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).

Development and optimization of the ENUBET beamline

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

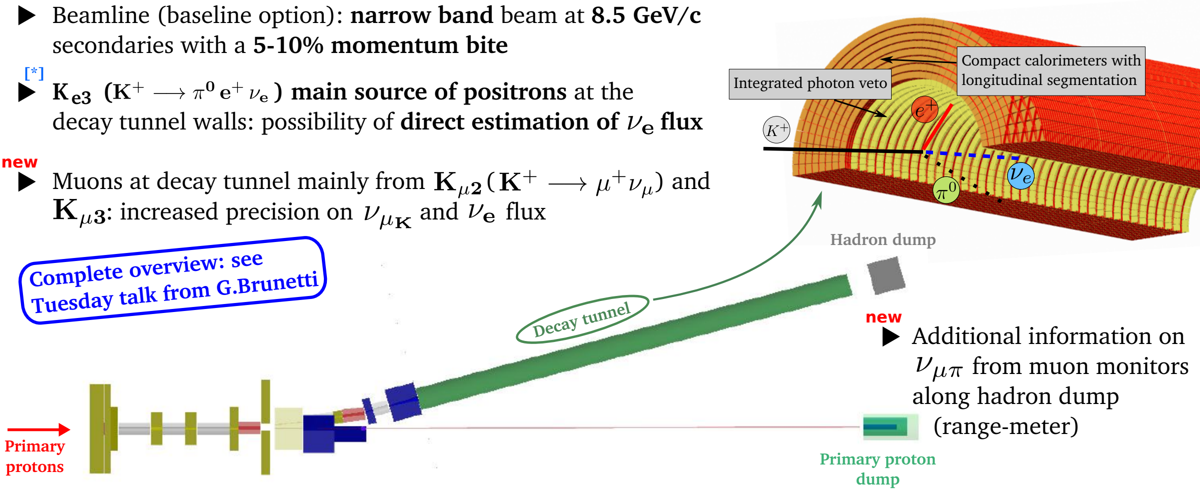
The ENUBET project

- 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

Complete overview: see Tuesday talk from G.Brunetti



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

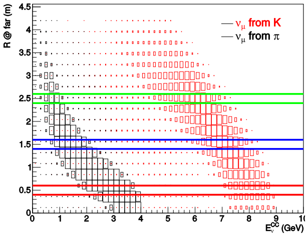
The ENUBET project

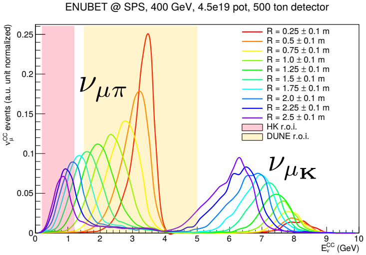
- Beamline (baseline option): **narrow band** beam at **8.5 GeV/c** secondaries with a **5-10% momentum bite**

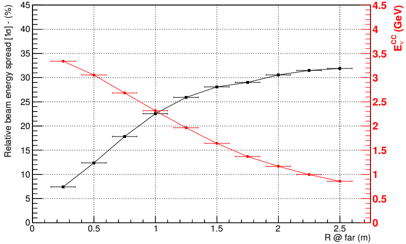
↳ **Narrow-Band Off-Axis (NBOA) technique [*]**

- 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

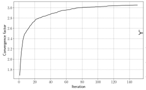


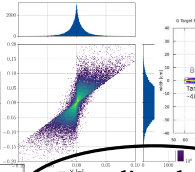


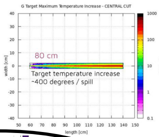


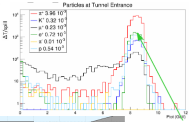
[*] F. Acerbi et al., CERN-SPSC-2021-013

