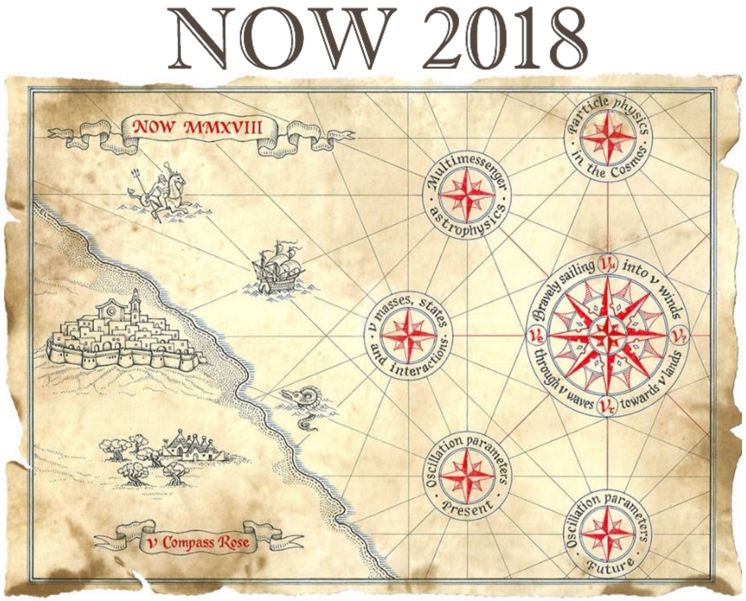
The ENUBET neutrino beam

F. Pupilli (INFN-Padova)

on behalf of the ENUBET Collaboration

52 physicists, 11 institutions



Ostuni, 9-16 September 2018

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).

The ENUBET neutrino beam

ENUBET is:

- A *narrow band beam* at the GeV scale with a **superior control of the flux, flavor and energy** of the neutrinos produced at source

It is **designed** for:

- A new generation of short-baseline experiments and a **1% precision** measurement of the **ν_e and ν_μ cross sections**

We **present** at NOW 2018

- The first **end-to-end simulation** of the ENUBET **beamline**
- The updated **physics performance**
- The latest results on the design and construction of the beamline **instrumentation**

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

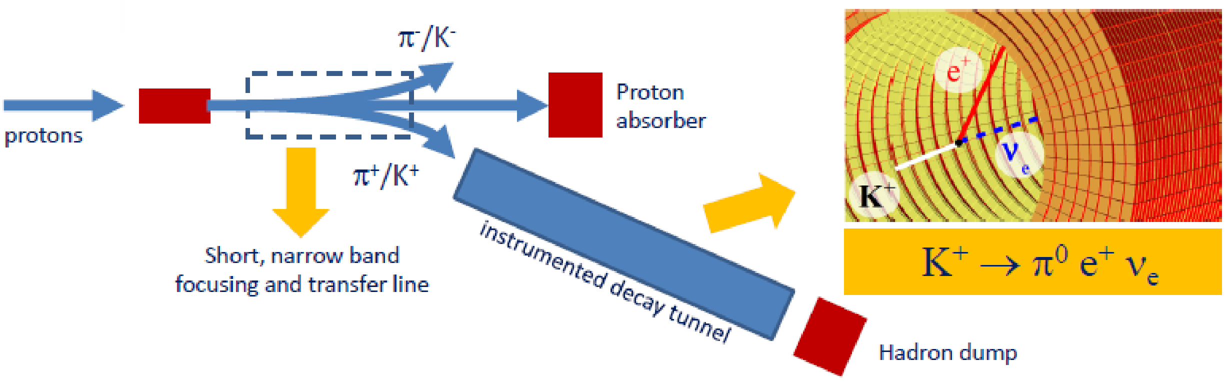
↓

The ideal tool to study **neutrino interaction in nuclei**

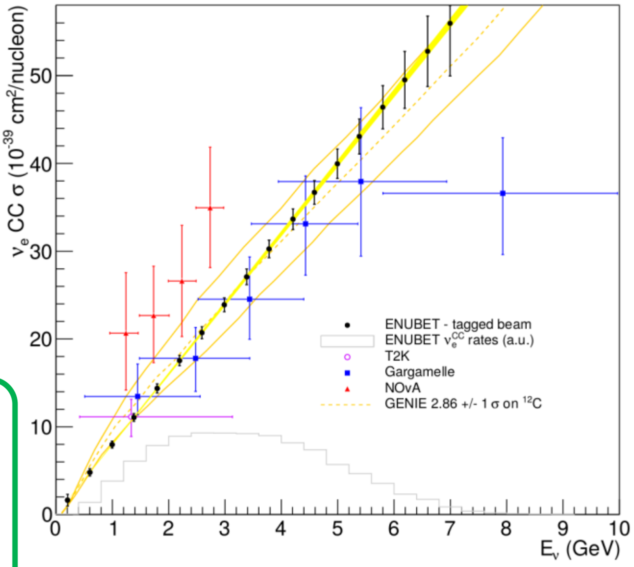
Flavor composition known at 1% level

↓

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

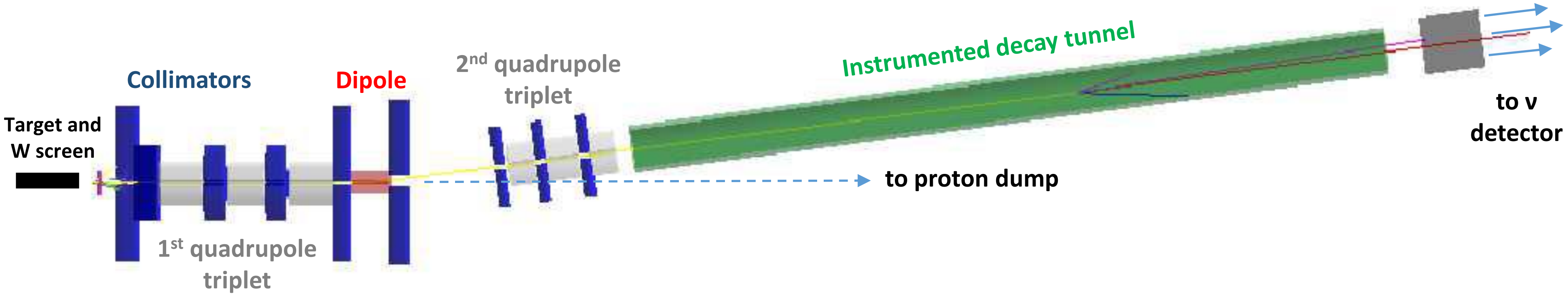


$K^+ \rightarrow \pi^0 e^+ \nu_e$



Goal of ENUBET *(ERC c.g., PI: A. Longhin, Jun 2016 – May 2021)*: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level** → direct measurement of the flux

The ENUBET beam line



- **Proton driver**: CERN SPS (400 GeV), Fermilab Main Ring (120 GeV), JPARC (30 GeV)
- **Target**: 1 m Be, graphite target. FLUKA 2011 (+check with hadro-production data)
- **Focusing**
  - Horn: 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**
  - Optics: optimized with TRANSPORT to a 10% momentum bite
  - Particle transport and interaction: full simulation with G4Beamline
  - All normal-conducting magnets, numerical aperture <40 cm, Two quadrupole triplet, one bending dipole
- **Decay tunnel**
  - Radius: 1m. Length 40 m *[re-optimized after beam envelope determination]*
  - Low power hadron dump at the end of the decay tunnel
- **Proton dump**: position and size under optimization (in progress)

The ENUBET beam line - Yields

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction length	π/cycle (10^{10})	K/cycle (10^{10})	Proposal (c)
Horn	97	7.9	2 ms (a)	438	36	X2
No horn	19	1.4	2 s (b)	85	6.2	**x5**

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle: this extraction scheme is currently under test at CERN

(b) Slow extraction. Detailed performance and losses currently under evaluation at CERN

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

Advantages of the static extraction:

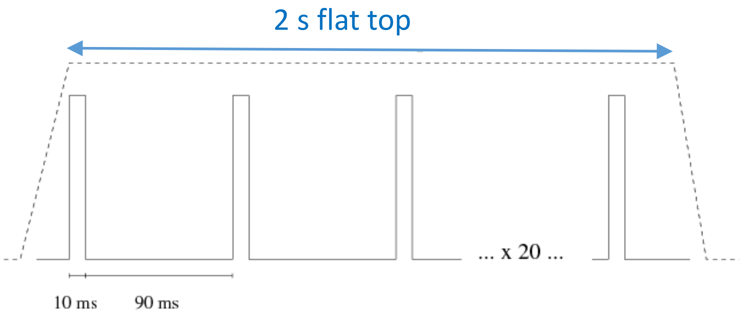
- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Possibility to monitor the muon rate after the dump at 1% level (flux of ν_μ from pion decay) [**NEW: under evaluation**]
- Pave the way to a "**tagged neutrino beam**", namely a beam where the neutrino interaction at the detector is associated in time with the observation of the lepton from the parent hadron in the decay tunnel

