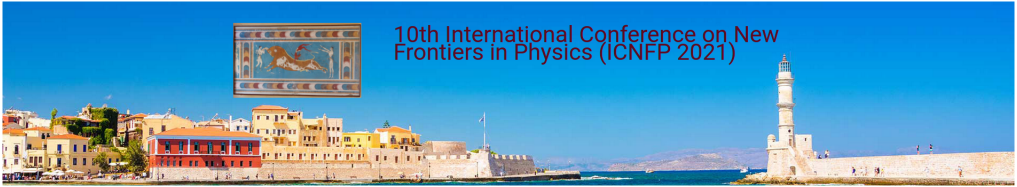
This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

Updates on the design of the ENUBET monitored neutrino beam

M. Pari (University and INFN Padova)
on behalf of the ENUBET Collaboration

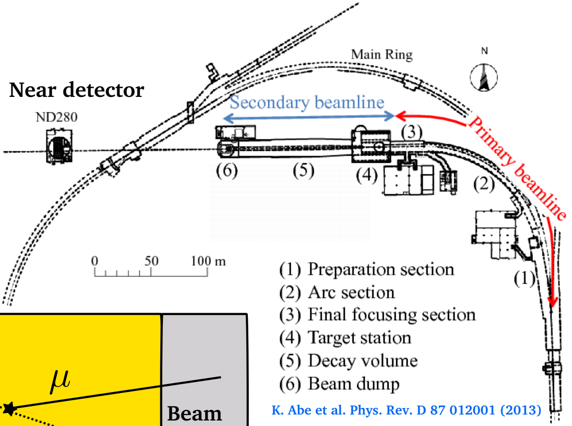


Accelerator neutrino beams

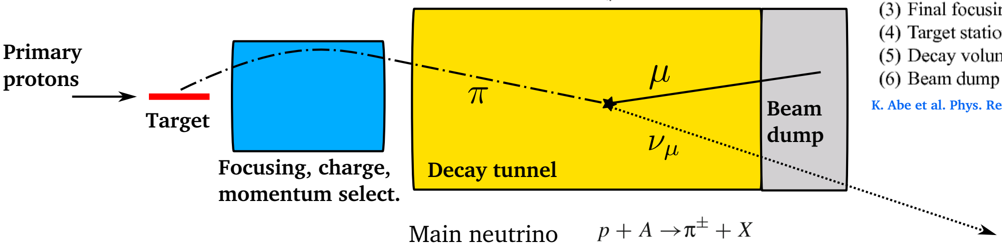
Particle accelerators are used to generate a controlled neutrino flux. Unlike other neutrino sources:

- → Control of neutrino energy
- → Control of source-detector distance

Typical neutrino energies of 1-20 GeV
Typical source-detector distances of 1-100 km



K. Abe et al. Phys. Rev. D 87 012001 (2013)



Main neutrino production channel:

$$p + A \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu/\bar{\nu}_\mu$$

Overview

Accelerator neutrino beams: limitations

Neutrino flux estimation for conventional neutrino beams is a complex task:

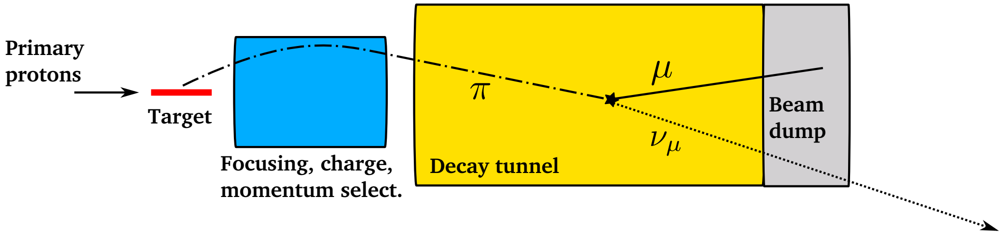
- → Extensive simulations
- → Dedicated hadro-production data
- → Short baseline flux measurements
- → Muon monitoring at the beam dump

Leading to an **overall flux uncertainty of ∼ O(10%)**

Solving open problems in ν-physics:

- Considerable increase of precision required
- Different solutions actively investigated

One possible approach: monitored neutrino beams



The ENUBET project: Enhanced NeUtrino BEams from kaon Tagging

ERC grant 2016-2022

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).

