A high precision narrow-band neutrino beam

The ENUBET project

G. Brunetti (INFN Padova)
On behalf of the ENUBET Collaboration

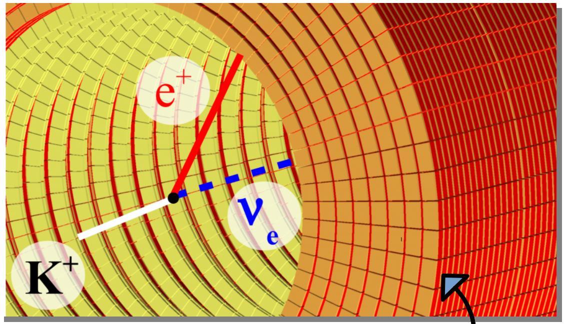
This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (G.A. n. 681647)

10-17 July 2019
Ghent, Belgium

European Physical Society
Conference on High Energy Physics

The goal of ENUBET

Demonstrate the technical feasibility and physics performance of a **neutrino beam** where **lepton production at large angle is monitored at single particle level**



(K_{e3} decays) $K^+ \to e^+ \; \nu_e \; \pi^0$

→ to tagger

→ to neutrino detector

Two pillars

- Build/Test a **demonstrator of the instrumented decay tunnel** → **calorimeters**
- Design/Simulation of **the hadronic beamline**

Outline

- **Beamline simulation & accelerator studies**
- Experimental validation of **detector prototype**
- Updated **physics performance**

The ENUBET Collaboration

60 physicists, 12 institutions

Since 2019, ENUBET is a CERN Neutrino Platform Experiment

NP06/ENUBET

A narrow-band beam for the precision era of ν physics

Absolute flux of ν_e and ν_μ at the 1% level

↓

Remove the leading source of uncertainty in **neutrino cross section measurement**

Energy of the neutrino known at the 10% level

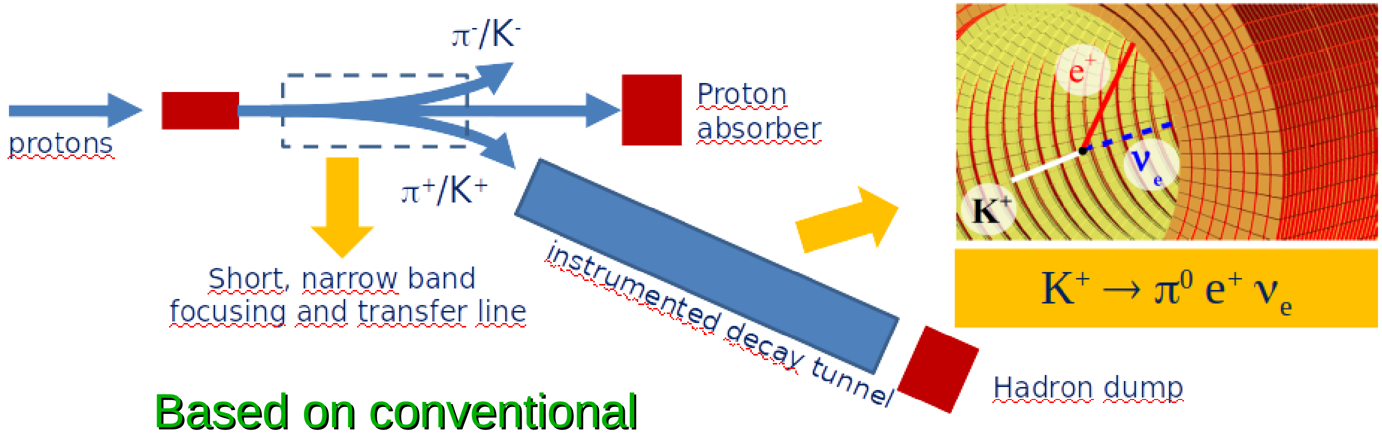
↓

The ideal tool to study neutrino interactions in nuclei

Flavor composition known at the 1% level

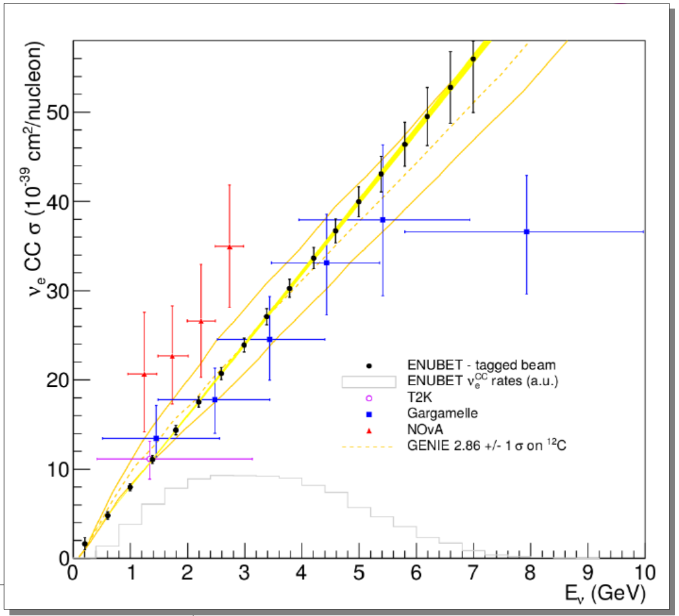
↓

The ideal tool to study NSI and sterile neutrinos at the GeV scale



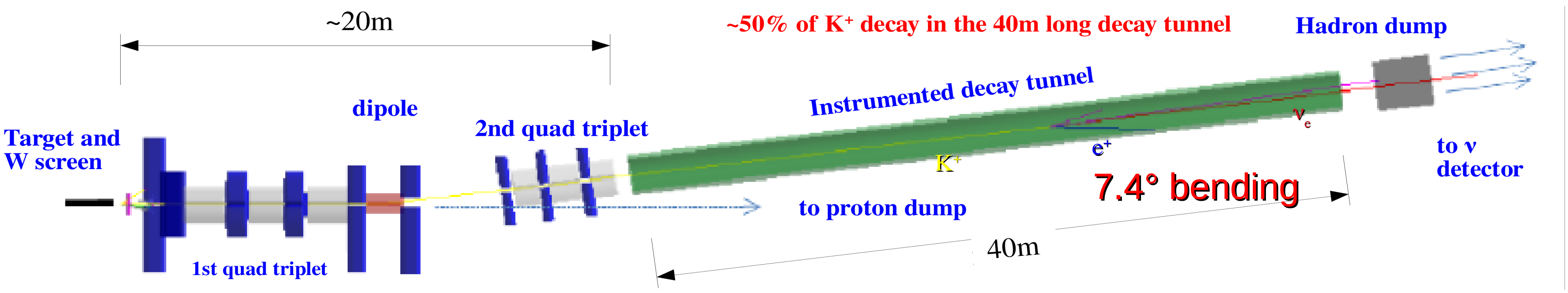
$K^+ \rightarrow \pi^0 e^+ \nu_e$

Based on conventional technologies



- Monitor the **decays** in which ν are produced **event-by-event**
- **"By-pass" uncertainties from POT,hadro-production, beamline efficiency**
- **Fully instrumented decay region → ν_e flux prediction = e+ counting**

The ENUBET Beamline



- **Proton driver: CERN** SPS (400 GeV), **Fermilab** Main Ring (120 GeV), **JPARC** (30 GeV)
- **Target**: Be/graphite target. FLUKA
- **Focusing**
  - Horn-based: [2 ms pulse, 180 kA, 10 Hz during the flat top] *[not shown in figure]*
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **Transfer line**
  - As short as possible (minimize early K-decays)
  - Optics: optimized with TRANSPORT to a **5-10% momentum bite centered at 8.5 GeV**
  - Particle transport and interaction: full simulation with G4Beamline
  - Normal-conducting magnets (numerical aperture<40 cm): Two quadrupole triplets, one (or two) bending dipole
- **Decay tunnel:** r = 1m, L = 40 m , low power hadron dump at the end
- **Proton dump**: position and size optimization in progress

The ENUBET Beamline - Yields

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction lenght	π/cycle (10^{10})	K/cycle (10^{10})	Proposal (b)
Horn	77	7.9	2ms (a)	438	36	x2
No horn	19	1.4	2 s	85	6.2	x4

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle

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

The horn-based option still allows x4 times more statistics, but...
Initial estimates of static option were 4 times too conservatives &

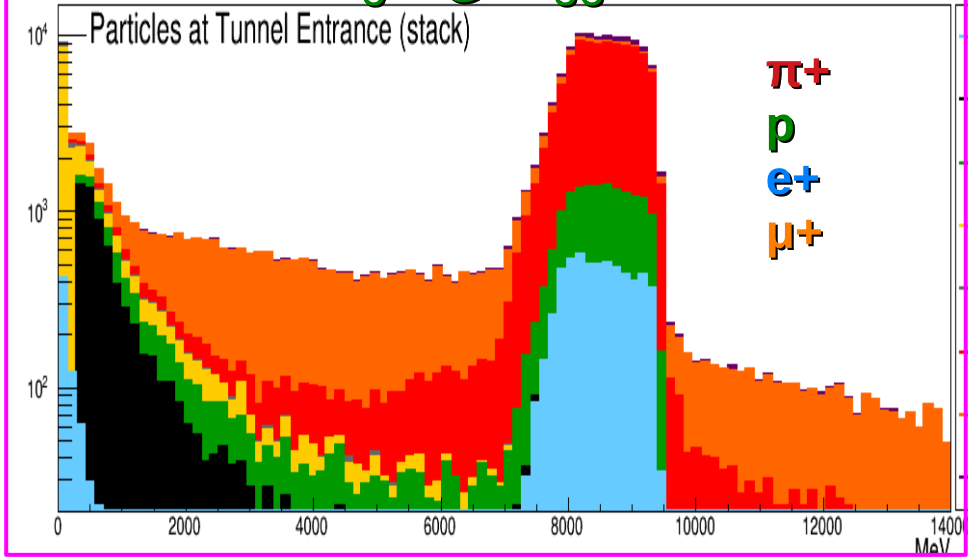
Advantages of the static extraction:

- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel (pile-up)
- Possibility to monitor the muon rate after the dump at % level (flux of ν_μ from pion decay) [**NEW: under evaluation**]
- Pave the way to a **"tagged neutrino beam"**: the neutrino interaction at the detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel

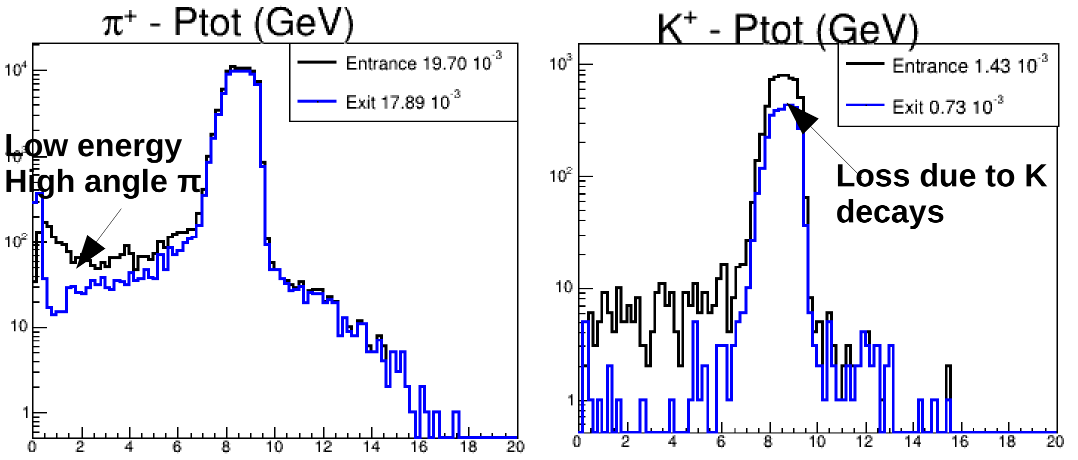
The Static Beamline

G4beamline simulation – Particles at tunnel Entrance/Exit

Particle budget @ Tagger Entrance



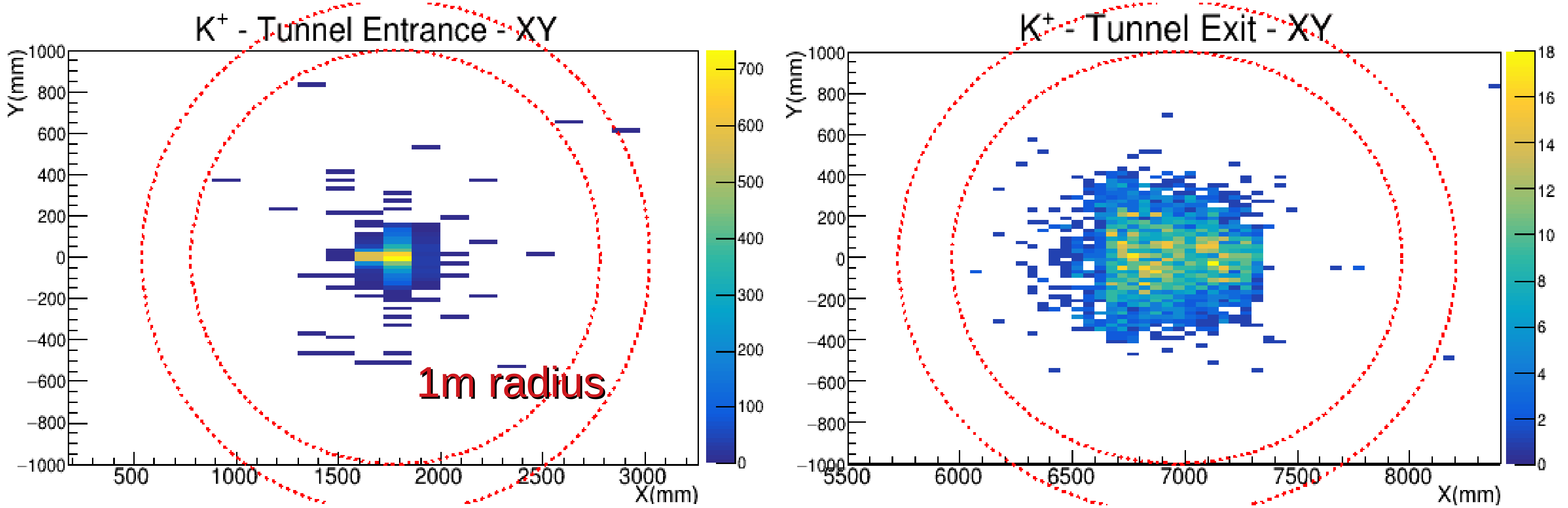
Spectra @ Tagger Entrance/Exit



Low energy High angle π

Loss due to K decays

Divergence of the kaon beam



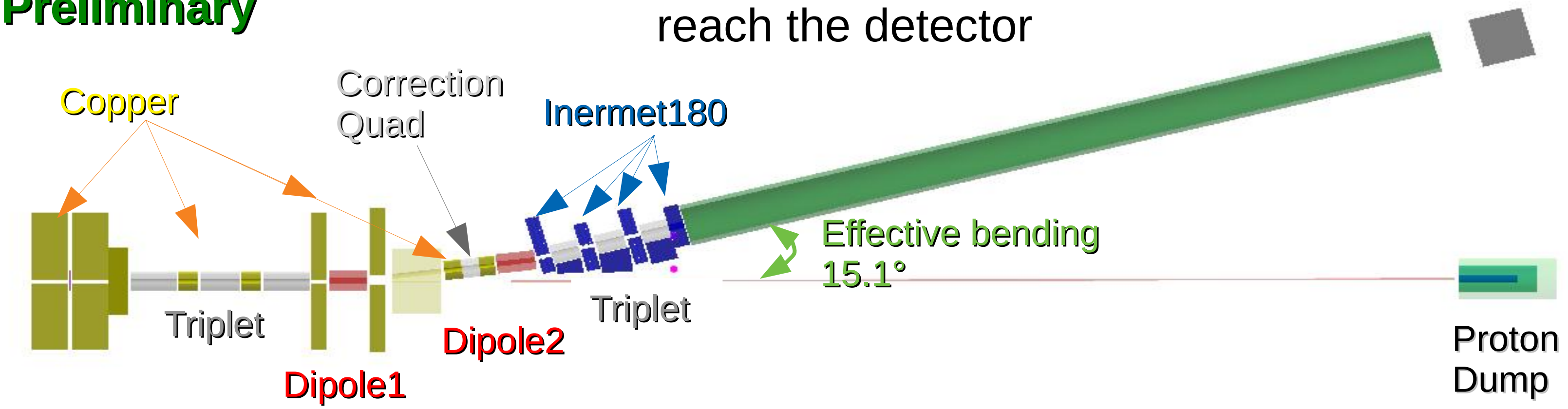
1m radius

Beamline Studies

- **Additional static focusing options under study**… → Put all inputs/schemes together → pindown the best design in terms of physics and technical feasibility

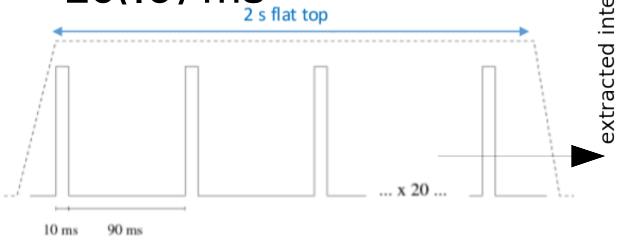
e.g.: 2 dipoles scheme → improve the quality of the beam in the tagger
→ larger bending angle (15.1°) reducing background from muons, less probable for neutrinos produced on the 0° line to reach the detector

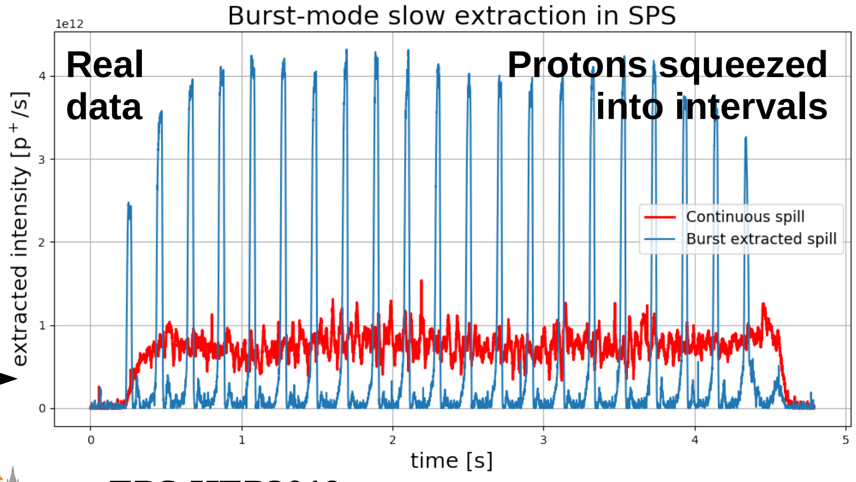
Preliminary



- **Machine studies for the horn-based option**: slow proton extraction (few ms) + horn pulsed for 2-10 ms → studies to implement the synchronization of a slow-extracted spill with a pulsed strong focusing system

Enhance output of neutrino flux keeping a reasonable pile-up threshold.
Burst slow extraction leads to a burst length optimization from 20 → 10(.6) ms

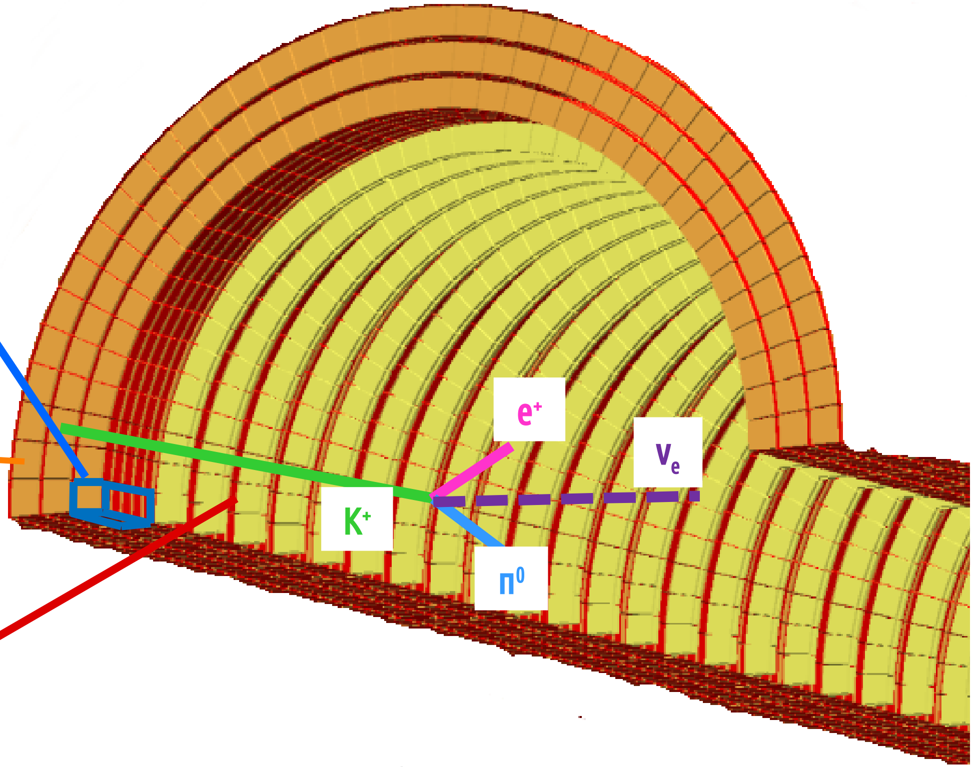




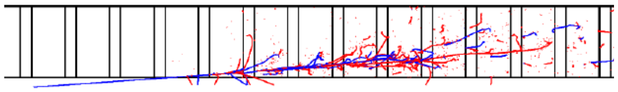
CERN-BE-OP-SPS
F.Velotti, M.Pari, V.Kain, B.Goddard

The ENUBET Tagger

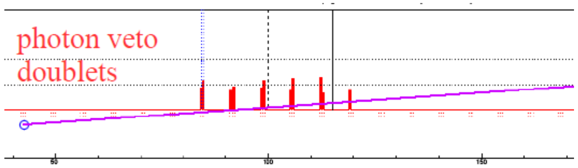
UCM
Ultra **C**ompact **M**odule
3x3x10 cm^3 – 4.3X$_0$

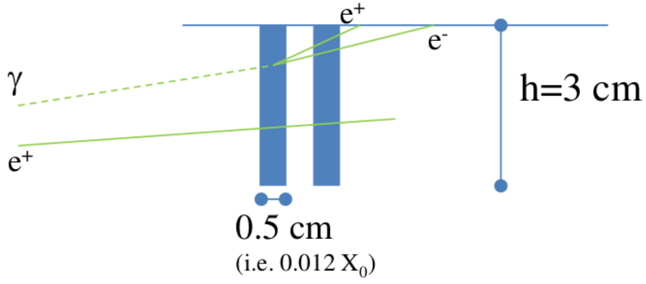


Calorimeter
Longitudinal Segmentation
Plastic scintillator + Iron absorbers
→ **e$^+$/π$^+$/μ separation**



