nuSCOPE: a monitored and tagged neutrino beam at CERN for high-precision cross-section measurements

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On behalf of the nuSCOPE coll.

IRN Lyon, 12 June 2025

https://arxiv.org/abs/2503.21589

27 Mar 2025

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

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Introduction

- 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).
- 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

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

Useful recent documents

NuTAG paper: https://link.springer.com/article/10.1140/epjc/s10052-024-13324-1

ENUBET paper: https://arxiv.org/pdf/2308.09402.pdf

https://link.springer.com/article/10.1140/epjc/s10052-023-12116-3

Neutrinos @ CERN workshop (Jan 2025)

https://indico.cern.ch/event/1460367/overview

ESPPU documents

https://arxiv.org/abs/2503.21589 →

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https://indico.cern.ch/event/1439855/contributions/6461501/attachments/3045874/5381803/SBN_at_CERN_backup_document_ESP

https://indico.cern.ch/event/1439855/contributions/6461501/attachments/3045874/5381802/SBN_at_CERN_main_document_ESPPl

A short-baseline neutrino beam at CERN
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Development

2015 conceptual paper EPJ C75 (2015) 155

The ENUBET ERC project 6/2016- 12/2022

Enhanced NeUtrino BEams from kaon Tagging ERC-CoG-2015, G.A. 681647

- ERC

INFN CSN 2
INFN CSN 1

ENUBET/NP06

- CERN Neutrino Platform

With SPSC:
- support of test beams of the tagger instrumentation at the PS
- monitoring of all neutrino flavors, including ν_μ from π and K decays

nuTAG

Short baseline neutrinos @ PBC

- Physics Beyond Colliders

ENUBET

2025: "ENUBET + nuTAG" =
→ (SBN@CERN) →

nuSCOPE

neutrino SPS COmplex for Precision Experiments

Neutrino cross sections in the 2030s

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%**

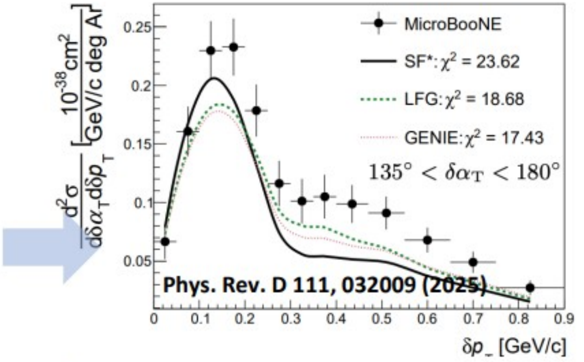
Future long-baseline experiments

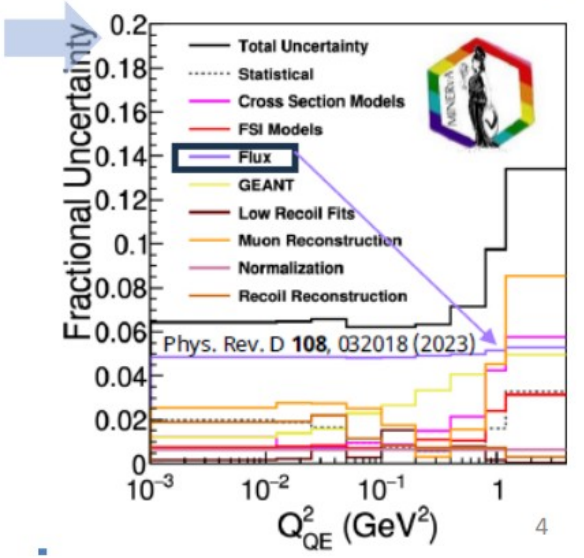
	Hyper-K (arXiv:1805.04163)	DUNE (arXiv:2002.03005)
Baseline	295 km	1300 km
N_μ^{rec} (ν-mode)	~10000	~7000
N_e^{rec} (ν–mode)	~2000	~1500

- In the 2030s, DUNE and Hyper-Kamiokande will be 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

- A **vibrant neutrino cross-section program using conventional beams** over the past decades has significantly advanced our understanding of ν 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**.

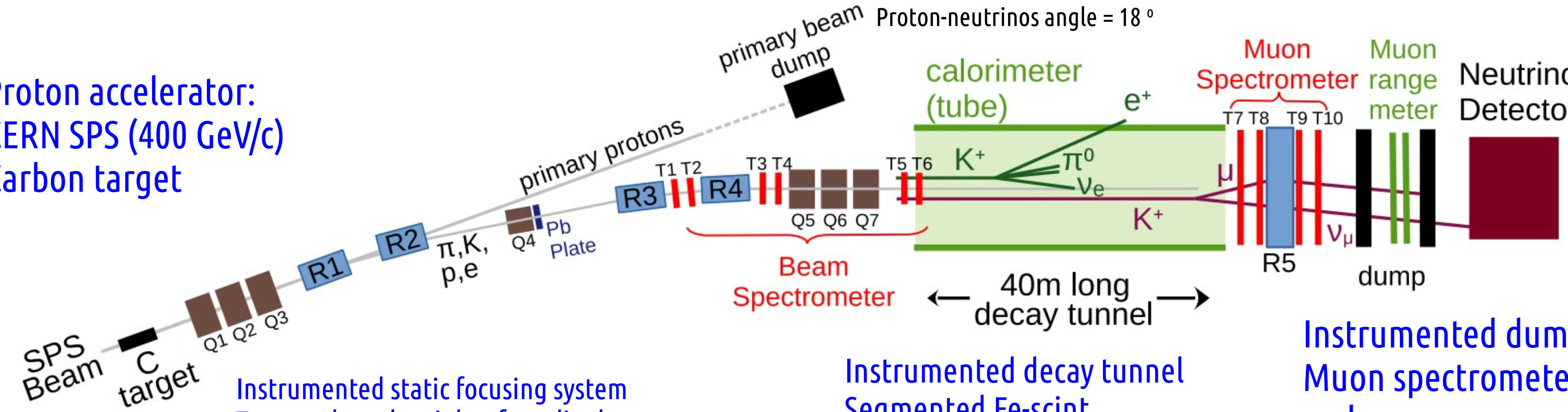




The nuSCOPE implementation

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

- An **instrumented decay tunnel** and **muon range-meter** to monitor the number of $K \to \pi^0 e \nu_e$, $\pi \to \mu\nu_\mu$, $K \to \mu\nu_\mu$ 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

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

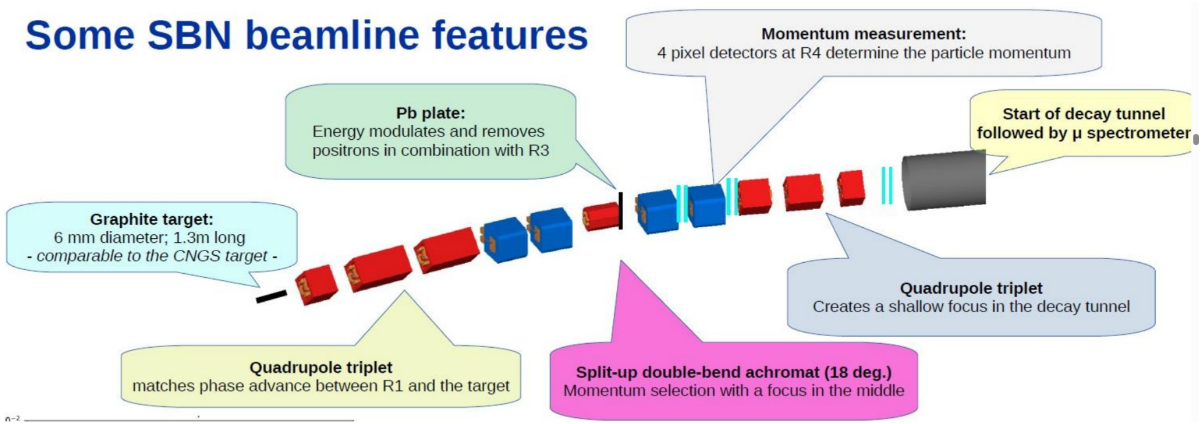
• achieve the original ENUBET physics goals with a **number of protons** compatible with the CERN fixed target program, including SHiP

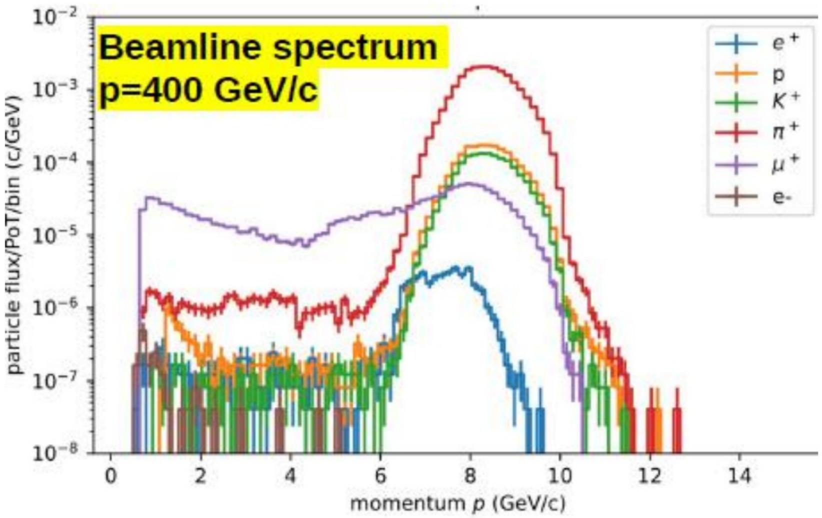
• reduce the instantaneous meson rate in the final dipoles to a level **compatible with particle tracking** (silicon trackers)

• **Suppress 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 momentum (GeV/c)	400
Beamline meson momentum (GeV/c)	max. 8.5
Proton-beam spill duration	slow (4.8 s to 9.6 s)
Spill intensity (protons/spill)	1.0×10^{13}
Event rate (THz)	1 – 2
Instantaneous power on target (W)	170 – 340
(K^+, π^+) yield per proton	$(1.3 \times 10^{-3}, 1.9 \times 10^{-2})$
(K^+, π^+) rate (GHz)	max. (2.7, 40)
Annual proton intensity (protons/year)	$2.1\text{–}3.2 \times 10^{18}$
Total proton requirement (protons)	1.4×10^{19}

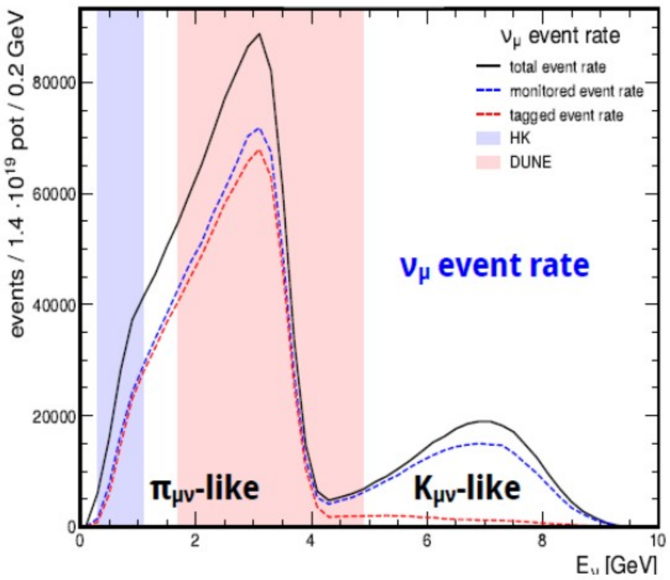


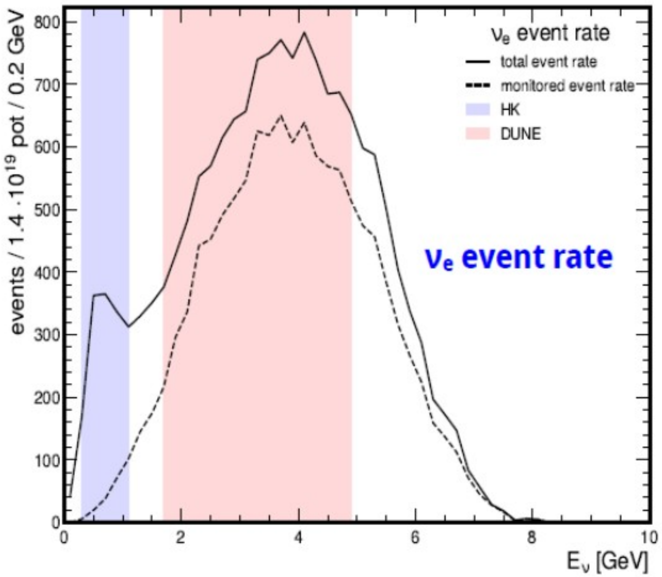


Beam performance and expected statistics

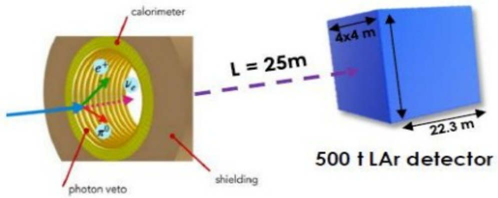
With our reference setup:

- **5-y neutrino run** mode with 8.5 GeV momentum secondaries [dedicated **low energy runs and anti-neutrino** under evaluation]
- 500 t Liquid Argon detector 4x4 m^2 face; length: 22.3 m, distance: 25 meter from the hadron dump
- Collected statistics: **10^6 ν_μCC events**, **12.000 ν_e^{CC} events**
- Projected event spectra estimated with GENIE from the output flux of the nuSCOPE BDSIM simulation (being also ported to GEANT4)
- Flux systematics from the ENUBET analysis. Tagging efficiency from tracker simulations.



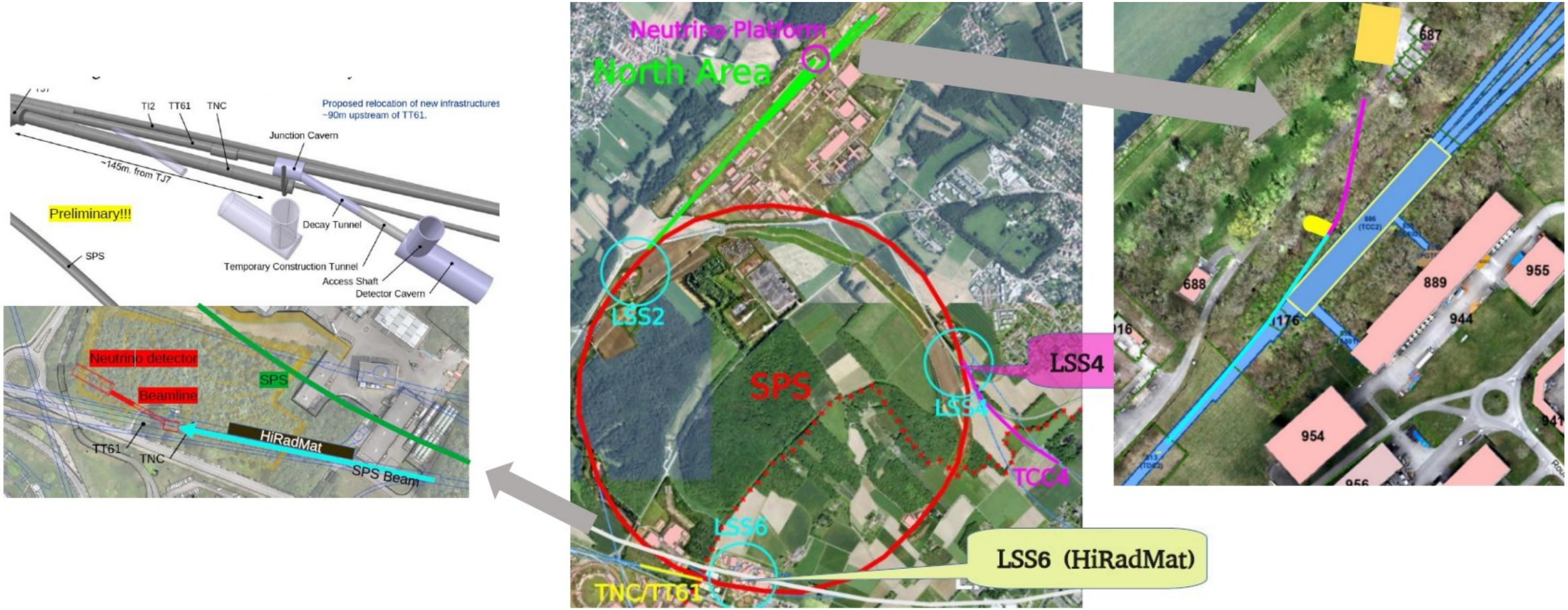


	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5



Implementation at CERN

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.



Pros and cons

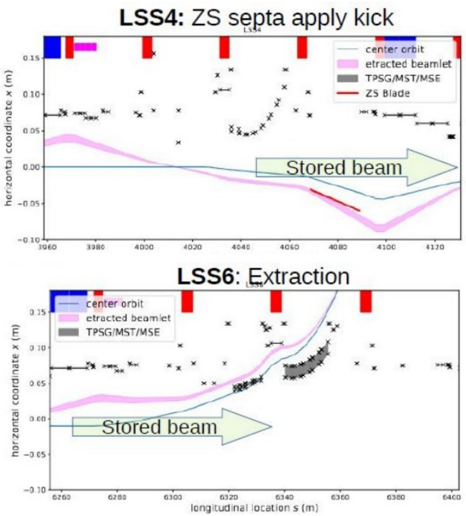
ECN4 (North Area, Prevessin)

- 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.

TNC/TT61/TCC6 (East Area, Meyrin)

- 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.

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



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

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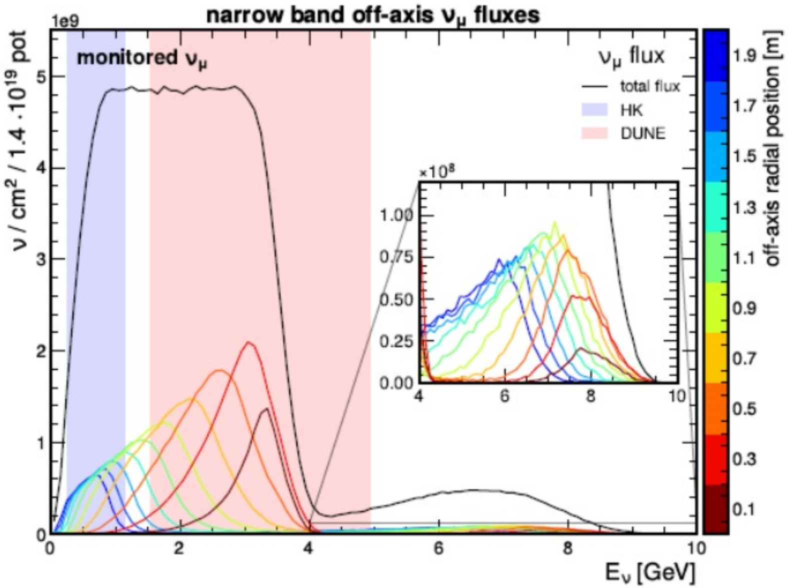
Physics performance

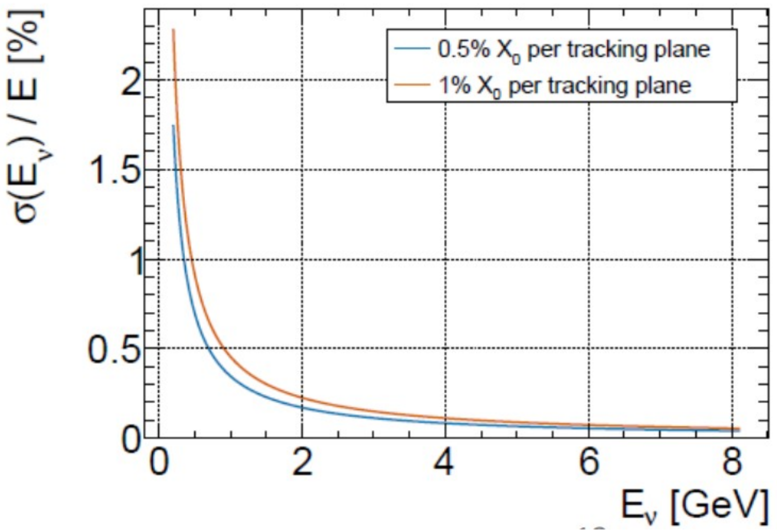
This facility addresses the most relevant issues for a full understanding of neutrino cross sections, especially for oscillation experiments.

- **Monitoring**: unprecedented control of the flux and a moderate precision on the neutrino energy ("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 numu CC sample from π decay for a 300 ps detector time resolution): the energy is reconstructed from the parent kinematics. It thus offers a golden sample of tagged neutrino with sub-% energy resolution



Measurements "menu"

1) Energy dependence of the neutrino cross section → know how to extrapolate from near to far detectors in oscillation experiments

2) Smearing of neutrino energy reconstruction → infer the shape of the oscillated spectrum in DUNE/HyperKamiokande

3) differences in the cross section for ν_e and ν_μ → reliably use ν_e appearance to probe CP violation

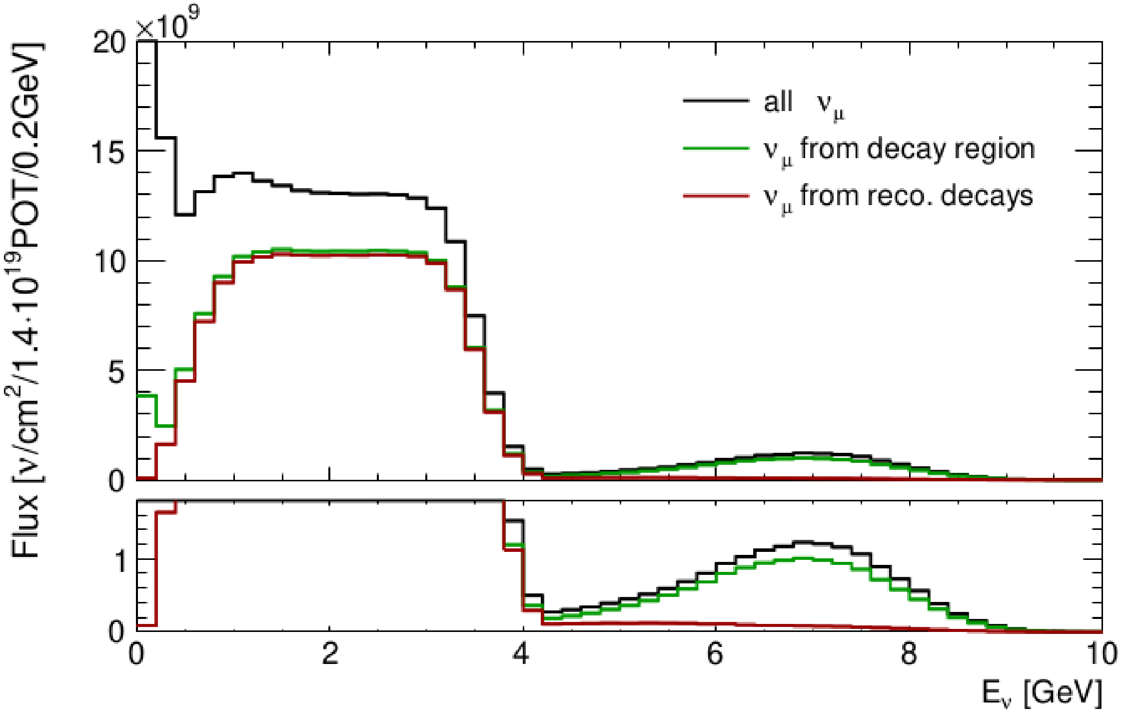
4) Interaction channels that constitute backgrounds
(e.g. NC-π^0 production)
→ how to interpret far detector event Rates in DUNE/HyperKamiokande

5) ν-N elastic scattering with tagged ν_μ
The axial counterpart of e-N elastic scattering

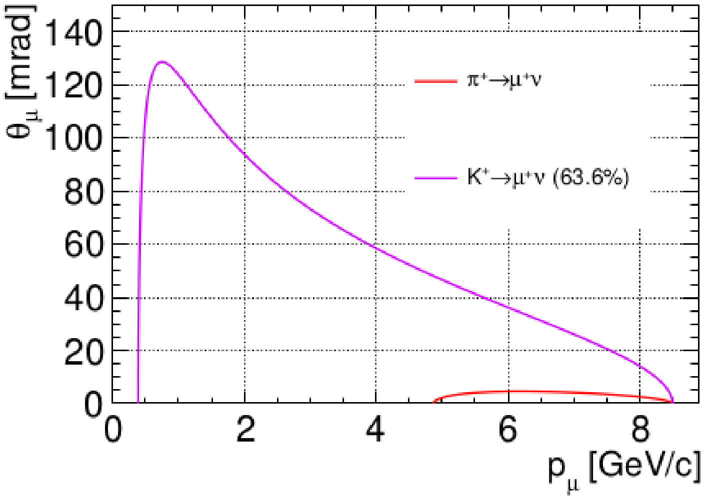
Many **other channels** not covered because they are work in progress exclusive channels, non-standard interactions, dark sector probes, sterile neutrinos, etc.

Taggable fraction

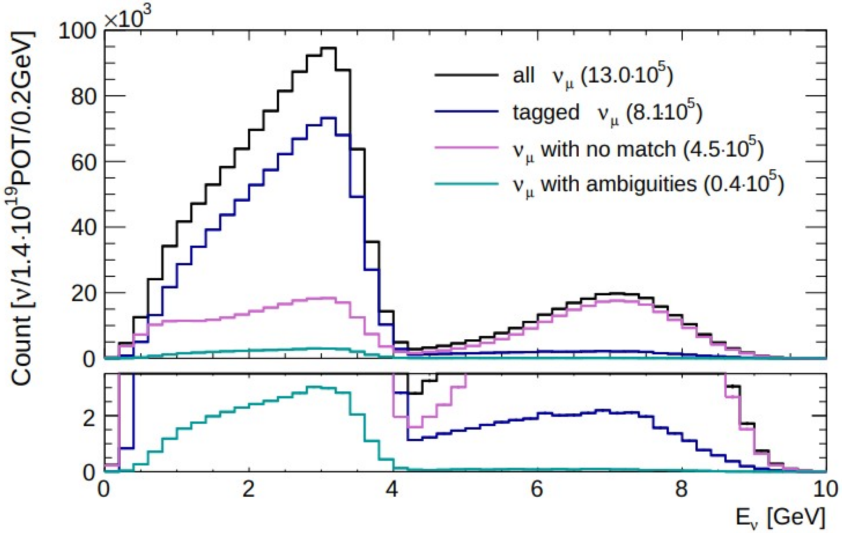
In terms of flux here

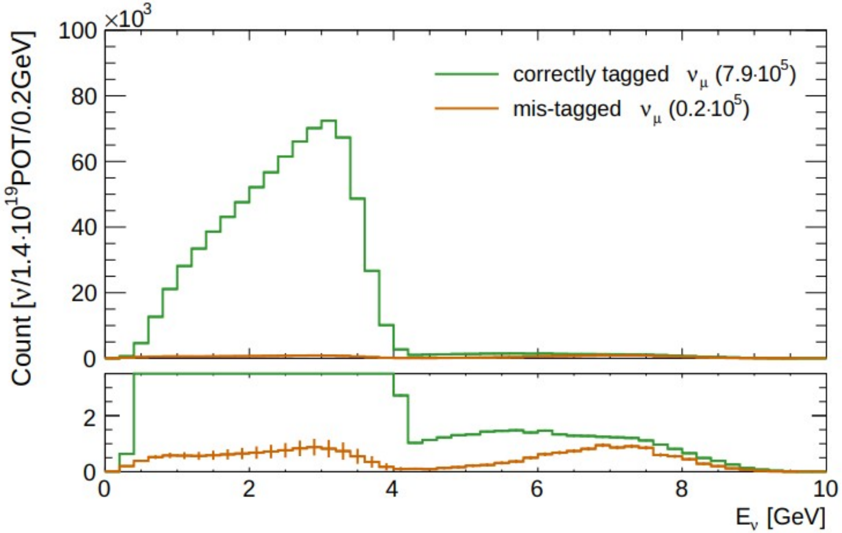


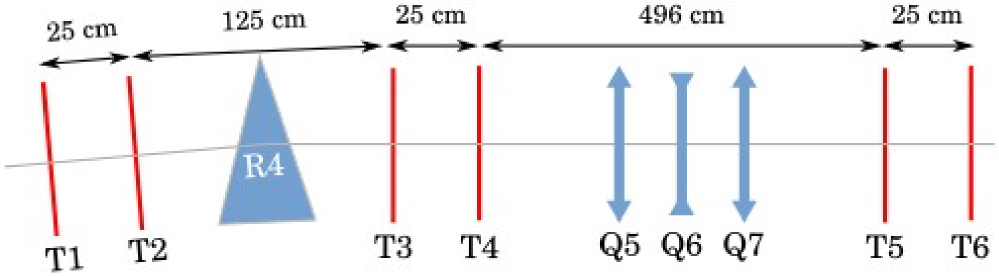
Complementarity:
3 body is the realm of the "calorimeter", 2 body Si-trackers and instrumented dump (kinematics)

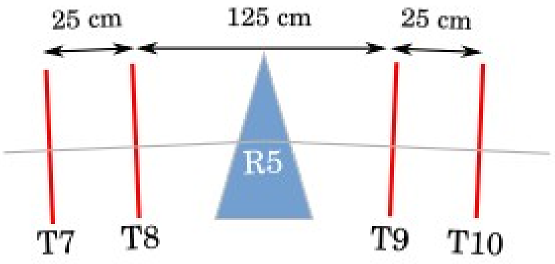


Tagging performance with trackers



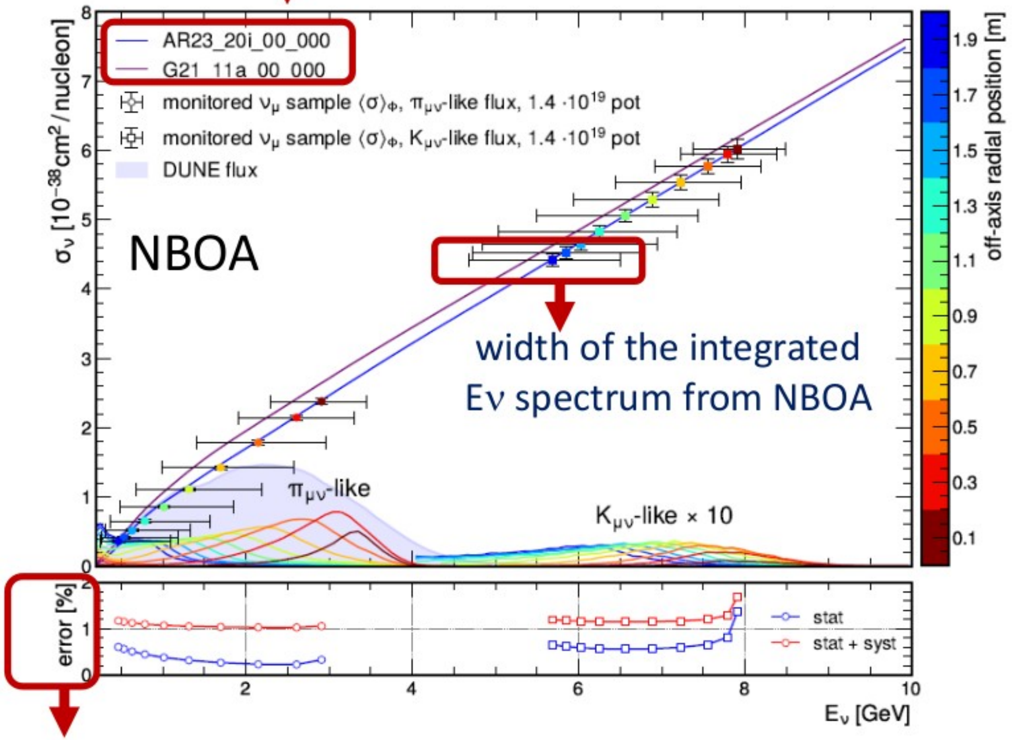






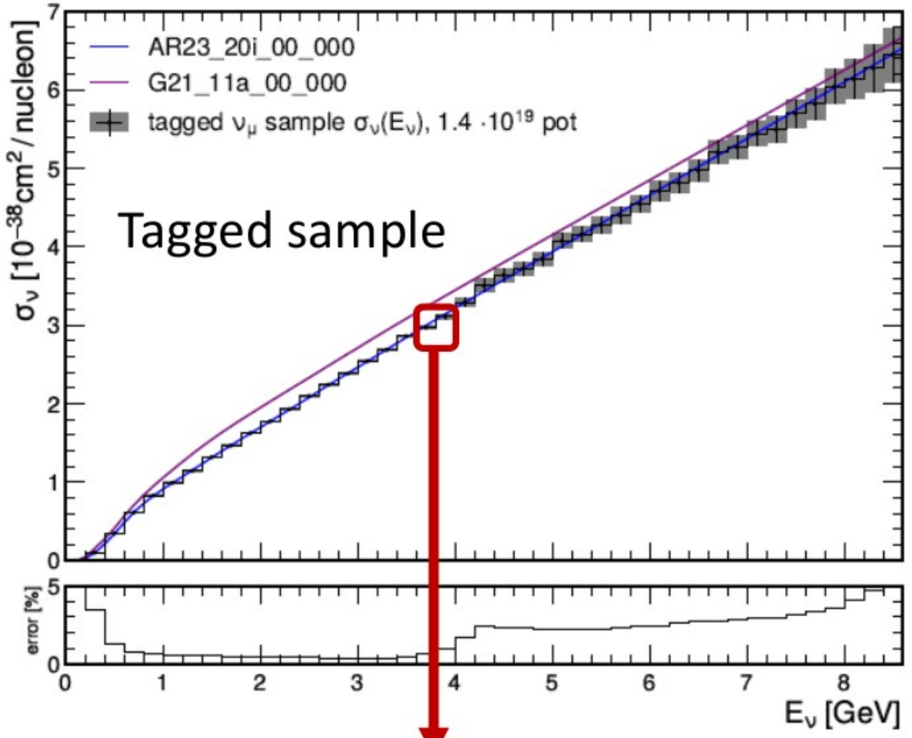
1) The energy dependence of the ν_μ cross section

it illustrates sensitivity to theory models



width of the integrated Eν spectrum from NBOA

stat.+sys. error

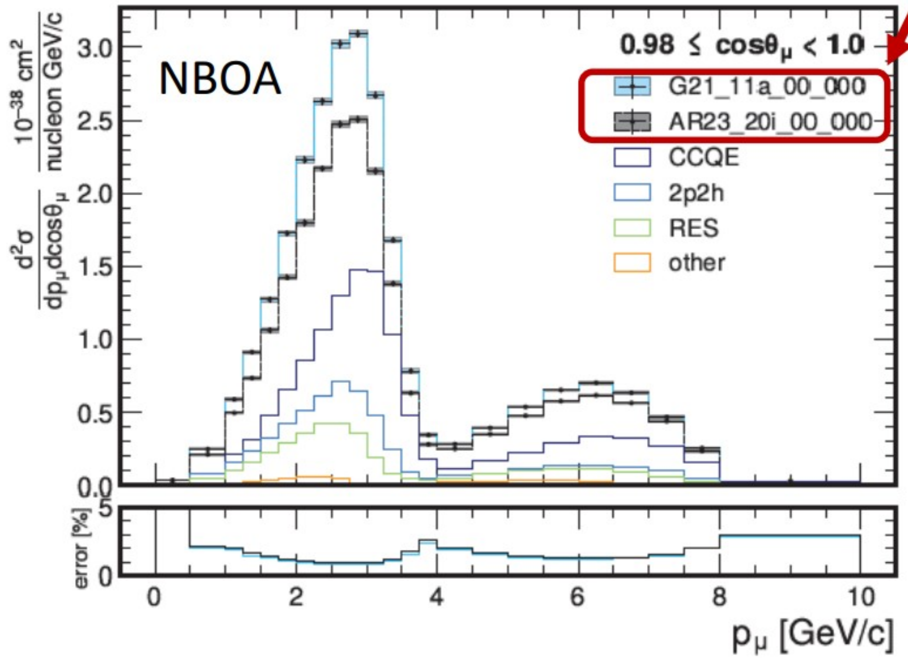


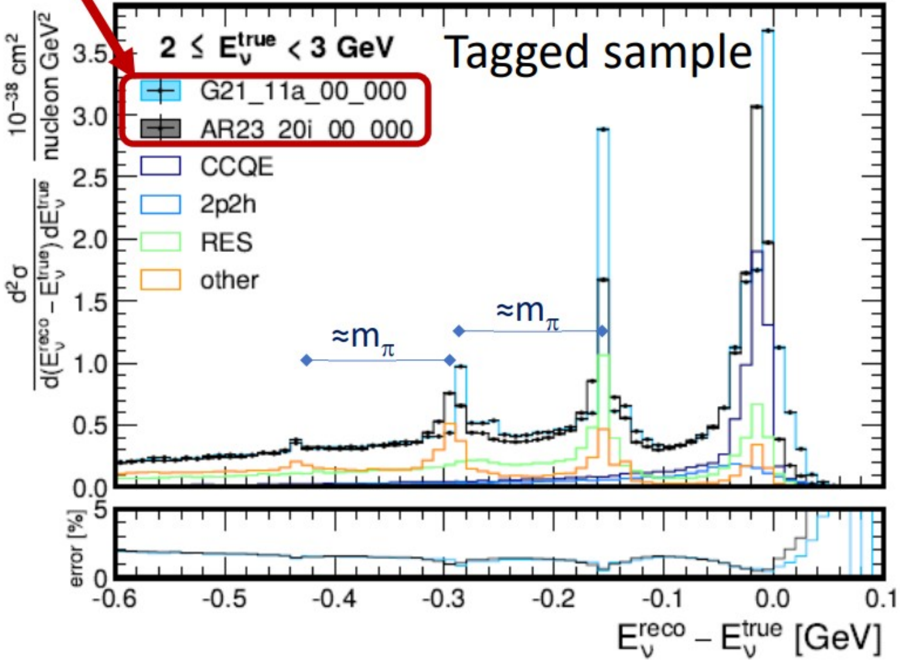
in the golden tagged sample, the bin width is no more driven by the energy uncertainty (<1% !!) but just by statistics

2) Smearing of E_ν^{reco}

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



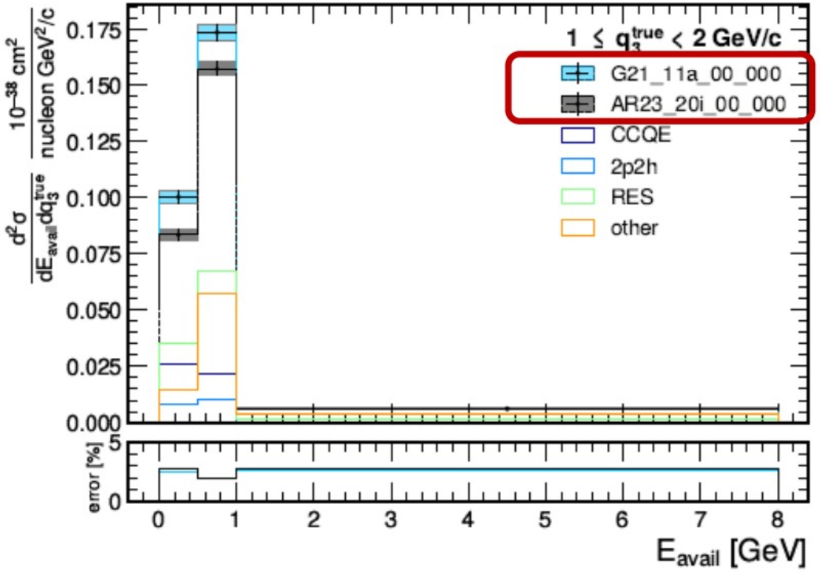


Without monitoring, the double differential cross section for "quasi elastic" (CC0π) would be systematic limited

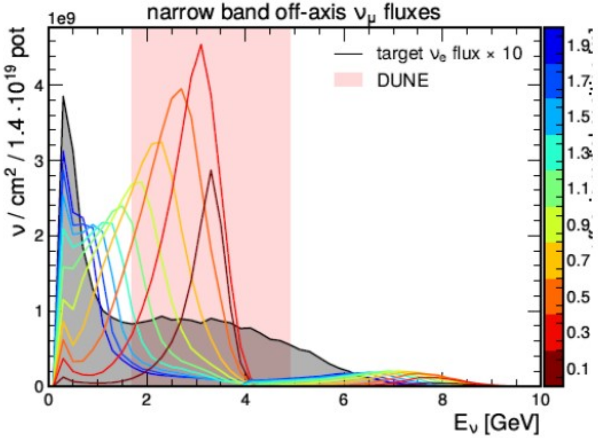
The tagged sample employs the knowledge of the "true" neutrino energy to directly measure the energy bias in bins of E_{true}

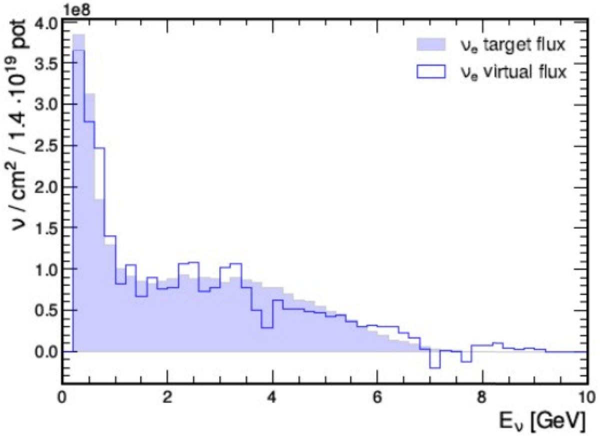
3) ν_e cross sections and ν_e / ν_μ ratio

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



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

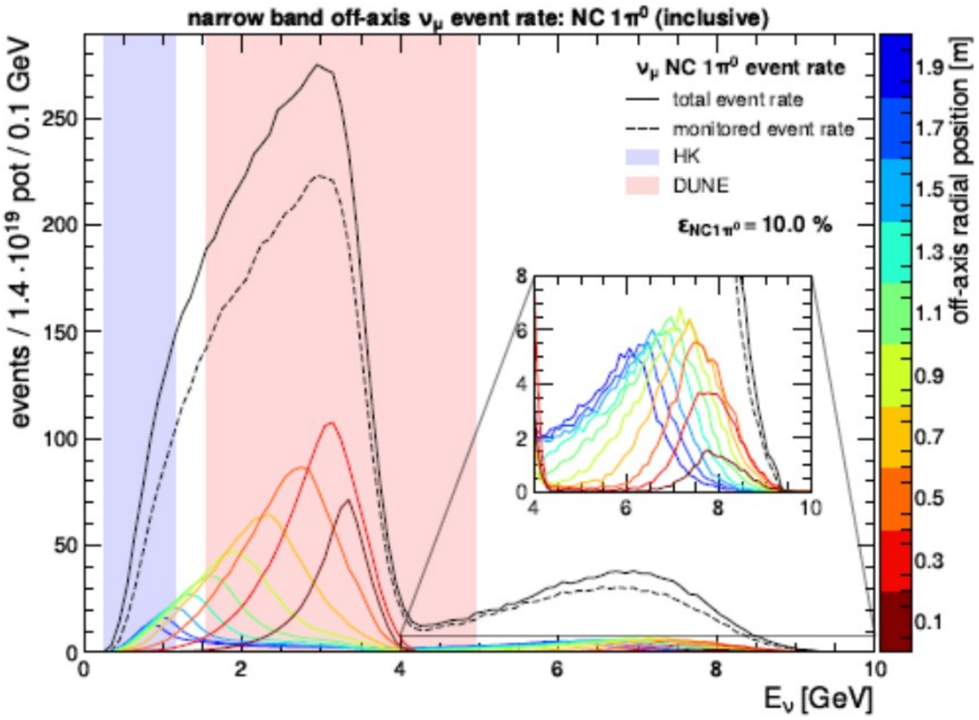




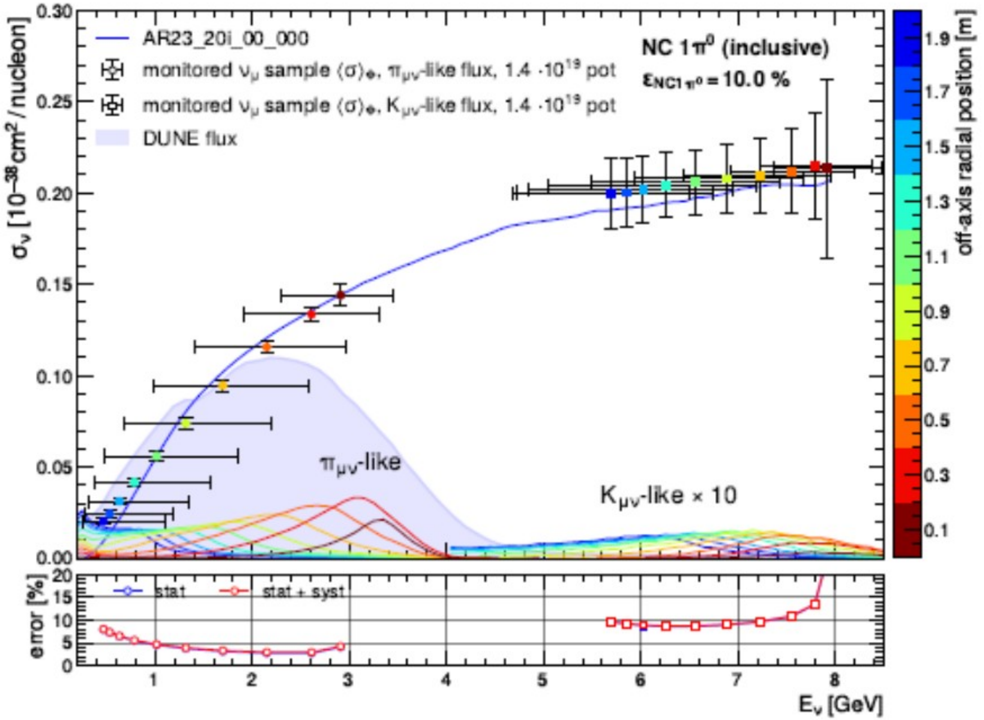
Since we cannot use either NBOA or tagging for ν_e , we measure the flux integrated ν_e cross section and compare it with the corresponding ν_μ cross section, which is built from narrow-width ν_μ fluxes obtained from the NBOA or tagged sample.

