The ENUBET project

A. Longhin (Padova University and INFN)
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).

Strasbourg, 5-6 Nov 2018

ENUBET: 52 physicists, 11 institutions

Monitored beams

Based on **conventional technologies**, aiming for a **1% precision on the ν_e flux**

protons → (K^+, π^+) → K decays → e^+ ν_e → neutrino detector

- Monitor (~ inclusively) the **decays in which ν are produced**
- "By-pass" **hadro-production**, **PoT**, **beam-line efficiency** uncertainties

- **Fully instrumented decay region**

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

- **ν_e flux prediction = e^+ counting**

Removes the **leading source of uncertainty in ν cross section measurements**

To get the correct spectra and avoid swamping the instrumentation → needs a **collimated momentum selected hadron beam** (only decay products in the tagger)
→ Correlations with interaction radius allows an **a priori knowledge of the ν spectra**

Neutrino beams for precision physics: the ERC ENUBET project

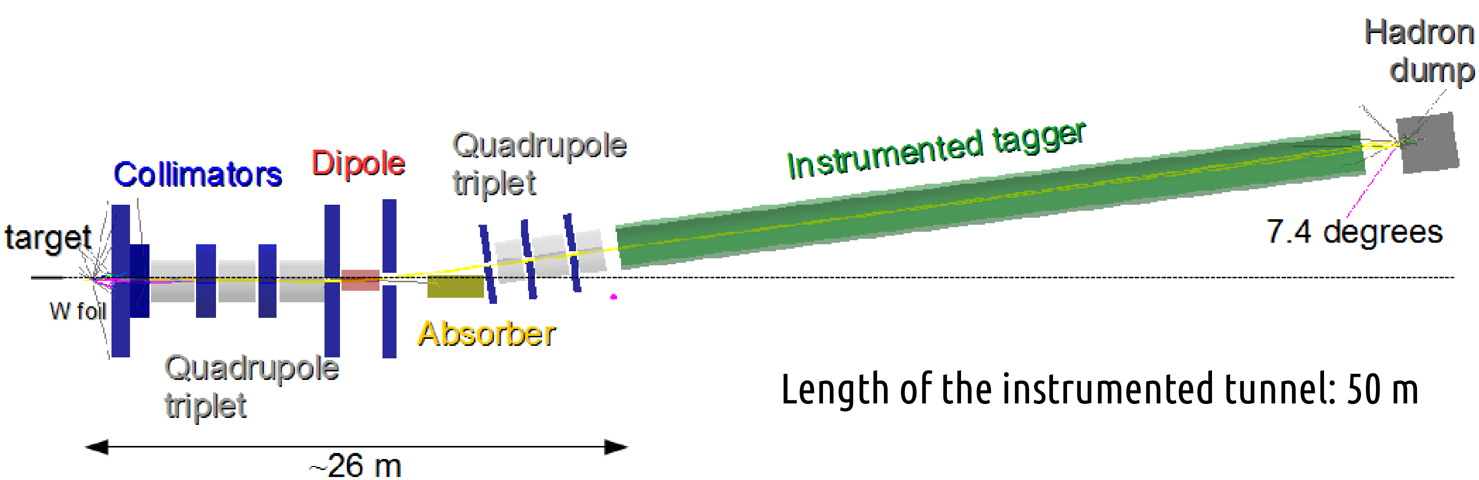
The next generation of **short baseline** experiments for **cross-section** measurements and for **precision ν physics** (e.g. sterile ν and NSI) should rely on:

- ✓ **a direct measurement of the fluxes**
- ✓ a narrow band beam: **energy known a priori** from beam width
- ✓ a beam covering the region of interest **from sub- to multi-GeV**

Enhanced NeUtrino BEams from kaon Tagging

ERC-CoG-2015, G.A. 681647 (2016-21)
PI A. Longhin, **Padova University, INFN**

The ENUBET facility fulfills simultaneously all these requirements



Length of the instrumented tunnel: 50 m

~ 500 t neutrino detector @ 100 m from the target

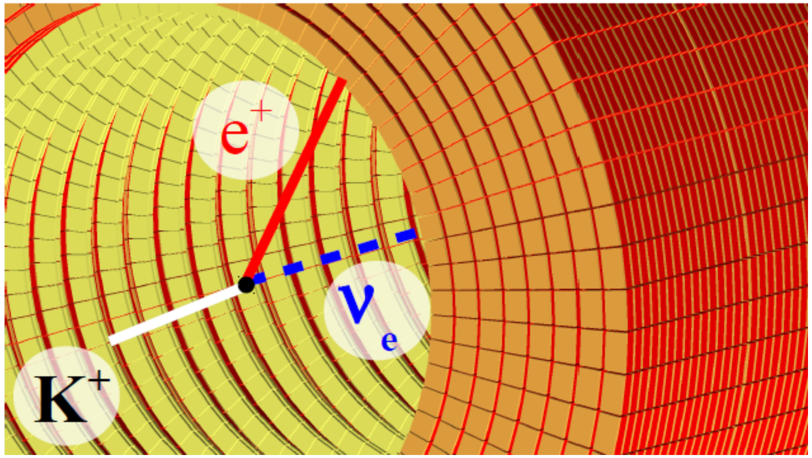
e.g.ICARUS@FNAL or ProtoDUNE-SP/DP@CERN

ENUBET goals and highlights

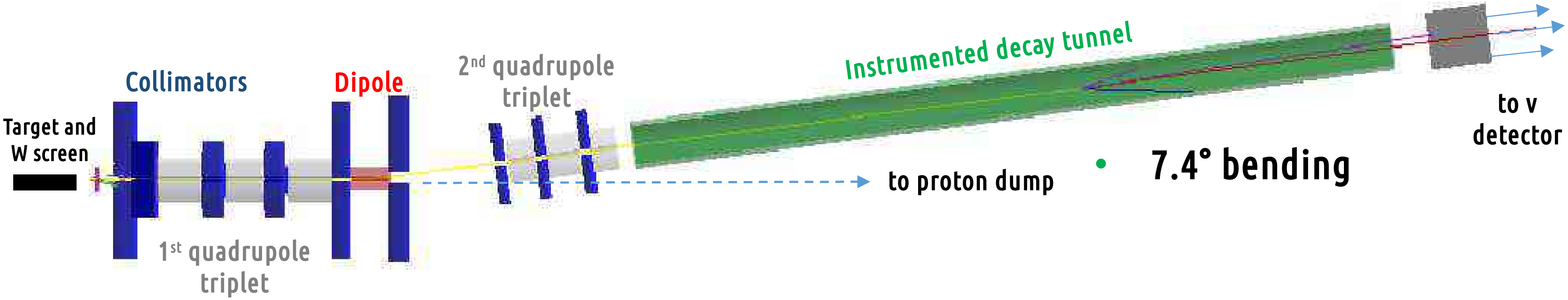
Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level.**

Two pillars:
- Build and test with data a **demonstrator** of the instrumented decay tunnel
- Design/simulate the layout of the **hadronic beamline**

Recent **achievements**
- **end-to-end simulation** of the hadronic **beamline**
- Updated **physics performance**
- Experimental results on the beamline **instrumentation prototypes**



The ENUBET beam line



- **<u>Proton driver</u>: CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **<u>Target</u>**: 1 m Be, graphite target. FLUKA.
- **<u>Focusing</u>**
  - **Horn**: 2 ms pulse, 180 kA, 10 Hz during the flat top *[not shown in fig.]*
  - **Static focusing system**: a quadrupole triplet before the bending magnet
- **<u>Transfer line</u>**
  - Optics: optimized with TRANSPORT to a 10% momentum bite centered at 8.5 GeV/c
  - Particle transport and interaction: full simulation with G4Beamline
  - Normal-conducting magnets
    2 quad triplets (15 cm wide, L < 2 m, B = 4 to 7 T/m)
    1 bending dipole (15 cm wide, L = 2 m, B =1.8 T)
- **<u>Decay tunnel</u>**
  - Radius: 1 m. Length: 40 m, low power hadron dump at the end of the decay tunnel
- **<u>Proton dump</u>**: position and size under optimization

The ENUBET beam line – particle 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	x 2
“static”	19	1.4	2 s [b]	85	6.2	**x 5**

(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(b) Slow extraction. Detailed performance and losses currently under evaluation at CERN
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

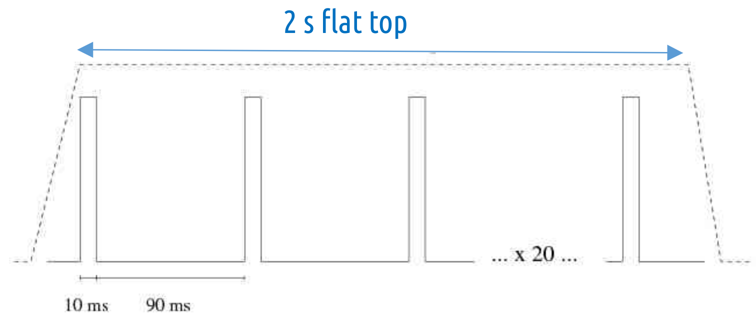
Advantages of the static extraction:

- No need for fast-cycling horn
- Strong reduction of the rate in the instrumented decay tunnel
- Monitor the μ after the dump at % level (flux of ν_μ from π) [**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**

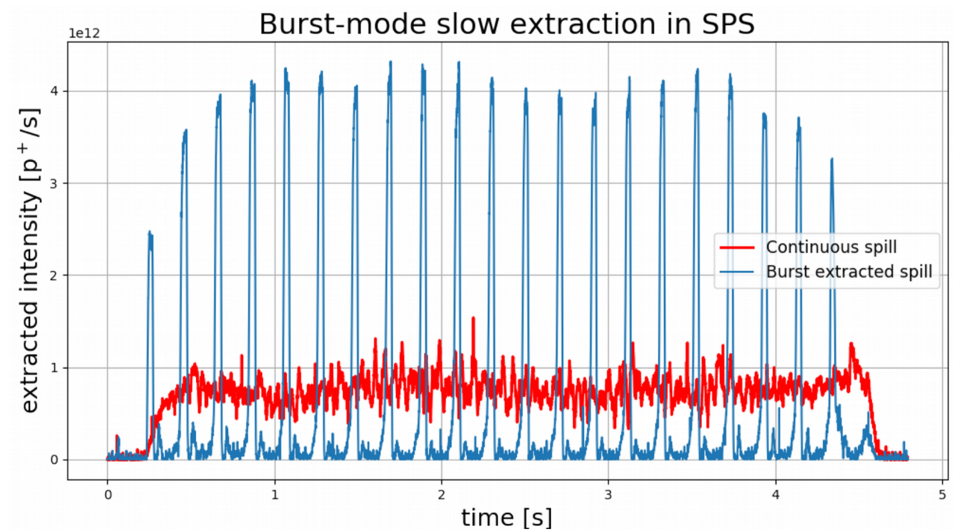
The ENUBET beam line: horn-based option

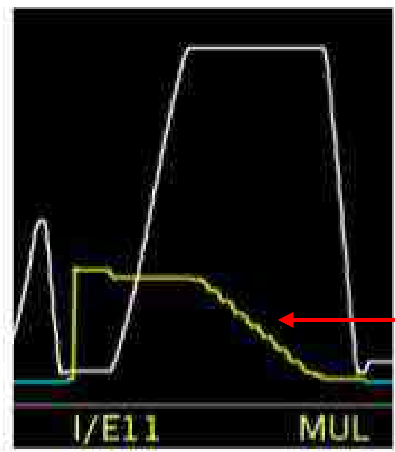
- **Machine studies @ SPS are currently on-going:**

Preliminary studies Jul/Aug 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

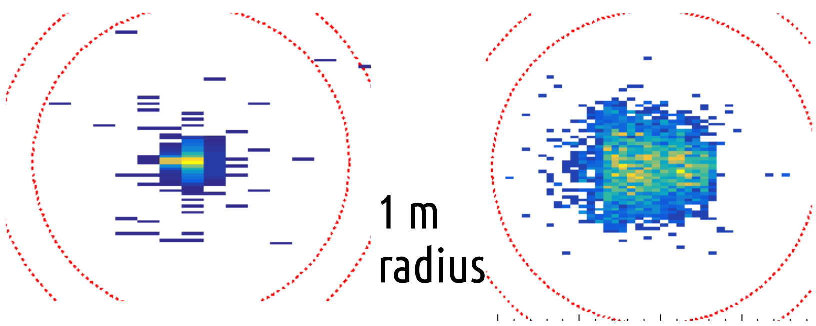
Proton current steps in correspondance of bunches

- Beam bunches in time with horn pulses
- **Further studies →** understand radiation losses. Iterative corrections. Sextupoles: sharper bursts.

