A short-baseline neutrino beam for high-precision cross-section measurements

nuSCOPE Collaboration ☺

F. Terranova on behalf of the ~~SBN@CERN Proto-Collaboration~~ – i.e. the merger of the ENUBET and NuTag Collaborations

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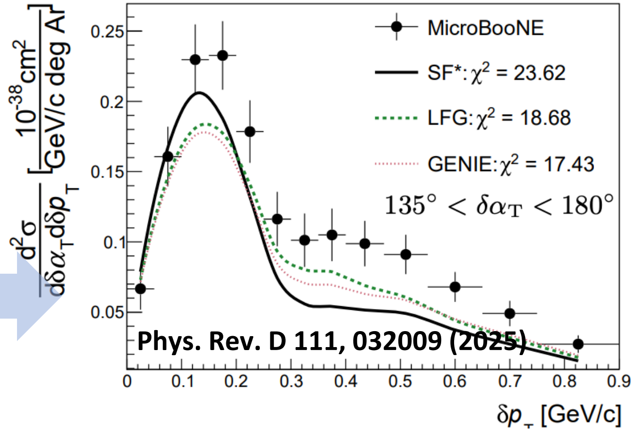
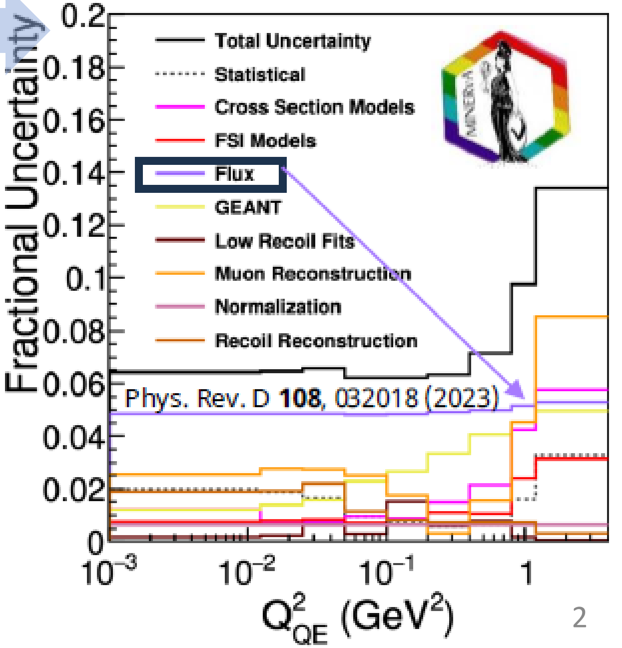
State of the Art circa 2025

A vibrant neutrino cross-section program using conventional beams over the past decade has significantly advanced our understanding of neutrino interactions in the energy range relevant for oscillation experiments, reducing uncertainties to the O(10%) level. However, several critical limitations have now become evident:

- Theoretical models **fail to reproduce high-statistics data** due to the complexity and richness of processes occurring in the nuclear medium during final-state particle interactions.
- Absolute cross section normalizations are typically affected by **flux uncertainties** in the 5-10% range
- Unlike electron–nucleon scattering, neutrino cross-section experiments **lack monochromatic beams**. As a result, cross-section measurements are usually averaged over a broad-band flux, rendering interpretation challenging. A significant **knowledge gap** persists between vector (e–N) and axial (ν–N) couplings, primarily due to the absence of a well-characterized neutrino source in terms of flavor, flux, and momentum.



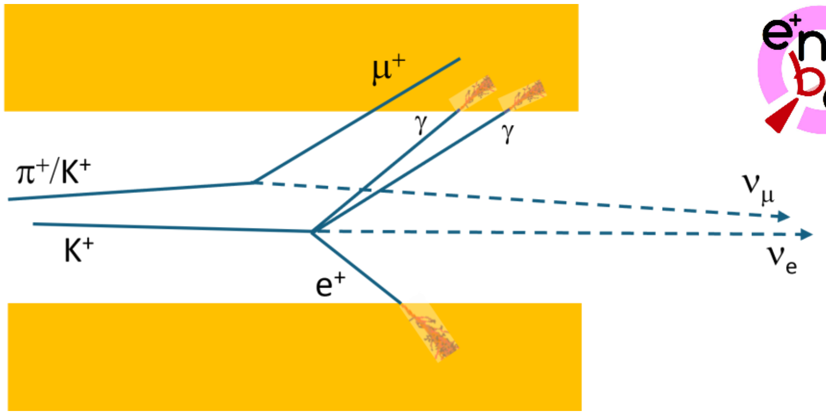


Neutrino monitoring and tagging

“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)

Monitoring: effective removal of systematic uncertainties associated with neutrino flux modelling

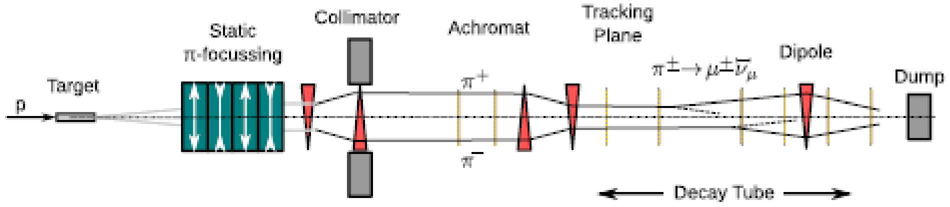
Pioneered in the 1980s, proposed with modern technologies in 2015 , R&D from the CERN NP06/**ENUBET** Collaboration



