The ENUBET project

High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

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on behalf of the ENUBET Collaboration

NUFACT2017

Uppsala, 25-30 September 2017

Outline

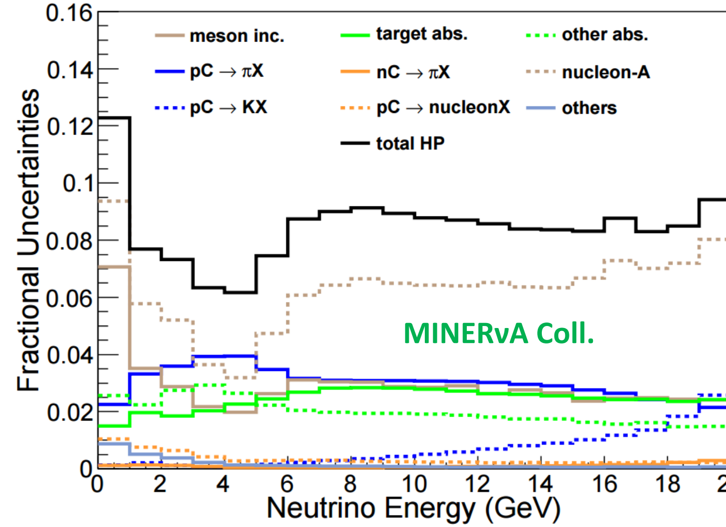
- The problem of flux uncertainty in conventional beams → monitored beams
- Challenges, goals and recent achievements for ENUBET
- Forthcoming activities and conclusions

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).

Neutrino cross sections and flux uncertainties

- An important ingredient for the success of the future neutrino oscillation experiments is the **precise knowledge of σ(ν)**

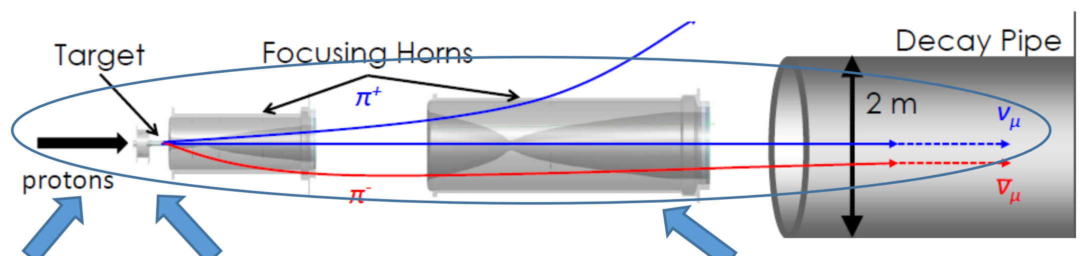
- **$\sigma(\nu_\mu)$**
  - ✓ **Remarkable progress** in the last 10 years (MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA…)
  - ✓ But still no absolute measurements below **7-10%**



- **$\sigma(\nu_e)$**
  - ✓ **$\sigma(\nu_\mu)$ ↔ $\sigma(\nu_e)$** delicate @ low energies
  - ✓ **Rare** and **not precise** measurements available, despite its relevance for CPV, NSI, sterile
  - ✓ No intense/pure source of GeV ν_e available (using the **beam contamination**)

- Main limiting factor: **syst. uncertainties** in the initial **flux** determination

Flux estimated through a well established but **indirect procedure**



PoT monitoring

Hadro-production data (SPY, HARP, NA61)

Full simulation of the beam-line

Monitored neutrino beams

A **direct measurement** of neutrino fluxes based on **conventional technologies**

Kaon-based monitored neutrino beams can provide a **pure and precise** (**O(1%)**) ν_e source:

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

- Monitoring the **decays in which ν are produced**
- **Get rid of systematics** from PoT, hadro-production, beam-line efficiency

Traditional

- **Passive** decay region
- ν flux relies on **ab-initio simulation** of the full chain
- **Large uncertainties**

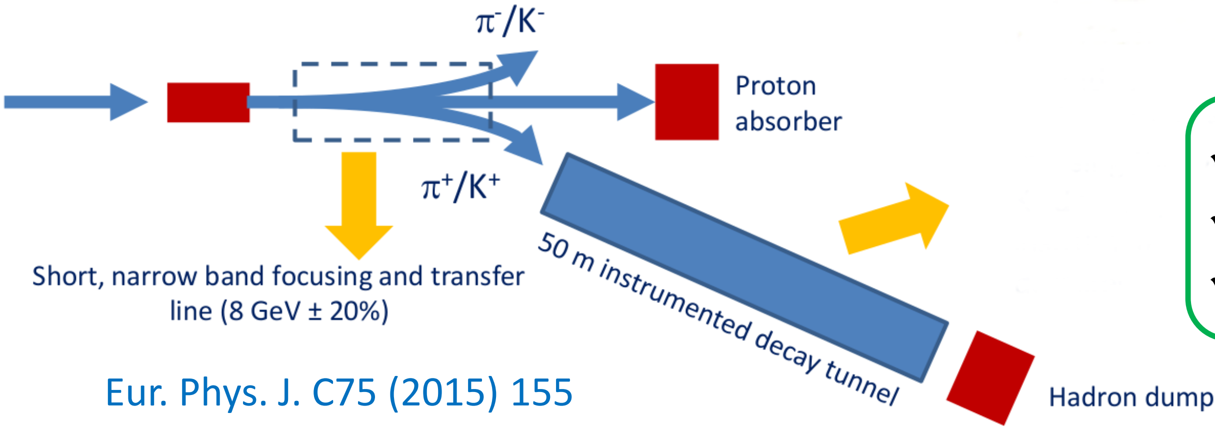
→

Monitored

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

The conceptual design: ENUBET

- **Hadron beamline:** charge selection, focusing, fast transfer of K^+/π^+
- **Tagger:** real-time, «inclusive» monitoring of K decay products



