The design of the ENUBET beamline

NuFact 2022

Elisabetta G. Parozzi - CERN, Università degli Studi Milano-Bicocca
on behalf of the ENUBET collaboration

Index

- The ENUBET Project
- Proton Extraction
- Target studies
- Baseline Configuration studies:
  - Optimization
  - Proton and Hadron Dump
- Multi Momentum line studies
  - Layout
  - Fieldmaps
- Conclusion

ENUBET: The Physics Goal

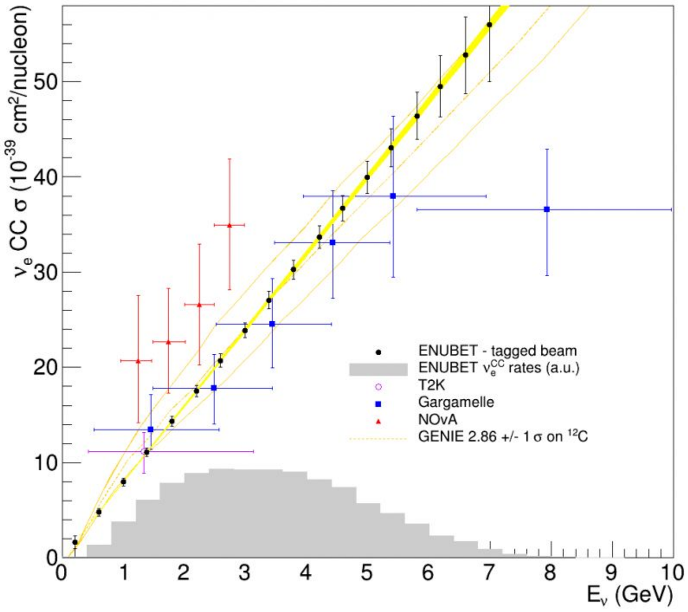
Weak interactions → $\sigma \sim 10^{-38}$ cm^2

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.

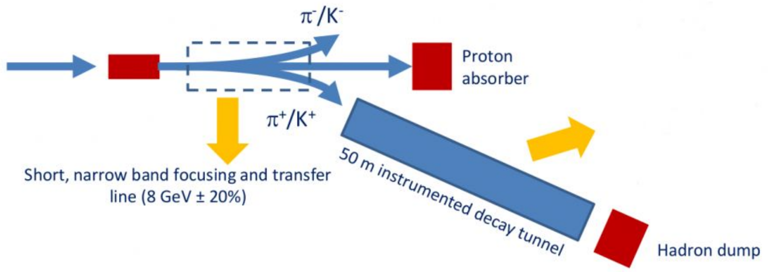


The ENUBET Project: Monitored neutrino Beams

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 NeUtrino BEams from kaon Tagging):

New monitoring technique from the 3-body decay: $K^+ \rightarrow \mu/e^+ \pi^0 \nu_\mu/\nu_e$ (Kμ3/Ke3) and $K^+ \rightarrow \mu^+ \nu_\mu$ ($K_{\mu\nu}$) inside the decay tunnel in order to reduce the systematic uncertainty on the initial ν_e/ν_μK flux and cross section knowledge down to the 1% level.

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 $K_{\mu 3}$, while $\pi_{\mu\nu}$ replacing hadron dump with range meter $\Longrightarrow$ determination of ν_μ flux;

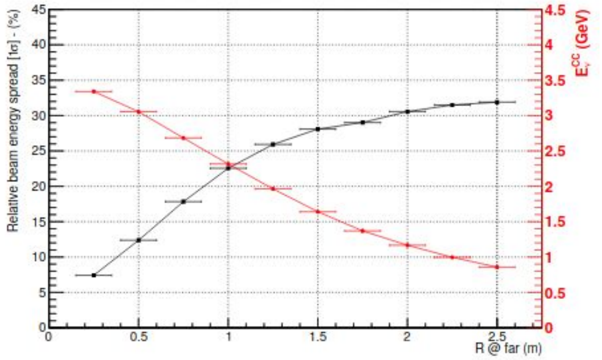
Main systematics contributions are bypassed: hadron production, beamline geometry & focusing, POT;

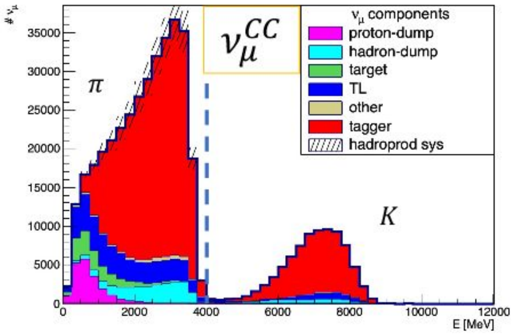
Advantage for $\nu_\mu \longrightarrow$ Estimation of $E\nu$: from impact radius at detector, without info on final state particles from ν_μ CC interaction.

