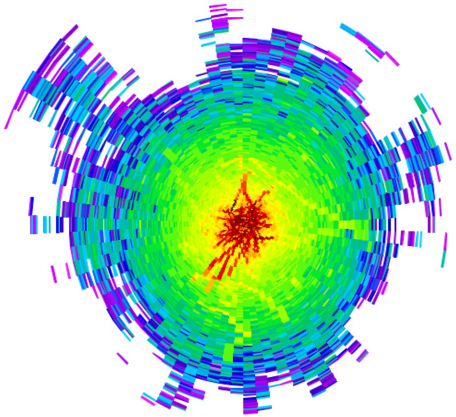
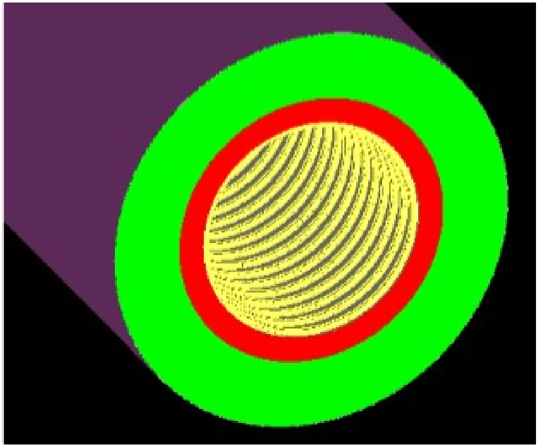
A monitored neutrino beam at the ESS

Status of the LEMNB facility design (WP6)

A. Longhin
Padova Univ. and INFN
on behalf of ESSnuSB+ WP6

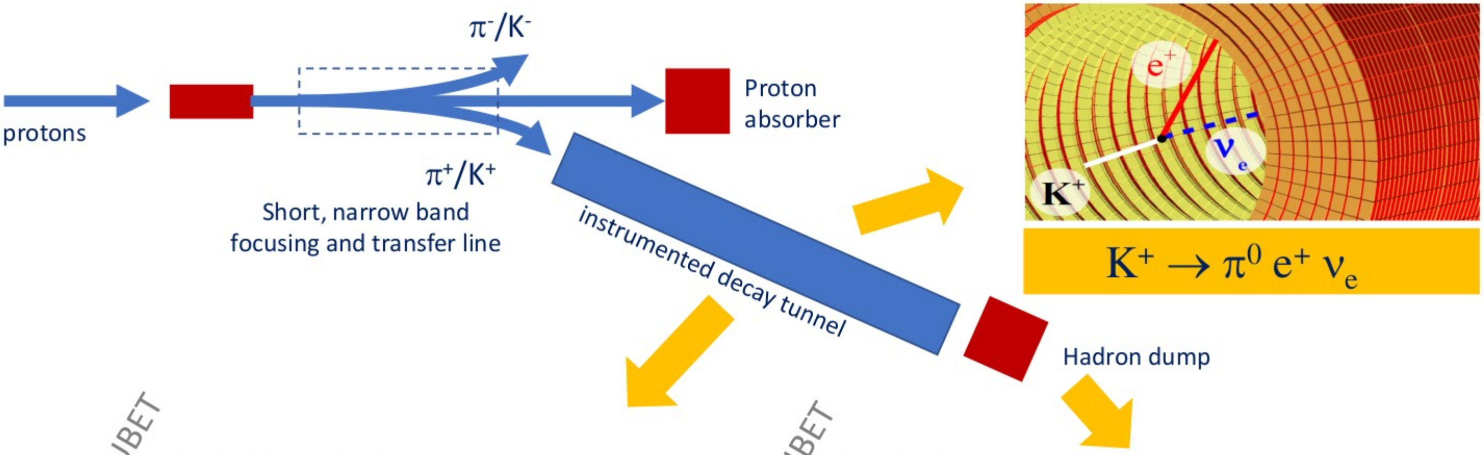




Nufact 2023, Seoul,
ESSnuSB+ workshop
20 Aug 2023

Monitored neutrino beams

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



NP06/ENUBET

NEW! (2019-20) muon identification and monitoring for

$K^+ \rightarrow \mu^+ \nu_\mu$

NP06/ENUBET

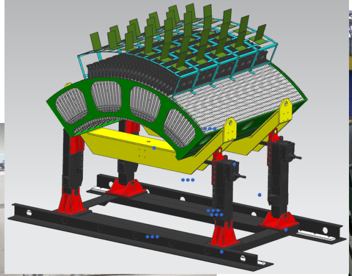
NEW! (2019-20) muon monitoring at single particle level replacing the hadron dump with a real range-meter

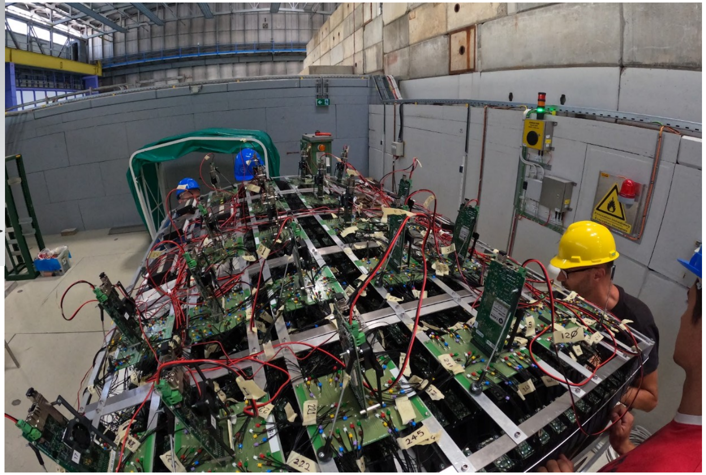
$\pi^+ \rightarrow \mu^+ \nu_\mu$

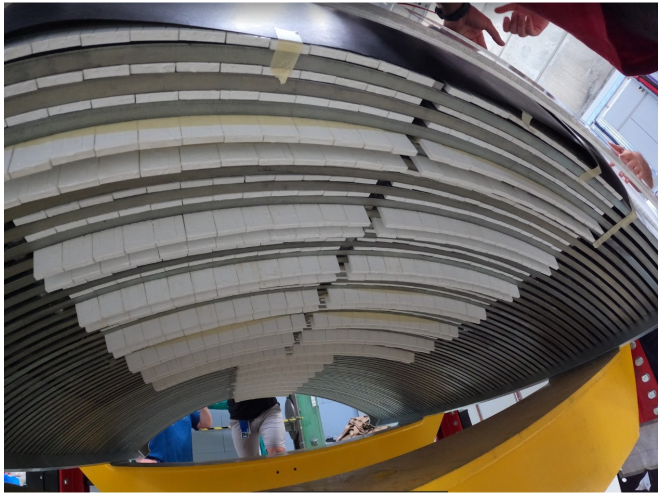
(*) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

“Monitored neutrino beams are beams where diagnostic can directly measure the flux of neutrinos because the experimenters monitor the production of the lepton associated with the neutrino at the single-particle level. “ (Wikipedia)

