# Towards the implementation of the ENUBET neutrino cross section experiment at CERN

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**On behalf of the ENUBET collaboration**

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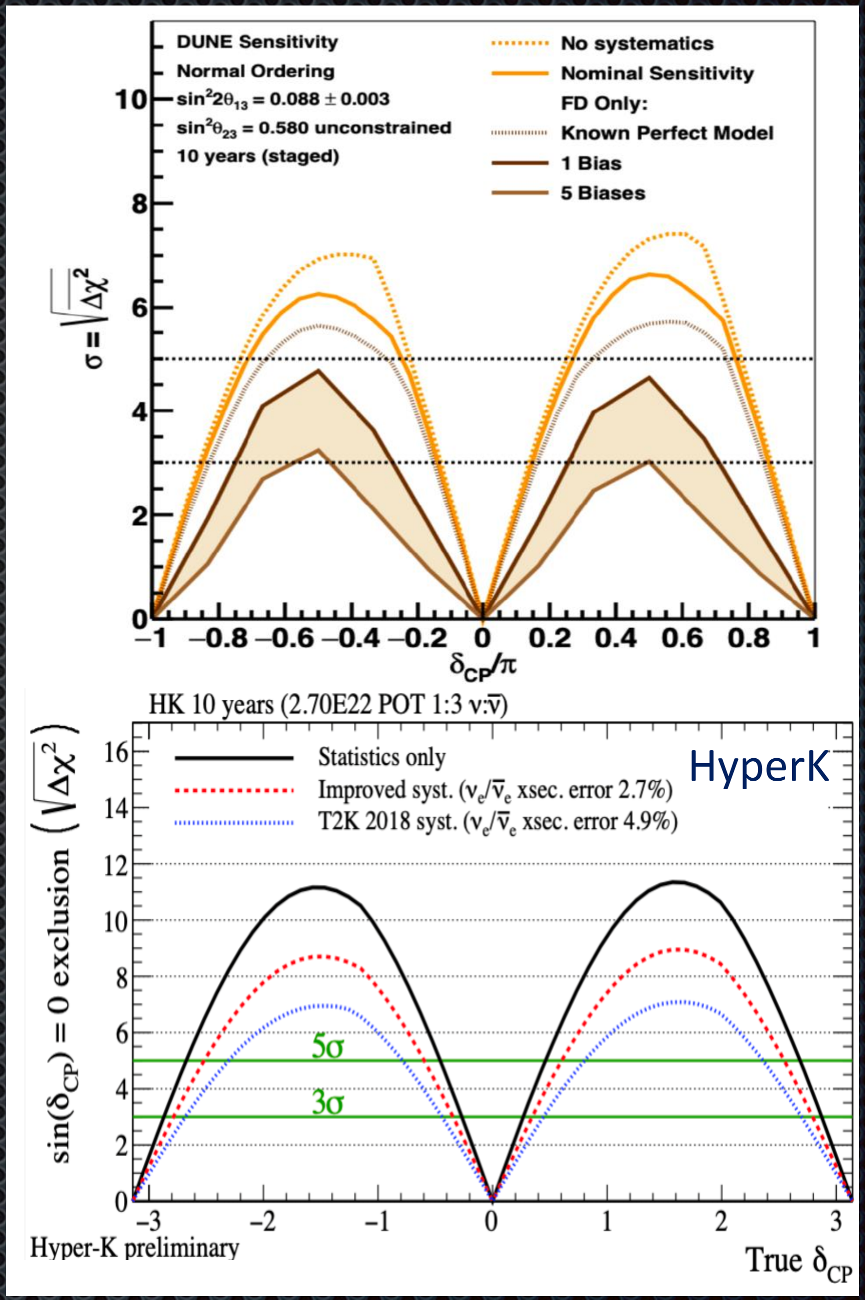
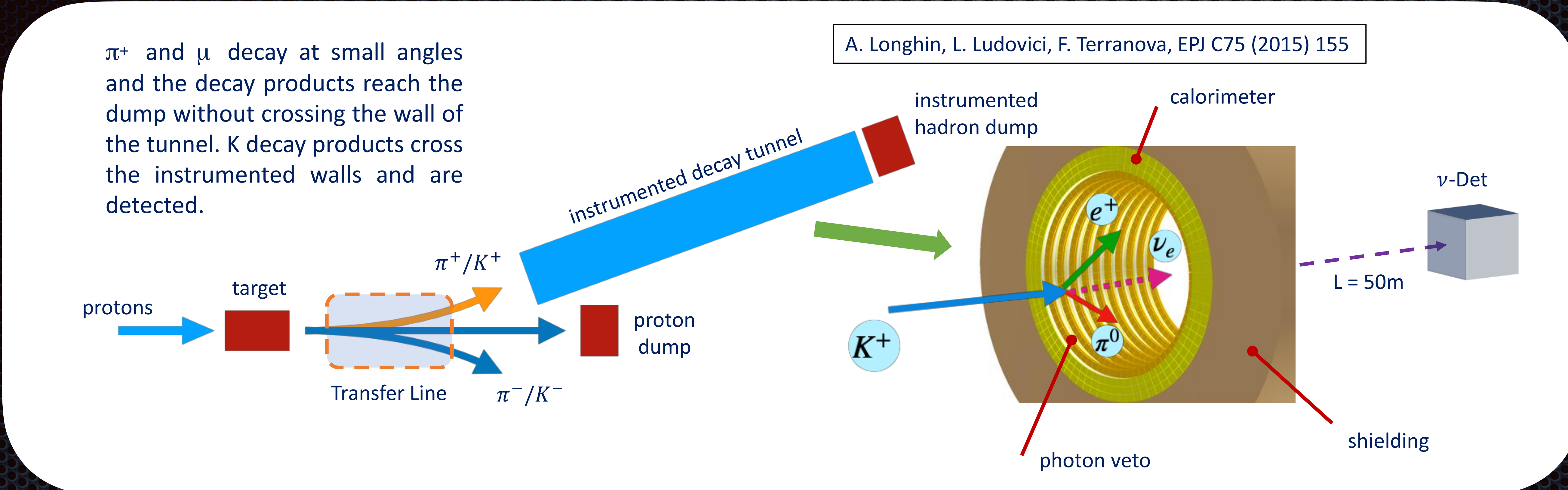
# Introduction

- Neutrino oscillation physics has moved **from discovery to precision** era, and next generation experiment such as DUNE and Hyper-Kamiokande aims at measuring the $\delta_{CP}$ phase to assess a possible CP violation in the leptonic sector.
- The sensitivity of future experiments is mostly limited by the systematics related to the **cross sections knowledge**, which are known today with an error at the level of 10 to 30%.
- The available measurements of cross sections are in turn dominated by the uncertainty on the neutrino flux which is generally at the level of 10%.
- As stated in the European Strategy for Particle Physics Deliberation document, "To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required."