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

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

DUNE optimized TL w/ 8.5 GeV beam and ongoing R&D: Multi-Momentum Beamline (4, 6 and 8.5 GeV) $\longrightarrow$ HyperK & DUNE optimized.





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.

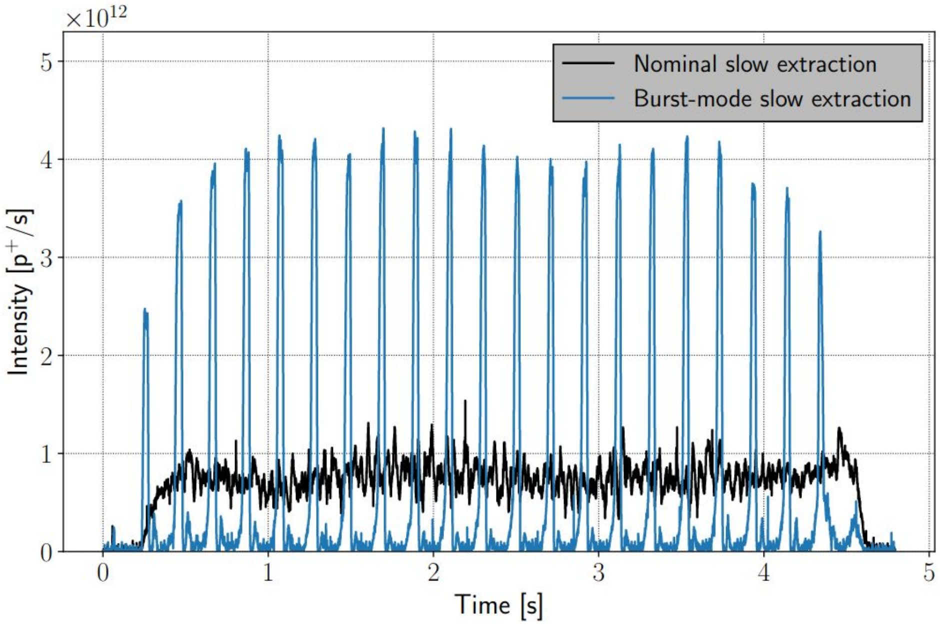
Proton Extraction

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.

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:

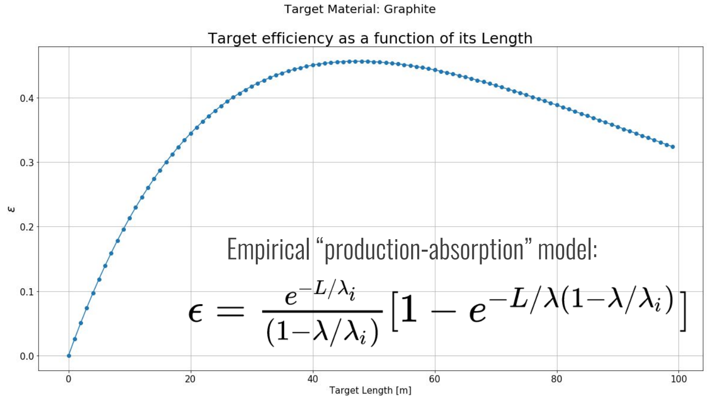
- different target materials → graphite (density 2.2 g/cm3), beryllium (density 1.81 g/cm3), Inconel (density 8.2 g/cm3) and various high-Z materials such as gold and tungsten.
- primary protons energy → 400, 150, 70, 50 GeV/c

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

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

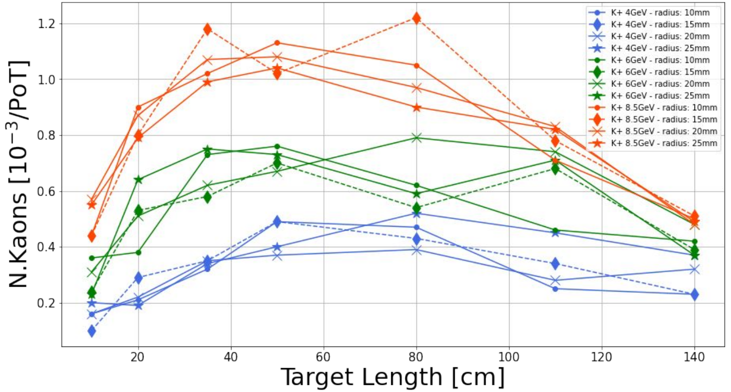
Before complete target design, further investigate the limitations of radiation damages imposed by Graphite.

