A Monitored and Tagged Neutrino Beam at CERN for High-Precision Cross-Section Measurements

nuSCOPE Collaboration ☺

F. Terranova on behalf of the ~~SBN@CERN Proto-Collaboration~~

University of Milano-Bicocca & INFN Milano-Bicocca

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Aims of this Seminar

After ≈8 years of R&D, a new technology has emerged as a potential paradigm shift in the production of artificial neutrino beams. Unlike Superbeams (T2K, NoVA, DUNE, Hyper-Kamiokande), these beams offer unprecedented control over the neutrino source and will enable a new generation of cross-section experiments targeting percent-level precision in neutrino–nucleus scattering.

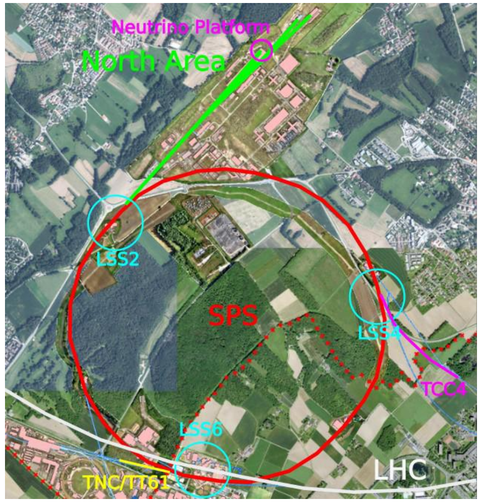
We believe this technology meets the goals set by the 2020 update of the European Strategy for Particle Physics (ESPPU).

DELIBERATION DOCUMENT
ON THE 2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

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 complementary

We are currently establishing an international collaboration to build the first monitored and tagged neutrino beam at the CERN SPS.

We have submitted a detailed input document to the 2026 ESPPU available here



Neutrino cross sections in the 2030s

Achieving percent-level precision in neutrino cross sections at the GeV scale is urgent if we want to fully exploit the physics potential (and the investment!) of DUNE and Hyper-Kamiokande.

Current long-baseline experiments

	T2K	NOvA
Baseline	295 km	800 km
N_μ^{rec} (ν-mode)	318	384
N_e^{rec} (ν-mode)	94	181

Current systematic uncertainties

Uncertainty on N_e^{rec}	T2K	NOvA
Cross Sections	**~4%**	**~3.5%**
All Syst.	**~5%**	**~3.5%**

Future long-baseline experiments

	Hyper-K (arXiv:1805.04163)	DUNE (arXiv:2002.03005)
Baseline	295 km	1300 km
N_μ^{rec} (ν-mode)	~10000	~7000
N_e^{rec} (ν-mode)	~2000	~1500

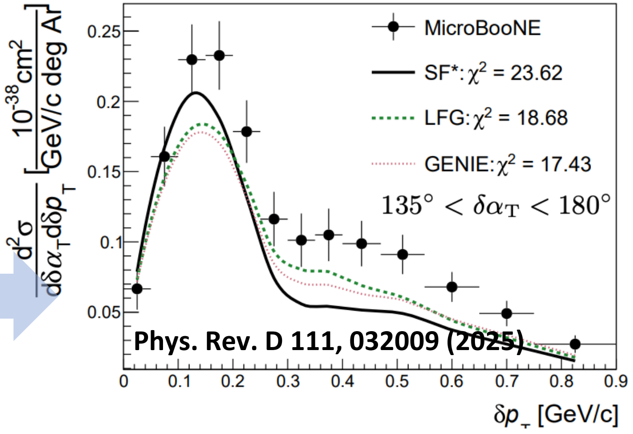
In the 2030s, DUNE and Hyper-Kamiokande will be completely limited by cross-section systematic uncertainties.

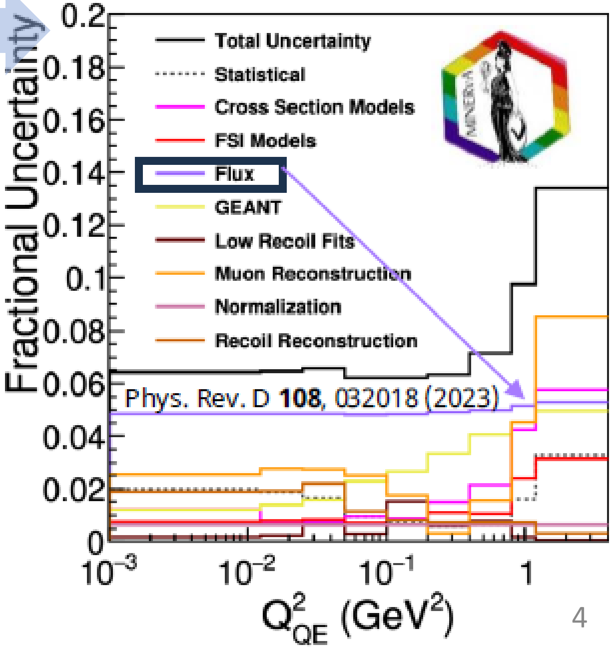
The lack of precision in neutrino cross-section measurements jeopardizes the €3B investment being made in high-precision oscillation experiments. **New cross-section experiments have a compelling physics case—equivalent to roughly doubling the mass of DUNE and Hyper-Kamiokande**.

State of the Art circa 2025

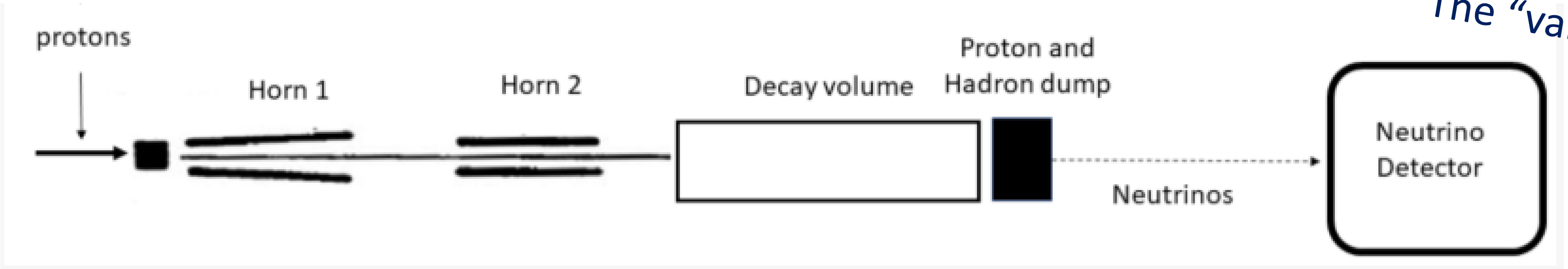
A vibrant neutrino cross-section program using conventional beams over the past decade has significantly advanced our understanding of neutrino interactions in the energy range relevant for oscillation experiments, reducing uncertainties to the O(10%) level. However, several critical limitations have 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 (ν–N) and axial (ν–N) couplings, primarily due to the absence of a well-characterized neutrino source in terms of flavor, flux, and momentum.





Re-thinking artificial neutrino beams



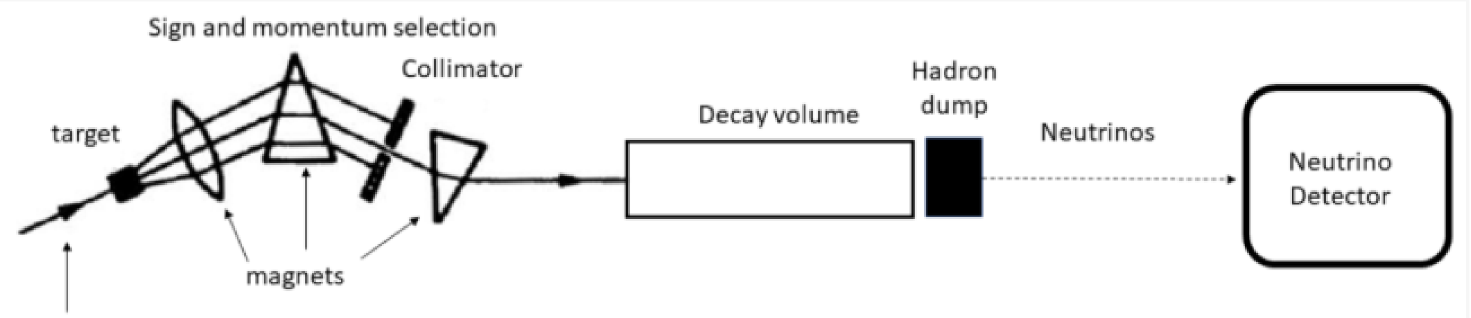
The "van der Meer paradigm"

	"Employ the most intense proton accelerator at your disposal"	"Focus as many pions/kaons as possible"	"Eliminate any material along the beamline in the decay tunnel"	"Build the largest possible neutrino detector"
Pros:		Large yield of pions per proton-on-target (pot)	Large number of neutrinos from pion decay	Large statistics of neutrino interaction events (CC and NC)
Drawbacks:		Lack of control on neutrino energy	Coarse beam diagnostics	Limited precision in the final state reconstruction

LBNF/DUNE is.... the FCC of the van der Meer paradigm ☺

But we don't need such an intense (and coarse) source to measure cross sections!

A new paradigm for high-precision beams



	protons over a long extraction (2-10 s)	horn-less static focusing system based on dipole/quadrupoles	instrumented decay tunnel	high granularity, fast, neutrino detectors

Pros:

- We select secondaries in a narrow energy band. We can track pions at single particle level using fast silicon tracker (tagging)
- We can measure charged leptons associated with the neutrino decay (direct monitoring of flux)
- Exquisite reconstruction of interaction vertex (NBOA – see later) and final state particles. Time correlation with parent pion and daughter muon (tagging)

Drawbacks:

- Limited neutrino beam intensity
- Need for fast, rad-hard detectors
- Limited statistics

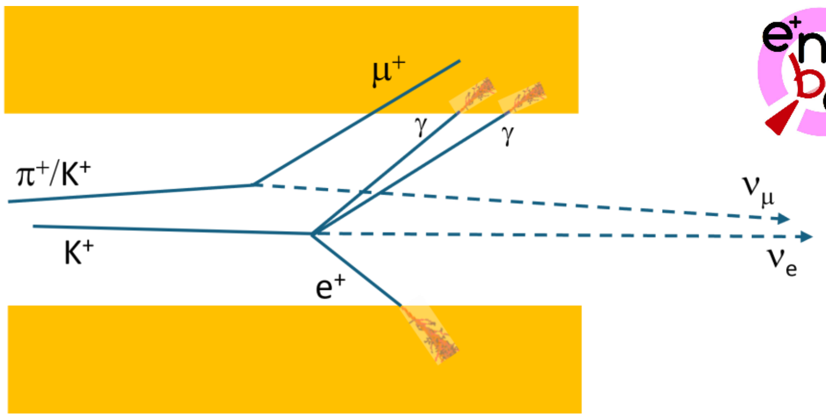
nuSCOPE is.... the LEP of neutrinos ☺ - we trade power for precision. It is ideally suited for **cross section measurements** and precision/BSM physics (NSI, sterile neutrinos, dark photons, etc.)