The ENUBET beam line – the horn-based option

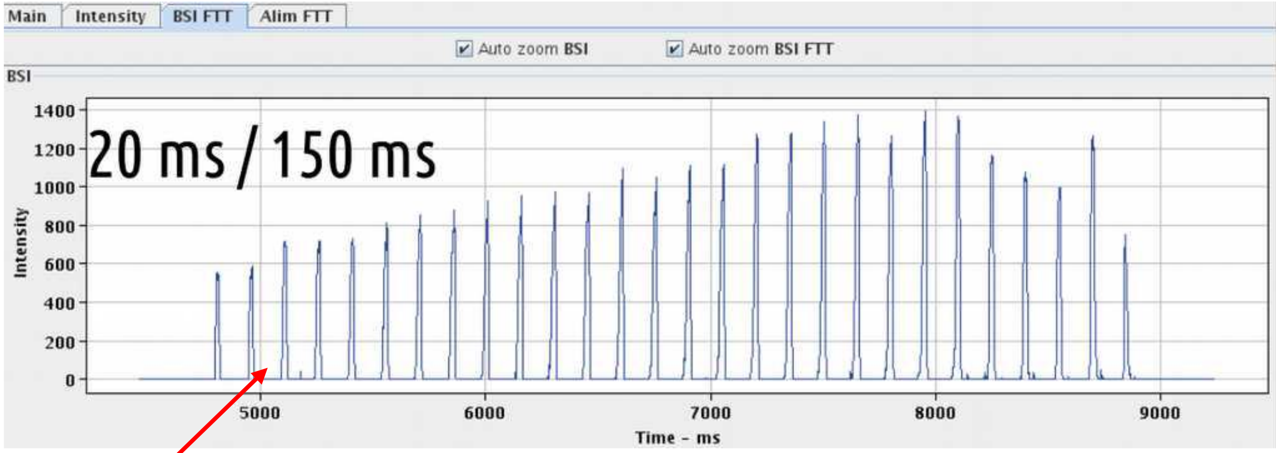
- **Machine studies @ SPS are currently on-going:**

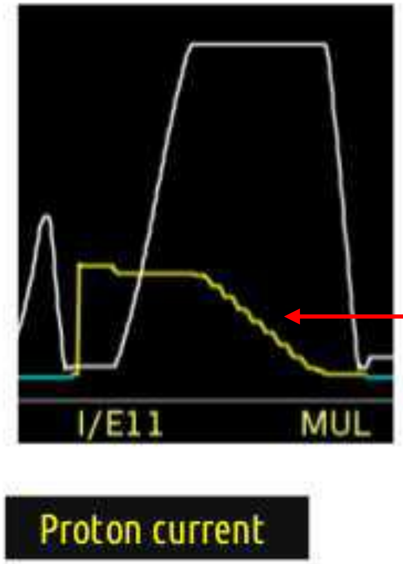
Preliminary studies July 2018

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



Slow extraction is induced by going to the third integer betatron resonance with a periodic pattern

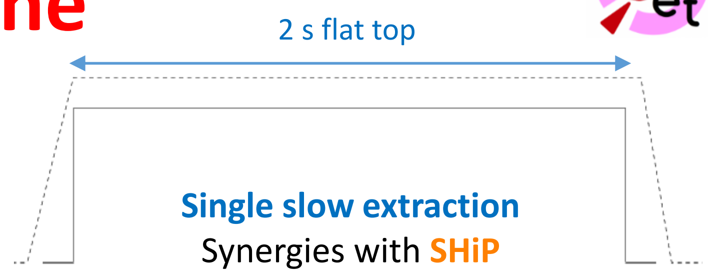




Proton current steps in correspondance of bunches

- Beam bunches in time with horn pulses
- **Further studies are required** to understand and address radiation problems