CONCLUSION: Graphite 70 cm length x 30 mm radius



Empirical "production-absorption" model:

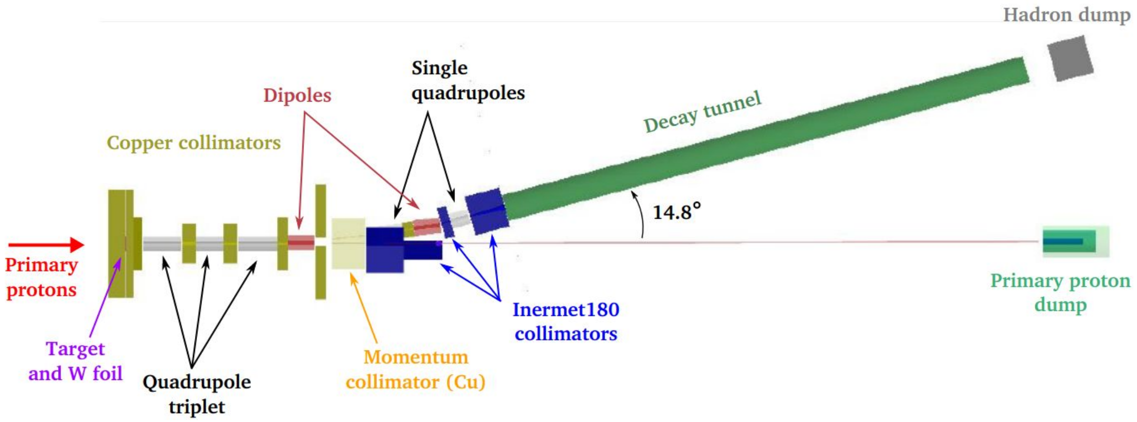
$$\epsilon = \frac{e^{-L/\lambda_i}}{(1-\lambda/\lambda_i)}\left[1 - e^{-L/\lambda(1-\lambda/\lambda_i)}\right]$$



Beamline Configurations

Baseline Configuration

Fully static Beamline → Slow extraction of a few seconds required by pile up constraints
Transfer line optimized for 8.5 GeV/c secondaries
optics design: TRANSPORT
tracking & background: G4Beamline/G4
doses & neutron shielding: FLUKA
systematics: GEANT4

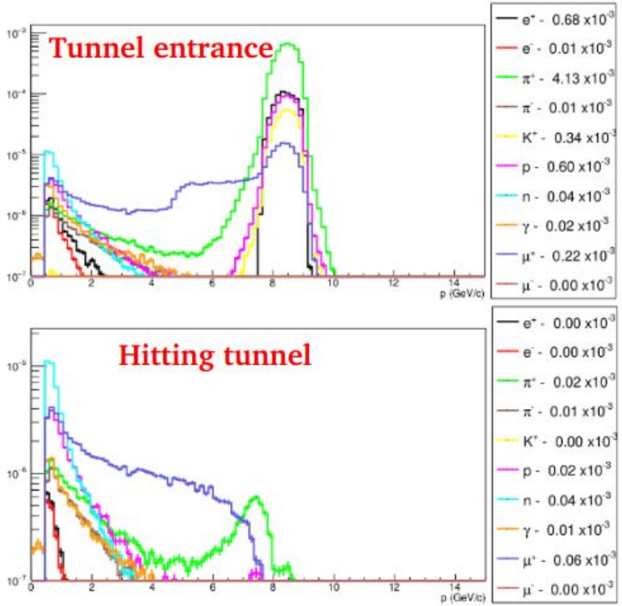


- Target: 70 cm graphite rod w/ 6 cm d
- Magnets:
  - normal conducting quad & dipoles
  - two 1.8 T dipoles for 14.8 deg total bending angle
- Decay tunnel:
  - length of 40 m w/ 1 m radius
  - borated PE shielding
- Dumps:
  - 3 cylindrical layers proton dump
  - same structure for hadron dump (reduced backscattering flux)