ENUBET: demonstrator



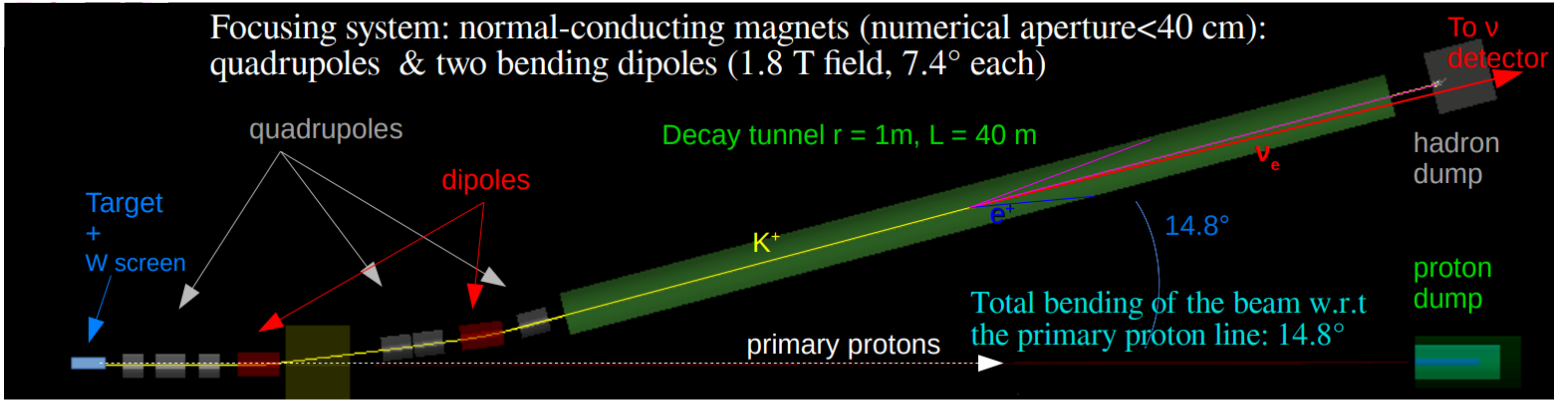




3 days ago @ CERN

Demonstrator: 1200 ch, 3.5 t

ENUBET: beamline

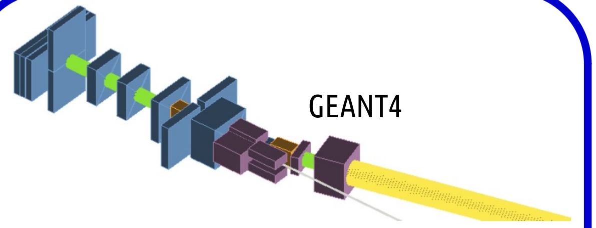


arXiv
being submitted to EPJC

Large bending angle of 14.8°: better collimation + less μ background and ν_e from early decays. ~1.5 $\times$ gain in signal.

Transfer Line:
- optics optimization w/ TRANSPORT (**5%** momentum bite centered @ **8.5 GeV**)
- G4Beamline for particle transport and interactions;
- FLUKA for irradiation studies, absorbers and rock volumes (see next →);
- optimized graphite target 70 cm long with 3 cm radius (optimized geometry, materials);
- W foil downstream target to suppress positron background;
- W alloy absorber @ tagger entrance to suppress backgrounds;

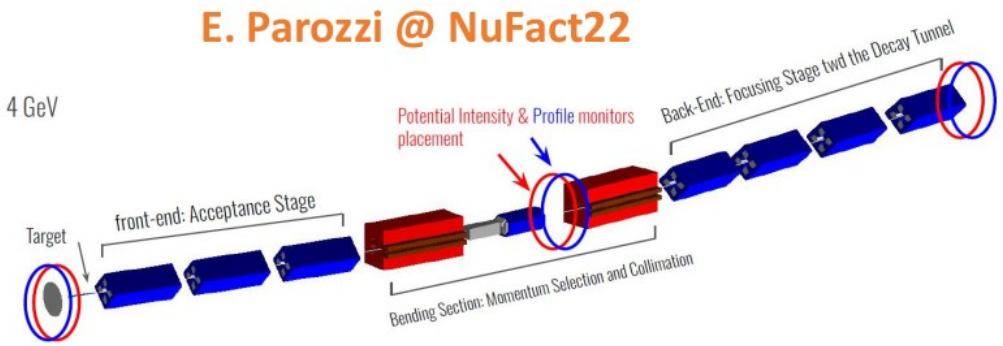
Dumps:
- Proton dump: three cylindrical layers (graphite core → aluminum → iron);
- Hadron dump: ~ proton dump to reduce backscattering flux in tunnel;



Full facility also implemented in GEANT4:
Easy control over all parameters;
Access to the particles histories;
assessment of the ν flux systematics

A "low-energy" (sub-GeV) monitored neutrino beam

Multi-momentum beamline @ CERN. A CERN-based beamline with multiple runs at 4,6,8 GeV/c secondary momenta: increase the statistics in the region of interest of HyperK. ν_μ from pion decay (high statistics), ν_e from kaon decay (low statistics)

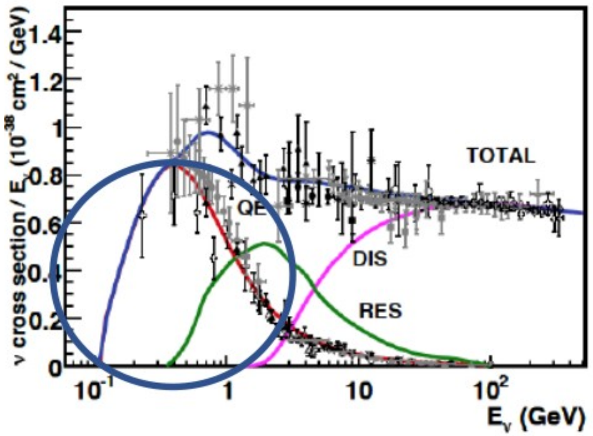


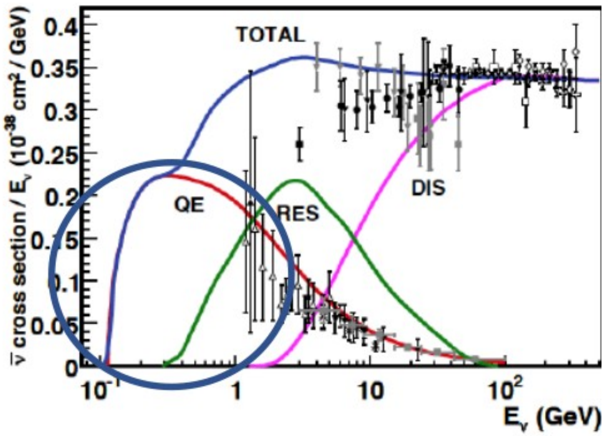
A monitored neutrino beam at ESS

Address specifically **the region below 1 GeV for Hyper-K and ESSnuSB and bring the flux uncertainty at the 1% level**

- ν_μ from pion decay ($\pi^+ \rightarrow \mu^+ \nu_\mu$)
- ν_e from decay in flight of muons

$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \bar{\nu}_\mu \nu_e \nu_\mu$





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

General strategy for WP6 in ESSnuSB+

Define the neutrino physics programme to be delivered at the ESS **before the upgrade needed for the long-baseline program** (construction of the accumulator to have us bunches, doubling of repetition rate and upgrade to 2.5 GeV).

Exploiting only a transfer line that bypass the accumulator and brings protons to a moderate intensity (300 kW) target station equipped with a dedicated focusing line.

The instrumented beamline tags muons from pion decay and produce a tagged neutrino beam for studies cross section studies.

Tasks

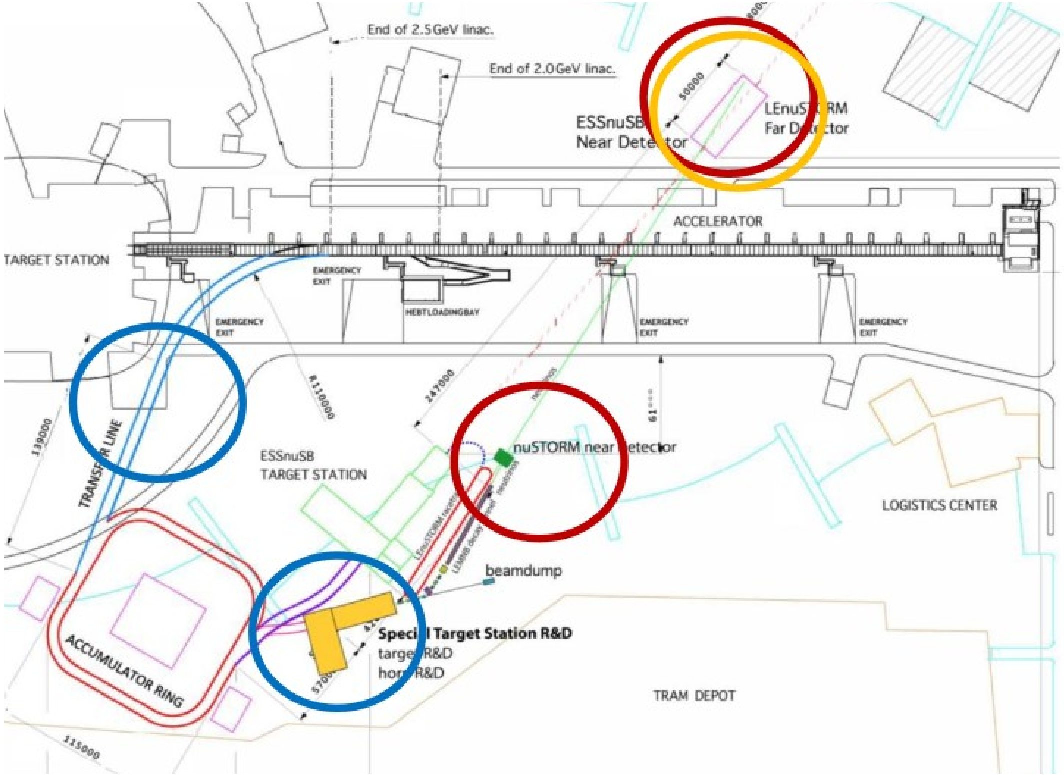
- Design the extraction line of the protons from the LINAC to the target station
- Design of the pion beamline and instrumented decay tunnel ← started
- Compute neutrino yield with expected flux systematic uncertainties ← started