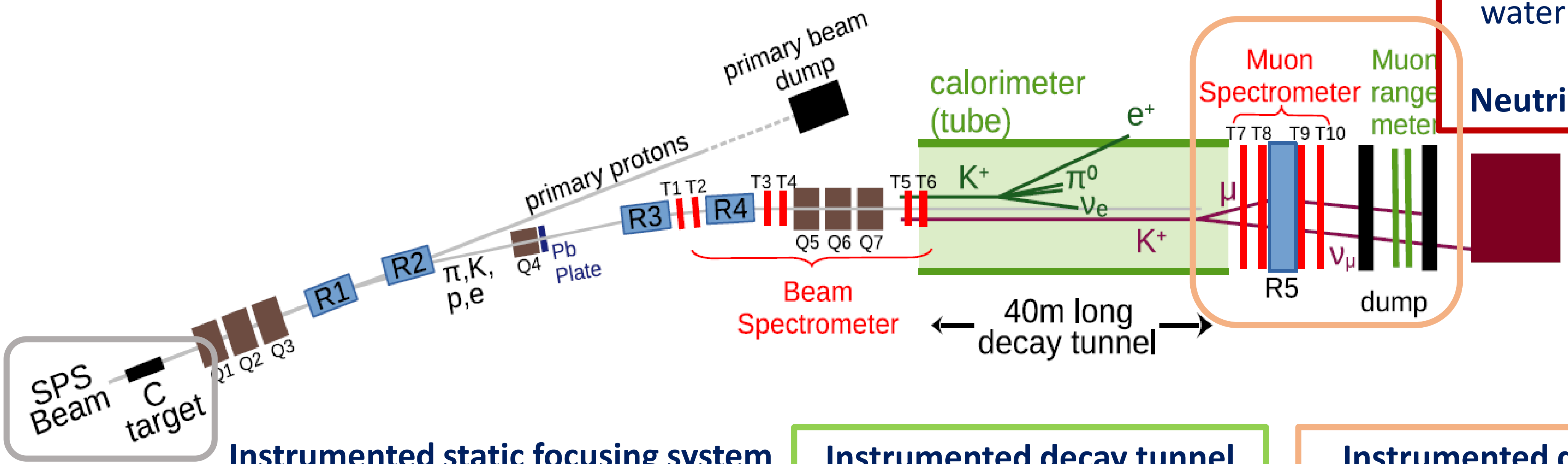
“If the time resolution of the particle detector in the tunnel and the neutrino detector outside the tunnel is very good (below 1 ns), the experimenters can associate unambiguously the neutrino observed in the detector with the charged lepton recorded in the tunnel.” (Wikipedia)

Tagging: Event-by-event knowledge of incoming neutrino energy

Proposed in the 1970s, developed in USSR in the 1980s, proposed with modern techniques in 2022, R&D from the NP06 and **NuTAG** Collaborations



The nuSCOPE implementation



Liquid argon and water Cherenkov/ WBLS
Neutrino detectors

Proton accelerator:
CERN SPS (400 GeV/c)
Carbon target

Instrumented static focusing system
Two quadrupole triplet, four dipoles, six silicon trackers for momentum measurement and tagging

Instrumented decay tunnel
Segmented Fe-scint calorimeter for lepton monitoring in the tunnel wall

