The physics prospects with a monitored and tagged neutrino beam at CERN

F. Bramati on behalf of the **nuSCOPE** Collaboration

Marciana 2025 - Lepton Interactions with Nucleons and Nuclei
Isola d'Elba, 22–27 Jun 2025

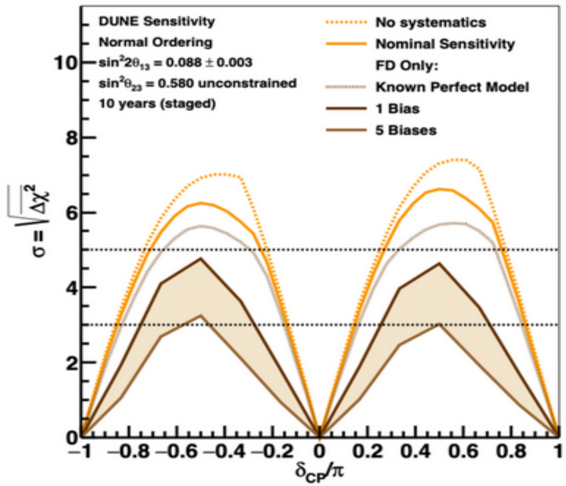
Neutrino cross sections … still poorly known !

- The next generation of long-baseline experiments (DUNE, HyperK) aims at high precision ν oscillation measurements :
  - test the 3 ν families paradigm
  - determination of the ν mass ordering
  - test CP asymmetry in the lepton sector

- The portal to test CP violation and mass hierarchy : high precision measurements of $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance probabilities, and corresponding for anti-neutrinos.

  ➢ **precise knowledge of ν_e and ν_μ cross sections is required !**

$$N_{\nu_\ell}(E_\nu) \propto P_{\nu_\mu \rightarrow \nu_\ell}(E_\nu) \cdot \sigma_\nu(E_\nu) \cdot \phi_\nu(E_\nu) \cdot \epsilon(E_\nu)$$

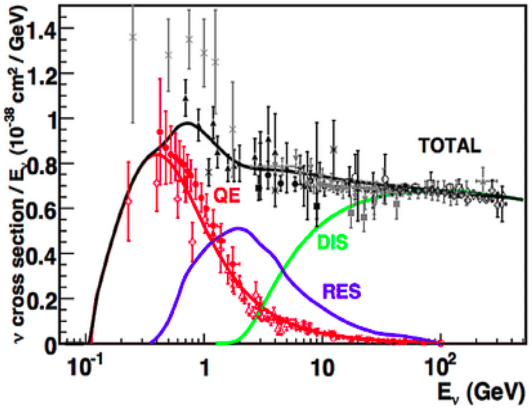


- Moreover, precise measurements of ν cross-sections are essential to improve theoretical knowledge of ν - nuclei interactions … and can provide valuable insights for nuclear physics.

- The ν_e and ν_μ cross sections are known at O(10 – 30%) level in the few GeV energy range :
  - → their precision is limited by systematic uncertainties.
  - → current measurements can be hard to interpret due to broad-band beams.

- **The leading source of systematics on cross-section measurements is the neutrino flux, generally known with a precision worse than O(5-10%) …**

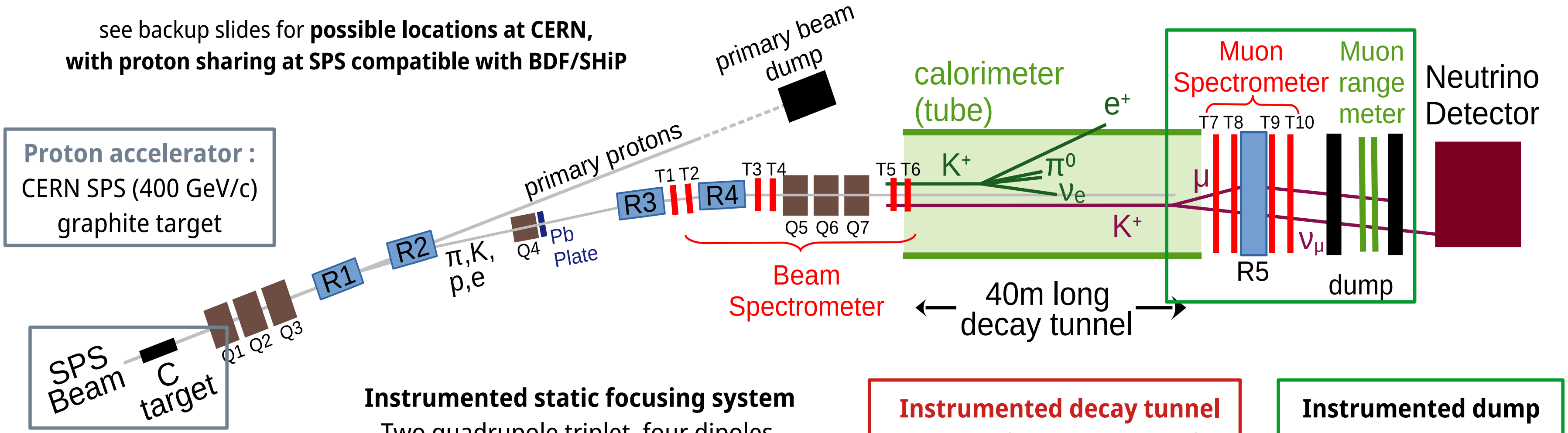
- **Moreover, the initial-state neutrino energy is not known on an event-by-event basis …**



nuSCOPE: a monitored and tagged neutrino beam

- **nuSCOPE** is non-conventional neutrino beam that **combines a monitored and tagged neutrino beam !**
  - → **high-precision neutrino cross-section measurements with %-level flux systematics and neutrino energy measurement on an event-by-event basis.**
- The ~~**SBN@CERN**~~ **nuSCOPE** reference document has been posted on arXiv:2503.21589, as an input document submitted to **ESPP 2026 Update**.

see backup slides for **possible locations at CERN, with proton sharing at SPS compatible with BDF/SHiP**



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

Instrumented decay tunnel
longitudinally segmented calorimeter modules for charged lepton monitoring

Instrumented dump
Muon spectrometer and muon range-meter

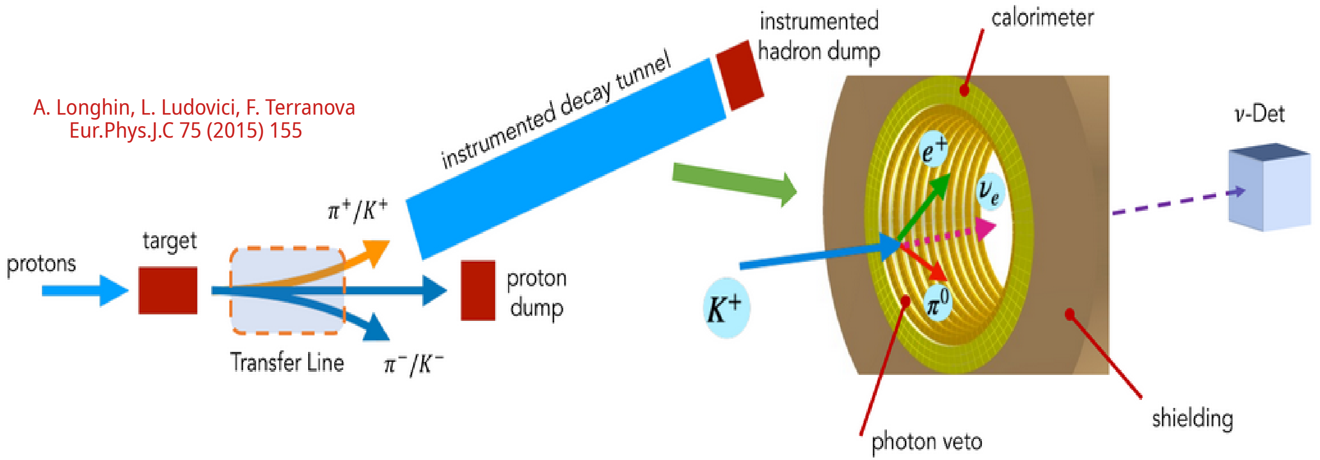
- **Slow extraction mode (10^{13} PoT / 9.6s) to reduce instantaneous rate (mitigated by proximity and large size of neutrino detector!).**
- **Narrow-band beamline**: secondary mesons K^+ / π^+ selected with **$p = 8.5$ GeV/c ± 10%**.

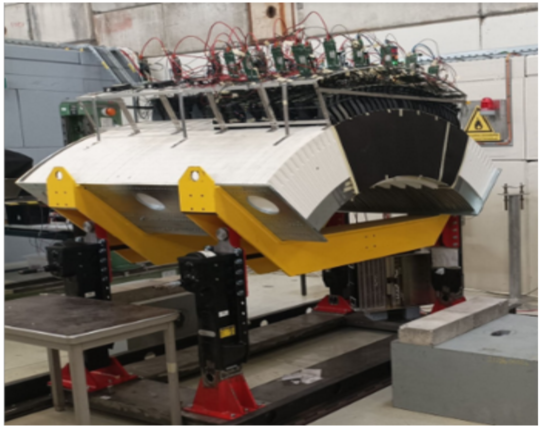
nuSCOPE : improved neutrino flux knowledge with charged lepton monitoring

- **Monitored neutrino beams** are a novel technology aimed at measure the flux and flavour of neutrinos produced at the source **at percent level**.

Conventional beamline with **instrumented decay tunnel** for the identification of charged leptons → measuring **charged lepton rate** ⇔ monitoring **ν flux**

A. Longhin, L. Ludovici, F. Terranova
Eur.Phys.J.C 75 (2015) 155



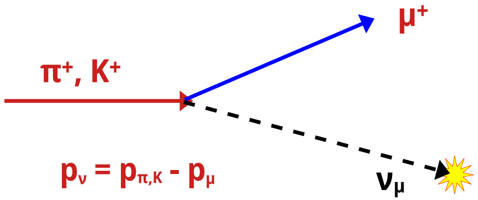


The **NP06/ENUBET prototype** of a section of the decay tunnel (1.65m length, 90° azimuthal coverage) tested at CERN PS T9.

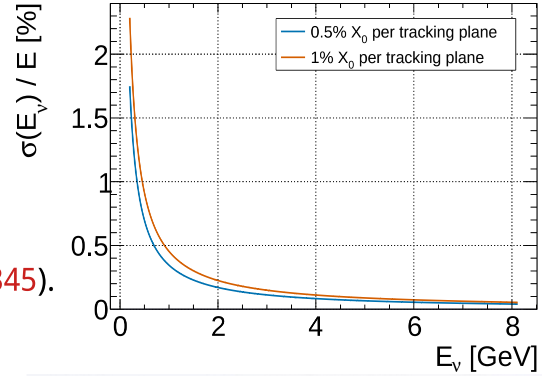
. Eur. Phys. J. C (2023) 83: 964

- **Monitoring: effective removal of systematic uncertainties associated with neutrino flux modelling.**
- The **NP06/ENUBET** experiment, to date, is the most advanced implementation of a monitored neutrino beam.
  - measure **positrons** from K_{e3} ($K^+ \rightarrow e^+ \pi^0 \nu_e$) decay by means of the **instrumented decay tunnel** ⇒ **ν_e flux measurement**
  - measure **muons** from $K_{\mu\nu}$ ($K^+ \rightarrow \mu^+ \nu_\mu$) with the **instrumented decay tunnel** and from $\pi_{\mu\nu}$ ($\pi^+ \rightarrow \mu^+ \nu_\mu$) **instrumenting** the **hadron dump** as a **range meter** ⇒ **ν_μ flux measurement**

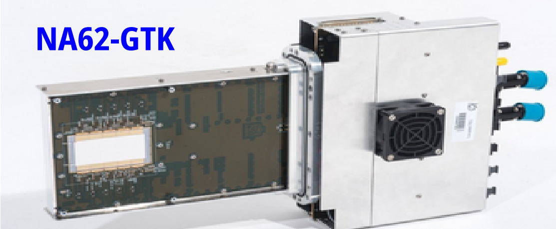
nuSCOPE : neutrino energy measurement using neutrino tagging



- In addition to a monitored neutrino beam, a **tagged neutrino beam** uniquely associate the neutrino with its accompanying particles in the beamline.
- The use of state-of-the-art **silicon trackers** is the core of the tagged neutrino beam proposed by **NuTag**:
  - **beam** and **muon spectrometers** are installed along the beamline to track **π**, **K** and **μ**.
  - **kinematic reconstruction of neutrinos** produced in $\pi^+ \to \mu^+ \nu_\mu$ and $K^+ \to \mu^+ \nu_\mu$ decays.
  - each ν_μ **interaction** observed in the neutrino detector is uniquely **associated** to its **parent meson** and **associated muon**.



- **NA62** reported a **first tagged neutrino candidate** from $K^+ \to \mu^+ \nu_\mu$ decay (Phys. Lett. B 863 (2025) 139345).
- The beam spectrometer technology is the main challenge for tagging :
  - high particle rate to cope with : 20 MHz/mm² at the center of the first beam spectrometer, 0.6 MHz/mm² at the muon spectrometer (9.6 s spills of 10^{13} PoTs).
  - 4D track reconstruction (space + time)
- **State-of-the-art** : NA62 beam tracker (GTK)
- **New silicon technologies** are developed in synergy with HL-LHC (LHCb-VELO upgrade) :
  - TimeSPOT, IGNITE at INFN, LA-PICOPIX at CERN



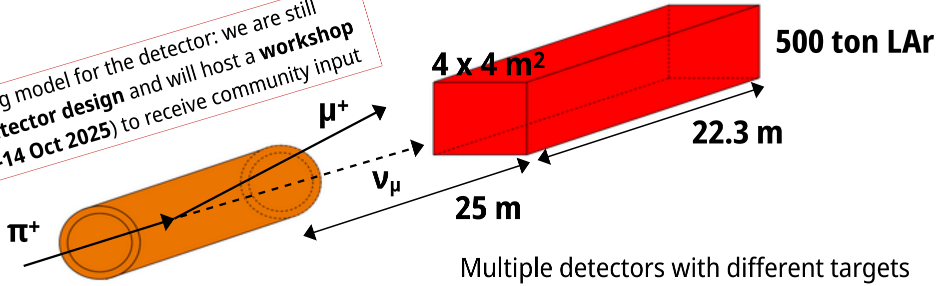
JINST 14 P07010

	Time Reso.	Pixel Pitch	Max. Radiation	Max. Flux
NA62-GTK	130 ps	300 μm	10^{14} n_{eq}/cm²	2 MHz/mm²
New Techno	<50 ps	45 μm	$10^{16\text{-}17}$ n_{eq}/cm²	10-100 MHz/mm²

The reference neutrino detector : ν_μ / ν_e event rates

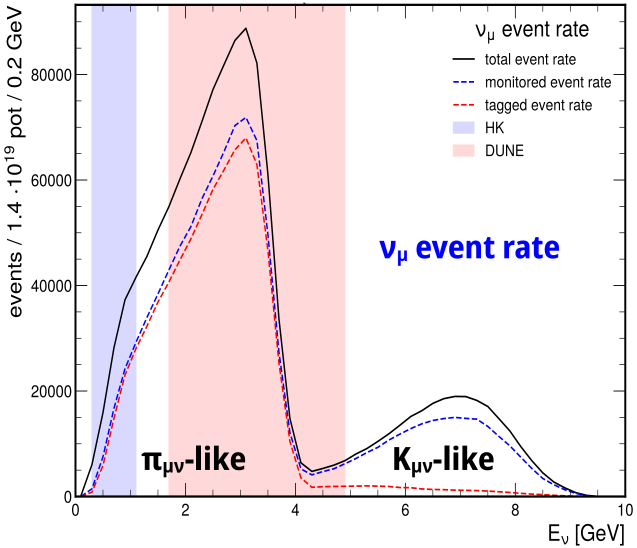
- The reference neutrino detector for studies in arXiv:2503.21589 :
  - **500 ton LAr** fiducial mass
  - **4 x 4 m²** front-face area, **22.3 m** long
  - located at a distance of **25 m** from the tunnel exit
- The **total pot statistic** is **$1.4 \cdot 10^{19}$ pot,** to be collected in ~ 5 years.
- The **projected event rates** are estimated using GENIE with **AR23_20i_00_000** model.
- Good overlap of event rate spectra with HyperK and DUNE regions of interest.

