The ENUBET neutrino beam

F. Pupilli (INFN-Padova)
on behalf of the ENUBET Collaboration

54 physicists, 12 institutions

Venice, 18-22 March 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 NeuTel 2018

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

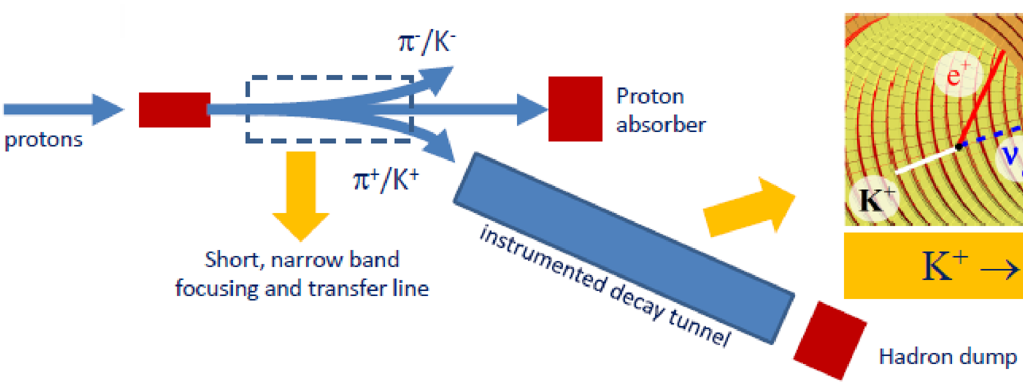
Poster by **M. Torti**

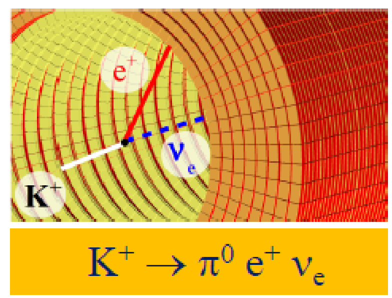
A narrow-band beam for the precision era of ν physics

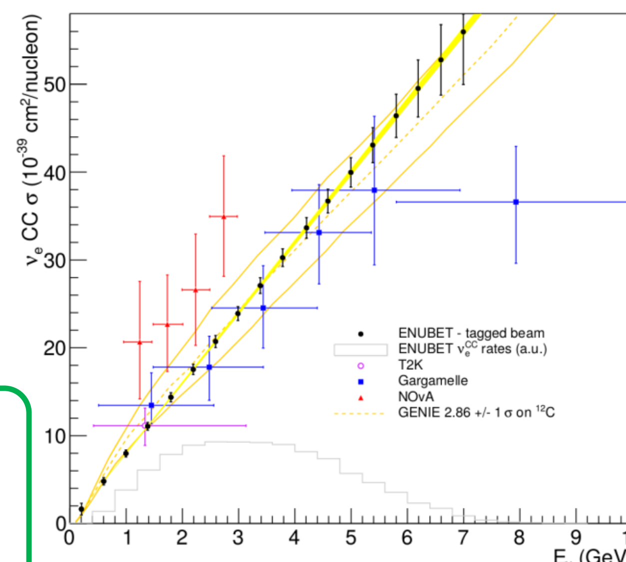
Absolute flux of ν_e and ν_μ at the 1% level
→ Remove the leading source of uncertainty in **neutrino cross section measurement**

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

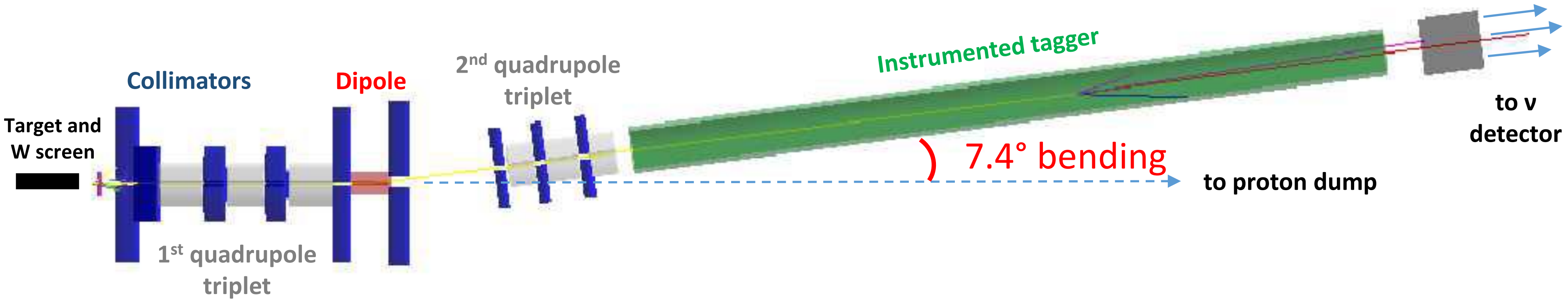






Goal of ENUBET *(ERC c.g., PI: A. Longhin, Jun 2016 – May 2021)*: demonstrate the technical feasibility and physics performance of a neutrino beam where **lepton production at large angles is monitored at single particle level** → direct measurement of the flux

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
- **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**
  - Kept short to minimize early K decays and those of off-momentum mesons out of tagger acceptance (untagged neutrino component)
  - 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 < 2m, B = 4 to 7 T/m)
1 bending dipole (15 cm wide, L = 2, B = 1.8 T)
- **Decay tunnel**: R = 1 m - L = 40 m, low power hadron dump at the end
- **Proton dump**: position and size under optimization

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 [(b)]
Horn	77	7.9	2 ms [(a)]	347	36	X2
"static"	19	1.4	2 s	86	6.3	**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

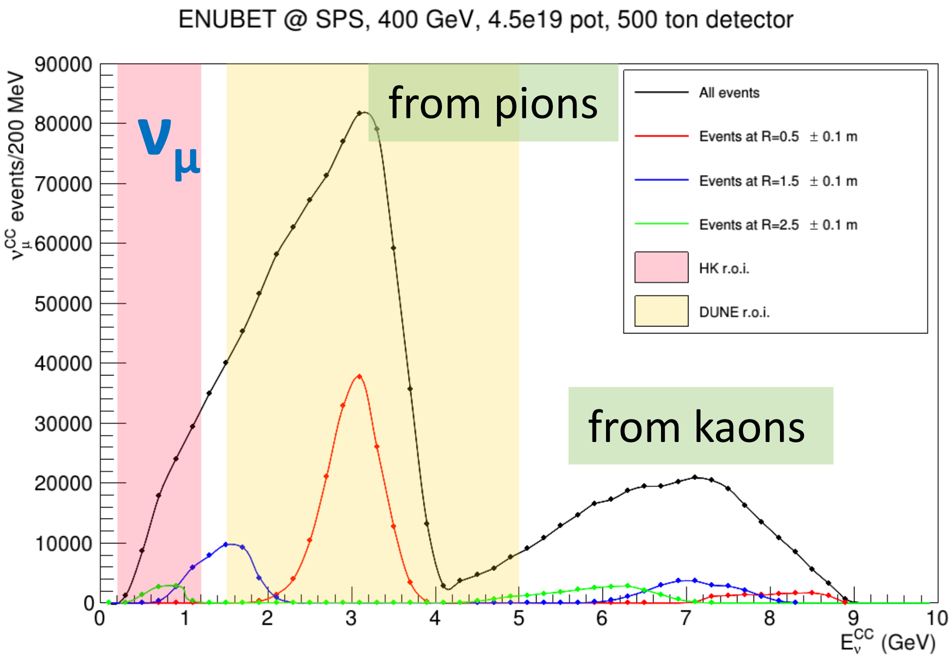
Horn option more efficient in terms of meson yields, but the static one gained momentum since yields are ~ **x 4** larger wrt to preliminary estimates as a result of optic optimization

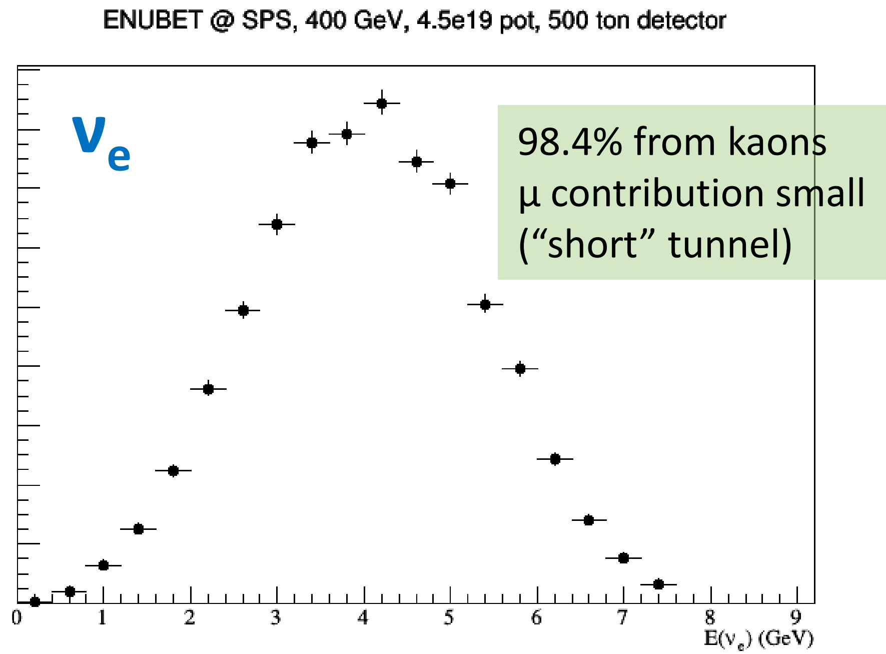
Advantages of the static extraction:

- No need for fast-cycling horn
- Strong **reduction of the rate** (pile-up) in the instrumented decay tunnel
- Monitor muons after the dump at 1% level (flux of ν_μ from π) [**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**

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 (0.5/1 year in dedicated/shared mode) or $1.5\ 10^{20}$ pot at FNAL





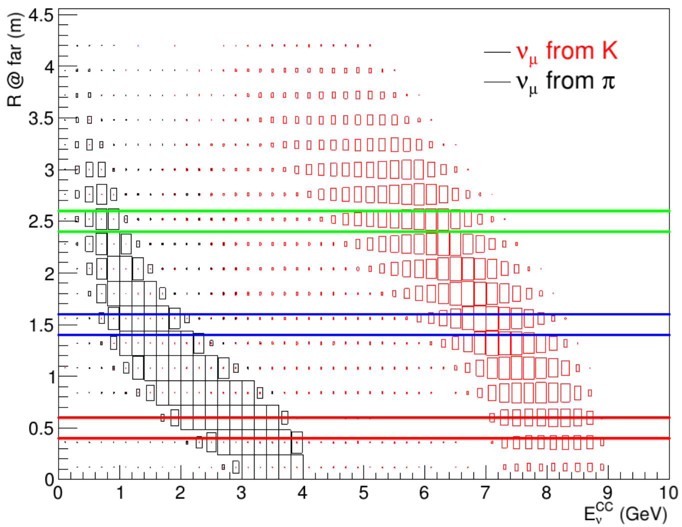
1.2×10^6 ν_μ charged current events per year

1.4×10^4 ν_e charged current events per year

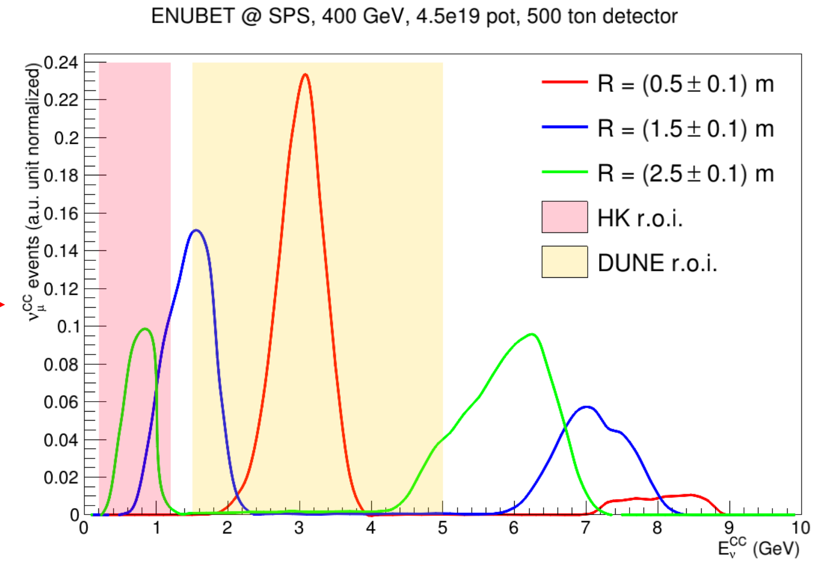
- **ν_μ** from K and π are **well separated** in energy (narrow band)
- **ν_e** and **ν_μ from K** are constrained by the **tagger measurement** (K_{e3}, mainly $K_{\mu 2}$)
- **ν_μ from π**: μ detectors downstream of the hadron dump (under study)

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 (R).



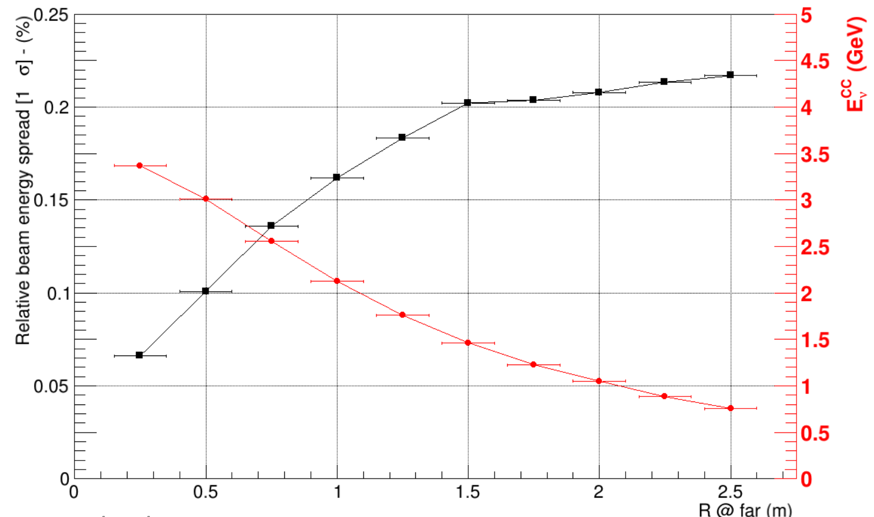
$\nu_\mu{}^{CC}$ in radial bins



"Narrow-band off-axis techinque"

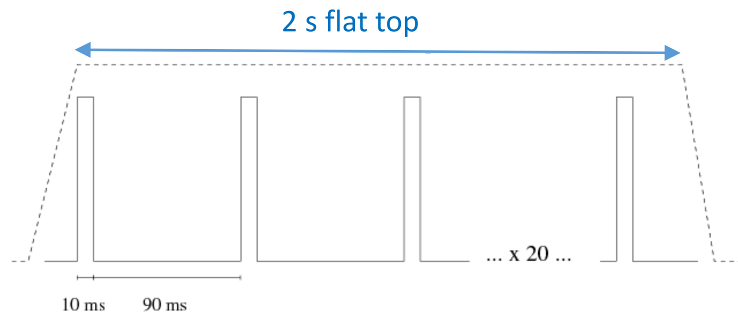
The beam width at fixed R
(≡ neutrino energy resolution)
for the pion component is:

- **8% for R ~ 25 cm, <E$_\nu$> ~ 3 GeV**
- **22% for R ~ 250 cm, <E$_\nu$> ~ 0.7 GeV**



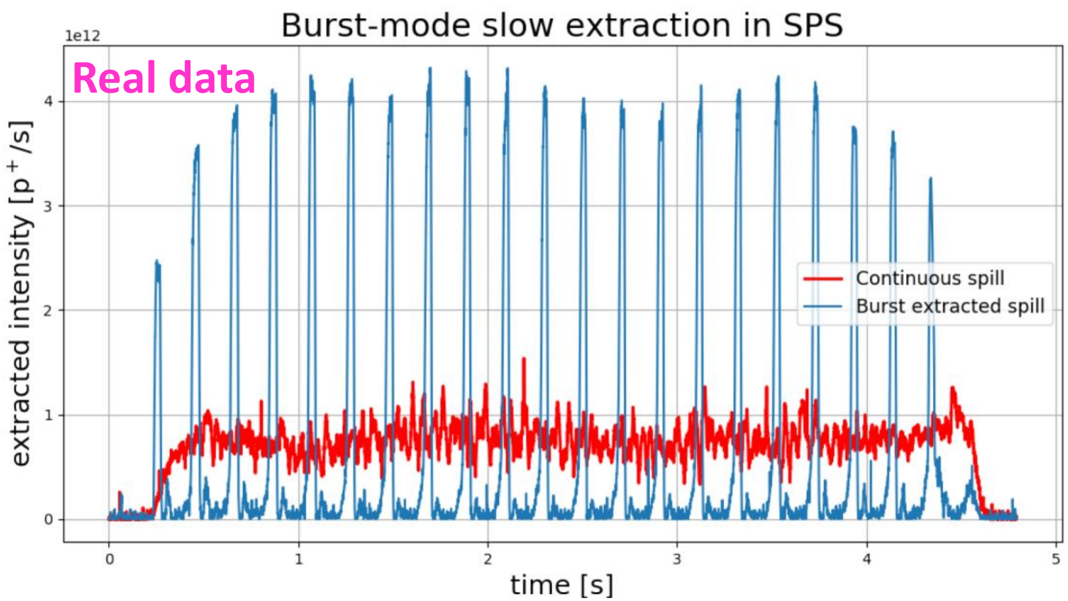
Machine studies for the horn-based option