4) NC-π^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

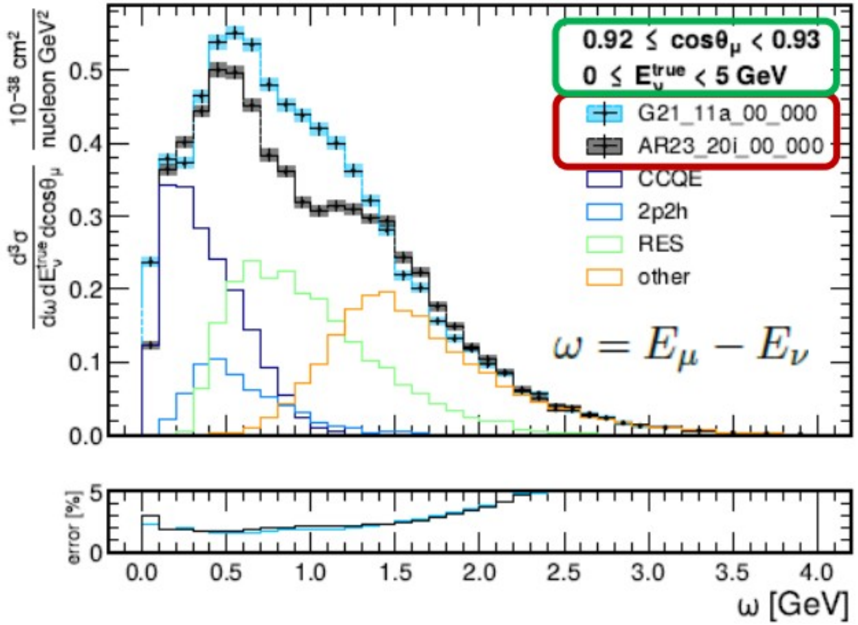
5) Electron-scattering-like measurements with tagged ν

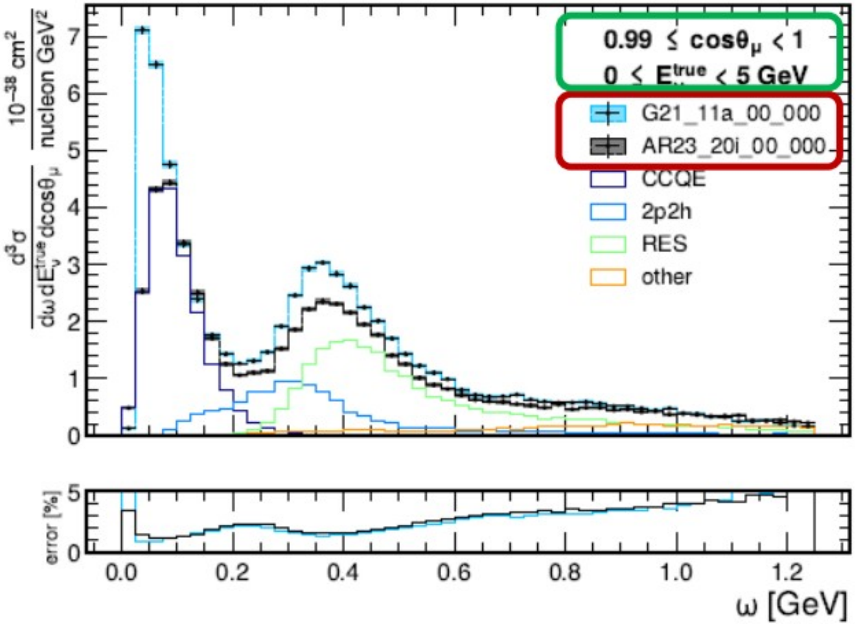
e-nucleon scattering experiments provide the primary experimental input for understanding nuclear effects and developing robust theoretical models. However, they only access **vector currents** since the probe is electromagnetic. Tagged ν_μ–nucleus interaction events exhibit the same features, but with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

nuclear-level form factors

collective nuclear effects

(already the dominant systematics on Δm^2_{32} for T2K)





nuSCOPE technical readiness

"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

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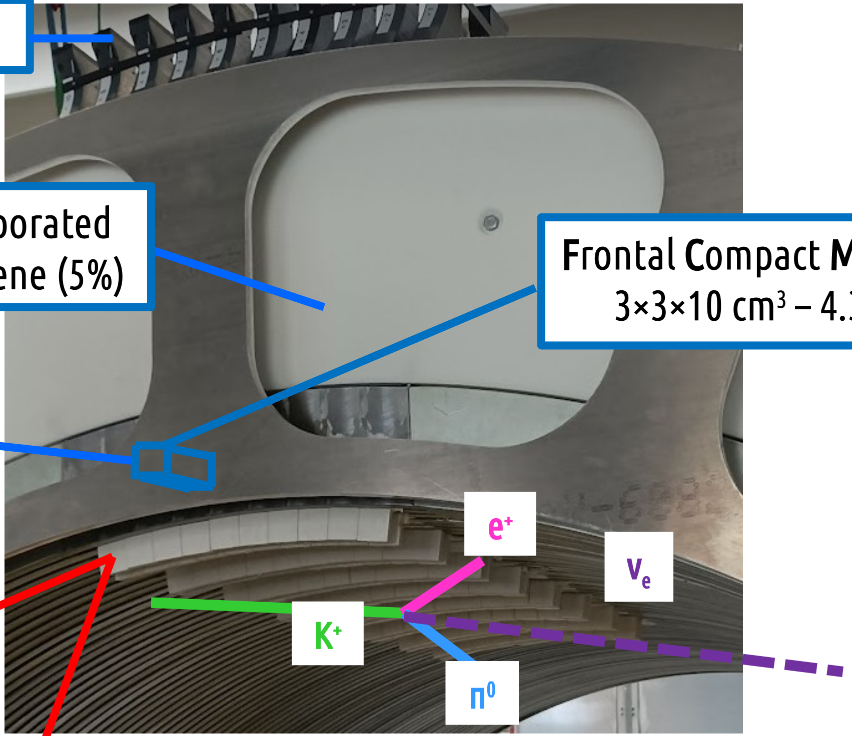
Lepton monitoring in the calorimeter



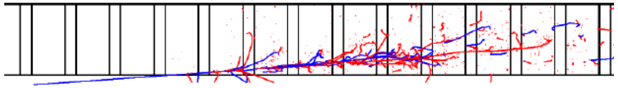
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

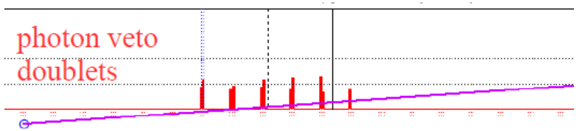
→ $e^+/\pi^\pm/\mu$ separation

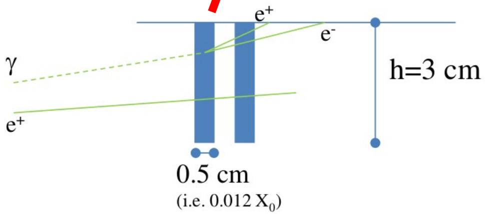


Integrated photon veto

Plastic scintillators rings of 3×3 cm² pads

→ π^0 rejection





e^+ (signal) topology

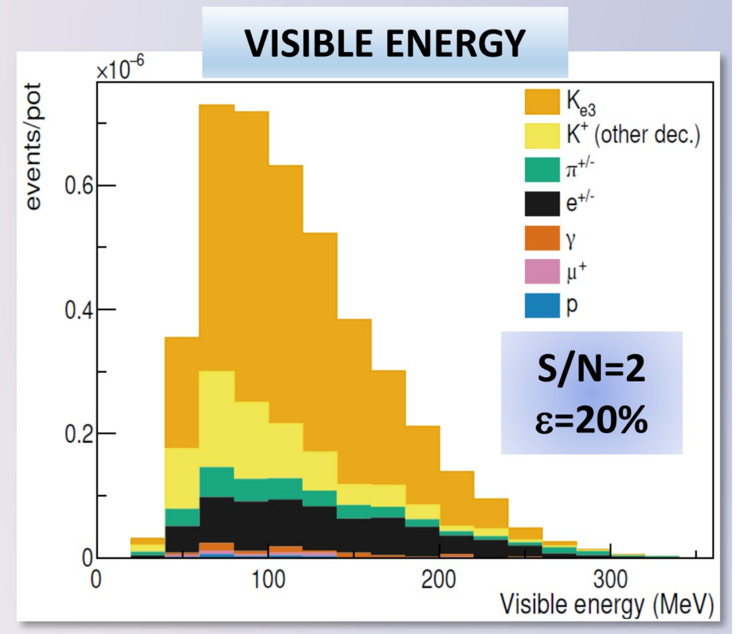
π^0 (background) topology

π^+ (background) topology

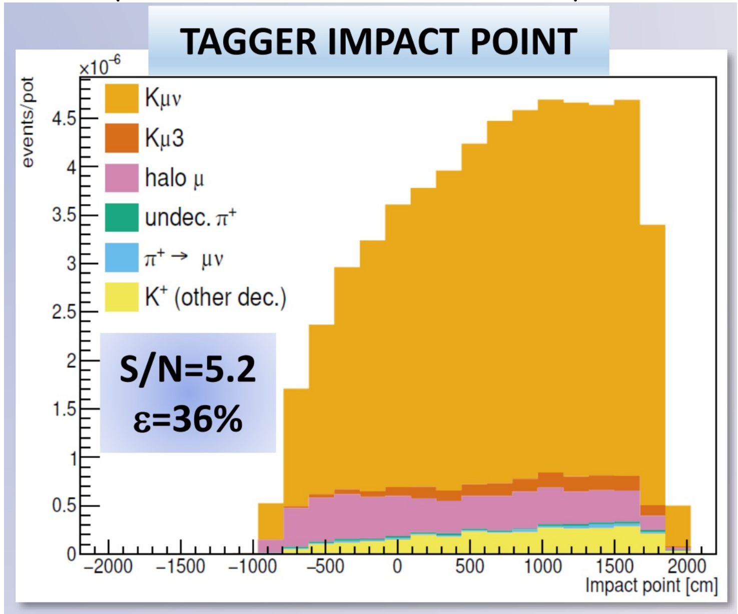
Lepton event-by-event reconstruction

GEANT4 simulation. Event building: clustering of cells in space and time (accounting for **pile-up**) → PID with a Multilayer Perceptron

K_{e3} positrons: constrain ν_e



$K_{\mu 2}$ muons: constrain ν_μ



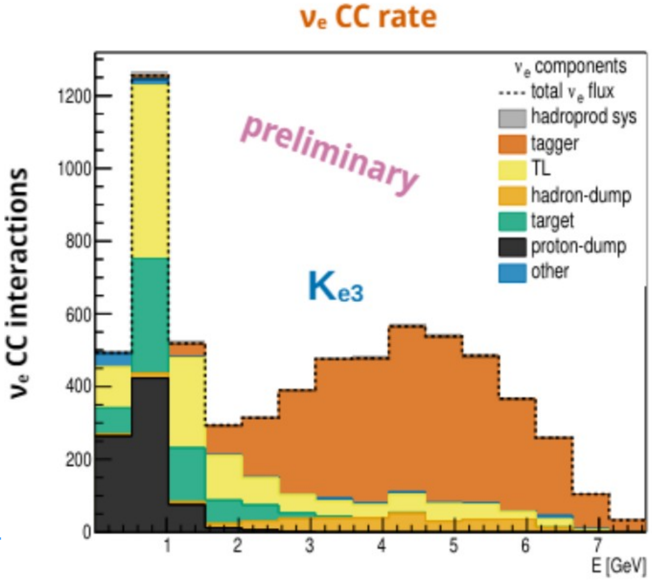
About half of the efficiency loss is from geometrical acceptance (lepton too forward)

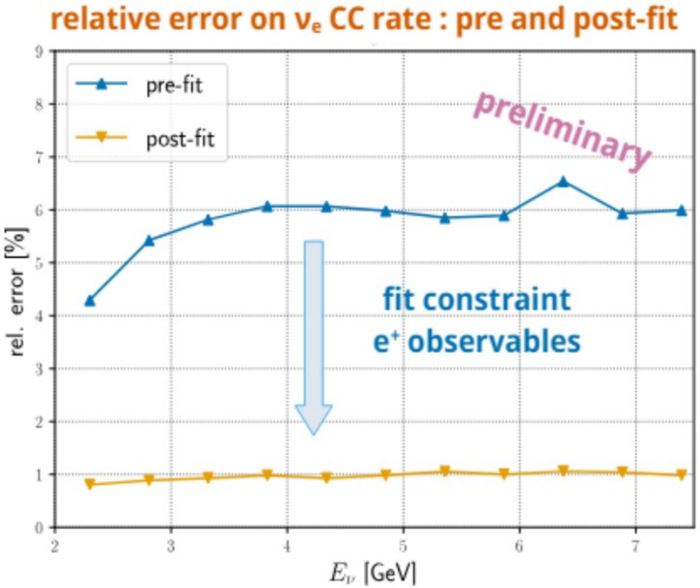
Precision on the electron neutrino flux from monitoring

• considered the dominant sys. (hadroproduction) extracted from hadroproduction experiments at the SPS (NA56/SPY), which gives a 6% uncertainty on flux
• added as an additional prior the rate, position and energy distributions of positrons from K decay reconstructed in the tagger

Flux uncertainty for ν_μ and ν_e drops from 6% to 1% using positrons only.

F. Bramati poster at Neutrino2024

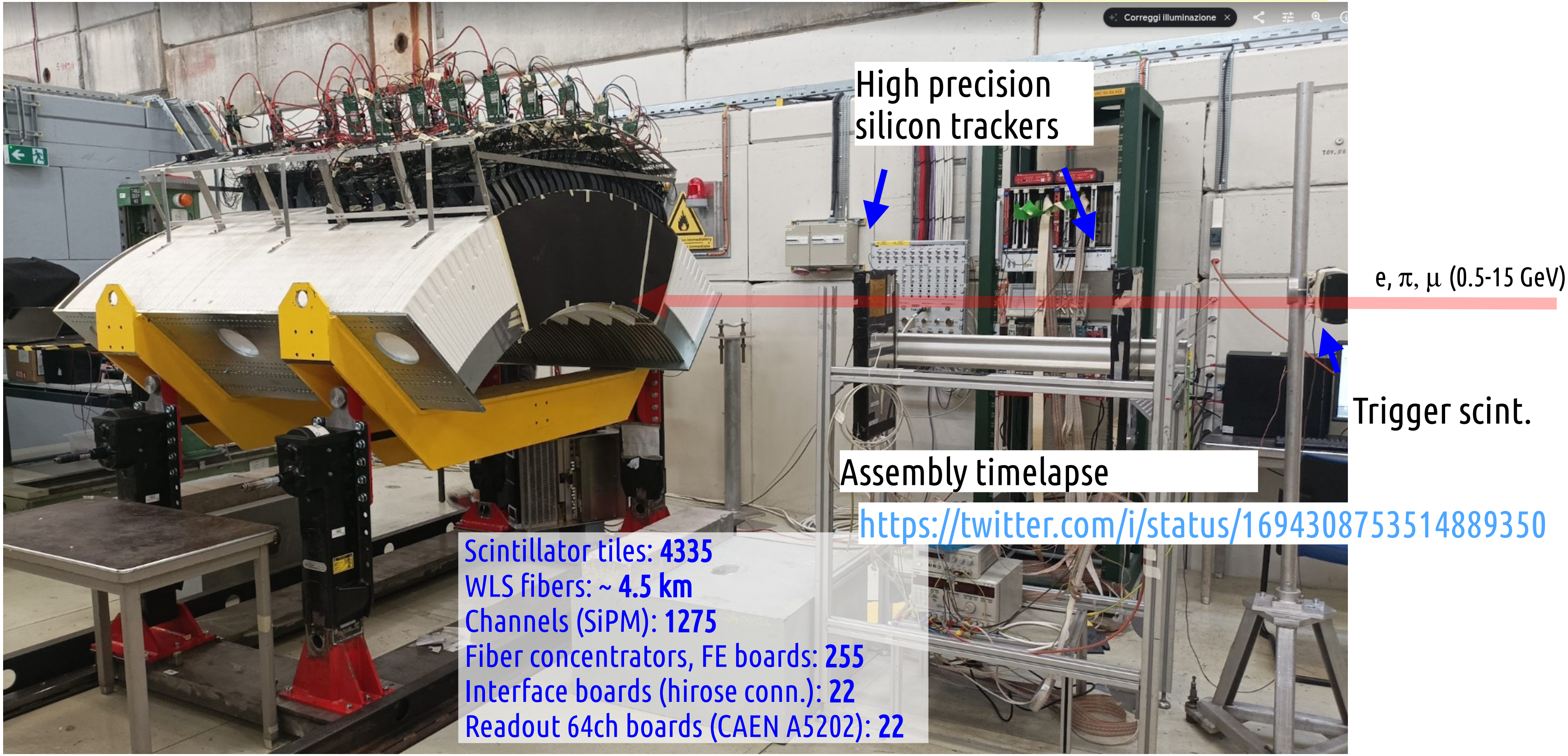




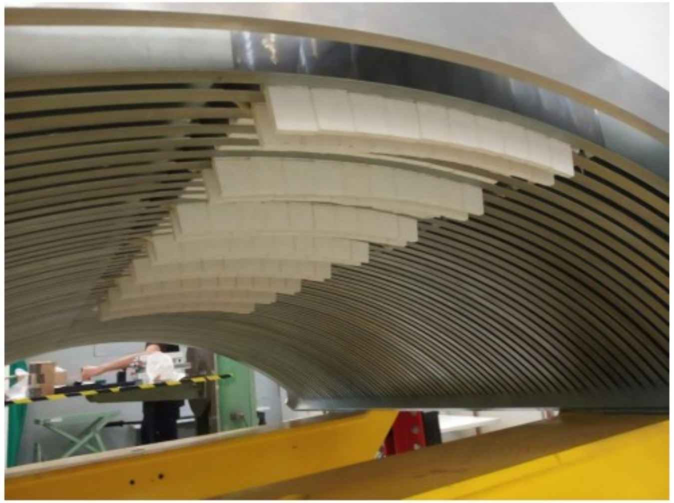
In progress: add detector effects, magnet currents, beam component, material budget uncertainty, (paper in preparation). Include improvement from the information from $K_{\mu3}$.

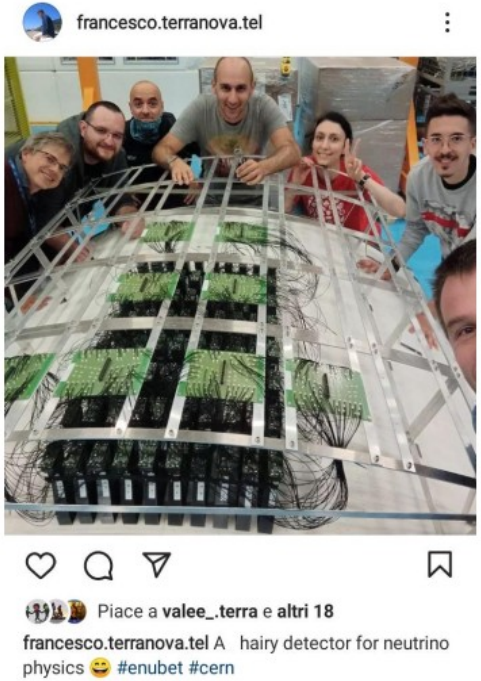
The calorimeter demonstrator

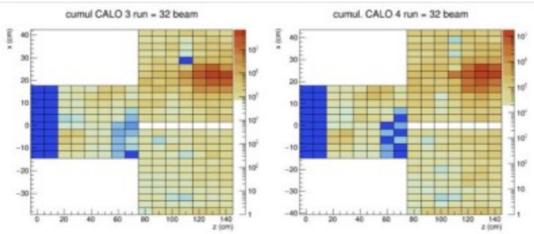
10/22 + 08/23 + 08/24 @ CERN-PS-T9

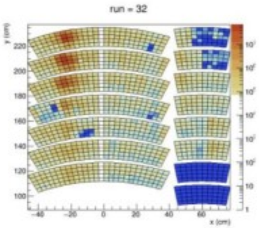


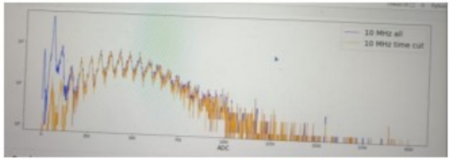
The ENUBET demonstrator at the CERN PS-EA in 2022-23-24



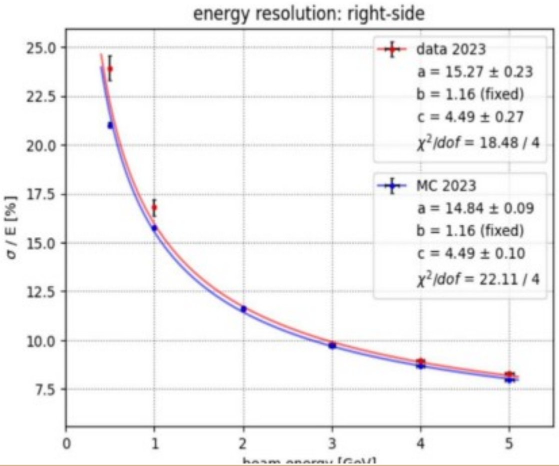






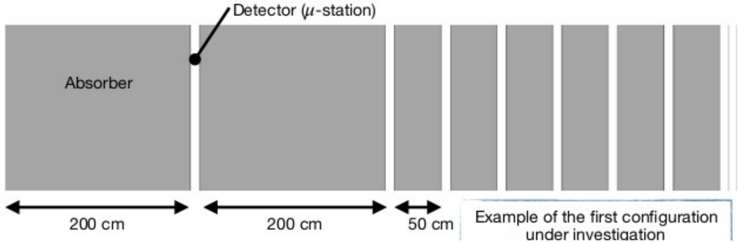


Aug 2024!



Instrumented hadron dump (I)

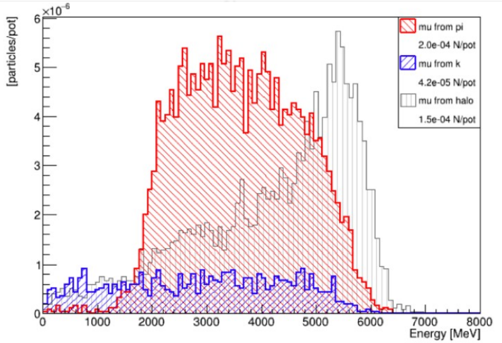
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.



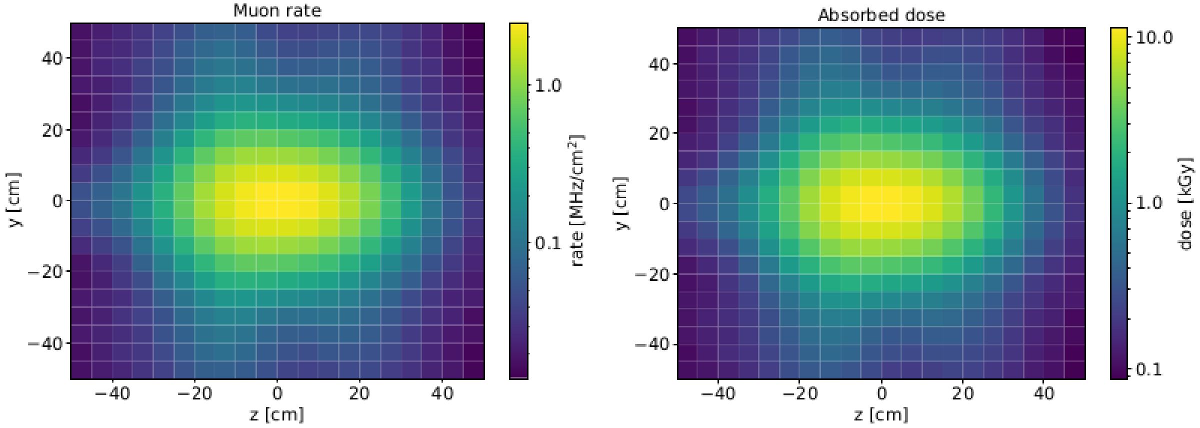
$\pi^+ \to \mu^+ \nu_\mu$

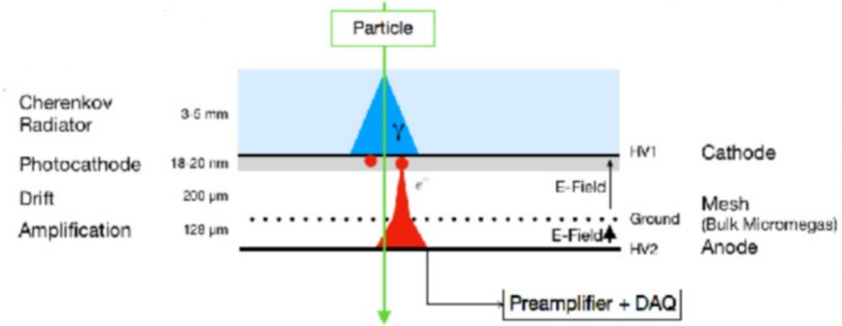
$K^+ \to \mu^+ \nu_\mu$

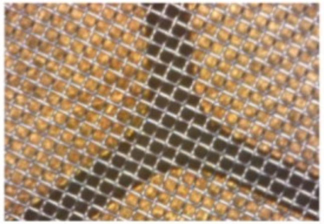
Halo μ^+



E (MeV)





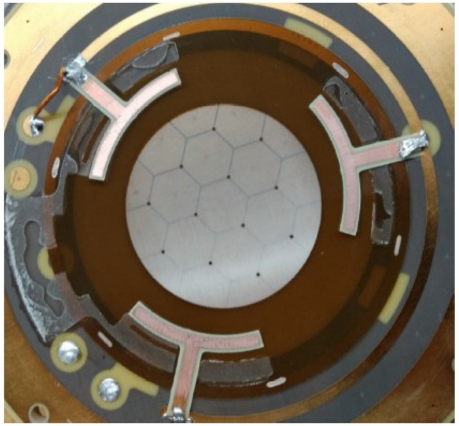


PICOSEC Micromegas detectors employing Cherenkov radiators + thin drift gap cutting-edge timing (O(10) ps).

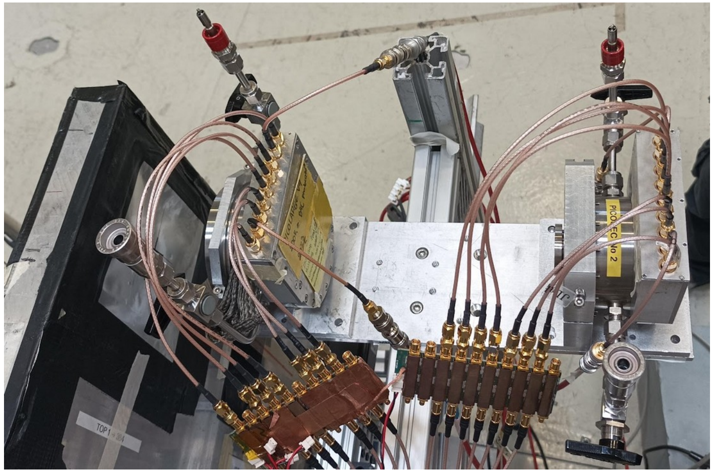
Instrumented hadron dump (II)

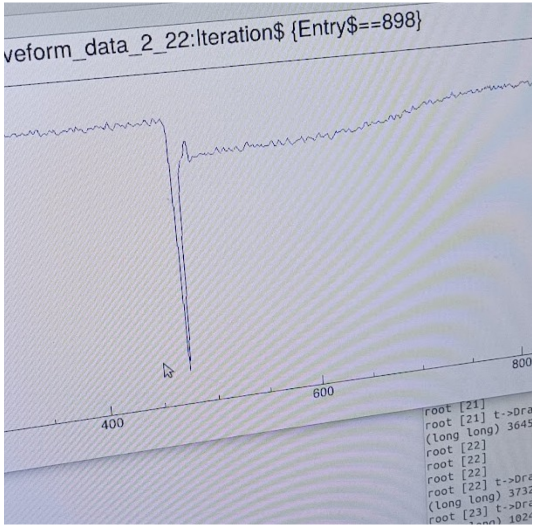
PIMENT ANR (**PI**cosecond **M**icrom**E**gas for e**N**ube**T**), ANR2022-25 CEA, Athens, CNRS, INFN, Thessaloniki, Zagreb we plan to use PICOSEC MicroMegas

Test beam approved 8-15 October @ PS-T9. Will expose some modules with iron in between and evaluate the response to “busy” events (showers). A preliminary test with demonstrator+single plane was already achieve in August 2024.

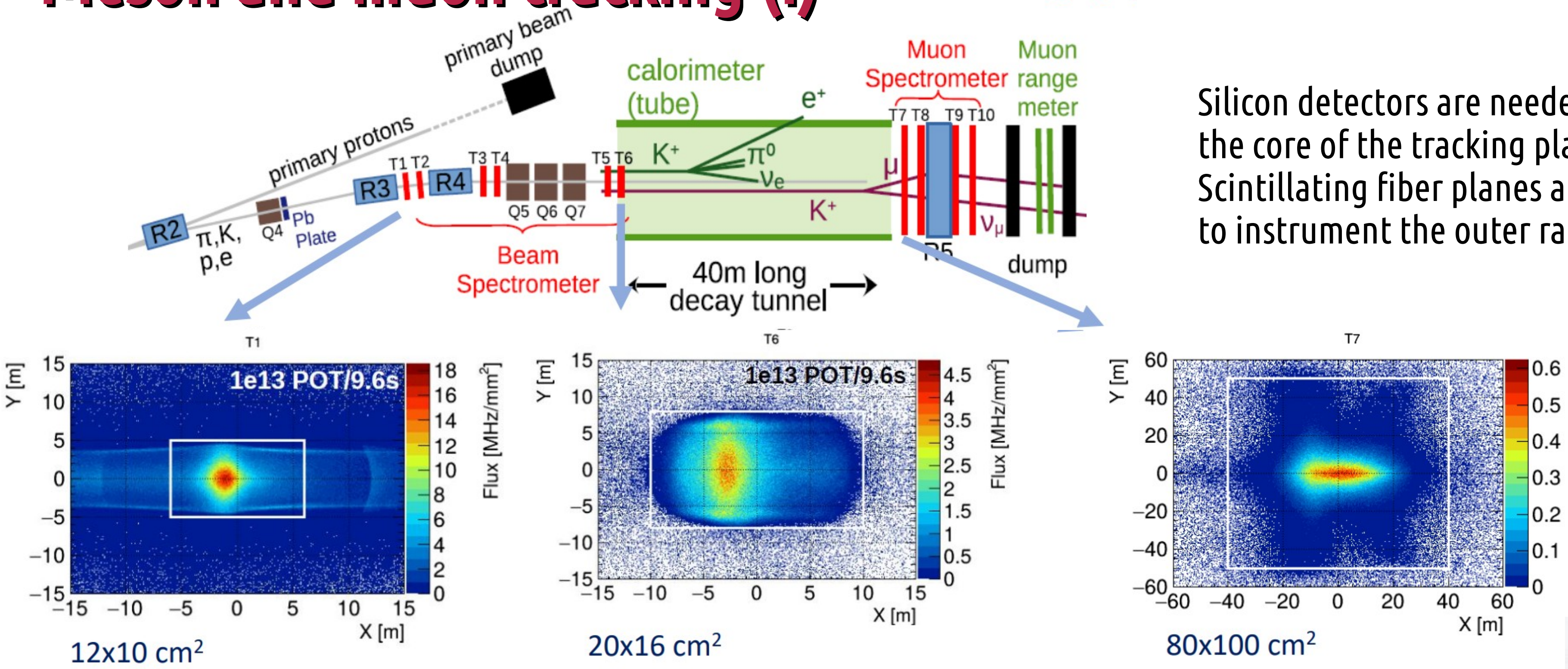


19 channel anode ⬡ 1 cm

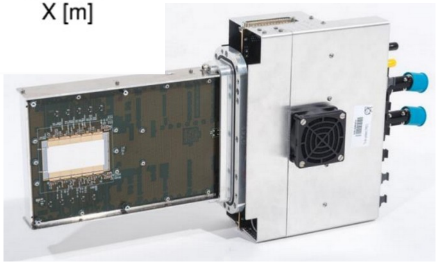




Meson and muon tracking (I)



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



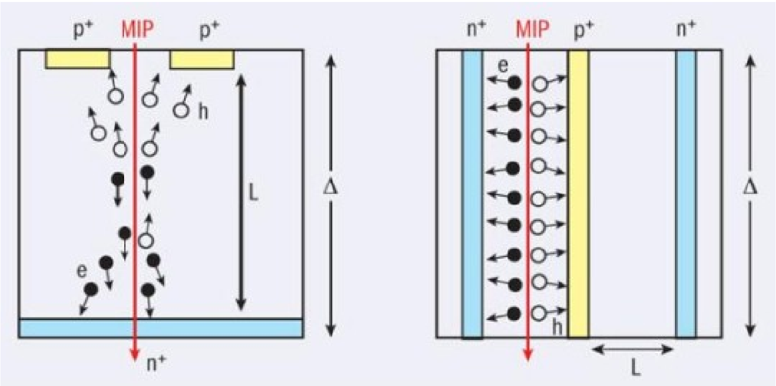
Particle rates in the hottest (central) planes: 20 MHz/mm² for 10^{13} pot in 9.6 s. Peak fluence (non-ionizing dose): 10^{16} $MeVn_{eq}/cm^2$ Requires σ_t O(100 ps) and a detector granularity of 300 μm. We thus benefit from the technology currently being developed for the **LHCb velo upgrade**, pioneered @ 2 MHz/mm² 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 [$1\mathrm{MeV}n_{eq}/\mathrm{cm}^2$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [$\mathrm{MHz/mm}^2$]	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)

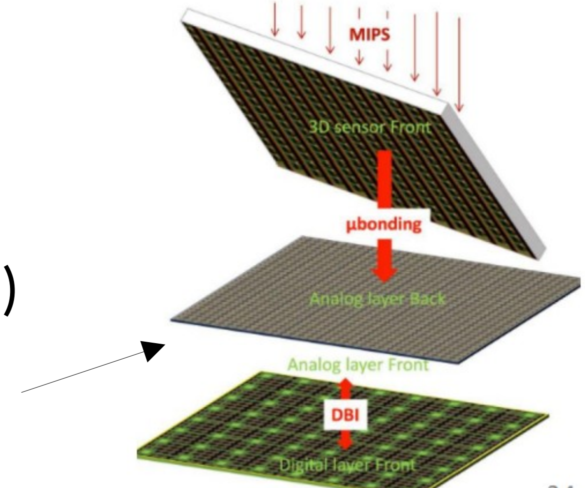


Readout ASIC

Three developments ongoing, all with 28nm CMOS technology

Timespot v2 and IGNITE (3D stacked) by INFN,

PicoPix by CERN, Nikhef



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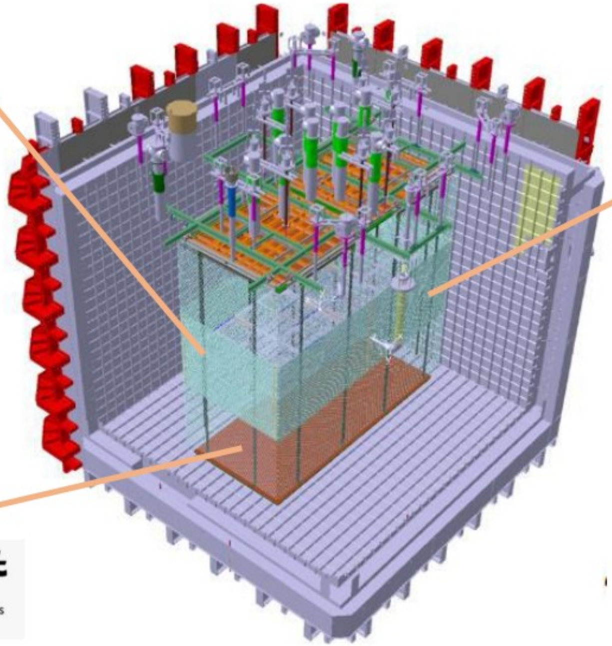
Liquid Argon detector

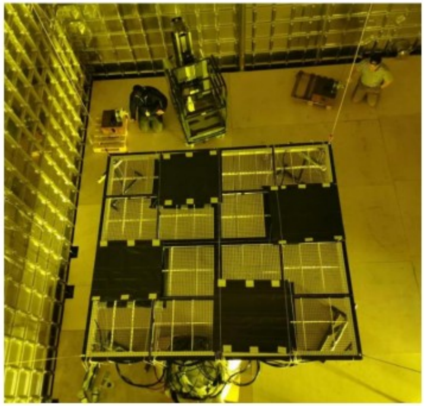
The Liquid Argon TPC technology developed by DUNE, in both its “Horizontal Drift” and “Vertical Drift” configurations, meets all the specifications of nuSCOPE except for the **time resolution** in tagging mode, which should be in the 200-500 ps range. It is limited by the light collection efficiency 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)

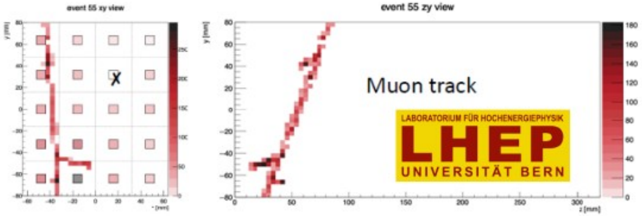
ProtoDUNE-VD Run III (2027-28)



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

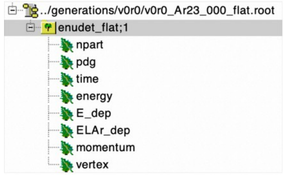
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

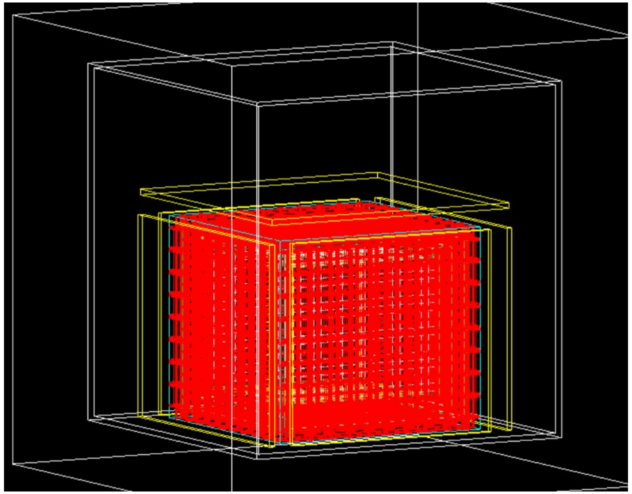
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

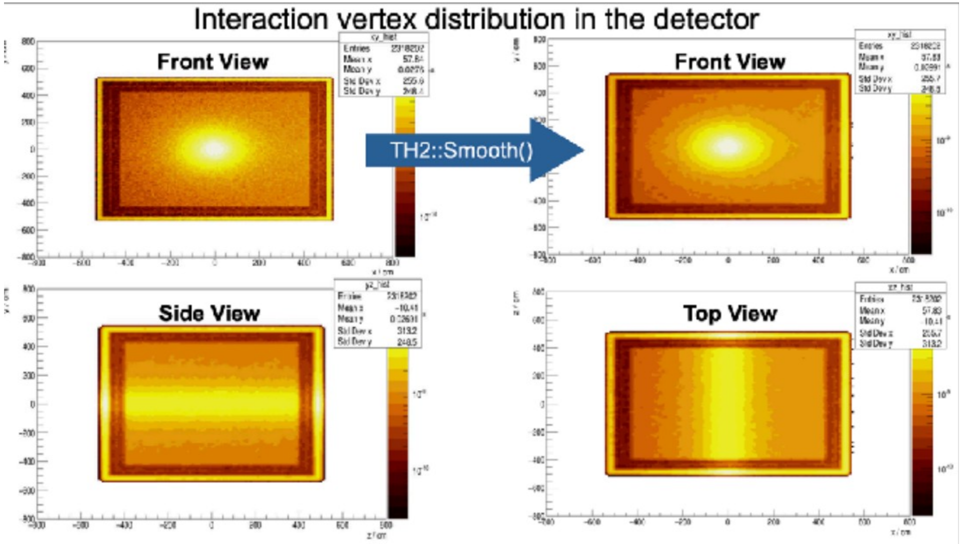
Simulation of the LAr detector

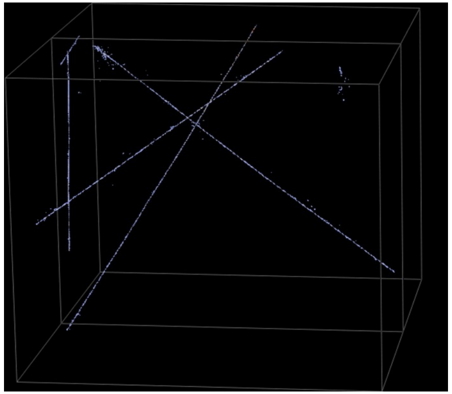
J. McElwee
Bordeaux

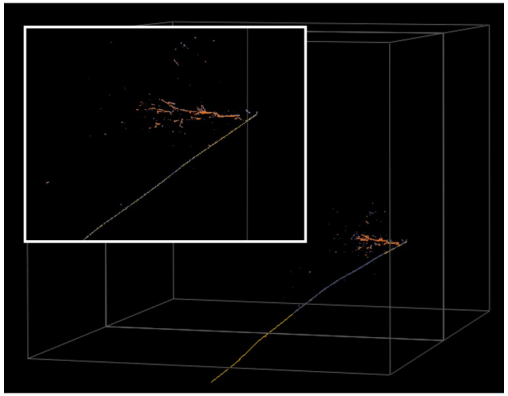
- We have a full simulation of the neutrino LAr detector (a` la Proto DUNE) using GENIE and CORSIKA.
- Working to finalize the cosmic ray tagger (CRT) .











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!

backup

Possible implementations at CERN

CNGS: deep underground downstream of LSS4 in TCC4 to point the neutrino beam towards Gran Sasso.

North Area: usually the prime location for fixed-target experiments. Availability of slow extraction at the long straight section 2 (LSS2). Existing infrastructure and beamlines. Ideal location could be the ECN3 cavern due to its depth and radiation-protection limits. However SHiP will occupy it from LHC Run 4.