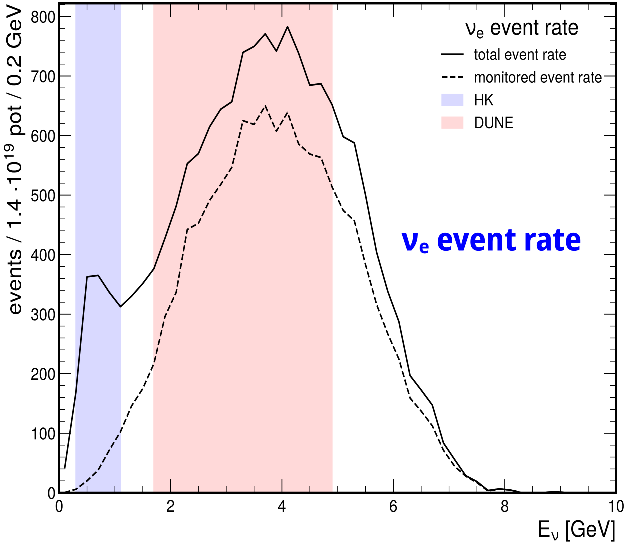
It is working model for the detector: we are still discussing **detector design** and will host a **workshop** at **CERN** (**13-14 Oct 2025**) to receive community input



Multiple detectors with different targets can be considered: **LAr**, **Water** and Water Based Liquid Scintillator (**WBLS**)

DUNE baseline model used for sensitivity studies and simulation





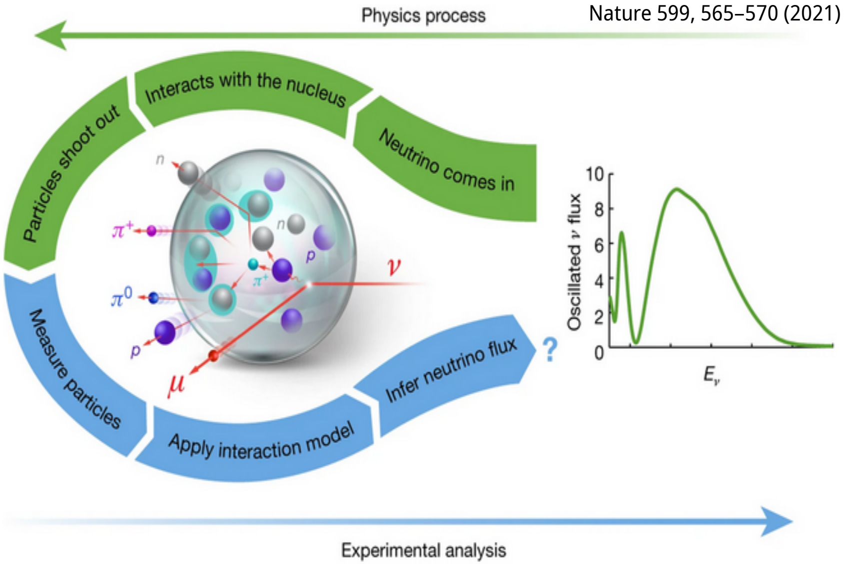
	events / $1.4 \cdot 10^{19}$ PoT
total ν_μ	1.3×10^6
total ν_e	1.7×10^4
total monitored ν_μ	1.0×10^6
total monitored ν_e	1.2×10^4
total tagged ν_μ	7.6×10^5

What do we need to know about neutrino interactions ?

- **A non exhaustive list of what we need to model about neutrino interactions :**

1. **The energy dependence of neutrino cross sections $\sigma(E_\nu)$**
   - ➞ to know how to extrapolate from near to far detectors in oscillation experiments
2. **The smearing and bias in neutrino energy reconstruction**
   - ➞ to infer the shape of the oscillated spectrum in DUNE/HK
3. **The differences in ν_e / ν_μ cross sections**
   - ➞ to use ν_e appearance to probe CP violation
4. **The background events in far detectors (e.g. NC π^0)**
   - ➞ to correctly interpret far detector event rates
5. **Neutrino energy measurement on an event-by-event basis**
   - ➞ electron scattering-like measurement with neutrinos

Nature 599, 565–570 (2021)



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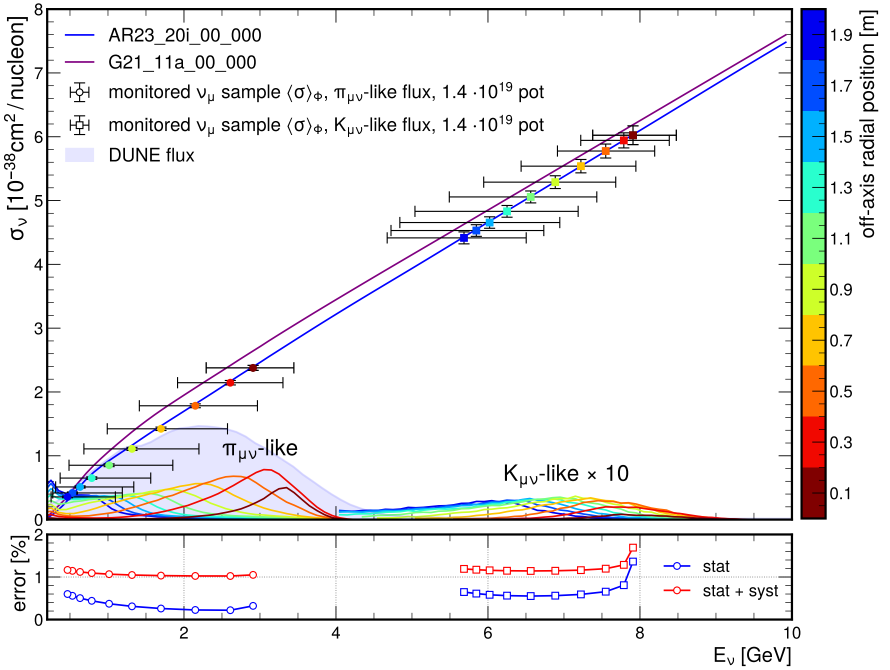

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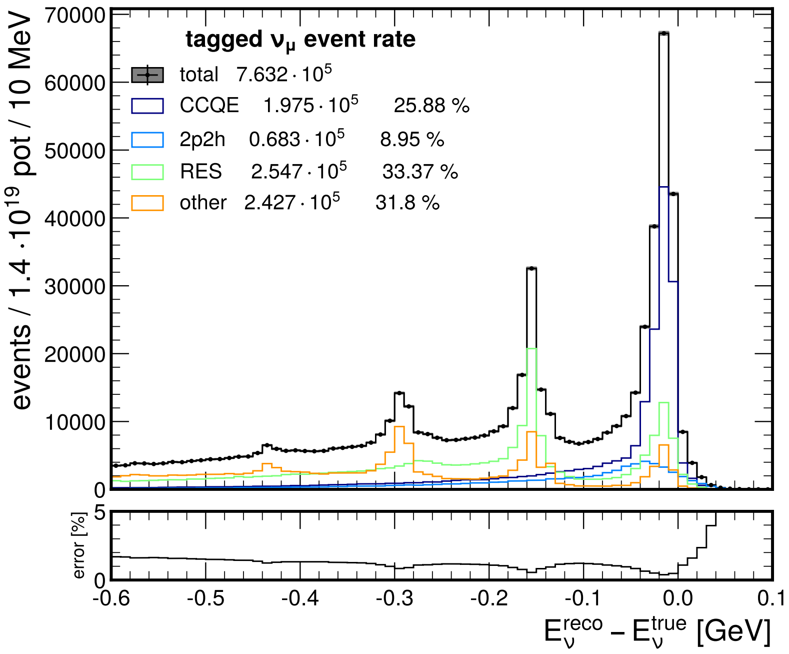

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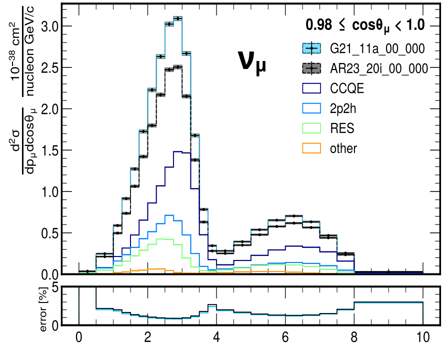

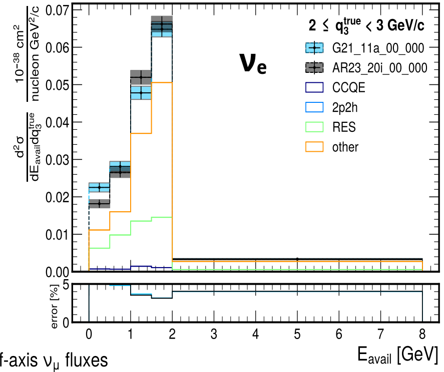

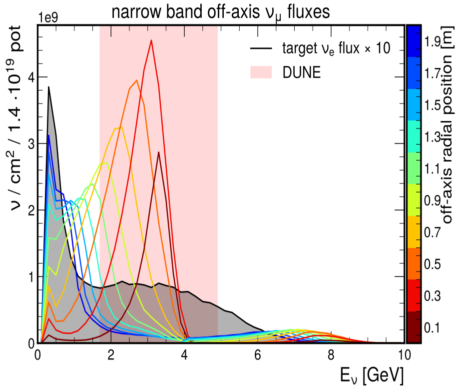

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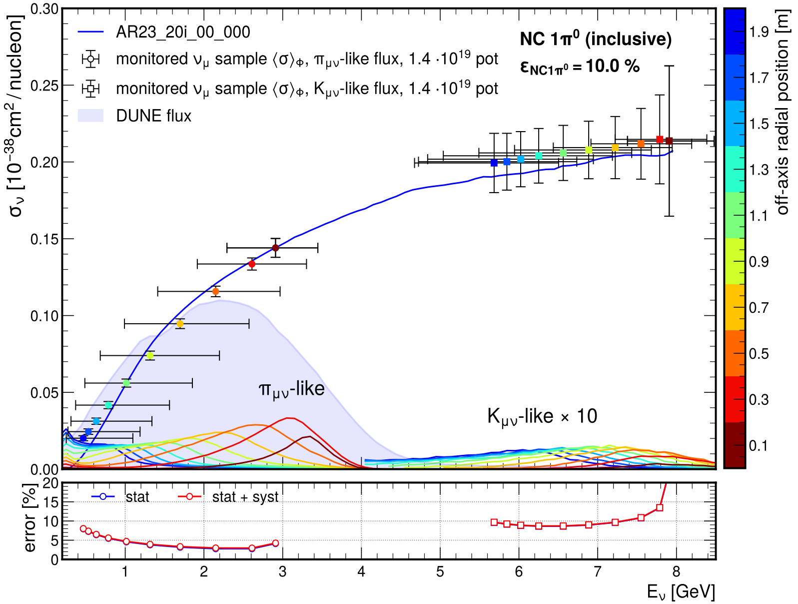

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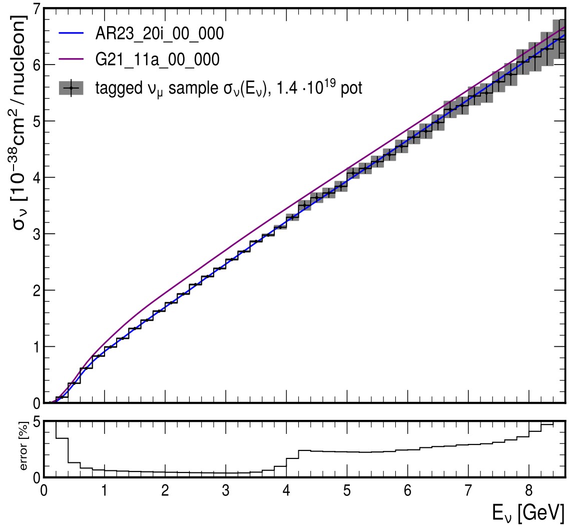
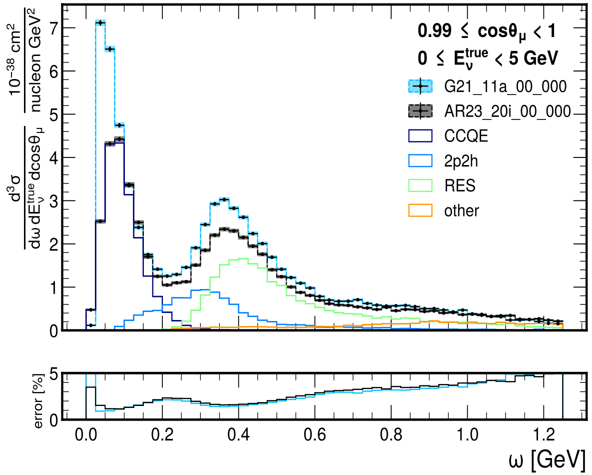




neutrino cross section measurements with the monitored neutrino sample

The narrow-band off-axis technique

Narrow-band off-axis technique

narrow momentum beam O(10%)

↓

(E_ν, r) are strongly correlated

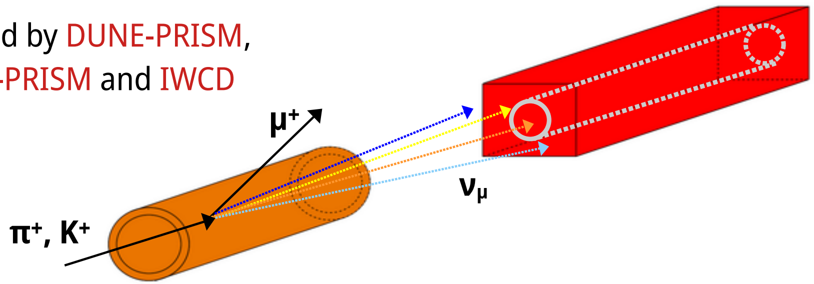
- **E_ν** = neutrino energy
- **r** = radial distance of interaction vertex from beam axis

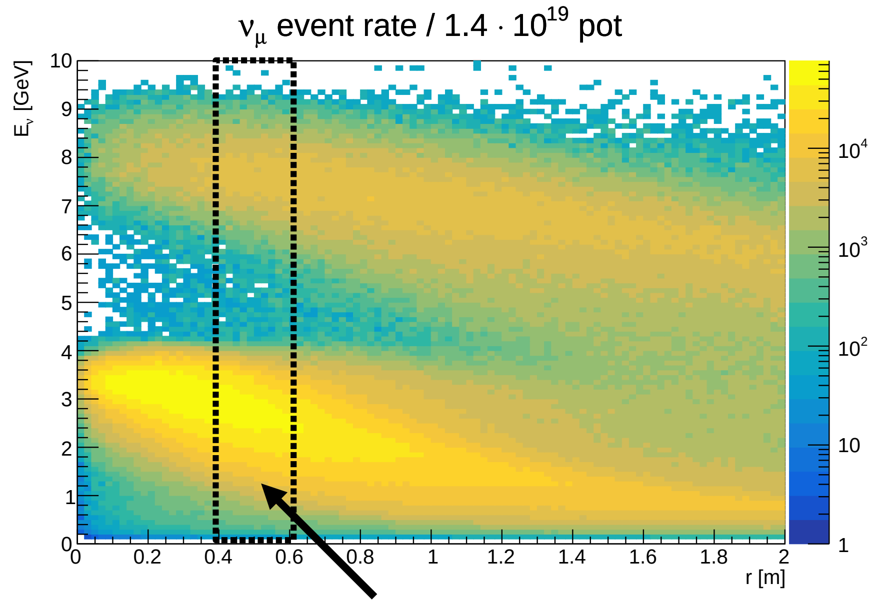
↓

precise determination of E_ν :

w/o relying on reconstruction of final state particles from ν_μ interactions

inspired by DUNE-PRISM, SBND-PRISM and IWCD





select ν_μ with given energy with a radial cut

- **ν_μ interacting at different off-axis angles span different energy ranges**.
- selecting a radial slice, a flux narrower than the total flux can be probed.
- **10 radial slices**, each spanning a **20 cm window**.
  - access to different energy spectra probing many off-axis angles (0 - 4.5°)