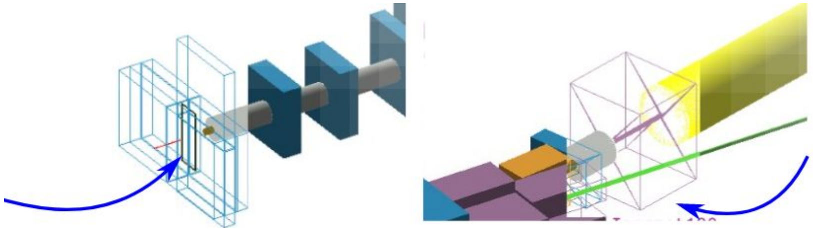
Baseline Configuration

Monte Carlo simulations to predict beamline performance.

1. TRANSPORT iterations for Optics design
2. Implementation and extensive validation with G4bl/G4
3. Background analysis: e+ and mu+ from other decays ⟶ Collimation and W positron filter.



50 mm-thick W foil for target e+ suppression



Final pre-tunnel collimator blocks for background & halo suppression

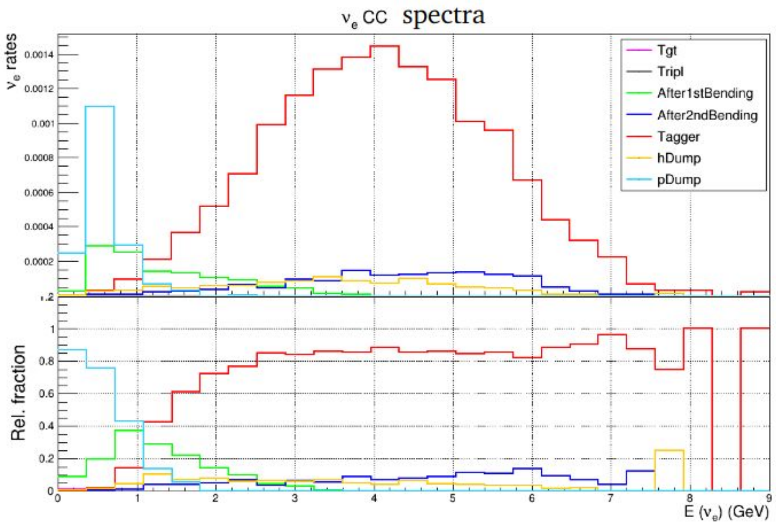
Baseline Configuration: Preliminary Results

Assuming 500 ton neutrino detector at 50 m with CERN-SPS as driver and 4.5×10^{19} POT/y:

10^4 ν_eCC in ~3 years of data taking

About 80% of total electron neutrino flux is produced by taggable neutrinos (i.e. produced by Ke3 decays in the decay tunnel)

Further Optimization of signal/noise (S/N) ratio of the beamline is a lengthy process based on full tracking and interaction of particles through all elements and materials.

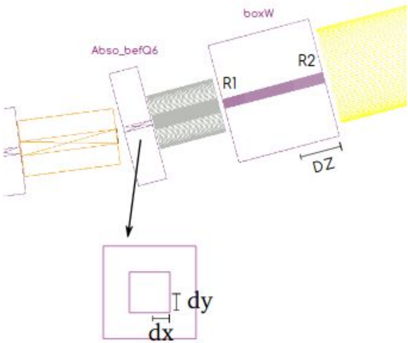


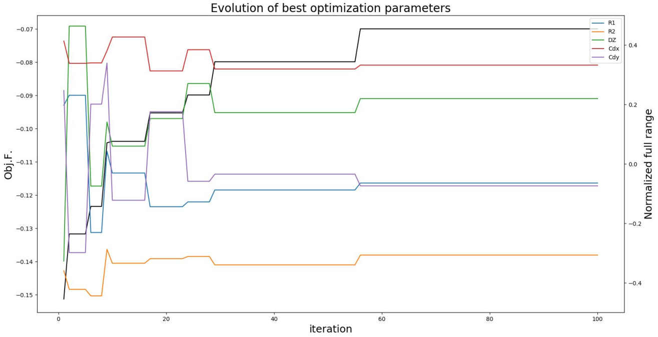
Rates at Tunnel Entrance	400 GeV PoT
$\pi^+[10^{-3}]$/PoT	$K^+[10^{-3}]$/PoT
4.13	0.34

Baseline Configuration: Optimization

An optimization framework based on a Genetic Algorithm (GA) and running on a computing cluster has been fully developed and applied to the beamline collimation.