After the construction of the accumulator? cannot use us-pulses for monitoring (pileup) but the program might continue using the accumulator as a transferline for some bunches or even like a “debuncher” to dilute protons beyond 2.86 ms.

The WP6 of ESSnuSB+

Participants: UniMib (Milano, IT), INFN (Padova, IT), RBI (Zagreb, KR), NCSRD (Athens, GR), AUTH (Thessaloniki, GR)

External support: from the ENUBET coll. i.e. on re-optimization of the horn-less beamline



Synergy with other WPs

- WP3: Target station [target, transfer line]
- WP4: Low energy nustorm
- WP5: Detector and physics performance [use of cross section, near detectors]

Current working assumptions

MDPI

Article

A monitored neutrino beam at the European Spallation Source

F. Terranova[3,4]*, F. Acerbi[1], I. Angelis[21], L. Bomben[2,3], M. Bonesini[3], F. Bramati [3,4], A. Branca[3,4], C. Brizzolari[3,4], G. Brunetti[3,4], S. Capelli [2,3], S. Carturan[7], M.G. Catanesi[8], S. Cecchini[9], F. Cindolo[9], G. Cogo [10], G. Collazuol[5,10], F. Dal Corso[5], C. Delogu[5,10], G. De Rosa[11], A. Falcone[3,4], A. Gola[1], L. Halić [20], F. Iacob[5,10], C. Jollet[12,14], A. Kallitsopoulou[24], B. Klicek [20], Y. Kudenko[13], Ch. Lampoudis[21], M. Laveder[5,10], P. Legou[24], A. Longhin[5,10], L. Ludovici[15], E. Lutsenko[2,3], L. Magaletti[8], G. Mandrioli[9], A. Margotti[9], V. Mascagna[22,23], S. Marangoni[3,4], N. Mauri[9], L. Meazza[3,4], A. Meregaglia[14], M. Mezzetto[5], A. Paoloni[17], , T. Papaevangelou[24], M. Pari[5,10], E.G. Parozzi[3,4,6], L. Pasqualini[9,18], G. Paternoster[1], L. Patrizii[9], M. Pozzato[9], M. Prest[2,3], F. Pupilli[5], E. Radicioni[8], A.C. Ruggeri[11], D. Sampsonidis[21], C. Scian[10], G. Sirri[9], M. Stipcevic [20], M. Tenti[9], M. Torti[3,4], S.E. Tzamarias[21], E. Vallazza[3], L. Votano[17]

- Guarantee the possibility of **running MNB@ESS in "parasitic" mode with material science users:**
  extract 3 x 10^{22} protons-on-target (300 kW, 6% of the ESS power)

- ESS in "standard configuration": 14 Hz, 2.86 ms extraction spill, max current 62.5 mA, 2 GeV p

- Neutrino detector: 1 kt water Cherenkov located 250 m from the target (ESSnuSB near detector) (other options: the near detector for LE-nuSTORM @ 50 m)

- 40 m instrumented decay tunnel with low-cost calorimeters (a la ENUBET) and an instrumented hadron dump (à la ENUBET/PIMENT)

A comparison with ENUBET @ 400 GeV

Current working assumptions

	ENUBET @ CERN	LEMNB @ ESS
Neutrino processes, kinematics of leptons, detector design	Cylindrical calorimeter for high angle leptons from K (ν_e from K_{e3}, ν_μ from $K_{\mu 2}$, $K_{\mu 3}$) + forward instrumentation for ν_μ from π. ~ no ν_e from muon (~all from K)	Pions daughters more forward but initial pion boost is much smaller → tried 30 m long cylinder with 0.5m r (40 m+ 1m r for ENUBET)
p energy + selection of secondaries for desired flux	400 + select 8.5 GeV sec. +/- 10% (~DUNE flux 1-5 GeV)	2 + select 1 GeV +/- 10% (HK, ESSnuSB, sub-GeV)
K^+ / π^+	~5-10% @8.5 GeV	0 → use ν_e from μ instead
meson yields per proton	Very large (scales ~ E_p)	much lower (scales ~ E_p)
Absolute proton yields	O(10^{13} POT/s) over several s	Much larger but over 2.86 ms only! → use ~6% of the protons Pileup… → play with granularity
Focusing "efficiency"	O(10^{-3} π^+/POT)	Less boosted but easier to focus @ lower p
Achievable neutrino samples	E O(1-5) GeV – σ(E) helps 500 t LAr @100 m from target	E sub GeV – σ(E) does not help 1 kt WC at 250 m (ESSnuSB ND)

First studies on muon reconstruction

A. Branca

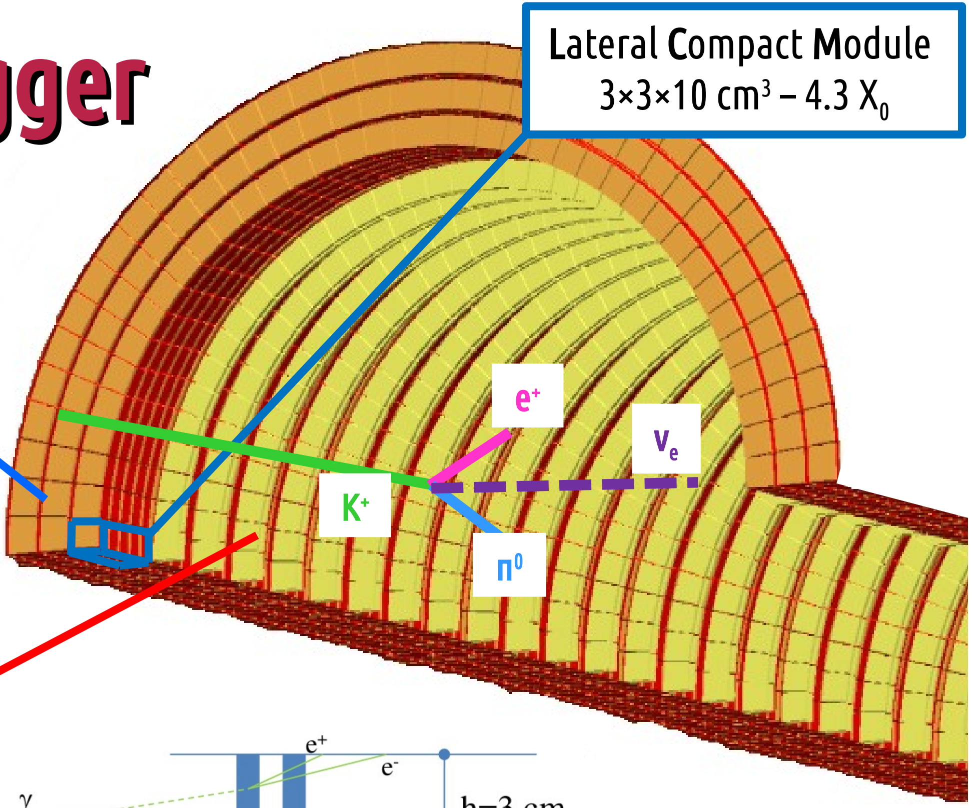
Purpose of this preliminary study:

- What is a proper configuration of the instrumented decay refion allowing the PID of muons from pion decays?
- Is the calorimetric technique, employed for ENUBET@CERN, a suitable choice also for MNB@ESS?