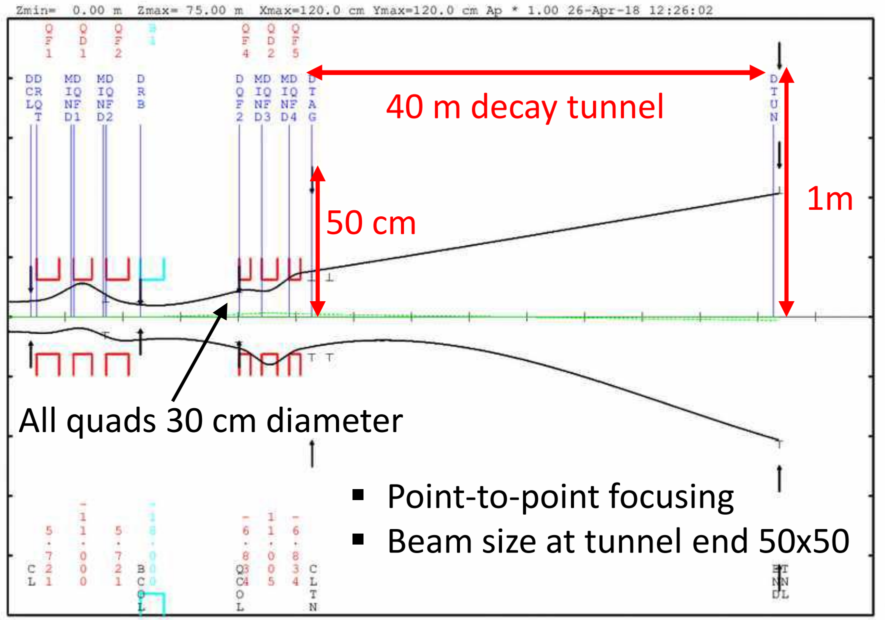
The static beamline



Single slow extraction

Synergies with **SHiP**

Optics optimized through **TRANSPORT**



40 m decay tunnel

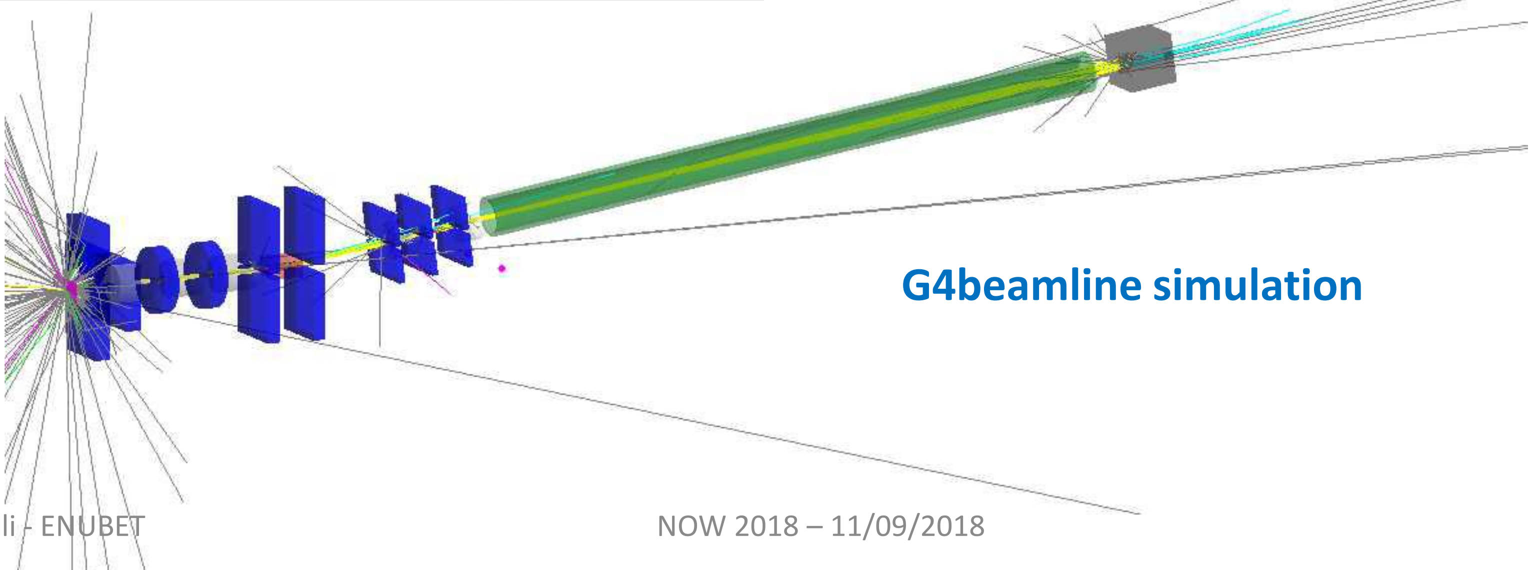
50 cm

1m

All quads 30 cm diameter

- Point-to-point focusing
- Beam size at tunnel end 50x50

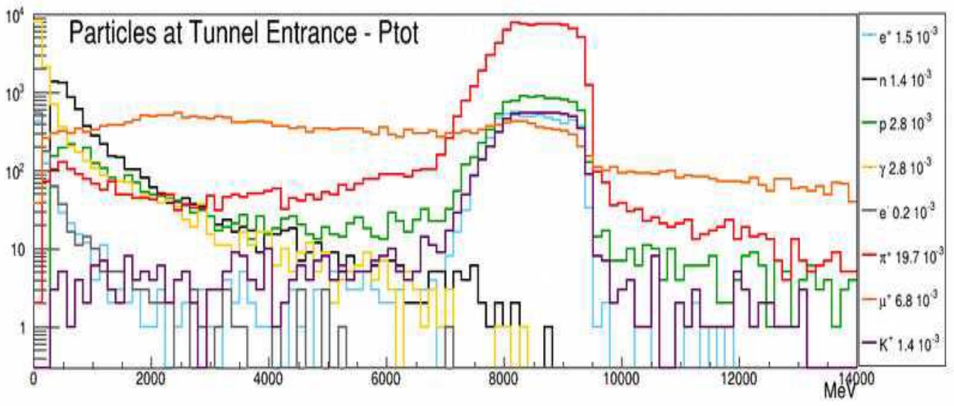
- Reference beam: 8.5 GeV/c, 10% mom. bite
- Conventional Quads:
  15cm apertures, lengths <2 m, Fields 4 to 7 [T]
- Conventional Dipole:
  15cm aperture, 2m long, Field 1.8 [T] → 7.4° bending
- Beam envelope at tunnel exit 50×50 cm (Tunnel radius 1m)

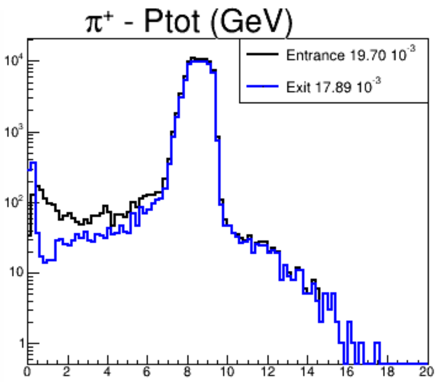


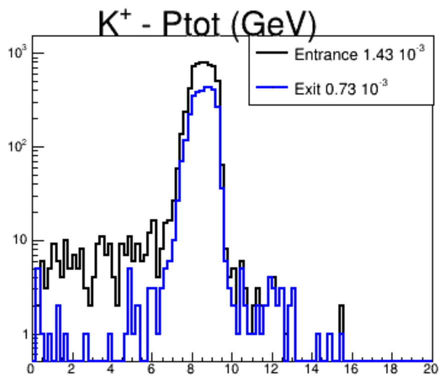
G4beamline simulation

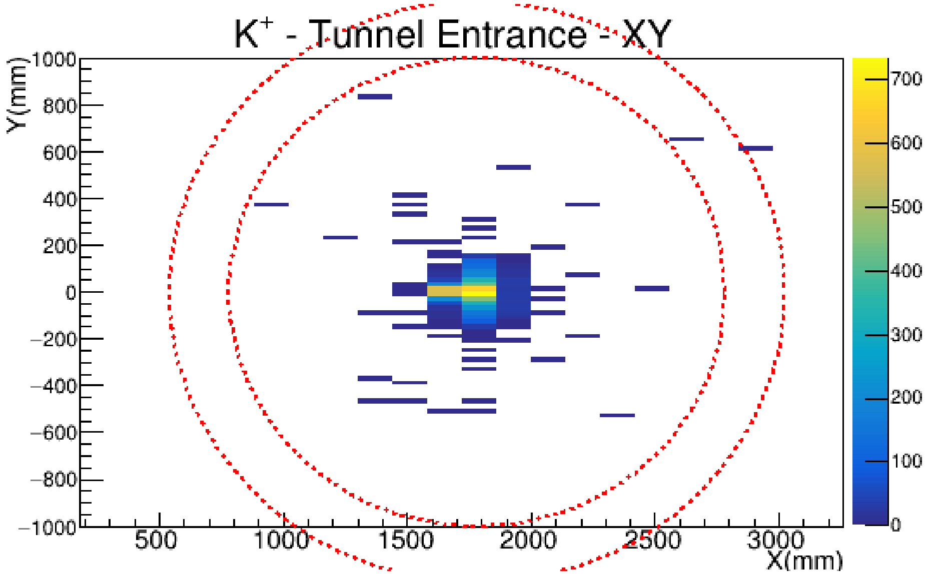
The static beamline

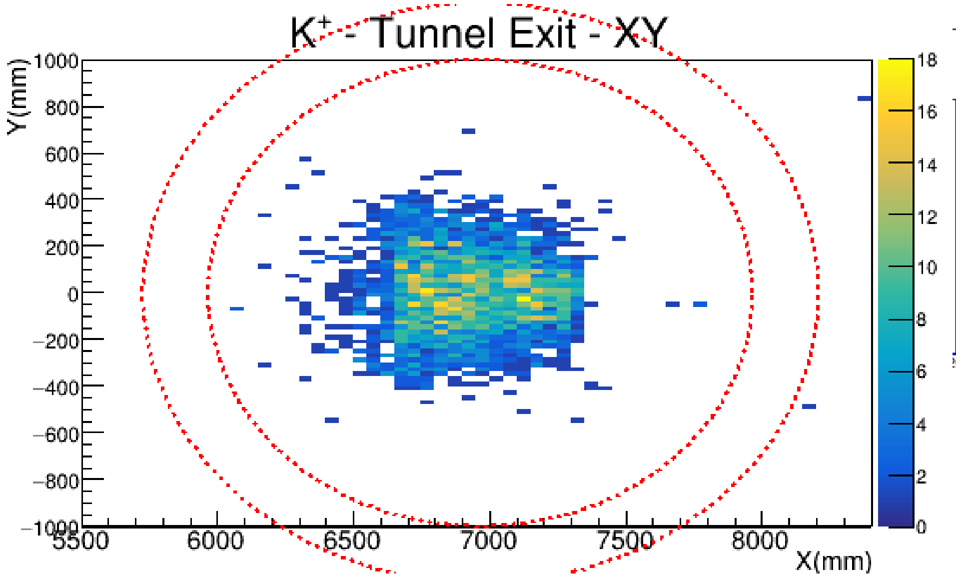
G4beamline simulation – Particles at tunnel Entrance/Exit











The Tagger

1) Longitudinally segmented Calorimeter

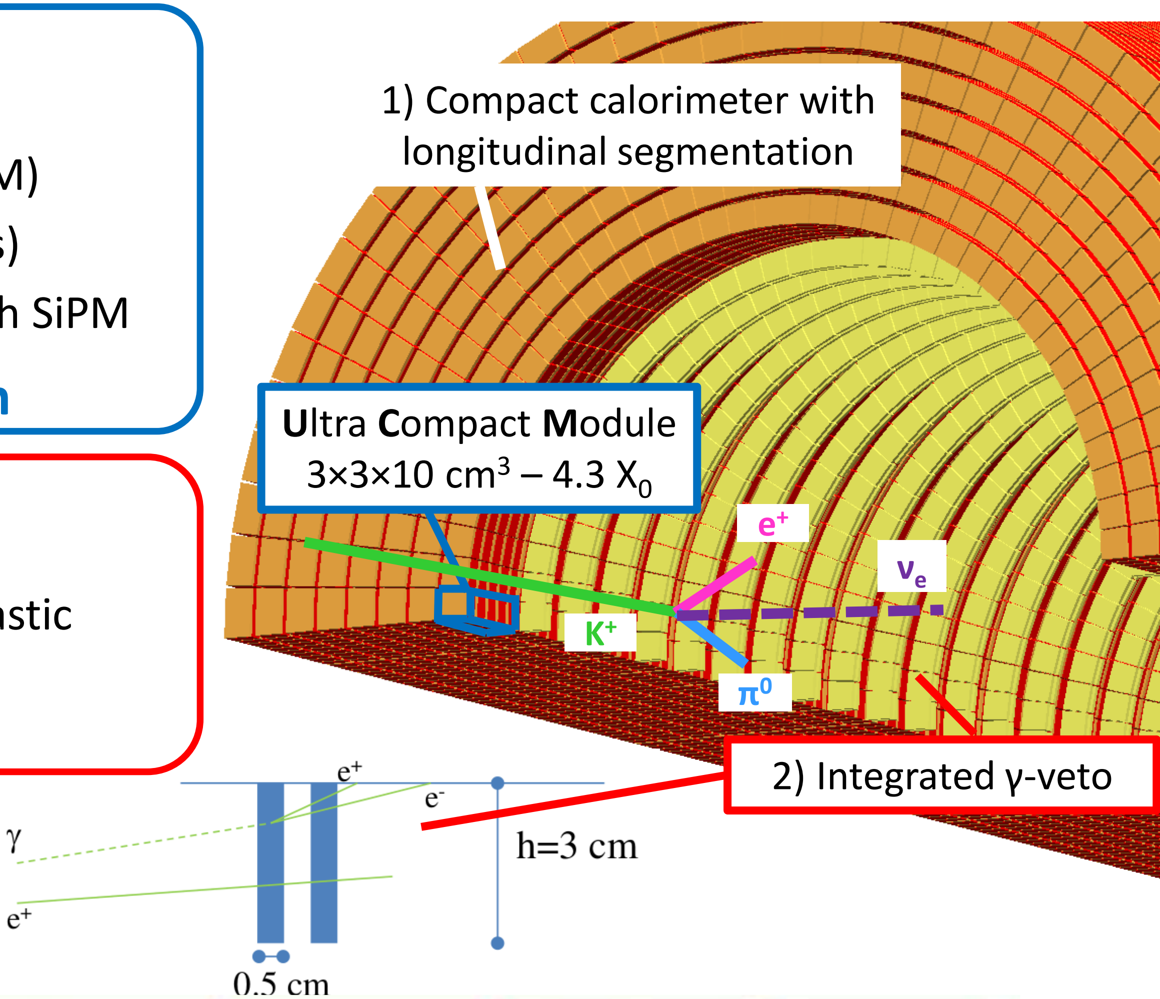
- Ultra Compact Module (UCM)
  (Plastic scint. + Fe absorbers)
- Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