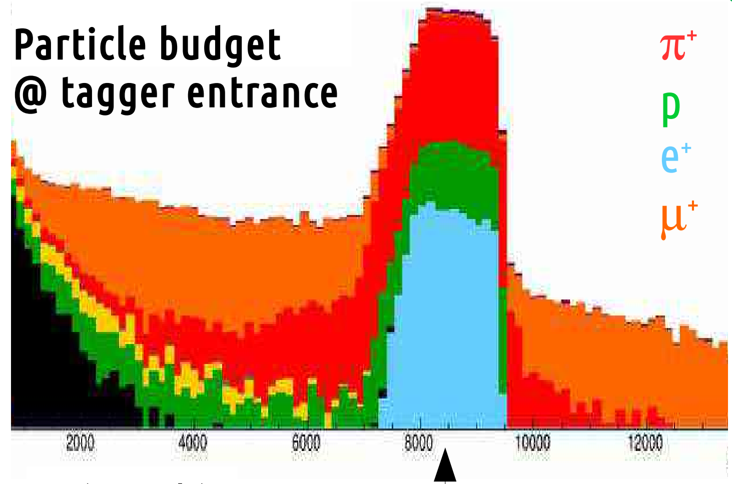
The static beamline: emittance, particle content

Divergence of the kaon beam

K^+ @ tagger entrance — exit

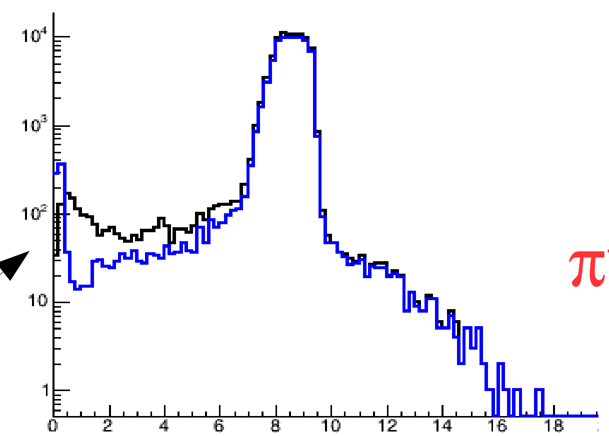


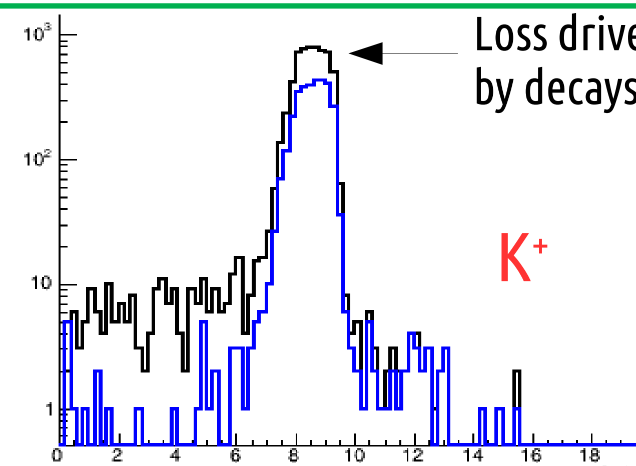
Particle budget @ tagger entrance



Spectra @ tagger entrance and exit

Low energy high angle π





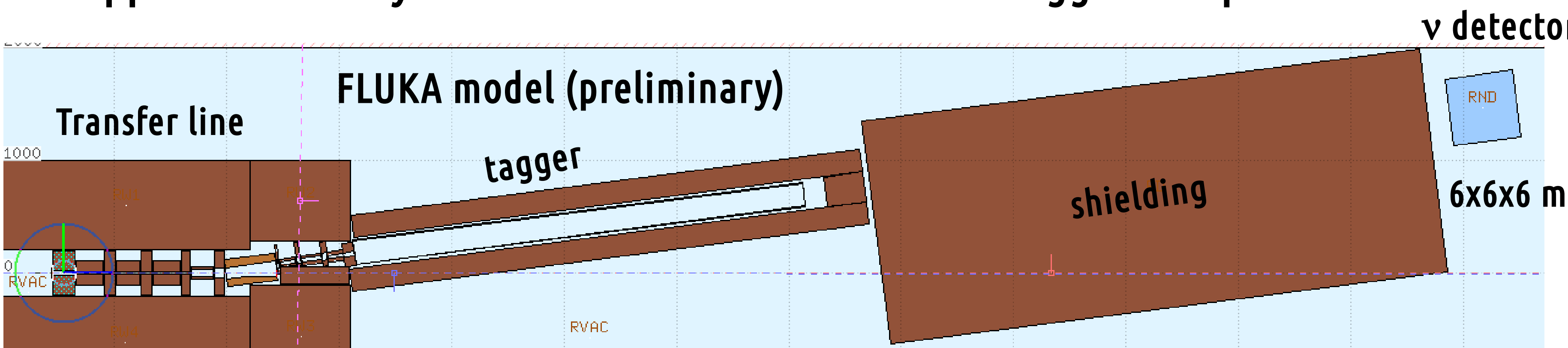
Loss driven by decays

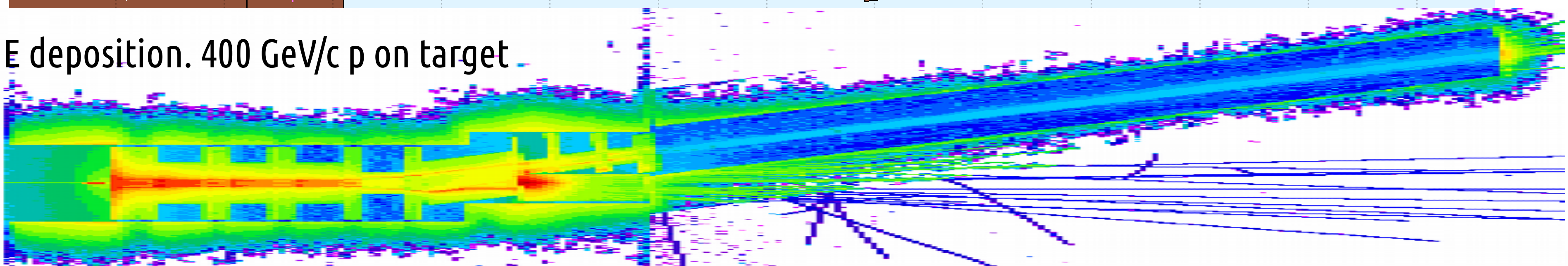
The static beamline: FLUKA simulation

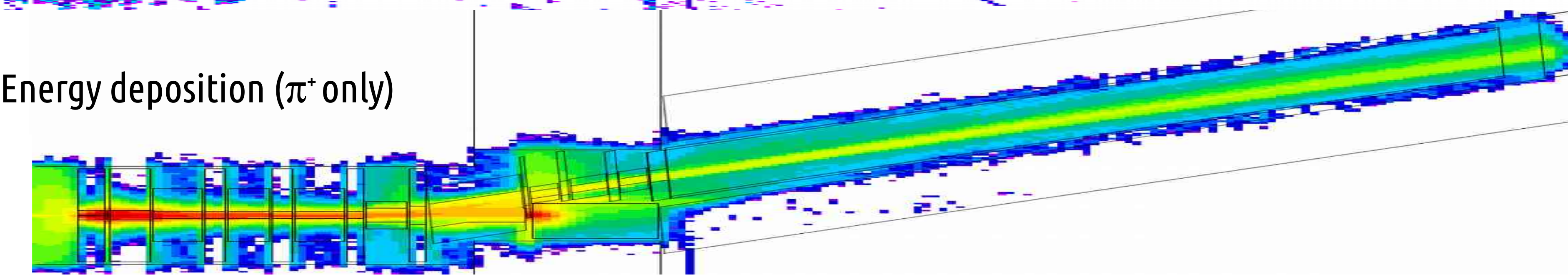
Assess the specs of **rad-hard upstream focusing quadrupoles**

Optimize shielding to:

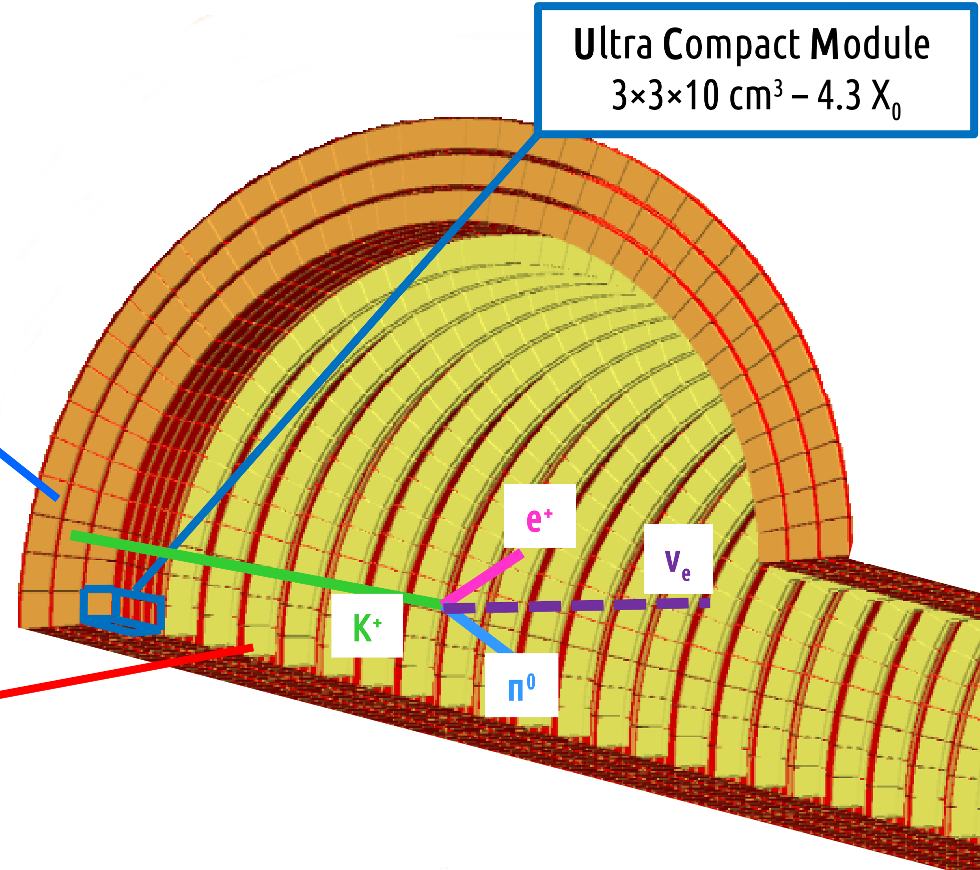
- **reduce halos** in the tagger region
- **suppress the decays** of off-momentum mesons **out of tagger acceptance**