Integrated photon veto
Plastic scintillators
Rings of 3x3 cm^2 pads
→ **π^0 rejection**





e$^+$ (signal) topology

π^0 (background) topology

π$^+$ (background) topology

The ENUBET Tagger: Detector R&D

- Very fruitful R&D: **several test beams and prototype testing over the years**

Shashlik with integrated readout, Test beam CERN-PS T9 line 2016-2017 → Response to MIP, e and π

Ballerini et al., JINST 13 (2018) P01028

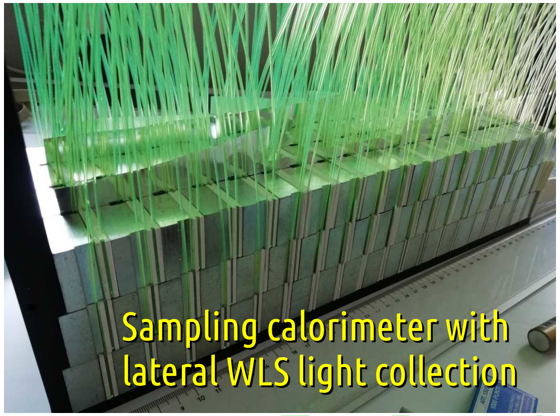
SiPM irradiation measurements, Test @ INFN-LNL → 1-3 MeV neutrons with fluences up to $10^{12}/\text{cm}^2$ in a few hours

F. Acerbi et al., JINST 14 (2019) P02029

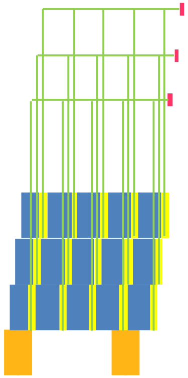
→ GOING FOR:

- **Lateral Readout Option**

Light collected from scintillator sides and **bundled** to a single SiPM reading 10 fibers (1 UCM)
SiPM not in immersed in hadronic shower →
Less compact BUT: **reduced neutron damage, better accesibility, possibility of replacement, better reproducibility of WLS-SiPM optical coupling**



Sampling calorimeter with lateral WLS light collection



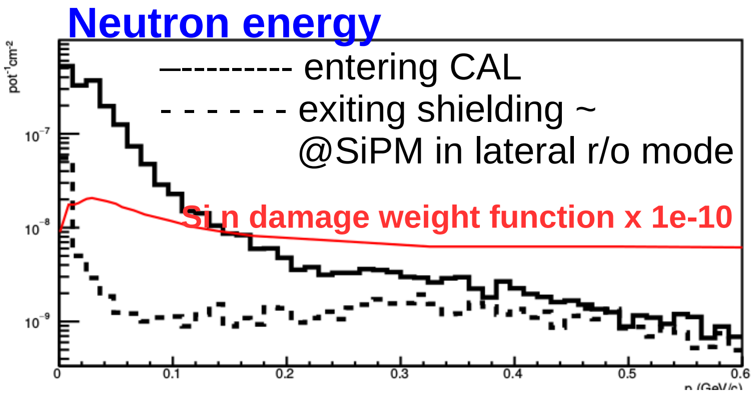
Large SiPM for 10 WLS $4\text{x}4\ \text{mm}^2$

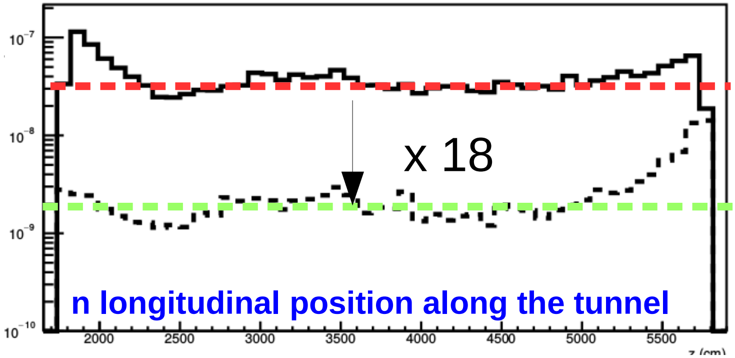
Test Beam May 2018 @ CERN PS

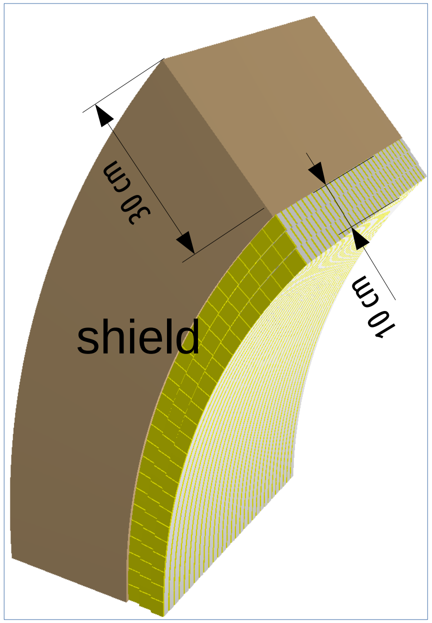
Achievable neutron reduction:

- 30 cm of borated polyethylene in front of SiPM
- FLUKA full simulation, **400 GeV protons**
- Very good suppression especially below 100 MeV
- **Factor ~18 reduction** (average over spectrum)

FLUKA
Preliminary

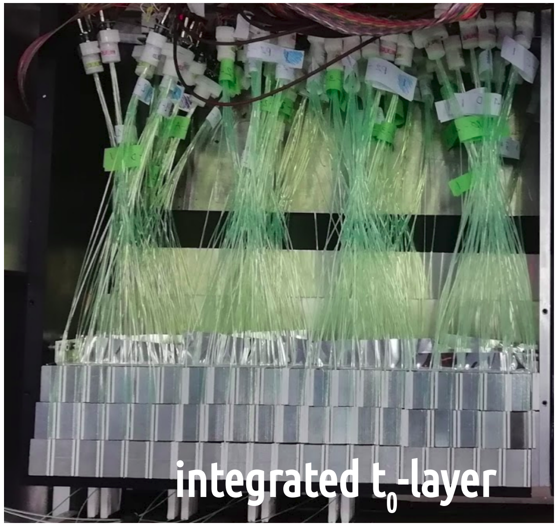




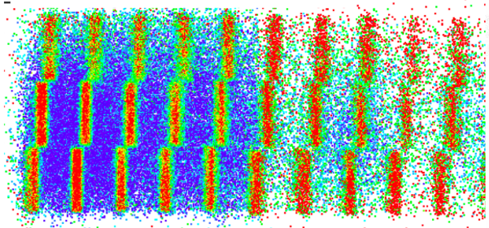


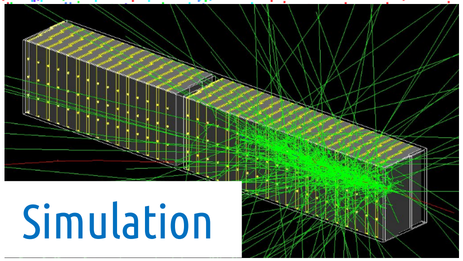
The ENUBET Tagger: Detector R&D

- **Module with hadronic cal. For pion containment and integrated t_0 layer**



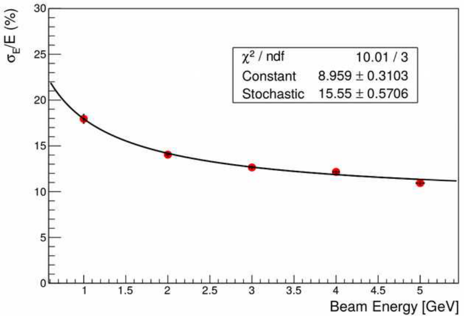
Efficiency maps



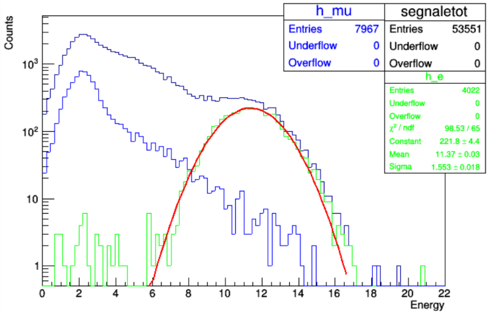


Simulation

Resolution



PID

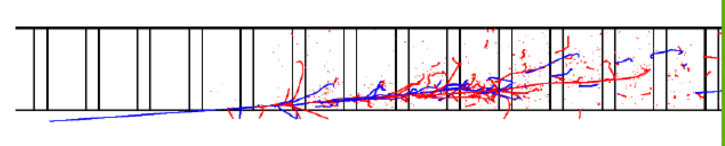


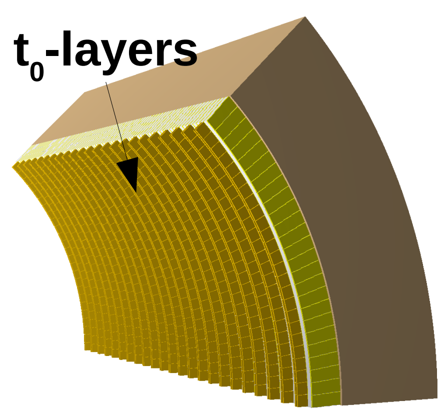
Test Beam (Sept. 2018 @ CERN PS)

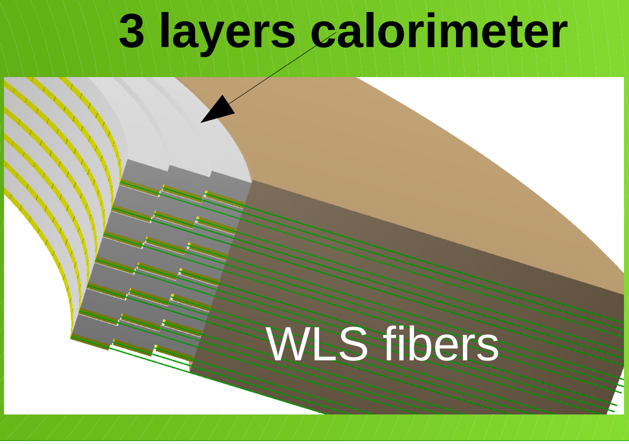
- Good signal amplitude
- Checking impact of light connection uniformity of WLS-SiPM in progress

The Tagger demonstrator

- Length **~3m** → containment of shallow angle particles in realistic conditions
- Fraction of Φ
- Due by 2021







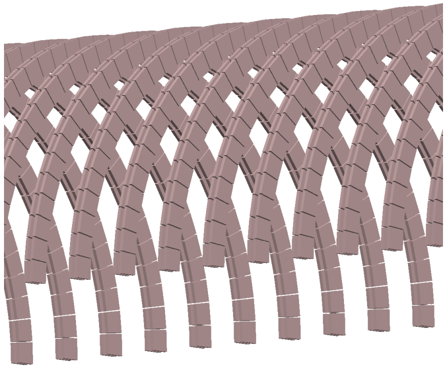
The Photon Veto

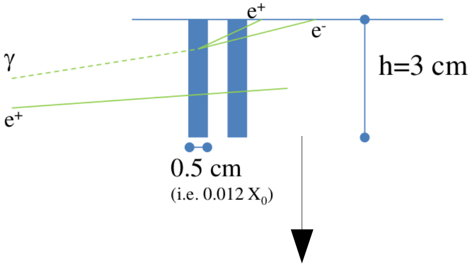
- **Test Beam @ CERN-PS T9 line 2016-2018**

