNE with a precision of 25% (1 GeV) – 10% (5 GeV), and at percent level for the "tagged sample"

A dedicated task force under the CBWG-NB working group will address a conceptual feasibility study of such a beamline at CERN:

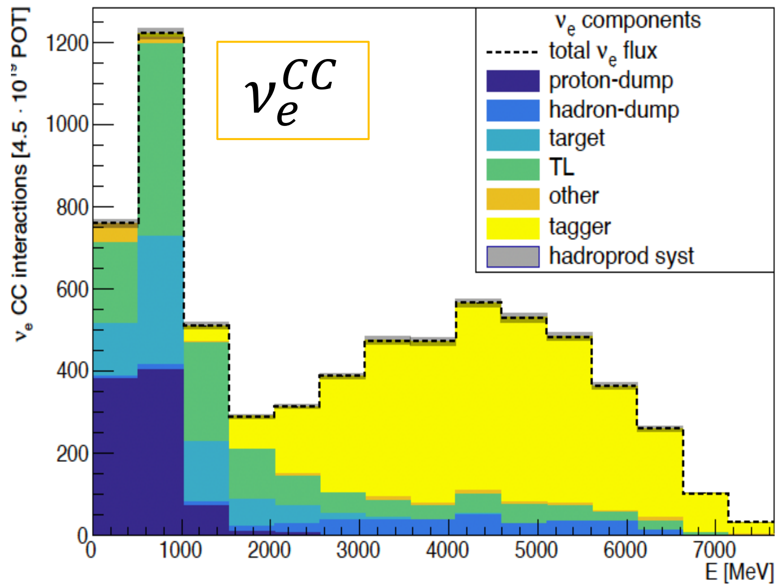
- Look into the constraints of a possible implementation, and study all different possible alternative locations at CERN
- Perform meson tracking using fast silicon trackers (NA62 and HL-LHC technologies) to enhance the energy resolution for ν_μ down to a few %, especially where NP06/ENUBET is less performing

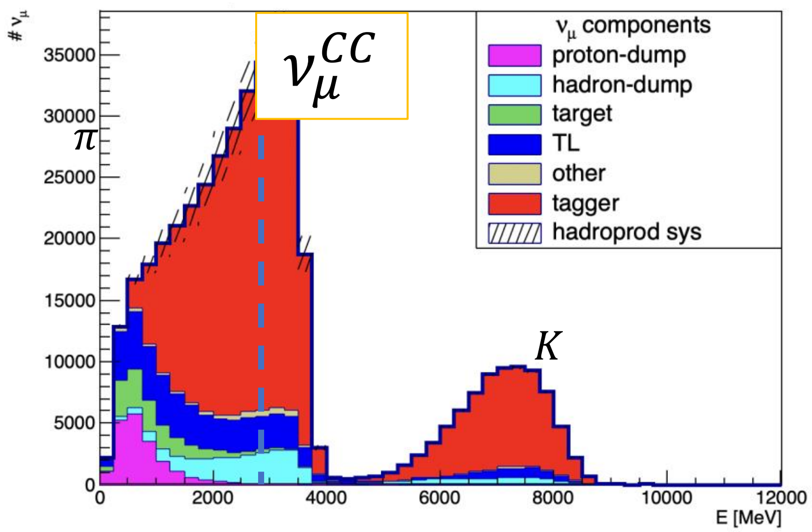
Is SBN@PBC able to fulfill all the requirements needed for the next generation of cross-section experiments?