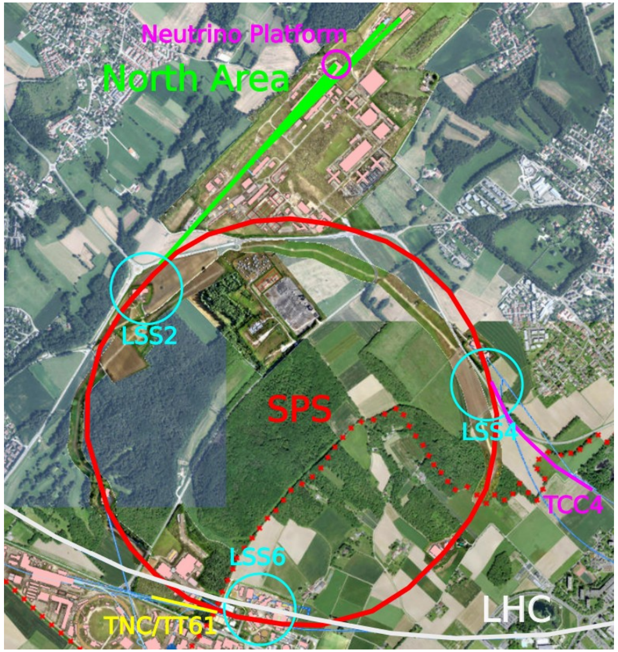
The beamline cannot be placed inside the surface halls EHN1 and EHN2 in CERN's North Area due to radiation constraints.

The beamline's bending angle makes it difficult to implement in experimental halls like EHN1 and EHN2, as these halls are predominantly long rather than wide.

A placement below EHN1 is also excluded due to the technical galleries below the building and the challenges of excavating underneath an existing building in the vicinity of the Lion river.

→ the ProtoDUNEs at the North Area's Neutrino Platform cannot be used in their current location as the neutrino detector must be placed no more than 50 m from the end of the decay tunnel. Building extensions and an experimental hall for the neutrino detectors would be necessary in the North Area.

A beamline bypassing EHN1 to approach the ProtoDUNEs has been excluded due to the vicinity of the fence and the SPS beam rigidity that results in a large bending radius.



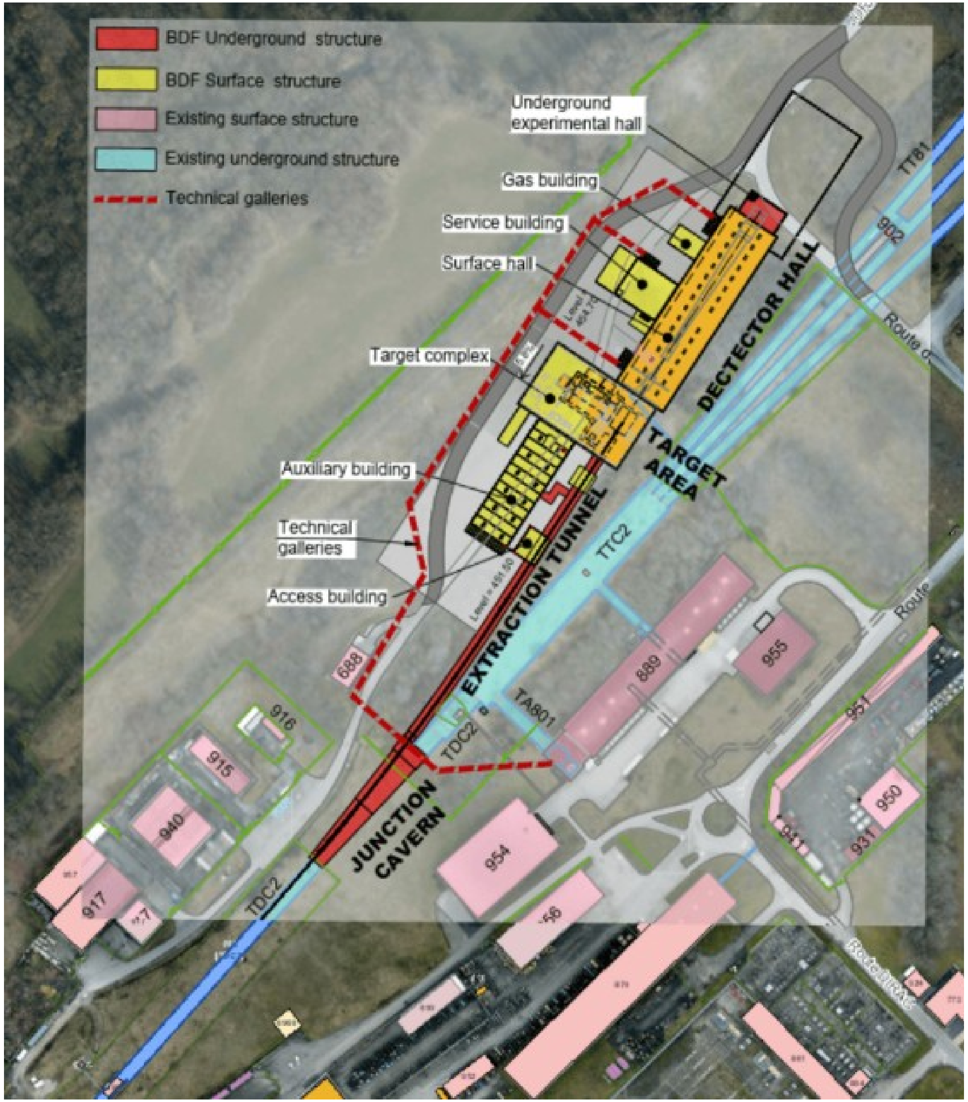
ECN4

Underground cavern as an option for the proposed BDF/SHiP facility. Would be on the Jura side of TCC2 – the underground cavern that houses the targets for the EHN1 beamlines.

SBN@CERN: similar requirements to BDF/SHiP but

the spill intensity of 1×10^{13} PoT/spill is 4x smaller
requires maximum of $2 - 3 \times 10^{18}$ PoT/year i.e. ~10x less

reduced amount of shielding, cooling, and dilution measures and offers greater flexibility in the location of the experimental hall.



SPS LSS6

LSS4 and LSS also feature extraction septa followed by transfer tunnels that serve:

- LSS4: LHC Beam 2 and TCC4 (AWAKE)
- LSS6: LHC Beam 1 and TCC6/TNC (HiRadMat) ← better for SBN@CERN due to lower depth, absence of AWAKE

deep underground (an advantage for radioprotection)

A conceptual analysis investigated the possibility of re-installing a slow extraction setup at SPS LSS6.

“non-local” extraction setup: the electrostatic ZS septa are not located in LSS6 but upstream in a different LSS (could be possible at LSS4 and LSS5)

The extracted beam oscillates through a considerable part of the SPS ring until it is fully extracted by the magnetic septa.

Similar non-local extraction scheme used in the PS.

Advantage: does not require any modifications to the fast extraction for the LHC.

SPS LSS6

TNC
5.6 m wide
HighRadMat
(only upstream)

TT61
4 m wide
empty

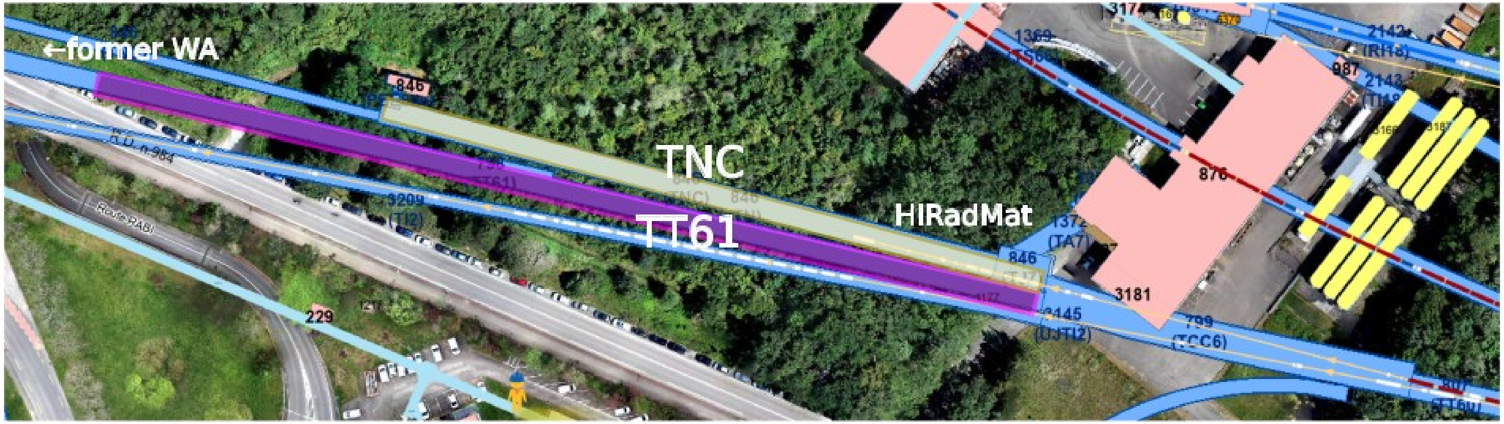


Figure 8: View of the TNC (yellow frame) and TT61 (purple frame) tunnels downstream of the extraction location in SPS LSS6. The first part of the TNC tunnel is occupied by the HiRadMat test facility, while the downstream tunnel (approximately 120 m) can be used for the beamline. The TT61 tunnel – although slightly narrower than the TNC tunnel – is currently not occupied.

Figure 9: In the current beamline design and pending further optimization, the beamline cannot be operated successfully at a reduced bending angle. For this reason, the beamline is placed with a straight transfer and requires the excavation for the neutrino detector and the final part of the decay tunnel.

Proton sharing at the SPS

Shared cycle with the other North Area experiments independent of the beamline placement

1.4×10^{19} PoT to collect up to 10^4 ν_e (10^6 ν_μ) CC events (500 ton detector, 25m after the decay region)

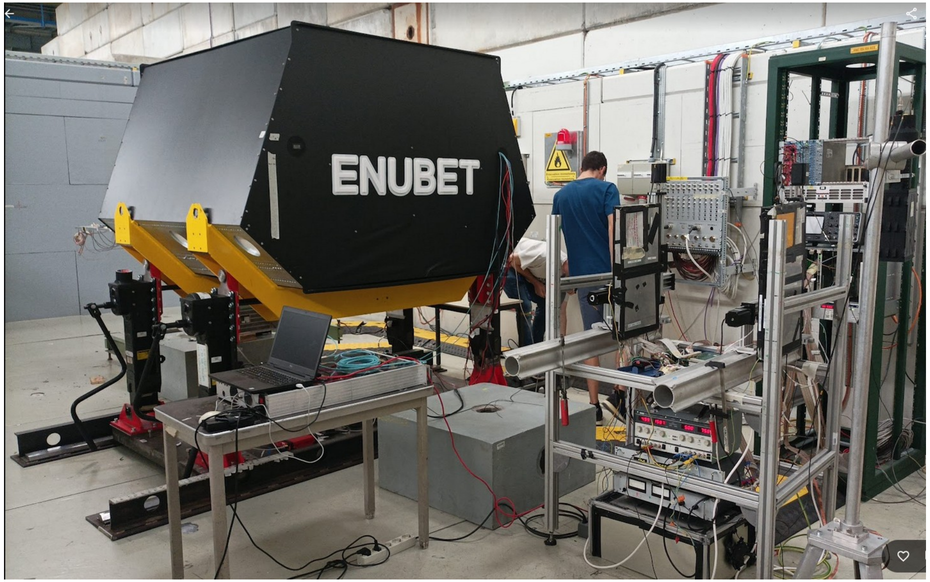
Flattop duration is 9.6 s, delivering 1.0×10^{13} PoT per spill to the SBN (25 % of the TCC2 intensity).

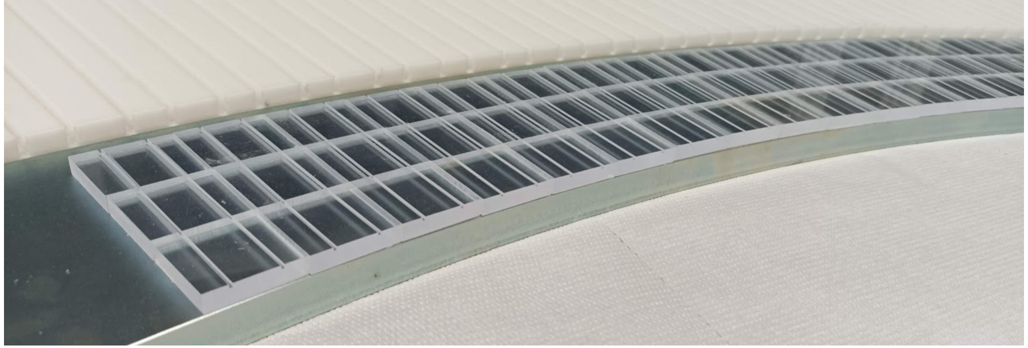
ECN3 (BDF/SHiP) receives the maximum requested 4.0×10^{19} PoT/year.
The SBN runtime for 10^4 ν_e^{CC} is **5.7 - 7.3 years** ($2.4 - 1.8 \times 10^{18}$ PoT/year).

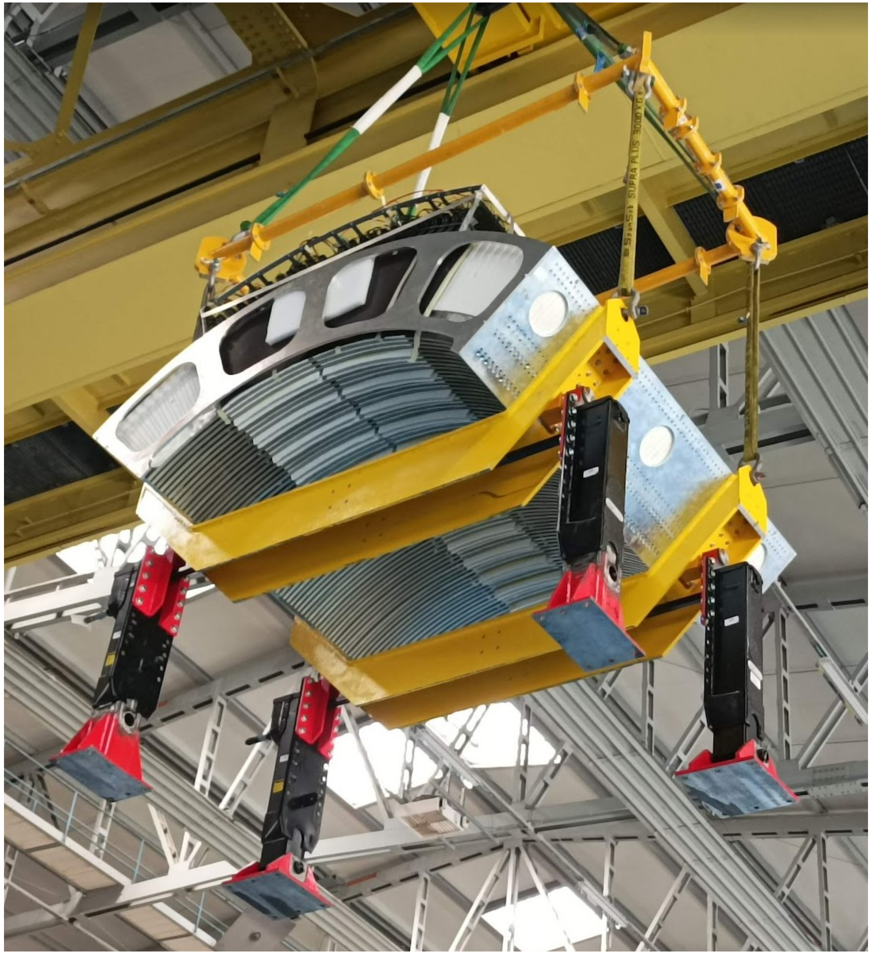
After 5 years, the statistical uncertainty on the inclusive ve cross-section would be better than 1.2 % in all cases

If SPS Flattop duration would remain at 4.8 s → **4.3-6.5 years**.

A statistical uncertainty of 1% on the inclusive ve cross-section is therefore
likely to be achievable within five years.
In case of an enhanced spill number for TCC2 in case the SHiP spill intensity is increased to 5 × 1013 PoT/spill.
This would increase the number of spills for the North Area (SHiP excluded) by roughly 25 % and would shorten the experiment's required runtime.

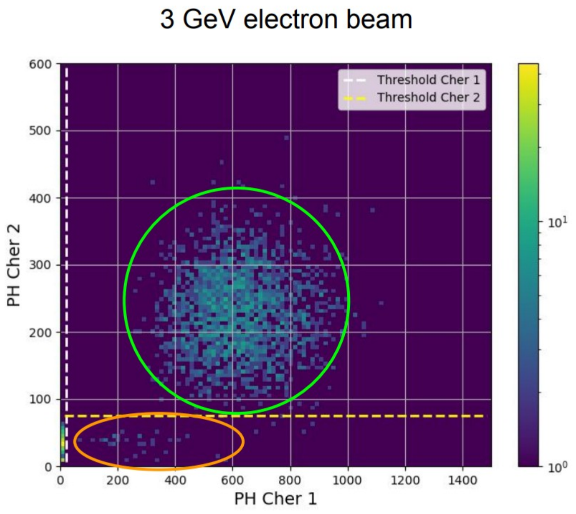

ENUBET

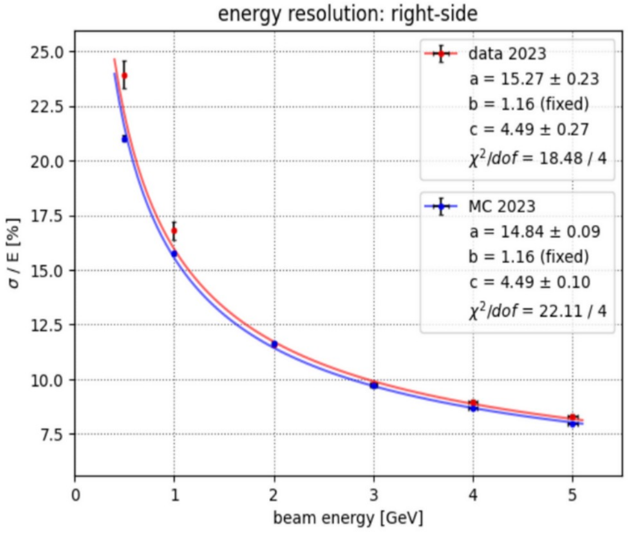


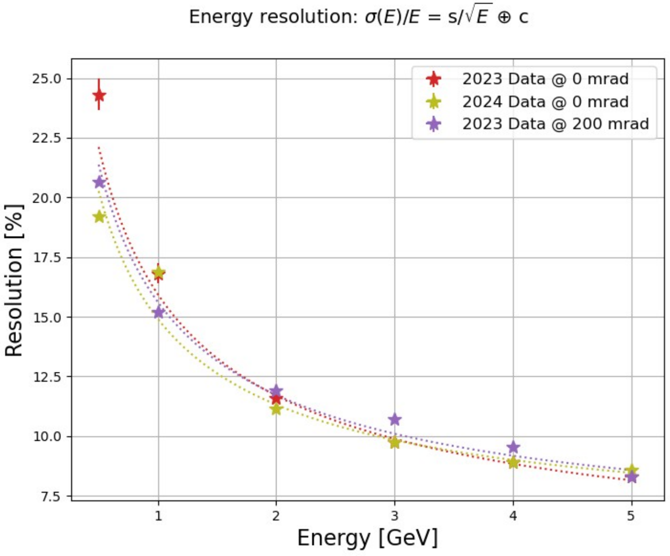


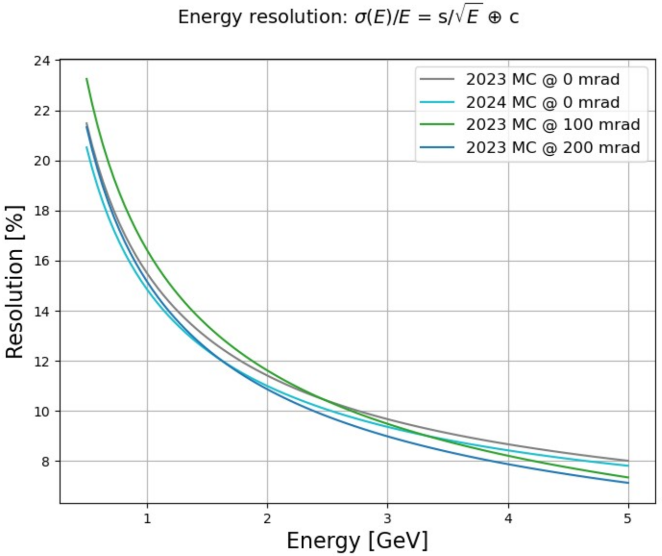
Analysis of the demonstrator data (Aug 24)

- Analysis is progressing well: 1 PhD from Zagreb, 1 from Insubria
- We have analysed the electron energy resolutions with inclined runs.
- Good data/MC agreement
- No indication for a significant deterioration of the resolution in data or MC
- In progress: increase MC statistics, evaluate errors on the parameters of the fitting model and make a comparison at that level



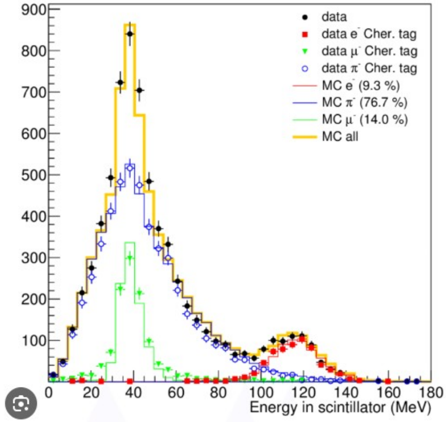






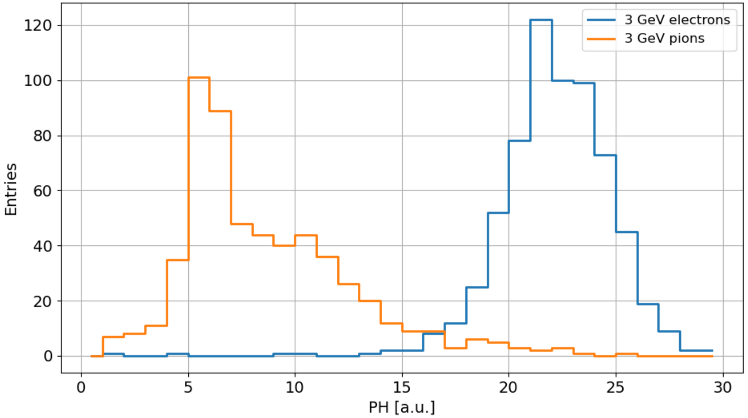
Analysis of the demonstrator data (Aug 24)

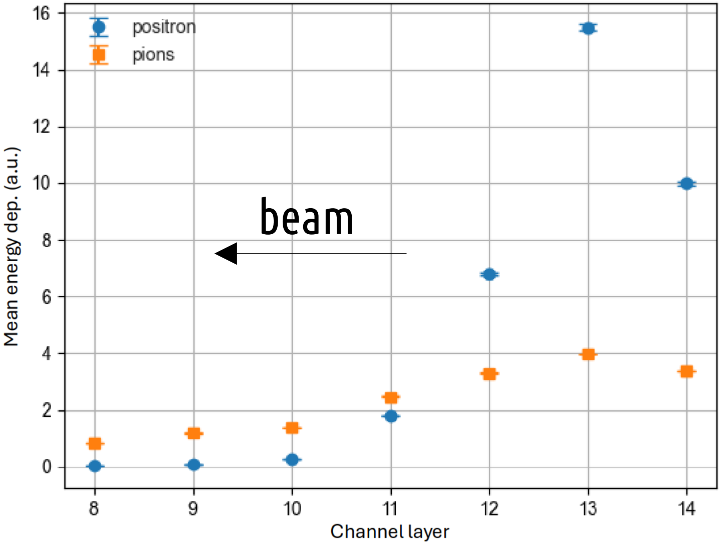
- We are addressing the **hadronic variables** recon (total-energy, depth profile)
- TODO: compare with simulation and produce plots similar to previous publications on early prototypes

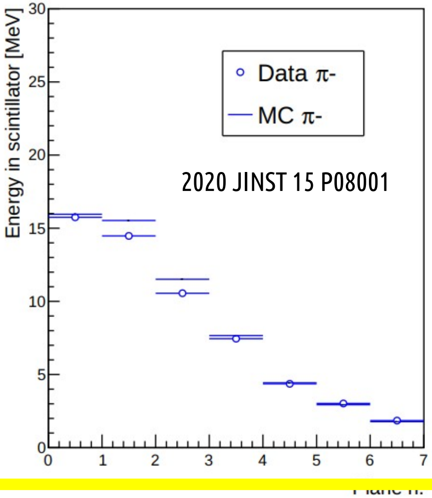


Preliminary 2024 energy longitudinal profile

Preliminary 2024 (3 GeV)



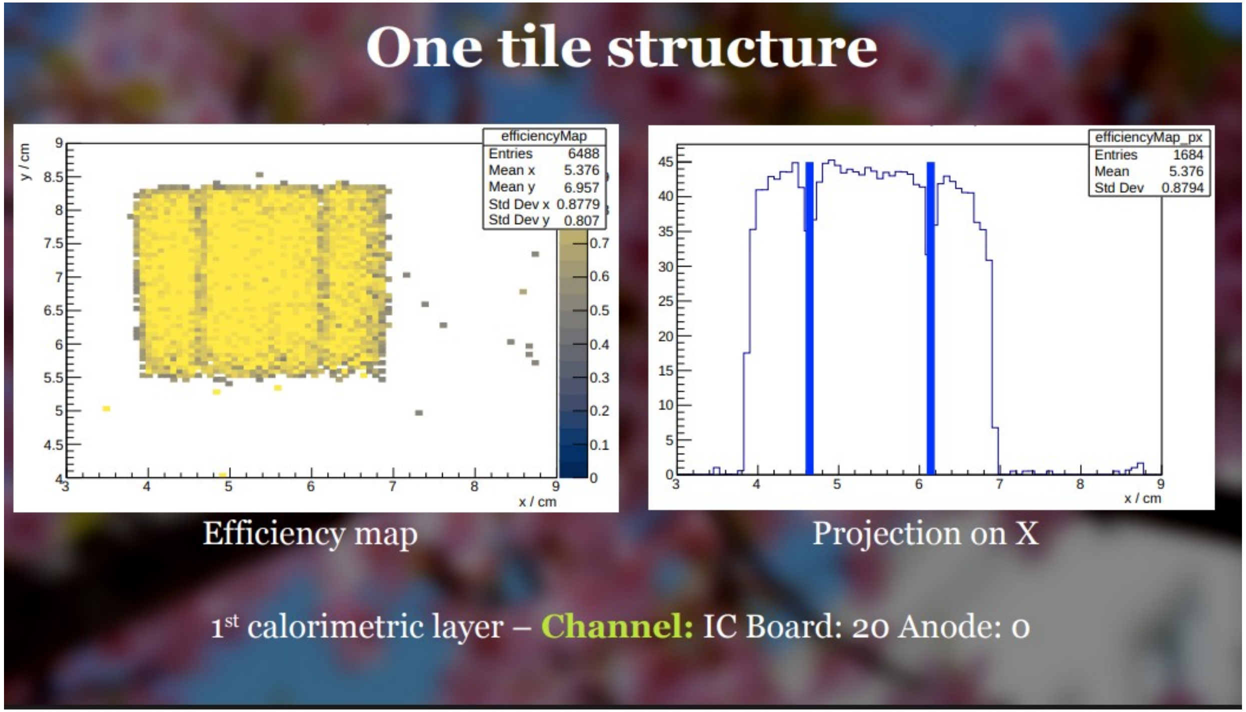


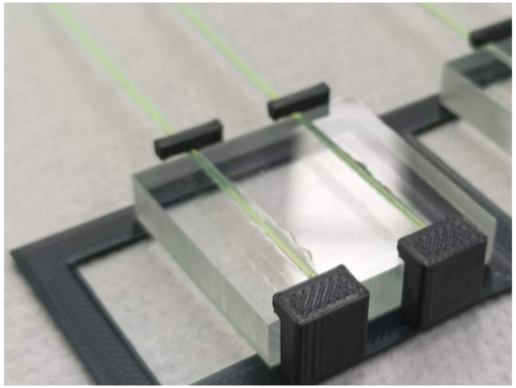


Analysis of the demonstrator data (Aug 24)

Leon Halic

- Efficiency maps at high spatial resolution

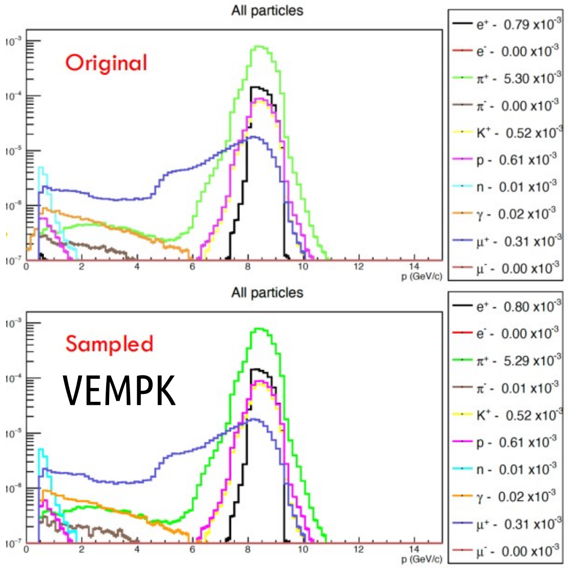




Systematical uncertainties

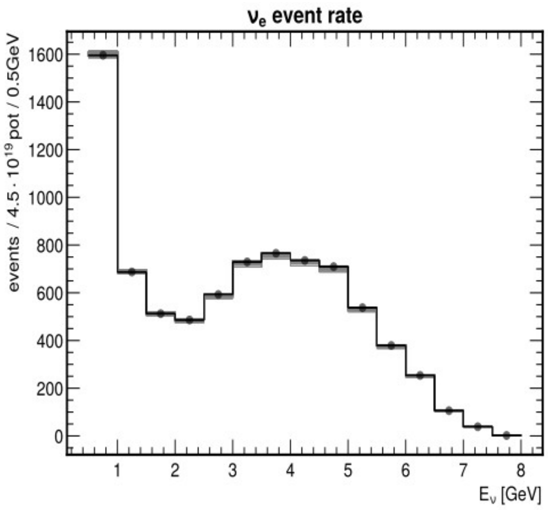
Antonio Branca, Filippo Bramati

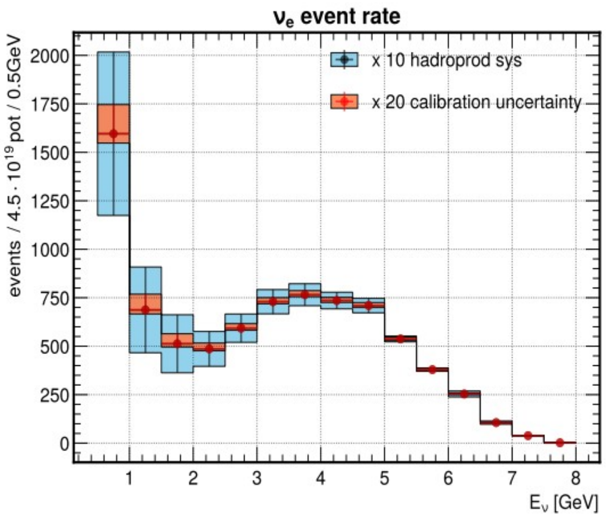
- We validated a sampling algorithm (VEMPK) that allows describing the phase space of incoming particles at the tagger level. Relieves the need to perform the full beamline simulation (quite CPU intensive) → high statistics
- We have introduced detector systematics in the flux prediction (seems to be always subdominant w.r.t. hadroproduction residual systematics)

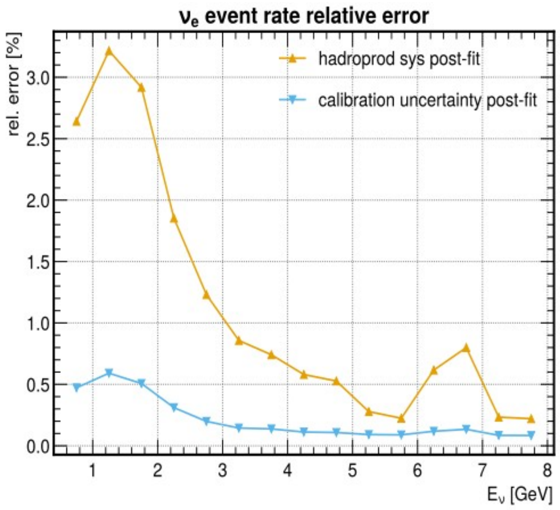


$$\mathcal{L}(\vec{p},\vec{\nu}) = \pi_{\text{hp}}(\vec{p})\,\pi_{\text{det}}(\vec{\gamma})\prod_i^n P(N_i|N_i^{\text{p}}(\vec{p},\vec{\nu}))$$

$$\pi_{\text{det}}(\vec{\gamma}) = \frac{1}{(2\pi)^{k/2}\cdot|V_{\vec{\gamma}}|^{\frac{1}{2}}}\cdot e^{-\frac{1}{2}\vec{\gamma}\cdot V_{\vec{\gamma}}^{-1}\cdot\vec{\gamma}^T}$$

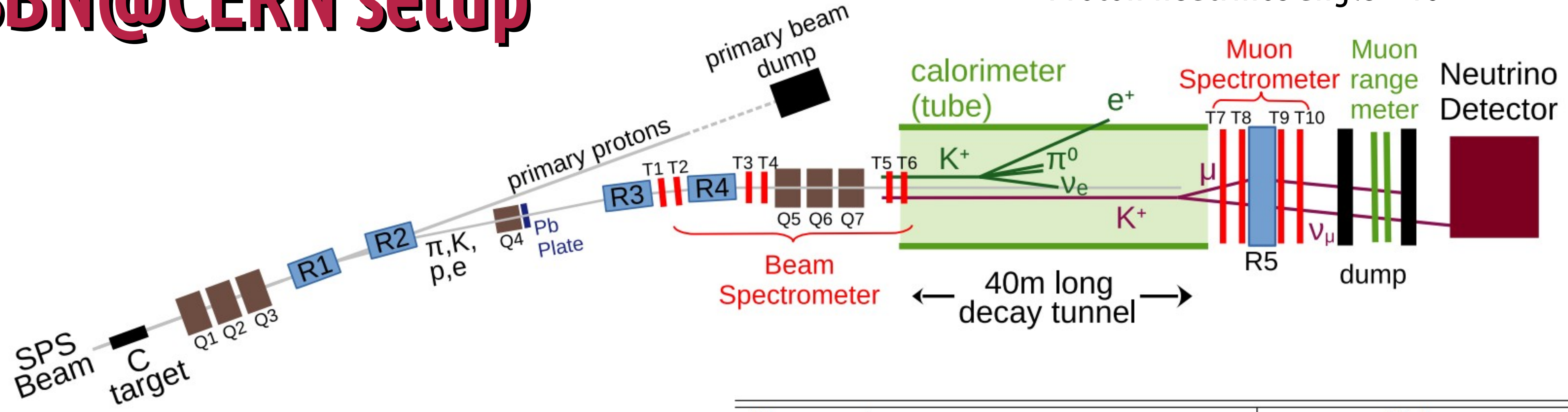






SBN@CERN setup

Proton-neutrinos angle = 18 °



Parameter	Value
Primary proton momentum (GeV/c)	400
Beamline meson momentum (GeV/c)	max. 8.5
Proton-beam spill duration	slow (4.8 s to 9.6 s)
Spill intensity (protons/spill)	1.0×10^{13}
Event rate (THz)	1 – 2
Instantaneous power on target (W)	170 – 340
(K^+, π^+) yield per proton	$(1.3 \times 10^{-3}, 1.9 \times 10^{-2})$
(K^+, π^+) rate (GHz)	max. (2.7, 40)
Annual proton intensity (protons/year)	$2.1\text{–}3.2 \times 10^{18}$
Total proton requirement (protons)	1.4×10^{19}

New beamline

Re-optimization of the detector:

Cross section 4x4 m^2 depth = 23 m @ 25m downstream of the decay tunnel (500 ton)

Beamline optimization

The production target and the beamline optics optimized in a self-consistent manner.

The pixel detectors that are introduced for particle tagging

mitigation of the large number of positrons that are produced in the graphite target: thin Pb plate was inserted into the beamline right after the Q4 quadrupole to degrade their energy outside the beamline acceptance.

It may be useful to adjust the thickness of the positron-absorbing Pb plate (using a motorized wedge with variable thickness) to effectively tune the flux on the pixel detectors.

Multi-objective genetic algorithm (MOGA). 26 beamline parameters.

• Drift spaces: The drift spaces in the upstream and downstream quadrupole triplets are optimised (7 free parameters)

• Quad parameters: For each quad in both triplets, the aperture, length, and gradient are optimised (18 free parameters)

• Production target: 18 different targets (one free parameter). The list includes the T2K, CNGS, ENUBET, and NuMi targets and variations. Lengths from 0.7 to 1.35 m, target radii from 2.5 mm to 30 mm. graphite densities from 1.70 g/cm3 to 2.26 g/cm3 .

Beamline optimization

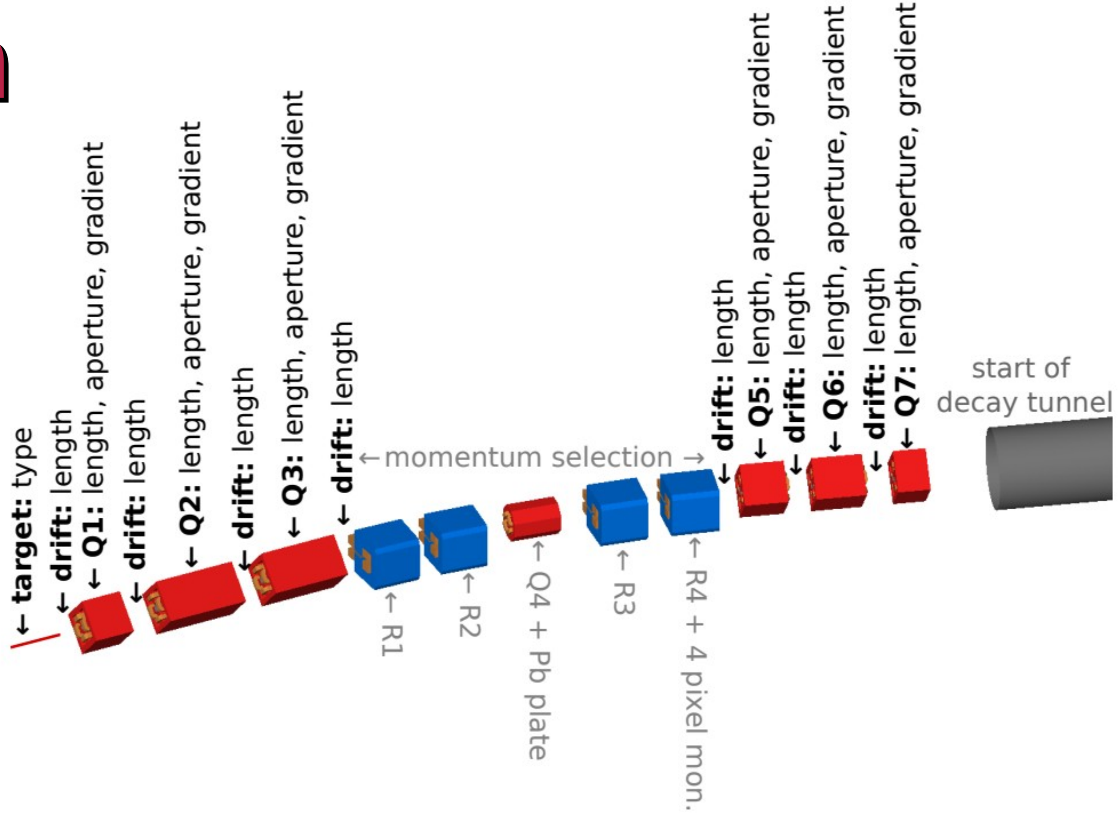
modified beamline acceptance that captures more of the K+ and π+ mesons that emerge from the production target

full start-to-end BDSIM simulation

Recently ported to GEANT4

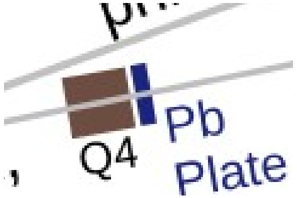
optimal target has been found to be a variation of the CNGS target with a length of 1.30 m, a radius of 3 mm, and a density of 2.26 g/cm2 . reduced to 2.0 g/cm3

beamline has become shorter by more than 5 m



Particle yield	ENUBET design	Optimized SBN design
$K^+/\mathrm{PoT}\ (10^{-4})$	3.6	12.6
$\pi^+/\mathrm{PoT}\ (10^{-2})$	0.4	1.9

Beamline optimization



10 – 40 MHz/mm²

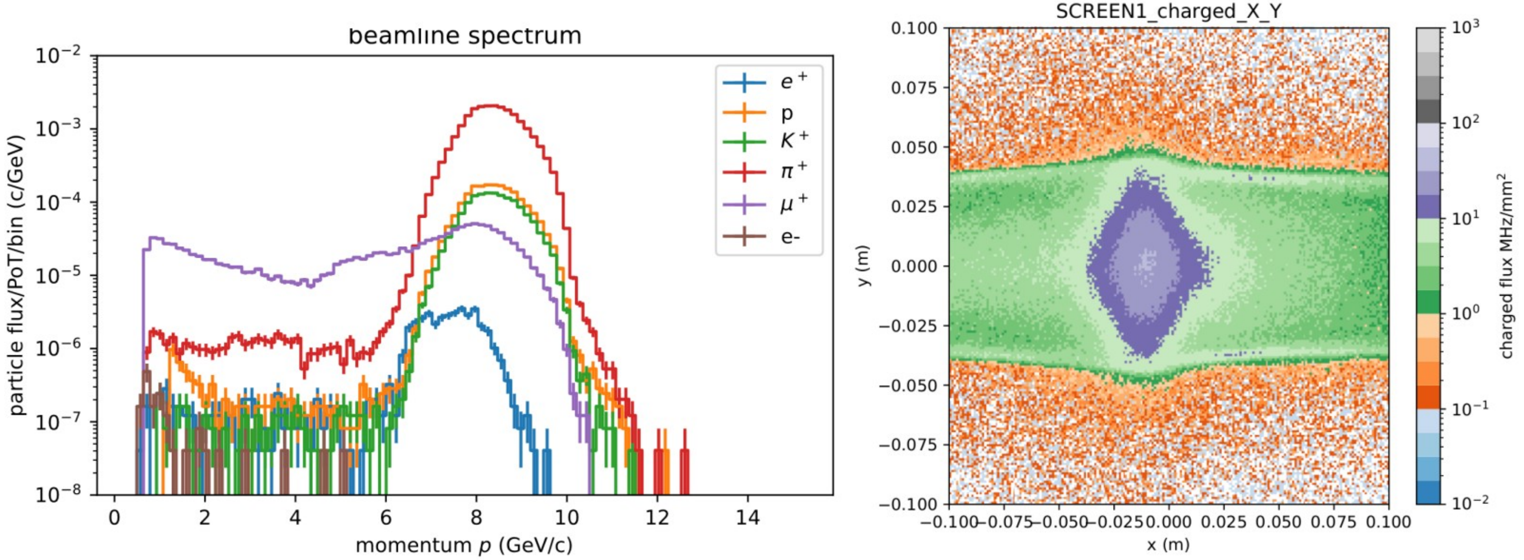
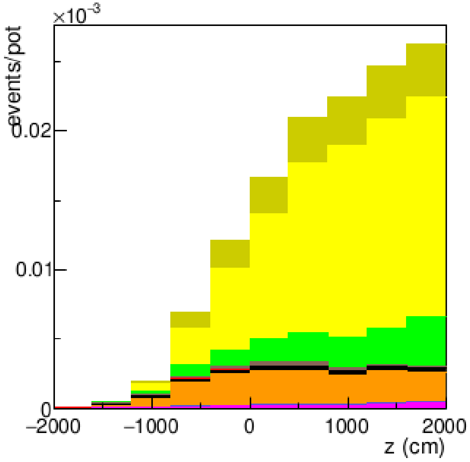
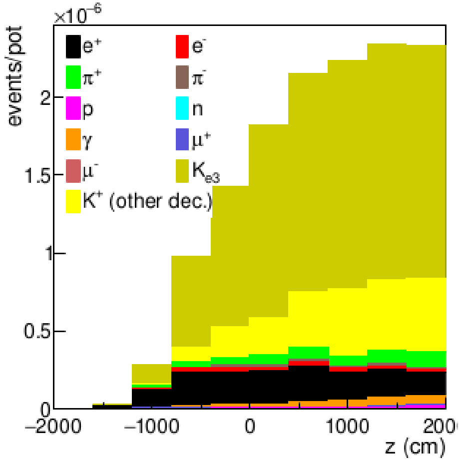
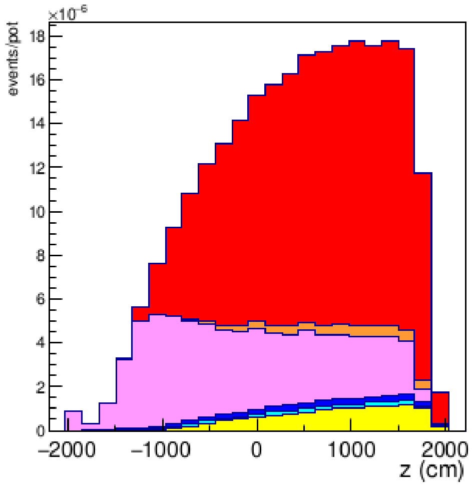


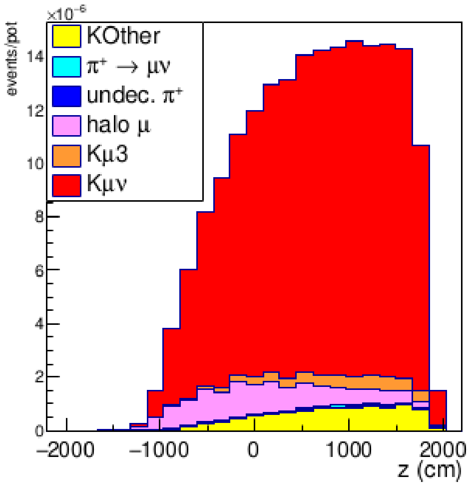
Figure 3: Left: Beamline spectrum after the optimisation process. Compared to any previous design, the positron transmission is strongly suppressed due to the Pb plate followed by two bending magnets. The study of the background level of low-energy leptons is still ongoing. Right: Flux of charged particles on the first pixel detector at the R4 bending magnet of the beamline with a spill intensity of 1×10^{13} PoT within a spill length of 4.8 s.

