# ENUBET: Enhanced NeUtrino BEams from kaon Tagging

A.Meregaglia (CENBG-Bordeaux)

**On behalf of the ENUBET collaboration**

30th Rencontres de Blois - Blois - 5th June 2018

# Introduction

- Neutrino oscillation physics has moved **from discovery to precision** era.
- Detectors have grown in terms of size, resolution and complexity, however on the beam side there is no major conceptual breakthrough since the 70's and they are "just" growing in intensity.
- **Experiments** in the precision era of neutrino physics have exquisite knowledge of the final state interactions but a **quite rough** (>5%) **knowledge of initial fluxes and beam contamination**.
- As a consequence, the physics reach of precision physics experiments is strongly linked to the **systematic reduction program** currently underway.

↓

ENUBET is a development on the beam side for a strong reduction of the systematics related to the flux and cross section knowledge

# Electron neutrino source

- The bulk of $\nu_\mu$ are produced in a conventional beam by the pion decay: $\pi^+ \rightarrow \mu^+ \nu_\mu$.
- The $\nu_e$ are given by:

meson of 8.5 GeV

| | | |
|---|---|---|
| $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \overline{\nu}_\mu \nu_\mu$ | (DIF) | mean angular spread of 28 mrad for $e^+$ |
| $K^+ \rightarrow \pi^0 e^+ \nu_e$ | ($K_{e3}$) | mean angular spread of 88 mrad for $e^+$ |

- A large angle positron is a clear indication of the production of a $\nu_e$.

**How to know the flux?**

**Conventional Beam**

- Passive decay region
- $\nu_e$ flux relies on ab-initio simulation of the full chain
- Large uncertainties from hadron production

**Monitored Beam**

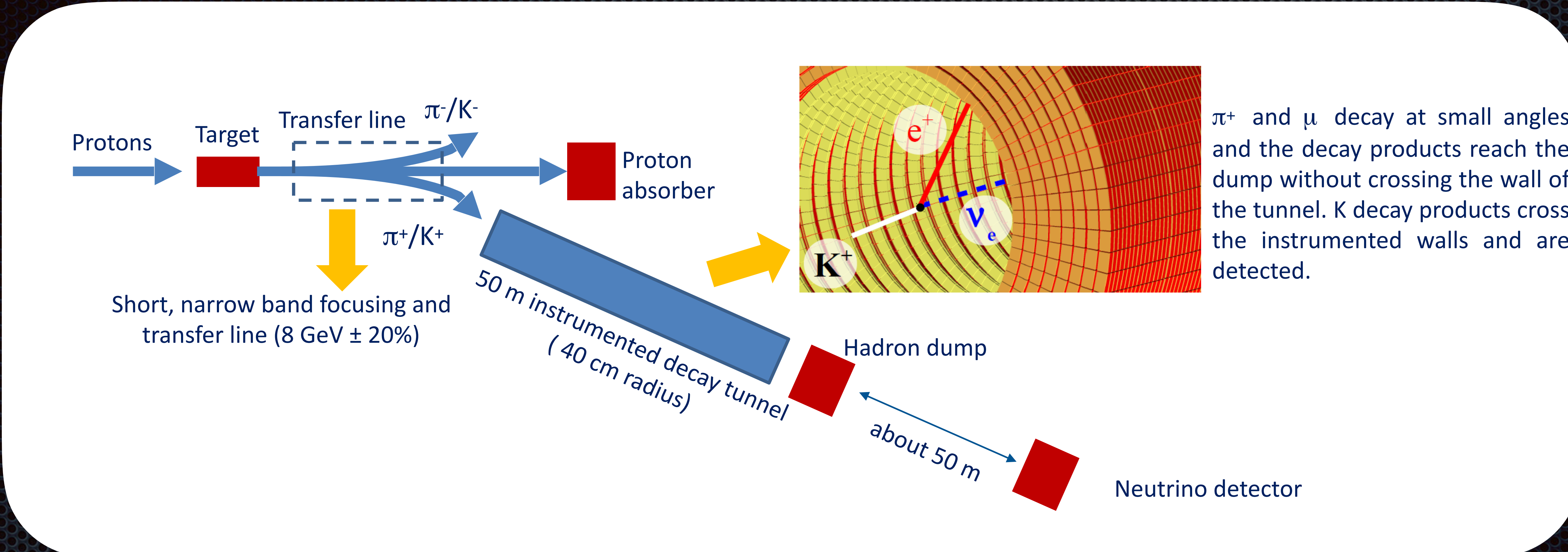
- Fully instrumented decay region
- $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle $e^+$
- $\nu_e$ flux prediction = $e^+$ counting

↓

**The ENUBET approach**

# The ENUBET approach

**Large angle positron monitoring**




- The advantage of the ENUBET approach is a pure $\nu_e$ source from K decay ($\mu$ DIF contribution below 3%) and the flux is determined from the $e^+$ monitoring at large angle.
- We can obtain tolerable rates / detector irradiation (< 500 kHz/cm2 , < 1 kGy).
- The disadvantage with respect to other proposed techniques such as nuSTORM is a large reduction of flux.

# The ENUBET collaboration

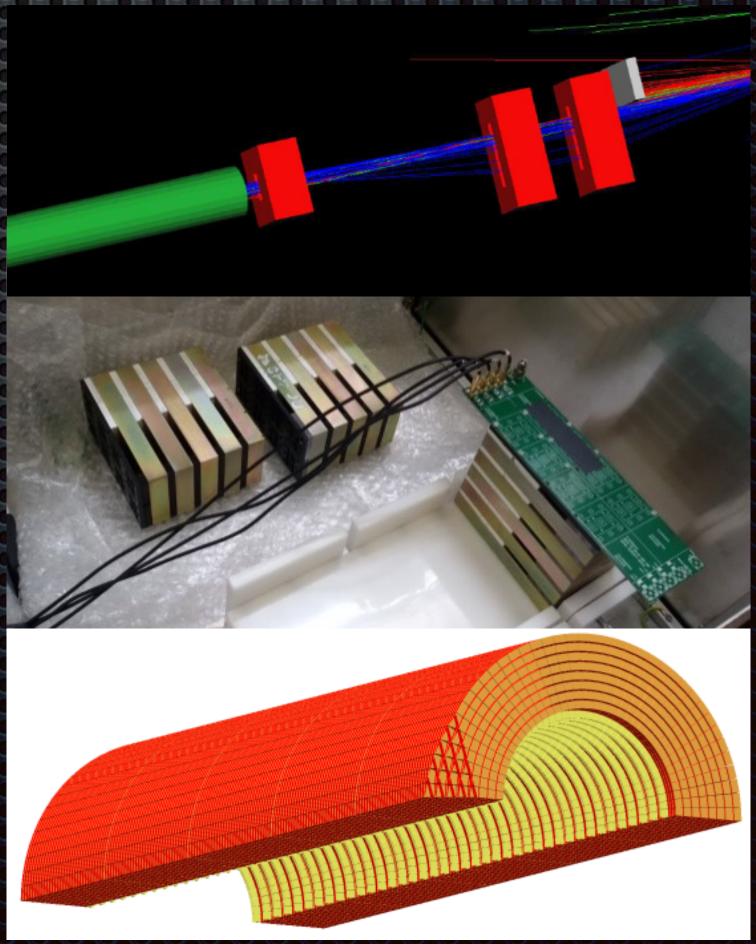
- ENUBET is a project approved by the European Research Council (ERC Consolidator Grant, P.I. Andrea Longhin) for a 5 year duration (Jun 2016 – May 2021) with an overall budget of 2 Meuro.

**ENUBET collaboration**

G. Ballerini, A. Berra, R. Boanta, M. Bonesini, C. Brizzolari, G. Brunetti, M. Calviani, S. Carturan, M.G. Catanesi, S. Cecchini, F. Cindolo, G. Collazuol, E. Conti, F. Dal Corso, G. De Rosa, A. Gola, R. A. Intonti, C. Jollet, Y. Kudenko, M. Laveder, A. Longhin, P.F. Loverre, L. Ludovici, L. Magaletti, G. Mandrioli, A. Margotti, V. Mascagna, N. Mauri, A. Meregaglia, M. Mezzetto, M. Nessi, A. Paoloni, M. Pari, L. Pasqualini, G. Paternoster, L. Patrizii, C. Piemonte, M. Pozzato, F. Pupilli, M. Prest, E. Radicioni, C. Riccio, A.C. Ruggeri, G. Sirri, M. Soldani, M. Tenti, M. Torti, F. Terranova, E. Vallazza, M. Vesco, L. Votano

**Activities**

- Beamline design.
- Test beams at CERN-T9 and INFN-LNF.
- Construction of 3m section of the instrumented decay tunnel.
- Design of the proton extraction scheme (CERN SPS).