γ/e+ discrimination + timing

scintillator (3x3x0.5 cm^3) + WLS fiber (40cm) + SiPM

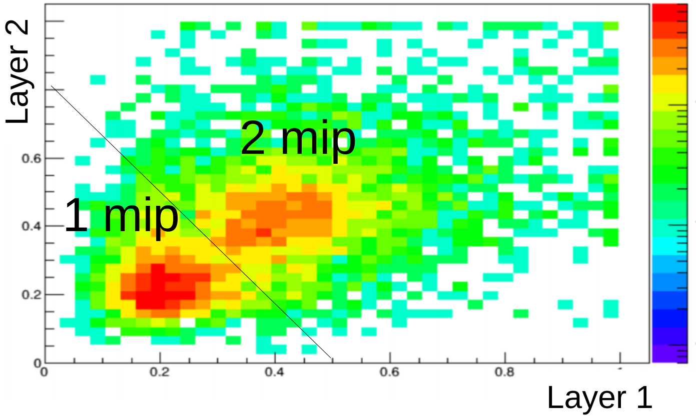
- Light collection efficiency → >95%
- Time resolution → **σ_t ~400 ps**
- **1mip/2mip separation**

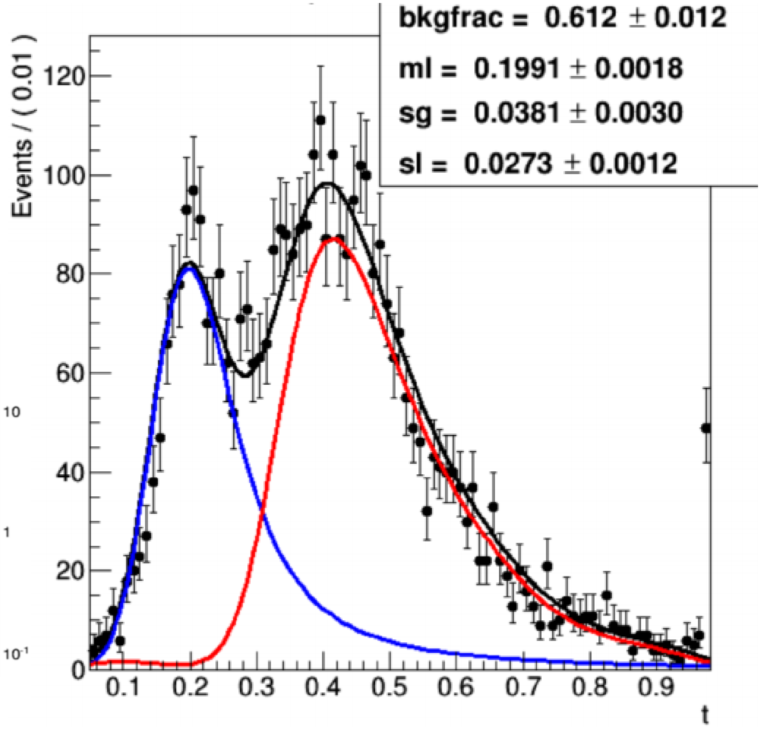




Charge exchange: **$\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma\gamma)$**

Trigger: PM1 + VETO + PM2





K_{e3} positron reconstruction

Full Geant4 simulation of the detector, validated by prototype tests at CERN in 2016-2018:

- From transferline to the tagger
- Particle propagation and decay
- hit-level detector response
- Pile-up effects

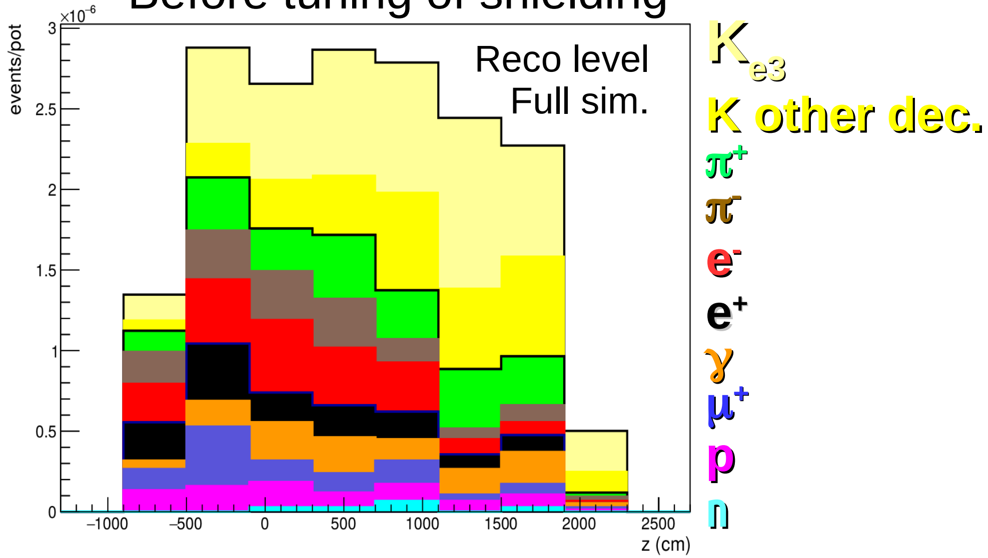
Analysis Chain

Event Builder → Identify the **seed** of the event (UCM with largest energy deposit in inner layer and > 20 MeV). **Cluster neighboring cells** close in time.

e/π/μ separation → **Multivariate** analysis based on **6 variables** (pattern of energy deposition in the calorimeters) with TMVA

e/γ separation → Signal on tiles of the **photon veto (0-1-2 mip)**

Before tuning of shielding



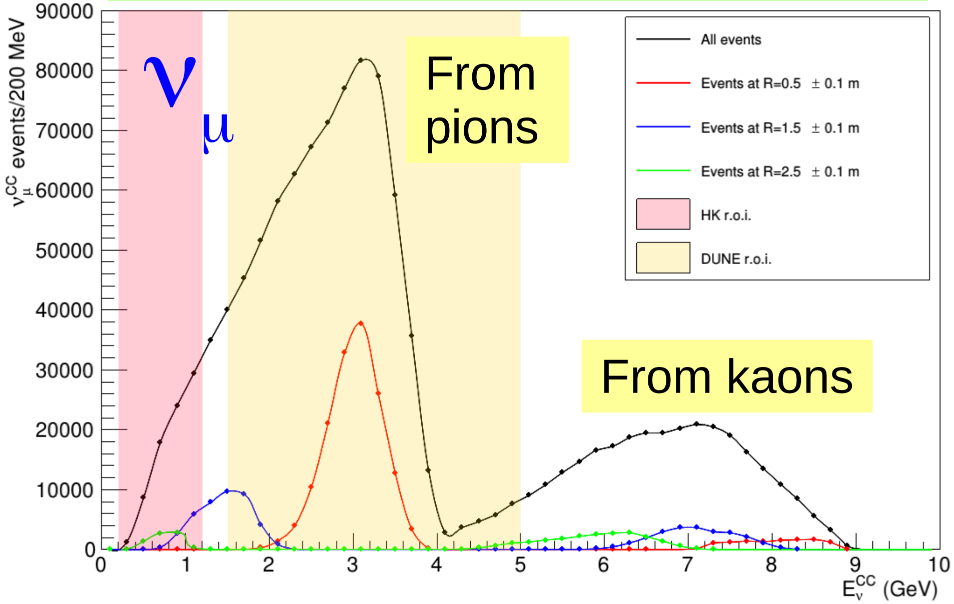
ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

φ cut → 0.46

Neutrino events per year at the detector

- **Detector mass: 500 t** (e.g. ProtoDUNEs @ CERN, ICARUS @ FNAL, WC @ J-Parc?)
- **Baseline** (beam dump-detector distance): **50 m**
- **4.5 10^{19} POT at SPS** (0.5/1 year in dedicated/shared mode) **or 1.5 10^{20} POT at FNAL**

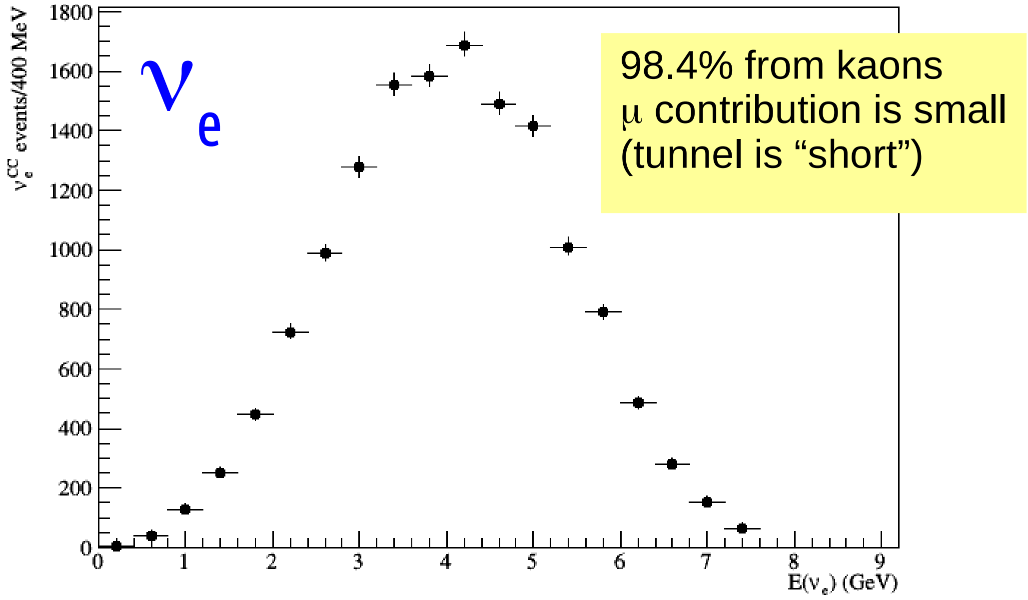
1.2 million ν_μ Charged Current per year



From pions

From kaons

14000 ν_e Charged Current per year

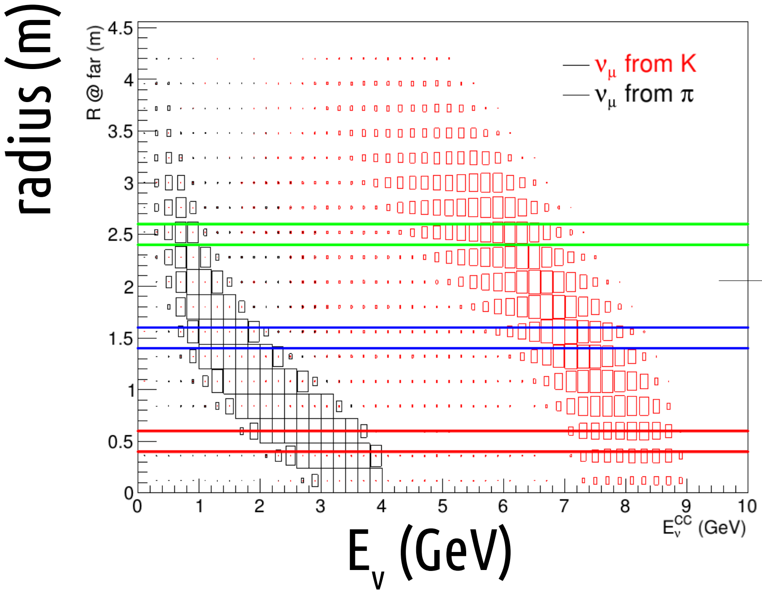


98.4% from kaons
μ contribution is small
(tunnel is “short”)