Last two collimators (Inermet 180) before decay tunnel: 5 parameters



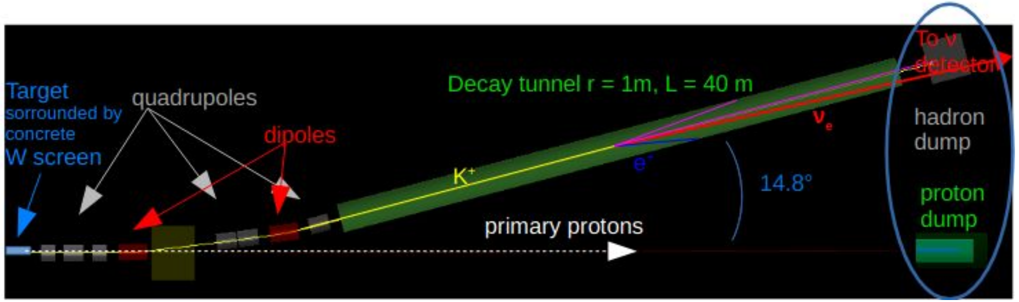


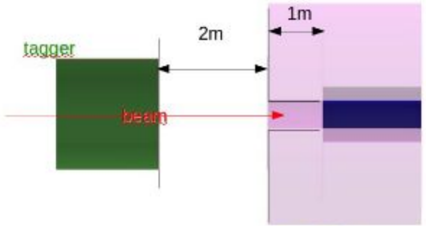
Rates at Tunnel Entrance	$\pi^+[10^{-3}]$/PoT	$K^+[10^{-3}]$/PoT
Design	4.13	0.34
Optimized	5.27	0.44

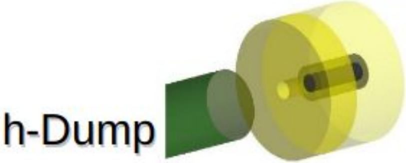
Preliminary Result → 28% gain in flux
→ **2.4 years data taking**

- Goal: improvement of S/N ratio
- **Figure of Merit (FOM)**: K+ at tunnel entrance scaled by bkg particles hitting tunnel walls (def. as positrons & pions from beamline and not from tunnel Ke3 events)
- Convergence in ~2 weeks; ~100 beamlines /iteration

Baseline: Proton and Hadron Dump Optimization





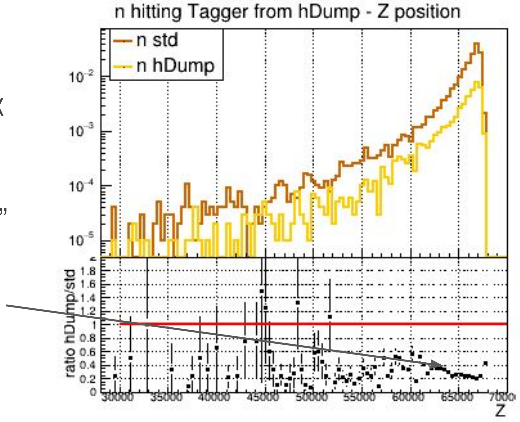


Similar structure, 3 cylindrical layers:

- Hadron Dump: graphite core (50 cm diameter), inside a layer of Iron (1 m diameter), covered by borated concrete (4 m diameter) + 1 m of borated concrete is placed in front of the hadron dump leaving the opening for the beam ⟶ design optimized to reduce the backscattering. Reduction by a significant amount of the flux all along the tagger

  In particular, last meters of the tunnel where the neutron fluence is more significant ⟶ Ratio w.r.t "standard" dump ~ 0.2

- Proton Dump: 3 m long graphite core, surrounded by aluminum, covered by iron



⟶ final position of the proton dump will be optimized to reduce the number of neutrinos in the Far Detector