# Beamline (1)

- Claiming an overall systematic budget <1% requires an end-to-end simulation of the neutrino beamline. Such simulation work (currently based on CERN-SPS) is ongoing.
- Two options are currently under investigation: a **horn** based option and a **static focusing** one.

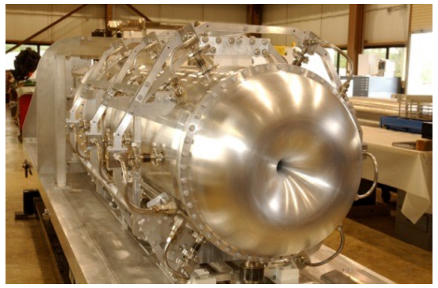
## Horn

**Proton extraction scheme**

2 s flat top


several few-ms extractions during the 2 s flat top

**Horn**



I(t) profile matching the extraction scheme (few ms, ~10 Hz during flat top)

**Pros**: large acceptance (flux)

**Cons**: unconventional parameters for p extraction and focusing of secondaries

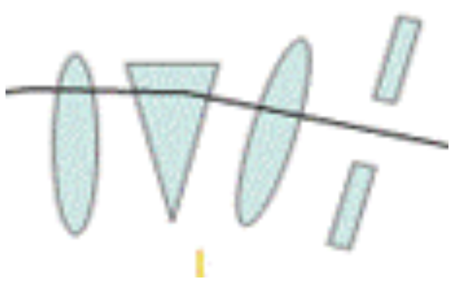
## Static focusing

**Proton extraction scheme**

2 s flat top

Identical to the one of SHIP@CERN

**Focusing**



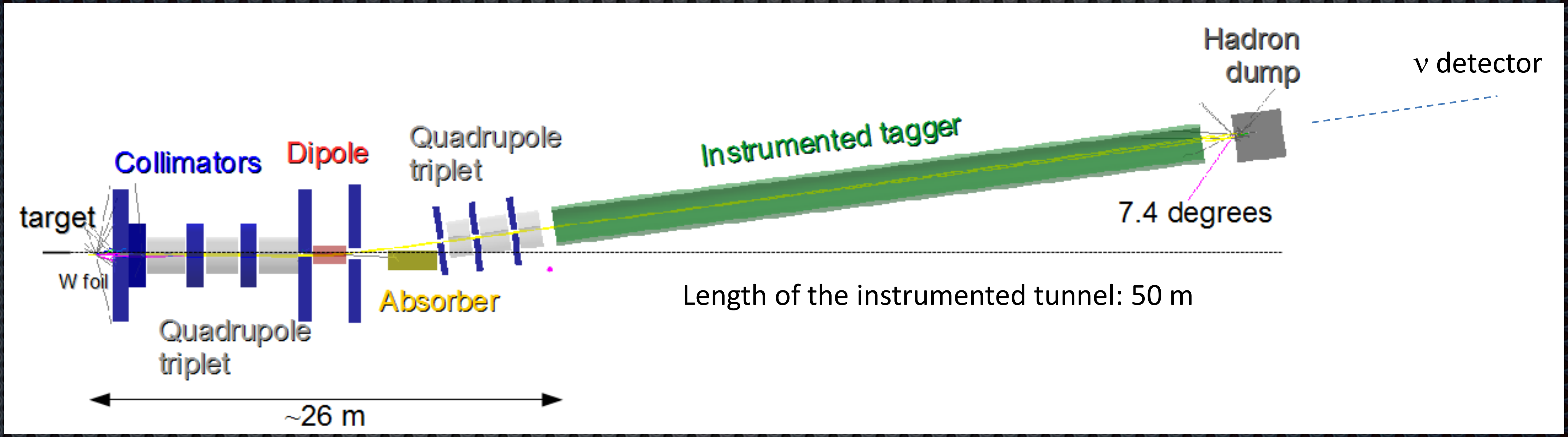
Static (quad, dipoles)

**Pros**: very low rates at the decay tunnel. Tagged neutrino beams.

**Cons**: small acceptance (flux). Cosmic ray background at the neutrino detector.

# Beamline (2)

- Preliminary studies for optimization of the Horn-based beamline were completed (background studies still ongoing).
- The optimization of the static focusing beamline is in progress however **preliminary results are very promising** despite the lower yield (detailed studies on the beam contamination is still ongoing).




**Hadronic rates at tunnel entrance**

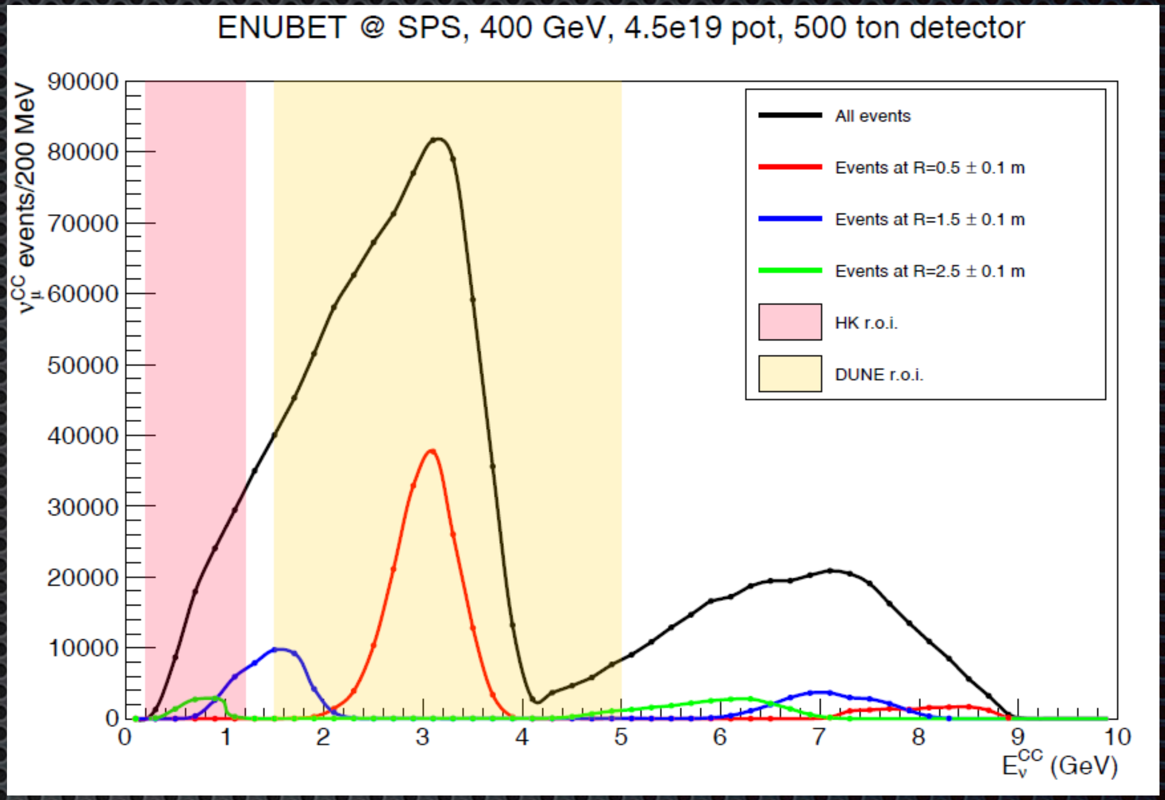
(Initial estimate from Eur.Phys.J. C75 (2015) no.4, 155 in parentheses)