Eur. Phys. J. C75 (2015) 155

Reference parameters

- ✓ $P_{k,\pi}$ **= 8.5±20% GeV/c**
- ✓ **Θ < 3 mrad** over **10×10 cm²**
- ✓ Tagger: **L = 50 m, r = 40 cm**

- Thanks to the short decay tunnel, **muon decay** gives a **negligible contribution** to the ν_e flux that is dominated **(~98%)** by neutrinos coming **from K_{e3}** decays
- Only **kaon decay** products are **measured** in the tagger, since pions and muons decay at small angles

- **Complete control on ν_e flux**
- **Tolerable rates / detector irradiation** (< 500 kHz/cm2 , < 1 kGy)

ENUBET: Enhanced NeUtrino BEam from kaon Tagging

http://enubet.pd.infn.it

Project approved by the European Research Counsil (ERC)
5 years duration (06/2016 – 06/2021)
Overall budget: 2 MEUR

ERC-Consolidator Grant-2015, n° 681647 (PE2)
P.I: **A. Longhin**
Host Institution: INFN

Expression of interest
(CERN-SPSC, Oct. 2016)

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- CERN-SPSC-2016-036; SPSC-EOI-014

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In the **CERN Neutrino Platform** (NP03, PLAFOND)

Constraining ν fluxes

ν_e flux

✓ K_{e3} (golden sample)

- $\pi+/\pi^0$ from K^+ can mimic an e^+

  e/π discrimination through:

  I. Longitudinal profile of showers

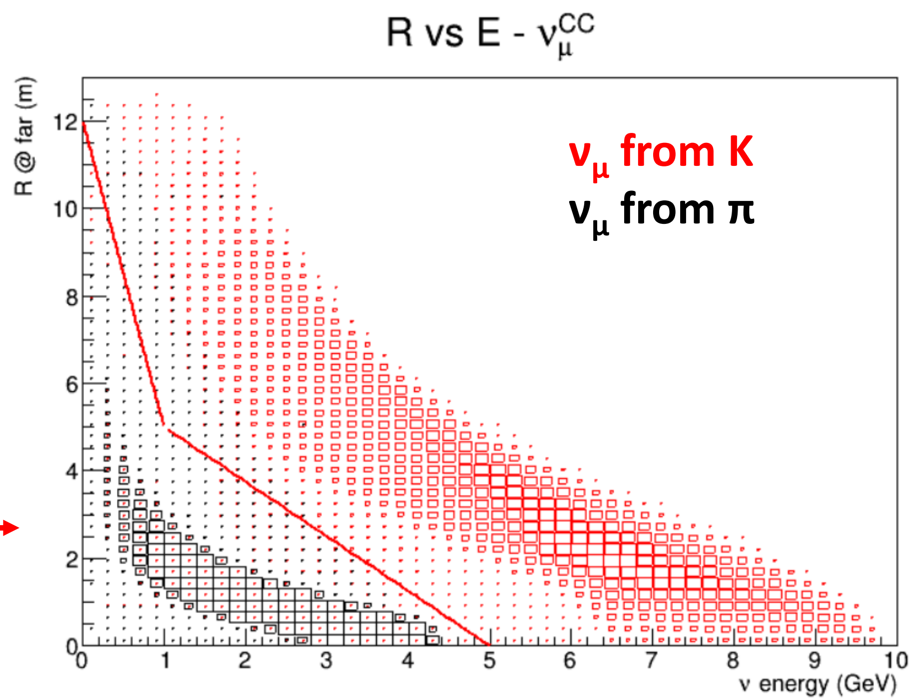
  II. Vertex reconstruction by timing

$K^+ \rightarrow e^+ \nu_e \pi^0$ (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%)

✓ Non K_{e3} (**silver sample**): exploitable, additional systematics only from K B.R.

ν_μ flux

- Kaons well constrained by the tagger (both from K_{e3} and hadronic decay rates)
- ν_μ from K can be selected at the nu_detector using **radius-energy correlations** → High precision $\sigma(\nu_\mu)$



