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ESS neutrino Super Beam plus

Status of WP6: a monitored neutrino beam at the ESS

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Summary

WP6 is aimed at the design of a Monitored Neutrino Beam that will run before the long baseline experiment, i.e. in the construction phase of the ESSnuSB accumulator to perform high precision cross section measurements below 1 GeV. As a consequence, the most important question we addressed at the start of the project is: is it possible to perform this measurement without any LINAC upgrade (2 GeV, 2.86 ms)? **We can now safely claim that the answer is positive.**

Main achievement in the last 12 months:

- Full simulation of the instrumented tunnel
- Particle identification algorithms for muons from pion decay
- Detector technologies

A new generation of cross section experiment: why?

Neutrino physics has entered its precision era with a knowledge of Standard Model processes that has improved enormously (50% → 10%) in the last 10 years but still **lags behind the standards of quark physics** (1%). This is unfortunate because high-precision cross sections can advance significantly our understanding of nuclear matter and ground on a solid base the physics reach of DUNE, HyperKamiokande and ESSnuSB.

We may hope to reach such an unprecedented precision if:

- We devise a facility that offers a control of the ν_e and ν_μ neutrino flux and flavor at 1% level [**flux**: main systematics of any cross-section measurement]
- Provide a monochromatic neutrino source with a precision of O(10%) [$\boldsymbol{\nu}$ **energy**: main systematics for differential cross sections due to bias in energy reconstruction]
- Provide a ν_e source that can bring the ν_e cross section uncertainty from 30% to a few %. [$\boldsymbol{\nu_e}$ **appearance** is the golden channel of neutrino oscillation experiment]

If this facility is available in the next future, we can conceive a new generation of cross section experiments with state-of-the-art detectors to study differential cross sections in the region of interest for neutrino oscillations. In particular, **at ESS, we want to study the sub-GeV region where electron and muon cross sections are expected to depart!**

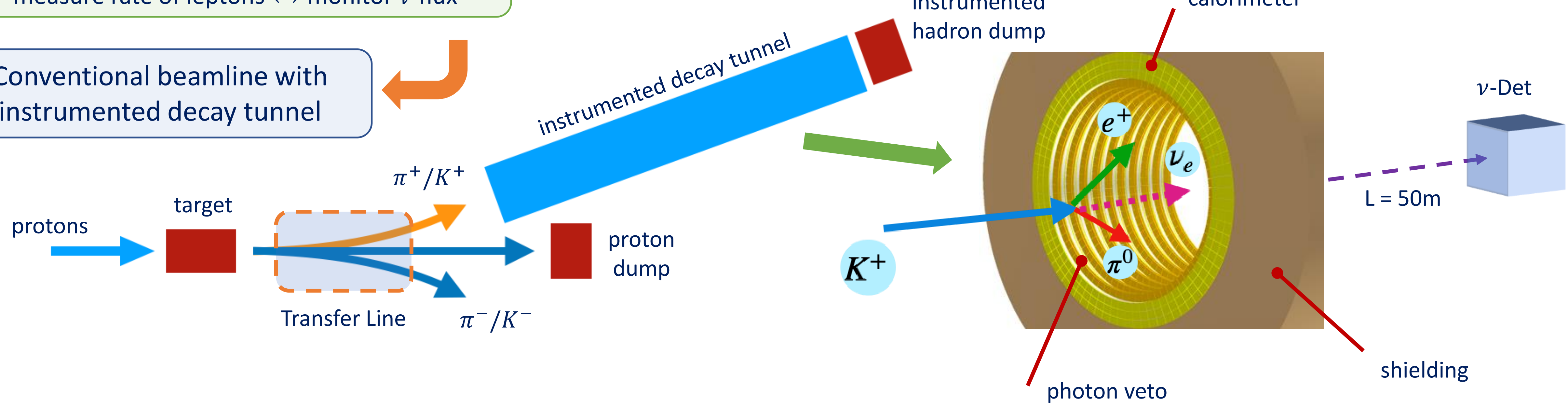
Monitored neutrino beams

How do we achieve such a precision on the neutrino cross-section, flavor composition and energy?

Monitored ν flux from narrow-band beam
measure rate of leptons $\Leftrightarrow$ monitor ν flux