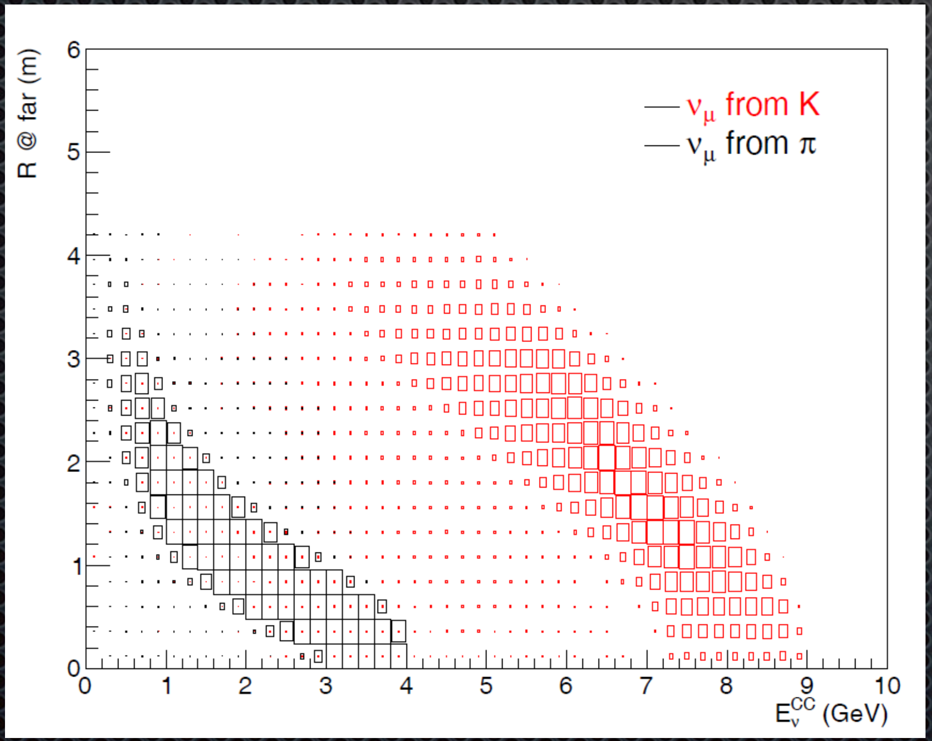
| Type of beamline | $\pi^+$/pot ($10^{-3}$) | $K^+$/pot ($10^{-3}$) | Increase factor w.r.t. initial estimates |
|---|---|---|---|
| Horn based | 77.3 (33.5) | 7.9 (3.7) | ~ 2.2 |
| Static | 19.0 (3.6) | 1.37 (0.43) | 3—5 |

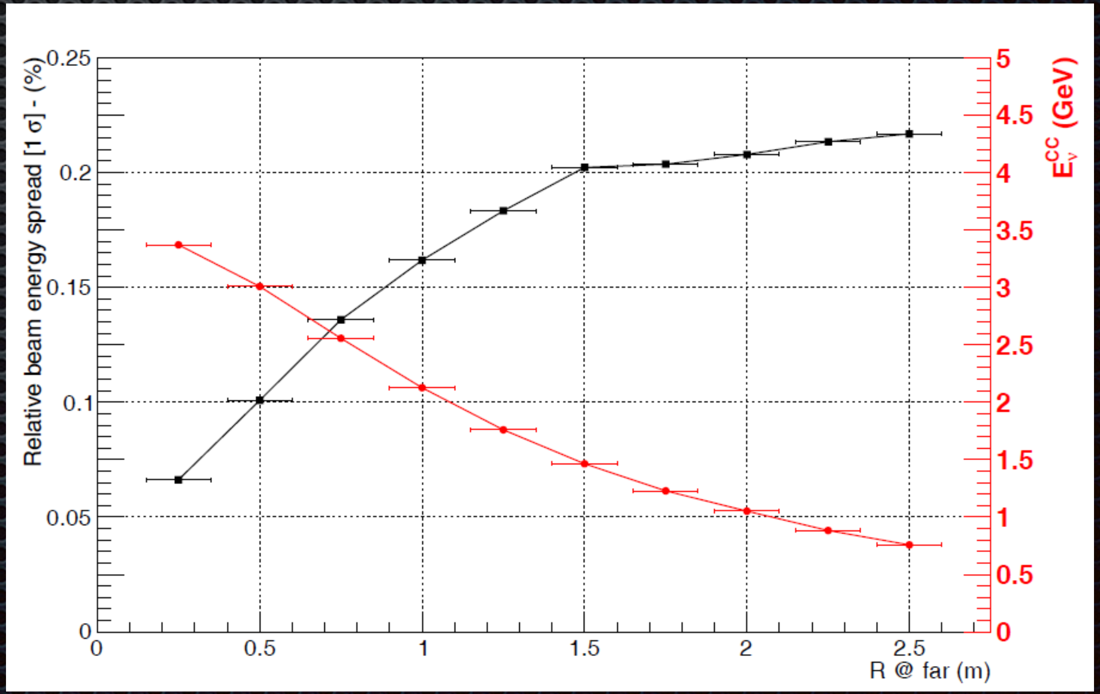
# Neutrino beam

- Reference parameters: **100 m baseline, 500 t detector** (e.g. ICARUS@FNAL or Protodune-SP/DP@CERN).
- Rates at the far detector: O($10^4$) $\nu_e$ CC events, O($10^6$) $\nu_\mu$ CC events in about 1 year of data taking at CERN SPS (400 GeV protons).
- 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%.

About 1 year of data taking at CERN SPS
500 t neutrino detector



# Detector concept

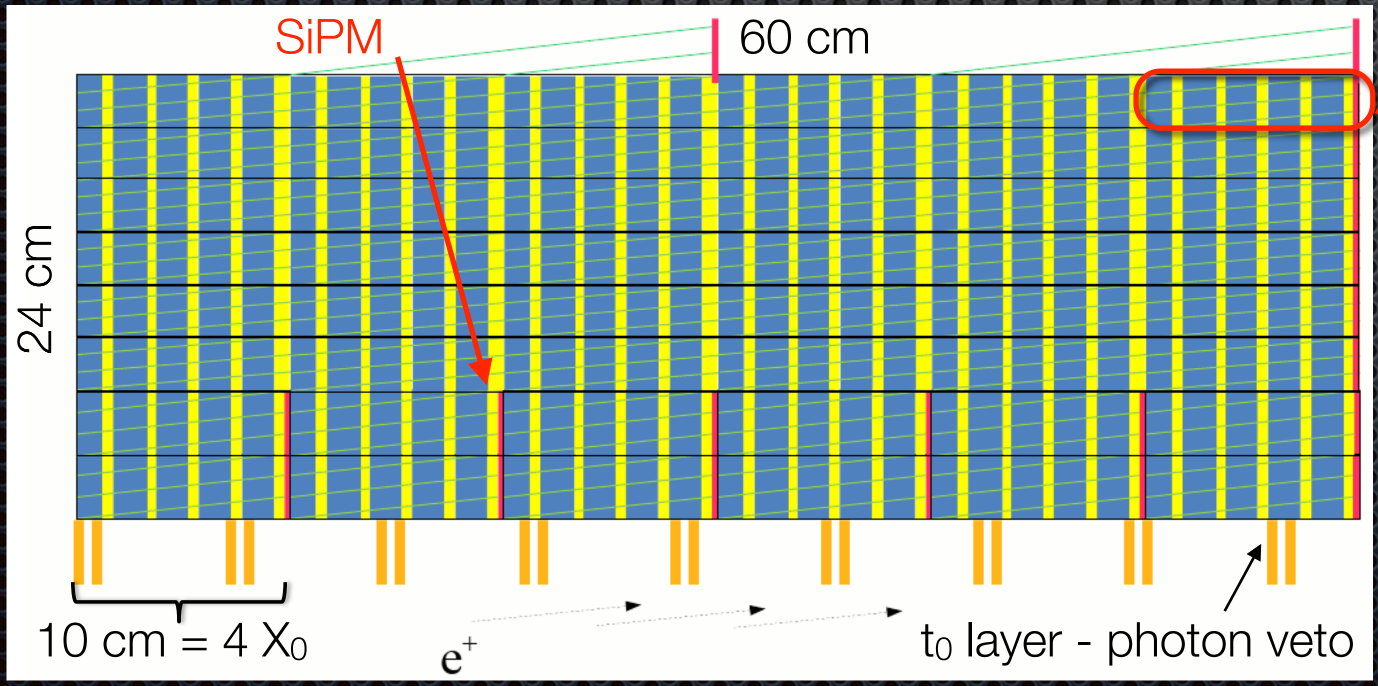
- Calorimetric techniques offer the cheapest and safest mean to distinguish between positrons and charged pions exploiting the longitudinal development of the shower, and the proposed **shashlik calorimeter (Iron/scintillator) coupled to a SiPM readout** solves the problem of longitudinal segmentation.

