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).

ENUBET - Enhanced NeUtrino BEams from kaon Tagging

Enabling high precision flux measurements in conventional neutrino beams

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

52 physicists, 11 institutions

The ENUBET Neutrino Beam

ENUBET is

- a narrow band beam at the GeV scale with a **superior control of the neutrino 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 **νe** and **$\nu\mu$ neutrino cross sections**

We present at NUFACT2018

- 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

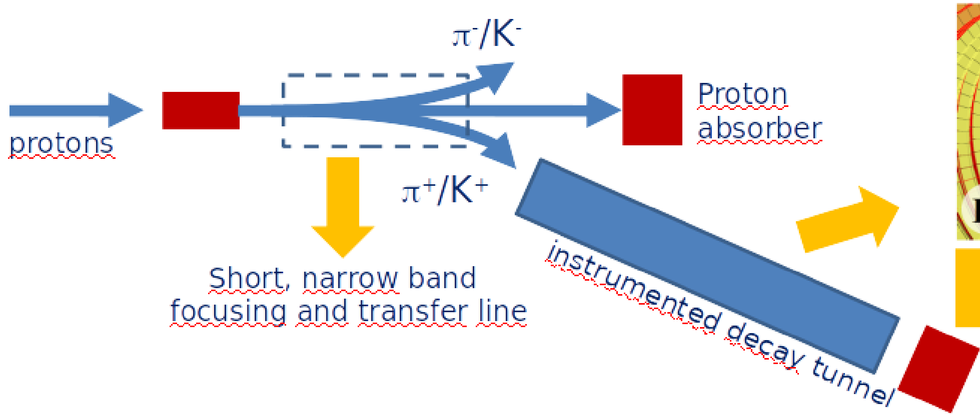
↓

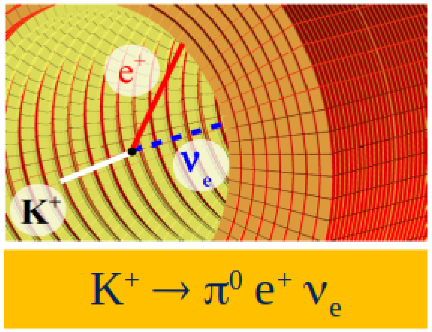
The ideal tool to study neutrino interactions in nuclei

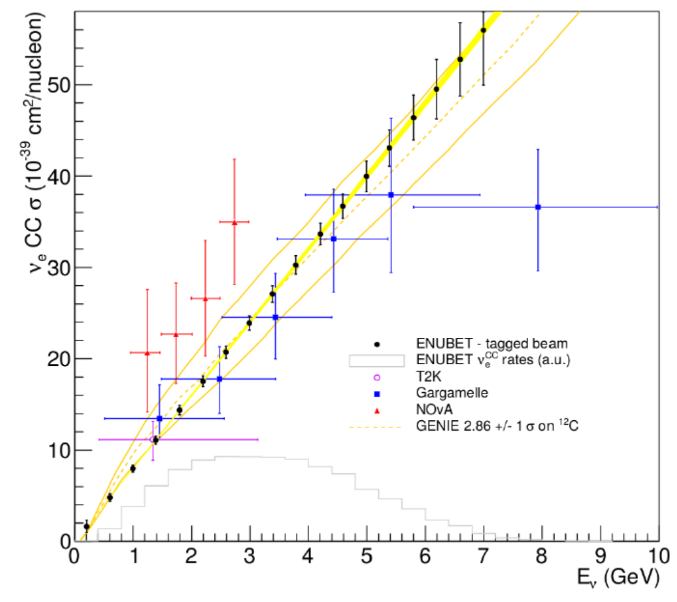
Flavor composition known at the 1% level

↓

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







Goal: 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 beamline

2 possibilities:

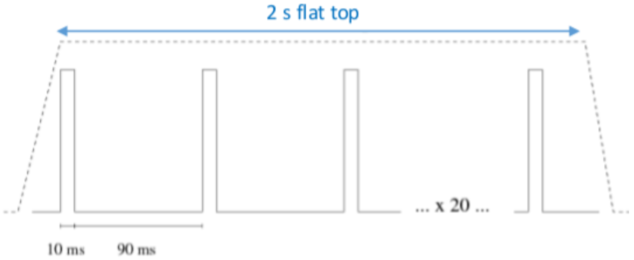
Event-count mode

- **HORN-BASED** beamline

  Target → horn → transport → Tunnel

→ **PROS**: focusing more π & K in the wanted P range before the transfer part to the decay tunnel

→ **Higher yields @ decay tunnel**



CONS:

- Horn pulse limit < O(1-10) ms
- Tagger rate limit reached with ~10^{12} POT/spill
- We need 10^4 νe-CC in a 500-ton detector → ~10^{20} POT = fraction of a year at present proton drivers
  ~10^8 spills → challenging/unconventional

→ Multi-Hz extractions + Horn Pulsing (2ms) → machine studies @ SPS

Event-by-event mode

- **STATIC-FOCUSING** beamline

  Target → transport → Tunnel

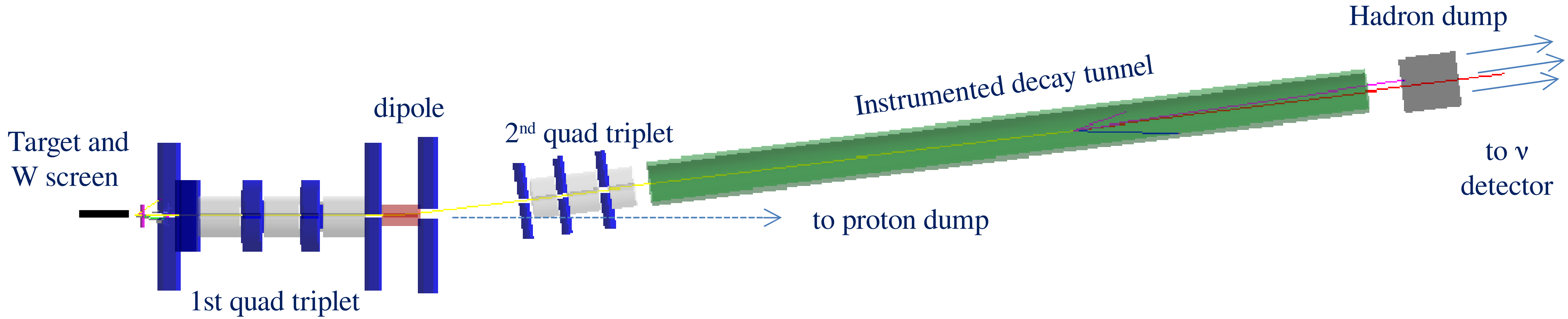
→ **PROS**: **Lower rates** @ decay tunnel (1e+/30ns) + Possibility of **event-by-event tagging** by coincidences between νe at the detector and e+ at the tagger

CONS:

- Less efficient focusing: lower yields, more POT needed

→ Single slow extraction

The ENUBET beamline



- 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, 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 beamline - Yields

Focusing system	π/pot (10^{-3})	K/pot (10^{-3})	Extraction lenght	π/cycle (10^{10})	K/cycle (10^{10})	Proposal [c]
Horn	97	7.9	2ms [a]	438	36	x2
No horn	19	1.4	2 s [b]	85	6.2	**x5**

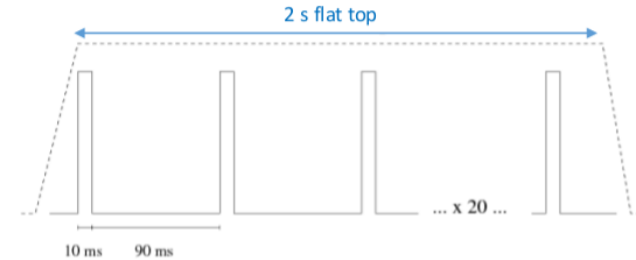
(a) 2 ms at 10 Hz during the flat top (2 s) to empty the accelerator after a super-cycle: this extraction scheme is currently under test at CERN
(b) Slow extraction. Detailed performance and losses currently under evaluation at CERN
(c) A. Longhin, L. Ludovici, F. Terranova, **EPJ C75 (2015) 155**

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 beamline – the horn-based option

- Machine studies @ SPS are currently on-going:

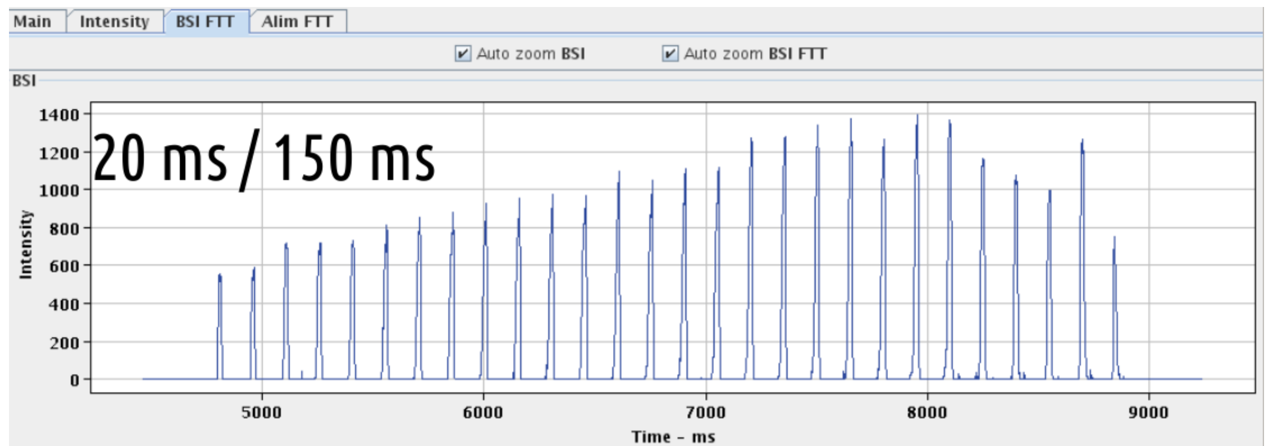


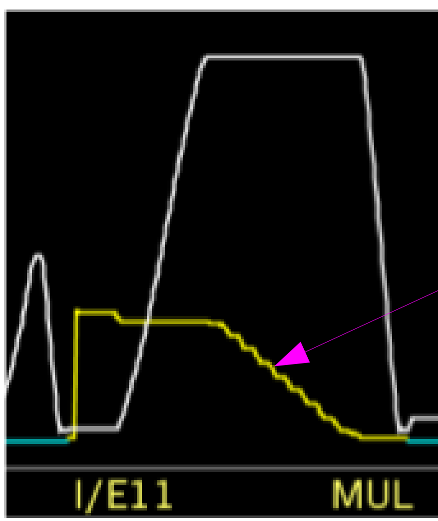
Preliminary studies July 2018

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

Multi-Hz resonant slow extraction

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



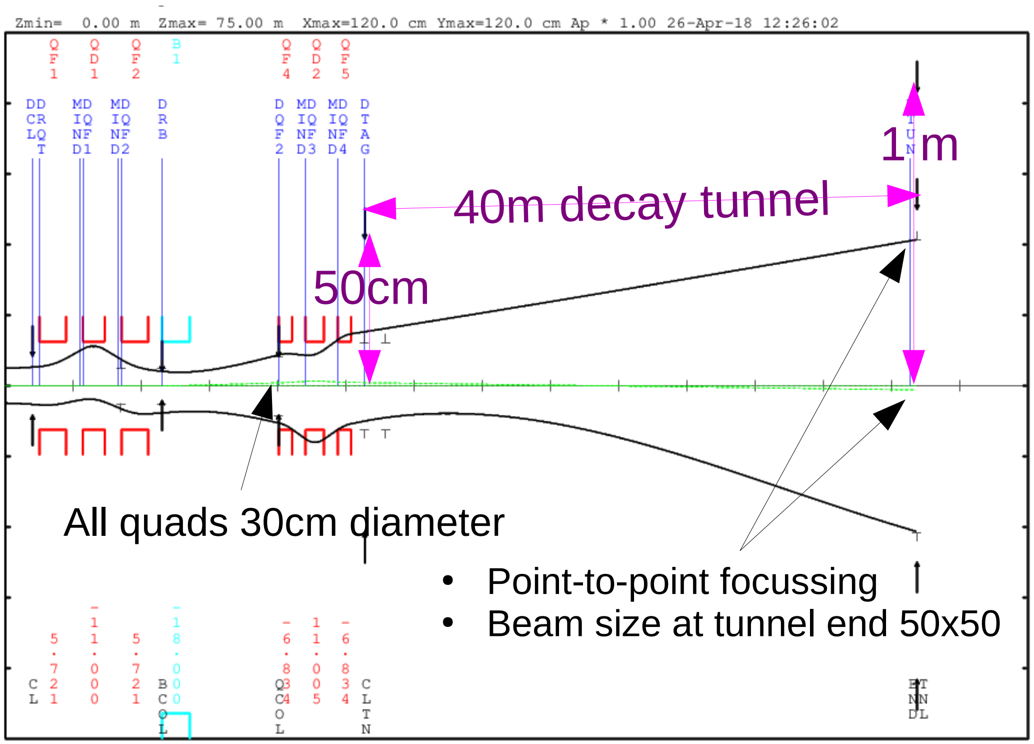


Proton current

Proton current steps in correspondance of bunches

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

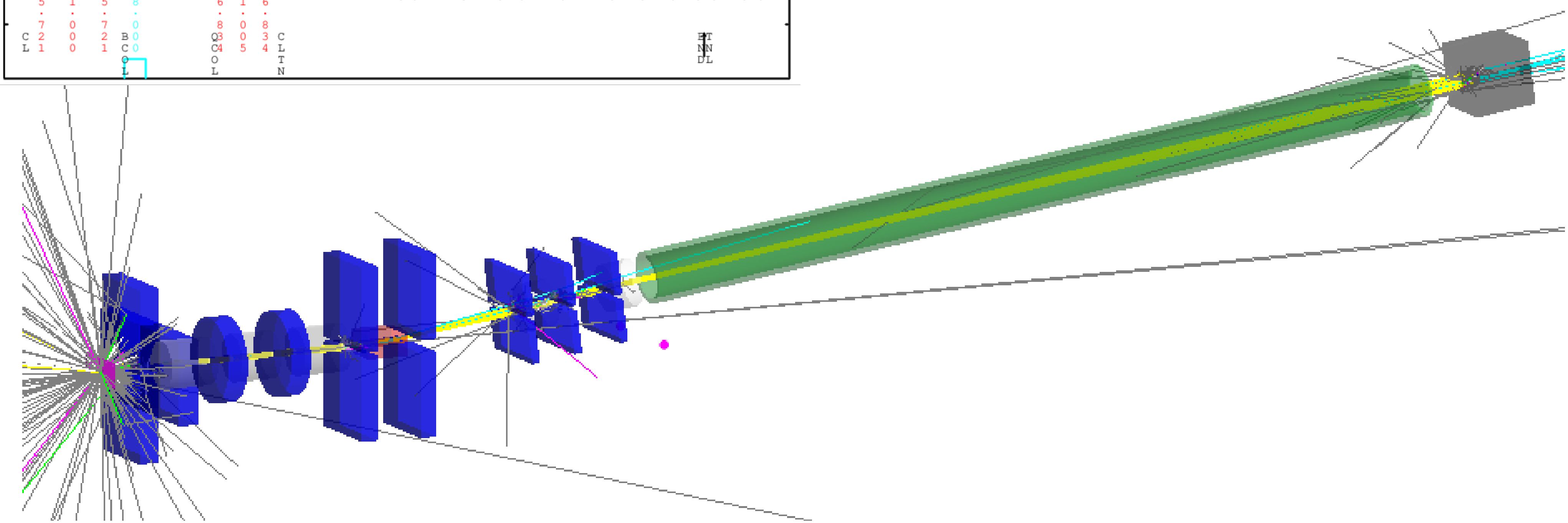
The Static Beamline - Optics



- Reference beam: 8.5 GeV/c, 10% mom. bite
- Conventional Quads

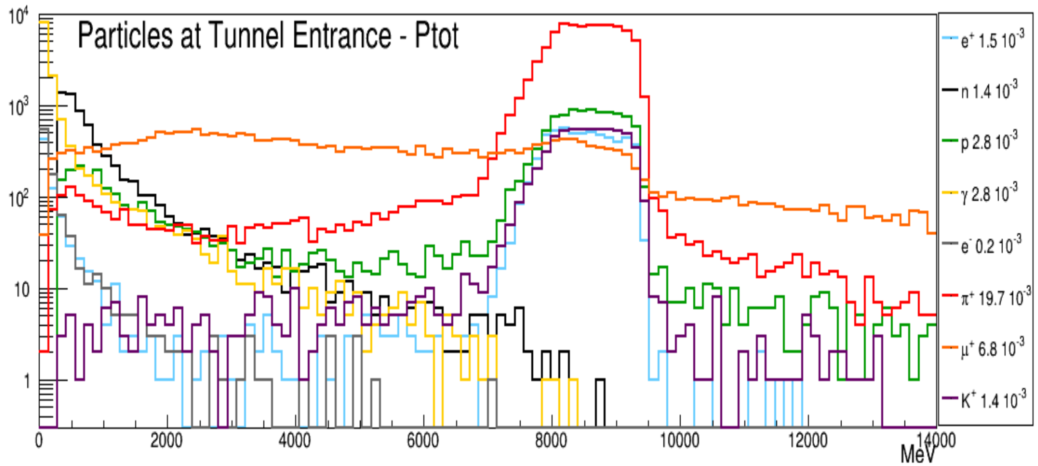
  15cm apertures, lengths <2 m, Fields 4 to 7 [T]
- Conventional Dipole

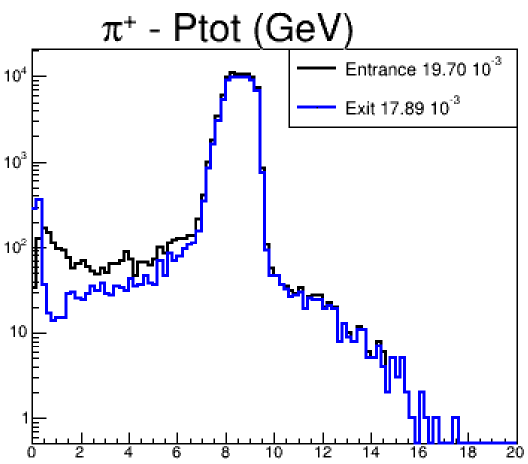
  15cm apertue, 2m long, Field 1.8 [T] → 7.4° bending
- Beam envelope at tunnel exit 50x50 cm (Tunnel radius 1m)

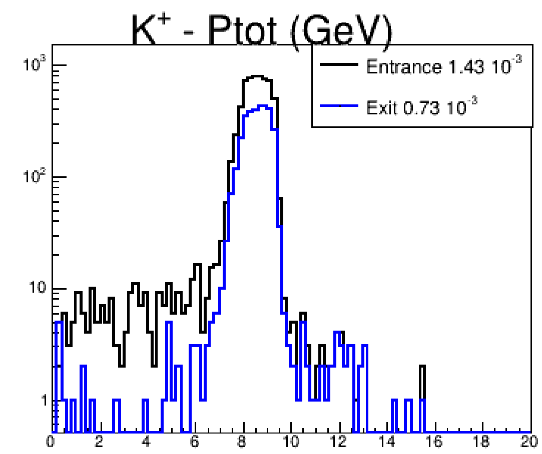


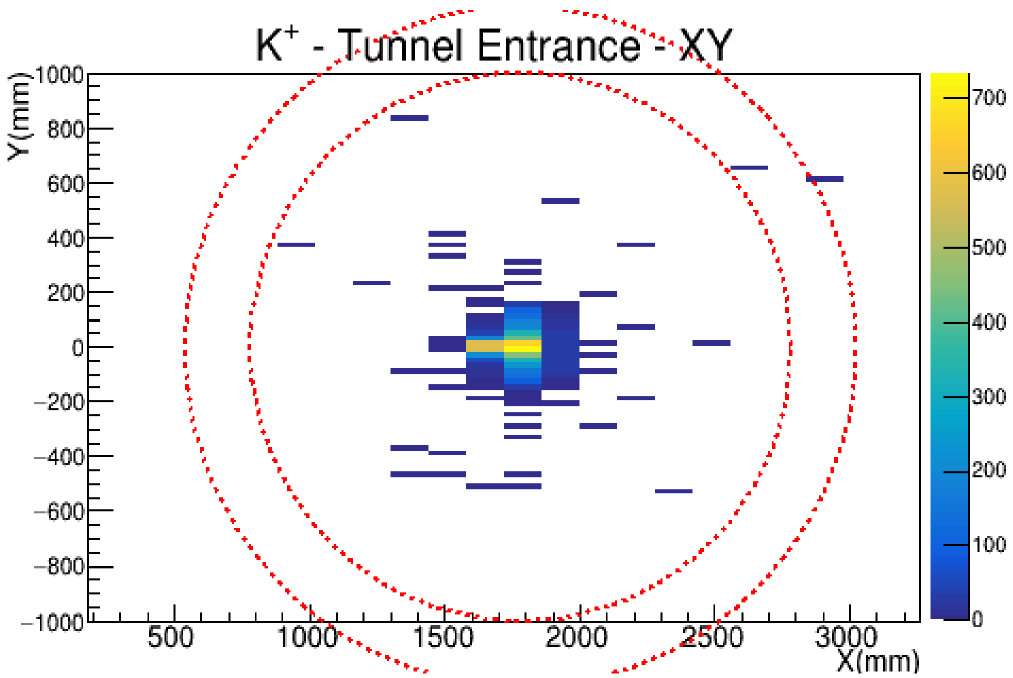
The Static Beamline

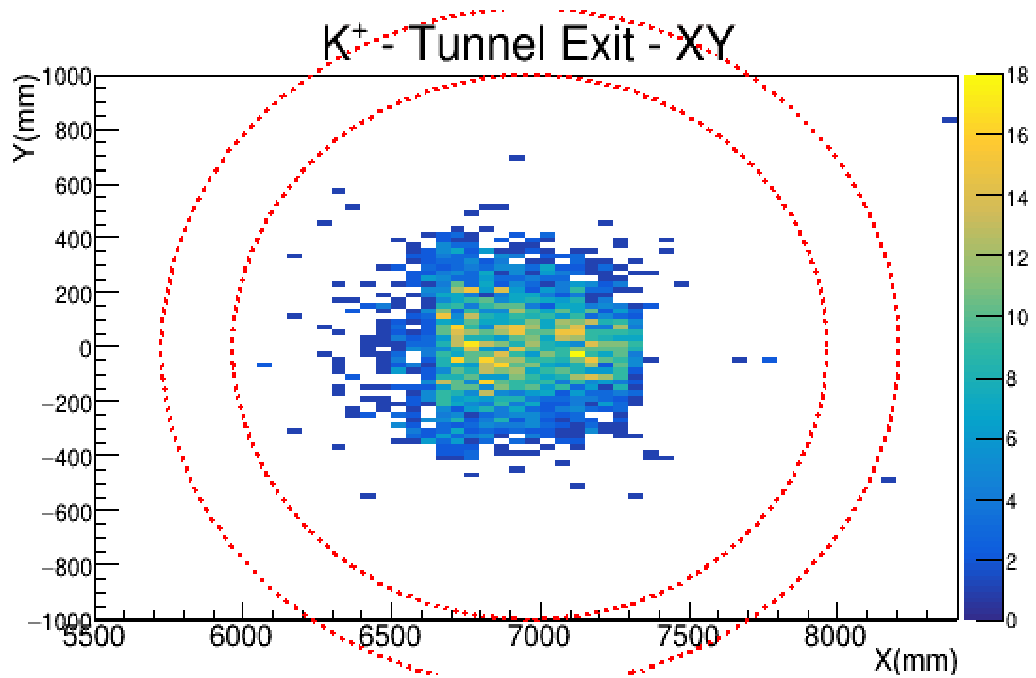
G4beamline simulation – Particles at tunnel Entrance/Exit