Lepton monitoring in the calorimeter tagger









Silicon trackers

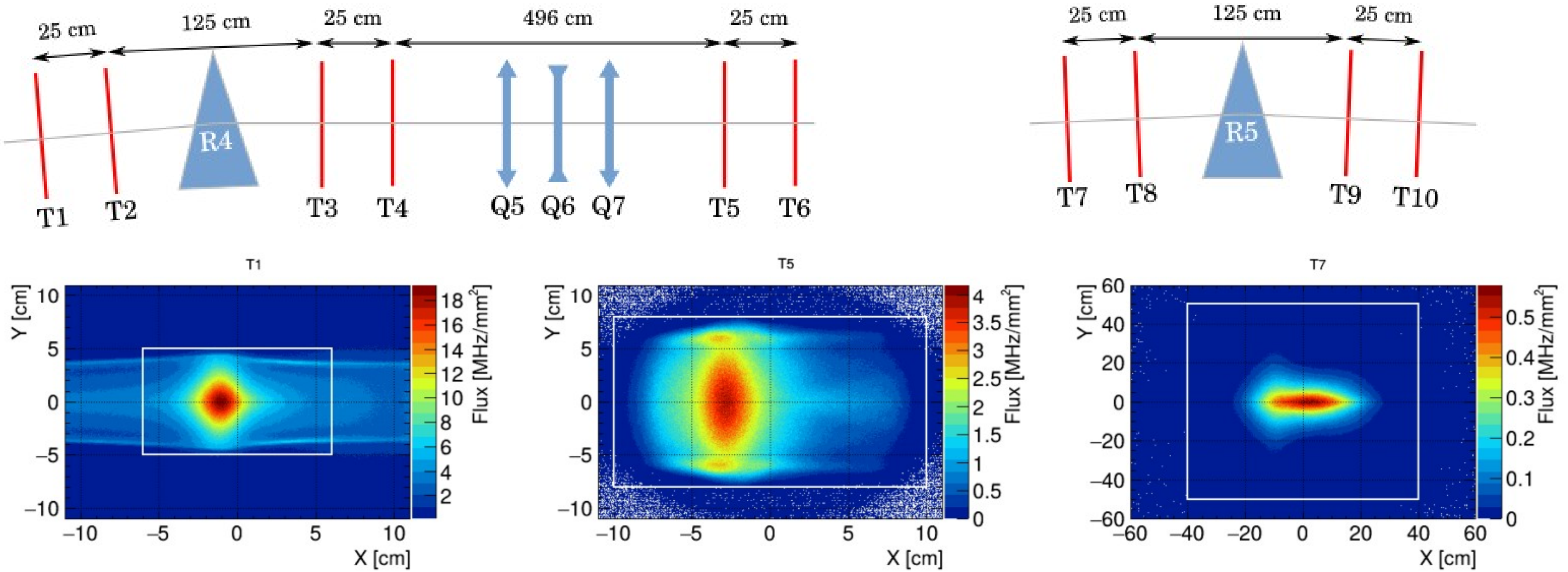


Figure 4: Spatial distribution of the charged particles in the plane transverse to the beam line at T1, T5 and T7 overlaid with the tracking plane acceptances (white line).

Silicon trackers

The tracking plane surfaces are 12 × 10 cm2 in T1-4, 20 × 16 cm2 in T5-6 and 80 × 100 cm2 in T7-10.

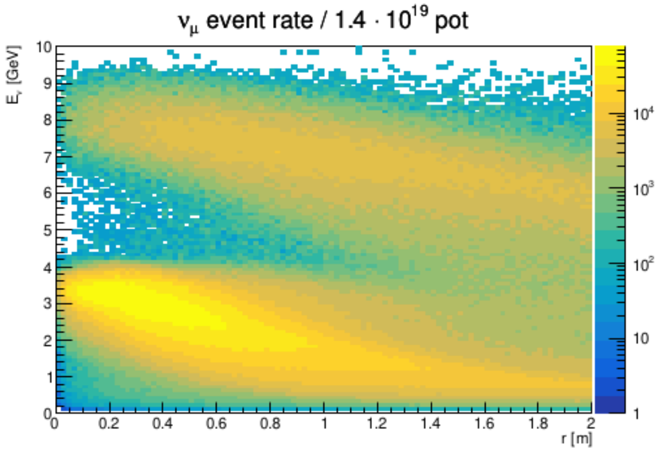
The particle flux at T1 is the highest. With 9.6 s spills of 1013 PoTs, it reaches 20 MHz/mm2 at the center of the tracking plane. In the muon spectrometer, the flux is significantly lower with a peak flux of 0.6 MHz/mm2 .

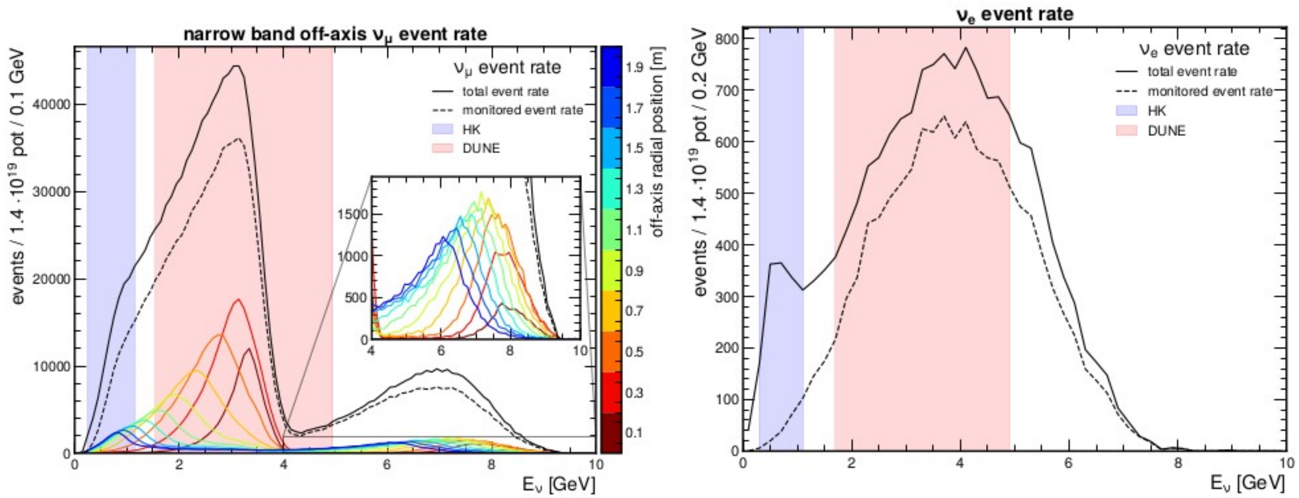
Time resolutions of ∼ 40 ps for the beam spectrometer tracking planes and ∼ 100 ps for the muon spectrometer ones should allow for the track and decay reconstructions.

Technological solutions on pixel sensors and integrated electronics, capable of standing the challenge in terms of time resolution and radiation hardness, have been developed and are still under study by the INFN TimeSPOT (2018-2021 and follow-ups) and IGNITE (2023, ongoing) projects.

Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1\text{MeVn}_{eq}/\text{cm}^2$]	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%

Narrow band off axis





(a) ν_μ (b) ν_e

Figure 26: Total ν_μ (a) and ν_e (b) charged current event rates. The black solid line shows the total event rate, and the dashed black line the monitored event rate. For the ν_μ case, the NBOA total fluxes are also shown with colored solid lines, where the colors correspond to different radial positions. The HK (blue) and DUNE (red) regions of interest are given by the shaded areas.

Narrow band off axis

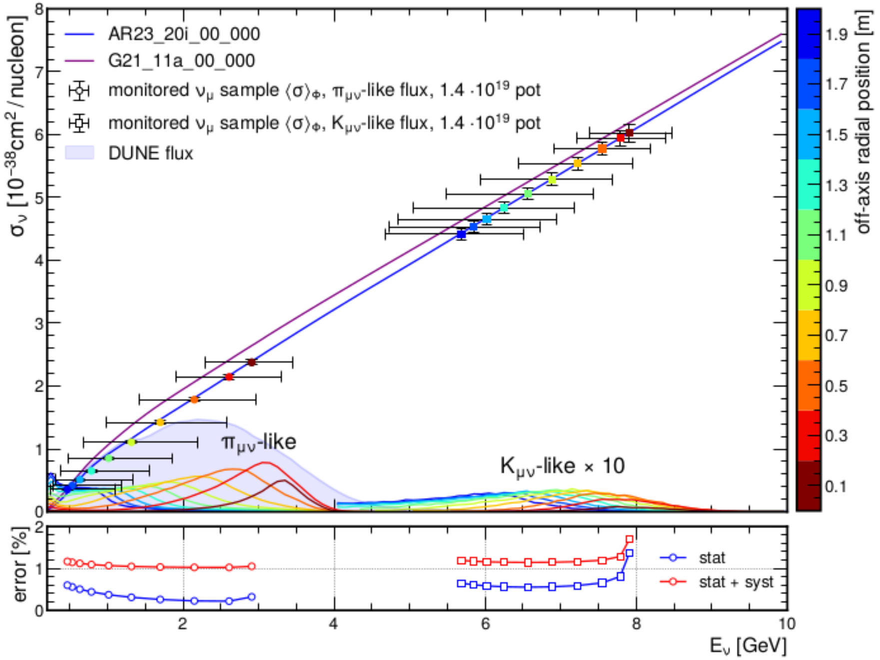
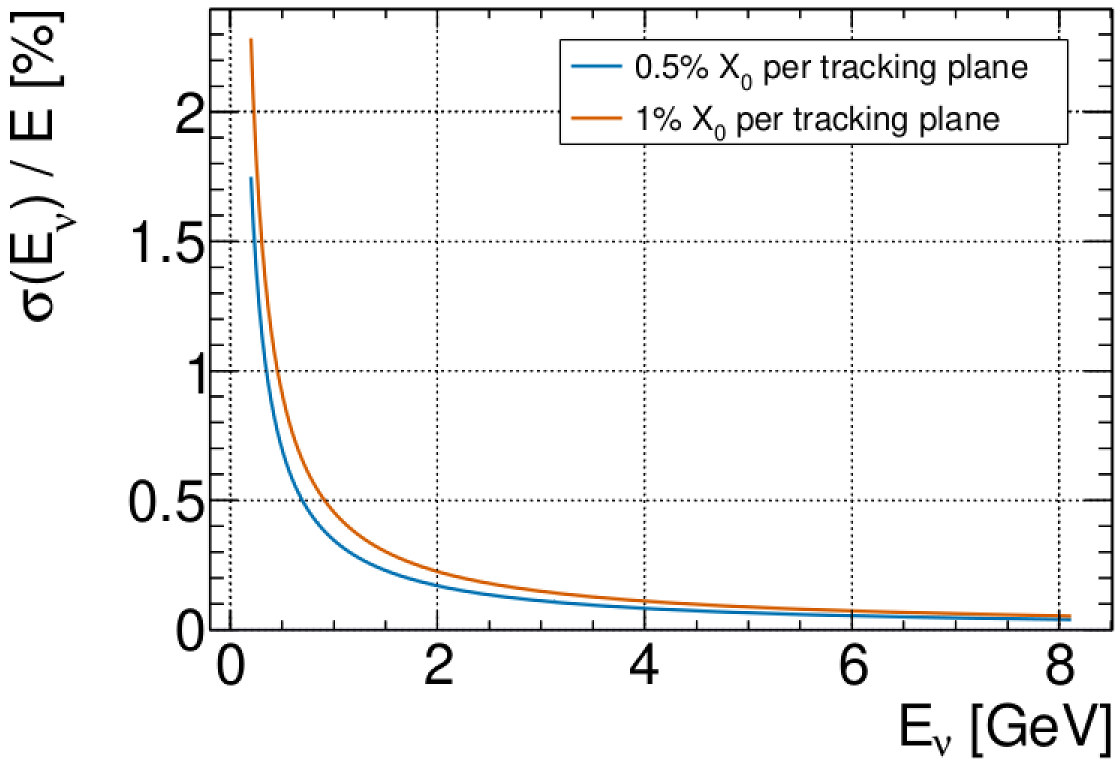
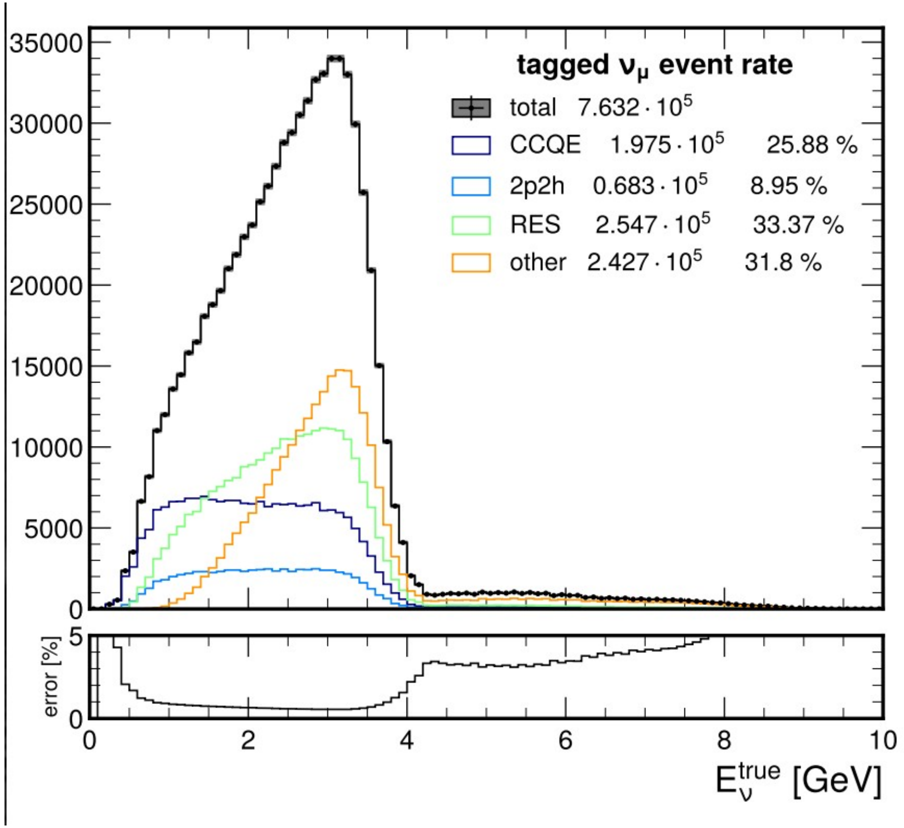


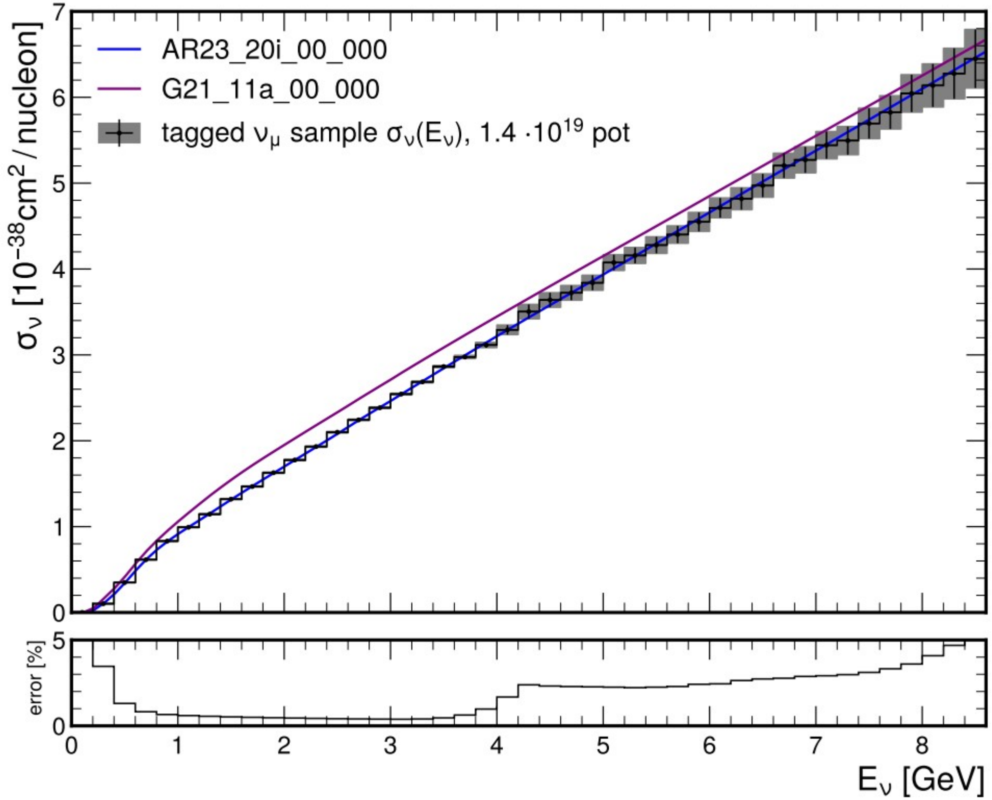
Figure 27: Flux averaged ν_μ CC inclusive cross-section as a function of neutrino energy using the NBOA technique. The colored lines correspond to the NBOA fluxes at different radial distances, given by the colored scale to the right of the figure. The $K_{\mu\nu}$ component of each flux has been artificially inflated by a factor of 10 for illustration purposes. Each NBOA flux has a corresponding predicted measurement point of the same color. Horizontal error bars encase the 68% percentiles with respect to the mean energy for the NBOA fluxes. The underlying figure shows the size of uncertainties due to available statistics (blue) and considering also systematic uncertainties related to the monitored flux prediction, assumed to be $\sim$1%, (red). The measurements are compared to the AR23_20i_00_000 model (blue) and the G21_11a_00_000 model (purple). The DUNE near-detector flux is shown for reference using an arbitrary normalization.

Energy res for tagged 2-body decays



Cross section of numuCC vs E with the tagged sample





Electron neutrino cross sections

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

$$q_3 = \sqrt{Q^2 + q_0^2}$$

$$Q^2 = 2(E_{lep} + q_0)(E_{lep} - |\vec{p}_{lep}|\cos\theta_{lep}) - m_{lep}^2$$

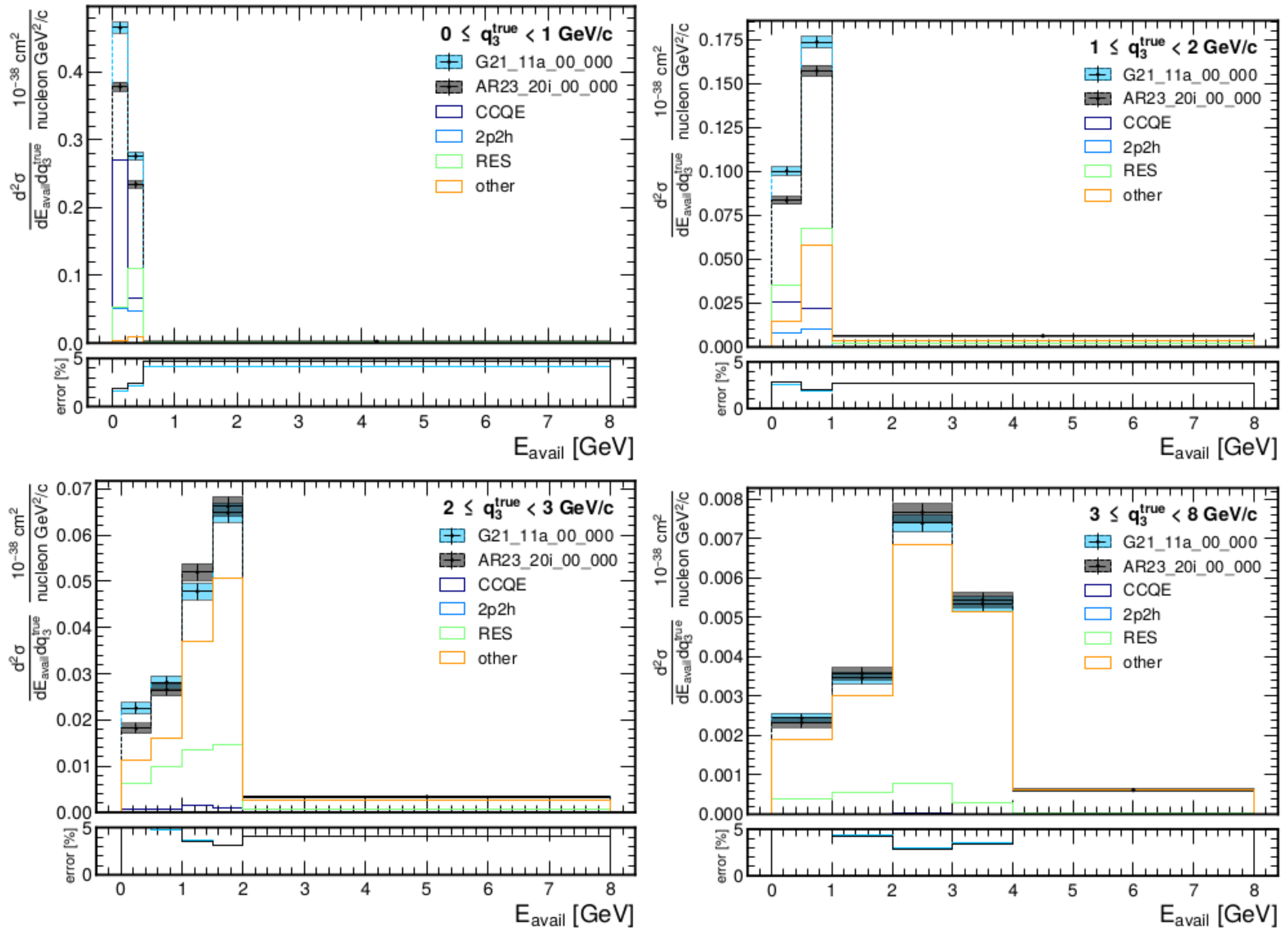


Figure 29: ν_e flux averaged cross-section for CC inclusive events as a function of available energy E_{avail} in true three-momentum transfer q_3^{true} bins, broken down by interaction mode.

PRISM decomposition with SBN@CERN

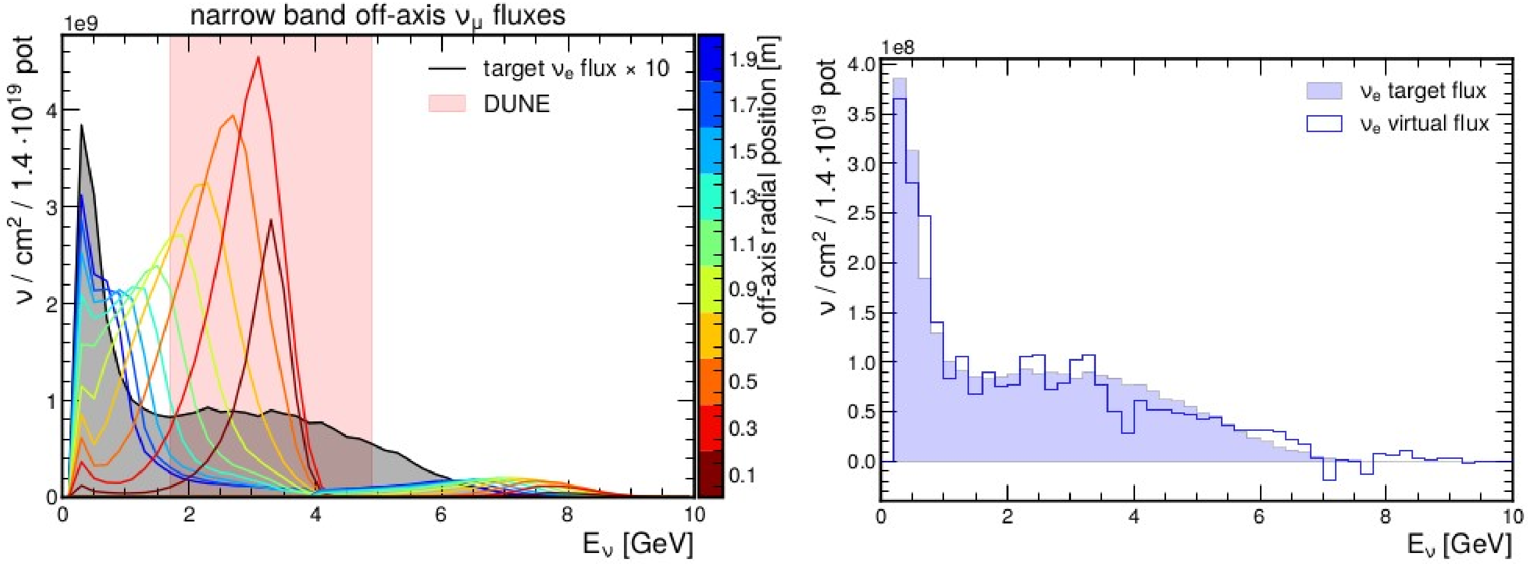
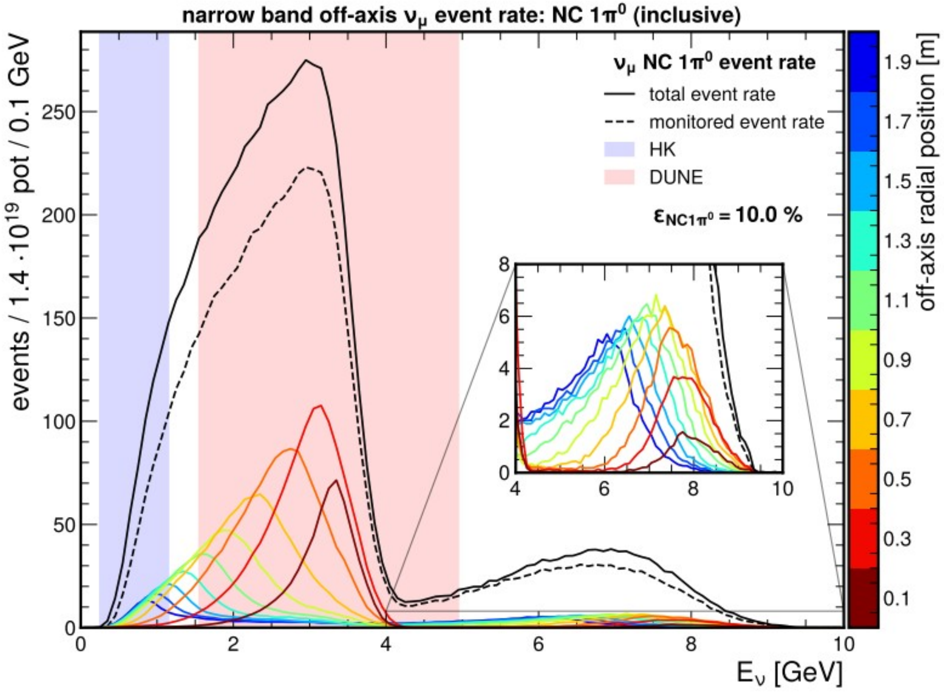
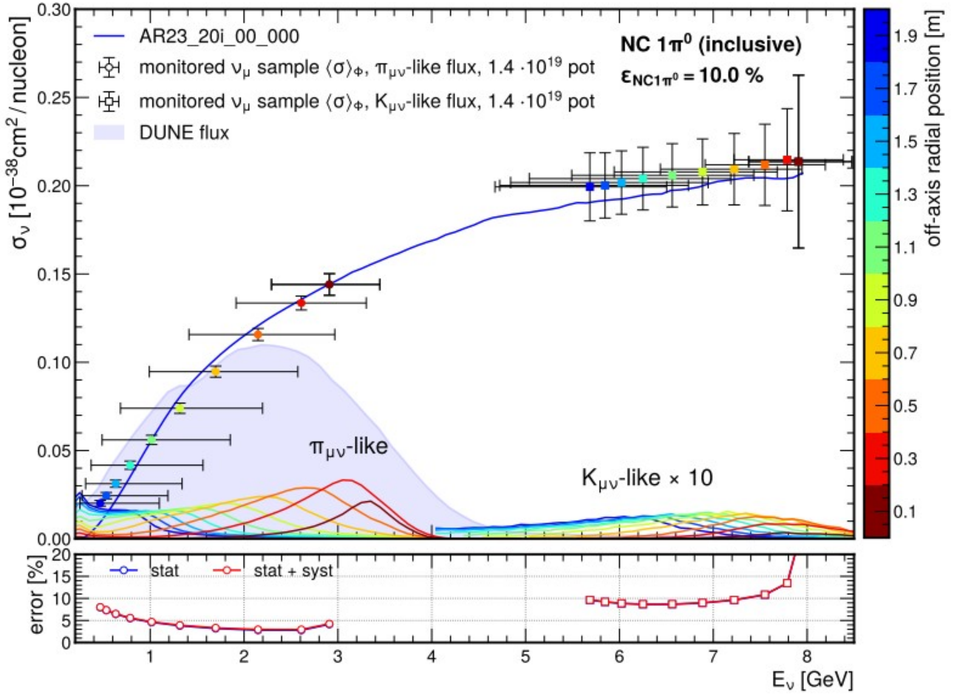


Figure 30: Left: ν_e target flux and ν_μ narrow band off-axis fluxes. The ν_e target flux is shown in grey and inflated by a factor of 10 to make it comparable with the ν_μ fluxes. The colored lines represent different NBOA fluxes, and the line color corresponds to the color scale showing the radial position with respect to the center of the exposed detector face. Right: the virtual ν_μ flux (blue lines) obtained by applying the PRISM technique, compared with the target ν_e flux (filled blue area).

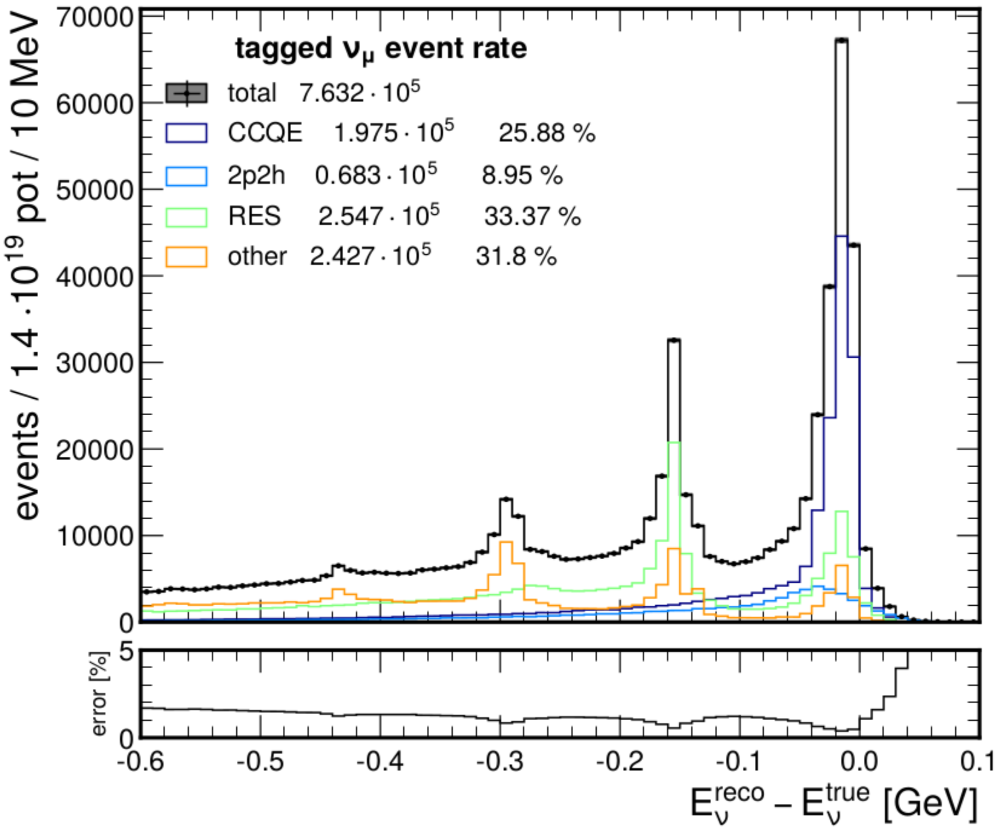
NCpi0


narrow band off-axis ν_μ event rate: NC $1\pi^0$ (inclusive)
ν_μ NC $1\pi^0$ event rate
total event rate
monitored event rate
HK
DUNE
$\varepsilon_{NC1\pi^0}$ = 10.0 %
events / $1.4 \cdot 10^{19}$ pot / 0.1 GeV
E_ν [GeV]
off-axis radial position [m]

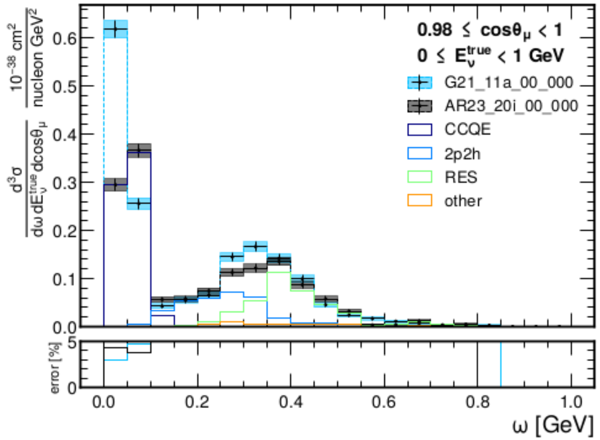

AR23_20i_00_000
monitored ν_μ sample $\langle\sigma\rangle_\Phi$, $\pi_{\mu\nu}$-like flux, $1.4 \cdot 10^{19}$ pot
monitored ν_μ sample $\langle\sigma\rangle_\Phi$, $K_{\mu\nu}$-like flux, $1.4 \cdot 10^{19}$ pot
DUNE flux
NC $1\pi^0$ (inclusive)
$\varepsilon_{NC1\pi^0}$ = 10.0 %
$\pi_{\mu\nu}$-like
$K_{\mu\nu}$-like × 10
σ_ν [10^{-38}cm^2 / nucleon]
stat
stat + syst
error [%]
E_ν [GeV]
off-axis radial position [m]

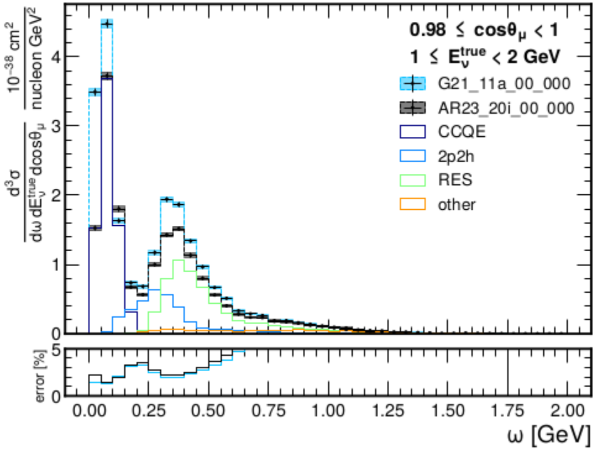
Mapping reco and true energy (from tagging)

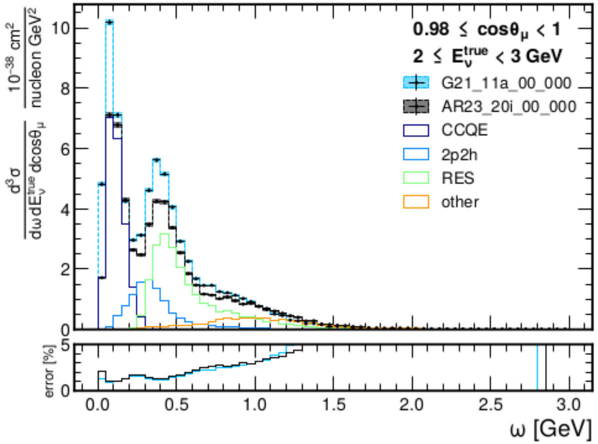
$$E_\nu^{\rm reco} = E_\mu + \sum_{i=\pi^\pm,p} T_i + \sum_{i=\pi^0,\gamma} E_i,$$

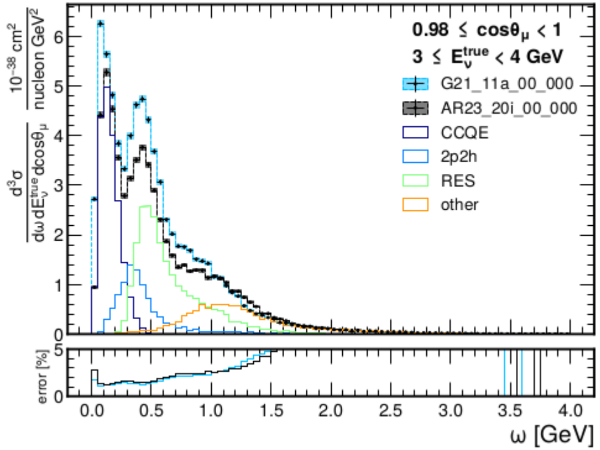


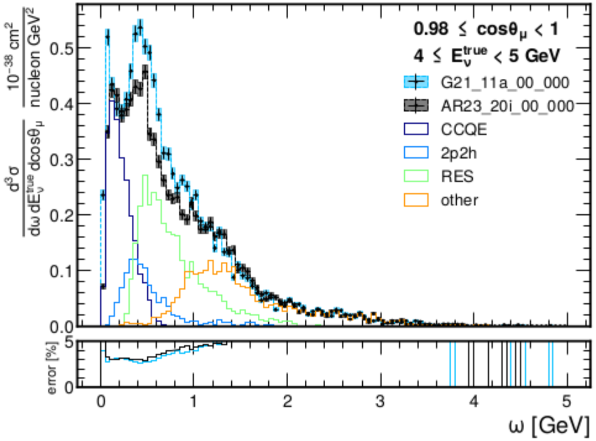
“Electron-like” measurements with neutrinos











$$\omega = E_\mu - E_\nu$$

E_ν from tagging!

7.8 Summary of the SBN@CERN physics potential

SBN@CERN offers the possibility to make a wide range of previously unattainable measurements that may be the key to allowing the next generation of long-baseline neutrino oscillation experiments to reach their ultimate precision. It directly confronts aspects of neutrino interaction physics expected to drive the leading sources of systematic uncertainty for neutrino oscillation experiments:

- The energy dependence of the cross-section is essential for extrapolating between near and far detectors; we demonstrate how this can be directly measured in Sec. 7.3 and Sec. 7.7.1.
- The smearing of neutrino energy must be understood to interpret far detector event rates as an oscillation probability. Measurements in a tagged neutrino beam offer a unique opportunity to directly measure this, as demonstrated in Sec. 7.7.2.
- The muon to electron neutrino cross-section ratio is projected to be a dominant systematic uncertainty for measurements of CP-violation, we show that this can be directly constrained using a monitored beam in Sec. 7.5, with potential improvements possible using a tagged beam.
- NC processes are a key background at the experiment's far detectors; we show how these can be precisely constrained in Sec. 7.6.

More generally, collecting high-statistics data with a tagged neutrino beam across the energies relevant to next-generation neutrino oscillation experiments offers a unique way to directly calibrate their cross-section and the energy smearing. A library of measurements with a tagged beam could be leveraged to determine how simulated events for DUNE or Hyper-Kamiokande are expected to look in their near or far detectors, thanks to the event-by-event characterization of neutrino energy. Measurements with a tagged neutrino could also be leveraged to explore nuclear physics with a neutrino probe at the GeV-energy scale in a previously impossible way, as explored in Sec. 7.7.3.

Future work will focus on expanding these studies to include simulations using a water-based target tailored to supporting Hyper-Kamiokande's physics program, anti-neutrino beam running, lower energy beam configurations, sensitivity to BSM physics, and a detailed assessment of the detector performance required to realize the full SBN@CERN physics program.

Triple differential cross sec

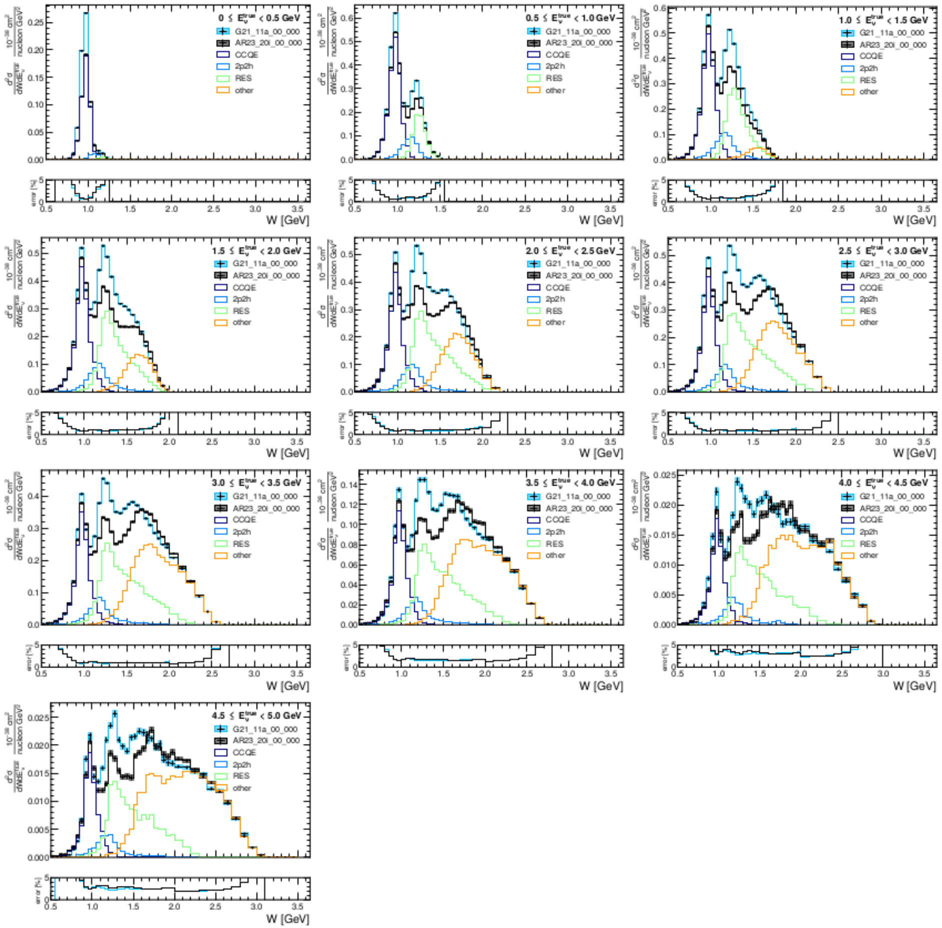
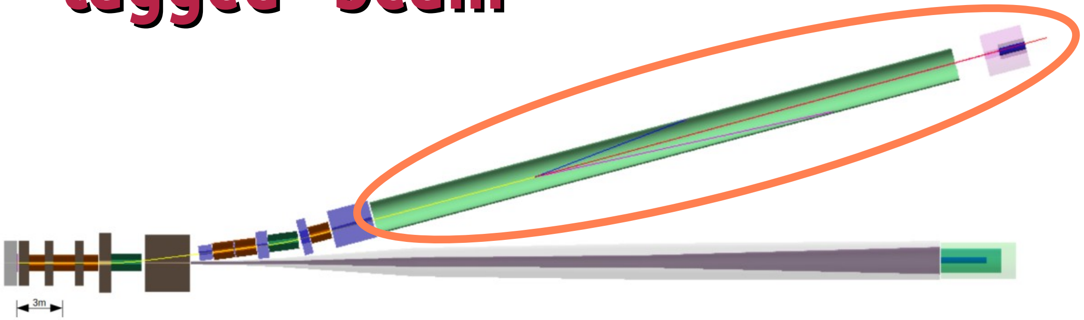


Figure 37: CC ν_μ double differential cross-section as a function of the invariant mass of the hadronic system, W, and different neutrino energy, E_ν^{true}, regions. The filled regions show the associated statistical uncertainty for the AR23_20i_00_000 (black) and G21_11a_00_000 (light blue) models. The breakdown by interaction mode is given for the AR23_20i_00_000 model. Each figure is accompanied by the evolution of the associated statistical uncertainty on the measurement, shown underneath.