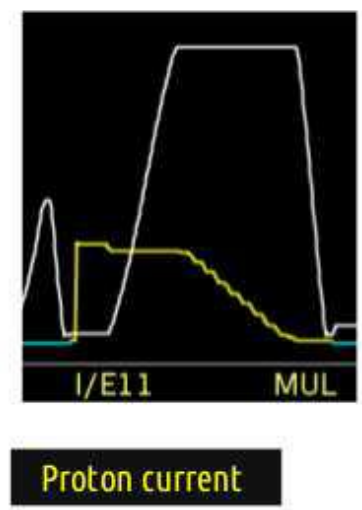
Idea: synchronize proton beam and horn current pulses, keeping rates compatible with tagger



Actual implementation: **"burst" slow extraction** (~10 ms pulses)

Jul/Aug/Nov 2018 @ SPS





Proton current steps in correspondance of bunches

Slow extraction is triggered by the third integer betatron resonance with a periodic pattern

- Same integrated pot extracted
- Protons squeezed into intervals when horn is pulsed

CERN-BE-OP-SPS

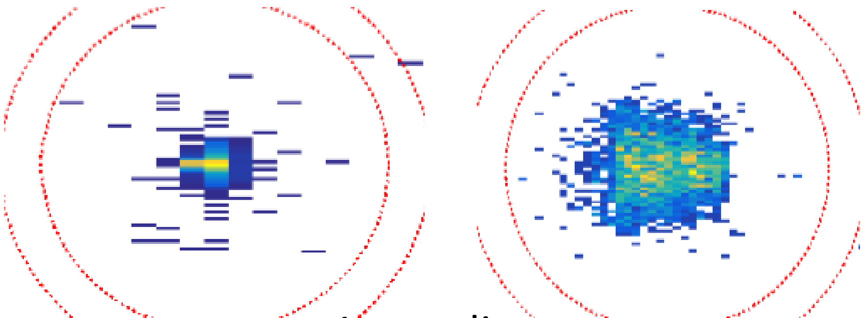
Velotti, Pari, Kain, Goddard

https://indico.cern.ch/event/777458/

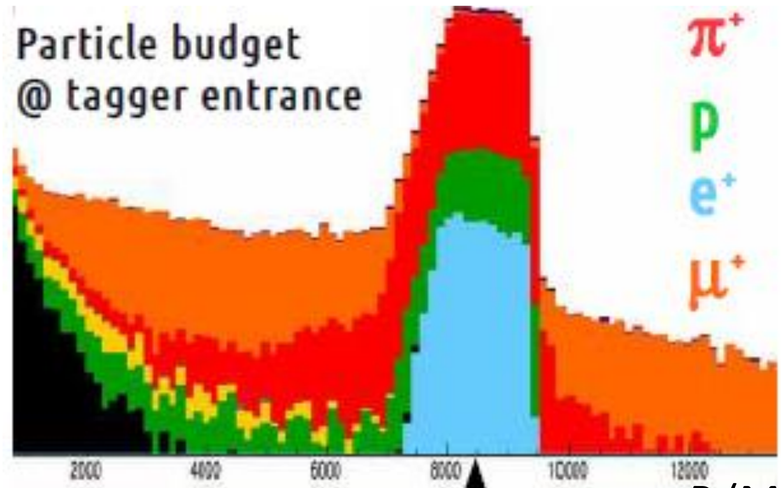
The static beamline: emittance, particle content

Divergence of the kaon beam

K⁺ @ tagger entrance K⁺ @ exit



1 m radius

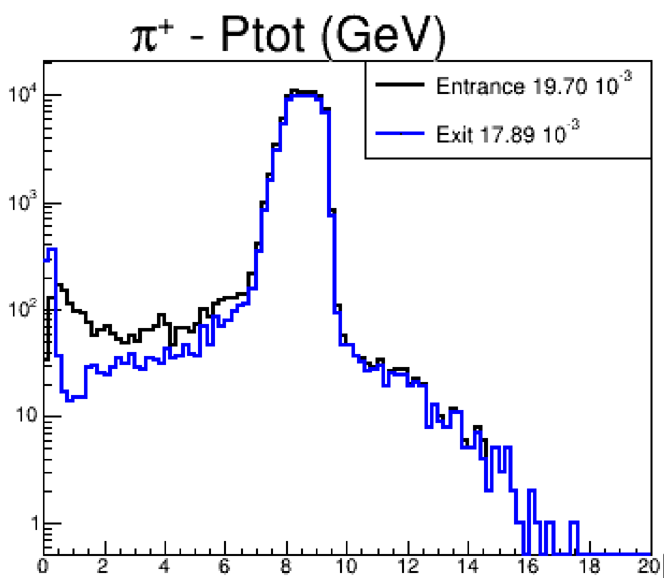


Momentum bite
(8.5 ± 10%) GeV/c

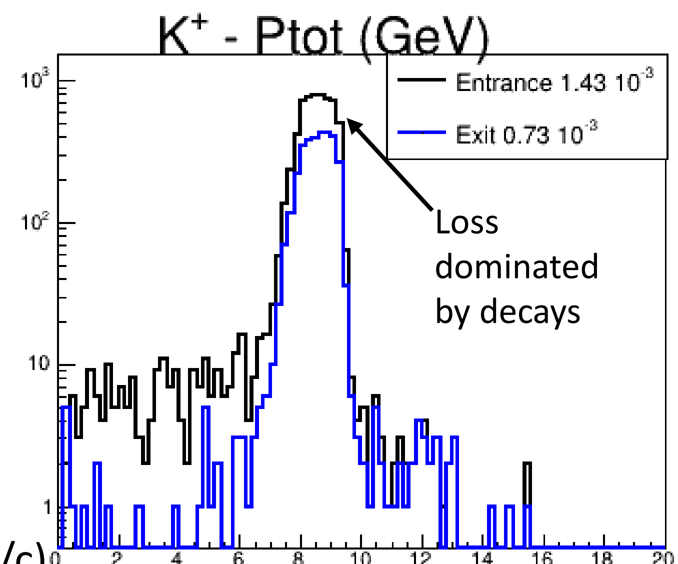
P (MeV/c)

Spectra at:

- Tagger entrance
- Tagger exit

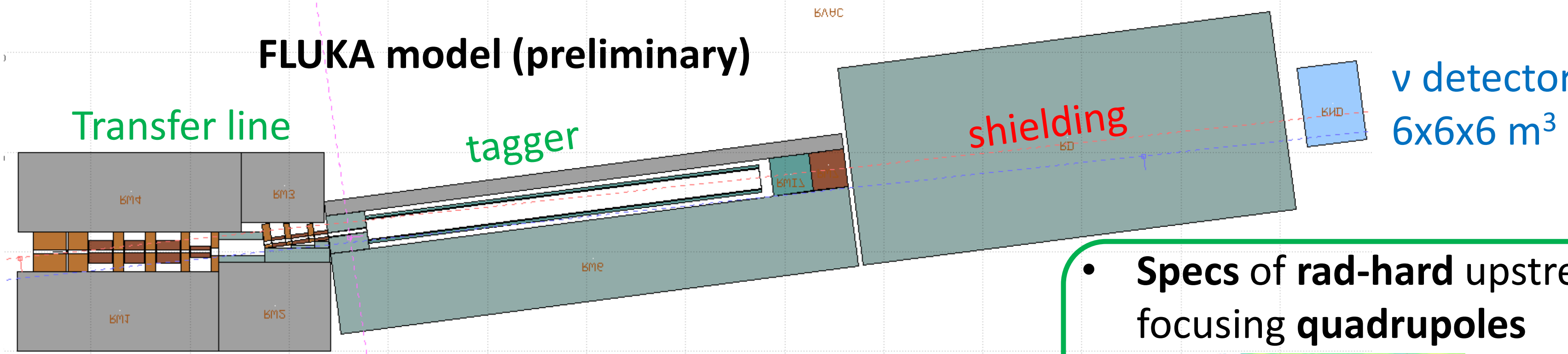


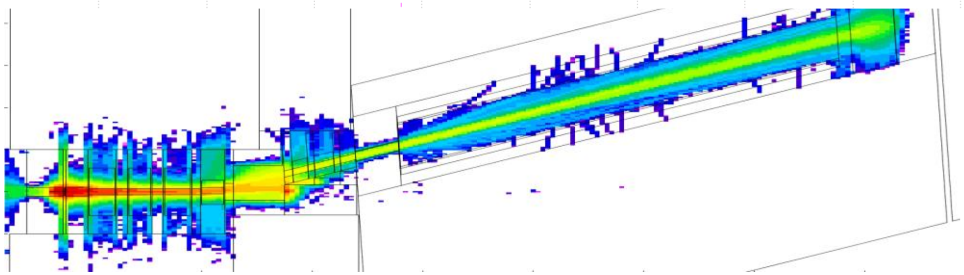
P (GeV/c)



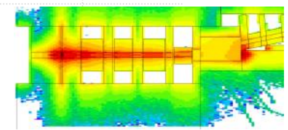
The hadronic beamline: FLUKA simulation

FLUKA model (preliminary)