Conventional beamline with instrumented decay tunnel

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

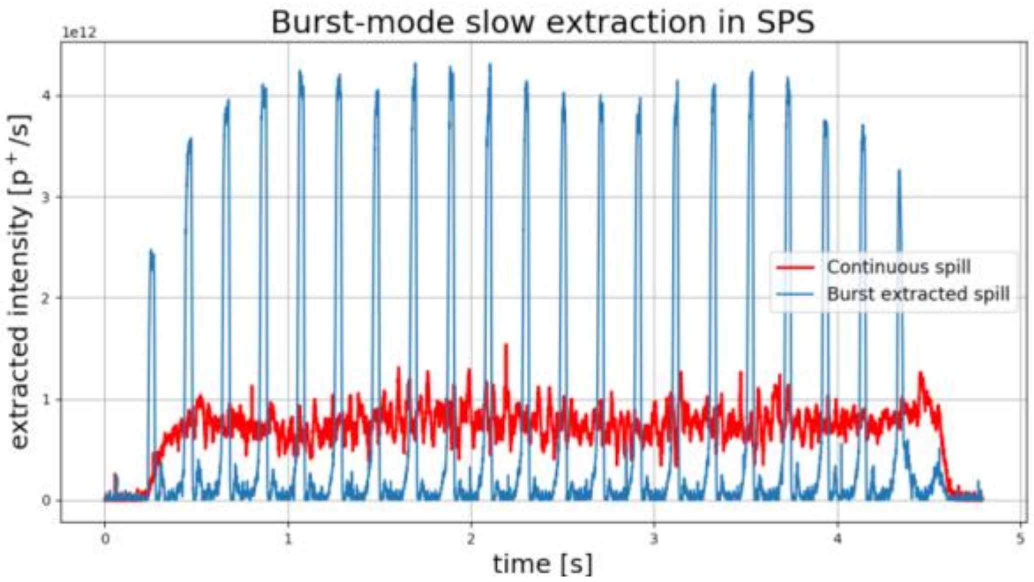


We proposed this idea in 2015 and, since then, the concept has been developed at international level by the ENUBET Collaboration. WP6 relies on the expertise and resources of ENUBET to design a Monitored neutrino beam that is ideally suited for the European Spallation Source and addresses the sub-GeV energy range.

The 2020 breakthrough: a high-intensity horn-less neutrino beam

When we first proposed ENUBET, we were aiming at a beam where the leptons in the decay tunnel are produced at **slow rate** because we were afraid of pile-up and saturation of the instrumentation in the tunnel

Original design: a horn pulsed every 100 ms with a 10 ms pulse ("burst proton extraction")



First demonstration of this proton extraction scheme in 2018 at CERN-SPS

M. Pari, M. A Fraser et al, IPAC2019

2020 design ("static focusing system"): a neutrino beam without a horn, where focusing (at 8 GeV/c at CERN) is accomplished by quadrupoles (like e.g. NuTeV but at much lower energy!)

The design was so successful that it achieved a flux that is just 2 times smaller than the corresponding horn-based design but protons are extracted in 2 seconds!! Rates are reduced by more than one order of magnitude!

Main challenge at ESS: get comparable performance with a shorter proton extraction (2.86 ms instead of 2s)

MNB@ESS

The physics case of a "low energy" monitored neutrino beam is very strong:

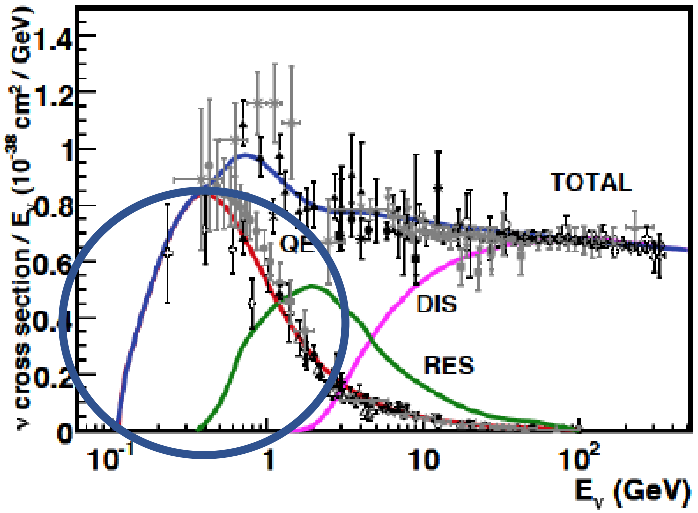
- It is the main energy of interest for ESSnuSB and HyperKamiokande
- It is the region where we expect the largest differences between ν_e and ν_μ cross sections
- It offers the cleanest environment for the study of nuclear matter effects because it is dominated by quasi-elastic interactions

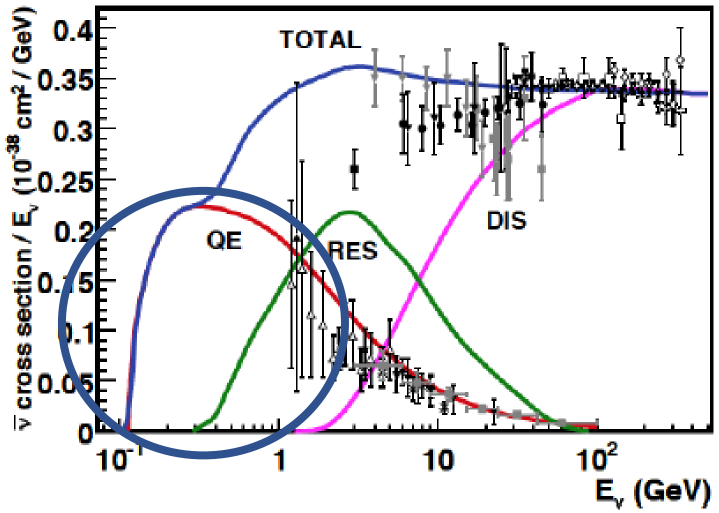
A monitored neutrino beam at ESS (ESSnuSB+)

Address specifically the region below 1 GeV

- ν_μ from pion decay ($\pi \to \mu\, \nu_\mu$)
- ν_e from decay in flight of muons

$$\pi \to \mu\, \nu_\mu \to e\, \nu_\mu \nu_e \overline{\nu}_\mu$$





Can we build a monitored neutrino beam (without relying on kaons) at the European Spallation Source?

An opportunity we cannot miss

The ESS linac is the most powerful LINAC in Europe and will be available for many users (Material Science, Biology, fundamental physics etc.) very soon. The power of the linac is so high that it can accommodate even neutrino physics users – at least for short-baseline experiments. A short baseline experiment is exactly what we need for cross section measurements!