The ENUBET tagger



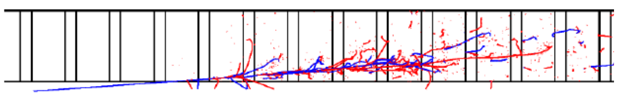
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

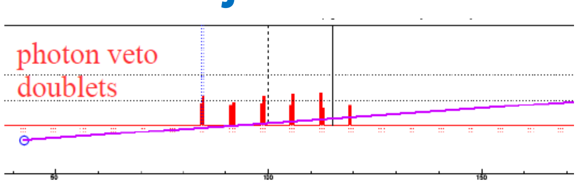


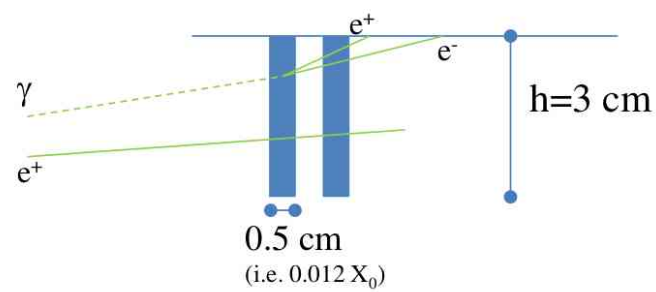
Integrated photon veto

Plastic scintillators

Rings of 3×3 cm^2 pads

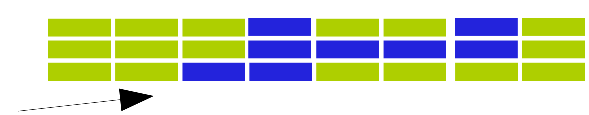
→ π^0 rejection





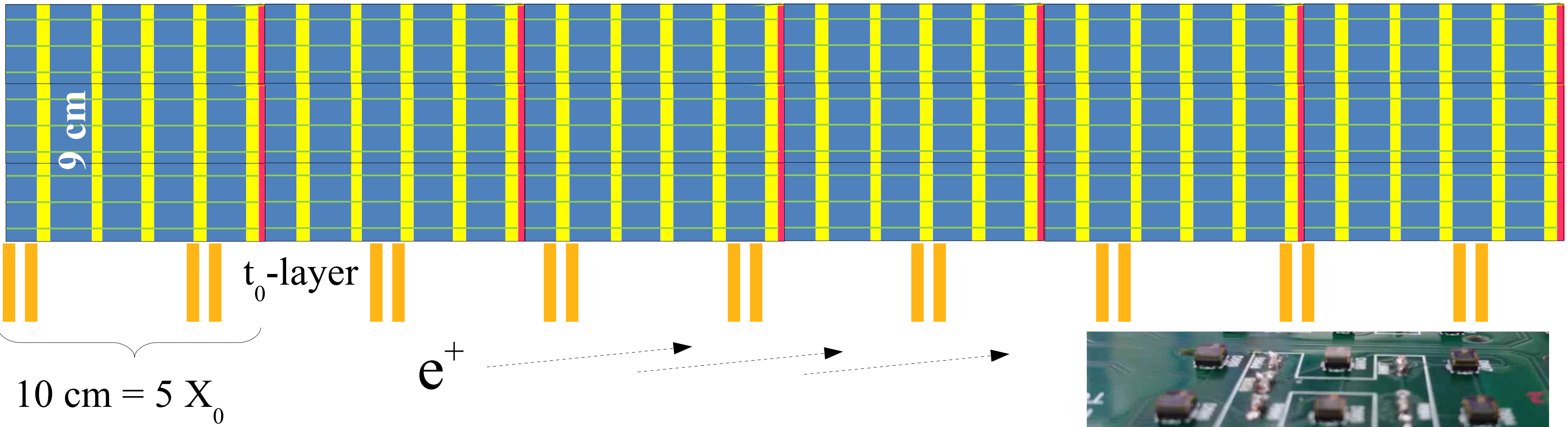
e^+ (signal) topology

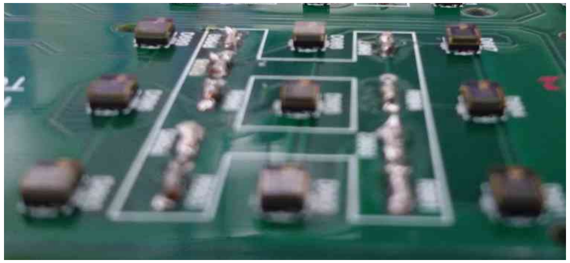
π^0 (background) topology

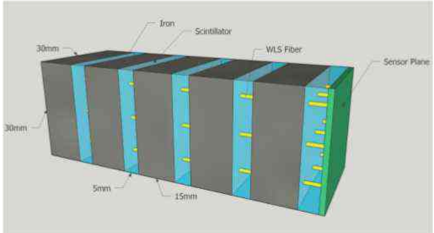


π^+ (background) topology

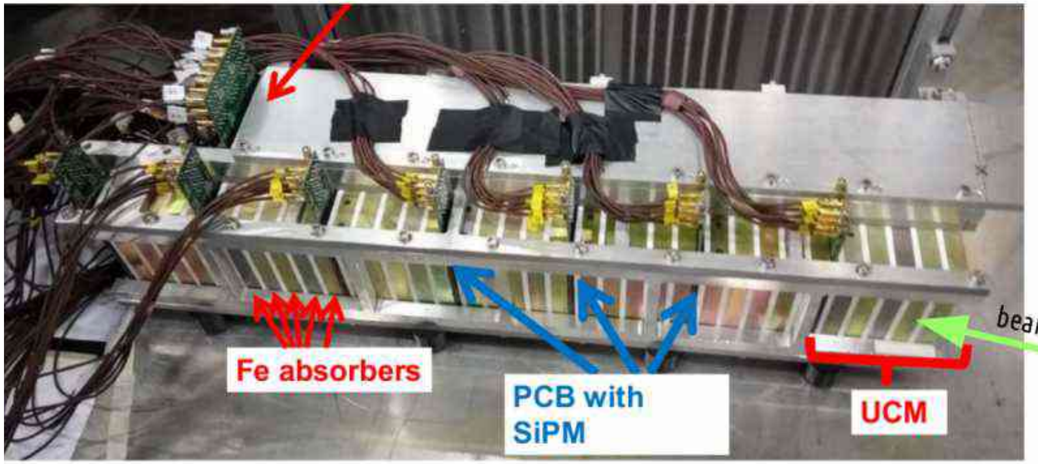
The tagger: shashlik with integrated readout

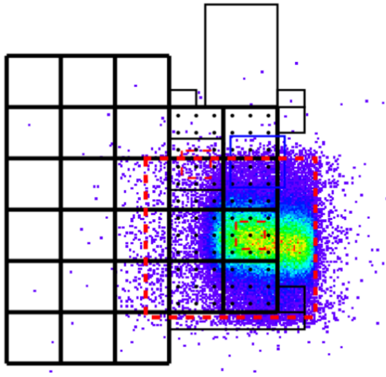






CERN PS test beam Nov 2016



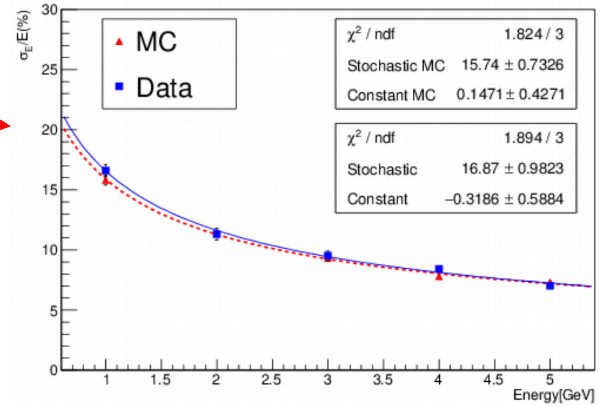


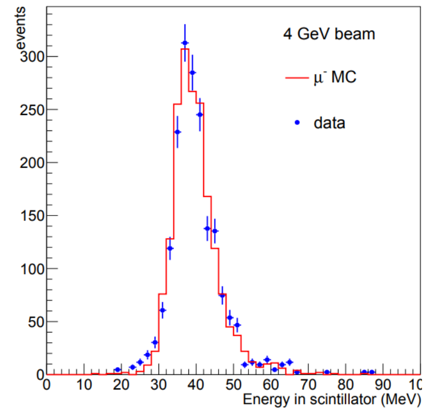
Test beam results with shashlik readout

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

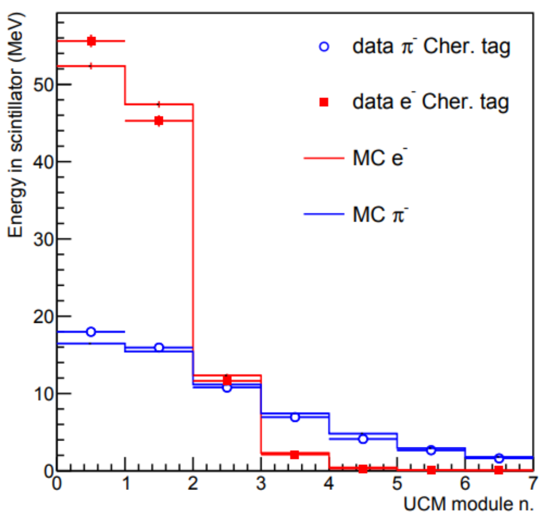
Tested response to MIP, e and π^-

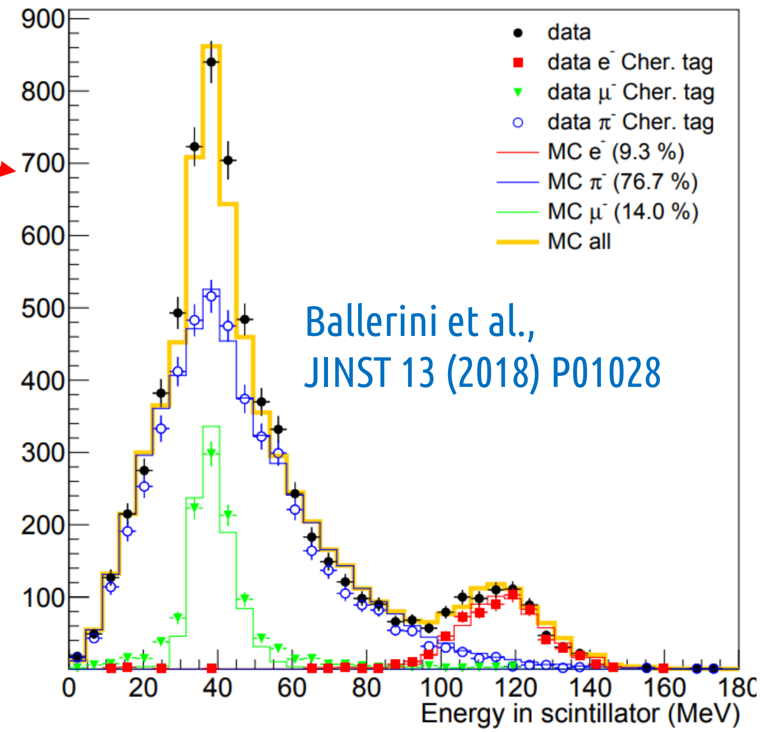
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement





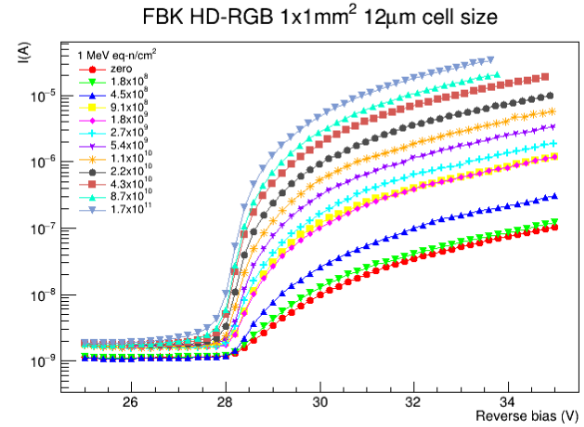
- longitudinal profiles of partially contained π reproduced by MC @ 10% precision





Ballerini et al.,
JINST 13 (2018) P01028

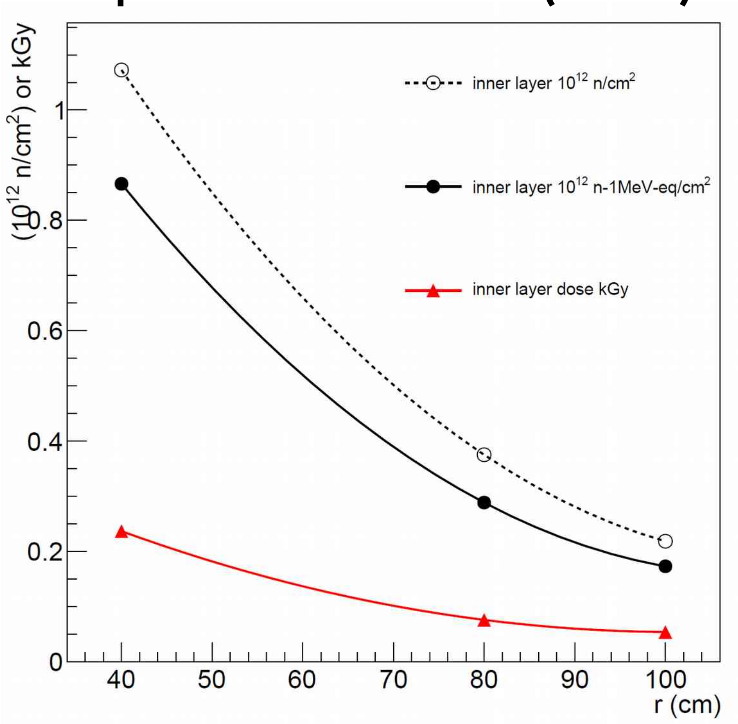
SiPM irradiation studies



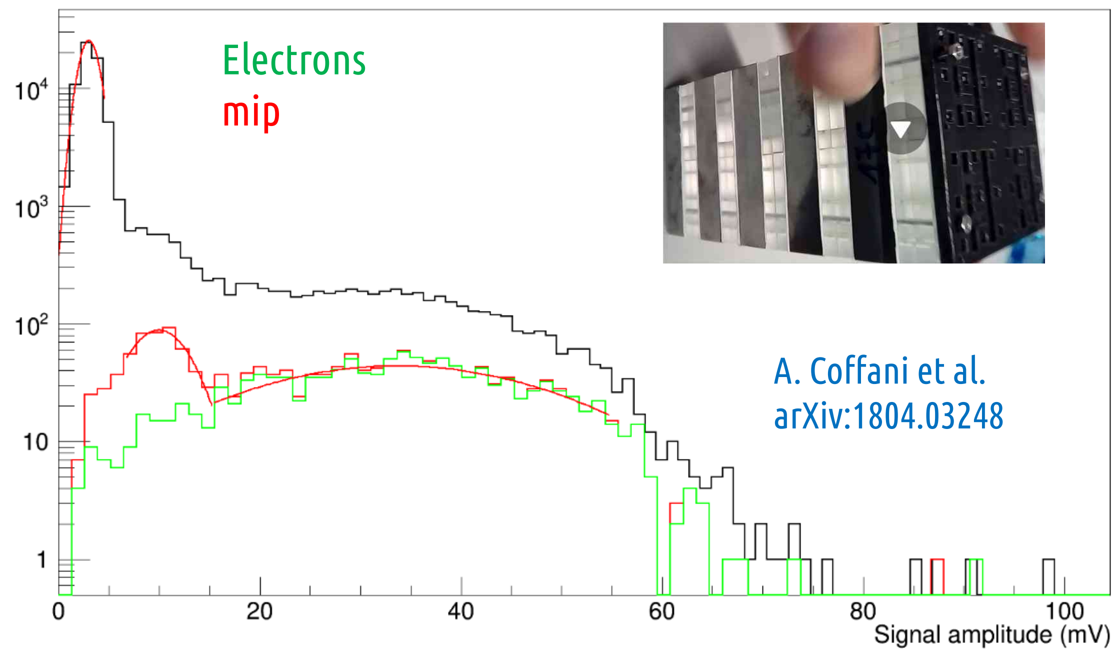
SiPM were **irradiated at LNL-INFN** with 1-3 MeV neutrons in Jun 2017

→ Characterization of 12,15 and 20 μm SiPM cells up to **1.2 x 10¹¹ n/cm²** 1 MeV-eq (max non ionizing dose for 10^4 ν_e^{CC} at a 500 t ν detector)

Expected neutron doses (FLUKA)



Irradiated SiPM tested at CERN in Oct 2017

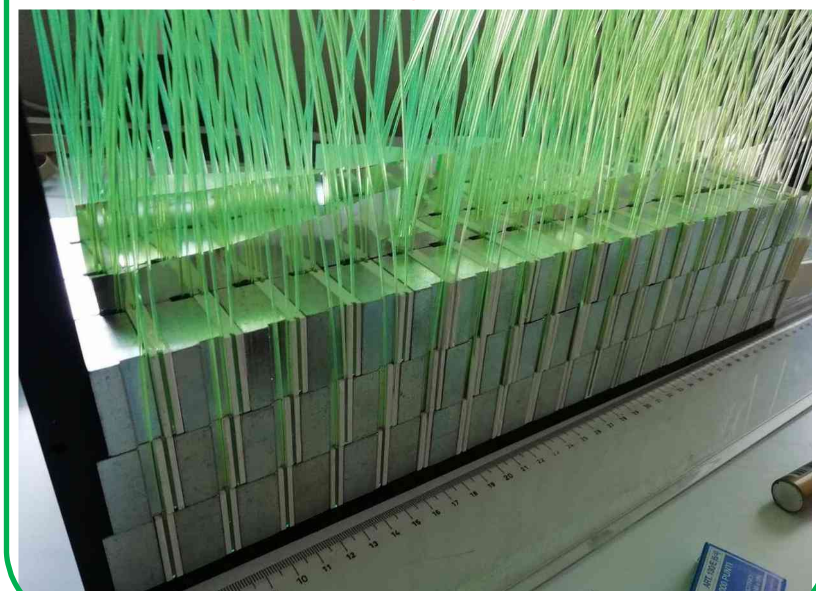


- Mips can be used from **channel-to-channel intercalibration** even after the maximal irradiation.
- Tests allowed **tuning of scintillator thickness** (or equivalently min p.e. yields) and **compensation with overvoltage** tuning.

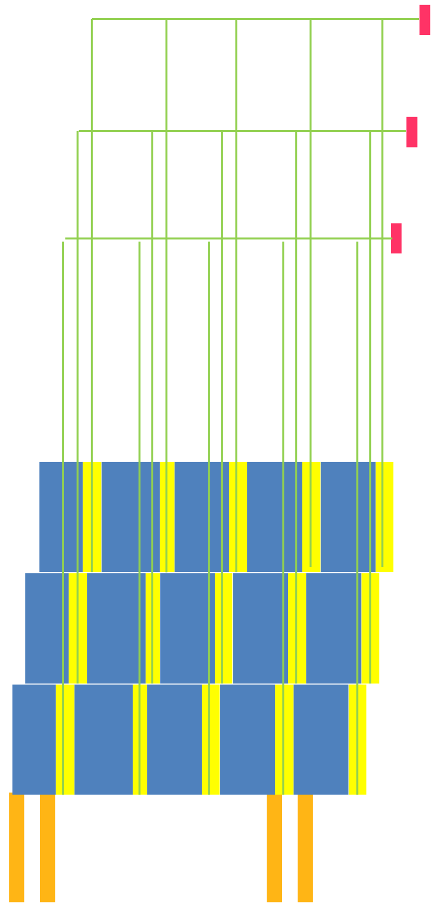
The tagger: lateral readout option

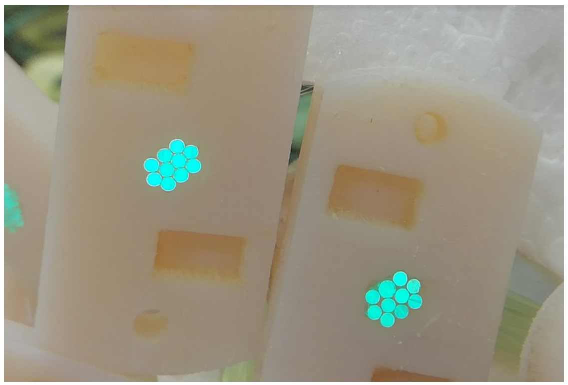
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM). SiPM are not immersed anymore in the hadronic shower → less compact but .. much **reduced neutron damage** (larger safety margins), better **accessibility**, safer **WLS-SiPM coupling**.

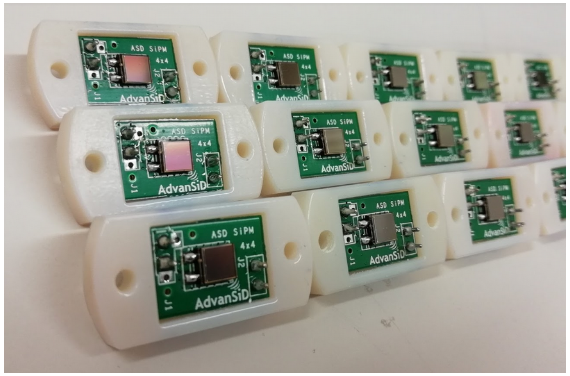
Sampling calorimeter with
lateral WLS light collection



May 2018, CERN-PS test beam



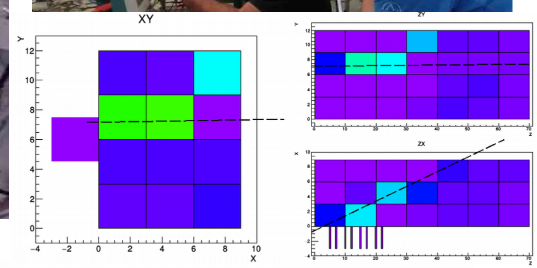




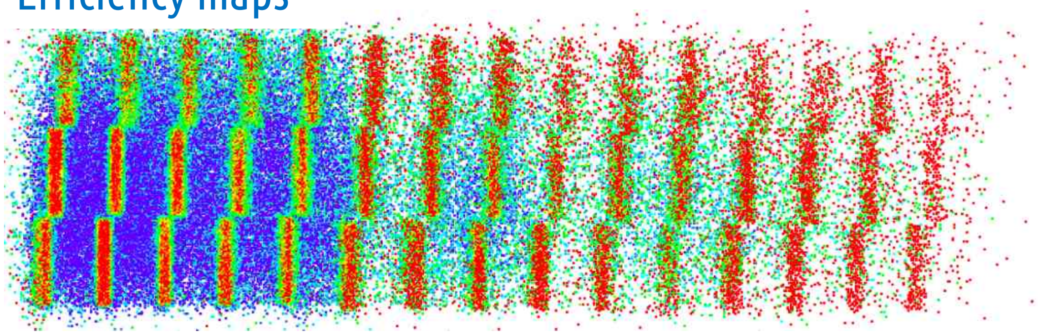
The Tagger – Detector R&D

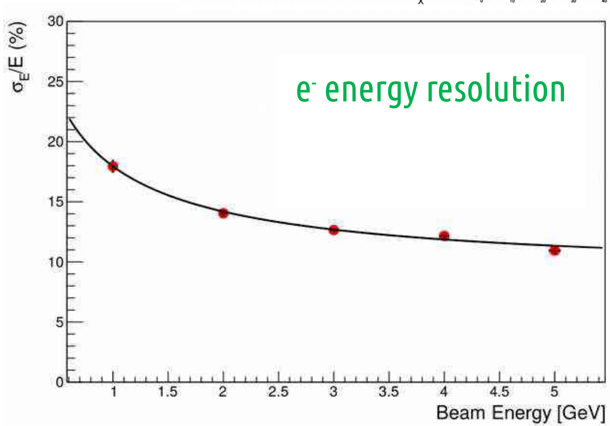
September 2018 CERN-PS: a module with hadronic cal. for pion containment and **integrated t_0-layer**

Resolution, light yield, uniformity, optical coupling to photo-sensors, e/π separation. In progress.



