Final design of the ENUBET monitored neutrino beam and its implementation at CERN

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On behalf of the ENUBET collaboration

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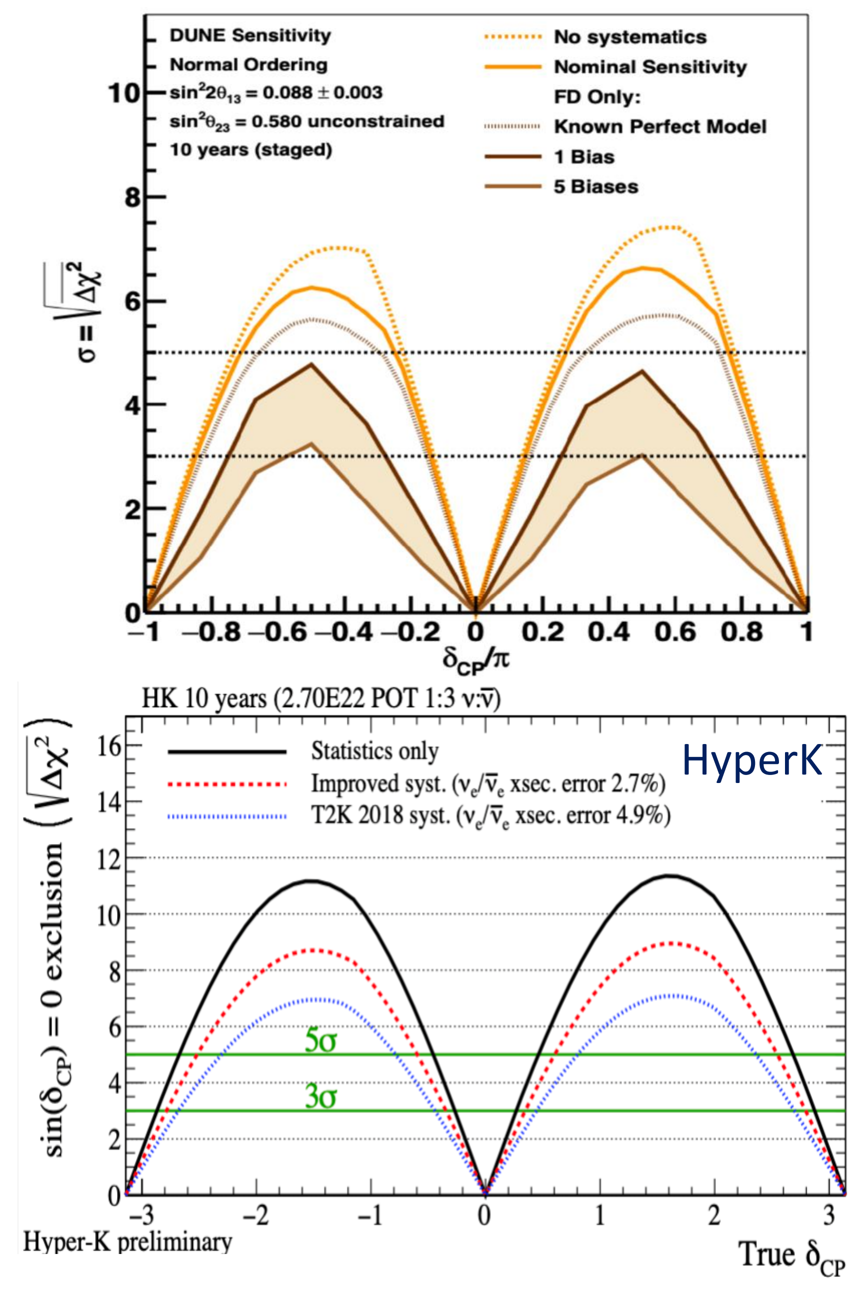
Introduction

- Neutrino oscillation physics has moved **from discovery to precision** era, and next generation experiment such as DUNE and Hyper-Kamiokande aims at measuring the δ_{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%.

