nuSCOPE

a monitored and tagged neutrino beam

Andrea Falcone on behalf of the nuSCOPE Collaboration

INFN – Sezione di Milano Bicocca

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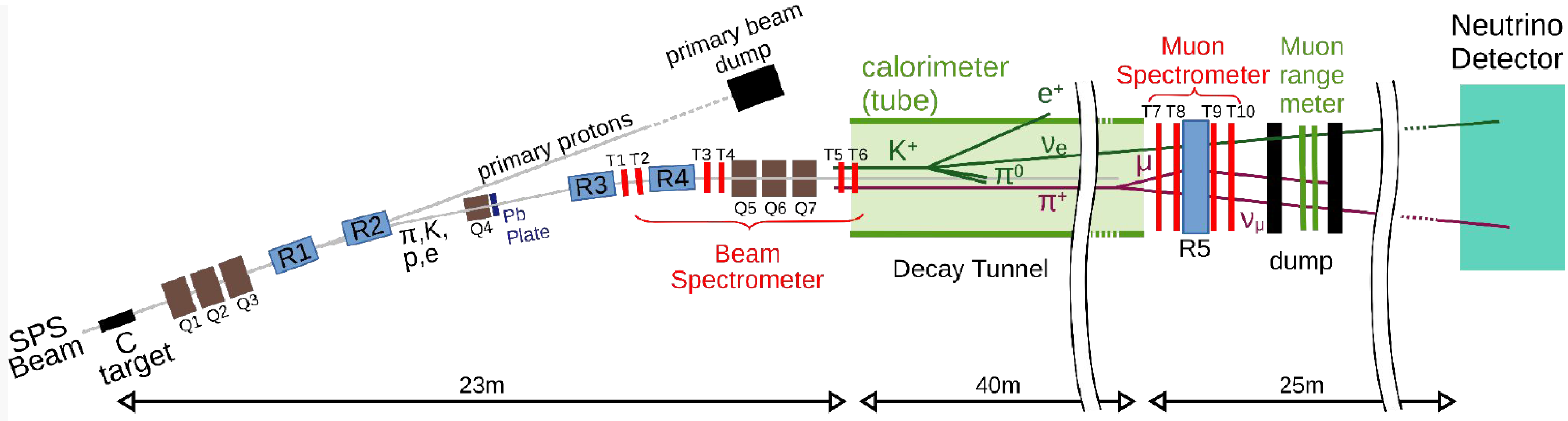
Mumbai, February 2-6, 2026

Istituto Nazionale di Fisica Nucleare

nuSCOPE: ν SPS Complex for Precision Experiments



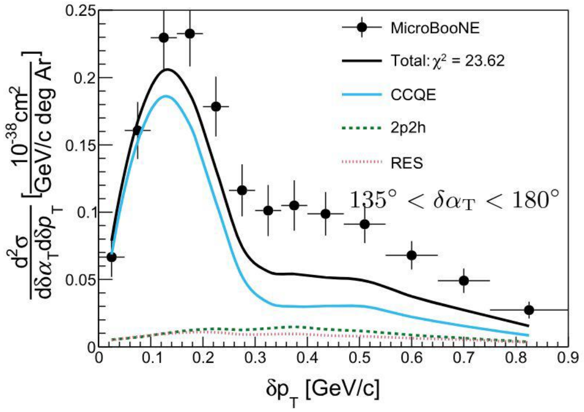
Neutrino cross section

✓ In the past decade, **neutrino cross section** measurements, utilizing conventional neutrino beams, reduced **uncertainties** to a level **O(10%)**.

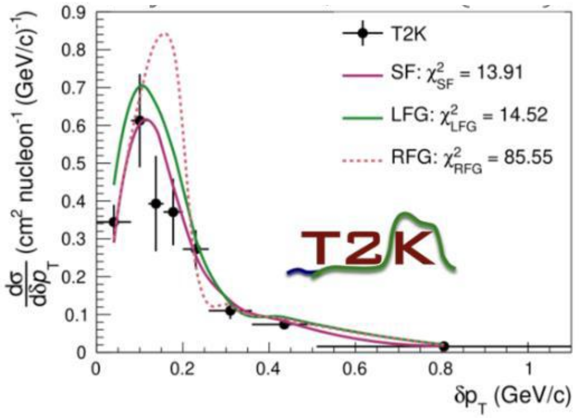
✓ ***ν*–nucleus interactions** in the GeV energy range involve multiple physical processes, including QE scattering, resonance production, and DIS.

✓ **Current theoretical models are unable** to describe all available neutrino scattering measurements.

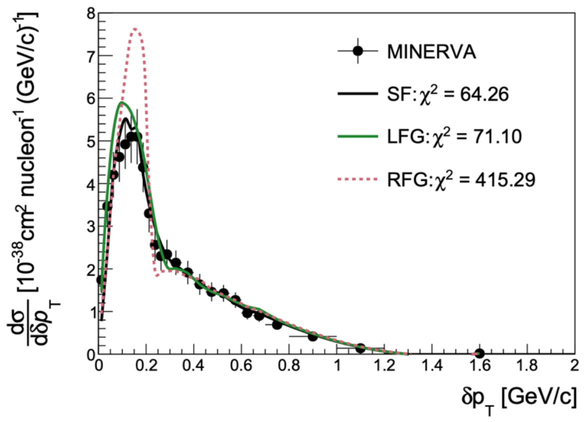
Phys. Rev. D 111, 032009 (2025)



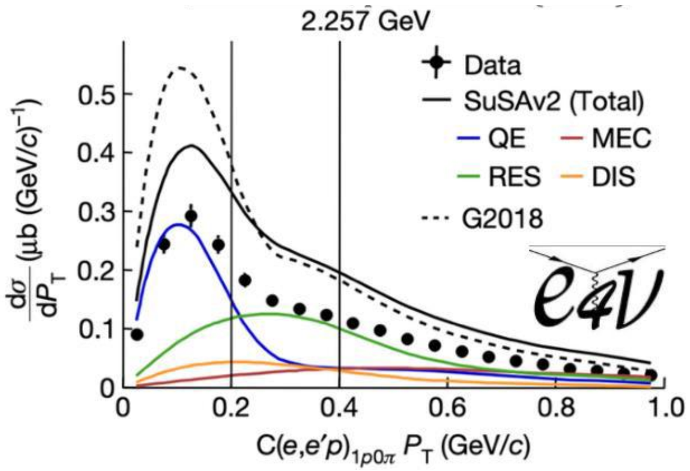
Phys. Rev. D 98, 032003 (2018)



Phys. Rev. Lett 121, 022504 (2018)



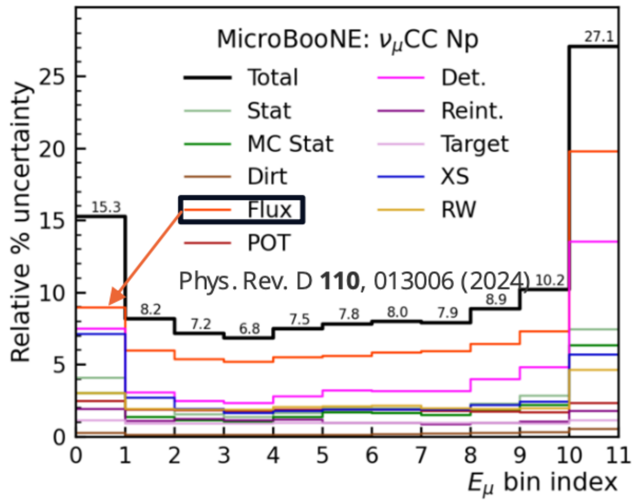
Nature 599, 565-570 (2021)

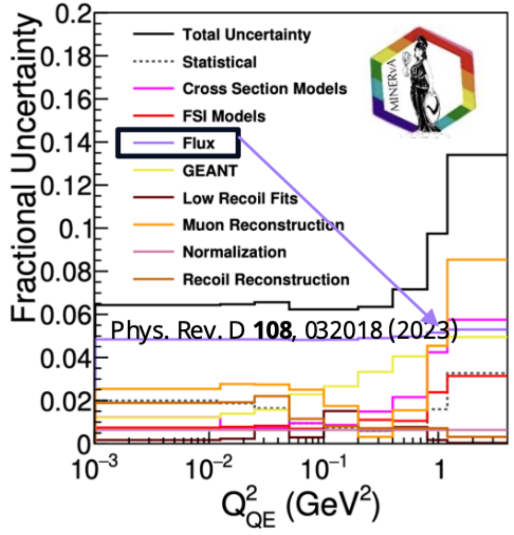


Neutrino cross section

- ✓ Unlike electron–nucleon scattering, **neutrino cross-section experiments lack a priori known E_ν**. 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.





Long baseline experiments

- ✓ Accelerator-based long baseline (LBL) neutrino experiments aim to precisely measure **neutrino oscillations** and probe **CP violation in the lepton sector**.

	T2K	NOvA
ν_μ events	318	384
ν_e events	94	181
SYST. uncertainty	~ 4%	~ 3.5%

Neutrino 2024 Talks

- ✓ The current generation of LBL ν experiments is **limited by statistics**.

Long baseline experiments

- ✓ Accelerator-based long baseline (LBL) neutrino experiments aim to precisely measure **neutrino oscillations** and probe **CP violation in the lepton sector**.

	T2K	NOvA	Hyper-K	DUNE
ν_μ events	318	384	~ 10000	~ 7000
ν_e events	94	181	~ 2000	~ 1500
SYST. uncertainty	~ 4%	~ 3.5%	~ 1%	~ 1%

Neutrino 2024 Talks   arXiv: 1805.04163   arXiv: 2002.03005

- ✓ The next generation will aim to significantly increase the statistics… rendering **systematic errors dominant**.

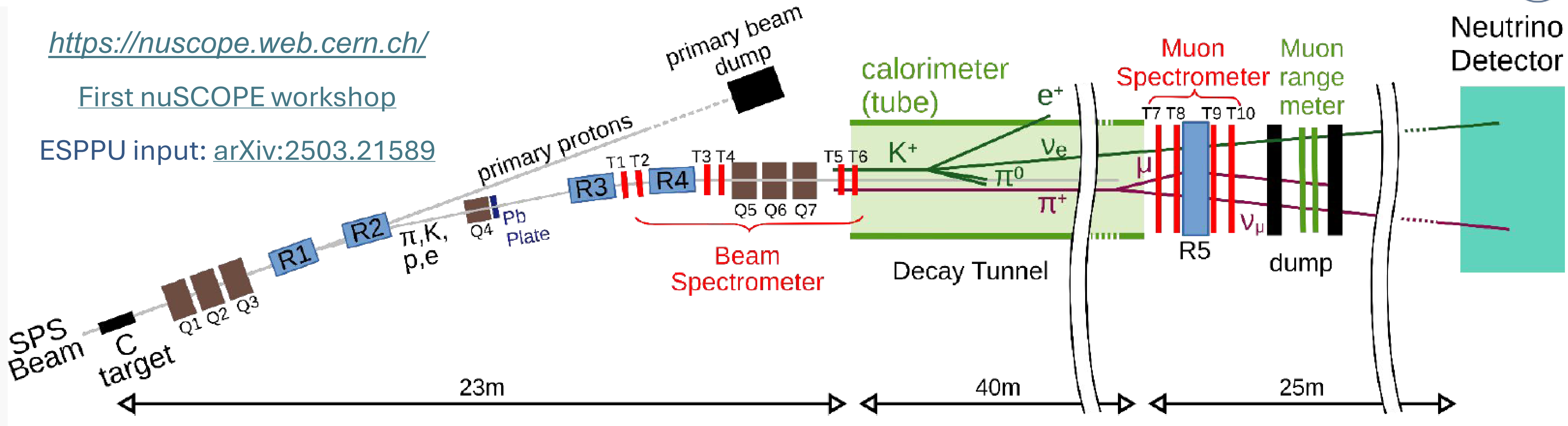
- ✓ Achieving **percent-level precision in neutrino cross sections** at the GeV scale is urgent if we want to fully exploit the physics potential of DUNE and Hyper-Kamiokande. New cross-section experiments have a compelling physics case-equivalent to **roughly doubling their mass**.