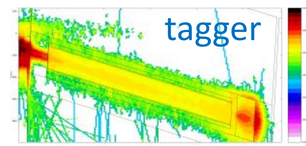




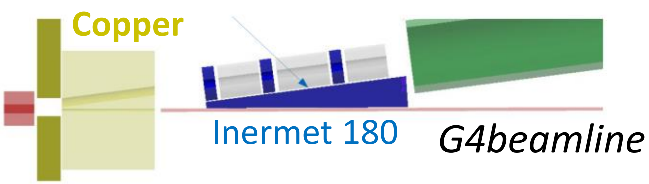
- **Specs** of **rad-hard** upstream focusing **quadrupoles**

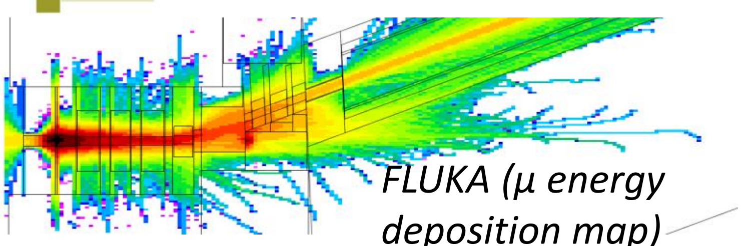


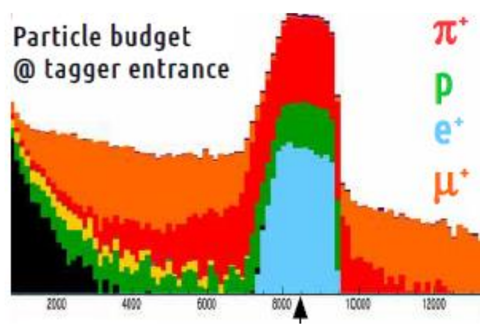
- **Neutron** irradiation studies

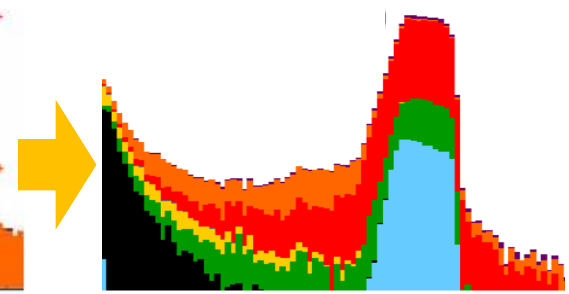


- Studies to **optimize** the **shielding** against muons and other backgrounds





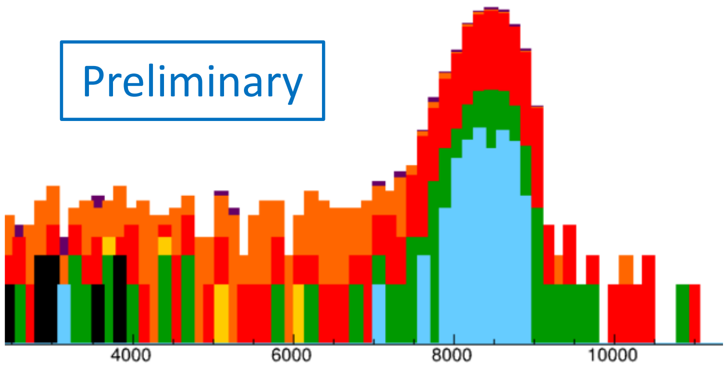




Factor >3 reduction of muons

Alternative beamline options

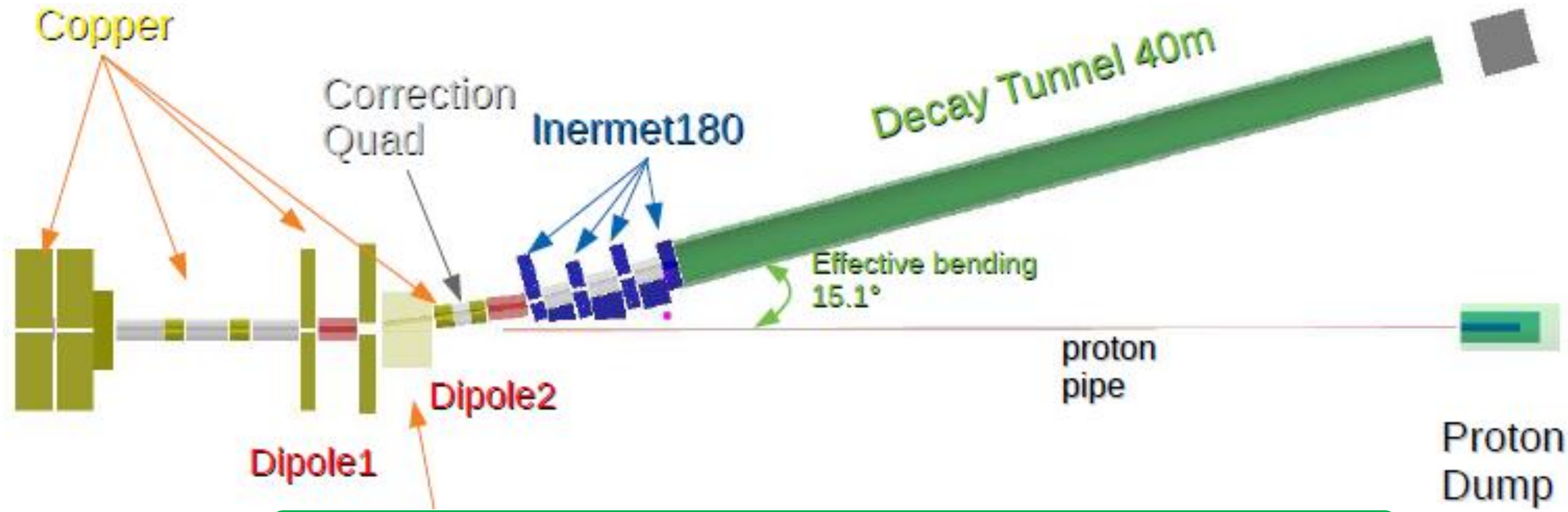
Other beamline schemes are also investigated:



2 dipoles with an intermediate quadrupole

Increased length of the beamline but…

- Better quality of the beam in the tagger
- Larger bending angle (15.1°) reducing:
  - Backgorund from muons
  - Probability for neutrinos produced in the straight section to reach the ν detector



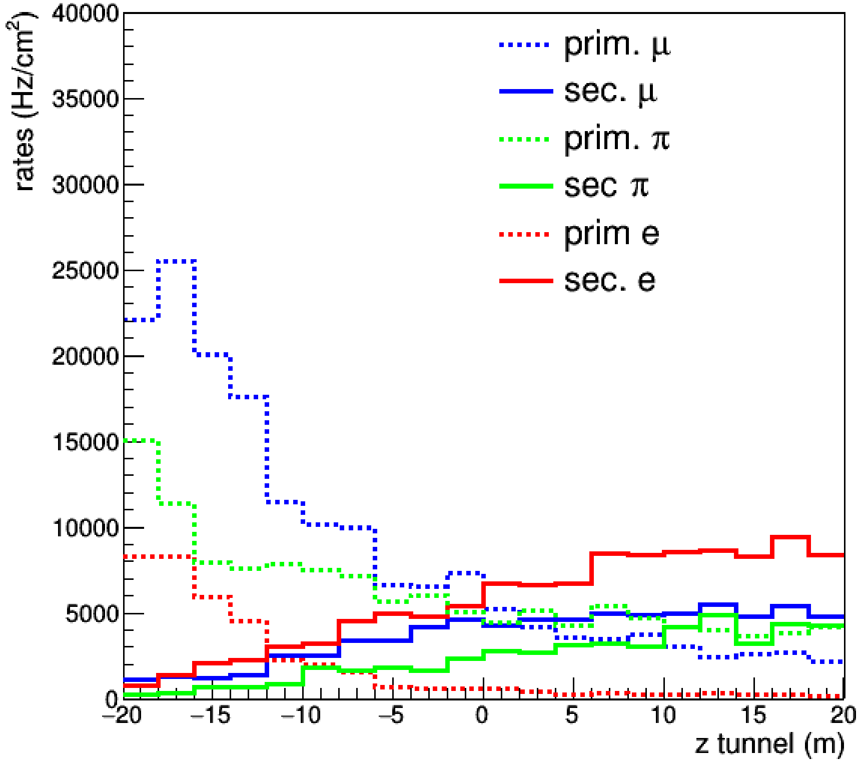
Putting all the input from simulation together to pinpoint the best scheme in terms of physics and technical feasibility

