The design of the ENUBET beamline

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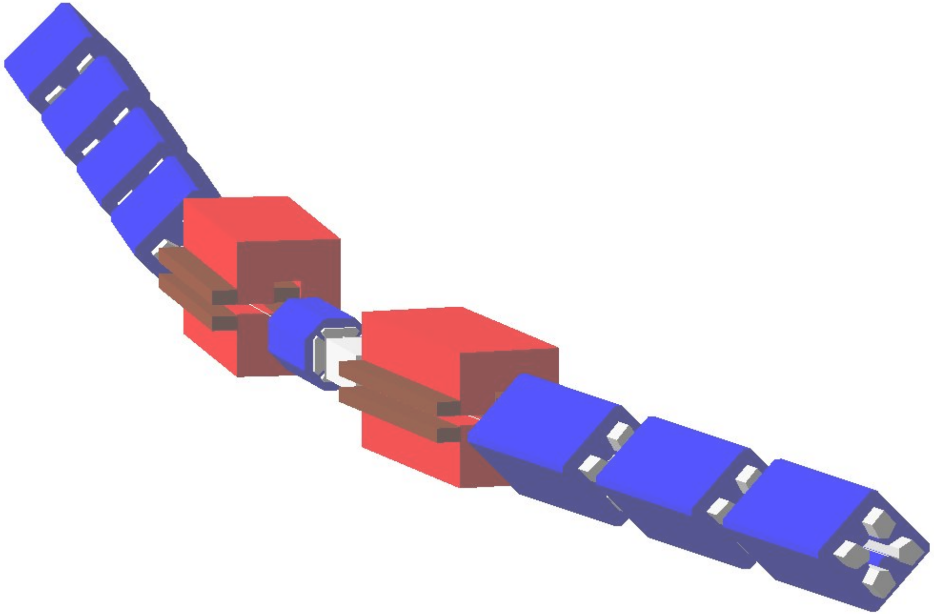
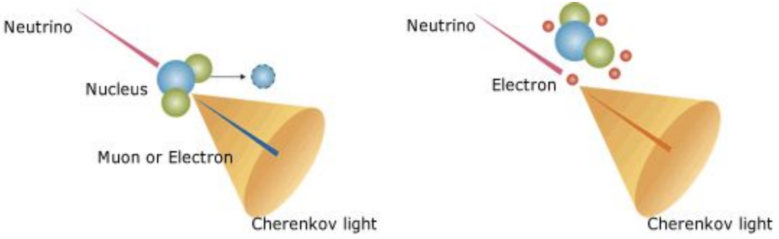


The Neutrino Particle

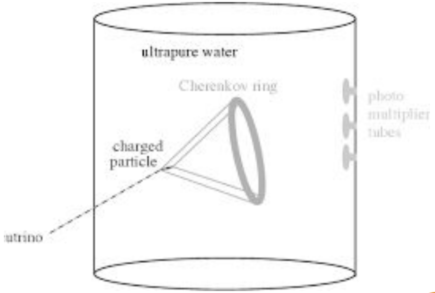
- Fundamental particle → Lepton with no electrical charge and very low mass
- Weak interactions → low interaction probability (σ~10^{-38} cm^2)
- Neutrinos oscillate!

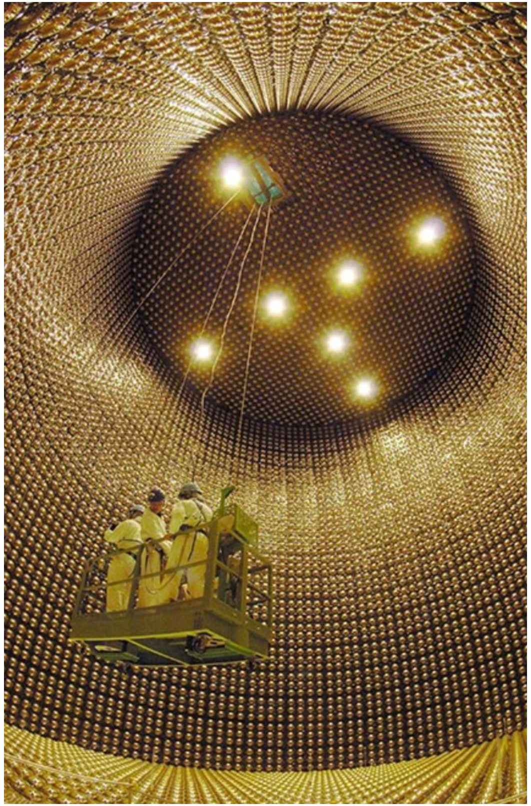
Most neutrinos will pass through Earth without interacting at all!

To detect them we need large and very sensitive detectors:



The generated charged particle emits the Cherenkov light.

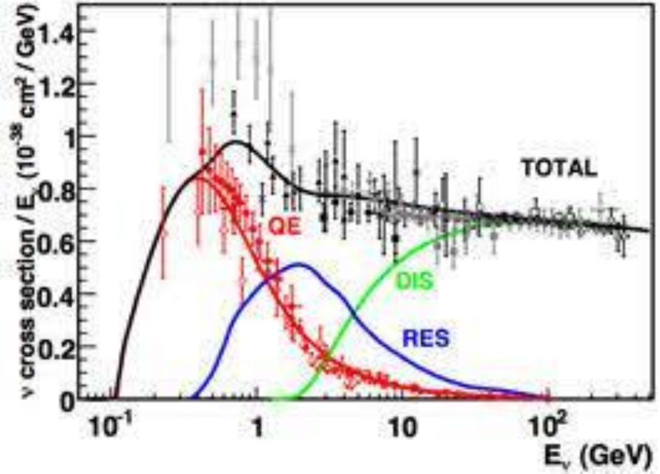




Why so interesting?

Neutrinos have many open questions:

- What is the neutrino mass?
- Which neutrino is the lightest?
- How many neutrino flavours exist?
- Is it a Dirac or a Majorana particle? $\bar{\nu} \rightarrow \nu$
- Do neutrinos violate physics symmetry?



Biggest contribute to this calculations come from σ_{ν} at O(GeV)

ENUBET: The Physics Goal

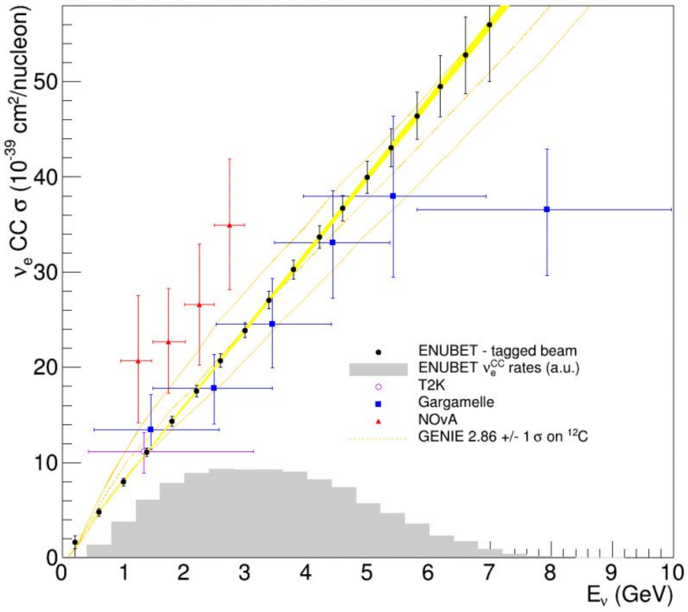
Weak interactions → $\sigma \sim 10^{-38}$ cm^2

Future experiments require precision O(1%):

- lepton CPV
- Mass hierarchy
- PMNS parameters
- Sterile Neutrino

Current neutrino flux and cross section precision measurement is O(5-10%).

ENUBET's physics goal: overall error on the intensity of the produced neutrinos at the 1 % level.

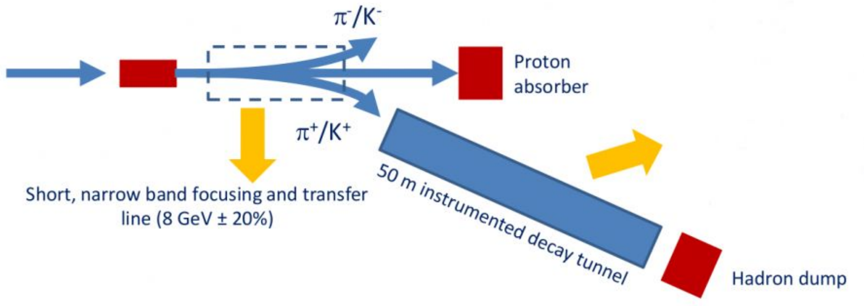


The ENUBET Project: Monitored neutrino Beams

Technique for better neutrino flux and flavour control at production.
In conventional neutrino beams, ν_μ and ν_e are measured indirectly ⇒ Beamline simulation and hadron-production data.
Main flux uncertainties are given by hadrons re-interactions in the beamline apertures.

⇒ Direct Measurement: Number of neutrinos produced is measured counting the number of leptons produced at large angle inside the decay tunnel.