nuSCOPE :a monitored and tagged beamline

https://nuscope.web.cern.ch/

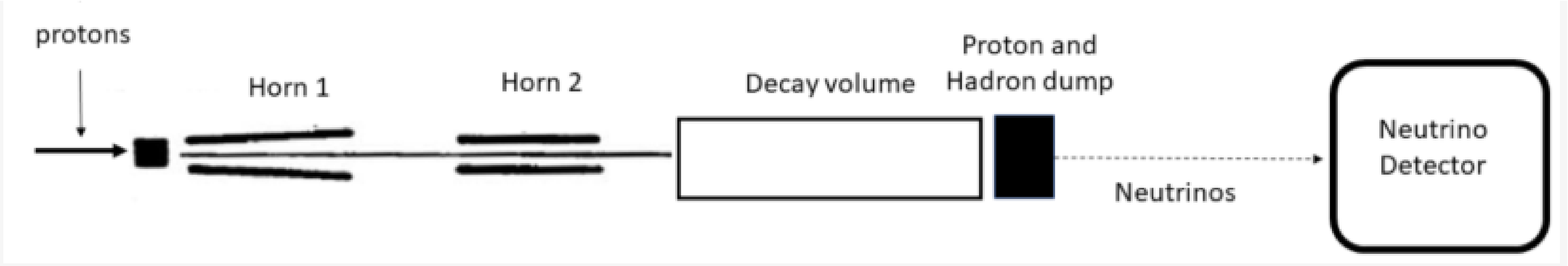
First nuSCOPE workshop

ESPPU input: arXiv:2503.21589



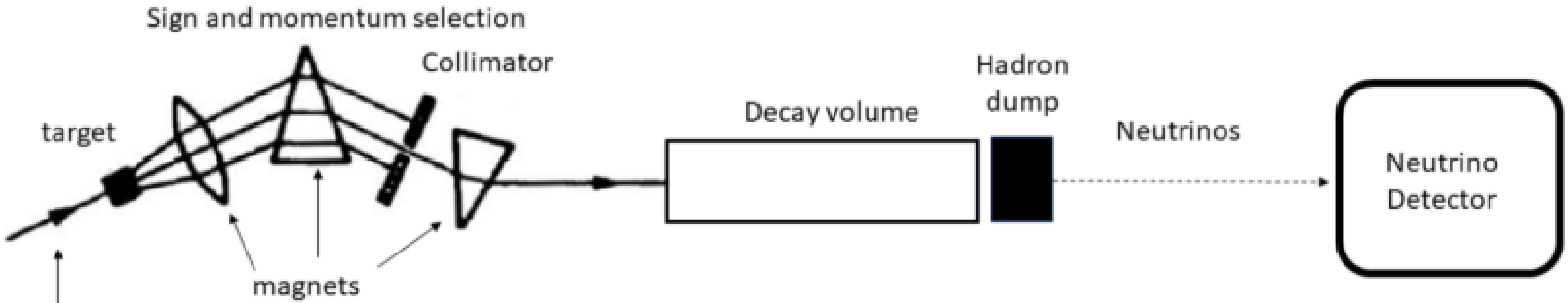
- nuSCOPE is a new facility that **overcomes the limitations of conventional neutrino beams** for precision cross-section measurements, formed from the merger of **ENUBET** and **NuTAG**.
- Neutrinos from **statically focused** pions and kaons are **monitored** by an **instrumented decay tunnel**, **tagged** by **silicon pixel detectors** along the beam axis, observed by a downstream detector.

Present neutrino beam



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

nuSCOPE: hornless neutrino beam



protons over a long extraction (2-10 s).

horn-less static focusing system based on dipole/quadrupoles.

instrumented decay tunnel.

high granularity, fast, neutrino detectors.

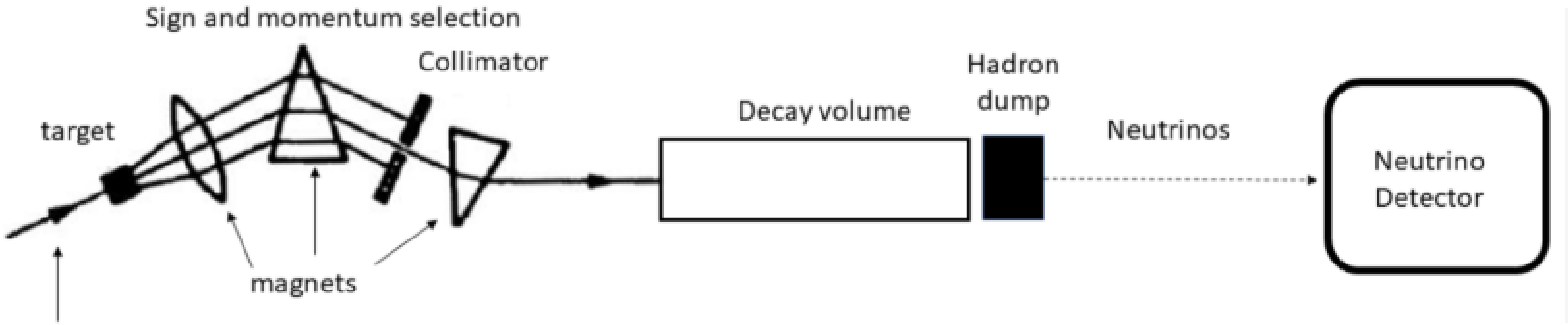
Select secondaries in a **narrow energy band**.

Track pions at single particle level using fast silicon tracker (**tagging**).

Measure charged leptons associated with the neutrino decay (**monitoring** of flux).

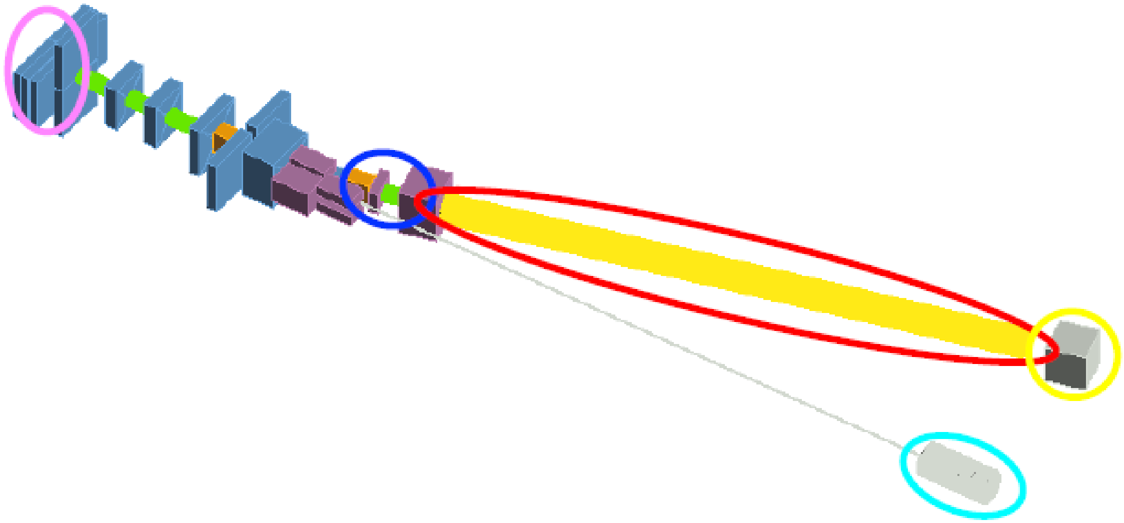
Reconstruction of interaction vertex (NBOA) and final state particles. Time correlation with parent pion and daughter muon (**tagging**).

nuSCOPE: hornless neutrino beam



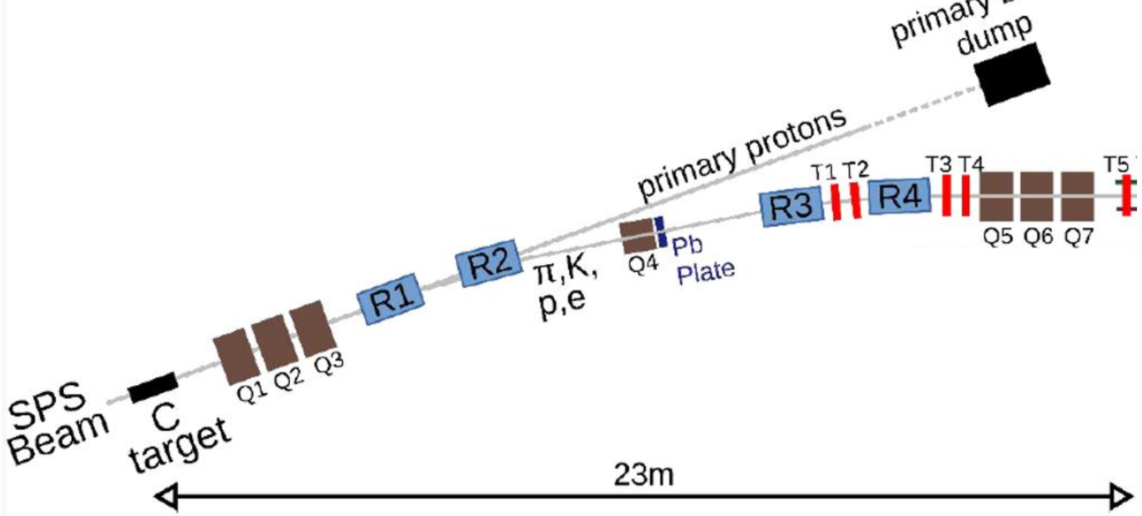
In 2020, the ENUBET collaboration devised an **end-to-end simulation of a horn-less neutrino beam** that provides enough statistics for percent level cross-section measurements.

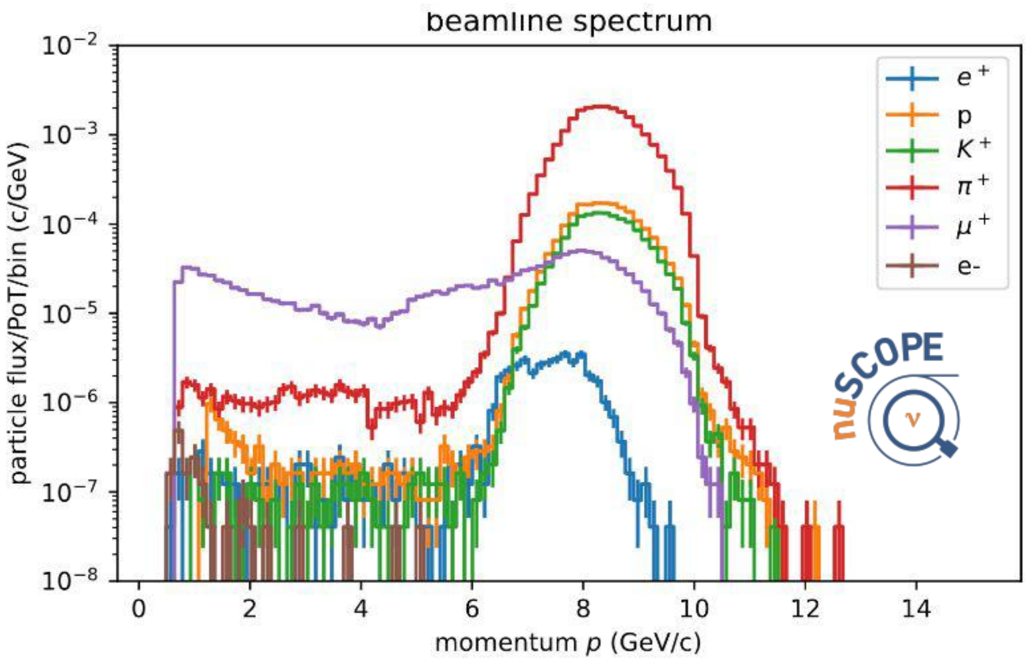
F. Acerbi et al EPJC 83 (2023) 964



Static focusing

- ✓ **4.8s to 9.6s** continuous spill;
- ✓ focusing utilizing two quadrupole **triplets** and four **dipole** magnets (bending magnet strength 1.8 T);
- ✓ optimized for 8 GeV/c meson momentum;
- ✓ achieve the original physics goals **with a number of protons compatible with the CERN fixed target program**, including SHiP.