Particles rates in the decay tunnel

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

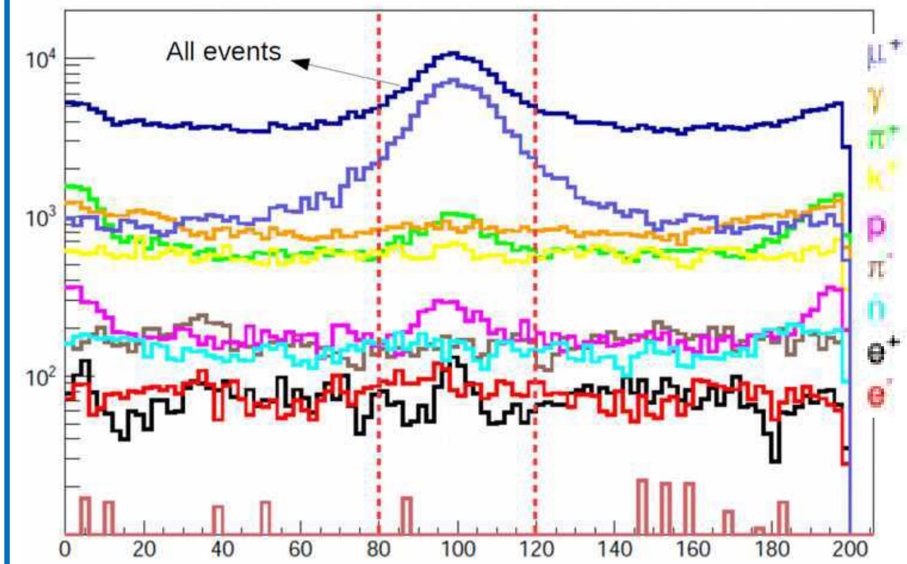
Radius = 1 m from the axis of the tunnel

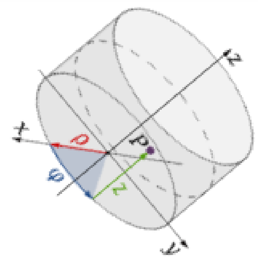
Rate as a function of the longitudinal position z in the tunnel



- **2nd part** of the tunnel **favoured** in terms of **S/N**
- With static focusing rates below **10 KHz/cm²**

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





- **Asymmetric** distribution of halo particles

The ENUBET Tagger

1) Longitudinally segmented Calorimeter

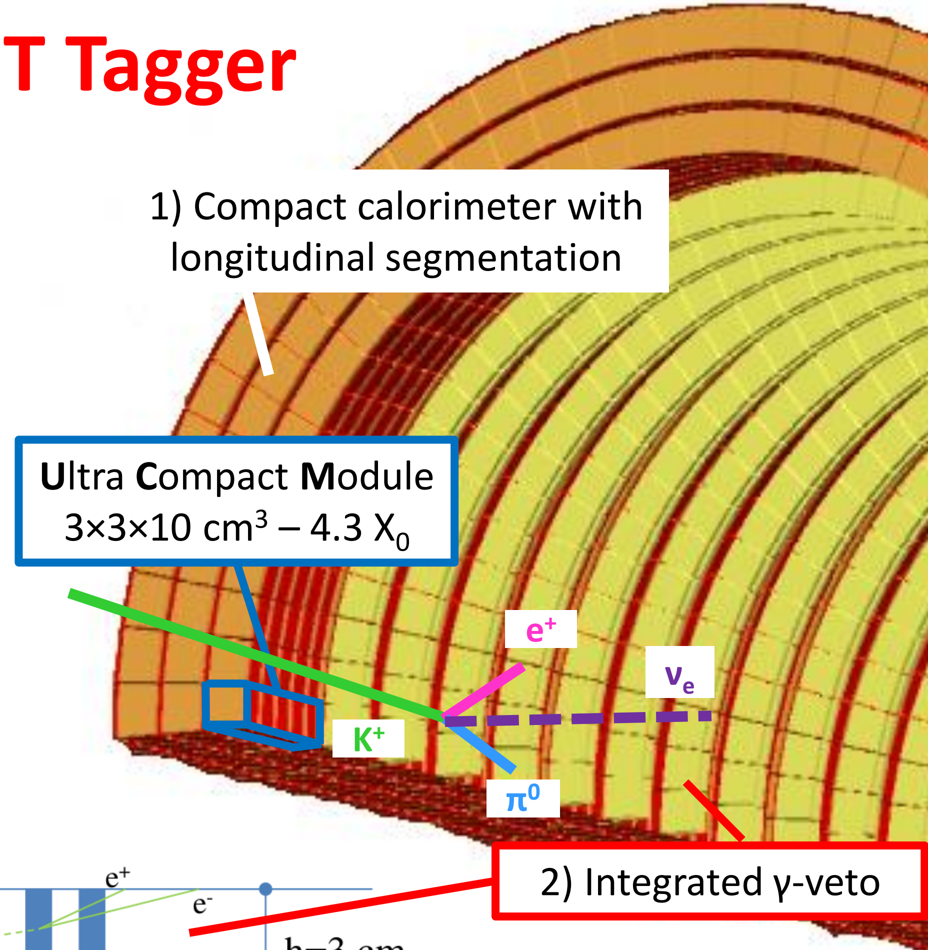
- Ultra Compact Module (UCM) (Plastic scint. + Fe absorbers)
- Integrated light readout with SiPM

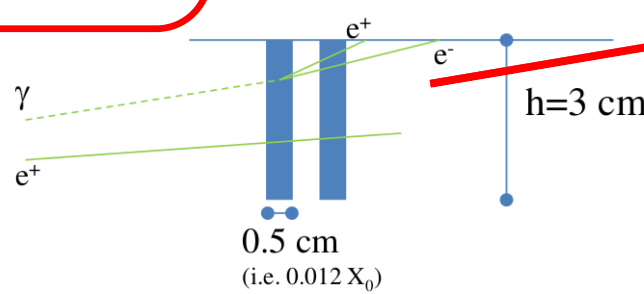
→ $e^+/\pi^\pm/\mu$ separation

2) Integrated γ-veto (t_0-layer)

- Rings of 3×3 cm^2 pads of plastic scintillator

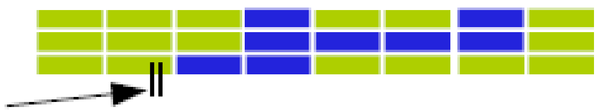
→ π^0 rejection





e⁺ (signal) topology

π⁰ (background) topology



π⁺ (background) topology

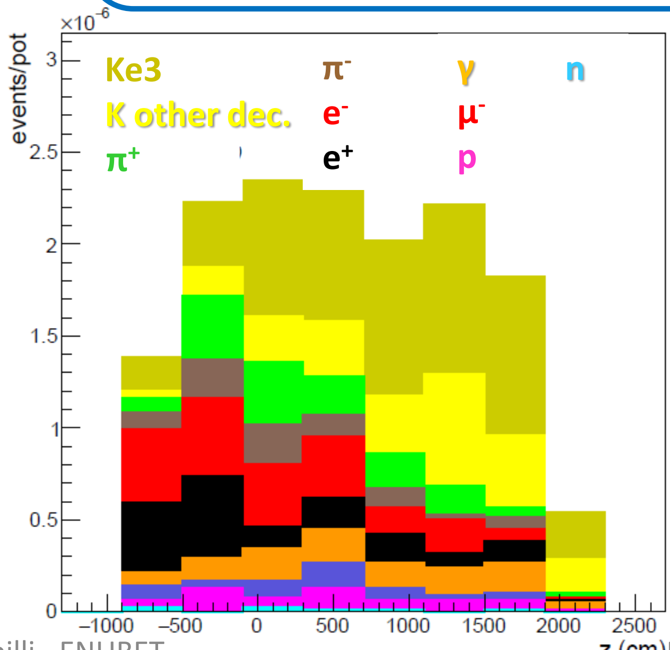
Ke3 positron reconstruction

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 cluster neighboring modules
- e/π/μ separation → TMVA multivariate analysis based on 6 variables (pattern of the energy deposition in the calorimeter)
- e/γ separation → Signal on the tiles of the photon veto



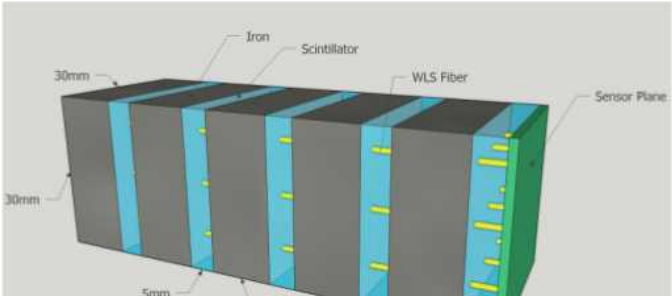
ε_{geom}	0.36
ε_{sel}	0.55
ε_{tot}	0.20
Purity	0.26
S/N	0.36