Instrumented dump
Muon spectrometer and muon range-meter

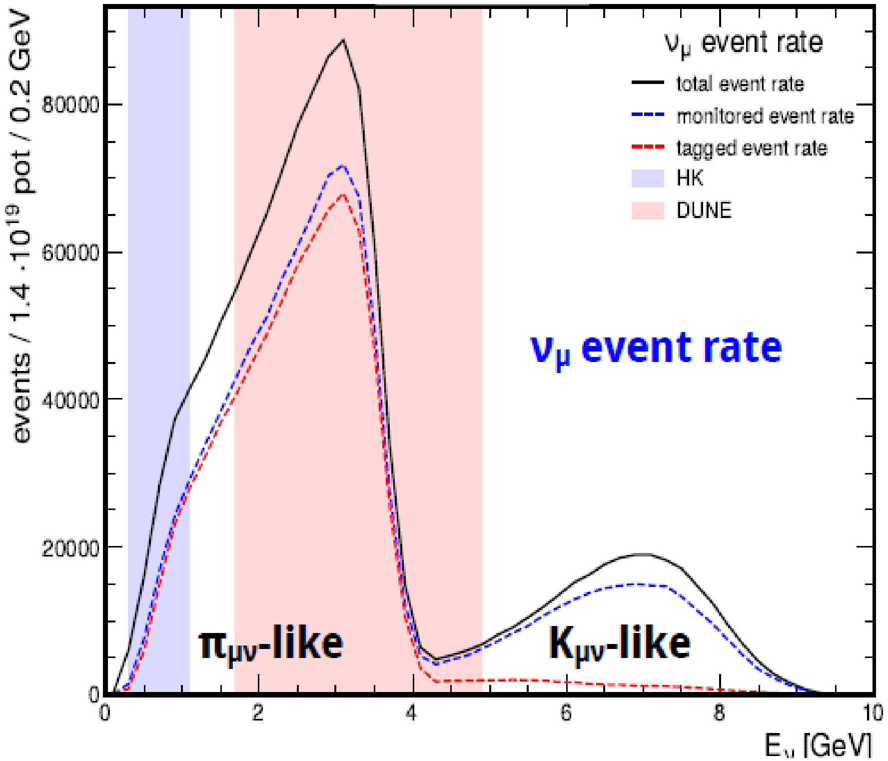
The CERN implementation exploits

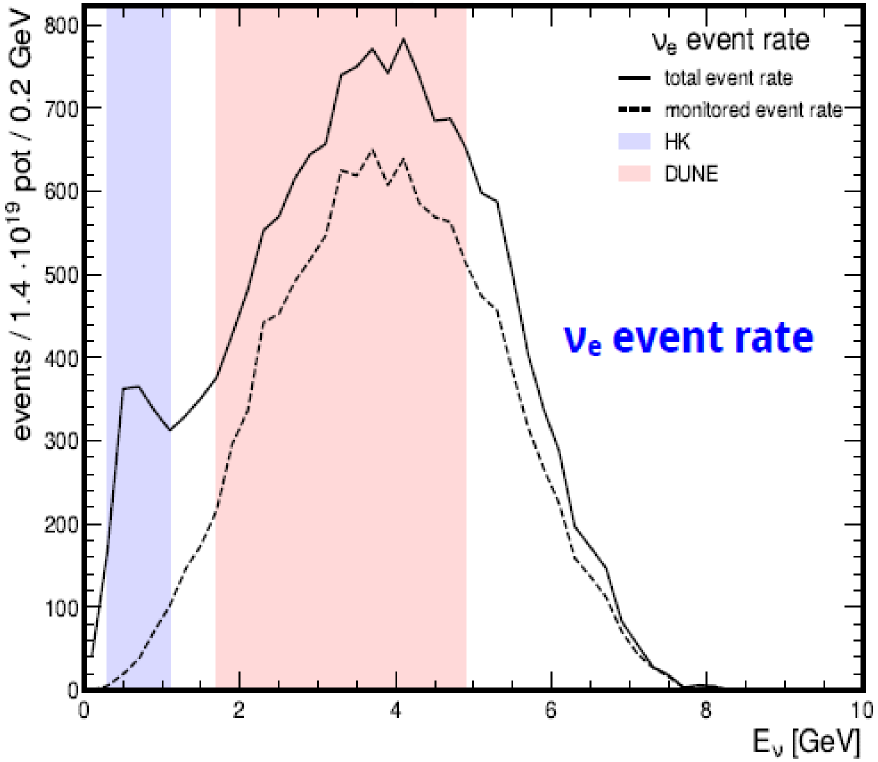
- An instrumented decay tunnel and muon range-meter to monitor the number of $K \to \pi^0 e \nu_e$, $\pi \to \mu \nu_\mu$, and $K \to \mu \nu_\mu$ decays, and to directly measure the ν_e and ν_μ fluxes from pions and kaons (**monitoring**).
- A static focusing system and muon spectrometer to tag pions/kaons and the muons from $\pi \to \mu \nu_\mu$ and $K \to \mu \nu_\mu$ decays. These are time-associated with the ν_μ observed in the detector, allowing reconstruction of the neutrino energy from the two-body kinematics of the parent K and π (**tagging**).

Beam performance and expected statistics

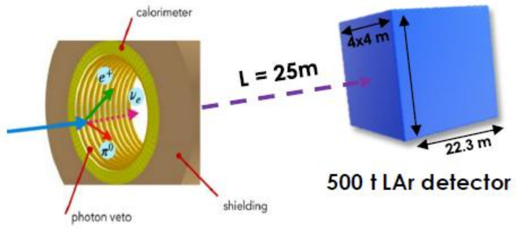
Reference setup:

- A 5-y neutrino run mode with 8.5 GeV momentum secondaries [dedicated low energy runs and anti-neutrino modes under evaluation]
- A 500 ton liquid argon detector 4x4 m^2 face; length: 22.3 m, distance: 25 meter from the hadron dump
- Collected statistics: 10^6 ν_μ CC events, 12000 ν_e CC events
- Projected event spectra estimated with GENIE from the output flux of the nuSCOPE BDSIM simulation. Flux systematics from the ENUBET analysis. Tagging efficiency from tracker simulations.





	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5

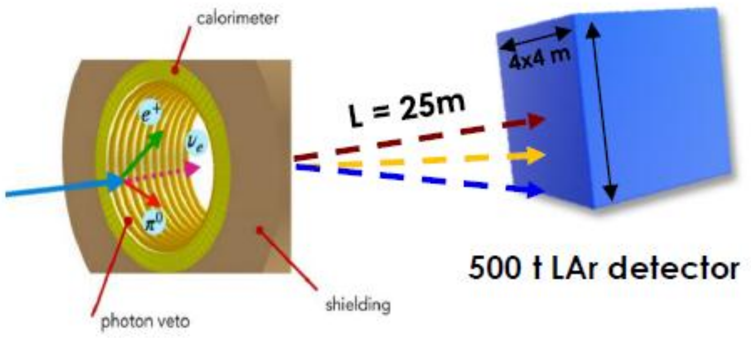


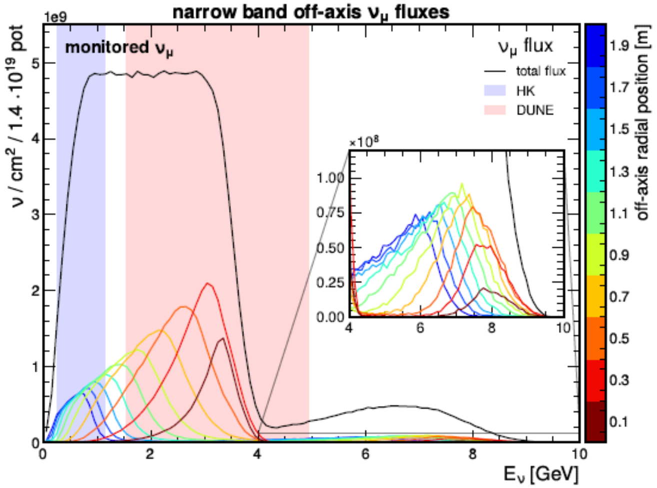
Physics performance

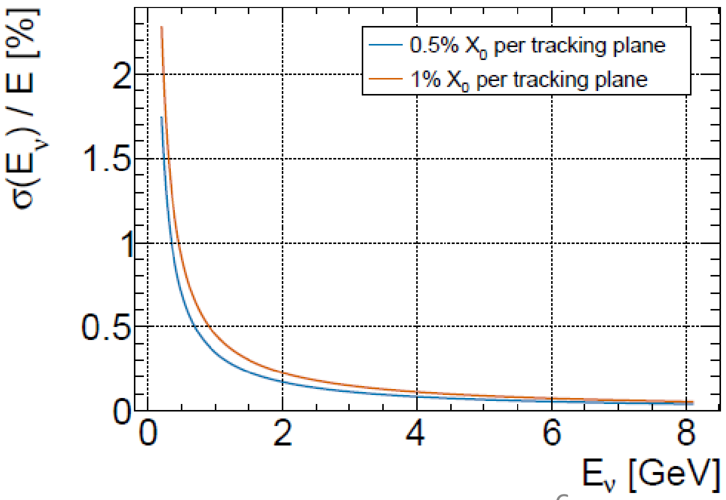
This facility addresses the most relevant issues for a full understanding of neutrino cross sections, especially for oscillation experiments. Monitoring provides **unprecedented control of the flux and a moderate precision on the initial neutrino energy** through the "Narrow band off axis" technique. Tagging, although technically more challenging, offer **superior energy resolution** for the incoming neutrino energy.