CERN Neutrino Platform experiment NP06/ENUBET

The ENUBET Collaboration: 60 Physicists, 12 Institutions

Goal:

Design of a monitored neutrino beam

↓

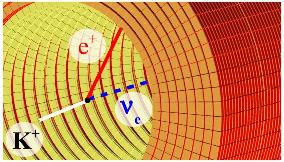
Reduction of neutrino flux systematics at the 1% level (additional: energy at 10%)

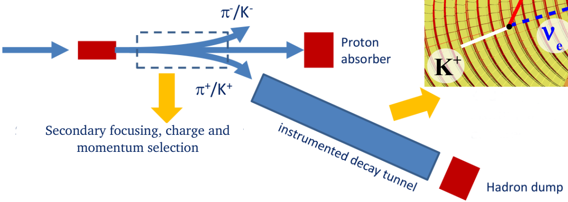
↓

Opening for high precision cross section measurement (1%)

Concept of monitored neutrino beam:

- Decay tunnel fully instrumented
- Direct estimation of neutrino flux from production vertex particles
- Bypassing high uncertainty hadro-production based flux extimation



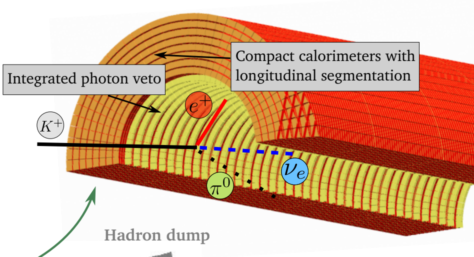


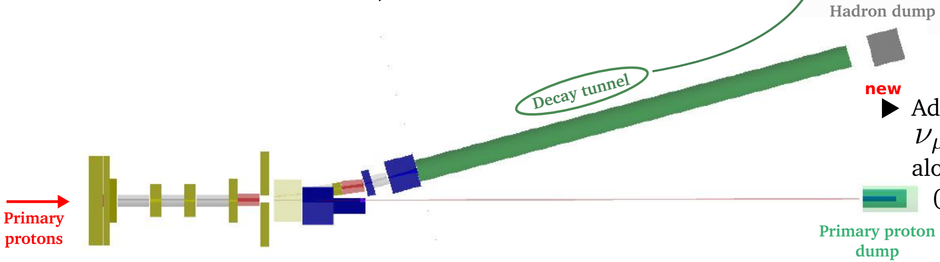
The ENUBET project

- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

[*]
- $\mathbf{K_{e3}}$ $\mathbf{(K^+ \longrightarrow \pi^0 \, e^+ \, \nu_e)}$ **main source of positrons** at the decay tunnel walls: possibility of **direct estimation of ν_e flux**

new
- Muons at decay tunnel mainly from $\mathbf{K}_{\mu 2}(\mathbf{K}^+ \longrightarrow \mu^+ \nu_\mu)$ and $\mathbf{K}_{\mu 3}$: increased precision on $\nu_{\mu_\mathbf{K}}$ and $\nu_\mathbf{e}$ flux





new
- Additional information on $\nu_{\mu\pi}$ from muon monitors along hadron dump (range-meter)

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

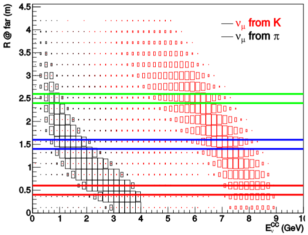
The ENUBET project

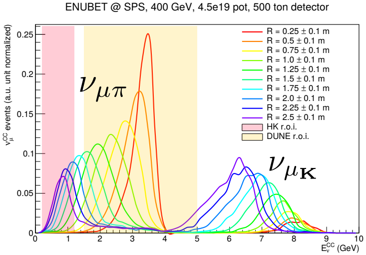
- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

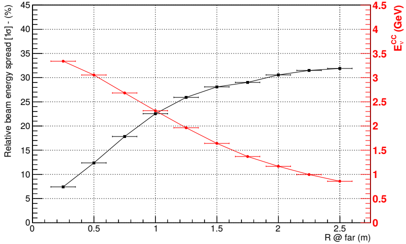
→ **Narrow-Band Off-Axis (NBOA) technique** [*]

- Full energy separation of ν_{μ_K} and $\nu_{\mu\pi}$ components
- Direct angle-momentum correlations from two-body decays