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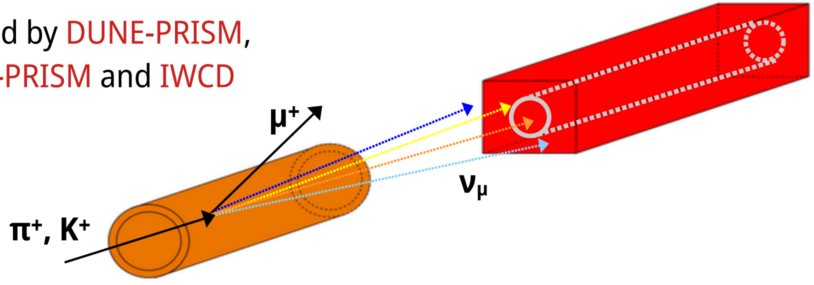

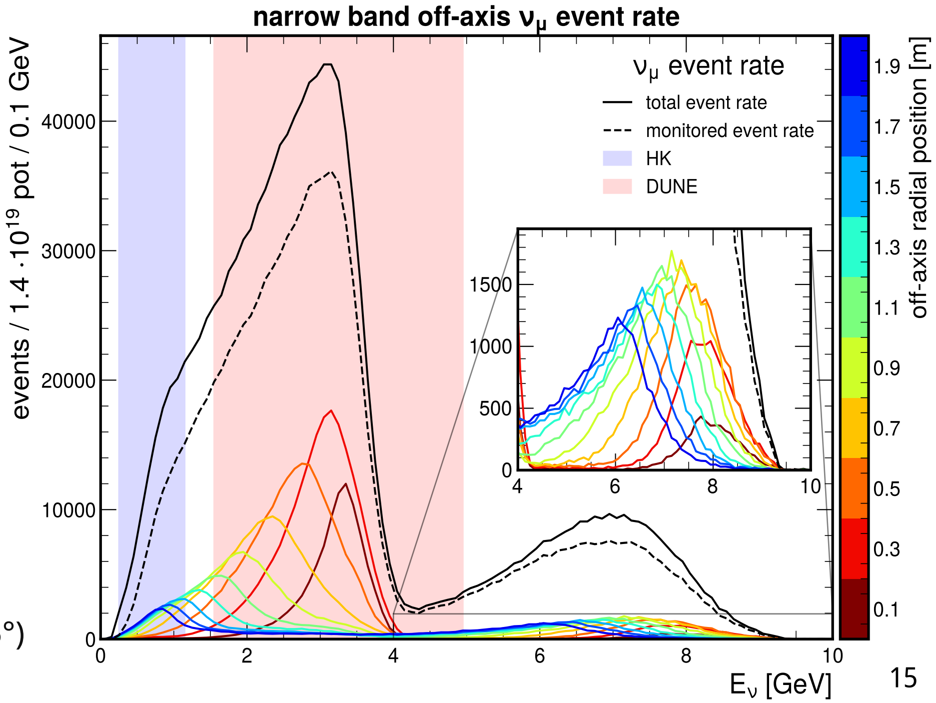

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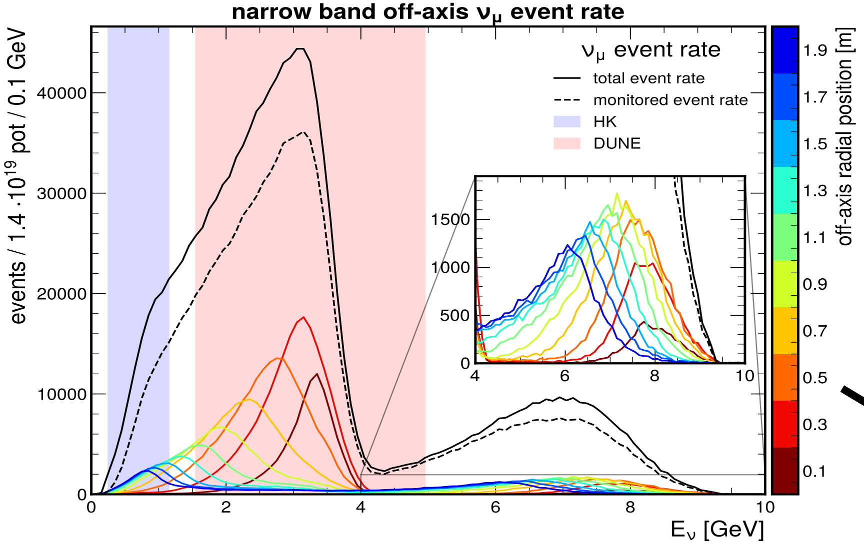
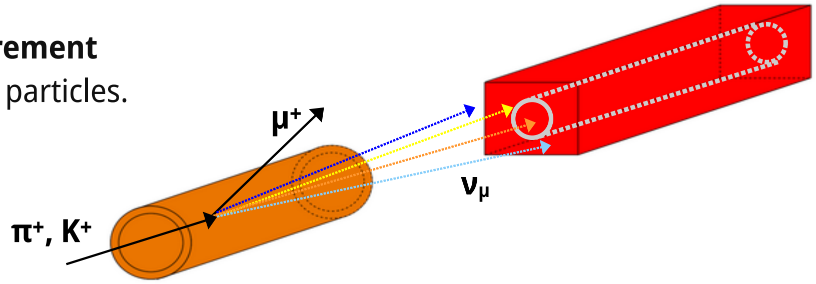
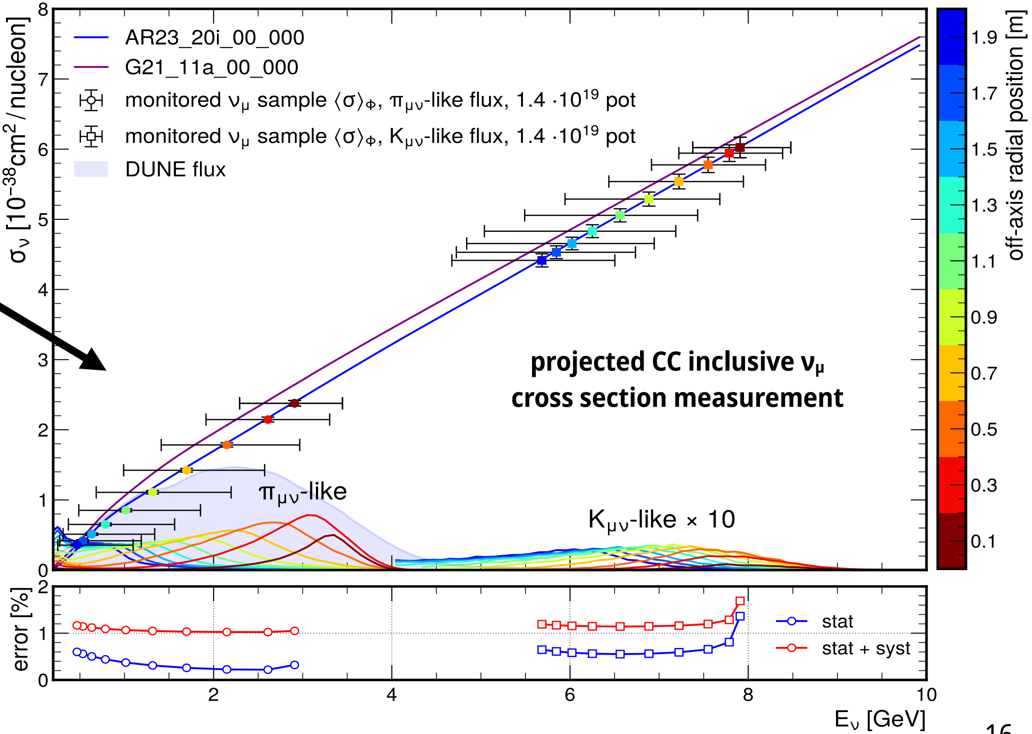
flux averaged ν_μ CC inclusive cross section measurement

- The narrow band off-axis technique can provide an **"a priori" measurement of neutrino energy** for ν_μ w/o relying on reconstruction of final-state particles.







horizontal error bars encase the flux width (68% percentiles wrt mean energy)

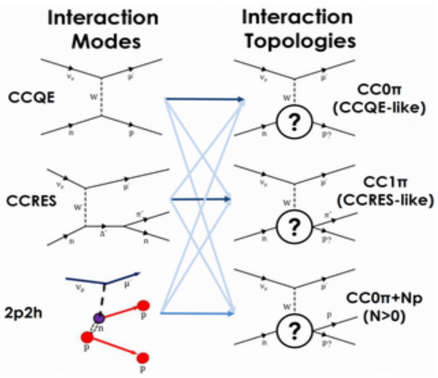
- The **$\pi_{\mu\nu}$- and $K_{\mu\nu}$-like** peaks in the narrow band off-axis fluxes can be separated using an energy cut at ~ 4 GeV.
- Since **$\pi_{\mu\nu}$** and **$K_{\mu\nu}$** peaks are well separated, **flux averaged neutrino cross section** can be measured using both peaks.

$$\langle\sigma\rangle_\Phi = \frac{N_{\text{events}}}{\Phi N_{\text{tgt}} N_{\text{PoT}}}$$

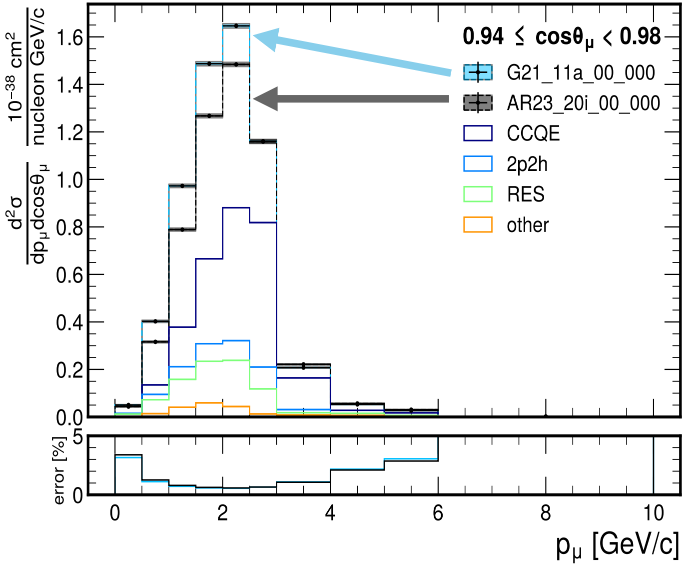
flux averaged ν_μ CC0π double differential cross section

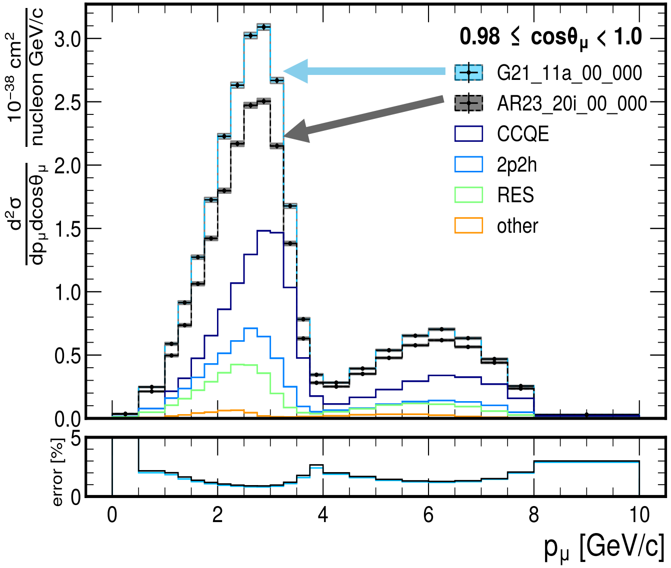
- The simplest channel to measure is **CCQE** : a single lepton and nucleon in the final state.
- The closest visible final state is **CC0π topology** : a single lepton and **no pions** in the final state.
  - contributions from CCQE, multi-nucleon interactions (2p2h), resonant pion production with pion absorption (RES), other process with no pions in the final state.
- **double differential ν_μ cross sections as a function of outgoing lepton kinematics p_μ , $\cos\theta_\mu$:**

➡ **lepton kinematics maps to the momentum q_3 and energy transfer $\omega = q_0$**
in neutrino scattering, averaged over the range of available neutrino energies.



same interaction topologies from different interactions due to **final state interactions** (**FSI**) taking place inside the nucleus





- **few %-level statistical uncertainty**
- w/o a monitored beam measurements become systematically limited
- statistical power of projected measurement enables to discriminate between different models
- different kinematic regions are sensitive to different aspects of modeling differences

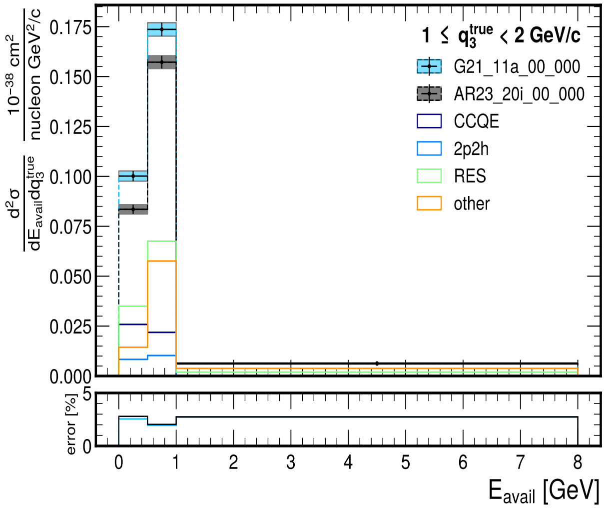
flux averaged ν_e inclusive double differential cross section

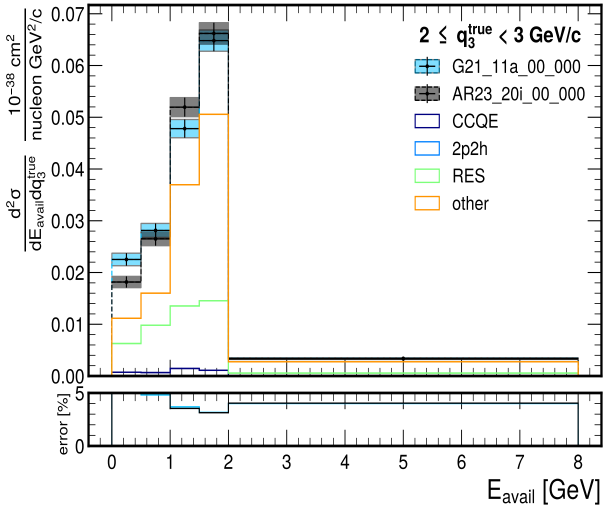
- **double differential ν_e cross sections as a function of calorimetric observables E_{avail} , q_3 :**
- The **available** (**recoil**) **energy E_{avail}** is the **calorimetric sum of the outgoing hadronic state** :
  - it is a **proxy for the energy seen in a detector** with a high tracking threshold, where **individual charged-pions are not identified**, and **no neutron energy is measured**.
- **q_3** is the projection of the momentum transfer q onto the incoming neutrino direction :
  - assuming that reconstructed q_3 from particle kinematics has been unfolded to its true value.
  - it is a model-dependent procedure, but the model dependence could be mitigated with tagging.