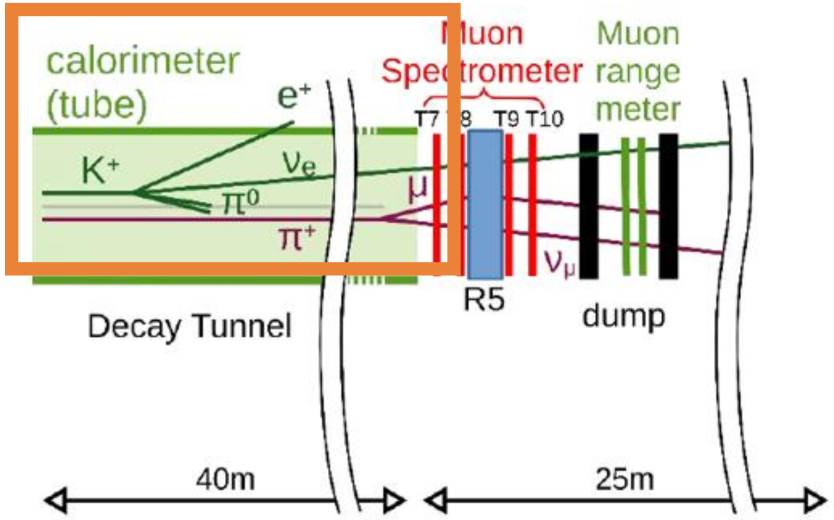
Parameter	Value
Primary proton momentum (GeV/c)	400
Beamline meson momentum (GeV/c)	max. 8.5
Proton-beam spill duration	slow (4.8 s to 9.6 s)
Spill intensity (protons/spill)	1×10^{13}
Event rate (THz)	1 – 2
Instantaneous power on target (W)	170 – 340
(K^+, π^+) yield per proton	$(1.3 \times 10^{-3},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

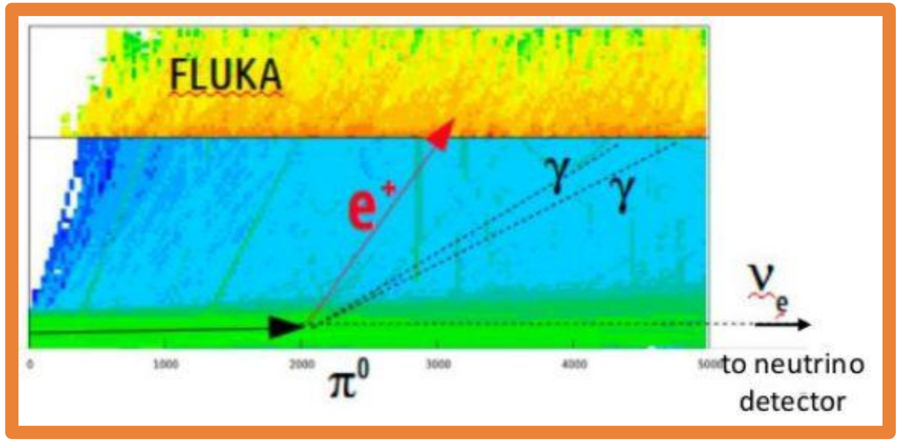
Monitoring

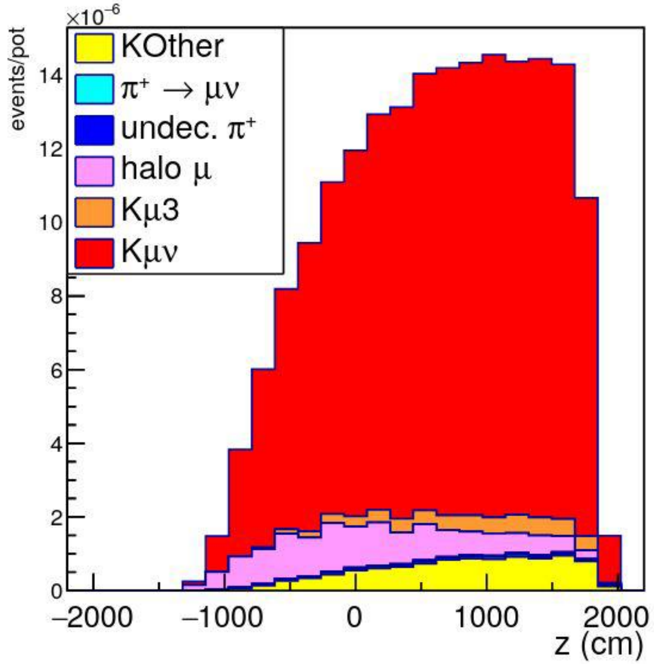
Neutrinos are **monitored** detecting the associated lepton.

In the decay tunnel via a **segmented iron-scintillator calorimeter**:

- ✓ **high angle leptons** impact the **instrumented tunnel walls**;
- ✓ particles are discriminated with **event topology**.







Monitoring

Shielding

- ✓ 30 cm of borated polyethylene;
- ✓ **SiPMs installed on top** -> factor 18 reduction in neutron fluence.

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

- ✓ **sampling calorimeter**: sandwich of plastic scintillators and iron absorbers;
- ✓ **three radial layers** of LCM / longitudinal segmentation;
- ✓ LCM: Lateral Compact Module - 5 x Iron+Scint - 3x3x10 cm^3 - 4.3 X_0 ;
- ✓ WLS-fibers/SiPMs for light collection/readout.

Photon-Veto allows π^0 rejection and timing:

- ✓ **plastic scintillator tiles** arranged in doublets forming inner rings;
- ✓ time resolution of ~400 ps.

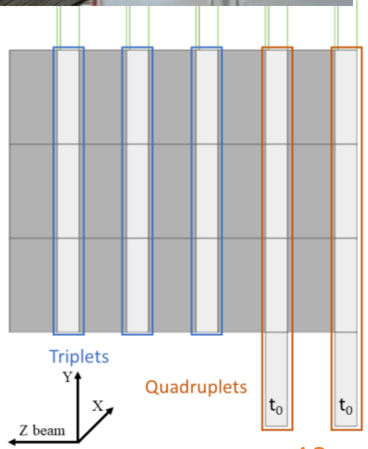
PID based on the **pattern of energy deposit** in the calorimeter module

e^+ (signal) topology

π^0 (background) topology

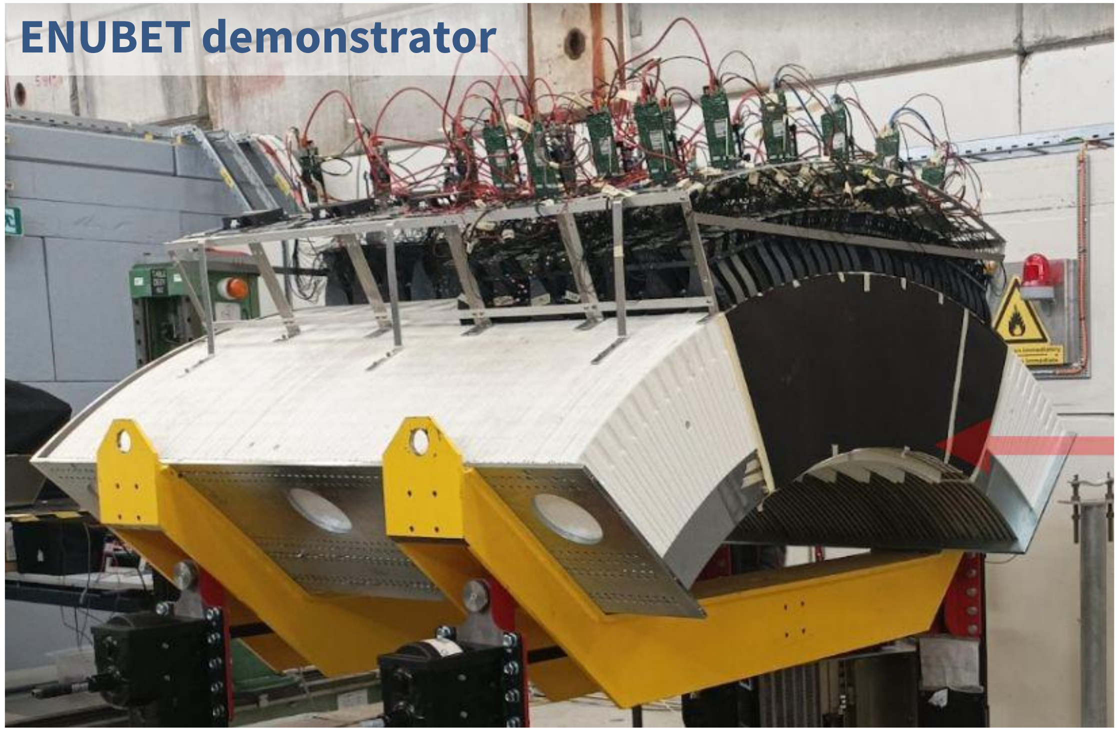
π^+ (background) topology

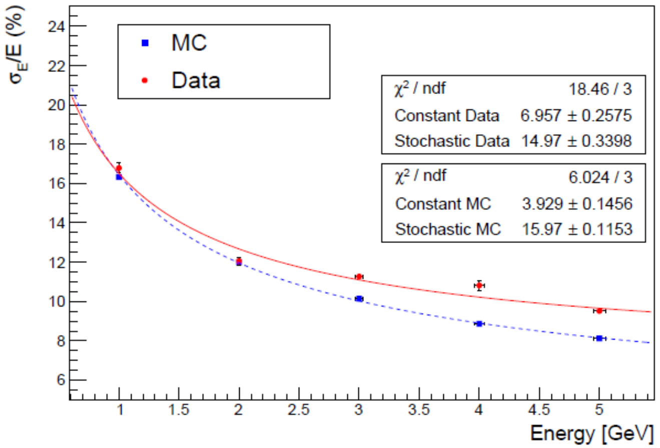
μ^+(signal/bkg) topology



Monitoring

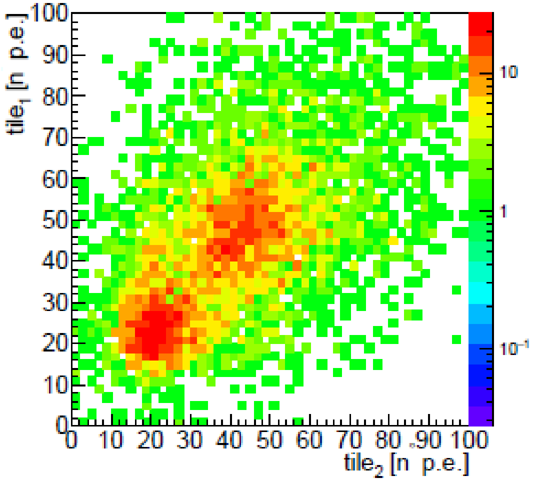
- ✓ The technology has been demonstrated by the **ENUBET Collaboration**.
- ✓ Prototype tested at the CERN T9.