The “flux challenge”: can we really reduce the flux systematics at <1%? Yes

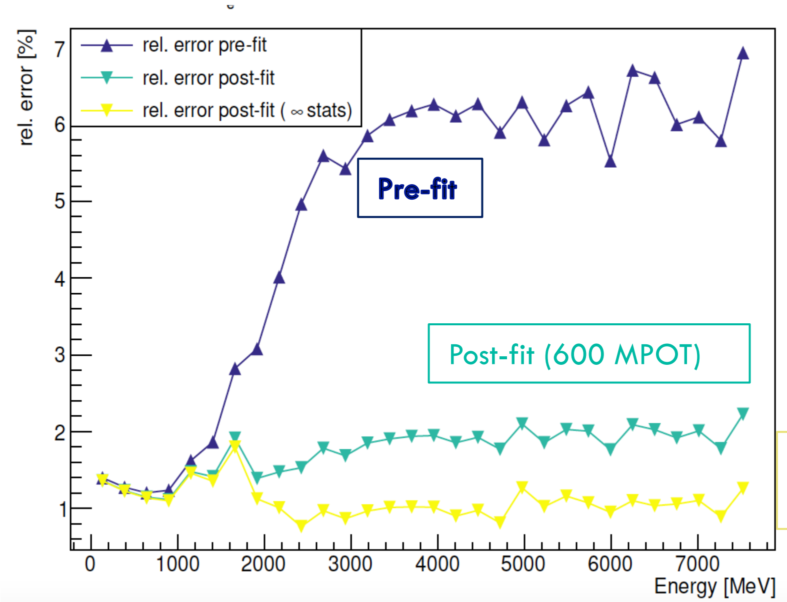
See F.. Acerbi et al. [ENUBET Coll.] EPJ C 83 (2023) 964

Neutrino interaction rates @ detector

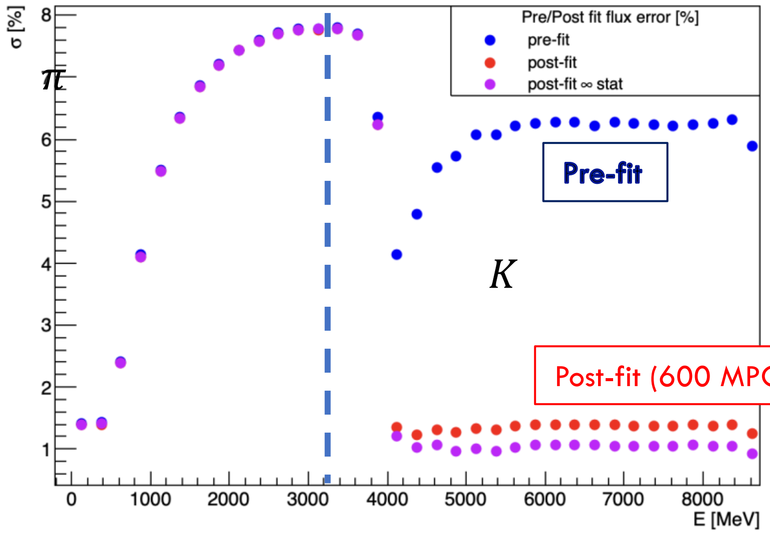




Pre & Post fit relative errors on rates



Infinite statistics



Infinite statistics

This was a major achievement by the ENUBET Collaboration and establishes the very concept of «monitored neutrino beam»