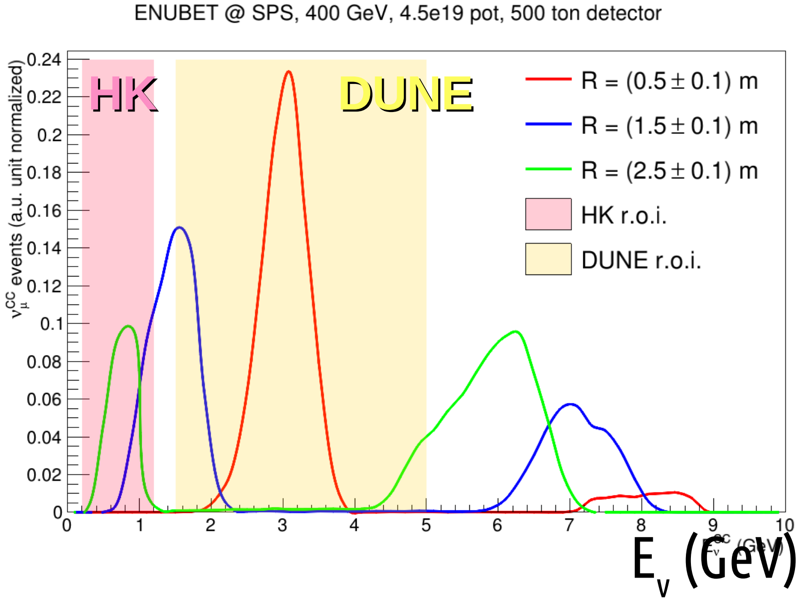
- **ν_μ from K and π** are **well separated** in energy (narrow band)
- **ν_e and ν_μ from K** are constrained by the tagger measurement (K_{e3}, mainly $K_{\mu2}$).
- **ν_μ from π**: μ detectors downstream of the hadron dump ? (under study)

ν_μ CC events @ the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis



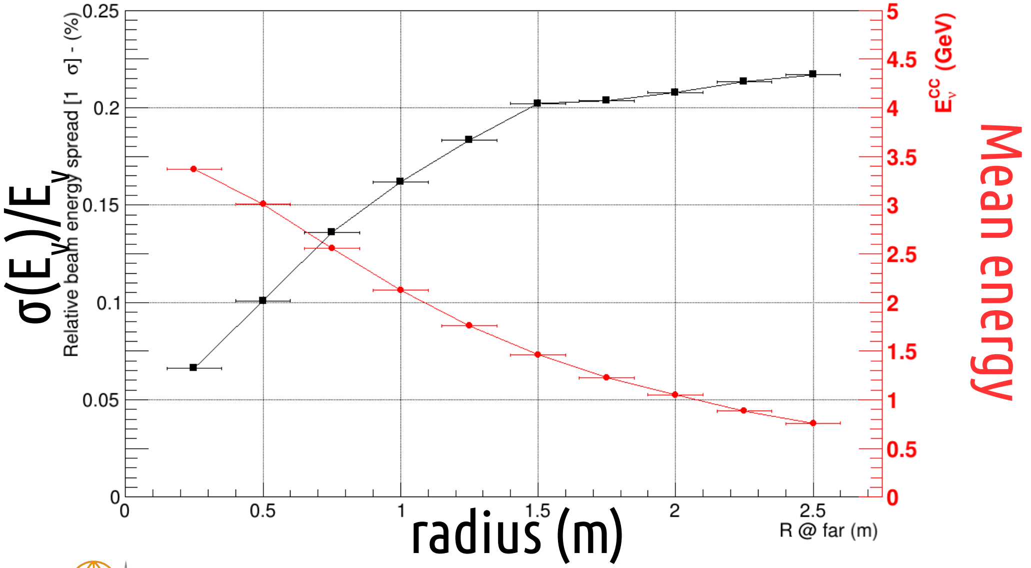
ν_μ-CC in radial bins (1 norm.)



The **beam width** at fixed R is:
(≡ν energy resolution for π component)

- 8% for r ~ 50 cm, <Eν> ~ 3 GeV
- 22% for r ~ 250 cm, <Eν> ~ 0.7 GeV

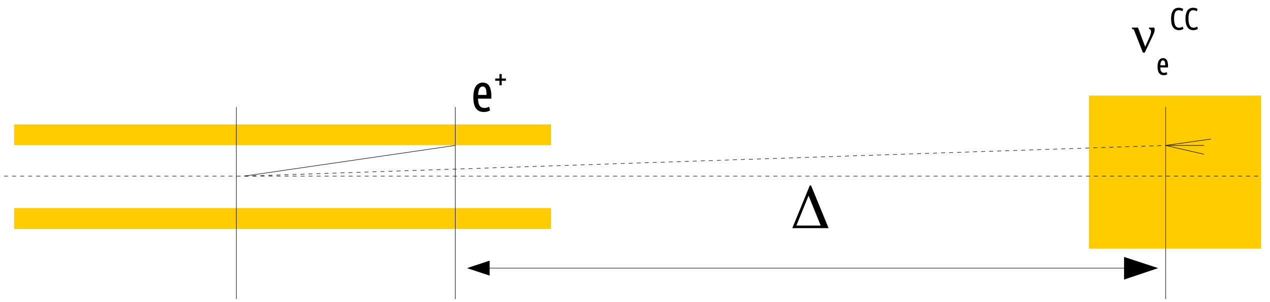
+ Binning in R allows exploring the energy domain of **DUNE/HK** and enrich samples of specific processes (QE, RES, DIS) for **cross-section measurements**



Time Tagged Neutrino beams?

Associating a single neutrino interaction to a tagged e+ through time coincidences

Time coincidence of ν_e^{CC} and e^+ $|\delta t - \Delta/c| < \delta$



δ = combined t-resolution (e^+ tagger and ν detector)

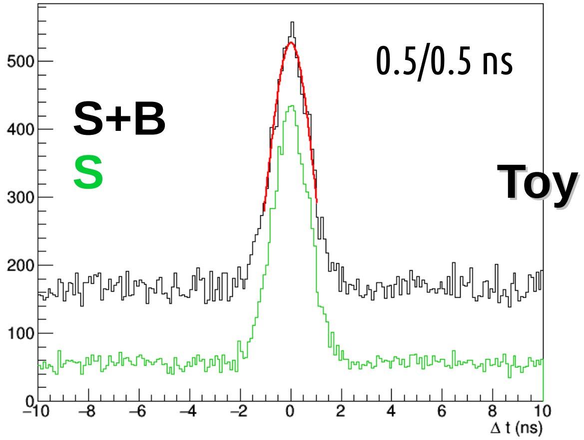
Static focusing + Slow extraction is mandatory

At present with 2.5 10^{13} POT/2s slow extraction:

Genuine Ke3 candidate → 80 MHz
1 every ~12 ns
Background Ke3 candidate: 2x
1 every ~4 ns

Assuming $\delta = 0.5 \oplus 0.5$ ns resolution

Already interesting! S/N ratio will likely improve with further tuning



Toy MC

Conclusions

ENUBET

a narrow band beam with a high precision monitoring of the flux at source (O(1%))
and control of the Eν spectrum (20% @ 1 GeV → 8% @ 3 GeV)

In the first two and a half years:

- First end-to-end simulation of the beamline
- Tested “burst” slow extraction scheme at the CERN-SPS
- Feasibility of a purely static focusing system
- Full simulation of e^+ reconstruction: single particle level monitoring
- Completed the test beams campaign before LS2
- Strengthened the **physics case**: → Slow extraction + **“narrow band off-axis technique”**

Very promising technique and results so far exceeded our expectations!

Next Steps:

- 2019: freeze **light readout technology** (shashlik versus lateral readout)
- 2019: further **tuning of the beamline design** (improve current S/N for e+)
- Full assessment of **systematics** on neutrino fluxes
- 2021: End of the project → CDR, **physics and costs**
- 2021: **Build the demonstrator prototype of the tagger**

Thank you!

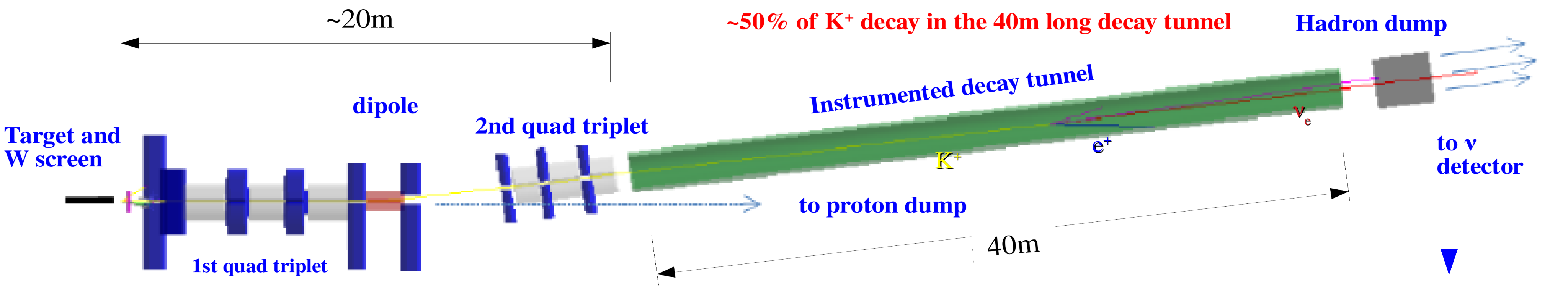
Back-Ups

The ENUBET Beamline

- ✓ A **direct measurement of the flux**
- ✓ **Energy know a priori** from beam width → narrow band beam
- ✓ Cover the region of interest **from sub- to multi-GeV**

- X-section measurements
- Precision ν-physics
  (CP violation, sterile, NSI...)

To get the correct spectra and avoid swamping the instrumentation → needs a **collimated momentum selected hadron beam** → Only decay products in the tagger



~500 t ν detector @ 100 m from the target

e.g. *ICARUS @ FNAL*
ProtoDUNE-SP/DP @ CERN
a Water Cher. @ J-PARC?

Systematics on the ν_e flux

Golden sample $\varepsilon \sim O(10^{-2})$

$\Phi(\nu_e) = \alpha\, N(K_{e3}) + \varepsilon\, N(\mu)$ → Uncertainties from K yields, efficiency and stability of the transfer line are by-passed by the **e^+ tagging**

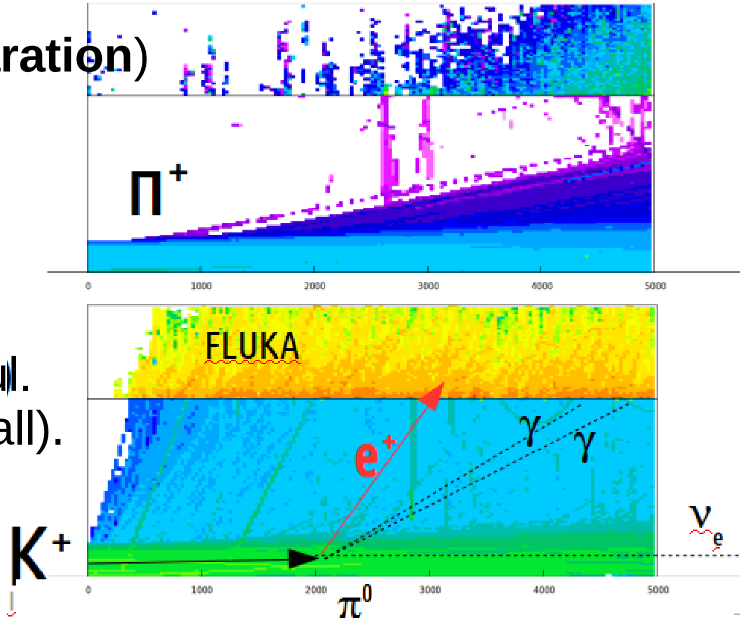
α encodes the residual geometrical (decay lengths, beam spread) and kinematic factors from K decays → “**easy” corrections**.

The background in the positron sample has to be controlled
→ simple robust detector validated at test beams (**$e/\pi^{\pm 0}/\mu$ separation**)

Silver sample

$\Phi'(\nu_e) = \alpha\, N(K) + BR(K_{e3})$

Measuring the **inclusive rate of K decays** is also very powerful.
Branching ratios known to < 0.1% (additional uncertainty is small).
Residual background is **stray pions from beam tails** (well characterized in terms of azimuth and longitudinal position)



- **can we get to 1% ?** assessment in progress: **toy Monte Carlos** + **full simulation**
- Address the effect of each uncertainty and the degree of **cancellations allowed by the large correlations between e^+ rate and ν_e flux**.