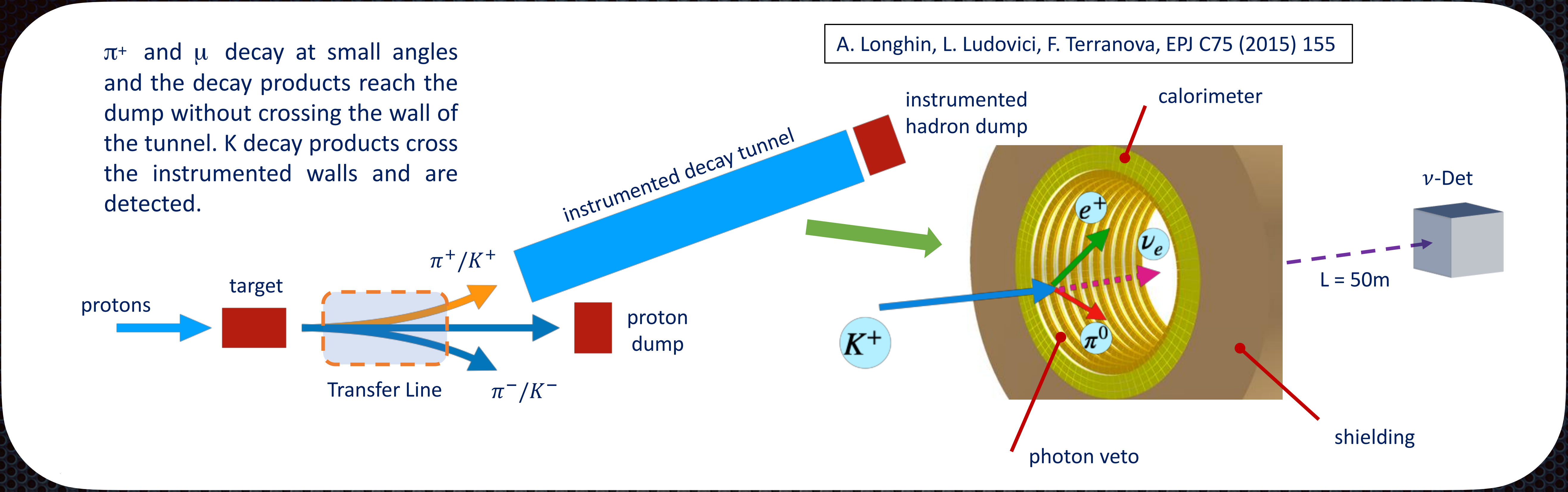
- The available measurements of cross sections are in turn dominated by the uncertainty on the neutrino flux which is generally at the level of 10%.

- 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



π^+ and μ decay at small angles and the decay products reach the dump without crossing the wall of the tunnel. K decay products cross the instrumented walls and are detected.

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

- **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 charged 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 positrons from K_{e3} decays ($K^+ \rightarrow \pi^0 e^+ \nu_e$) in the instrumented decay tunnel to determine the ν_e flux.

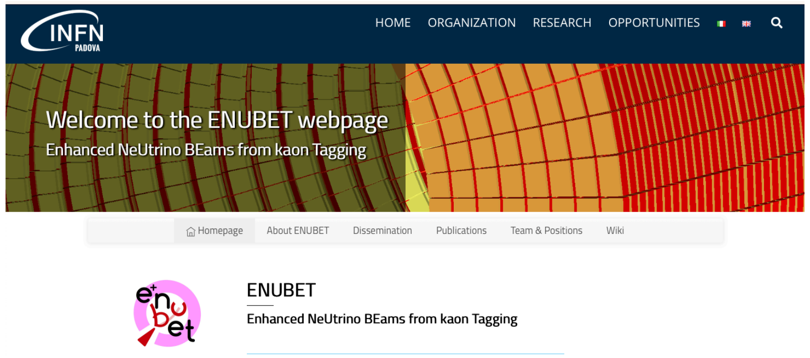
- **CERN experiment NP06 since 2019**: extend measurement in the decay tunnel to μ from $K_{\mu\nu}$, and replace the hadron dump with a muon range meter to measure μ from $\pi_{\mu\nu}$ to determine the ν_μ flux.

ENUBET: the collaboration

74 physicists, 17 institutes from 6 countries

Official web page

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



Welcome to the ENUBET webpage

Enhanced NeUtrino BEams from kaon Tagging

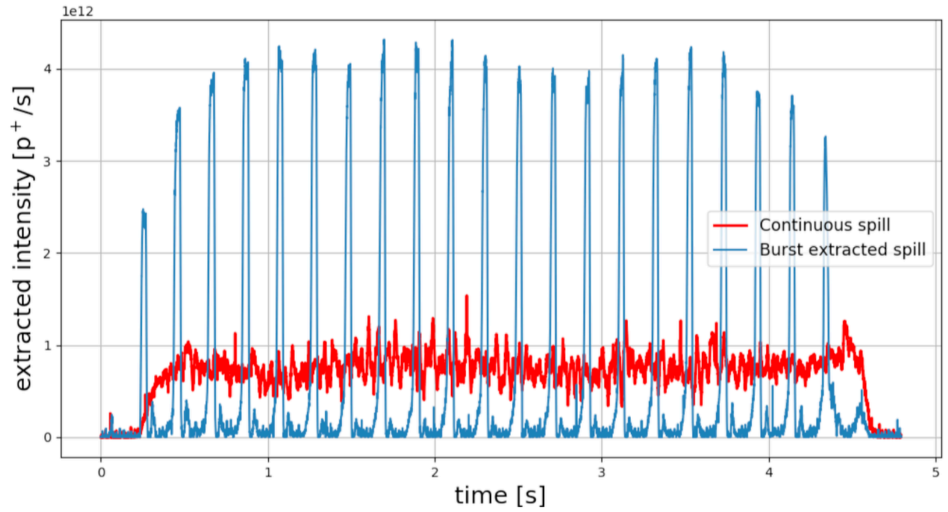
ENUBET

Enhanced NeUtrino BEams from kaon Tagging

Thanks to the results obtained between 2016 and 2023, ENUBET is being investigated in the framework of Physics Beyond Collider for possible implementation at CERN

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.