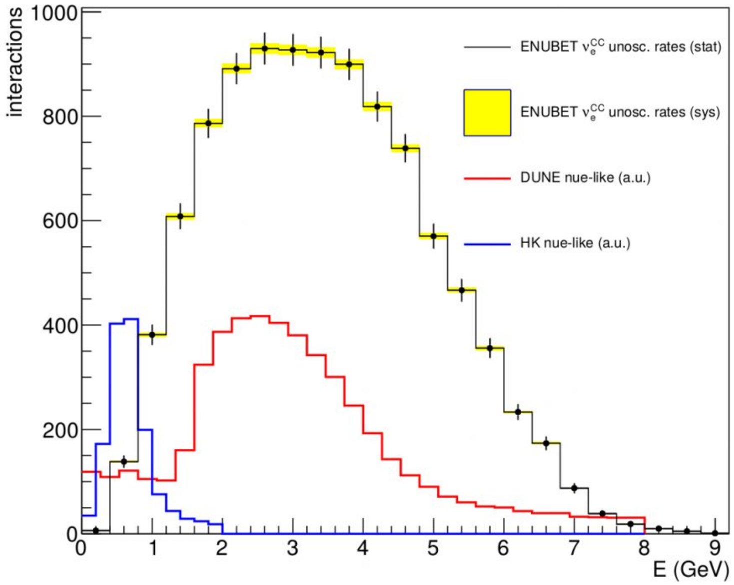
(A. Longhin, L. Ludovici and F. Terranova, Eur. Phys. J. C 75 (2015) 155)



ENUBET (Enhanced **NeU**trino **BE**ams from kaon **T**agging**):**

$K^+ \rightarrow \mu/e^+ \pi^0 \nu_\mu/\nu_e$ (Kμ3/Ke3) $K^+ \rightarrow \mu^+ \nu_\mu$ ($K_{\mu\nu}$)

The need of a Multi Momentum Beamline



Future and current experiments (HyperK and T2K) rely on 0.5-1 GeV/c ν_e.

Current beamline design: 8.5 GeV/c K^+

4 and 6 GeV/c K^+ beamline ⟶ higher statistics for lower momenta neutrinos

Multiple momenta Narrow Band beam achievable by different magnet's currents configurations: "Multi Momentum Beamline"

Design Softwares

- Target Optimization ⟶ FLUKA/G4BL
- Particle Ray-Tracing: R-Matrix calculations ⟶ TRANSPORT/MADX
- Monte Carlo Particle Tracking ⟶G4BL/GEANT4 for optimization
- Collimation and Instrumentation ⟶ GEANT4/G4BL
- Background & Dosimetry ⟶ FLUKA

FLUKA: interaction and transport of particles and nuclei in matter with limited scalability developed using the FORTRAN language

TRANSPORT: program for first and second order fitting capabilities for matrix multiplication intended for the design of static-magnetic beam transport systems.

G4BL: particle tracking and simulation program based on the Geant4 toolkit that is specifically designed to easily simulate beamlines and related systems.

MADX (Methodical Accelerator Design): Designing accelerators and testing beam behaviour. Calculate optics parameters from machine description. Compute (match) desired quantities. Simulate and correct machine imperfections. Simulate beam dynamics.
PTC: Library embedded in MADX as an addition to better support small and low energy accelerators.

Parameters of ENUBET's Beamline

A beam line that can transport a broader momentum range hadrons, i.e from 4 - 8.5 GeV/c with well defined momentum, but at the same time keep the narrow-band properties of the ν beam.

Requirements and key parameters:

- Target that maximizes the K and π production and endures the proton beam power
- Short Length (~25-30 m)
- Small momentum bite (ideally < 10%)
- Reduced Background (collimation - halo beam) at tunnel entrance
- Relatively large acceptance for satisfactory rate
- Rate: 1E10 kaons / (slow) spill @ the entrance of the decay tunnel to obtain 10k neutrinos at the detector.

Note: A rate too high might cause more halo background inside the tagger

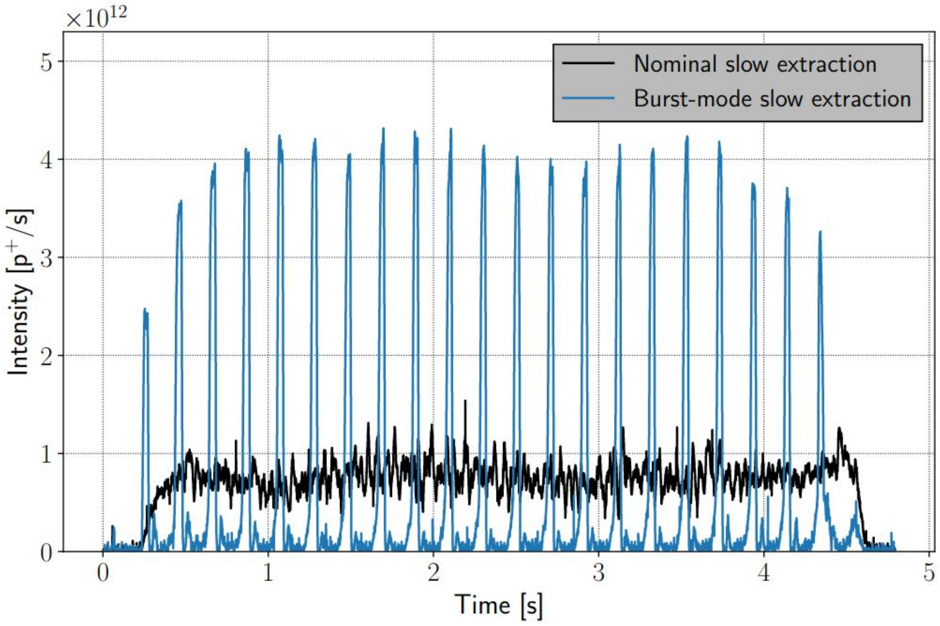
Proton Extraction

Slow extraction scheme:

- Particle-by-particle monitoring
- Local rate at 1 MHz/cm2 at tagger
- Shorter Beamline

Baseline Beamline: Static, slow extraction up to several seconds.

Pulsed Horn: a new ms-scale pulsed slow extraction scheme ("burst-mode slow extraction") studied at CERN-SPS.



The spill profiles have been measured with a secondary emission monitor at the SPS.
work by Michelangelo Pari

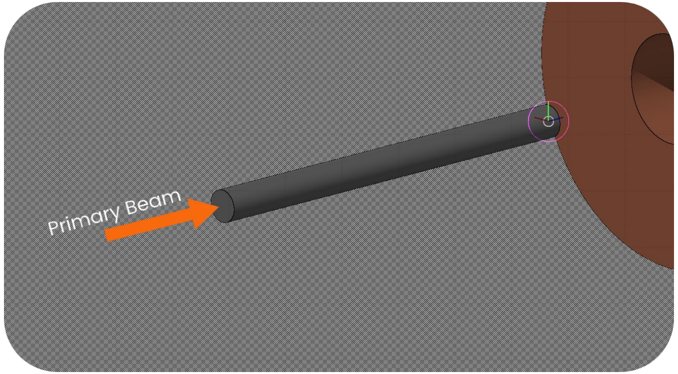
Target Studies

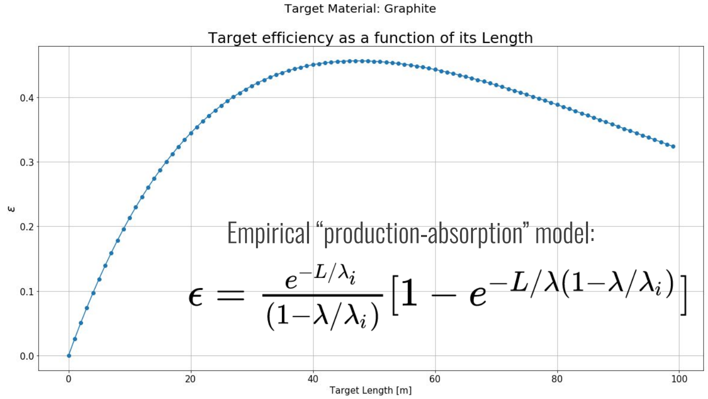
The ENUBET secondary beam will be produced using a high-energy proton beam impinging on a solid target.

Optimization studies with FLUKA and G4BL:

- different target materials → **graphite** (density 2.2 g/cm3), **beryllium** (density 1.81 g/cm3), **Inconel** (density 8.2 g/cm3) and various high-Z materials such as gold and tungsten.
- primary protons energy → 400, 150, 70, 50 GeV/c

Empirical production absorption model to test the efficiency of every target material.



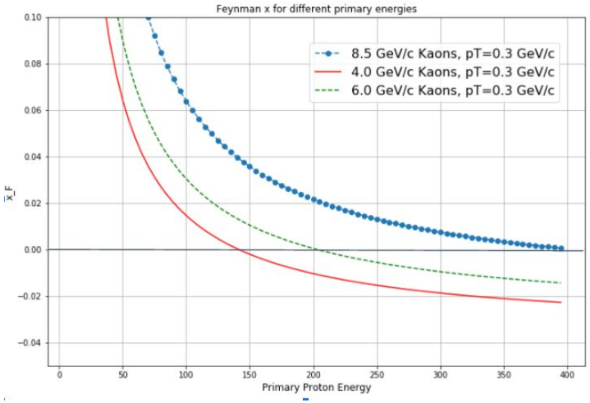


Target Studies

Primary

Feynman-x study to verify the optimal primary energy then tested with FLUKA simulations.

Nominal energy of the SPS (400 GeV/c) is so far the optimal choice for kaons compared to lower primary energies.

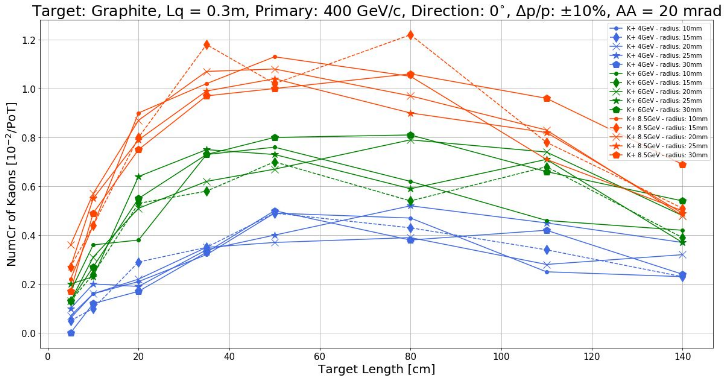


Material and Geometry

Scan of lengths and radii per material to maximize hadrons yield.