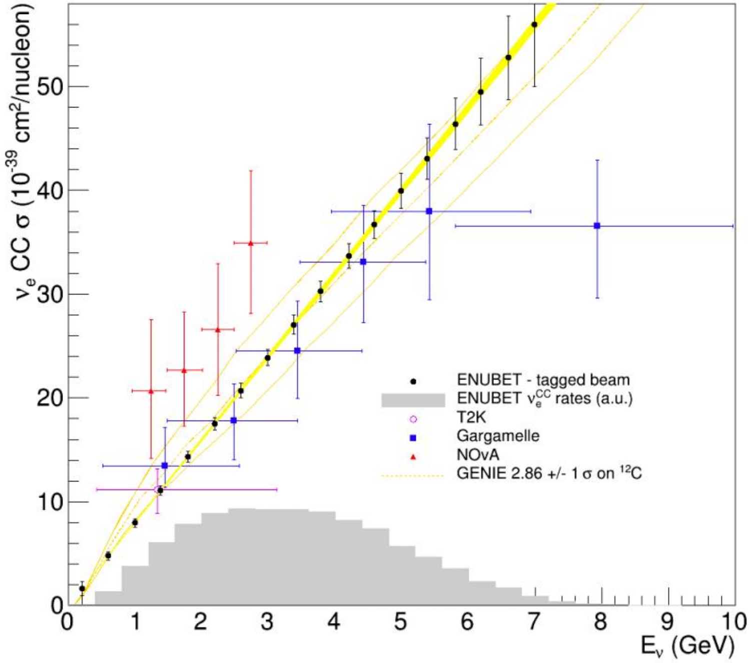
Final results will be published in 2024

Achieved ENUBET goal of 1% systematics from monitoring lepton rates

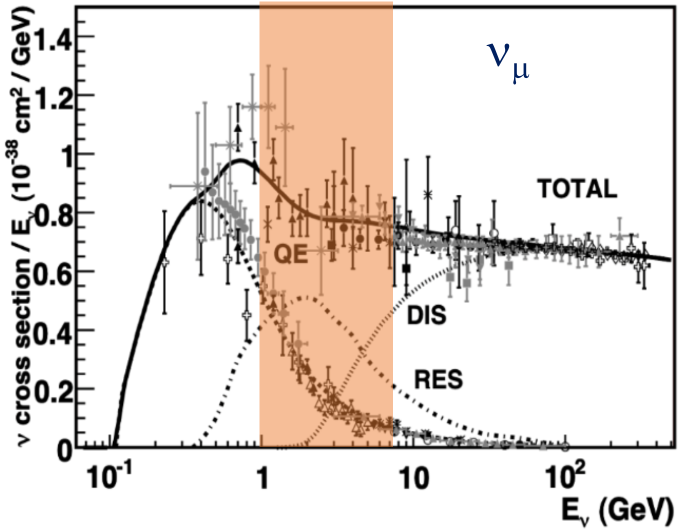
Impact on neutrino physics (I)

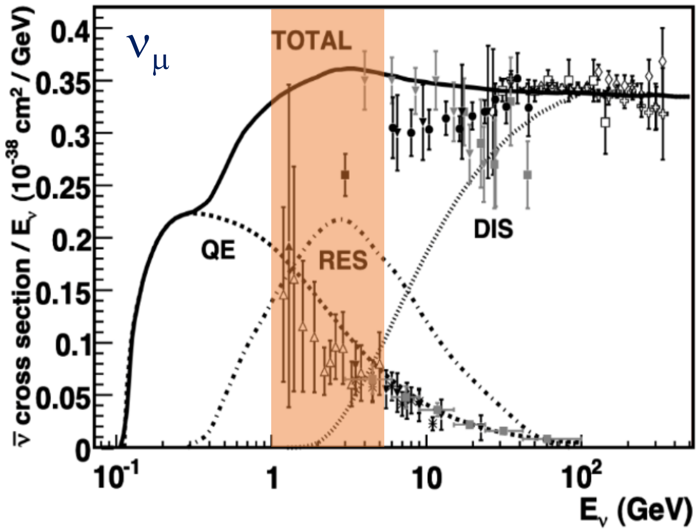
Achieving an overall normalization uncertainty at <1% for both ν_e and ν_μ is a breakthrough in neutrino physics, which won't be matched by any experiment in the foreseeable future

Impact on σ_{ν_e}



Impact on $\sigma_{\nu\mu}$



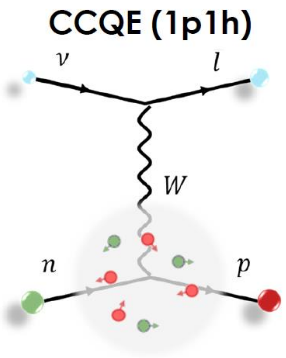


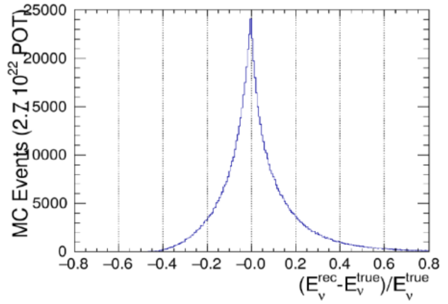
Normalization errors play a key role in double differential cross-sections and BSM searches, especially when using high resolution neutrino detectors as the ProtoDUNE. These opportunities are being investigated, as well – **work in progress**