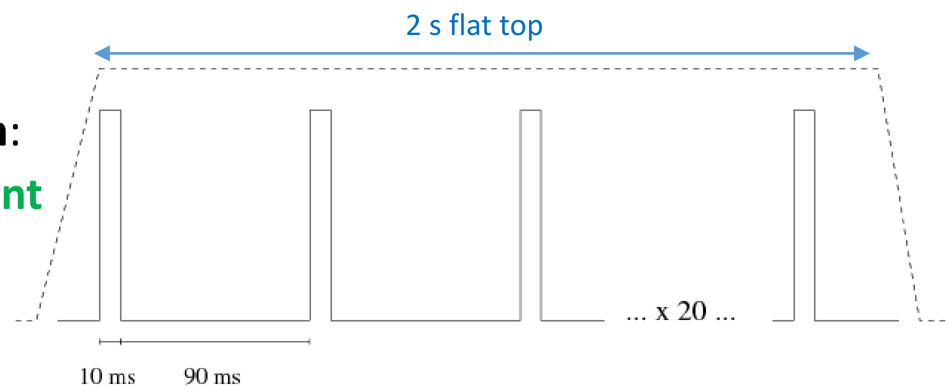
Hadron beam-line scenarios

Baseline choice: magnetic horns focusing

- **Tagger rate limit** (~500 kHz/cm^2) reached with ~10^{12} PoT/spill
- **Horn pulsing limit**: $t_{impulse}$ < O(1-10) ms
- Needs for **10^4 ν_e^{CC}** in a **500 t** ν-det at **100 m**:

  ~10^{20} PoT **a fraction of a year run at present proton drivers**

  ~10^8 spills **challenging/unconventional**



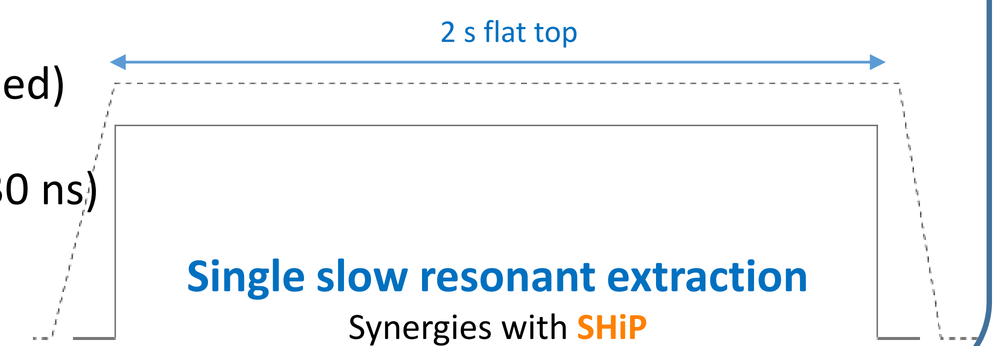
Solution: **multi-Hz slow resonant extraction + horn pulsing** → machine studies at SPS

Alternative choice: static focusing + long extraction

Cons: Less efficient focusing (more PoT needed)

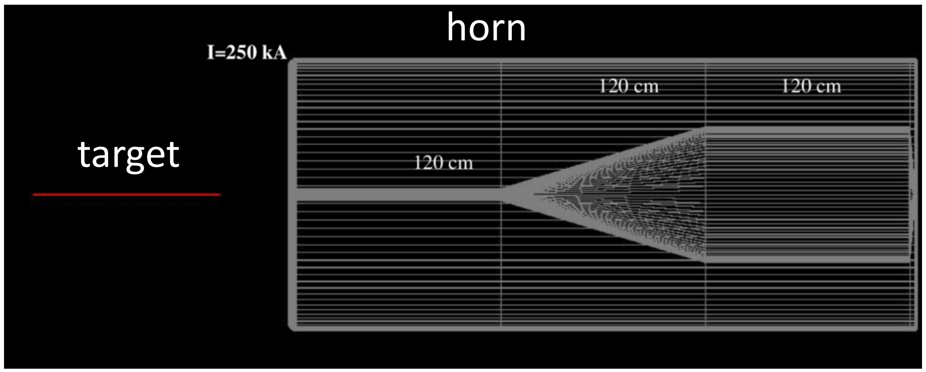
Pros: Lower rates at the decay tunnel (1 e^+/30 ns)

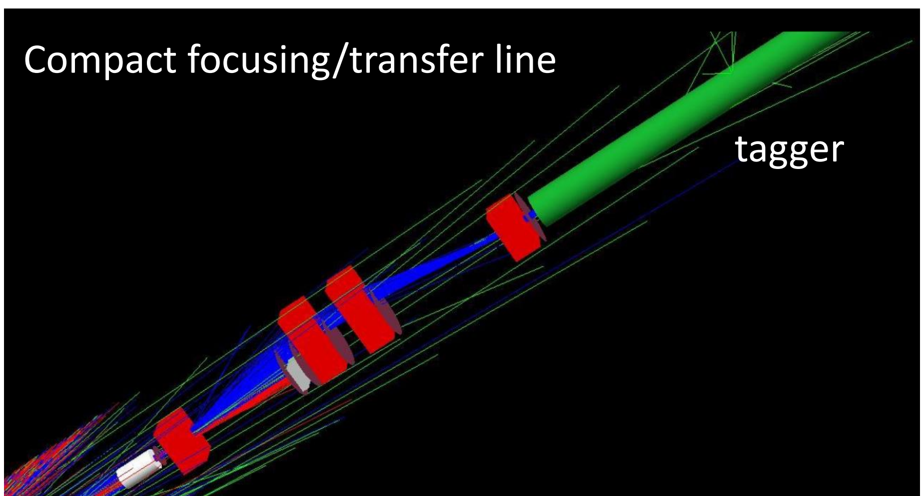
Event time tagging → coincidences among tagger and ν-detector