ESSnuSB+ can deliver first-class physics even in the construction phase of ESSnuSB because we need a small power of the existing linac and we do not need the accumulator (in fact, the longer the proton extraction, the better)

	ENUBET@CERN	MNB@ESS	Notes
Proton driver	400 GeV/c	2 GeV	At ESS we exploit pion decays and muon decays in flight [no K]
Secondaries	8.5 GeV/c	About 1-2 GeV	
Proton extraction	2 s	2.86 ms	This is a key item WP6 has assessed in 2023
Decay in flight of muons	Negligible	It is the main source of ν_e at the ESS	

The Work Package 6 of ESSnuSB+

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Participants: Unimib (Milano, Italy), INFN (Padova, Italy), RBI (Zagreb, Croatia), NCSRD (Athens, Greece), AUTH (Thessaloniki, Greece)

D. Use of resources

Period M1-M12(Men/Month)	UNIMIB	INFN	RBI	NCSRD	AUTH	UNIPD	Total
Planned for 2023-2026	30	27	30	8	12	1	108
Actual	1.51	0.78	5.6	1	0.3	0	9.18
Fraction (%)	5.03	2.89	18.67	12.5	2.5	0	8.5

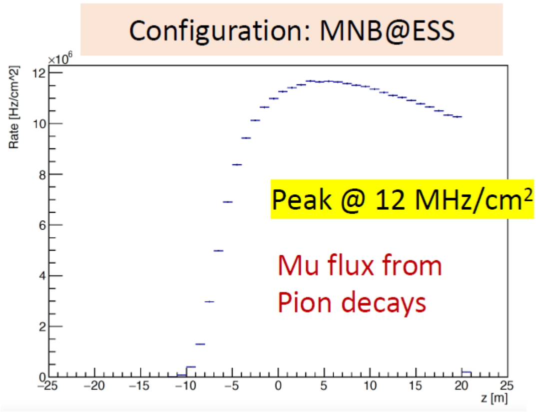
The main difficulty we had to address is related to recruitment: we opened a PhD position in Milano Bicocca but the winner finally declined, and we will have a new PhD working full time in WP6 only starting from November 2024 (Anna Scanu). Similarly, the post-doc position from INFN has been awarded only in Summer 2024 (Daniele D'Ago).

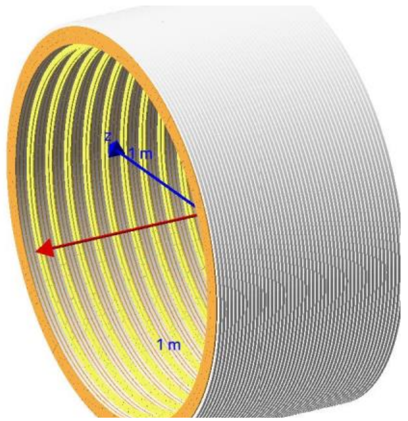
We were able to advance significantly the tasks of WP6 because we were supported by the ENUBET collaboration, and we were able to employ most of the simulation tools developed in the past.

The challenge of the 3ms proton extraction

We addressed the most critical item using a full simulation of the meson yield at target and an estimate of the static focusing system efficiency to understand whether the particle rate at instrumentation are compatible with the ESS extraction spill (2.86 ms).

	8.3 10^{14} pot/spill			8.3 10^{13} pot/spill			8.3 10^{12} pot/spill		
Recovery time [ns]	Eff [%]	Eff in acceptance [%]	Good tracks [%]	Eff [%]	Eff in acceptance [%]	Good tracks [%]	Eff [%]	Eff in acceptance [%]	Good tracks [%]
1	11.8	19.1	4.1	20.0	32.4	60.8	21.3	34.4	95.5
0.5	16.8	27.2	10.5	20.8	33.6	77.5	21.4	34.5	97.6
0.2	19.5	31.6	36.7	21.1	34.1	90.8	21.3	34.5	99.1
0.1	19.1	30.9	58.6	18.9	30.5	95.0	18.8	30.5	99.5





Task 6.2: Design of the transfer line and focusing system

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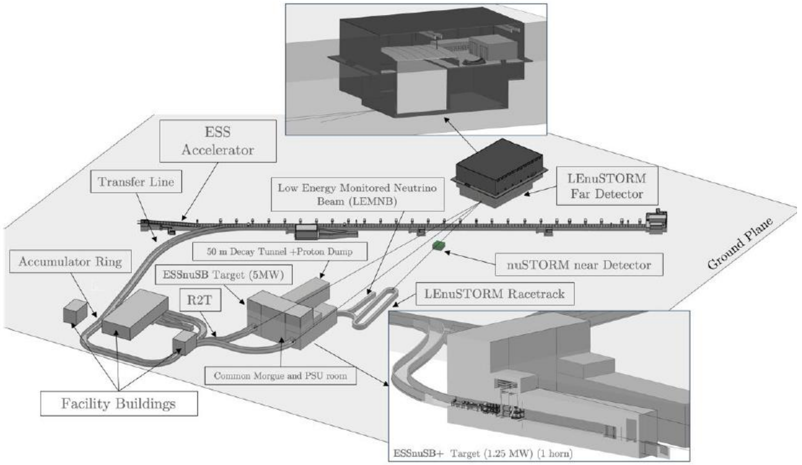
The outcome of this study shows that MNB@ESS can use a standard transfer line from LINAC to the target withouty beam manipulation provided that the spill intensity is around 1 10^{14} pot/spill

This finding was instrumental to define the layout of the transfer line from the linac and, therefore, in achieving MS4



Item for a general discussion: can we envisage an operation mode of the LINAC at 1 10^{14} pot/spill that does not significantly affect the standard ESS physics programme?