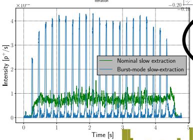
The ENUBET project

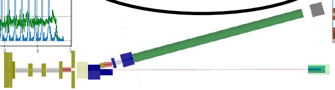


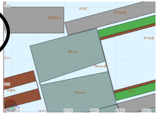




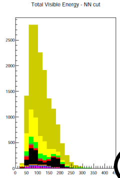


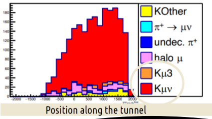




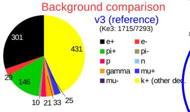


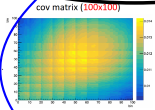
Beamline design and simulation

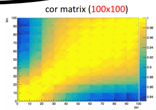




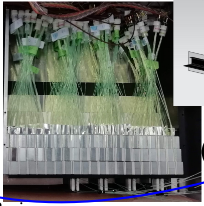
Assessment of systematics and performance

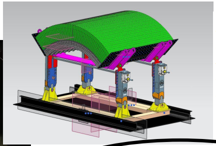


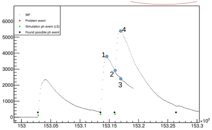




See today talks from F.Pupilli and A.Branca

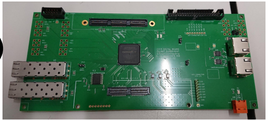




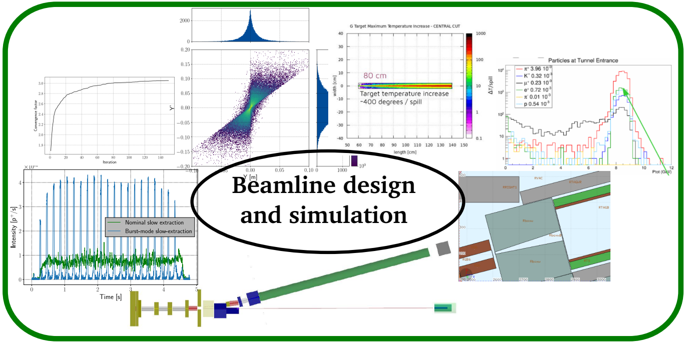


See today talk from F.Iacob

Detector developement and characterization



The ENUBET project



In this talk: focus on beamline, new and ongoing developments

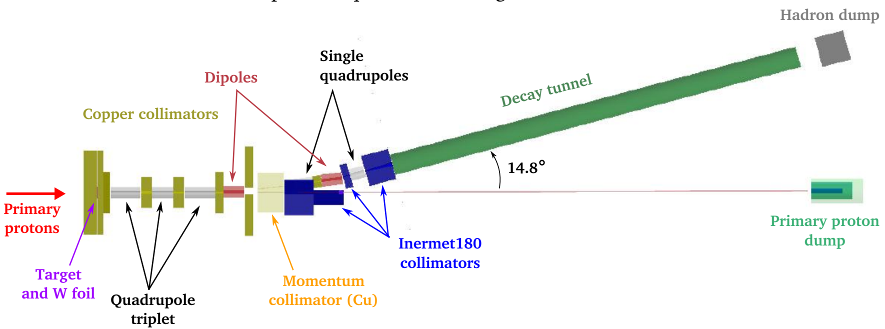
- Baseline design: overview and results
- Recent results on target optimization
- Studies on proton extraction
- Magnetic horn and optimization
- Further beamline optimization
- Multi momentum beamline

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 (SX) of a few seconds required by pile-up constraints (differently from majority of nu-beams)



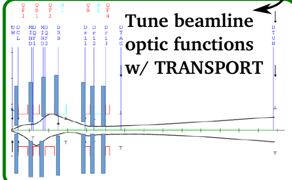
The CERN-SPS is a good candidate: for now SX of ∼2 s of 400 GeV proton is assumed.

Other possible candidates are MI (FermiLab, 120GeV) and MR (J-PARC, 30 GeV).