ENUBET is a development on the beam side for a strong reduction of the systematics related to the flux and cross section knowledge to reach a precision at the level of 1% on the neutrino cross section

# ENUBET: the first monitored neutrino beam



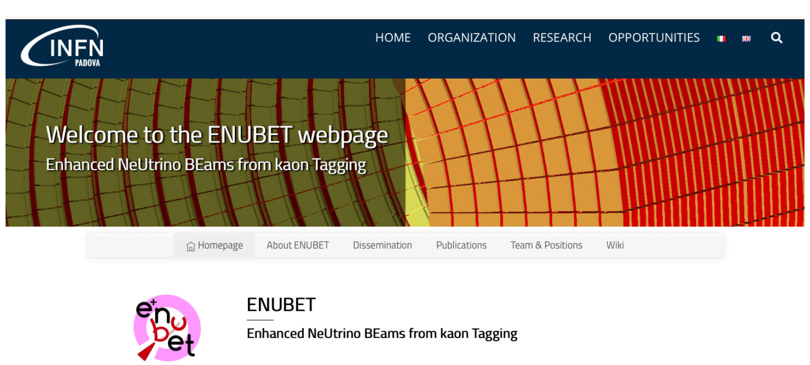

- **ENUBET** (Enhanced NeUtrino BEams from kaon Tagging) is the project for the realization of the first monitored neutrino beam. It is a **conventional beamline** with an instrumented decay tunnel to **measure the neutrino flux directly counting the leptons**.
- With the proposed approach most systematics contributions are avoided: hadron production, beam line geometry and focusing, and protons on target.
- **ERC project (2016-2022)**: measurements of positions from $K_{e3}$ decays ($K^+ \rightarrow \pi^0 e^+ \nu_e$) in the instrumented decay tunnel to determine the $\nu_e$ flux.
- **CERN experiment NP06 since 2019**: extend measurement in the decay tunnel to $\mu$ from $K_{\mu\nu}$, and replace the hadron dump with a muon range meter to measure $\mu$ from $\pi_{\mu\nu}$ to determine the $\nu_\mu$ flux.

# ENUBET: the collaboration

**17 institutes from 6 countries**

**Official web page**

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




**71 physicists**

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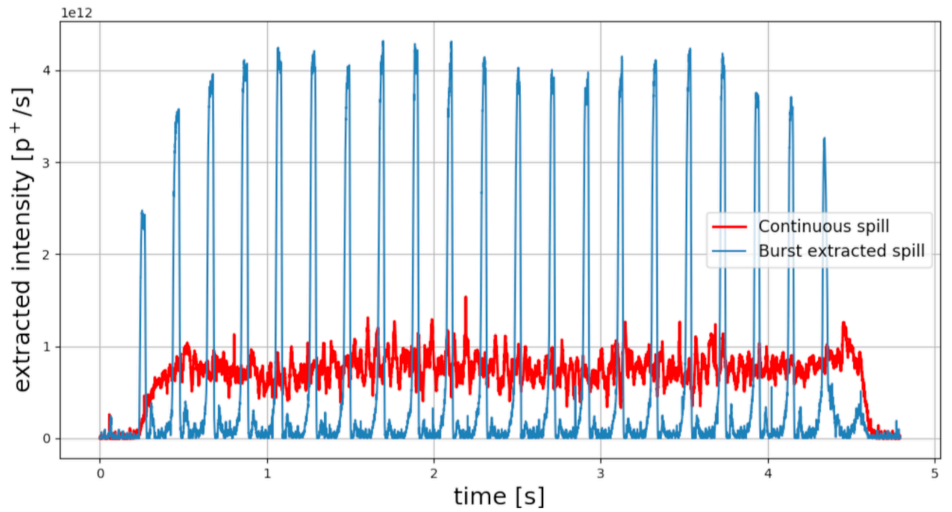
# Beamline

- Claiming an overall systematic budget <1% requires an end-to-end simulation of the neutrino beamline. Such simulation work has been carried out based on CERN-SPS.
- The first option was based on standard **horns** with **slow extraction rate** to avoid pile-up and saturation of the instrumentation in the tunnel.




Demonstration of extraction with 10ms pulse every 100ms achieved at CERN SPS in 2018

- The 2020 design is based on the "**static focusing system**" obtained using dipoles and quadrupoles for a continuous extraction in 2 seconds.
- The design was successful resulting in a reduction of the neutrino flux by a factor of 2 but with protons extracted on a much larger timescale, reducing therefore the pile-up by more than one order of magnitude.

# Beamline (2)

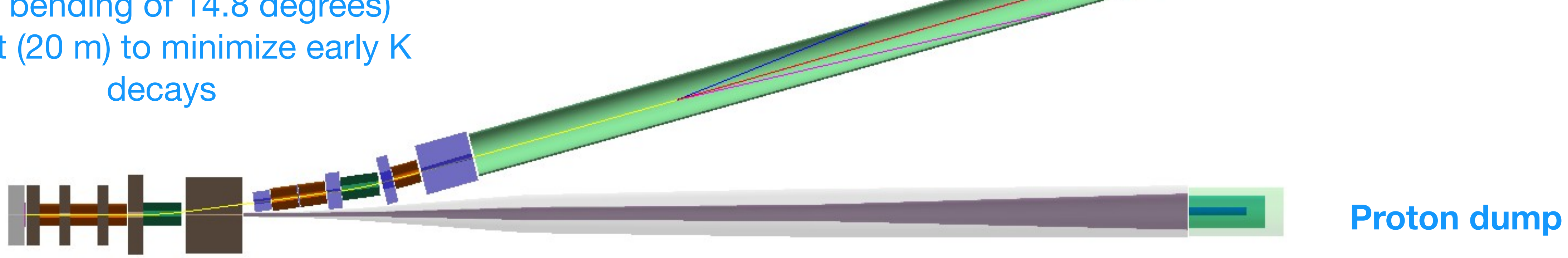
- The 14.8 degrees **large bending** helps reducing muons background and $\nu_e$ from early decays.
- The transfer line was optimized with G4Beamline to have a **narrow band beam** (asking for 5% momentum bite centered at 8.5 GeV/c) to study particle transport and interactions.
- The length of the transfer line (26.7 m) is optimized to reduce the K decays (loss of 30%).
- The optimization included the graphite target (70 cm long and 3 cm radius), the different absorbers, in particular the 5 cm tungsten foil downstream (to reduce the positrons background).
- FLUKA was used to study the irradiation of the different elements and to evaluate the hadron production from protons on target
- The two dumps (graphite, aluminium and iron layers) were optimized to avoid backscattering flux in the tunnel.