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

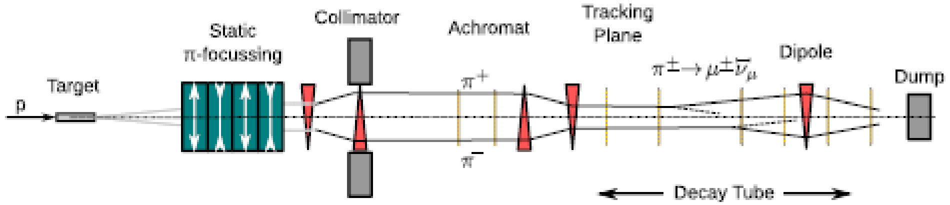
Pioneered in the 1980s, proposed with modern technologies in 2015 , R&D from the CERN NP06/**ENUBET** Collaboration



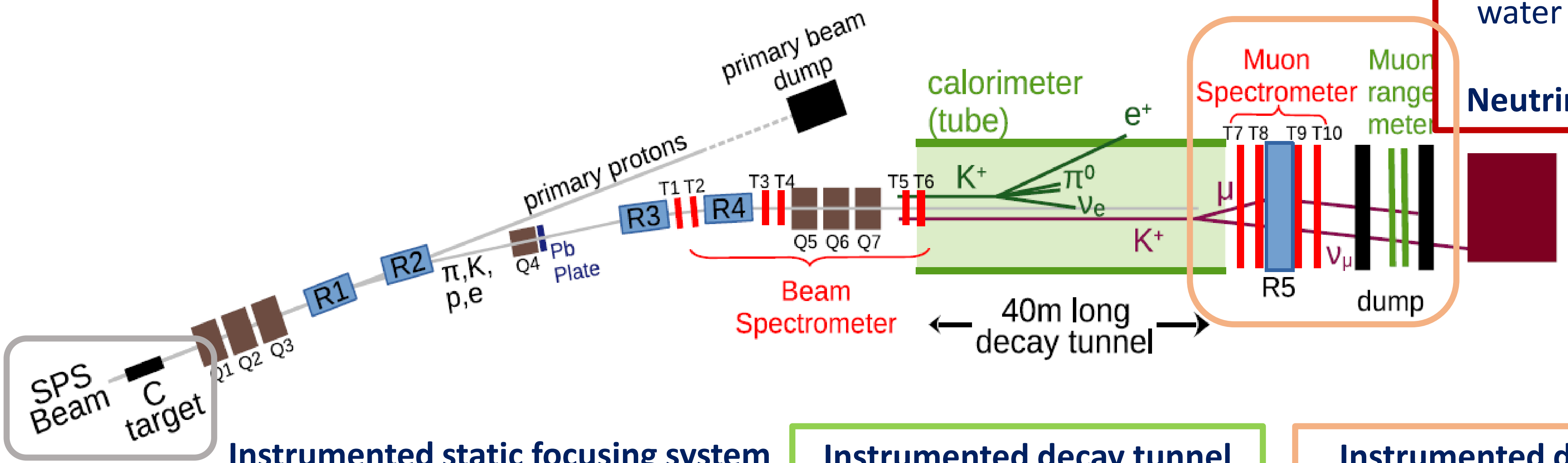
"If the time resolution of the particle detector in the tunnel and the neutrino detector outside the tunnel is very good (below 1 ns), the experimenters can associate unambiguously the neutrino observed in the detector with the charged lepton recorded in the tunnel." (Wikipedia)

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 ν_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**).

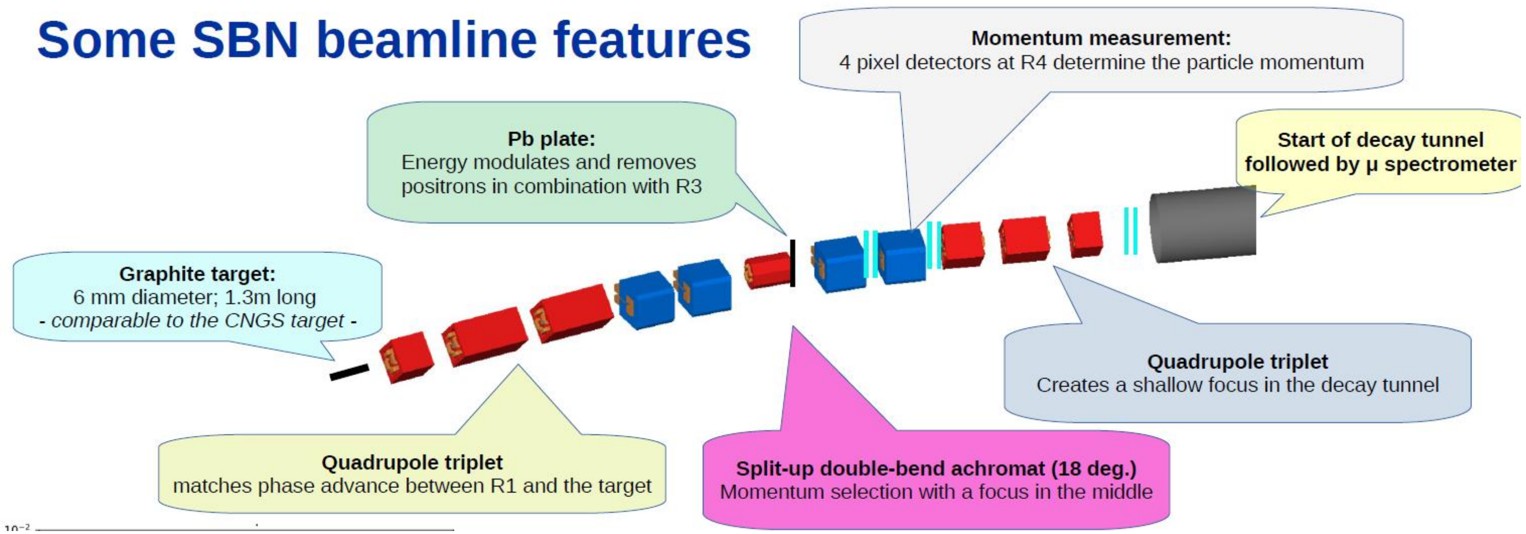
Beam parameters and optimization

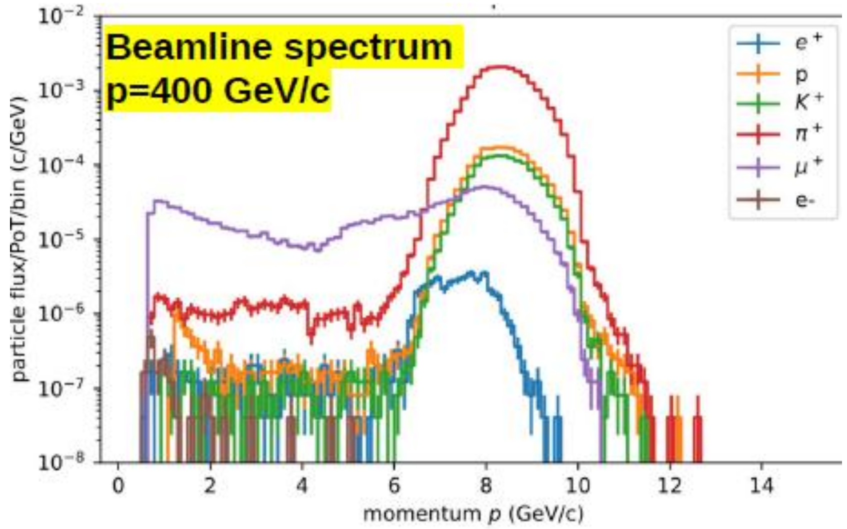
The beamline design originates from the ENUBET design but has been re-optimized to:

- achieve the original ENUBET physics goals with a number of protons compatible with the CERN fixed target program, including SHiP
- reduce the instantaneous meson rate in the final dipoles to a level compatible with particle tracking (silicon trackers)
- Suppress intrinsic backgrounds, such as neutrinos originating outside the decay tunnel that hit the detector, and positrons produced by tertiary interactions.
- Enable a realistic implementation within the CERN accelerator complex.

Parameter	Value
Primary proton energy	400 GeV/c
Beamline momentum (mesons)	up to 8.5 GeV/c
Extraction type	slow: 4.8s or 9.6s from the SPS
Spill intensity	1.0E13 protons/spill
Event rate	1 – 2 THz
Instantaneous power	170 – 340 W
K^+ / π^+ per proton	1.3E-3 / 1.9E-2
K^+ / π^+ rate	up to 2.7 GHz / 40 GHz
Annualized proton requirement	2E18 – 3E18 protons/year
Total proton requirement (1% stat. error on ν_e x-section)	1.4E19 protons
Beamline length to decay tube	23 m
Bending magnet strength	1.8 T