What has been done:

- Simulate pion beam with GEANT4 implementation of the instrumented tunnel walls of ENUBET@CERN:
  - Fine tune parameters: tunnel radius, calorimetric modules size, POT;
- Characterization of muons from pion decays in the new configuration:
  - Muon rates / distributions;
- Assess muon reconstruction performance:
  - Employing same algorithm developed for ENUBET@CERN;

The ENUBET lepton tagger



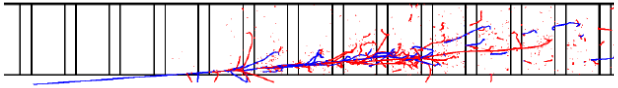
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

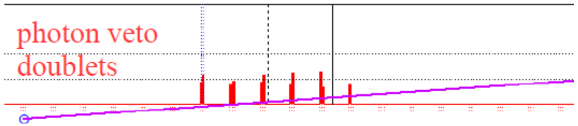
→ $e^+/\pi^\pm/\mu$ separation

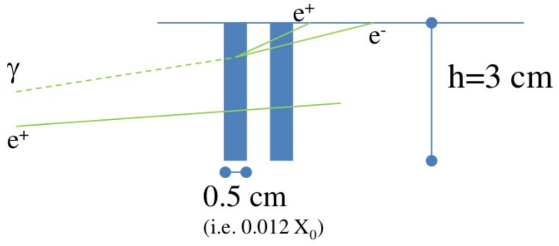


Integrated photon veto

- Plastic scintillators rings of 3×3 cm^2 pads

→ π^0 rejection





e^+ (signal) topology

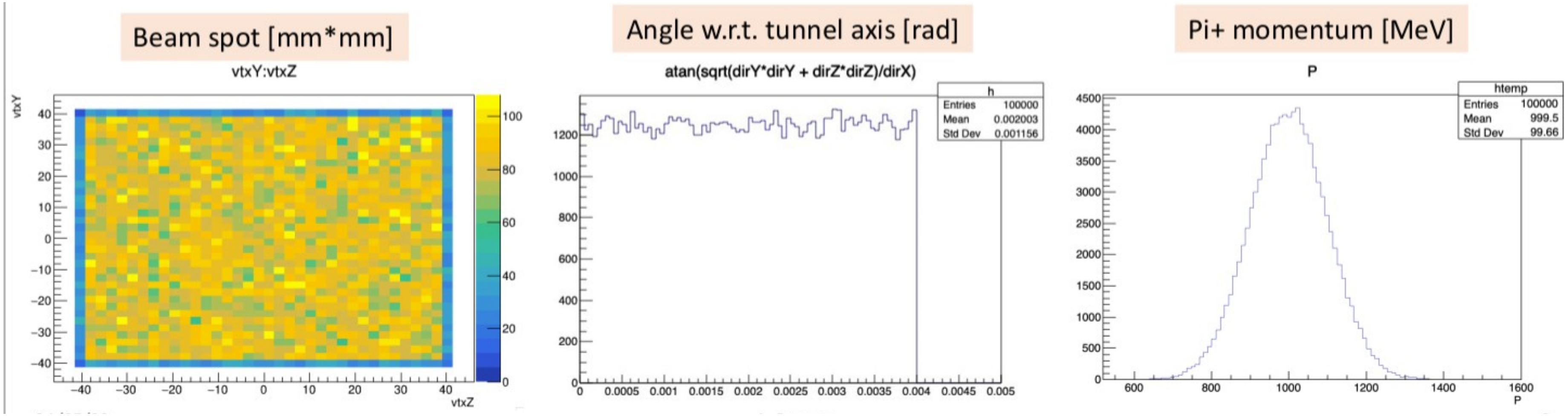
π^0 (background) topology

π^+ (background) topology

μ reco: input beam working assumptions

A. Branca

- We have not yet a detailed design of the focusing beamline as for ENUBET →
- **This is THE major next step**. As of now only very prel. attempts. For these results we assume to be capable of collecting at the tagger entrance π^+ with a
  - momentum: 1 GeV ± 10% gaussian
  - XY Uniform in a 8x8 cm^2 window
  - polar angle uniform in [0, 4] mrad
  - Intensity: 8.3 x 10^{14} protons/2.86 ms spill (standard)
  - Pion collection efficiency: π^+ / POT = $1\cdot10^{-4}$ → 8.3 x 10^{10} π^+/2.86 ms (450 GHz/cm^2)



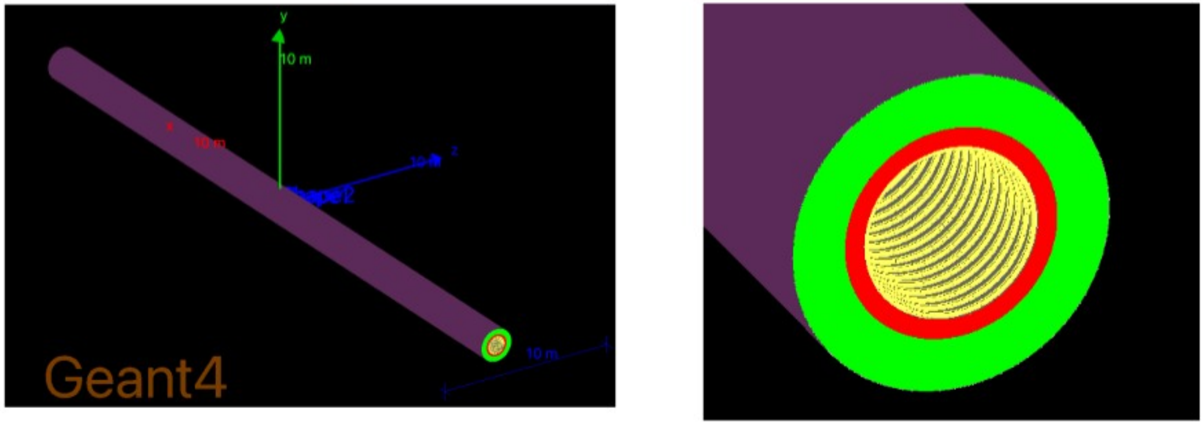
μ reco: input beam working assumptions

A. Branca

Tagger geometry:

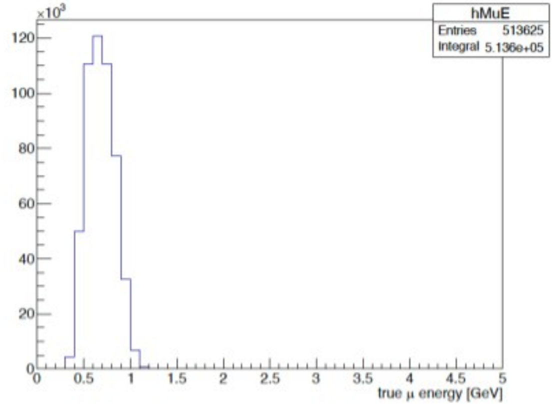
- R = 0.5 m:
  - reduced by a factor of 2 w.r.t. ENUBET@CERN
  - Need to improve acceptance for muons, emitted at relatively small angles (see next slide);
- L = 40 m;
- Basic calorimetric module: 3x3 cm^2 cross-section / 11 cm length
  - 5 tiles of iron absorber 1.5 cm thick interleaved with 5 tiles of plastic scintillators 0.7 cm thick