The “energy challenge”

A «monochromatic neutrino source» is a holy grail in neutrino physics because all experiments to date reconstruct the neutrino energy from final state particles in neutrino-nucleus interactions. As a consequence the energy reconstruction is plagued by nuclear re-interactions, detector inefficiencies, PID limitations. These effects:

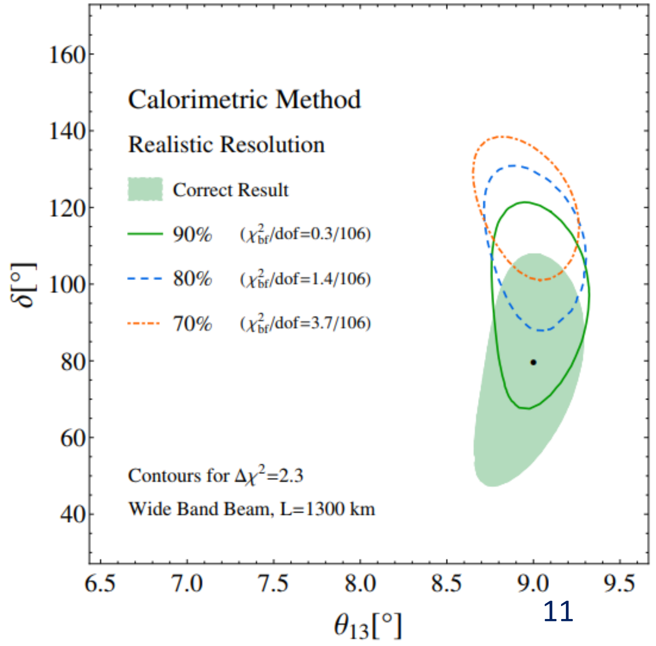
- require model-dependent deconvolutions in cross-section measurements
- bias physics observables in long-baseline (oscillation) experiments





Three approaches:

- Correct for nuclear effects relying on data-driven theory models (T2K, Nova, DUNE, etc.)
- Use a narrow-band beam and exploit the correlation between the production angle and the neutrino energy [currently exploited with a broad-band beam by SBN@Fermilab]
- Use a tagged neutrino beam, where the neutrino energy is computed by the momentum of the parent track [a technology breakthrough]



For a review see e.g. S. Dolan at Nuphys 2019

The "energy challenge": narrow-band off-axis technique

Narrow-band off-axis Technique

Narrow momentum beam O(5-10%)