Beamline: the baseline design

Design process:

Iterate

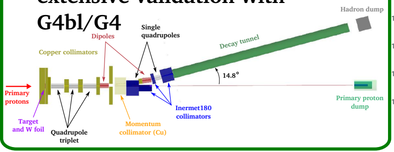


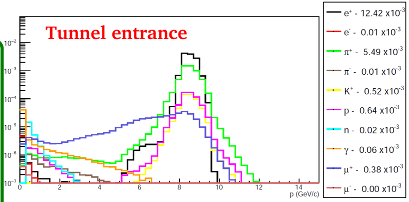
Tune beamline optic functions w/ TRANSPORT

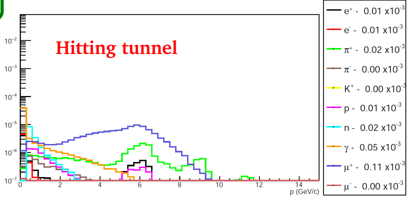
Iterate

Iterate

Implementation and extensive validation with G4bl/G4

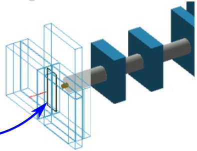


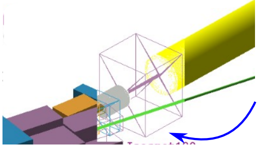




- → Full tracking and interaction of beam w/ beamline elements fundamental to assess beamline performance
- → Positrons & muons from beamline represents important background, as **ENUBET signals are e^+ and μ^+**
- → After several beamline iterations: tight collimation plays an important role. W-positron filter also required

5 mm-thick W foil for target-pos suppression

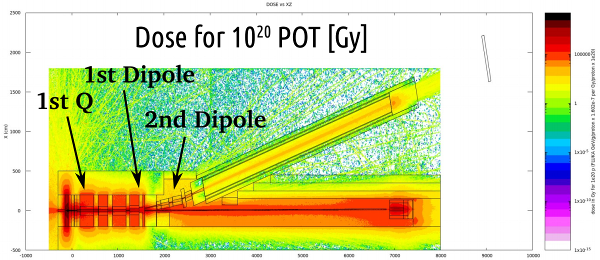


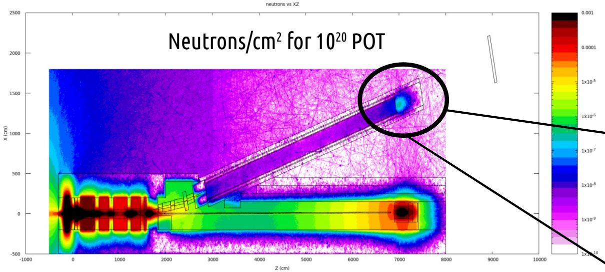


Final pre-tunnel collimator blocks for background & halo suppression

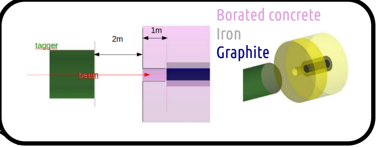
Baseline design: irradiation

- Irradiation studies of the beamline performed using FLUKA: both charged part. & neutrons
- Hottest point: first collimator & quadrupole is 100-300 kGy
- New layer of borated-PE shielding for SiPMs & electronics: factor 18 dose reduction wrt previous case





Dose @2nd dipole significantly lower than @1st: potential use of super-conducting dipole for increased bending angle (less bkg collinearity, pure nu beam). **Studies are ongoing.**



Baseline design: targets

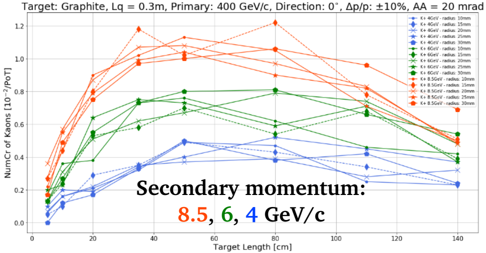
Recent target optimization based on FLUKA & G4beamline model led to successful results and two candidates:

→ **Graphite rod 70 cm-long by 6 cm-diameter**

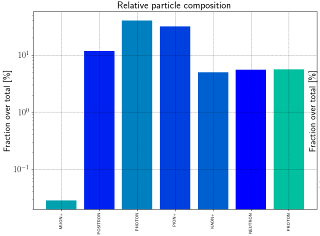
- Well studied target material and feasible implementation
- **Chosen as target for the baseline design**