Graphite is a known and well-tested material employed in several neutrino beams thanks to its heat endurance and production yields.

Before complete target design, further investigate the limitations of radiation damages imposed by Graphite.



CONCLUSION: Graphite 70 cm length x 30 mm radius

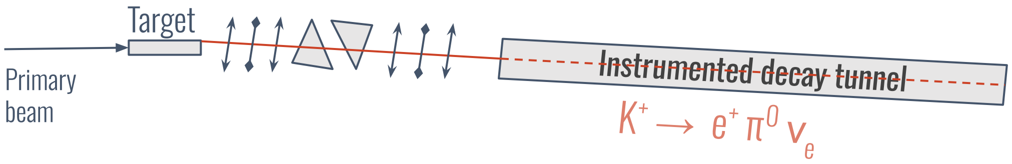
Optics Design

Multi Momentum Beamline: Optics

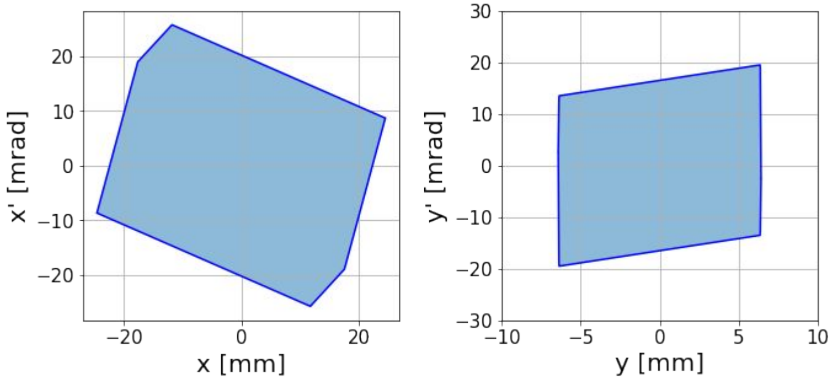
Current beamline design: 8.5 GeV K+ DUNE optimized

HyperK and T2K rely on 0.5-1 GeV ν_e.

4 and 6 GeV K+ beamline → higher statistics for lower energies neutrinos within HK range.



Narrow-band-beam: Focused beam, full momentum recombination, minimum divergence.
Key parameters: Beam Acceptance, Filtering and Collimation, Focusing.



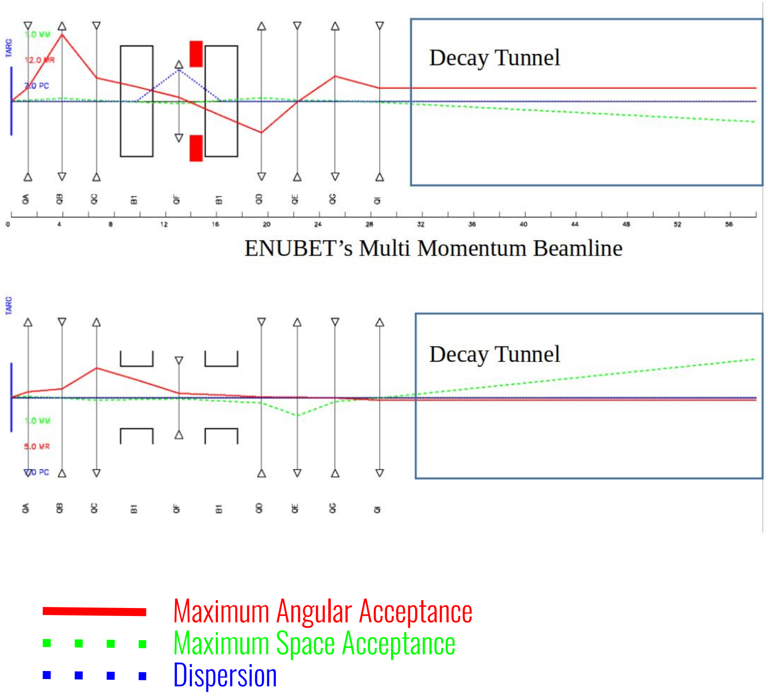
Multiple momenta narrow band beam achievable by different magnet's currents configurations: "Multi Momentum Beamline"

Optics Design: TRANSPORT

First and second order fitting for matrix multiplication.

Requirements: Parallel beam at Tunnel Entrance and focusing at collimation

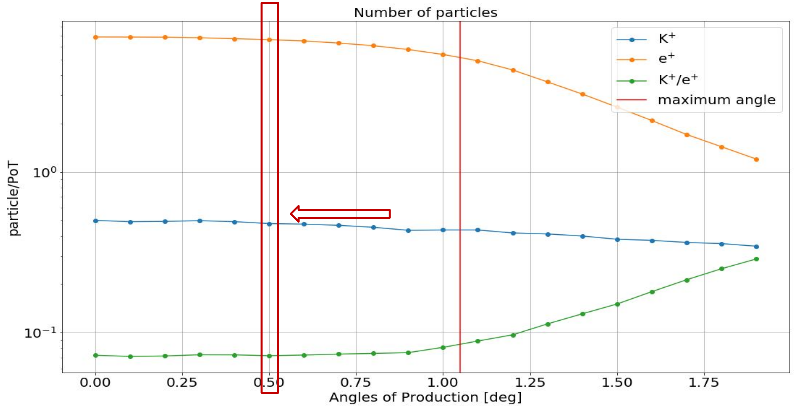
	R11/R33 [mm/mm]	R12/R34 [mm/mr]	R16 [mm/pc]
Max Value	2.9/-15.6	4.9/6	4.2
@ TExit	–33.2/62.8	1.2/0.65	0

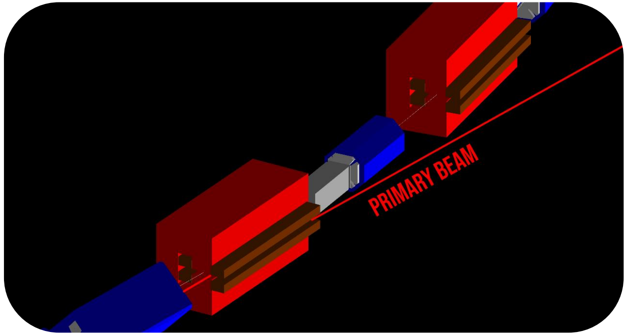


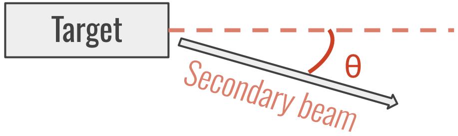
Multi Momentum Beamline: Production Angle

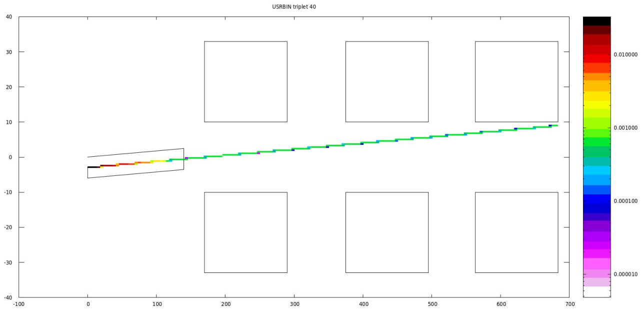
PROs: significant cut for possible positrons background

CONs: reduced kaons rate - however still sufficient
Current kaons expected rate at tagger ~10^{-3}/PoT









Maximum angle within magnets acceptance and heat endurance: 1°

Proposed direction: ~0.5°

Optics Design: Parameters optimization

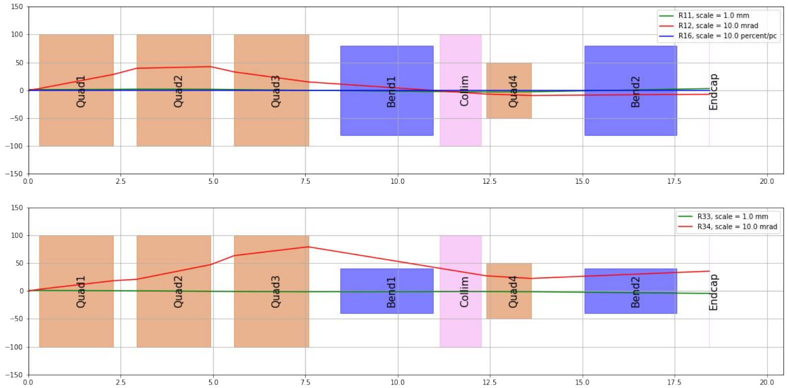
Algorithm to iterate through all possible drifts and strengths imposing maximum magnets currents and minimum drifts.