View of the calorimeter G4 simulation

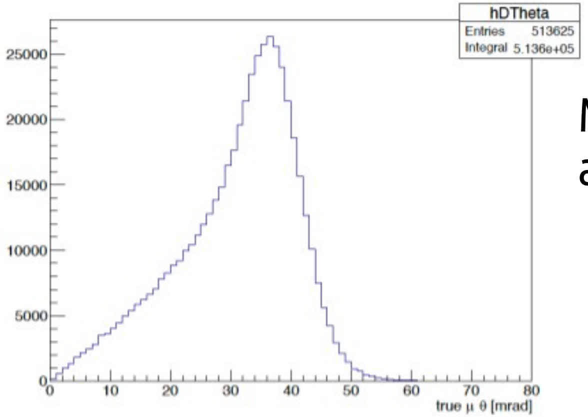


Pion decays in the decay volume

A. Branca

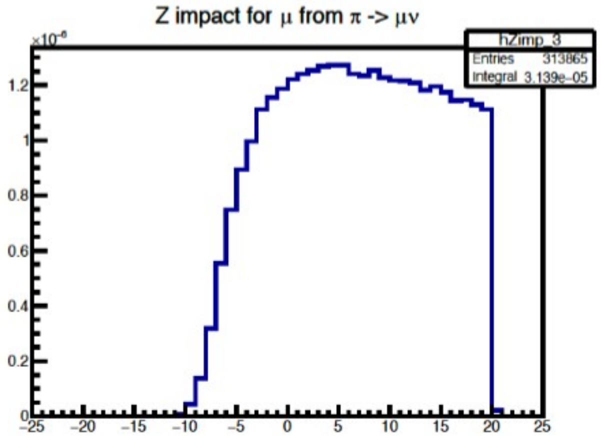


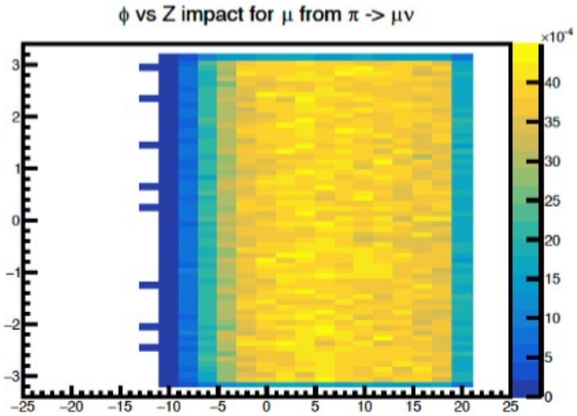
~700 MeV mu
(60 cm in iron)



Muon angle wrt beam axis peaking at 36 mrad

Impact point along the calorimetric walls





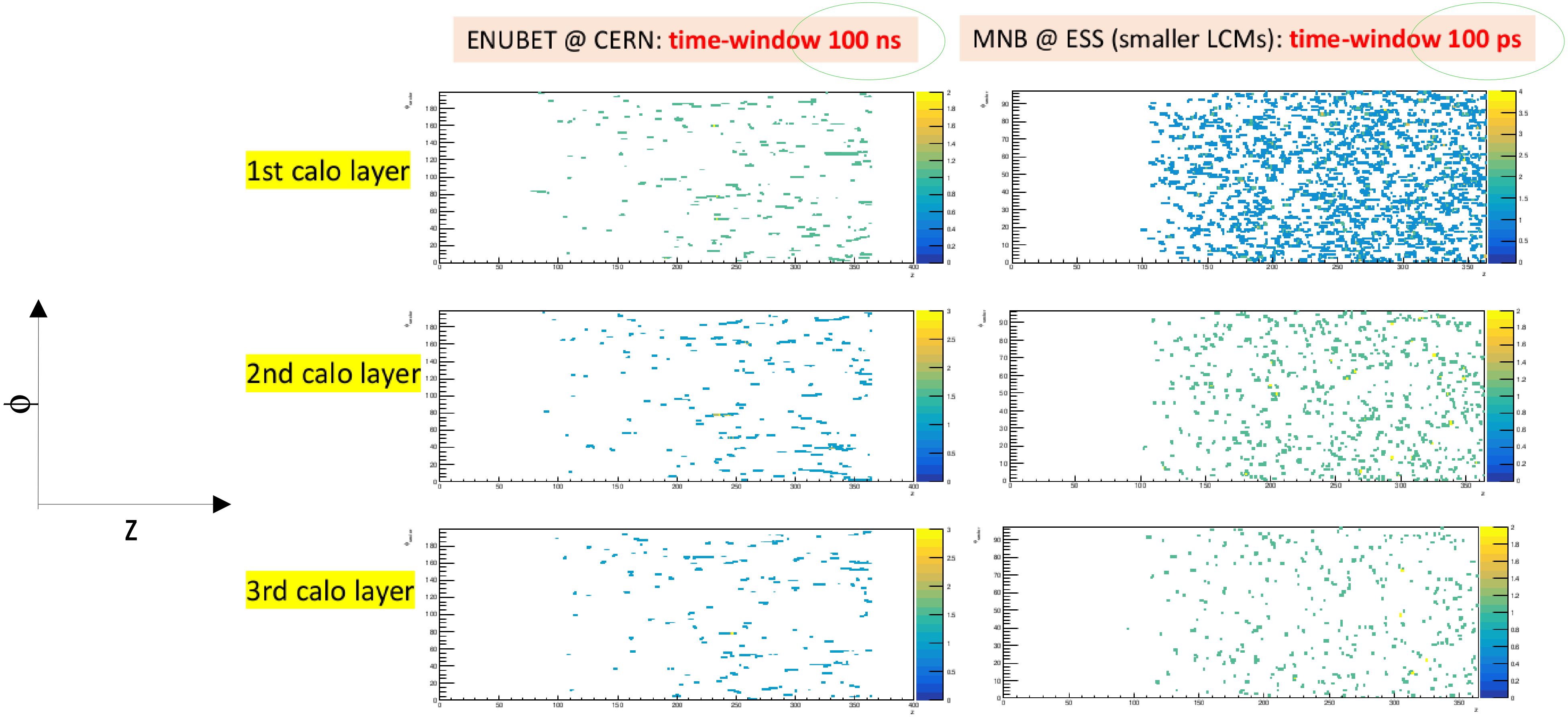
	N	%
π^+ @ entrance	10^6	/
Decays in tunnel volume	513625	51.4 %
Muon impacting calo walls	313865	31.4 %

About 60% of pion decays in the tagger have a muon in the geometrical acceptance

Tagger occupancy comparison

A. Branca

At the ESS the very high occupancy makes the algorithm find fake deposits correlated in space-time with seed



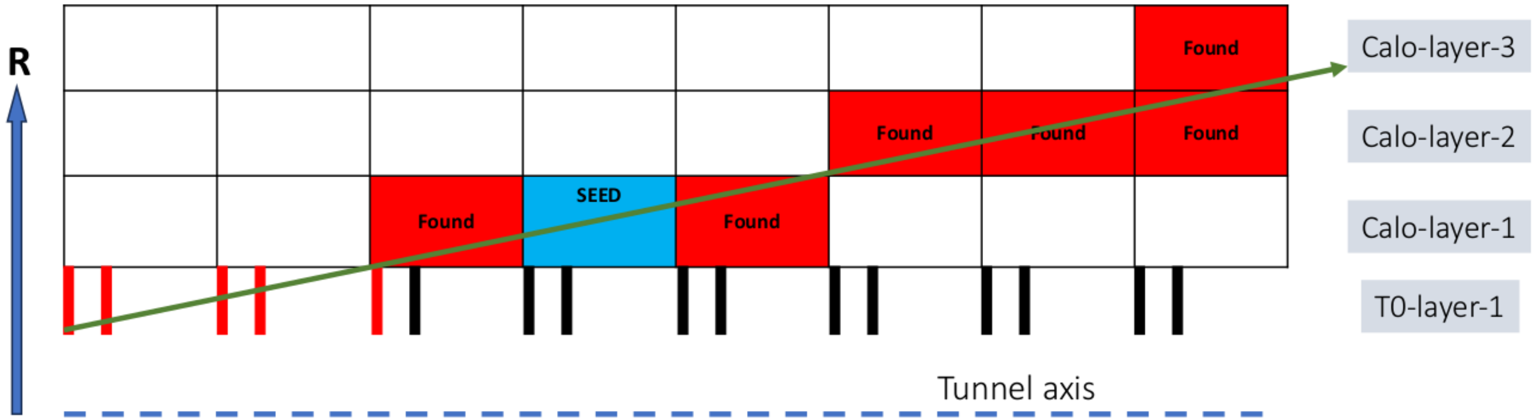
μ reco: muon tracks clustering

A. Branca

- Start point an energy deposition compatible with a mip in the first calorimetric layer (SEED);
- Cluster all energy depositions which position is compatible with a muon track topology and time is compatible with the muon propagation time (within time resolution);