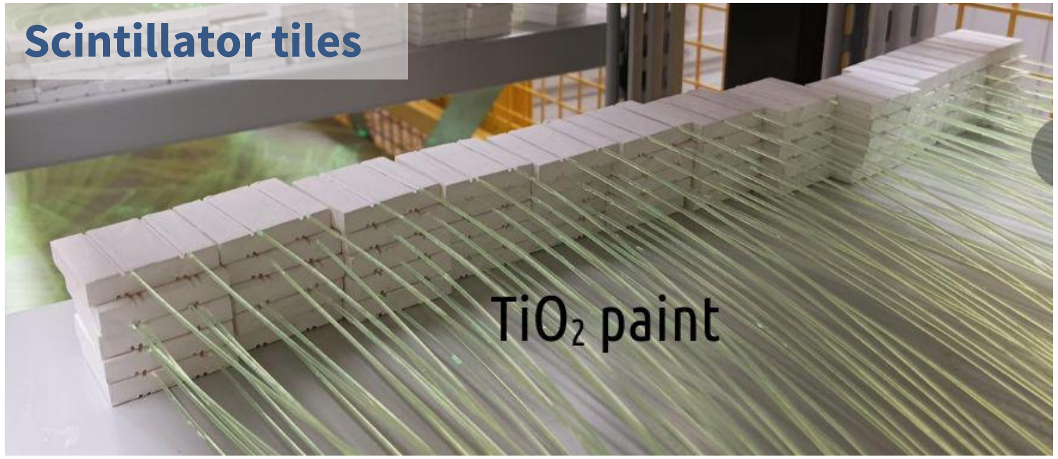




Energy resolution

γ-veto performances



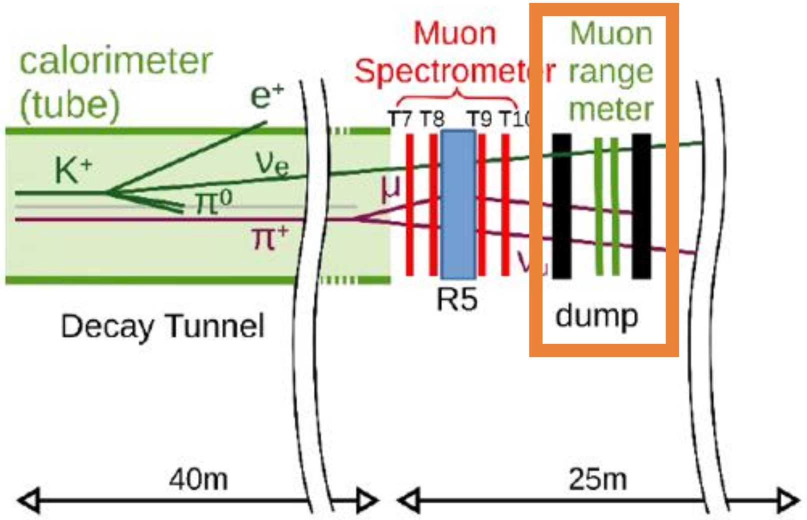


Monitoring

Neutrinos are **monitored** detecting the associated lepton.

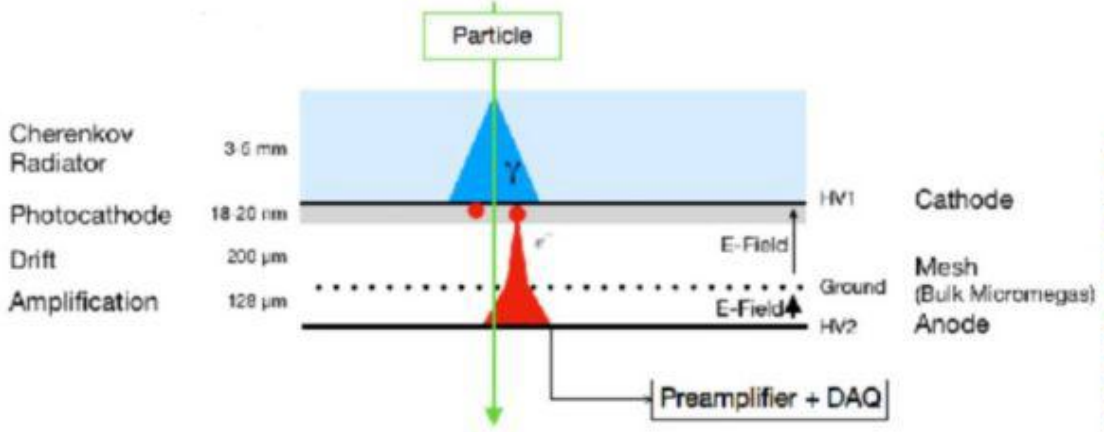
At the tunnel end via a **muon range meter**:

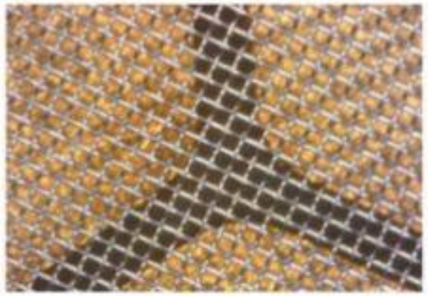
- ✓ **lower angle** leptons are detected at **tunnel end**;
- ✓ along beam axis => **high rate**.



The forward monitoring will be provided by **an instrumented hadron dump**. A possible solution is to employ **picosecond micromegas** (PIMENT project):

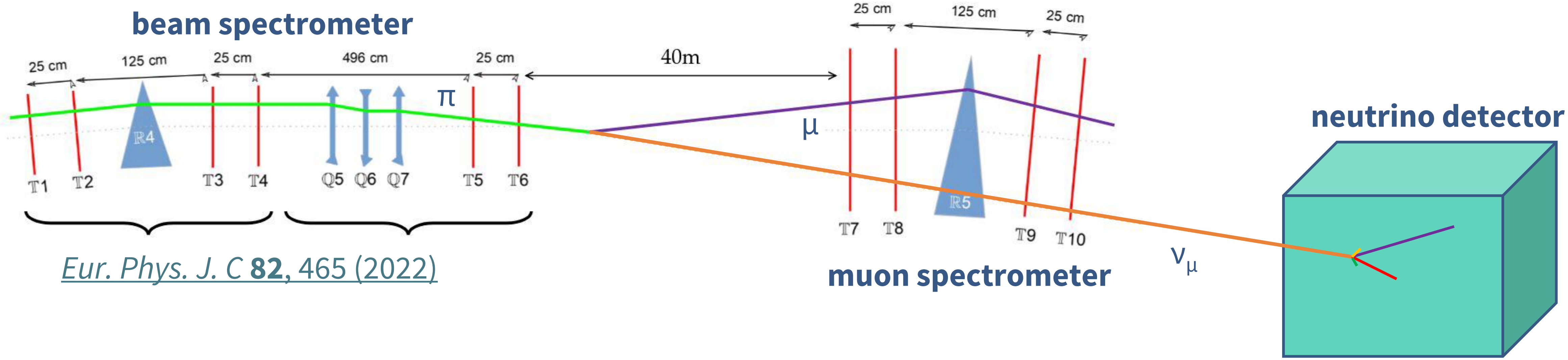
- ✓ R&D in progress…



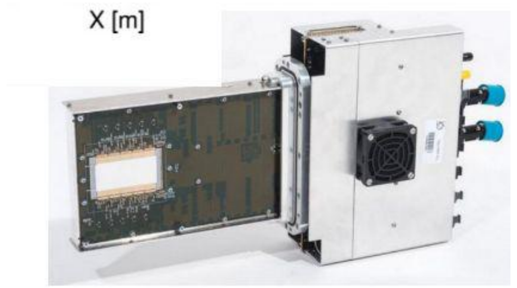


Tagging

- ✓ Both the **parent π** meson and **associated μ** are **tracked**;
- ✓ the **neutrino track** can be precisely reconstructed.



Eur. Phys. J. C **82**, 465 (2022)

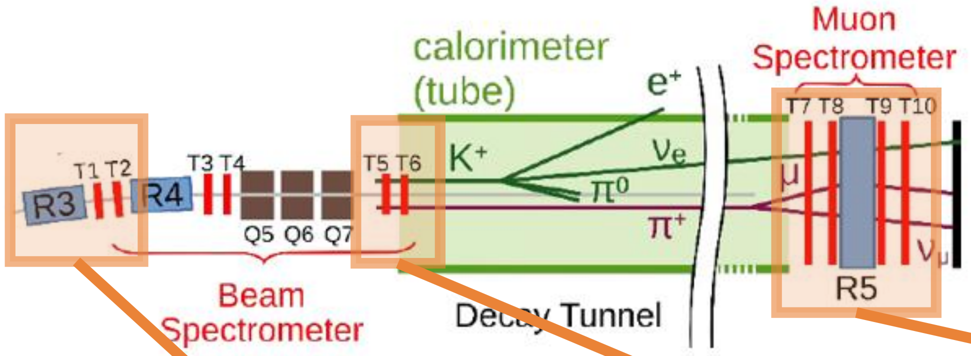


- ✓ Trackers are **silicon pixel detectors**, technology pioneered by **NA62**.
- ✓ **First ever tagged neutrino** PLB 863 (2025) 139345.

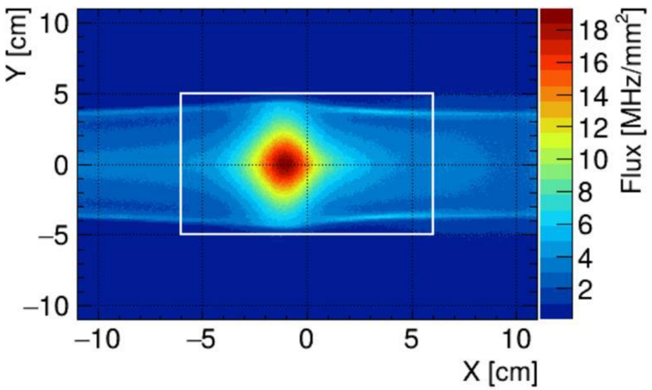
Tagging

✓ Challenging **particle rate**.

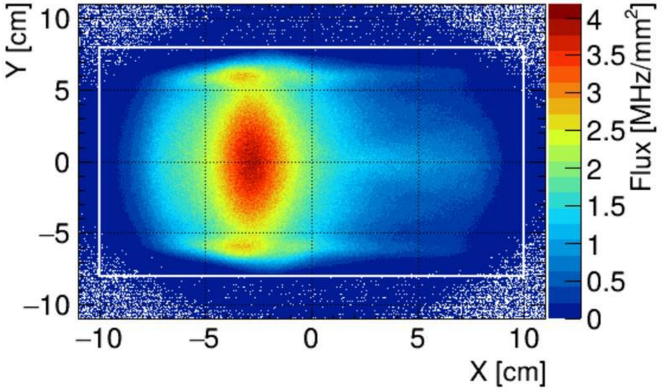
Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1\mathrm{MeVn_{eq}/cm^2}$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [$\mathrm{MHz/mm^2}$]	20	0.6	10 – 100	2
Time Resolution [ps]	< 40	< 100	< 50	< 130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



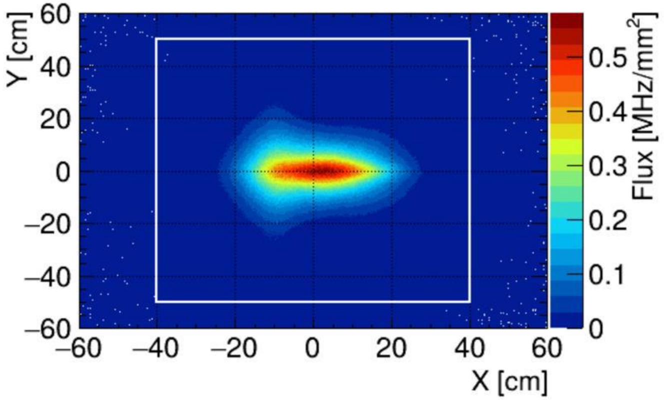
Peak rate ~ 20 MHz/mm²



Peak rate ~ 4 MHz/mm²

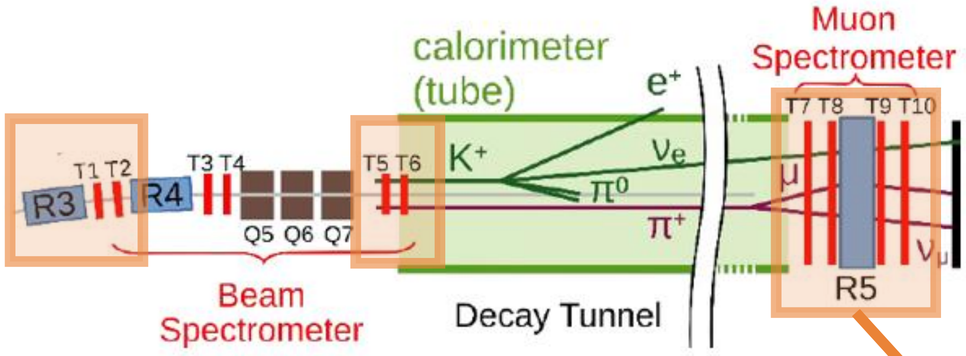


Peak rate ~ 0.6 MHz/mm²



Tagging

✓ Challenging **particle rate**.