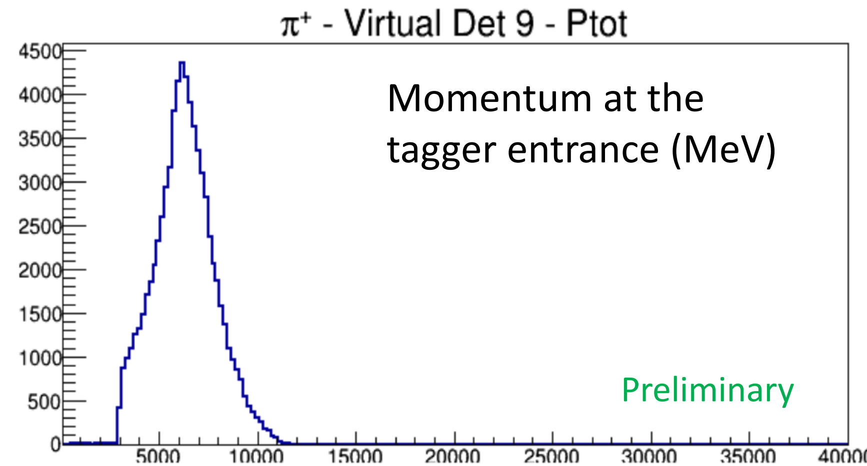


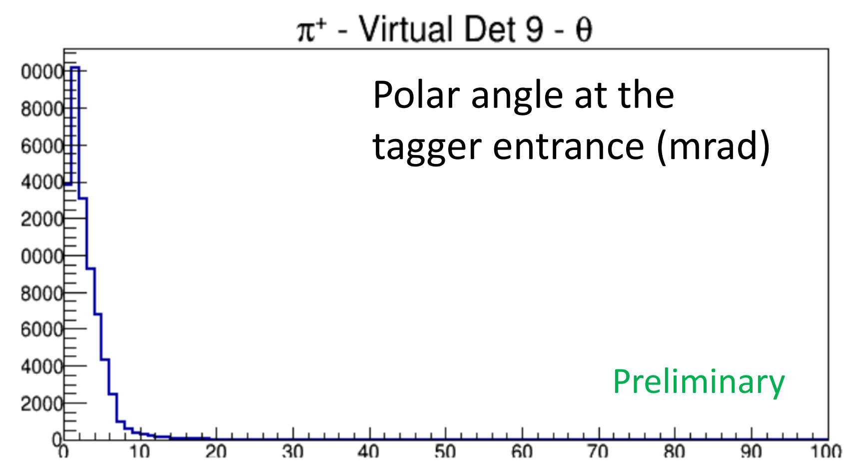
Horn focusing

- **Realistic implementation** of the beam-line/focusing layout
- **Site independent**. We are considering existing proton driver energies
- **FLUKA/G4Beamline** (+ **Transport** for optics optimization) simulations in progress
- Assess **beam-related backgrounds**