Goal: Maximize phase space acceptance → maximize Number of secondary hadrons

Comparison between first line version and Optimized version: optimized has bigger phase space but doesn't allow for production angle.

drifts[m]	V. 1	Opt.
d1	0.3	0.3
d2	0.658	0.64
d3	0.658	0.64
ph.sp.	1612	1625

str[m^{-2}]	V. 1	Opt.
k1	-0.358	-0.255
k2	0.347	0.347
k3	-0.234	-0.233

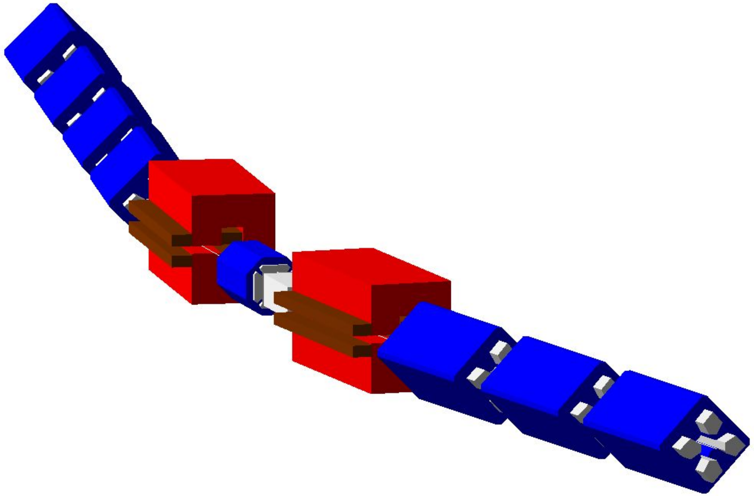


Optics Design: G4Beamline implementation

Once the optics parameters are optimized → G4BL implementation to monitor the flux and the magnet's efficiency.

With G4BL it's possible to place "Virtual Detectors" at any point of the line to visualize and analyze the particle rates and transport along the line.

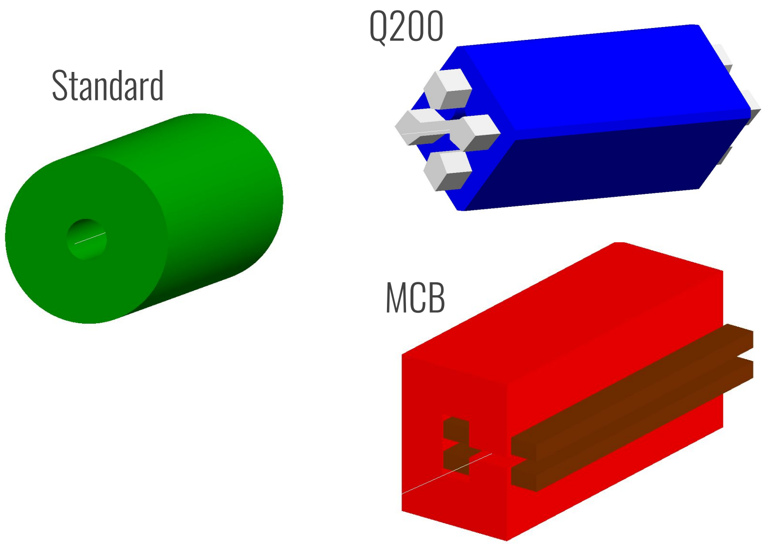
Particle tracking allows for further magnets optimization as it's possible to individuate possible background sources.



Magnets

Magnets used in the beamline design:

Type	Max Field [T, Tm^{-1}]	Aperture [mm]	Length [m]
Q200	10.5	100	2
QFL	18.9	50	1.2
MCB	1.8	80	2.5

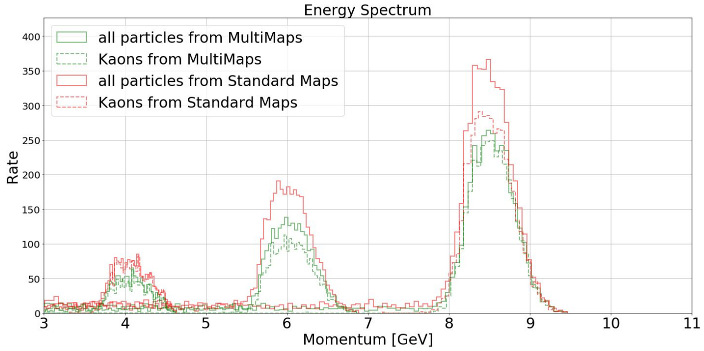


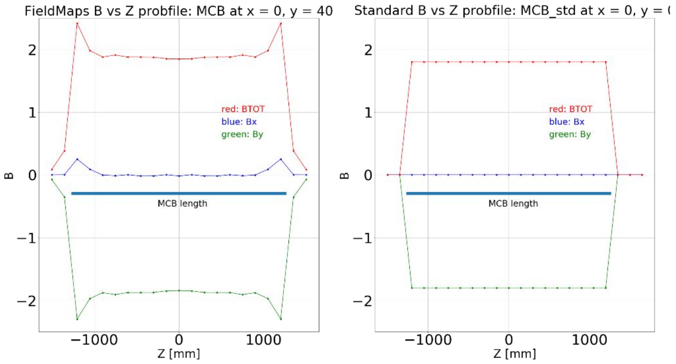
Real magnets currently present and in use at the CERN North Area.
Geometry and fieldmaps implemented on G4BL based on magnets' designs and simulations with OPERA.

Multi Momentum Beamline: Fieldmaps

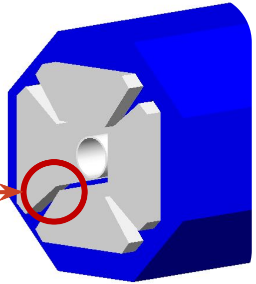
Particle tracking and Optics testing in G4BL → Magnets geometry and Field implementation

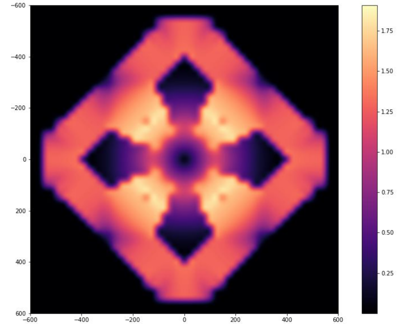
The problem: G4beamline standard magnets are not a realistic representation of the magnets used → Not reliable for background studies.





Edge example

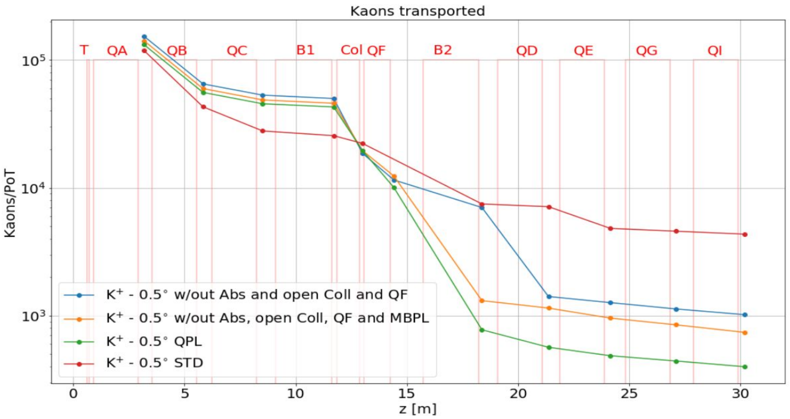


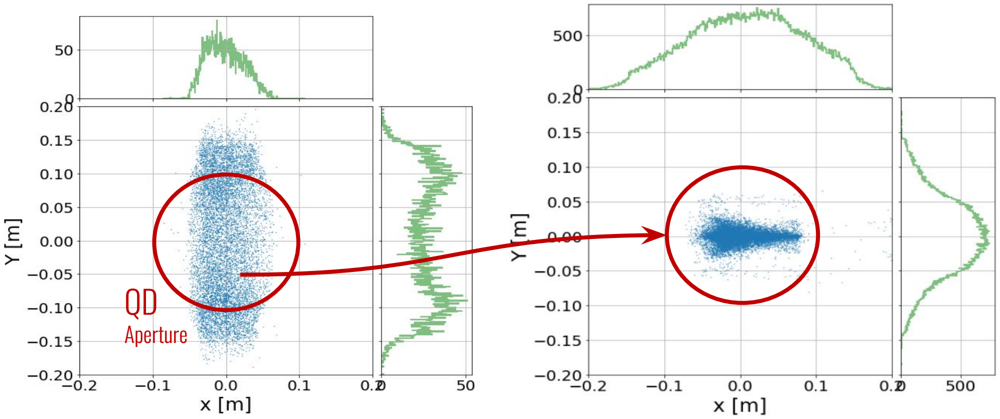


Fieldmaps Studies

Problem in the y-axis ⟶ Beam larger than magnets' aperture

Fieldmaps are more efficient in the triplet but squeeze the beam in the x axis ⟶ standard magnets.





The effects of the fieldmaps on the vertical axis are being investigated.
⟶ More efficient particle transport than standard magnets

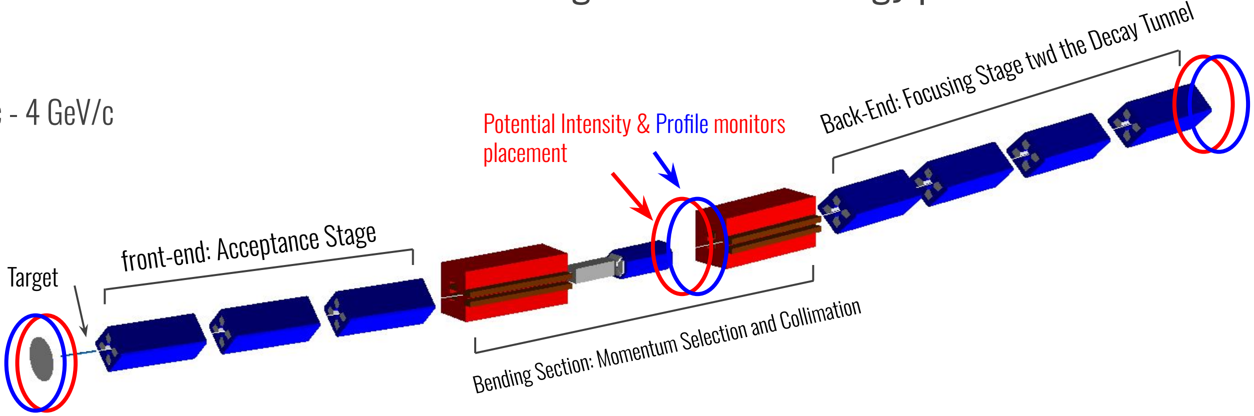
Multi Momentum Beamline: G4BL Layout and Instrumentation

Layout summary:

- First quadrupole distance from the target: 30 cm
- Target 0.5° tilt from beamline to reduce background and primary re-interaction.
- 5 mm W absorber after collimation → to reduce the positrons bgk.
- ~4s slow extraction with 4.5x10^{13}~POT per spill on the target → 10^{10} Kaons/spill
- Short Secondary Beamline (29 m)
- Primary Momentum: 400 GeV/c
- Secondary Momenta: 8.5 GeV/c - 6 GeV/c - 4 GeV/c

Beam Profile and Intensity measurements at two points in the line as well as at the Tunnel Entrance.