2) Integrated γ-veto

- Rings of 3×3 cm² pads of plastic scintillator

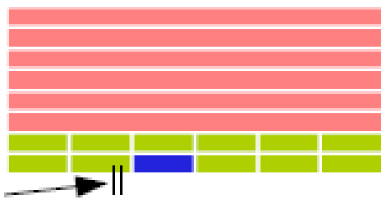
→ π^0 rejection



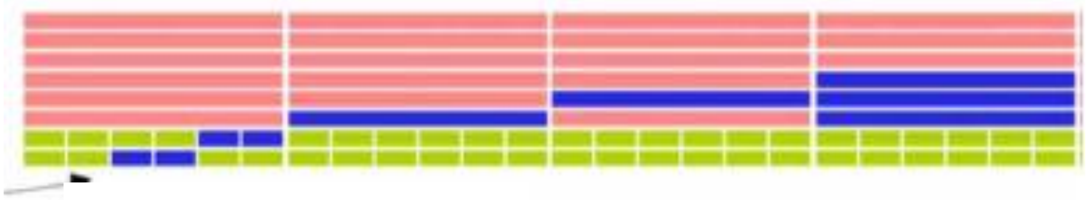
1) Compact calorimeter with longitudinal segmentation

Ultra **C**ompact **M**odule
3×3×10 cm³ – 4.3 X_0

2) Integrated γ-veto



e⁺ (signal) topology

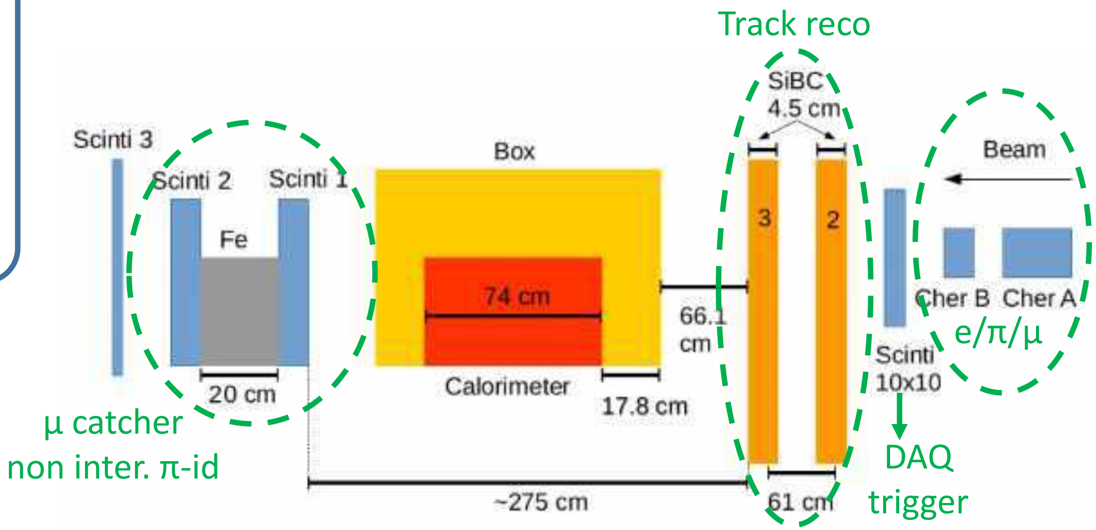


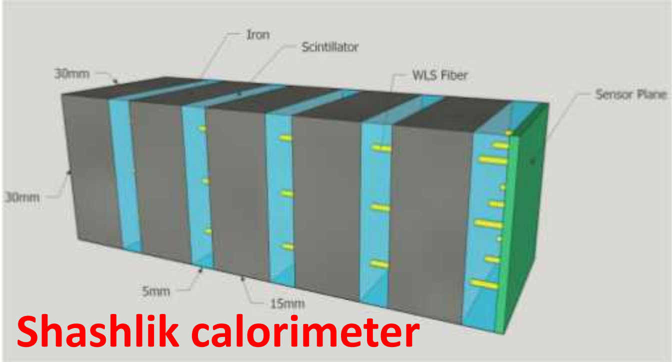
π⁺ (background) topology

The Tagger – Test Beam

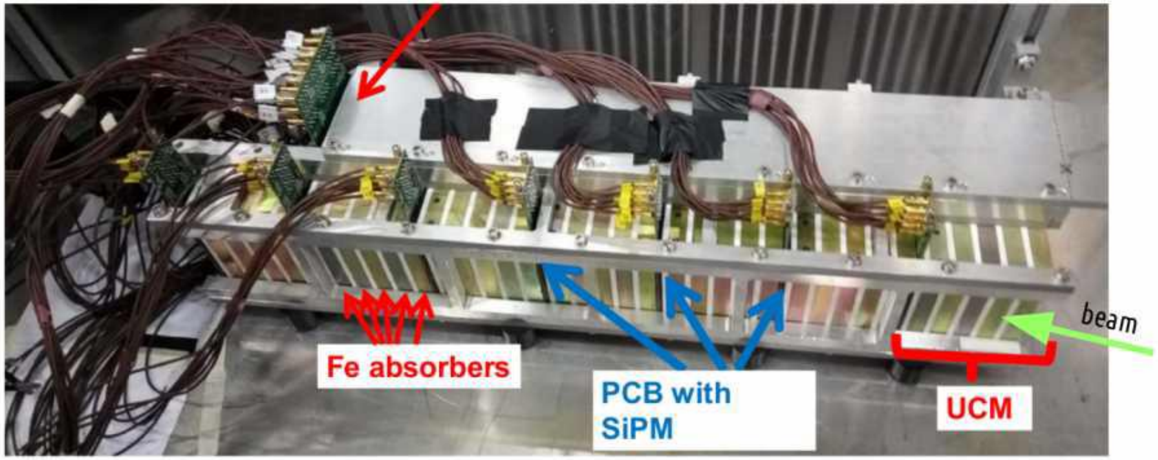
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

- 56 UCM arranged in 7 longitudinal block (~30 X_0) + hadr. Layer (coarse sampling)
- e/μ tagged with Cherenkov counters and muon catcher
- Beam Composition @ 3GeV:
  9% e, 14% μ , 77% hadrons