- The chosen ultra compact module (UCM) is a 4 $X_0$ e.m. module where the light is readout connecting WLS fibers directly to a 1 $mm^2$ SiPM in a plastic holder.

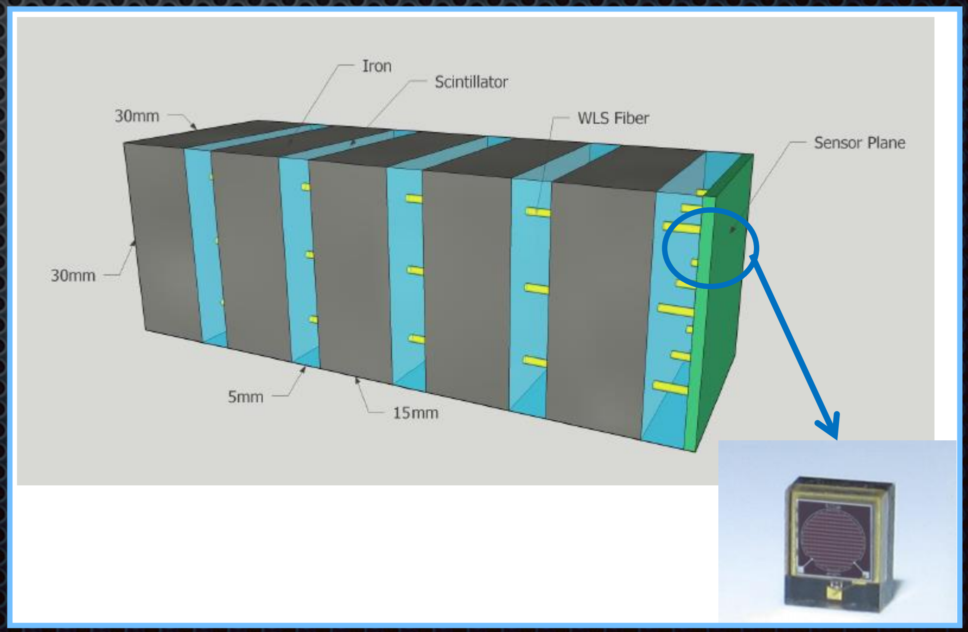
- A full module is made of 2 e.m. layers and few (exact number under study) hadronic layers (same structure but read out after 60 cm i.e. 2.6 interaction lengths.

- The photon veto, or "$t_0$ layer", has to be instrumented in the decay tunnel and it will be used as a trigger and as a veto for gammas from $\pi^0$ decays ($K^+ \rightarrow \pi^+\pi^0$).

**Full module**

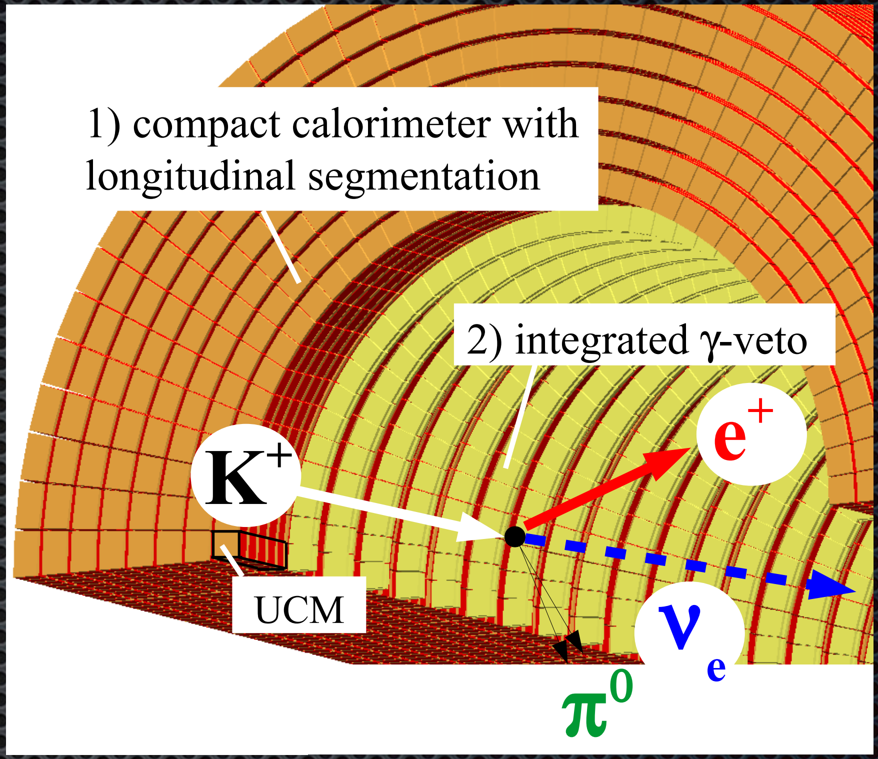



**UCM**

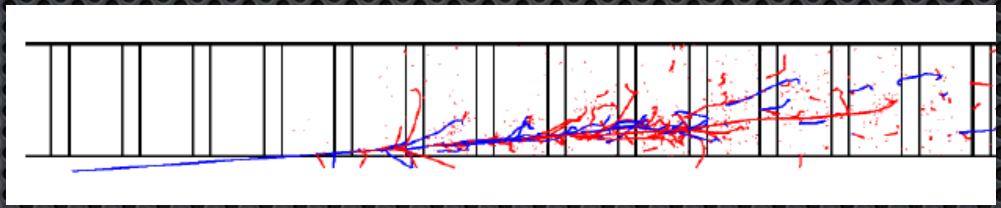


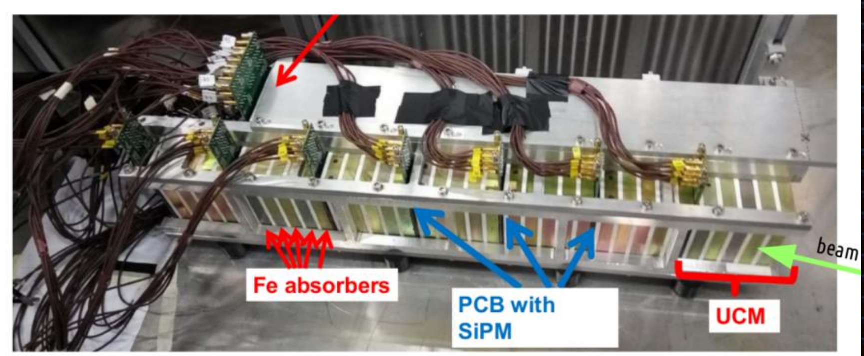
# Detector simulation (1)

- The software framework was set up at the CC-IN2P3 in Lyon.
- A full GEANT4 simulation of the instrumented tunnel is now available to study particle identification.