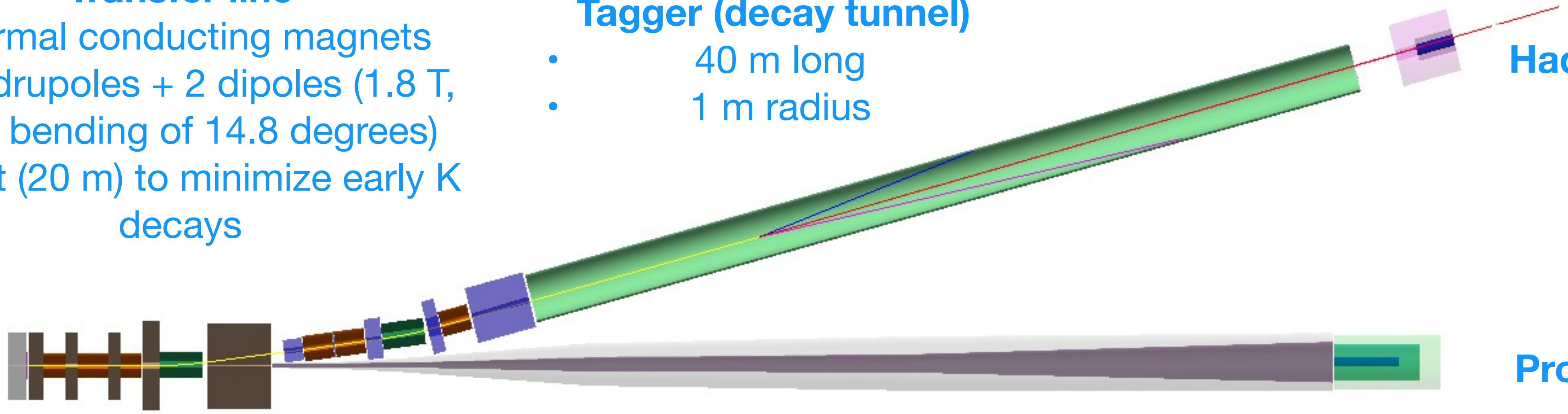


Demonstration of extraction
with 10ms pulse every 100ms
achieved at CERN SPS in 2018

- 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 ν_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 of the target (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