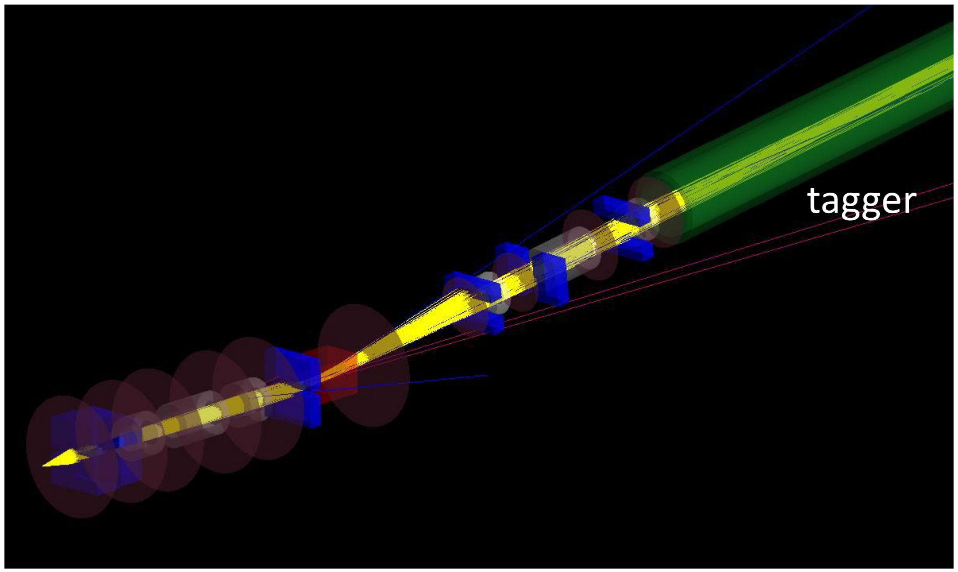


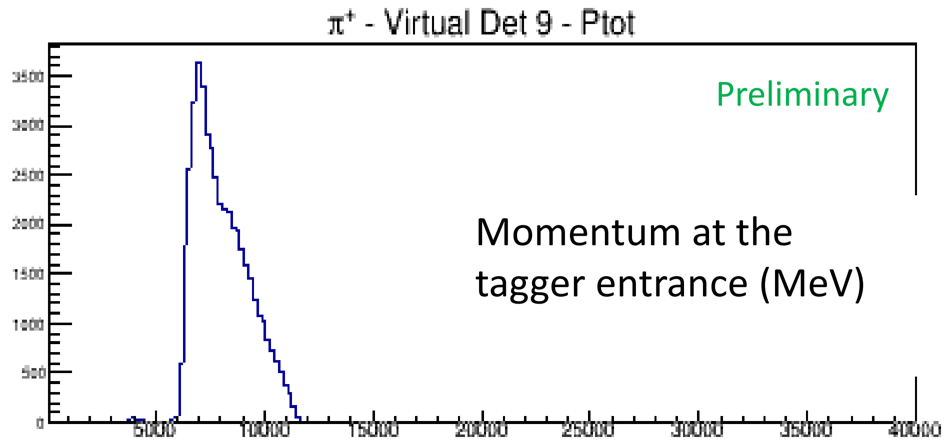


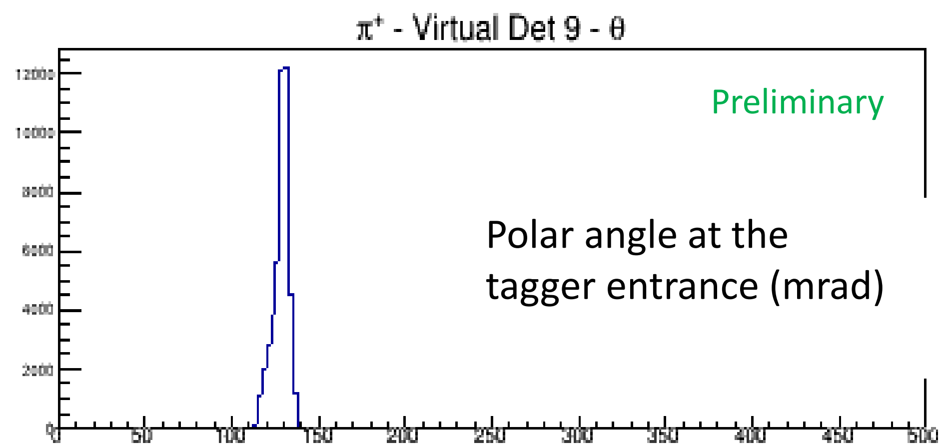


Static focusing

- Used the same simulation machinery as in the horn option **(FLUKA + G4Beamline+Transport)**
- More promising configuration: **Quadrupole triplet + Dipole + Quadrupole triplet**
- **Compact beam-line:** ~28 m length







Preliminary results:

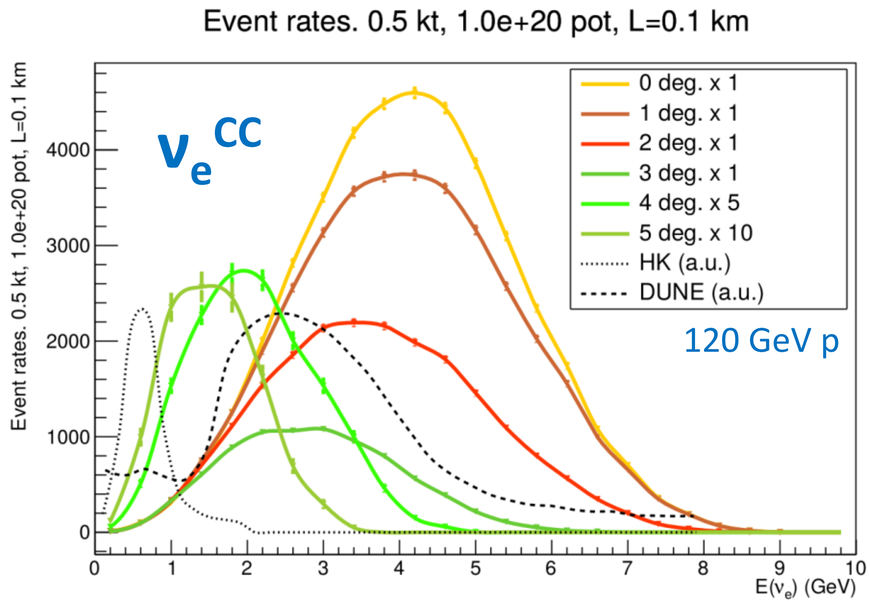
competitive with respect to the horn-based focusing in terms of **secondary meson yield** (~ 1/4)

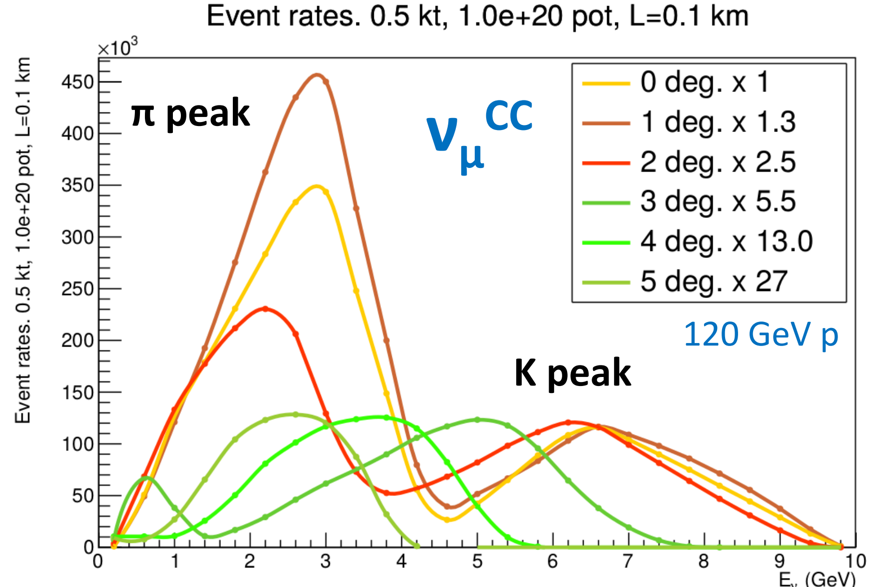
Neutrino samples

- 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 ($6 \times 6 \times 10$ 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 the ν_e 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