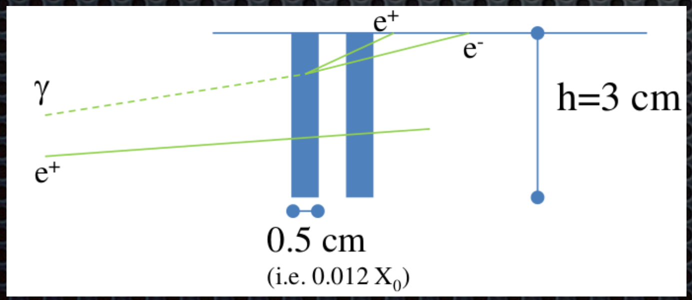


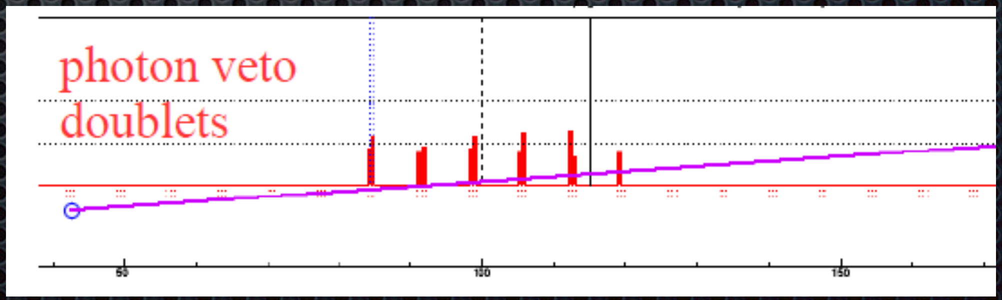

$e^+/\pi^+/\mu^+$ separation → **Shashlik calorimeter** made of UCM

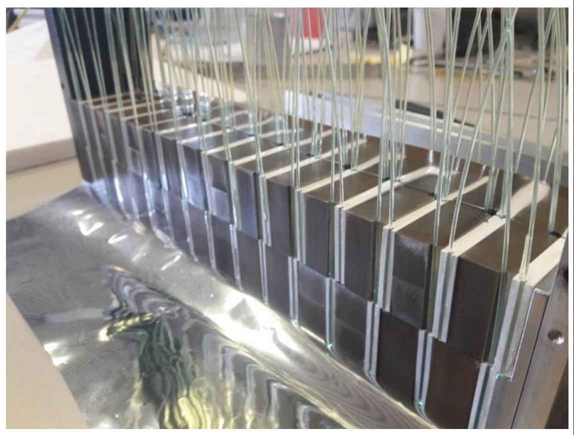





$e^+/\gamma$ separation → **Plastic scintillator** exploiting 1-2 mip separation



# Detector simulation (2)

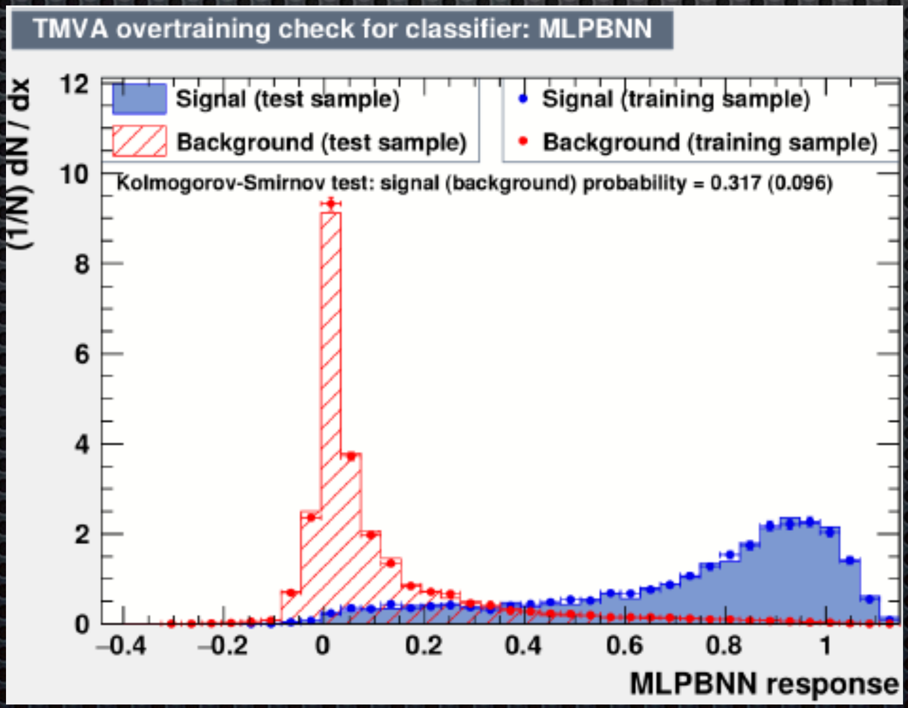
- A preliminary event builder was developed to consider neighboring modules and avoid pile-up.

- The identification algorithms separate positrons from neutral and charged pions combining information from calorimeter modules and $\gamma$ veto.

$e^+/\pi^+/\mu^+$ separation → **Neural Network** → $e^+/\gamma$ separation → **Sequential Cuts** → $e^+$ signal

TMVA multivariate analysis based on 5 variables exploiting the pattern of the energy deposition in the calorimeter

Information from the $\gamma$ veto

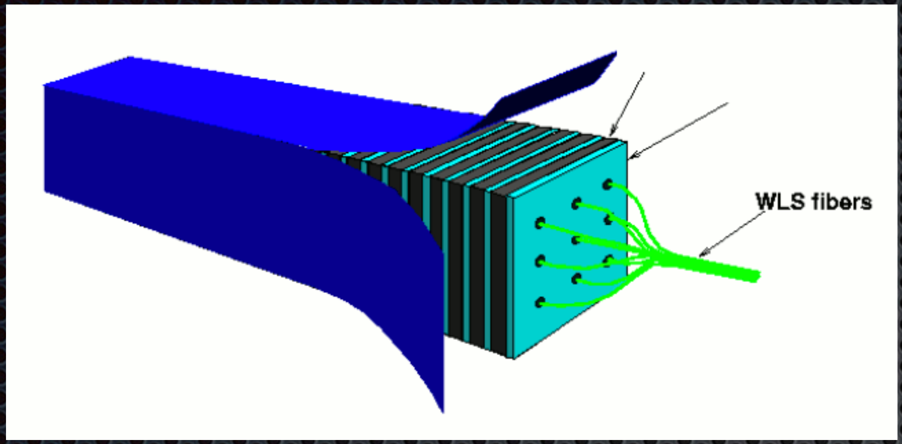



| | geometrical efficiency | global efficiency |
|---|---|---|
| $e^+$ | 90.7% | 49.0% |
| $\pi^+$ | 85.7% | 2.9% |
| $\pi^0$ | 95.1% | 1.2% |

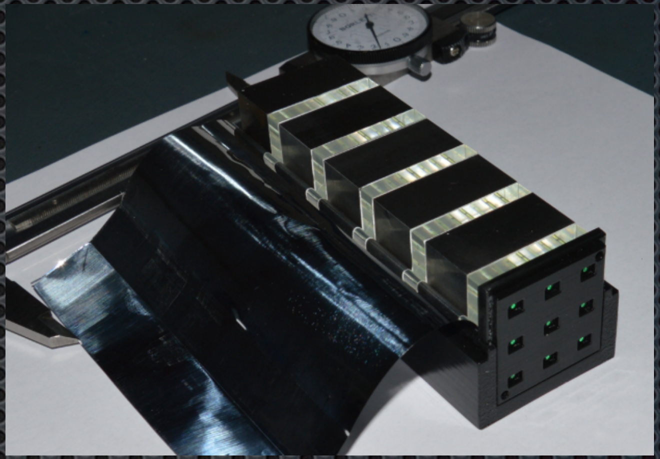
**Confirmation of early results from fast simulation**

# Prototypes (1)

- Detector prototyping for shashlik calorimeter with longitudinal segmentation is ongoing since 2015 founded by INFN R&D (SCENTT).