In SBN@CERN: a “monitored” + “tagged” beam

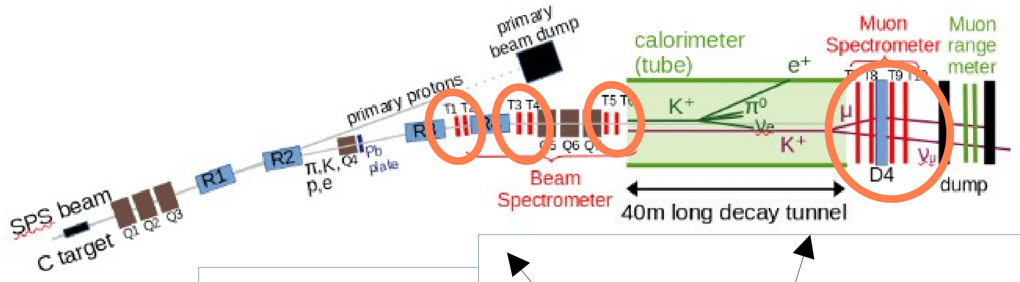
Monitored beam

ENUBET: measure the decay lepton (e/μ) rates with a coarse/large acceptance calorimeter and an instrumented hadron dump



Tagged beam

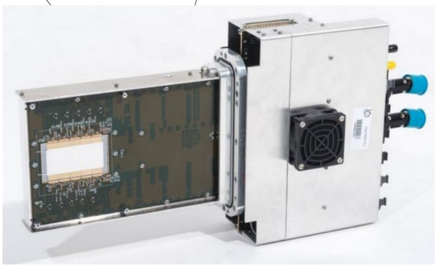
NuTAG: measure the parent meson and forward decay muons for K and π 2-body decays



NuTAG leveraged on **excellent timing and granularity** (“4D”) achievable using silicon trackers (à la “NA62++”) → can provide **resolutions at the %** on E(ν_μ) thanks to full reconstruction of 2-body decays of pions and kaons.

→ Mathieu’s talk

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



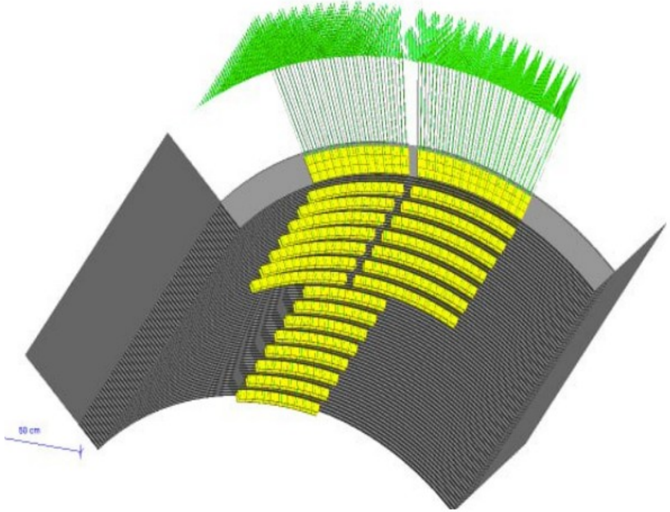
Additional constraint on the flux of ν_e from the knowledge of B.R.($K_{\mu 2}$)/B.R.(K_{e3})

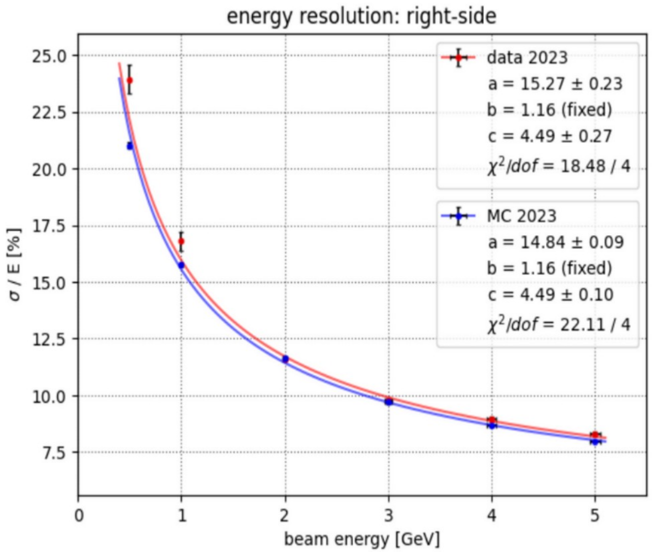
Reamining program within SPSC scope + timeline

Items more closely related to the SPSC:

Publication of the paper on the demonstrator: we have completed the equalization of 2024 data and evaluated the energy resolution. Results compatible with 2023. Tilted runs: a lot of work to simulate precisely the exact conditions of the exposure (geometry+beam profile). TODO: evaluate data-MC agreement on pion variables (straight+inclined runs).

Expected finalization summer 25.





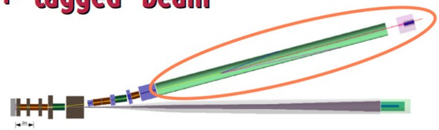
Beyond ENUBET

- A big work has been done within the group born with Physics Beyond colliders to put forward a credible proposal for possible setup at CERN (presented to the community at the workshop **Neutrinos@CERN**). Merging of ENUBET and NuTAG techniques (**SBN@CERN** study group): monitored+tagged beam. **Proton economics**. Studies on possible **siting**. **Document for the strategy** in preparation. Will be circulated to form a wider proto-collaboration.
- In this context we have developed a **new, more efficient, beamline** and we are working to **replicate the complete study** (irradiation, physics reach, constraint of the systematics) with this setup. Moving from BDSIM to GEANT4 in progress (master student in Padova).
- Finalizing the analysis of the systematics on the flux considering **detector and beamline uncertainties** (the main component of hadroproduction has been considered so-far)

https://indico.cern.ch/event/1460367/overview

In SBN@CERN: a "monitored" + "tagged" beam

Monitored beam
ENUBET: measure the decay lepton (e/μ) rates with a coarse/large acceptance calorimeter and an instrumented hadron dump



Tagged beam
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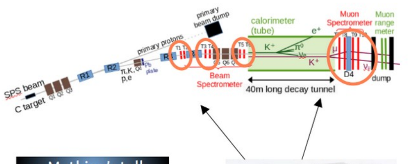

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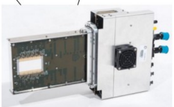


Additional constraint on the flux of ν_e from the knowledge of B.R.($K_{\mu 2}$)/B.R.(K_{e3})

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

SBN@CERN
A short-baseline neutrino beam at CERN for high-precision cross-section measurements

January 21, 2025

1 A high precision neutrino beam at CERN

Neutrino physics entered its precision era in 2012 when accelerator and reactor experiments demonstrated that all mixing angles, including θ_{13}, are large [1]. This groundbreaking discovery paved the way for a comprehensive exploration of the lepton Yukawa sector of the Standard Model. Oscillation experiments can now probe the neutrino mass hierarchy, the mixing angles, and the Dirac CP-violating phase, providing a nearly complete picture of neutrino properties. The only remaining piece—the determination of the absolute neutrino mass and the Dirac/Majorana nature—requires dedicated measurements beyond oscillation experiments. A key finding of the 2020 European Strategy for Particle Physics [2] was the recognition that the ambitious goals of neutrino physics are critically hindered by the limited understanding of standard neutrino interactions, particularly neutrino cross-sections at the GeV scale. This concern has grown over the past five years, emphasizing the

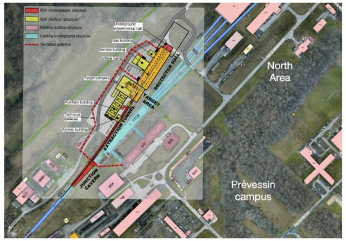
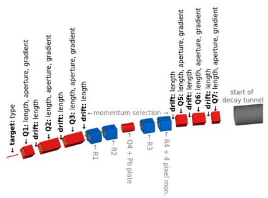


Figure 5: Schematic drawing of ECN4 solution studied as a possibility to house the BDF/SHiP facility. Taken from [28].

list of targets covers target lengths from 0.7 m to 1.35 m, target radii from 2.5 mm to 30 mm and graphite densities from 1.70 g/cm³ to 2.26 g/cm³.



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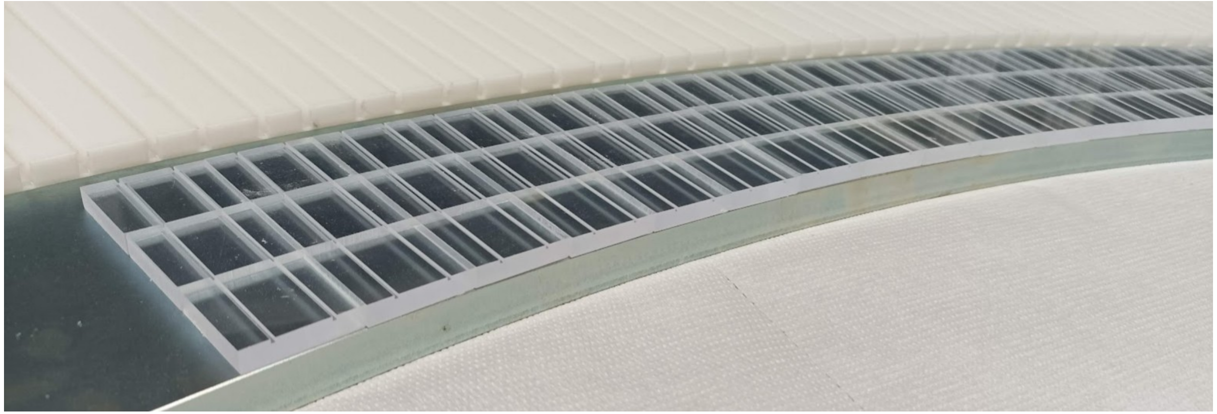
https://indico.cern.ch/event/1460367/overview

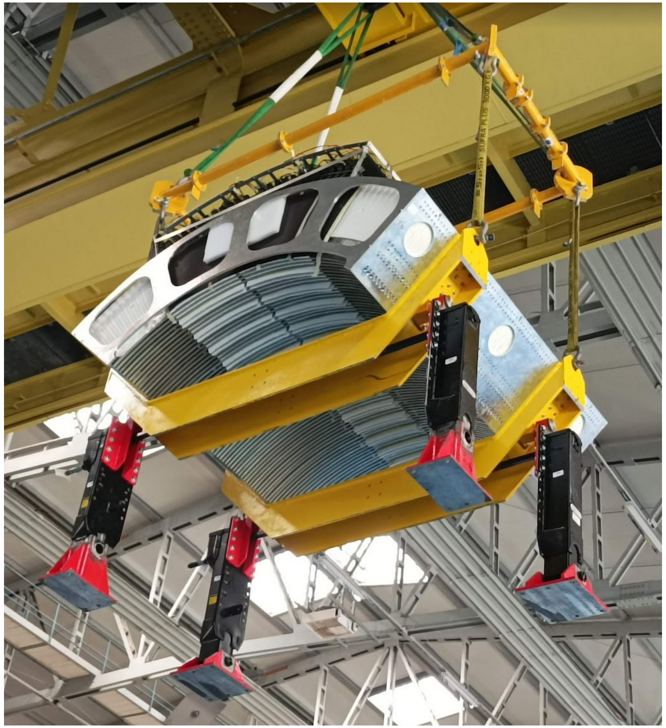
Slides shown at Neutrinos@CERN

Beamline overview & the neutrino monitoring system

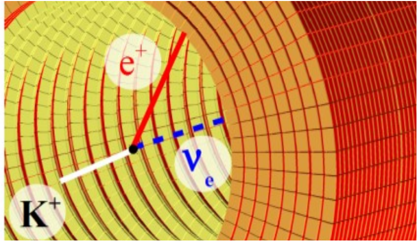
Andrea Longhin
Padova Univ. and INFN
on behalf of the SBN@CERN study group and ENUBET coll.

Neutrinos at CERN, 23-24 Jan 2025



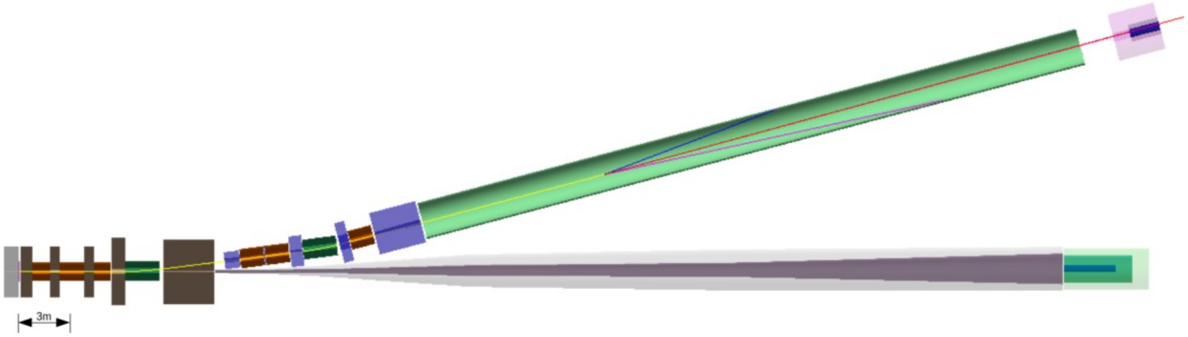


Role of a monitored neutrino facility



- A dedicated short baseline neutrino beam with a 1% precision in ν_e and ν_μ fluxes aimed to high-precision neutrino detectors located close to the source
- Reduce the dominant systematics on flux → precise cross section measurements → consolidate the long-baseline program by reducing systematics with high quality experimental inputs

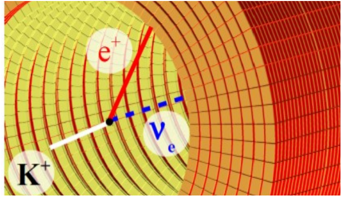
→ Stephen's talk



A bit of history

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

X @enubet



The initial paper — A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

ENUBET coll. 74 auth, 17 institutions

CEMS

université de BORDEAUX

FONDAZIONE BRUNO KESSLER

The ENUBET ERC project 6/2016- 12/2022

Enhanced **N**e**U**trino **BE**ams from kaon **T**agging ERC-CoG-2015, G.A. 681647,
PI A. Longhin, **Padova University**, **INFN**

- ERC

HORIZON 2020

INFN CSN 2
INFN CSN 1

ENUBET/NP06

PI: A. Longhin, F. Terranova.
Techn. Coord: V. Mascagna

- CERN Neutrino Platform

With SPSC:
- support of test beams of the tagger instrumentation at the PS
- monitoring of all neutrino flavors, including ν_μ from π and K decays

SBN@CERN
Short baseline neutrinos @ PBC

- Physics Beyond Colliders

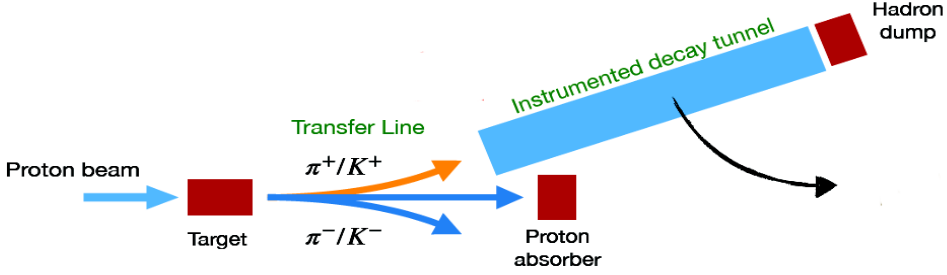
Merging the ideas of **ENUBET** and **nuTAG** towards an experiment proposal

→ Mathieu's talk

→ Marc's talk

ENUBET

the first **"monitored neutrino beam"**:

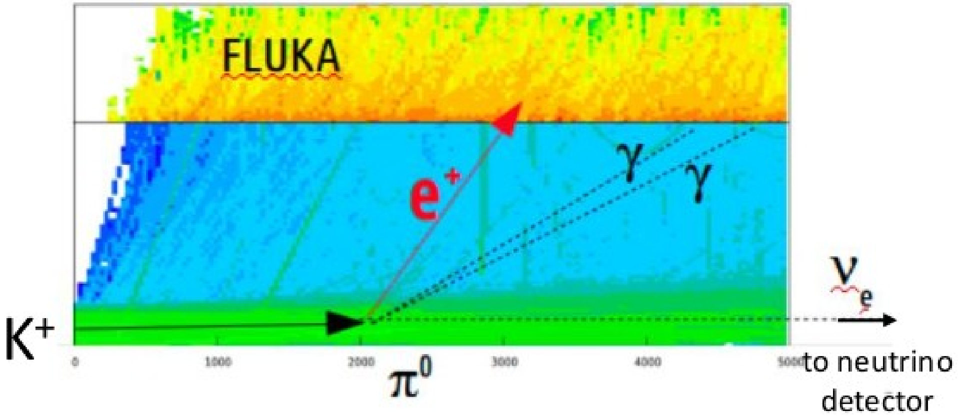


production of neutrino-associated leptons monitored at single particle level in an instrumented decay region

$K^+ \to e^+ \nu_e \pi^0 \to$ (large angle) e^+

$K^+ \to \mu^+ \nu_\mu \pi^0$ or $\to \mu^+ \nu_\mu \to$ (large angle) μ^+

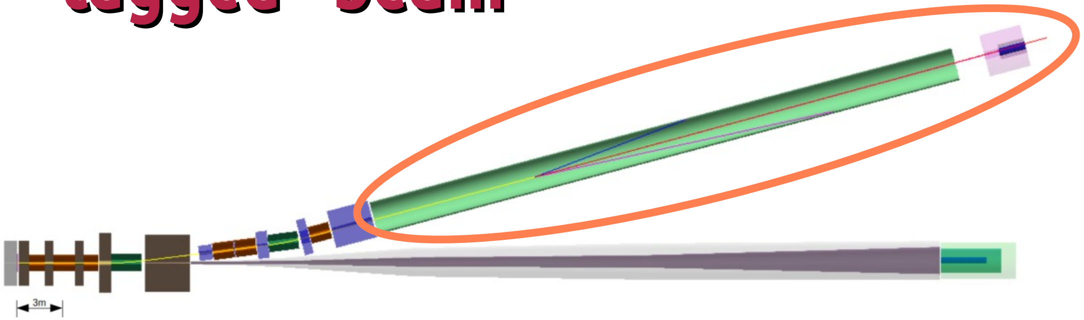
- ν_e **and** ν_μ **flux prediction from** e^+/μ^+ **rates**



- Needs a **collimated mom-selected hadron beam** → only the decay products hit the tagger
  → manageable rates and irradiation in the detectors
- Needs a **"short" decay region** : ~all ν_e from K, only ~1% ν_e from μ (large flight length)

NB: it requires a **specialized beam**, not a "pluggable" technology for existing super-beams (unfortunately!)

In SBN@CERN: a "monitored" + "tagged" beam



Monitored beam

ENUBET: measure the decay lepton (e/μ) rates with a coarse/large acceptance calorimeter and an instrumented hadron dump

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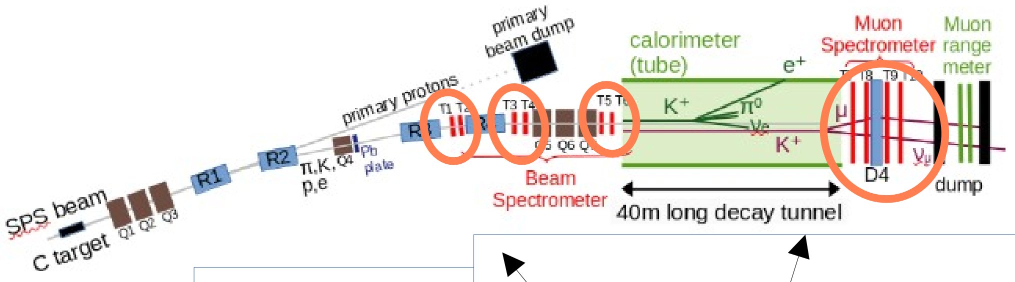

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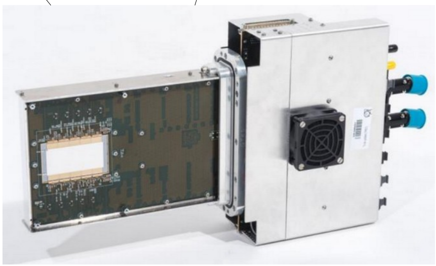


Additional constraint on the flux of ν_e from the knowledge of B.R.($K_{\mu 2}$)/B.R.(K_{e3})

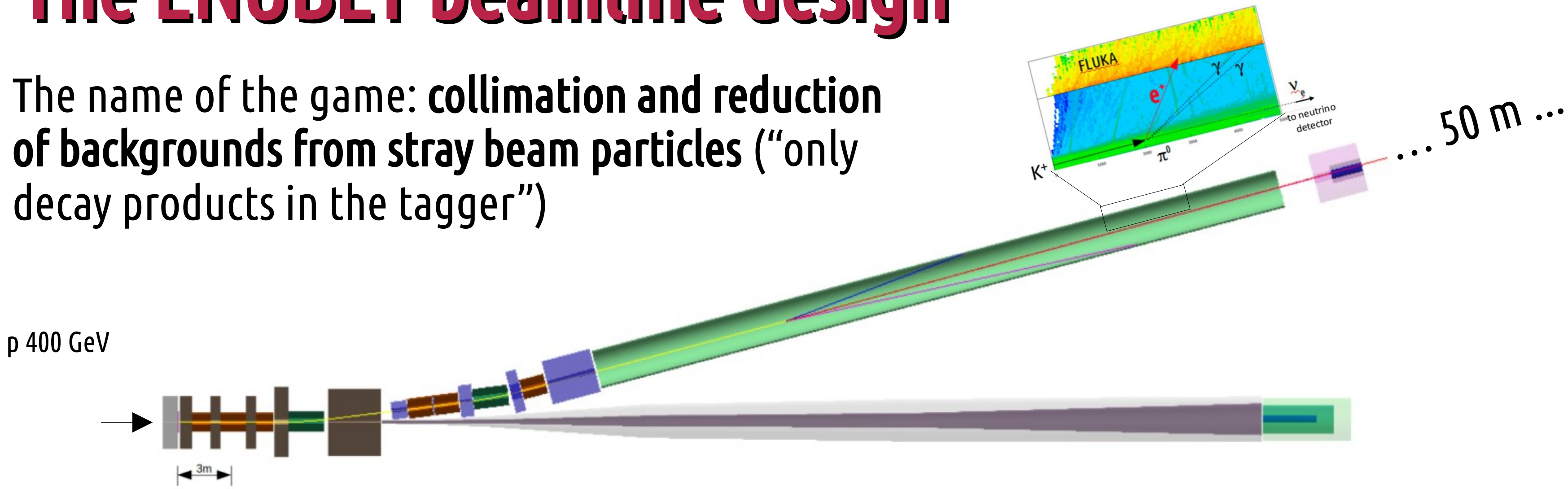
Essential achievements of ENUBET in a nutshell

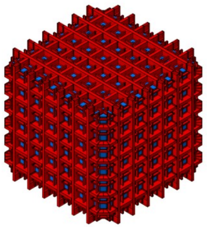
- Revamped the idea of **tagged (monitored) neutrino beams in the modern context of GeV neutrino cross sections**
- Set up a **design/end-to-end simulation** of a facility with which it demonstrated that:
  - **meson focusing with DC elements** (like quadrupoles/dipoles, i.e. without magnetic horns !) - and a slow extraction (= very little pileup in the tagger) is adequate → **enough neutrinos with reasonable amount of POTs** (no need of reconciling pulsed magnetic horns with slow extraction (*))
  - a **lepton selection** with a sufficient purity/efficiency is feasible at these high rates with a cheap/coarse grained detector
  - constraining the **lepton rates actually work in reducing the flux systematics**
  - showed that we can **know the neutrino energy** by exploiting the energy/production angle (i.e. interaction vertex in the neutrino detector) correlation (see below →)
- Built and tested a **demonstrator of the tagger** instrumentation
  - cost-effective, fast, rad-hard

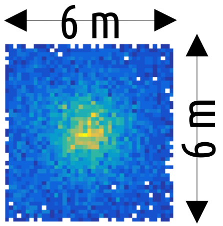
(*) as an intermediate byproduct we also managed to get a pulsed slow-extraction at the SPS (backup)

The ENUBET beamline design

The name of the game: **collimation and reduction of backgrounds from stray beam particles** (“only decay products in the tagger”)







- Focuses 8.5 GeV +/- 10% **mesons** (ν spectrum ROI ~ DUNE)
  - Length: 26 m
  - Tagger length: 40 m
  - Neutrino detector (500 t) 50 m after the hadron dump
  - 14.8° bending angle
- documented in **EPJ-C 83, 964, 2023** →

Design and performance of the ENUBET monitored neutrino beam

F. Acerbi[1], I. Angelis[21], L. Bomben[2,3], M. Bonesini[3], F. Bramati[3,4], A. Branca[3,4], C. Brizzolari[3,4], G. Brunetti[3,4], M. Calviani[6], S. Capelli[2,3], S. Carturan[7], M.G. Catanesi[8], S. Cecchini[9], N. Charitonidis[6], F. Cindolo[9], G. Cogo[10], G. Collazuol[5,10], F. Dal Corso[5], C. Delogu[5,10], G. De Rosa[11], A. Falcone[3,4], B. Goddard[6], A. Gola[1], D. Guffanti[3,4], L. Halić[20], F. Iacob[5,10], C. Jollet[16], V. Kain[6], A. Kallitsopoulou[24], B. Kliček[20], Y. Kudenko[13], Ch. Lampoudis[21], M. Laveder[5,10], P. Legou[24], A. Longhin[a,5,10], L. Ludovici[15], E. Lutsenko[2,3], L. Magaletti[8,14], G. Mandrioli[9], S. Marangoni[3,4], A. Margotti[9], V. Mascagna[22,23], N. Mauri[9,18], J. McElwee[16], L. Meazza[3,4], A. Meregaglia[16], M. Mezzetto[5], M. Nessi[6], A. Paoloni[17], M. Pari[5,10], T. Papaevangelou[24], E.G. Parozzi[4], L. Pasqualini[9,18], G. Paternoster[1], L. Patrizii[9], M. Pozzato[9], M. Prest[2,3], F. Pupilli[5], E. Radicioni[8], A.C. Ruggeri[11], G. Saibene[2,3], D. Sampsonidis[21], C. Scian[10], G. Sirri[9], M. Stipčević[20], M. Tenti[9], F. Terranova[3,4], M. Torti[3,4], S.E. Tzamarias[21], E. Vallazza[3], F. Velotti[6], L. Votano[17]

https://arxiv.org/pdf/2308.09402.pdf

https://link.springer.com/article/10.1140/epjc/s10052-023-12116-3

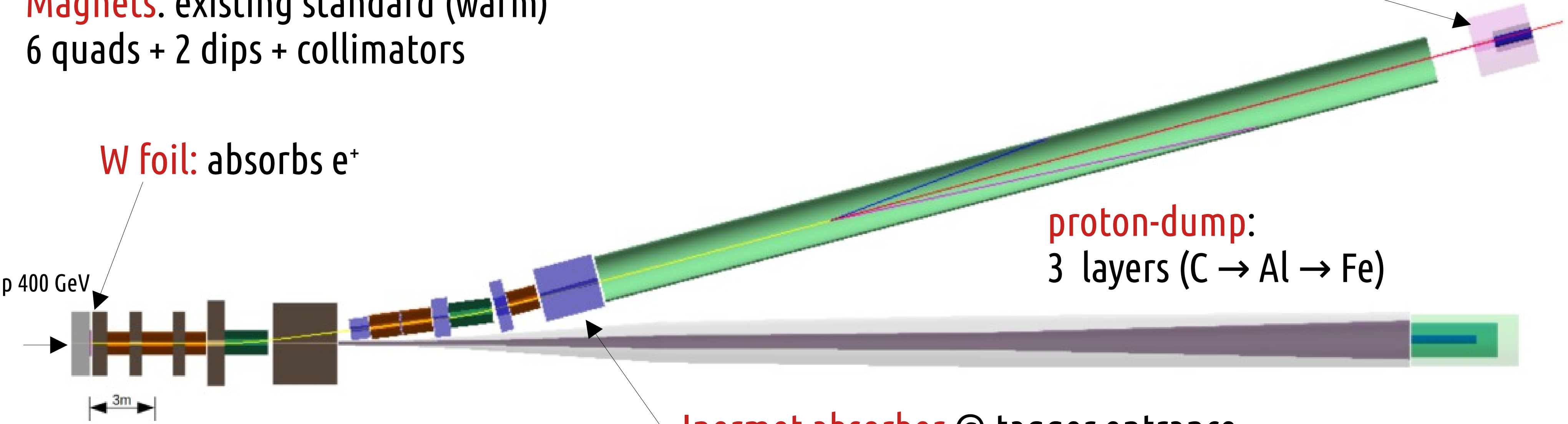
… a closer look

hadron-dump: ~
optimized to reduce back-scattering in the tunnel & fraction of not-monitored flux

Magnets: existing standard (warm)
6 quads + 2 dips + collimators

W foil: absorbs e^+

proton-dump:
3 layers (C → Al → Fe)



Inermet absorber @ tagger entrance
with conical channel

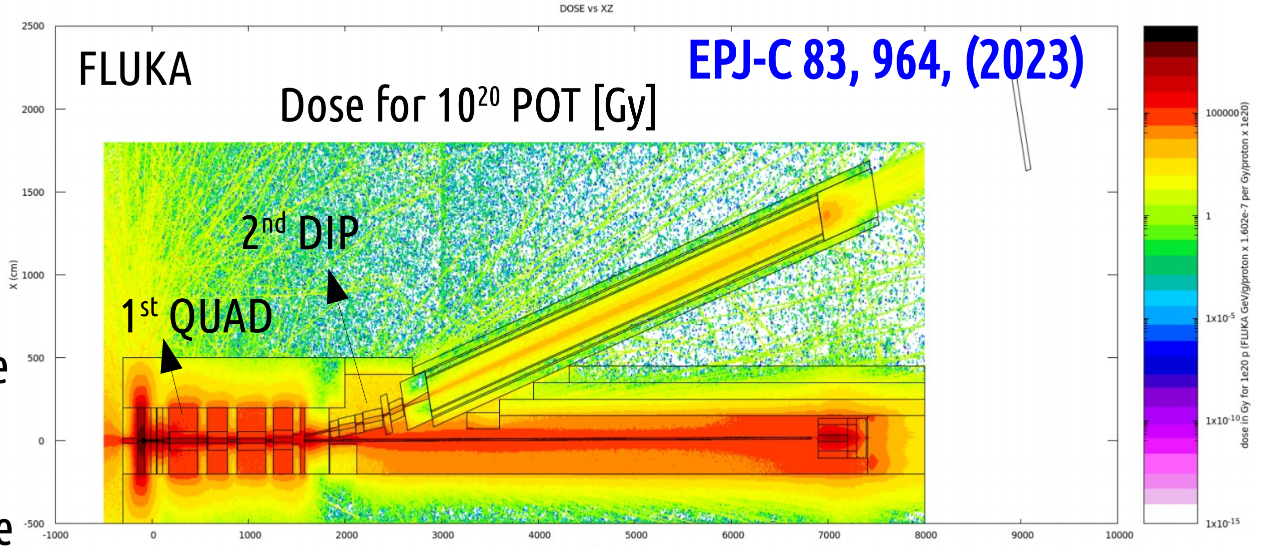
Target: graphite L = 70 cm, r = 3 cm

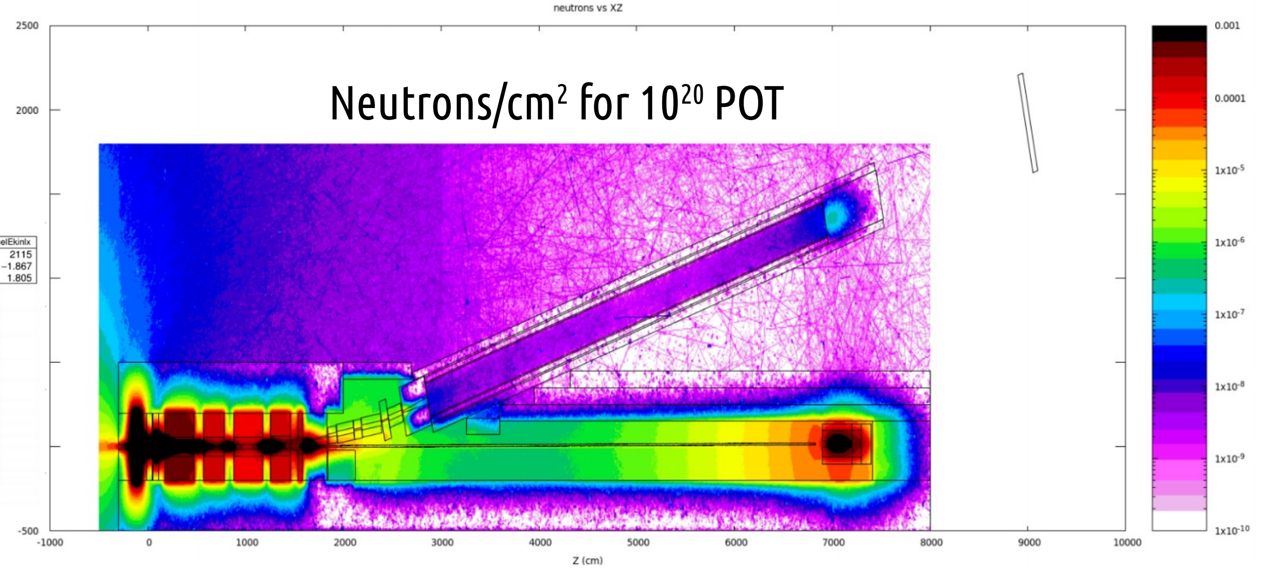
Simulation: optics optimization (TRANSPORT). Design: G4beamline.
Irradiation (FLUKA). Systematics (GEANT4, fully parametric, access to particle history).

Irradiation levels

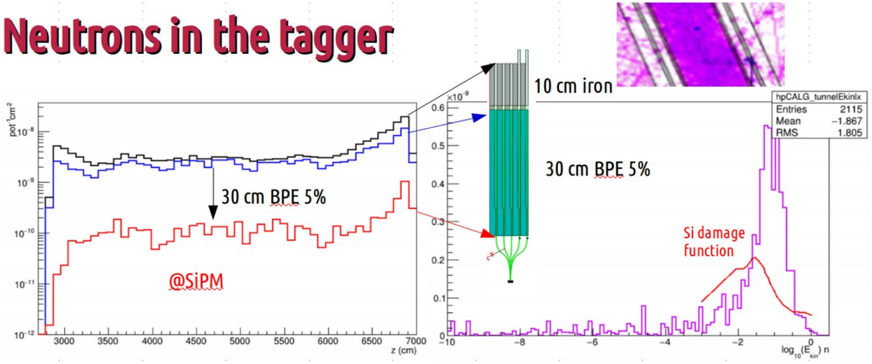
Dose is sustainable by magnets even in the hottest regions (<300 kGy/10^{20} pot).

Neutrons simulations guided the design of the instrumentation → 30 cm of Borated PE (5%) added to protect the Silicon Photomultipliers. Good lifetime (7x10^9 n/cm^2/10^{20} pot). Accessible eventually.





Neutrons in the tagger

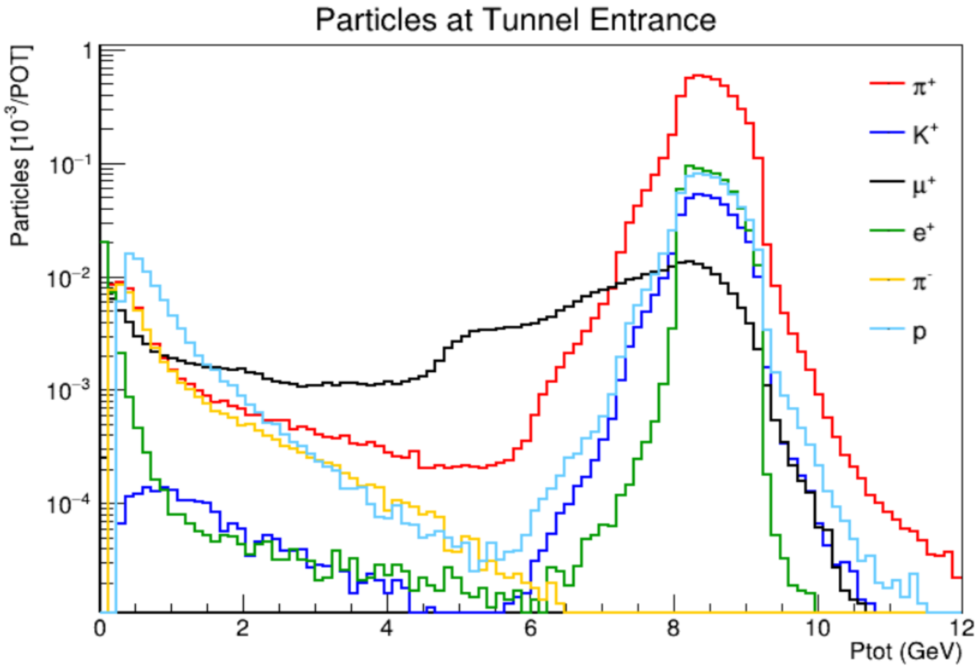


Particle budget and rates

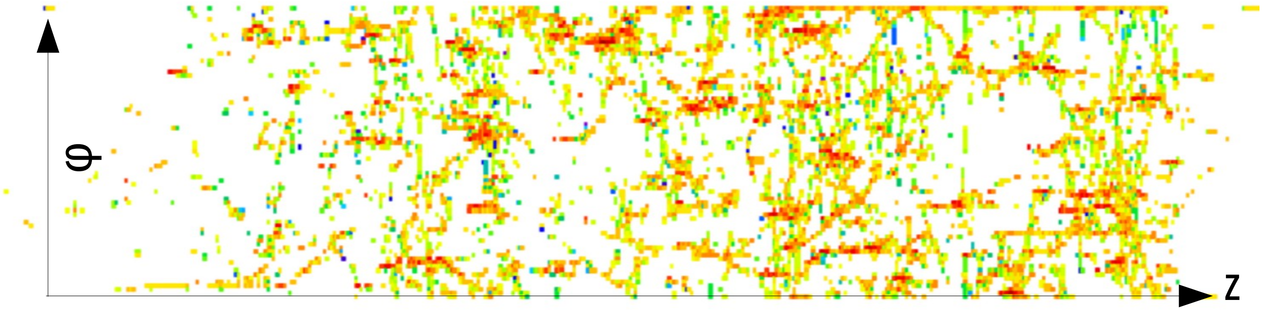
Entering the tagger:
$4.6 \times 10^{-3}\ \pi^+$/pot
$0.4 \times 10^{-3}\ K^+$/pot

The hottest regions of the tagger see ~ 500 kHz/cm^2 with 2.5×10^{13} pot/2.4 s (slow extraction)
Pile-up mostly non critical but has to be treated.