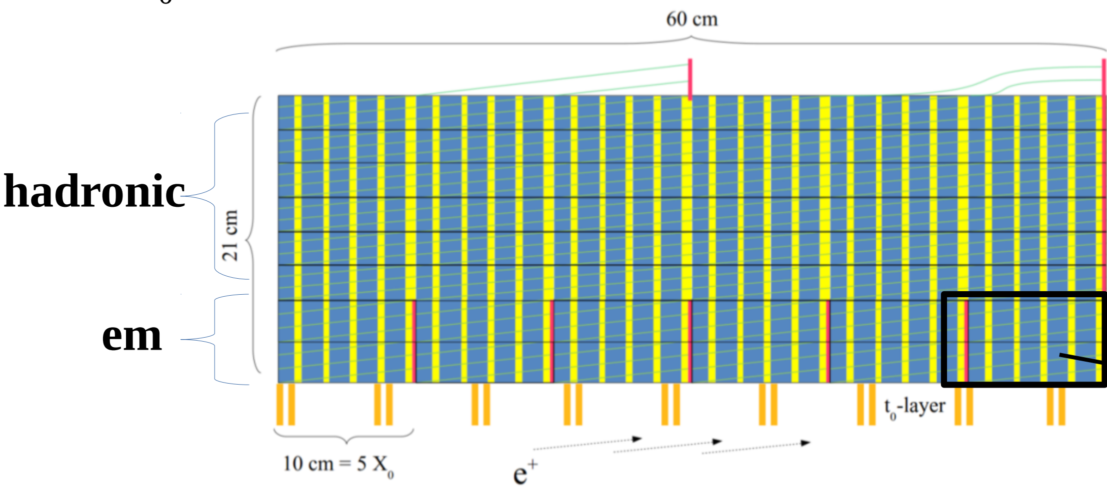
The Tagger

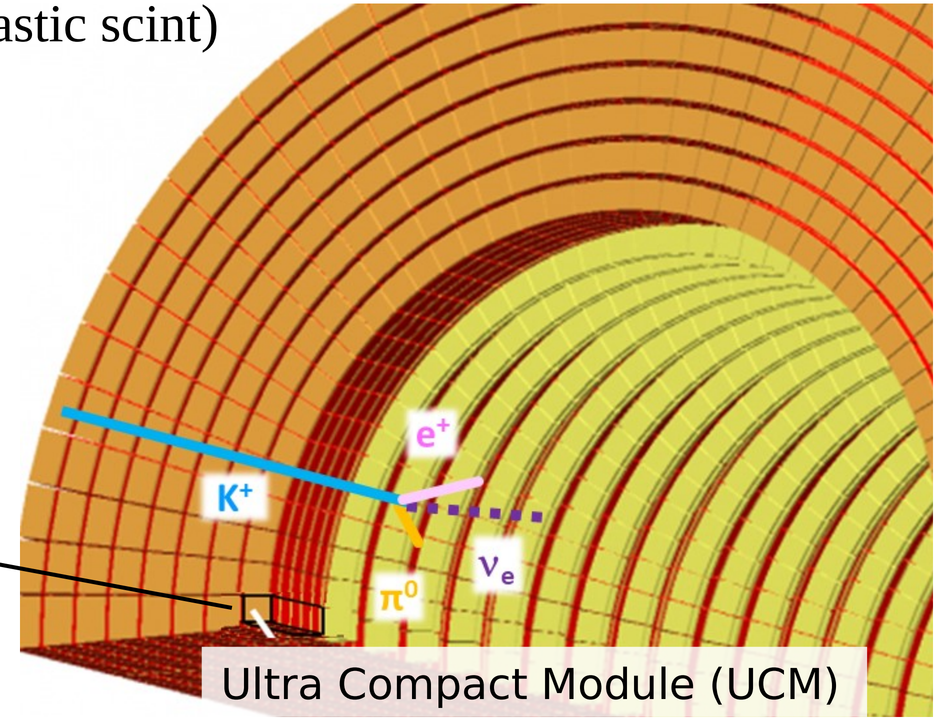
1) Longitudinally Segmented Calorimeters

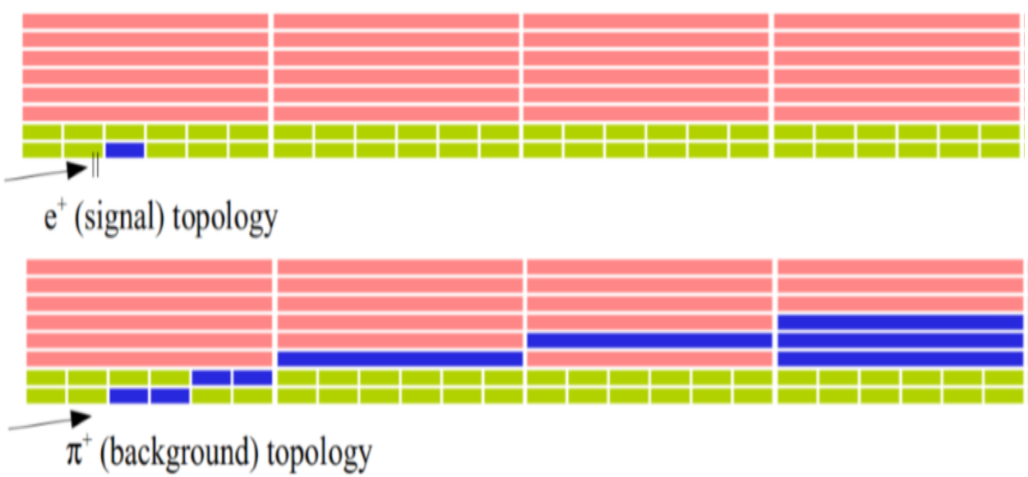
1)Ultra Compact Module (UCM) (Fe absorber+Plastic scint)

2)Light Readout with SiPM

→ $4X_0$ Longitudinal sampling: **e+/π± separation**



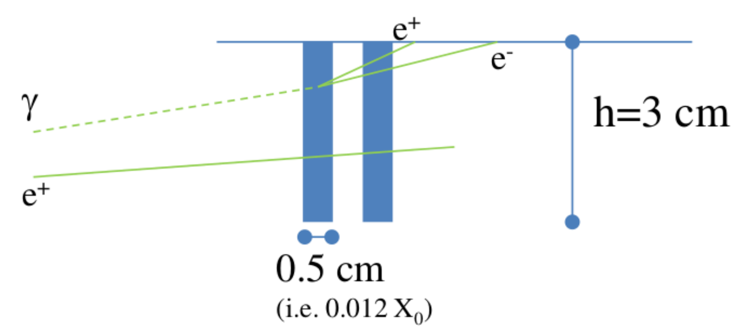




2) Integrated Photon-veto

3)3x3 cm^2 plastic scintillator pads

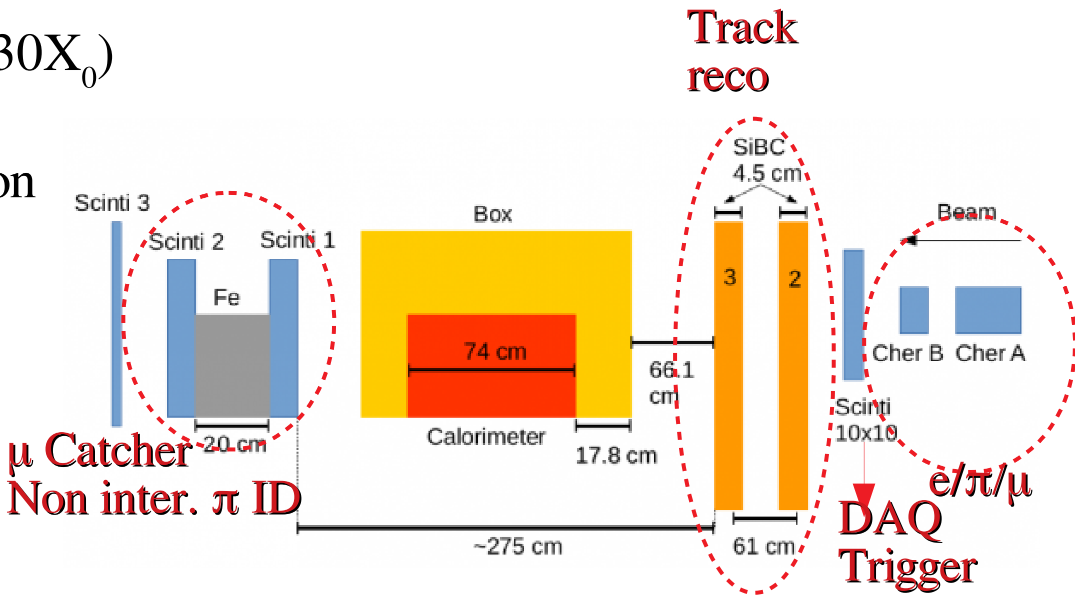
→ **e+/π0 separation (π0 rejection)**

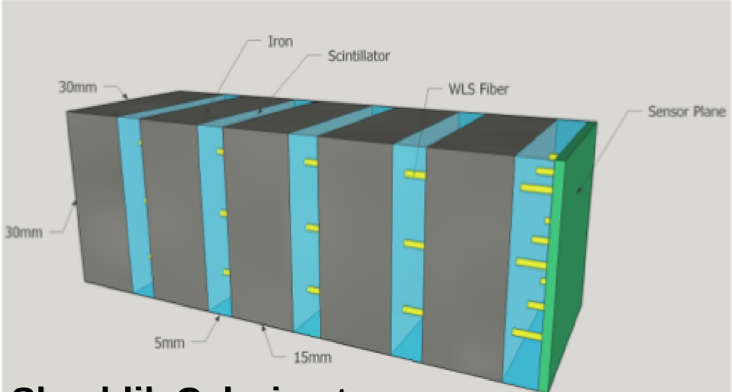


The Tagger – Test Beam

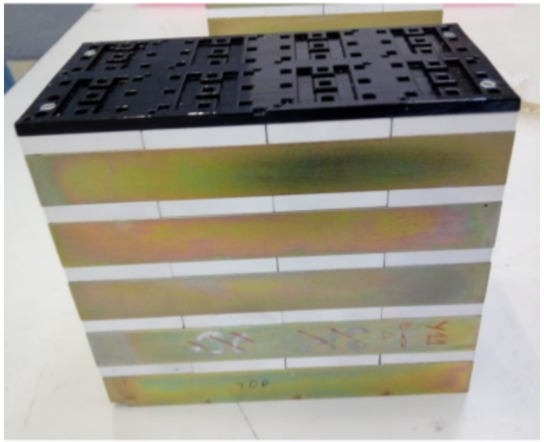
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