Cuts are fine-tuned, based on multiplicity distributions in slide 5:

- Seed with E=[5,15] MeV in layer 0;
- At least 12 tiles in t0 layer / 3 LCMs in layer 1 / 1 LCMs in layer 2 / No requirements on layer 3;
- Tested different time resolution: 1 – 0.5 – 0.2 – 0.1 ns;



Particle rates @ tagger walls

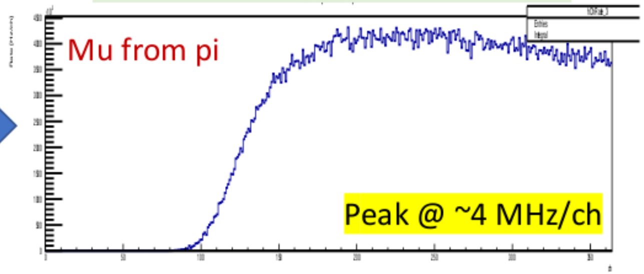
With the configurations studied:

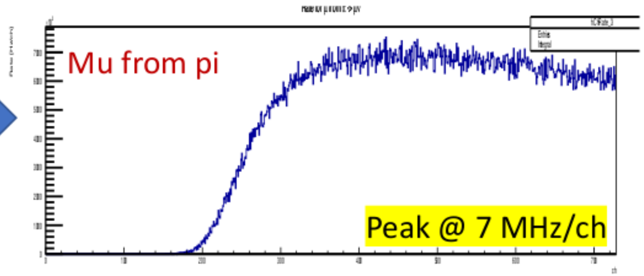
-> standard LCM size: need to reduce POT/spill by factor of 100 to reach a plateau in the reconstruction performance (already at a recovery time of 1 / 0.5 ns);

1 cm^2 transversal size – 5.5 cm length

-> smaller LCM: need to reduce POT/spill by factor of 10 to reache plateau in reco performance (around 0.5 / 0.2 ns recovery time);

Rate per channel VS impact point





To reach reasonable performance for muon reconstruction we need to achieve about 5/10 MHz per channel at most!

Taking into account that at peak we have 12 MHz/cm2 @ tagger R_0 = 50 cm, empirically the channel area (A_{ch}) for a tagger with a given radius (R) and at a given POT should be:

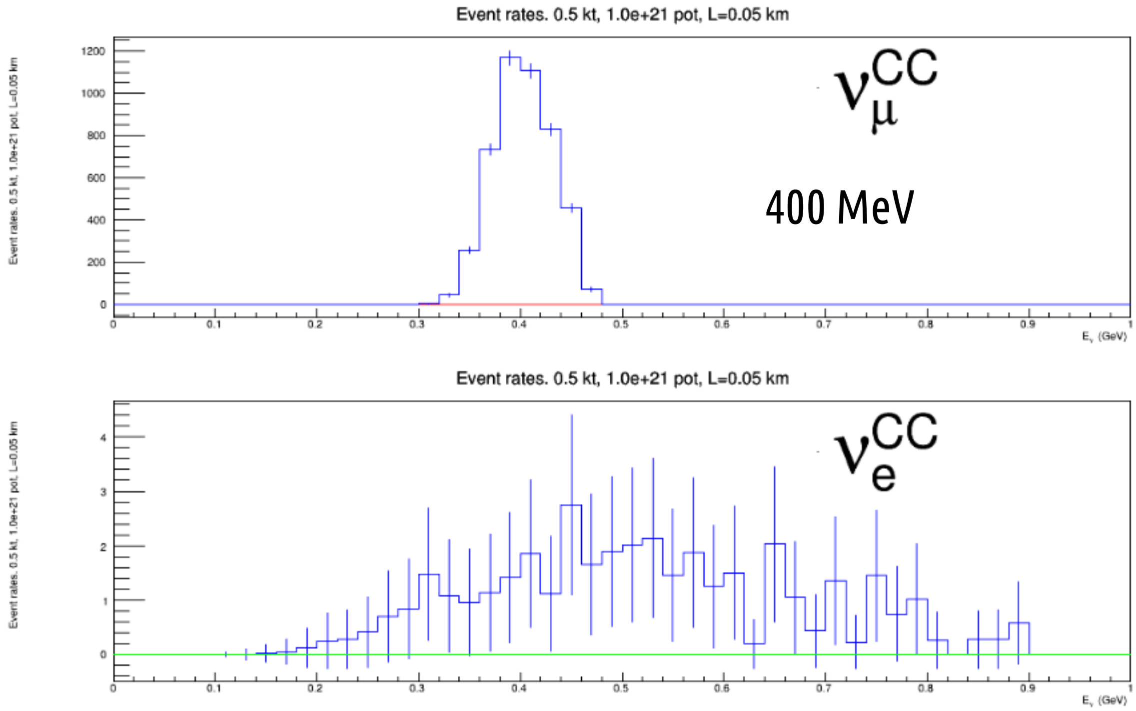
$$A_{ch} = \frac{5\ MHz/ch}{12\ MHz/cm^2} \cdot \frac{R}{R_0} \cdot \frac{N_{POT}^{def}}{N_{POT}}$$

24/05/23 A. Branca 13

Neutrino fluxes (very preliminary)

F. Pupilli

1e21 POT on the MNB target ~ 1 year (roughly)



~4700 ν_μ^{CC} interactions with $1x10^{21}$ pot

Quite sharp peak energy spectrum centered at ~400 MeV

Reported also the ν_e^{CC} (~40) as a measure of the muon DIF

Conclusions and next steps

A monitored neutrino beam at the ESS before the construction of the accumulator could pin down error on fluxes allowing precise cross section measurement in the sub-GeV region: we have **not found substantial showstoppers** so far.