Estimation of neutrino energy from impact radius @detector

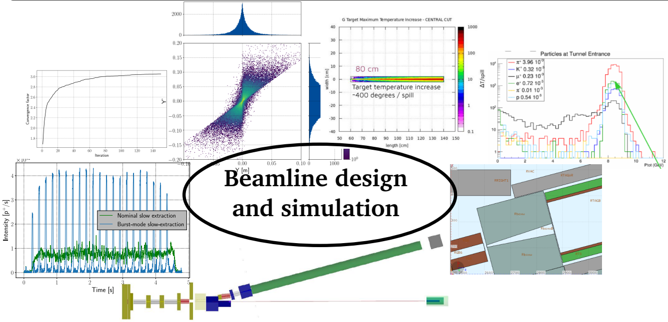




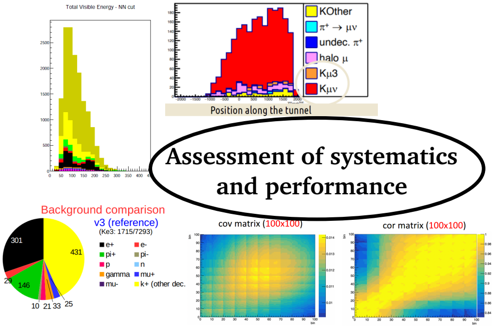


[*] F. Acerbi et al., CERN-SPSC-2021-013

The ENUBET project

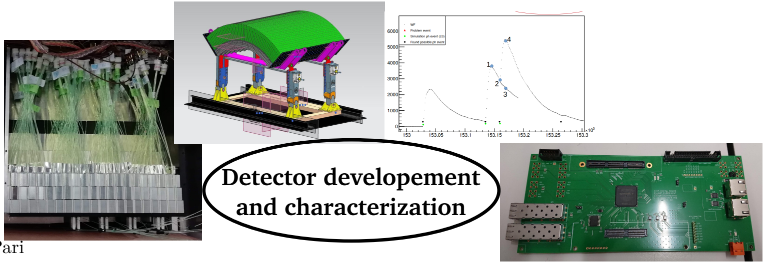


Beamline design and simulation



Assessment of systematics and performance

Next slides: new developements in different WPs



Detector developement and characterization

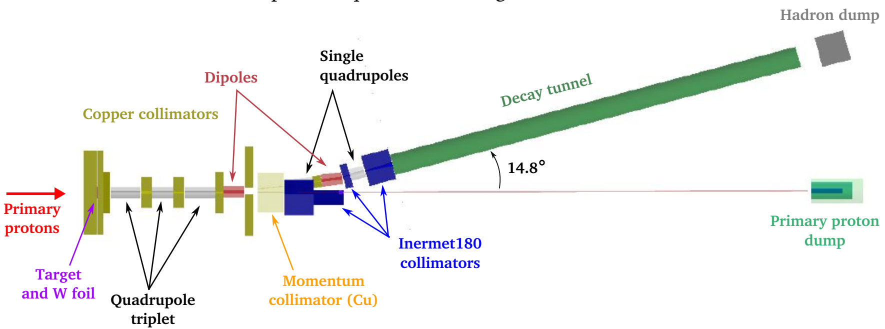
The ENUBET beamline

Baseline option: **fully static beamline**

- Target and hadro-production: FLUKA ✓
- Transfer line:
  - optics optimization: TRANSPORT ✓
  - tracking & background: G4Beamline/G4 ✓
  - doses & neutron shielding: FLUKA ✓
  - systematics: GEANT4 **[in progress]**
- Neutron shielding added at hadron dump ✓
- Proton dump will require further eng. studies

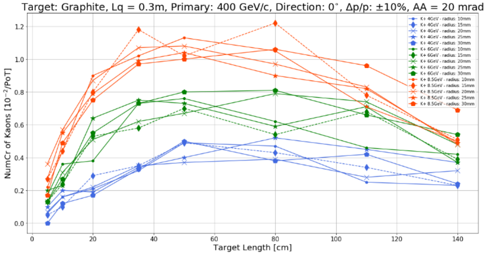
Static = slow extraction of a few seconds required by pile-up constraints (differently from majority of nu-beams)

CERN-SPS good candidate (400 GeV p+)



The ENUBET beamline

Results from recent target optimiz. (70 cm graphite rod): new beamline version with x2 Kaon flux wrt previous and x1.5 less e+ bkg



@SPS

π/pot (10^{-3})	K/pot (10^{-3})	Extraction length	π/cycle (10^{10})	K/cycle (10^{10})	Proposal [(c)]
19	1.4	2 s	85	6.2	**x 4**

new

Assuming 500 ton neutrino detector at 50 m and CERN-SPS as driver:

10^4 ν_eCC in ~2 years of data taking (preliminary)

Static advantages:

- ✓ cost effective
- ✓ stable operation
- ✓ low rate

But:

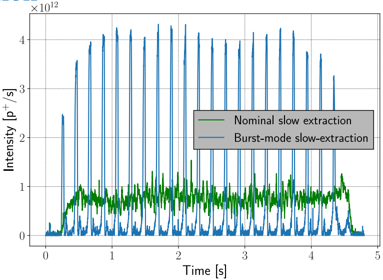
potential flux increase from magnetic horn also appealing

