The ENUBET neutrino beam

A. Longhin (Padova University and INFN)
on behalf of the ENUBET Collaboration

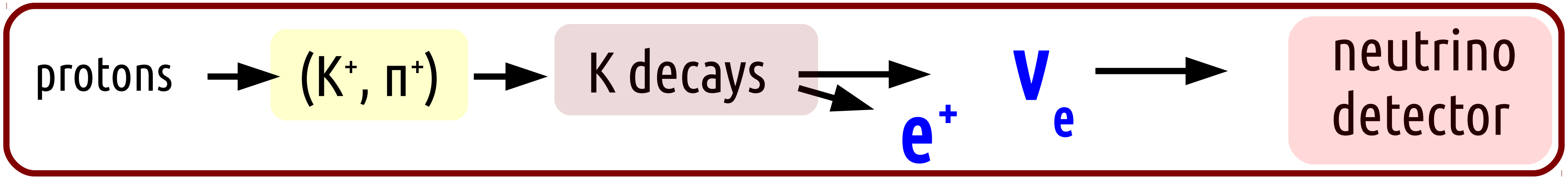
NUINT 2018
L'Aquila, 15-19 Oct 2018

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).

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**

  $K^+ \rightarrow e^+ \nu_e \pi^0$ → 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** → Correlations with interaction radius allows an **a priori knowledge of the neutrino spectra**

Neutrino beams for precision physics: the ERC ENUBET project

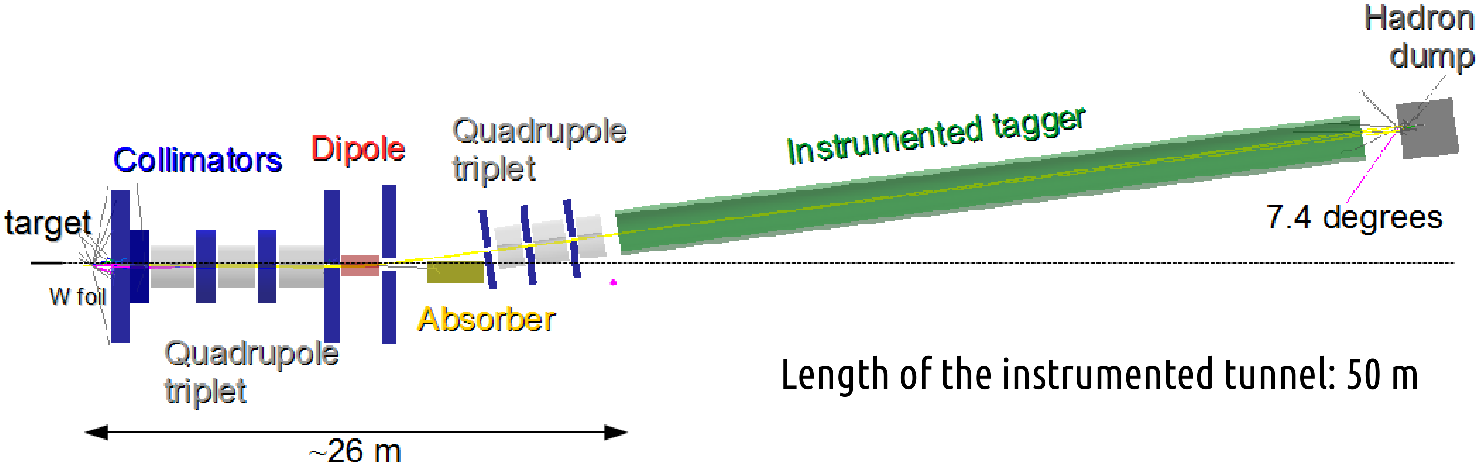
Enhanced NeUtrino BEams from kaon Tagging

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

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**

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

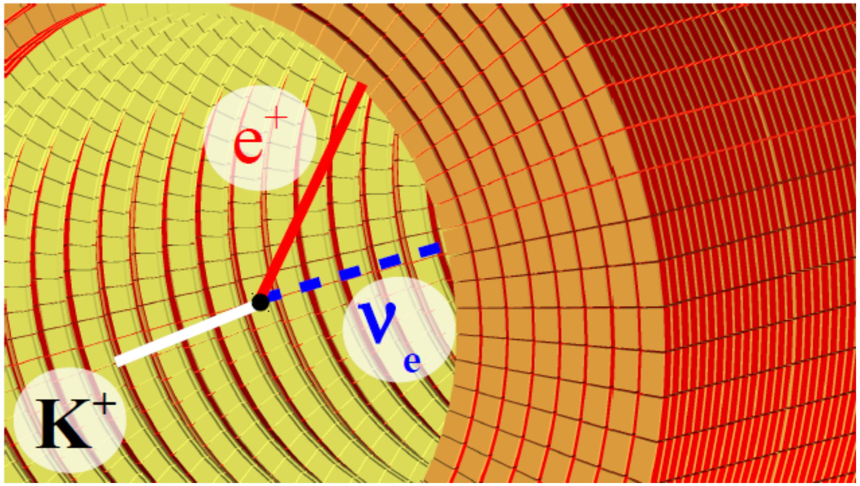
Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level.**

Two pillars:

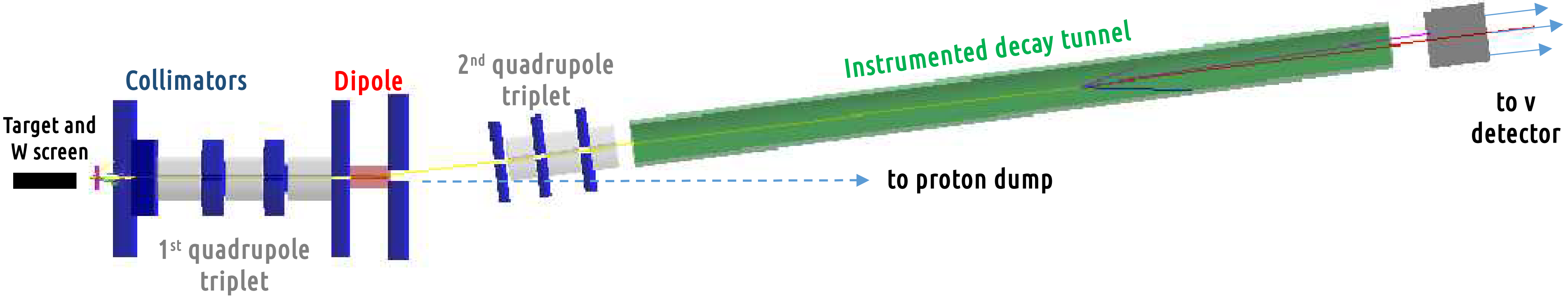
- Build and test with data a **demonstrator** of the instrumented decay tunnel
- Design/simulate the layout of the **hadronic beamline**

We **present** at **NUINT 2018**

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



The ENUBET beam line



- **Proton driver**: **CERN** (400 GeV), **FNAL** (120 GeV), **J-PARC** (30 GeV)
- **Target**: 1 m Be, graphite target. FLUKA 2011
- **Focusing**
  - **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
- **Transfer line**
  - Optics: optimized with TRANSPORT to a 10% momentum bite centered at 8.5 GeV/c
  - Particle transport and interaction: full simulation with G4Beamline
  - All normal-conducting magnets, standard aperture, 2 quad triplets, 1 bending dipole
- **Decay tunnel**
  - Radius: 1 m. Length: 40 m
  - 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
“static”	19	1.4	2 s (b)	85	6.2	x5

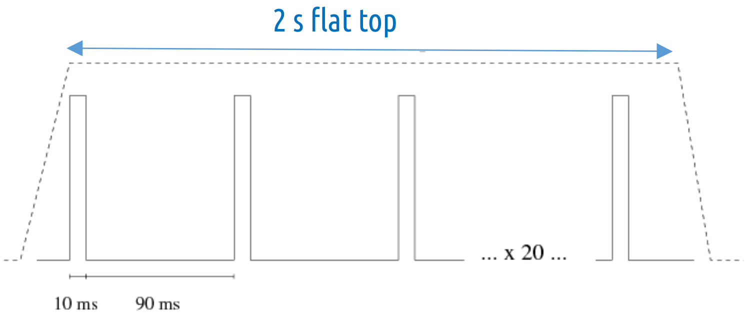
(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle.
(b) Slow extraction. Detailed performance and losses currently under evaluation at CERN
(c) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155.

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**

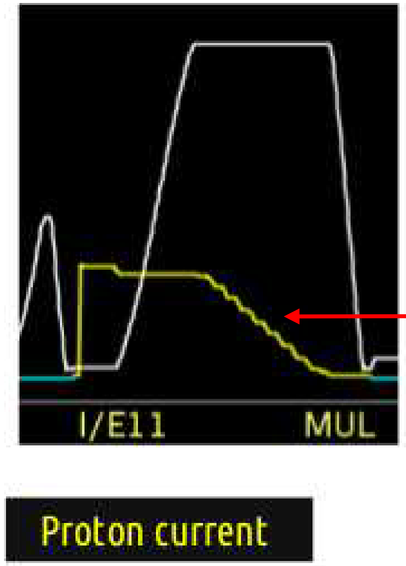
The ENUBET beam line: horn-based option

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

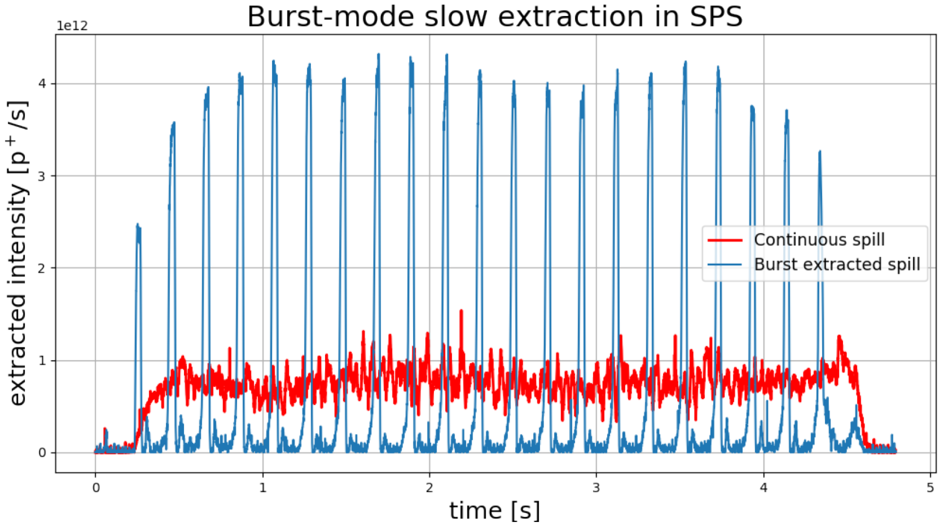


Preliminary studies Jul/Aug 2018
CERN-BE-OP-SPS, Velotti, Pari, Kain, Goddard

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



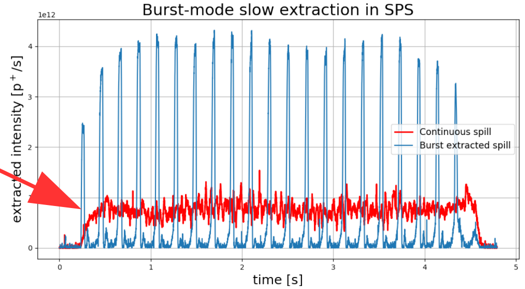
Proton current steps in correspondance of bunches