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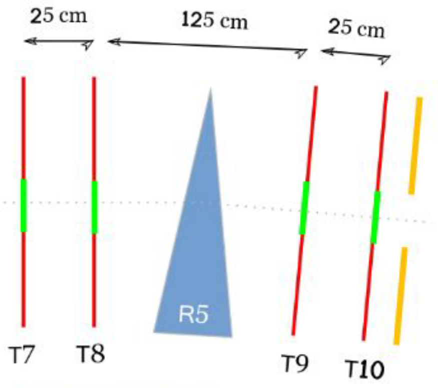
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel Pitch [μm]	300		45	300
Material Budget [X_0]	$< 1\%$		0.8%	0.5%

Specs are within reach but **size (~1m²) is challenging**

Hybrid solution:

- **inner region: pixel detectors**
  GTK or MAPS (cheaper, thinner)
- **outer region**:
  micromegas + **downstrean timing layer (picosec)**

Pixel ($$$)
✓ material
✓ space reso
✓ time reso



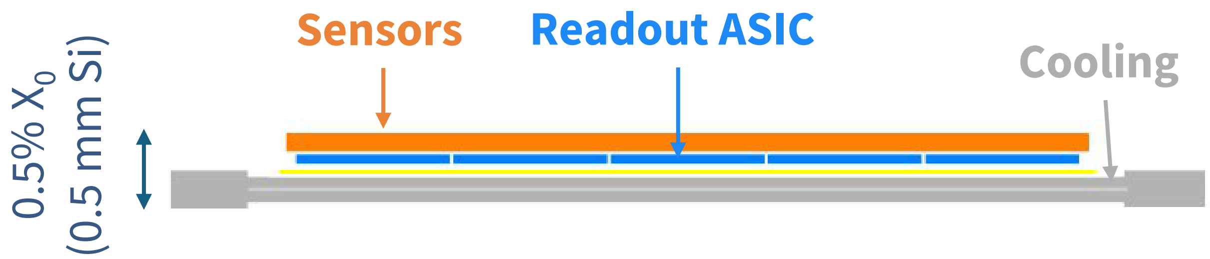
Micromegas ($)
✓ material
✓ space reso
✗ time reso

PICOSEC ($)
✗ material
✗ space reso
✓ time reso

13/10/2025 nuSCOPE Workshop | Neutrino Tagging | Mathieu PERRIN-TERRIN 15

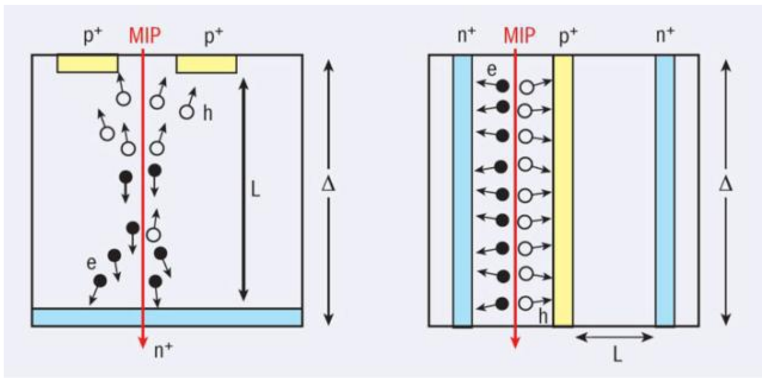
Tagging

- ✓ High intensity pixel detectors architecture.



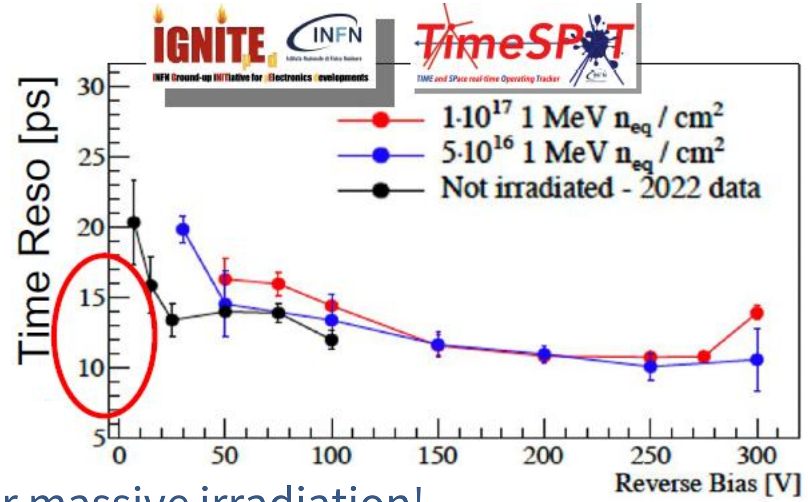
- ✓ **New sensors**: planar -> trenched 3D (FBK through INFN TimeSpot).

Planar 3D



- ✓ **New ASIC** - Three developments ongoing, all with 28nm CMOS technology:
  - -Timespot and IGNITE by INFN;
  - -PicoPix by CERN, Nikhef.

- ✓ **Powerful cooling** (>1W/cm^2) using silicon micro-channel cooling plates pioneered by NA62/LHCb.

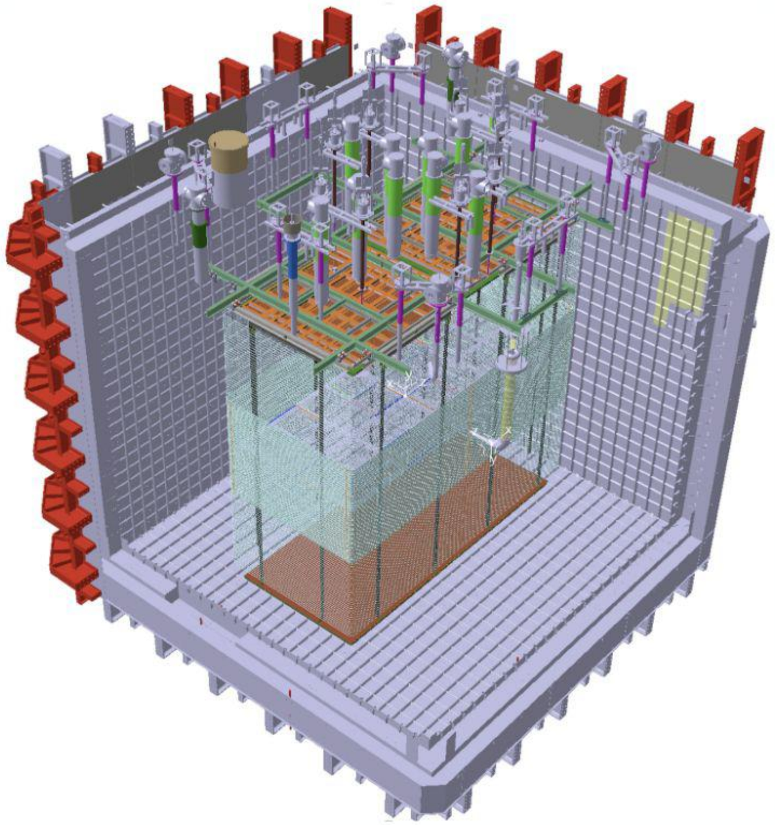


20 ps reso after massive irradiation!

Neutrino detector

Main requirements: **few cm level vertex resolution** and **sub ns time resolution**.

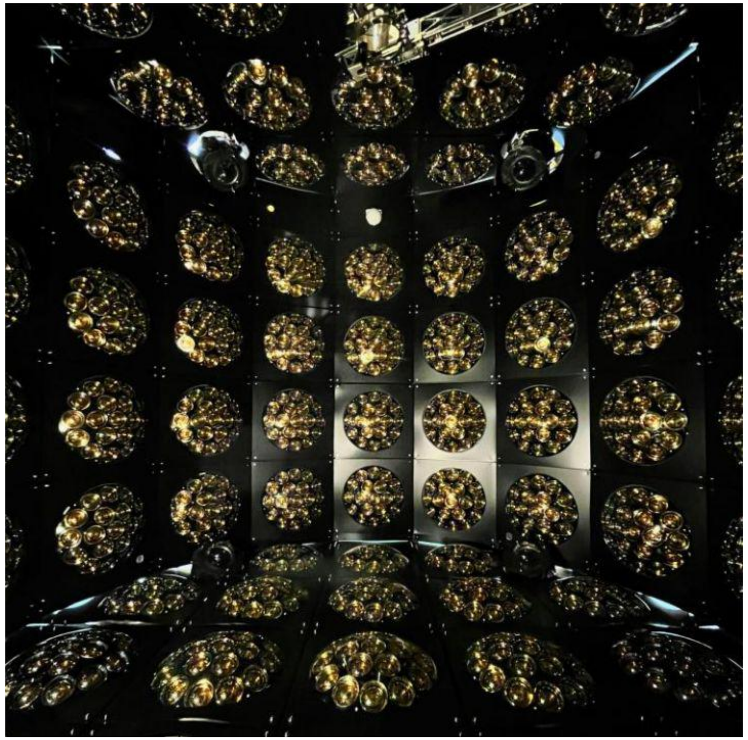
LAr TPC
ProtoDUNE-VD Run III (2027-2028)



optimal **spatial** resolution

⟵ ⟶

optimal **temporal** resolution



WCTE
Water Cheremkov/scintillator

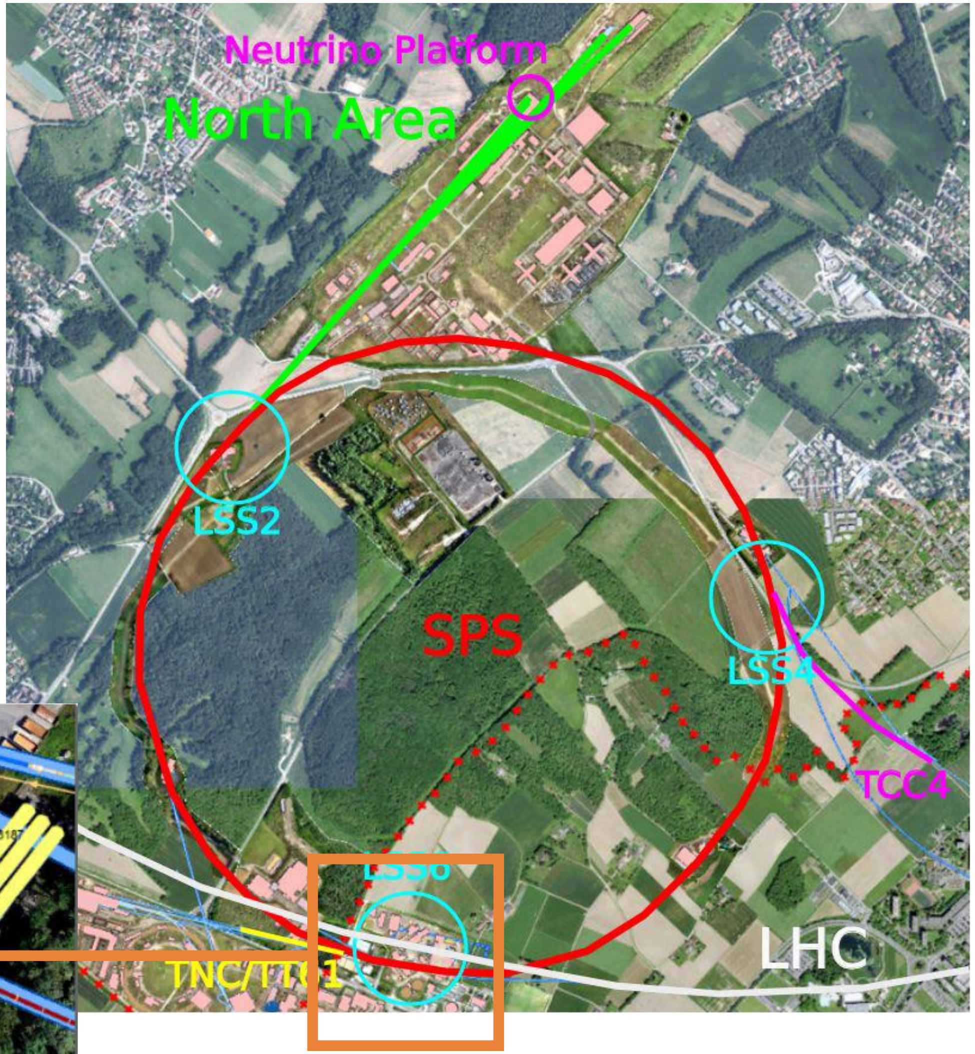
Focus on **improving light coverage** to reach **sub-ns resolution** on whole event and muon containment.