**Transfer line**

- Normal conducting magnets
- Quadrupoles + 2 dipoles (1.8 T, total bending of 14.8 degrees)
- Short (20 m) to minimize early K decays

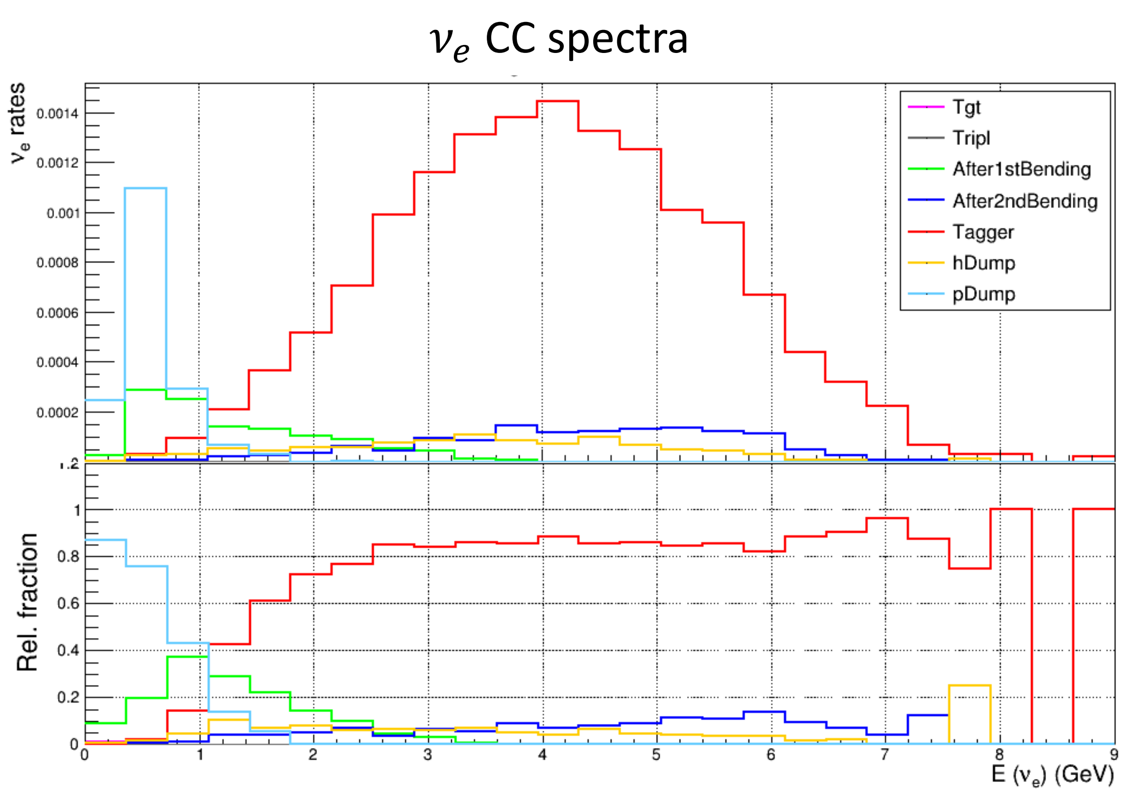
**Tagger (decay tunnel)**

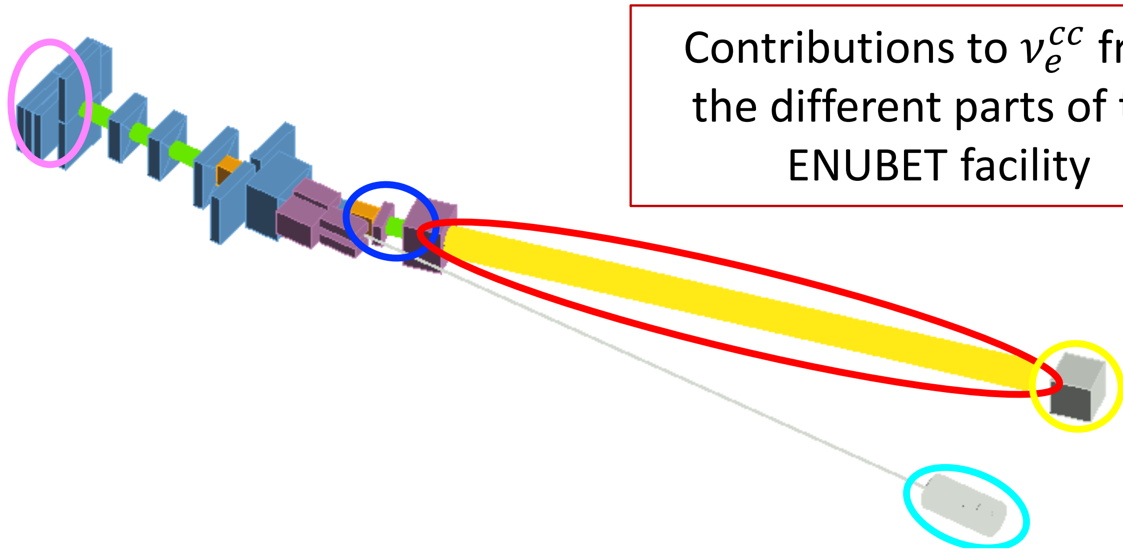
- 40 m long
- 1 m radius



# Neutrino beam: $\nu_e$ CC

- Assuming a **500 t detector** (such as Protodune-SP/DP@CERN) at **50 m** from the end of the tunnel, the **SPS** as accelerator with **4.5 x $10^{19}$ p.o.t. per year**, we expect a statistics of **$10^4$ $\nu_e$ CC in about 2 years**.
- For neutrinos with energy above 1 GeV, **80%** of the $\nu_e$ is produced by decays in the tunnel and it can therefore be **monitored**.
  - ➡ The component below 1 GeV comes from the proton dump and it can be easily discarded with an energy cut.
  - ➡ The unmonitored component above 1 GeV is due to elements before the tagger and from the hadron dump and the knowledge of such a component is based on the simulation.