Time tagged neutrino beams: challenges

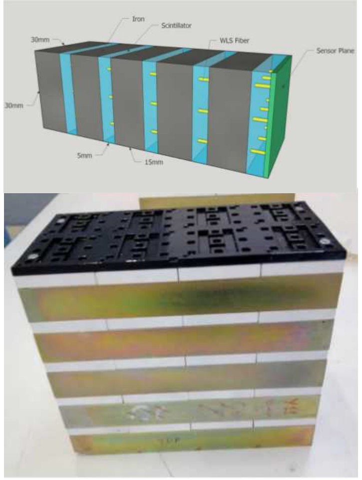
- Proton **extraction ~ 2s** → Static focusing with slow extraction is mandatory
- s_t of the tagger < 1 ns → OK
- s_t of the n detector < 1 ns → **Feasible but at the limit of present technology**
- Cosmic background x 10 → Foresee overburden/cosmic ray tagger
- small K^+ momentum bite → **Feasible but implies flux reduction**
  (not to spoil the ν_e energy reco.)
- Tagger-detector time sync. << 1 ns → OK (direct optical links)

In parallel to the **t_0-layer baseline option** (light plastic scintillator tracker) we are considering alternative technologies (NUTECH project MIUR).
Improve the timing both:

- at the tagger
  - direct readout of **cherenkov light**, **LYSO** crystals with embedded SiPM, MicroMegas
- and at the neutrino detector side
  - SiPM based readout of **Ar scintillation light**

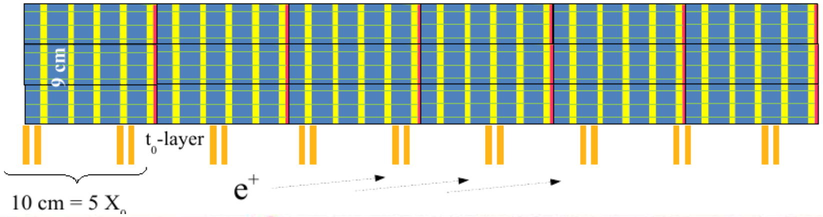
The ENUBET Tagger: Detector R&D

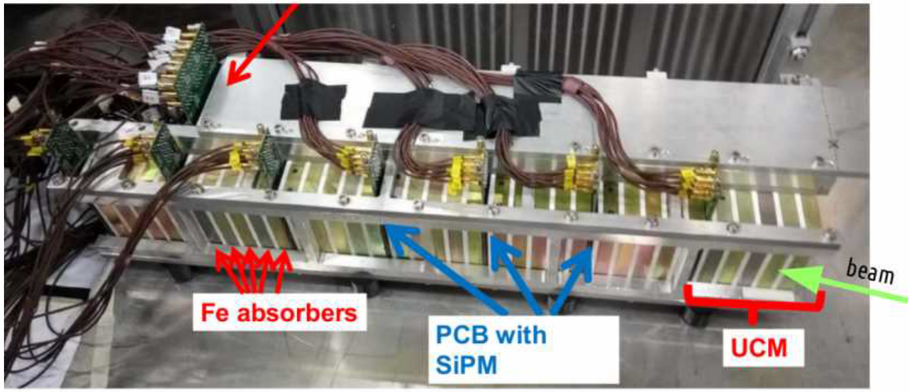
- **Shashlik with integrated readout**



UCM=Ultra Compact Module

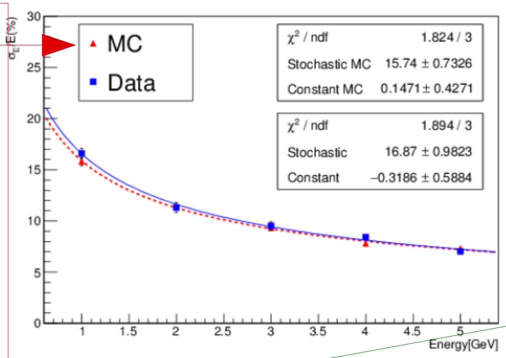
SiPM and electronics embedded in the shashlik calorimeter

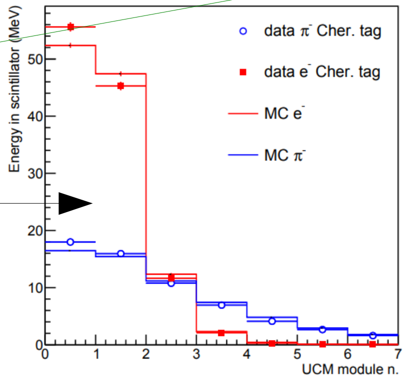


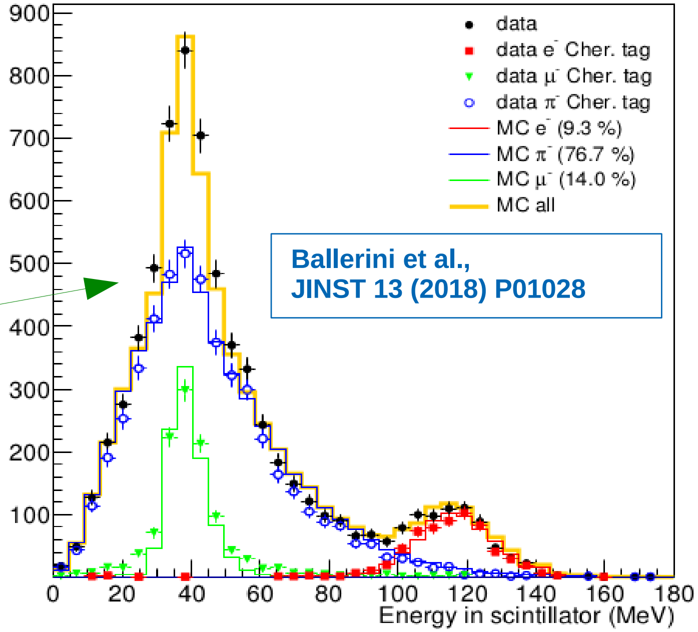


Test beam (CERN-Ps T9 line 2016-2017) → **Response to MIP, e and π**

- em energy res 17%/√E(GeV)
- Linearity <3% in 1-5 GeV
- From 0 to 200mrad tilts tested → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- MC/data already in good agreement
- Longitudinal profiles of partially contained π reproduced by MC @ 10% precision







Ballerini et al.,
JINST 13 (2018) P01028

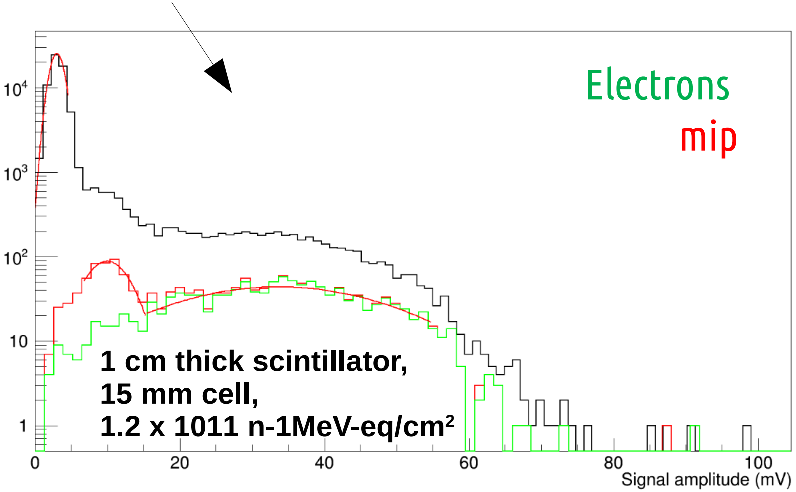
The ENUBET Tagger: Detector R&D

- **SiPM irradiation measurements**
  Test @ INFN-LNL → **1-3 MeV neutrons with fluences up to $10^{12}/cm^2$ in a few hours**

F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

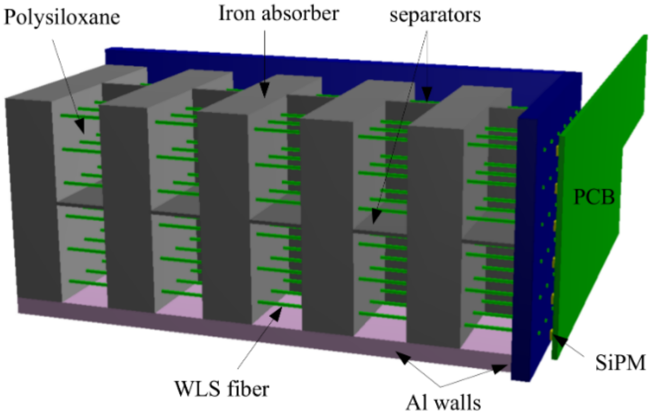
A shashlik calorimeter equipped with **irradiated SiPM then tested @ CERN-PS T9** in Oct2017

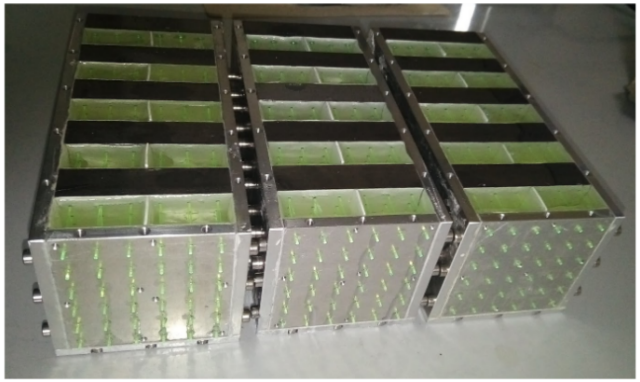
- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signal remains well separated from noise even after typical irradiation levels**
- Mips can be used from channel-to-channel intercalibration even after maximum irradiation



- **Polysiloxane shashlik prototypes**
- Pros: **higher resistance to irradiation** and **simpler** (just pouring+reticulation)

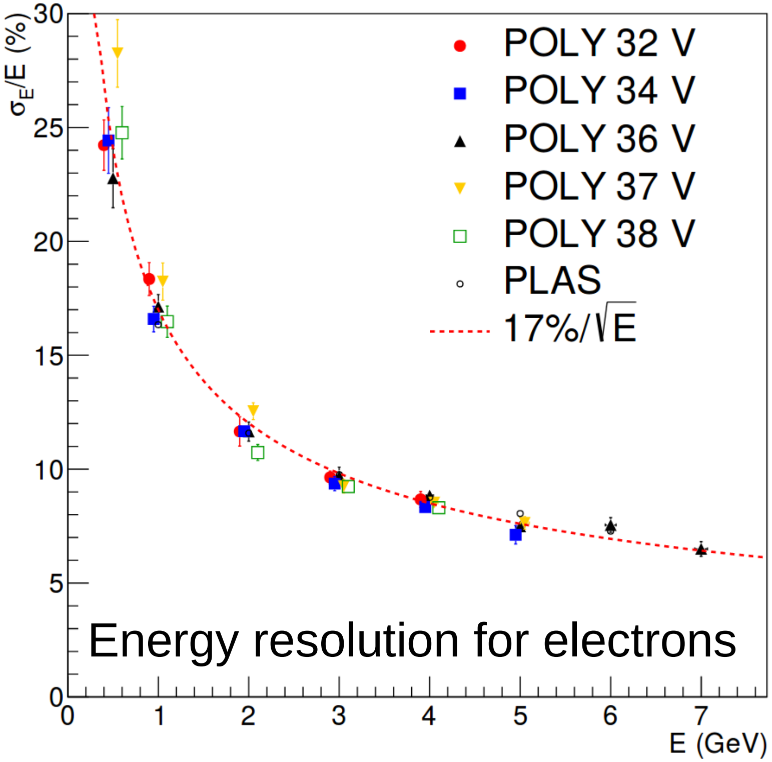
Test (Oct 2017 and May 2018)
$13X_0$ prototype
→ *first application in HEP*