Hadron dump

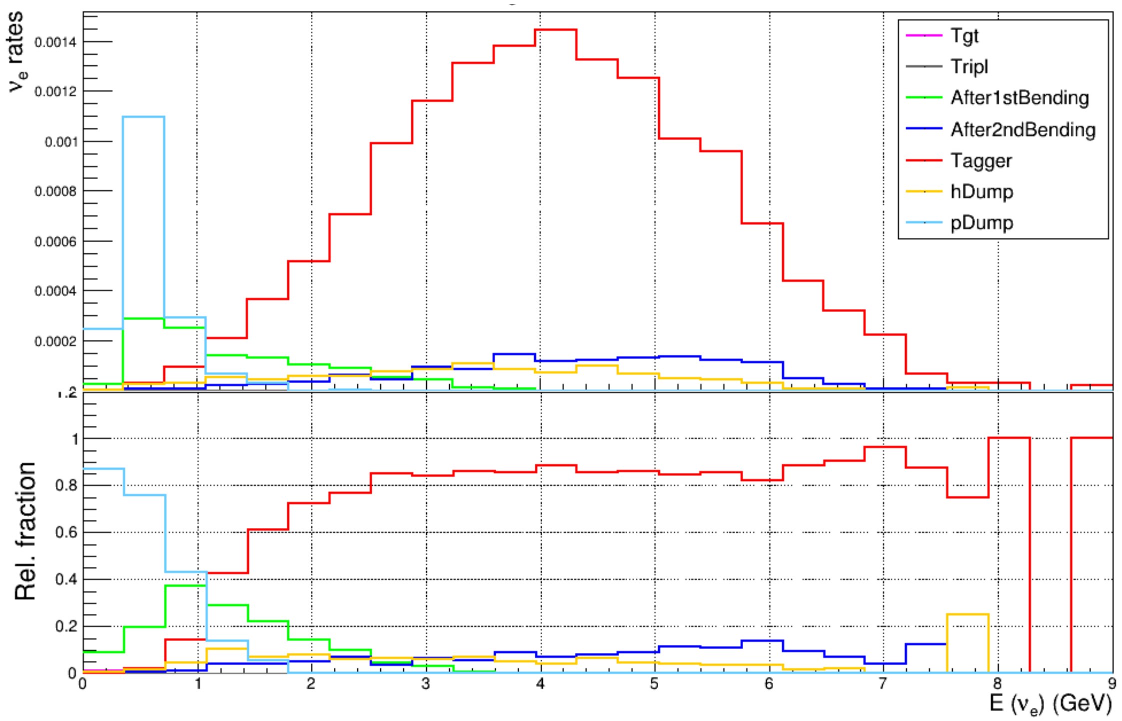
Proton dump

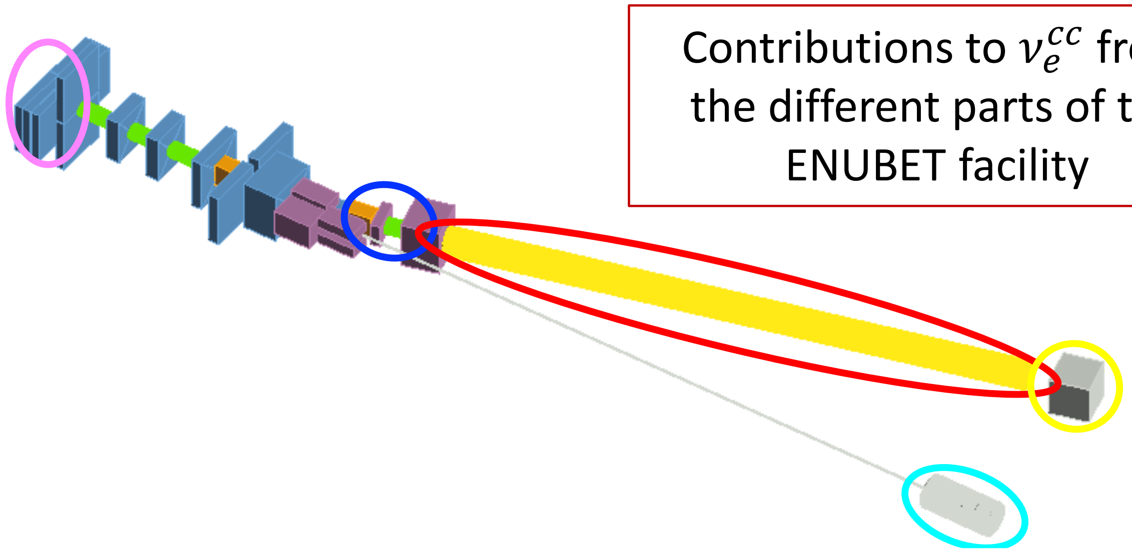
[EPJ C 83 (2023) 964]

Neutrino beam: ν_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 ν_e CC in about 2 years**.
- For neutrinos with energy above 1 GeV, **80%** of the ν_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.

ν_e CC spectra





Contributions to ν_e^{CC} from the different parts of the ENUBET facility

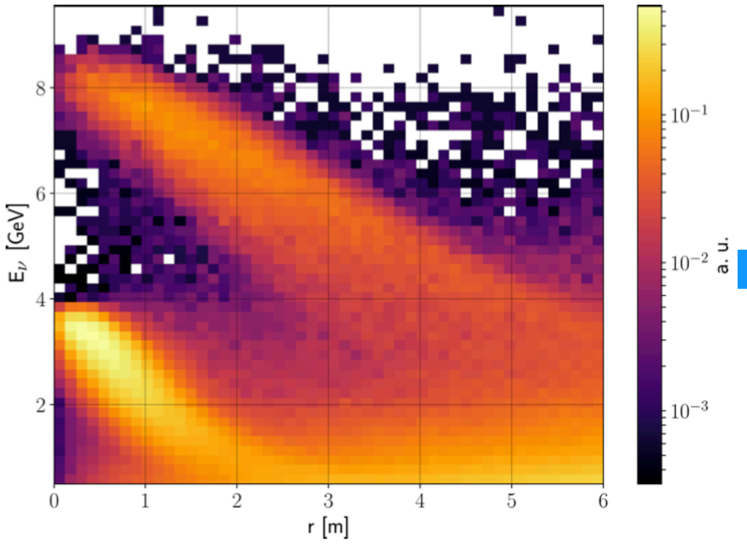
Neutrino beam: ν_μ CC

- 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 ν_μ CC in about 2 years**.
- With the **narrow band off axis technique** we have a strong **correlation between** the neutrino energy **E_ν** and the radial distance of the interaction vertex from the beam axis **R**.
- A precise determination of E_ν can be obtained without relying on the final state particles in ν_μ CC interactions.

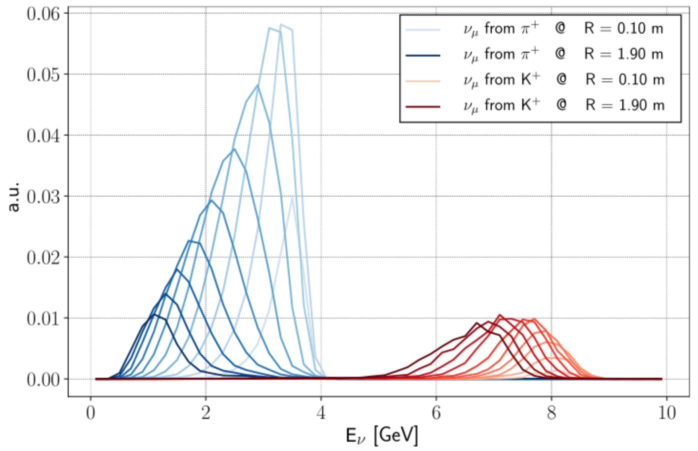
➡ 10-25% E_ν resolution from π in DUNE energy range.