Some SBN beamline features

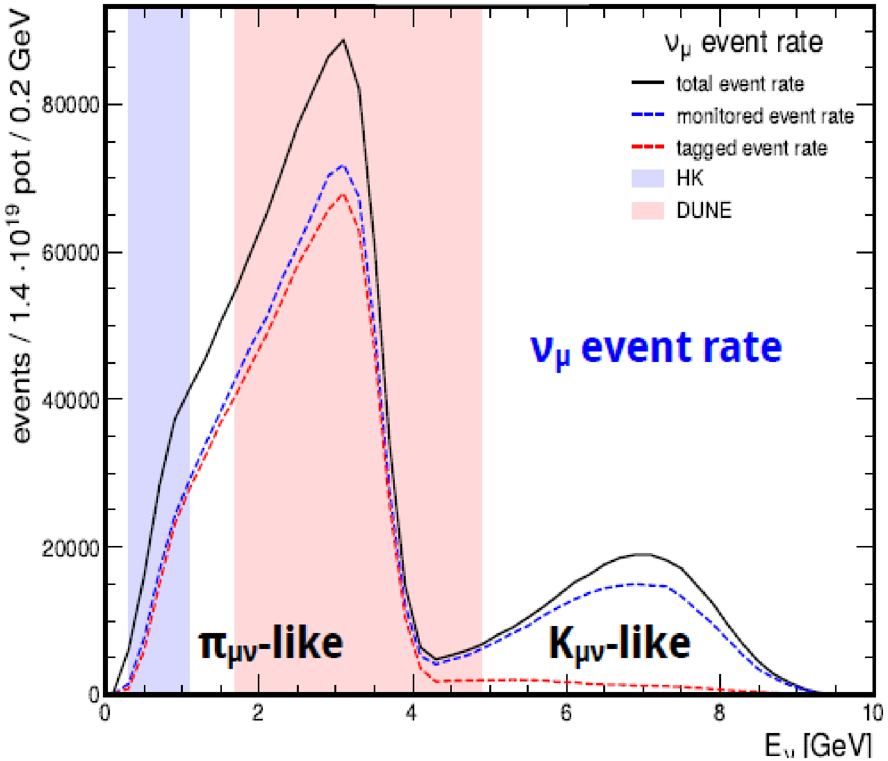


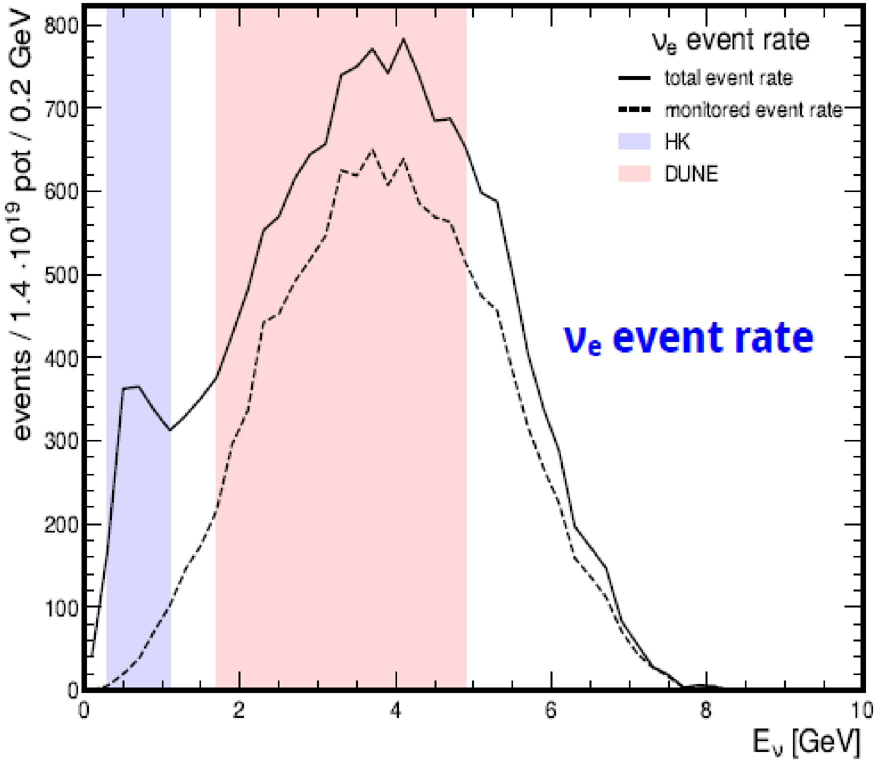


Beam performance and expected statistics

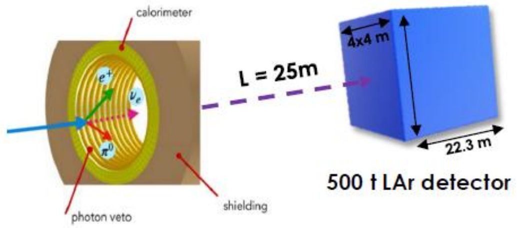
Reference setup:

- 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.



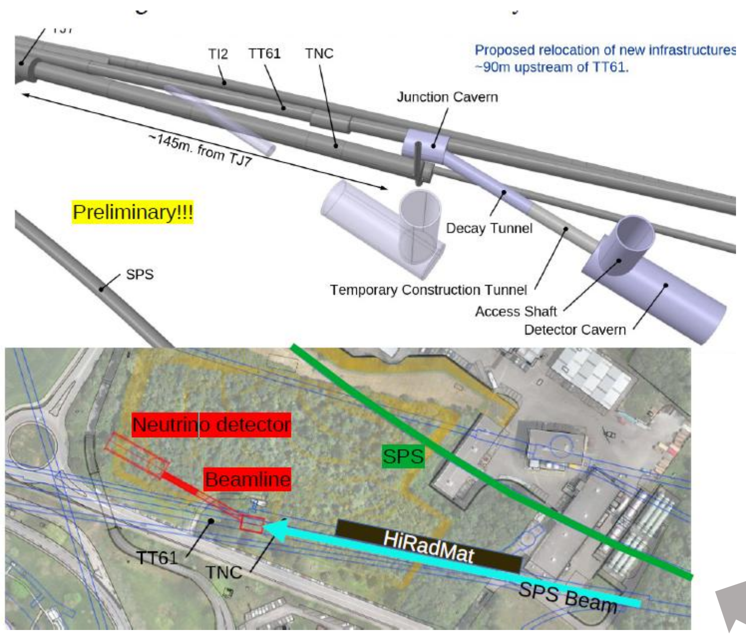


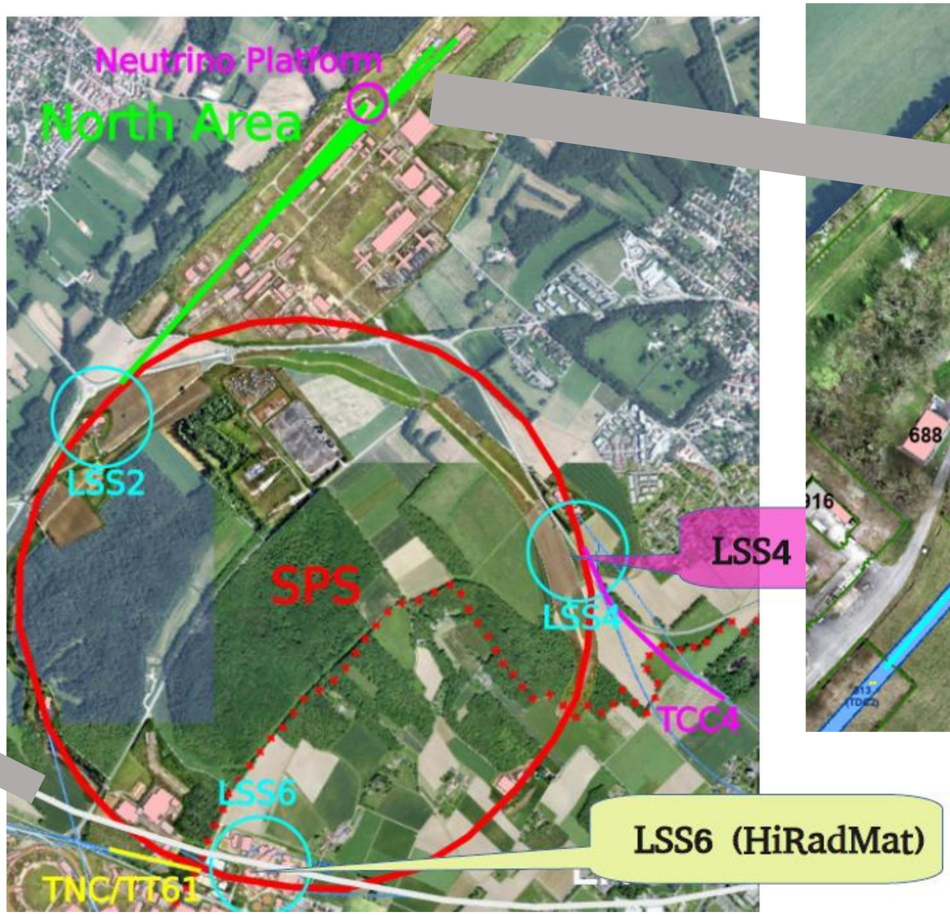
	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5



Implementation in the CERN accelerator complex

The implementation of the facility in the CERN complex is currently being studied in the framework of the CERN Physics Beyond Collider (PBC) program. The most promising locations are in a new experimental Hall (ECN4) in the Prevessin campus and in an extension of existing tunnels near the SPS Long Straight Section 6 (LSS6), close to HighRadMat in the Meyrin Campus. Some of the work affecting the LHC injector needs to be done in a Long Shutdown





Pros and cons

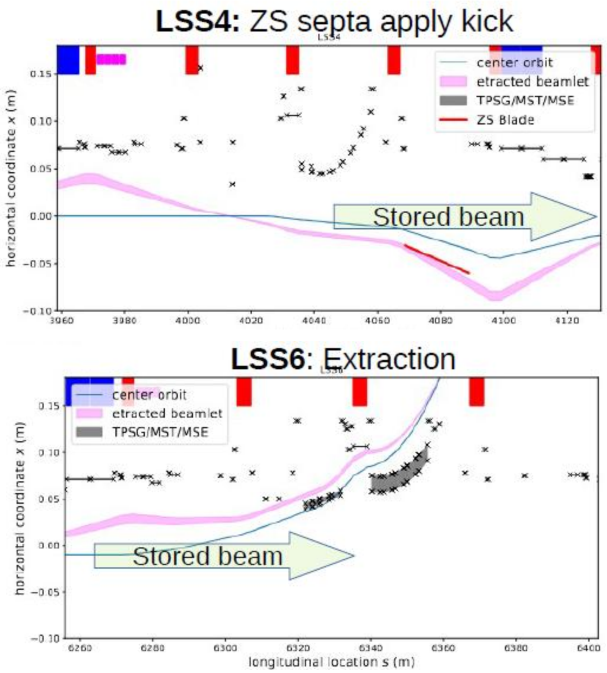
ECN4 (North Area, Prevessin):

- A dedicated experimental hall provides greater flexibility for detector installation and the addition of new detectors for cross-section studies with specific targets.
- Slow extraction is already implemented in LSS2.
- The beam splitter presents significant technical challenges.
- Neutrino detectors have minimal overburden, leading to increased cosmic ray background during long extractions.
- May require a dedicated cycle for nuSCOPE, potentially increasing the impact on proton availability for other experiments.

In both cases, nuSCOPE requires <25% of the TCC2 intensity and, hence is compatible with the CERN fixed target programme in 2030-40

TNC/TT61/TCC6 (East Area, Meyrin) – currently our favorite option:

- Detectors are located underground
- Minimal interference with proton sharing among fixed target experiments
- Requires enlargement of existing tunnels to accommodate neutrino detectors.
- Implementation of a non-local slow extraction is needed, similar to the system used at the PS.



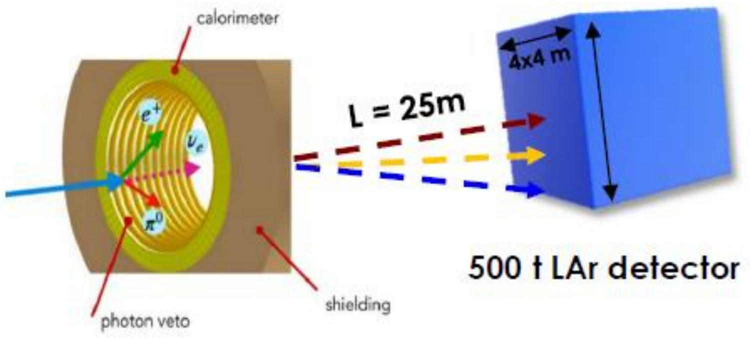
M. Jebramcik et al., CERN-PBC-NOTE 2024-006