→ the detector has to be fast enough, radiation hard, cost-effective (large area)



Hit map for e$^+$ in a few ns

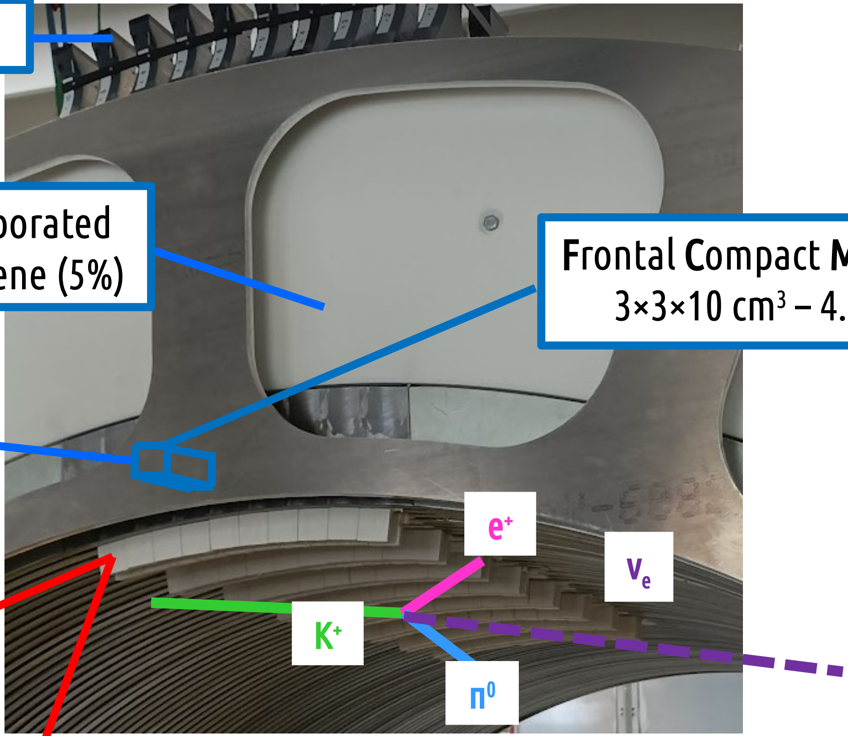


The lepton tagger

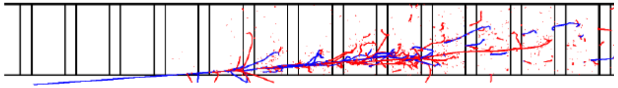
Light r/o (SiPM)

30 cm of borated polyethylene (5%)

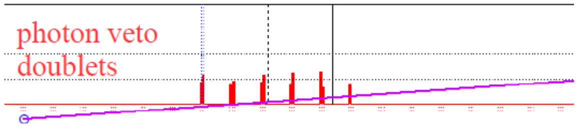
Frontal Compact Module
$3{\times}3{\times}10\ cm^3$ – 4.3 X_0

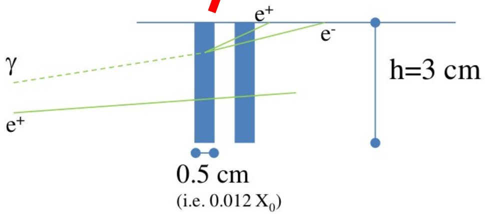


Calorimeter
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Integrated light readout with SiPM
→ $e^+/\pi^\pm/\mu$ separation



Integrated photon veto
Plastic scintillators rings of $3{\times}3\ cm^2$ pads
→ π^0 rejection





e^+ (signal) topology

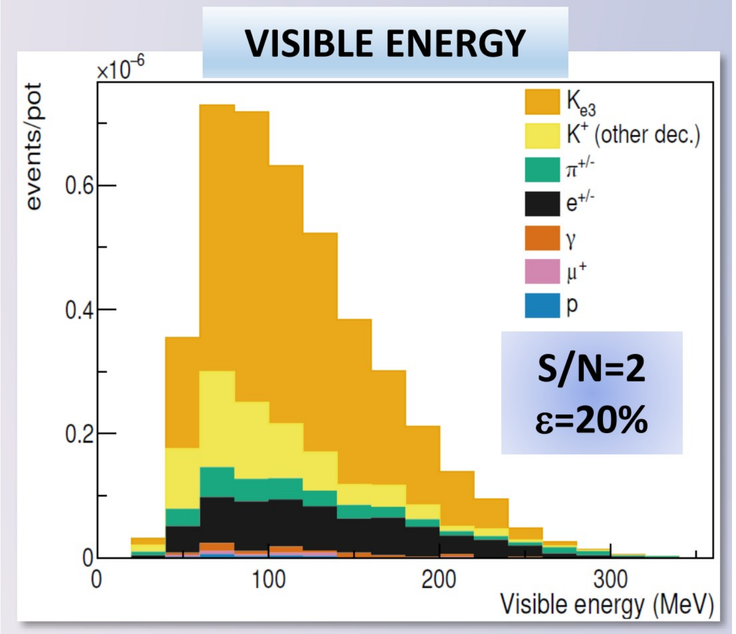
π^0 (background) topology

π^+ (background) topology

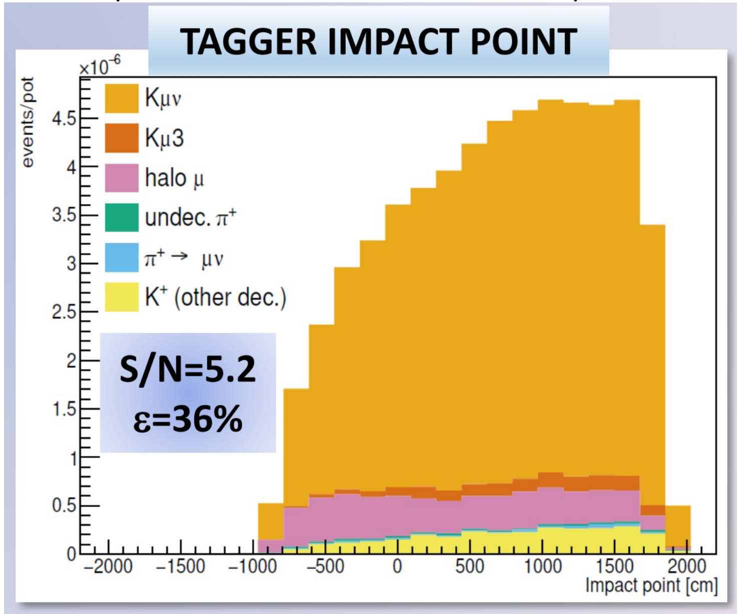
Lepton event-by-event reconstruction

GEANT4 simulation. Event building: clustering of cells in space and time (accounting for **pile-up**) → PID with a Multilayer Perceptron

K_{e3} positrons: constrain ν_e



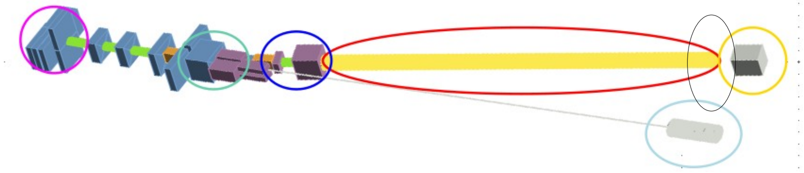
$K_{\mu 2}$ muons: constrain ν_μ

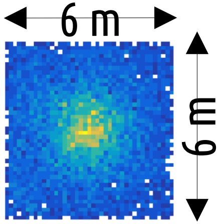


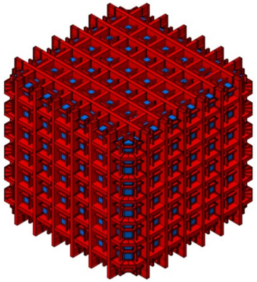
About half of the efficiency loss is from geometrical acceptance (lepton too forward)

$\nu_{\mu/e}$ CC spectra at detector

EPJ-C 83, 964, (2023)



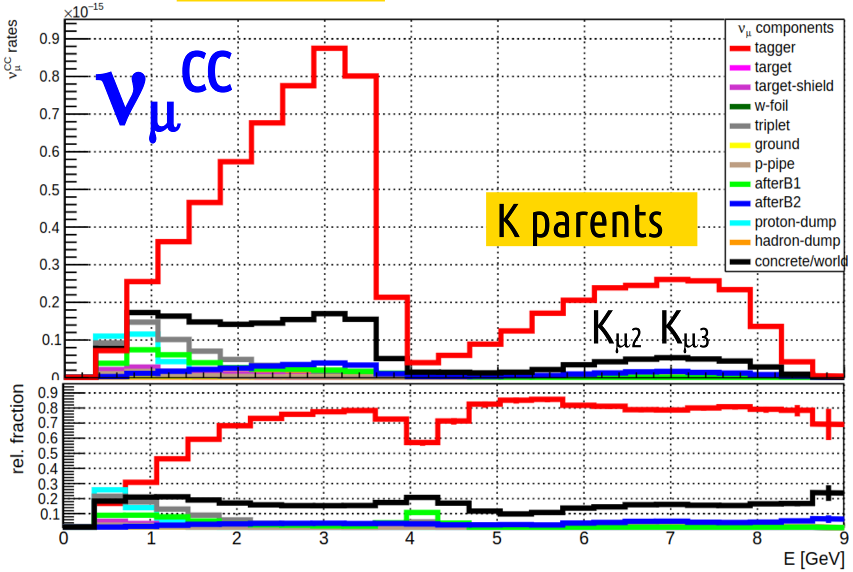


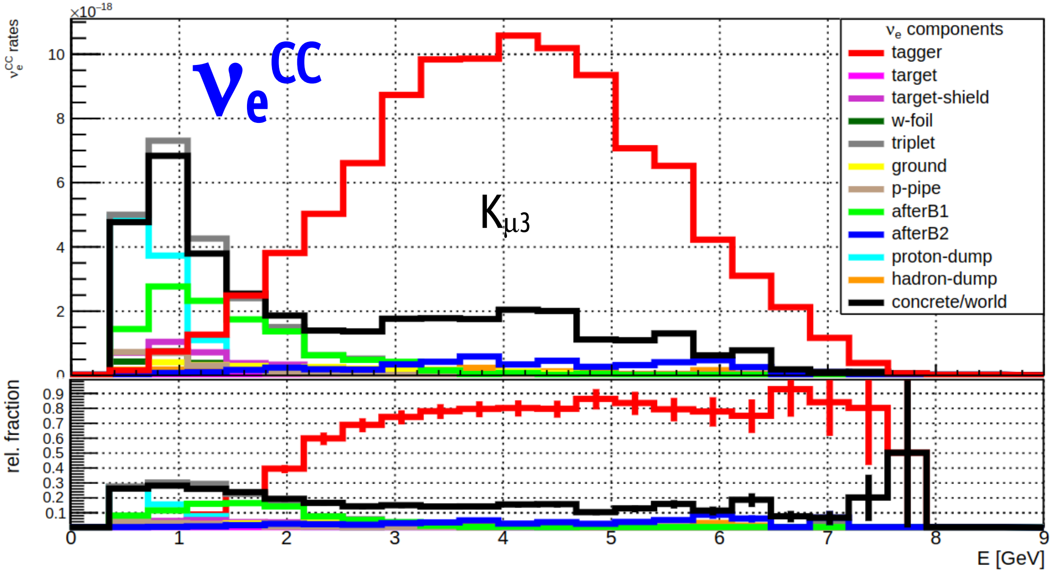


The protoDUNE(s) could be such a detector (an evident asset for a possible siting at CERN)

→ Marc's talk

π parents



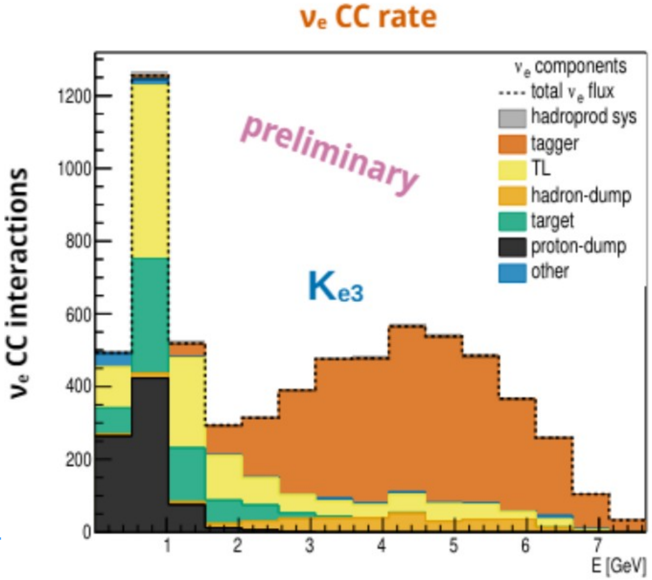


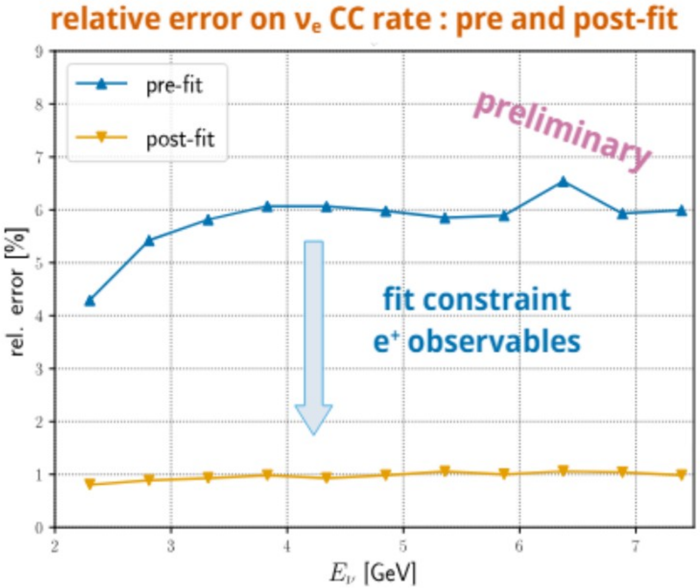
Precision on the electron neutrino flux

• considered the dominant sys. (hadroproduction) extracted from hadroproduction experiments at the SPS (NA56/SPY), which gives a 6% uncertainty on flux
• added as an additional prior the rate, position and energy distributions of positrons from K decay reconstructed in the tagger

Flux uncertainty for ν_μ and ν_e drops from 6% to 1% using positrons only.

F. Bramati poster at Neutrino2024

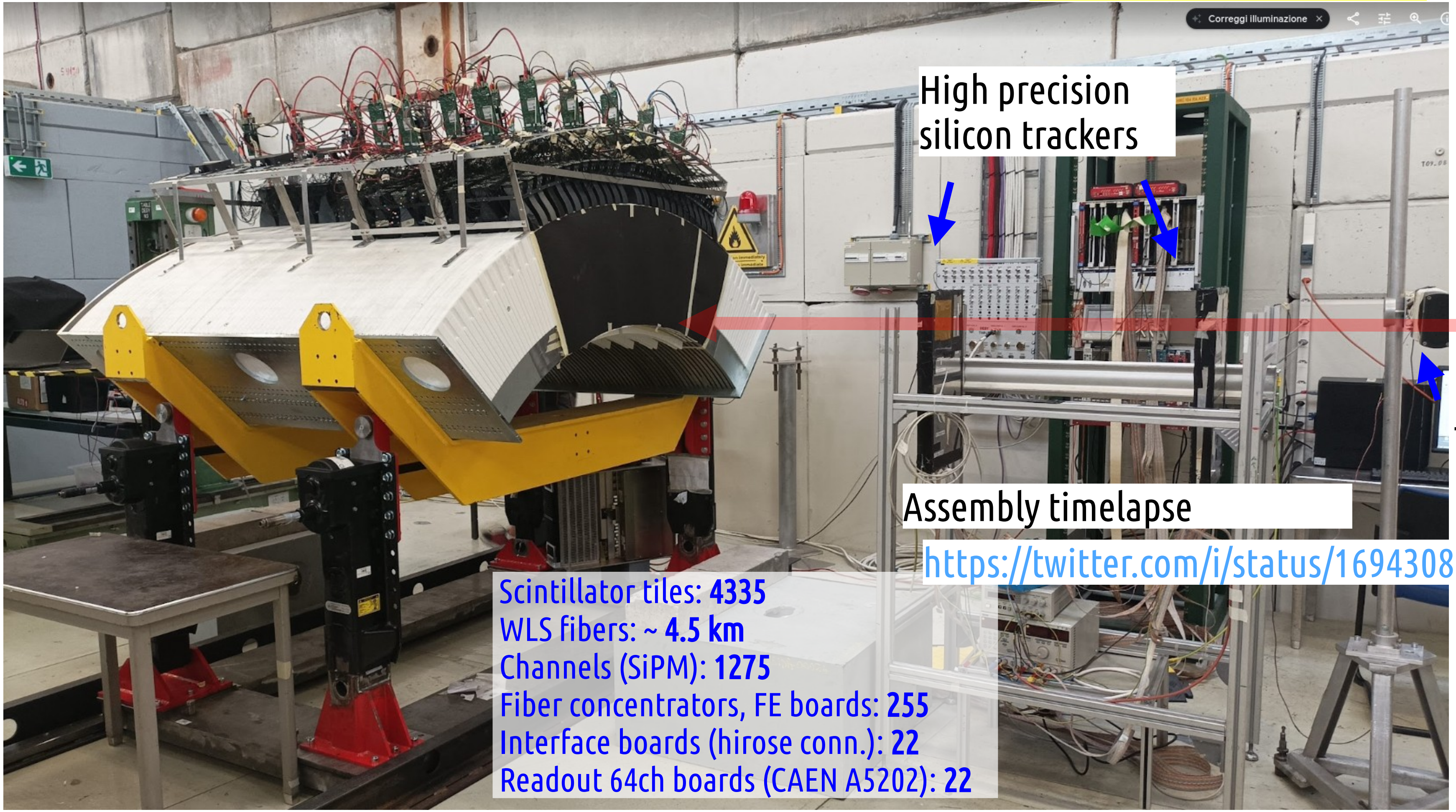




In progress: add detector effects, magnet currents, beam component, material budget uncertainty, (paper in preparation). Include improvement from the information from $K_{\mu 3}$.

The calorimeter demonstrator

10/22 + 08/23 + 08/24 @
CERN-PS-T9

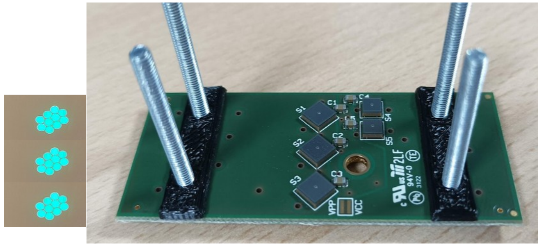


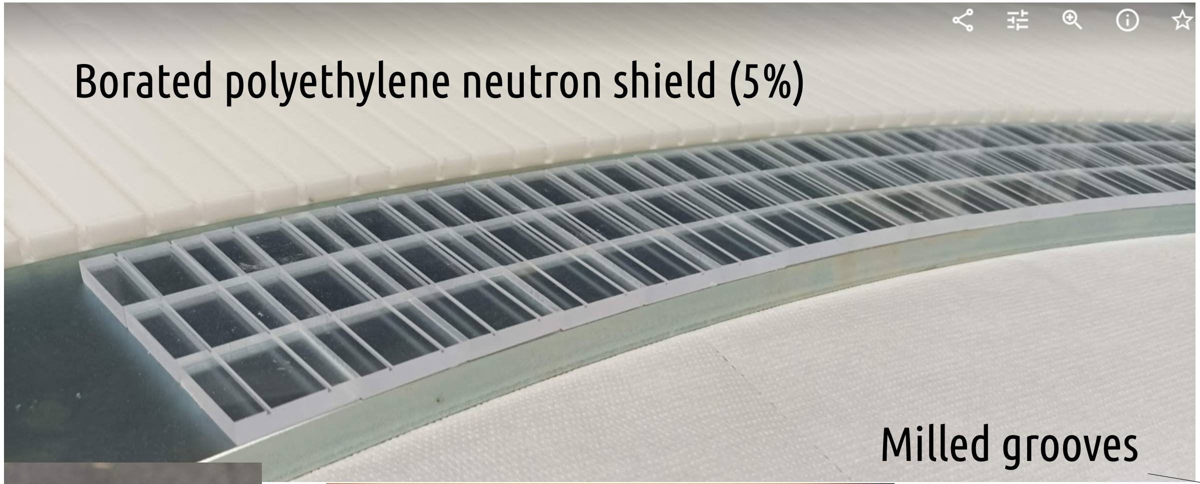
Scintillator tiles: **4335**
WLS fibers: ~ **4.5 km**
Channels (SiPM): **1275**
Fiber concentrators, FE boards: **255**
Interface boards (hirose conn.): **22**
Readout 64ch boards (CAEN A5202): **22**

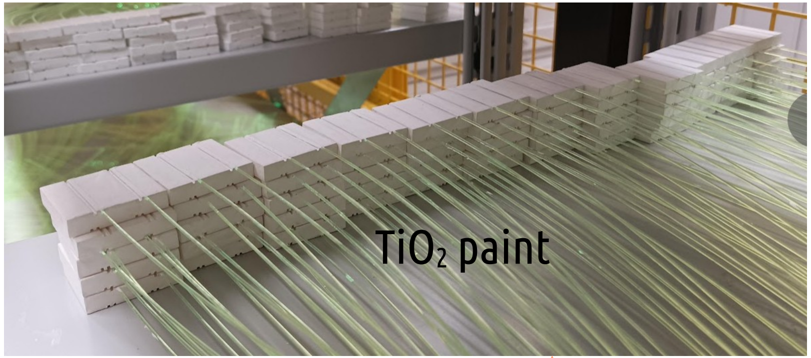
The calorimeter detector technology

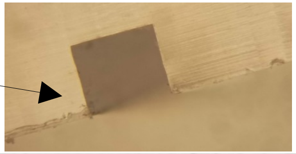
Key feature: a smart layout to transport light out of the calorimeter bulk to prevent an excessive irradiation of Silicon Photomultiplier sensors.

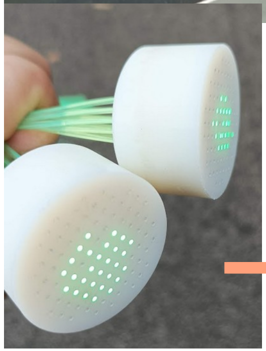
SiPMs

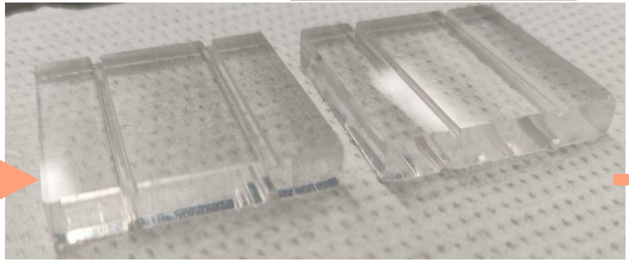


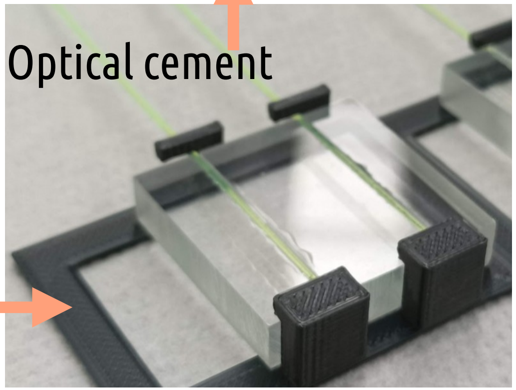






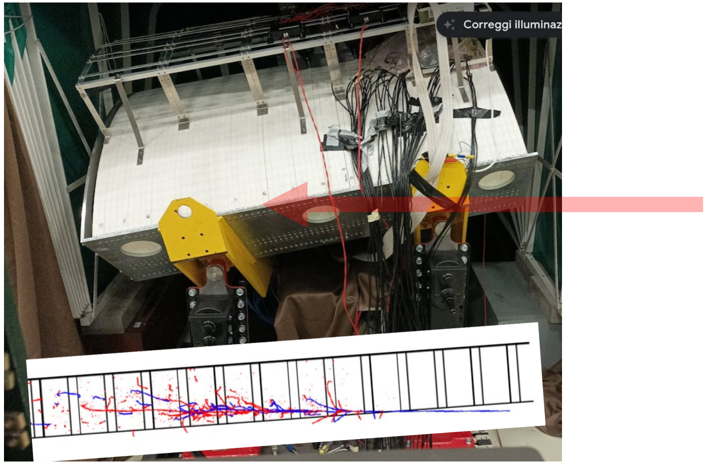




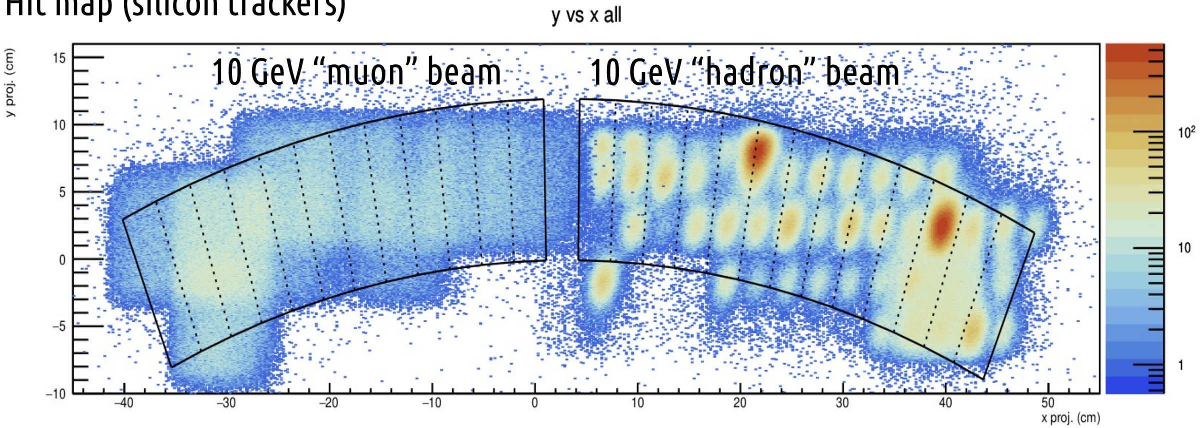


Examples: inclined and calibration runs

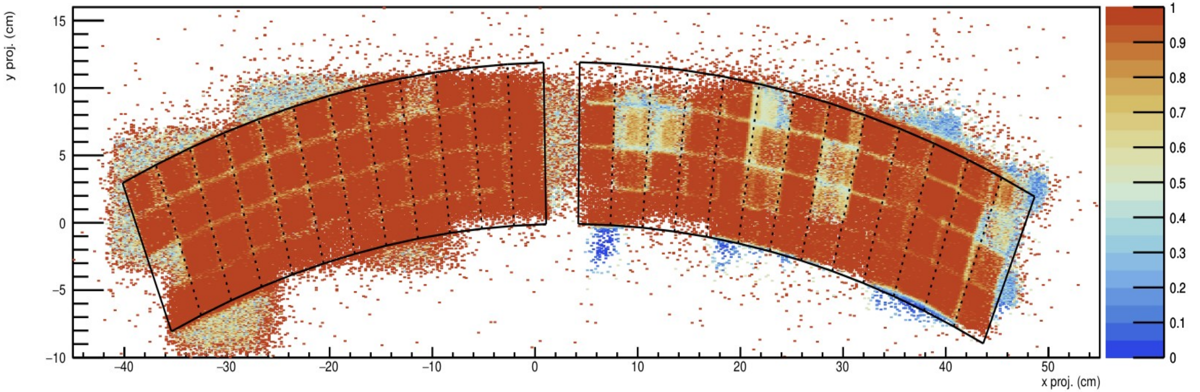
200 mrad tilt run

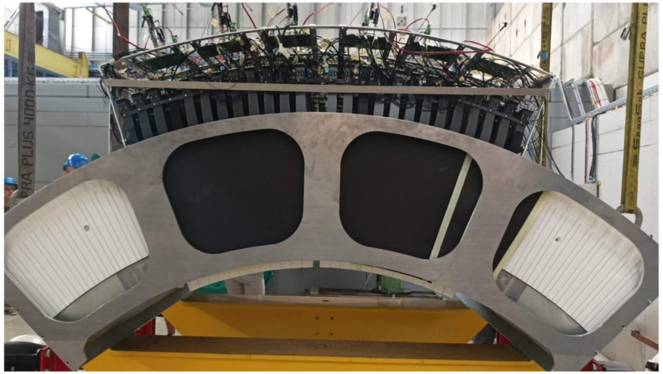


Hit map (silicon trackers)

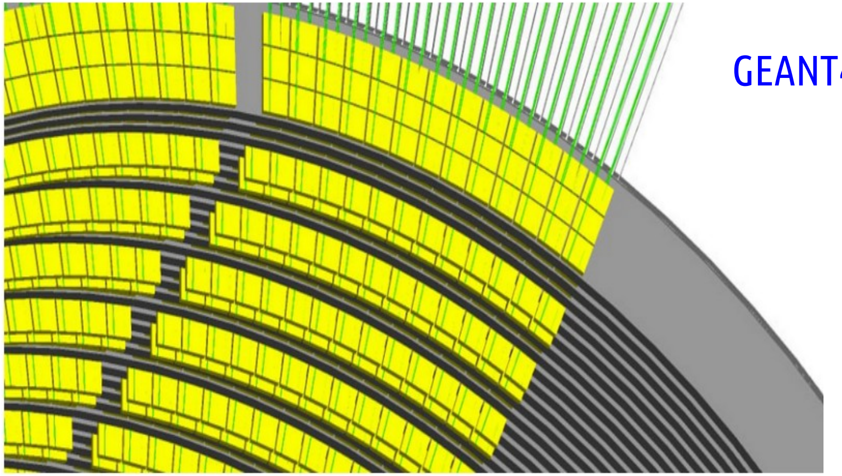


Efficiency map

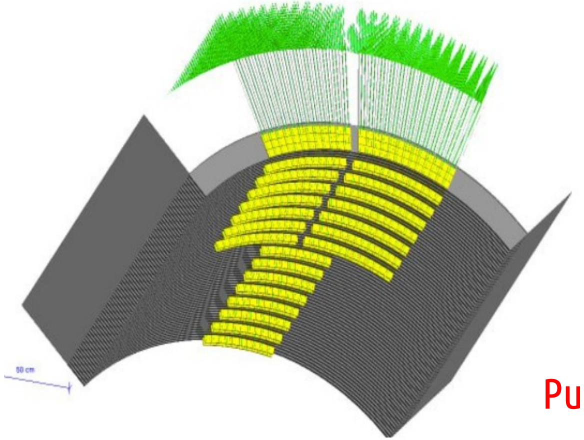


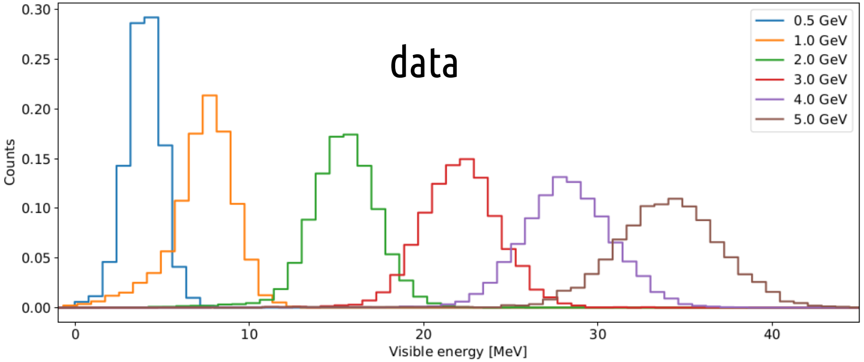


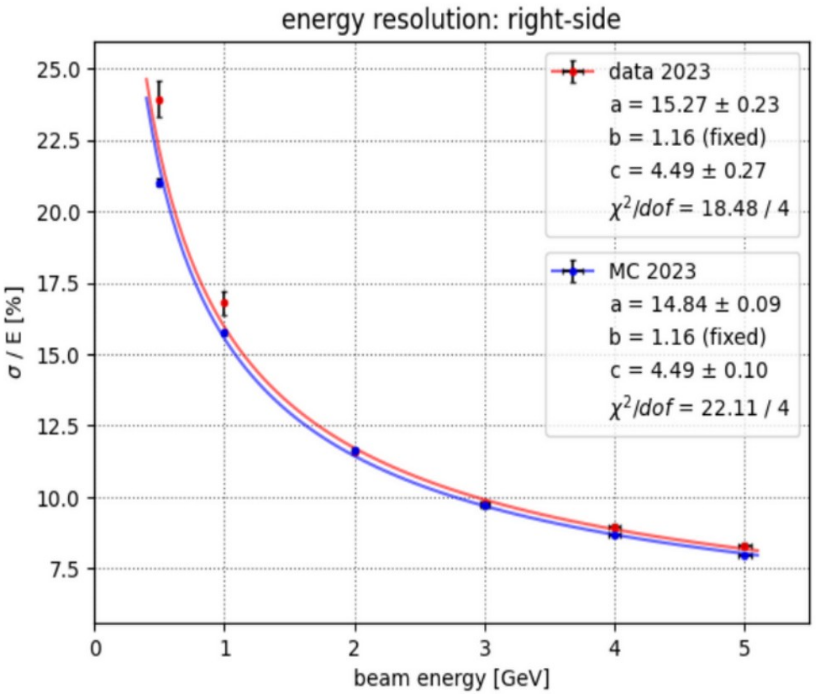
Electron energy resolution



GEANT4







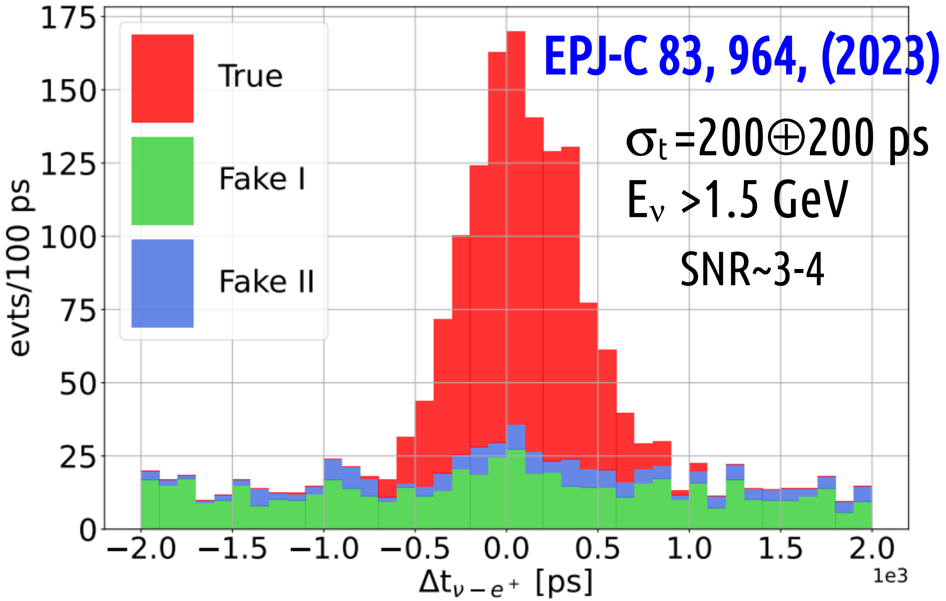
Publication in preparation

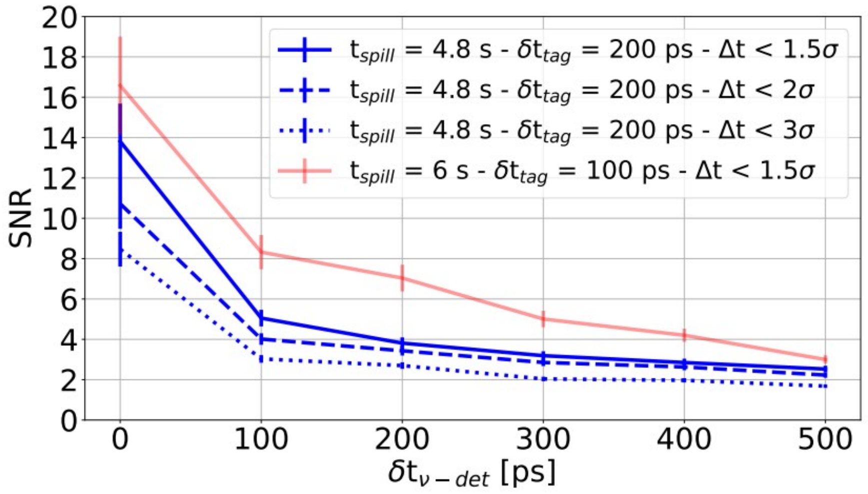
Calorimeter-only time-tagging potential

By applying a cut on the Δt bewteen the ν_e and e^+ candidates the SNR passes from ~2 (for the inclusive e^+ sample) up to ~8-10 for neutrino-associated e^+

Precise value depends on σ_t of tagger and neutrino detector and the slow extraction spill duration (4.8 – 6 s)

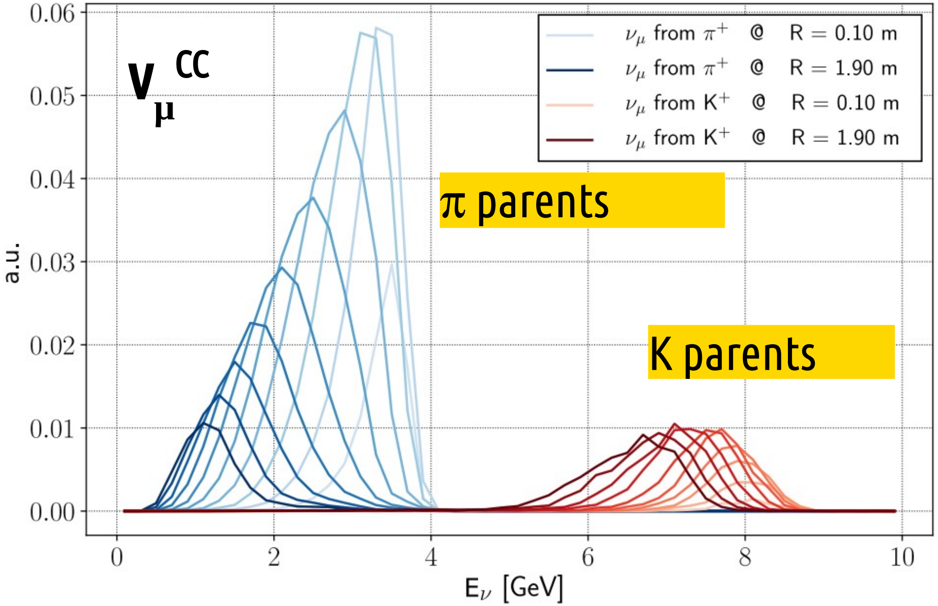
Difference in path between the e^+ and ν_e (decay vertex position is unconstrained → we assume e^+ and ν_e to be collinear) → **"irreducible" time spread**: **$\sigma_{\Delta t}$ = 74 ps(*)**

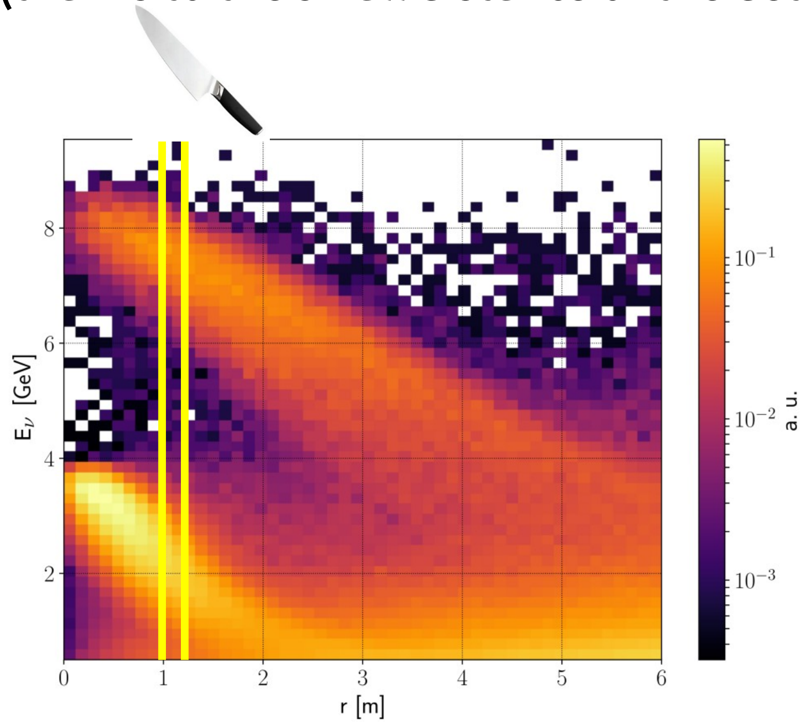




ν_μ fluxes decomposition: NBOA (~PRISM)

"Narrow-band off-axis technique" (NBOA): bins in the **radial distance from the center of the beam →** **single-out well separated neutrino energy spectra** → strong prior for **energy unfolding**, independent from the reconstruction of interaction products in the neutrino detector. "Easy" rec. variable. A kind of "off-axis" but without having to move the detector (thanks to the small distance of the detector) !





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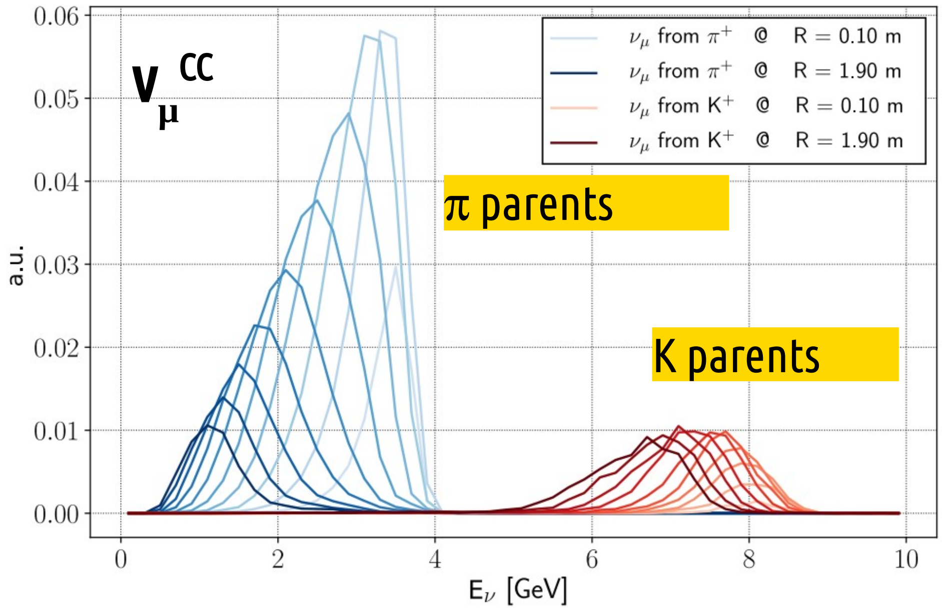
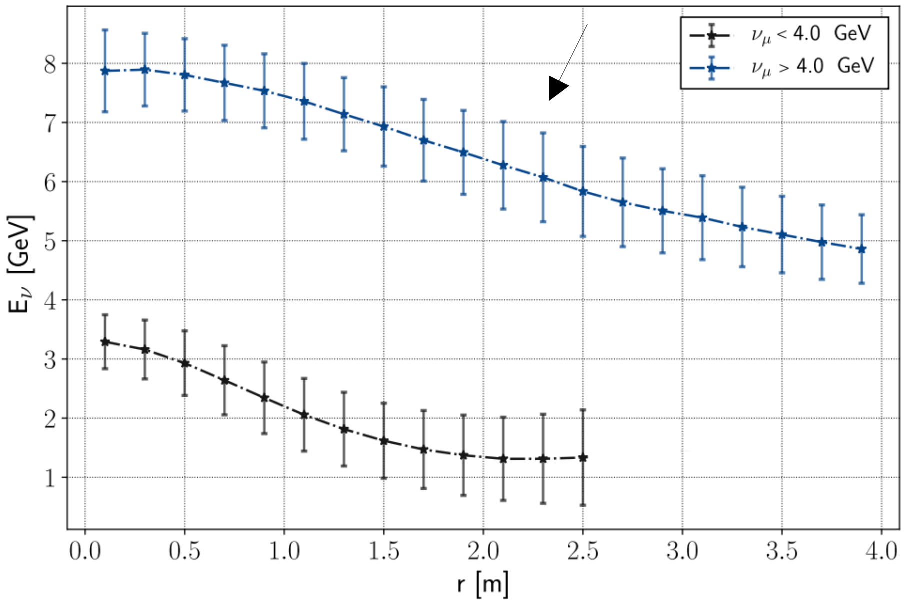


Error bands visualize the rms of the energy distributions



Achievements of the SBN@CERN study group

The baseline ENUBET beamline had three limitations:

a) amount of PoT, difficult to reconcile with the CERN fixed target programme and SHiP
b) limited performance in the low-energy neutrino region (<2 GeV)
c) neutrino energy a priori with moderate resolution (10-25%), worse at low E_ν

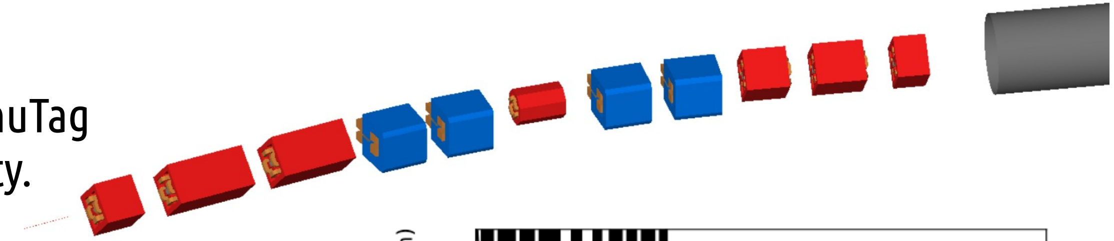
These limitations were successfully addressed by CERN accelerator physicists at PBC with a **new beamline design** (a, b) and by new ideas originating from the **NuTAG** collab. (b,c).

The SBN@CERN beamline design

Marc Jebramcik

link to talk @ PBC annual meeting
link to NBI2024
link to Neutrino2024 poster

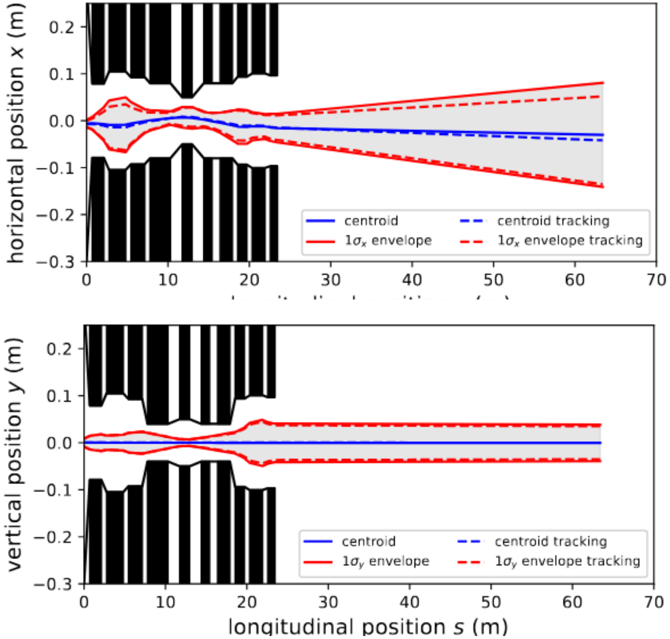
The new design → multi-objective optimization of the beamline, a CNGS-like target, shorter length →



It incorporates by design the possibility of placing the nuTag Silicon trackers in the regions with lower particle density.

1.3 × 10^{-3} K^+/PoT → 3.5 × higher meson acceptance: helps a lot in terms of proton-economics!

O(10^4) ν_e CC events and 5x10^5 ν_μ^{CC} could be reached in ~ 5 years with a PoT investment between 13% and 26% of the North Area PoT (1.4 x 10^{19} PoT)



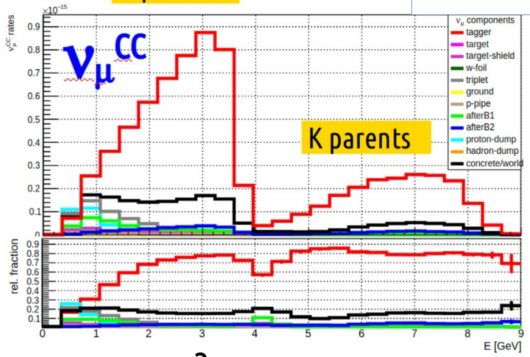
All the studies performed within ENUBET are being repeated for this beamline. Preliminary results show a similar S/B ratio and physics reach.

How can we get a high precision beam also at lower energies?