Shashlik calorimeter



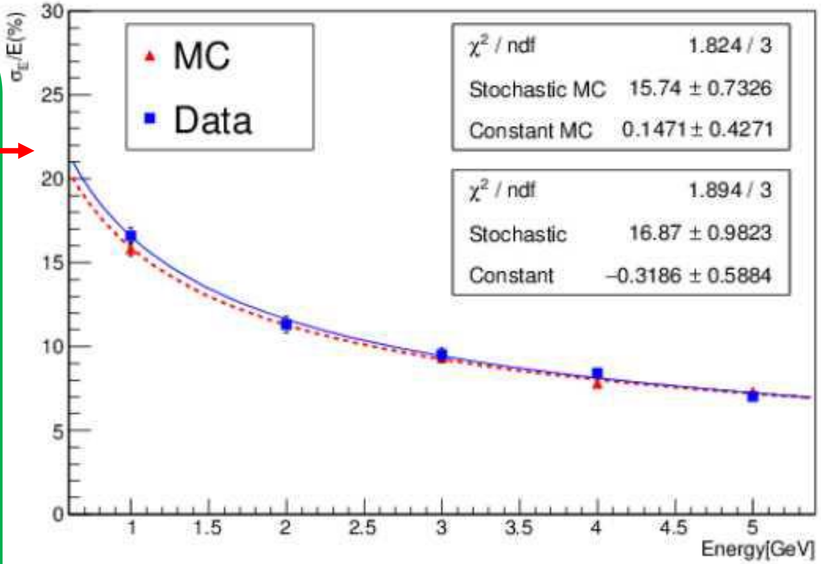
The Tagger – Test Beam

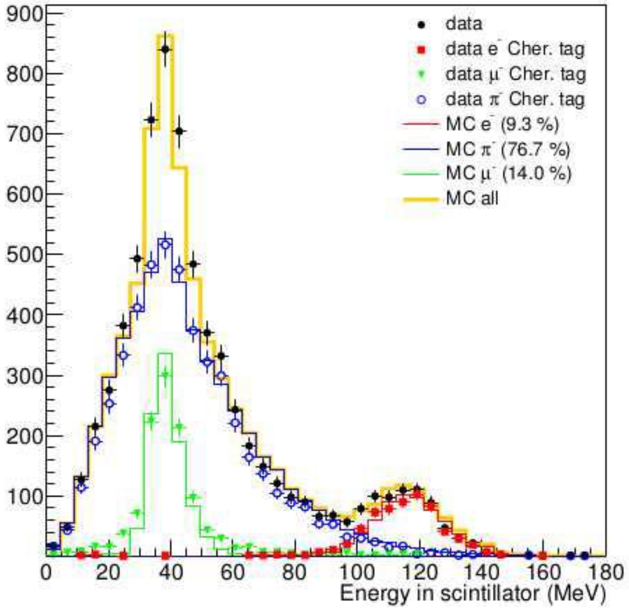
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

Tested response to MIP, electrons and charged pions

- e.m. energy resoluton: 17%/√E (GeV) →
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad tilts tested → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities (effect corrected equilizing UCM response to mip)
- 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 Tagger – Test Beam

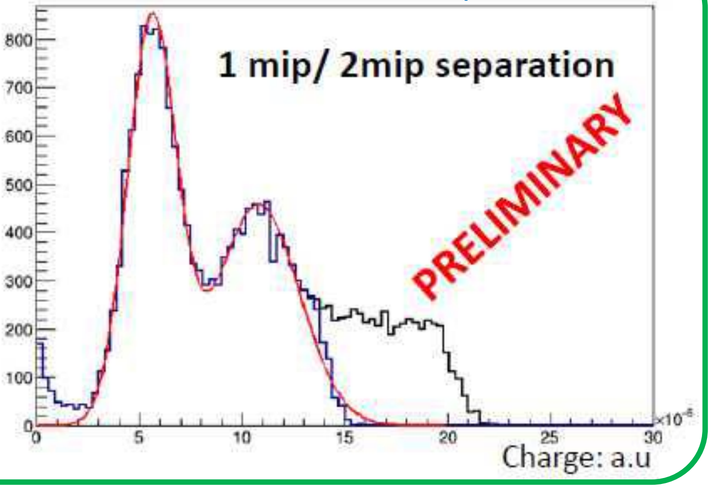
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

• γ/e+ discrimination (Photon-Veto)

t0 layer: scintillator (3×3×0.5 cm^3) + WLS Fiber + SiPM

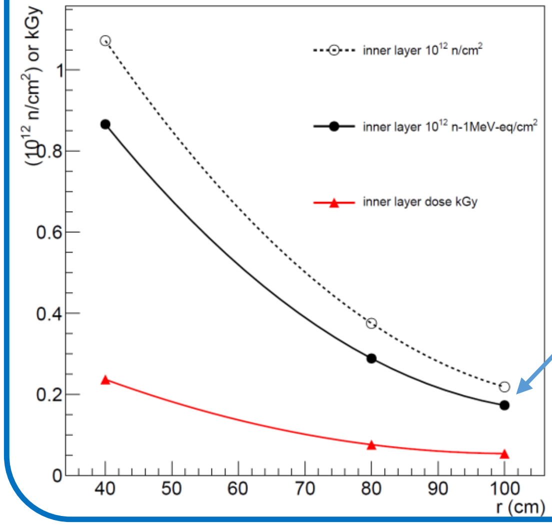
→ Goal:
- Study light collection efficiency → >95%
- First measure of time res → σ~400ps
- First 1mip/2mip separation using photon conversion from π^0 gammas (π^0 by charge exchange of π^+ with low density target after SiC)

We are able to discriminate γ from Ke3 e$^+$

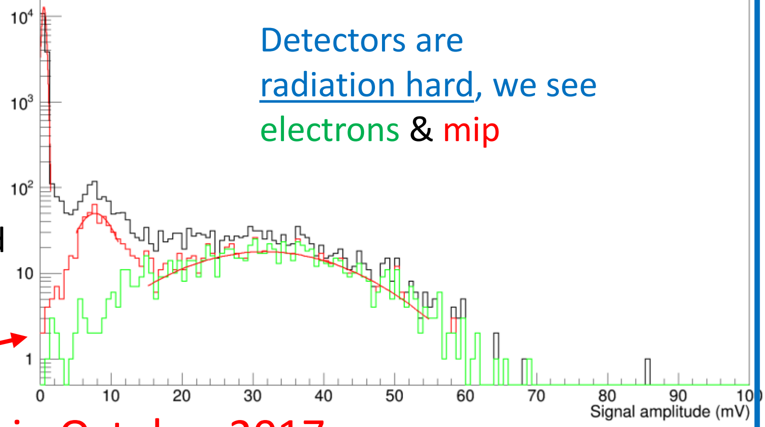


• Irradiation Studies

SiPM were **irradiated at LNL-INFN** with 1-3 MeV neutrons in June 2017



→ Characterization of 12,15 and 20 μm SiPM cells up to **1.2 10^{11} n/cm^2** 1 Mev-eq (i.e. max non ionizing dose accumulated for 10^4 ν_e^{CC} at neutrino detector)



Detectors are radiation hard, we see electrons & mip

Irradiated SiPM tested at CERN in October 2017

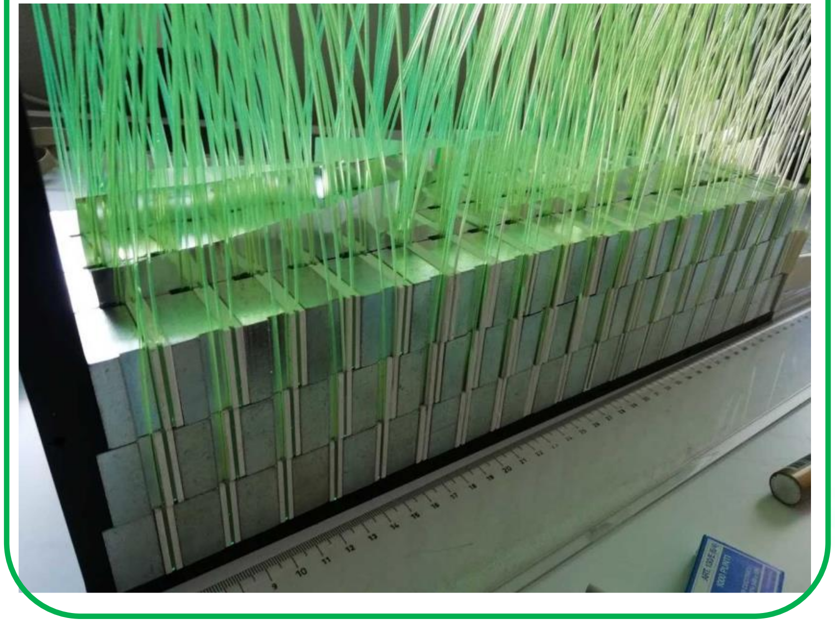
A. Coffani et al., arXiv:1801.06167

The Tagger – Detector R&D

2018

Many R&D activities currently on-going
test-beam @ CERN in May ...