Multi Momentum Beamline: Optics

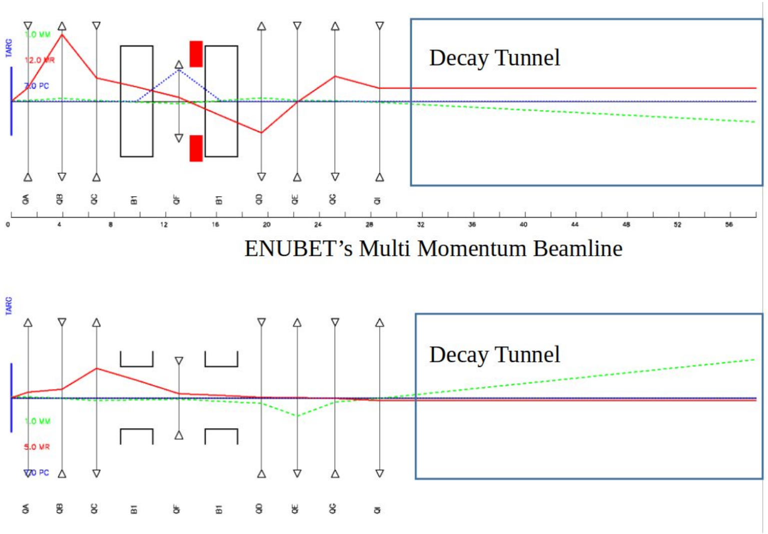
Current beamline design: 8.5 GeV K+ DUNE optimized

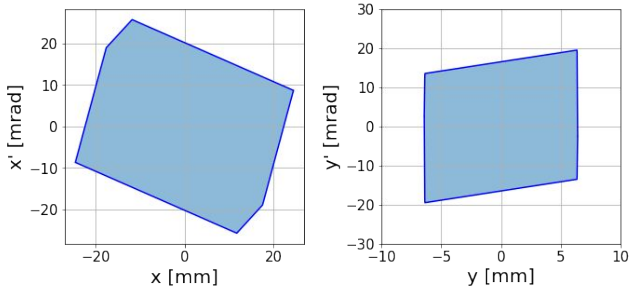
HyperK and T2K rely on 0.5-1 GeV ν_e.

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"

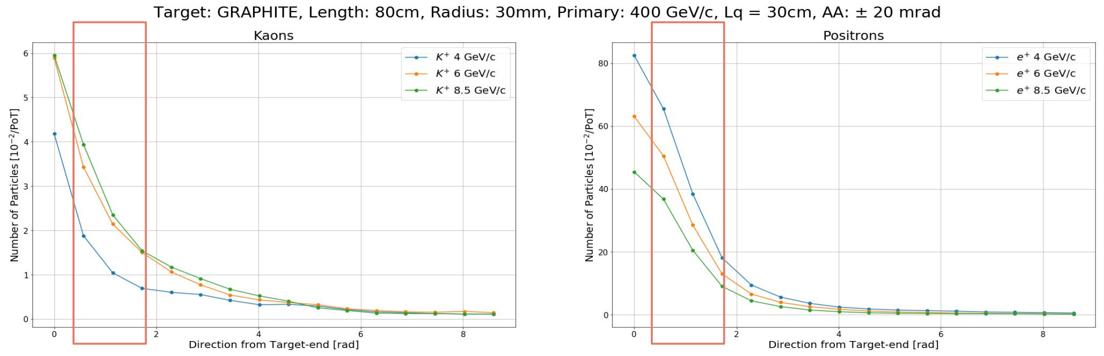




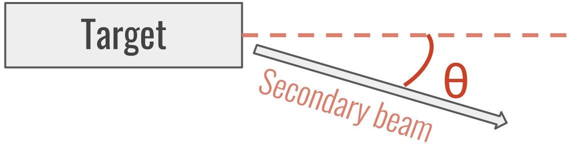
Multi Momentum Beamline: Production Angle

PROs: significant cut for possible positrons background

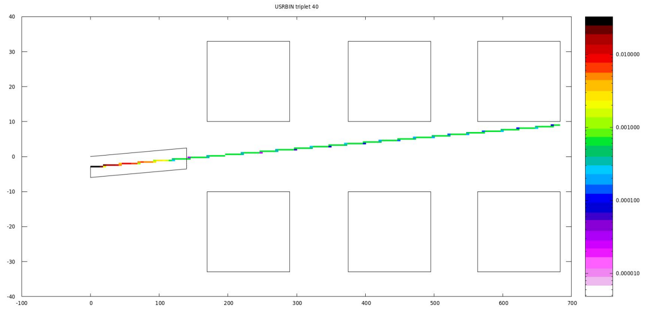
CONs: reduced kaons rate - however still sufficient
Current kaons expected rate at tagger ~10^{-3}/PoT