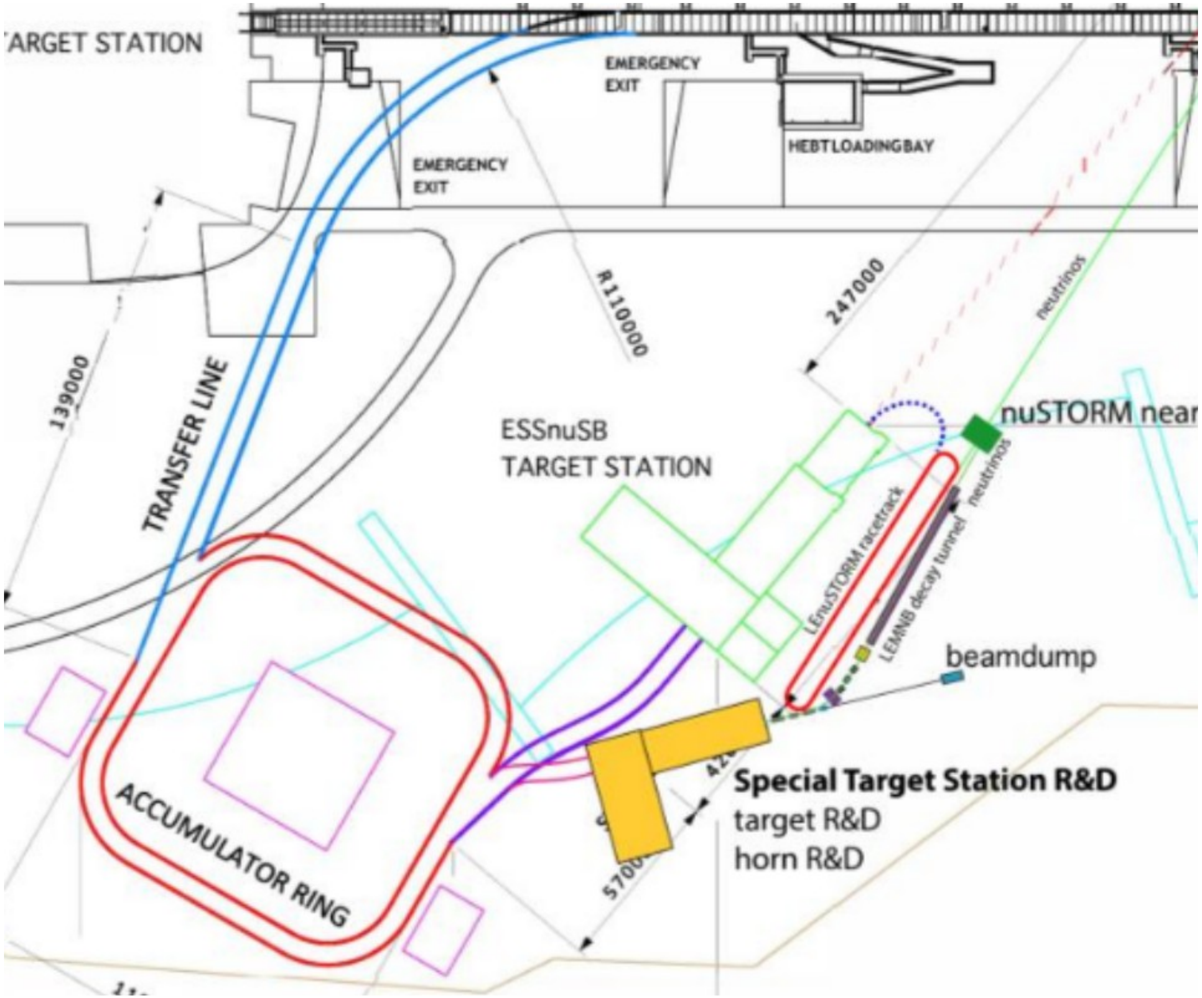
Still… monitoring pion decays over a **2.86 ms time window is tough** (2 s in ENUBET!). Need to consider **a higher granularity detector wrt to ENUBET** (from 3x3x11 cm^3 with 1 ns resolution to 1x1x5.5 cm^3 with <500 ps) to achieve reasonable pileup + **use only about 10% of the available protons** (shared mode).

Considering other detector technologies rather than a sampling calorimeter+tracker (less need for calorimetry as we are only basically using it as a tracker). Joint working group studying the use of fast micromegas within the ENUBET forward region and at LEMNB@ESS.

Within these constraints we can get usable muon neutrino rates on a 1kt scale detector: O(5000) numuCC/10^{21} pot

Next important step: design a realistic pion focusing line to confirm the rule of thumb assumptions we made so far on the pion capture efficiency.

End



ARGET STATION
EMERGENCY EXIT
EMERGENCY EXIT
HEBT LOADING BAY
R110000
247000
139000
TRANSFER LINE
neutrinos
ESSnuSB
TARGET STATION
nuSTORM near
LEnuSTORM racetrack
LEMNB decay tunnel
neutrinos
beamdump
ACCUMULATOR RING
Special Target Station R&D
target R&D
horn R&D

Short term planning (2023)

- Update the expected performance with respect to the original proposal
- Reoptimize the optics with MADX/transport
- Simulate the beamline with GEANT4 (optional: G4beamline)
- Re-tune the muon identification algorithms accounting for p extraction (3 ms versus 2 s) and retune the protons-on-target (pot) per spill
- Redesign the detectors in the decay tunnel
- Estimate flux and narrow-band-off-axis technique at neutrino detector
- Update the optimization and doses at the target

Low rate

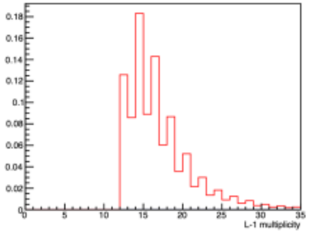
A. Branca

Reco muons performace @ low rate

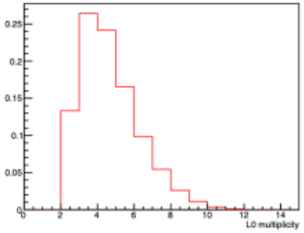
Just to cross-check that the reco algorithm is working also in this case: made a production with pi+ rate @ 1 Hz

- Seed with E=[5,15] MeV in layer 0;
- At least 12 tiles in t0 layer;
- At least 3 LCMs in layer 1;
- At least 1 LCMs in layer 2;
- No requirements on layer 3;

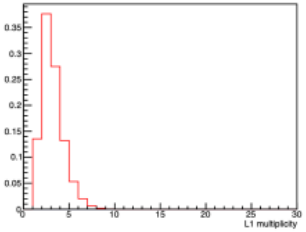
T0 tiles



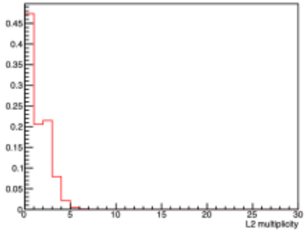
LCM layer 1



LCM layer 2

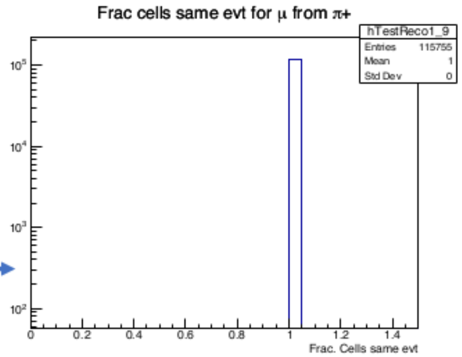


LCM layer 3



Reco efficiency = 22.5%

Of course, in this case we recover the clusterization of muons, and distributions of multiplicity from reco events are similar to the true MC ones.
100% of the clustered deposits belong to the actual muon producing the hits.



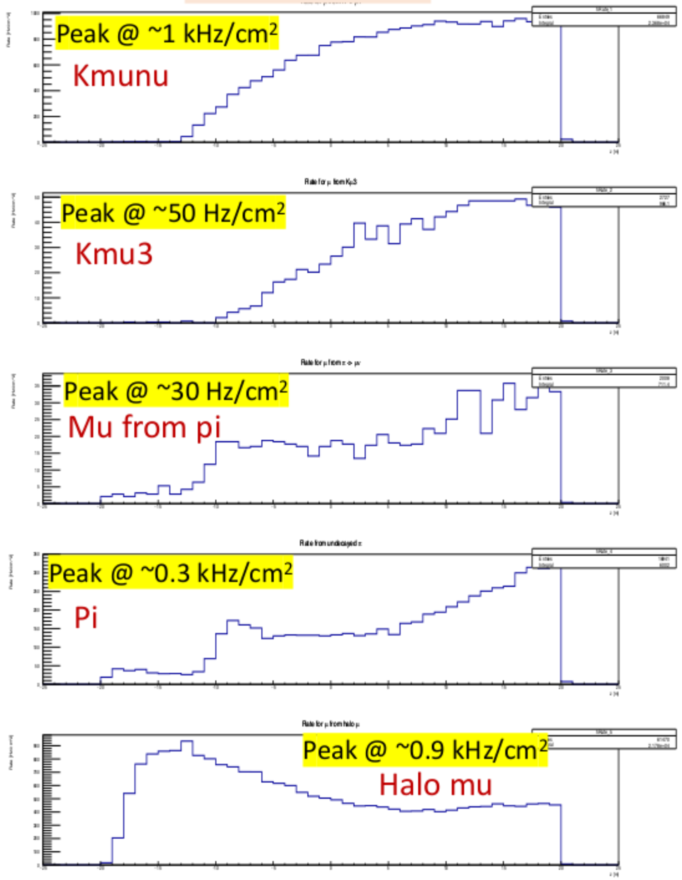
Particle rates @ tagger walls

The distributions show the particle rates in Hz/cm2 as a function of the longitudinal impact point on the calo walls