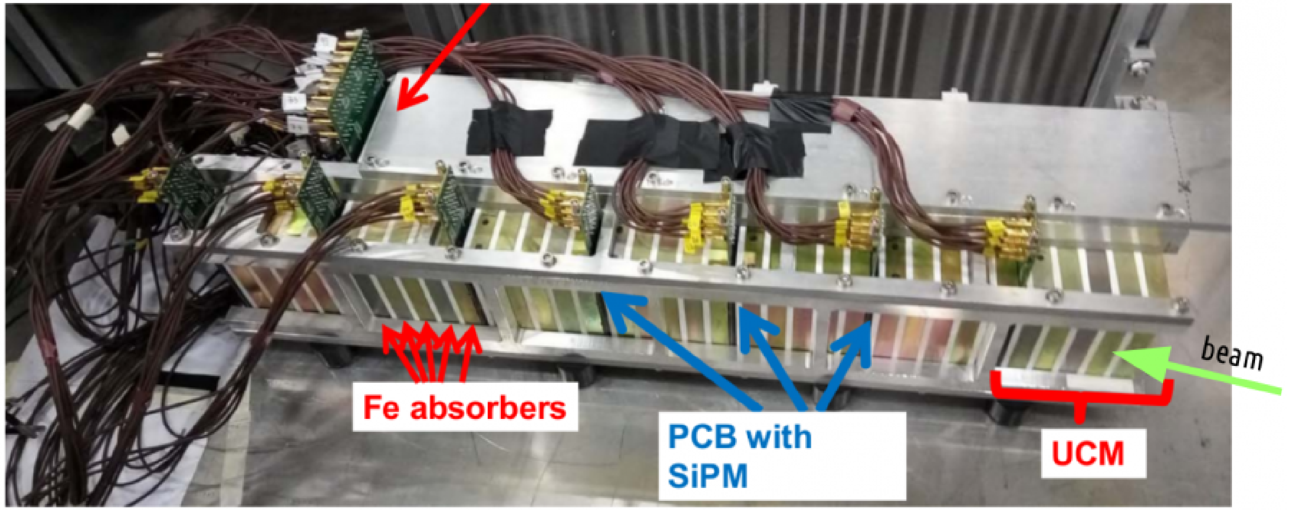
- 56 UCM arranged in 7 longitudinal block (~$30X_0$) + hadr. Layer (coarse sampling)
- e/µ tagged with Cherenkov counters and muon catcher
- Beam Composition @ 3GeV:
  9% e-, 14% µ , 77% hadrons





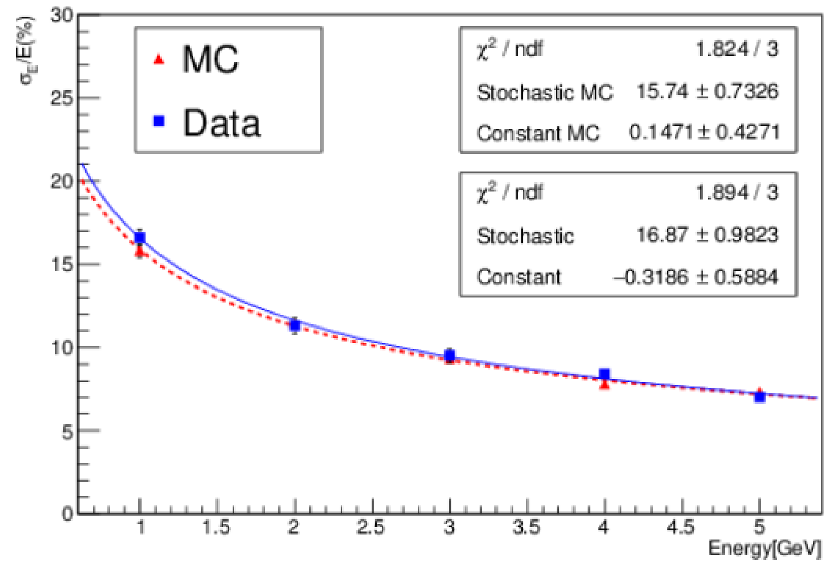
Shashlik Calorimeter





The Tagger – Test Beam

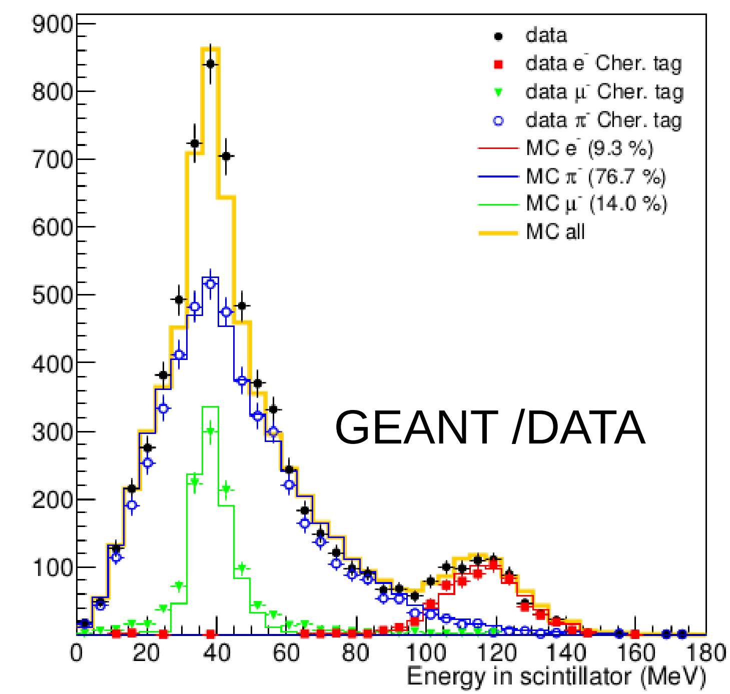
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017



Tested response to MIP, electrons and charge pions

- em energy res 17%/√E(GeV)
- Linearity <3% in 1-5 GeV
- From 0 to 200mrad tilts tested→no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities (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

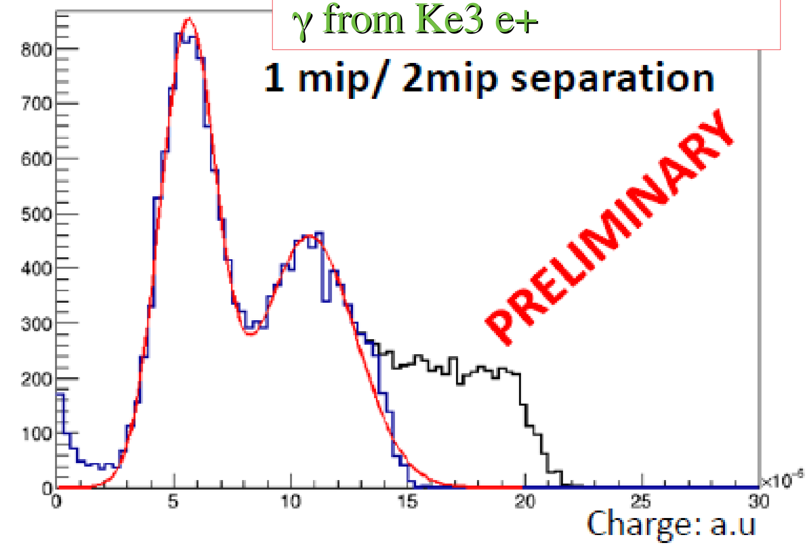


The Tagger – Test Beam

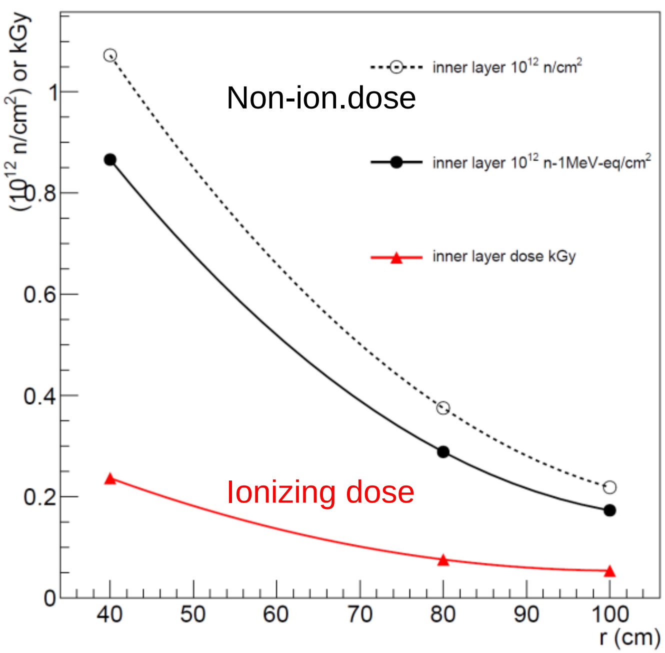
Calorimeter prototype performance with test-beam data @ CERN-PS T9 line 2016-2017

- γ/e+ discrimination (Photon-Veto)
  t0 layer scintillator (3x3x0.5 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 π0 gammas. (π0 by charge exchange of π+ with low density target after silicon chambers)

We are able to discriminate γ from Ke3 e+



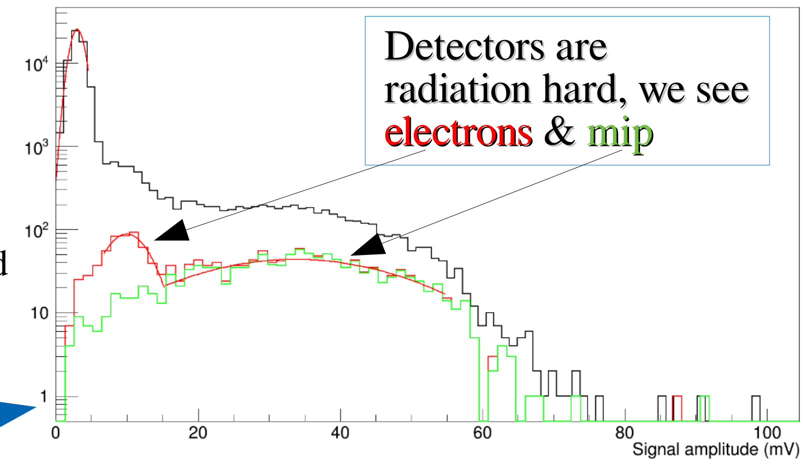
- Irradiation Studies – Full evaluation of doses
  SiPM were irradiated at LNL-INFN with 1-3 MeV neutrons in June 2017



→ 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 νeCC at neutrino detector)