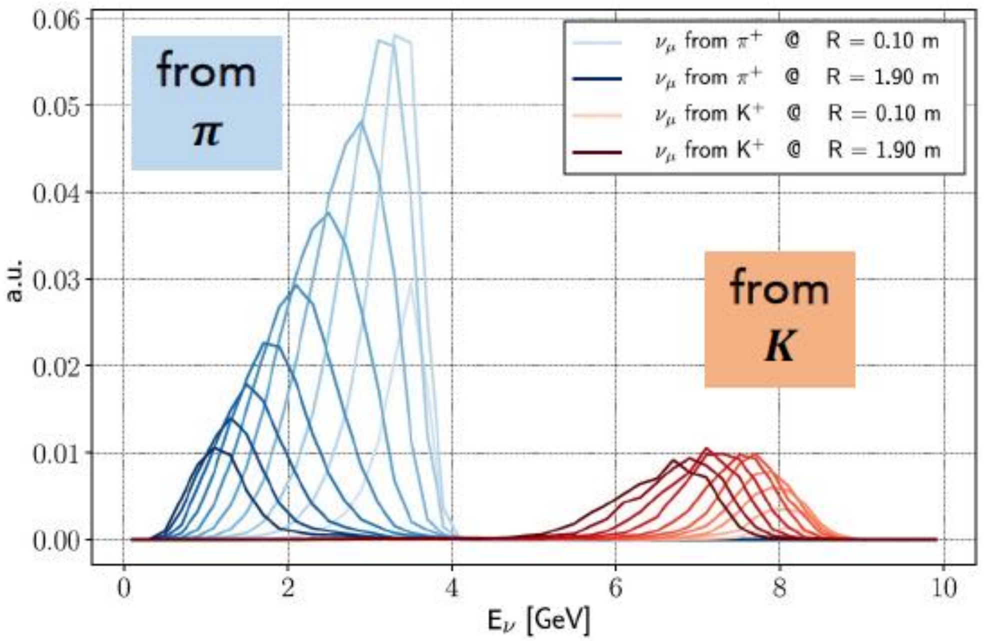
(E_ν,R) are strongly correlated

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

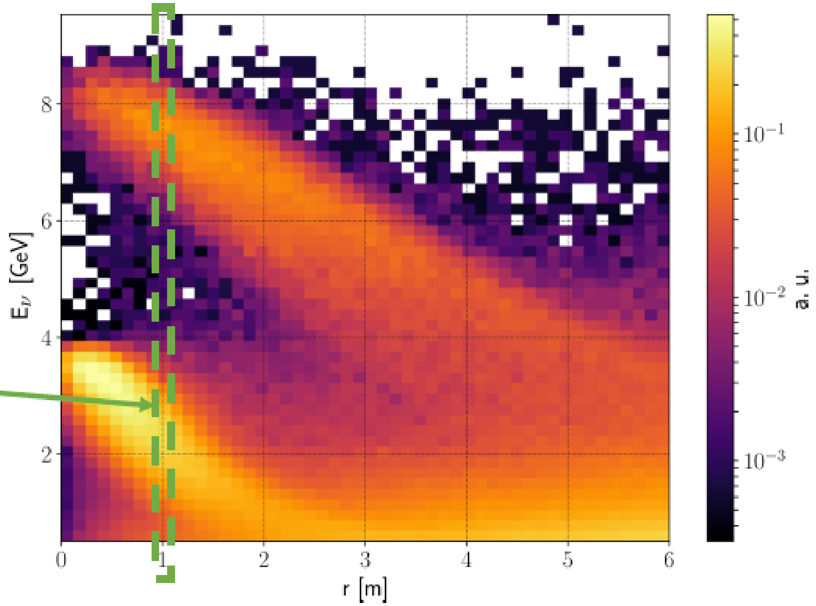
10-25% E_ν resolution from π in the DUNE energy range



π/K populations well separated

Select ν_μ with given energy by performing cut on R

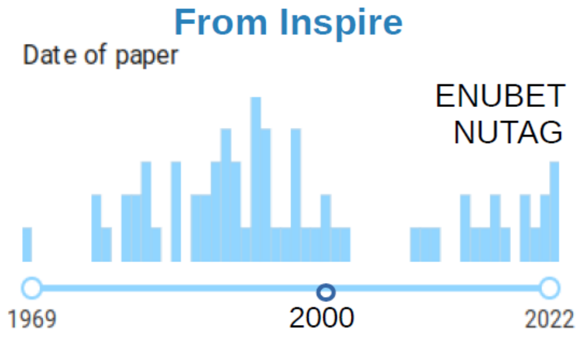
All ν_μ^{CC}: backgroun @ low E and high R