The "Narrow-band off-axis" technique exploits the observed neutrino interaction vertex, since its distance from the beam axis correlates with the neutrino energy—provided the parent meson momentum has a small spread (10% in nuSCOPE).

"Neutrino tagging" (≈80% of the full ν_μ CC sample from π decay for a 300ps detector time resolution): the energy is reconstructed from the parent kinematics. It thus offers a golden sample of tagged neutrino with **sub-percent energy resolution**







What will we be measuring?

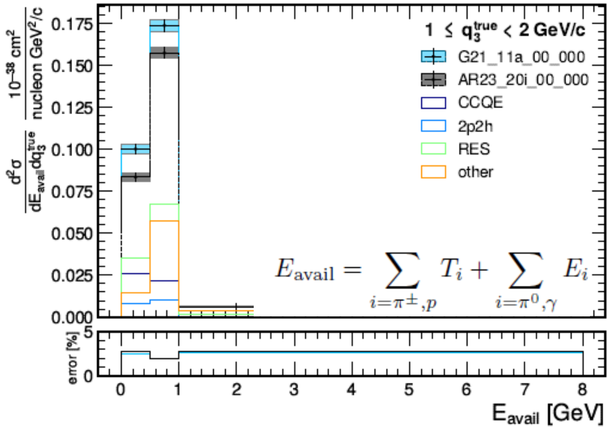
The energy dependence of the neutrino cross section	So, we know how to extrapolate from our near to far detectors in oscillation experiments
The smearing of our neutrino energy reconstruction	So we can infer the shape of the oscillated spectrum in DUNE/HyperKamiokande
The differences in the cross section for ν_e and ν_μ	So we can reliably use ν_e appearance to probe CP-violation
The interaction channels that constitute backgrounds in DUNE/HyperKamiokande (e.g. NCπ^0 production)	So we know how to interpret far detector event rates
ν-N elastic scattering with tagged ν_μ	The axial counterpart of e-N elastic scattering
Many other channels not covered in this talk because they are work in progress	Exclusive channels, non-standard interactions, dark sector probes, sterile neutrinos, etc.

What will we be measuring?

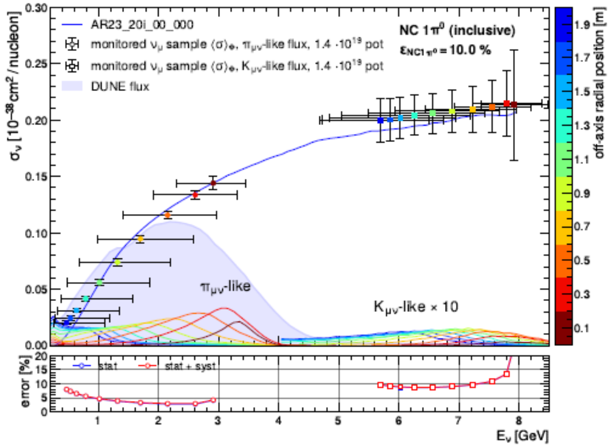
The energy dependence of the neutrino cross section → See below

The smearing of our neutrino energy reconstruction → See below

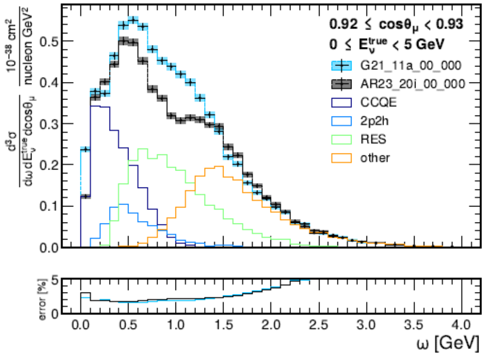
The differences in the cross section for ν_e and ν_μ

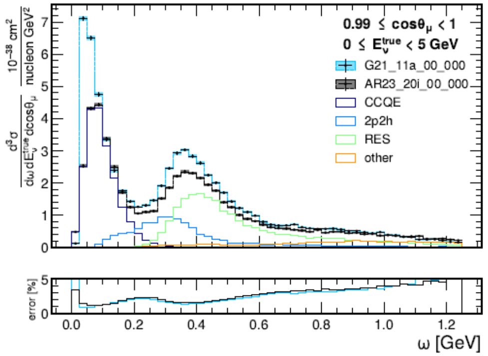


The interaction channels that constitute backgrounds in DUNE/HyperKamiokande (e.g. $NC\pi^0$ production)