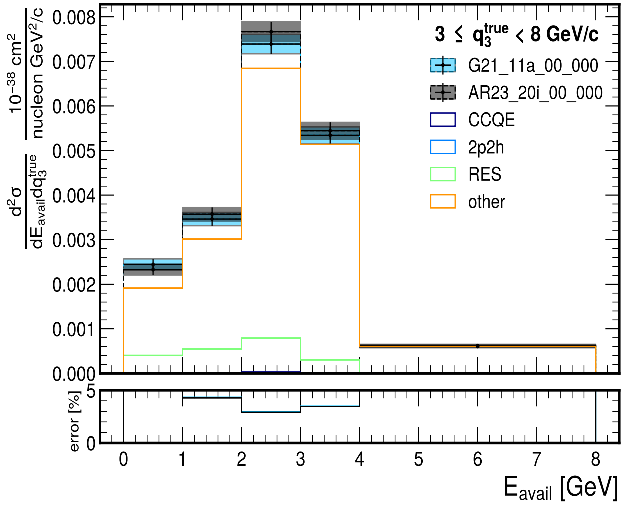
$$E_{\text{avail}} = \sum_{i=\pi^{\pm},p} T_i + \sum_{i=\pi^0,\gamma} E_i$$

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

$$Q^2 = 2(E_l + q_0)(E_l - |\vec{p}_l|\cos\theta_l) - m_l^2$$







PRISM technique using narrow band off-axis fluxes : ν_e / ν_μ cross section ratio

- **differences between ν_e and ν_μ cross-sections** is an important systematic for the measurement of **$\nu_\mu \rightarrow \nu_e$** oscillation :
  - **few direct constraints on ν_e cross-section exist … extrapolated from ν_μ beam at near detector**.
  - assuming lepton universality, differences in ν_e and ν_μ cross-sections are due to lepton mass terms, significant at relatively low energy transfers → differences in $\sigma(\nu_e)$ / $\sigma(\nu_\mu)$ ratio of the order of 3% predicted by nuclear models in these regions.

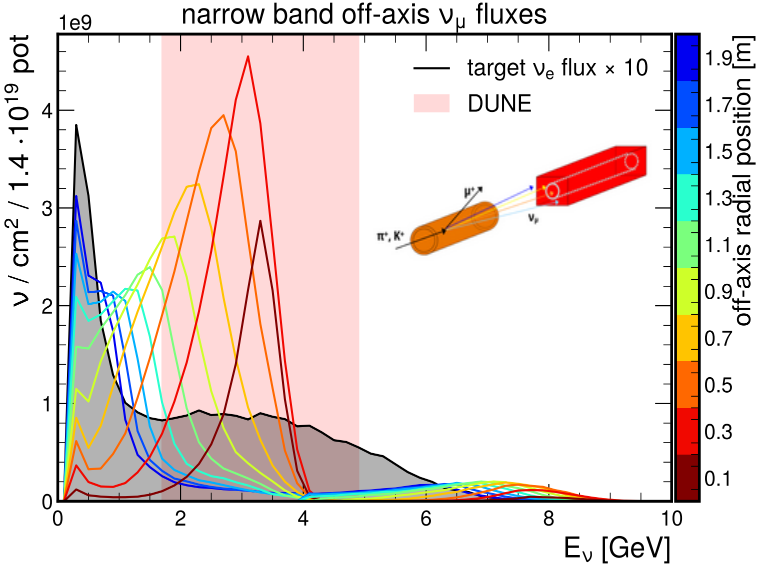
- The **PRISM** technique is being investigated by HK, SBND and DUNE to create virtual fluxes from linear combinations of off-axis fluxes.
- In nuSCOPE, it is possible to **create a virtual ν_e flux (target) using linear combinations of narrow ν_μ off-axis real fluxes.**

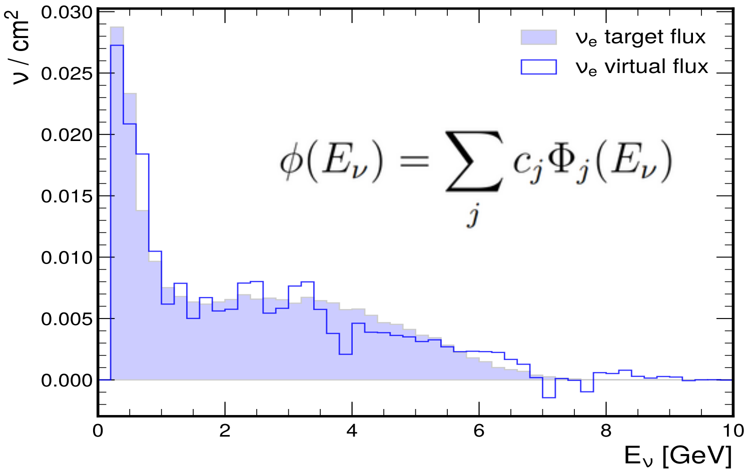
→ **$\sigma(\nu_e)$ / $\sigma(\nu_\mu)$ ratio measurement at 2%**

$$\frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}} = 1.02 \pm 0.02$$

⟶ neutrino tagging may further improve it!

narrow band off-axis ν_μ fluxes



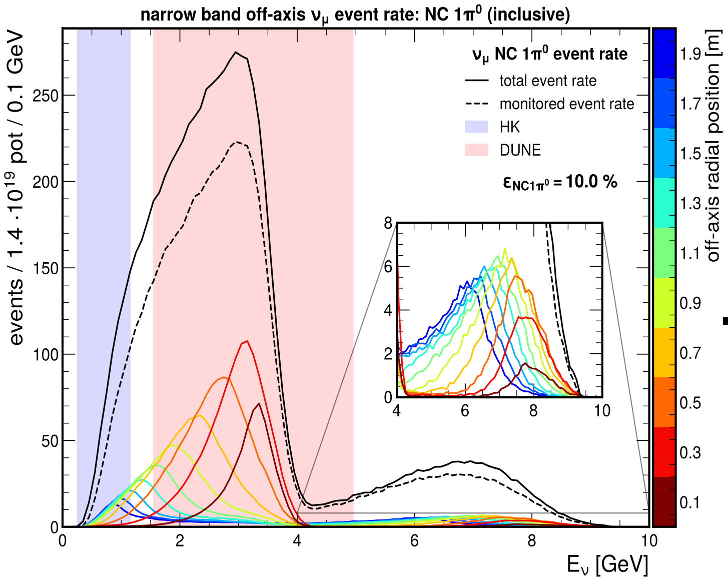


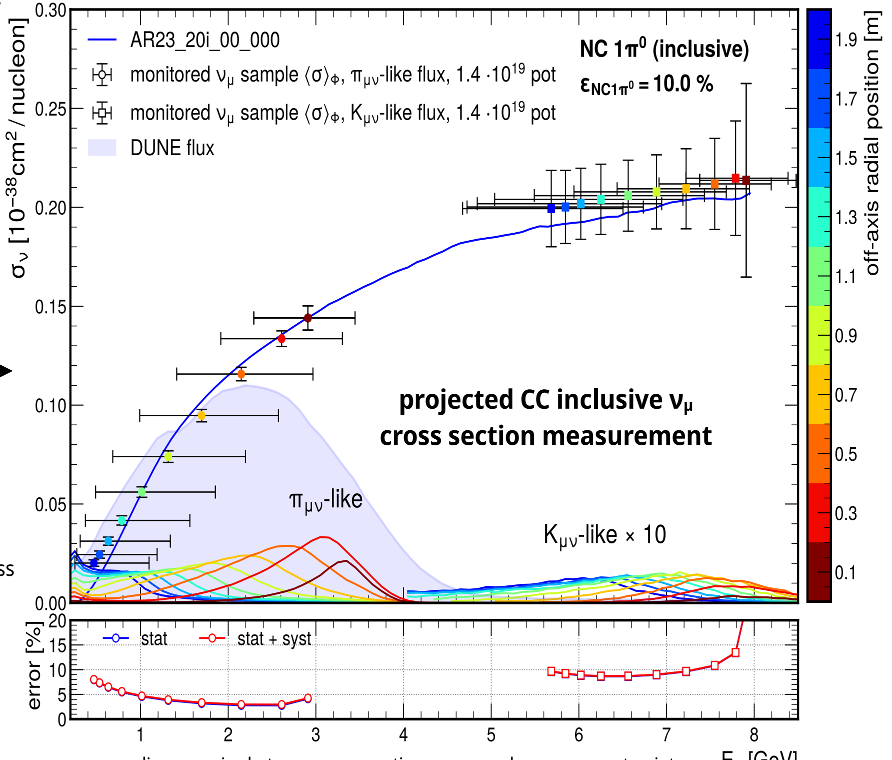
$$\phi(E_\nu) = \sum_j c_j \Phi_j(E_\nu)$$

we measure the **ν_e flux integrated cross section** and compare it with the corresponding ν_μ cross section built from narrow-width fluxes.

flux averaged ν_μ NC π^0 cross section measurement

- NC interactions constitute a source of **background** for neutrino oscillation :
  - **production of neutral pions in NC interactions**, i.e. **NC π^0 topology**, is the main channel contributing to this background.
  - photons can be mis-reconstructed as electrons → NC events are mis-attributed to CC events with a final state electron.
- This process was measured by **MicroBooNE**, see Phys. Rev. D 107, 012004.





expected stat. error below 10% across the majority of DUNE energies and below 5% in the peak region.

MicroBooNE	
stat.	**6%**
syst.	**16%**
flux syst.	12%

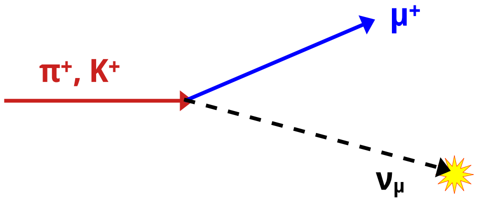
discrepancies between cross-section curves and measurement points are due to statistical fluctuations due to reduced statistics of this topology

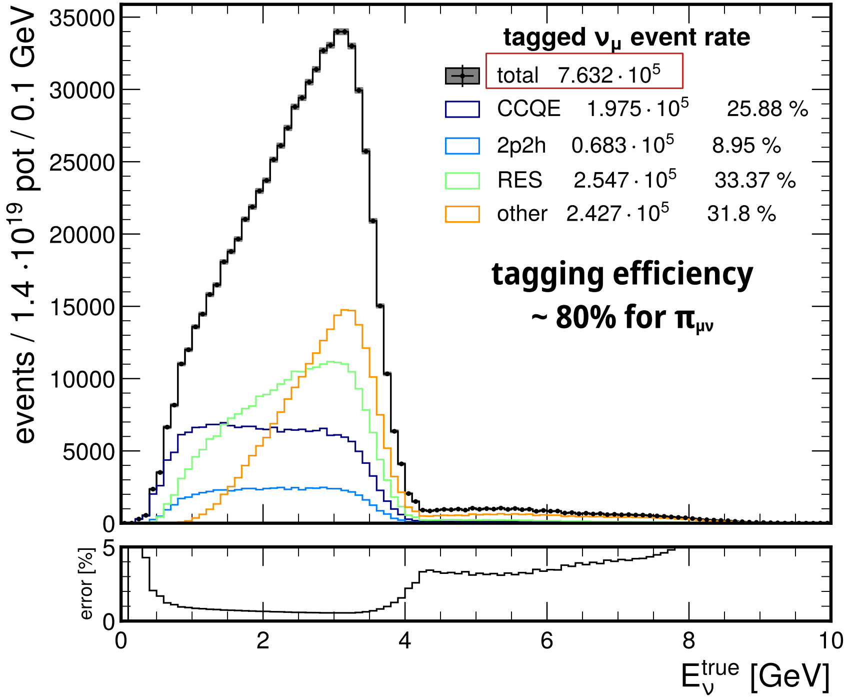
- **10% efficiency** applied to the total number of NCπ^0
- selection of events with **1π^0** in the final state and either **zero** or **one proton with momentum above 300 MeV/c**.

neutrino cross section measurements with the tagged neutrino sample

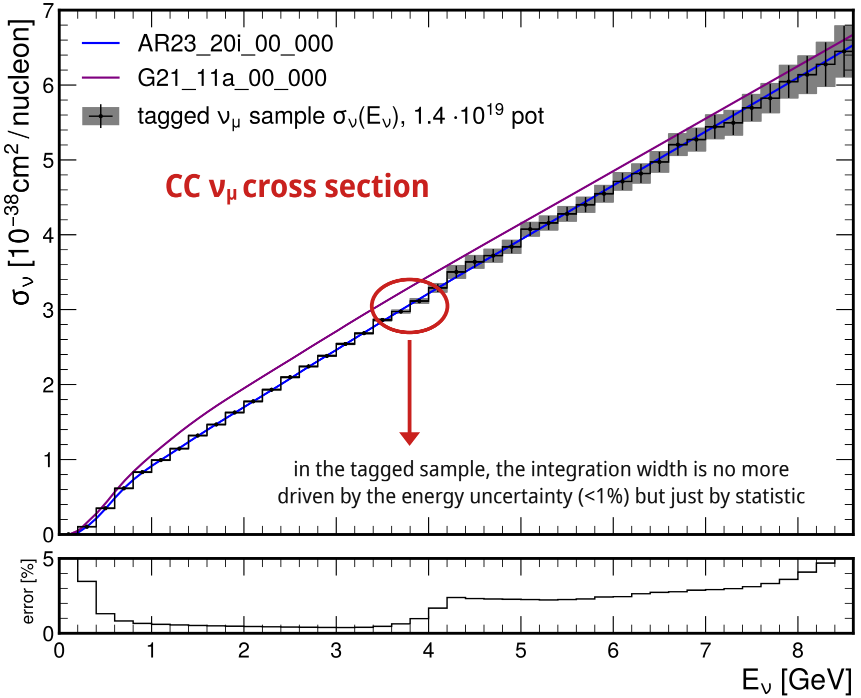
neutrino tagging : ν_μ energy measurement and CC inclusive cross section

- In a **tagged neutrino beam** the **neutrino energy is known on an event-by-event basis** with **sub-% energy resolution.**
- **Neutrino tagging** can be used to directly measure:
  1. **The CC ν_μ cross section $\sigma(E_\nu)$ as a function of true E_ν**





Tagged sample

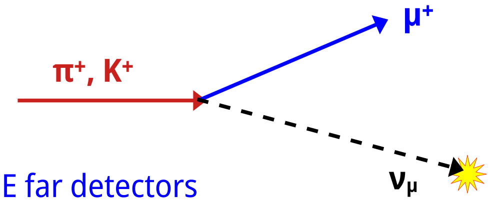


neutrino tagging : ν_μ energy measurement and CC inclusive cross section

- In a **tagged neutrino beam** the **neutrino energy is known on an event-by-event basis** with **sub-% energy resolution.**

- **Neutrino tagging** can be used to directly measure:

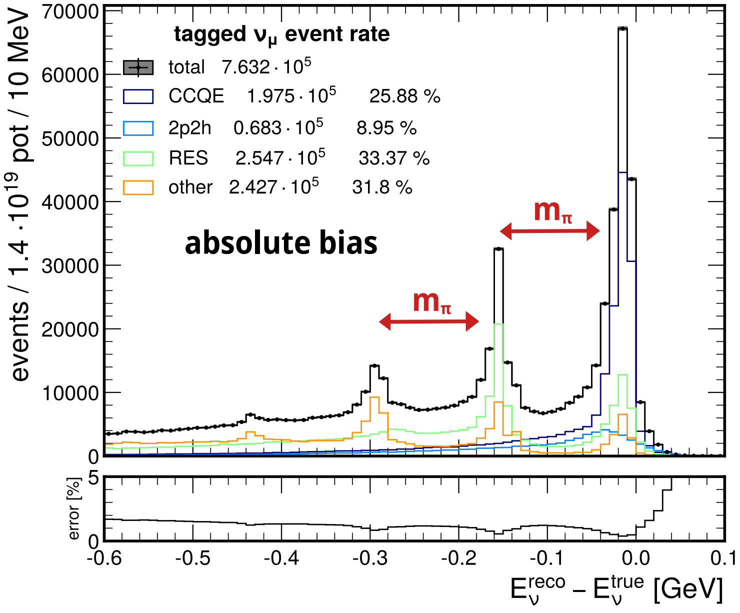
  1. **the ν_μ cross section $\sigma(E_\nu)$ as a function of true E_ν**
  2. **the neutrino energy bias** → calibrate neutrino energy bias of DUNE far detectors