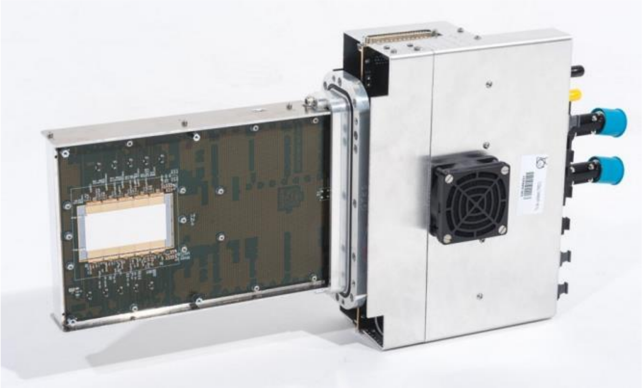
Energy measurement by neutrino tagging: the NuTAG concept

See A. Baratto-Roldan et al. [NuTAG] arXiv: 2401.17068

Unlike monitored neutrino beams, a «tagged neutrino beam» uniquely associate the neutrino with its accompanying particles in the beamline. The use of these state-of-the-art silicon trackers is the core of the NuTAG concept



	Available	Max. Radiation	Max. Flux
NA62-GTK	since 2015	10^{14} n_{eq}/cm^2	2 MHz/mm^2
HL-LHC	before 2028	10^{16-17} n_{eq}/cm^2	10-100 MHz/mm^2



This technique is ideally suited for two-body decays because:

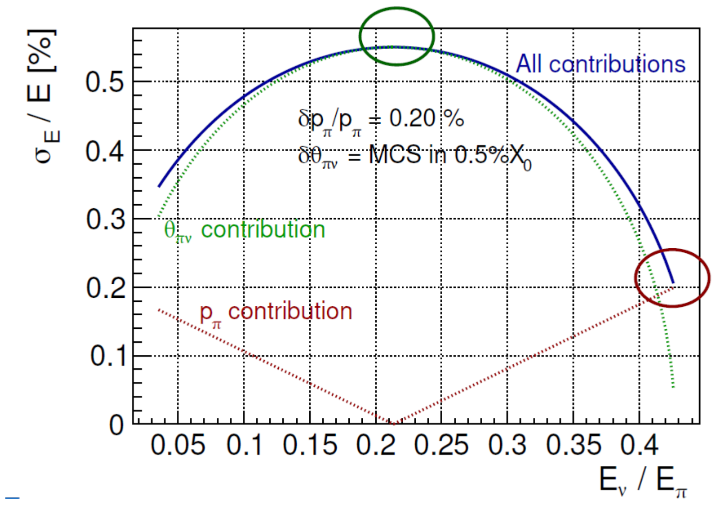
- We just need the parent momentum (tracking before and after a SBN@PBC dipole) and the neutrino production angle (i.e. the interaction vertex in ProtoDUNE or WCTE) to reconstruct the neutrino energy
- All ν_μ and anti-ν_μ in SBN@PBC originate from 2-body decays of pions or kaons. The ν_μ CC statistics is enormous even in a low-intensity beam as SBN@PBC
- We can also track muons and predict the neutrino position in protoDUNE relaxing the time resolution requirements to perform matching

$$E_\nu = \frac{\left(1 - m_\mu^2/m_\pi^2\right) p_\pi}{1 + \gamma^2 \theta_\nu^2}$$

Performance and challenges

Operating a monitored neutrino beam in «neutrino tagging mode» would be a **breakthrough in experimental physics**. It may come since the beginning of the SBN@PBC data-taking or as a Phase II upgrade. The general strategy we are pursuing at PBC is the following:

- Design the beamline optics to ensure proper defocusing at the last beamline dipole, which results in a lower particle density at the tracker
- If needed, schedule low-intensity runs devoted to collecting a sample of about 10^4 tagged ν_μ CC
- Ensure early operation with WCTE because water Cherenkov has a 100 ps time resolution needed for time tagging. [Tracker resolution: $\ll$100 ps]
- Investigate the maximum resolution that can be achieved in ProtoDUNE when overhauled for DUNE Phase II. Note that the DUNE Phase II far detectors will be equipped with an enhanced photon detection system and the corresponding light yield will improve time resolution for GeV neutrinos below 1 ns. This R&D is being pursued by ENUBET together with the DUNE-SoLAR Collaboration and is instrumental in exploiting liquid argon in a tagged neutrino beam.