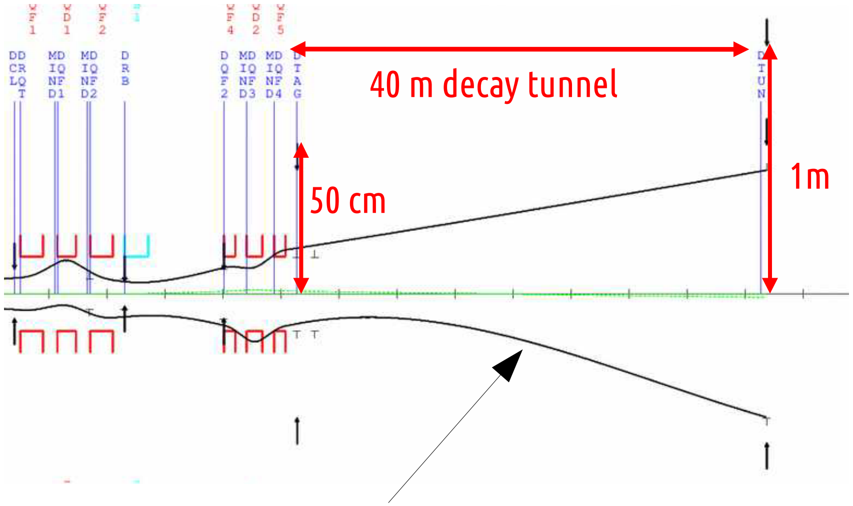
- Beam bunches in time with horn pulses
- **Further studies →** understand radiation losses. Iterative corrections. Sextupoles: sharper bursts.

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
- Dipole: 15 cm wide, L = 2 m, B =1.8 T → **7.4° bending**
- Envelope at tunnel exit 50 ×50 cm (Tunnel radius 1m)