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Project Number:
101094628
Project Acronym:
ESSvSBplus
Call identifier:
HORIZON-INFRA-2022-DEV-01

Project Full Title:
Study of the use of the ESS facility to accurately measure the neutrino cross-sections for ESSvSB leptonic CP violation measurements and to perform sterile neutrino searches and astroparticle physics

Start date of project: **2023-01-01**

Duration: **4 years**

MS 6.1

Milestone title: **Identification of the location and layout of the LINAC transfer line (WP6)**

Due delivery date: **2023-12-31**

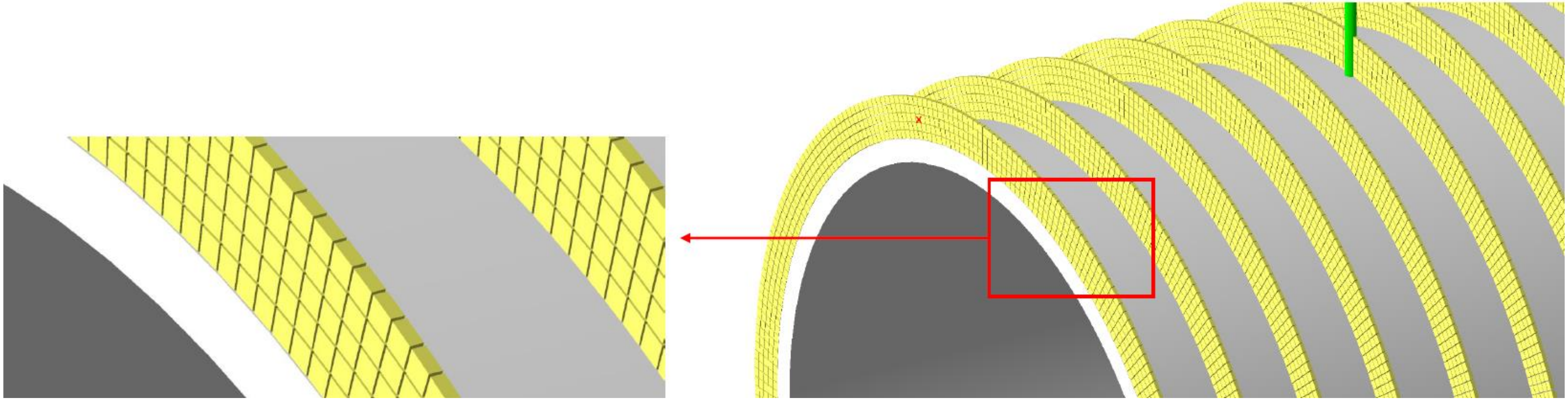
Actual delivery date: **2023-12-22**

Organisation name of lead contractor for this milestone: **University of Milano Bicocca (Unimib)**

Task 6.3: Design of the instrumented decay tunnel

The instrumented decay tunnel was simulated employing the ENUBET software framework starting from the baseline configuration of ENUBET@CERN and moving to an optimized scenario for MNB@ESS

- Full GEANT4 simulation of the tunnel assuming either ~~calorimeters~~ or trackers **complete**
- Event builder based on seed connected to neighboring hits **complete**
- Muon identification algorithm **under optimization**



Task 6.3: Design of the instrumented decay tunnel

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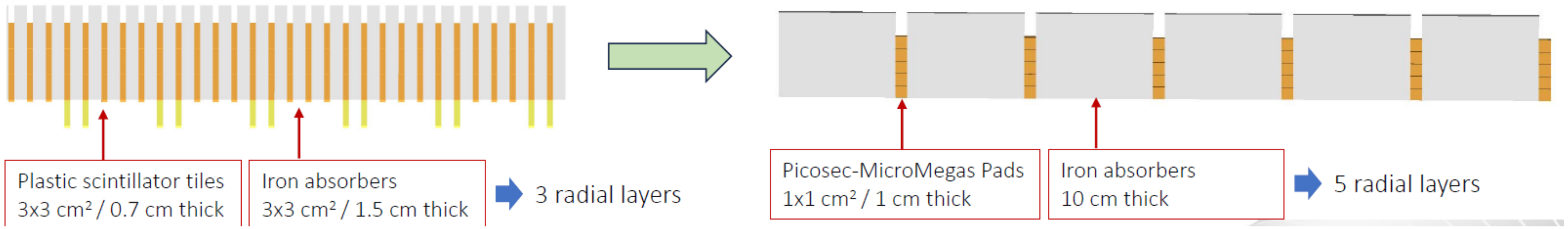
The outcome of the simulation indicates that:

- A fast, high-granularity tracker better performs at ESS than the calorimeter of ENUBET@CERN
- To reach good performance we need to reduce the channel size to 1 cm^2 and the pot/spill at the level of 10^{14}.
- A time resolution of 200 ps is optimal to mitigate pile-up at ESS

See talk by A. Branca

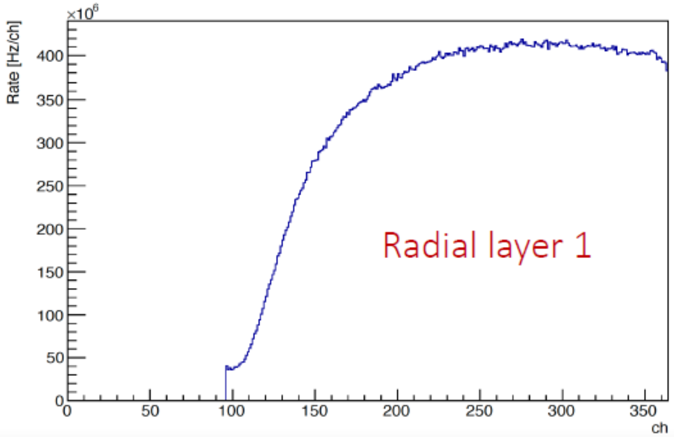


Default parameters considered for simulation

- 2.86 ms extraction spill;
- POT/spill = $8.3 \cdot 10^{14}$;
- π^+/POT = $0.1 \cdot 10^{-3}$;