→ **INCONEL rod 50 cm-long by 6 cm-diameter**

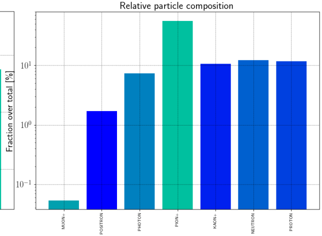
- A relatively new solution: also nuSTORM is considering it
- Observed promising reduction in positrons (& distr.) for a similar number of kaons wrt graphite.
- Considered for alternative beamline designs: work ongoing



GRAPHITE



INCONEL



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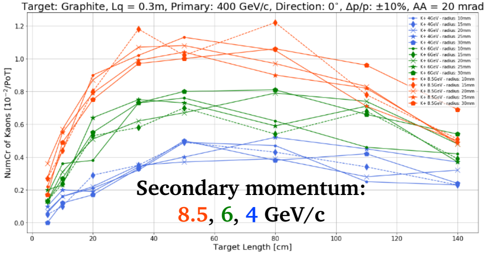

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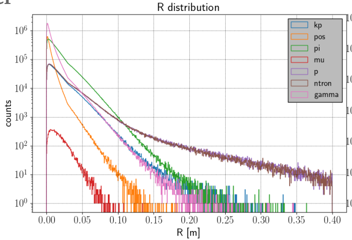
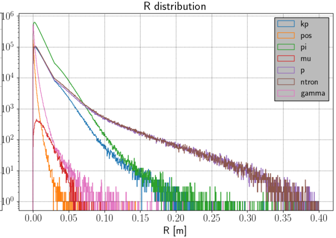


INCONEL



Baseline design: results & considerations

Results using new optimized graphite target: new baseline design 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:

$10^4\ \nu_{e}\mathrm{CC}$ **in ~2 years of data taking (preliminary)**

Considerations:

Good performance, design converged to successful result, based on slow extraction

Important advantages: ✓cost effective (std magnets) ✓stable operation ✓low rate

But:

Potential flux increase from magnetic horn is appealing

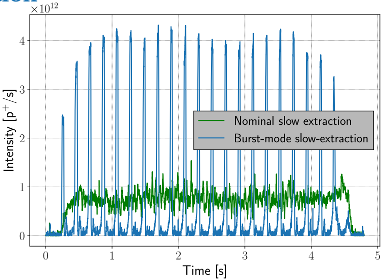
Crucial constraint: no fast extraction (!)

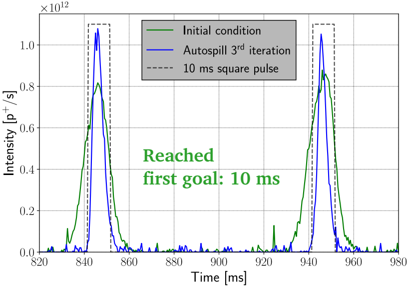
Proton extraction studies

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

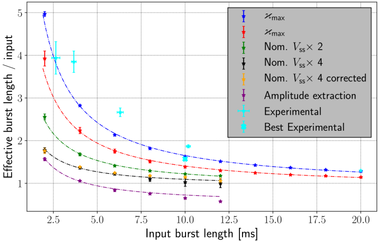
horn-compatible slow extraction

- 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)

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

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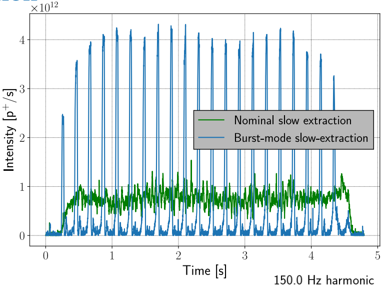

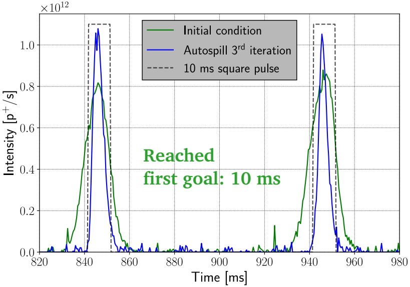

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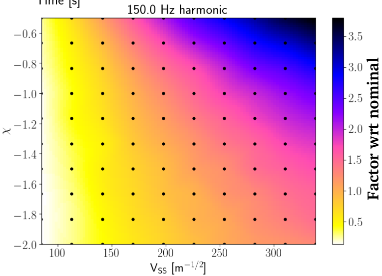