Efficiency maps



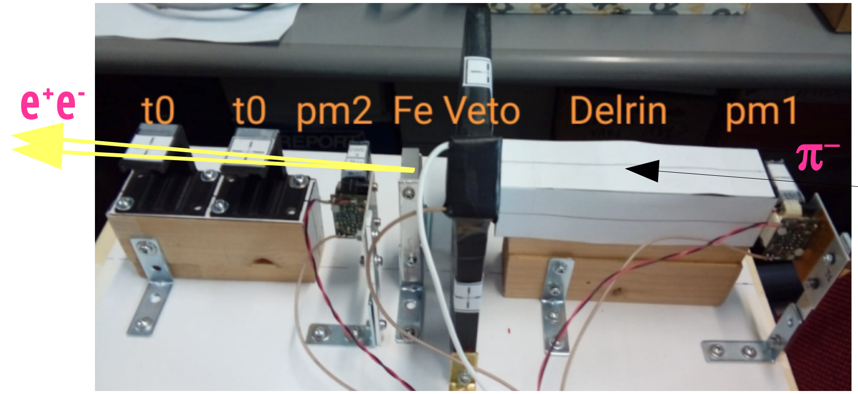


The photon veto – test beam

@ CERN-PS T9 line 2016-2018

charge exchange: $\pi^- p \rightarrow n\, \pi^0\ (\rightarrow \gamma\gamma)$

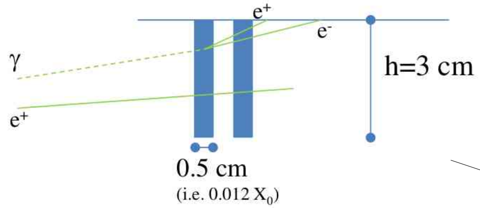
Trigger: PM1 + VETO +PM2

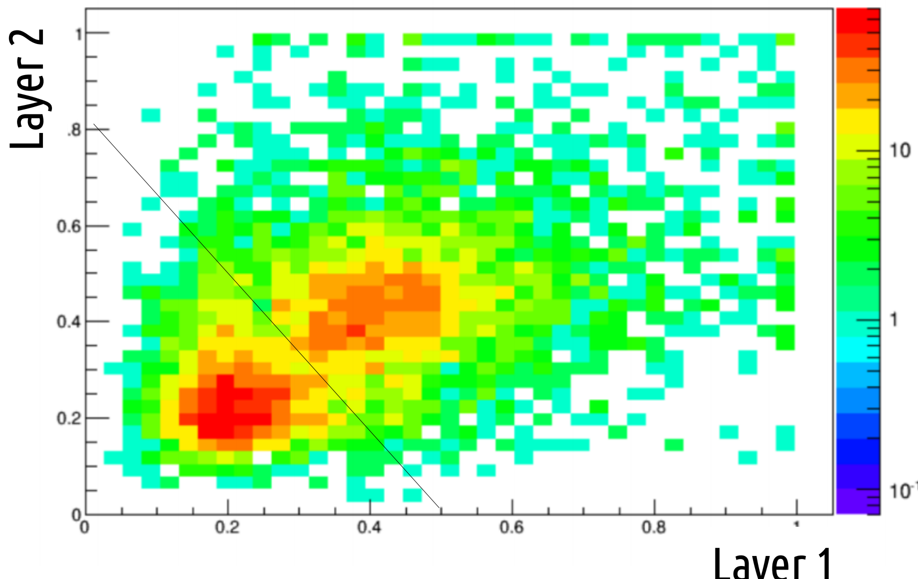


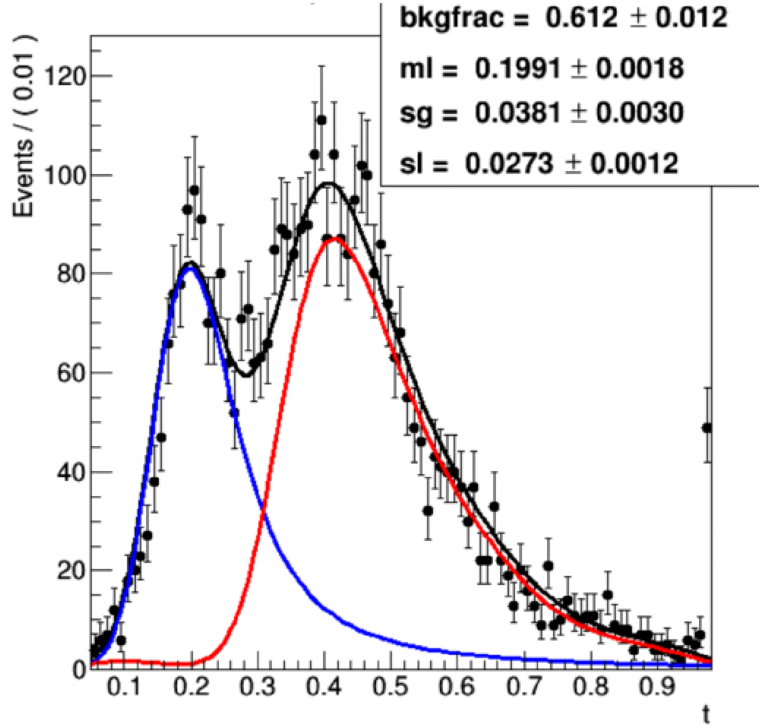
- **γ / e^+ discrimination + timing**

scintillator ($3\times3\times0.5$ cm^3) + WLS Fiber + SiPM

- light collection efficiency → >95%
- time resolution → σ ~ 400ps
- 1mip/2mip separation





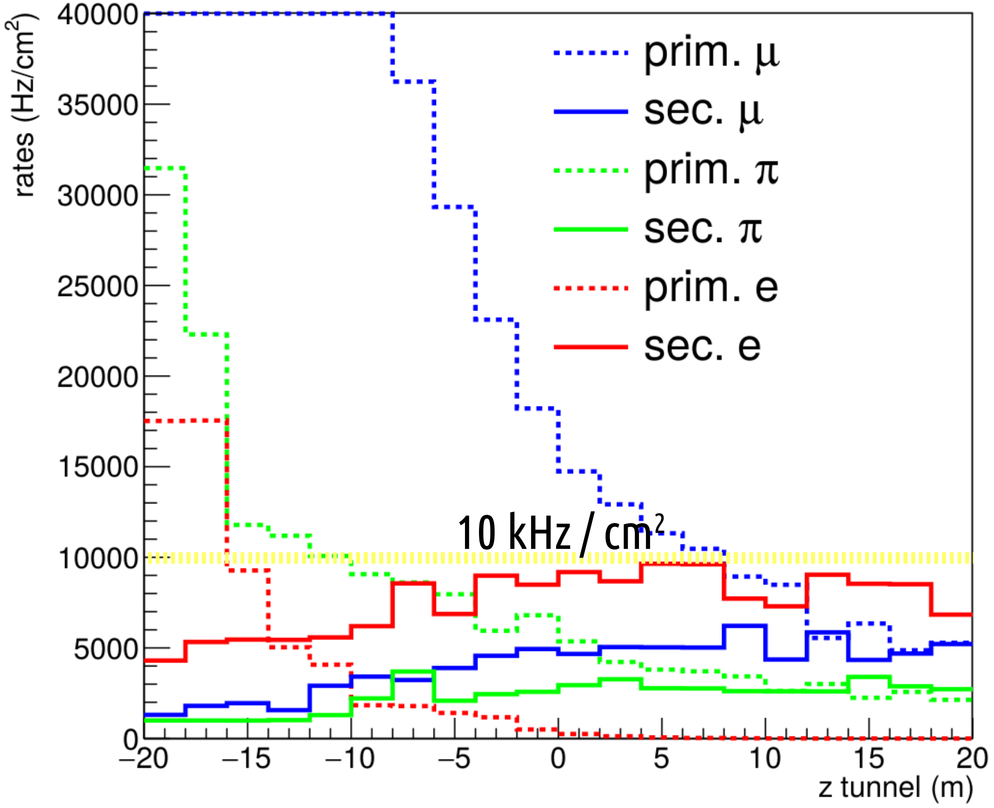


Particle rates in the tunnel

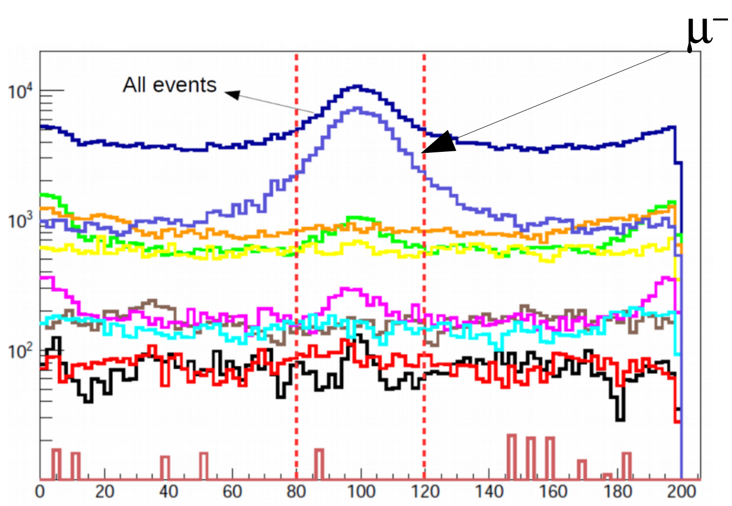
Static focusing system
4.5 x 10^{13} pot in 2 s (400 GeV)

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 vs longitudinal position in the tunnel



Rate vs the azimuthal angle in the tunnel



The bulk of the muons lies on the dipole Bending plane → can be easily removed

Positron ID from K decay

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

Analysis chain

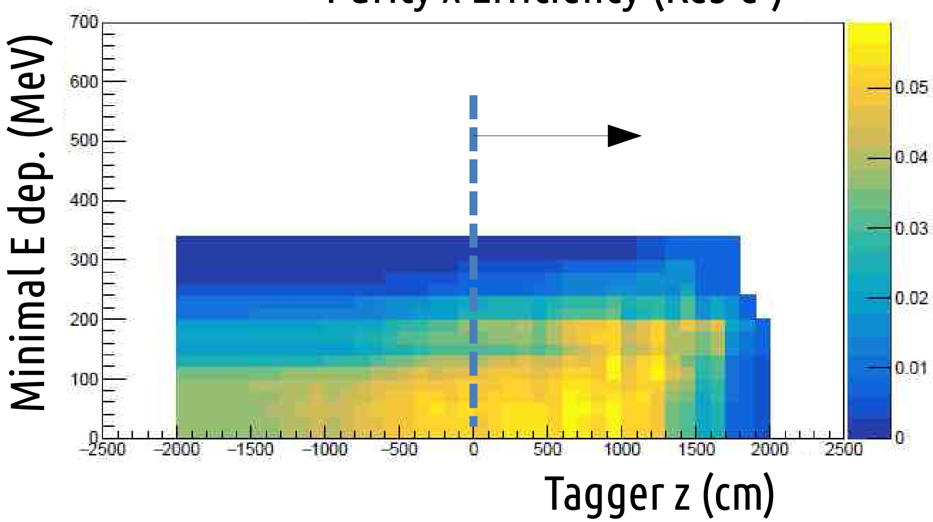
F. Pupilli et al., PoS NEUTEL2017 (2018) 078