➡ 30% E_ν resolution from π in HyperK energy range (transfer line optimized for DUNE with 8.5 GeV beam).

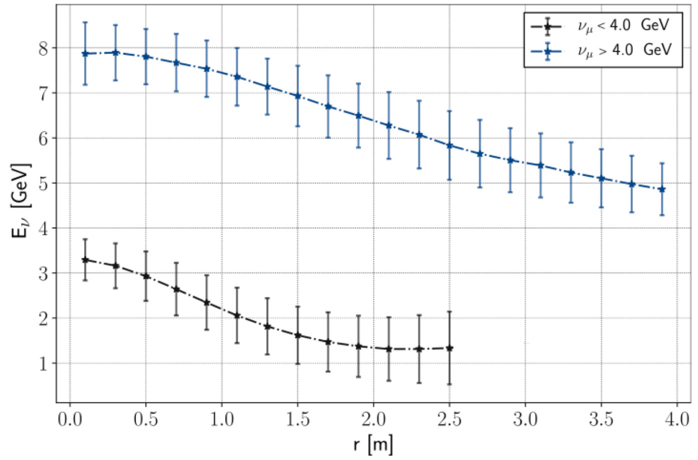
➡ Ongoing R&D for optimization of multi momentum beam line (4.5, 6 and 8.5 GeV) for DUNE and HK.



Select slices in R windows



π/K populations well separated



Resolution between 10% and 25%

Decay tunnel instrumentation

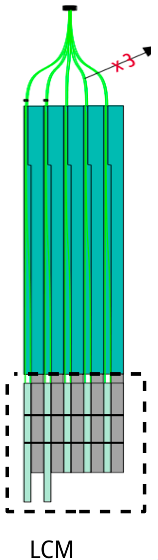
- The concept of the tagger is based on 3 layers of longitudinally segmented calorimetric modules for a $e^+/\pi^+/\mu^+$ separation, and a photon veto.

Shielding

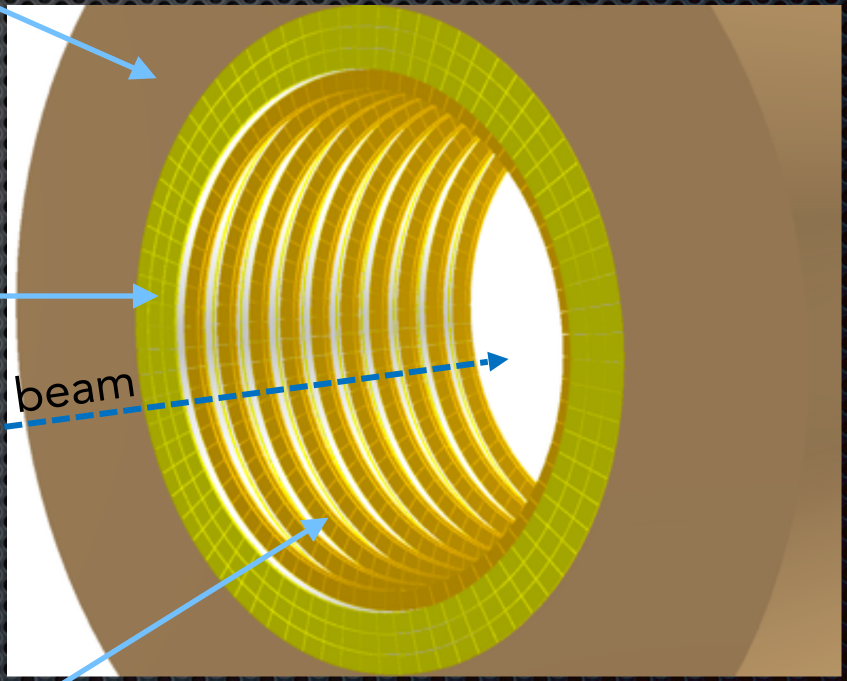
- 30 cm of borated polyethylene.
- SiPMs on top (reduction of a factor of 18 in neutron flux).

Calorimeter

- 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 cm³ (4.3 X_0).
- The scintillation light is extracted with 30 cm WLS fibers to SIPMs.