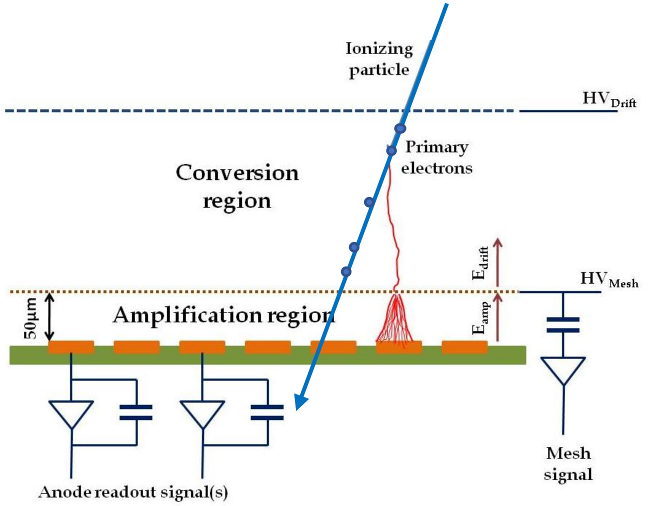
Corresponding to $2.9 \cdot 10^{13}$ Hz of pions at tunnel entrance.

Radial layer	Peak Rate [MHz/channel]
1	400
2	160
3	100
4	65
5	45



Instrumented decay tunnel: (picosec)-micromegas

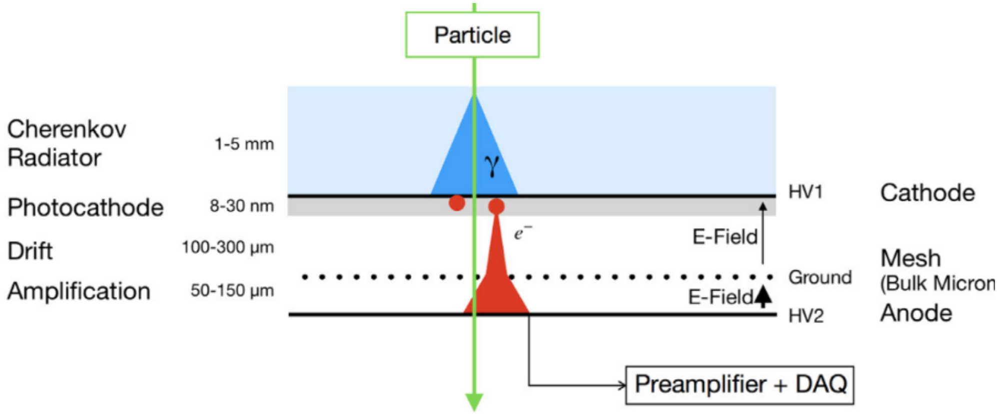
See talk by A. Kallistopoulou



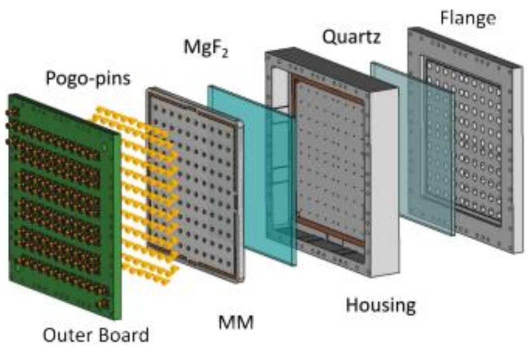
Y. Giomataris, P. Rebourgeard, J.P. Robert and G. Charpak,
"Micromegas: A high-granularity position sensitive gaseous detector for high particle-flux environments",
Nuc. Instrum. Meth. A 376 (1996) 29

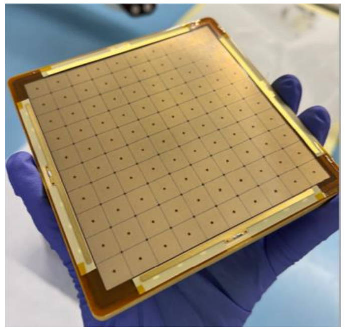
Gas micromegas offer the granularity, coverage, and time resolution needed for ESS at moderate cost and excellent radiation hardness

Further improvements can be obtained exploiting the superior time resolution of picosec-micromegas developed in France by the PIMENT collaboration. Members of PIMENT are also contributing to WP6!