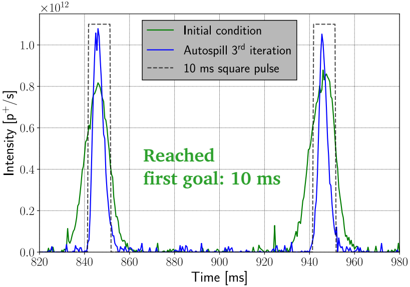
Proton extraction studies

Dedicated slow extraction studies at CERN-SPS: [*]

horn-compatible slow extraction

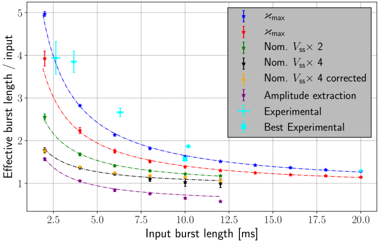
- From experimental campaign:
  - ⟶ Implemented **new pulsed slow extraction** (burst-mode)
  - ⟶ Optimized in operation down to **10 ms pulses @10 Hz**





- From simulations:
  - ⟶ **3-10 ms range of pulse lengths**

General extraction method: could be used for other applications (e.g. cosmic veto)



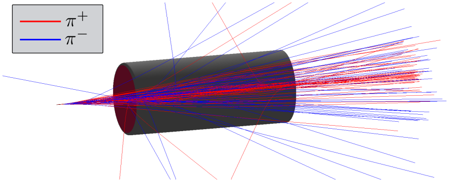
Dedicated study of frequency noise on std slow extraction also recently finalized, showing possible improvements

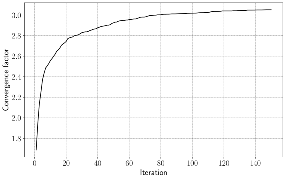
[*] M.Pari, PhD Thesis (2020)
M.Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

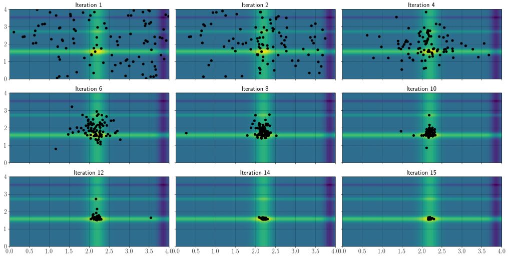
Magnetic horn

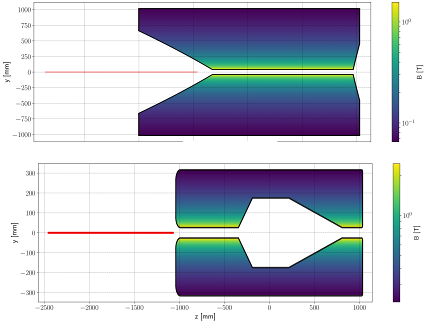
Previous proton extraction results open for a horn option:

- Developed simulation model of horn based on GEANT4
- Genetic algorithm used for optimization of horn geometry (> 10 par)
- Hardware constraints enforced
- Developed fully automatic optimization framework
- First candidates available





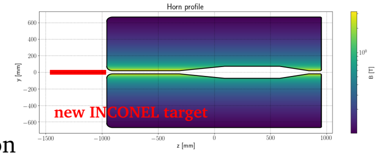


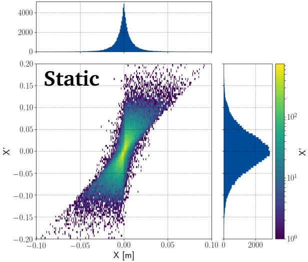


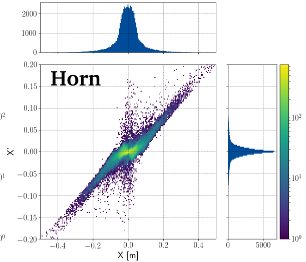
Magnetic horn

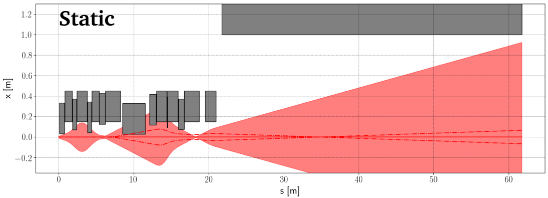
First results from standalone (i.e. first quad) horn optimization point to dedicated study on horn-beamline option:

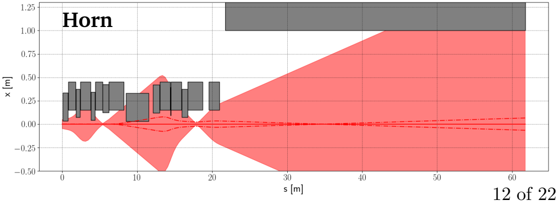
⟶ Development of horn-beamline currently on-going (based on FLUKA, G4, MADX) in parallel to the nominal static option