ϕ cut → 0.46

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

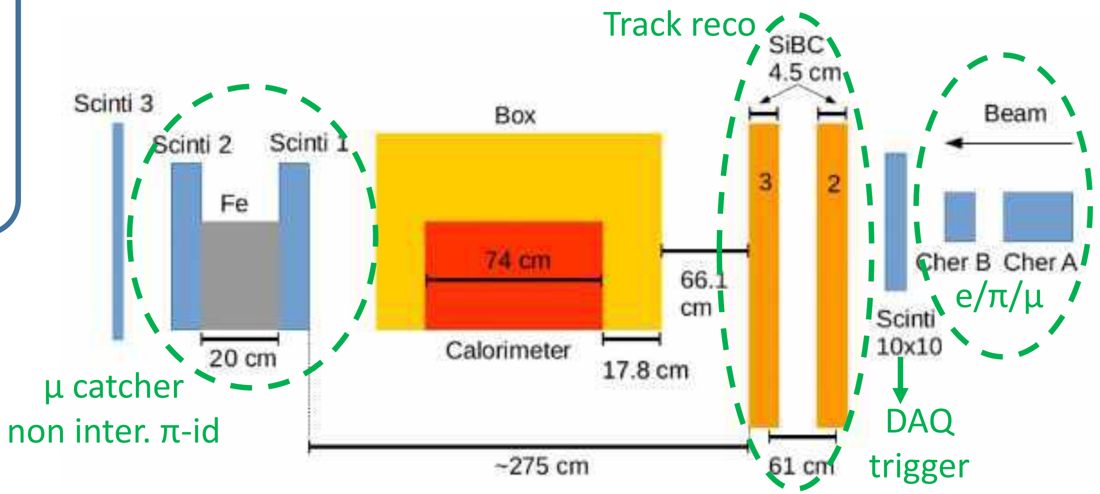
The Tagger – Shashlik with integrated readout

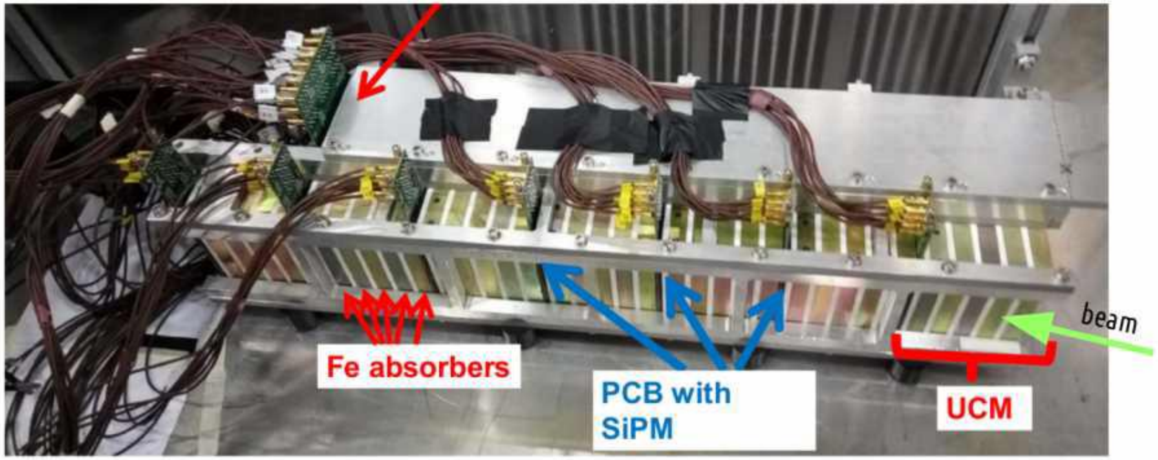
- 56 UCM arranged in 7 longitudinal block (~30 X_0) + hadr. Layer (coarse sampling)
- e/μ tagged with Cherenkov counters and muon catcher
- Beam Composition @ 3GeV:
  9% e, 14% μ , 77% hadrons



Shashlik calorimeter

Test beam @ CERN-PS T9 line 2016-17





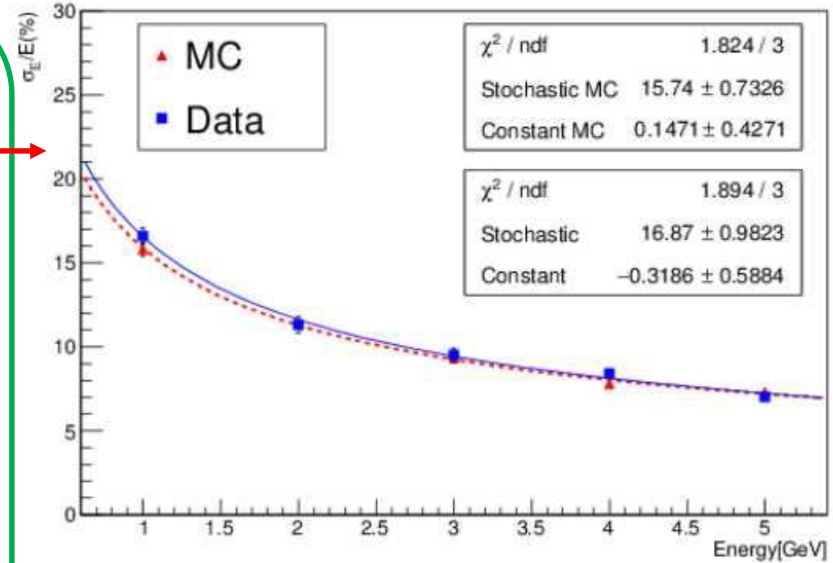
The Tagger – Test Beam results

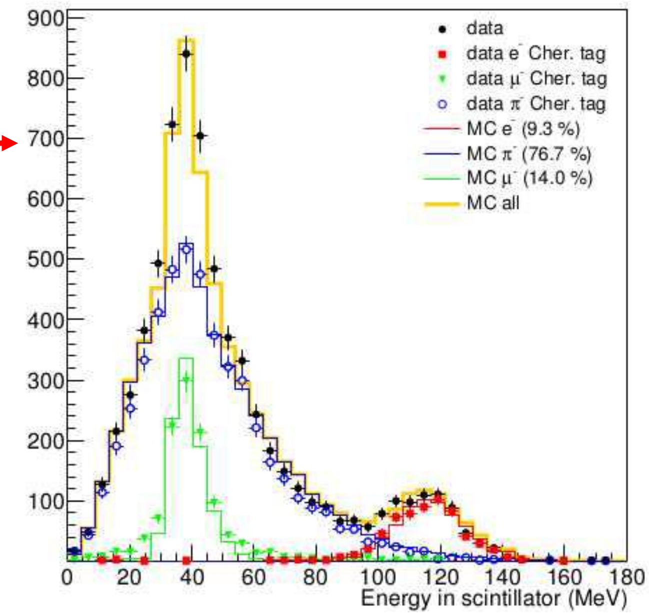
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

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 – t_0-layer and SiPM irradiation

Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2018

• γ/e+ discrimination (Photon-Veto)

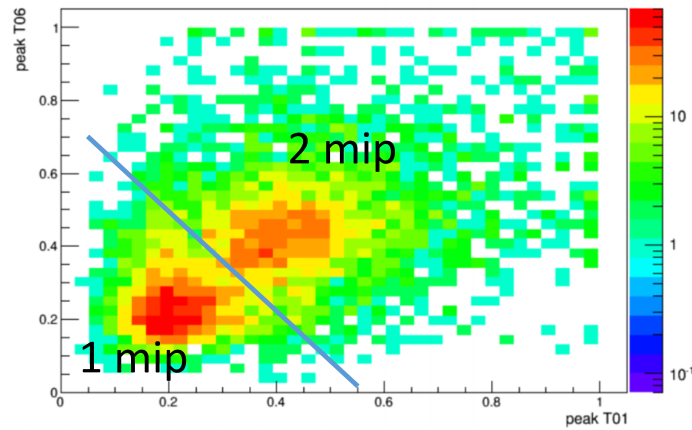
t0 layer: scintillator (3×3×0.5 cm^3) + WLS Fiber + SiPM

→ • **light collection efficiency** → >95%

• **time resolution** → σ~400ps

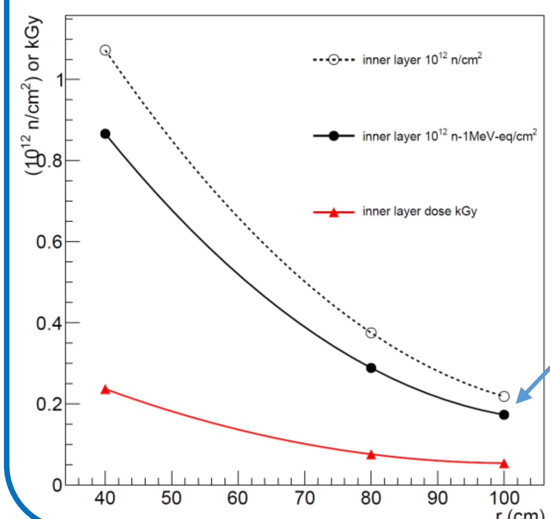
• First 1mip/2mip separation using photon conversion from π^0 gammas (π^0 by charge exchange of π^+ with low density target after SiC)