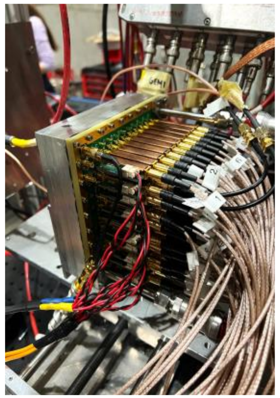


J.Bortfeldt, et al., *"PICOSEC: Charged particle timing at sub-25 picosecond precision with a Micromegas based detector"*,
https://doi.org/10.1016/j.nima.2018.04.033





100 channel anode ☐ 1 cm



Task 6.4: Assess the flux systematics

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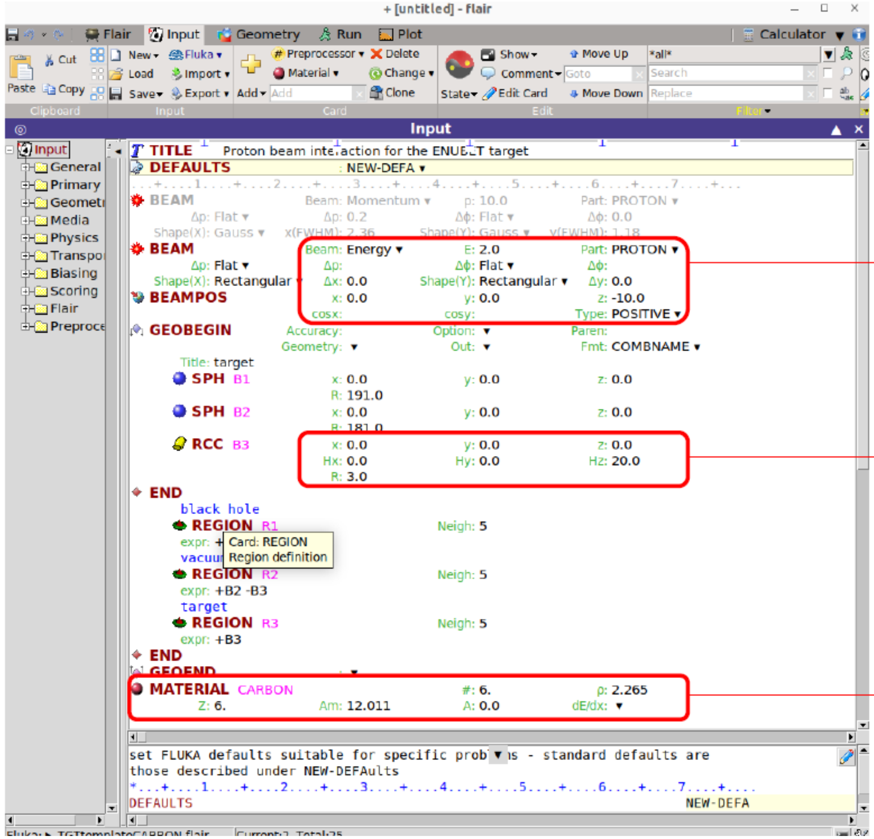
This task is in the early stage (as expected) since it relies on the full simulation of the beamline. Still, we addressed a key issue – the size of the statistical error at the neutrino detector because it sets the scale of the systematic reduction needs.

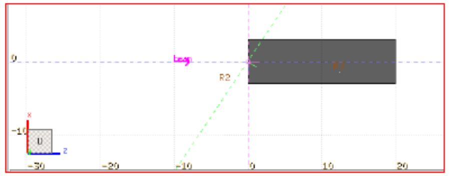
- Full FLUKA simulation of the graphite target **complete**
- Target optimization **in progress**
- Beamline focusing efficiency **in progress**
- Pion propagation and decay **complete**
- Detector simulation (in collaboration with WP5) **in progress**