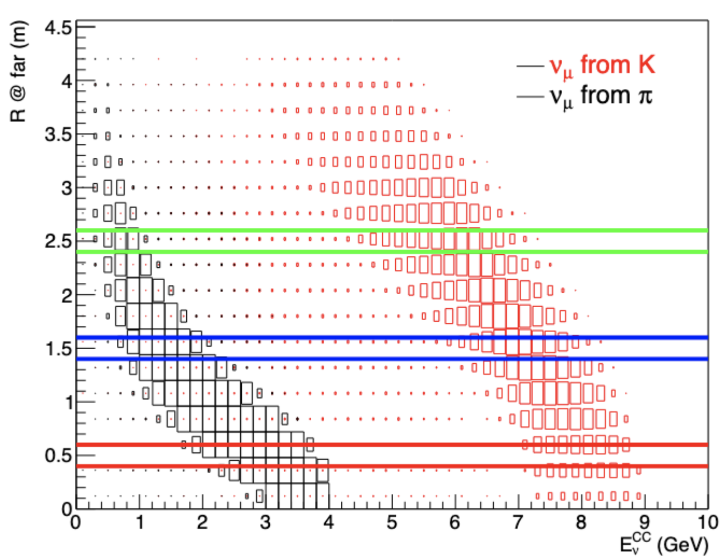


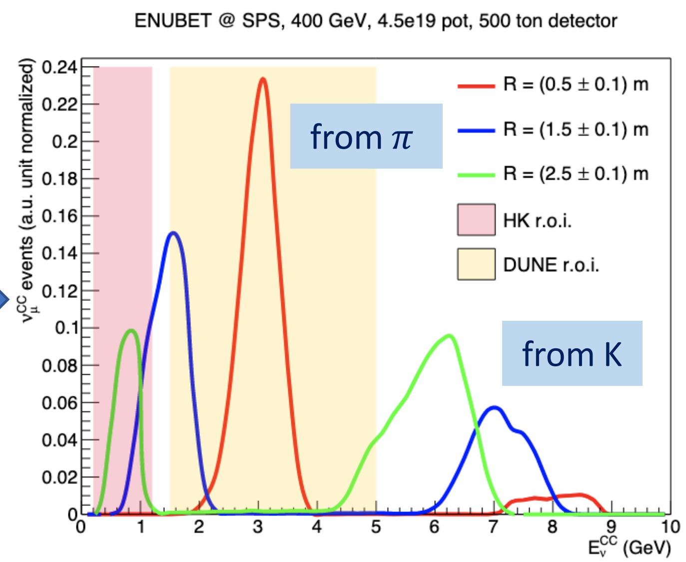
Contributions to $\nu_e^{CC}$ from the different parts of the ENUBET facility

# Neutrino beam: $\nu_\mu$ CC

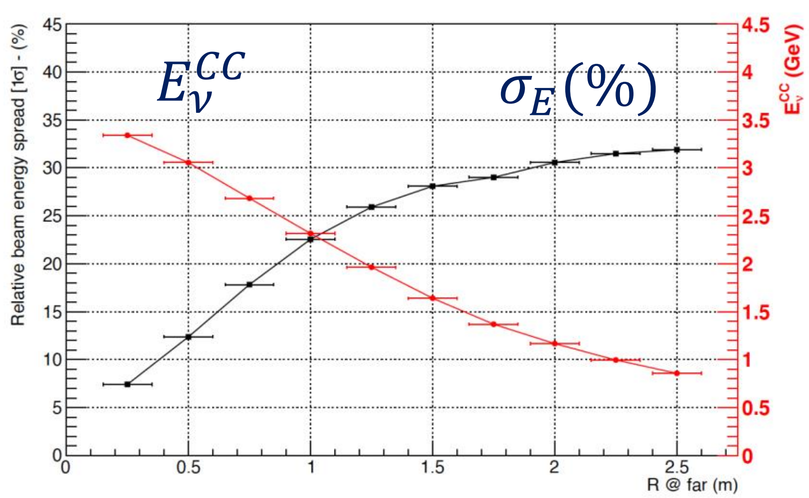
- Assuming a **500 t detector** (such as Protodune-SP/DP@CERN) at **50 m** from the end of the tunnel, the **SPS** as accelerator with **4.5 x $10^{19}$ p.o.t. per year**, we expect a statistics of **$10^6$ $\nu_\mu$ CC in about 2 years**.
- With the **narrow band off axis technique** we have a strong **correlation between** the neutrino energy **$E_\nu$** and the radial distance of the interaction vertex from the beam axis **R**.
- A precise determination of $E_\nu$ can be obtained without relying on the final state particles in $\nu_\mu$ CC interactions.
  - ➡ 8-25% $E_\nu$ resolution from $\pi$ in DUNE energy range.
  - ➡ 30% $E_\nu$ resolution from $\pi$ in HyperK energy range (transfer line optimized for DUNE with 8.5 GeV beam)
  - ➡ Ongoing R&D for optimization of multi momentum beam line (4.5, 6 and 8.5 GeV) for DUNE and HK.




select slices in R windows




$\pi$/K populations well separated




from pion peaks at different R

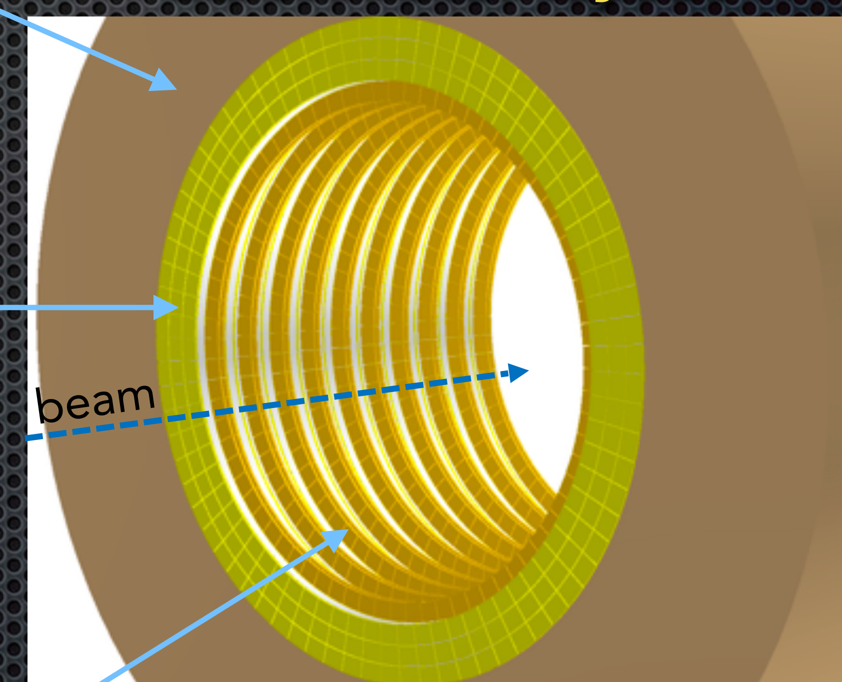
# Decay tunnel instrumentation

- The concept of the tagger is based on 3 layers of longitudinally segmented calorimetric modules for a $e^+/\pi^+/\mu^+$ separation, and a photon veto.

**Shielding**

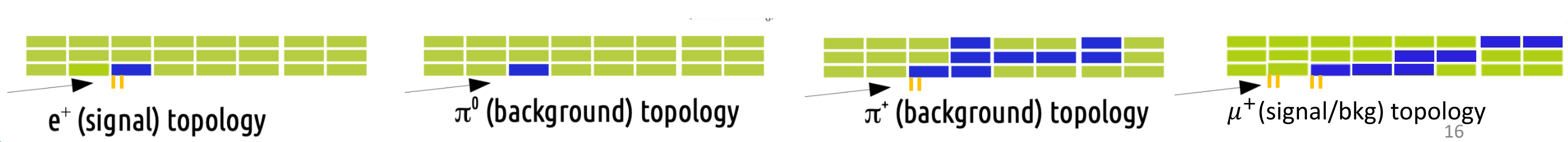
- 30 cm of borated polyethylene.
- SiPMs on top (reduction of a factor of 18 in neutron flux).