Detectors are radiation hard, we see electrons & mip



Irradiated SiPM tested at CERN in October 2017

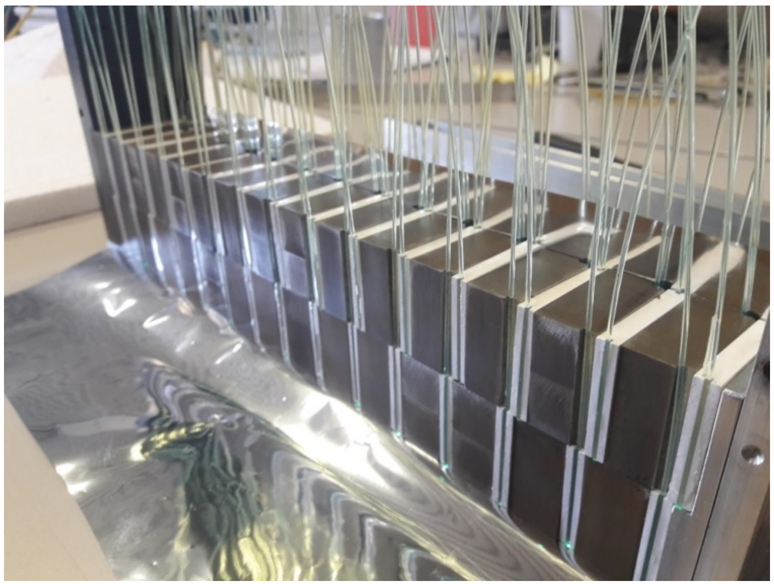
A. Coffani et al., arXiv:1801.06167

The Tagger – Detector R&D

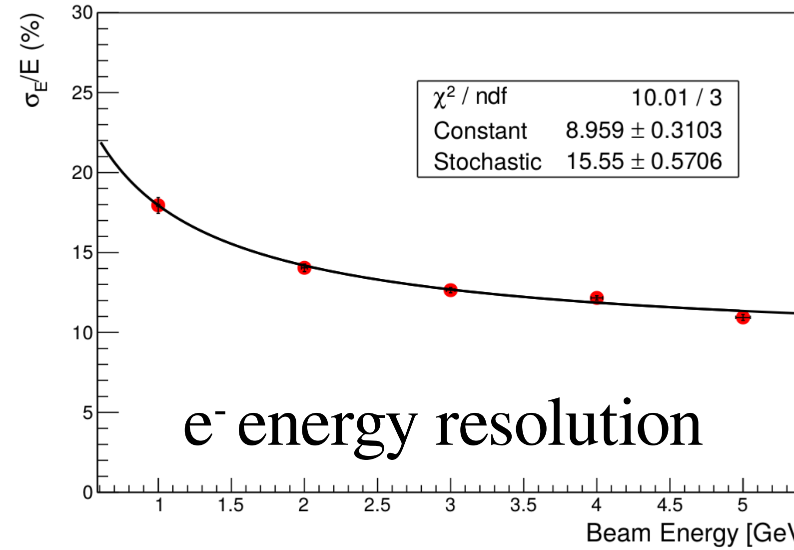
2018 Many R&D activities currently on-going
test-beam @ CERN in May + ...

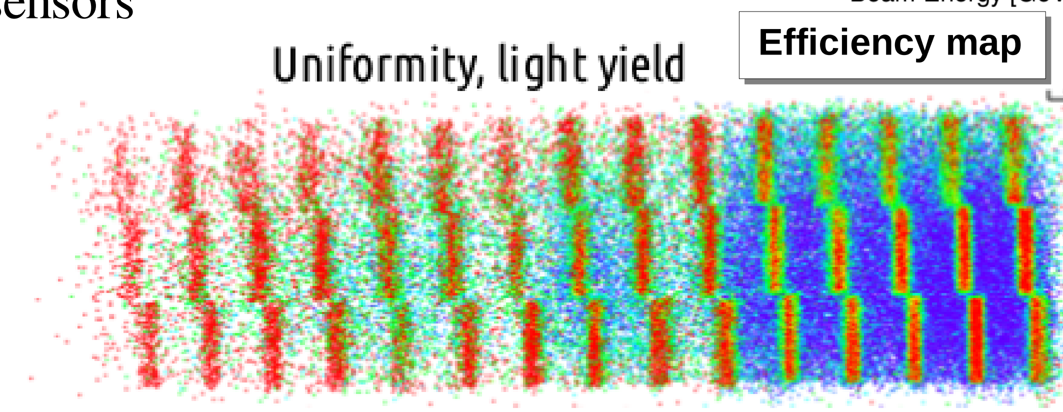
Sampling calorimeter with
lateral WLS light collection

First results



Test of
- Light yield
- Uniformity
- Resolution
- optical coupling to photosensors





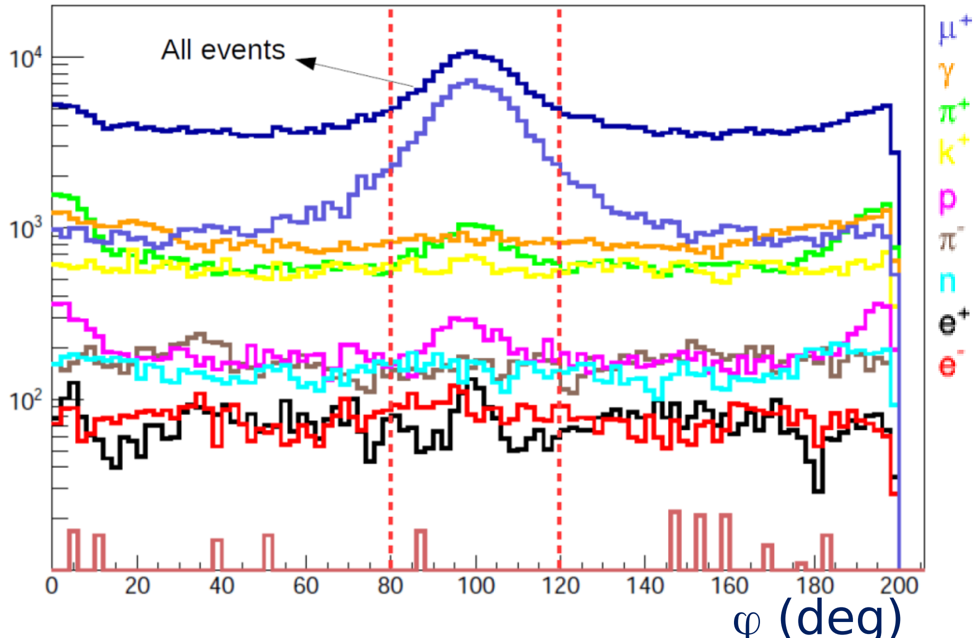
… another test-beam ahead (in September): will test module with hadronic cal. for pion containment

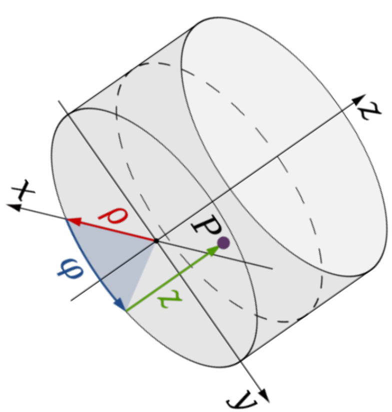
The Tagger – Particles in the decay tunnel

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

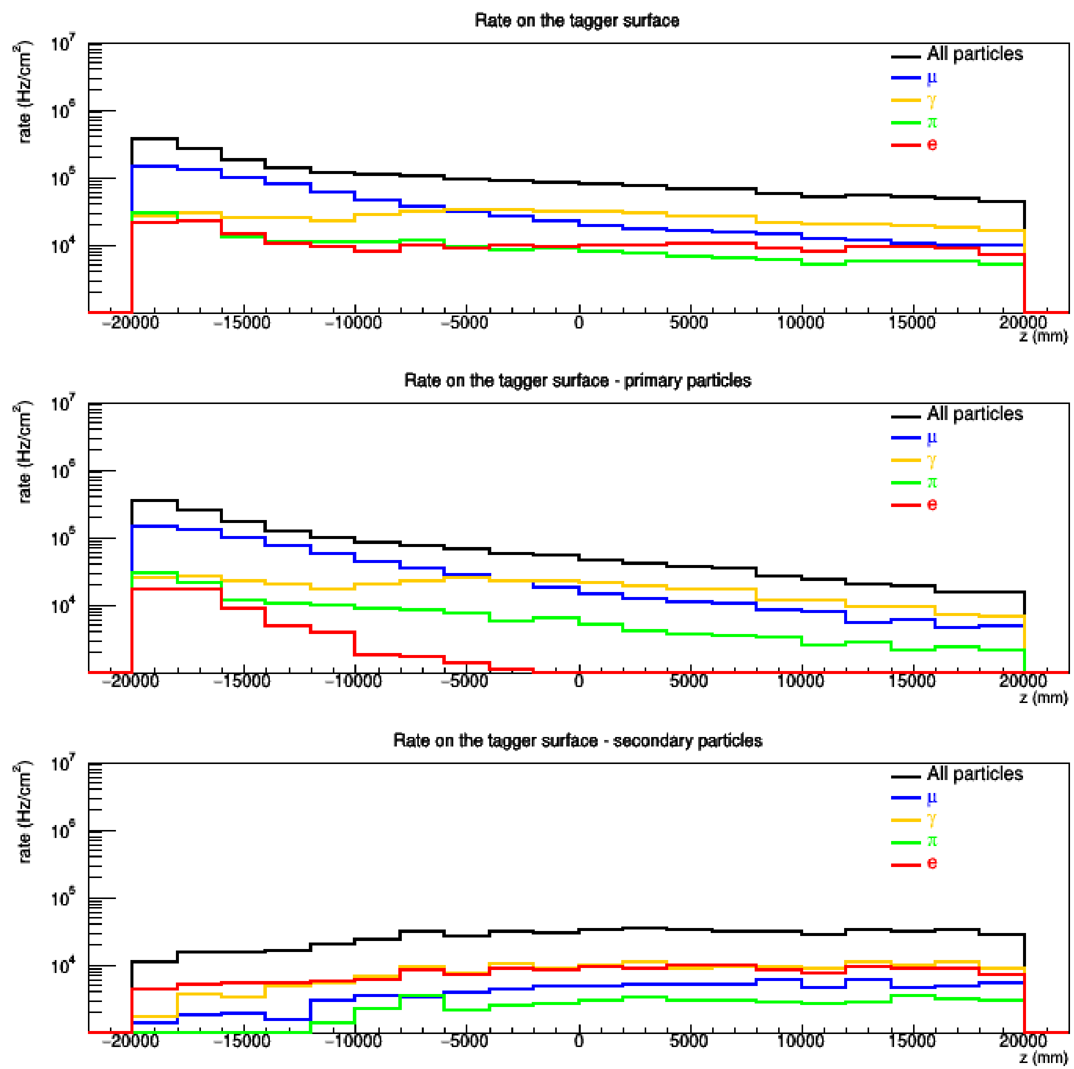
Calorimeter 1 m from the axis of the tunnel (r_{inner}=1.00 m)
Three radial layers of UCM (r_{outer}=1.09 m)

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





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



The Tagger – e+ ID from K decay

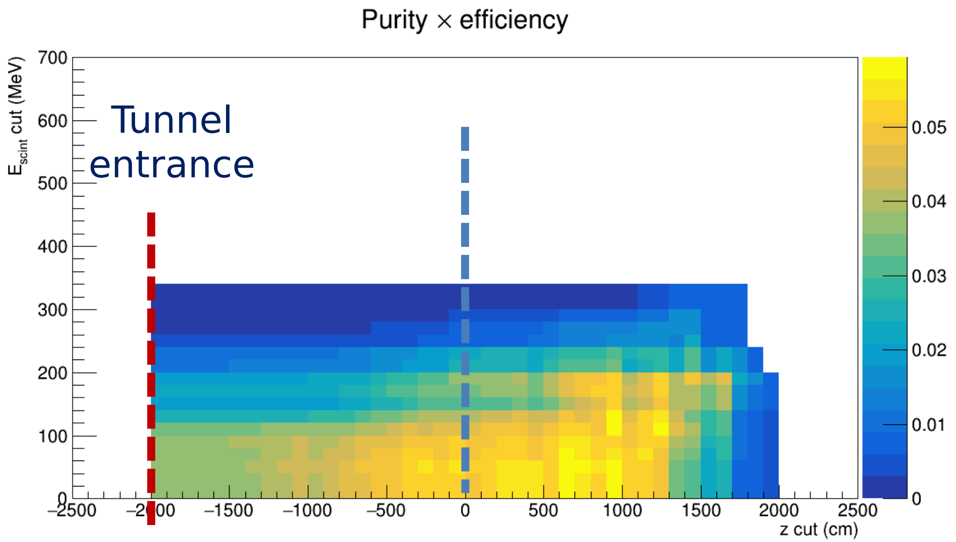
Full GEANT4 simulation of the detector, validated by prototype tests at CERN in 2016-2018. The simulation include particle propagation and decay, from the transfer line to the detector, hit-level detector response, pile-up effects.