⟶ Standalone gain factor ∼3 reached with horn optimization, BUT

⟶ Phase space very different: significant design changes required

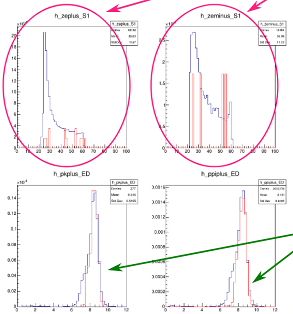
Further optimization

Optimization framework developed for the horn upgraded to be fully generic:

→ Application to fine tune beamline collimators for baseline static option

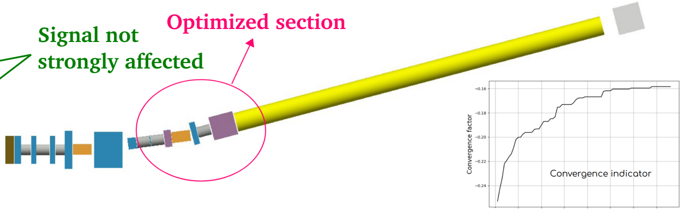
→ First results promosing: significant bkg reduction (preliminary & ongoing)

Main bkg particles suppressed



Signal not strongly affected

Optimized section



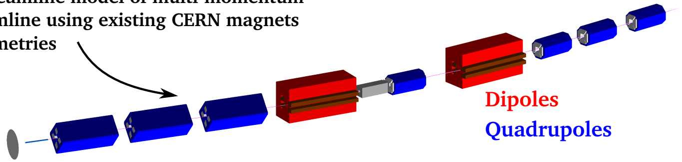
Multi-momentum beamline

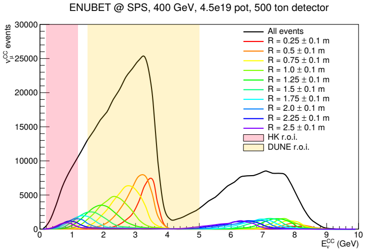
The current ENUBET beamline generates neutrinos peaked in the DUNE region of interest (~4 GeV):

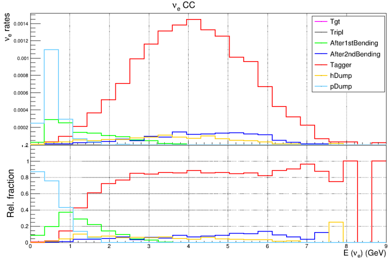
⟶ Study on development of multi-momentum beamline currently ongoing in collabolation w/ CERN

⟶ Goal is modifiable energy range so to cover full range of interest (HK R.o.I. included)

G4beamline model of multi-momentum beamline using existing CERN magnets geometries



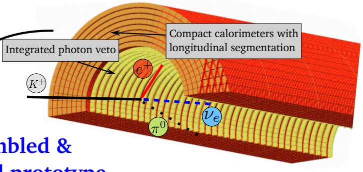




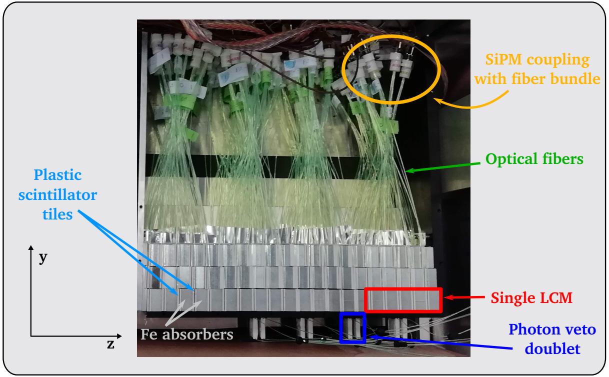
⟶ Promising first estimations of K+ fluxes, background studies are ongoing

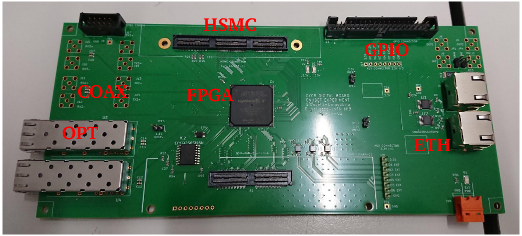
Instrumentation of decay tunnel [*]

- After dedicated studies (simulations, prototyping, test beams):
  - → **Chosen final design**: compact scintillating sampling calorimeters (4.3 radiation lengths) will be used to instrument the ~40m decay tunnel (3 layers). One internal layer of photon veto (scintillator doublet)
  - → Lateral readout to SiPM via bundled WLS fibers (space for shielding: factor 18 dose reduction)
  - → Custom DAQ under development