The key ingredients are:

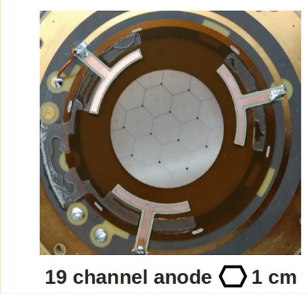
- 1) extending the acceptance of the lepton monitoring in the forward region where most of muons from pion decays go

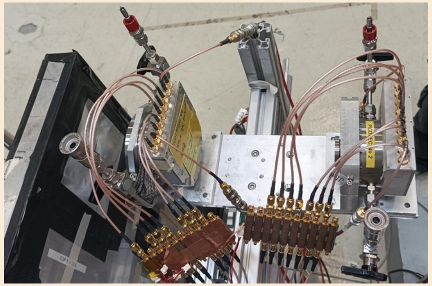
8.5 GeV focusing

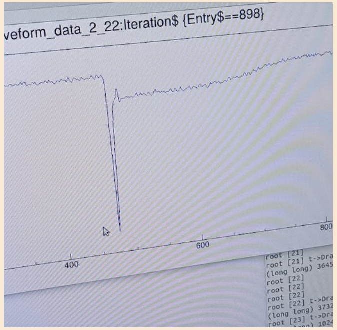


3

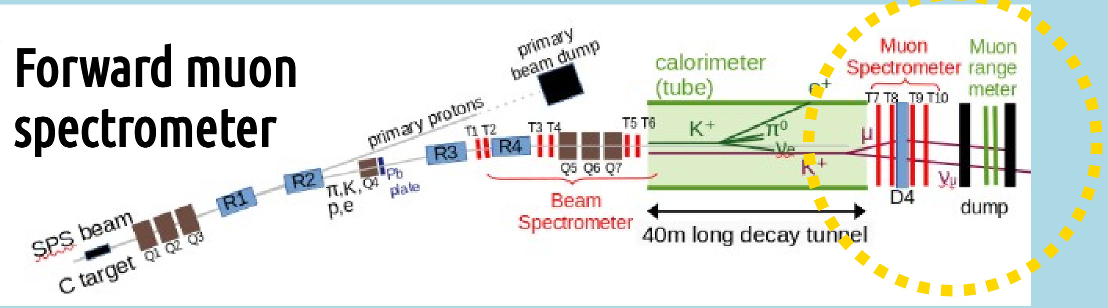
Instrumented hadron dump
PIMENT (**PI**cosecond **M**icrom**E**gas for e**N**ube**T**), ANR2022-25
Prototype tested with the ENUBET demonstrator **at T9** in Aug. 2024 → few 10s of ps resolutions achieved
Athens, CNRS, INFN, Thessaloniki, Zagreb







Forward muon spectrometer

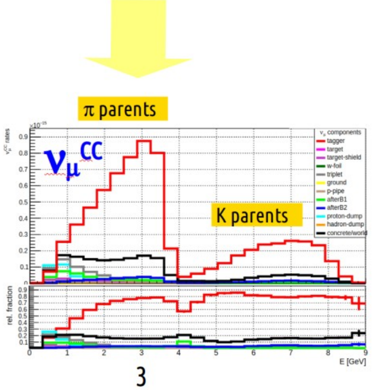


How can we get a high precision beam also at lower energies?

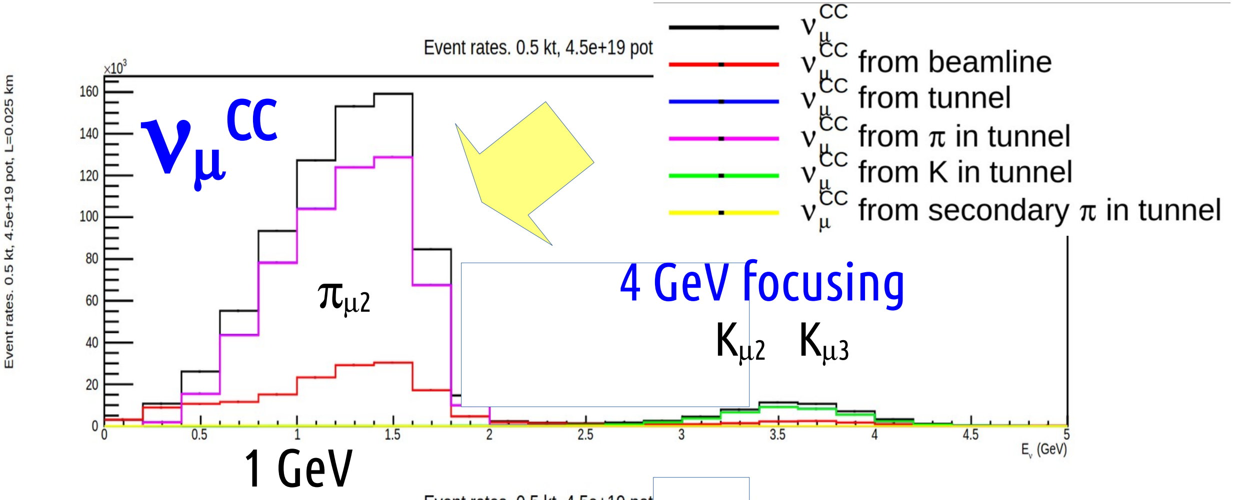
The key ingredients are:

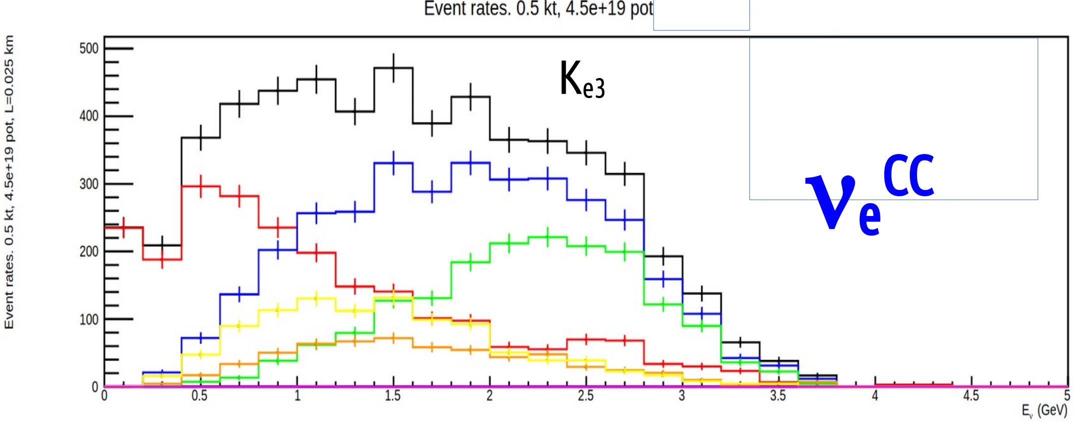
- 2) Selecting lower-energy mesons by tuning the dipole magnetic fields
  - @ 4GeV the $\pi_{\mu 2}$ low-E ν_μ peak moves from 3 to ~1.5 GeV. Rather clean and extending within the Hyper-Kamiokande region.
  - ν_e are less and polluted by non tagged components. But flux could be estimated from the knowledge of decays branching ratios.

8.5 GeV focusing



CC spectra using the PBC beamline without further optimization but a scaling of the dipole currents to focus 4 GeV pions/kaons





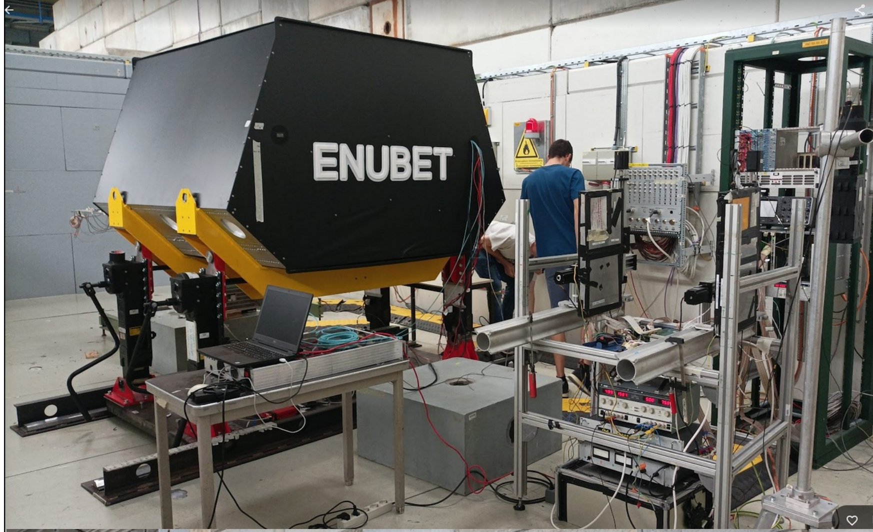
CERN Aug. 2024 →

Conclusions

- The current design prepared within SBN@CERN (ENUBET+NUTAG) could be a **“killer-facility” for precision cross sections in the DUNE-HK era**.

- Large progress in terms of **improved compatibility** with the CERN infrastructures:

  - more in the following talks (Mathieu, Marc)



Conclusions

- A **contribution to the** European Strategy (ESPPU) is in preparation
  - ➢ The importance of the involvement of a **larger community** does not need to be emphasized!
  - ➢ We are going to **circulate the document soon to the LBL-ν community** to gather interest

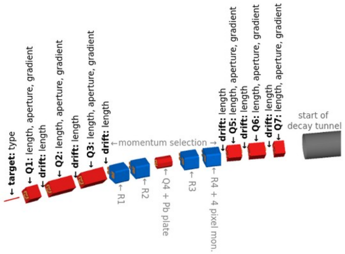
SBN@CERN
A short-baseline neutrino beam at CERN for high-precision cross-section measurements

January 21, 2025

1 A high precision neutrino beam at CERN

Neutrino physics entered its precision era in 2012 when accelerator and reactor experiments demonstrated that all mixing angles, including θ_{13}, are large [1]. This groundbreaking discovery paved the way for a comprehensive exploration of the lepton Yukawa sector of the Standard Model. Oscillation experiments can now probe the neutrino mass hierarchy, the mixing angles, and the Dirac CP-violating phase, providing a nearly complete picture of neutrino properties. The only remaining piece—the determination of the absolute neutrino mass and the Dirac/Majorana nature—requires dedicated measurements beyond oscillation experiments. A key finding of the 2020 European Strategy for Particle Physics [2] was the recognition that the ambitious goals of neutrino physics are critically hindered by the limited understanding of standard neutrino interactions, particularly neutrino cross-sections at the GeV scale. This concern has grown over the past five years, emphasizing the

list of targets covers target lengths from 0.7 m to 1.35 m, target radii from 2.5 mm to 30 mm and graphite densities from 1.70 g/cm³ to 2.26 g/cm³.



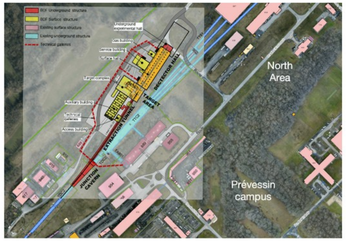


Figure 5: Schematic drawing of ECN4 solution studied as a possibility to house the BDF/SHiP facility. Taken from [28].

beamlines (H2, H4, H6, and H8). A placement below EHN1 is also excluded due to the technical galleries below the building alongside the underground involving the Lion river and the challenges of excavating underneath an existing building. This eventually means that the now existing ProtoDUNEs in the North Area's Neutrino

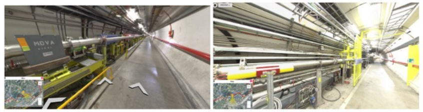
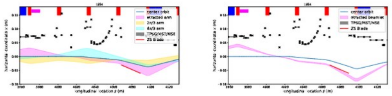


Figure 6: Left: Picture of the drift space in LSS4 that could be used for a potential ZS placement obtained from the CERN GIS portal. Right: Respective picture of the drift space in LSS5 behind the SPS beam dump. Figure taken from Ref. [29].



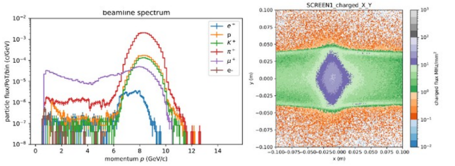
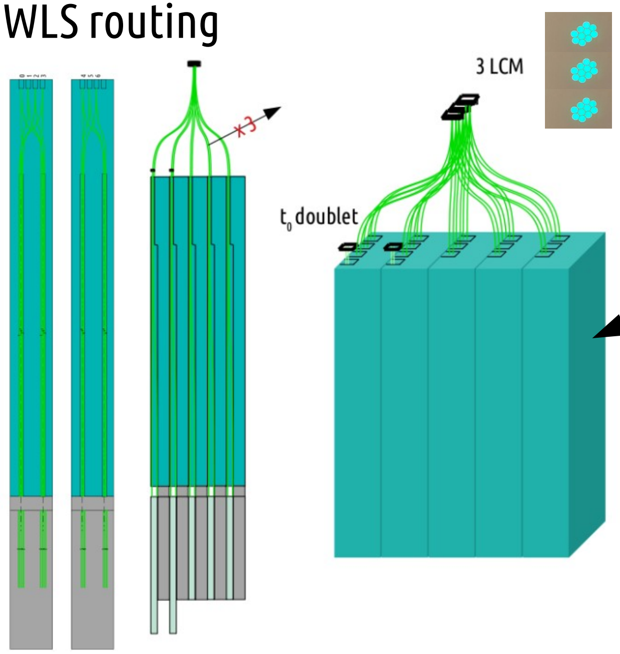
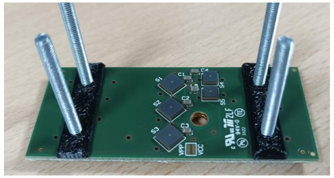


Figure 3: Left: Beamline spectrum after the optimisation process. Compared to any previous design, the positron transmission is strongly suppressed due to the Pb plate followed by two bending magnets. The study of the noise level of low-energy leptons is still pending. Right: Flux of charged particles on the first pixel detector at the R4 bending magnet of the beamline with a spill intensity of 1×10^{13} PoT within a spill length of 4.8 s.

The demonstrator

WLS routing



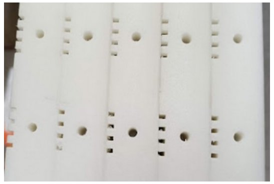


Demonstrate detector performance (PID, homogenity, eff.), scalability, cost effectivess...

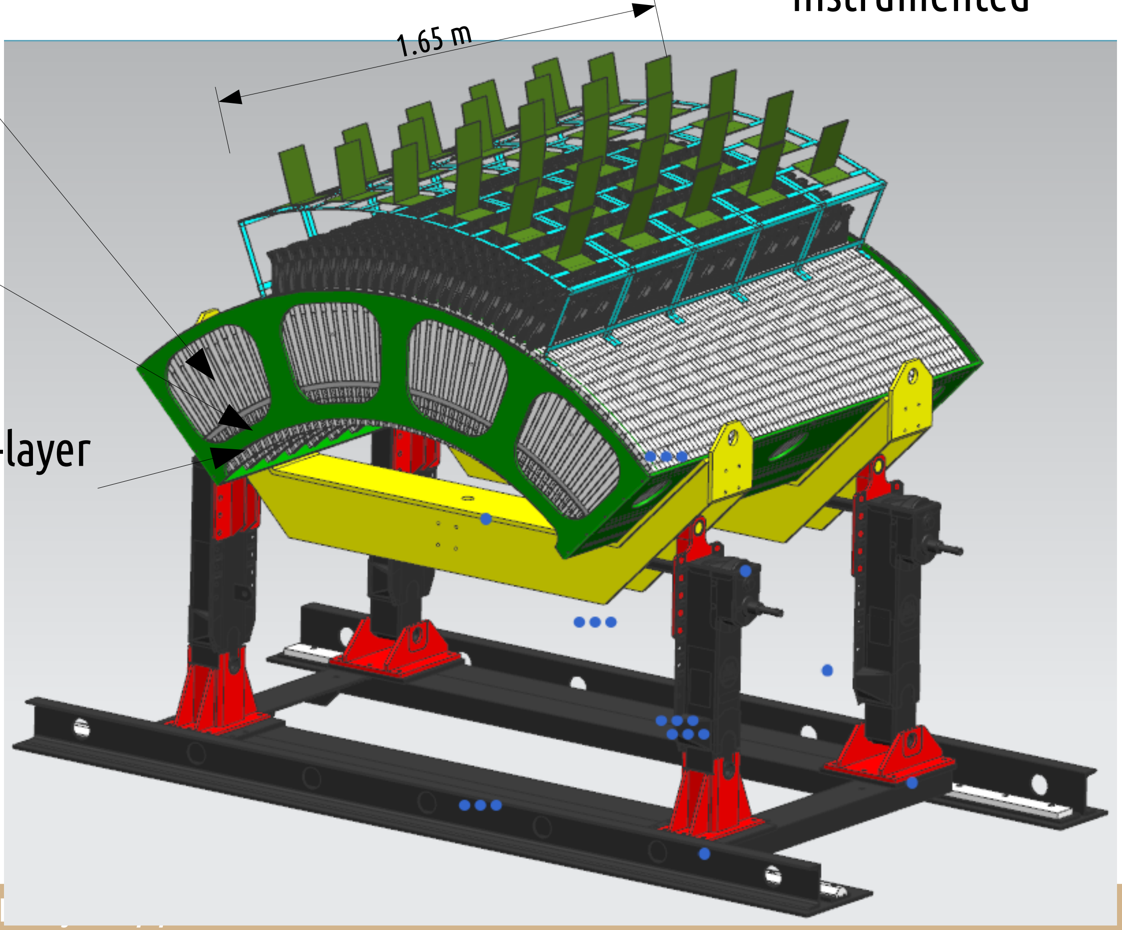
90°, partially instrumented

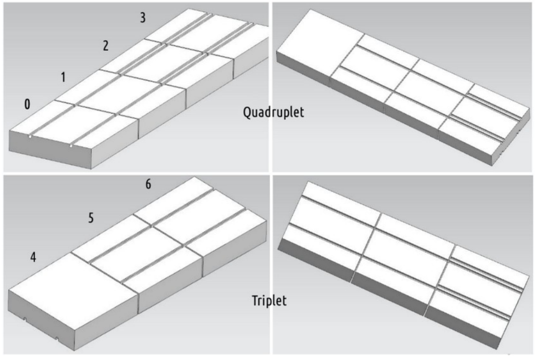
BPE 5%

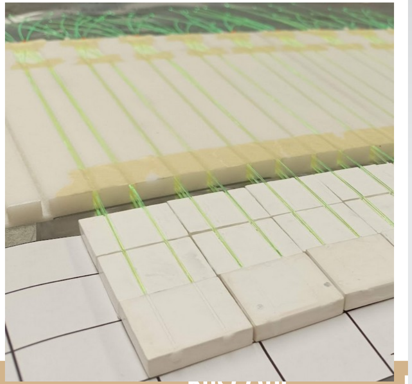
Sampling iron/scint calo



t_0-layer

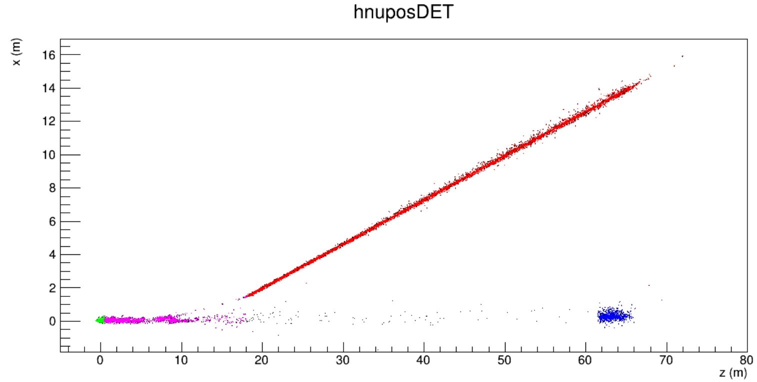


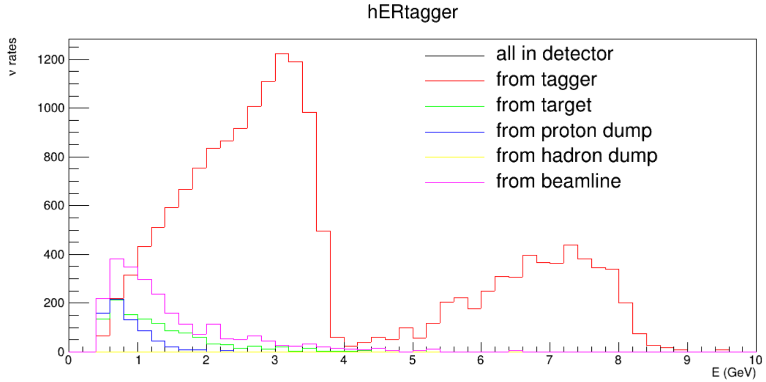




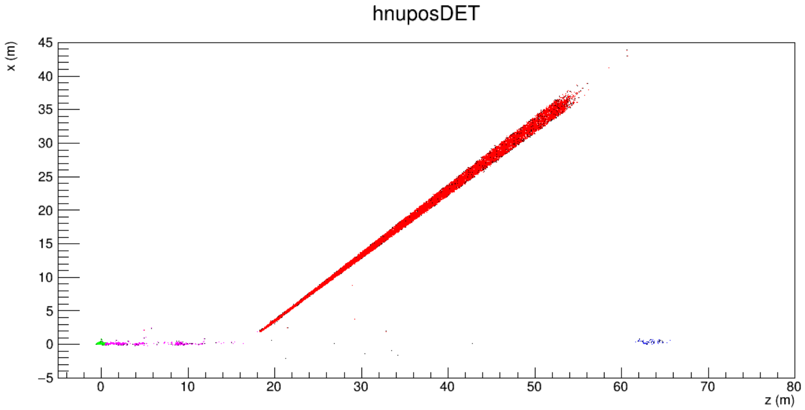
ν_μ^{CC} spectra at detector

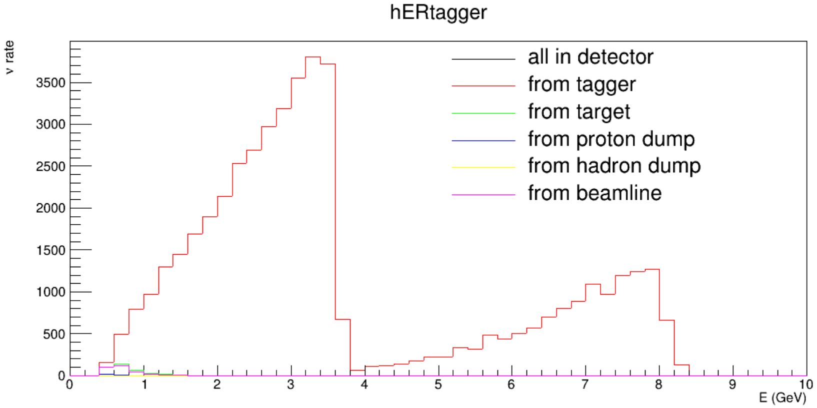
tlr6v6





With a SC second dipole

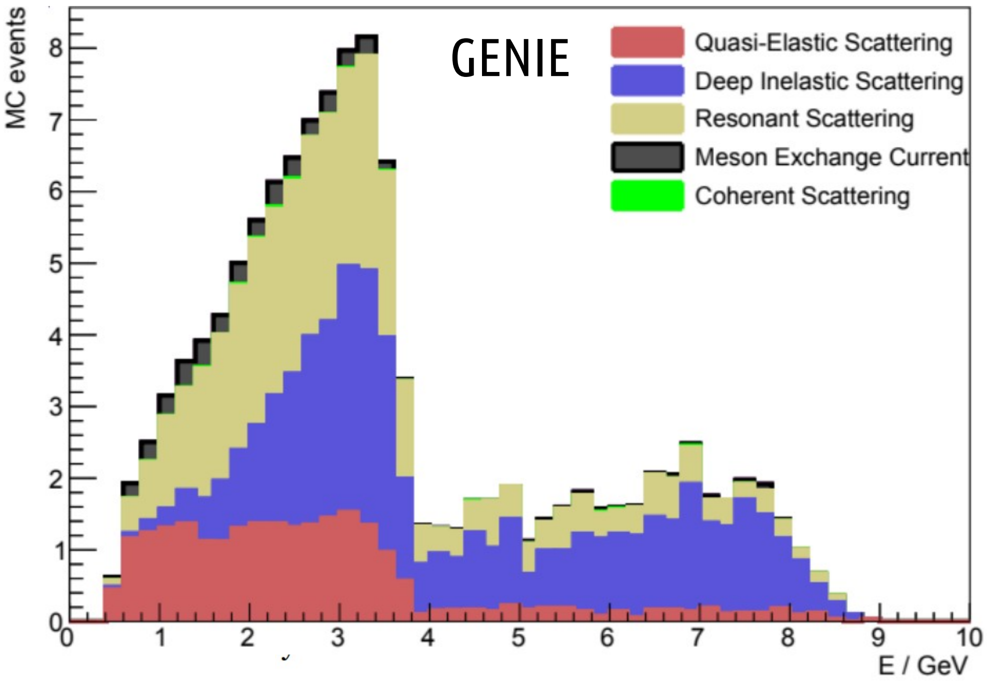


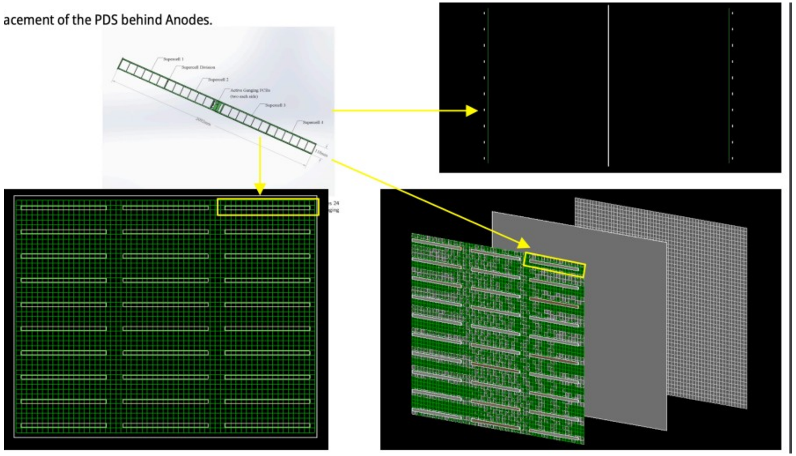


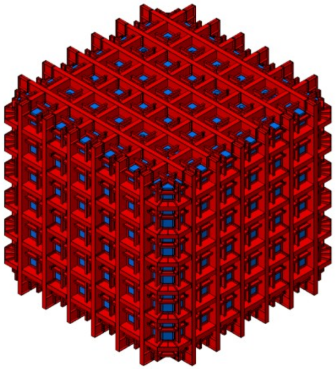
ν detector studies (ENUDET)

This R&D is being pursued by ENUBET together with the DUNE-SoLAR coll. and is instrumental in **exploiting liquid Argon in a tagged neutrino beam**. A dedicated task force is addressing:

- The **achievable σ_t of ProtoDUNE** overhauled for DUNE Phase II. It will be equipped with an **enhanced photon detection system**. The corresponding light yield will improve time resolution for GeV neutrinos below 1 ns.
- **Simulation of neutrino interactions (GENIE)** and **reconstruction effects** (i.e. role of **cosmic rays** background) to **assess the physics reach on the cross section for specific channels**

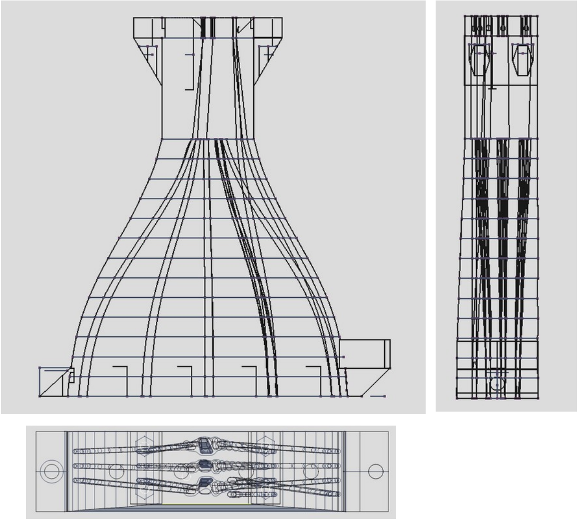




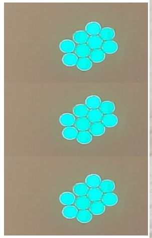


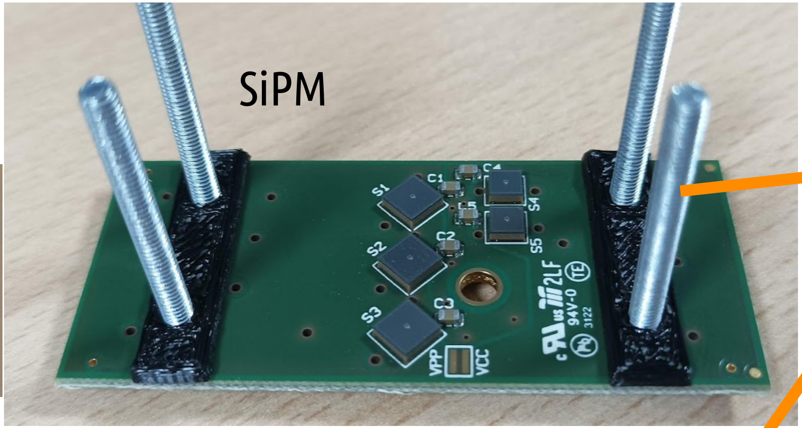
Fiber bundling with “concentrators”

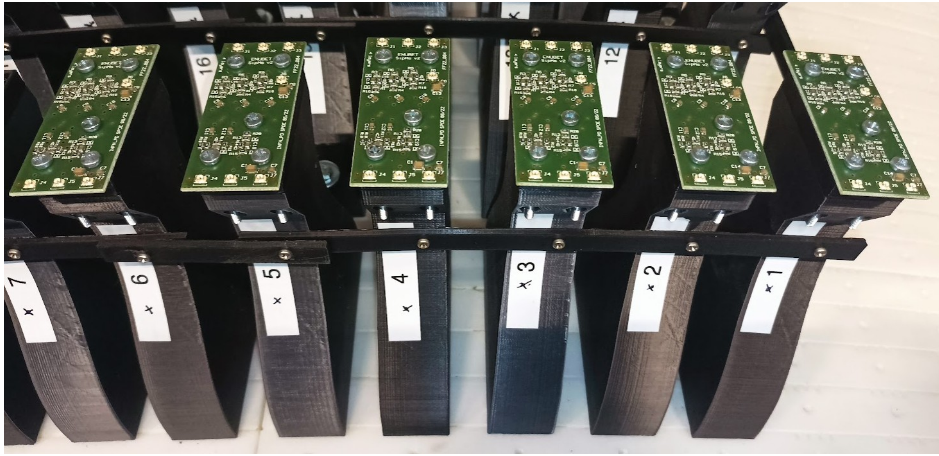
bundling of the WLS fibers with 3D printed “fiber concentrators”+ in situ polishing

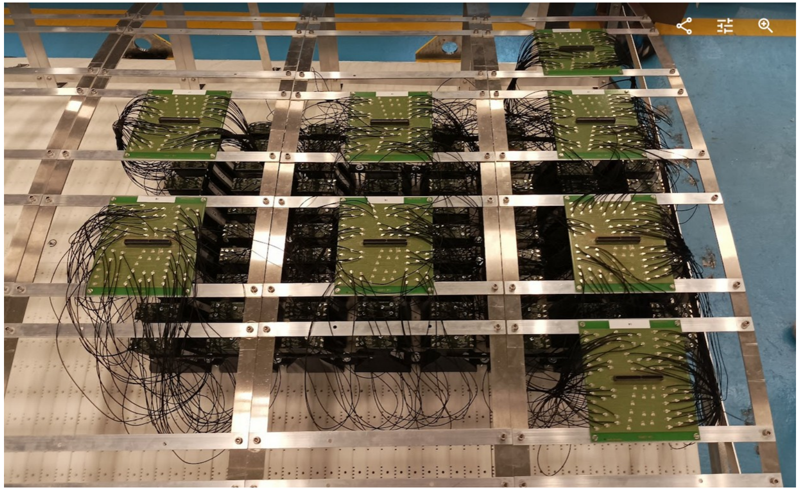


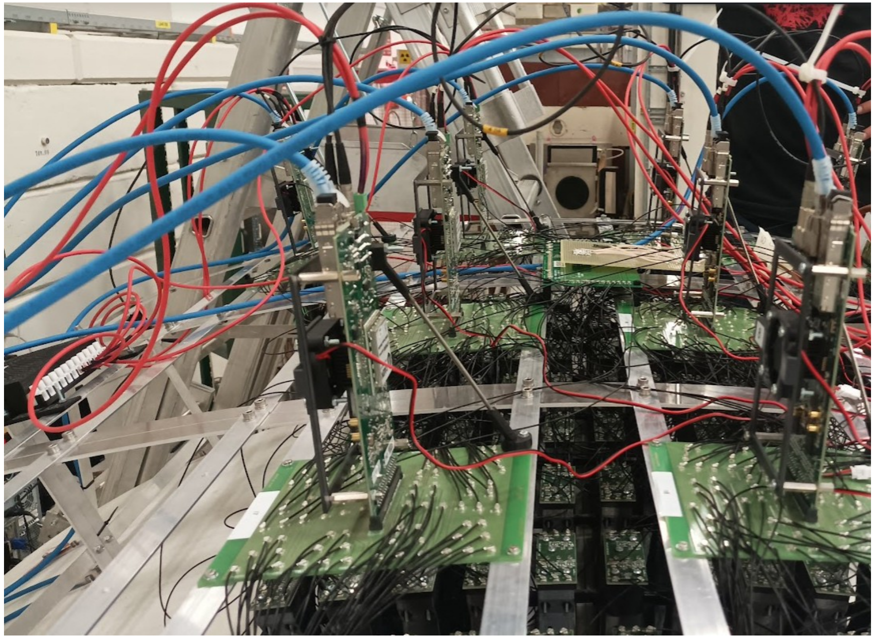
Readout scheme





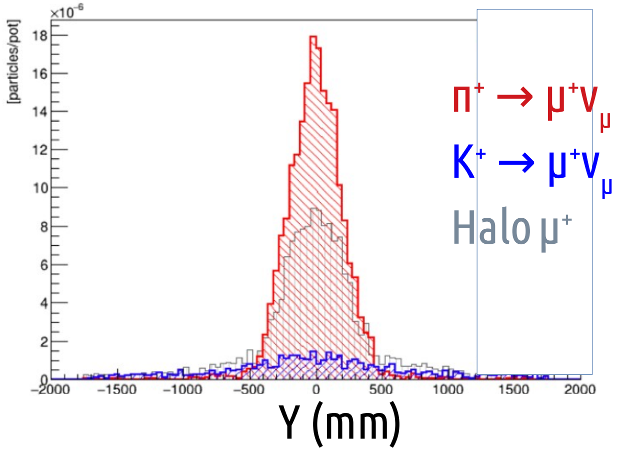


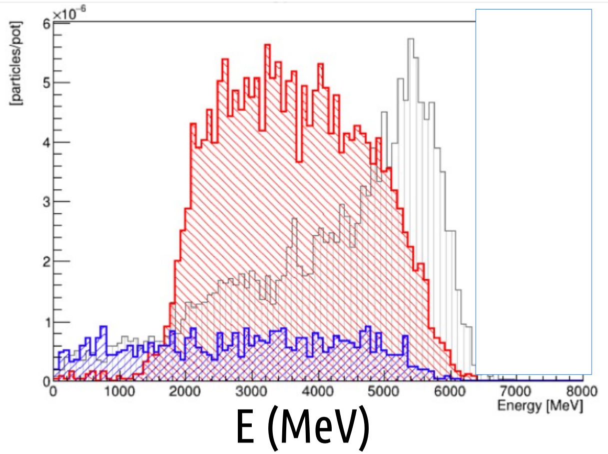


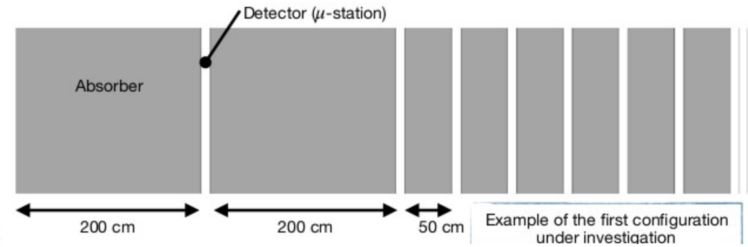


Forward region muons reconstruction

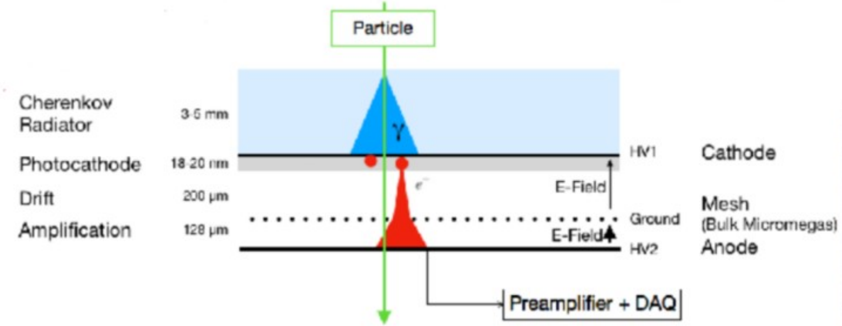
Range-meter after the hadron dump. Extends the tagger acceptance in the forward region to constrain $\pi_{\mu 2}$ decays contributing to the low-E ν_μ.

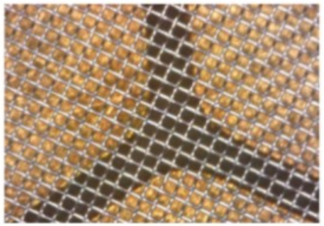






The most upstream (hottest) detector needs to cope with a muon rate of ~ 2 MHz/cm^2 and about 10^{12} 1 MeV-n$_{eq}$/cm^2.





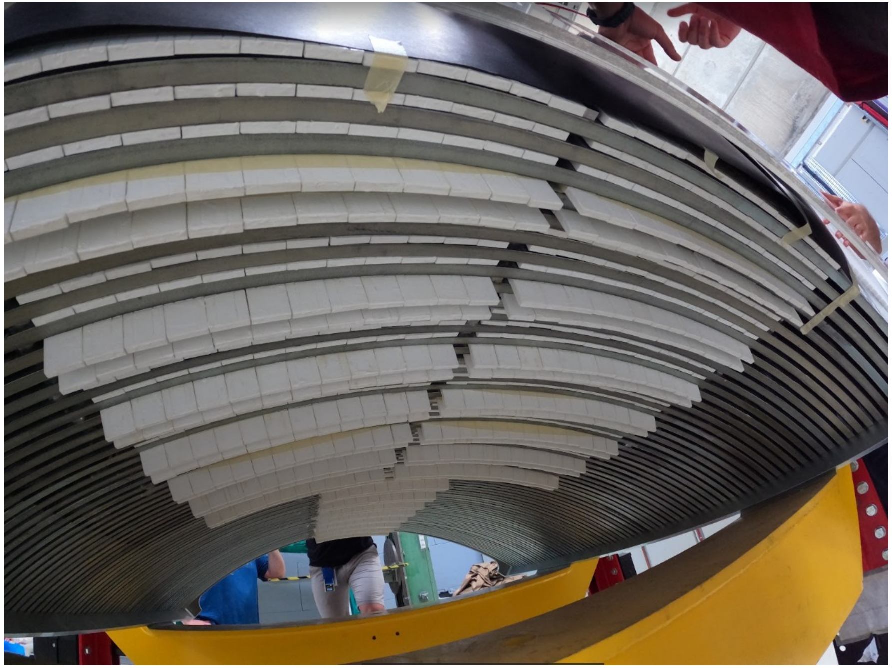
Micromegas detectors employing Cherenkov radiators + thin drift gap ?
Bonus: cutting-edge timing (O(10) ps).