Analysis chain

Event Builder → Identify the seed of the event (UCM with large energy deposit) and link neighboring modules

e/π/μ separation → (Neural Network) 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



after E and z-cut

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

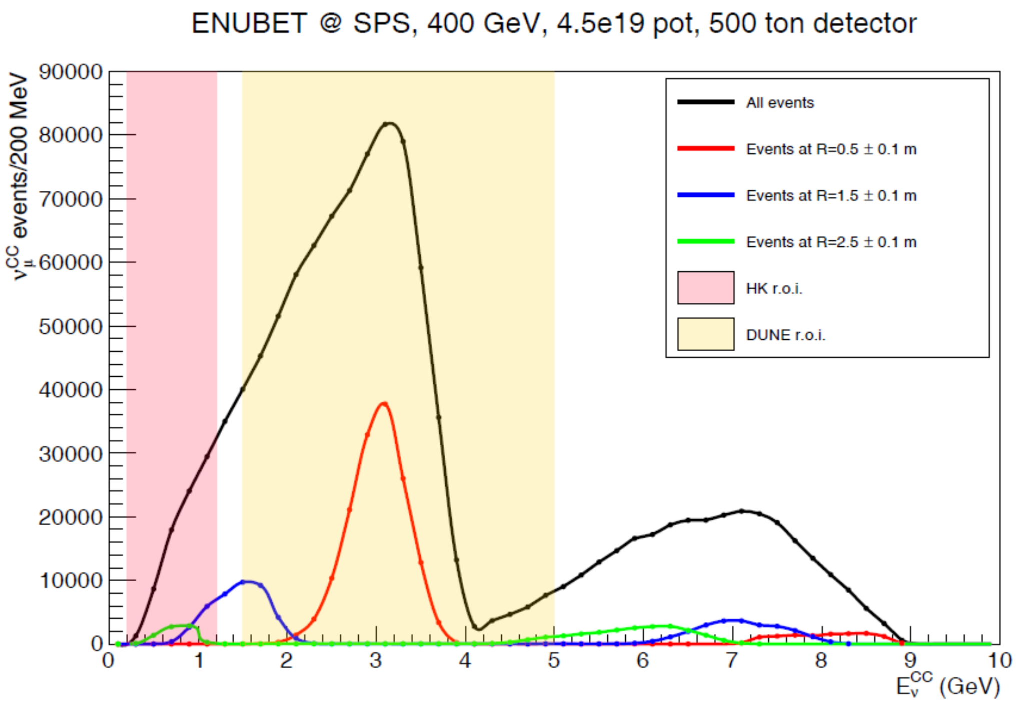
Neutrino Events per year at the detector

Detector mass: 500 tons (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab)

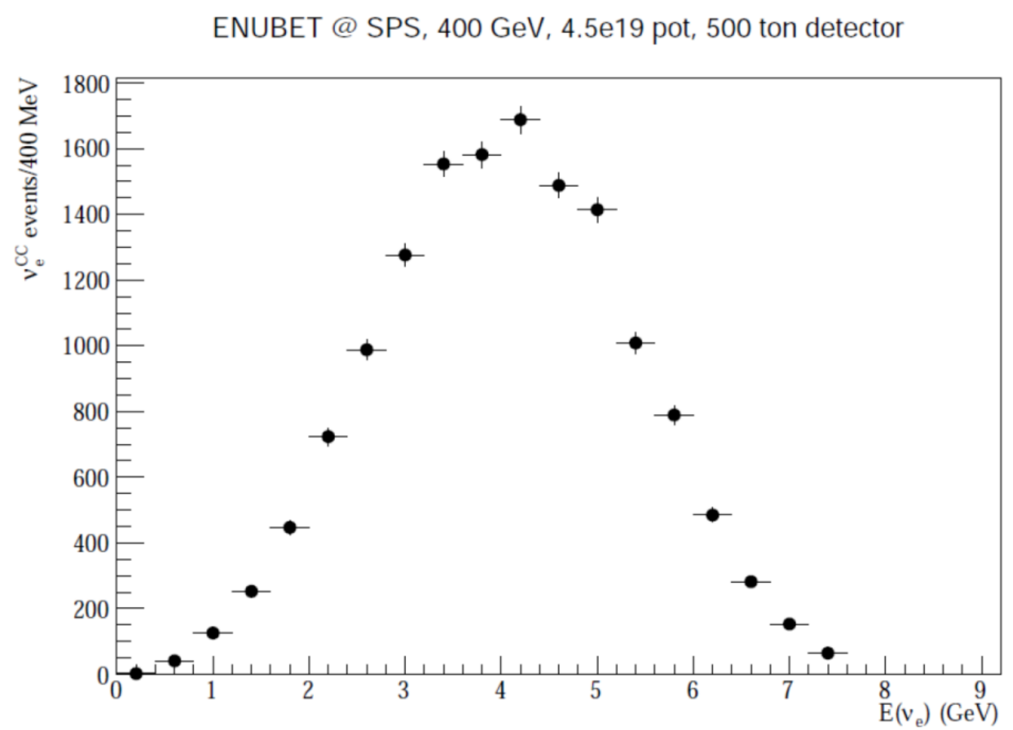
Baseline (i.e. distance between the detector and the beam dump) : 50 m

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!



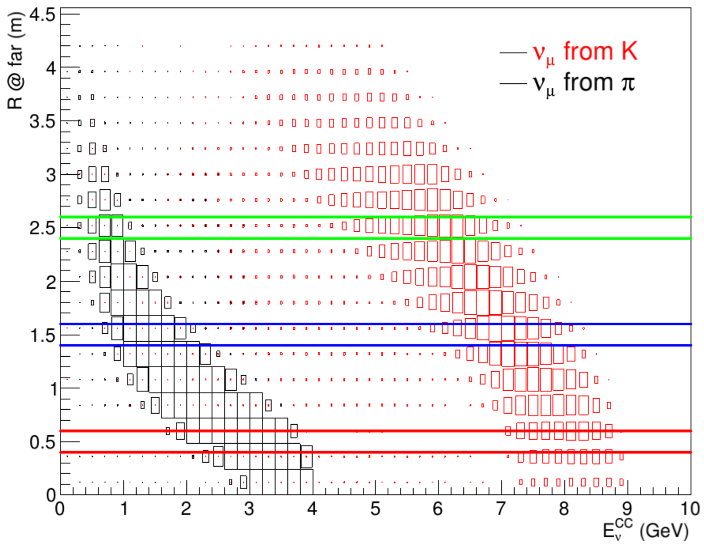
1.2 10^6 ν_μ charged current events per year

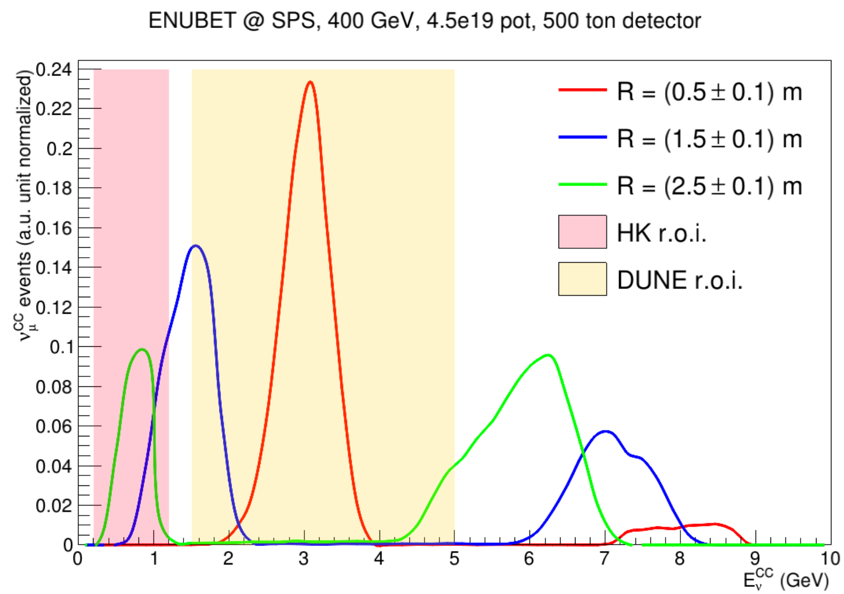


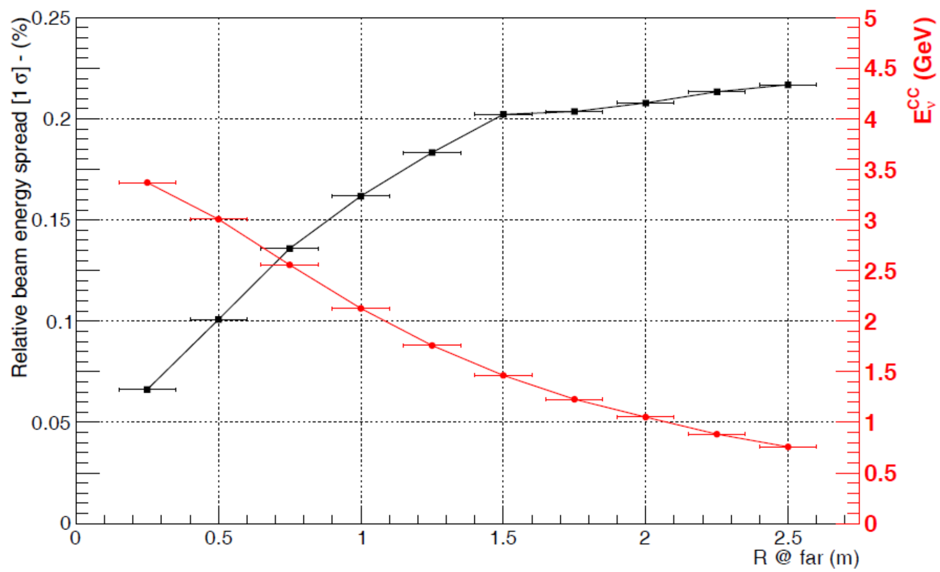
1.4 10^4 ν_e charged current events per year

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 $\nu\mu$ CC per year, 10^4 νe 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 the other decay modes of K and of pions, the outline of the physics performance for cross-section measurement and cost estimates

Next Steps

1) Systematic assessment (ν_e from K_{e3} e^+)
2) ν_μ flux from $K_{\mu 2}$ → work in progress
3) μ counting: μ from π can be counted after the h-dump: static transfer line with 2s extraction → we expect 1MHz/cm² in the dump
4) 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!