Event Builder → Identify the seed of the event (UCM with large energy deposit) and cluster neighboring modules (in time and space)

$e/\pi/\mu$ separation → Multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter) with TMVA

e/γ separation → Signal on the tiles of the photon veto

Purity x Efficiency (Ke3 e^+)



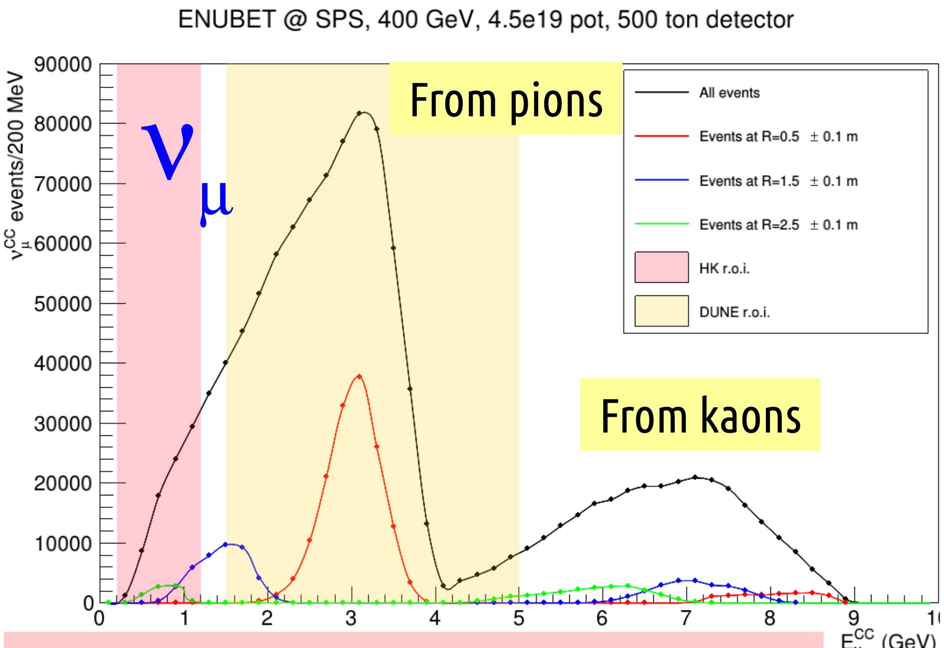
ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

ϕ cut → **0.46**

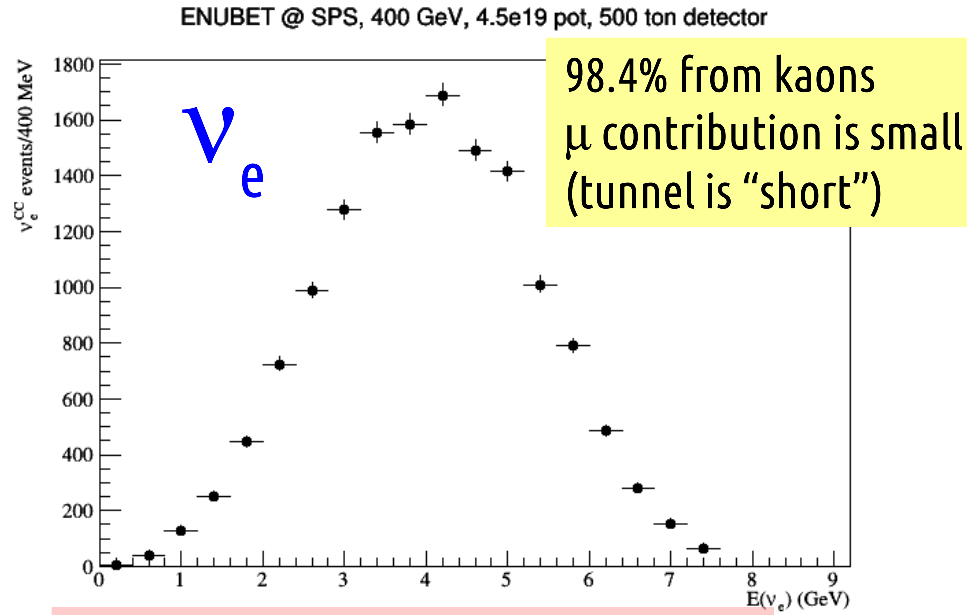
Instrumenting half of the decay tunnel:
K_{e3} e^+ at single particle level with a S/N = 0.46

Neutrino events per year at the detector

- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5 x 10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5 x 10^{20} pot at FNAL



1.2 million ν_μ Charged Current per year



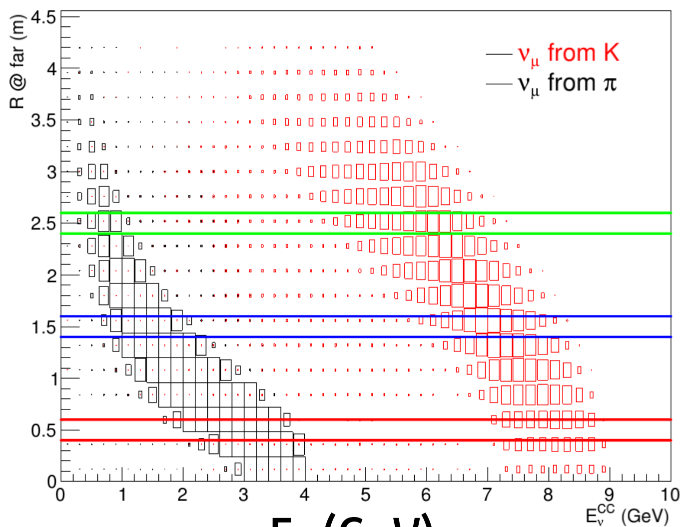
14000 ν_e Charged Current per year

- 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 at the ENUBET narrow band beam

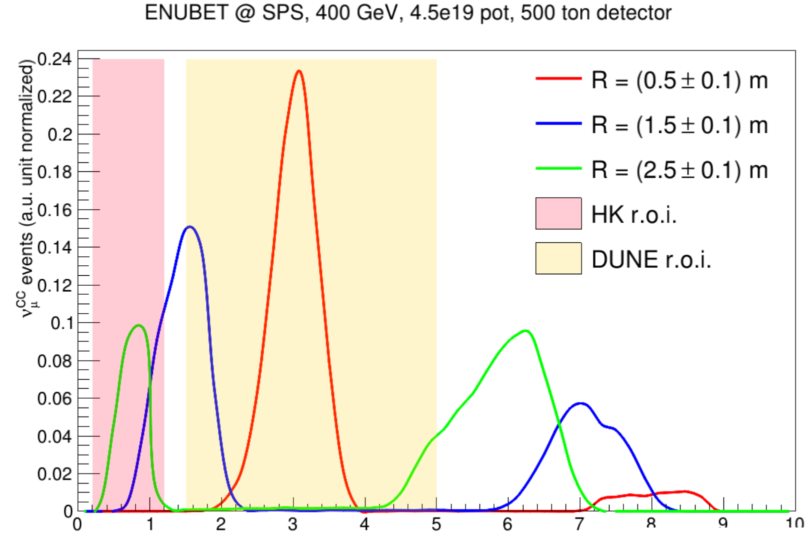
The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.

radius (m)



E_ν (GeV)

ν_μ CC in radial bins (1 norm.)

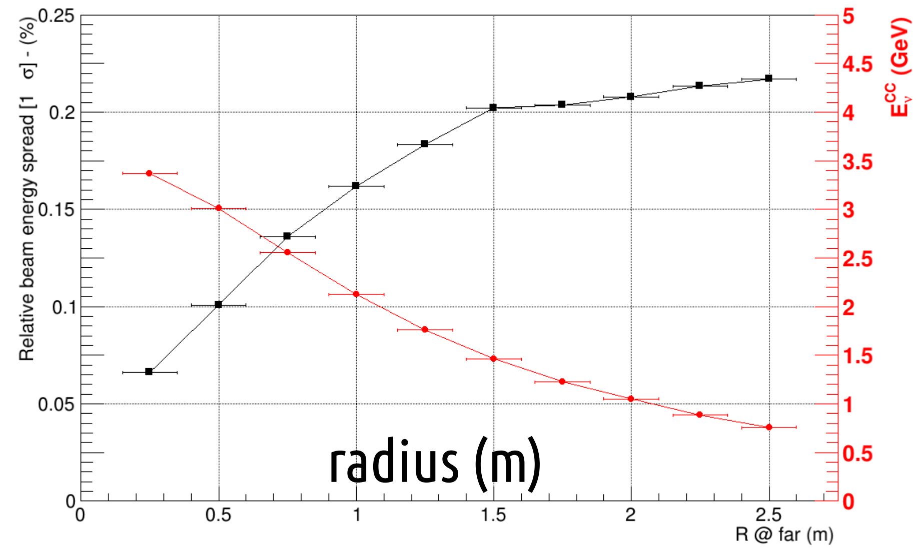


E_ν (GeV)

The beam width at fixed R
(≡ neutrino energy resolution) for
the pion component is

- 8 % for r ~ 30 cm, $<E_\nu>$~ 3 GeV
- 22% for r ~ 250 cm, $<E_\nu>$ ~ 0.7 GeV

$\sigma(E_\nu)/E_\nu$

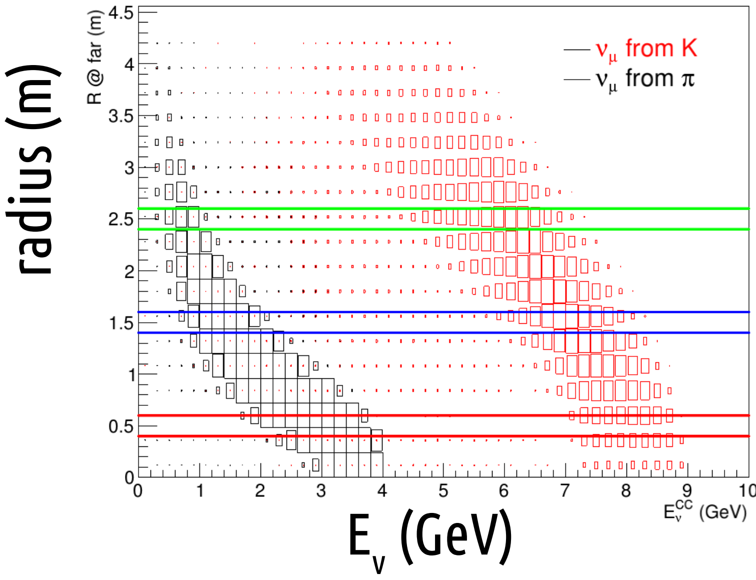


radius (m)

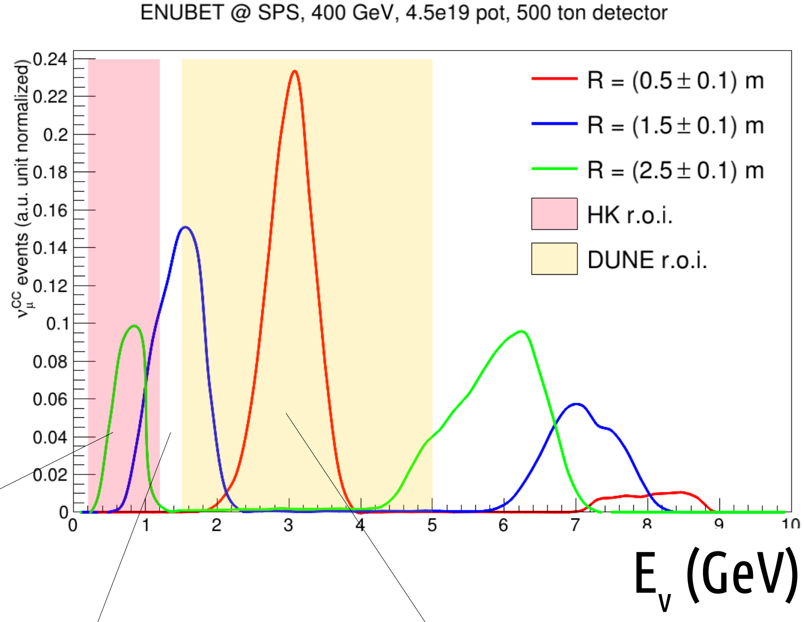
Mean energy

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.