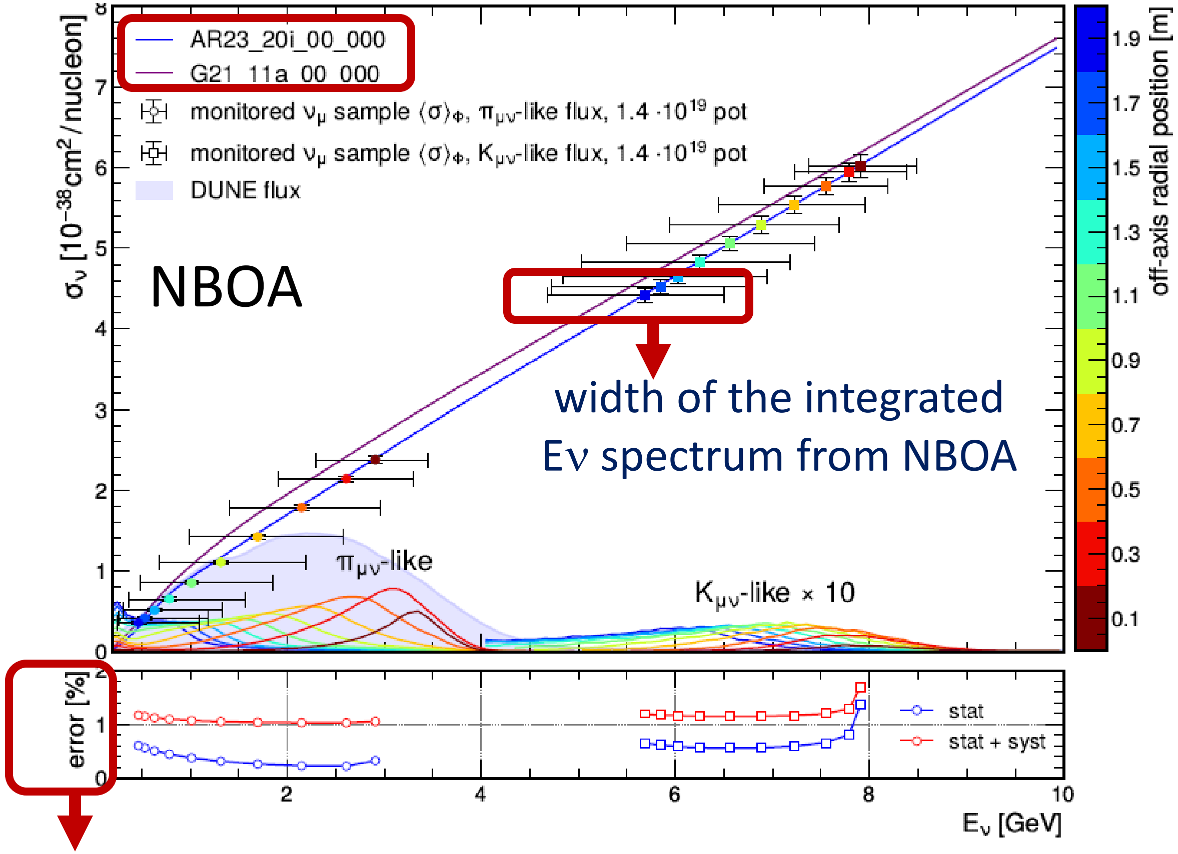
ν-N elastic scattering with tagged ν_μ





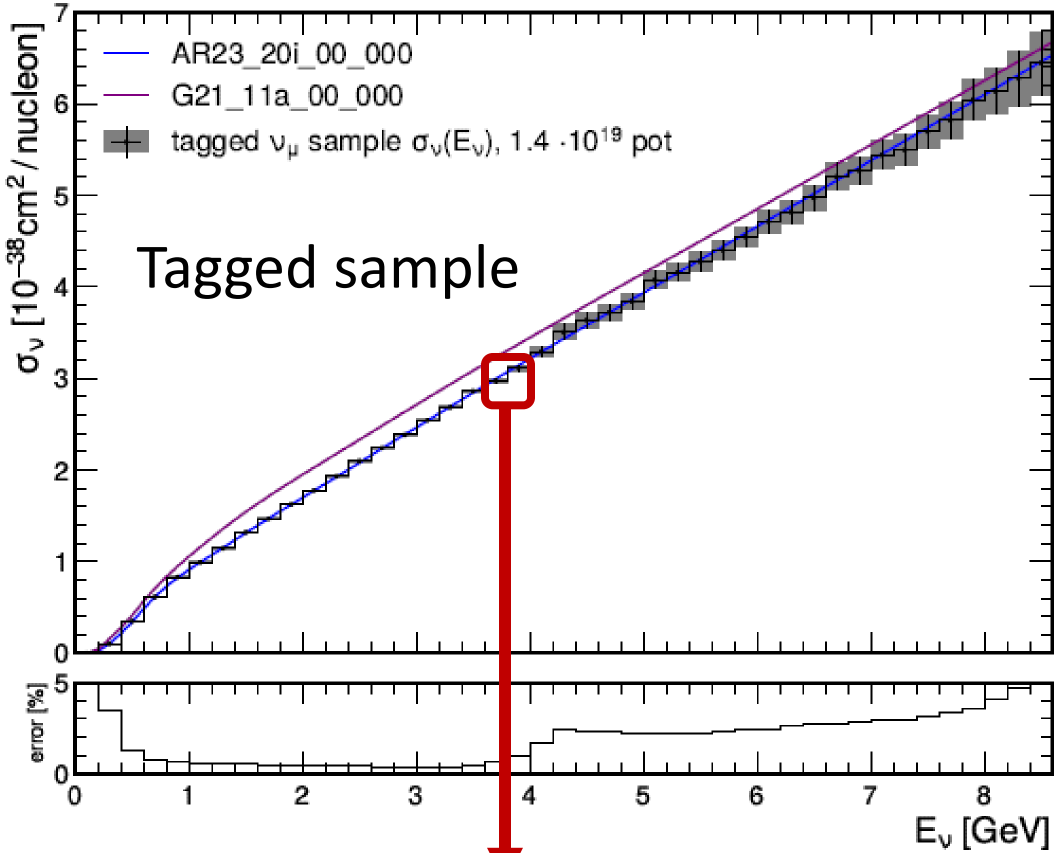
The energy dependence of ν_μ cross section