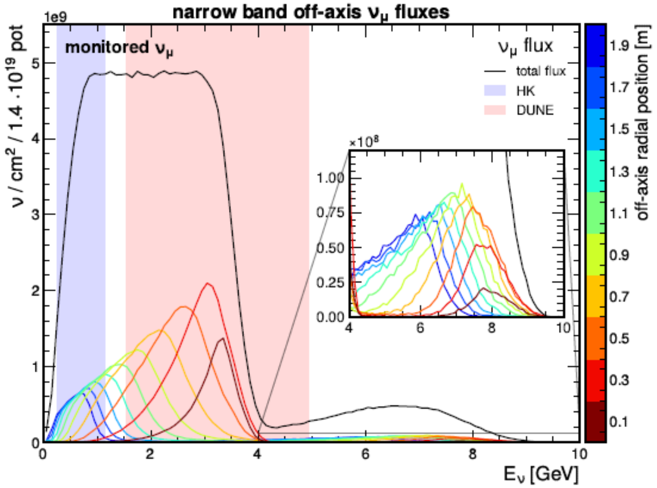
Physics performance

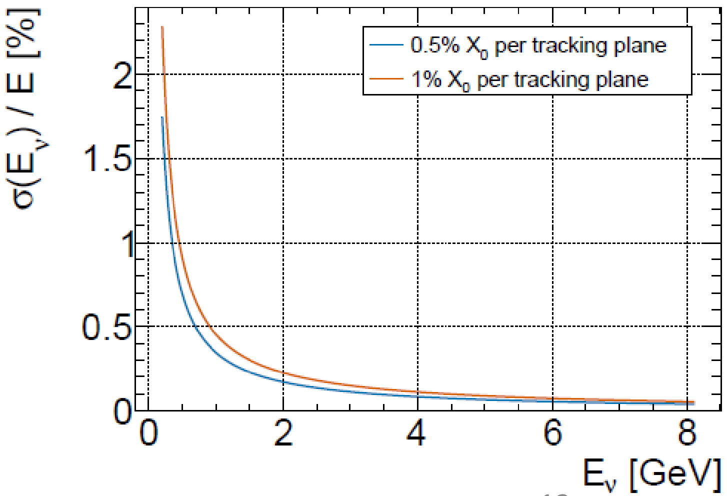
This facility addresses the most relevant issues for a full understanding of neutrino cross sections, especially for oscillation experiments. Monitoring provides **unprecedented control of the flux and a moderate precision on the initial neutrino energy** through the "Narrow band off axis" technique. 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. NC π^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

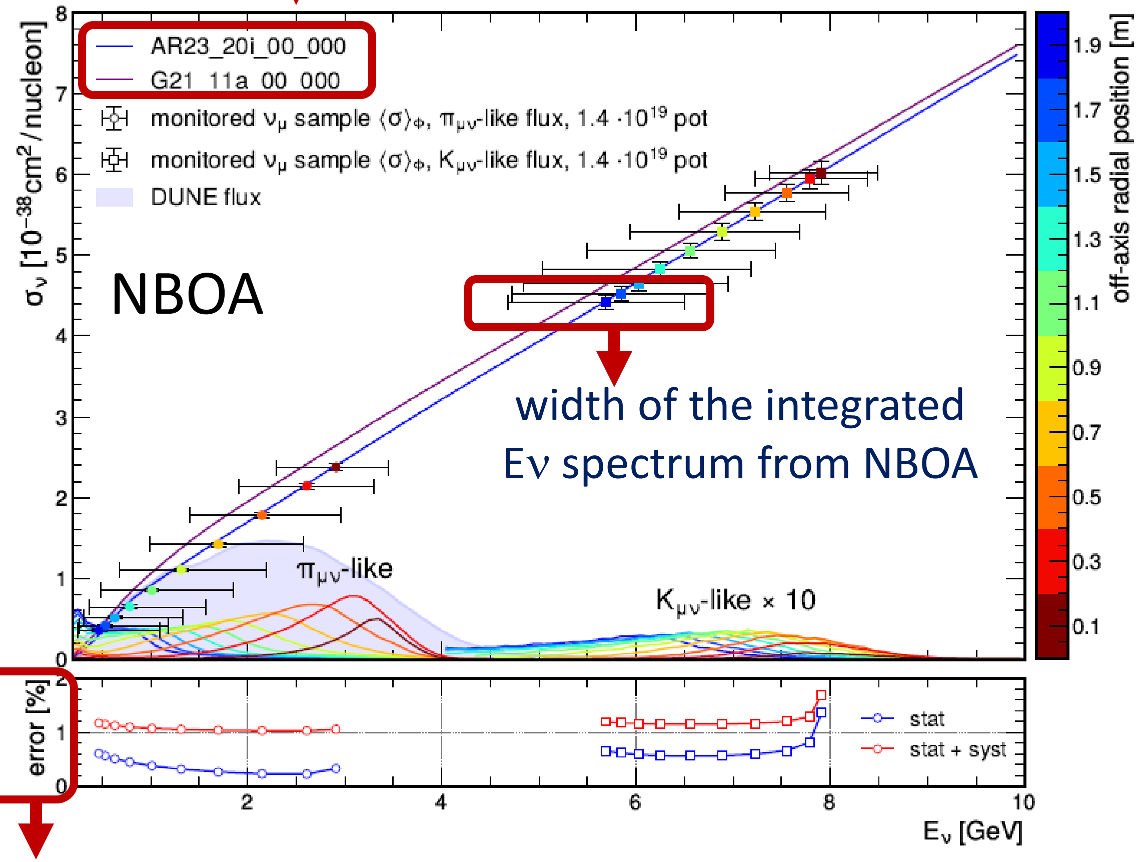
Many other channels not covered in this seminar because they are work in progress

↓

exclusive channels, non-standard interactions, dark sector probes, sterile neutrinos, etc.

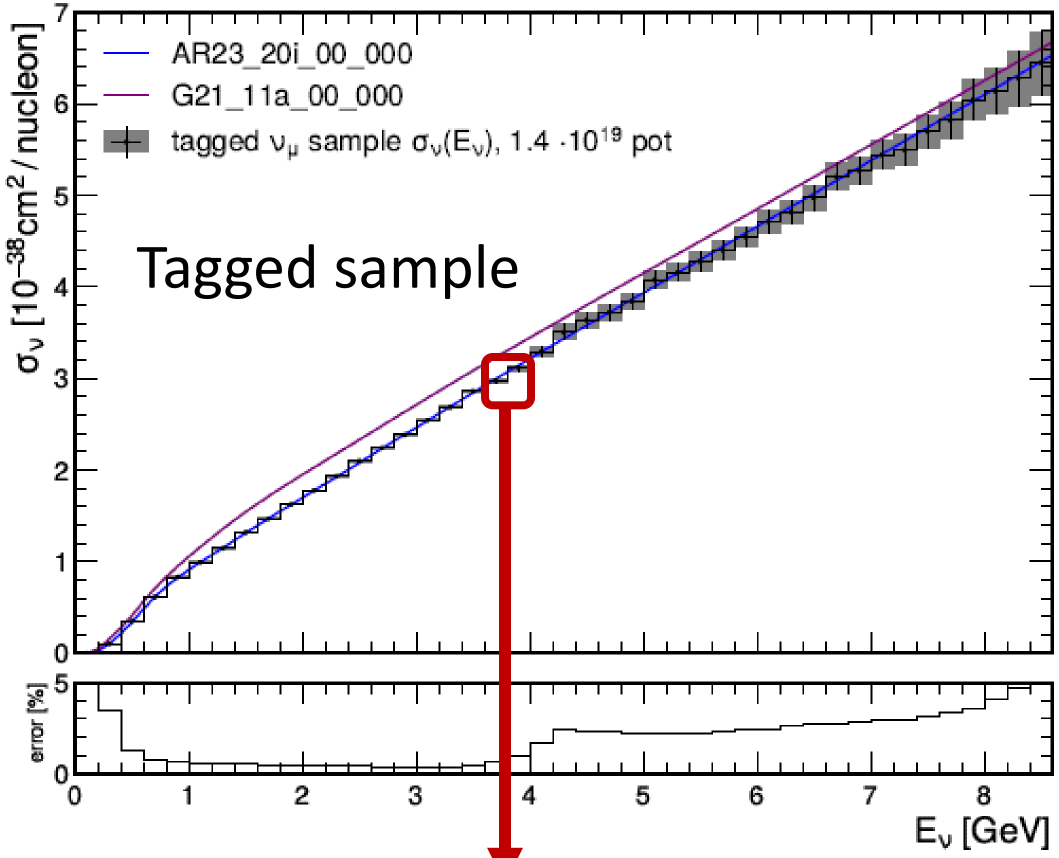
The energy dependence of ν_μ cross section

it illustrates sensitivity to theory models



width of the integrated Eν spectrum from NBOA

stat.+sys. error

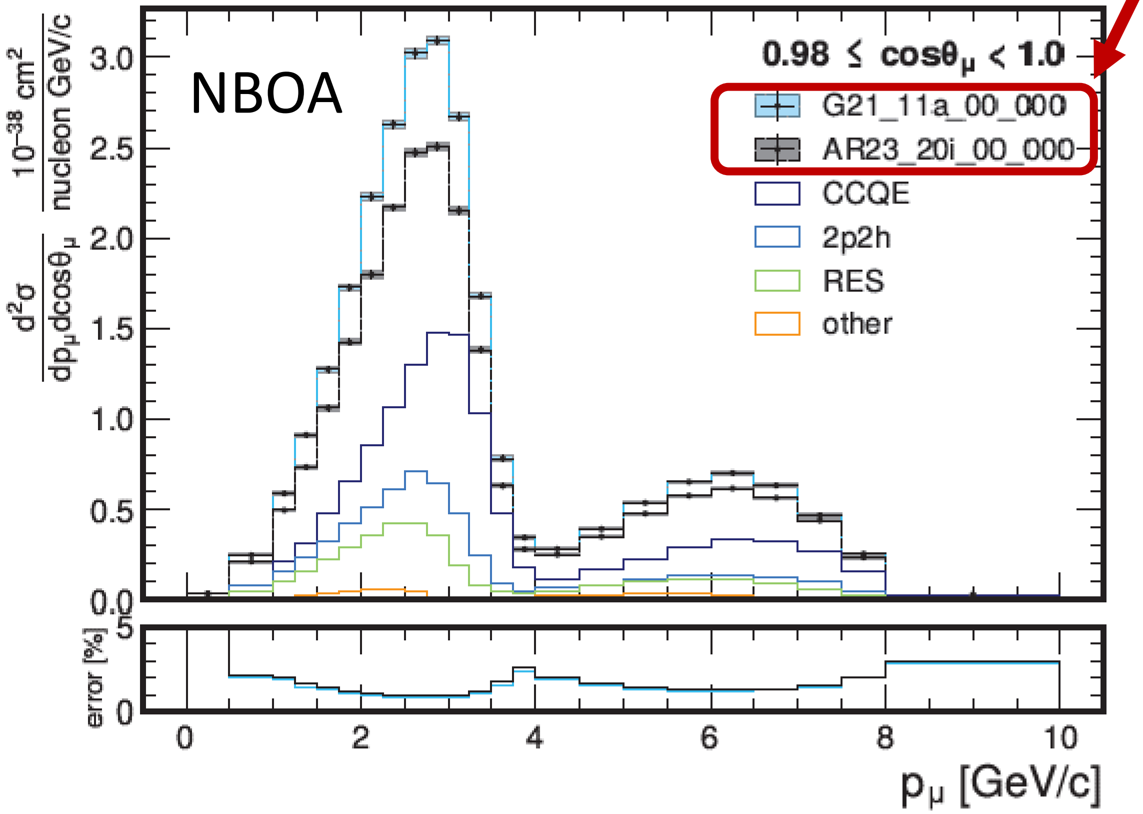


in the golden tagged sample, the integration width is no more driven by the energy uncertainty (<1% !!) but just by statistics