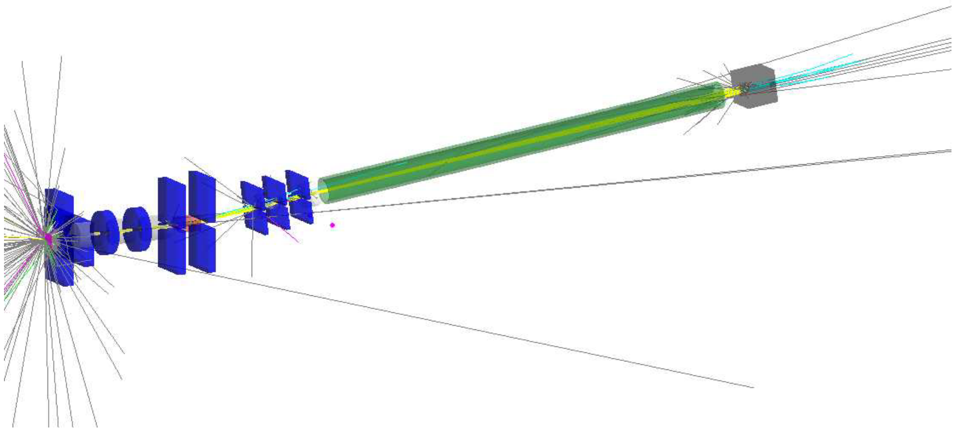
Optics optimized through **TRANSPORT**



Beam envelope

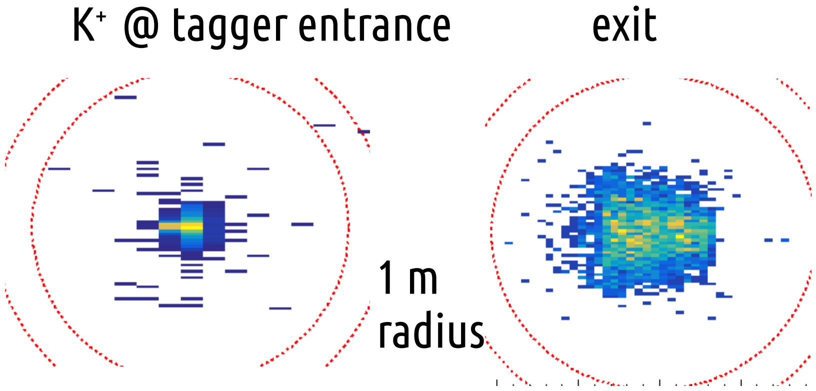
G4beamline

“full simulation” → efficiencies, backgrounds

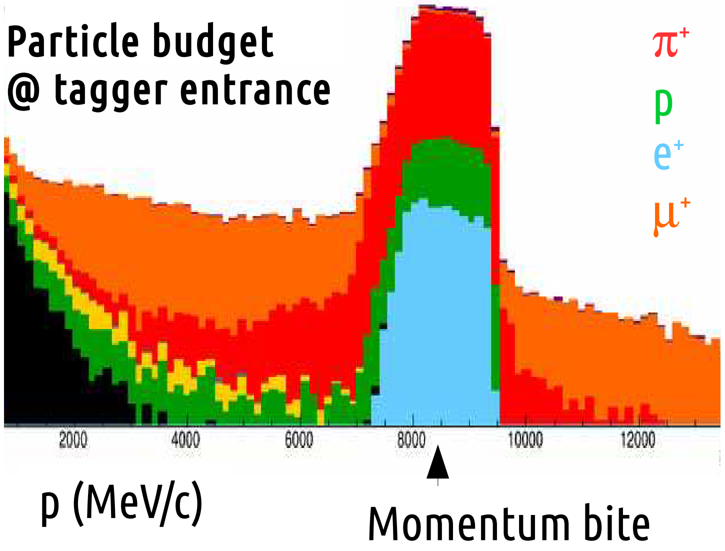


The static beamline: emittance, particle content

Divergence of the kaon beam

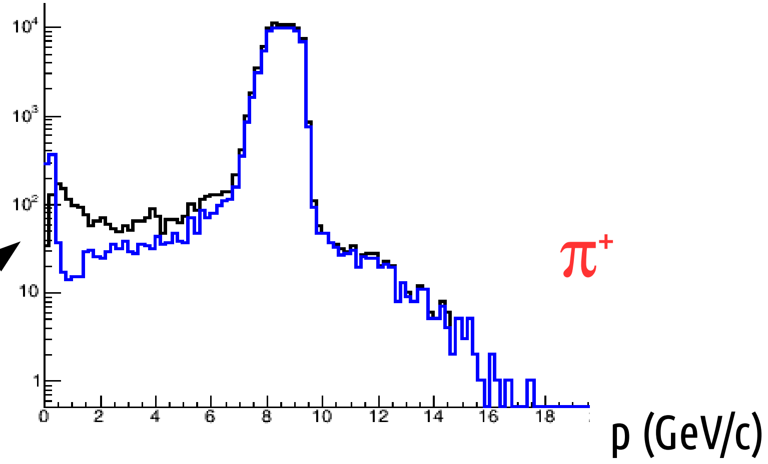


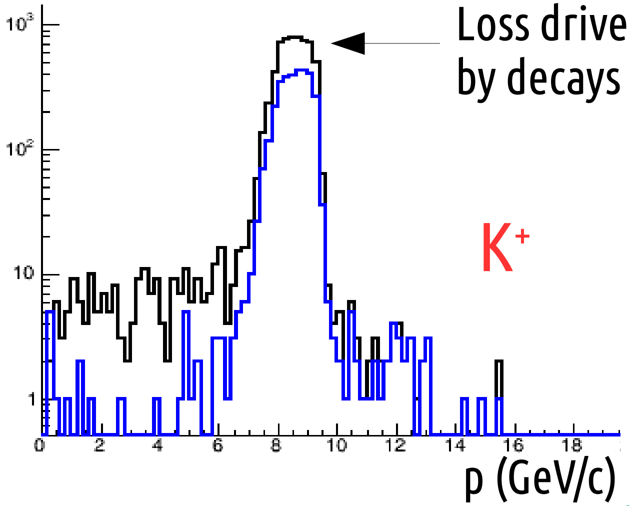
Particle budget @ tagger entrance



Spectra @ tagger entrance and **exit**

Low energy high angle π





Loss driven by decays

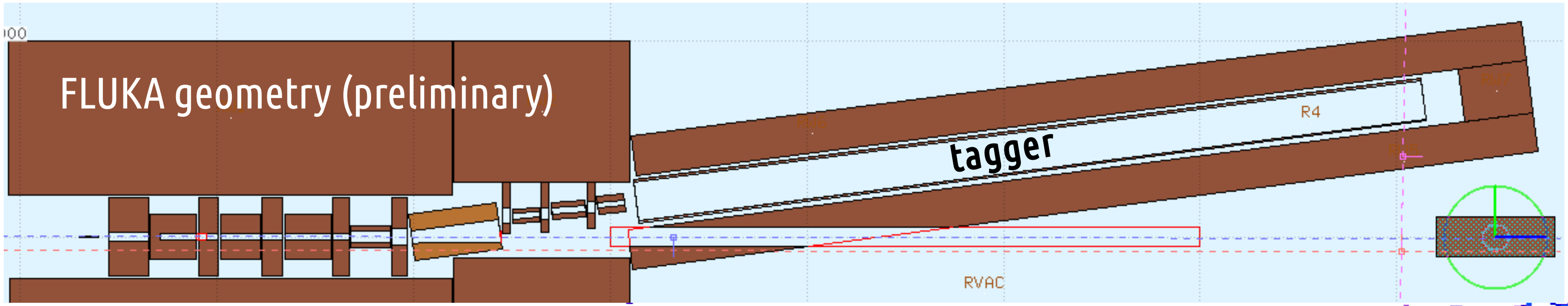
The static beamline: FLUKA simulation

Goals: assess the specs of **rad-hard upstream focusing quadrupoles**

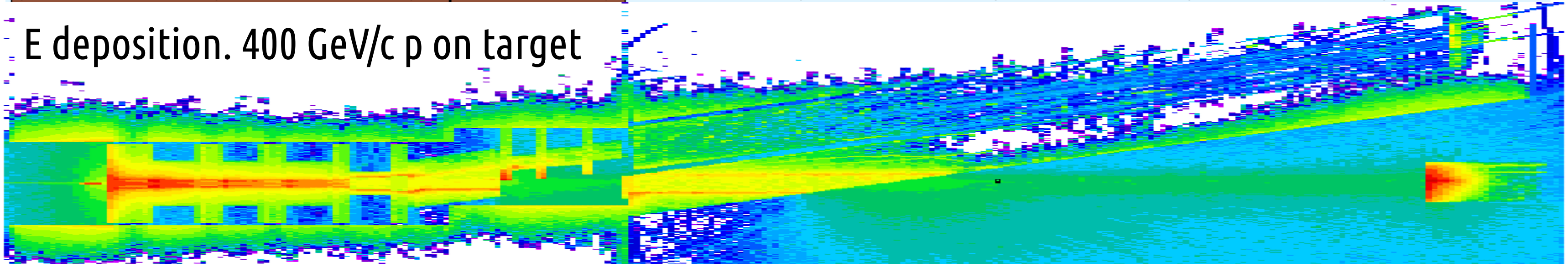
Optimize shielding to

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

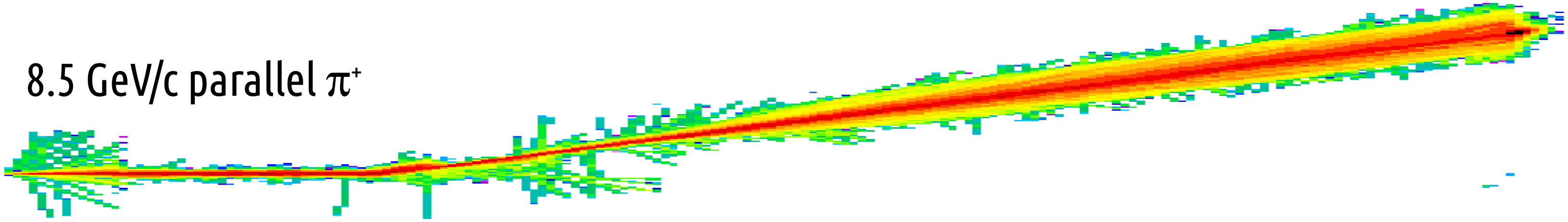
Work in progress. Study the **location of the proton dump**.



FLUKA geometry (preliminary)



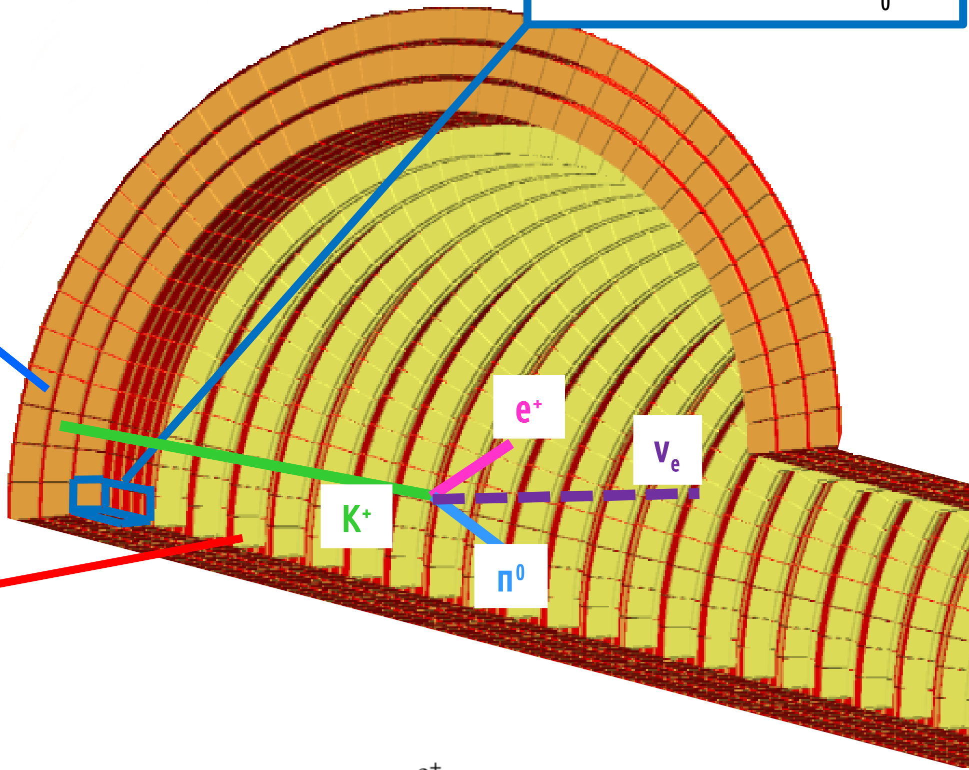
E deposition. 400 GeV/c p on target



8.5 GeV/c parallel π^+

The ENUBET tagger

Ultra Compact Module
3×3×10 cm³ – 4.3 X_0



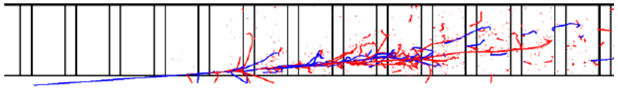
Calorimeter

Longitudinal segmentation

Plastic scintillator + Iron absorbers

Integrated light readout with SiPM

→ $e^+/\pi^\pm/\mu$ separation

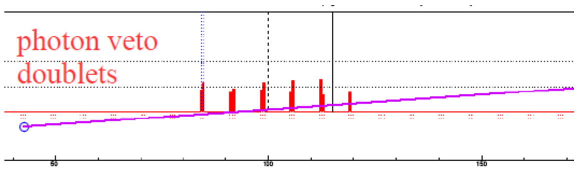


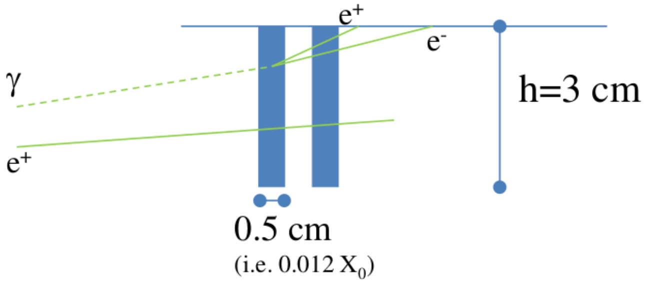
Integrated photon veto

Plastic scintillators

Rings of 3×3 cm² pads

→ π^0 rejection



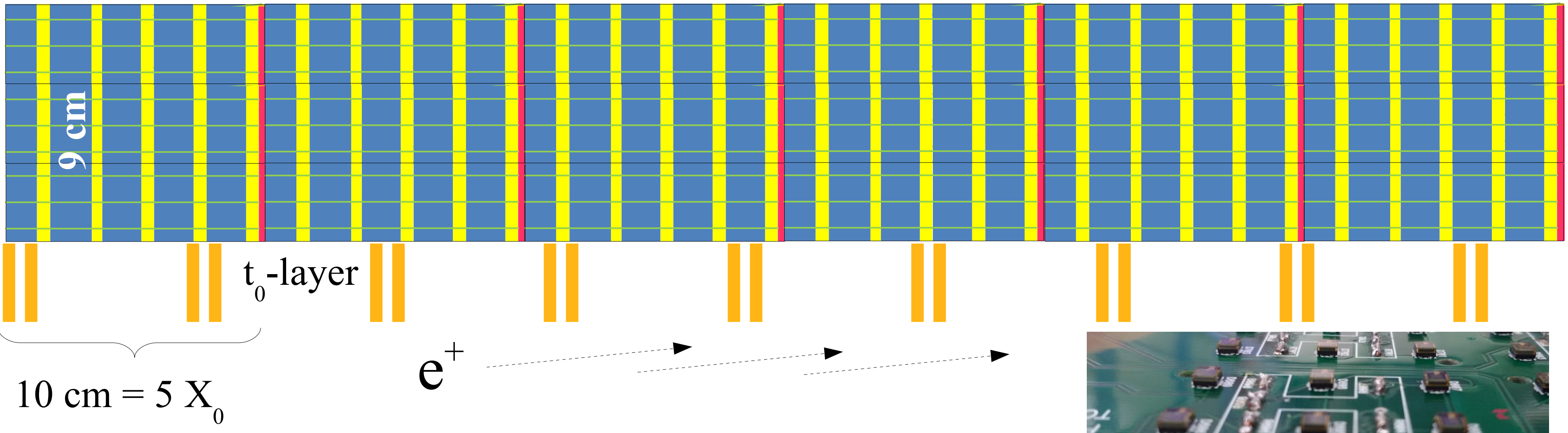


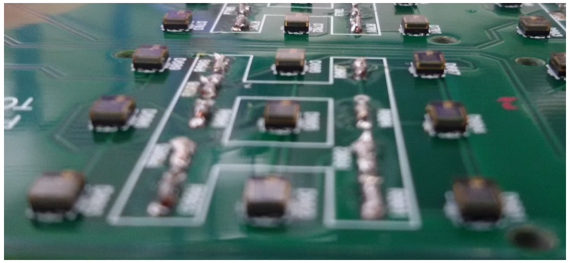
e^+ (signal) topology

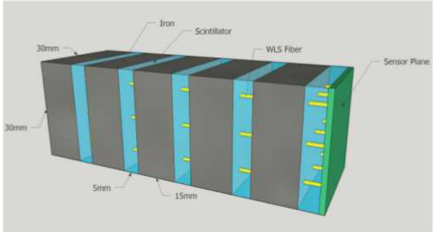
π^0 (background) topology

π^+ (background) topology

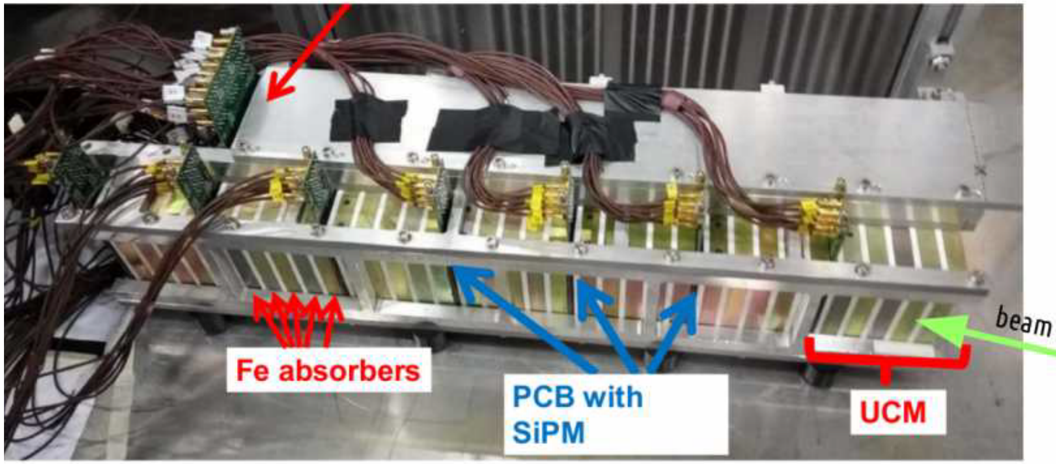
The tagger: shashlik with integrated readout