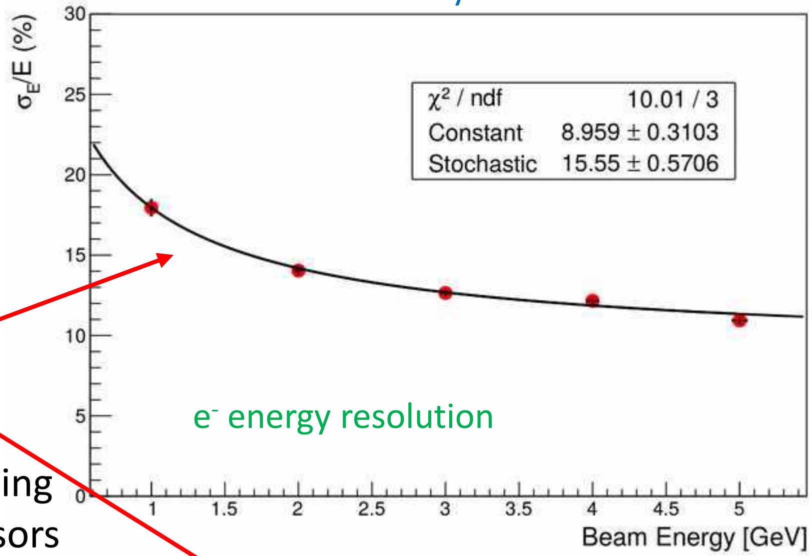
Sampling calorimeter with
lateral WLS light collection



Very promising solution:
avoid SiPM irradiation damages

Test of
- resolution
- light yield
- uniformity
- optical coupling to photosensors

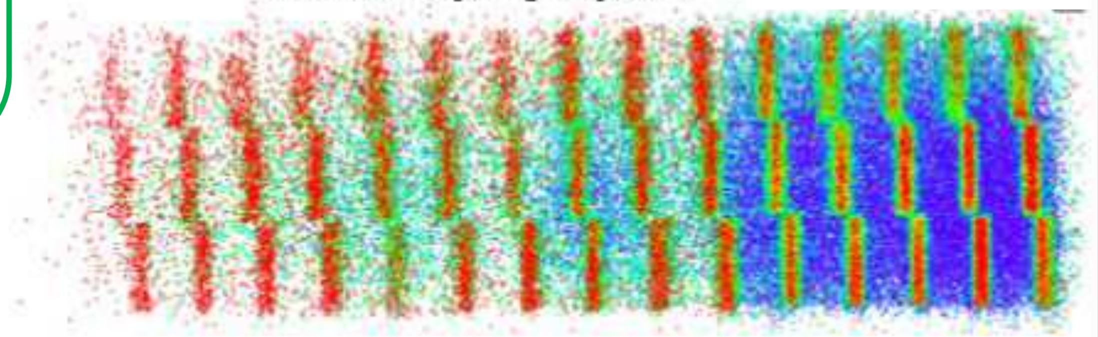
Preliminary results



e^- energy resolution

Uniformity, light yield

Efficiency map



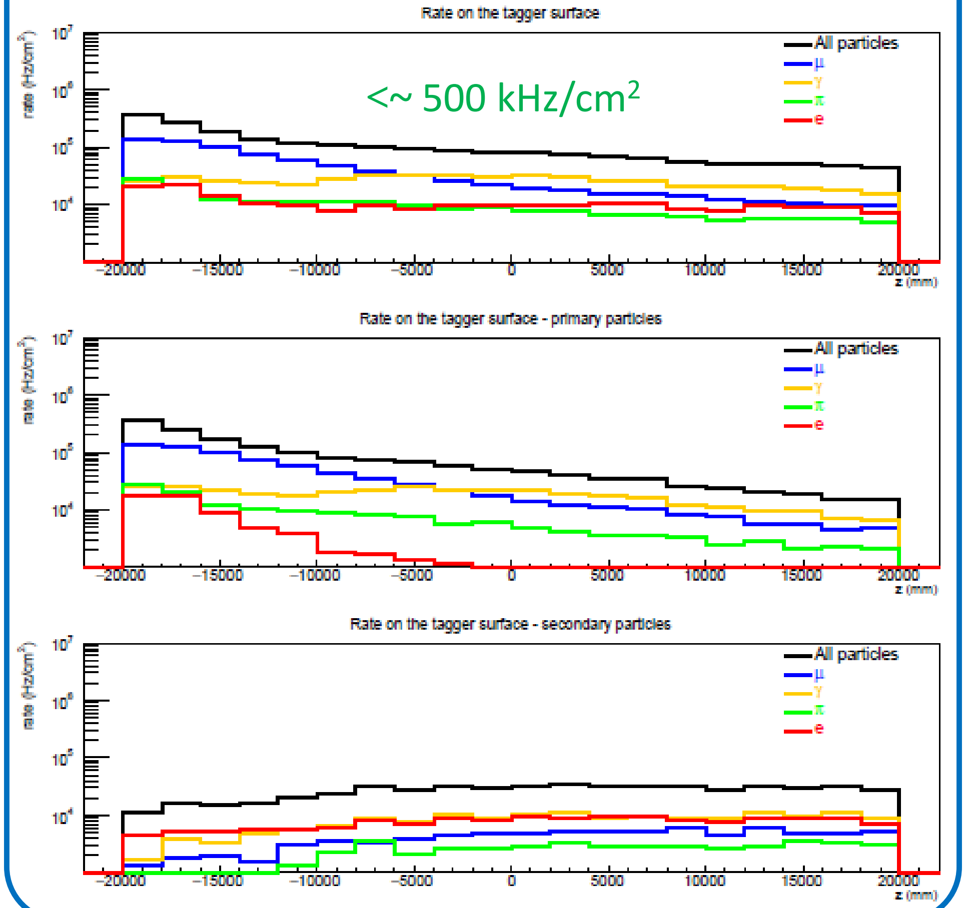
… another test-beam (in these days): testing a module with hadronic cal. for pion containment

The Tagger – Particles in the decay tunnel

Static focusing system, 4.5 10^{13} pot in 2 s (400 GeV)

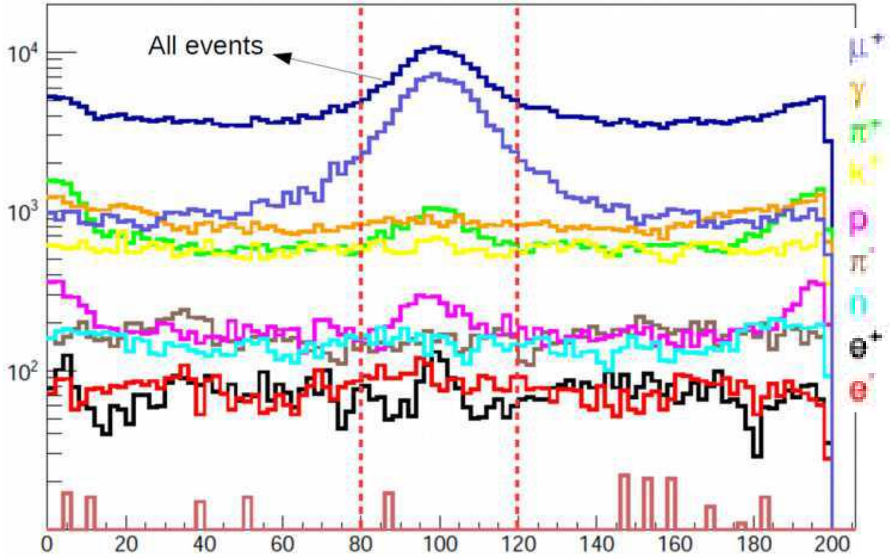
Calorimeter 1 m from the axis of the tunnel (R_{inner}=1.00 m)
Three radial layers of UCM (R_{outer}=1.09 m)

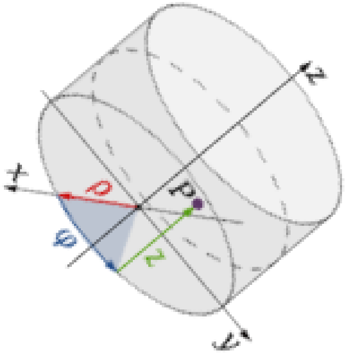
Rate as a function of the longitudinal position z in the tunnel



<~ 500 kHz/cm²

Rate as a function of the azimuthal angle ϕ in the tunnel





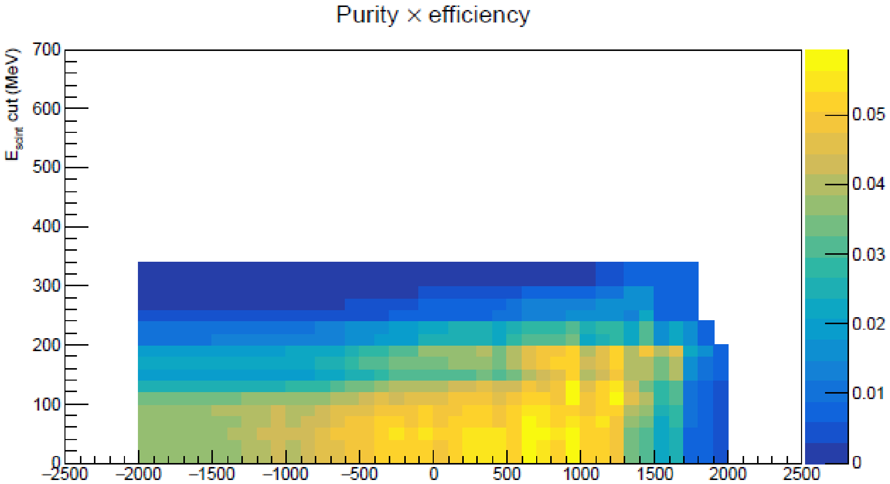
The Tagger – positron ID from K decay

Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. The simulation include particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain

F. Pupilli et al., PoS NEUTEL2017 (2018) 078

Event Builder →	Identify the seed of the event (UCM with large energy deposit) and link neighboring modules
e/π/μ separation →	TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)
e/γ separation →	Signal on the tiles of the photon veto