<u>**Thank you!**</u>

Back-Ups

TMVA

Define 11 variables for the e/π separation NN:

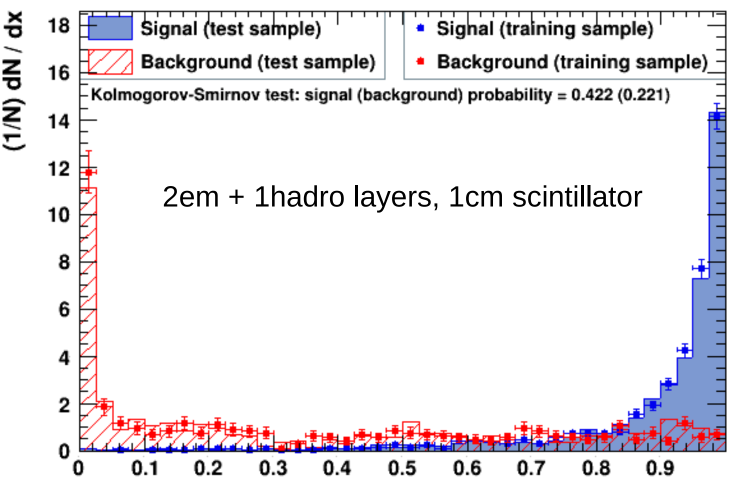
1) Fraction of the energy in the UCM in layer0 with the larger deposit over the total calorimeter energy
2) Fraction of the energy in the UCM in layer1 with the larger deposit over the total calorimeter energy
3) Fraction of the energy in the UCM in layer2 with the larger deposit over the total calorimeter energy
4) Fraction of energy in layer0
5) Fraction of energy in layer1
6) Fraction of energy in layer2
7) Fraction of energy in layer0 + Fraction of energy in layer1
8) Fraction of energy released in the UCM of layer 0 with the larger deposit and in the downstream UCM over the total calorimeter energy
9) Fraction of energy released in the UCM of layer 1 with the larger deposit and in the downstream UCM over the total calorimeter energy
10) Fraction of energy released in the UCM of layer 2 with the larger deposit and in the downstream UCM over the total calorimeter energy
11) Total energy released in the calorimeter

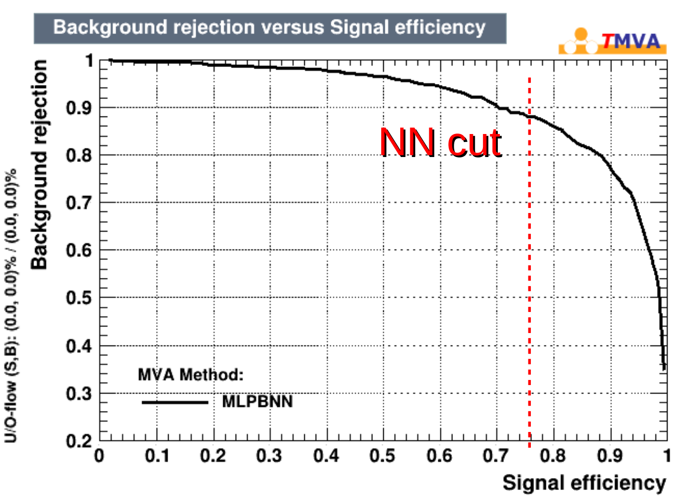
The Tagger – e+ ID from K decay

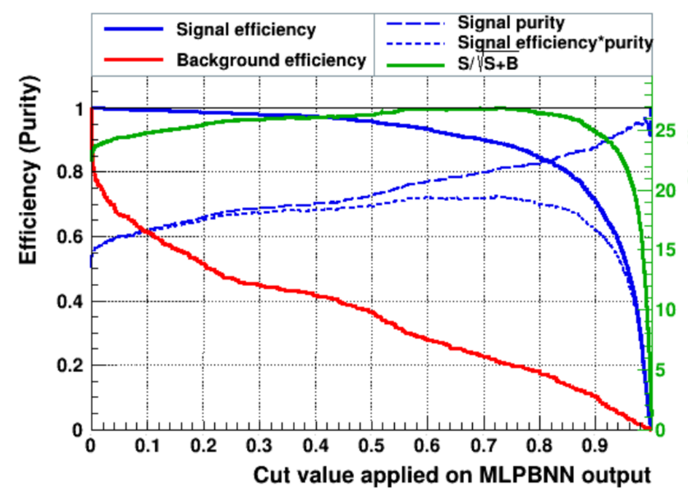
Event Builder → Seed of the event = UCM in first layer with energy deposit > 20 MeV → link neighboring modules with time (1ns) and position requirement

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

Response to Signal and Background







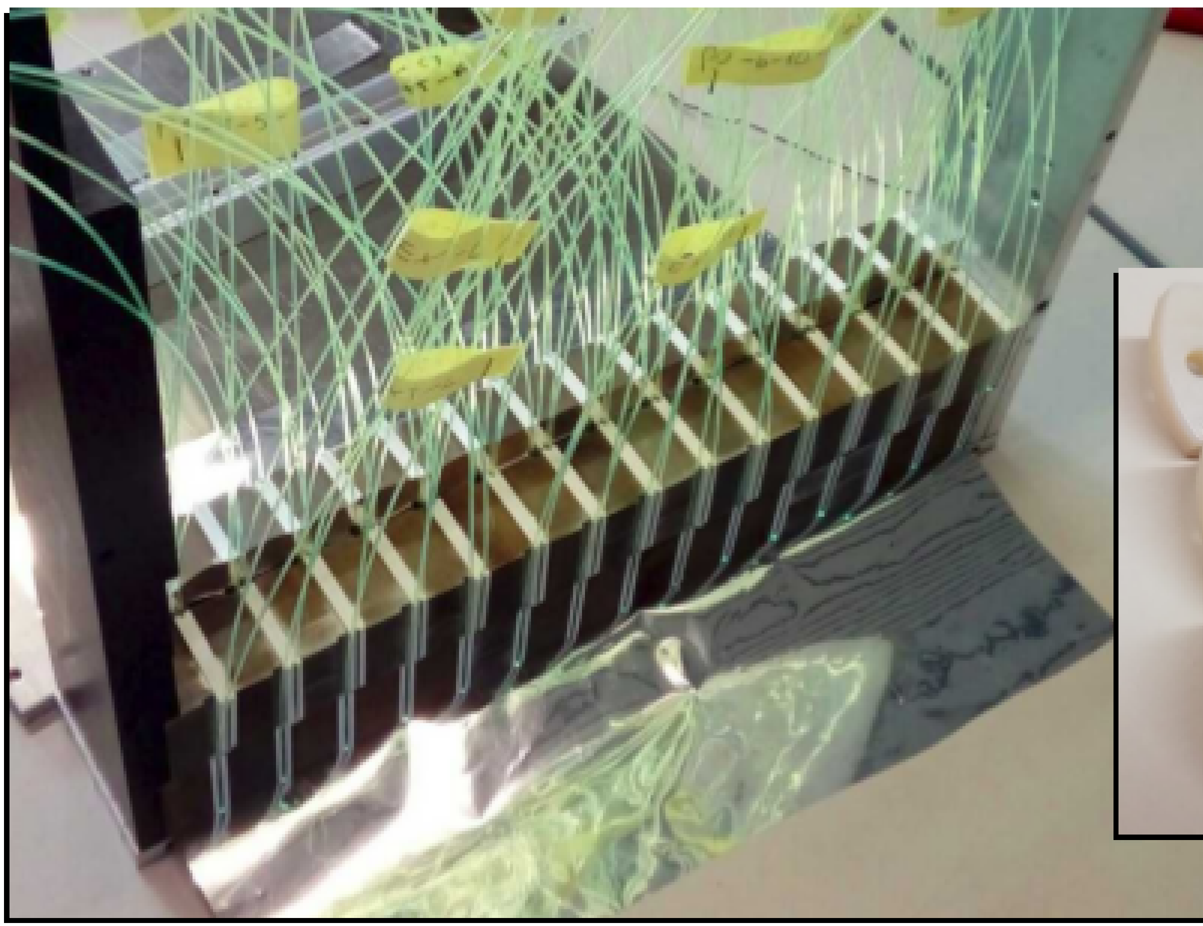
e/γ separation → π0 rejection: we require 3 layers of t0 before first calorimeter energy deposit compatible with a mip (0.65-1.7 MeV)

Test Beam - 2018

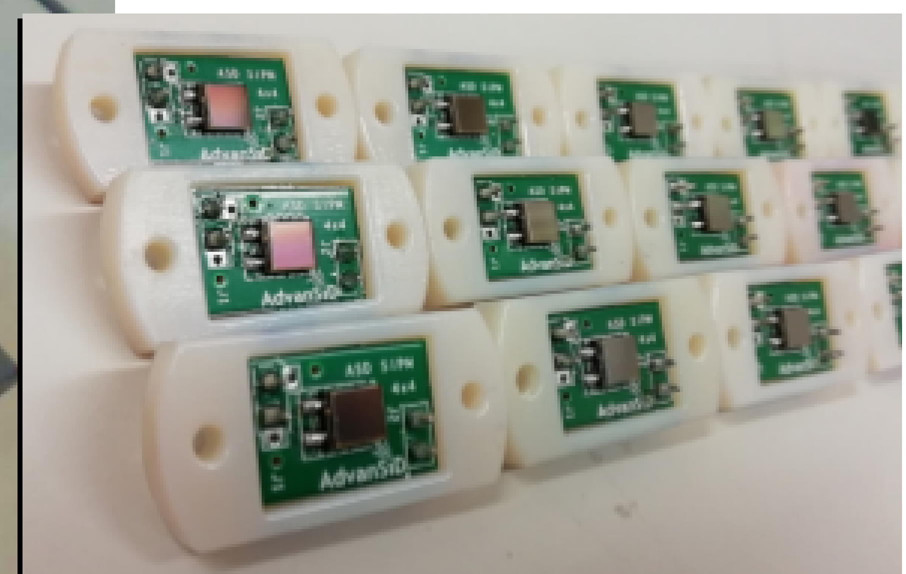
- Non-shashlik module - May 2018

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

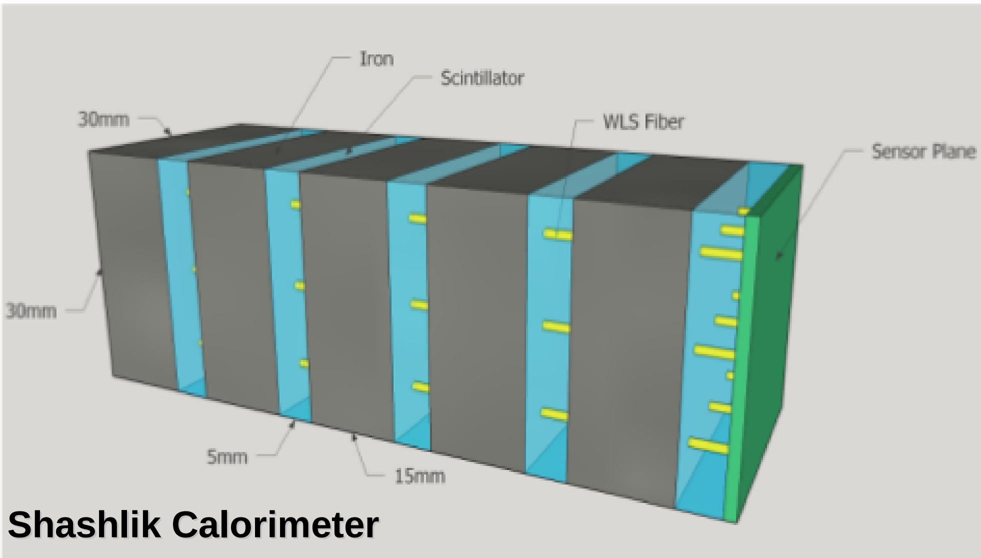
Test of Light yield, uniformity, resolution, optical coupling to photosensors (FBK Advansid 3x3 mm 2)