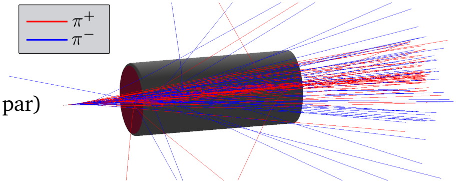
Dedicated study of frequency noise on std SX also recently finalized, showing possible improvements in spill quality

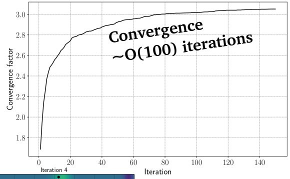
[*] M.Pari, PhD Thesis (2020)
M.Pari et al., Phys. Rev. Accel. Beams 24, 083501 (2021)

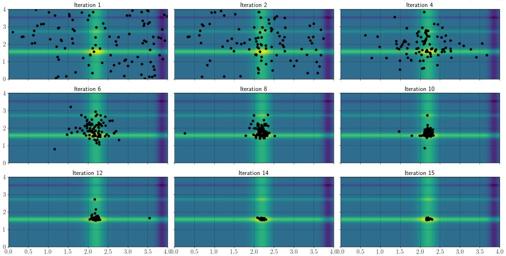
Magnetic horn

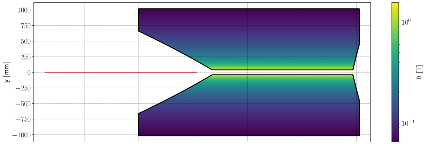
Previous proton extraction results open for a horn option:

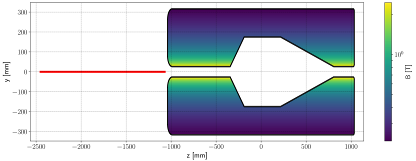
- Developed simulation model of horn based on GEANT4
- Different designs available: MiniBooNE, double-parabolic, conic
- Genetic algorithm implemented for optimization of horn geometry (> 10 par)
- Basic hardware constraints enforced
- Developed fully automatic cluster-based optimization framework
- First candidates available









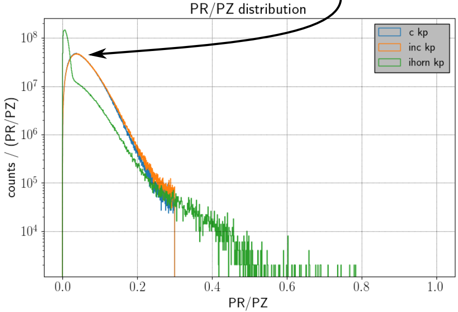


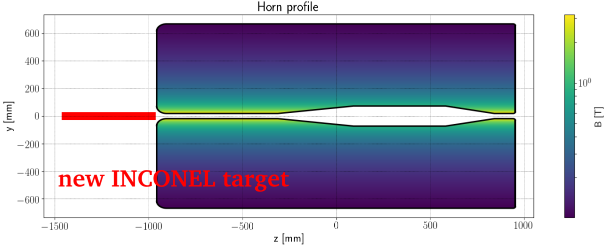
Magnetic horn

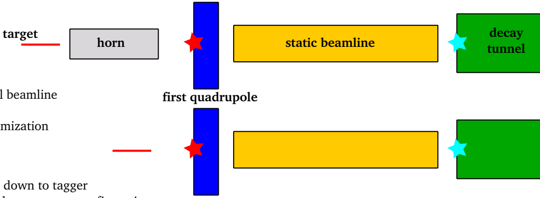
Results from standalone (i.e. first quad) horn optimizations show consinstent flux gain of factor ~3 (@momentum bite):

→ Solution based on INCONEL target seems promising: short external target & good horn parameters.

→ Gain comes from squeezed angles due to horn focusing power.