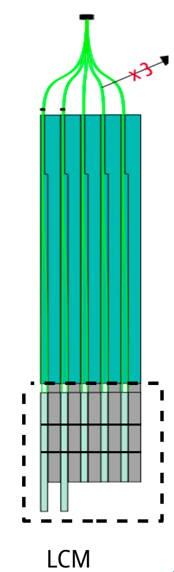
**Calorimeter layout**




**Calorimeter**

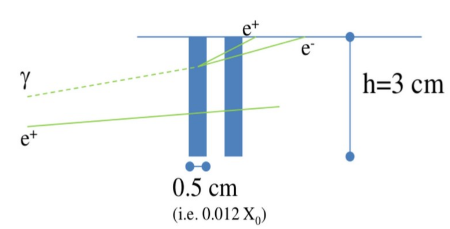
- Three radial layers of Lateral readout Calorimetric Modules (LCM).
- Sampling calorimeter: each LCM is a sandwich of 5 x 0.7 cm plastic scintillator interleaved with 5 x 1.5 cm of iron absorber.
- Each LCM is 3 x 3 x 11 $cm^3$ (4.3 $X_0$).
- The scintillation light is extracted with 30 cm WLS fibers to SIPMs.




**Photon veto**

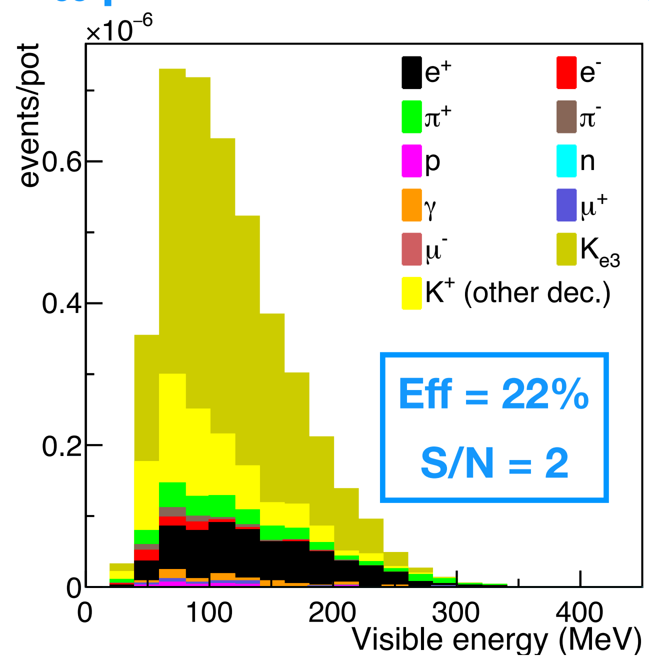
- Plastic scintillator tiles arranged in doublets forming inner rings.
- Time resolution of about 400 ps.



# Lepton reconstruction

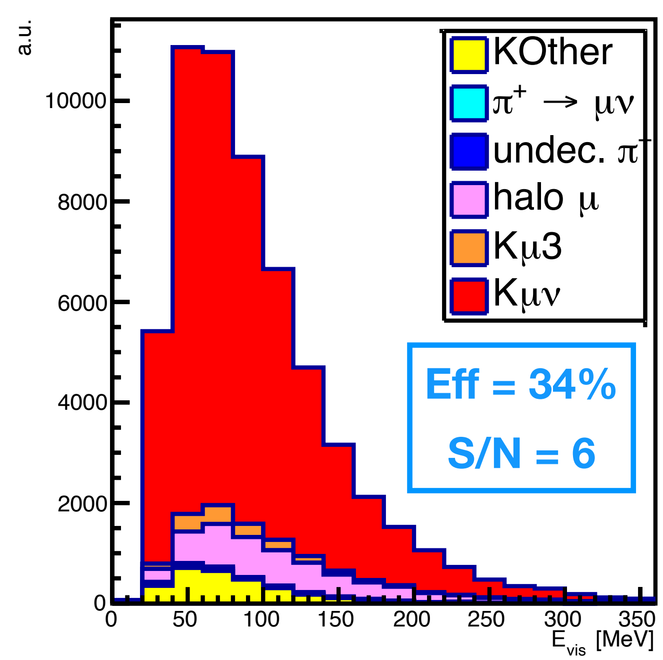
- A **full GEANT4 simulation** of the detector has been developed.
  - ➡ The simulation was validated on prototype tests at CERN between 2016 and 2018.
  - ➡ Pile-up effects are included (waveform treatment in progress).
- **Event building and PID algorithms** have been developed between 2016 and 2020.
  - ➡ The events are selected searching for patterns (space and time) compatible with large angle positrons (electromagnetic showers) or muons (straight tracks).
  - ➡ The PID is carried out using a MLP-NN based on a set of discriminating variables (energy deposited, topology and photon veto).