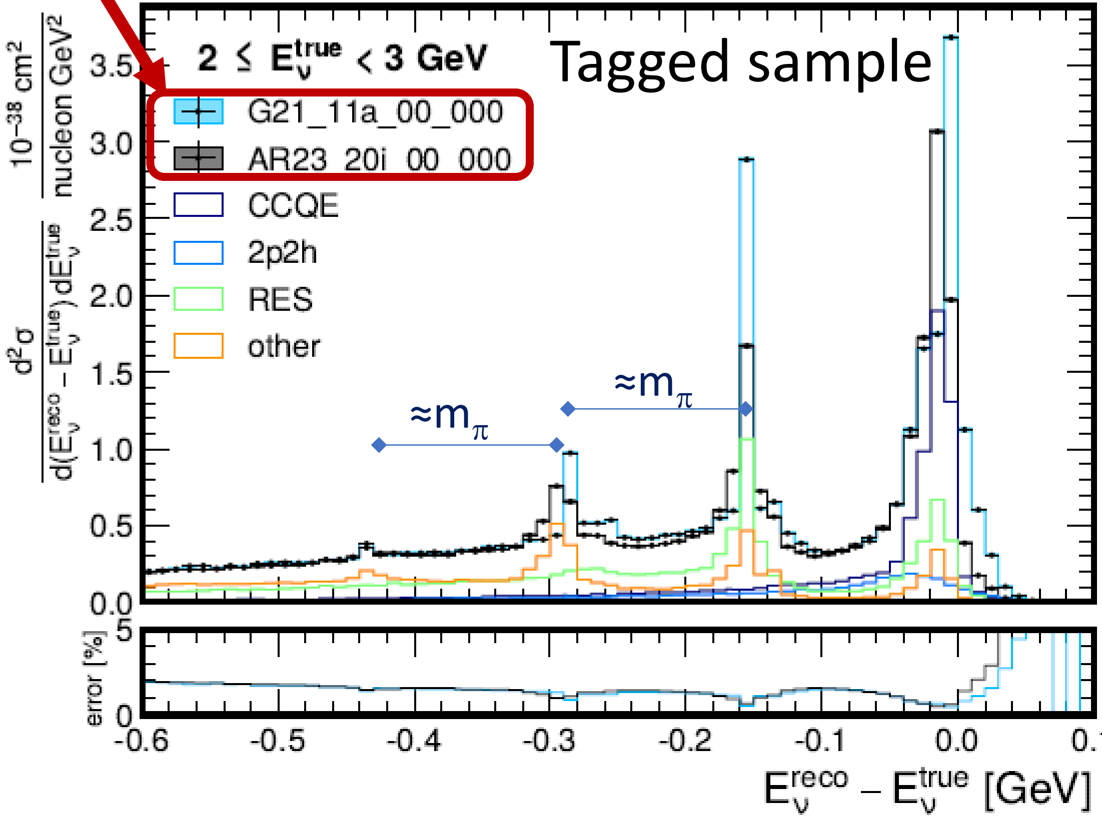
The smearing of reconstructed neutrino energy due to nuclear effects

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



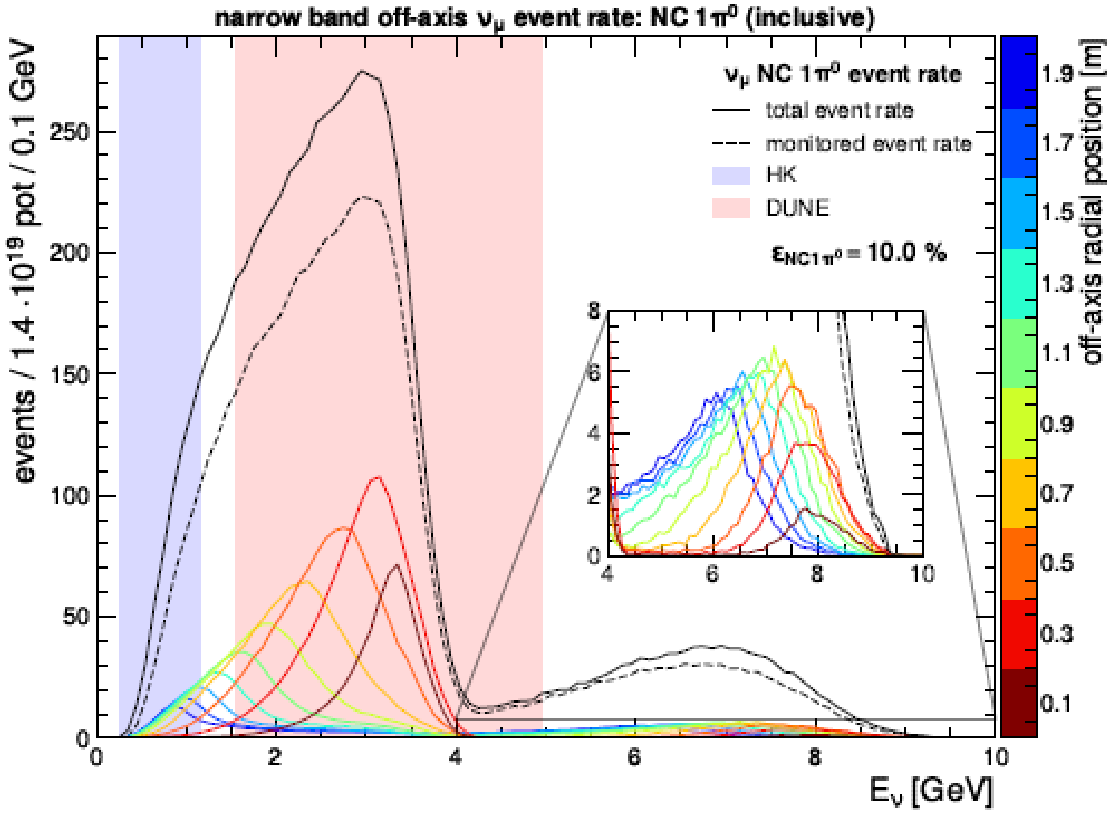
Without **monitoring**, the double differential cross section for “quasi elastic” (CC0π) would be systematic limited



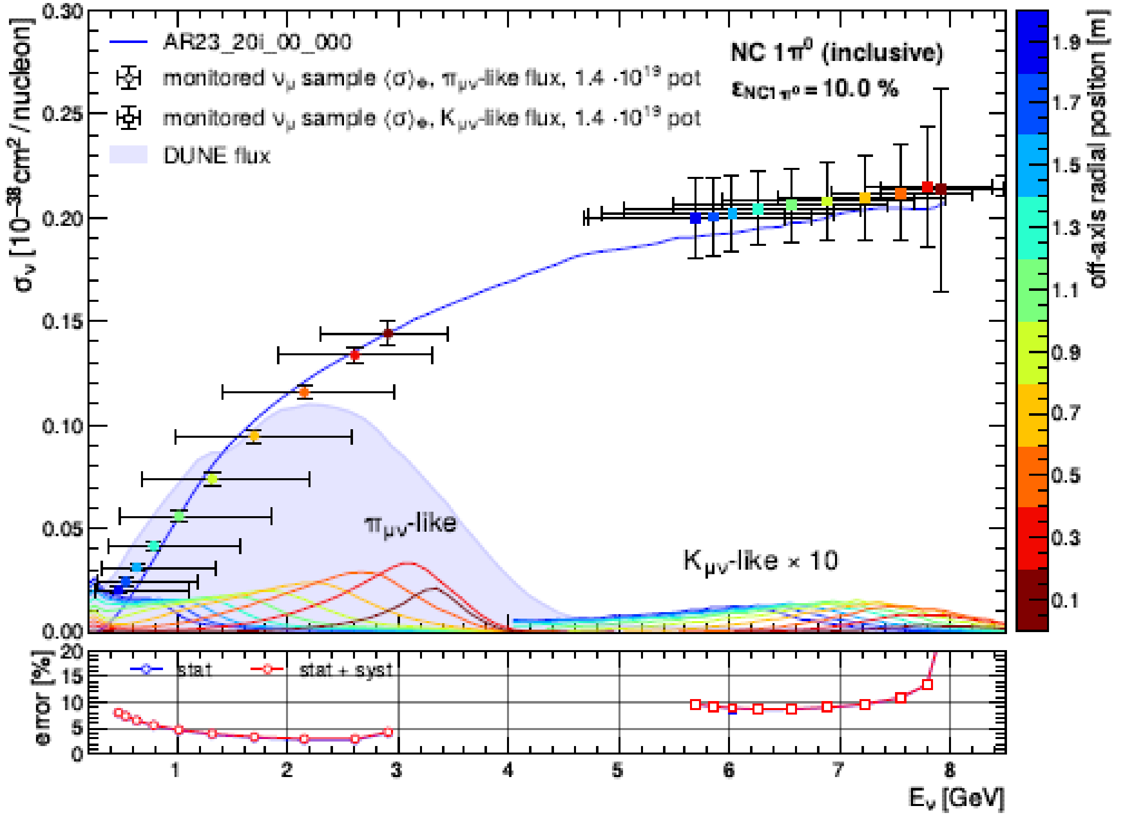
The **tagged** sample employs the knowledge of the “true” neutrino energy to directly measure the energy bias in bins of E_{true}

The NCπ^0 background to neutrino oscillation experiments

π^0 production without outgoing leptons (NC) is the leading background for ν_e appearance in most oscillation experiments. In this case, the a priori knowledge of the true neutrino energy plays a crucial role, since we cannot rely on the outgoing lepton to reconstruct the neutrino energy