See talk by G. Brunetti



Pencil-like beam impinging on the center of the target

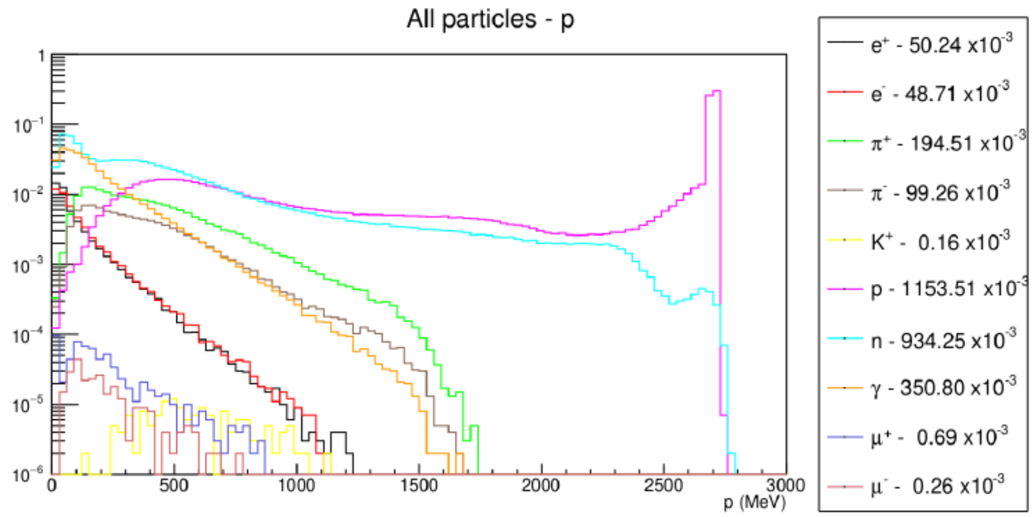
Target with L=20 cm and R=3 cm

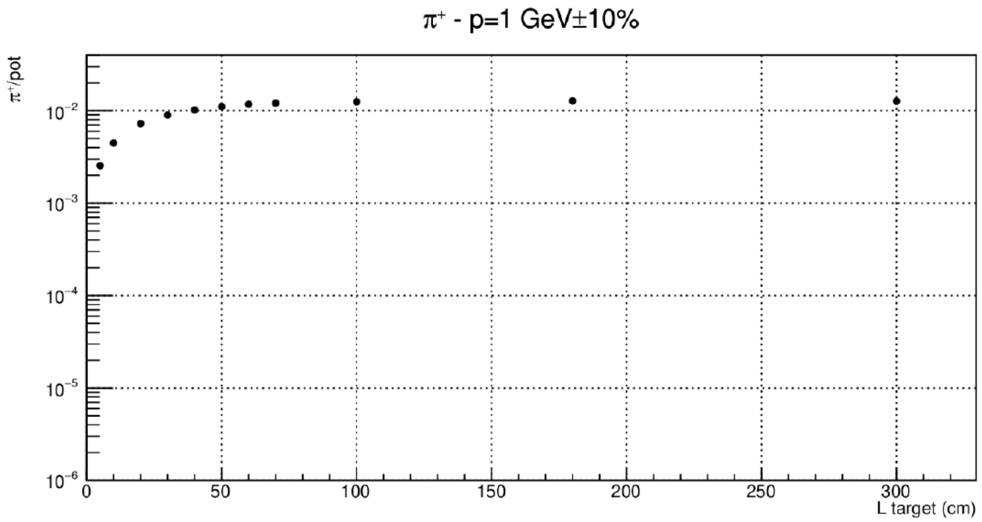


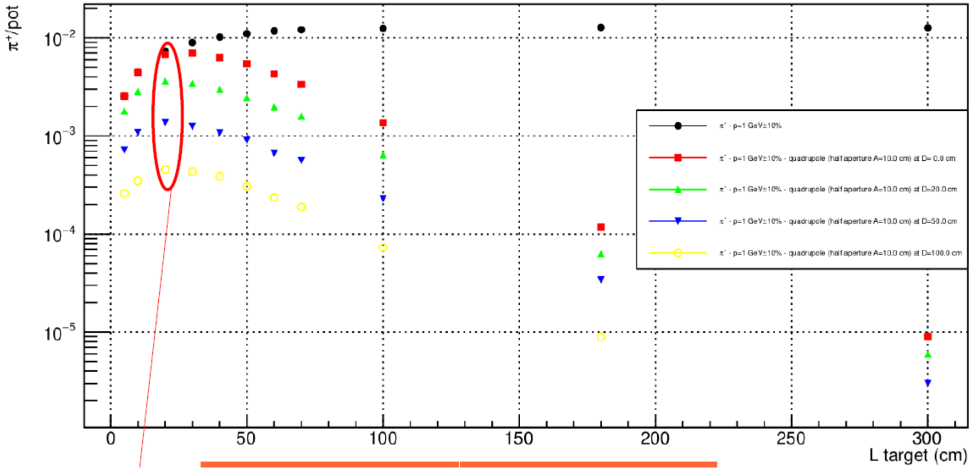
Target material: graphite

Yields at the target

The target optimization was performed enhancing the pion production in the momentum range of MNB@ESS