In progress: R&D on possible detectors that can sustain high rate for low energy particles



Multi Momentum Beamline: Shielding

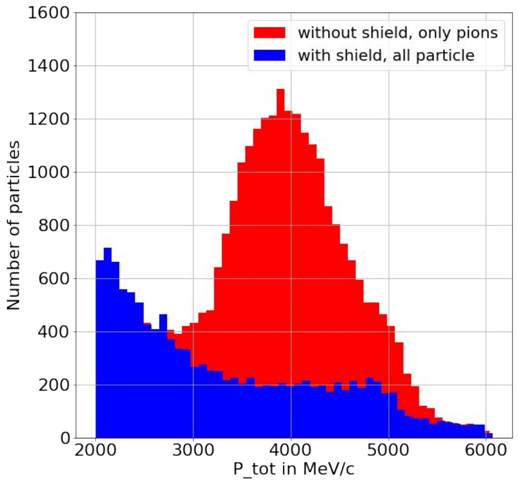
Shielding is fundamental for several reasons:

- Radiation protection
- Background suppression

Shielding material: Concrete with Iron core
Shielding placement: along magnets' entrances avoiding primary's trajectory.
Shape: rectangular blocks as the ones generally used at CERN.
Dimensions: custom to fit in the drifts and magnet's apertures.

The proper shielding is optimized monitoring the particles entering the Decay Tunnel.

Main source to shield: 4 GeV/c secondary peak entering the decay tunnel.



Example of background reduction on the 4 GeV/c peak with and without shielding.

For computational reasons, the no shielding simulations were run only with pions.

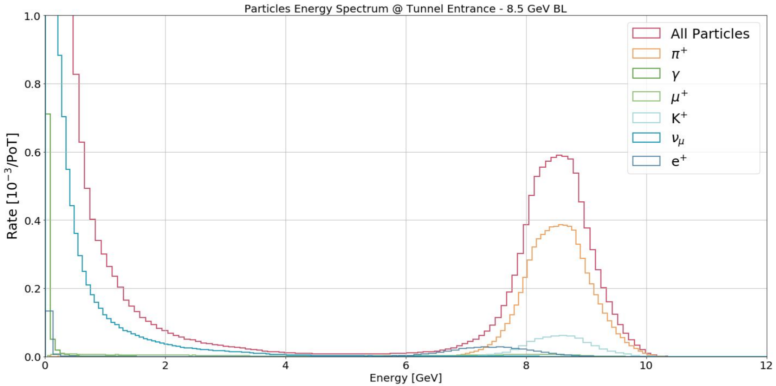
Multi Momentum Beamline: Shielding

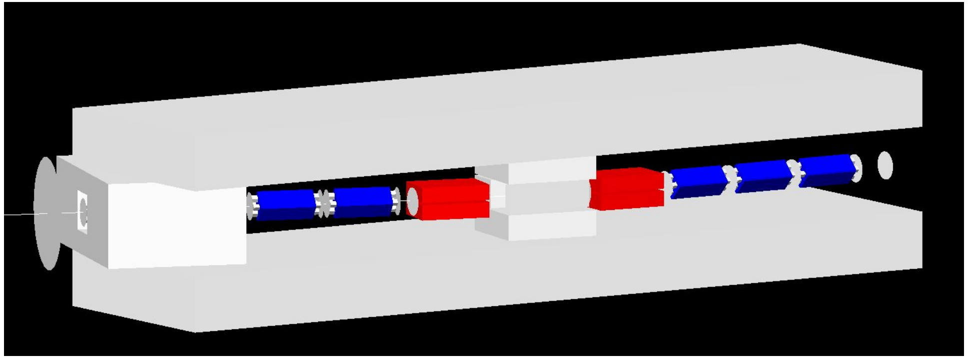
Final shielding. Main elements:

- Target shielding
- Collimator: momentum selection
- Tunnel Entrance and last Quadrupole

Clean spectrum of secondaries entering the tunnel peaked at the selected momenta.

A possible experimental hall is temporarily simulated by a concrete ceiling and pavement.



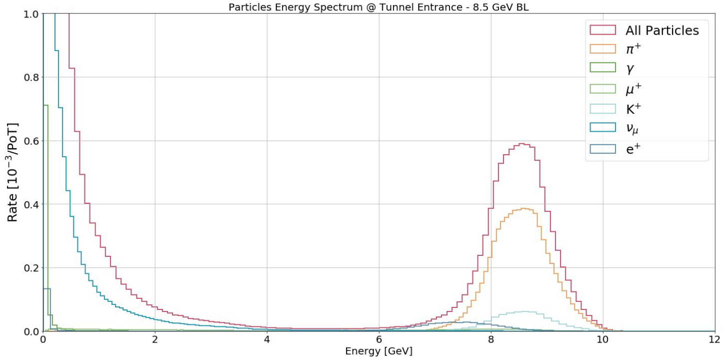


Shielding modelled by Maike Saphorster under my supervision.

Performance and Results

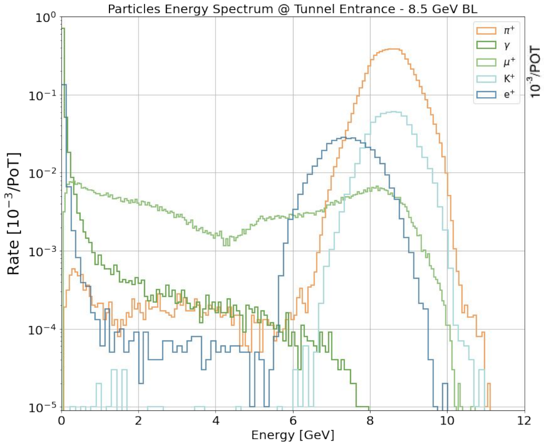
Multi Momentum Beamline: Performances and Results

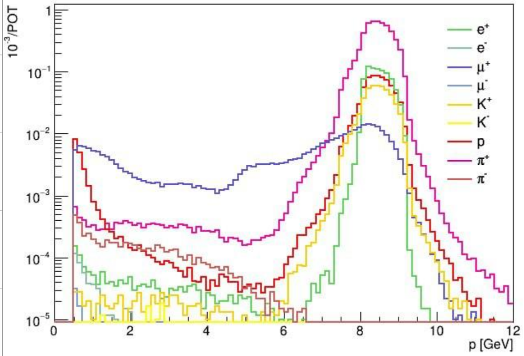
Pions and Kaons Rate:



MMB log

Baseline log

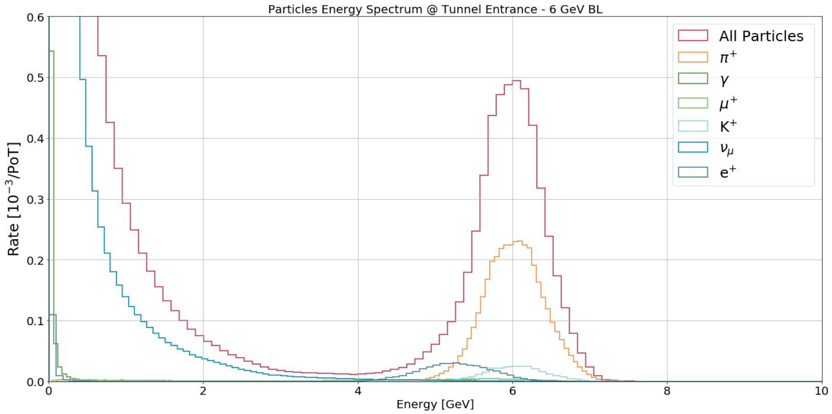


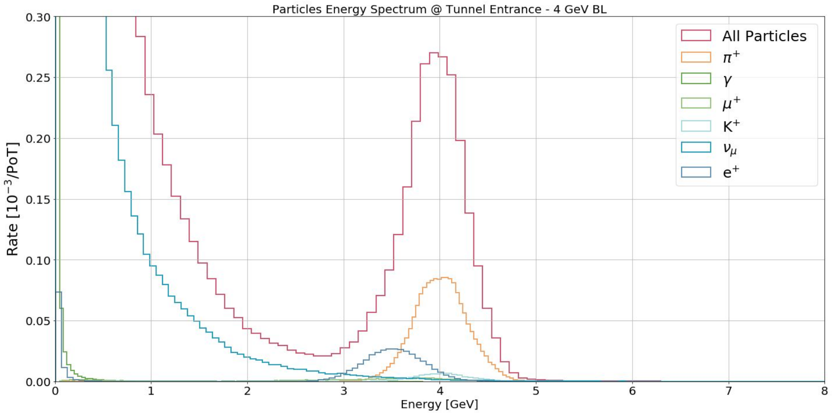


Rates at Tunnel Entrance	400 GeV/c primaries
π^+[10^{-3}]/PoT	K^+[10^{-3}]/PoT
MMB 7.9	0.68
BL 3.97	0.36

2.4 years data taking to collect 10^4 ν_eCC

Results: 6 and 4 GeV/c





	π^+[10^{-3}]/PoT	K^+[10^{-3}]/PoT
6 GeV/c	4.1	0.28
4 GeV/c	1.7	0.08

Lower energy configurations to serve T2K and HK physics case and tag neutrinos at 1 GeV/c range coming from pions decay.