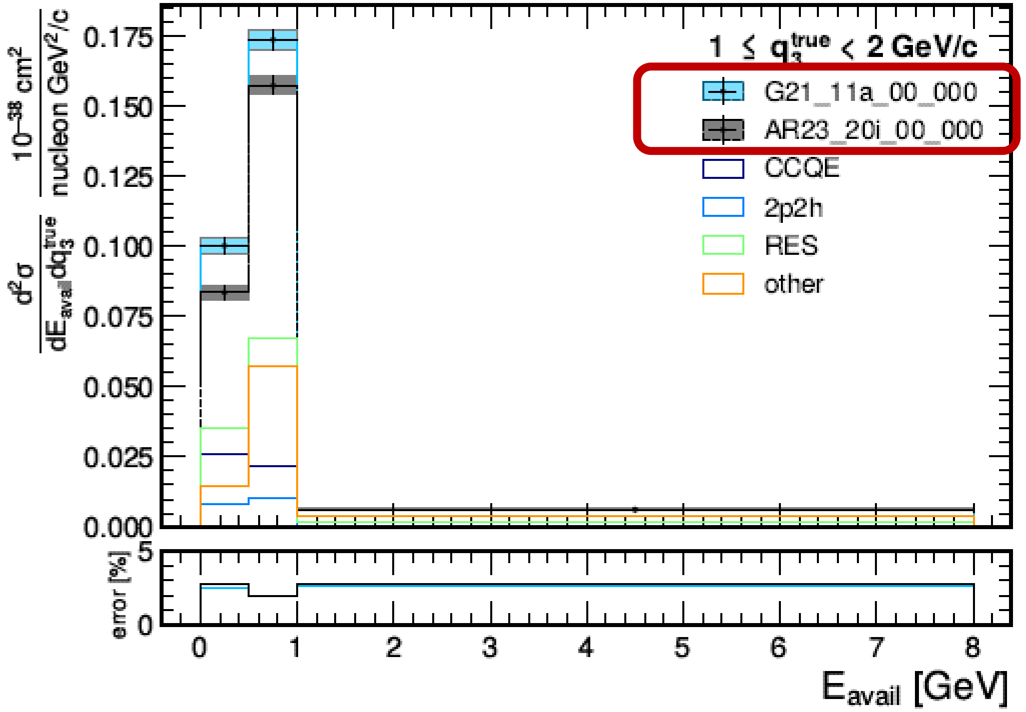
Event rate



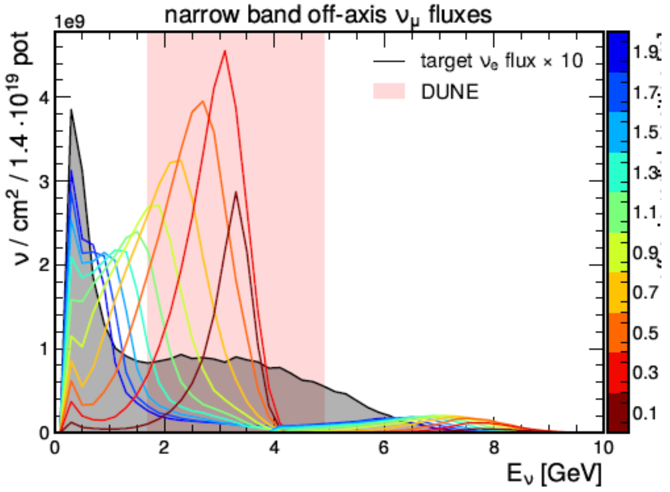
Flux averaged cross section

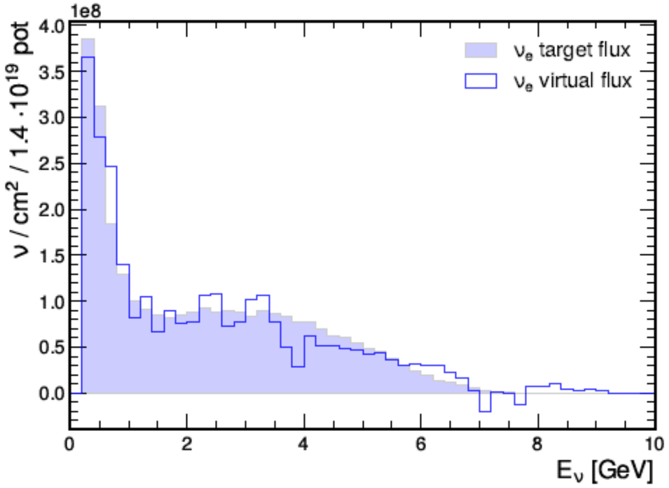
ν_e cross sections and ν_e / ν_μ ratio

Oscillation experiments cannot fully rely on lepton universality to account for the ν_e cross sections due to phase-space-induced effects. Electron neutrino cross sections are therefore particularly valuable and, in nuSCOPE, mainly originate from kaon decays. These can be monitored with a precision at the 1% level. Additionally, a 2% level measurement of the ν_e/ν_μ ratio can be performed using the PRISM technique.



$$E_{\text{avail}} = \sum_{i=\pi^{\pm},p} T_i + \sum_{i=\pi^0,\gamma} E_i$$

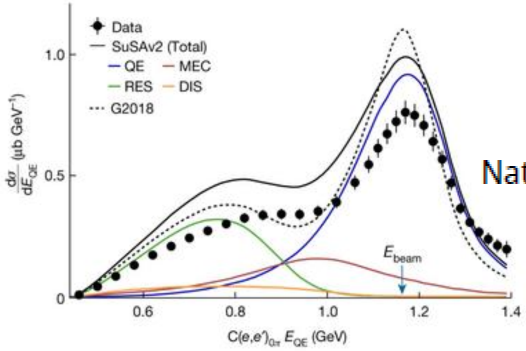




Since we cannot use either NBOA or tagging for ν_e, we measure the flux integrated ν_e cross section and compare it with the corresponding ν_μ cross section, which is built from narrow-width ν_μ fluxes obtained from the NBOA or tagged sample.

Electron-scattering-like measurements with tagged neutrinos

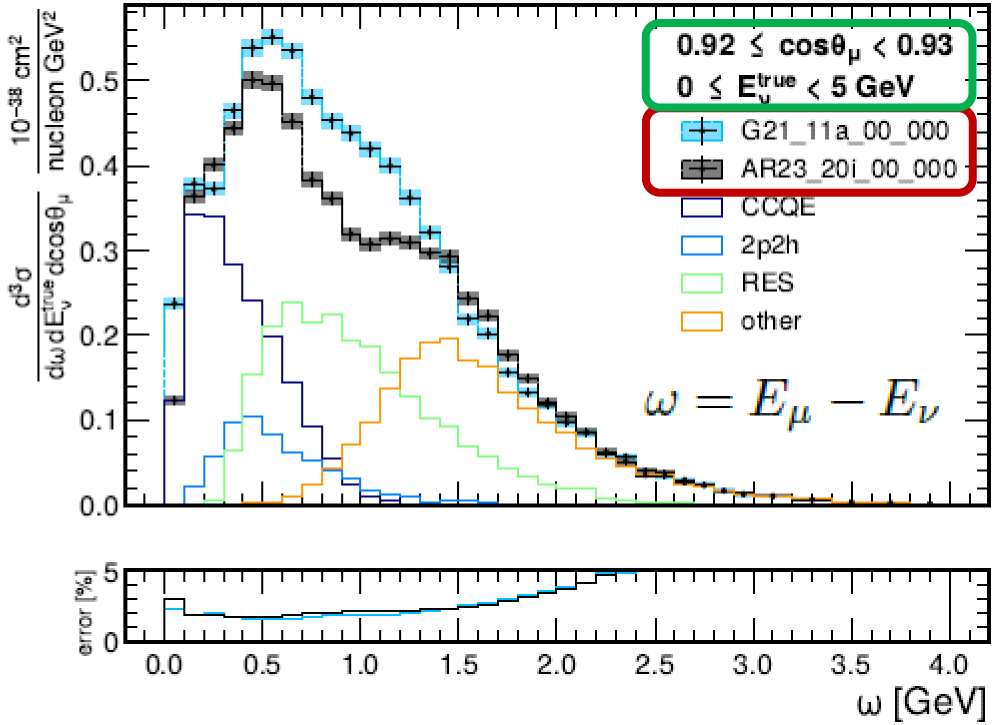
Electron-nucleon scattering experiments provide the primary experimental input for understanding nuclear effects and developing robust theoretical models. However, they only access vector currents since the probe is electromagnetic. Tagged ν_μ–nucleus interaction events exhibit the same features, but with a neutrino probe, which also provides access to the axial component. For example, the exploitation of the "true" energy transfer ω to probe:

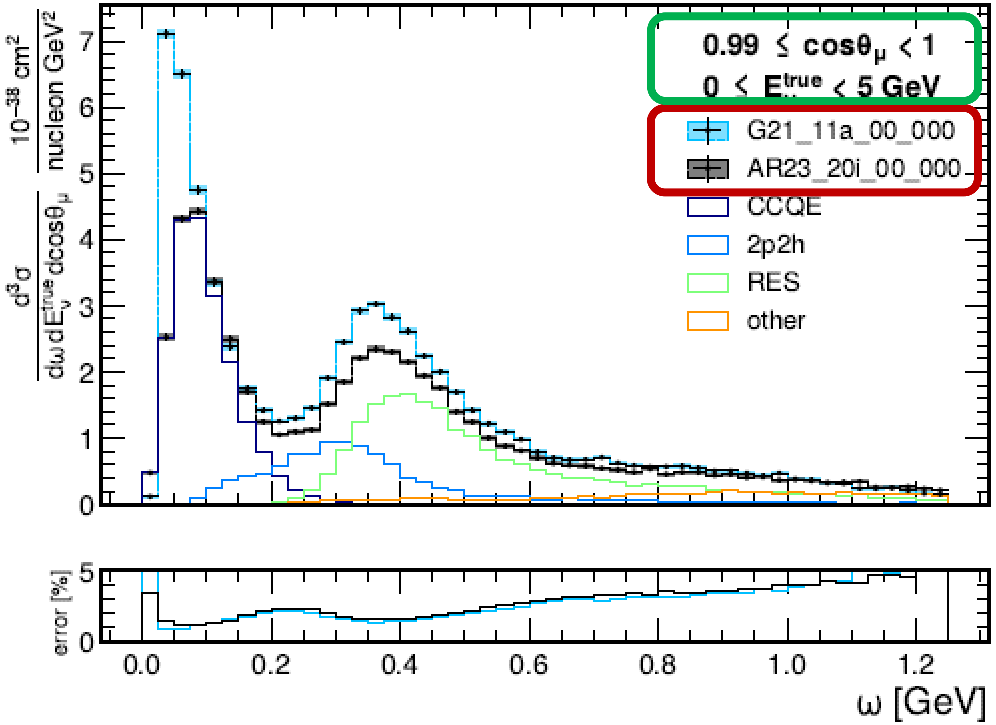


Nature 599, 565–570 (2021)

regions sensitive to nuclear-level form factors

regions sensitive to collective nuclear effects





the dominant T2K systematics for Δm^2_{32}

Technical readiness of nuSCOPE

Is nuSCOPE "ready for construction"? While most of the facility relies on validated technologies, there are still areas that require full confirmation. In particular,

Beamline		
Design	OK	Still room for improvement in reduction of non-monitored ν
Components	OK	Standard and existing (at CERN) components
Slow extraction	in progress	Depends on final implementation
Infrastructure	in progress	Depends on final implementation

Diagnostics for lepton monitoring/tagging		
Decay tunnel instrumentation	OK	ENUBET R&D (2016-2022)
Hadron dump	in progress	ENUBET+PIMENT R&D (2021-ongoing)
Silicon tracking planes	R&D	The technologies are identified within HL-LHC R&D but not yet fully validated
Outer tracking planes and muon spectrometer	in progress	Technologies are identified but design and validation in progress

Neutrino detectors		
Liquid argon	in progress	Based on ProtoDUNE's technologies with enhanced light detection (ProtoDUNE Run III)
Water Cherenkov - WBLS	OK	Based on WCTE's technology or Water Based Liquid Scintillators (WBLS)
Muon catcher and cosmic ray veto	in progress	Depends on final implementation

Lepton monitoring the decay tunnel

Shielding

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

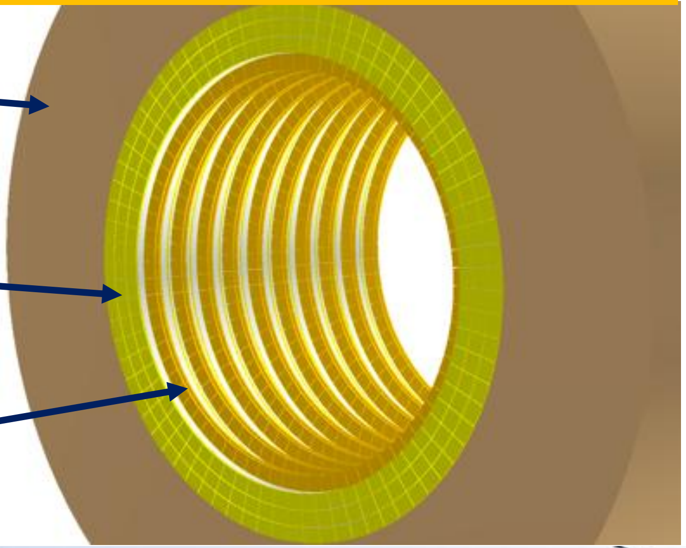
Calorimeter with $e/\pi/\mu$ separation capabilities:

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

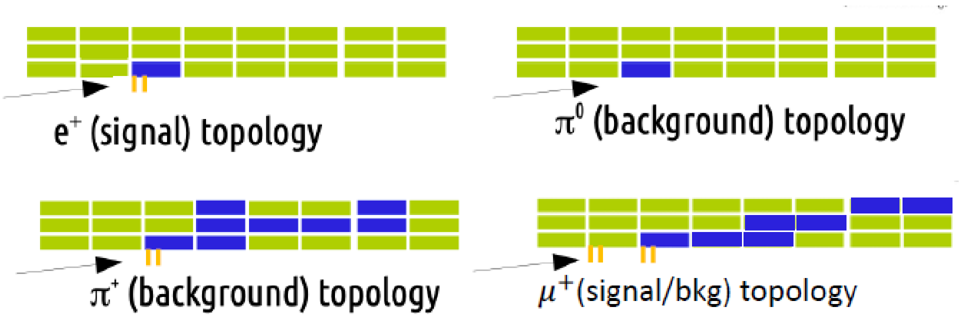
Photon-Veto allows π^0 rejection and timing:

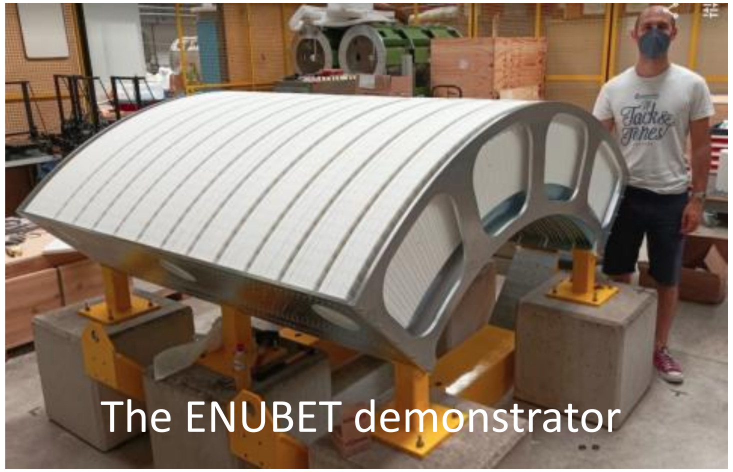
- plastic scintillator tiles arranged in doublets forming inner rings with a time resolution of ~ 400 ps;

Layout of the instrumented tunnel

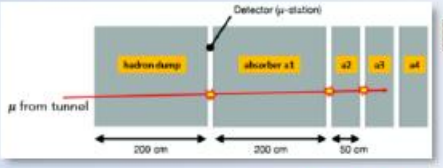


Pattern identification based on the pattern of energy deposit in the calorimeter modules





+ hadron dump instrumentation



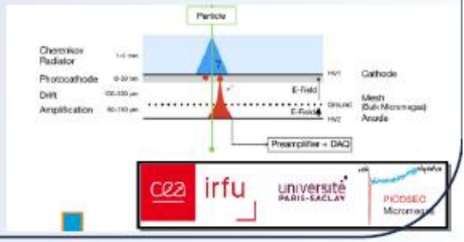
Muon stations

μ from π decays

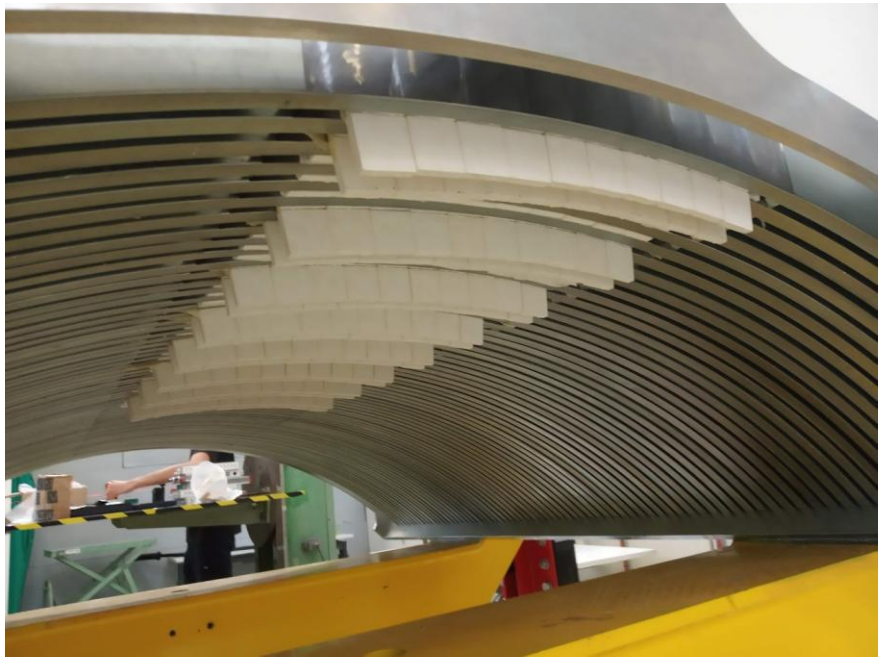
PIMENT

PIcosec Micromegas Detector for ENnubeT

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



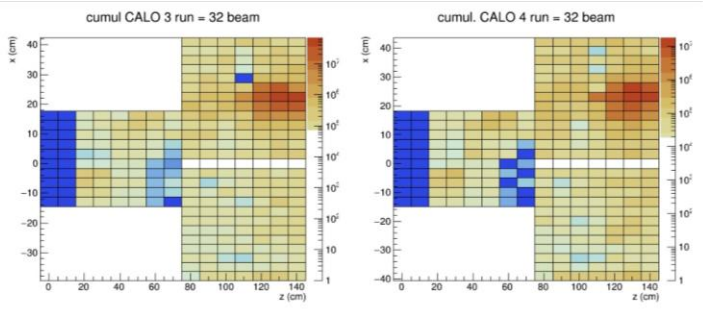
The ENUBET demonstrator at CERN PS-EA in 2022, 2023, and 2024

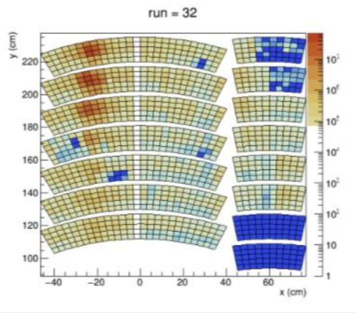


francesco.terranova.tel

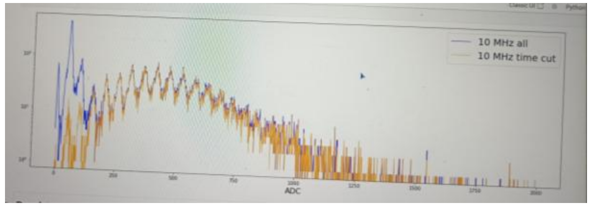
Piace a **valee_.terra** e **altri 18**

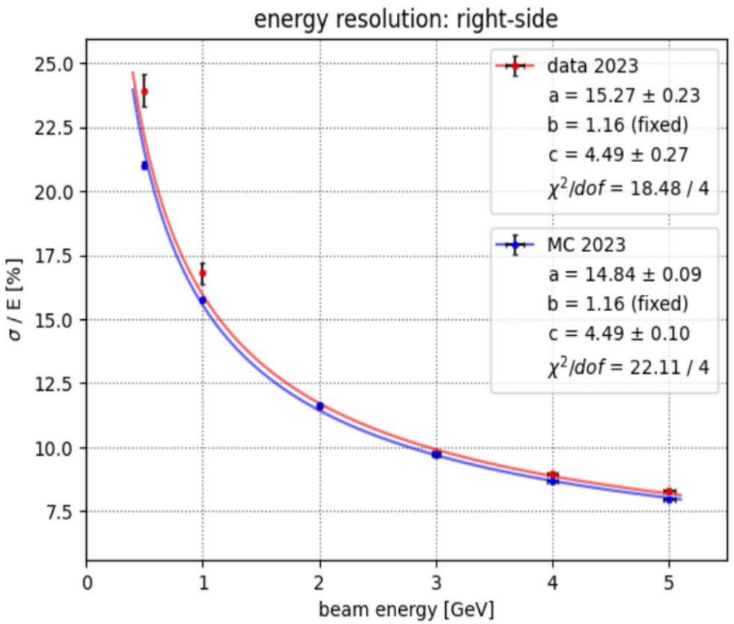
francesco.terranova.tel A hairy detector for neutrino physics 😄 #enubet #cern



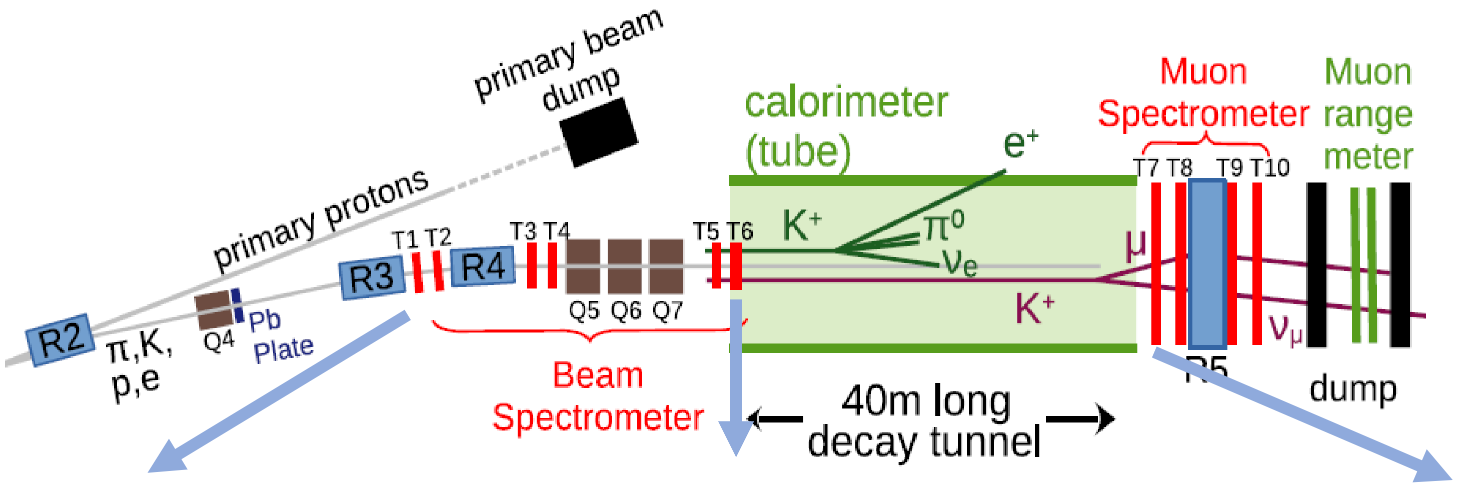


Aug 2024!