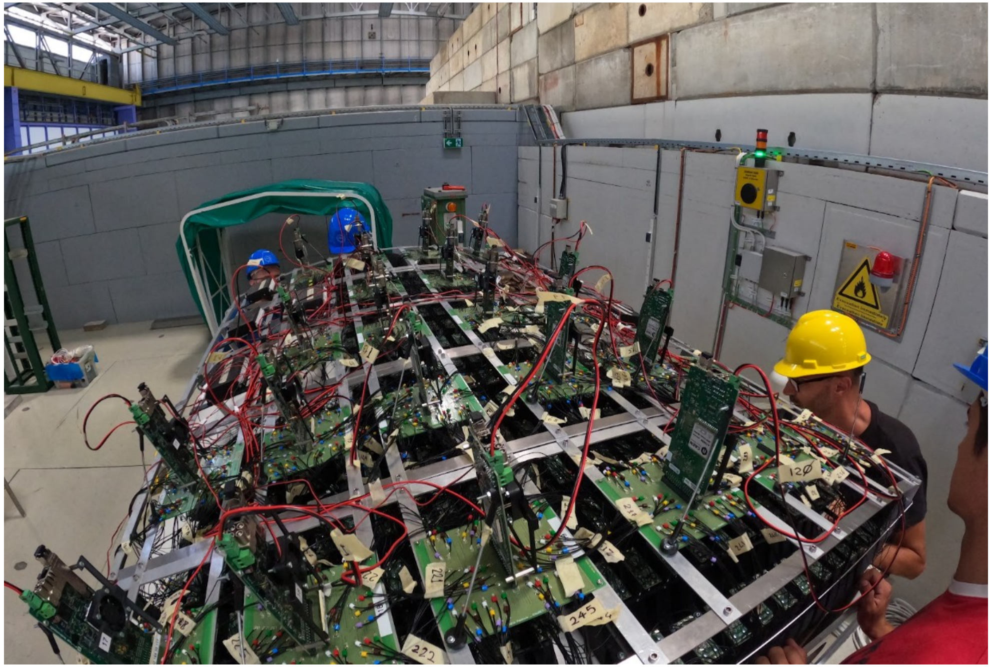
→ PIMENT project ! →

ENUBET: demonstrator

Assembly timelapse

https://twitter.com/i/status/1694308753514889350

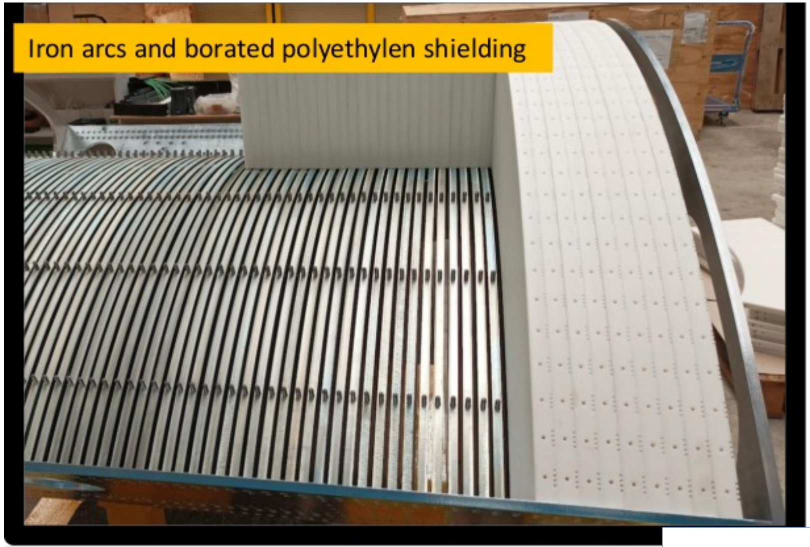


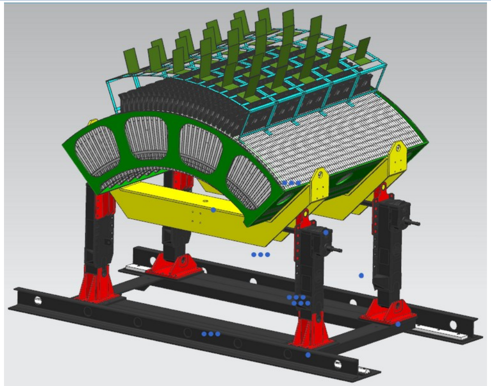


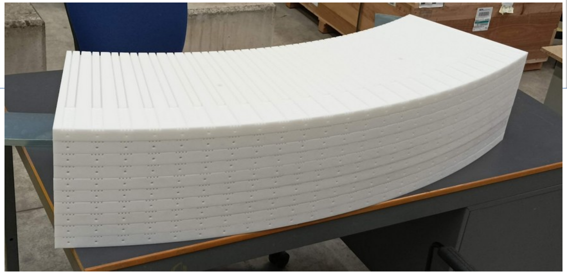
The ENUBET demonstrator in numbers

- Scintillator tiles: **1360**
- WLS: ~ **1.5 km**
- Channels (SiPM): **400**
  - Hamamatsu **50 um** cell
    - **240** SiPM **4x4** mm^2 (calo)
    - **160** SiPM **3x3** mm^2 (t_0)
- Fiber concentrators, FE boards: **80**
- Interface boards (hirose conn.): **8**
- Readout 64 ch boards (CAEN A5202): **8**
- Commercial digitizers: **45 ch**
- hor. movement ~**1m**
- tilt **>200 mrad**

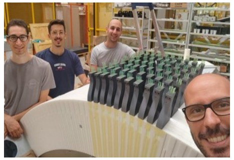
Demonstrator construction at LNL-INFN labs

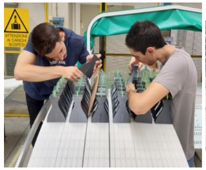


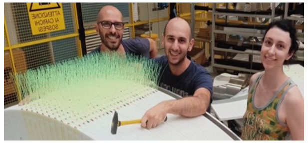


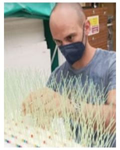


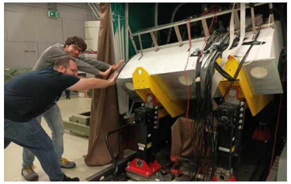
Group pictures







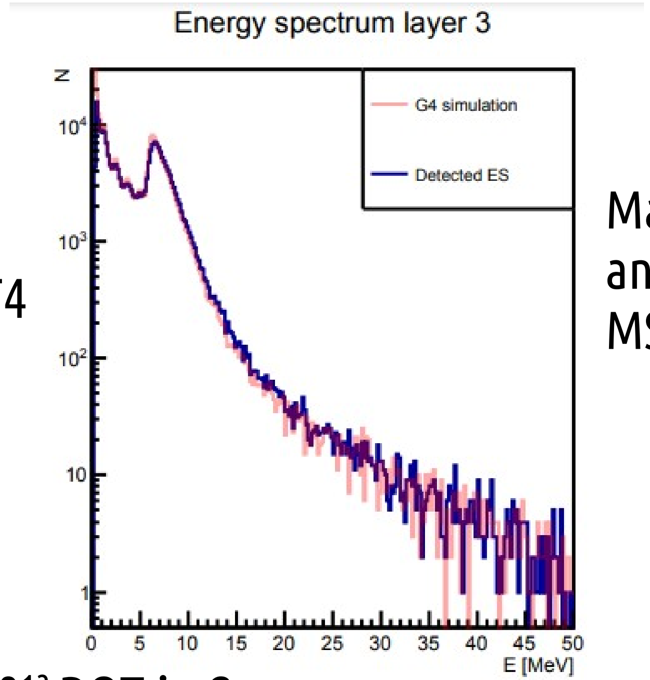




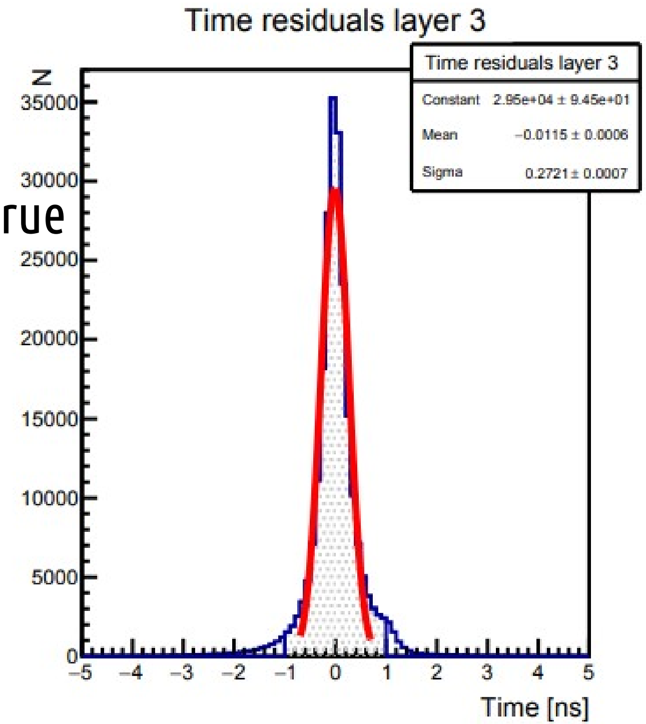
Event pile-up analysis

The energy is now reconstructed as it will happen for real data i.e. considering the **amplitudes digitally-sampled signals at 500 MS/s**. **Pile-up** effects treated rigorously by "fitting" superimposing waveforms.

Matching between true level energy deposits from GEANT4 and fully reconstructed waveforms



Matching between true and rec. time (500 MS/s). 270 ps.



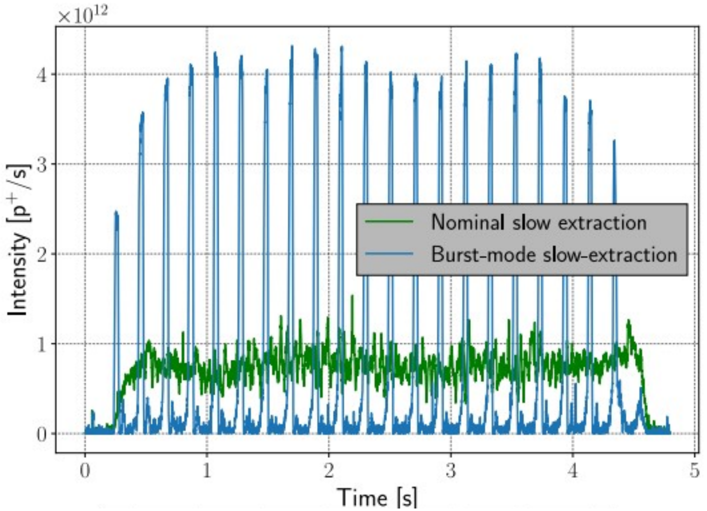
With 4.5 x 10^{13} POT in 2s

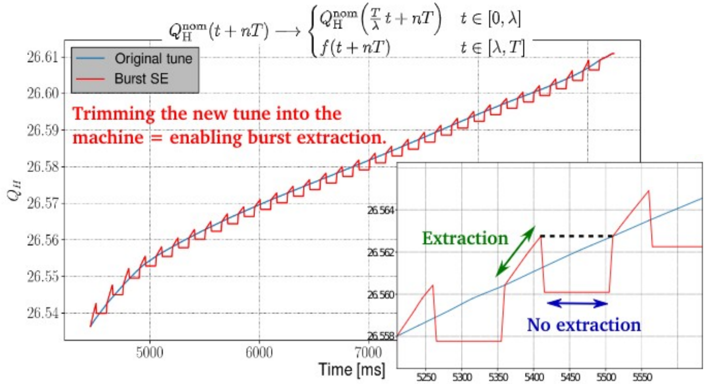
- 1.1 MHz rate in the hottest channels
- Peak finding efficiency = 97.4 %

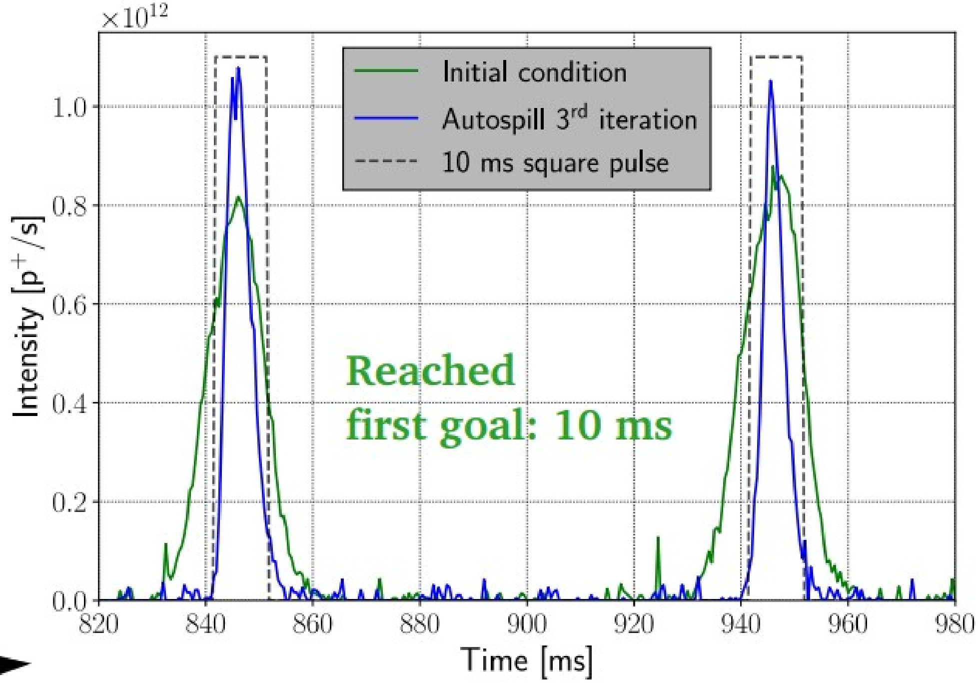
Proton extraction R&D for horn focusing

CERN-TE-ABT-BTP, BE-OP-SPS
Velotti, Pari, Kain, Goddard

before LS2: burst mode slow extraction achieved at the SPS. Iterative feedback tuning allowed to reach ~10 ms pulses without introducing losses at septa





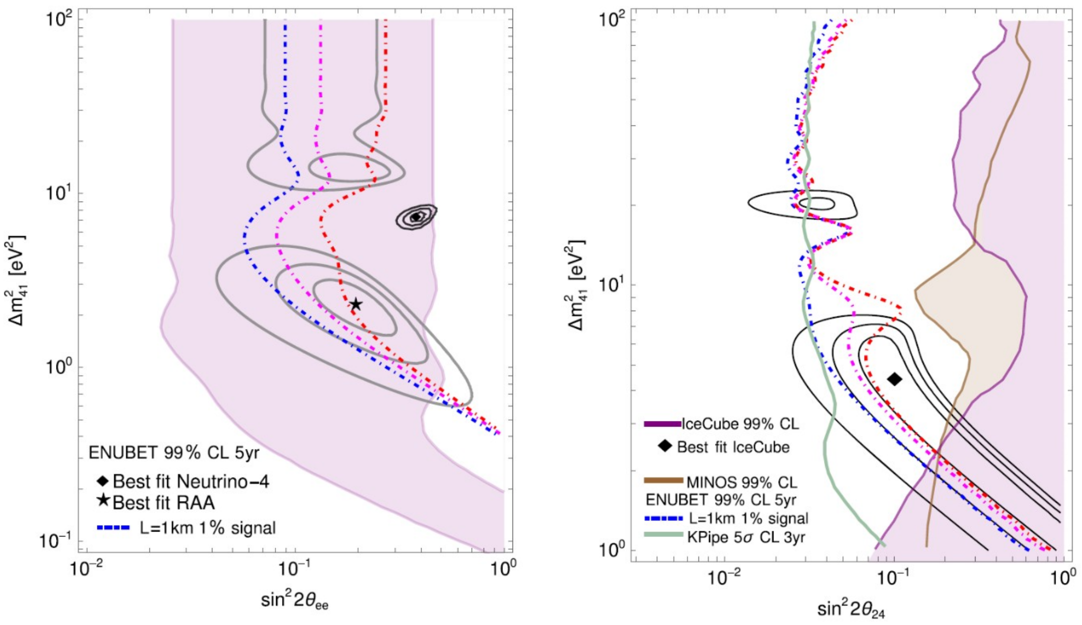


PhD thesis of M. Pari (UniPD + CERN doctoral).
Defended 23/2/21.

BSM

Sterile neutrinos: some results already available

L.A. Delgadillo, P. Huber, PRD 103 (2021) 035018



Work ongoing for studies of **Dark Sector** and **non-standard neutrino interactions** to assess potential of SBL versus Near detectors:

- Pros: energy control of the incoming flux. Outstanding precision on flux and flavor
- Cons: limited statistics

Instrumented proton and hadron dump:

P. S. Bhupal Dev, Doojin Kim, K. Sinha, Yongchao Zhang, Phys. Rev. D 104, 035037 [ALP]
J. Spitz, Phys. Rev. D 89 (2014) 073007 [KDAR]

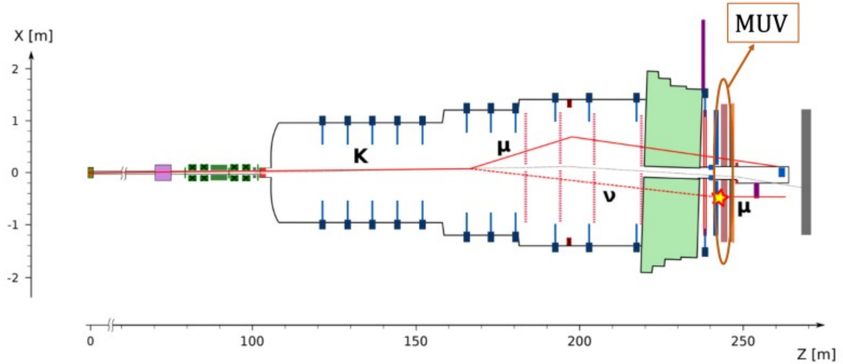
At Nufact 2023

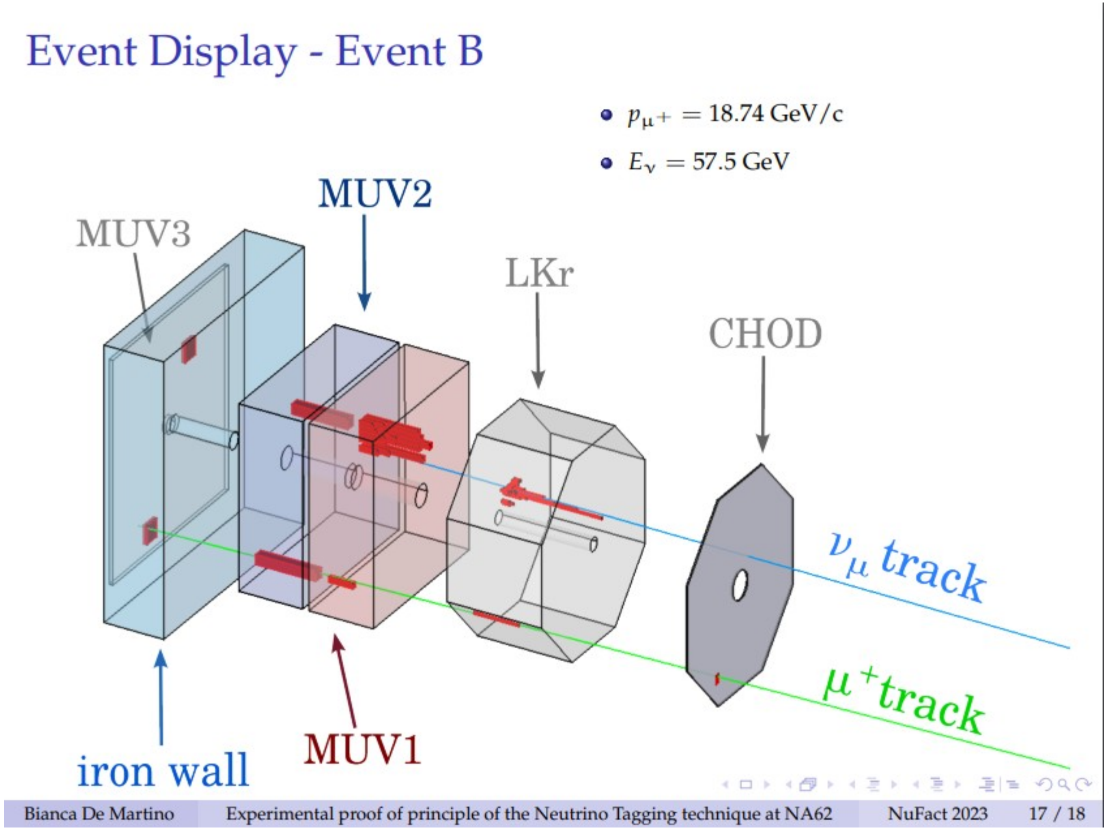
https://indico.cern.ch/event/1216905/contributions/5448754/attachments/2702123/4690877/NuFACT_NuTagging_DeMartino.pdf

Bianca De Martino (NA62)

S/B=5.5, 2 candidates

Muon from K decay + neutrino interaction in Xe calorimeter in an existing experiment!

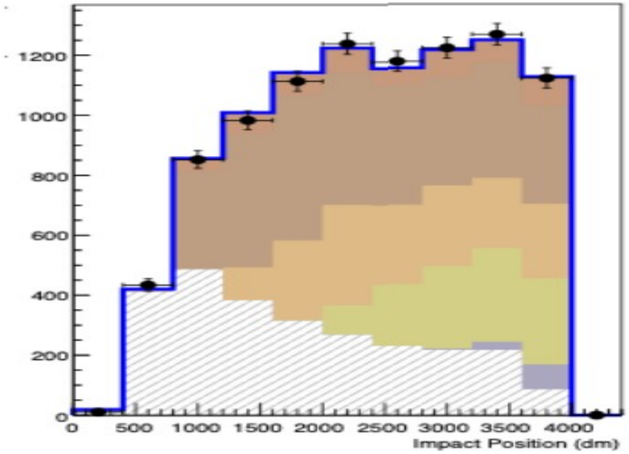




Constraint from lepton rates → flux systematics reduction

- Build S+B model to fit lepton observables
  - 2D distributions in z(lepton) and reconstructed-energy
- include hadro-production (HP), transfer line (TL), detector systematics as nuisance parameters (α, β, ...)

$$L(N|N_{exp}) = P(N \mid N_{exp}) \cdot \prod_{bins} P(N_i \mid PDF_{Ext.}(N_{exp}, \vec{\alpha}, \vec{\beta})_i) \cdot pdf_\alpha(\vec{\alpha} \mid 0,1) \cdot pdf_\beta(\vec{\beta} \mid 0,1)$$



Each histogram component corresponds to a bin in E_ν

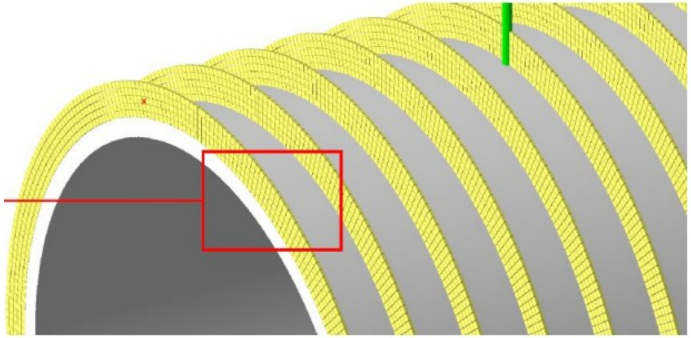
→ Extended Maximum Likelihood fit

Use a parametric model fitted to hadro-production data from **NA56/SPY experiment**:

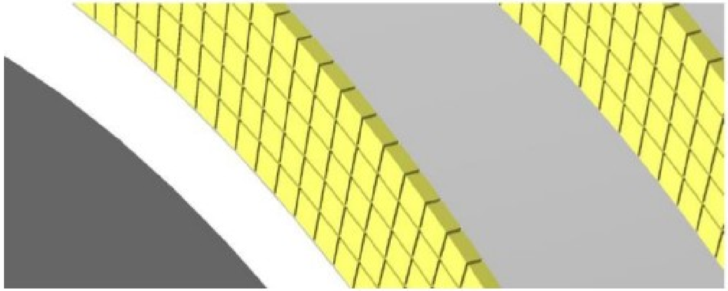
- compute variations ("envelopes") using multi-universe method ("toy exp") for the lepton observables and the flux of neutrinos
- evaluate "post-fit" variance of the expected flux

A low-E_ν monitored beam at ESS ?

- MNB@ESS WP6 of the ESSnuSB
- **E_p = 2 GeV**. No K and π multiplicity very low. Mitigated by a very LARGE intensity.
- Must **monitor muons**. They are not as forward as for ENUBET due to lower boost → cyl. geom. still OK.
- Design based on (PICOSEC) MicroMegas
- The spill structure (2.86 ms) makes **pileup** more delicate than for ENUBET (→ finer granularity 1cm^2)
- Use only a **fraction of the extracted protons**
- → Constrain on the flux **seems feasible**
- with a **sufficient statistics of neutrinos**
- End-to-end studies as for ENUBET being carried on



A. Branca link



	ENUBET@CERN	MNB@ESS	Notes
Proton driver	400 GeV/c	2 GeV	At ESS we exploit pion decays and muon decays in flight [no K]
Secondaries	8.5 GeV/c	About 1-2 GeV	
Proton extraction	2 s	2.86 ms	This is a key item WP6 has assessed in 2023
Decay in flight of muons	Negligible	It is the main source of ν_e at the ESS	

t-tagging for interacting ν

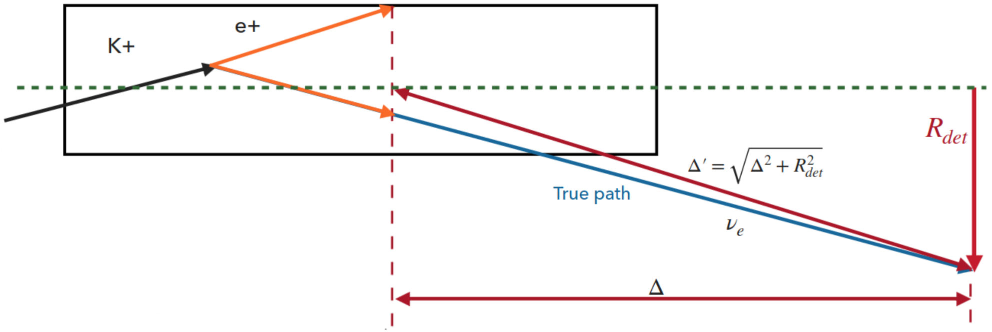
EPJ-C 83, 964, (2023)

The goal of ENUBET (monitored beam): get a sample of associated leptons to constrain the flux. To do this an event-by-event information is needed. Timing has to be "just" good enough to limit the pileup (not too aggressive).

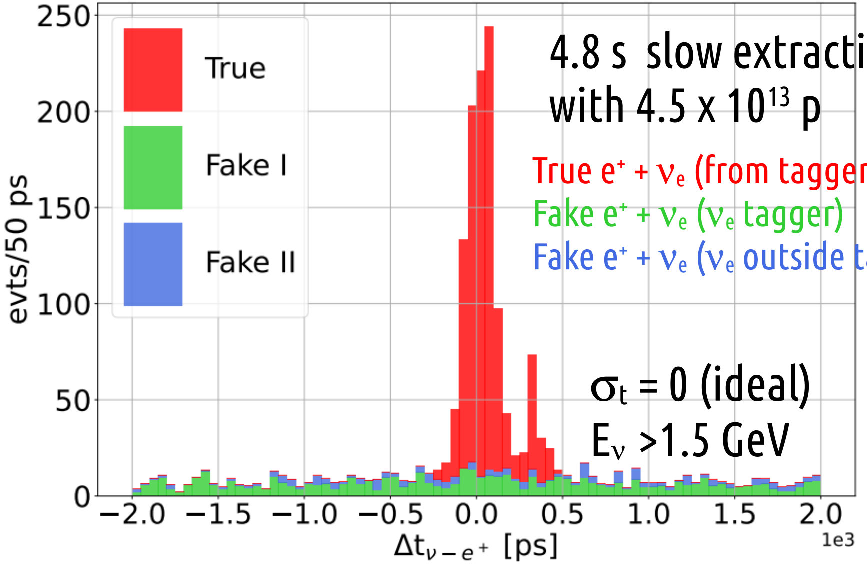
→ Time correlation btw K_{e3} e^+ and ν_e candidates with the full simulation (reconstruction, backgrounds) →

Difference in path between the e^+ and ν_e (decay vertex position is unconstrained → we assume e^+ and ν_e to be collinear) → **"irreducible" time spread**: **$\sigma_{\Delta t} = 74$ ps(*)**

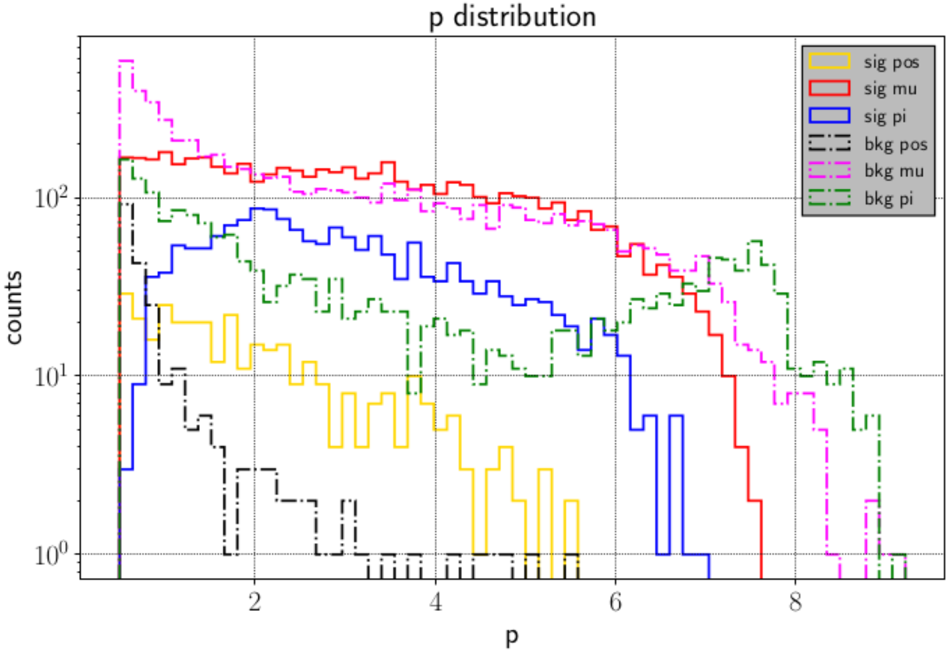
(*) already corrected for the position of the neutrino vertex
(**) could improve decreasing the tagger radius

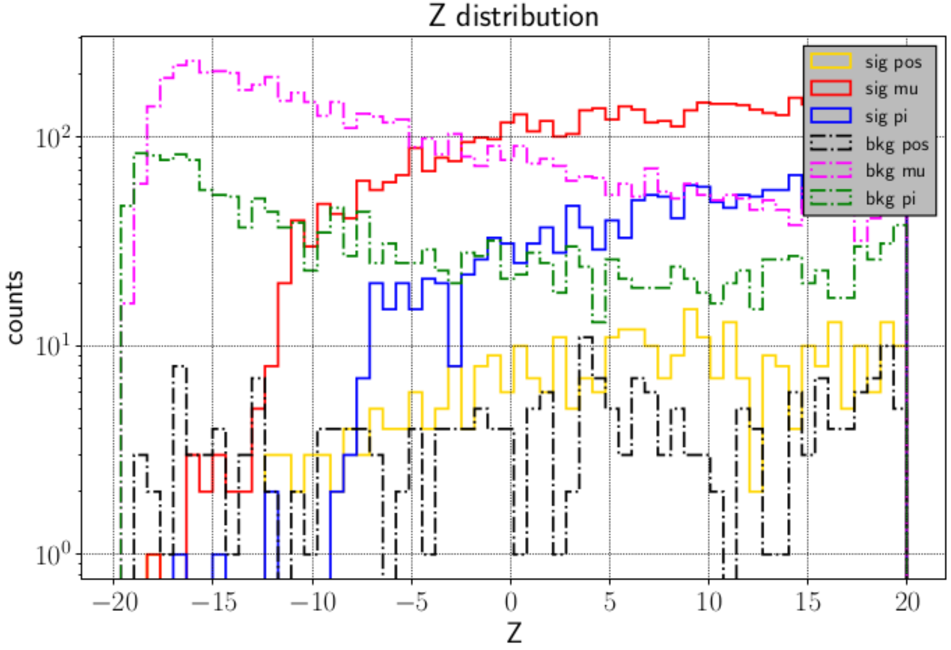


$$\Delta t = t(\nu_e) - [t(e^+) + \Delta'/c]$$

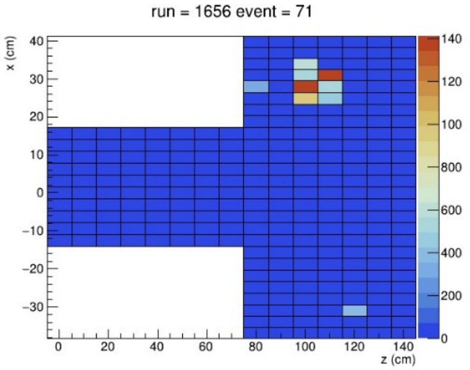


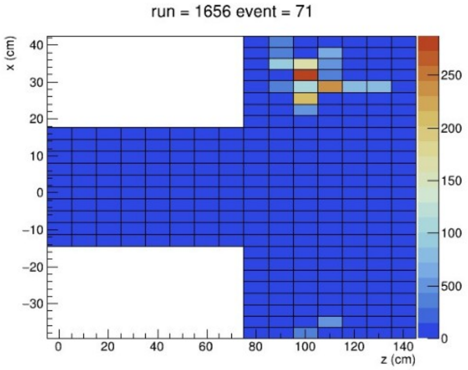
Tagger particle budget at true level

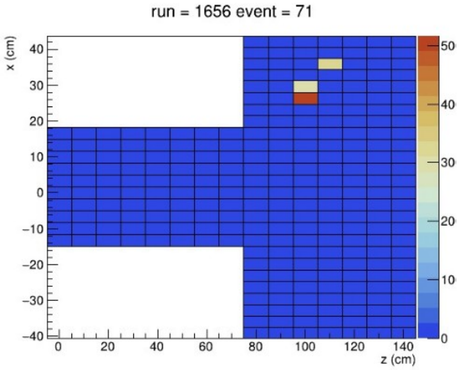


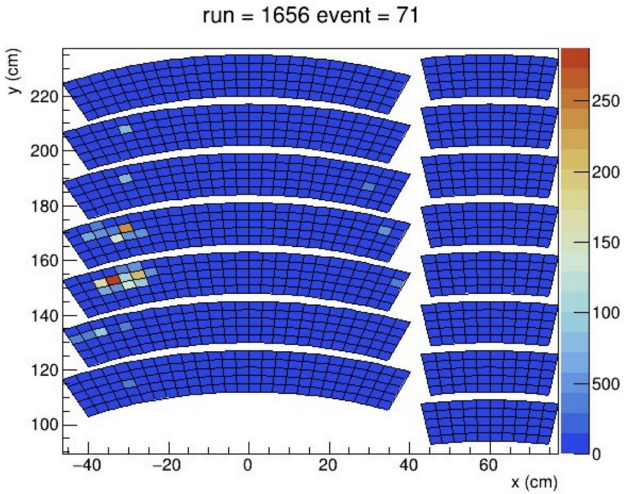


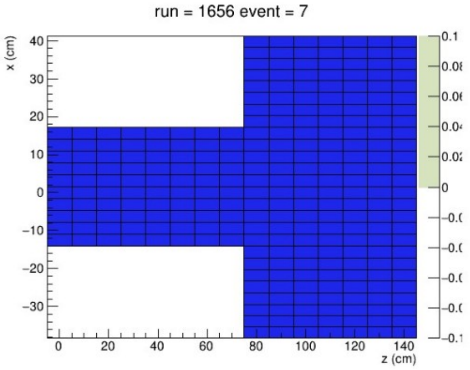
Event display (10 GeV hadrons and muons)

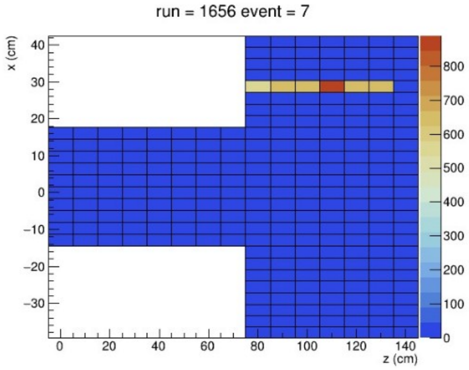


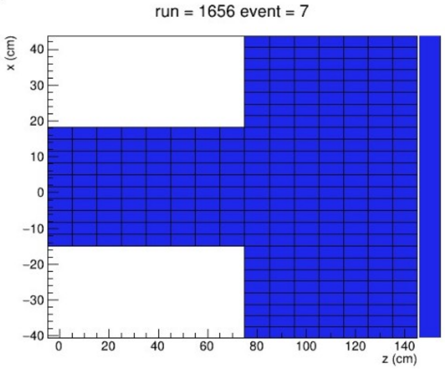


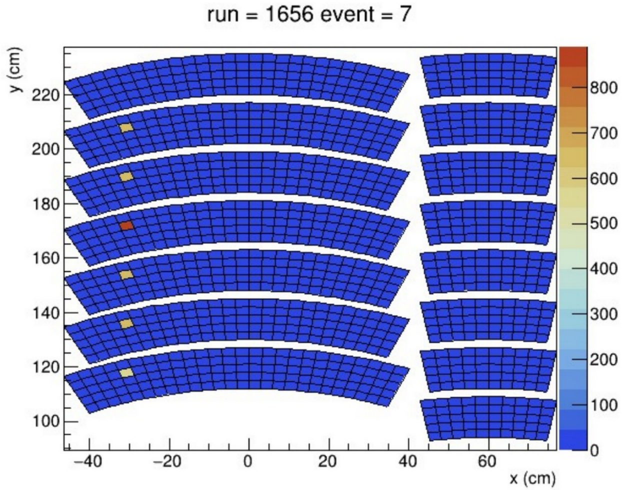










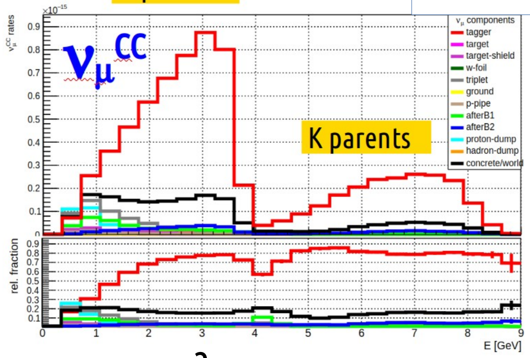


Forward monitoring/tracking = accessing ν_μ at low-E

The key ingredients are:

- 1) extending the acceptance of the lepton monitoring in the forward region where most of muons from pion decays go

8.5 GeV focusing



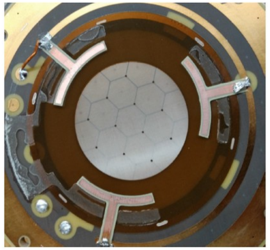
3

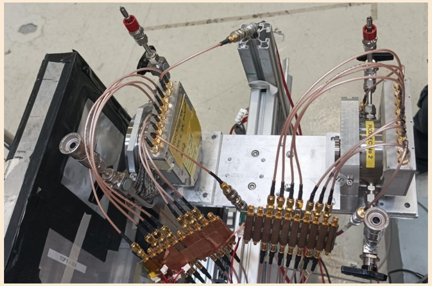
Instrumented hadron dump

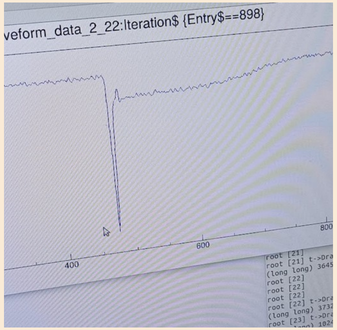
PIMENT (**PI**cosecond **M**icrom**E**gas for e**N**ube**T**), ANR2022-25

Prototype tested with the ENUBET demonstrator **at T9** in Aug. 2024 → few 10s of ps resolutions achieved

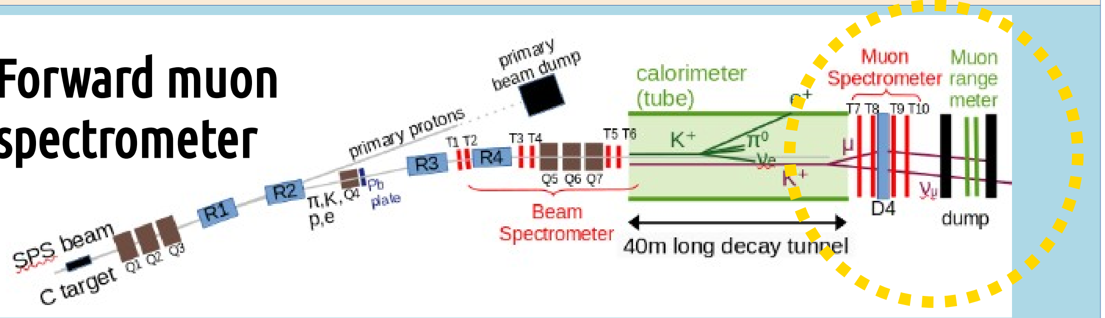
Athens, CNRS, INFN, Thessaloniki, Zagreb **New test October 2025!!**


19 channel anode ⬡ 1 cm



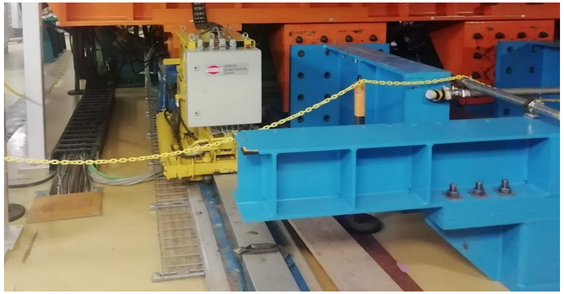


Forward muon spectrometer

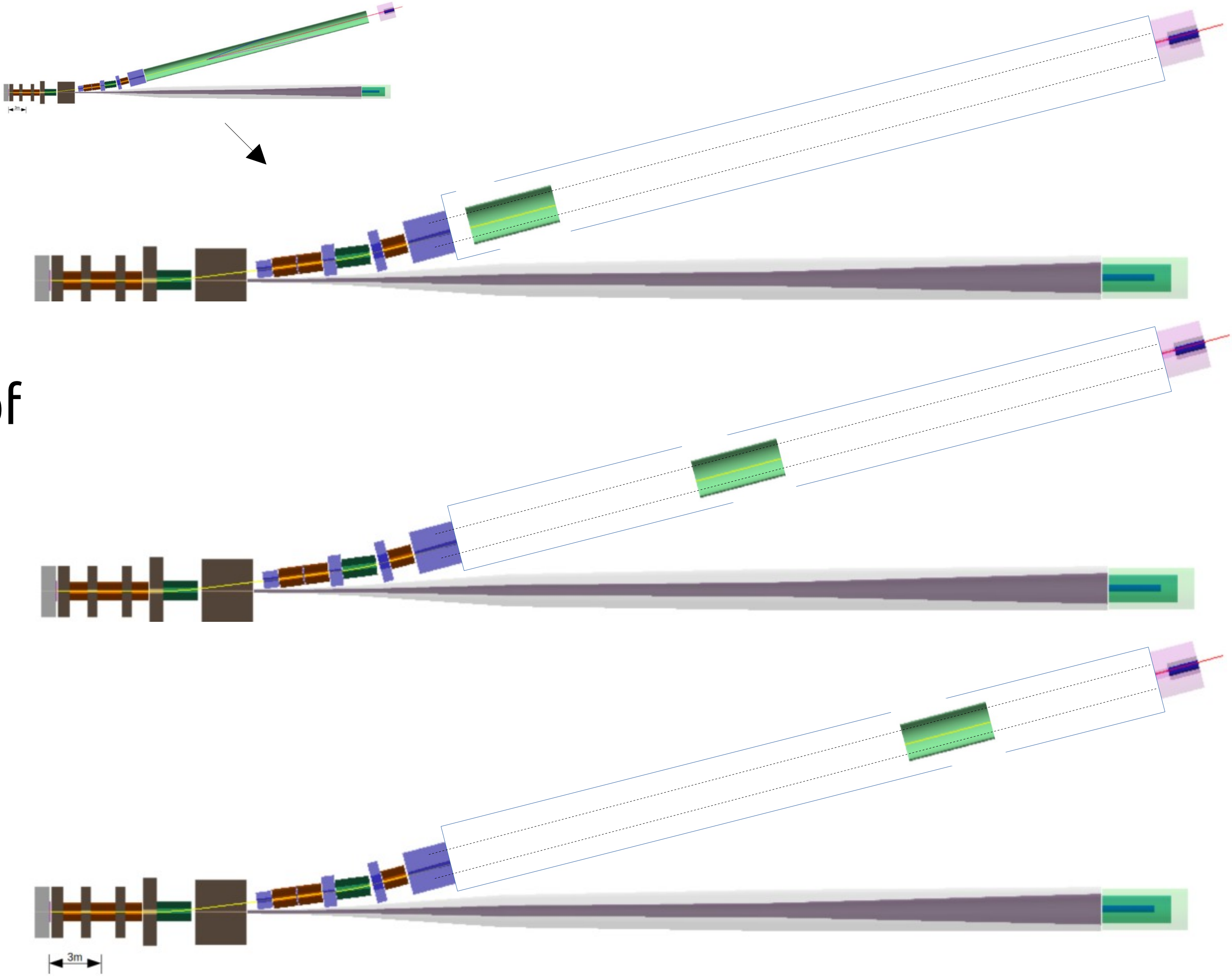


An option

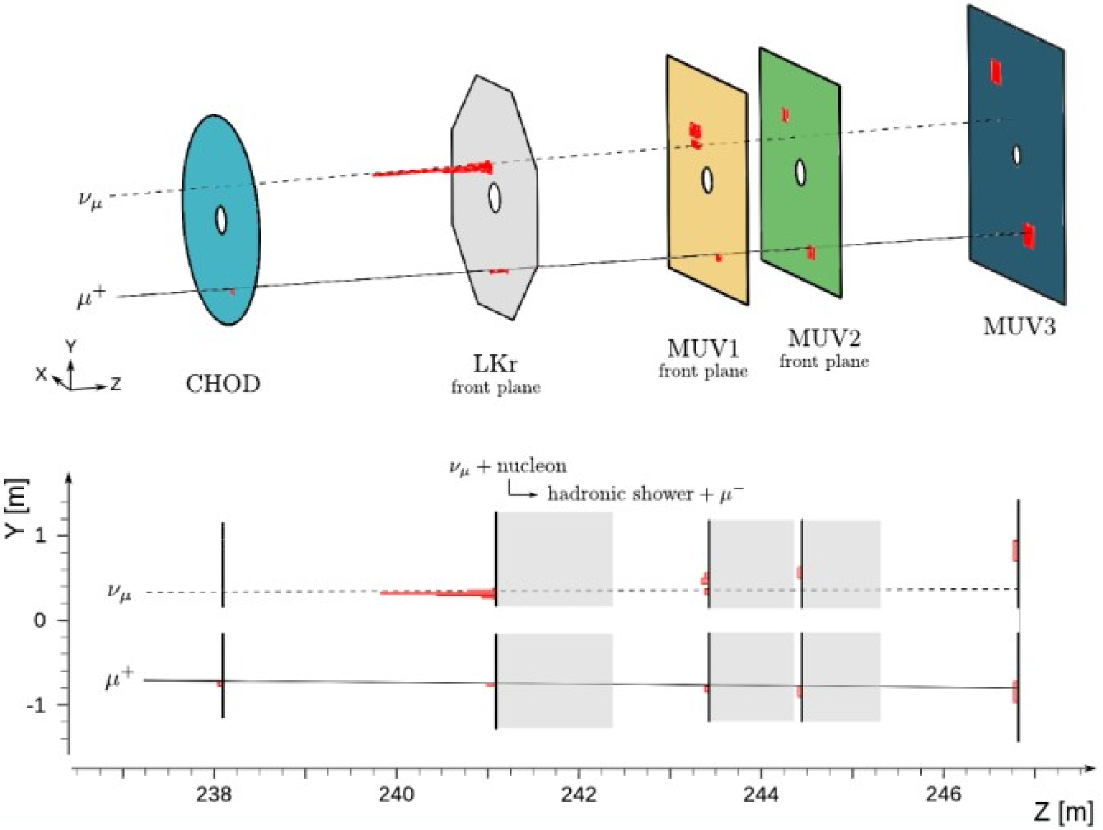
Study the systematics introduced but a partial "instantaneous" coverage of the full decay region



UA1/NOMAD/T2K magnet rail system



NA62 Tagged Neutrino Candidate



Mathieu PERRIN-TERRIN (CPPM)