Results: Neutrino Fluxes

ENUBET monitors the decay of the K and π mesons, which produce muon and electron neutrinos with forward emission.

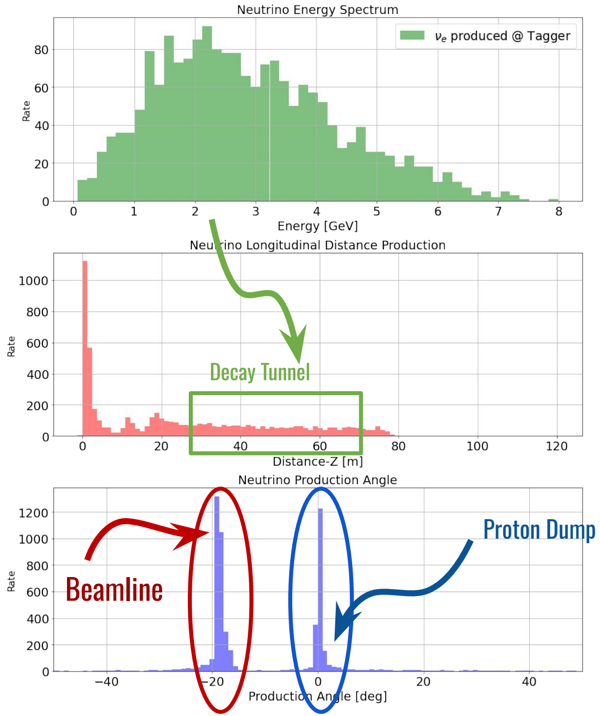
The decay-charged leptons are detected within the decay tunnel,

→ The neutrinos interact within a large mass neutrino detector located approximately 50 m from the end of the tagger.

The Far Detector is simulated as a Virtual Detector with a radius of 6m downstream of the tagger after a block of concrete (a hadron dump) and ground.

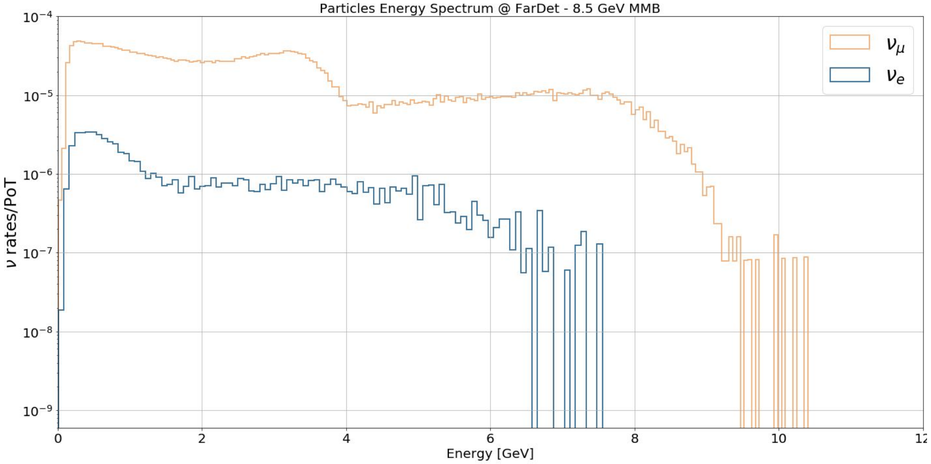
The spectra are weighted by the cross section and energy.

Monitoring the angle of production allows to separate neutrinos produced by the main channel decay and possible proton dump contamination.

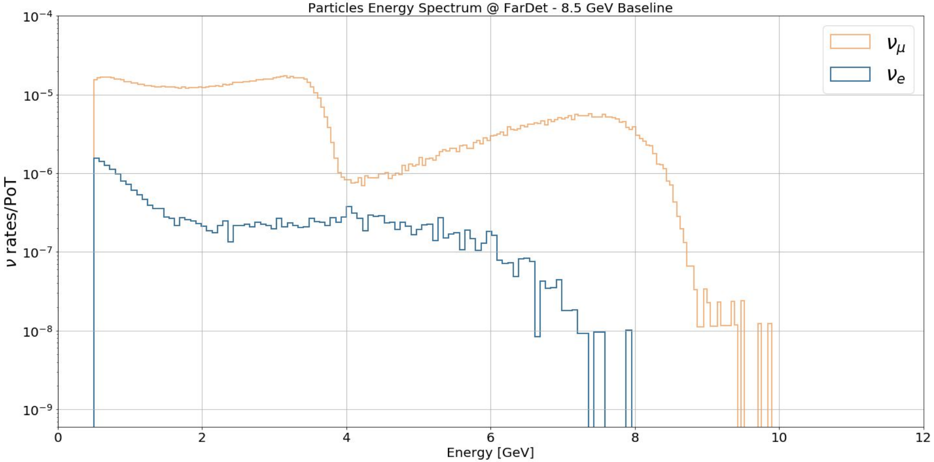


Neutrino Fluxes

MMB



Baseline



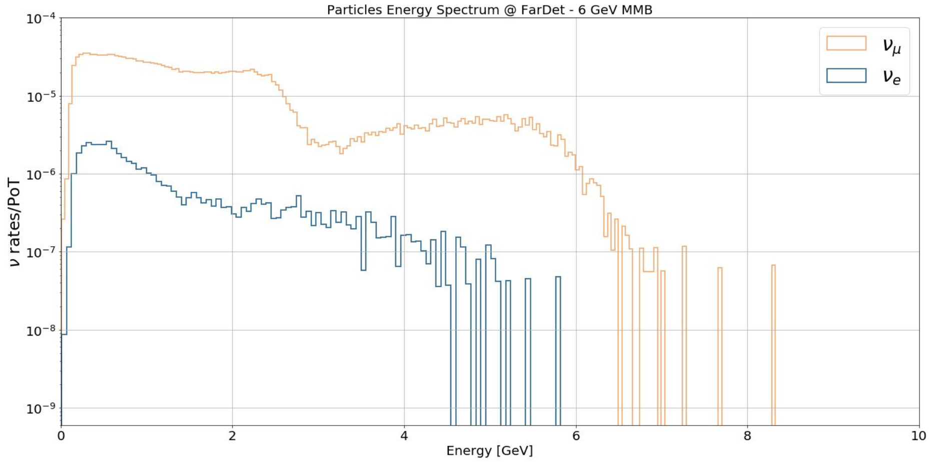
Comparison of the neutrino fluxes originated by an 8.5 GeV/c secondary beam, on the left the MMB and the baseline on the right.
The baseline spectrum was obtained from a simulation with a lower energy cut below 0.5 GeV/c.

The overall rate is greater in both the electron and muon neutrinos' spectra at the MMB, however the separation of muon neutrinos originated from pion and kaon decays is sharper in the baseline.

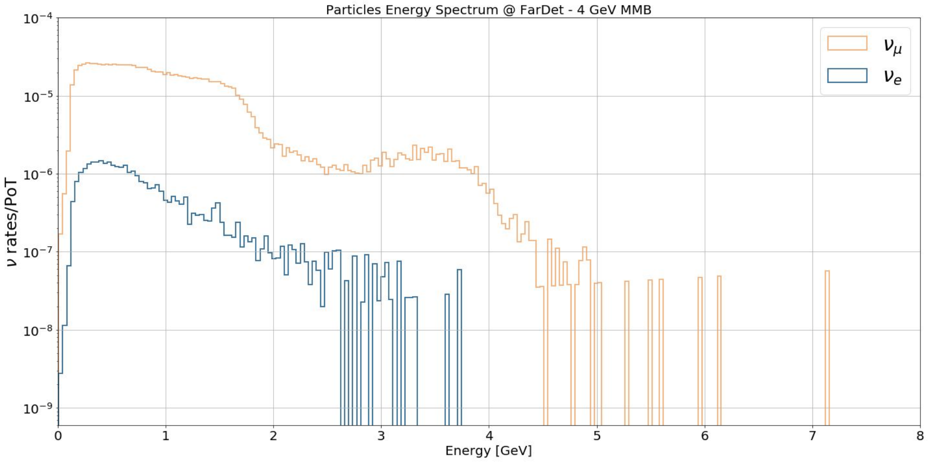
A future study capable of separating the decay channels originating the particles reaching the Far Detector could improve the comparison study.

Neutrino Fluxes

6 GeV/c



4 GeV/c



Muon and electron neutrinos reaching the far detector originated from the 6 and 4 GeV/c optimized MMB. While the electron neutrinos lose of intensity as a consequence of the lower intensity secondary beams, the muon neutrinos need to be properly separated based on their decaying channel of origin.