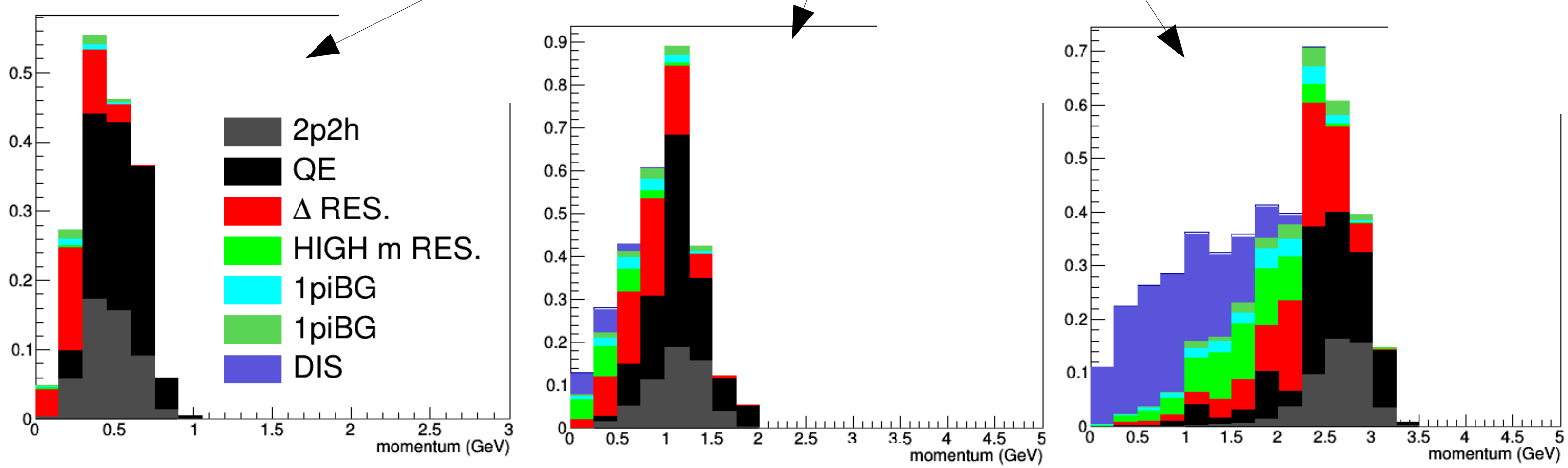


ν_μ CC in radial bins (1 norm.)



Momentum of ν_μ^{CC} μ^- on Ar.

GiBUU generator (Gauss flux approx.)



Conclusions

ENUBET is a **narrow band beam** with a high **precision monitoring** of the flux at source (O(1%)) and control of the E_ν spectrum (20% at 1 GeV ➞ 8% at 3 GeV)

2018 has been a special year, we have

- provided the first **end-to-end simulation of the beamline** (Jul)
- Proved the feasibility of a **purely static focusing system** (10^6 ν_μ^{CC} , 10^4 ν_e^{CC} /y/500 t)
- **full simulation of e^+ reconstruction**: **single particle level** monitoring. S/N ~ 0.5
- Tested with machine data the **"burst" slow extraction** scheme at the CERN-SPS (Aug)
- **completed the test beams** campaing (Sep) before LS2
  → identified best options for instrumentation (**shashlik** and **lateral** readout)
- Strengthened the **physics case**:
  → slow extraction + "**narrow band off-axis technique**"

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

Next steps

- In **2019** we need to:
  - **decide on the light readout technology** for the final demonstrator (shashlik versus "lateral readout")
  - **improve the design of the beamline** to reduce beam halo contamination (current e^+ S/N can be significantly improved)
  - re-optimise the **tunnel radius** to increase geometrical acceptance

- **Systematic assessment on predicted neutrino fluxes**
- Develop new ideas to **enhance precision also on ν_μ**
  - from $K_{\mu 2}$ with μ id in the tagger
  - from π : counting μ from π in hadron-dump (could be feasible with a 2s extraction).
- **CDR** at the end of the project (2021): **physics** and **costing**
- Build a **demonstrator prototype** of the tagger (2021)


CERN Nov 2016

Padova June 2016

CERN Aug 2017

CERN Oct 2017

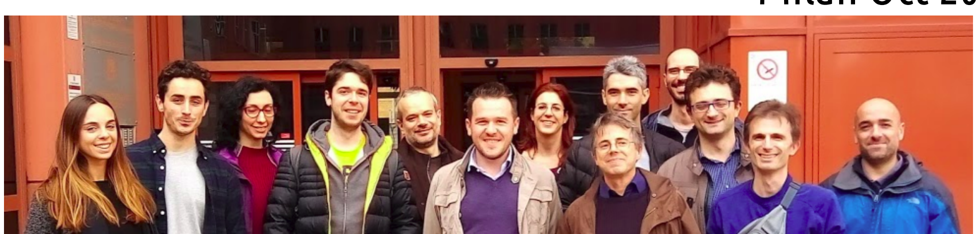
INFN-LNL Jun 2017

THANKS!

CERN May 2018

CERN Sep 2018

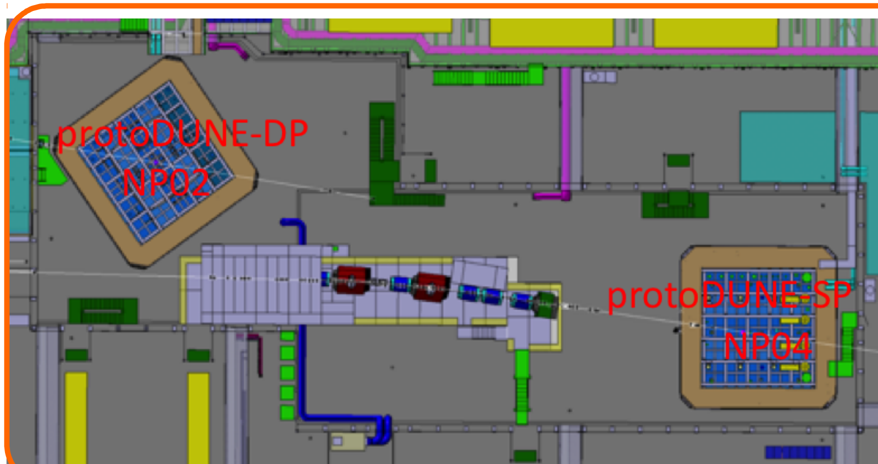
Milan Oct 2017



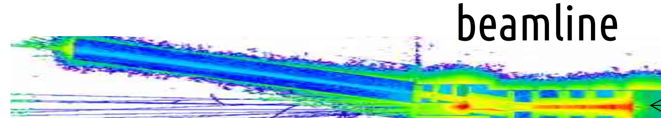
ENUBET in the European strategy

The ENUBET mission is to demonstrate the **feasibility** of the tagged neutrino beam approach at CERN, J-PARC or FNAL (**site independent**).

Still… the protoDUNE prototypes would be **ideal** detectors for a future experiment: right **mass**, **timeliness**, redundancy from **dual baseline**, appropriate logistics, an opportunity for a **coherent development of the original physics program** (reduction of syst. for DUNE-HyperK).

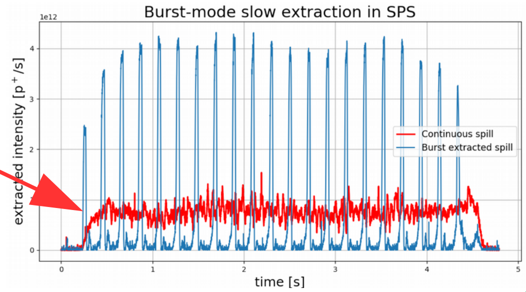


~ to scale
(simply a sketch)

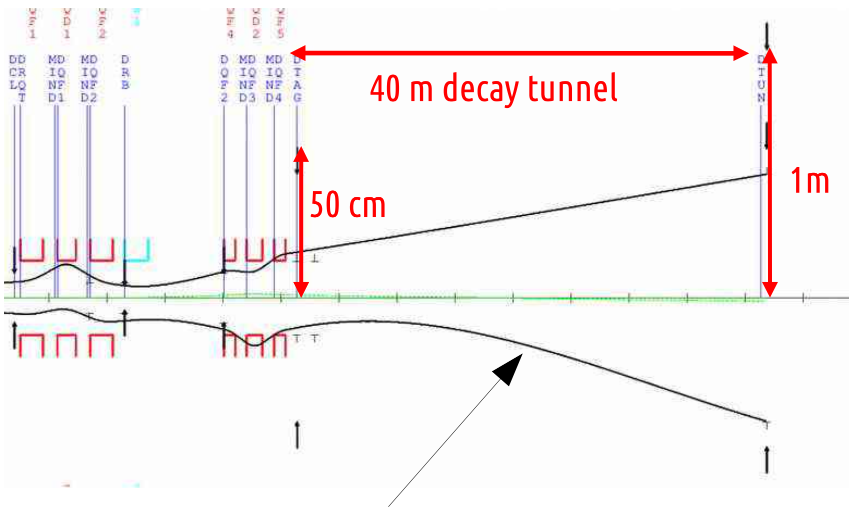


The ENUBET beamline: "static" option

- Proton extraction scheme: Single slow extraction (2-4 s).
- Reference beam: 8.5 GeV/c, 10% momentum bite
- Quadrupoles: 15 cm wide, L < 2 m, B = 4 to 7 T/m
- Dipole: 15 cm wide, L = 2 m, B =1.8 T → **7.4° bending**
- Envelope at tunnel exit 50 ×50 cm (Tunnel radius 1m)