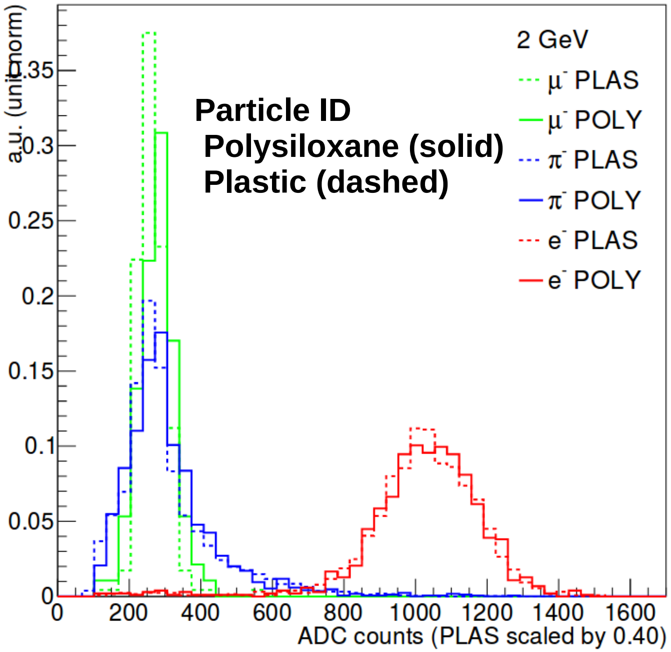


Polysiloxane shashlik prototypes

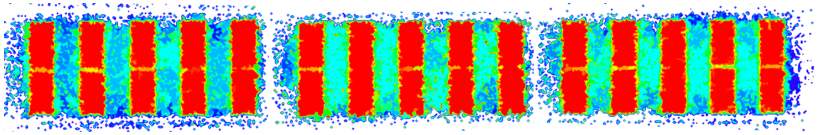
Light yield (normalized to thickness) is ~ 1/3 of plastic scintillator
→ tests light transmission on WLS fibers in absence of air gap
Energy resolution, particle-ID and uniformity in line with the one achieved with plastic scintillator



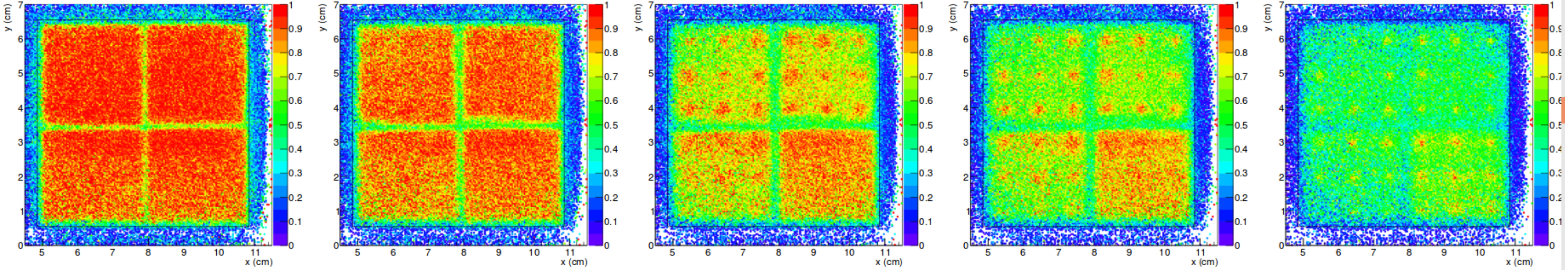
Energy resolution for electrons



Particle ID
Polysiloxane (solid)
Plastic (dashed)



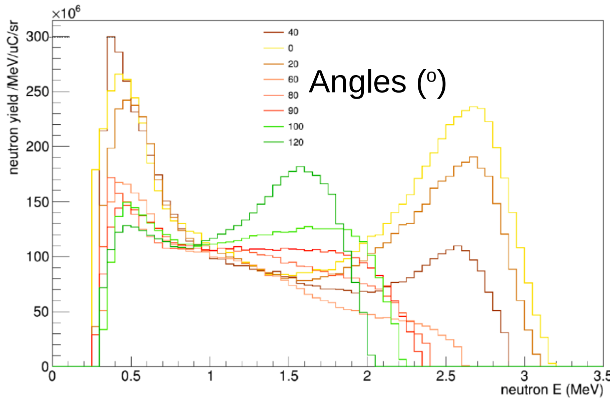
Efficiency maps at increasing thresholds →

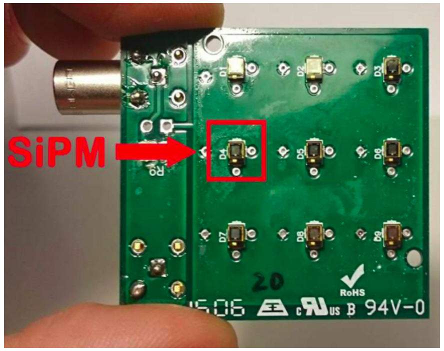


SiPM irradiation measurements at INFN-LNL

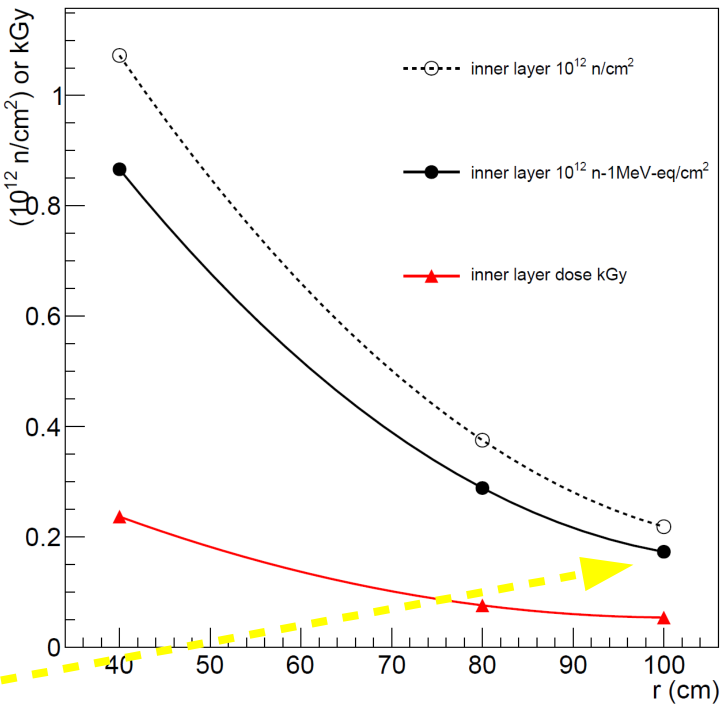
- SiPM were irradiated at the CN Van de Graaf on July 2017
- 7MV and 5 mA proton currents on a Be target
- ^{9}Be(p,n)^{9}B, ^{9}Be(p,np)2α, ^{9}Be(p,np)^{8}Be and ^{9}Be(p,nα)^{5}Li
- → 1-3 MeV n with fluences up to 10^{12}/cm^{2} in a few hours

n spectra (from previous works at the same facility)

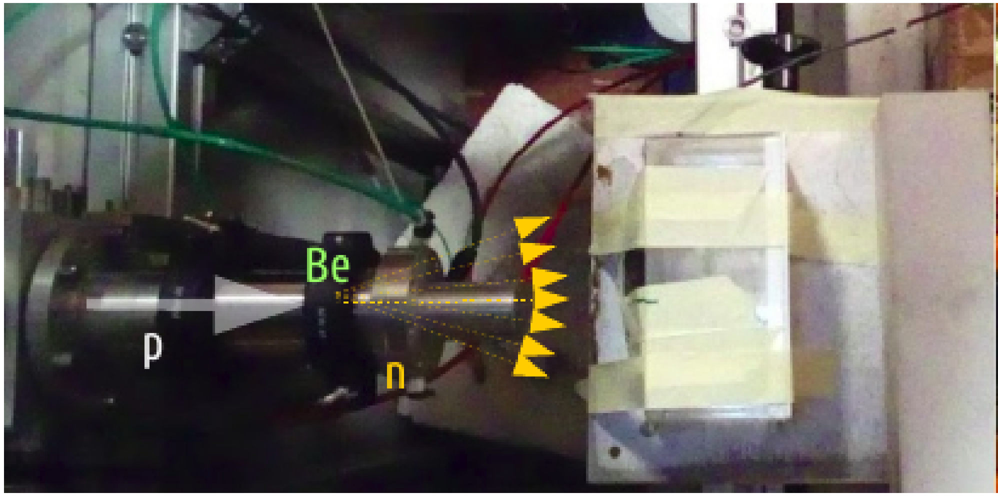




Expected n doses from K decays (FLUKA)

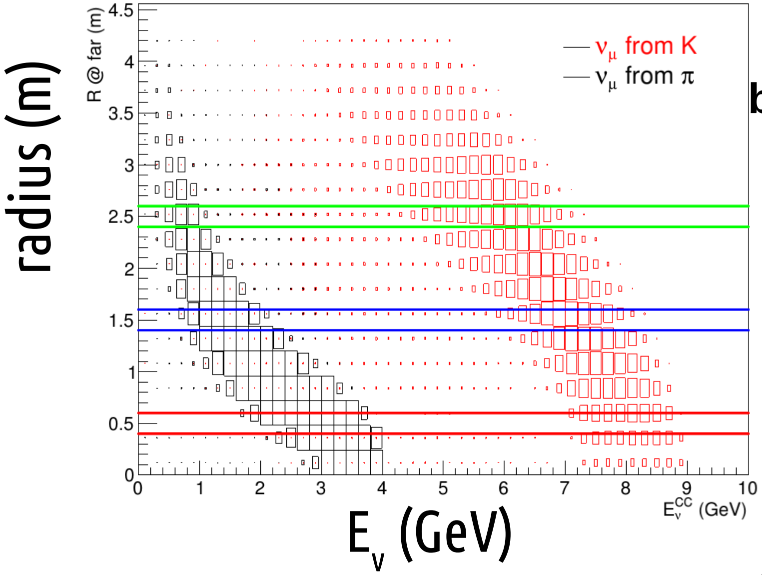


→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm^{2}** 1 MeV-eq (max non ionizing dose for 10^{4} ν_e^{CC} at a 500 t n detector at r = 1 m)