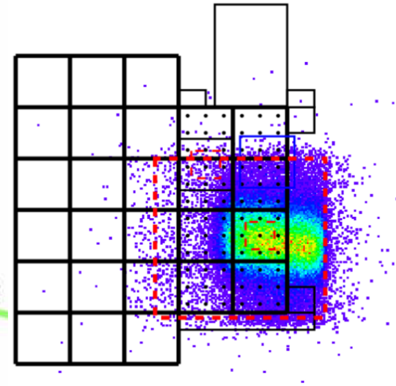






CERN PS test beam Nov 2016





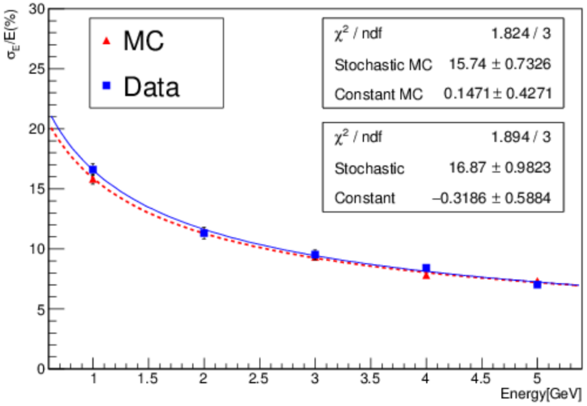
Test beam results with shashlik readout

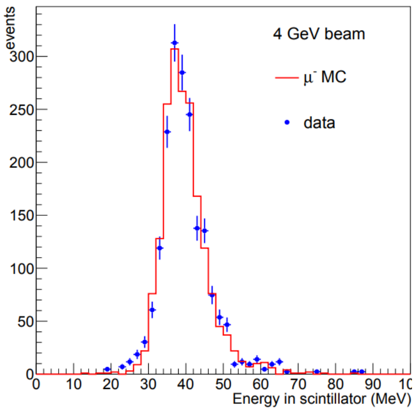
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

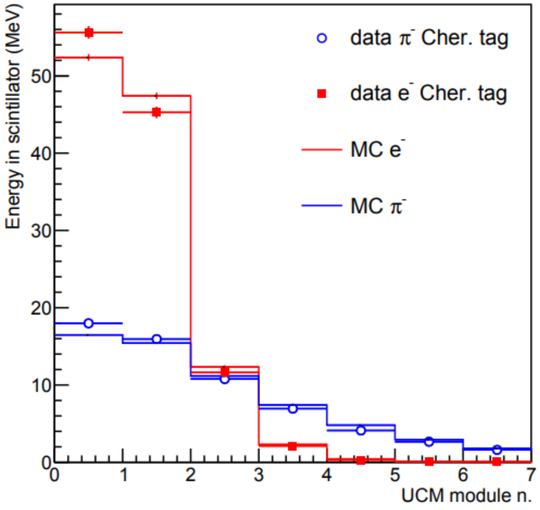
Tested response to MIP, e and π⁻

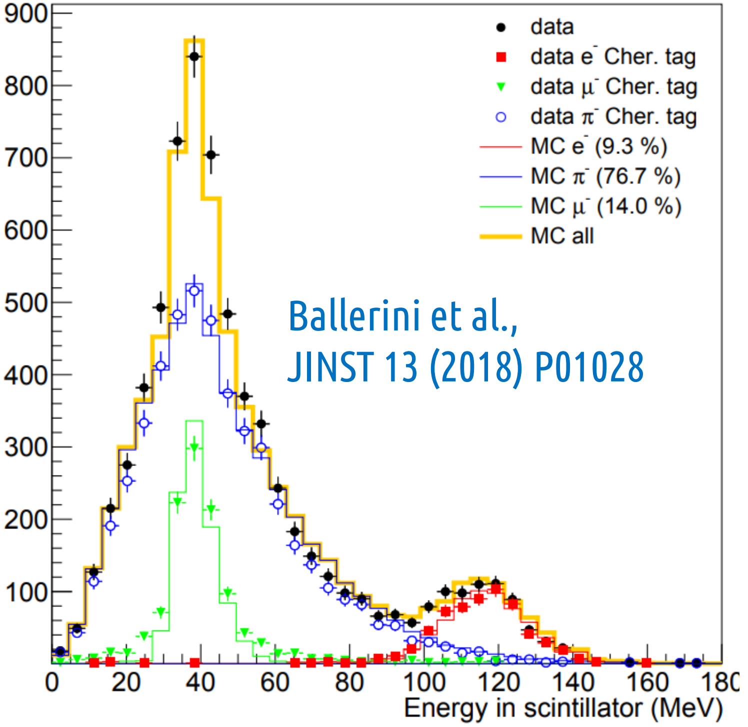
- e.m. energy resoluton: 17%/√E (GeV)
- Linearity deviations: <3% in 1-5 GeV range
- From 0 to 200 mrad → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities
- Equalizing UCM response with mips MC/data already in good agreement

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



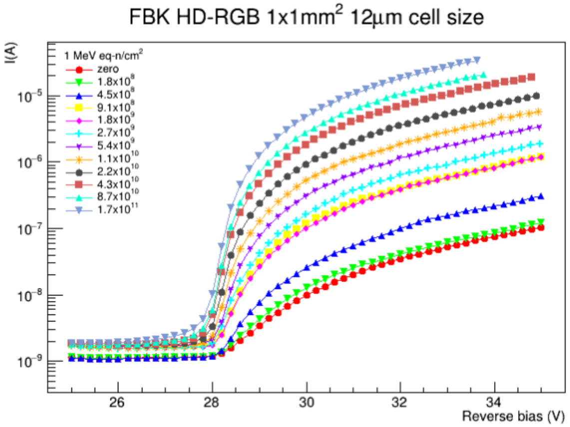






Ballerini et al., JINST 13 (2018) P01028

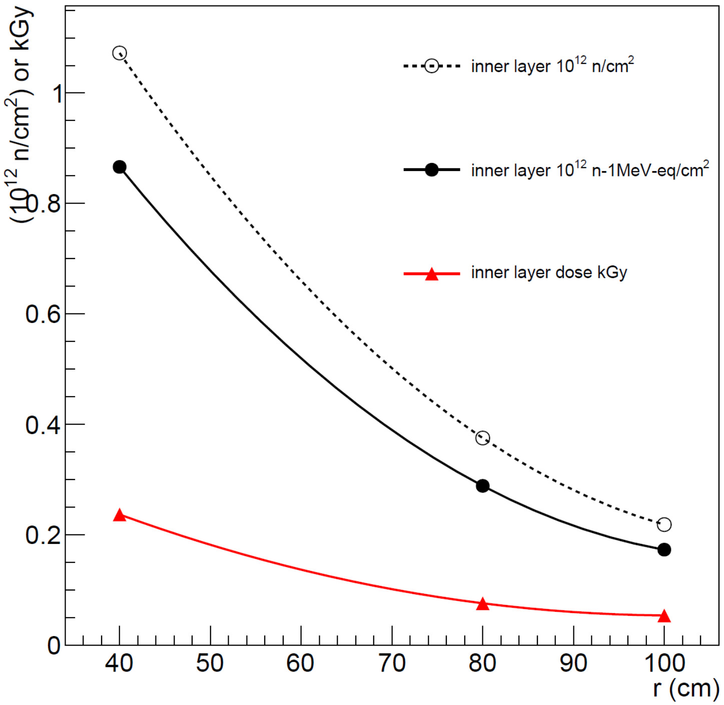
SiPM irradiation studies



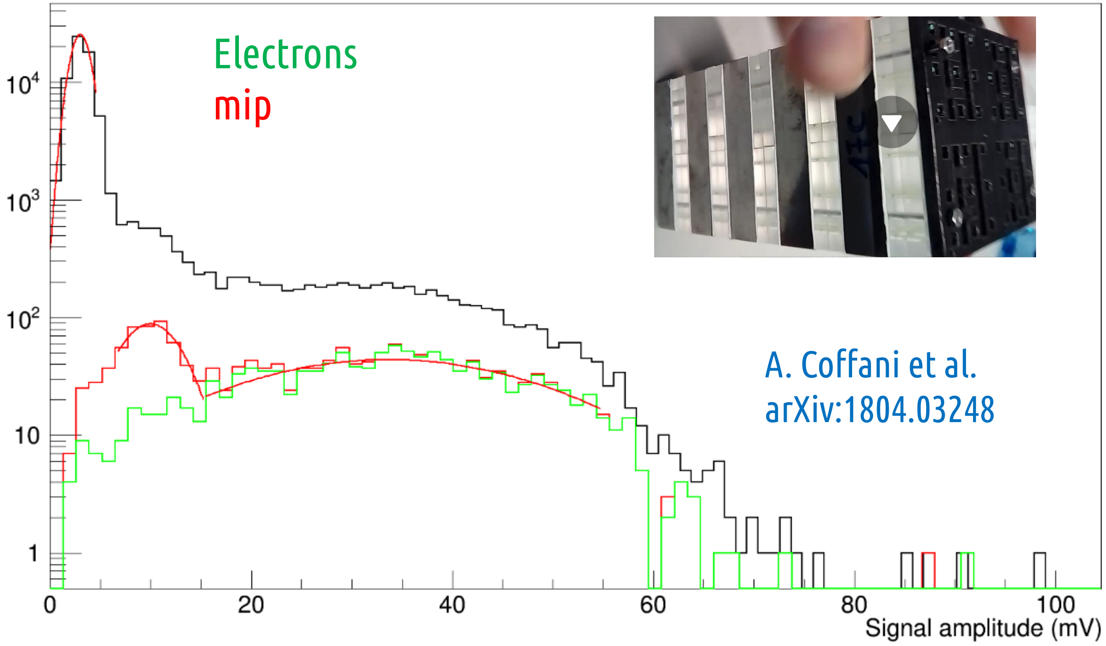
SiPM were **irradiated at LNL-INFN** with 1-3 MeV neutrons in Jun 2017

→ Characterization of 12,15 and 20 μm SiPM cells up to **1.2×10^{11} 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



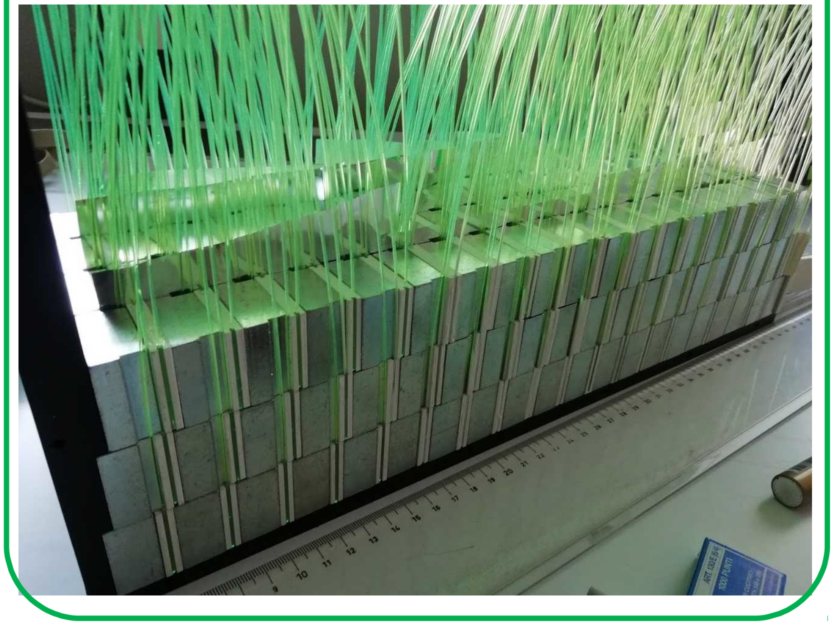
A. Coffani et al.
arXiv:1804.03248

- 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.