Focus on improving **energy resolution**, **PID** for final state particle (**hadrons**) and hermeticity.

Implementation at CERN

SPS 400 GeV/c protons: number of protons compatible with the CERN fixed target program, including SHiP.

The most studied option is **LSS6 (HiRadMat)**:
- ✓ slow extraction can be implemented;
- ✓ deep underground;
- ✓ excavation needed.



N. Charitonidis at nuSCOPE workshop

Technical readiness

Most of the facilities **rely on validated technologies**, some areas **require full confirmation**.

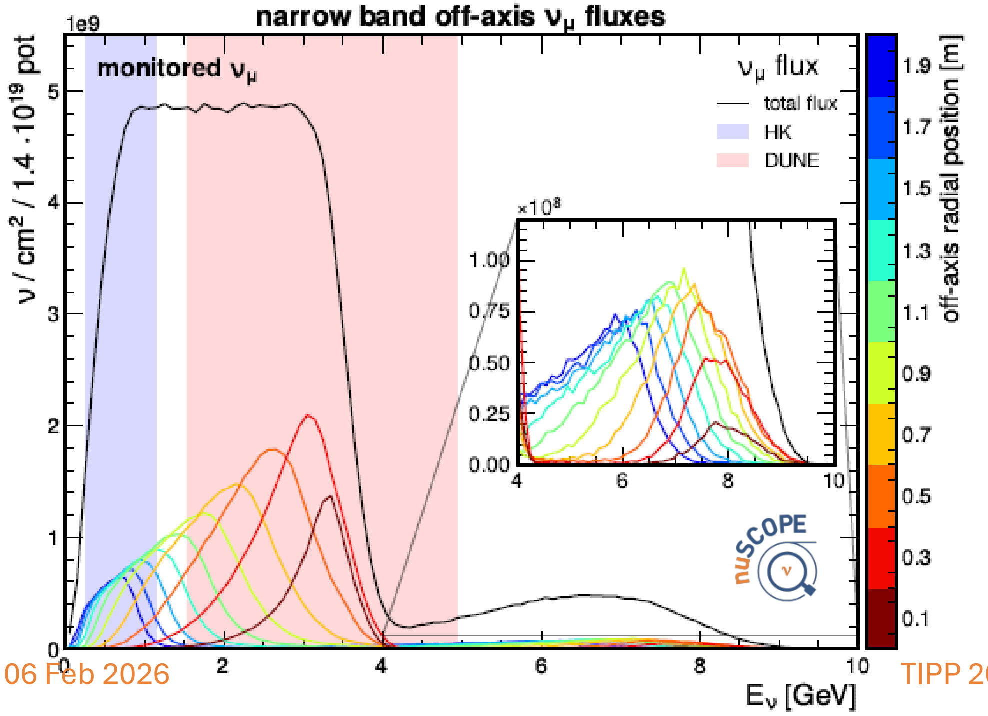
Beamline		
Design	OK	Still room for improvement in reduction of non-monitored nu
Components	OK	Standard and existing (at CERN) components
Slow extraction	in progress	Depends on final implementation
Infrastructure	in progress	Depends on final implementation

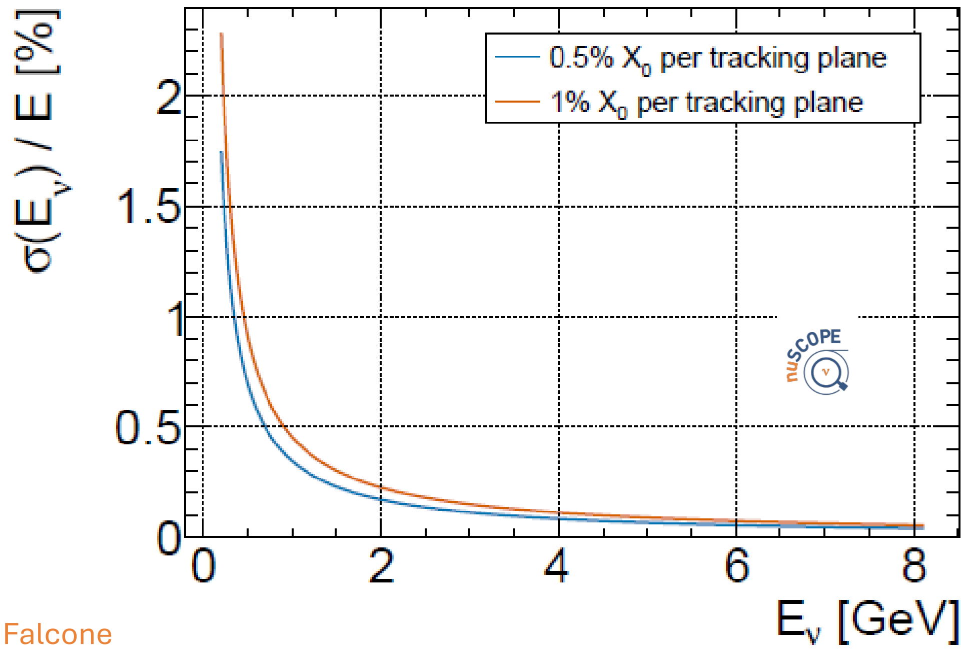
Diagnostics for lepton monitoring/tagging		
Decay tunnel instrumentation	OK	ENUBET R&D (2016-2022)
Hadron dump	in progress	ENUBET+PIMENT R&D (2021-ongoing)
Silicon tracking planes	R&D	The technologies are identified within HL-LHC R&D but not yet fully validated
Outer tracking planes and muon spectrometer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

Neutrino Detectors		
Liquid Argon TPC	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 tagger	in progress	Depends on final implementation

Neutrino flux and energy measurement

- ✓ **Monitoring** provides **unprecedented control of the flux** and a **moderate precision on the initial 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).
- ✓ **Tagging**, although **technically more challenging**, offers **superior energy resolution** for the incoming neutrino energy.
- ✓ "**Neutrino tagging**" (≈80% of the full sample from decay for a 300ps detector time resolution): the **energy is reconstructed from the parent kinematics**. It thus offers a golden sample with **sub-percent energy resolution**.



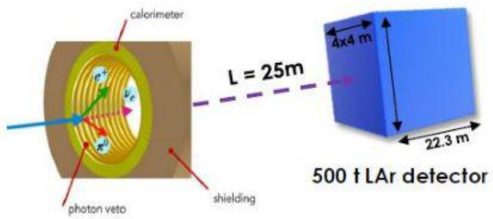


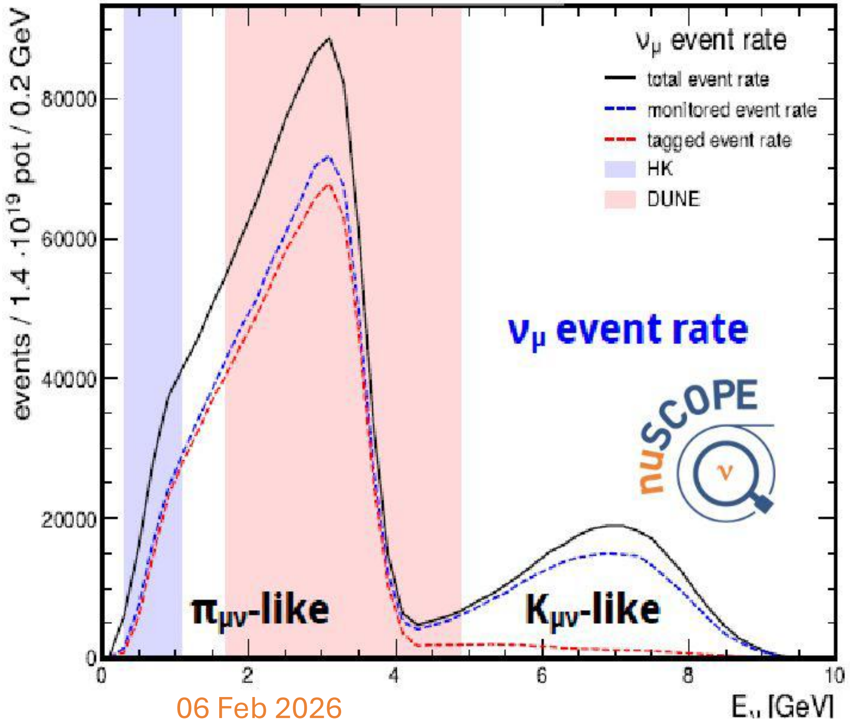
Performance and expected statistics

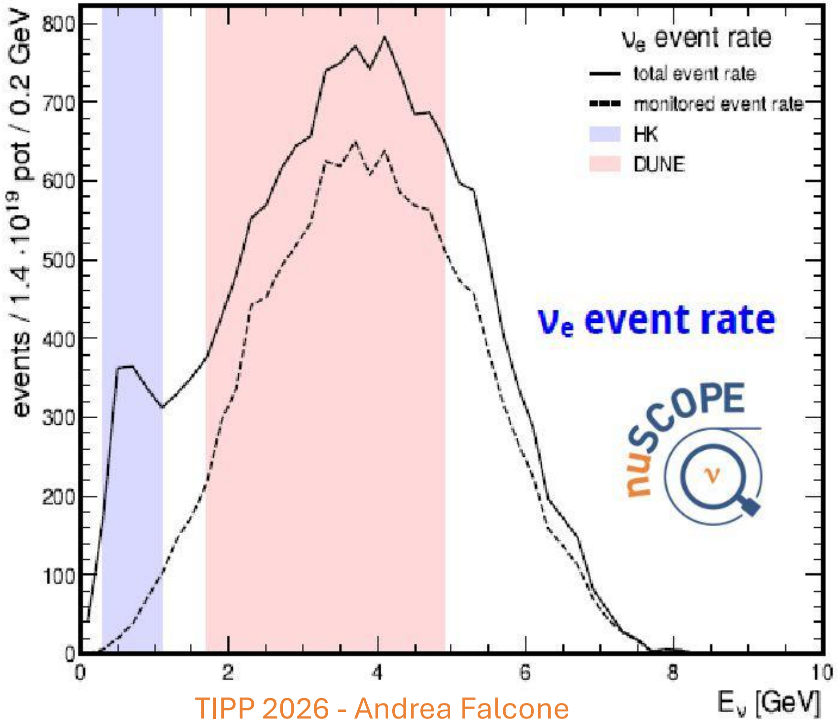
For the reference setup at **SPS** for **5 years** of neutrino run mode with **8.5 GeV/c momentum secondaries**:

- ✓ **500-ton LArTPC**, 4m x 4m x 22.3m, 25m from the hadron dump:
  - ○ 10^6 ν_μ CC events monitored, 7.6×10^5 tagged
  - ○ 1.2×10^5 ν_e CC events
- ✓ **100-ton Water Cherenkov** detector
  - ○ 1.4×10^5 ν_μ CC events tagged (52k tagged ν_μ CC0π)

	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







- ✓ Projected event spectra estimated with **GENIE**.
- ✓ **Flux systematics** from the ENUBET analysis. **Tagging efficiency** from tracker simulations.