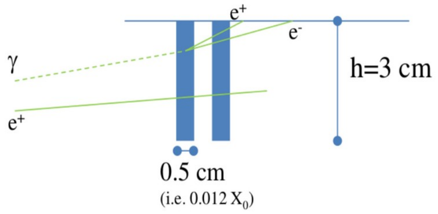


Calorimeter layout



Photon veto

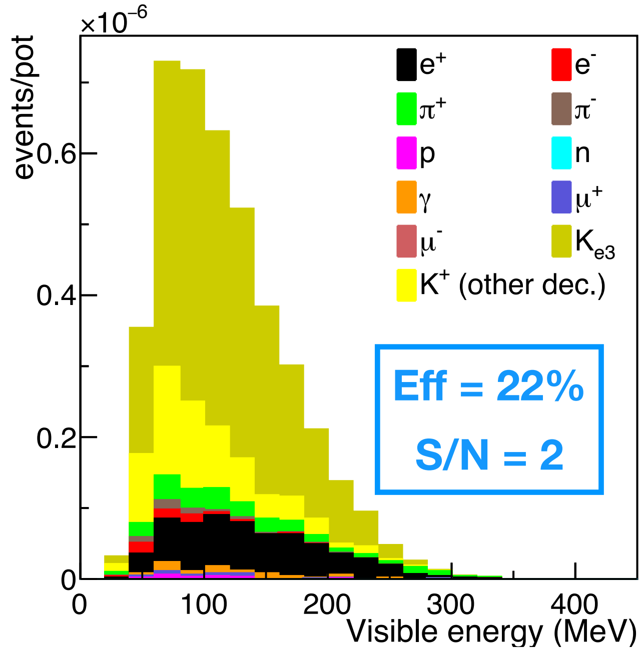
- Plastic scintillator tiles arranged in doublets forming inner rings.
- Time resolution of about 400 ps.



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).