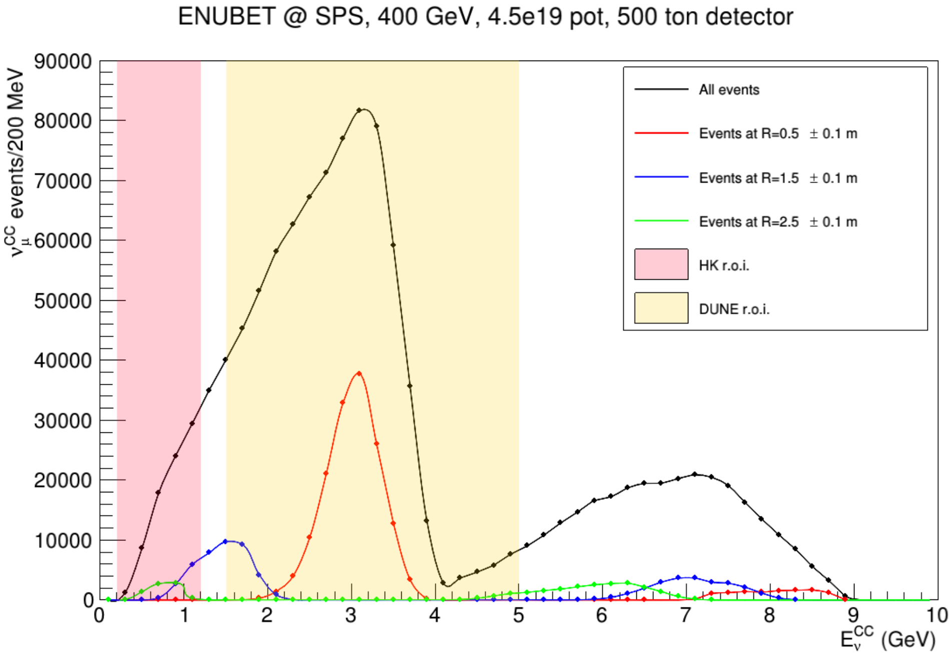
ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

ϕ cut → **0.46**

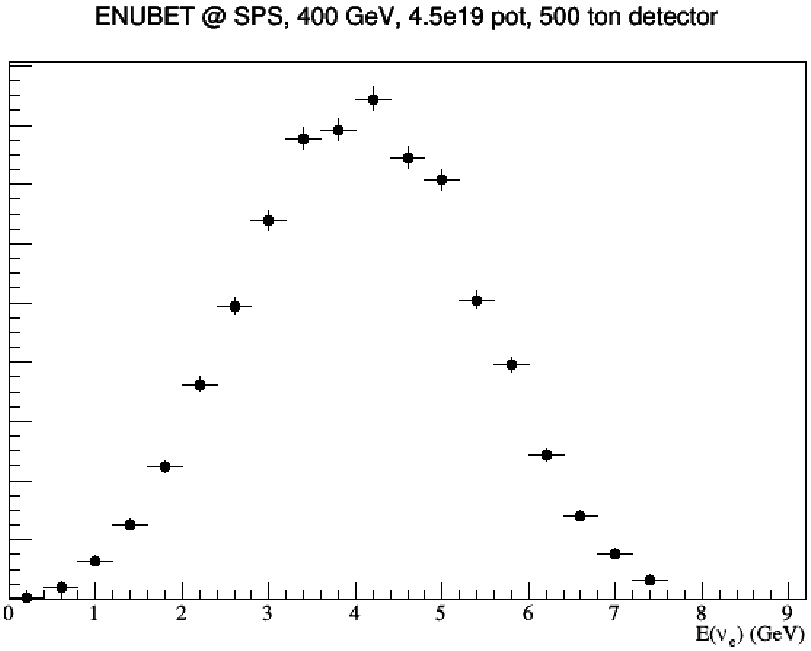
Instrumenting half of the decay tunnel we identify positrons from K decay at single particle level with a S/N = 0.46

Neutrino events per year at the detector

- **Detector mass**: 500 tons (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- **Integrated pot**: 4.5 10^{19} at SPS (6 months in dedicated mode, ~1 year in shared mode) or, equivalently, 1.5 10^{20} pot at the Fermilab Main Ring.
- Warning: detector response not simulated!



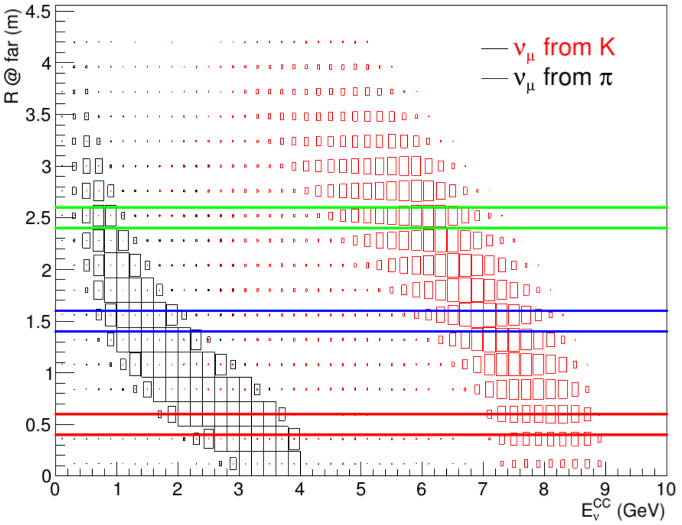
1.2×10^6 ν_μ charged current events per year

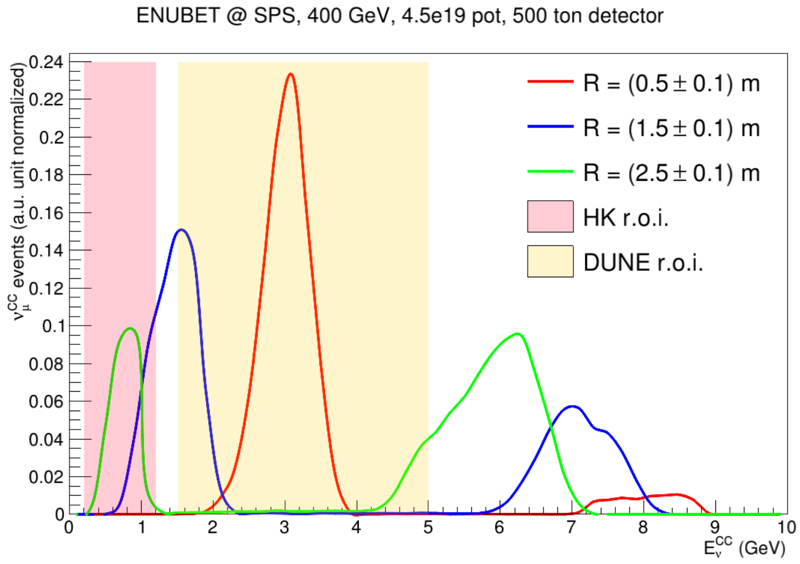


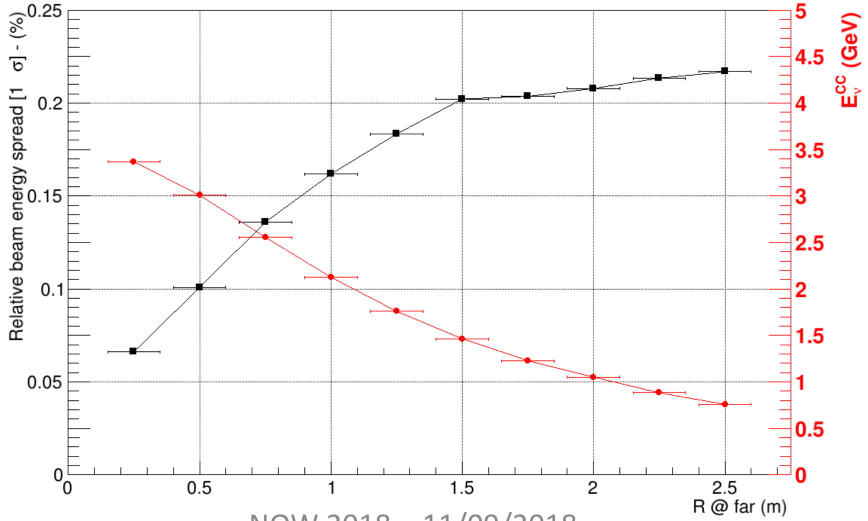
1.4×10^4 ν_e charged current events per year

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 (R). The beam width at fixed R (≡ neutrino energy resolution at source) is 8-22%







Conclusions

- **ENUBET** is a **narrow band beam** with a high **precision monitoring** of the flux at source (1%), neutrino energy (20% at 1 GeV → 8% at 4 GeV) and flavor composition (1%)

- In the last year, we
  - provided the first **end-to-end simulation** of the beamline
  - proved the feasibility of a **purely static focusing system** (10^6 ν_μ^{CC} per year, 10^4 ν_e^{CC} per year with a 500 ton detector)
  - identified the best options for the instrumentation of the decay tunnel (shashlik and lateral readout: final decision in 2019)
  - completed the **full simulation of the positron reconstruction**: the results confirm that monitoring at the single particle level can be performed with S/N = 0.5

- We are proceeding toward the **Conceptual Design** (2021) that will include the full assessment of the systematics, the monitoring of other decay modes of K and pions, the outline of the physics performance for cross-section measurement and cost estimates

Next steps

- Systematic assessment (ν_e from K_{e3} e^+)
- ν_μ from from $K_{\mu2}$ → work in progress
- μ counting: μ from π can be counted after the h-dump: static transfer line with 2s extraction → we expect 1MHz/cm^2 in the dump
- Update the physics performance of the narrow band beam

The ENUBET technique is very promising and the results we got in the last twelve months exceeded our expectations

We look forward to seeing ENUBET up and running in the DUNE/HyperK era!