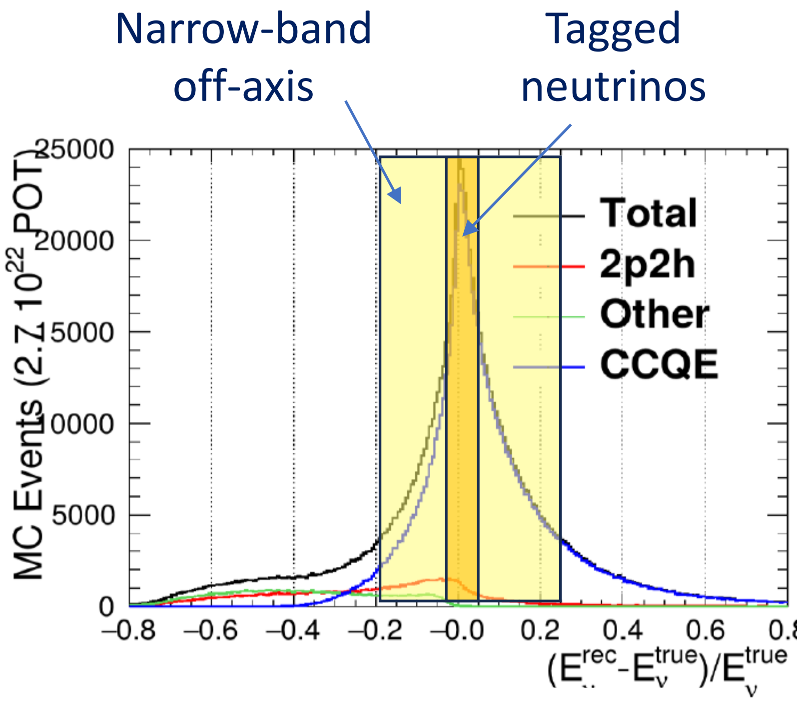
Neutrino energy resolutions at per-cent level are readily available using this technique

Goals: we aim at collecting 10^4 «tagged» ν_μ CC events in the course of the SBN@PBC data taking, possibly with both water and argon as a target. **Work in progress**

Impact on neutrino physics (II)

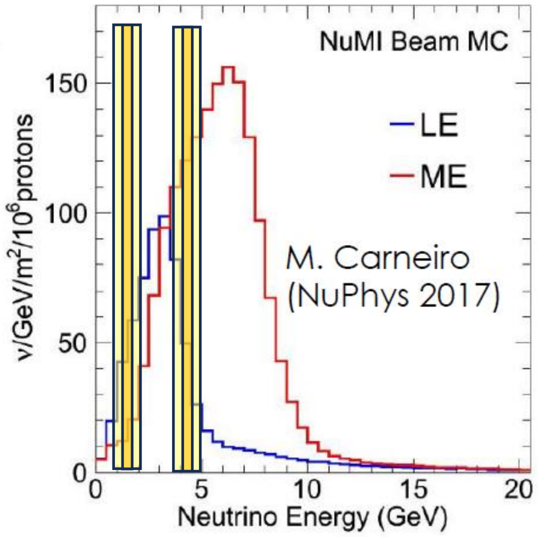
SBN@PBC can collect:

- A sample of about 10^5 ν_μ CC events in liquid argon with an energy resolution of 10% in the energy range 2-5 GeV, of relevance for DUNE and for cross-section measurements in the region dominated by resonant production (RES) and deep-inelastic (DIS)
- A sample of a few 10^4 ν_μ (10^3) ν_μ CC events in liquid argon (water) with an energy resolution of about 20-25% in the region-of-interest of HyperKamiokande
- A sample of a few 10^4 ν_μ (10^3) **tagged** ν_μ CC events in liquid argon (water) with an energy resolution of a few percent