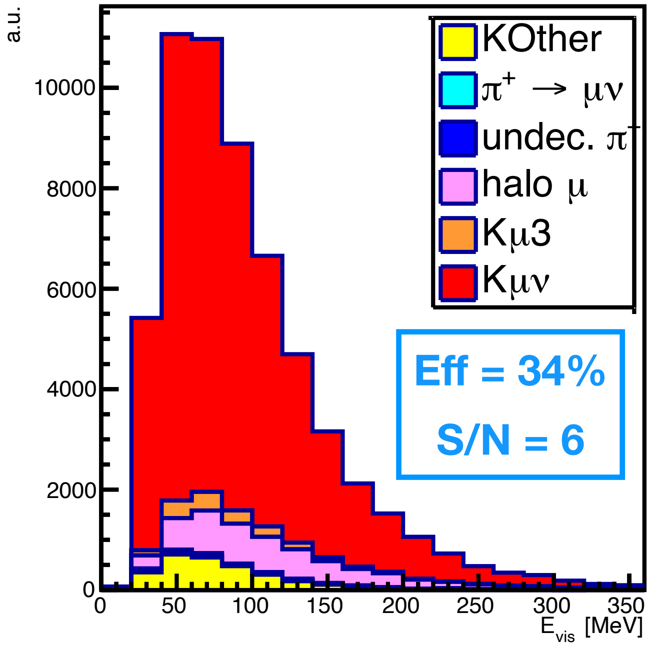
K_{e3} positrons → constrain ν_e



Efficiency is half geometrical

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

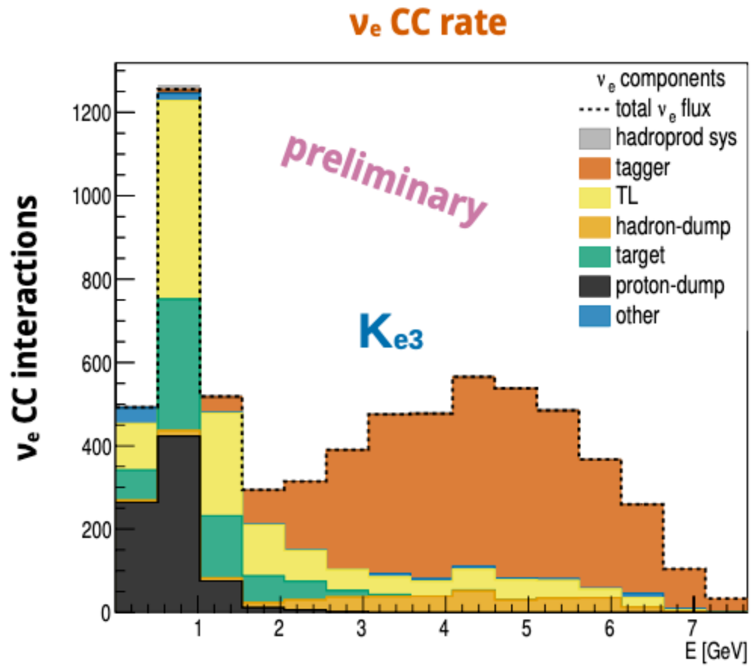
$K_{\mu 2}$ muons → constrain ν_μ



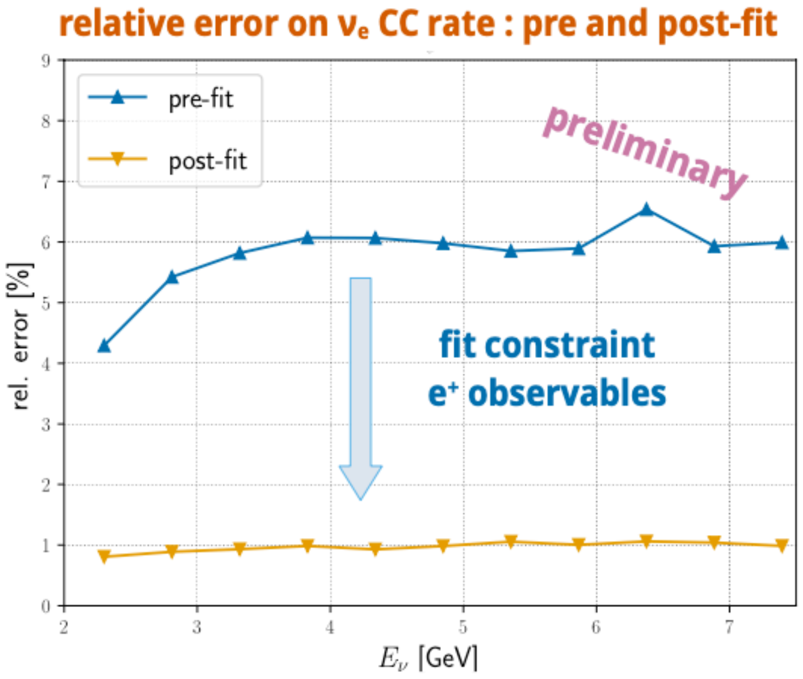
Efficiency is half geometrical

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**.



ν_e CC rate



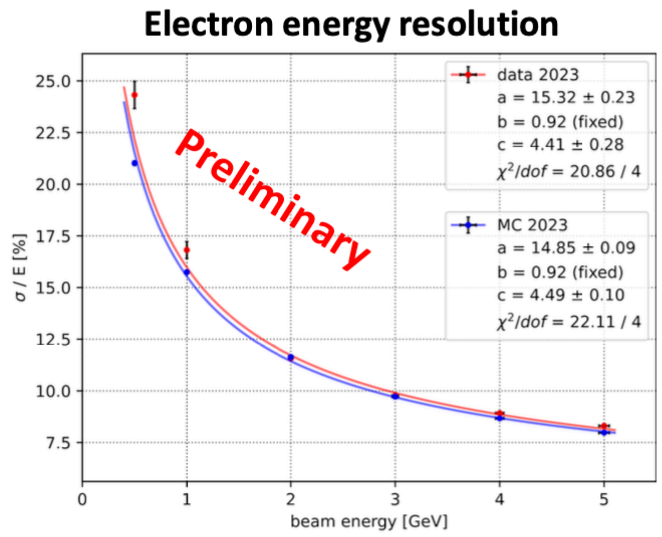
relative error on ν_e CC rate : pre and post-fit

Total rates in 1 year of data taking

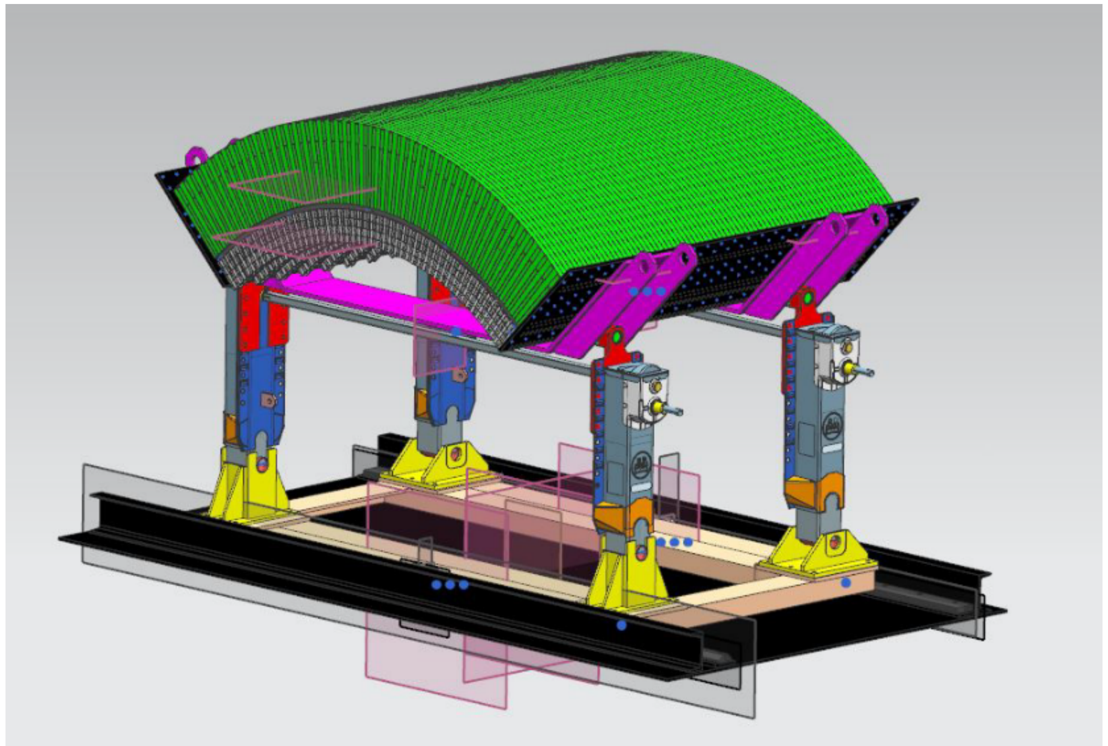
- @ SPS with 4.5 x 10^{19} POT/year
- 500 ton detector @ 50 m from tunnel end