We are able to discriminate ν from Ke3 e^+



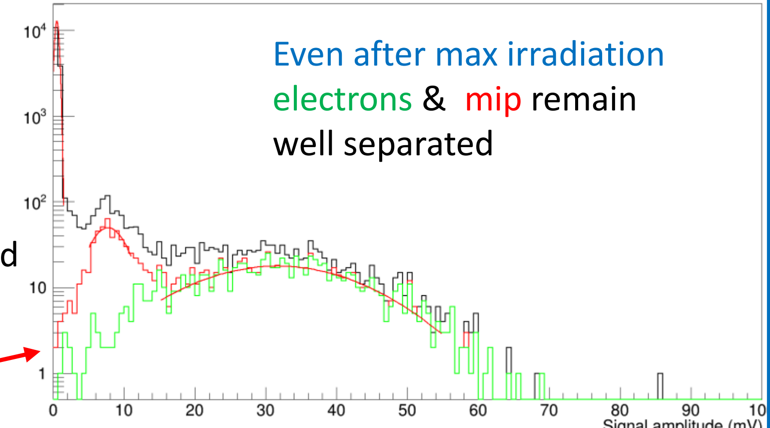
• Irradiation Studies

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)



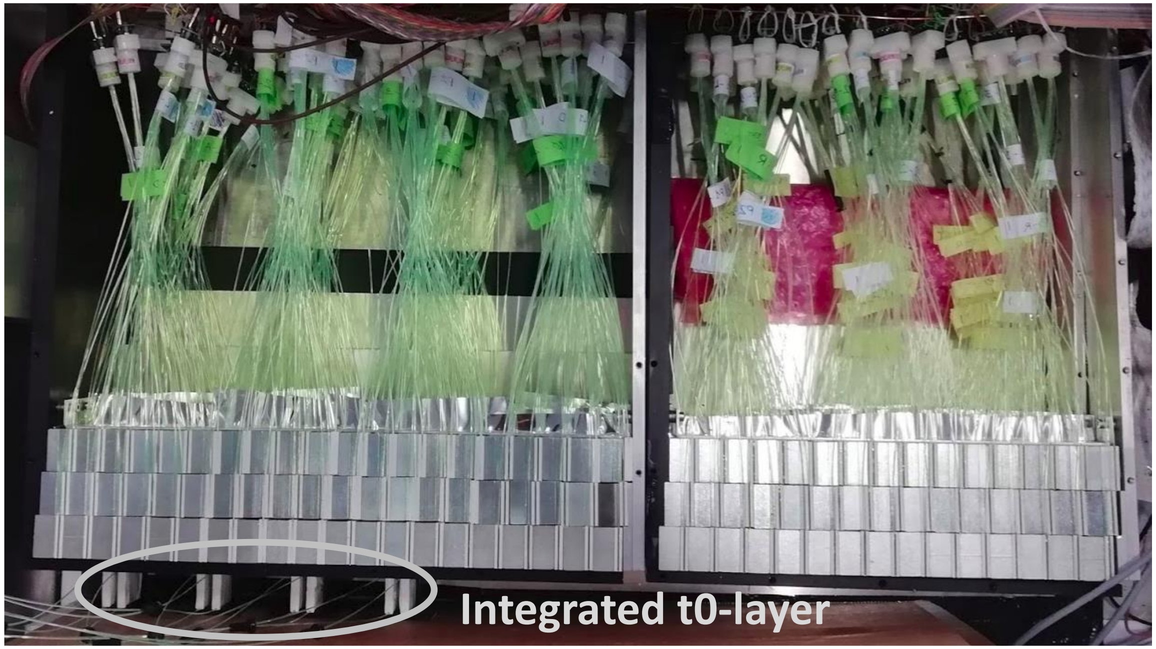
Irradiated SiPM tested at CERN in October 2017

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

The Tagger – Lateral readout option

Light **collected from scintillator sides** and bundled to a **single SiPM** reading 10 fibers (1 UCM)

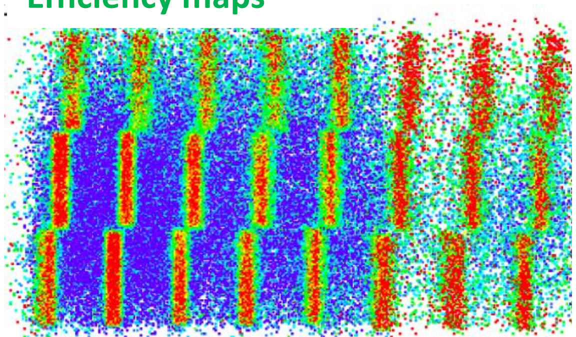
- **Pros**: **reduced** SiPM **irradiation damage**, better **accessibility**, possibility of **replacement**



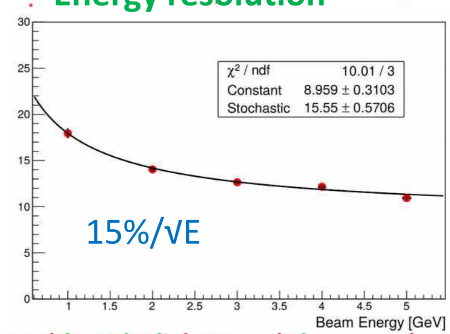
CERN-PS – September 2018

- Tested a module with longitudinal containment of hadronic showers and full e.m. showers containment
- Integrating a t0-layer
- Analysis on going

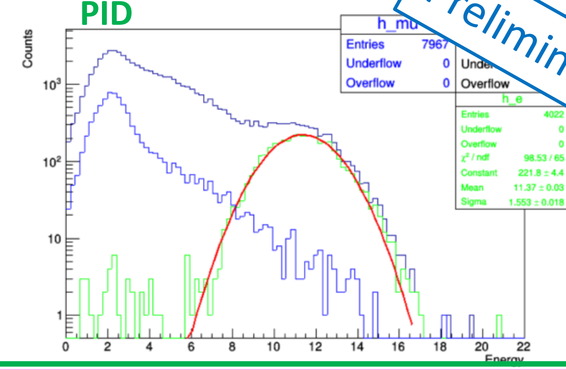
Efficiency maps



Energy resolution



PID



Further details and R&D on **M. Torti poster**

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 3.5 GeV) and flavor composition (1%)

- **In the last 2 years**, we have
  - provided the first **end-to-end simulation** of the beamline
  - tested with data the **“burst” slow extraction** scheme at CERN SPS
  - 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 with S/N = 0.5
  - identified the best options for the instrumentation of the decay tunnel (shashlik and lateral readout: final decision in 2019)

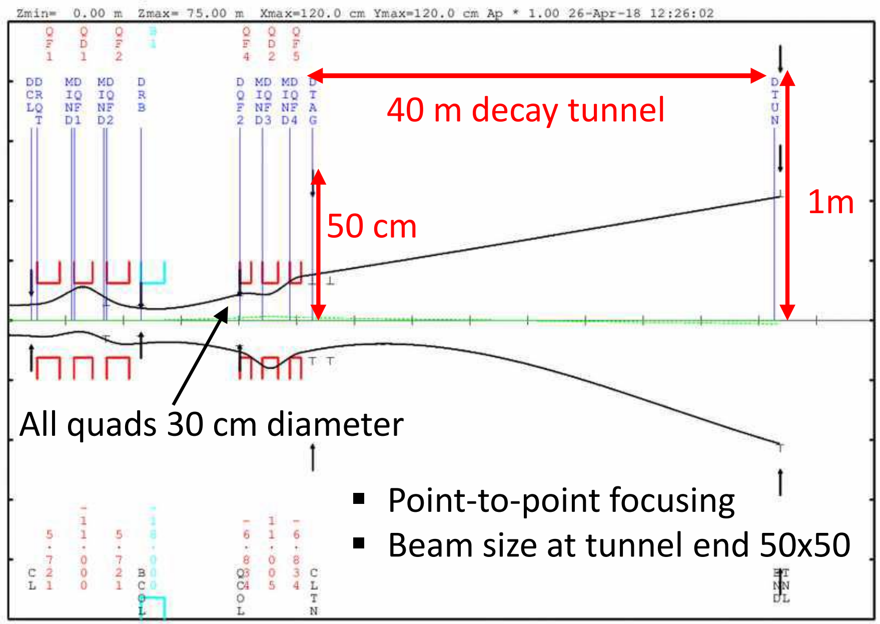
The **ENUBET** technique is **very promising** and the results we got in the last months **exceeded our expectations**

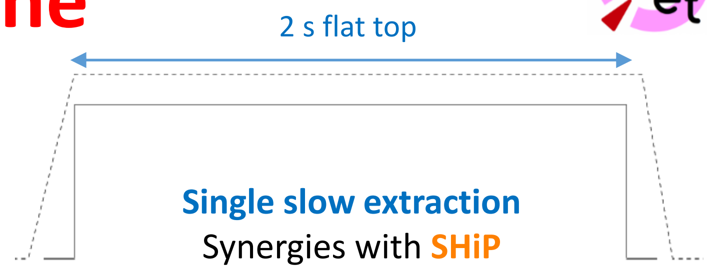
- **Next steps**
  - Improve the **beamline design** to reduce beam halo contamination (**increase S/N**)
  - Assess **systematics** on predicted **neutrino fluxes**
  - enhance precision **in ν_μ flux**: μ **tagging** from **$K_{\mu 2}$** - count **μ from π** after had-dump
  - Build a **demonstrator** prototype of the tagger (2021)
  - **CDR** at the end of the project (2021): **physics** and **costing**