it illustrates sensitivity to theory models



width of the integrated $E\nu$ spectrum from NBOA

stat.+sys. error

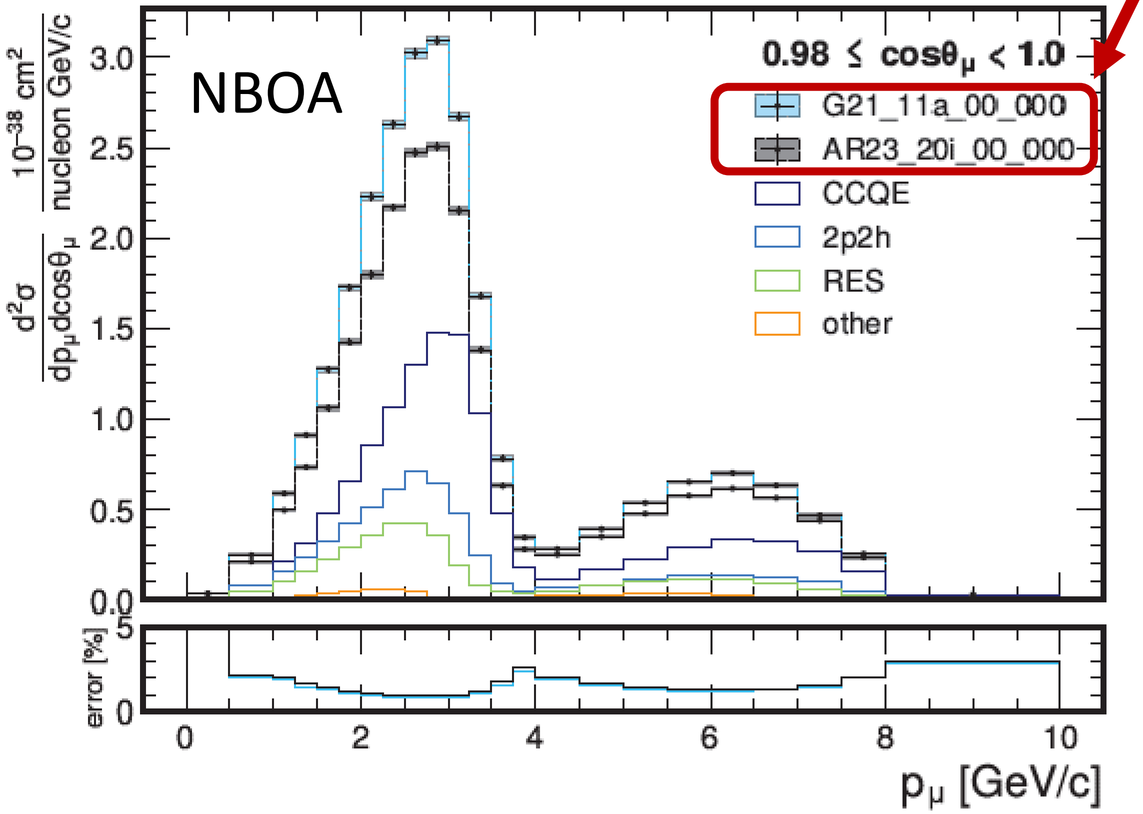


in the golden tagged sample, the integration width is no more driven by the energy uncertainty (<1% !!) but just by statistics

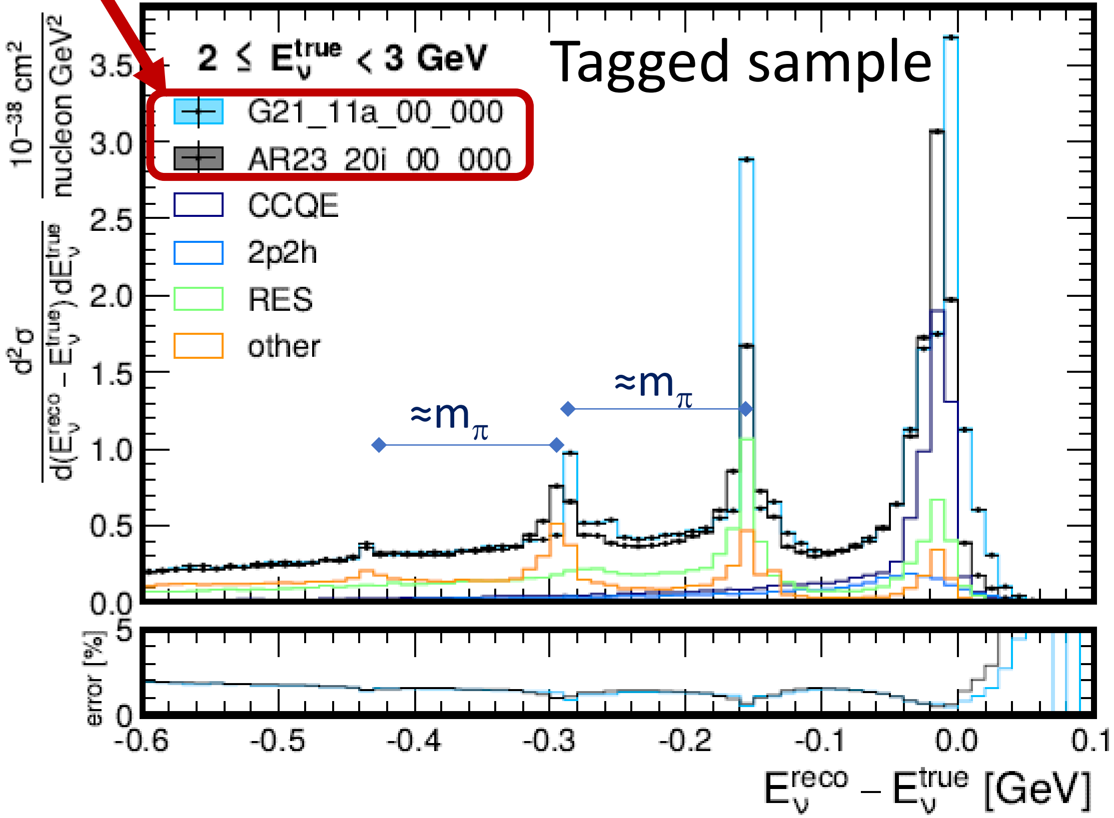
The smearing of reconstructed neutrino energy due to nuclear effects

We can address this key issue by performing high-precision measurements of double differential cross sections using the NBOA technique or by directly measuring the energy bias from the tagged neutrino sample.