Possible measurements

The energy dependence of the neutrino cross section

So we know how to extrapolate from our near to far detectors in oscillation experiments

The differences in the cross section for ν_e and ν_μ

So we can reliably use ν_e appearance to probe CP-violation

Many other channels not covered in the ESPPU paper because they are work in progress

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

L. Munteanu at nuSCOPE workshop

The smearing of our neutrino energy reconstruction

So we can infer the shape of the oscillated spectrum in DUNE/HyperKamiokande

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

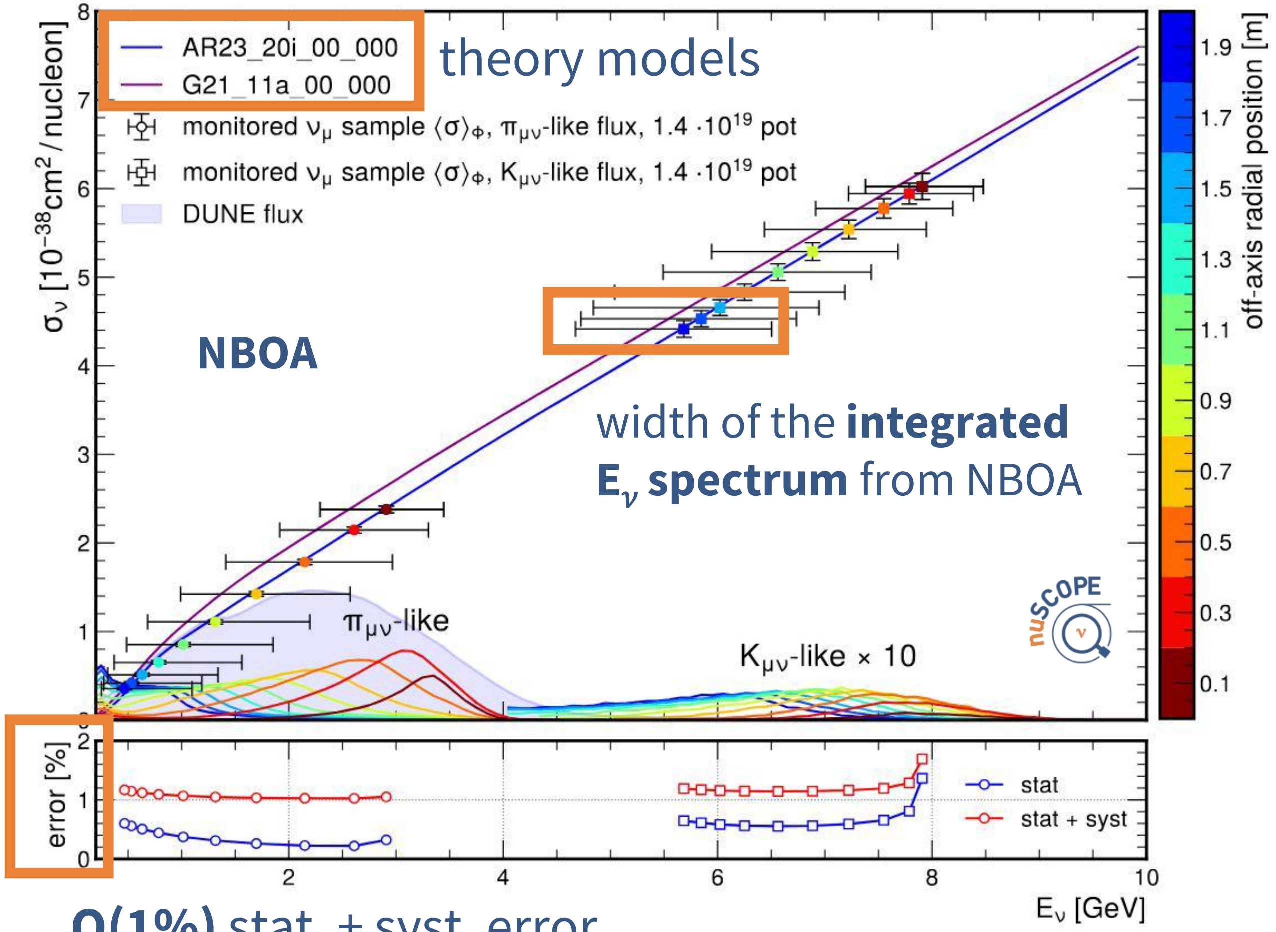
So we know how to interpret far detector event rates

ν-N elastic scattering with tagged ν_μ

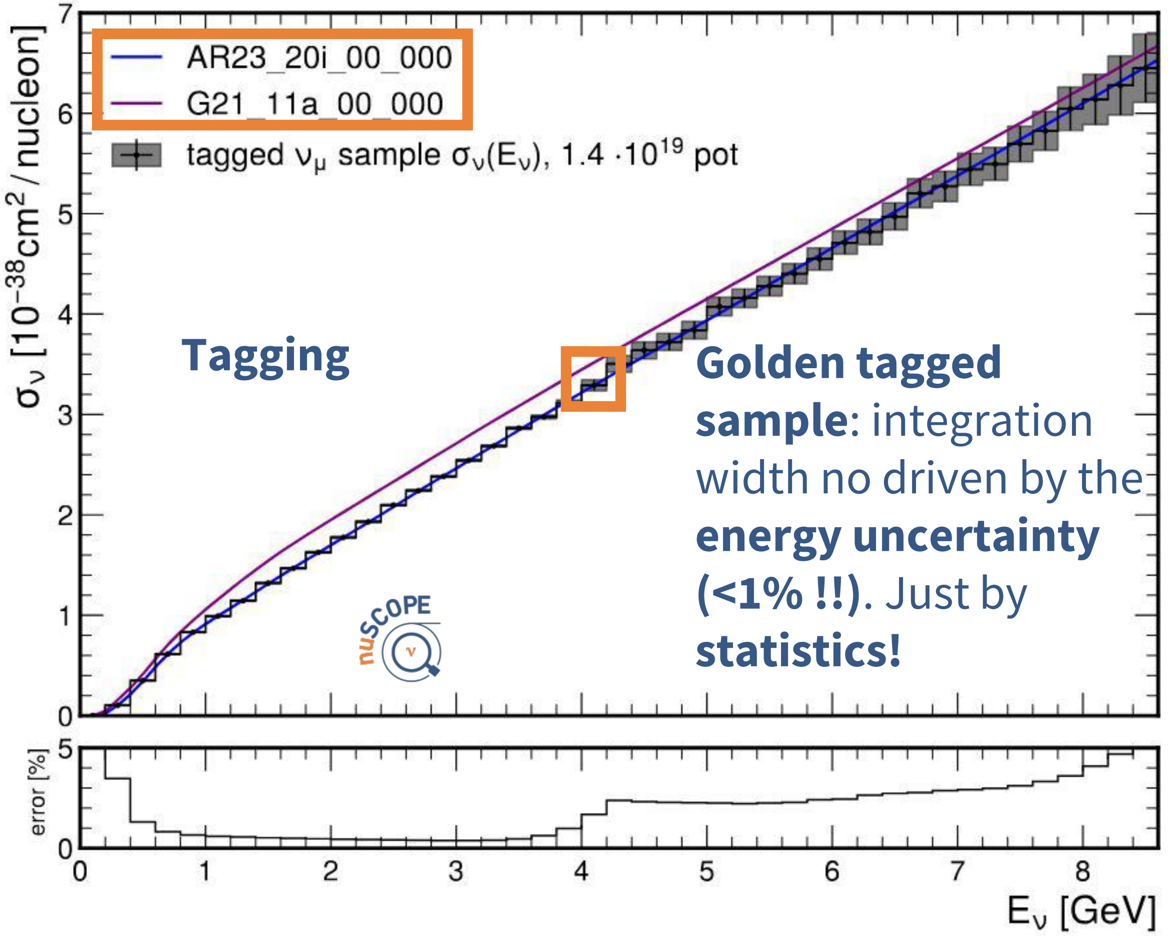
The axial counterpart of e-N elastic scattering

Energy dependence of ν_μ cross section

Both the monitoring and tagging techniques are **sensitive to theory models**.



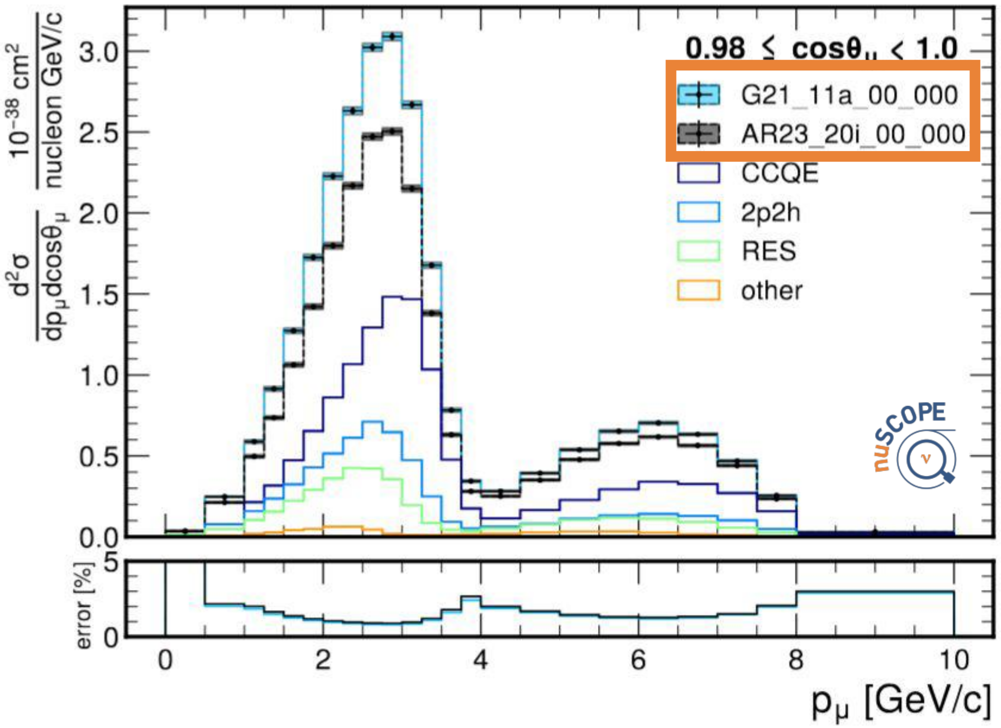
O(1%) stat. + syst. error



Golden tagged sample: integration width no driven by the **energy uncertainty (<1% !!)**. Just by **statistics!**

ν reco energy smearing due to nuclear effects

It can be addressed performing **high precision measurements of double-differential cross sections** using the NBOA technique.