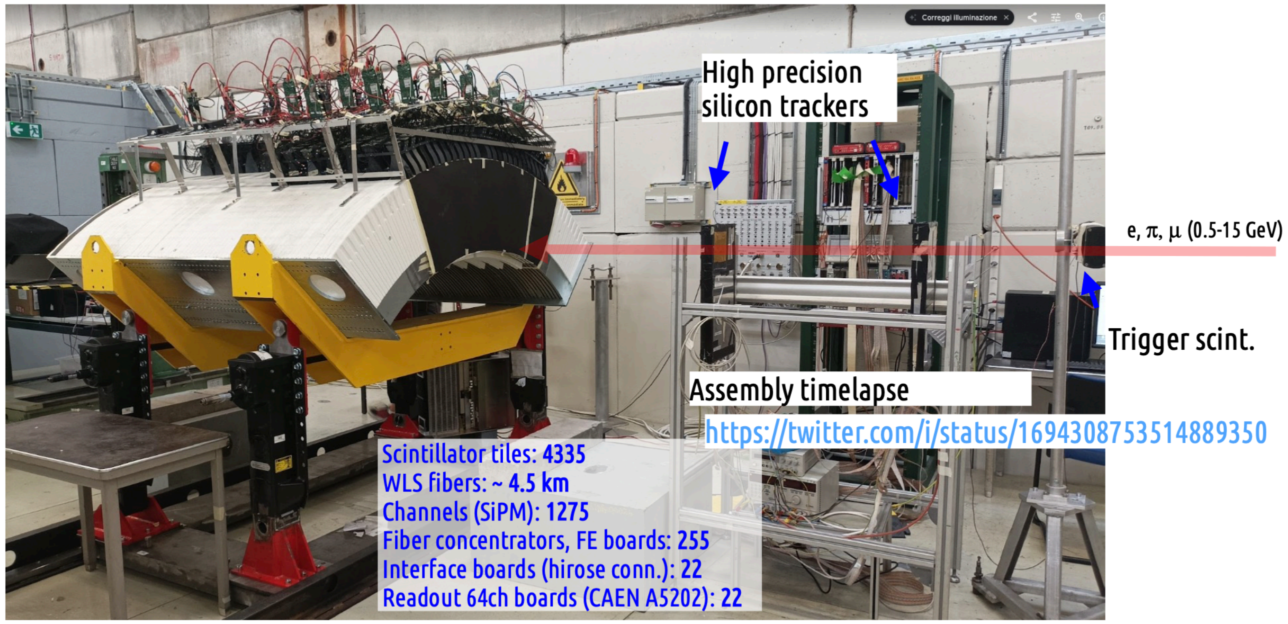
ENUBET demonstrator

- A section of the decay tunnel was **built and tested at CERN in October 2022 and 2023**.
  - ➡ 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.
  - ➡ 10/25 (depending on the layer) sectors in φ are instrumented (18/45 degrees).
  - ➡ New light readout tested with frontal grooves instead of lateral ones.
- Data analysis ongoing.



Electron energy resolution





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

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

PS-T9 East Area at CERN in August 2023

Possible implementation at CERN

- The current ENUBET design has three limitations:
  - The facility is optimized for DUNE but we want to cover the energy range of HyperKamiokande, as well.
  - The number of protons-on-target (pot) is too large if we want to run ENUBET at CERN in parallel with SHiP.
  - We want to further improve the energy resolution, especially below 2 GeV (HyperKamiokande).
- A proposal – called "short-baseline neutrinos @ Physics Beyond Collider" (SBN@PBC) is currently under study by CERN, ENUBET, NuTAG, and the CERN Neutrino Platform to address these limitations and provide a solid foundation for the next generation of cross-section experiments.
- First results of SBN@PBC showed that an optimized baseline can achieve the same neutrino statistics with 1/3 of the p.o.t.
- We are **moving towards an experiment proposal and studying the implementation at CERN** using existing detectors (the ProtoDUNEs and WCTE) and existing beam components to reduce the project cost.
- 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.
- 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.

We plan to submit a document at the European Strategy for Particle Physics (March 2025) and a White Paper that describes the physics performance with ProtoDUNE and WCTE (inclusive, double differential, exclusive cross sections for ν_μ and ν_e, non-standard-interactions, sterile neutrinos, and BSM physics)