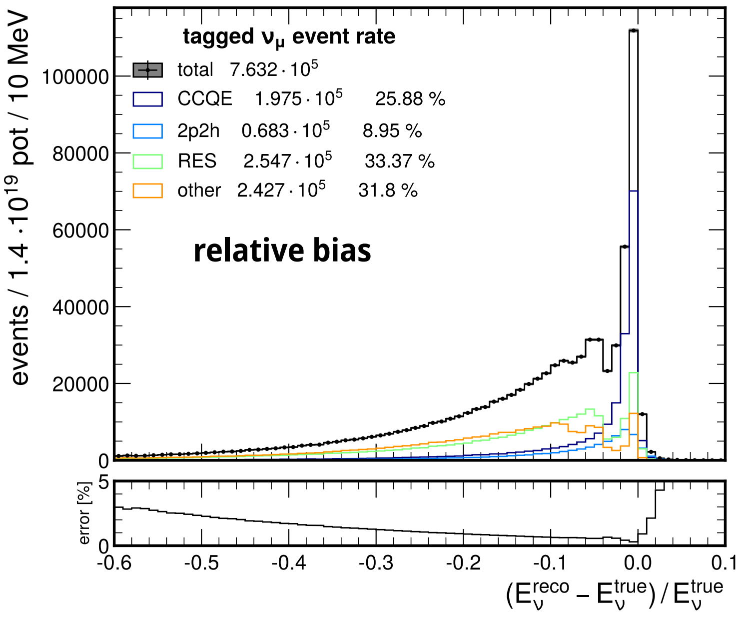


Sources of bias :

1. **position → charged pions multiplicity**
   $\Delta E_\pi = N_\pi \cdot m_\pi$
2. **position → nucleon removal energy**
   $\Delta E_{nucleons}$
3. **width → spread in removal energy**
4. **neutrons → missing fraction of energy carried by neutrons**

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



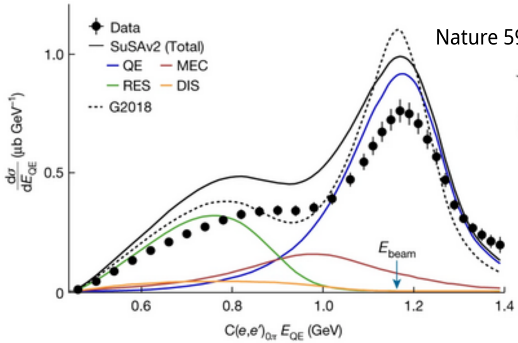


neutrino tagging : electron scattering-like measurements with neutrinos

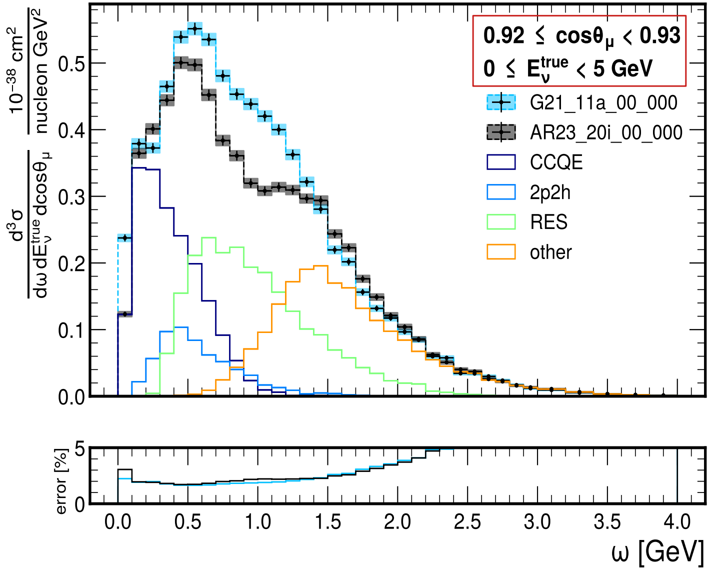
- In a **tagged neutrino beam** the **neutrino energy is known on an event-by-event basis** with **sub-% energy resolution**.

- **Neutrino tagging** can be used to directly measure:

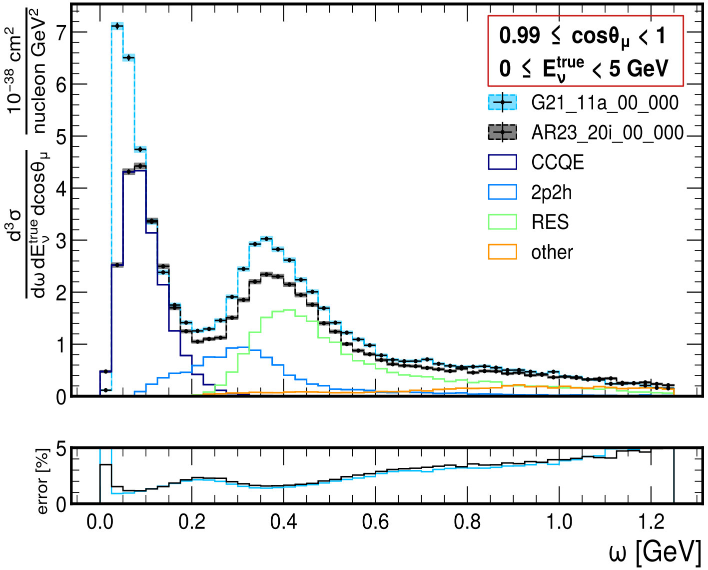
  1. **the ν_μ cross section $\sigma(E_\nu)$ as a function of true E_ν**
  2. **the neutrino energy bias**
  3. **electron scattering-like measurements with tagged neutrinos !**



Nature 599, 565–570 (2021)



regions sensitive to nuclear-level form factors



regions sensitive to collective nuclear effects

energy transfer

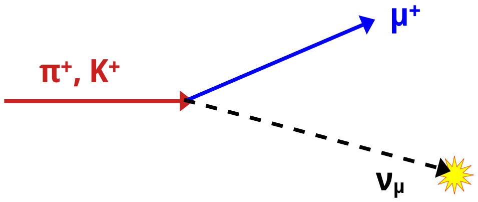
$$\omega = E_\mu - E_\nu$$

neutrino tagging : electron scattering-like measurements with neutrinos

- In a **tagged neutrino beam** the **neutrino energy is known on an event-by-event basis** with **sub-% energy resolution.**

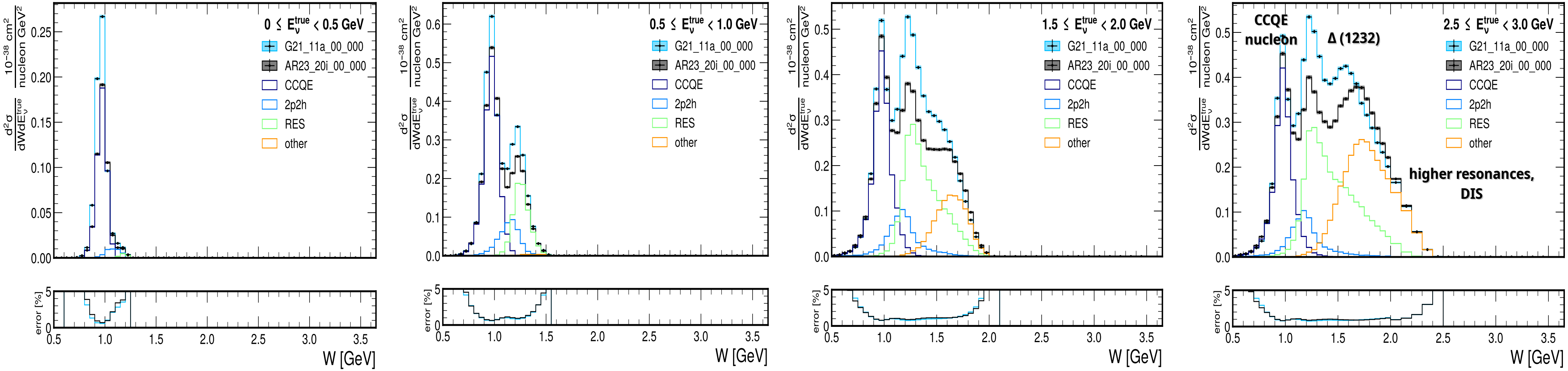
- **Neutrino tagging** can be used to directly measure:

  1. **the ν_μ cross section $\sigma(E_\nu)$ as a function of true E_ν**
  2. **the neutrino energy bias**
  3. **electron scattering-like measurements with tagged neutrinos !**



invariant rest mass of nucleons W

$$W = \sqrt{M_N^2 + 2M_N\omega - Q^2}$$



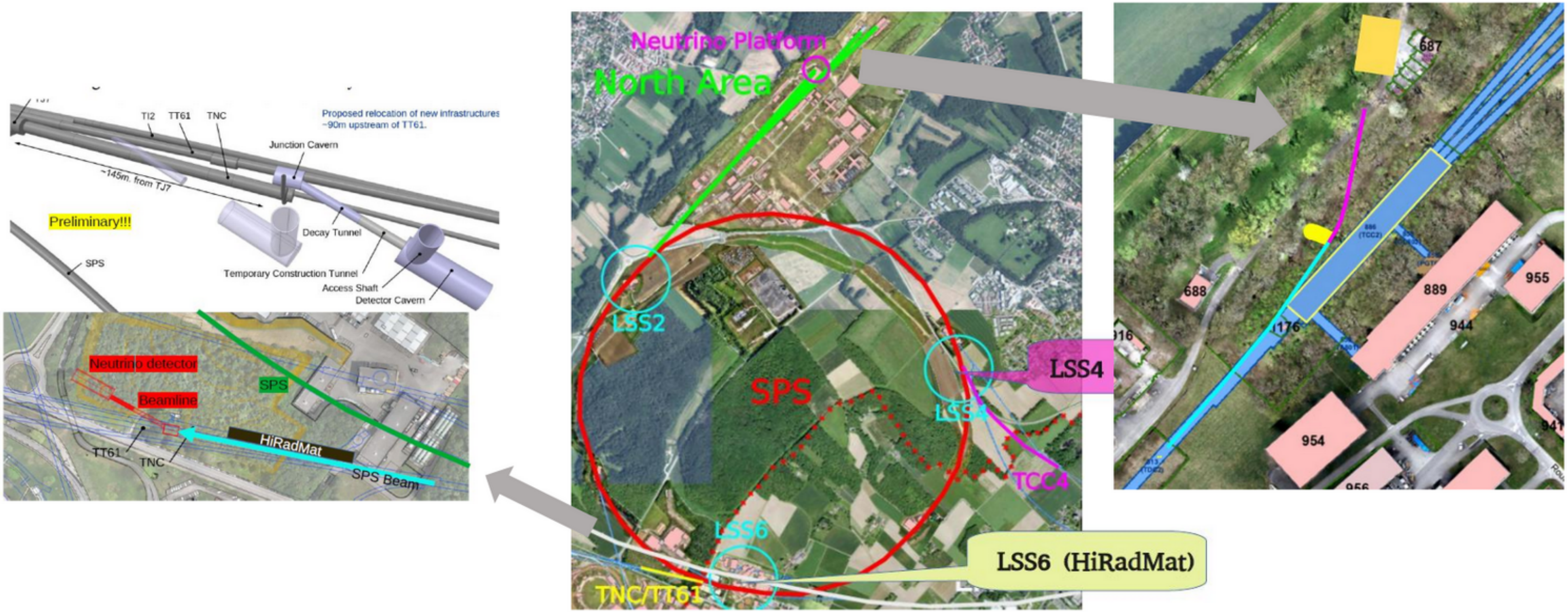
Conclusions

- Improving the 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, and it represents a major advance in the understanding of ν - nuclei interactions.
- **nuSCOPE** offers a unique possibility to provide **high-precision neutrino cross sections at GeV scale**, thanks to the efforts of the ENUBET and NuTag collaborations.
- The **monitored neutrino sample** can :
  - reduce **flux systematic uncertainties** to **1% level** using monitoring of charged leptons in instrumented decay tunnel
  - neutrino energy dependence of cross section **$\sigma(E_\nu)$**, **ν_μ / ν_e** double differential cross-section
  - **PRISM** technique using **narrow band off-axis fluxes** → primary access to **$\sigma(\nu_e)$ / $\sigma(\nu_\mu)$ ratio**
  - constrain far detector **backgrounds** (**NC π^0**)
- The **tagged neutrino sample** further opens the door to a range of game-changing measurements :
  - **event-by-event measurement of neutrino energy**
  - **electron-scattering physics with neutrinos**
- Neutrino tagging would be a paradigm changing for nuclear physics measurements !
- A dedicated **workshop** will be hosted at **CERN** on **October 13 - 14** TBA very soon !

Backup

nuSCOPE implementation at the CERN accelerator complex

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

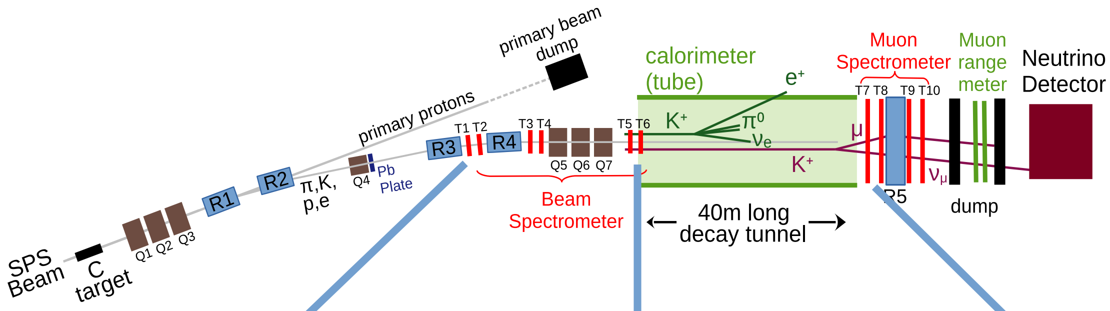


Implementation at CERN : pros and cons

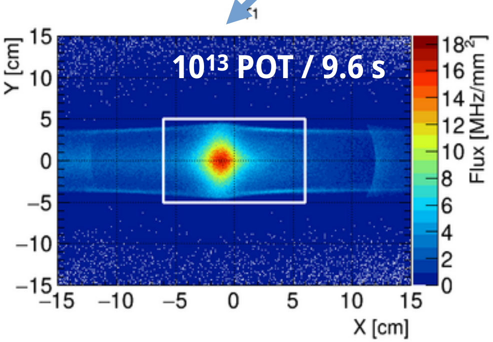
- **ECN4 (North Area, Prevessin) :**
  - A dedicated experimental hall provides greater flexibility for detector installation and the addition of new detectors for cross-section studies with specific targets.
  - Slow extraction is already implemented in LSS2.
  - The beam splitter presents significant 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) – currently our favorite option :**
  - Detectors are located underground.
  - Minimal interference with proton sharing among fixed target experiments.
  - Requires enlargement of existing tunnels to accommodate neutrino detectors.
  - Implementation of a non-local slow extraction is needed, similar to the system used at the PS.