ν_μ Flux

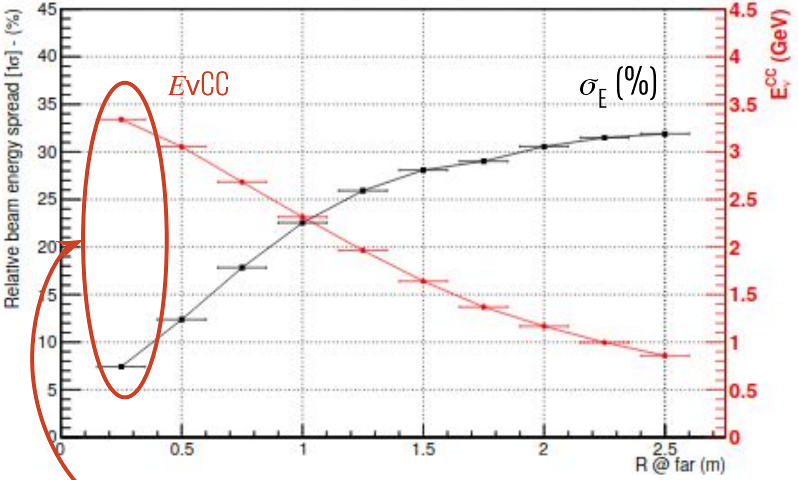
- **ERC project** focused on: measure positrons w/ instrumented decay tunnel from $Ke3 \Longrightarrow$ determination of ν_e flux;
- **As CERN NP06 project**: extend measure to muons with instrumented decay tunnel from $K_{\mu\nu}$ and $K_{\mu3}$, while $\pi_{\mu\nu}$ replacing hadron dump with range meter $\Longrightarrow$ determination of ν_μ flux;

Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

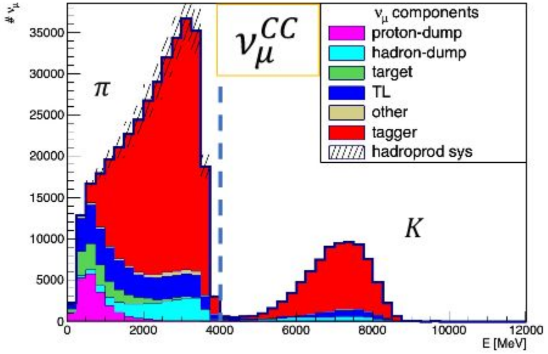
Advantage for ν_μ $\longrightarrow$ Estimation of $E\nu$ from impact radius at detector, without info on final state particles from ν_μCC interaction.

• 8-25% $E\nu$ resolution from π in DUNE energy range

• 30% $E\nu$ resolution from π in HyperK energy range



→Less spread at higher momenta



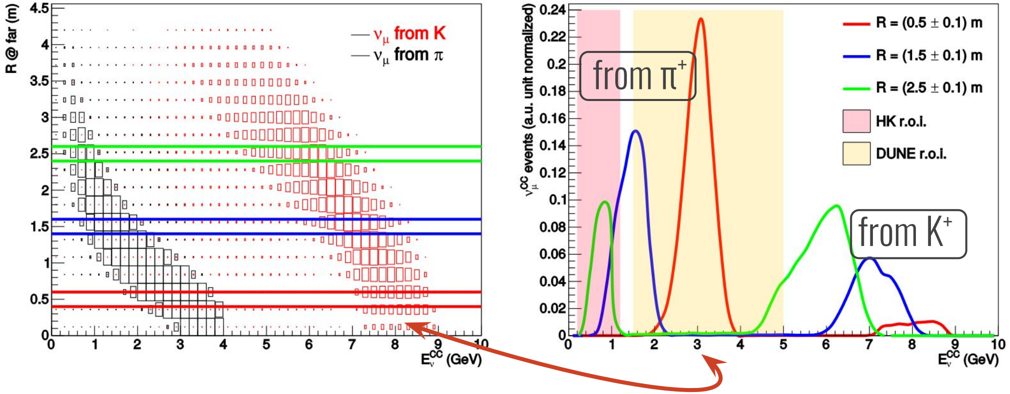
Results: ν_μ Separation

As a result of the narrow band beam, the contributions of ν_μ coming from K^+ decays and from π^+ are well separated.

In conclusion, the MMB shows a kaon and pion yield at the entrance of the tagger that is about twice the baseline ENUBET beamline.

By employing the runs at 4 and 6 GeV/c, the MMB provides the degree of tunability needed to enhance the number of observed neutrino interactions at the detector in the 1 GeV region both for ν_e and ν_μ.

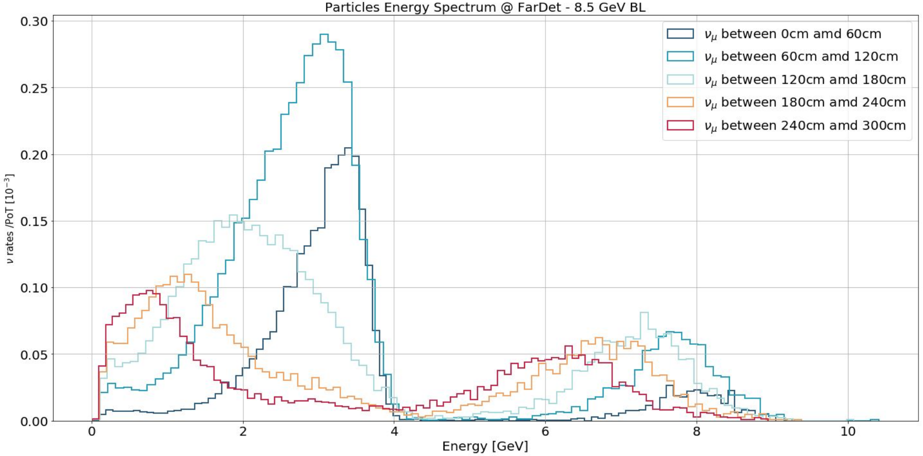
(E_ν ,R) are strongly correlated
R = radial distance of interaction vertex from beam axis;



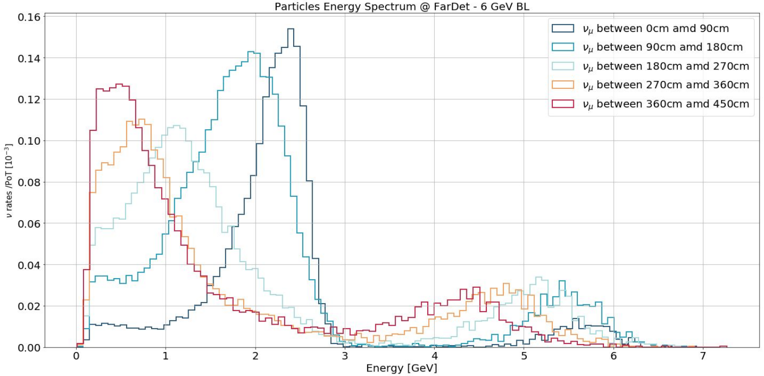
Left plot: correlation between the energy of ν_μCC events at the neutrino detector (horizontal axis) and the radial distance from the beam axis (vertical axis) in the baseline ENUBET beamline.
Right plot: momentum spectrum of the neutrinos at different radial ranges.

Results: ν_μ Separation

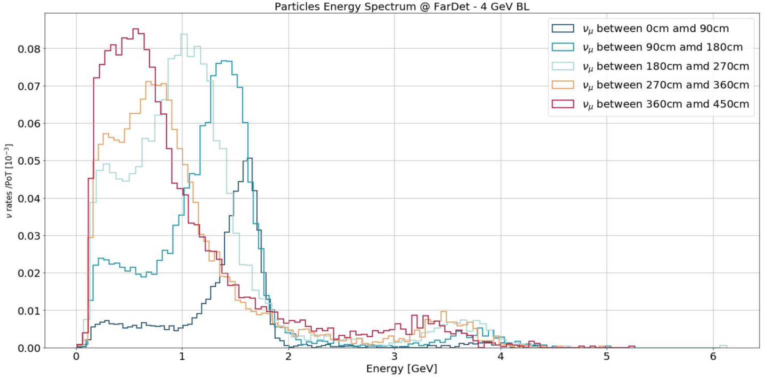
8.5 GeV/c BL



6 GeV/c BL



4 GeV/c BL



Linear momentum spectrum of the ν_μCC events (i.e. cross-section weighted flux) reaching the neutrino detector for the 8.5, 6, and 4 GeV/c beamline at different radial ranges.

Performances: Background Reconstruction and W absorber

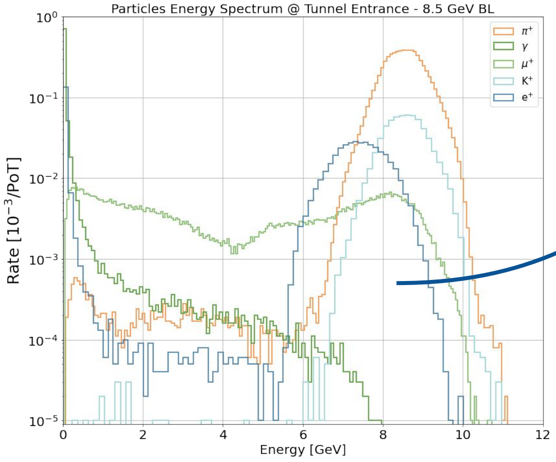
Full GEANT4 simulation of the detector

- Event builder: start from event seed and cluster energy deposits compatible in space and time;
- Particle separation: multivariate analysis (MLP-NN from TMVA) exploiting 19 variables

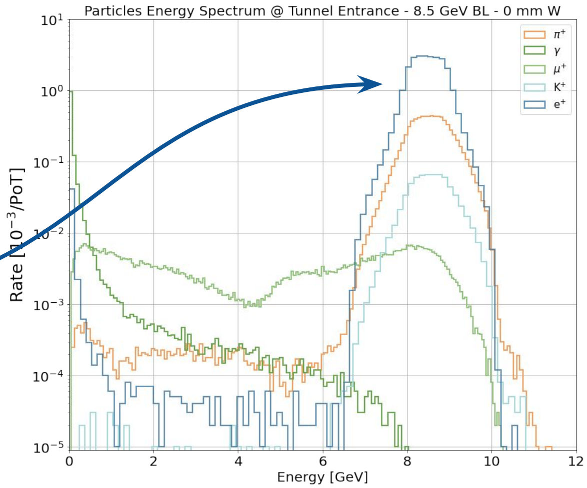
→ e+ impinging on Tagger walls.