Selected K at ★ :

- Not dependent on full beamline
- Fast to compute
- Good for relative optimization

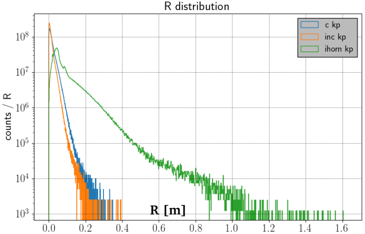
Selected K at ★ :

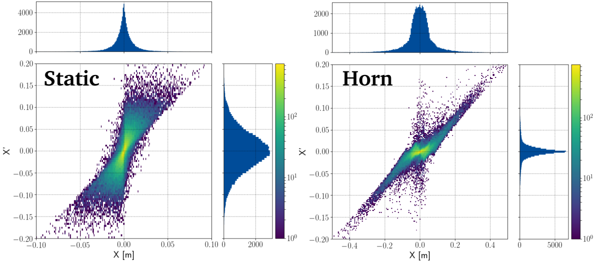
- Requires full tracking down to tagger
- Yields exact flux gain between two configurations

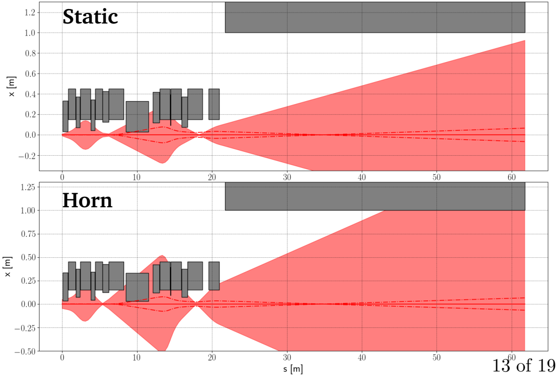
Magnetic horn

But:

- → This comes at expenses of increased beam dimension and very different initial phase space
- → Current version of baseline beamline not optimized for this type of beam
- → **Started development of dedicated horn-beamline design: significant changes required wrt static design**

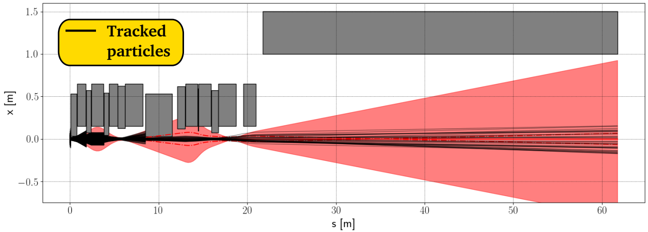


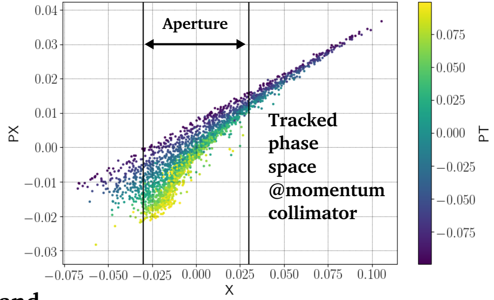




Magnetic horn: roadmap

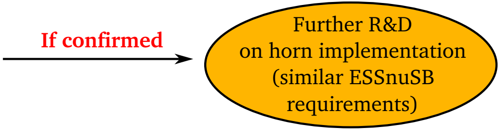
- ☑ **New developed MADX framework for design and optimization of new beamline (goal: faster optics opt.)**





- ☐ **Particle distributions and gains will be assessed w/ G4 and compared w/ baseline design**

- ☐ **Goal: prove a substantial flux increase maintaining the narrow-band beam & bkg requirements of ENUBET**



Further optimization

From the previous horn study: optimization framework upgraded to be fully generic

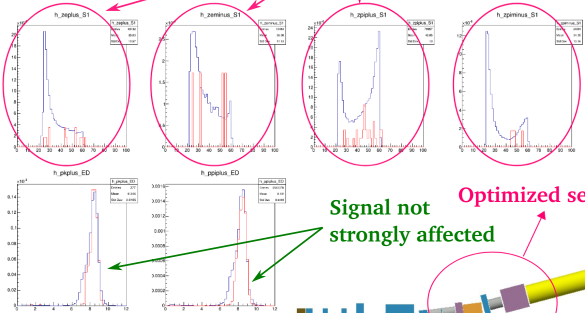
→ Can be applied to any optimizable multi-dim. beamline design issue