Backup slides

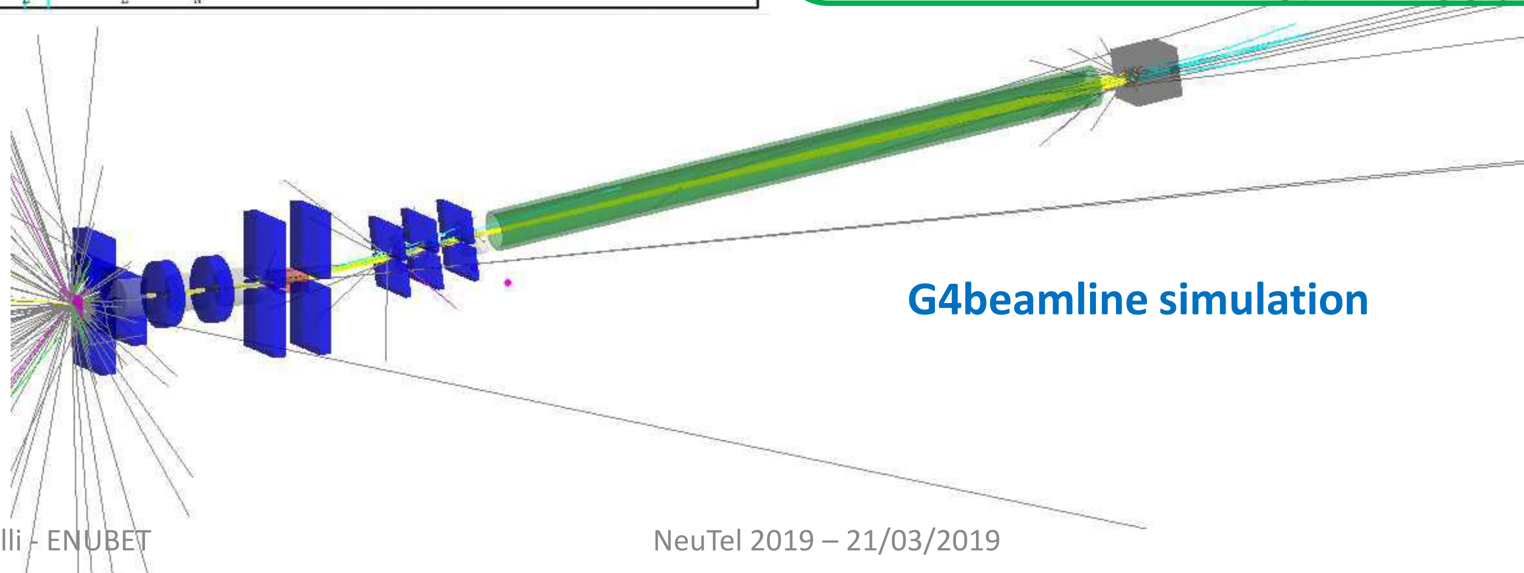
The static beamline

Optics optimized through **TRANSPORT**





- 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

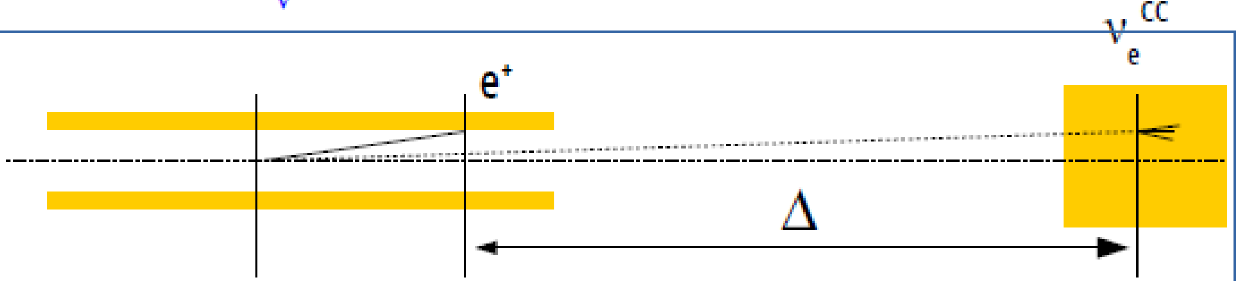
Time tagged neutrino beams ?

- Event time dilution → **Time-tagging**
- **Associating a single neutrino interaction to a tagged e^+ with a** small "accidental coincidence" probability through **time coincidences**

E_ν and flavor of the ν measured "a priori" event by event.

Compare "E_ν from decay kinematics" ↔ "E_ν from ν interaction products"

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



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

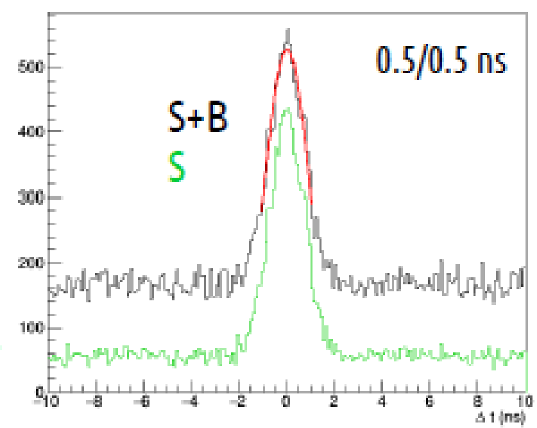
Presently with 2.5e13 pot / 2s slow extraction:

genuine K_{e3} cand. : 80 MHz → **1 every ~ 12 ns**

background K_{e3} cand. ~ 2 x → 1 cand. every ~ 4 ns

With δ=0.5 ⊕ 0.5 ns resolutions already interesting!

S/N ratio will likely improve with further tuning.



Toy MC

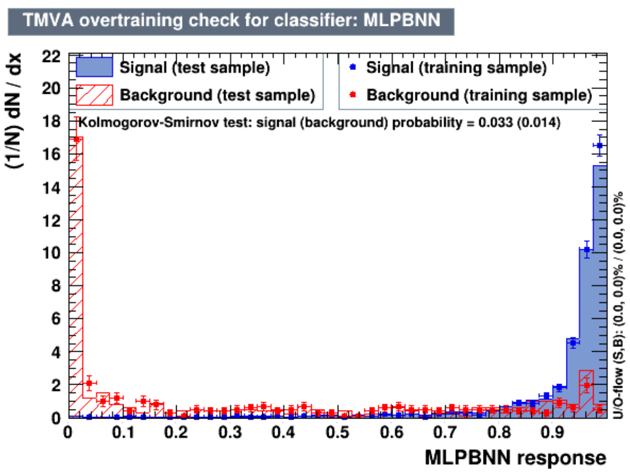
A. Longhin - ENUBET CERN-SPSC – 23/01/2019 21

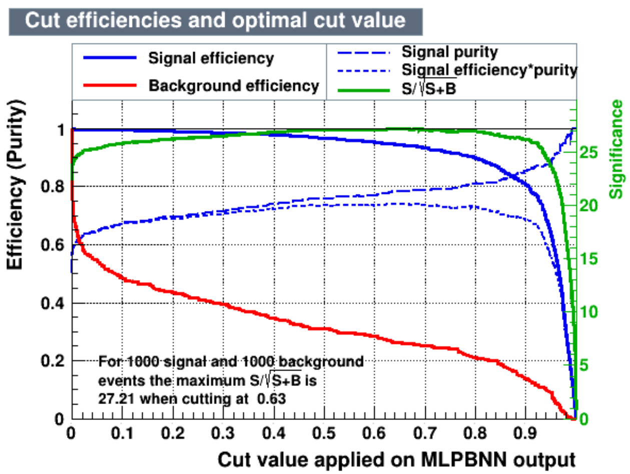
The Tagger – positron ID from K decay

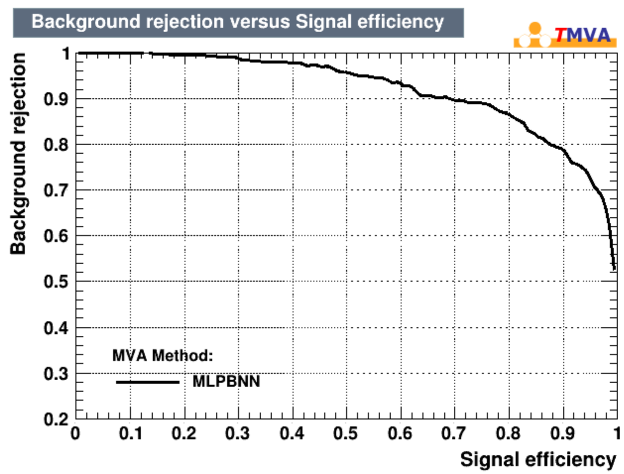
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV → link nighboring modules with time (1ns) and position requirements

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







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)