Removing the absorber in the focusing section allows for more positrons but parallel and fully contained until the tunnel exit

5 mm W



0 mm W

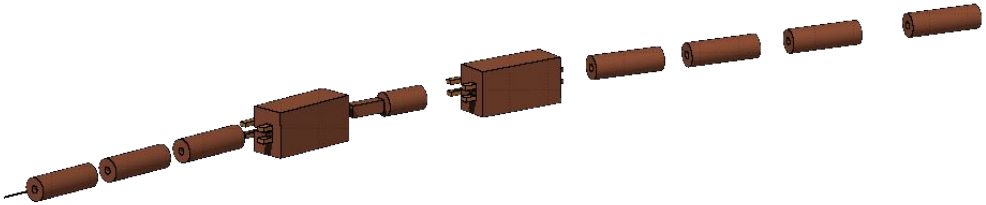


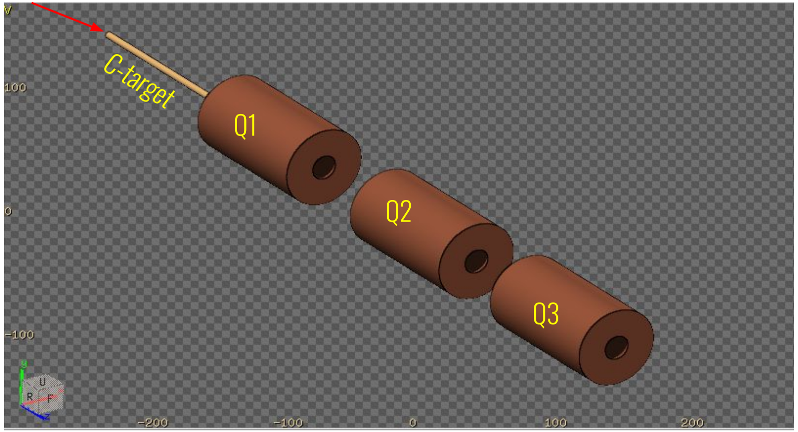
FLUKA

Multi Momentum Beamline implementation in FLUKA for magnets' deterioration studies.

A primary beam like the one at SPS CERN of 400 GeV/c with $4{\times}10^{13}$ protons over 2 s can cause stress damage to the target and the magnets.

A realistic plan for a beamline realization implies studies of heat endurance and radiation damage of the magnets via the use of the FLUKA software.



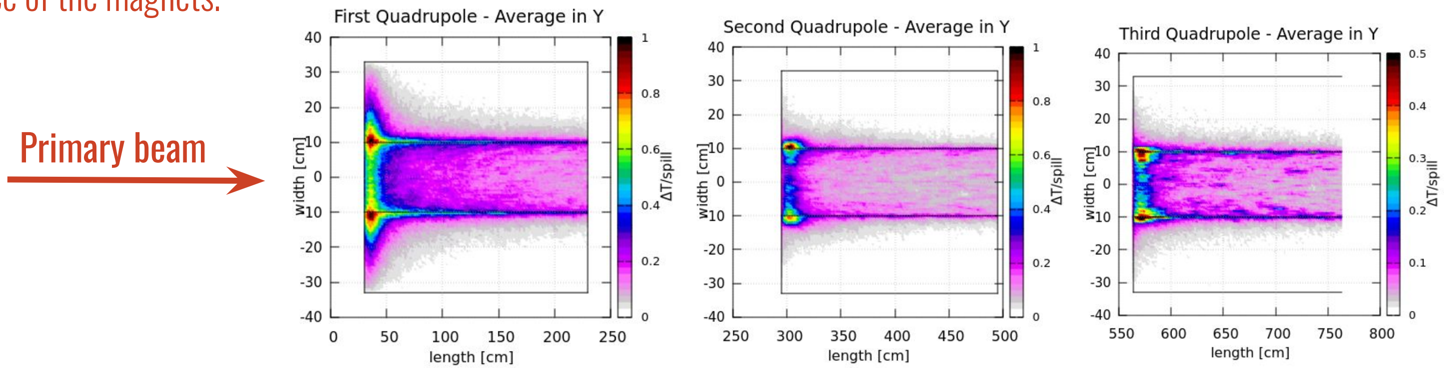


FLUKA: Temperature Increase

The beam-induced heating can be a source of degradation of the magnets and can even hamper significantly the operation.

Here is a first preliminary study of the adiabatic heat increase of the magnets. The overall temperature is calculated both with a central cut in X and averaged over Y along all Z for all three quadrupoles.

The temperature increase is of the order of 1-5K per primary spill on target, and the greatest impact is at the entrance of the magnets.



Conclusions

MMB stable design with existing CERN Magnets and full G4BL and FLUKA implementation.

The MMB shows a kaon and pion yield at the entrance of the tagger that is about twice the baseline ENUBET beamline.

NEXT STEPS for the MMB:

- 1% level on flux achieved w/ Baseline Beamline option (Hadro Production) → MMB to be validated.
- Beamline instrumentation studies → Ongoing
- Radiation studies with FLUKA → Ongoing
- Genetic optimization showing promising flux improvements to be applied to the MMB.

Thanks to the University of Milano-Bicocca and the BE-EA-LE Section at CERN.

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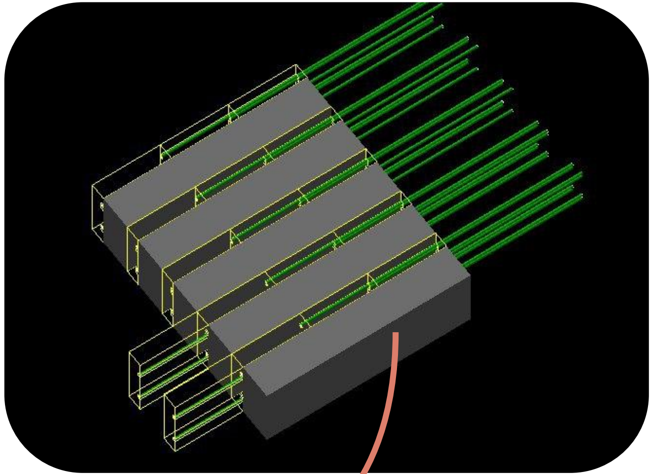
Conferences and Publications

- Poster session at WIN2021: „The ENUBET monitored neutrino beam“ - http://win2021.umn.edu/
- Internal WP1 ENUBET meetings: regular status report on a weekly basis
- Internal BE-EA-LE section meetings: regular status report on a weekly basis
- PBC – Conventional Beams – Neutrino Subgroup Scientific Secretary - https://indico.cern.ch/category/14376/
- INFN School of Statistics 2022 in Paestum - https://agenda.infn.it/event/28039/
- Talk at NuFACT 2022 - https://www.physics.utah.edu/nufact-2022/
- Poster session at IPAC22: „The ENUBET Multi Momentum Secondary Beamline Design“ and "Future Neutrino Beam Studies at CERN in the Framework of the Physics Beyond Colliders Initiative". - https://www.ipac22.org/

- **Design and Diagnostics of High-Precision Accelerator Neutrino Beams** Applied Sciences
  2021-02-11 | journal-article DOI: 10.3390/app11041644
- **Decay tunnel instrumentation for the ENUBET neutrino beam** Journal of Instrumentation
  2020 | journal-article DOI:10.1088/1748-0221/15/05/C05059
- **Polysiloxane-based scintillators for shashlik calorimeters** Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
  2020 | journal-article DOI: 10.1016/j.nima.2019.163379
- **Silicon Photomultipliers for the decay tunnel instrumentation of the ENUBET neutrino beam** Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
  2020 | journal-article DOI: 10.1016/j.nima.2020.164482
- **The ENUBET ERC project for an instrumented decay tunnel for future neutrino beams** Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
  2020 | journal-article
- **The ENUBET positron tagger prototype: Construction and testbeam performance** Journal of Instrumentation
  2020 | journal-article DOI: 10.1088/1748-0221/15/08/P08001
- **Shashlik calorimeters for the ENUBET tagged neutrino beam** Journal of Physics: Conference Series
  2019 | conference-paper DOI: 10.1088/1742-6596/1162/1/012032
- **Shashlik calorimeters: Novel compact prototypes for the ENUBET experiment** Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
  2019 | journal-article DOI: 10.1016/j.nima.2018.11.041
- **Status of the ENUBET Project** Proceedings of Science
  2019 | conference-paper
- **The ENUBET neutrino beam** Proceedings of Science
  2019 | conference-paper
- **Status of the ENUBET project** Proceedings of Science
  2018 | conference-paper
- **The ENUBET narrow band neutrino beam** Proceedings of Science
  2018 | conference-paper

ENUBINO



Prototype of the ENUBET calorimeter tested in November 2021 at the CERN East Area T9 then simulated in Geant4.

Single UCM in vacuum:

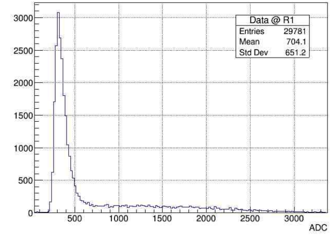
- Sinctillators: rectangular 5.2x30x30 mm generic plastic material 1.03 g/cm^3.
- Absorbers: simple iron parallelepiped 15x30x90 mm.

Beam: 15 GeV/c of mainly protons tested in November → 15 GeV/c electron, muons and pions beams simulated in Geant4.

Taking into account the total thickness of the prototype and the length of radiation, the test performed in T9 was equivalent to a uniform exposure of the detector to mips.

Demonstrator tested in October 2022

Data



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