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

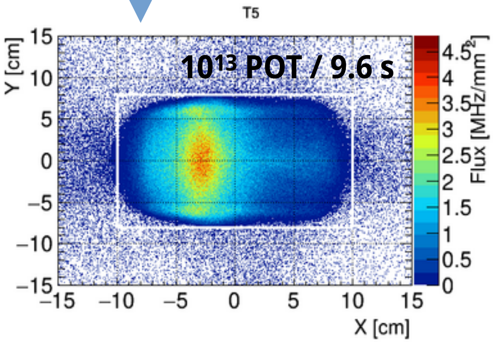
Meson and muon tracking



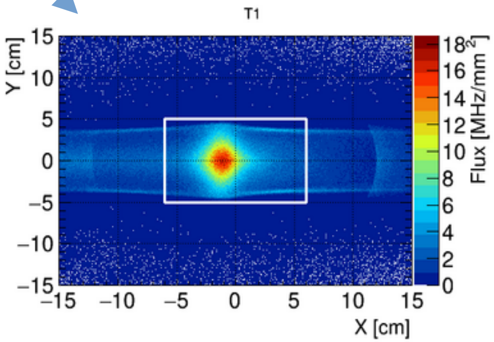
Specifications [units]	Beam Spectro.	Muon Spectro.	LHCb-VELO (2028)	NA62-GTK (since 2014)
Peak Dose [Mrad]	700	60	$> 10^3$	16
Peak Fluence [$1\text{MeV}n_{eq}/\text{cm}^2$]	1×10^{16}	6×10^{14}	5×10^{16}	4.5×10^{14}
Peak Rate [MHz/mm^2]	20	0.6	$10 - 100$	2
Time Resolution [ps]	< 40	< 100	< 50	< 130
Pixel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



12 x 10 cm²



20 x 16 cm²



80 x 100 cm²

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

- **Parent and muon tracking requires a time resolution of O(100 ps) and a detector granularity of 300 μm.**
- **Particle rates in the hottest (central) planes are 20 MHz/mm² for 10^{13} pot in 9.6 s. The peak fluence (non-ionizing dose) is 10^{16} MeV n_{eq} /cm².**
- **We thus benefit from the technology currently being developed for the LHCb velo upgrade and pioneered at the 2 MHz/mm² level by NA62.**

Technical readiness of nuSCOPE

F. Terranova seminar at Imperial College London, UK, 30 May 2025

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

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

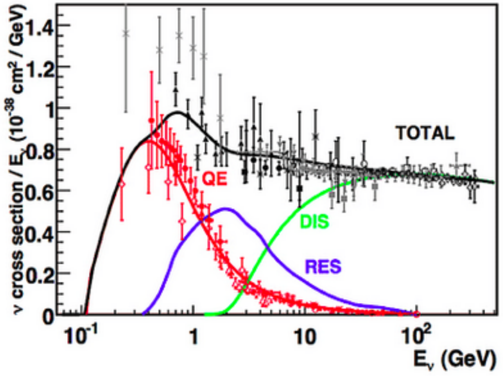
Diagnostics for lepton monitoring/tagging		
Decay tunnel instrumentation	OK	ENUBET R&D (2016-2022)
Hadron dump	in progress	ENUBET+PIMENT R&D (2021-ongoing)
Silicon tracking planes	R&D	The technologies are identified within HL-LHC R&D but not yet fully validated
Outer tracking planes and muon spectrometer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

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

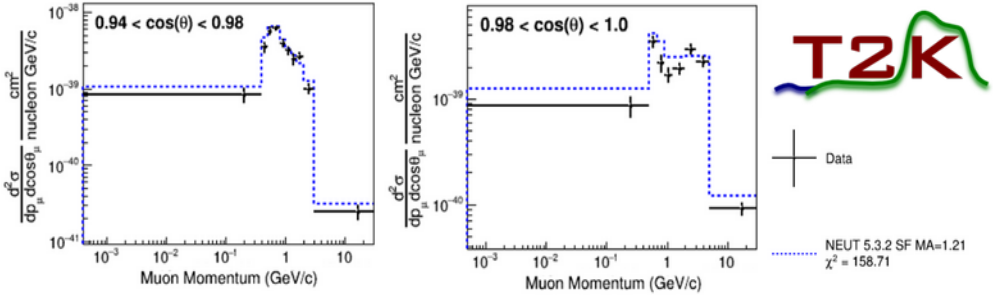
20

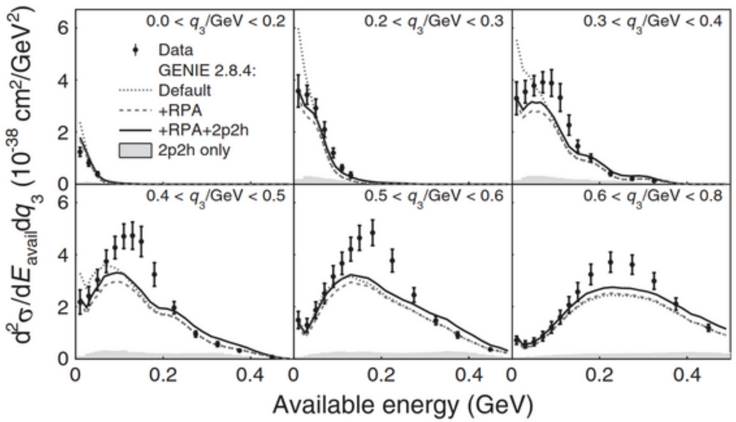
flux averaged ν_μ and ν_e double differential cross section measurements

- The flux averaged ν_μ inclusive cross section measurement using narrow band off-axis fluxes can set a constrain on total neutrino cross section $\sigma(E_\nu)$.
- However, the total cross section $\sigma(E_\nu)$ gets contributions from several channels regulated by different dynamic processes :
  - their relative contribution and underlying physics of each process are pivotal info for the success of future experiments.



- The individual mechanisms can be probed by a variety of measurements, we took inspiration from measurements made by current experiments :
  - **ν_μ CC0π double differential cross section → T2K** : Phys. Rev. D 108, 112009
  - **ν_e CC inclusive double differential cross section → MINERvA** : Phys. Rev. Lett. 116, 071802





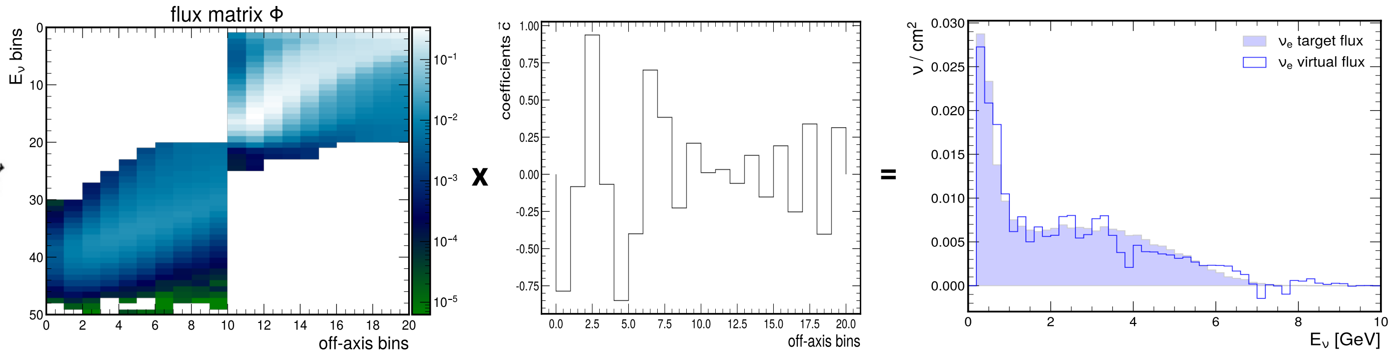
PRISM technique using narrow band off-axis fluxes

- The **PRISM** technique can be used to create virtual fluxes from linear combinations of narrow band off-axis fluxes.
  - **create a virtual electron neutrino flux (target) using linear combinations of real muon netrino fluxes.**

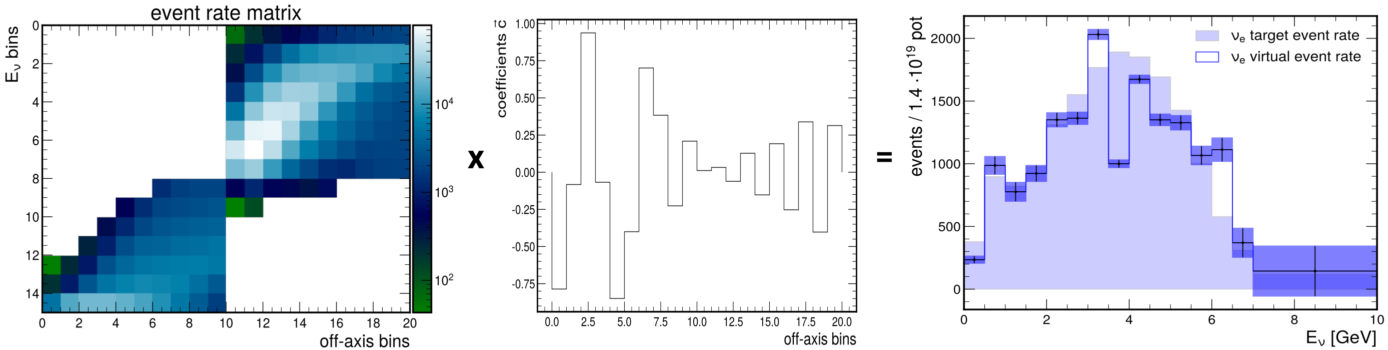
$$\phi(E_\nu) = \sum_j c_j \Phi_j(E_\nu)$$

- the set of linear equations encoded does not have a unique solution : ill-posed linear algebra problem.
- **Tikhonov regularization** : find a stable approximated a solution with less variance; variations between adjacent elements of c are reduced → introduce bias to reduce the variance, adjusted via a regularisation strength.

$$\vec{\phi} = \Phi \cdot \vec{c}$$



$$\vec{n} = N \cdot \vec{c}$$



virtual-flux-integrated ν_μ cross-section measurement with **2%** statistical unc.

ν_e flux-integrated cross-section measurement using the ν_e flux with a statistical error of **~1%.**

projected measurement of **$\sigma(\nu_e)$ / $\sigma(\nu_\mu)$ ratio** averaged over the ν_e flux with a **statistical precision of ~2%**.

$$\frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}} = \frac{N_{\nu_e}}{N_{\nu_\mu}} \cdot \frac{\int \Phi_{\nu_\mu}(E_\nu)\, dE_\nu}{\int \Phi_{\nu_e}(E_\nu)\, dE_\nu}$$

$$\frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}} = 1.02 \pm 0.02$$

PRISM technique using narrow band off-axis fluxes : Tikhonov regularization

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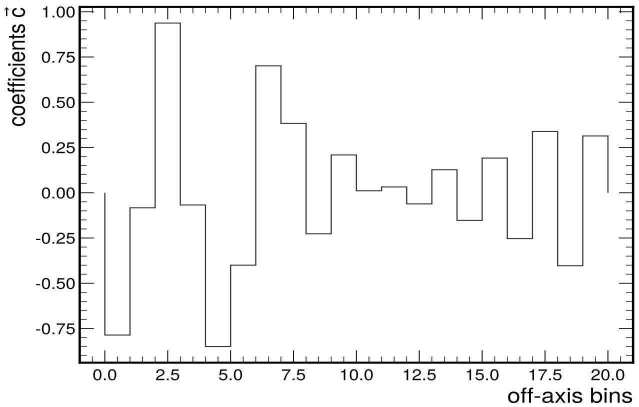
  - **create a virtual electron neutrino flux (target) using linear combinations of real muon netrino fluxes.**
- The set of linear equations encoded does not have a unique solution : **ill-posed linear algebra problem**.
  - solving with least-squares, statistical fluctuations in the target flux lead to large variations.
  - **Tikhonov regularization** : find a stable approximated a solution with less variance, where the variations between adjacent elements of c are reduced.
    This introduces a bias to reduce the variance, which can be adjusted via a regularisation strength.

$$\phi(E_\nu) = \sum_j c_j \Phi_j(E_\nu)$$

$$\vec{c} = \left[\Phi^T \Phi + \Gamma^T \Gamma\right]^{-1} \Phi^T \vec{\phi}$$

$$\Gamma = \tau \cdot A$$



$$A = \begin{bmatrix} 1 & -1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & -1 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & -1 & \dots & 0 & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 & -1 \\ 0 & 0 & 0 & 0 & \dots & 0 & 0 \end{bmatrix}$$

PRISM technique using narrow band off-axis fluxes : Tikhonov regularization

- **Tikhonov regularization** : find a stable approximated a solution with less variance, where the variations between adjacent elements of c are reduced.
  This introduces a bias to reduce the variance, which can be adjusted via a regularisation strength.

$$\phi(E_\nu) = \sum_j c_j \Phi_j(E_\nu)$$

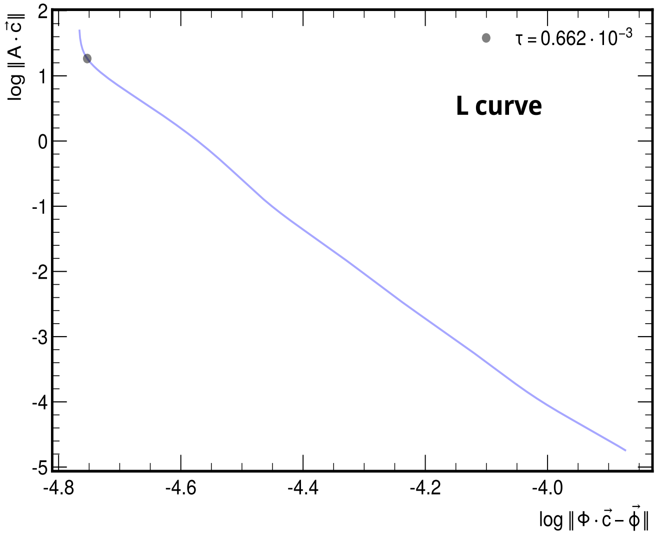
$$\vec{c} = \left[\Phi^T \Phi + \Gamma^T \Gamma\right]^{-1} \Phi^T \vec{\phi}$$

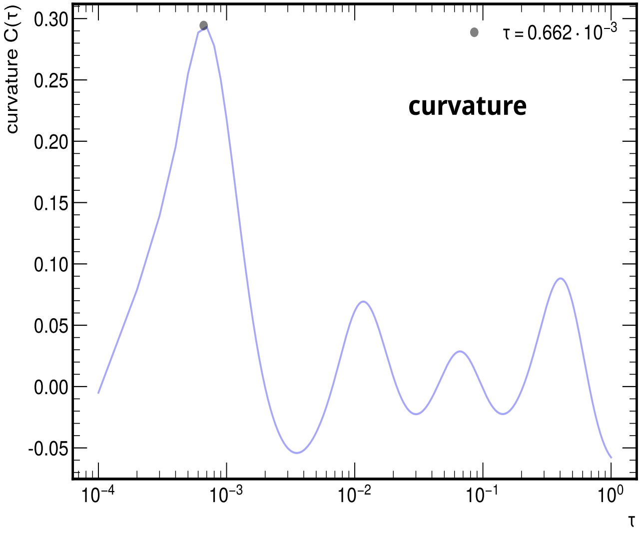
$$L_x = \log \left\| \Phi \cdot \vec{c} - \vec{\phi} \right\|$$

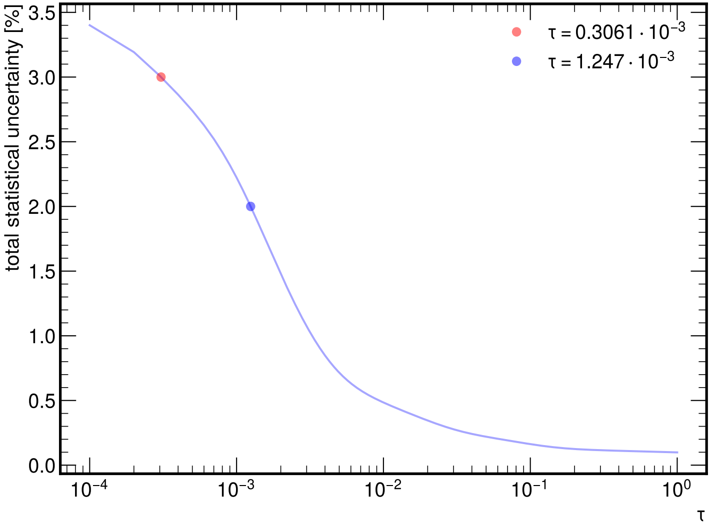
$$L_y = \log \| A \cdot \vec{c} \|$$

$$\mathcal{C} = \frac{d^2 L_y dL_x - d^2 L_x dL_y}{[(dL_x)^2 + (dL_y)^2]^{\frac{3}{2}}}$$

- choose optimum **regularisation strength** corresponding to **2% statistical uncertainty** on total event rate.