Assembled & tested prototype

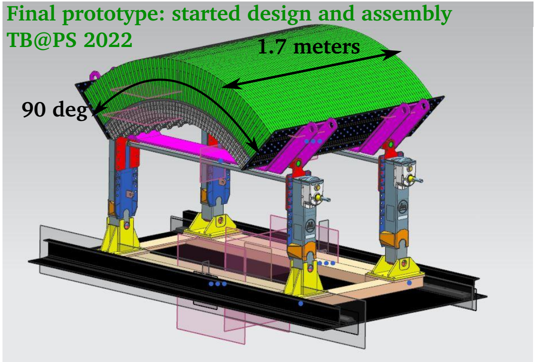


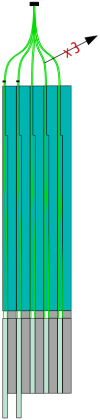


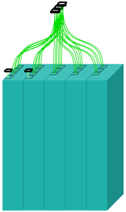
[*] JINST 15(2020)08, P08001; JINST 14 (2019) 02, P02029; NIM A 956(2020)163379

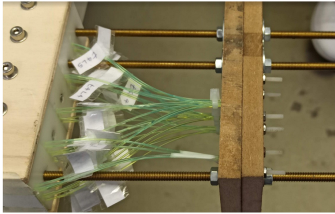
Prototype for exp. validation

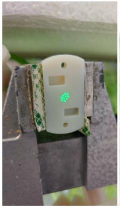
A prototype of the tagger is under construction for a final experimental validation at CERN-PS in 2022:









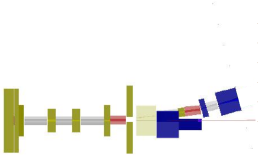


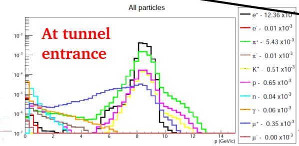
Goal: proof of principle of the ENUBET detector design and concept.

Detector performance & systematics

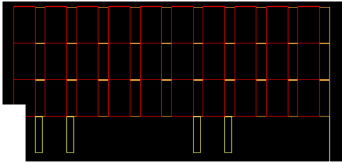
Production using full beamline simulation (G4/G4beamline/FLUKA)

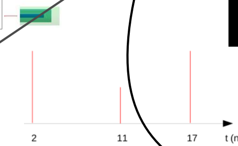
beam





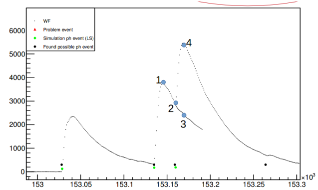
Complete simulation of ENUBET tagger detector (G4)



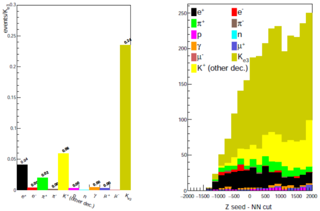


Energy deposition vs time for each sub-module

Waveform generation (SiPM) simulation: energy and time reconstruction



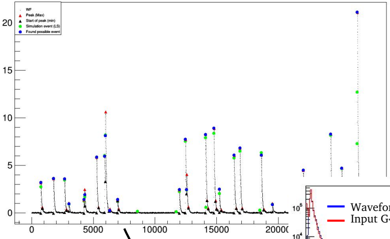
Event reconstruction algorithm

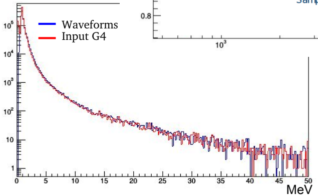


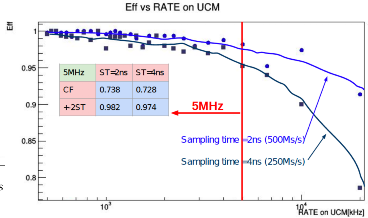
Waveform simulation and reconstruction

Full simulation chain for waveform generation and analysis is near completion:

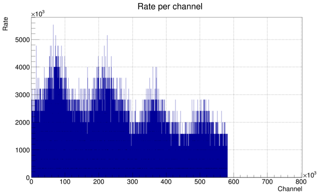
- Digitized electrical signal generated from G4 input
- Different peak detection algorithms developed and tested for energy and time reconstruction
- Model also used to set boundaries on tunnel event rate and digitizer sampling time

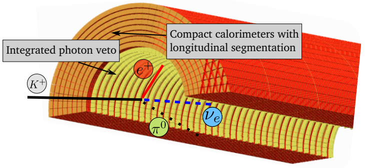






Transfer line and extraction scheme	Hit rate per LCM	detection efficiency
TLR5 slow	1.1 MHz	97.4%
TLR5 fast	10.4 MHz	89.7%
TLR6 slow	2.2 MHz	95.3%