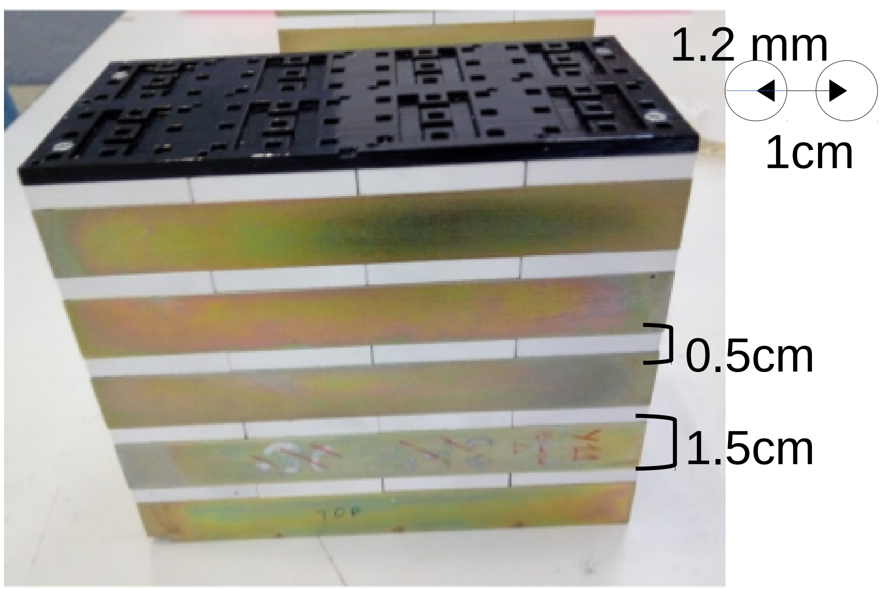


Silicon PM



Reference design
Shahlik option





Constraining ν Fluxes

IDEAL SOLUTION FOR NEW GENERATION SHORT-BASELINES

- 1% precision on νe fluxes for x-section measurements (“**monitored neutrino beams**”)
- Comparable precision on νμ fluxes from K for x-section measurements
- Narrow-band facility where neutrino energy is well-known thanks to small momentum bite
- With static-focusing transfer line option possibility of complete K-decay kinematic reconstruction → νe energy event-by-event (“**tagged neutrino beam**”)

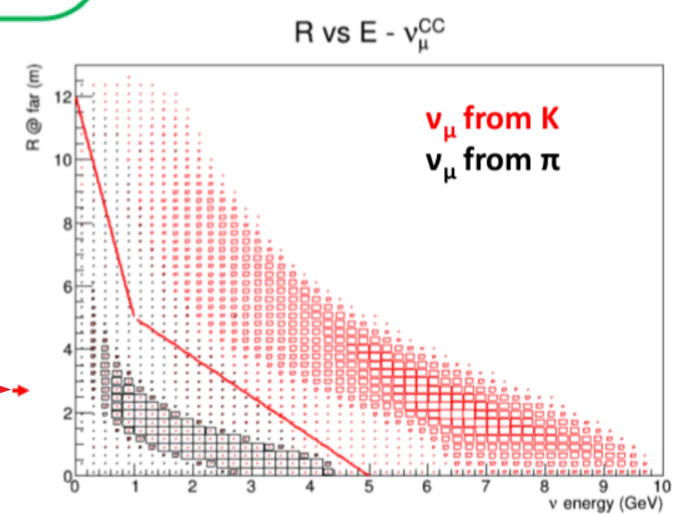
νe Flux

- **Ke3 golden sample**
  - π+/π0 from K+ can mimic an e+
    e/π discrimination through
    I. Shower Longitudinal profile
    II. Vertex reconstruction by timing
- Non Ke3 (silver sample) exploitable

$K^+ \rightarrow e^+ \nu_e \pi^0$ (5.1%)
$K^+ \rightarrow \pi^+ \pi^0$ (20.7%)
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$ (5.6%)
$K^+ \rightarrow \pi^+ \pi^0 \pi^0$ (1.8%)
$K^+ \rightarrow \mu^+ \nu_\mu$ (63.6%)
$K^+ \rightarrow \mu^+ \nu_\mu \pi^0$ (3.3%)

νμ Flux

- K well constrained by tagger (from Ke3 and hadronic decays)
- νμ from K can be selected at the neutrino detector using radius-energy correlations
  → high precision σ(νμ)

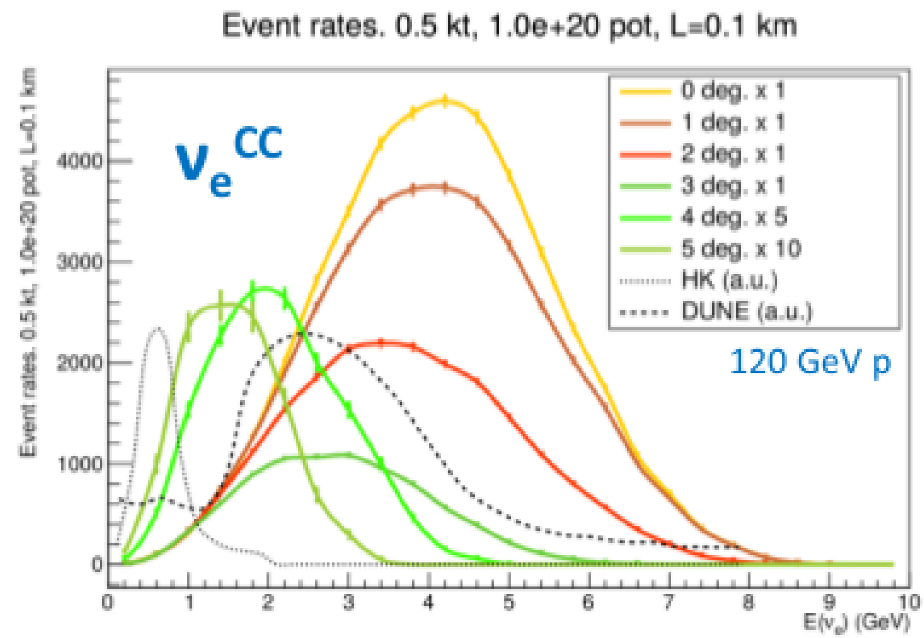


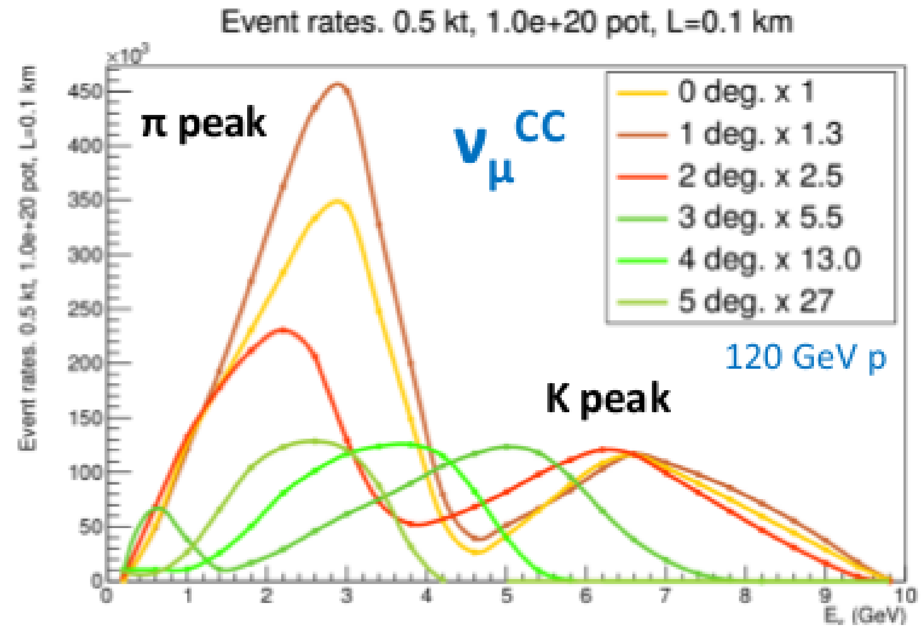
Neutrino Samples

- Need good e-tagging capabilities, like:
  - ICARUS/μBOONE @ **FNAL**
  - Proto-DUNE SP/DP @ **CERN**
  - Water Cerenkov (e.g. E61 @ **JPARC**)
- Assumed a 500 t LAr det (6×6×10 m^3) @ 100 m

E_p (GeV)	PoT (10^{20}) for 10^4 ν_e^{CC} (on-axis)	Run duration (w/ nominal int)
30	1.03	**~ 0.2 JPARC y**
120	0.24	**~ 0.4 NUMI y**
400	0.11	**~ 0.25 CNGS y**

- **Reference design** better suited for **multi-GeV** (e.g. **DUNE**)
- **Hyper-K** r.o.i accessible in **off-axis** configuration, but **larger exposures** needed
- Studying the possibility to **reduce** the initial **hadron momentum**
- Can exploit also **ν_μ from π (~10^5 @ low E)**, estimating the **initial π flux** with **BCT** and **K** constraint **from the tagger** → *to be investigated*





Systematics on νe Flux

Positron tagging eliminates the most important contributions. Assessing in detail the **viability of the 1% systematics** on the flux is one of the final goals of ENUBET. Full analysis is being setup profiting from a **detailed simulation** of the beamline, the tagger and inputs from **test beams**.

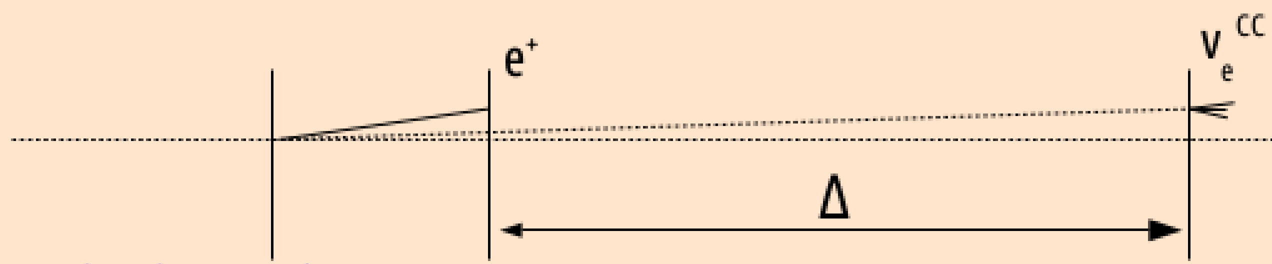
Source of uncertainty	Estimate
statistical error	<1% (10^4 ν_e^{CC})
kaon production yield	irrelevant (positron tag)
number of integrated PoT	irrelevant (positron tag)
secondary transport efficiency	irrelevant (positron tag)
branching ratios	negligible + only enter in bkg estimation
3-body kinematics and mass	<0.1%
phase space at the entrance	to be checked with low intensity pion runs
ν_e from μ-decay	constrain μ from K by the tagger and μ from π by low intensity runs
e/π separation	being checked directly at test beams

Going beyond: "time-tagged" beams

- Event time dilution → **time-tagging**
- Associating **a single ν interaction** to a **tagged e⁺** with a small "accidental coincidence" probability through **time coincidences**
- **E_ν and flavor of the neutrino know "a priori" event by event.**

Superior purity. Combine E_ν from decay with the one deduced from the interaction.

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



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

Accidental tag probability using 10^{10} hadrons/burst: **$A \sim 2{\times}10^7\ \delta/T_{extr}$**

T_{extr} = 1s (~ 1 observed e^+ / 30 ns) + **δ = 1 ns** → **A = 2 %** **OK !**

Time-tagging not possible using magnetic horns, (scenario A):

T_{extr} = 2 ms (1 e^+ / 70 ps) even δ = 50 ps gives A = 50%