**$K_{e3}$ positrons → constrain $\nu_e$**




**Efficiency is half geometrical**

**$K_{\mu2}$ muons → constrain $\nu_\mu$**

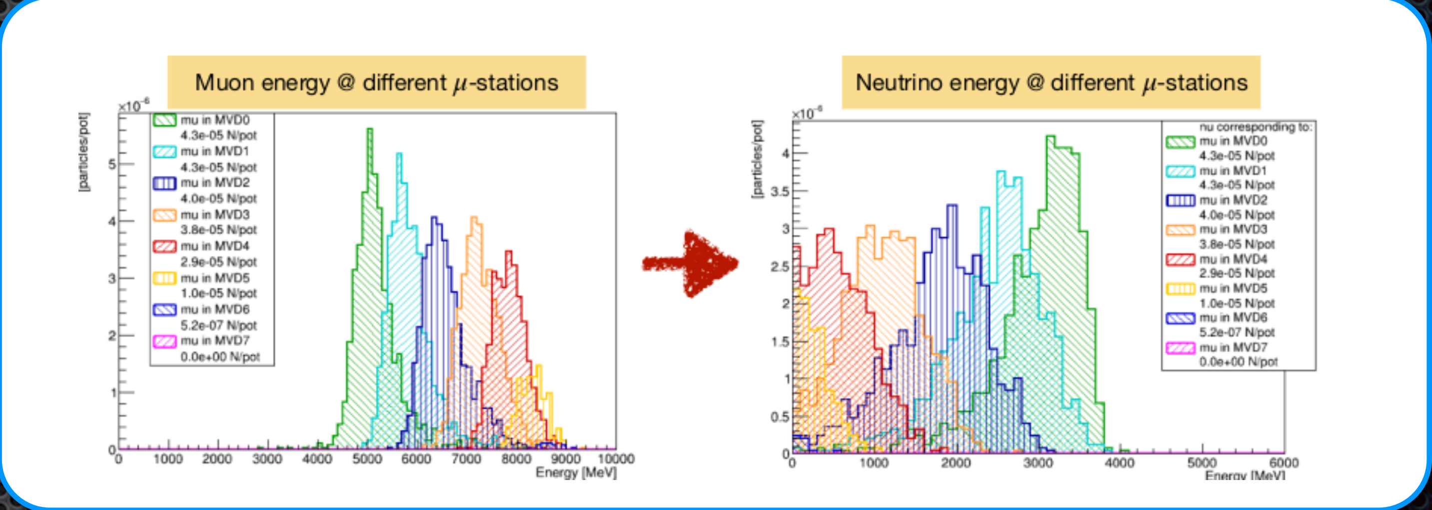



**Efficiency is half geometrical**

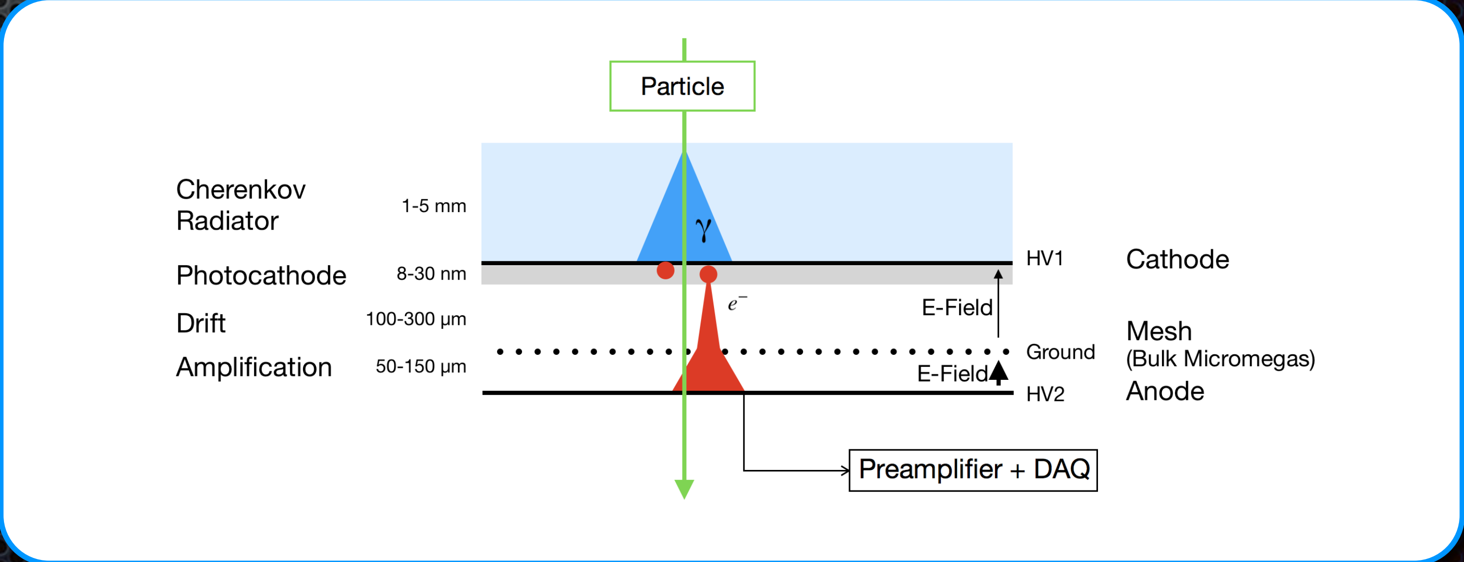
**BR ~ 5% and K make ~ 5-10% of beam composition**

# Forward lepton reconstruction

- The **measurement of $\pi_{\mu2}$ muons** would allow to **constrain the low energy $\nu_\mu$**.
- Low angle muons are out of the tagger acceptance and needs muon stations after the hadron dump to be observed.
- The constraints come from muon rate (about 2 MHz/cm$^2$) and radiation hardness (about $10^{12}$ 1 MeV-n$_{eq}$/cm$^2$).
- The correlation between the number of traversed stations (muon energy from range-out) and neutrino energy can be exploited.



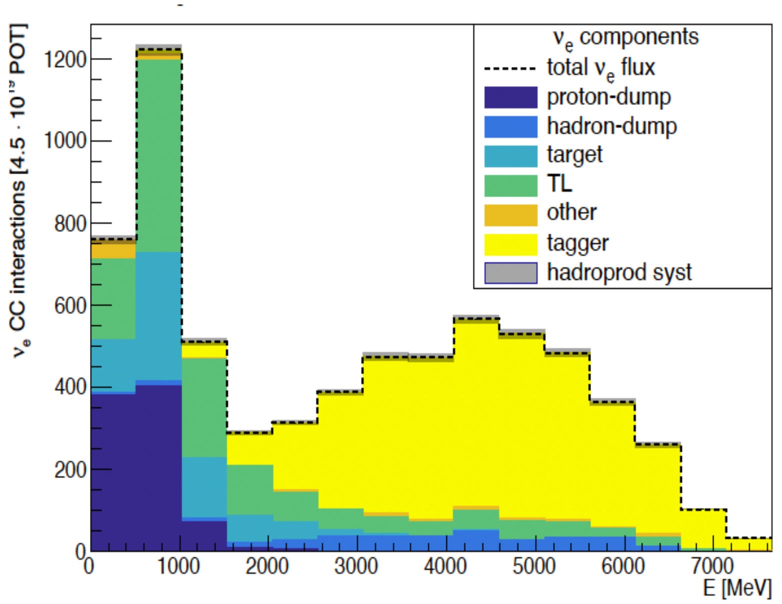

- Possible candidates are fast Micromega detectors with Cherenkov radiators (PIMENT ANR).



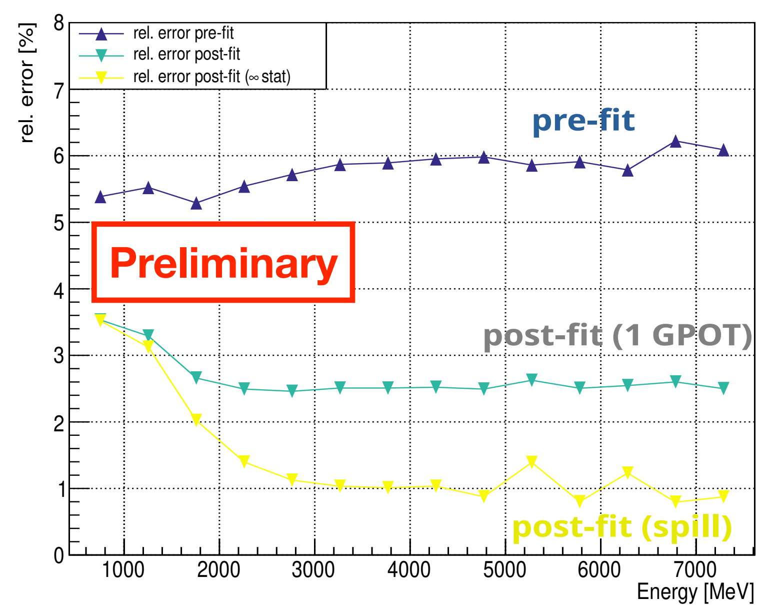
# Flux systematics

- Monitoring leptons and fitting the observable using a model of signal plus background allows to **reduce the hadro-production uncertainties** on the neutrino flux.
- Without constraints given by the lepton measurement the error on the neutrino flux is at the level of 6%.
- Using the lepton observable the error goes down to about 1% showing therefore that the **goal of ENUBET of 1% on the systematics can be reached**.