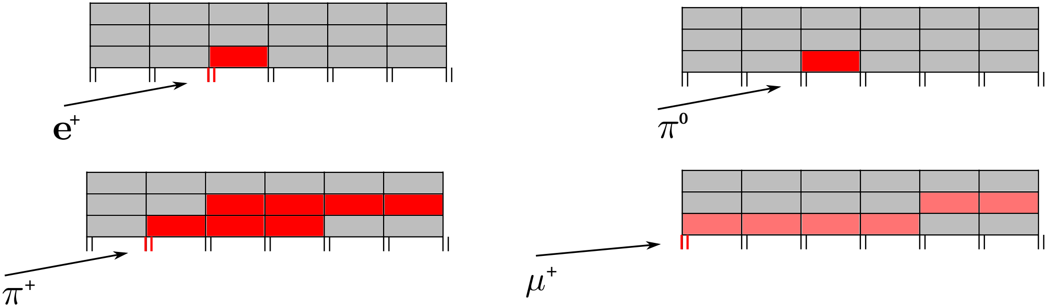


Energy clusters deposited in each sub-module used to reconstruct an event:

→ Two main signals for ENUBET:

positrons from Ke3 | **muons from Kmu2/3** (new)

→ Basic discrimination idea: use tagger granularity to separate EM showers / Hadronic showers / MIP + photon veto



Event reconstruction

More in detail:

→ 15 parameters neural network trained over pure samples.

→ Reconstruction performance in terms of Signal to Noise ratio (S/N) and efficiency can be computed against input G4 information

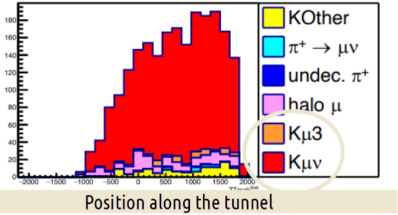
→ **Main results:**

For **muons**:

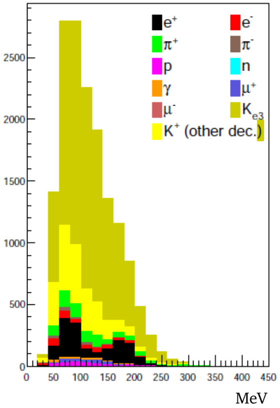
S/N: 6.1
Efficiency: 34%
(dominated by geometrical)

For **positrons**:

S/N: 2.1
Efficiency: 24%
(dominated by geometrical)



Visible Energy (NN)



Conclusions and next steps

- Main design phase of ENUBET terminated:
  - ⟶ Simulations nearly completed and detector technology frozen
  - ⟶ Satisfactory performance confirmed from simulations and data taking
  - ⟶ **A final demostrator of the tagger will be built and tested at the renovated CERN-PS East Area by 2022**
- Promising results up to now: **project on schedule, prototype assembly started**
- **The final systematics on the neutrino fluxes (electron and muon) are under evaluation and will be released by 2021**

baseline

- Studies of non-baseline options proceed as planned, pointing to promising results and potential improvements:
  - ⟶ Successful development of pulsed slow extraction and horn design option could further increase nu-flux
  - ⟶ Genetic optimization on the static beamline for S/N increase
  - ⟶ Studies on a multi-momentum beamline for different nu-energy currently ongoing

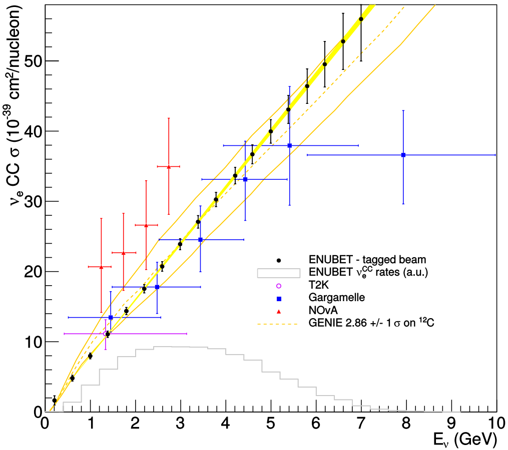
Updated fluxes and spectra with these final beamlines by 2022

further studies

Thank you for your attention

Backup

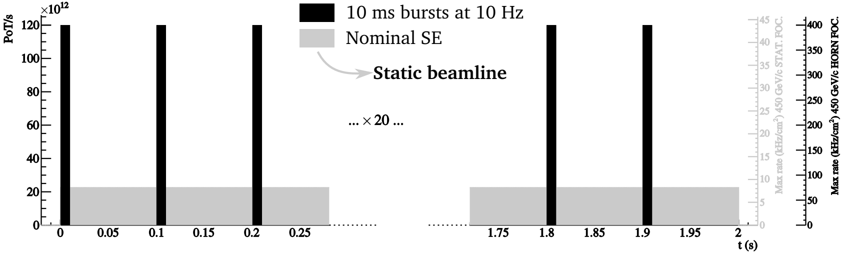
ENUBET: reach



The ENUBET beamline

Baseline option: **fully static beamline**

A tolerable pile-up level at tagger (< 500 kHz/cm²):
fast extraction of protons impractical ⟶ **slow extraction required**