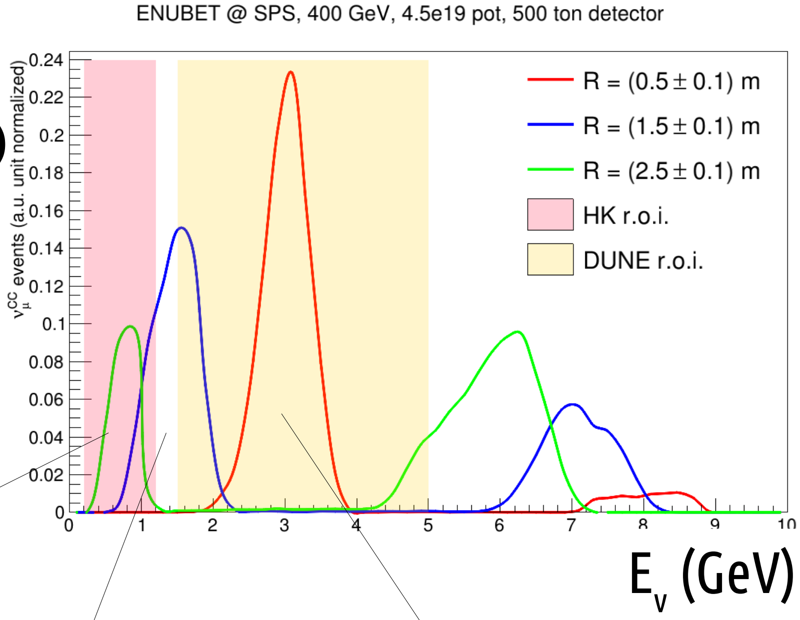


ν_μ CC events at the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

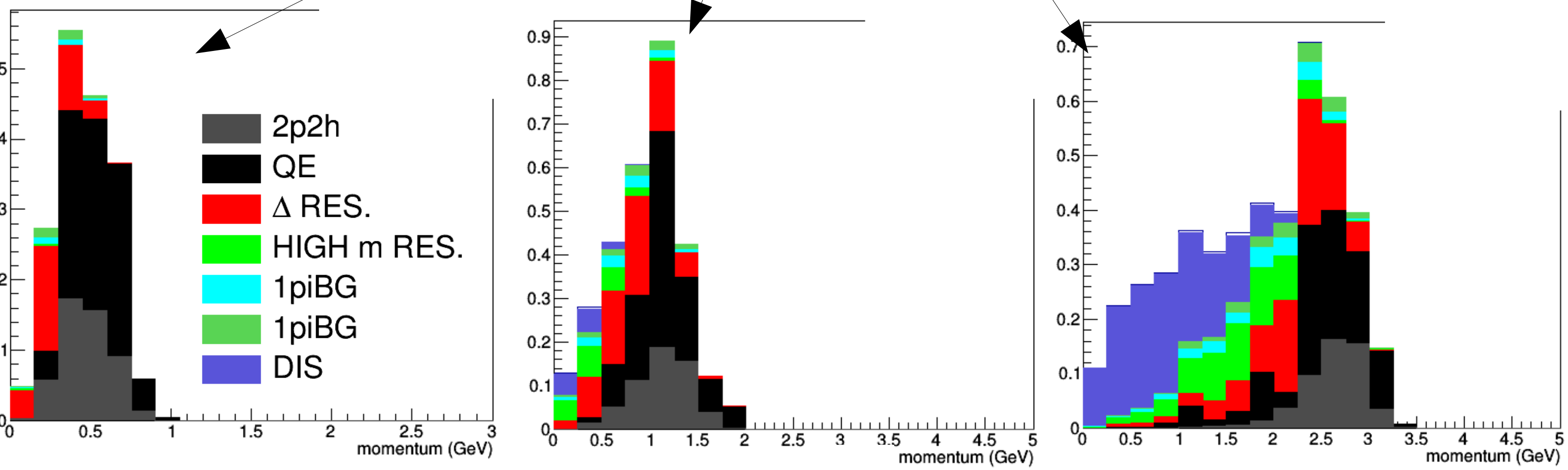


ν_μ ^{CC} in radial bins (1 norm.)


ENUBET @ SPS, 400 GeV, 4.5e19 pot, 500 ton detector

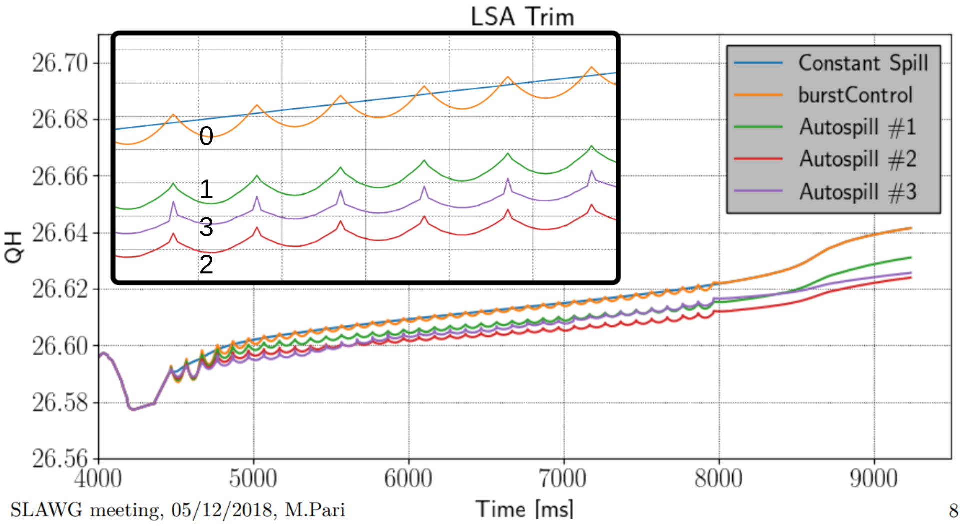
Momentum of ν_μ ^{CC} μ^- on Ar.

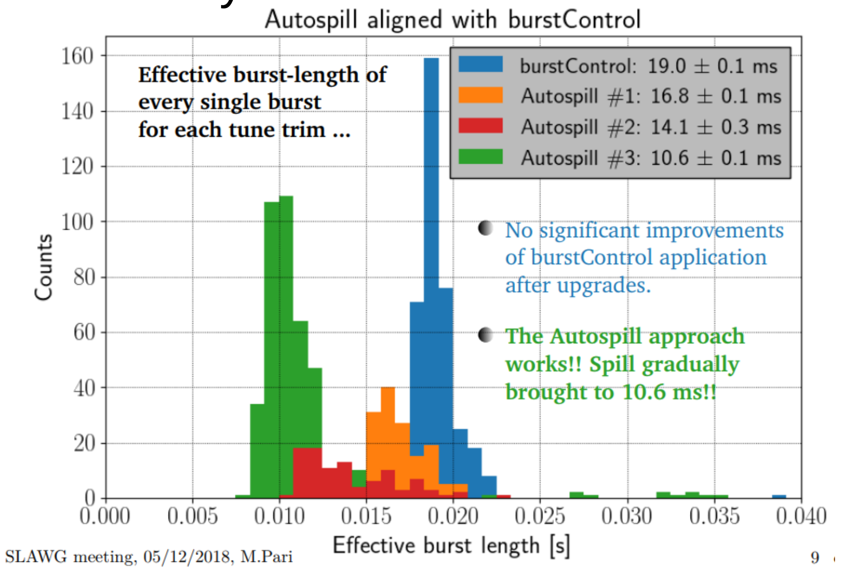
GiBUU generator (Gauss flux approx.)



Machine studies for the horn-based option

- Difficult to get below 20 ms → implemented a feed-forward mechanism using BCT data
- Iterative procedure (AutoSpill) → can “sharpen” peaks **up to 10 ms in 3 iterations**
- at the cost of a somewhat larger variance in peak intensity.

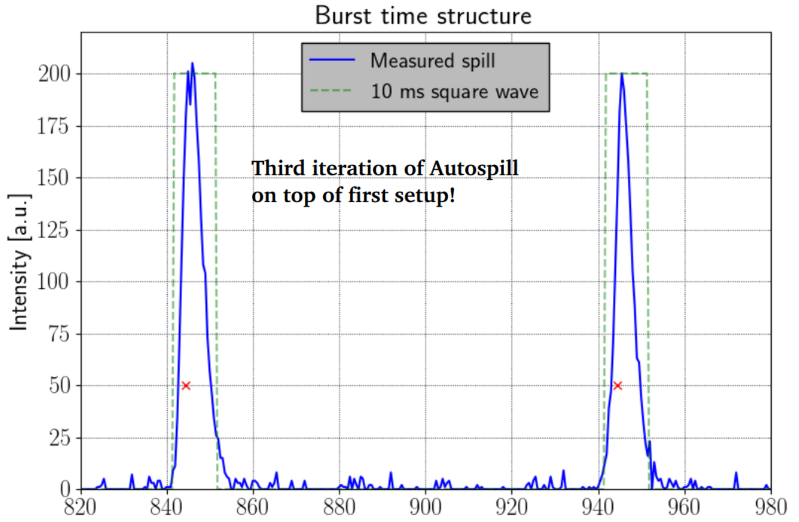




Effective burst-length of every single burst for each tune trim ...

- No significant improvements of burstControl application after upgrades.
- **The Autospill approach works!! Spill gradually brought to 10.6 ms!!**

- Versatile/general: **mixed continuous-burst possible**.
- General **software tool** developed for CR operations.
- Present studies suggest that this mode **does not increase significantly radiation losses at septa**
- ENUBET: would the static focusing be preferred, burst mode could be used to **constrain cosmics background**.
- Now focusing on simulation/further ideas, improvement in diagnostics used for feedback (BCT).
- Studies performed in a limited time → will **benefit greatly of more data in the future**!



Third iteration of Autospill on top of first setup!

CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

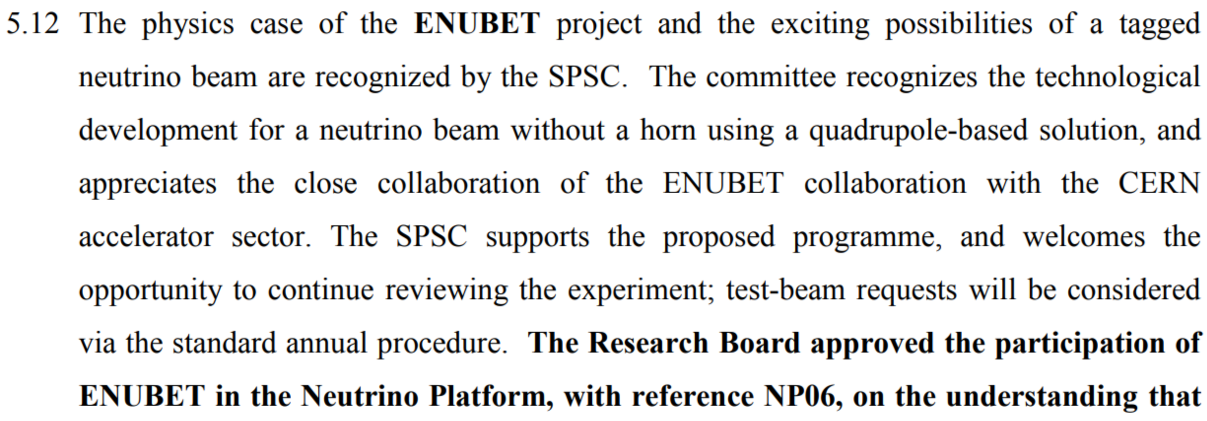
ENUBET in the CERN Neutrino Platform

- **CERN already gave a prominent contribution for the success of ENUBET**
  - **machine studies performed at the SPS**
  - **East Area beamline** for the characterization of the prototypes
- For **2019-2021 → recognition in the Neutrino Platform as ENUBET/NP06**
  - support and consulting from CERN accelerator experts
  - test of the final proton extraction scheme in the SPS after LS2
  - use of the renovated East Area for the final validation of the demonstrator

132th meeting of the SPSC, 22nd–23rd/01/2019
https://cds.cern.ch/record/2654613/files/SPSC-132.pdf

228th meeting of the Research Board, 5/3/2019
https://cds.cern.ch/record/2668519/files/M-228.pdf

MoU being finalized



5.12 The physics case of the **ENUBET** project and the exciting possibilities of a tagged neutrino beam are recognized by the SPSC. The committee recognizes the technological development for a neutrino beam without a horn using a quadrupole-based solution, and appreciates the close collaboration of the ENUBET collaboration with the CERN accelerator sector. The SPSC supports the proposed programme, and welcomes the opportunity to continue reviewing the experiment; test-beam requests will be considered via the standard annual procedure. **The Research Board approved the participation of ENUBET in the Neutrino Platform, with reference NP06, on the understanding that**