Proposed direction: ~1°



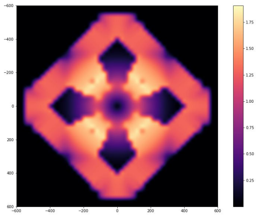
Maximum angle within magnets acceptance and heat endurance: 1°

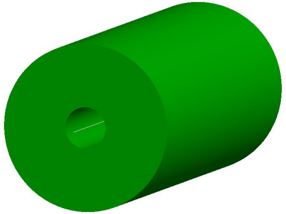


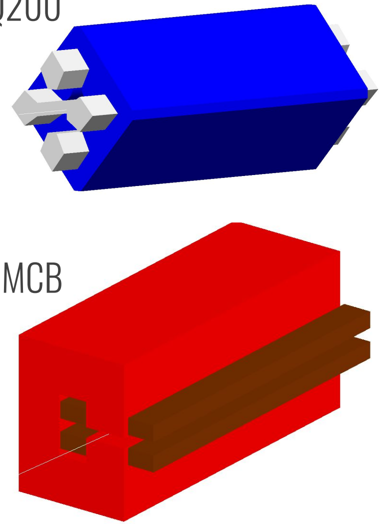
Multi Momentum Beamline: Fieldmaps

Optics based on existing magnets at CERN:

- Q200 (200 mm aperture)
- QFL (100 mm aperture)
- MCB (80 mm aperture)

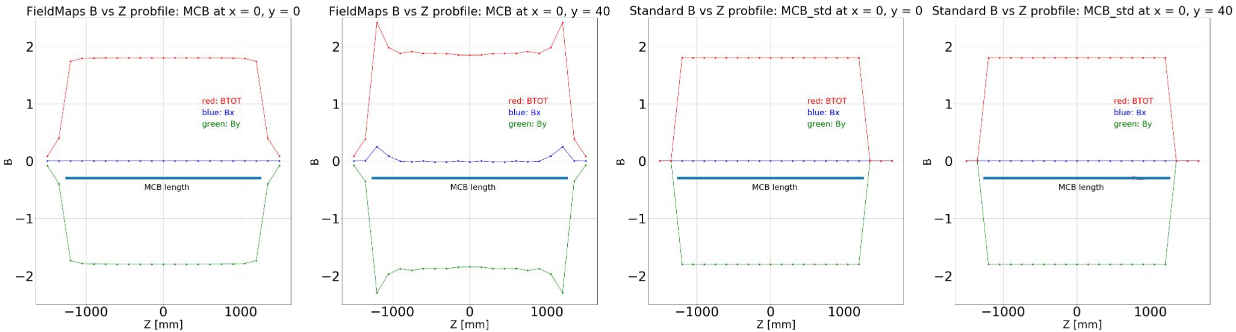


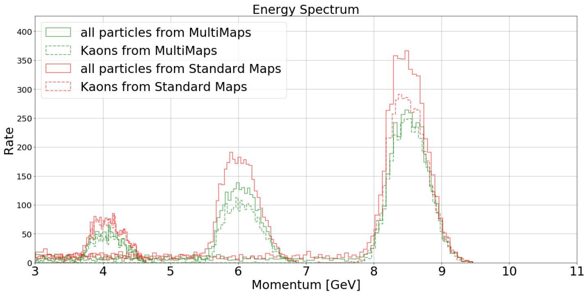




Particle tracking and Optics testing in G4BL → Magnets geometry and Field implementation