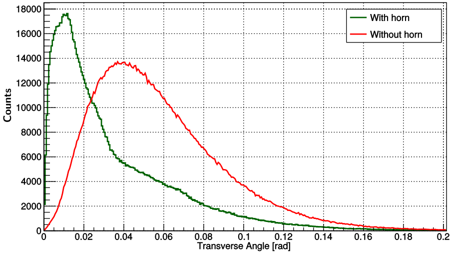
Two possible **slow-extraction** schemes compatible:

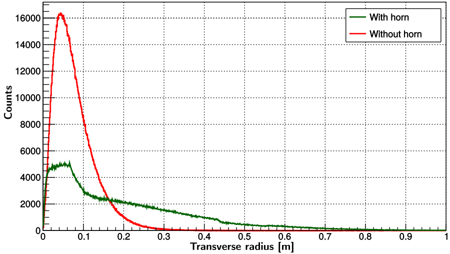
⟶ Static (standard)

⟶ Pulsed (novel)

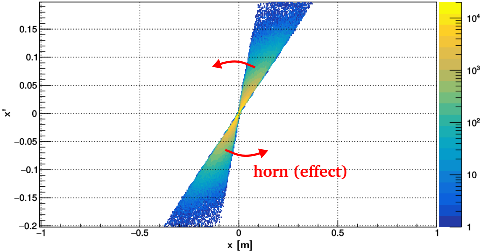
Could allow operation of magnetic horn: significant increase in flux.

Effect of horn on beam

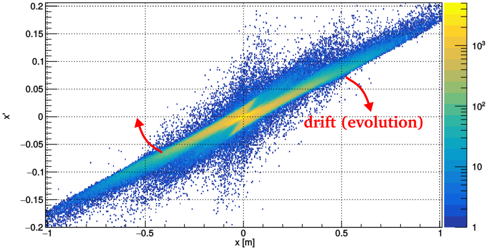


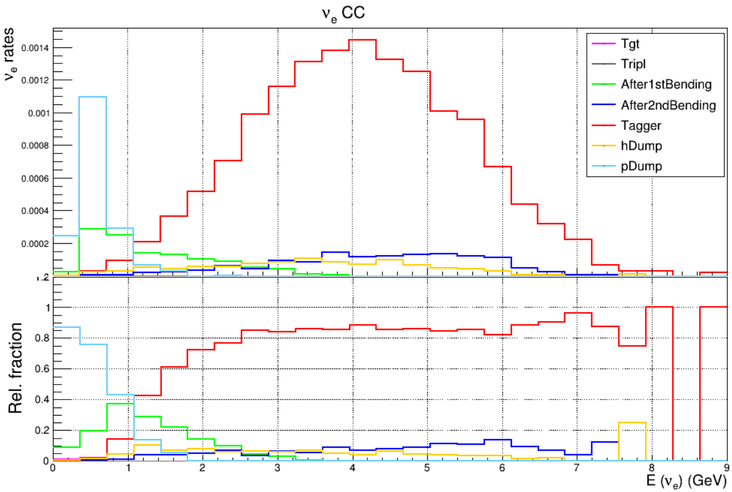


Phase space after target

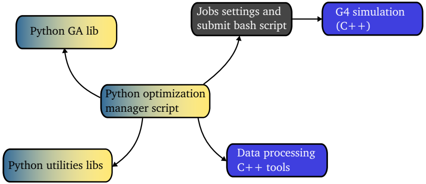


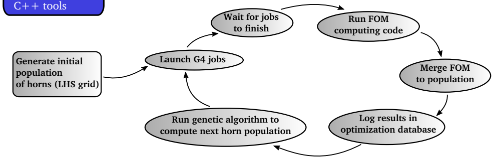
Phase space after horn





ν_e CC
ν_e rates
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
Tgt
Tripl
After1stBending
After2ndBending
Tagger
hDump
pDump
Rel. fraction
1
0.8
0.6
0.4
0.2
0
0 1 2 3 4 5 6 7 8 9
E (ν_e) (GeV)


Python GA lib
Jobs settings and submit bash script
G4 simulation (C++)
Python optimization manager script
Python utilities libs
Data processing C++ tools


Generate initial population of horns (LHS grid)
Launch G4 jobs
Wait for jobs to finish
Run FOM computing code
Merge FOM to population
Log results in optimization database
Run genetic algorithm to compute next horn population