Tagger

1) Calorimeter ("shashlik")

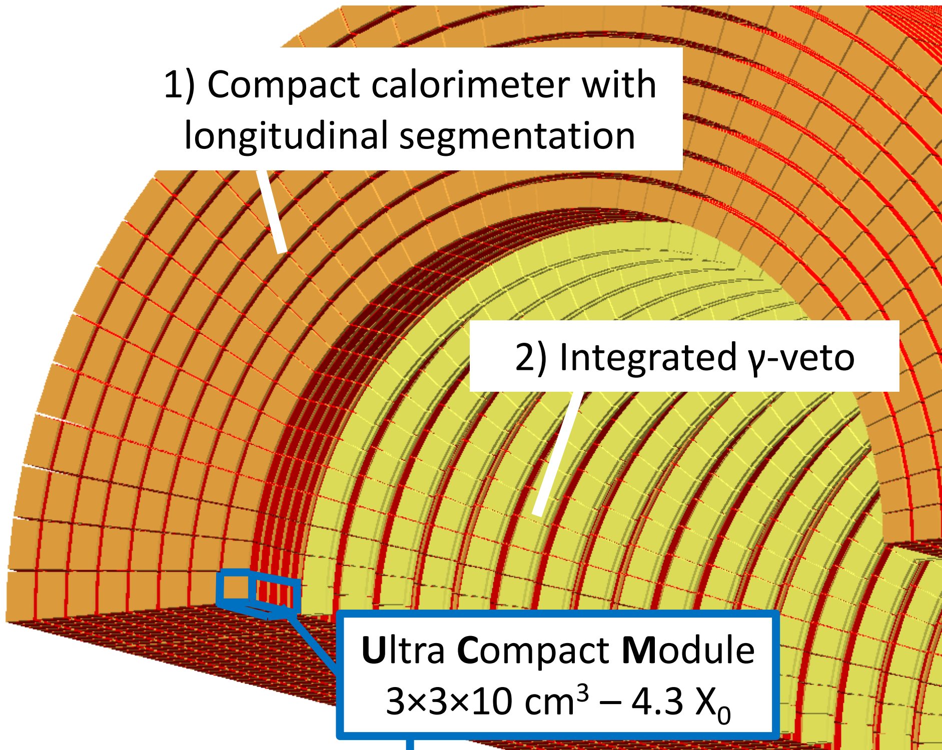
- Ultra Compact Module (UCM)
  (Plastic scint. + Fe absorbers)
- Integrated light readout with SiPM