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





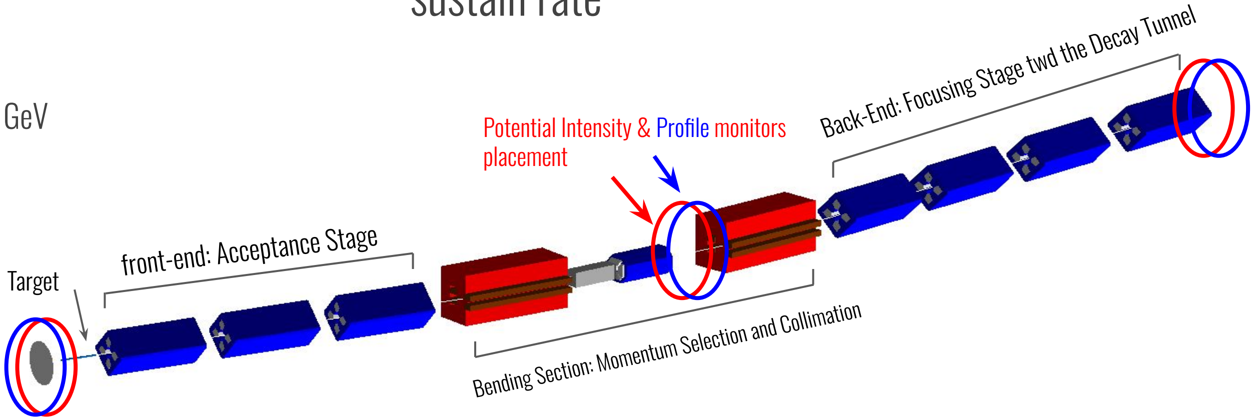
Multi Momentum Beamline: G4BL Layout and Instrumentation

Layout summary up to date:

- First quadrupole distance from the target: 30 cm
- Target 1° tilt from beamline to reduce background and primary re-interaction.
- 5 mm W absorber after collimation → to reduce the positrons bgk.
- ~2s slow extraction with 4.5×10^{13}~POT per spill on the target → 10^{10} Kaons/spill
- Short Secondary Beamline (29 m)
- Primary Momentum: 400 GeV
- Secondary Momenta: 8.5 GeV - 6 GeV - 4 GeV

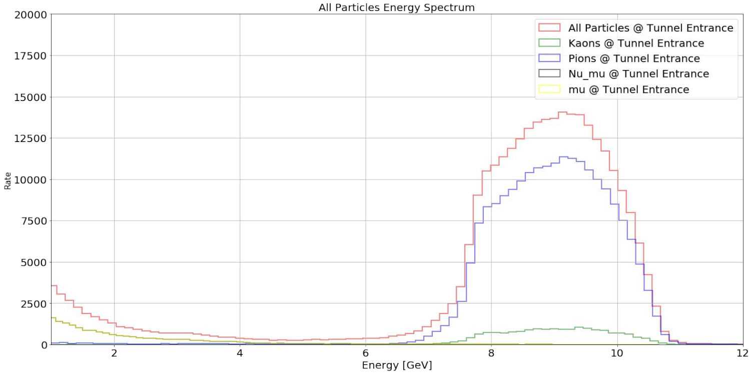
Beam Profile and Intensity measurements at two points in the line as well as at the Tunnel Entrance.

In progress: Possible detectors that can sustain rate



Multi Momentum Beamline: Preliminary Results

Pions and Kaons Rate:



Rates at Tunnel Entrance	400 GeV PoT
$\pi^+[10^{-3}]$/PoT	$K^+[10^{-3}]$/PoT
2.7	0.44

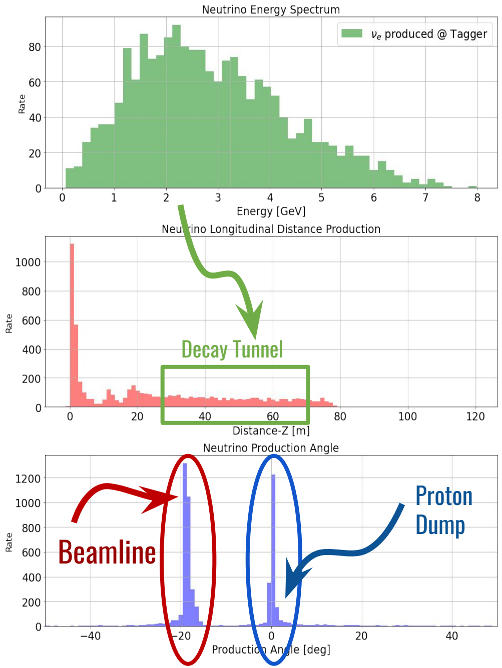
Monitoring the angle of production allows to separate neutrinos produced by the main channel decay and possible proton dump contamination.

2.4 years data taking

Fine elements fieldmaps calculated with Opera. realistic geometry for bkg interactions.

Next step:

- Collimation
- Possible Optimization via genetic algorithms
- Neutrino spectrum at Far Detector



Conclusions

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

Baseline Beamline → 10^4 ν_eCC in ~2/3 years of data taking.

NEXT STEPS:

- 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 also to MMB.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).