Neutrino interaction rates @ detector




Pre & Post fit relative errors on rates

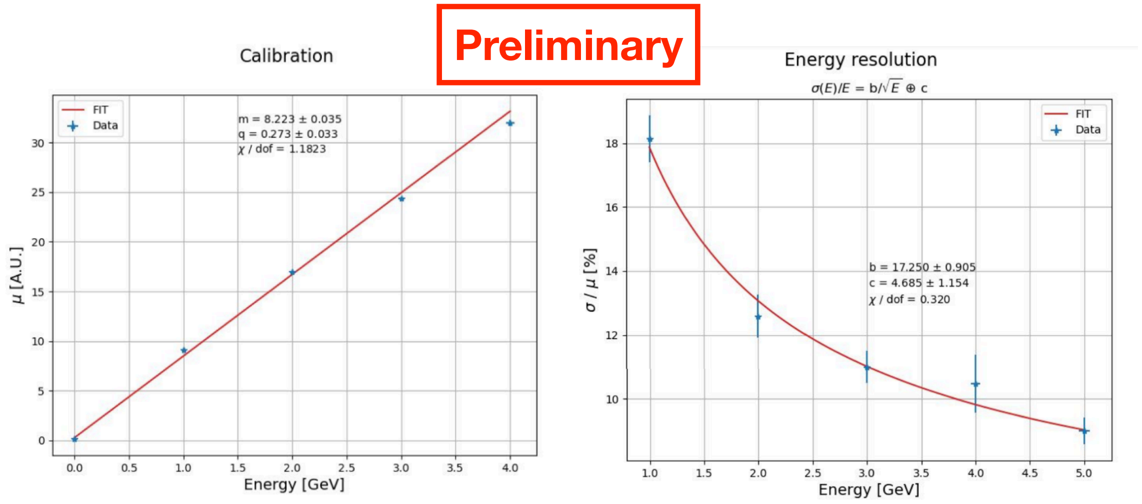


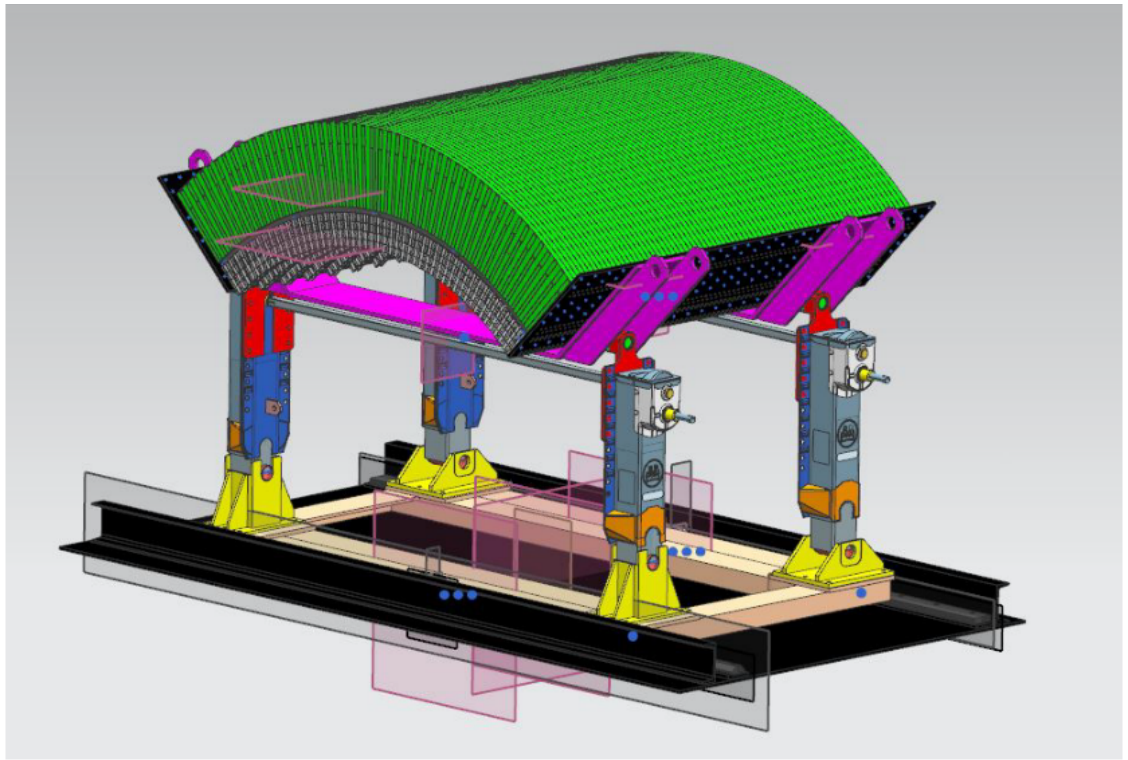

Total rates in 1 year of data taking

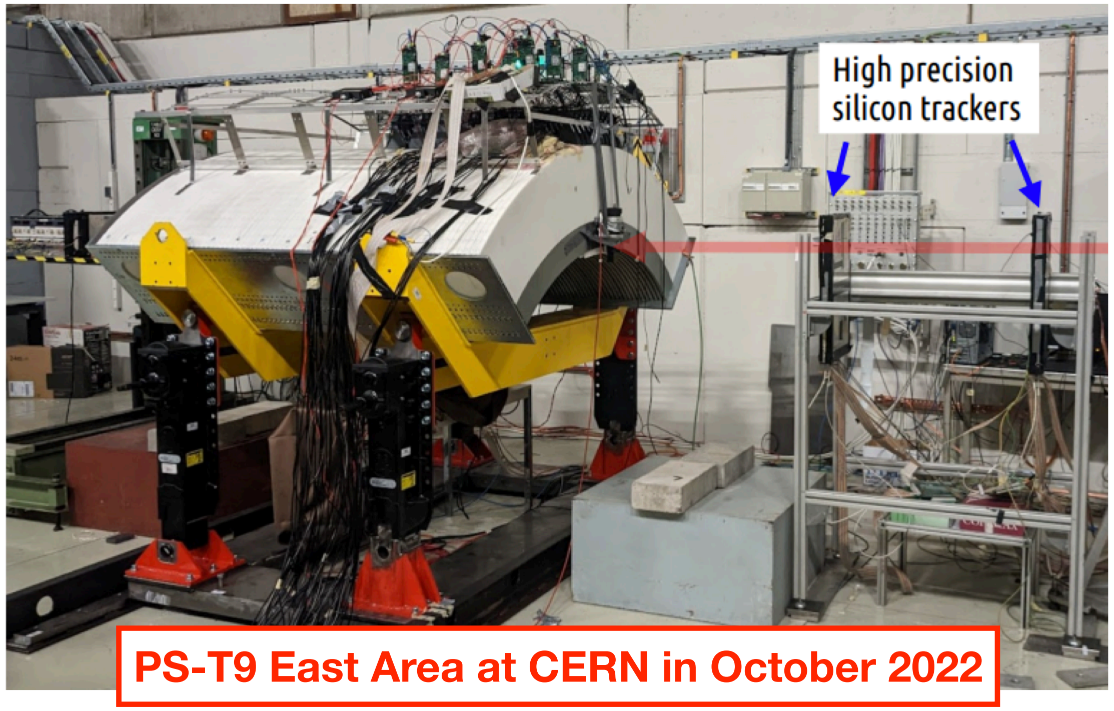
- @ SPS with 4.5 x $10^{19}$ POT/year
- 500 ton detector @ 50 m from tunnel end

# ENUBET demonstrator

- A section of the decay tunnel was **built and tested at CERN in October 2022**.
  - ➡ Length of 1.65 m, mass of 3.5 ton and 90 degrees coverage.
  - ➡ 75 layers 1.5 cm thick iron and 7 mm scintillator tiles.
  - ➡ 10 sectors in $\varphi$ are instrumented (18 degrees).
  - ➡ New light readout tested with frontal grooves instead of lateral ones.
- Data analysis ongoing and larger coverage foreseen for a teastbeam in 2023.



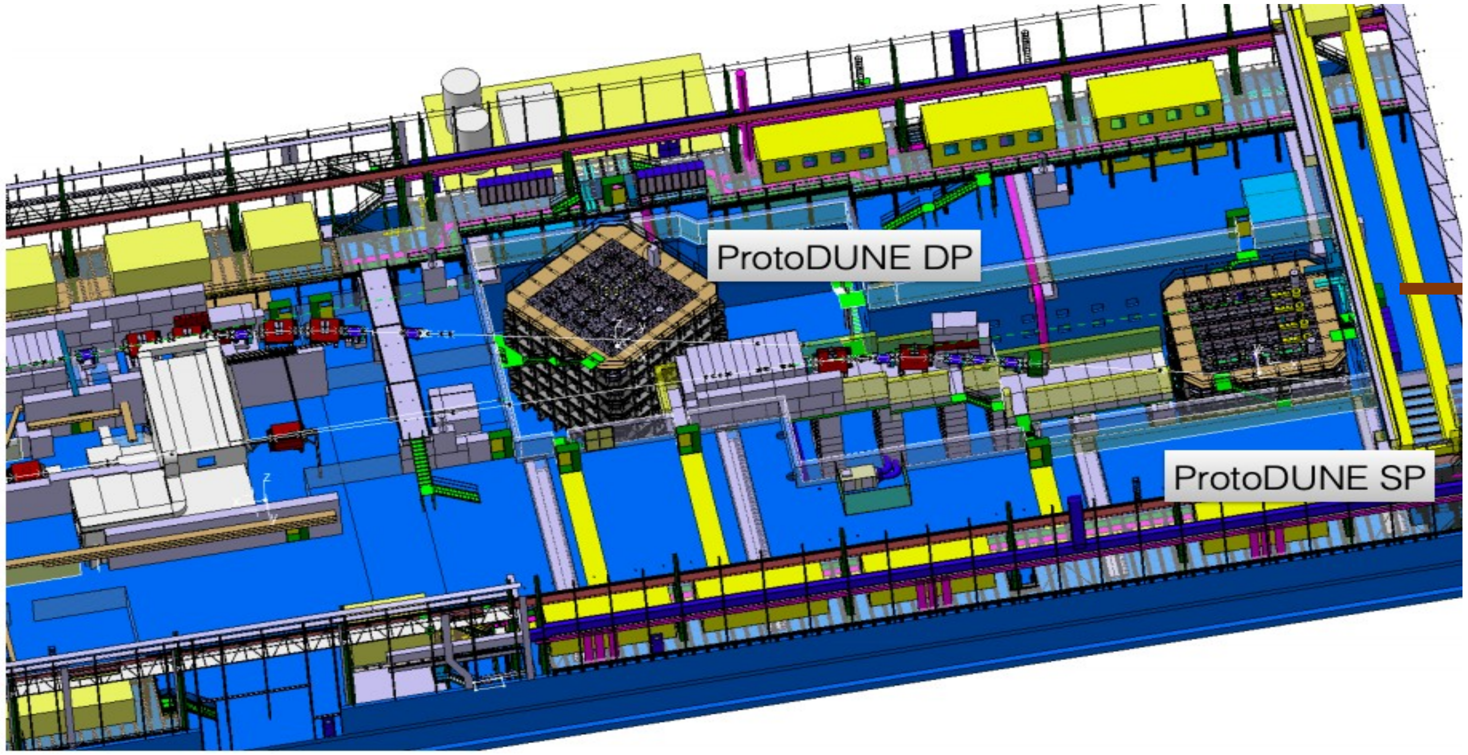






PS-T9 East Area at CERN in October 2022

# Possible implementation at CERN

- We would like to **propose a short baseline beam experiment at CERN in 2029** (Run 4 of LHC in parallel with DUNE and HyperK).
- This could be done in the CERN North Experimental Area possibly exploiting the ProtoDUNE-SP and ProtoDUNE-VD detectors.
- A dedicated extraction line in the North Area would be the cheapest and easiest solution however interference with existing experiment and radiations could be an issue. Alternatively a new dedicated extraction line could be considered.



# Conclusions

- **Monitored neutrino beams are a reality**: the proof of concept is almost complete and NP06/ENUBET has demonstrated it both by simulation and experimental validation.
- A monitored neutrino beam would be a critical asset for next generation of cross section experiments.
- The ERC project is over (final design concept paper in preparation) and we have started the process of addressing the real implementation at CERN and aim at a proposal in 2024-2025 to be in data taking for LHC Run IV (2029).
- This is a major effort that requires:
  - ➡ Careful assessment of physics performance.
  - ➡ Assets and limitations for the use of ProtoDUNE (e.g. cosmic rejection in a slow extraction, kinematic reconstruction of final states, etc.).
  - ➡ Optimal location at CERN to exploit the SPS slow extraction.
- We are trying to create consensus in the neutrino community to move on to the next phase, to have the experiment up and running in parallel with DUNE and HyperK.