The aim of the ENUBET project

- **The purpose of ENUBET**: design a narrow-band neutrino beam to measure
  - **ν cross section** and **flavour** composition at **O(1%) precision** level
  - **ν_μ energy** at **O(10%) precision** level

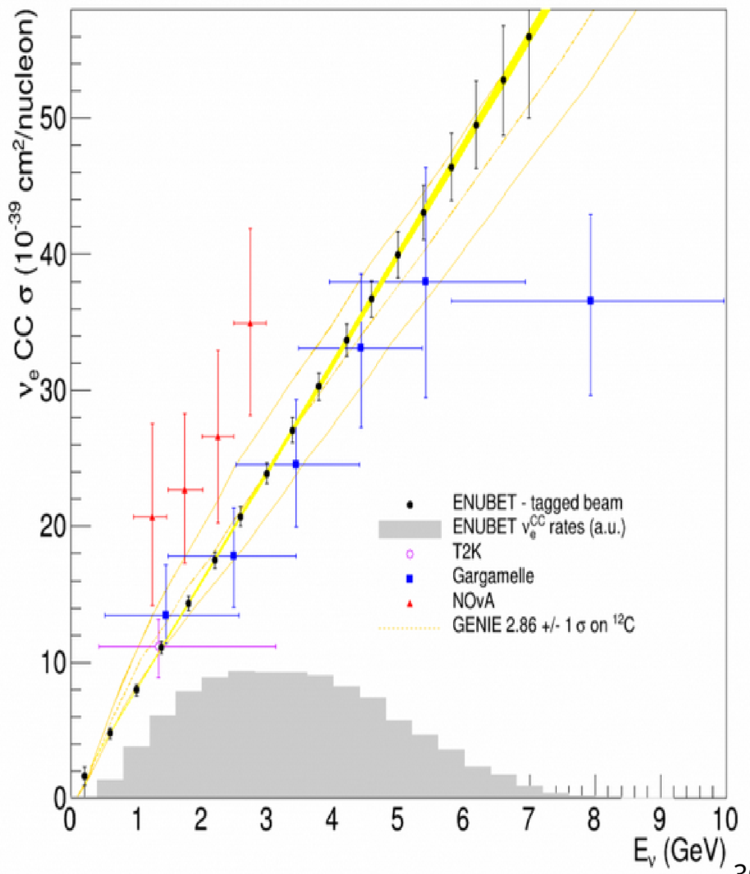
From the "***European Strategy for Particle Physics Deliberation document***" :
(10.17181/ESU2020Deliberation)

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.

From the "**Physics Briefbook for the European Strategy for Particle Physics**" :
(arXiv:1910.11775)

A dedicated study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or nuSTORM) with conclusion in a few years time.

ENUBET impact on ν_e cross section



The ENUBET transfer line : the final design

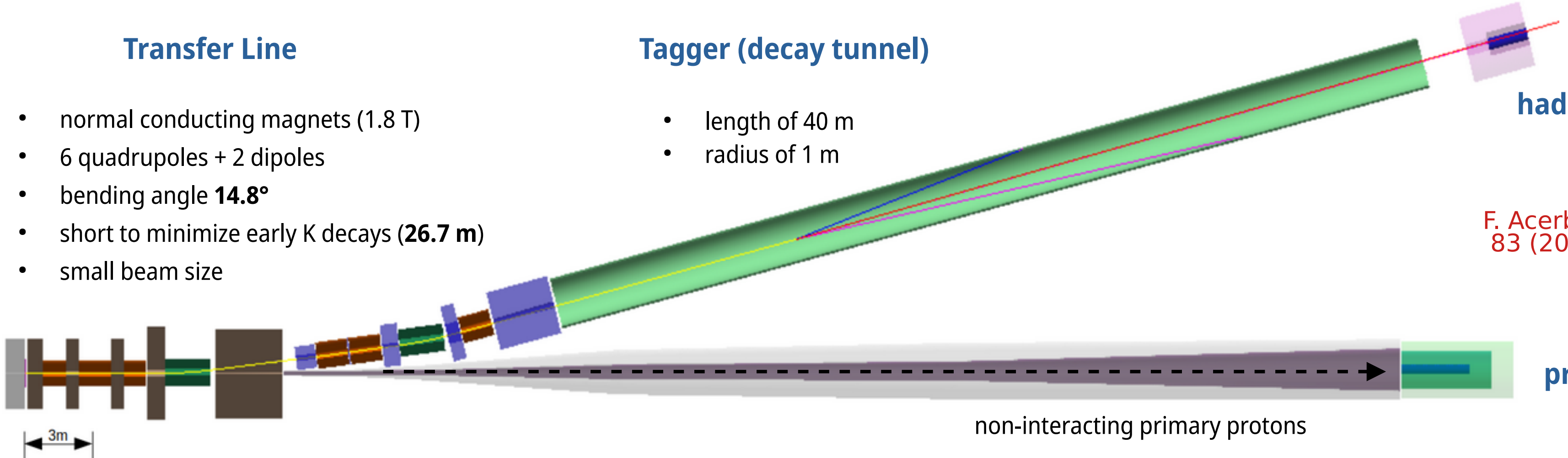
- The beamline is based on **static focusing** elements ("direct current"), i.e. **without** employing a **pulsed magnetic horn** :
  - **slow extraction of primary protons** ⇒ full intensity continuously extracted in few seconds (**~ 2 sec**)
    - particle rate in the tunnel reduced at a sustainable level for detectors (< 100 kHz/cm^2)
    - static focusing elements : **dipoles** and **quadrupoles** ⇒ cost-effective and operationally more stable
  - **short length** to minimize kaon decays ⇒ w/ L = 20 m about 30% of K are lost, and K/π abundance ratio drops by ~ 25%
  - optimized **graphite target** (L = 70 cm, R = 3 cm)
  - **tungsten foil** (5 cm) after target to screen e^+ background
- **Narrow-band beamline**: secondary mesons K^+ / π^+ selected w/ **p = 8.5 GeV/c ± 10%**. → Optimized for the DUNE r.o.i. (E_ν ~ 3 GeV)

Transfer Line

- normal conducting magnets (1.8 T)
- 6 quadrupoles + 2 dipoles
- bending angle **14.8°**
- short to minimize early K decays (**26.7 m**)
- small beam size

Tagger (decay tunnel)

- length of 40 m
- radius of 1 m



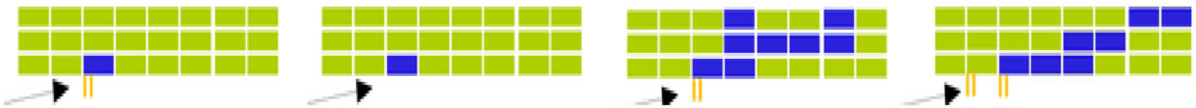
F. Acerbi et al. EPJ C 83 (2023) 964

The instrumentation of the decay tunnel

- Design of a compact, efficient and radiation-hard detector with **e^+ / π^+ / μ^+ separation capabilities** using a cost-effective technology.
- The decay tunnel is **40 m** long and instrumented with **3 radial layers of longitudinally segmented calorimeter modules** and with a **system for photon rejection** made by plastic scintillator rings.

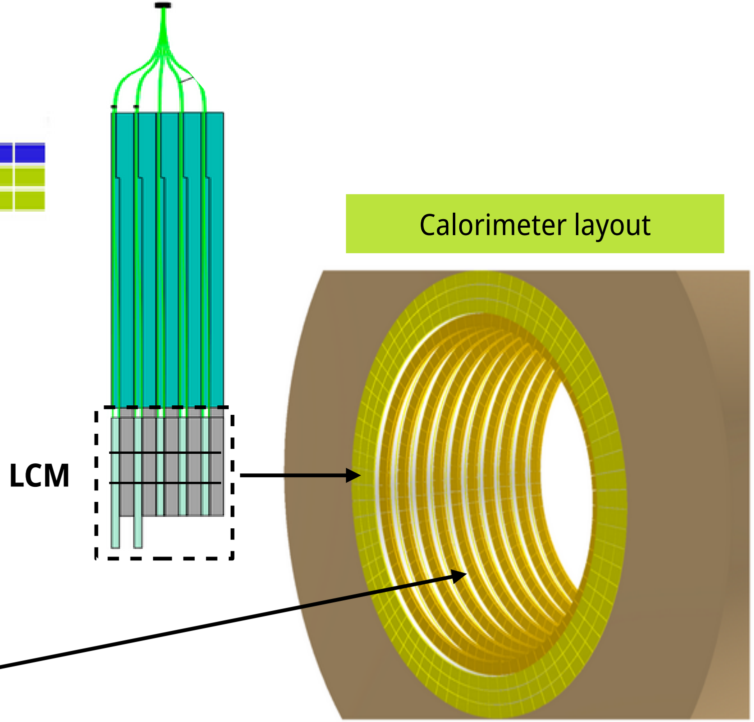
Lateral readout Compact Modules (LCMs)

- **Sampling calorimeter** : stack of 1.5 cm iron slabs interleaved w/ 0.7 cm plastic scintillator tiles.
- LCM : 3 x 3 x 11 cm^3 (= 4.3 X_0)
- **Longitudinal segmentation** ⇒ exploit event topology for **e^+ / π^+ / μ^+ PID**



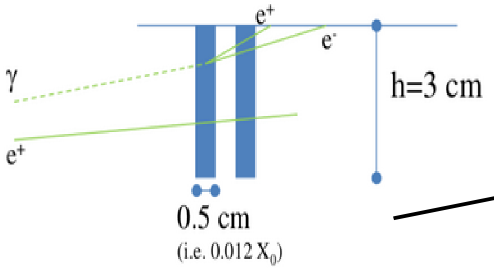
e^+ topology (signal) | **π^0 topology (bkg)** | **π^+ topology (bkg)** | **μ^+ topology**

- Scintillation light collected by WLS fibers and readout by external SiPMs shielded by 30 cm of borated poliethylene (BPE) ⇒ factor 18 reduction in neutron fluence



Photon Veto

- System for **π^0 rejection**
- **Timing** : time resolution σ_t ~ 400 ps
- Scintillator doublets : 3 x 3 x 0.7 cm^3 (= 0.012 X_0)



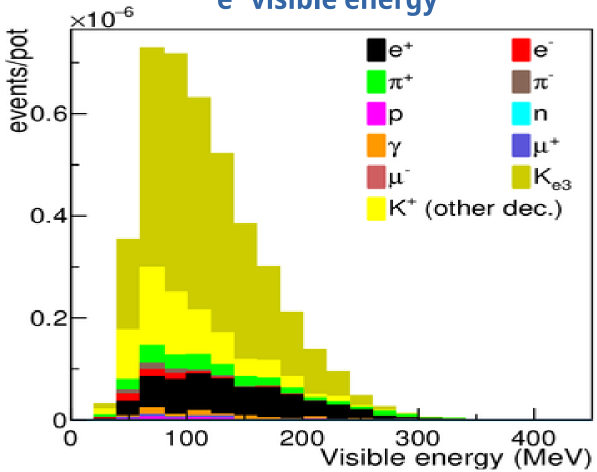
Charged lepton reconstruction and identification performance

- **Full GEANT4 simulation of the instrumented decay tunnel** :
  - validated by prototype tests at CERN in 2016-2018
  - hit-level detector response
  - pile-up effects included (waveform treatment in progress)
  - **event building** and **PID** algorithms

Reconstruction and event selection :

1. **Event bulding** : association of energy deposition patterns compatible in space and time w/ an EM shower (e^+) or a straight track (μ^+)
2. **Identification e^+ / π^+ / μ^+ / γ** : multivariate analysis (MLP-NN of TMVA) trained on a set of discriminating variables :
   - energy deposition patterns in the calorimeter
   - event topology
   - photon veto

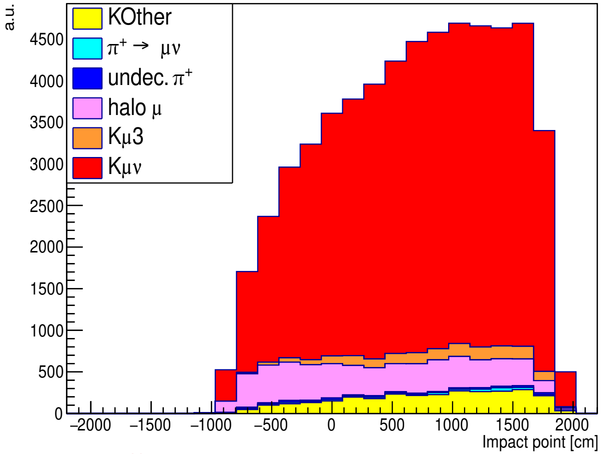
e^+ visible energy



Selection of e^+ from K_{e3} :

S/N = 1.8
ε = 25.8%

μ^+ impact point along the calorimeter



efficiency ~ 53% geometrical

Selection of μ^+ from $K_{\mu\nu}$:

S/N = 6.3
ε = 37.4 %

Time tagging in ENUBET

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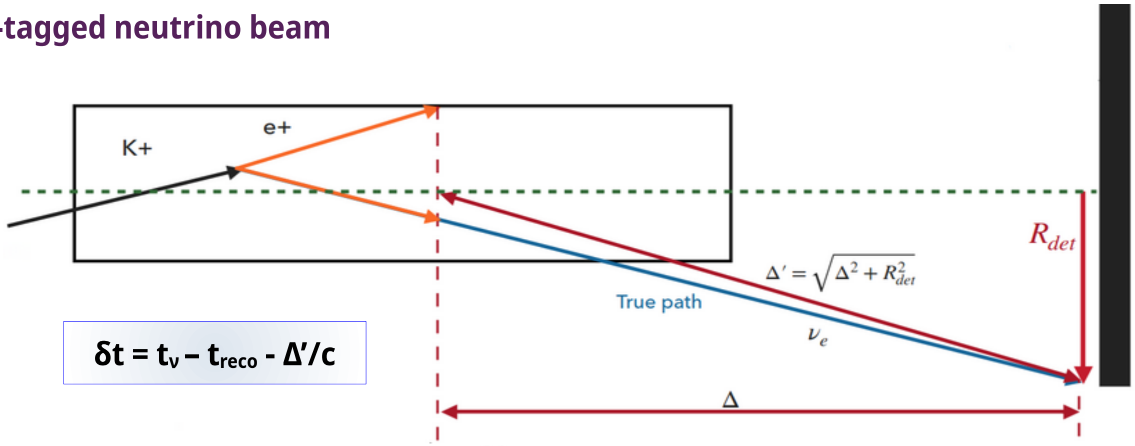
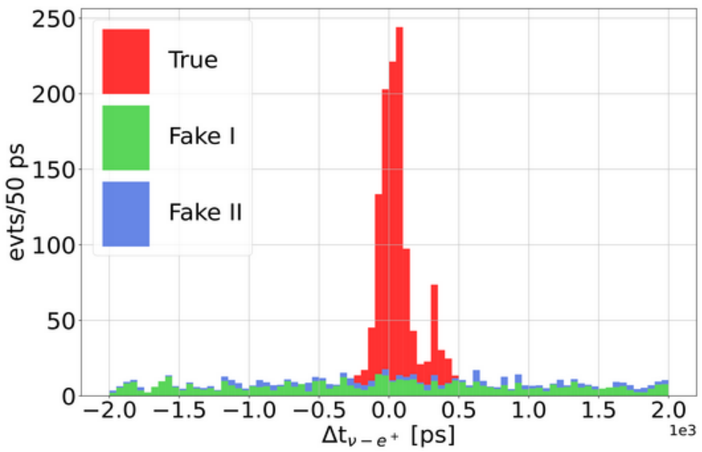
- Investigating the possibility to operate ENUBET as a **time-tagged neutrino beam**
  - **Time coincidences** of ν_e and e^+
  - **Flavour** and **energy** determination enriched by charged lepton observation at decay level