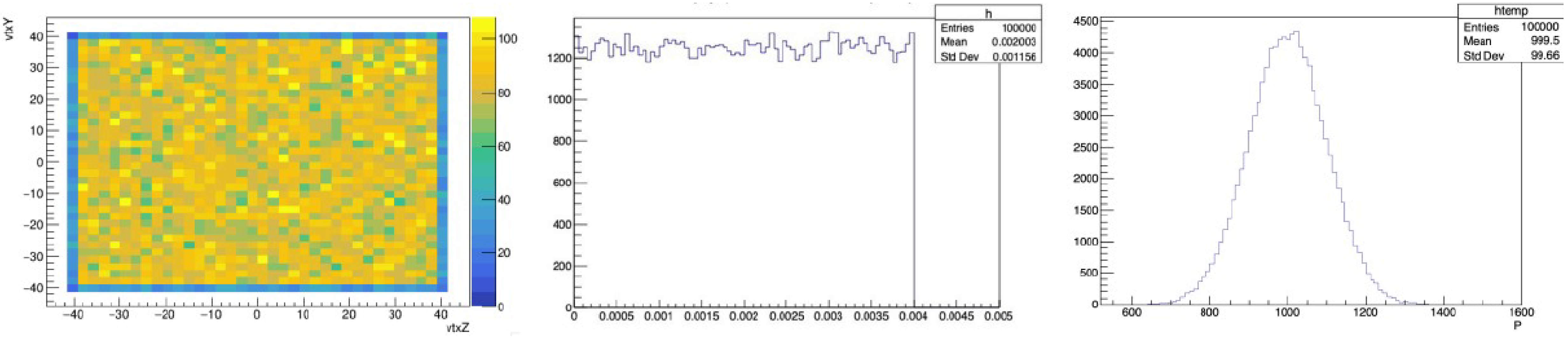




D (cm)	π^+ yield (10^{-3}/pot)
0	6.77
20	3.64
50	1.37
100	0.45

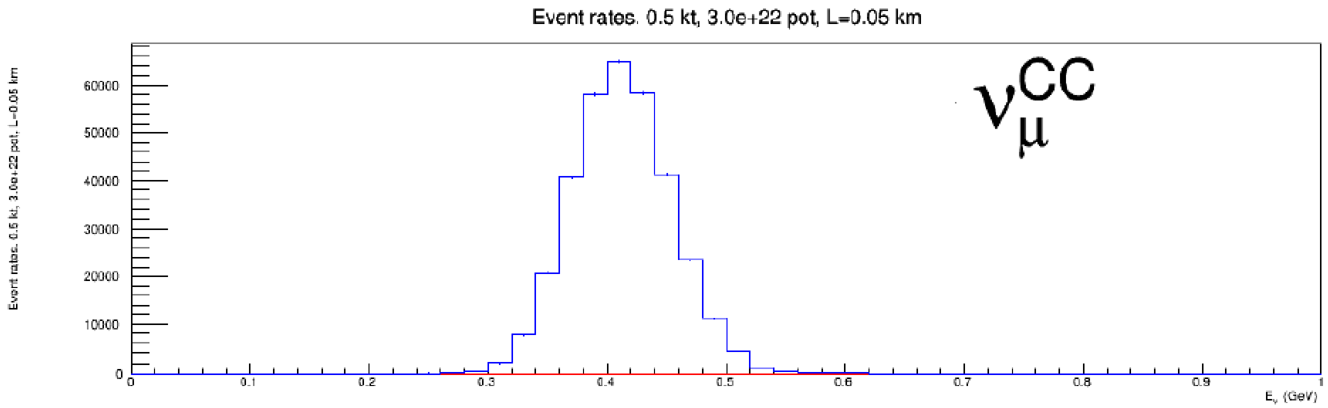
Static focusing system

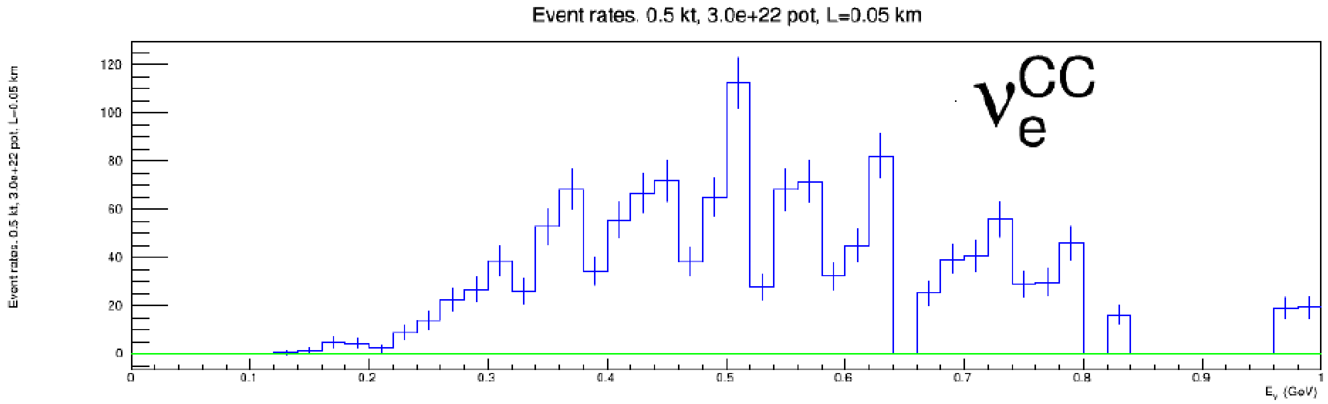
- A transfer line from the target to the tunnel entrance suitable to focus 1 GeV π^+ has not been designed yet
- Assuming conservatively a pion yield of 0.1×10^{-3}/pot (~1/5 of the lower yield previously estimated)
- Uniform spatial distr. (8x8 cm^2)
- Uniform angular distr. (0 to 4 mrad)
- Momentum Bite: 1 GeV±10% (gaussian smeared)

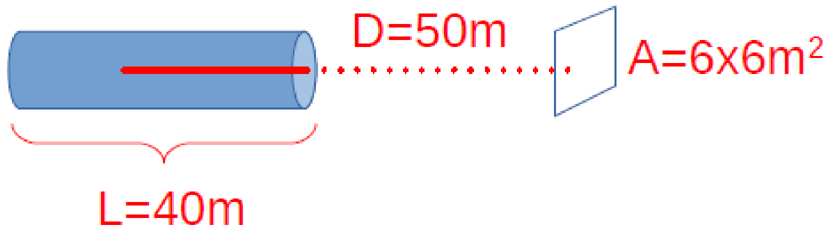


- Decay tunnel length (L): 40 m [radius: 50 cm]
- Simulated with Geant4 10^6 pions at the tunnel entrance (corresponding to 10^{10} pot)

Neutrino events at the detector







With 3×10^{22} pot: (10% of the available pot at ESS)

$\sim 3.3\times10^5\ \nu_\mu^{CC}$
$\sim 1.3\times10^3\ \nu_e^{CC}$

Item for a general discussion: it is now time to integrate the findings on the LEMMOND design with the needs of MNB@ESS

Outlook of the milestones and deliverables

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The activities of WP6 are on track but, due to the aforementioned hiring issue, we experienced delay in the design of the static focusing system. In this very moment, we are working on the optics of the system, while the G4beamline implementation is still to come.

This delay will affect

- D6.1 Design of the post-target transfer line [Month 24] (i.e. the focusing system)
- MS7 Implementation of the static focusing system in MADX and G4beamline [Month 18]

This delay is not critical for the completion of the Project because:

- The static focusing work proceeds in parallel with the work needed for the other deliverables
- The results obtained up to now are excellent and have further strengthened the physics case of MNB@ESS

Conclusions

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The WP6 activities are in full swing and important results have already been achieved. In particular:

- We have a full-fledged GEANT4 simulation of the tunnel instrumentation and an optimized FLUKA simulation of the target
- Thanks to these tools, we were able to demonstrate that the 2.86 ms extraction of ESS is tenable for MNB@ESS. As a consequence, we achieved Milestone MS4 and delivered the associated document
- We established the technology for the instrumentation of the tunnel and a first estimate of the expected rate at the neutrino detector
- We had to face hiring issues, which were compensated by contributions from the ENUBET collaboration and the use of the MNB simulation framework

Next steps:

- Define the performance of the focusing system (i.e. beamline simulation)
- Integrate LEMMON in the MNB@ESS optimization