it illustrates sensitivity to theory models

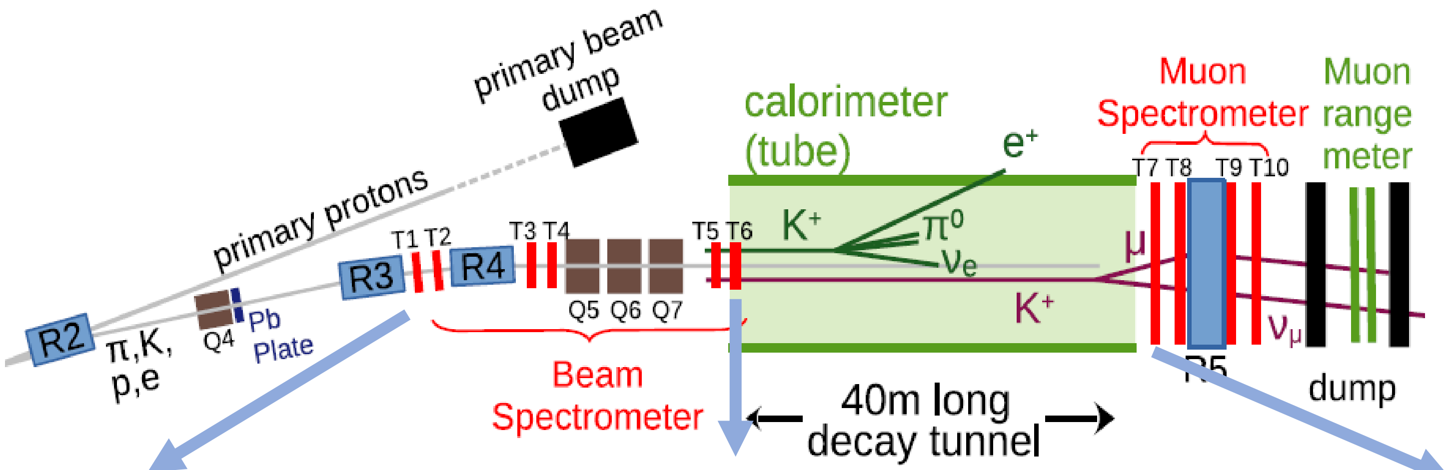


Without **monitoring**, the double differential cross section for “quasi elastic” (CC0π) would be systematic limited

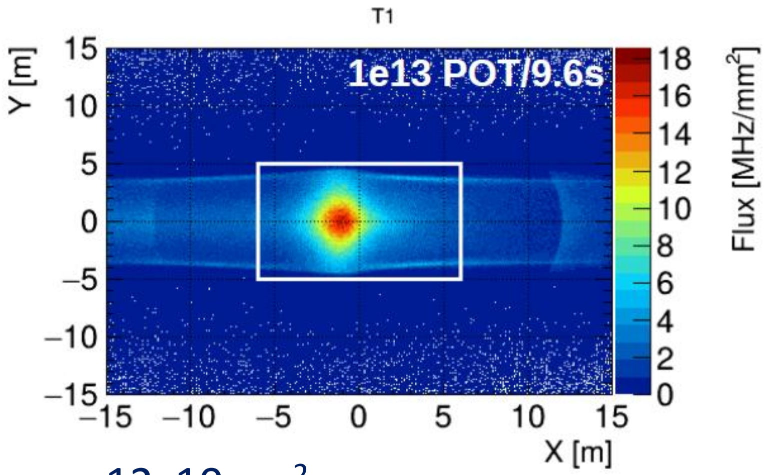


The **tagged** sample employs the knowledge of the “true” neutrino energy to directly measure the energy bias in bins of E_{true}

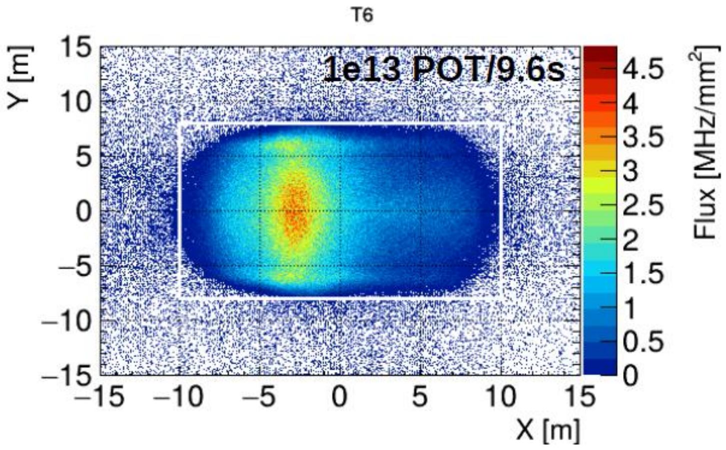
Meson and muon tracking



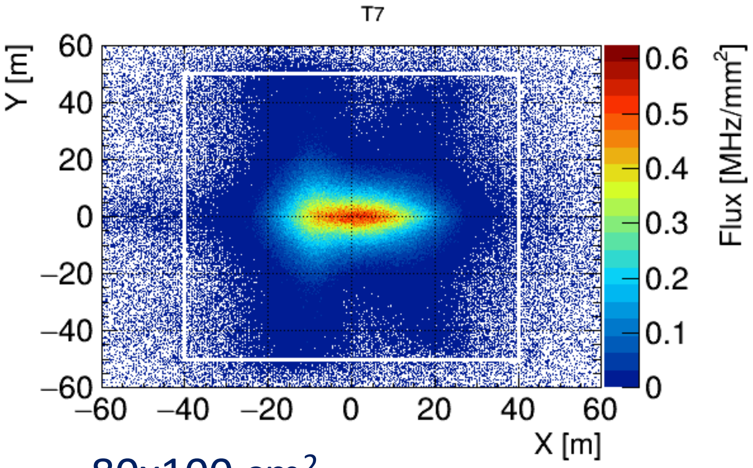
Silicon detectors are needed only at the core of the tracking planes. Scintillating fiber planes are sufficient to instrument the outer radii



12x10 cm^2



20x16 cm^2



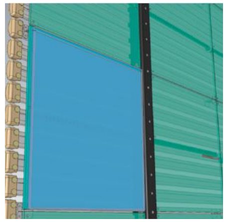
80x100 cm^2

Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [1MeVn$_{eq}$/cm^2]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	10 – 100	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X$_0$]	< 1%		0.8%	0.5%