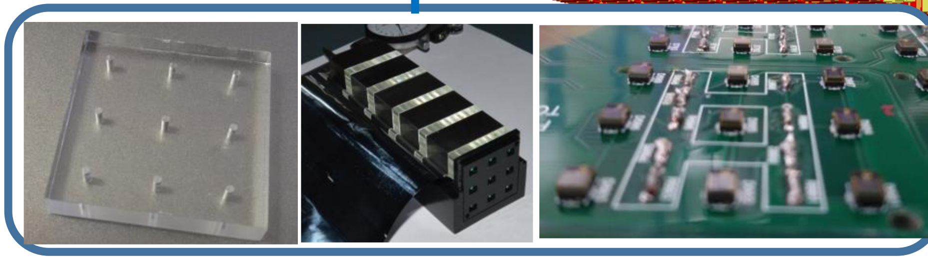
→ $e^+/\pi^\pm/\mu$ separation

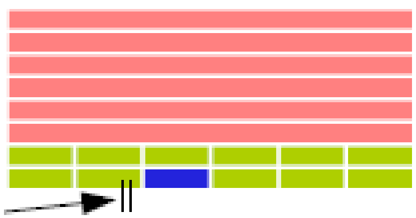
2) Integrated γ-veto

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

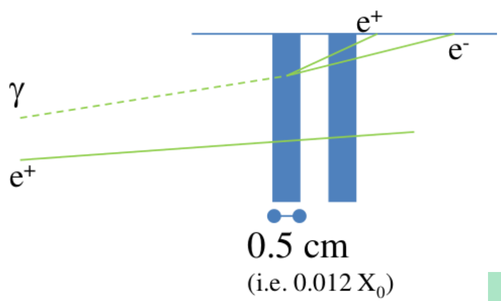
→ π^0 rejection

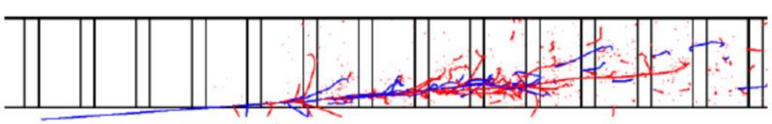






e⁺ (signal) topology

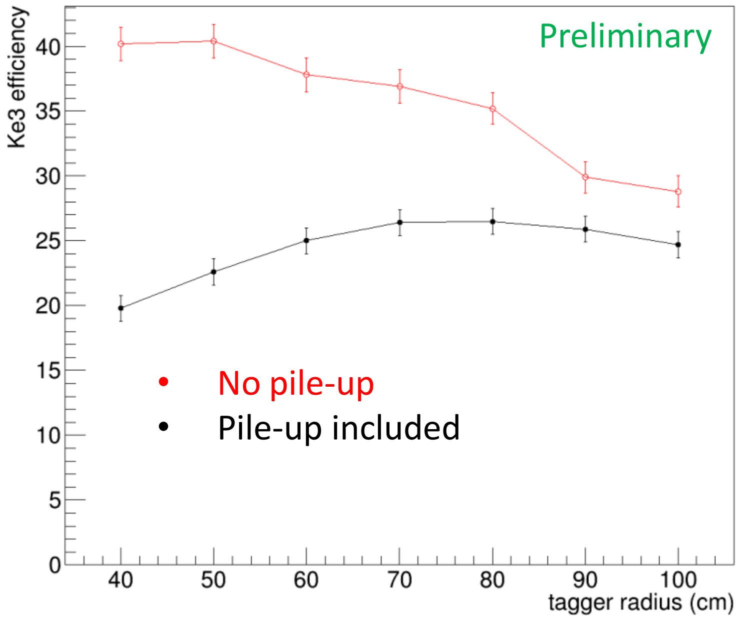


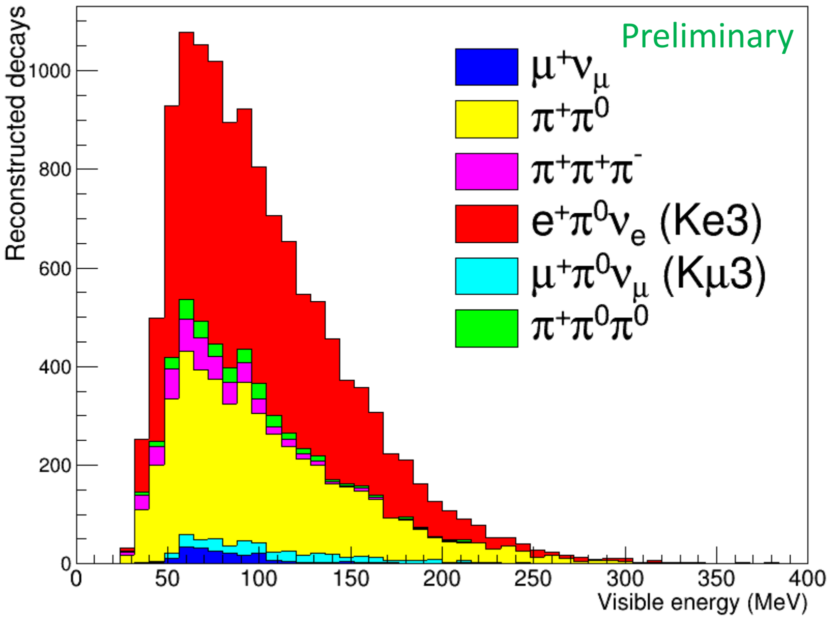


First milestone: build/test a scalable **demonstrator** consisting of a 3 m long section of the instrumented tunnel by **2021**

Simulation of the decay tunnel and event reconstruction

- **Full GEANT4 simulation** of the instrumented tunnel
- **"Event building": clustering of energy deposits** based on position and timing of signal waveforms in UCM, with realistic treatment of background (up to 500 kHz/cm^2!). **Pile-up effects** fully included
- **Multivariate analysis** exploiting the **pattern** of the **energy deposition** in the calorimeter to select e+ and simultaneously reject π^+ and π^0