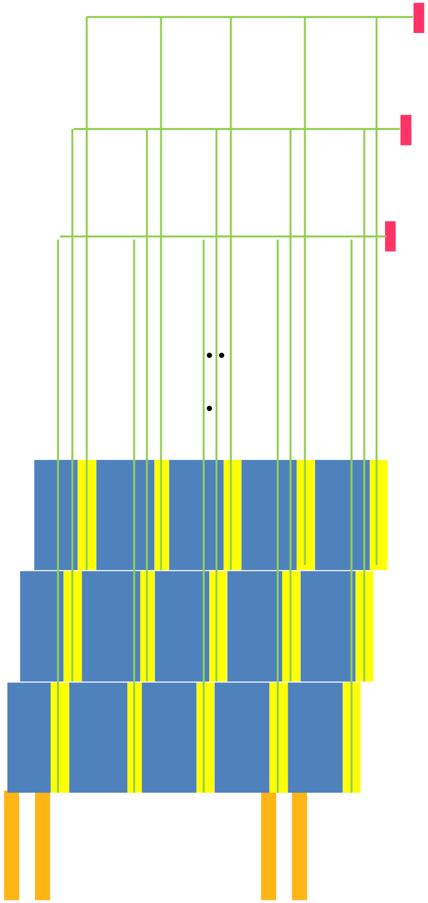
The tagger: lateral readout option

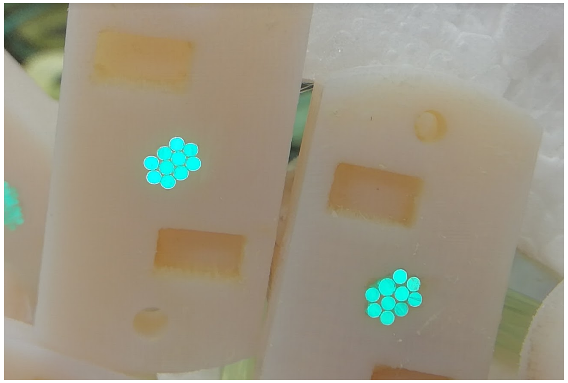
Light **collected from scintillator sides** and **bundled** to a single SiPM reading 10 fibers (1 UCM). SiPM are not immersed anymore in the hadronic shower → less compact but .. much **reduced neutron damage** (larger safety margins), better **accessibility**, safer **WLS-SiPM coupling**.

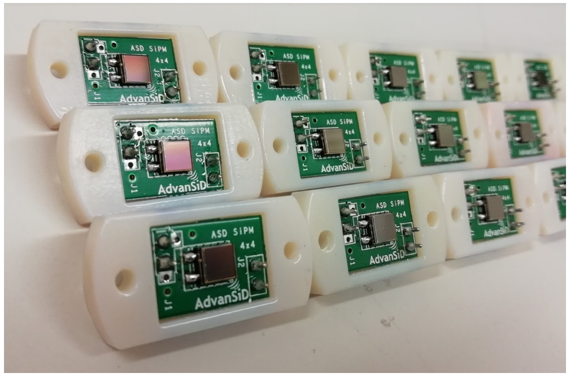
Sampling calorimeter with lateral WLS light collection



May 2018, CERN-PS test beam

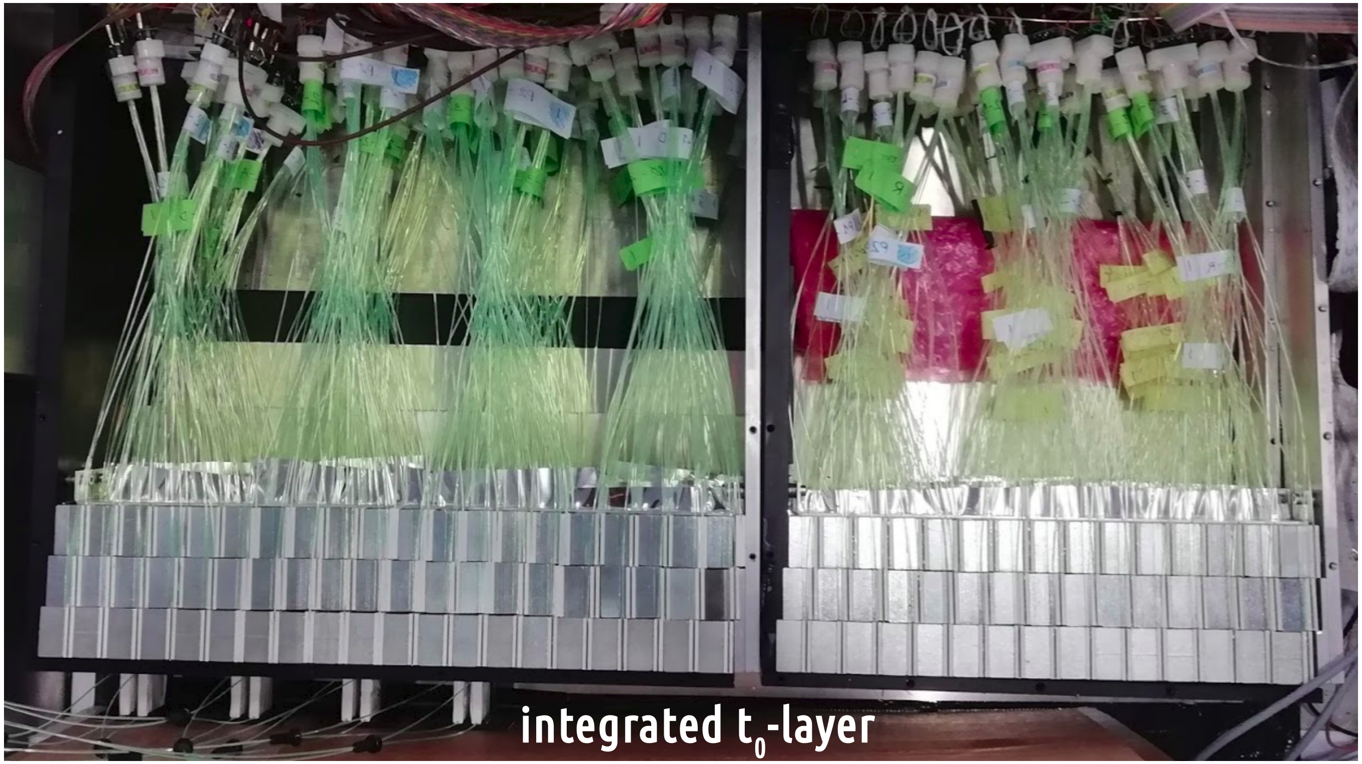




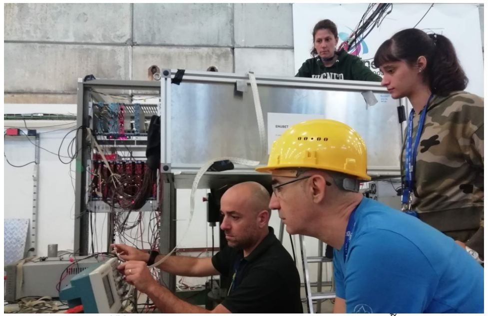


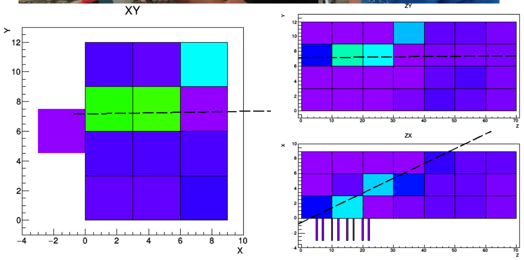
The Tagger – Detector R&D

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

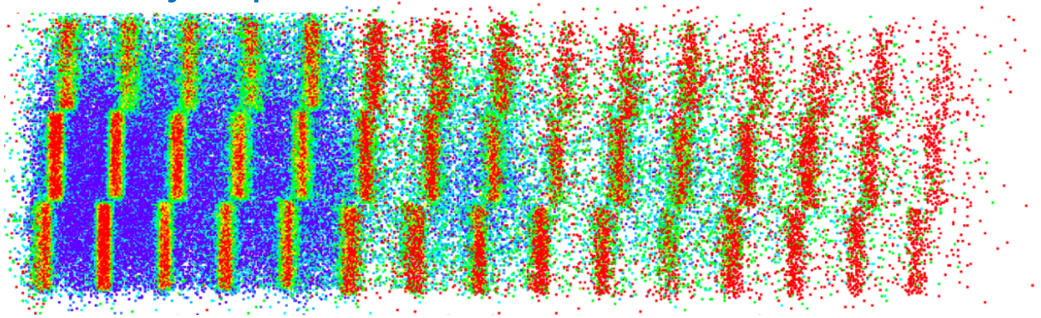


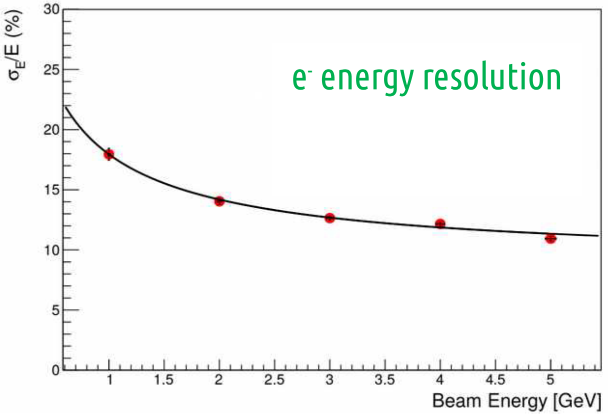
Resolution, light yield, uniformity, optical coupling to photo-sensors, e/π separation. In progress.