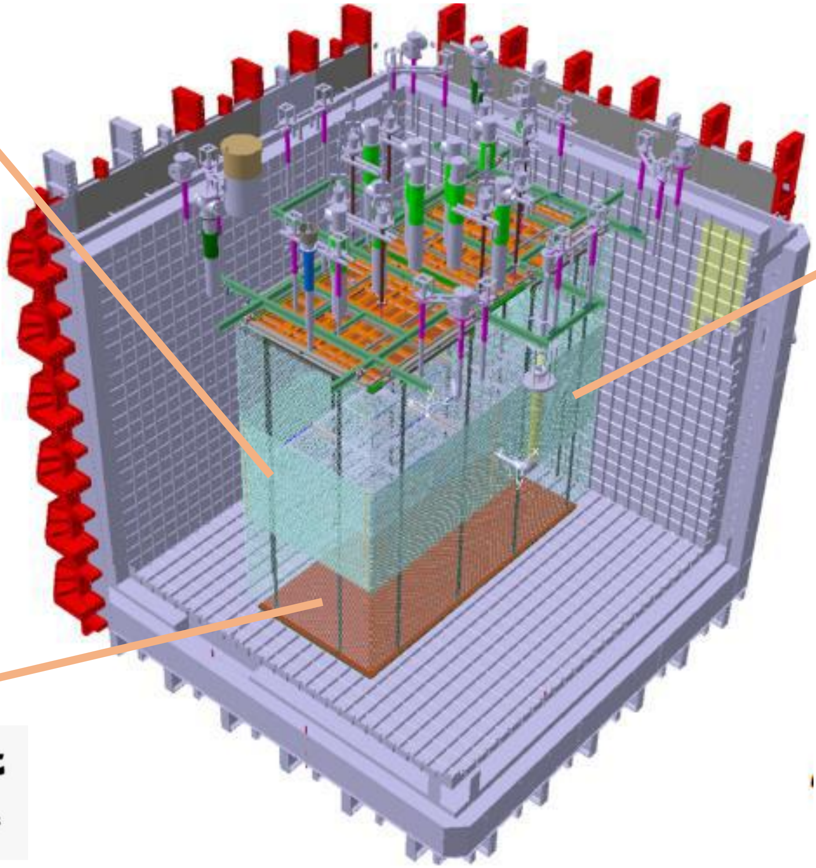
Liquid argon detector

The Liquid Argon TPC technology developed by DUNE, in both its "Horizontal Drift" and "Vertical Drift" configurations, meets all the specifications of nuSCOPE except for the time resolution in tagging mode, which should be in the 200-500 ps range. It is limited by the light collection efficiency due to poor coverage. This limitation will be overcome by the third and fourth DUNE modules, which anticipate full 4π photon coverage.

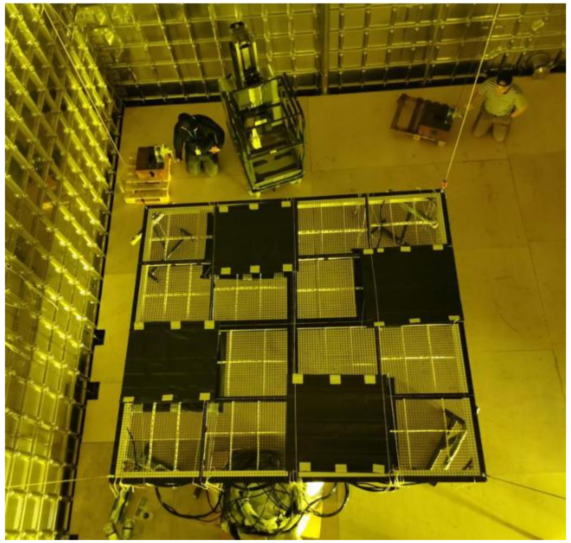
Field cage equipped with Photon Detectors (128 nm)



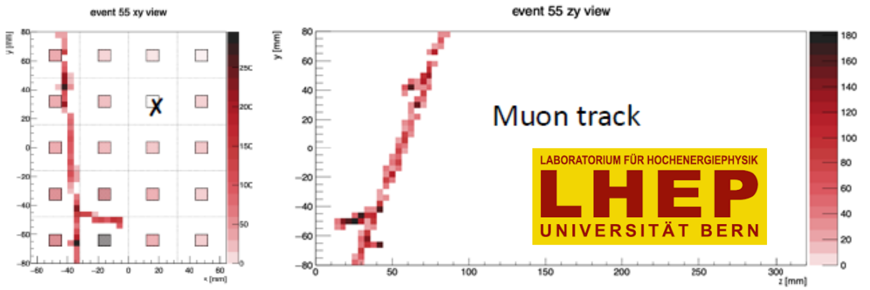
ProtoDUNE-VD Run III (2027-28)



Cathode equipped with Photon Detectors (128 nm) as in DUNE Vertical Drift, validated in ProtoDUNE-VD (2025)



Anode equipped with VUV (128 nm) SiPMs



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Conclusions

- Improving our knowledge of neutrino cross sections at the GeV scale by an order of magnitude is essential to unlock the full physics potential of future neutrino oscillation experiments. This would also represent a major advance in our understanding of electroweak nuclear physics.
- The technology for neutrino monitoring and tagging has reached maturity, thanks to the efforts of the ENUBET and NuTAG collaborations from 2016 to 2024.
- We are now ready to propose a new facility to tackle this field with percent-level precision, with the goal of implementing it at CERN.
- The physics case is compelling, and we are continuing to explore its full potential.
- The technology readiness is well advanced, but key challenges remain regarding CERN integration, meson tracking, and sub-nanosecond neutrino detection.

A new international collaboration is now forming. We aim to bring together experts in neutrino cross sections, collaborators from DUNE and HyperKamiokande, and detector specialists — including those involved in the development of NA62 and LHCb technologies.

We are organizing a dedicated workshop at CERN on October 13-14.
We look forward to seeing you there!