→ **First application:** fine tune beamline collimators for baseline static option

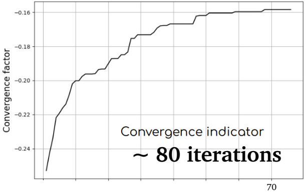
→ First results promising: **significant bkg reduction (preliminary & ongoing)**

FoM:
Kaons/bkg hitting tunnel

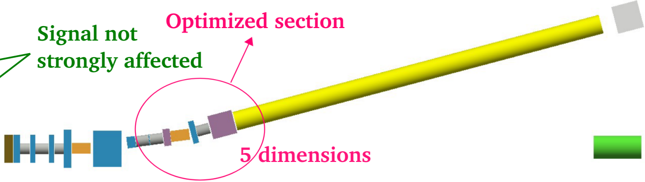
Main bkg particles suppressed



Signal not strongly affected



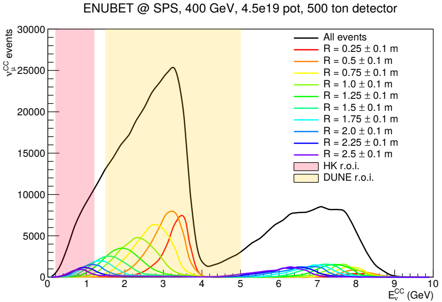
Optimized section

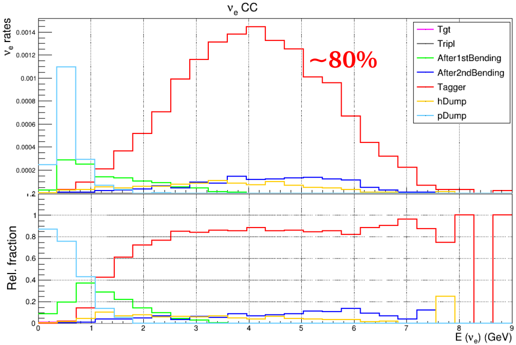


5 dimensions

Neutrino flux and energy

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



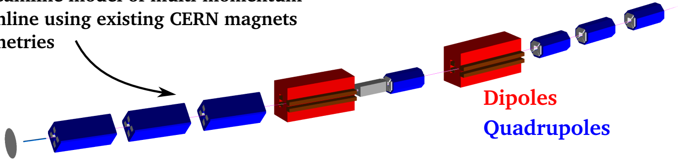


Would be useful being able to cover also different neutrino energy ranges

To this end:

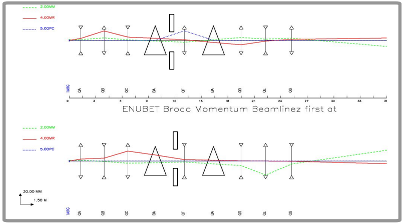
- → Study on development of multi-momentum beamline currently ongoing in collaboration w/ CERN
- → Goal is modifiable energy range so to cover full range of interest (HK R.o.I. included)

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

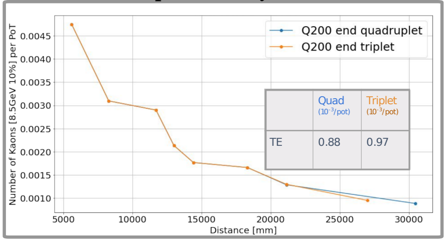


- → Promising first estimations of K+ fluxes, background studies are ongoing

Optics design: TRANSPORT



Kaon fluxes (G4beamline, preliminary)



Conclusions and next steps

- Main design phase of ENUBET static beamline terminated:
  - ⟶ Simulations all nearly completed
  - ⟶ Satisfactory performance reached
- Promising results up to now: **project on schedule**
- **The final systematics on the neutrino fluxes (electron and muon) are under evaluation and will be released by 2021 (see talk from A.Branca)**

baseline

- Studies of non-baseline options proceed as planned, pointing to promising results and potential improvements:
  - ⟶ Investigation of use of SC dipole after results from doses estimation are ongoing
  - ⟶ Successful development of pulsed slow extraction opened for horn design option
  - ⟶ Genetic opt. of horn pointed to $\sim$3 flux gain: dedicated beamline underway
  - ⟶ Application of genetic opt. on the static beamline for S/N increase
  - ⟶ Studies on a multi-momentum beamline for different nu-energy ongoing