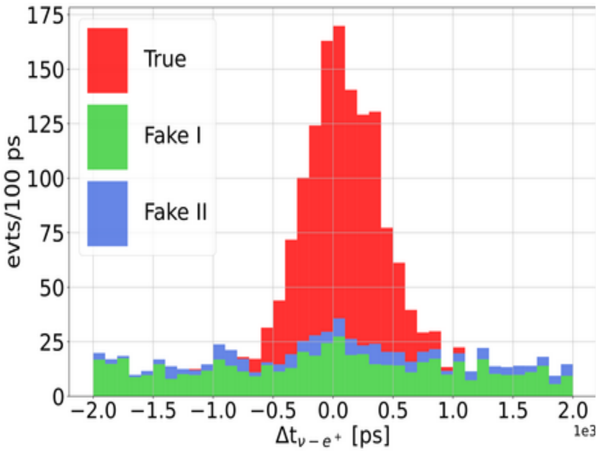


$\delta t = t_\nu - t_{reco} - \Delta'/c$

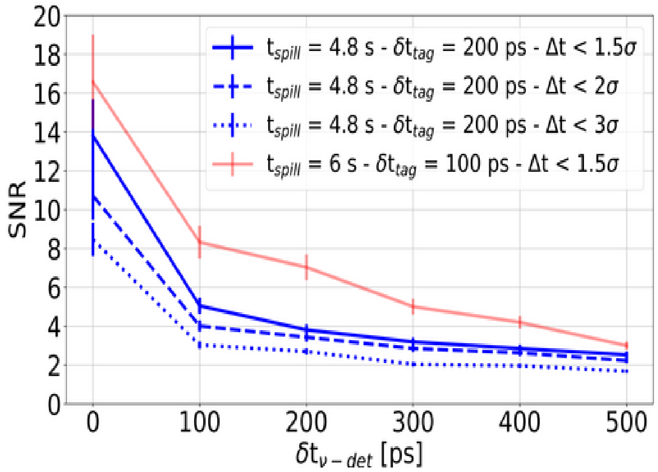
- Employed full beamline simulation and PID algorithms



Infinite time-resolution both for tagger and ν-detector
Intrinsic 74 ps spread (1σ) due to the size of calorimeter modules (11 cm) and indetermination of the decay point



Smearing of the distribution
δt_{tag} = 200 ps and δt_{det} = 200 ps

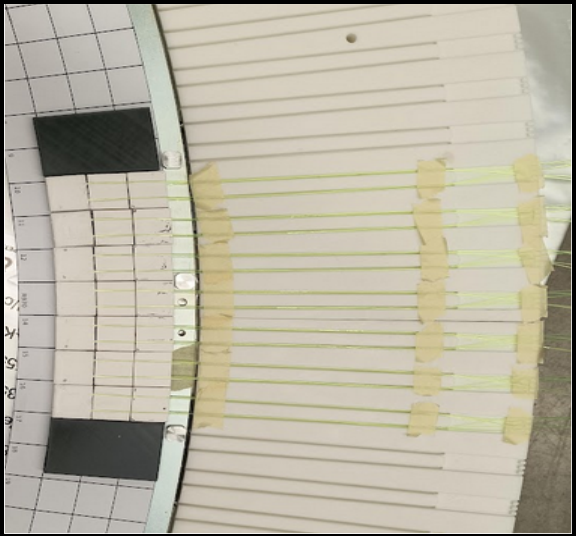


ε = 75.6% and S/N = 3.8
with δt_{tag} = 200 ps and δt_{det} =200 ps

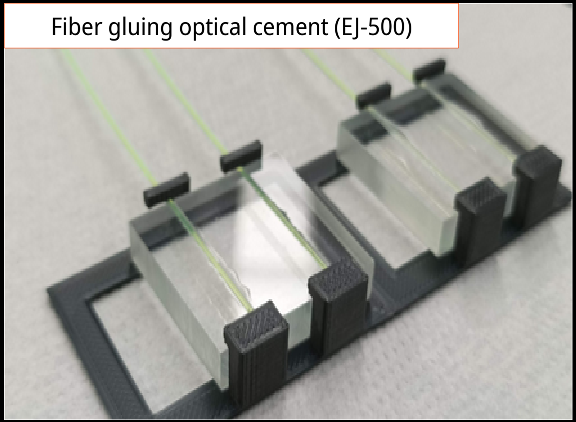
The ENUBET demonstrator: construction at INFN-LNL

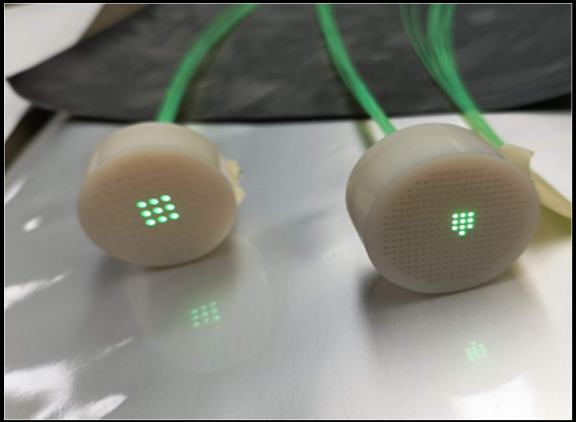
The ENUBET demonstrator: construction at INFN-LNL [cont’]


EJ-204 scintillator tiles – grooves for WLS fibers

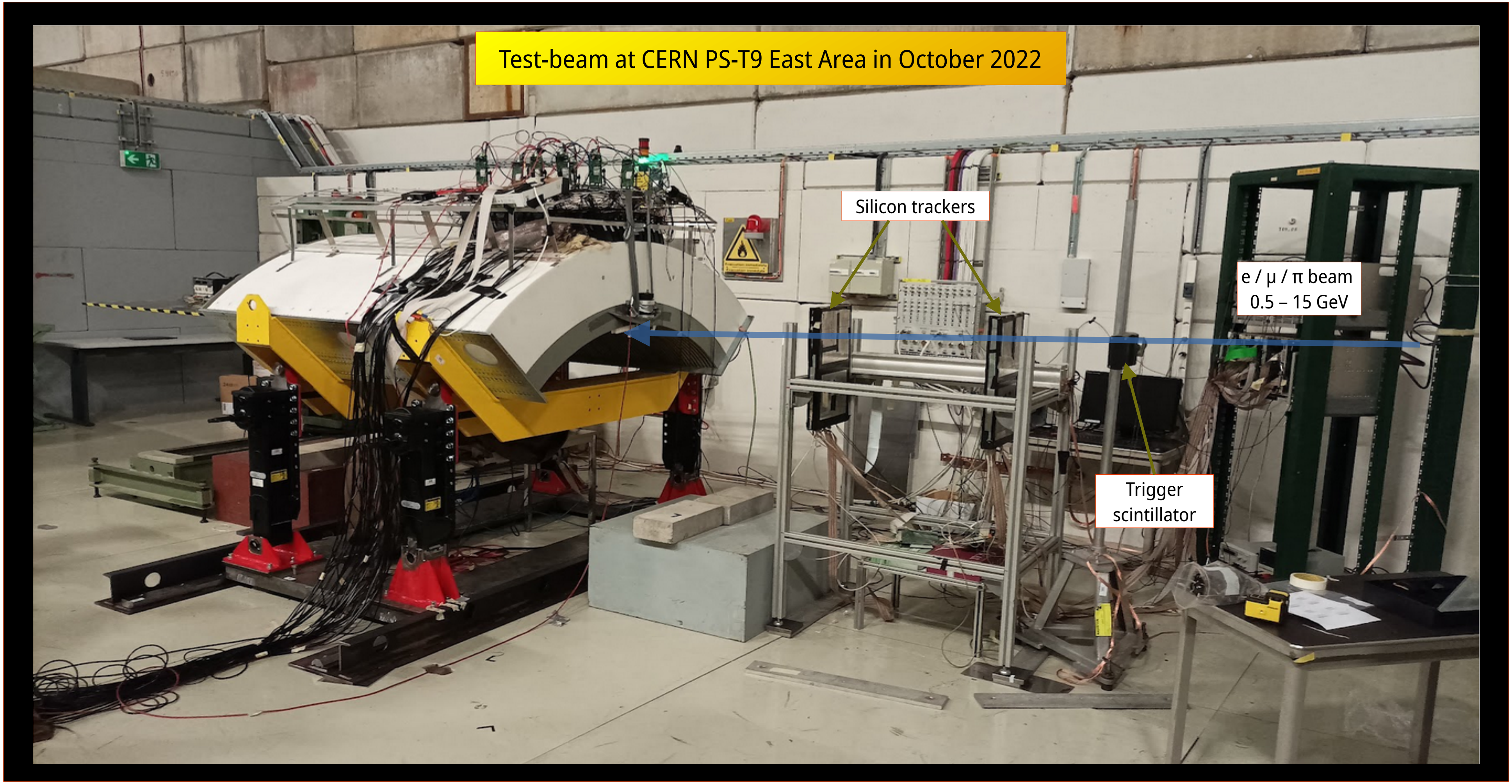



Tile painting (EJ-510 / Ti02)

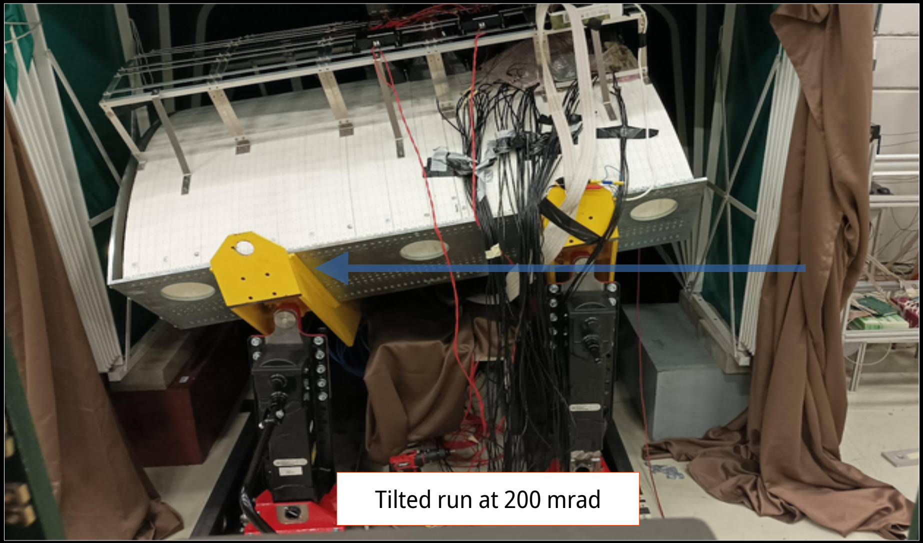

Fiber gluing optical cement (EJ-500)

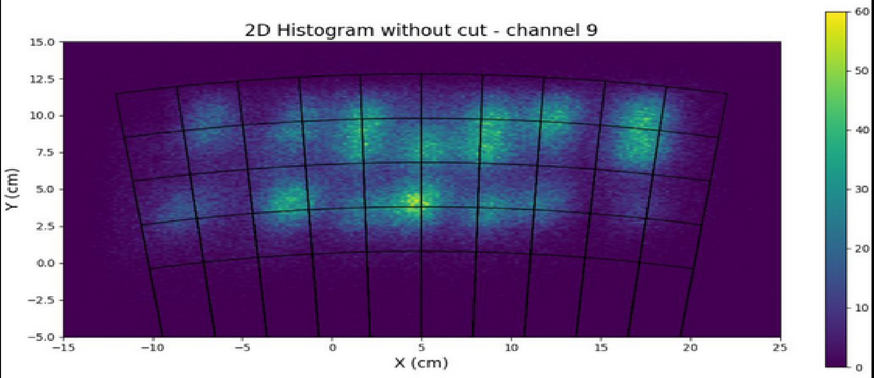


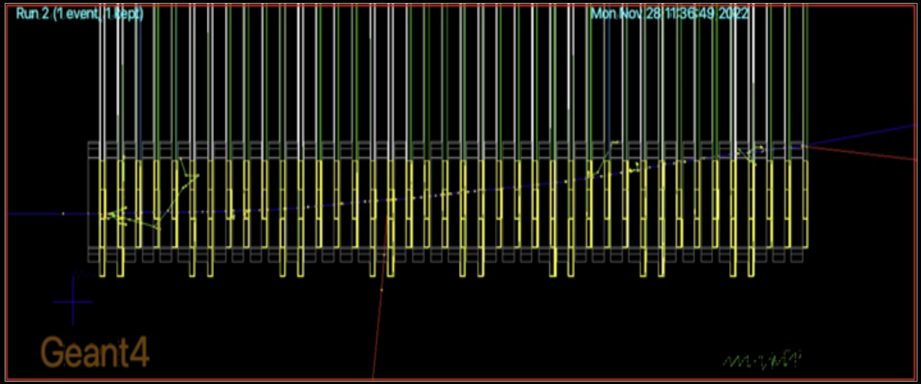
The ENUBET demonstrator: test-beam at CERN in fall 2022



The ENUBET demonstrator: test-beam at CERN in fall 2022 [cont']

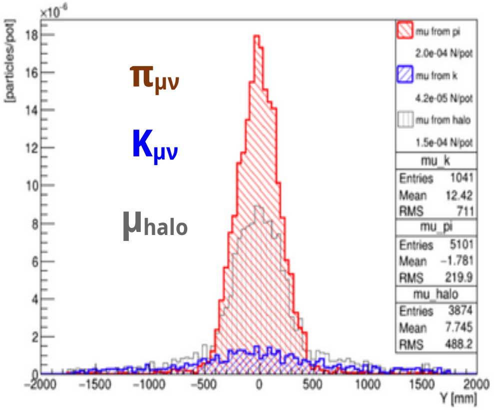


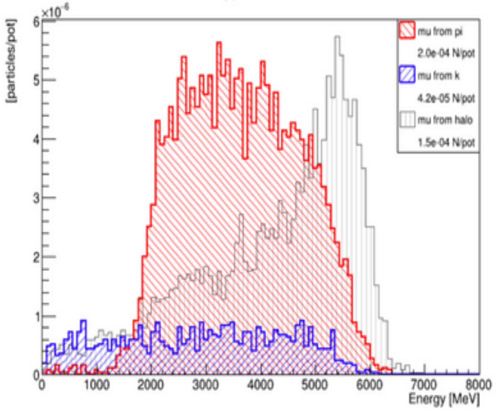


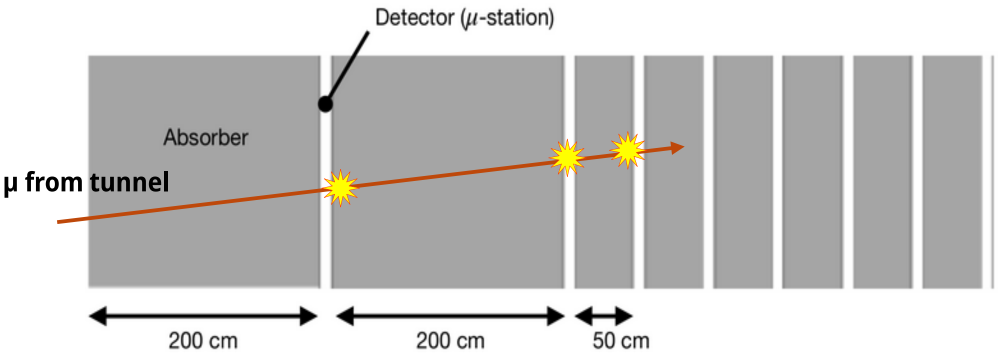


The instrumentation of the hadron dump

- Reconstruction of **muons** from **$\pi_{\mu\nu}$** (**$\pi^+ \rightarrow \mu^+ \nu_\mu$**) decay to constrain the **low energy ν_μ flux**.
- Low angle muons : out of tagger acceptance, muon stations after hadron-dump are needed.







Exploit differences in distributions to disentangle components

- Hottest detector (upstream station) : it must be capable to cope with ~ 2 MHz/cm^2 muon rate and ~ 10^{12} 1 MeV-n$_{eq}$ / cm^2.
- Exploit:
  - correlation between number of traversed stations (muon energy from range-out) and neutrino energy.
  - difference in distribution to disentangle signal from halo-muons.
- Possible candidate technology : fast Micromega detectors with Cherenkov radiators (PIMENT project).