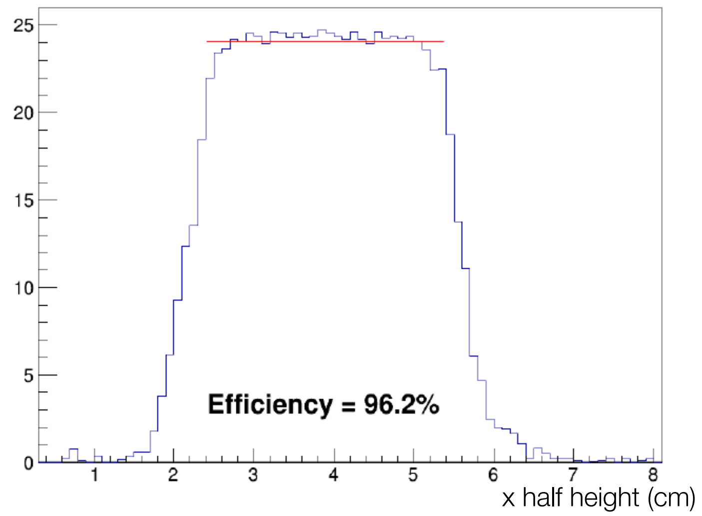



Cheap, fast (<10 ns) and radiation hard (ENUBET needs 1.3 kGy: not critical) is the base unit of ENUBET

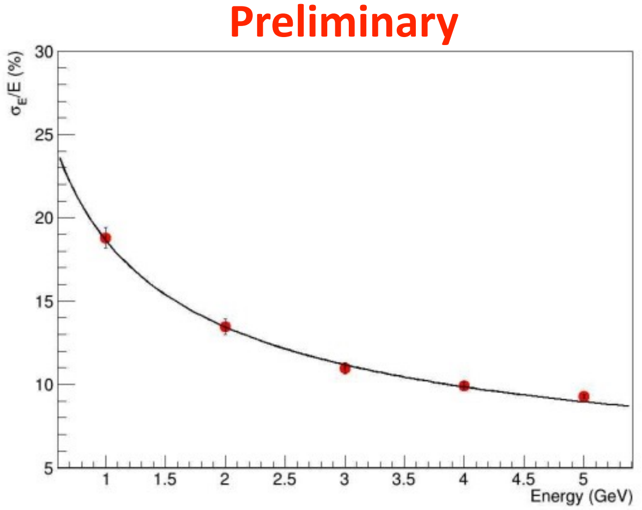


One SiPM for each fiber in the back of each module. Summed signals (9 SiPM per ADC) to reduce cost

**Characterisation of 12 UCMs at CERN PS-T9 (1-5 GeV, e and $\pi$, 28 June -13 July 2016)**




**mip sensitivity but no saturation for e.m. showers up to 4 GeV**

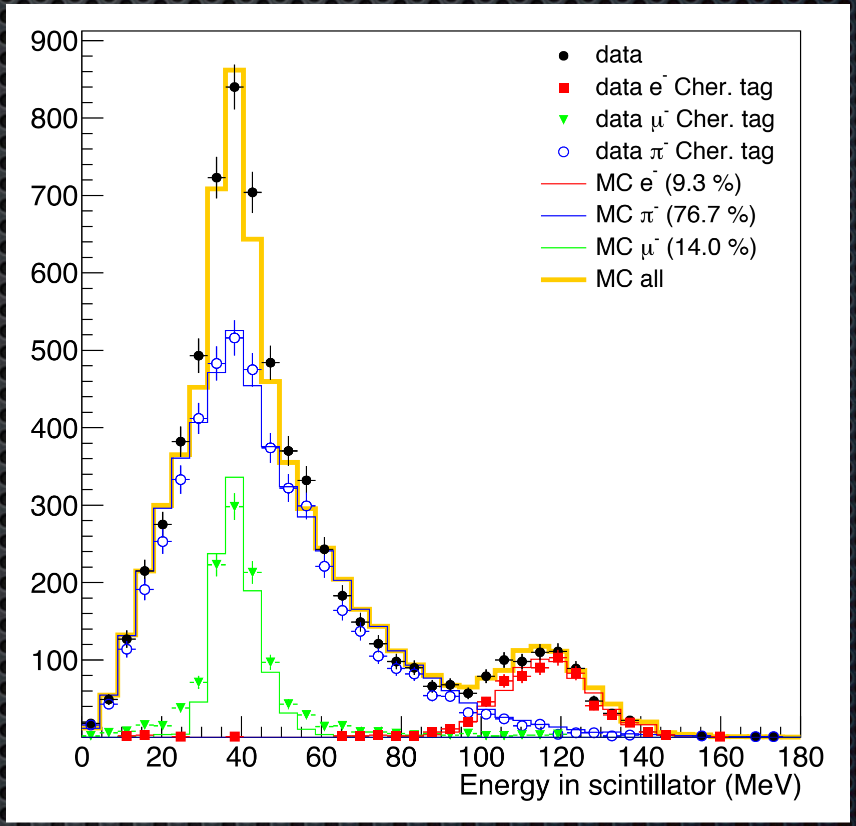



**energy resolution <25%/$E^{1/2}$**

# Prototypes (2)

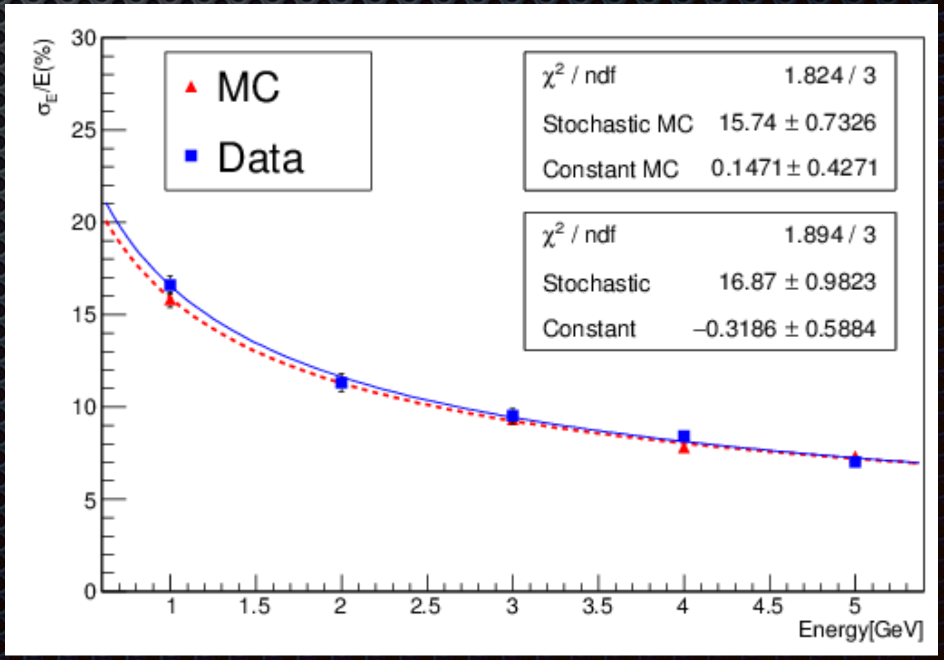
- A test beam was carried out at CERN-PS T9 beamline in Nov 2017 56 UCM arranged in 7 longitudinal block (~$30X_0$).

- The response to mip, electrons and pions was studied yielding a **very good agreement between data and MC** [*Ballerini et al., JINST 13 (2018) P01028*].




## Results summary

- **Energy resolution 17%/√E(GeV).**
- Linearity <3% in 1-5 GeV. 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 equalizing UCM response to mip).
- MC/data already in good agreement, longitudinal profiles of partially contained π reproduced by MC @ 10% precision.

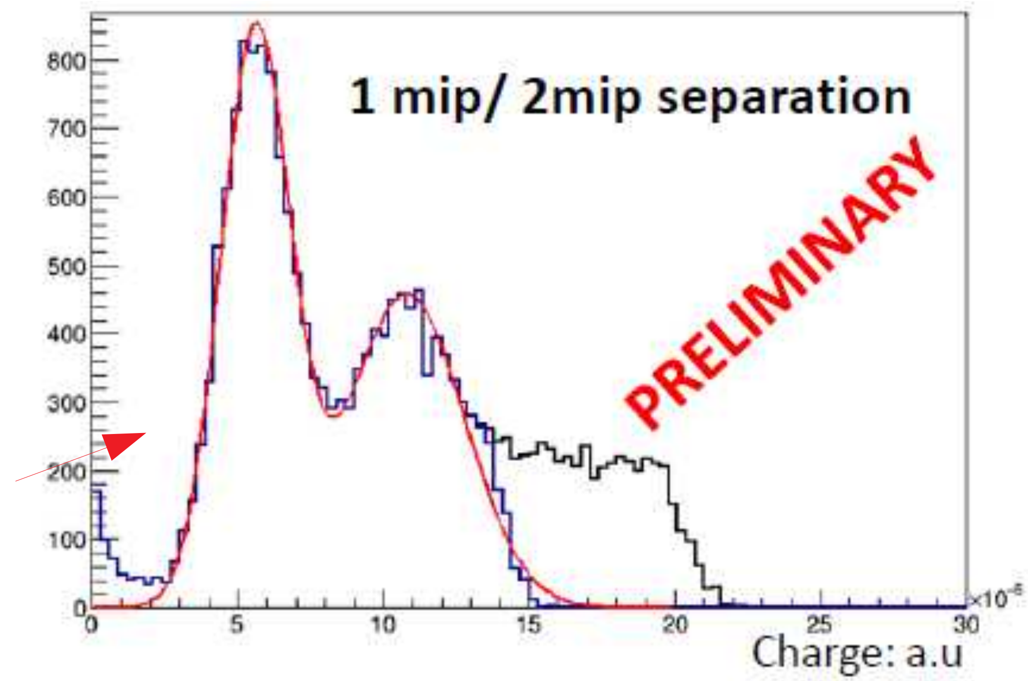


# Prototypes (3)

## $e^+/\gamma$ separation studies

- t0 layer scintillator (3x3x0.5 $cm^3$ ) + WLS Fiber + SiPM Tested @ CERN T9 in July+October.
- Light collection > 95%.
- Time resolution ~400 ps.
- 1 mip/2 mip separation clearly observed.