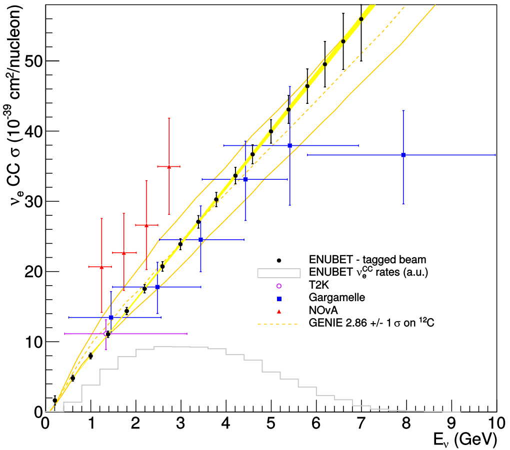
Updated fluxes and spectra with these final beamlines by 2022

further studies

Thank you for your attention

Backup

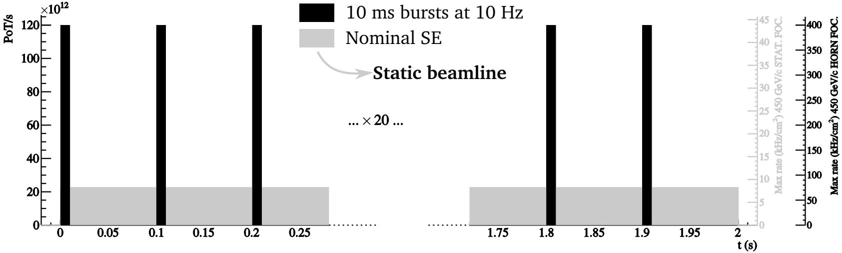
ENUBET: reach



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**



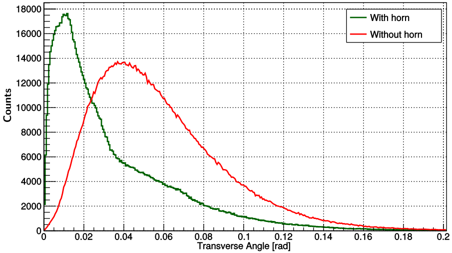
Two possible **slow-extraction** schemes compatible:

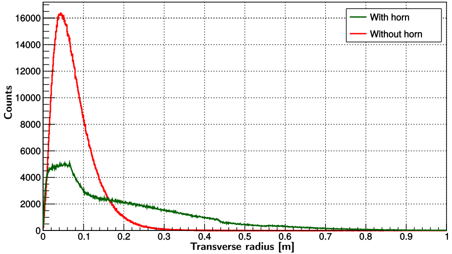
→ Static (standard)

→ Pulsed (novel)

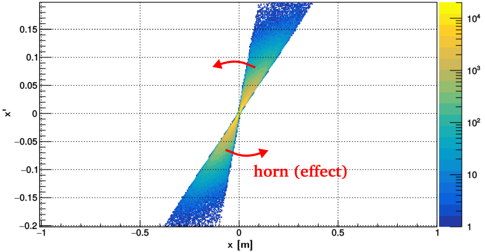
Could allow operation of magnetic horn: significant increase in flux.

Effect of horn on beam

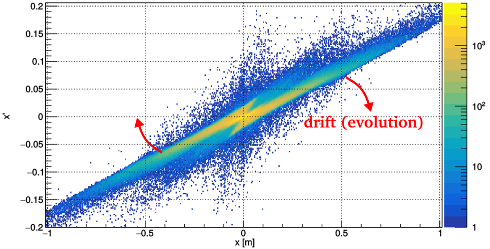




Phase space after target



Phase space after horn



Event reconstruction

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