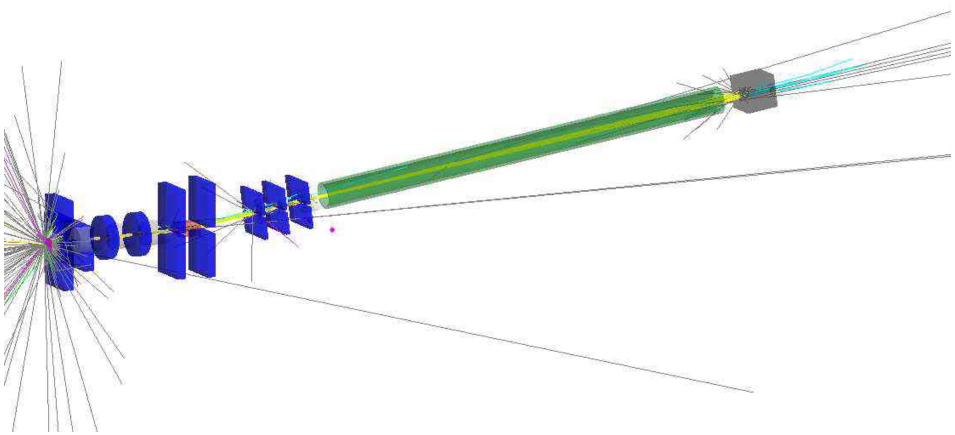
Optics optimized through **TRANSPORT**



Beam envelope

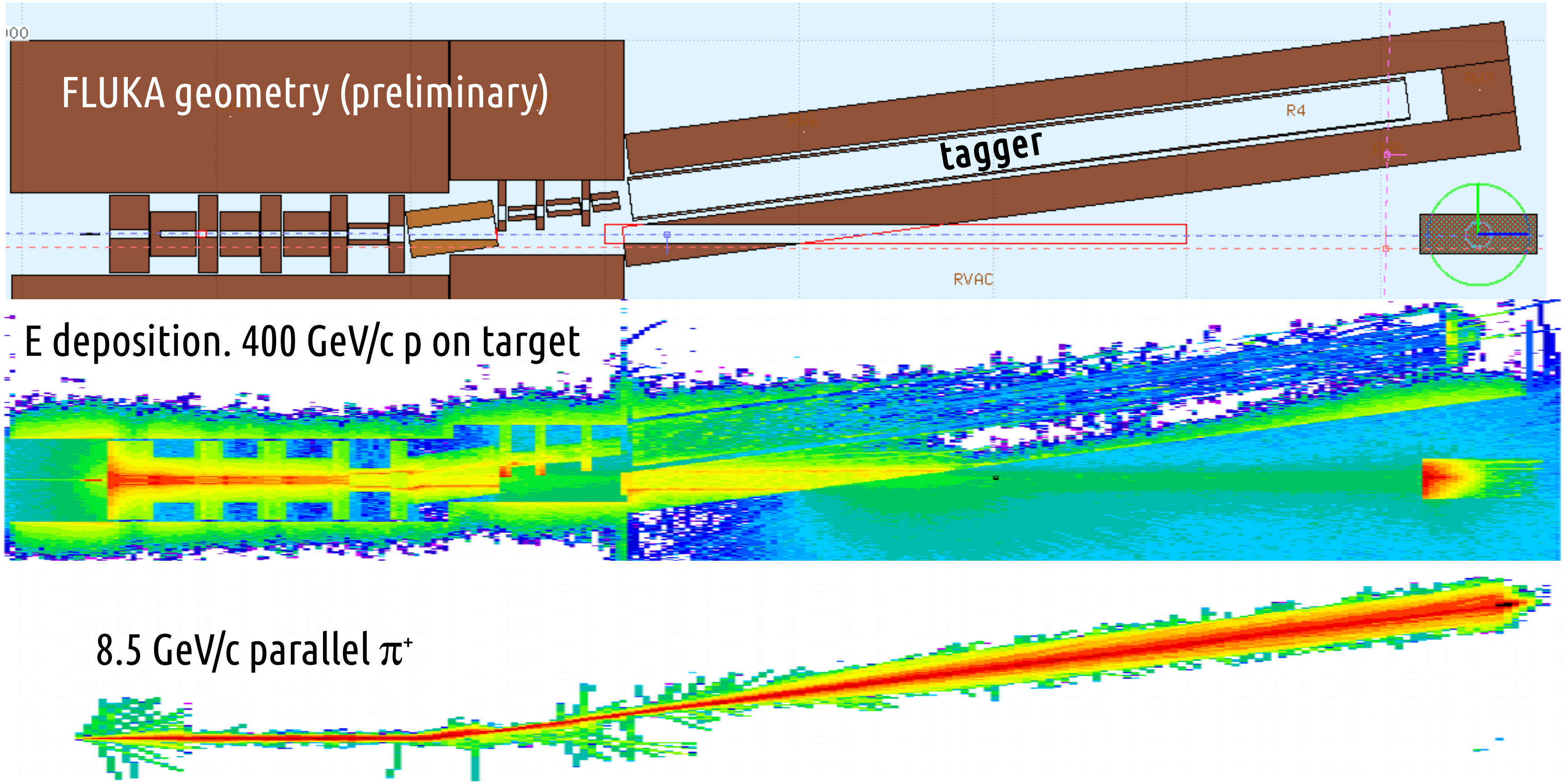
G4beamline

"full simulation" → efficiencies, backgrounds



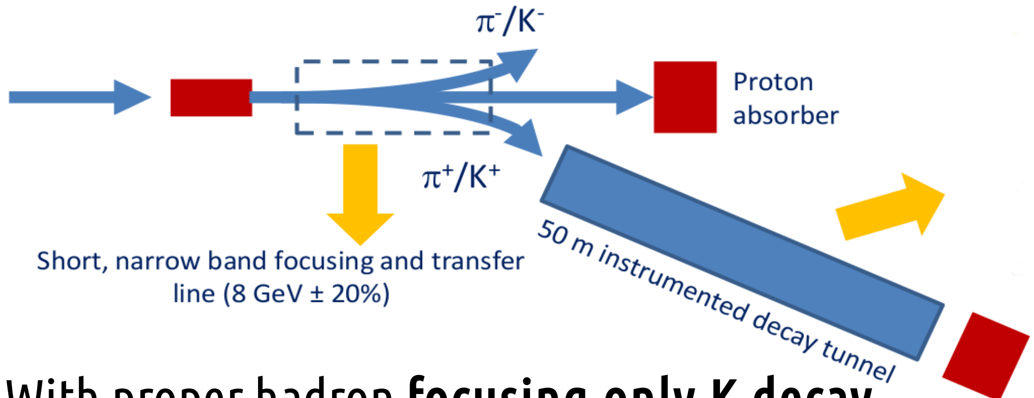
The static beamline: FLUKA simulation

Assess the specs of **rad-hard upstream focusing quadrupoles**
Optimize shielding to
- **reduce halos** in the tagger region
- **suppress the decays** of off-momentum mesons **out of tagger acceptance**



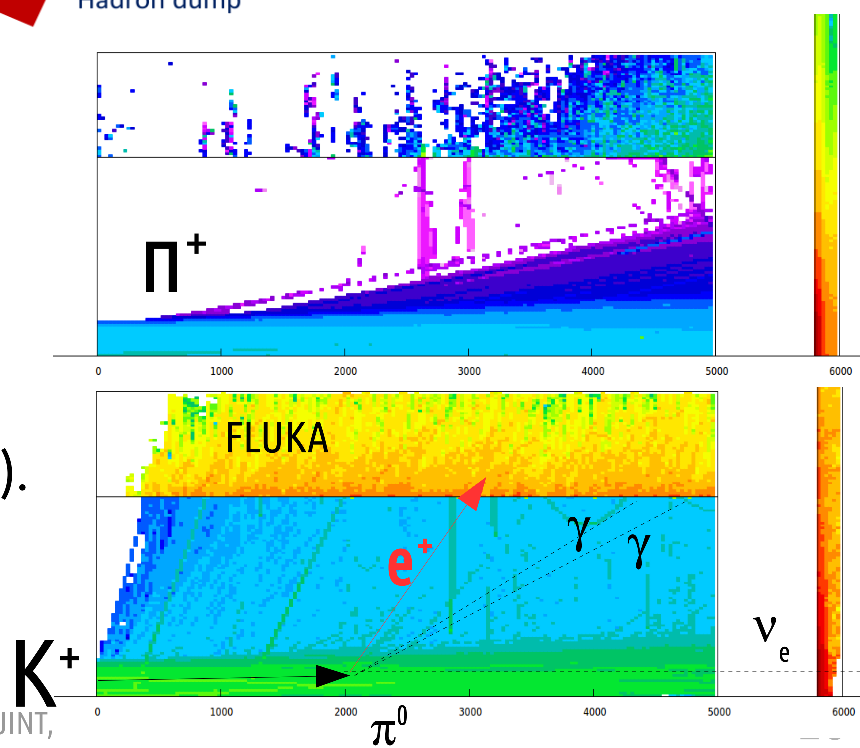
The ENUBET monitored beam

- **Hadron beam-line**: charge selection, focusing, fast transfer of π^+/K^+
- **Tagger**: real-time, "inclusive" **monitoring** of K decay products



- $p_{K,\pi}$ = 8.5 ± 20% GeV/c
- θ < 3 mrad over 10 x 10 cm^2
- Tagger: L = 50 m, r = 40 cm

- With proper hadron **focusing only K decay products** are measured in the tagger being emitted at **large angles** (unlike pion decay products) allowing
  - a **complete control** of produced ν_e using e$^+$ from K_{e3} (~98%). Muon decays gives a small contribution thanks to the short tunnel (~50 m).
  - **tolerable rates / detector irradiation** < 500 kHz/cm^2, O(~1 kGy)

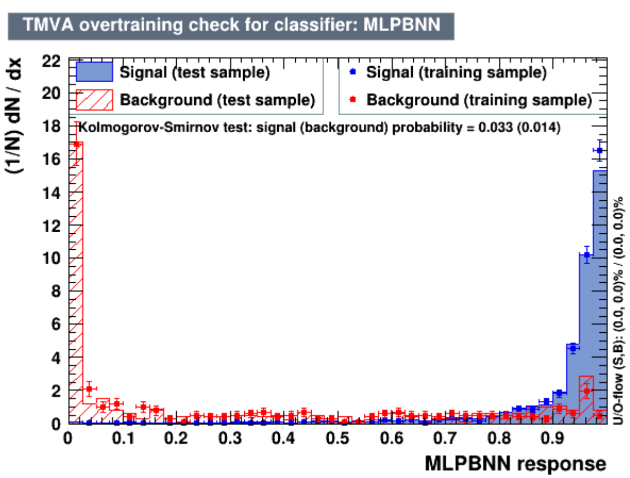


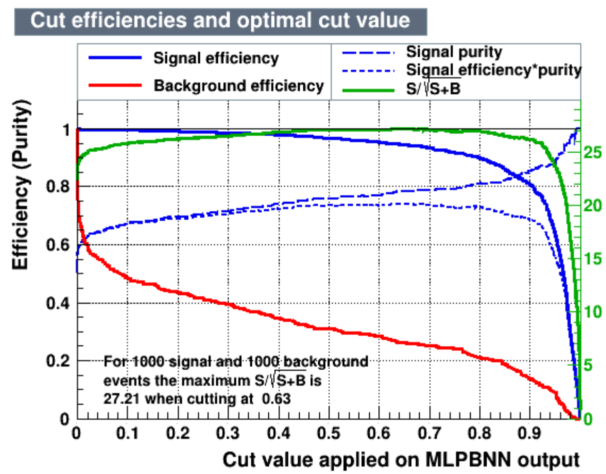
The Tagger – positron ID from K decay

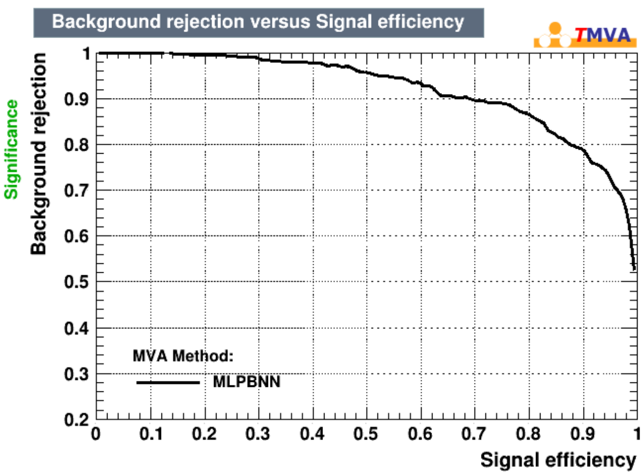
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV link neighboring modules with time (1ns) and position requirements

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







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)