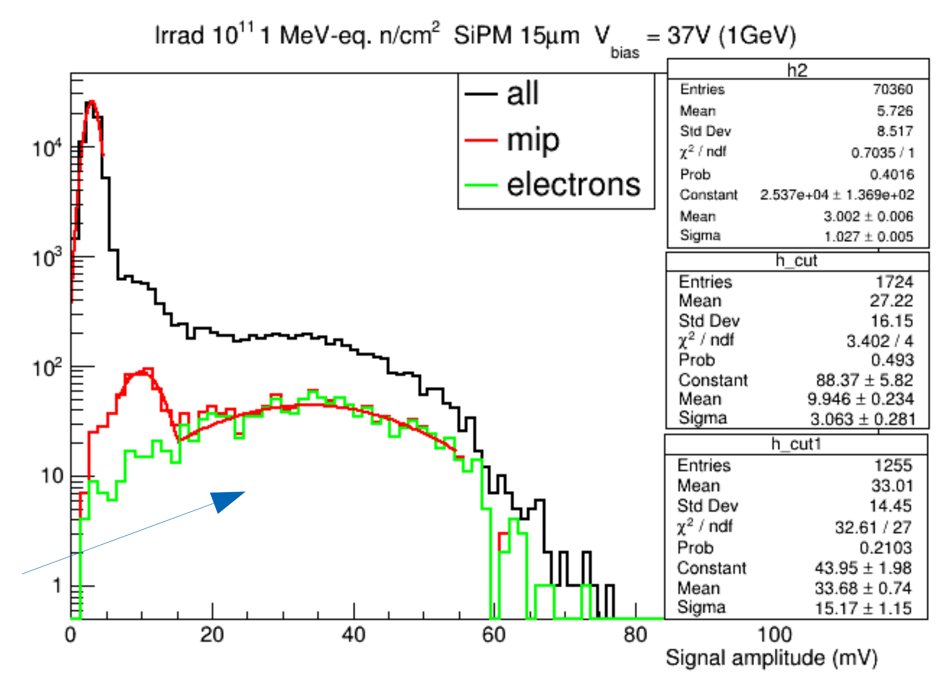
**We are able to discriminate $\gamma$ from Ke3 $e^+$**




## Irradiation studies

- SiPM were irradiated at LNL-INFN with 1-3 MeV neutrons in June 2017.
- Characterization of 12,15 and 20 $\mu$m SiPM cells up to $1.2 \times 10^{11}$ n/$cm^2$ 1 MeV-eq (i.e. max non ionizing dose accumulated for $10^4$ $\nu_e$CC at neutrino detector).
- Irradiated SiPM tested at CERN in October 2017.

**Detectors are radiation hard (we see mip and electrons)**



# Summary

- In about one year ENUBET moved from a conceptual study to a concrete Reference Design.

| Item | baseline option | alternatives | status |
|---|---|---|---|
| **Proton extraction** | Few ms spills at O(10) Hz during the flat top (2 s) | Single slow extraction | Not tested yet |
| **Focusing** | Horn based | Quadrupole based | Optimization ongoing |
| **Transfer line** | Quad+dipoles | | Full simulation ongoing |
| **Detector for e/π separation** | Shashlik calorimeter with SiPM readout | Polysiloxane scint. Non-shashlik readout | Full simulation and prototyping ongoing |
| **Photon veto** | Scint. Pads with fiber readout | Direct readout LAPPD | Full simulation and prototyping ongoing |
| **Particle ID and detector optimization** | 3×3×10 $cm^3$ UCM | Different radii and granularities | Full simulation and prototyping ongoing |
| **Systematic assessment** | Positron monitoring (Ke3 decay) | Enhanced exploting other K decay modes | Just started |

# Conclusions

- The precise knowledge of neutrino cross section is a key element for future generation neutrino experiments aiming at the CP violation measurement.
- The intrinsic limit on the $\nu$ cross section (flux uncertainty) can be **reduced by one order of magnitude exploiting the $K^+ \rightarrow \pi^0 e^+ \nu_e$ channel ($K_{e3}$)**.
- In the next 4 years ENUBET will investigate this approach.
- Results obtained so far are promising:
  - ➡ **Full simulation** of the decay tunnel **supports** the **effectiveness of the calorimetric approach** for large angle lepton identification.
  - ➡ **First prototypes** demonstrate that shashlik calorimeters with longitudinal segmentation can be built without compromising energy resolution (16% at 1 GeV) and **provide the performance requested by the ENUBET technology**.

**ENUBET goal**

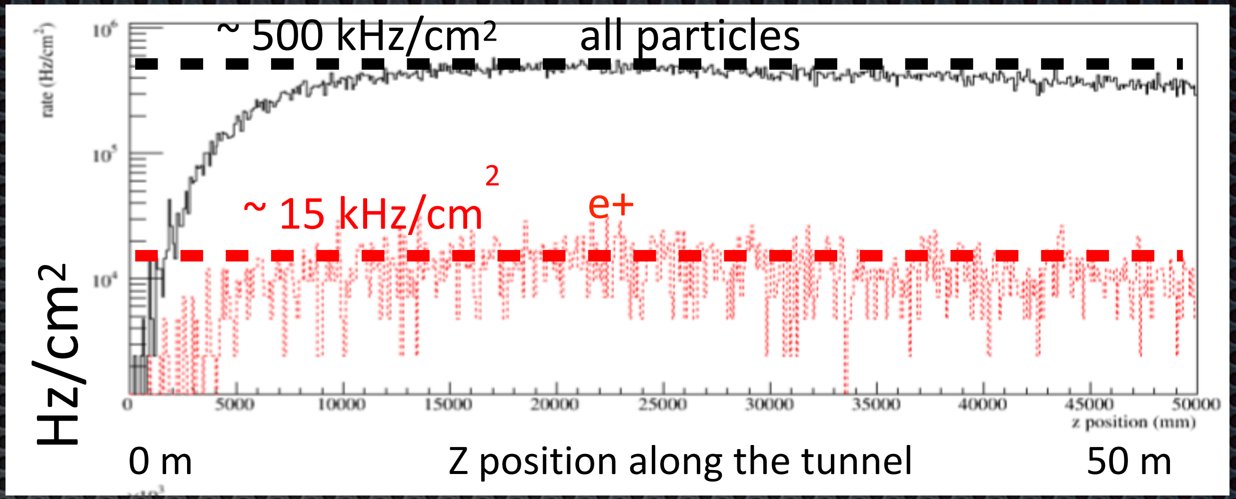
Demonstrate that a "positron monitored" $\nu_e$ source based on $K_{e3}$ can be constructed using existing beam technologies and can be implemented at CERN, Fermilab or JPARC.

Demonstrate that a 1% measurement of the absolute $\nu_e$ cross section can be achieved with detector of moderate mass (500 ton).