A. Branca

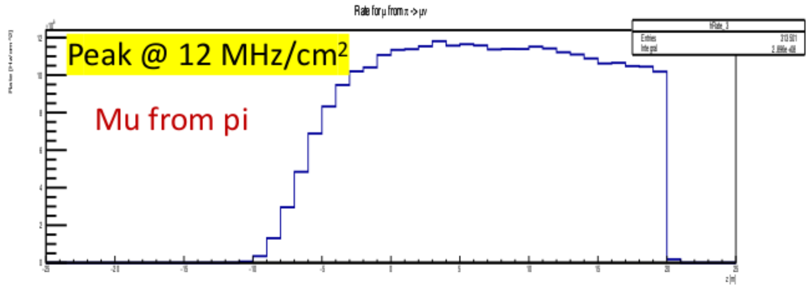
Particle rates @ tagger walls

ENUBET@CERN



The distributions show the particle rates in Hz/cm^2 as a function of the longitudinal impact point on the calo walls

MNB@ESS



How to achieve a good identification of muons for MNB@ESS

- Scan different values for POT/spill;
- Reduce calorimetric module size;

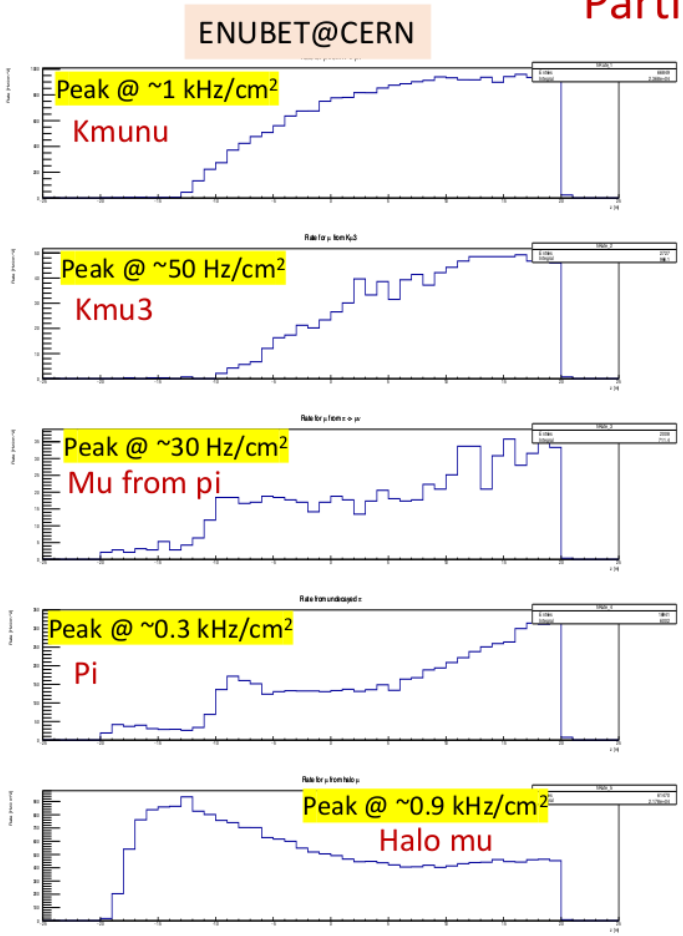
Performed study to check what is the impact of tweaking these parameters.

Particle rates @ tagger walls

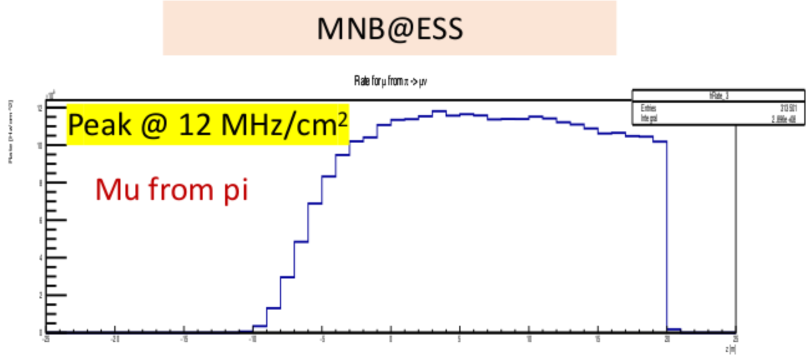
The distributions show the particle rates in Hz/cm2 as a function of the longitudinal impact point on the calo walls

A. Branca

Particle rates @ tagger walls



The distributions show the particle rates in Hz/cm^2 as a function of the longitudinal impact point on the calo walls



How to achieve a good identification of muons for MNB@ESS

- Scan different values for POT/spill;
- Reduce calorimetric module size;

Performed study to check what is the impact of tweaking these parameters.

Inputs and suggestions from other WP's

- Neutrino detector: we should exploit both the LEnustorm detector (50 m) and the Essnusb near detector (250 m). Fluxes should be evaluated at both positions.

- The design of the transfer line can be either done tangent to the accumulator site (baseline) or independently of it. We should discuss it with WP4 but it is not a priority at the startup of the work (to be defined in 2024)

- T. Ekelof: Can we imagine to run MNB@ESS using the same target station as ESSnuSB?

  Tentative answer: the MNB@ESS transfer line requires steering of the pions by at least 10-20 degree and cannot be on-axis- This is not a showstopper but should be taken into account. We will consider it in the short-term plan.

Deliverables and personnel

Description of work

Task 6.1: Coordination of the WP (**UNIMIB**)

Responsibility for this task includes coordination of the WP's objectives, milestones and deliverables.

Task 6.2: Design of the transfer line and focusing system (**INFN**, UNIMIB)
Design the extraction scheme and the location of the transfer line in the option of no accumulator and in the option of a parallel run with ESSνSB as soon as the accumulator is available. Design the secondary focusing and transport after the target.

Task 6.3: Design of the instrumented decay tunnel (**UNIMIB**, INFN, RBI, AUTH) NCSRD
Optimise the geometry and civil engineering of the 30 m decay tunnel. Design the active components (muon and positron tagger) in the wall of the tunnel and hadron dump, their simulation and PID algorithms. The design includes the technology assessment for the instrumentation, full simulation of detector response, doses, pile-up effects, and real-time detector calibration.

Task 6.4: Assess the flux systematics benefiting from the reconstructed lepton rate in the decay tunnel (**AUTH**, UNIMIB, INFN, RBI). NCSRD
This task encompasses the evaluation of neutrino fluxes from the decay tunnel, the systematic uncertainty arising from the Monte Carlo simulation and hadroproduction, and the substantial improvement that can be reached monitoring muons at single particle level. It also investigates the size of the tagged neutrino sample, where the neutrinos interacting in the neutrino detector can be uniquely associated in time with the corresponding lepton (tagged neutrino beam).

Deliverables
D6.1: Design of the transfer line: month 24
D6.2: Completion of the end-to-end simulation of the beamline: month 30
D6.3: Physics performance of the monitored neutrino beam: month 36
D6.4: Update of LEMNB physics performance including the full systematic budget: month 46

1 post-doc full time (INFN) + resources from ENUBET staff personnel
1 PhD full-time (Unimib) + resources from ENUBET staff personnel (including AUTH and RBI)
Resources from ENUBET + AUTH + RBI + NCSRD/Demokritos

General strategy on a broader perspective

Construction phase of ESSnuSB

- High power p LINAC. 3 ms pulses @ 2 GeV. Max intensity 4 MW; needed intensity O(500 kW)
- The ESSnuSB near detector and/or dedicated (500-1000 t) detectors.

  Top priority: water target.

  Additional opportunity: the NUSTORM detector.

  More aggressive option: liquid deuteron or hydrogen (!)
- A transfer line that operates **when the accumulator is under construction**

In ESSnuSB+ we want to focus on the construction phase!

Operation phase of ESSnuSB

With the accumulator. MNB@ESS cannot operate with too short beams and we do not want to employ the **accumulator** (**pile up** in the instrumentation):

- The accumulator can be used as a transfer line for the linac bunches devoted to MNB@ESS
- More aggressive: we can use the accumulator as a debuncher to have a long (enubet-like) extraction and further reduce pile up (at the expenses of cosmic background).