A tremendous impact in the field of neutrino physics:

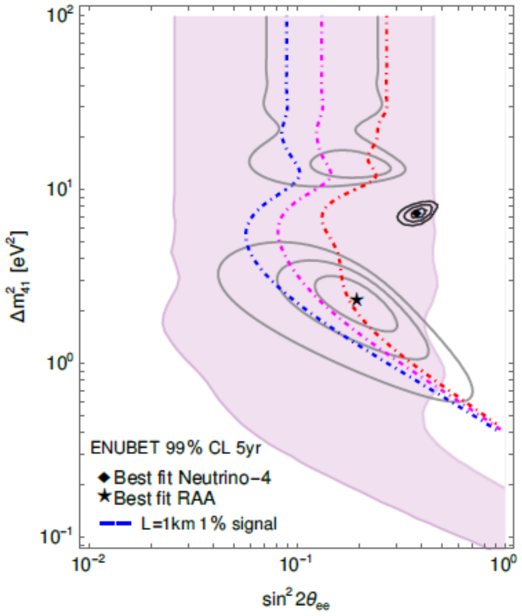
- study of quasi-elastic, resonant and deep inelastic cross sections free of nuclear bias
- reduction of the systematic bias due to model dependence in long-baseline experiments
- a key measurement for the development of nuclear models - comparable with electron-nucleus scattering but performed with neutrinos!

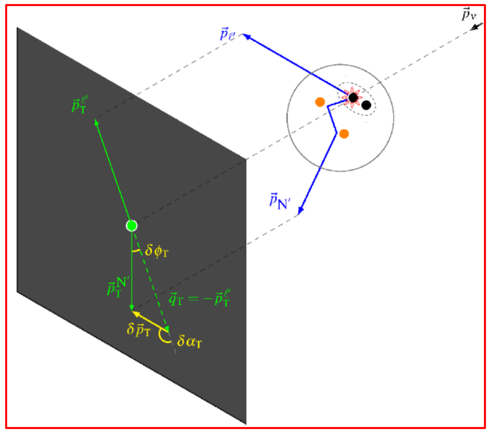


A physics whitebook for SBN@PBC

Since the physics capabilities of SBN@PBC are being clarified and we aim to have a proposal in about 2 years, we have started a systematic assessment of the physics potential. Such an effort is carried out by ENUBET+NuTAG in close collaboration with the CERN Neutrino Platform and our collaborators in DUNE and HyperKamiokande. In particular, we are assessing:

- The impact on inclusive cross sections for both neutrinos and antineutrinos
- A realistic simulation of ProtoDUNE, including light yield for timing measurements and cosmic ray rejection (ENUBET WG5, **in progress**)
- Deconvolution of double differential cross sections and constraints on nuclear model parameters
- Non-standard interactions, sterile neutrinos (see e.g. Phys.Rev.D 103 (2021) 035018) and, more generally, BSM physics.





This work is being pursued in parallel with the assessment of the feasibility and cost of the facility at CERN, which is the focus of **Marc Jebramcik's talk**.

Conclusions

PBC has fostered the creation of a shared effort to design a high-precision neutrino beam at CERN reaping the achievements of ENUBET and NuTAG. This effort is now in full swing and early results are very encouraging

- The physics goals are to produce cross sections with a precision of 1% in the energy range of interest for DUNE and HyperKamiokande
- The current design (see the next talk) already achieved this goal for the dominant cross-section systematics: the neutrino flux
- We achieved a significant improvement with respect to the original ENUBET design because the energy range was extended down to 1 GeV and the proton needs reduced by a factor of ~3
- Concerning the "energy challenge", we expect a typical energy resolution of 10-20% without neutrino tagging and a resolution of a few % with neutrino tagging
- We established the physics reach of the facility for inclusive cross-sections and working on differential cross-sections, exclusive processes, and physics beyond the standard model

We take this opportunity to thank CERN and PBC for such an important contribution!