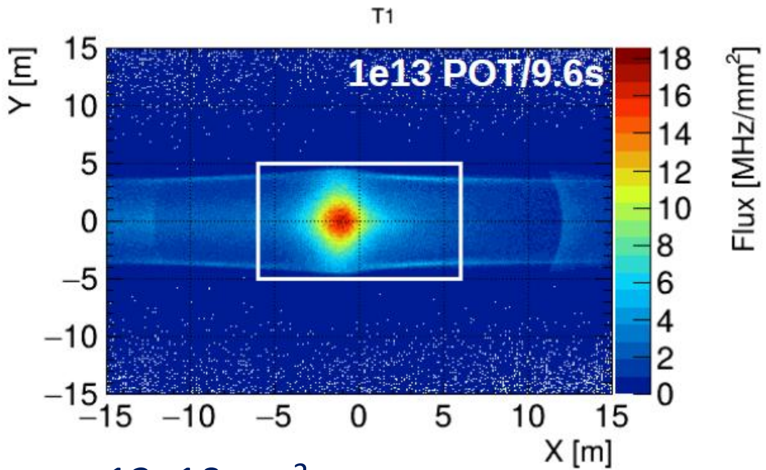




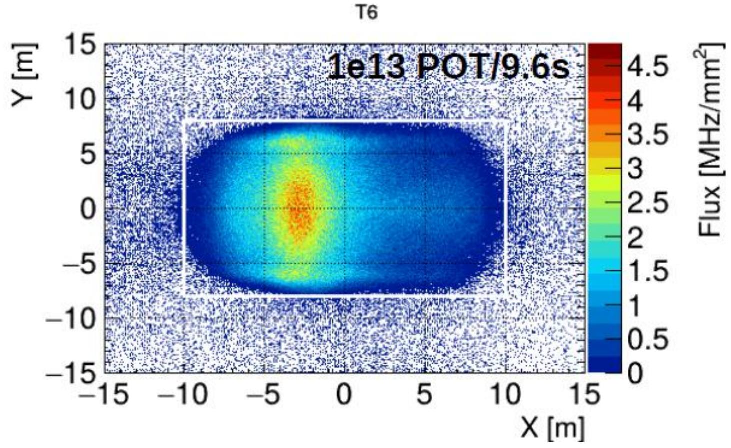
Meson and muon tracking (I)



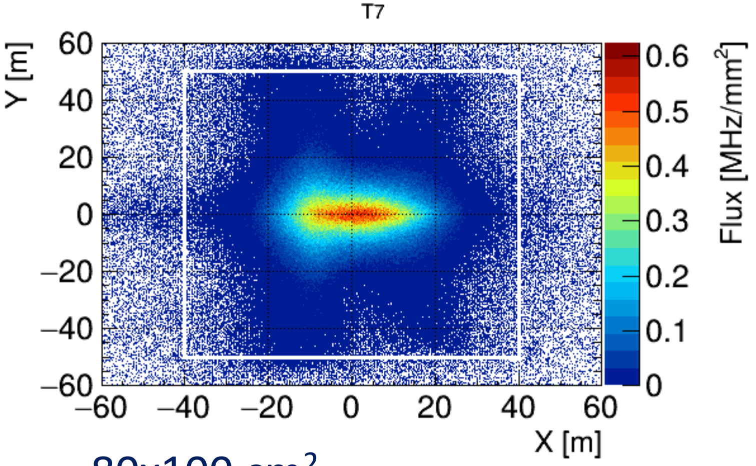
Silicon detectors are needed only at the core of the tracking planes. Scintillating fiber planes are sufficient to instrument the outer radii



$12x10\ cm^2$



$20x16\ cm^2$



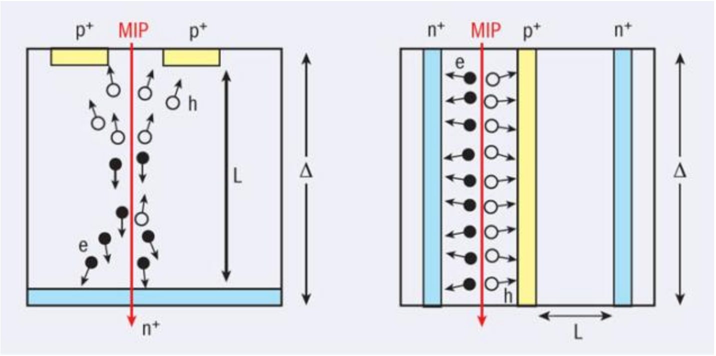
$80x100\ cm^2$

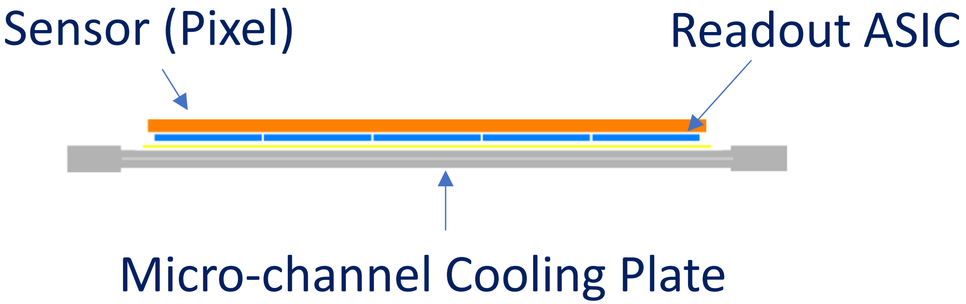
Parent and muon tracking requires a time resolution of O(100 ps) and a detector granularity of 300 μm. Particle rates in the hottest (central) planes are 20 MHz/mm^2 for 10^{13} pot in 9.6 s. The peak fluence (non-ionizing dose) is 10^{16} MeVn_{eq}/cm^2 **We thus benefit from the technology currently being developed for the LHCb velo upgrade and pioneered at the 2 MHz/mm^2 level by NA62**

Meson and muon tracking (II)

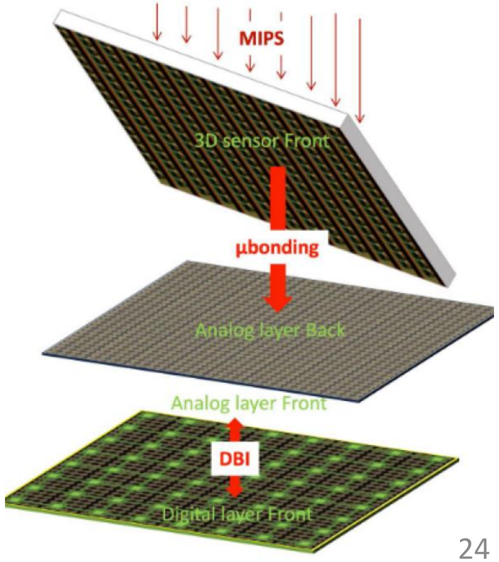
Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1MeVn_{eq}/cm^2$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	$10 - 100$	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X_0]	$< 1\%$		0.8%	0.5%

3D trench sensors
(FBK through INFN TimeSpot)





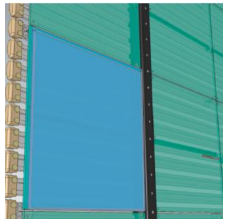
Readout ASIC
Three developments ongoing, all with 28nm CMOS technology
Timespot v2 and IGNITE (3D stacked) by INFN
PicoPix by CERN, Nikhef



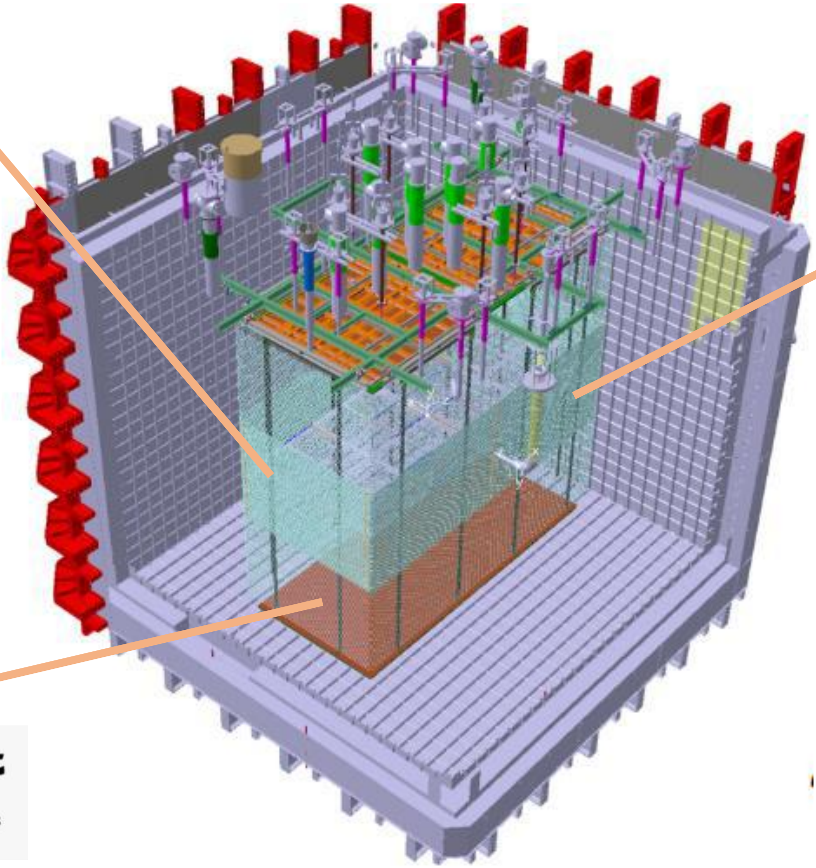
Liquid argon detector

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.

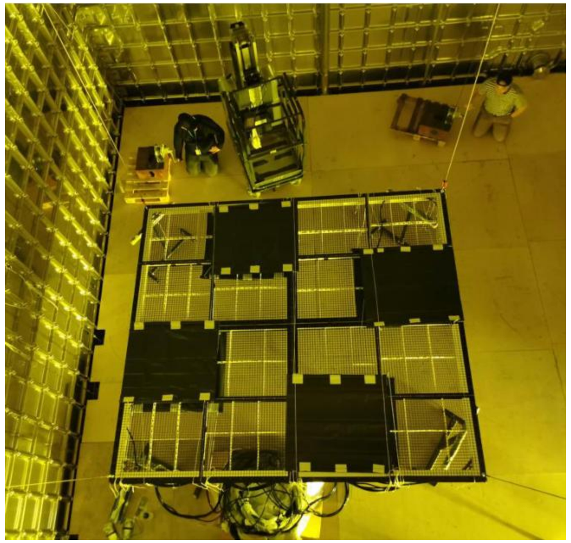
Field cage equipped with Photon Detectors (128 nm)



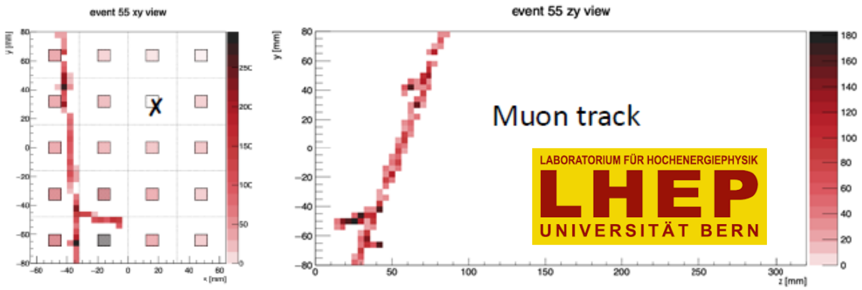
ProtoDUNE-VD Run III (2027-28)



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



Anode equipped with VUV (128 nm) SiPMs



SoLAr

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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!