Efficiency maps





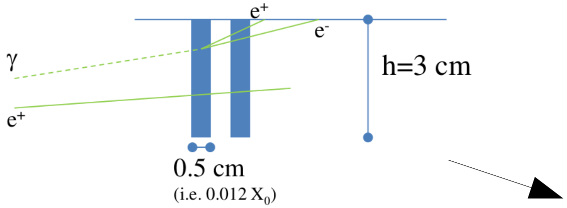
The photon veto – test beam

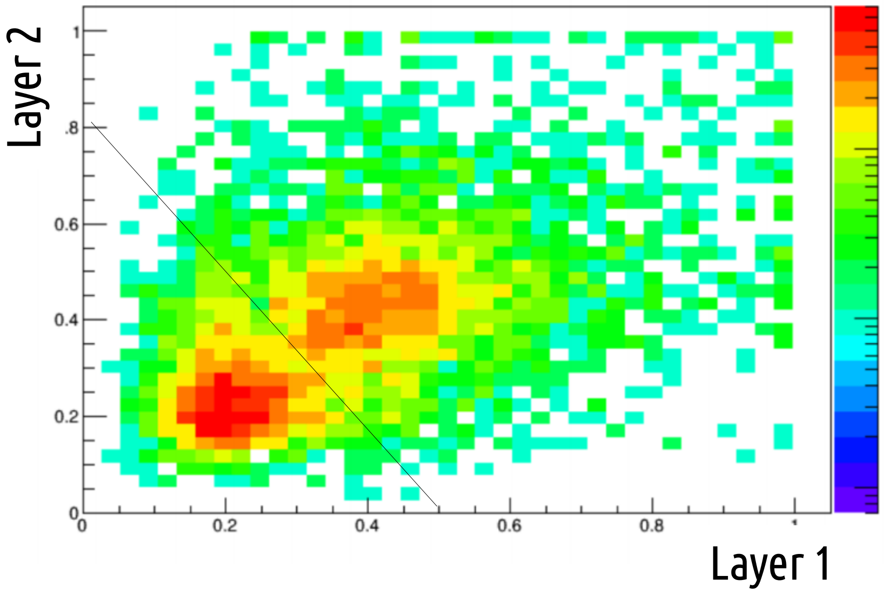
@ CERN-PS T9 line 2016-2018

- **γ / e^+ discrimination + timing**

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

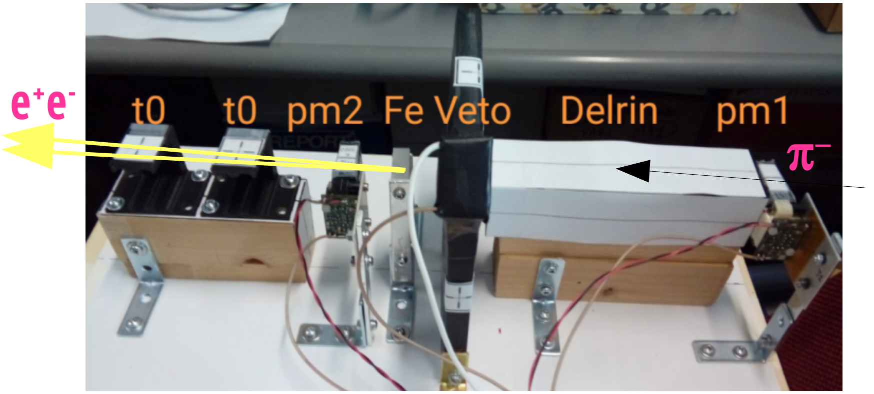
- light collection efficiency → >95%
- time resolution → $\sigma \sim 400$ps
- 1mip/2mip separation

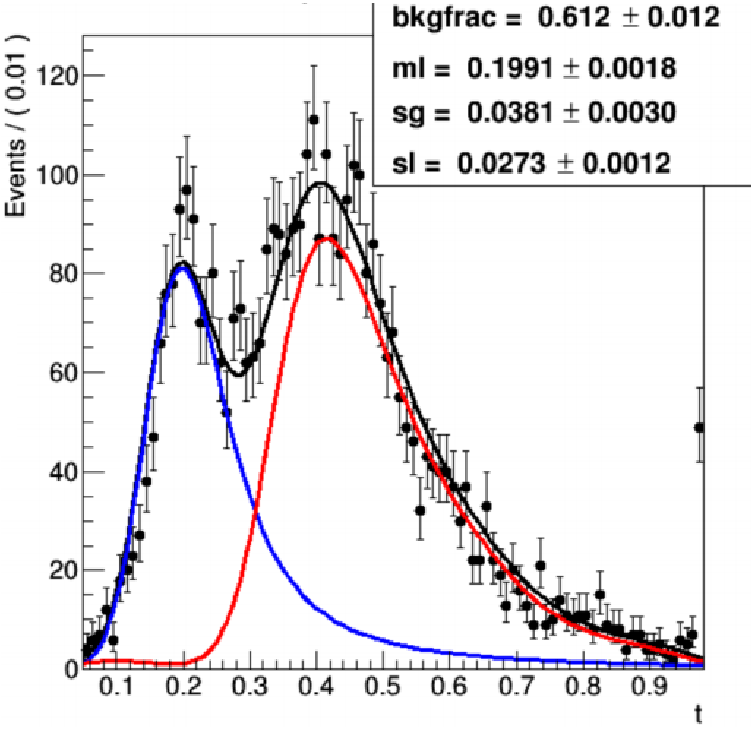




charge exchange: $\pi^- p \rightarrow n\, \pi^0\, (\rightarrow \gamma\gamma)$

Trigger: PM1 + VETO +PM2



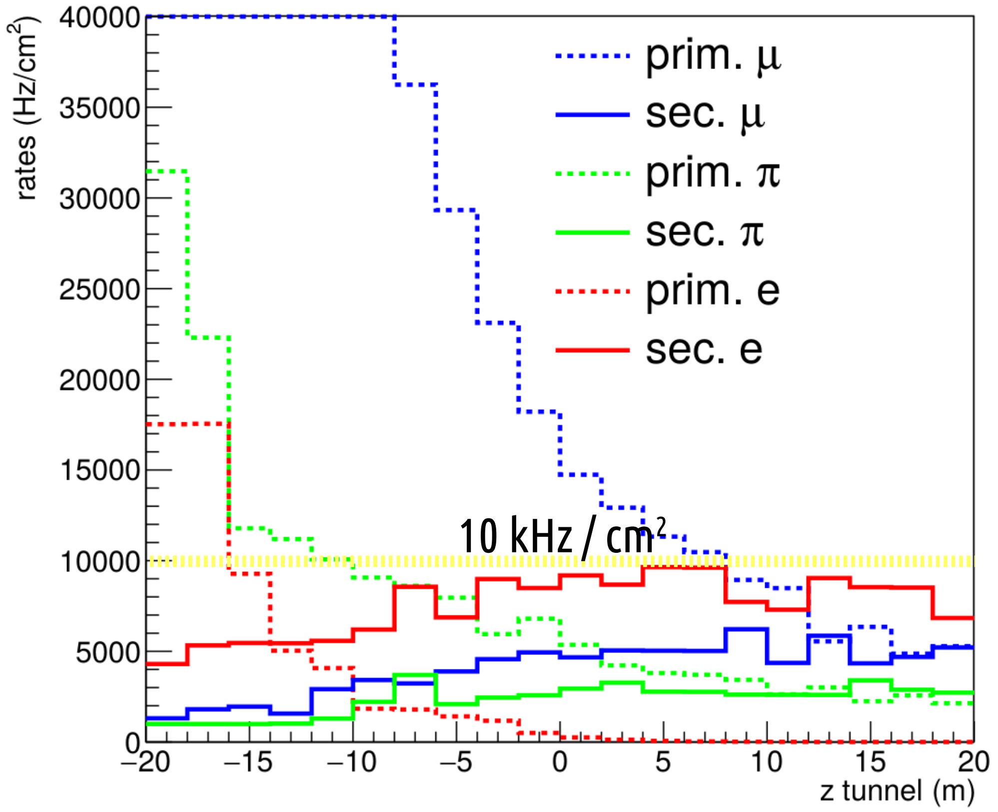


Particle rates in the decay tunnel from full sim.

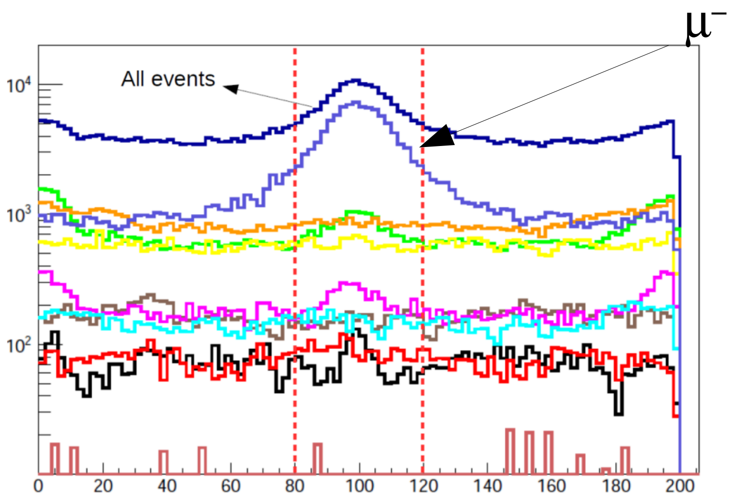
Static focusing system, 4.5 10^{13} pot in 2 s (400 GeV)

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 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.

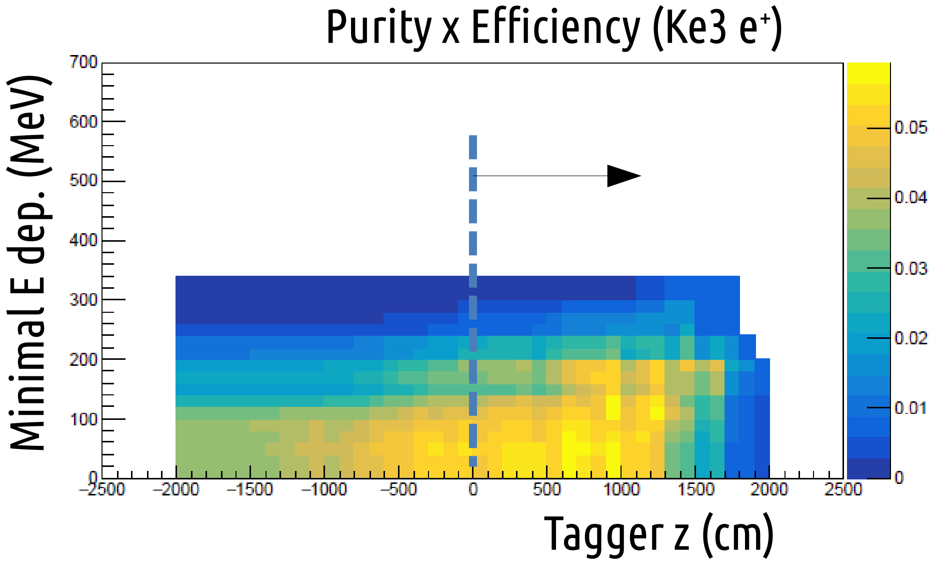
Analysis chain

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/π/μ 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⁺)