# Backup

# Rates

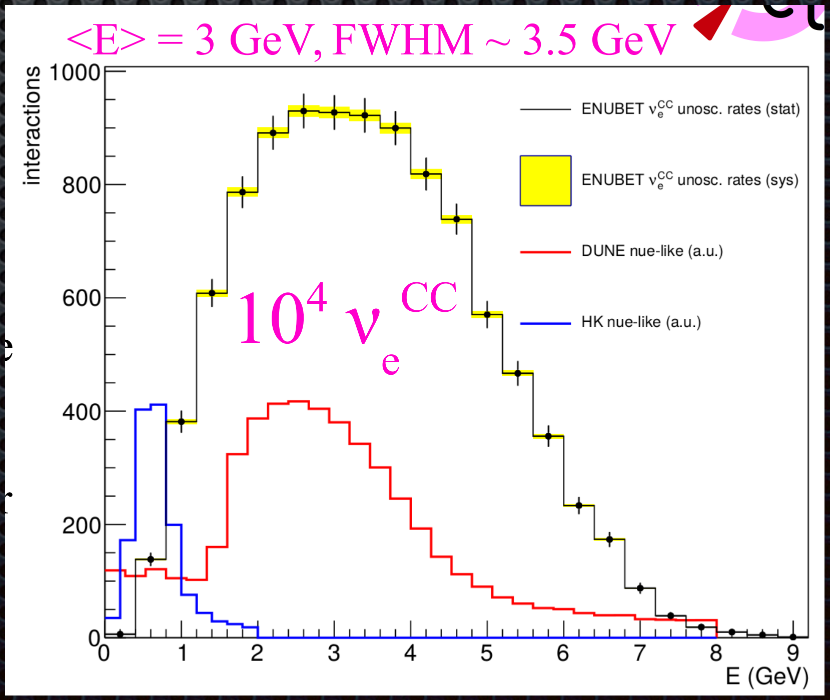
- Rates **below 1 MHz/cm²**.




- Number of protons on target **well within reach** of present accelerators.

| | E (GeV) | $\pi^+$/PoT ($10^{-3}$) | $K^+$/PoT ($10^{-3}$) | PoT for a $10^{10}$ $\pi^+$ spill ($10^{12}$) | PoT for $10^4$ $\nu_e$ CC ($10^{20}$) |
|---|---|---|---|---|---|
| JPARC | 30 | 4.0 | 0.39 | 2.5 | 5.0 |
| Protvino | 50 | 9.0 | 0.84 | 1.1 | 2.4 |
| | 60 | 10.6 | 0.97 | 0.94 | 2.0 |
| | 70 | 12.0 | 1.10 | 0.83 | 1.76 |
| Fermilab | 120 | 16.6 | 1.69 | 0.60 | 1.16 |
| CERN-SPS | 450 | 33.5 | 3.73 | 0.30 | 0.52 |

- Interesting **energy region of future long baseline experiment is covered** (further tuning would allow even lower energies).



# Systematics

- The positron tagging eliminates the most important source of systematics but **can we get to 1%? Very likely…but to be fully demonstrated by ENUBET.**

| Source of uncertainties | Size |
|---|---|
| Statistical error | <1% |
| Kaon production yield | Irrelevant (positron tag) |
| Number of integrated PoT | Irrelevant (positron tag) |
| Geometrical efficiency and fiducial mass | <0.5% |
| 3-body kinematics and mass | < 0.1% |
| $\nu_e$ contamination from $\mu$ DIF | To be checked with low intensity pion runs |
| Phase space at entrance | To be checked with low intensity pion runs |
| Branching Ratios | Irrelevant (positron tag)<br>except for BG estimation (<0.1%) |
| $e/\pi^+$ separation | To be checked directly at test beam |

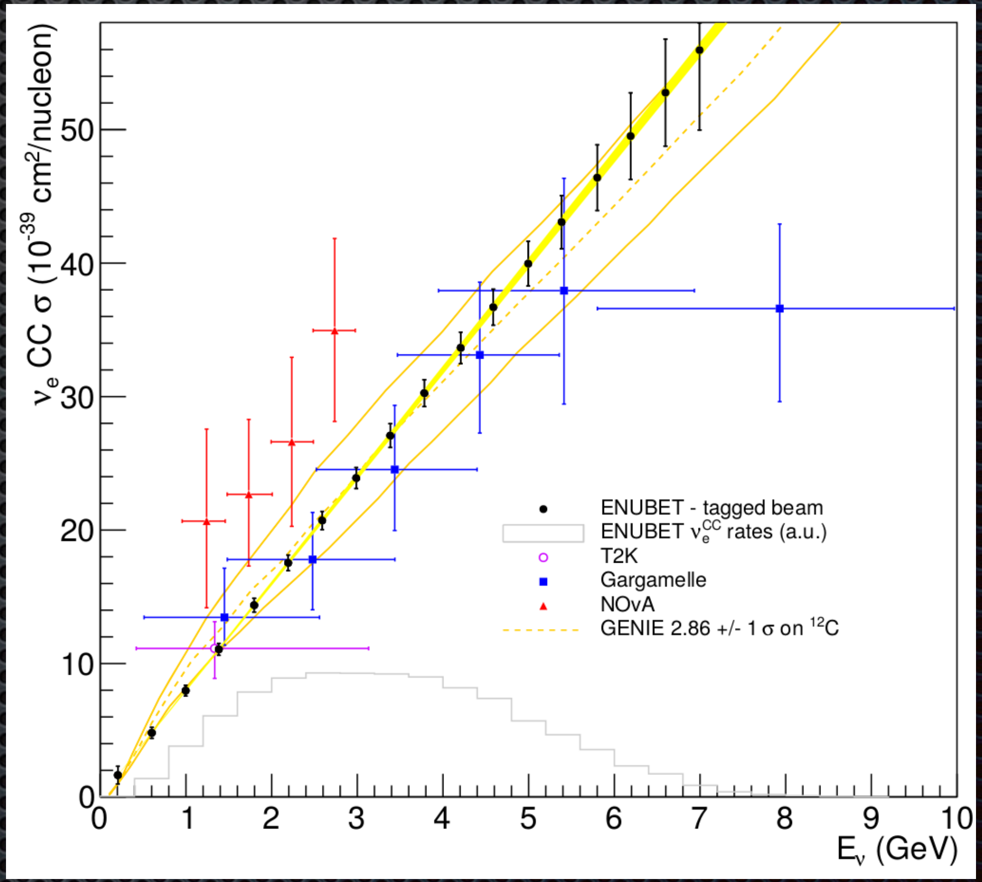
# ENUBET implications

- The ENUBET technology is well suited for short baseline experiments where the intensity requirements are less stringent. There are three possible main applications.

1. **A new generation of cross section experiment** with a neutrino source controlled at the **<1% level**. This is a unique tool for the precision era of neutrino physics and the **main goal of ENUBET as founded by the ERC**.

2. A phase II sterile neutrino search, especially in case of positive signal from the Fermilab SBL program.

3. The first step toward a real tagged neutrino beam where the $\nu_e$ CC interaction at the detector is time-correlated with the observation of the lepton in the decay tunnel.




Impact on $\nu_e$ cross section measurement based on A. Longhin, F. Terranova and L. Ludovici, Eur.Phys.J. C75 (2015) 4, 155

# Background

Eur.Phys.J. C75 (2015) 4, 155

| Source | BR | Misid | $\epsilon_{X \to e^+}$ (%) | Contamination |
|---|---|---|---|---|
| $\pi^+ \to \mu^+ \nu_\mu$ | 100 % | $\mu \to e$ misid. | <0.1 | Neglig. (outside acceptance) |
| $\mu^+ \to e^+ \bar{\nu}_\mu \nu_\mu$ | DIF | genuine $e^+$ | <0.1 | Neglig. (outside acceptance) |
| $K^+ \to \mu^+ \nu_\mu$ | 63.5 % | $\mu \to e$ misid. | <0.1 | Negligible |
| $K^+ \to \pi^+ \pi^0$ | 20.7 % | $\pi \to e$ misid. | 2.2 | 13 % |
| $K^+ \to \pi^+ \pi^+ \pi^-$ | 5.6 % | $\pi \to e$ misid. | 3.8 | 5 % |
| $K^+ \to \pi^0 \mu^+ \nu_\mu$ | 3.3 % | $\mu \to e$ misid. | <0.1 | Negligible |
| $K^+ \to \pi^+ \pi^0 \pi^0$ | 1.7 % | $\pi \to e$ misid. | 0.5 | Negligible |