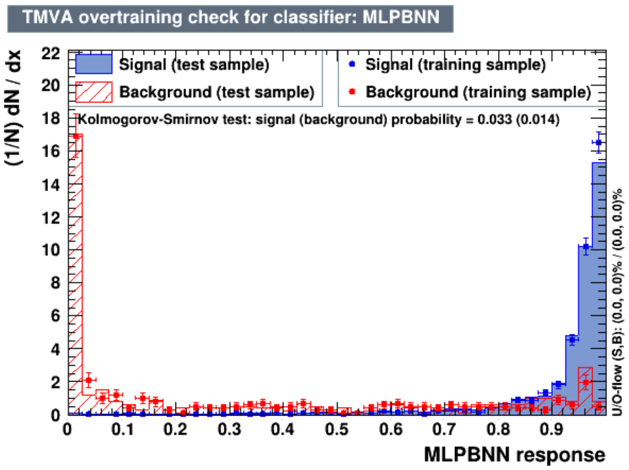
Backup

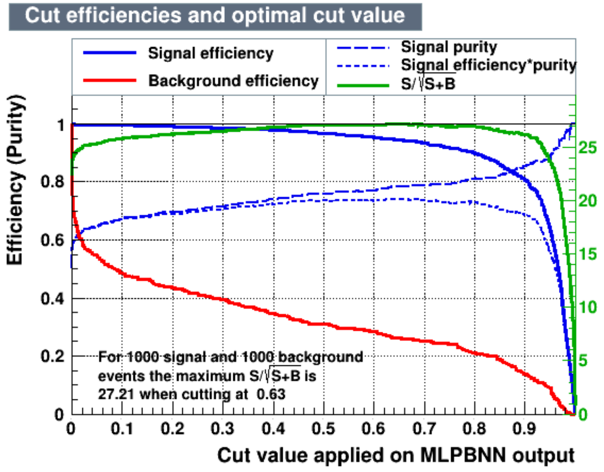
The Tagger – positron ID from K decay

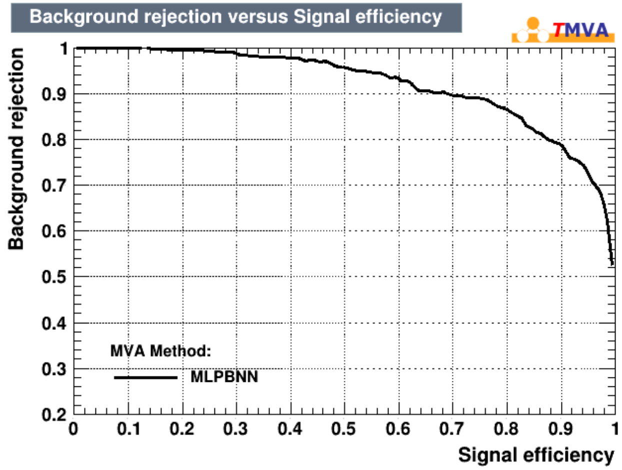
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV → link nighboring modules with time (1ns) and position requirements

e/π separation → Neural network → TMVA multivariate analysis based on 5(+6) variables (pattern of the energy deposition in the calorimeter)

Response to signal and background


TMVA overtraining check for classifier: MLPBNN


Cut efficiencies and optimal cut value


Background rejection versus Signal efficiency

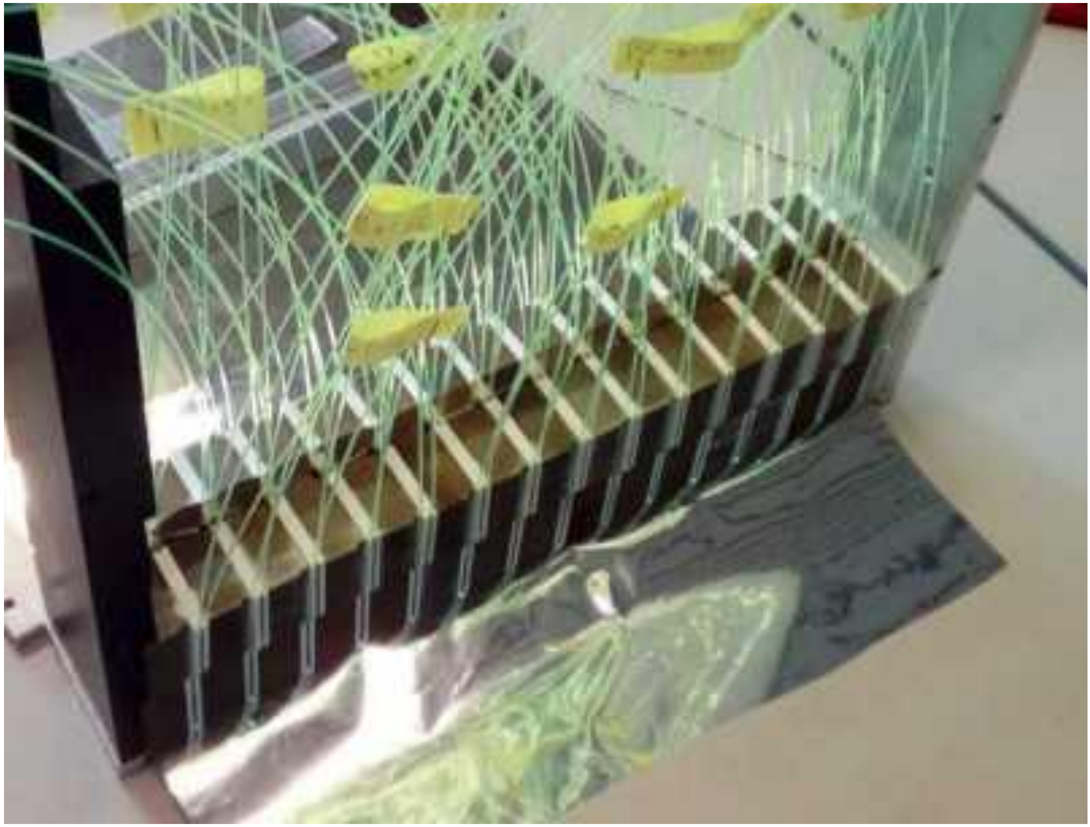
e/γ separation → π^0 rejection: we require 3 layers of t0 before first calorimeter energy deposit compatible with a mip (0.65-1.7 MeV)

Test Beam - 2018

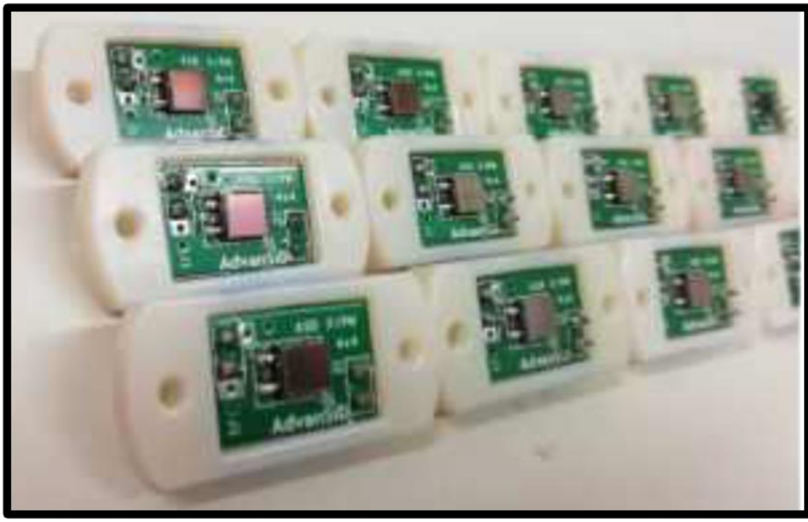
Non-shashlik module – May 2018

Sampling calorimeter (15 mm Fe + 5 mm EJ204 tiles) with lateral WLS light collection.

Test of light yield, uniformity, resolution, optical coupling to Silicon PM (FBK Advansid 3×3 mm^2)



SiPM



Particles hitting the tunnel walls