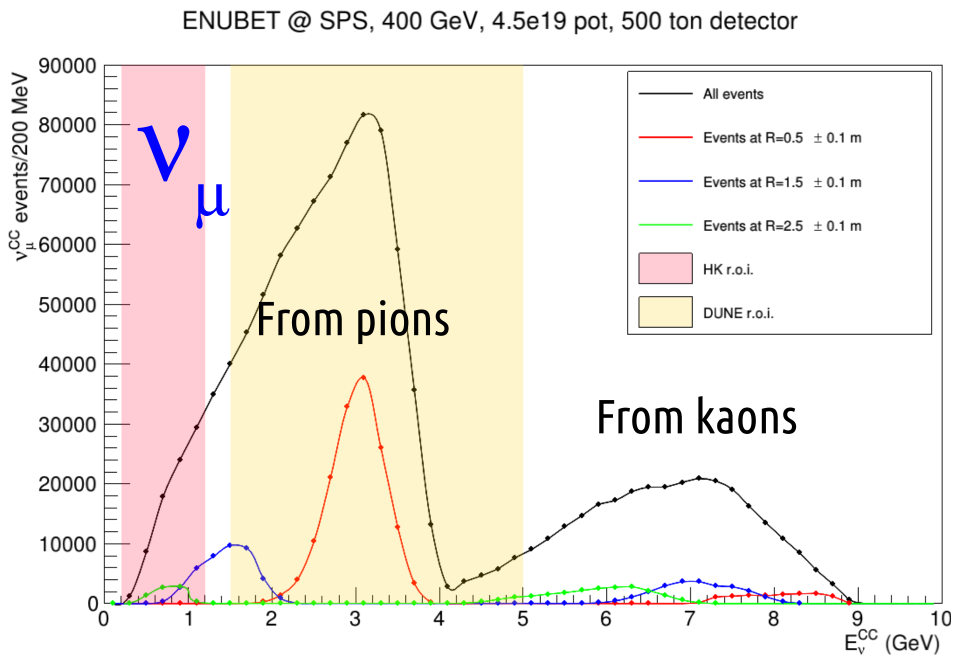
ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

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

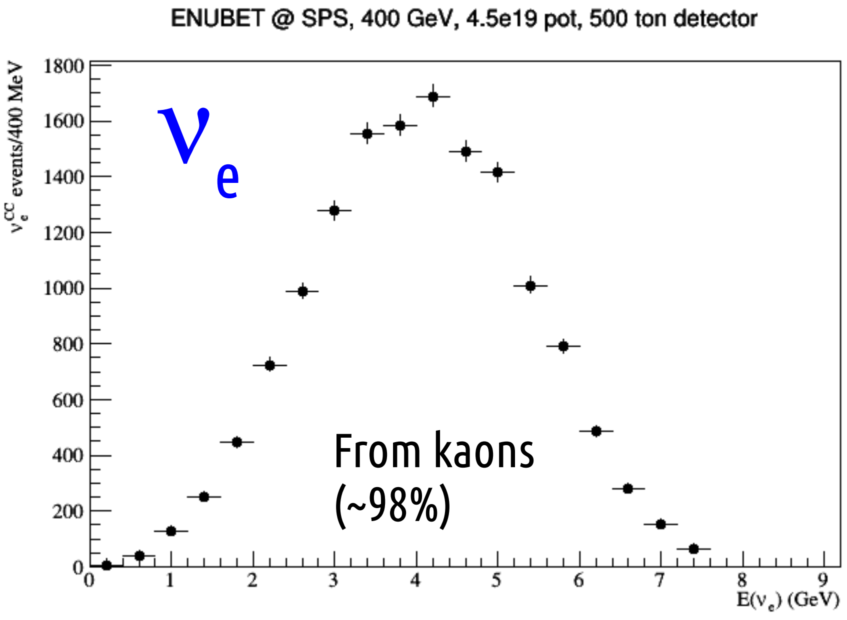
- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- **Integrated pot**: 4.5 x 10^{19} at SPS (6 months in dedicated mode, ~1 year in shared mode) or, equivalently, 1.5 10^{20} pot at the Fermilab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



From pions

From kaons

1.2 million ν_μ Charged Current per year

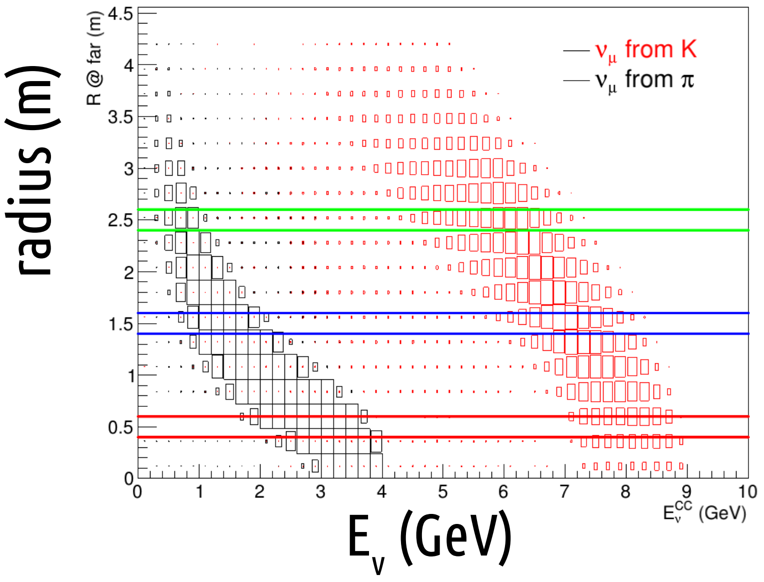


From kaons (~98%)

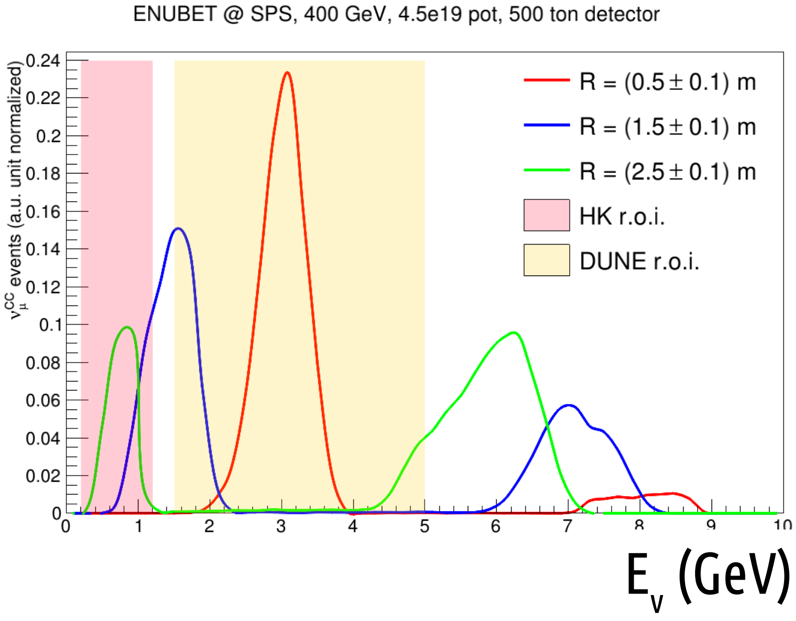
14000 ν_e Charged Current per year

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.

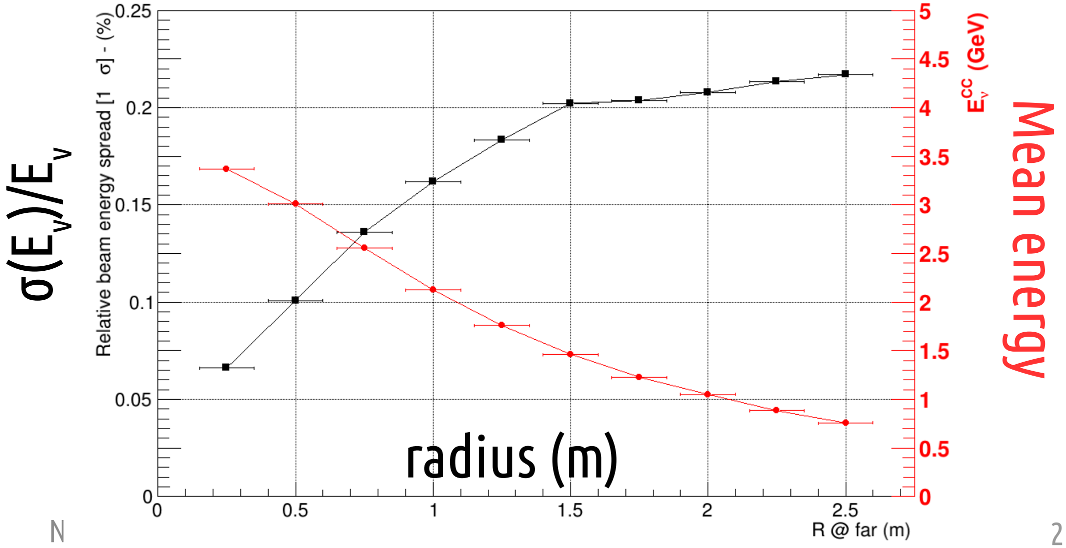


ν_μ ^{CC} in radial bins (1 norm.)



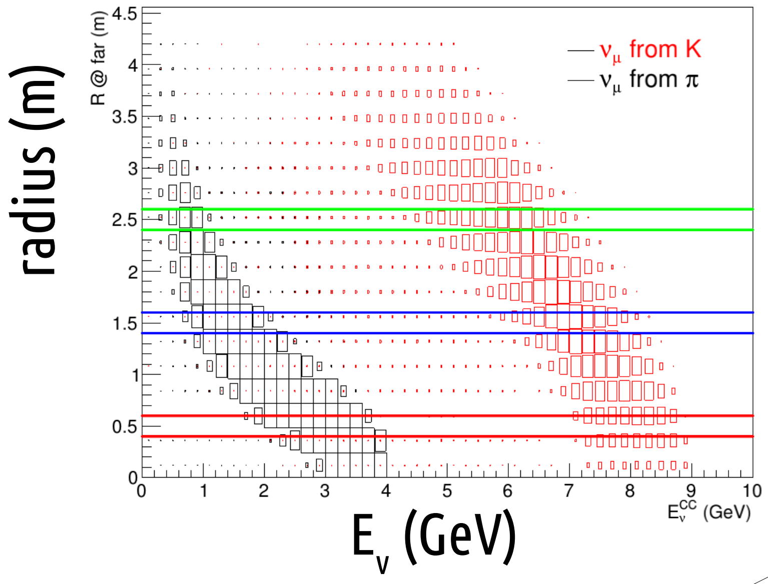
The beam width at fixed R
(≡ neutrino energy resolution) for
the pion component is