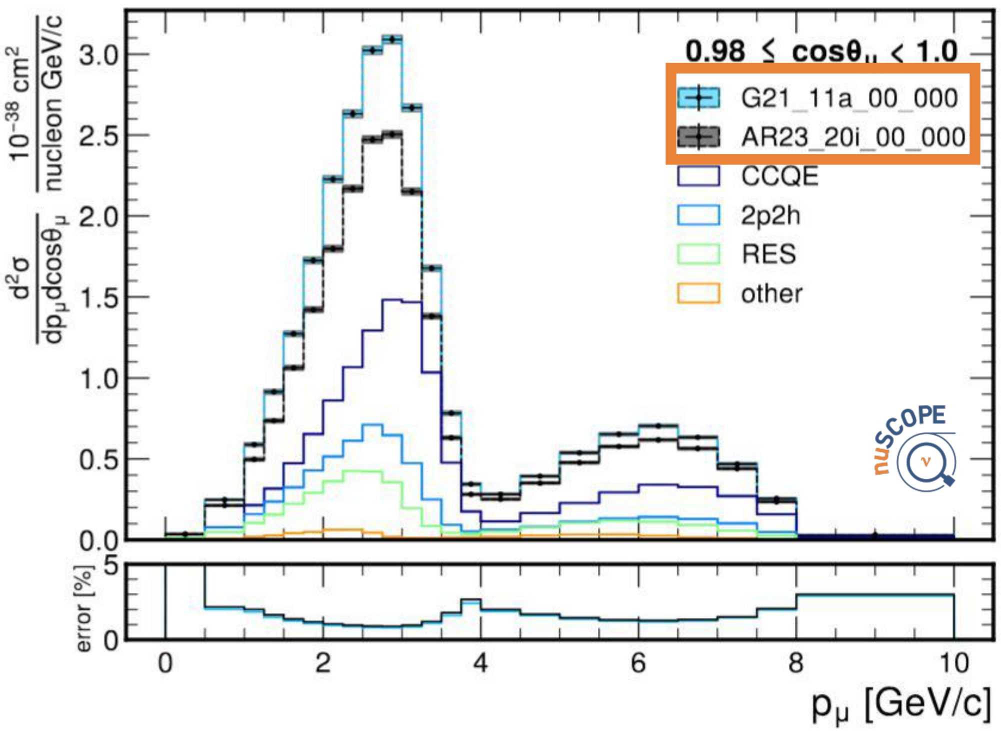
Without **monitoring**, the double differential cross section for “quasi elastic” (CC0π) would be **systematic limited**.

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

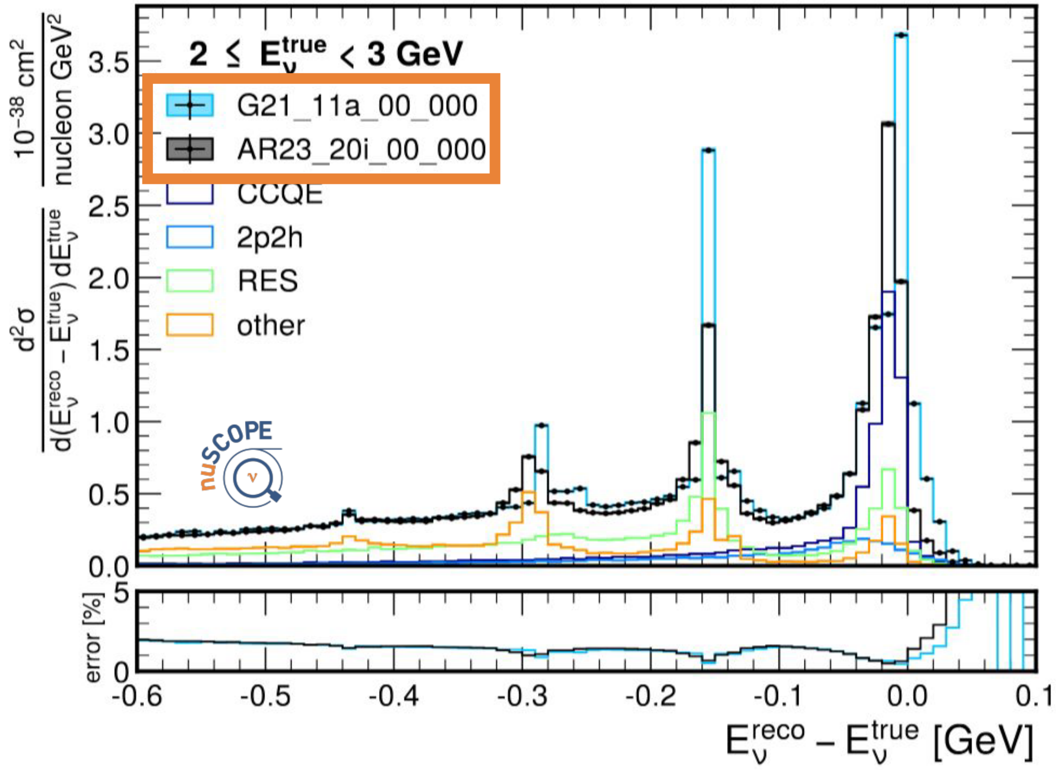
“visible” energy using calorimetric method

ν reco energy smearing due to nuclear effects

It can be addressed performing **high precision measurements of double-differential cross sections** using the NBOA technique or by directly measuring the energy bias from the tagged ν sample.



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

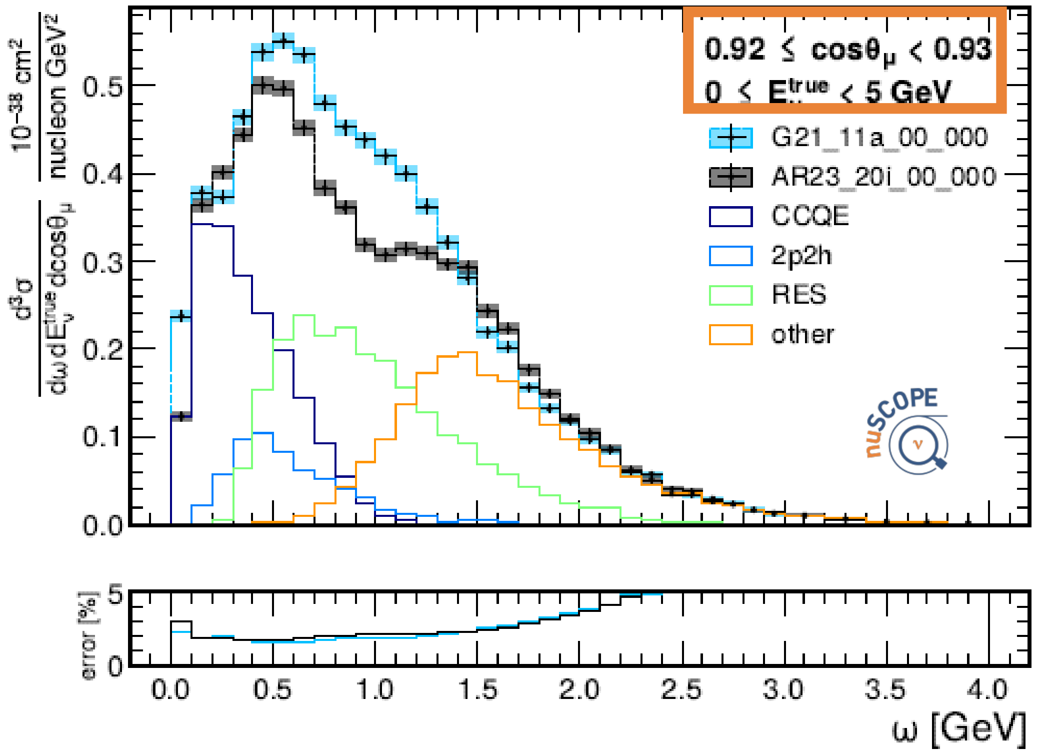


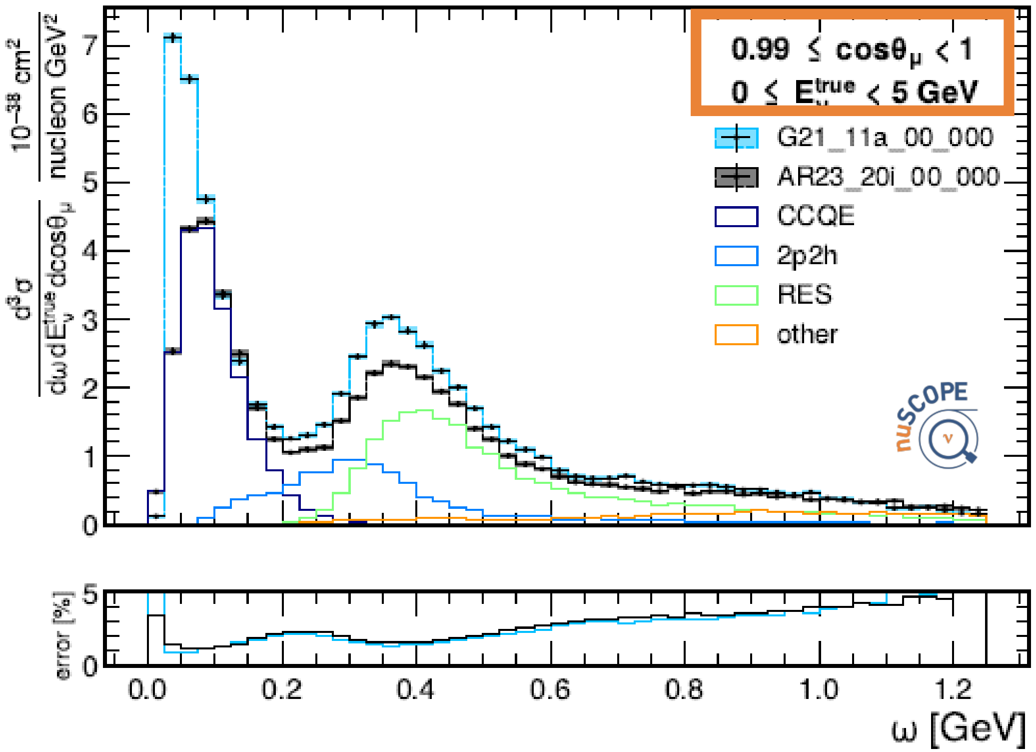
The tagged sample employs the knowledge of the "true" neutrino energy to **directly measure the energy bias** in bins of E_{true} .

e-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





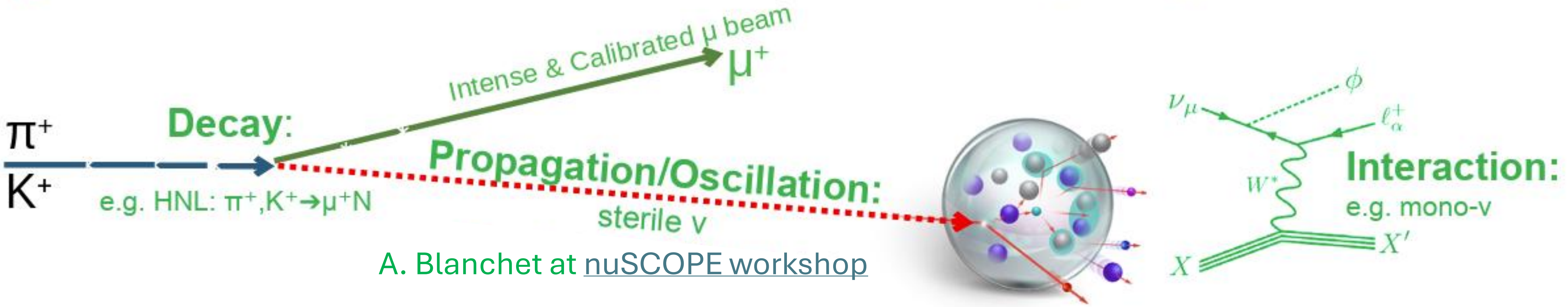
regions sensitive to collective nuclear effects, i.e. the dominant T2K systematics for Δm^2_{32}

Even richer physics program

Neutrino Interactions

large ν interaction samples.
flux knowledge, energy resolution

Beyond Standard Model



A. Blanchet at nuSCOPE workshop

Kaon Physics

ultra rare decay exploiting large stats

Nuclear Physics/QCD

repeat electron scattering exp. but with ν as probe
access axial structure…

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.
- ✓ Key challenges remain regarding CERN integration, meson tracking, and sub-nanosecond neutrino detection.
- ✓ 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.

Get in touch if you'd like to get involved!

nuSCOPE