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

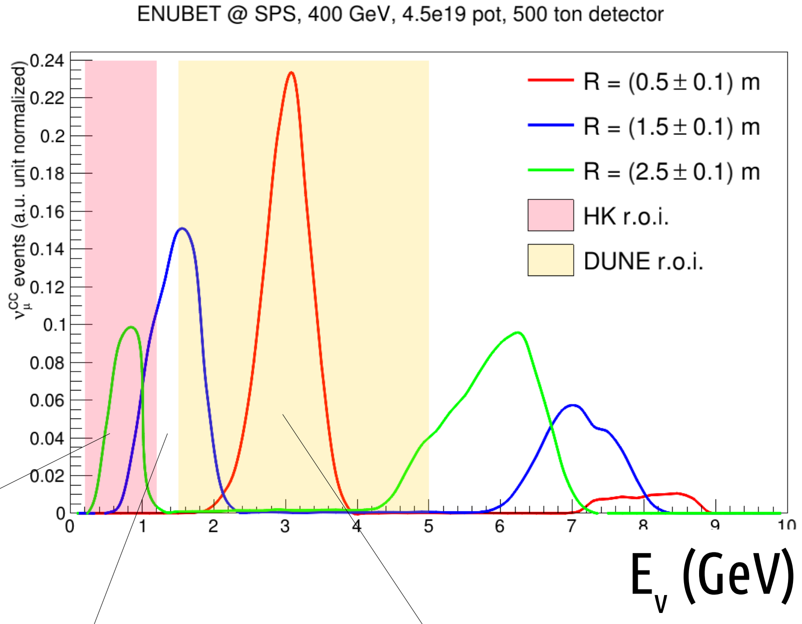


ν_μ CC events at the ENUBET narrow band beam

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

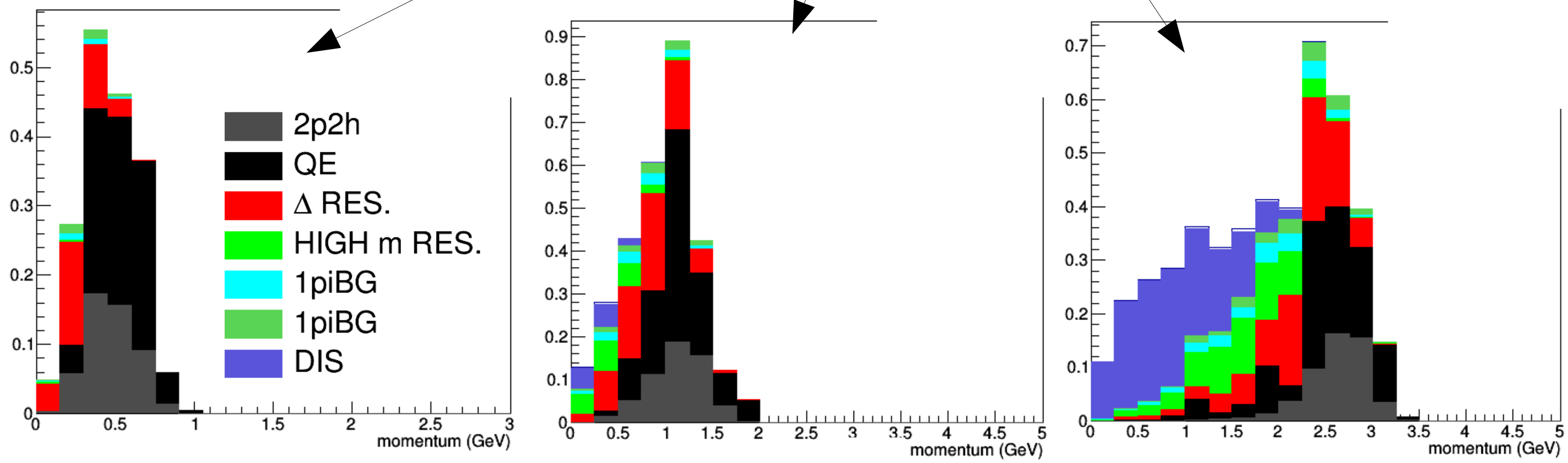


ν_μ CC in radial bins (1 norm.)



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”) → Sept. data analysis completion.
  - **Improve the design of the beamline** to reduce beam halo contamination (current S/N can be significantly improved)
  - Re-optimise the **tunnel radius** to increase geometrical acceptance

- **Systematic assessment on predicted neutrino fluxes**
- New ideas to enhance precision also on ν_μ
  - from $K_{\mu 2}$ with μ id in the tagger (in progress)
  - from π: counting μ from π in h-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)

Padova June 2016

CERN Nov 2016

CERN May 2017

CERN Oct 2017

INFN-LNL Jun 2017

THANKS!

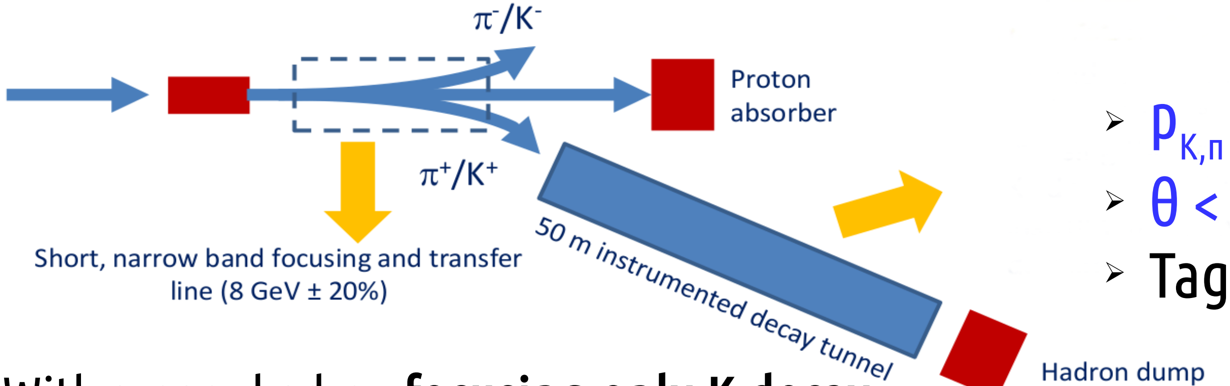
CERN May 2018

CERN Sep 2018

Milan Oct 2017

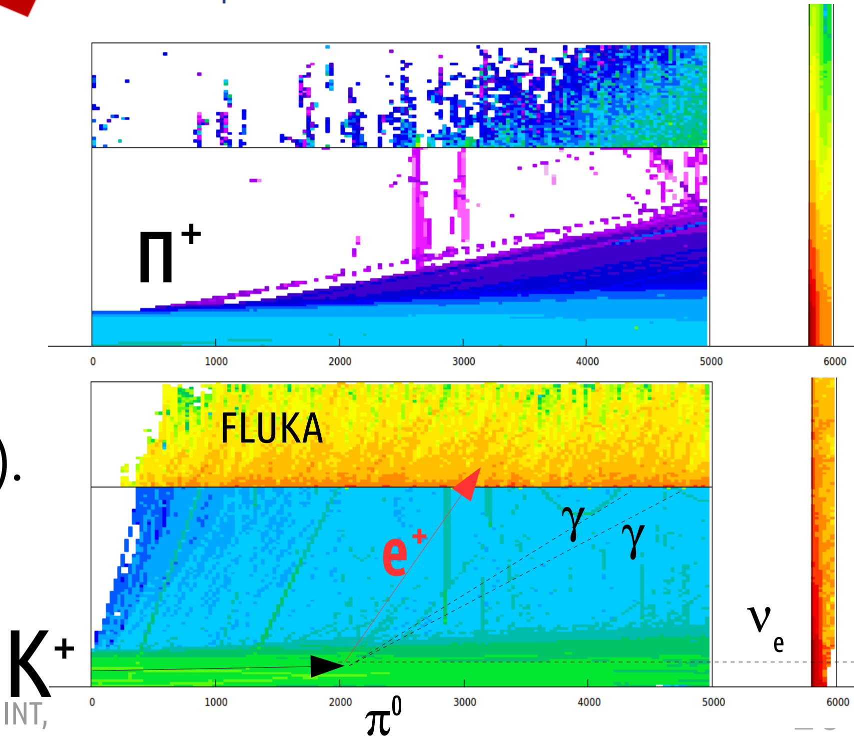
The ENUBET monitored beam

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



- $p_{K,\pi} = 8.5 \pm 20\%$ GeV/c
- $\theta < 3$ 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)

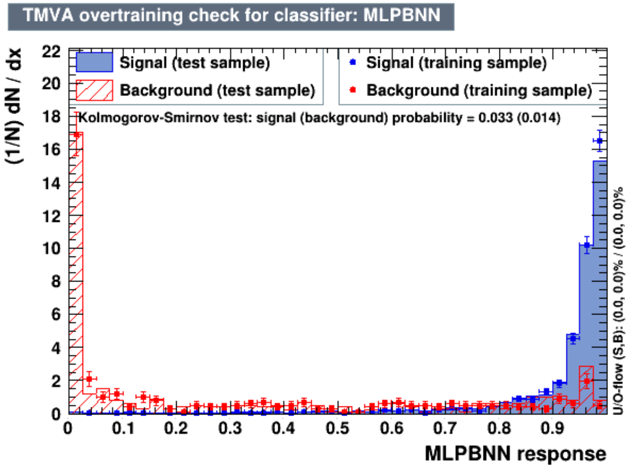


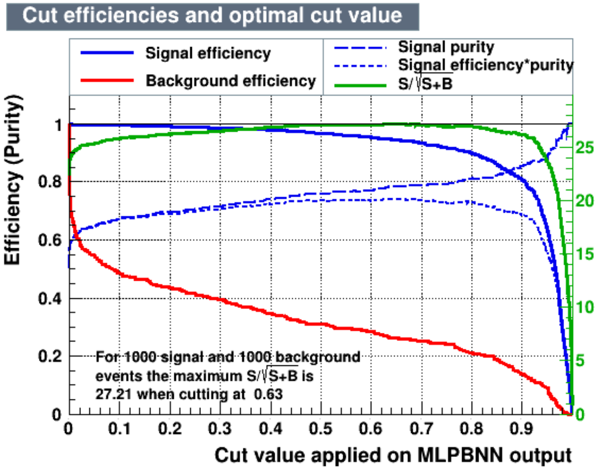
The Tagger – positron ID from K decay

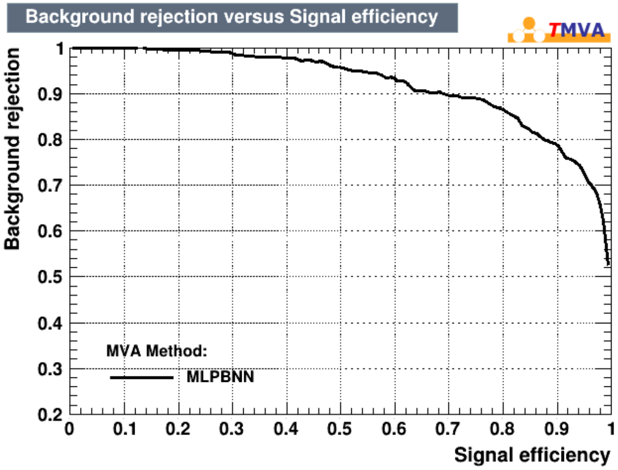
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV ▭ link neighboring modules with time (1ns) and position requirements

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)