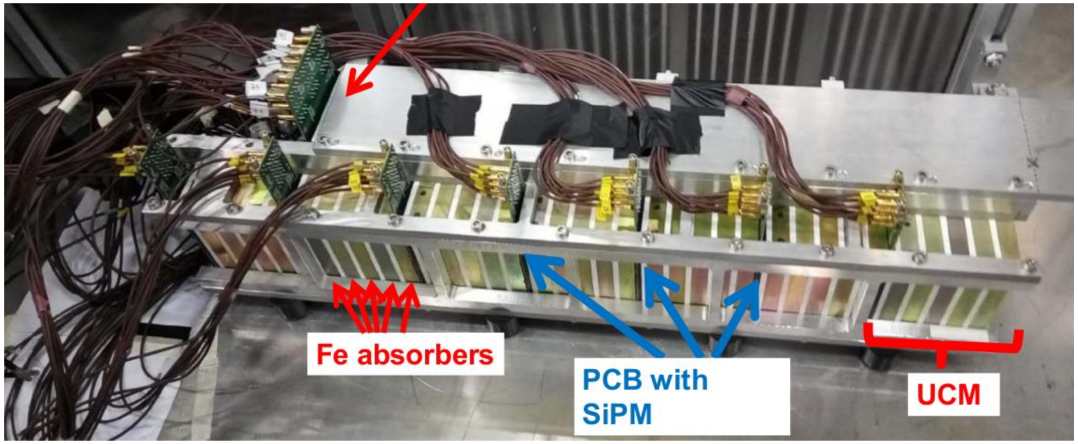


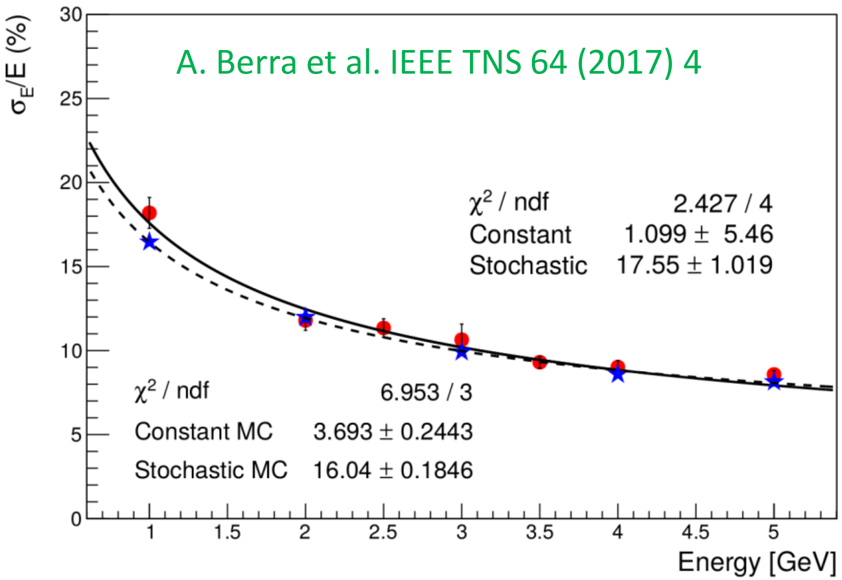


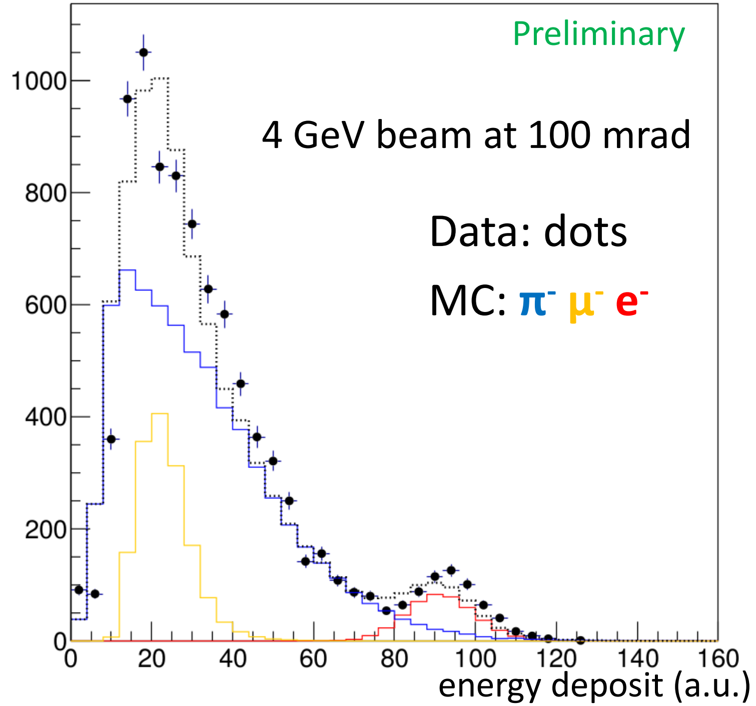
Instrumentig the decay tunnel at 1 m radius allow **e^+ ID** with **~25% efficiency** (**~50% purity**)

Calorimeter prototype performances with test beam data

- **TB @ CERN-PS T9** beamline (Nov. 16)
- 56 UCM arranged in 7 longitudinal blocks **(~30 X_0)** + had. layer (coarse sampling) at grazing incidence (oriantable cradle)
- e/μ tagged with Cherenkov counters and a muon catcher



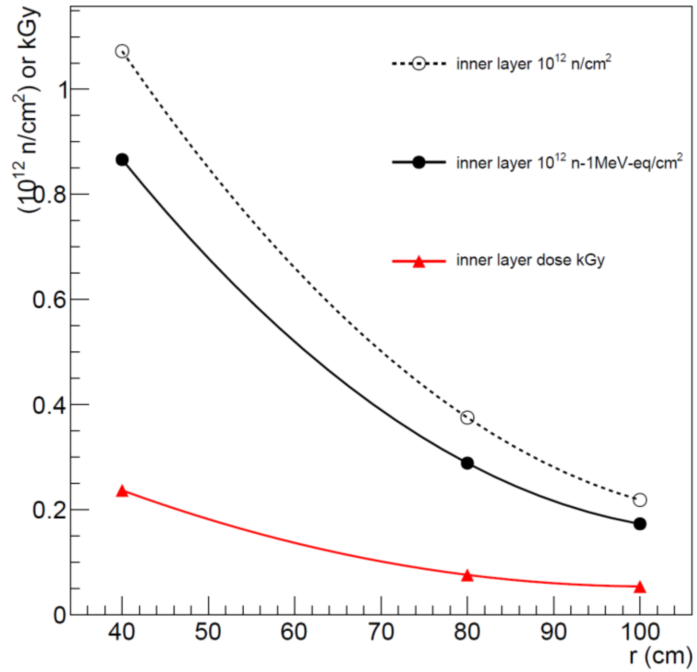


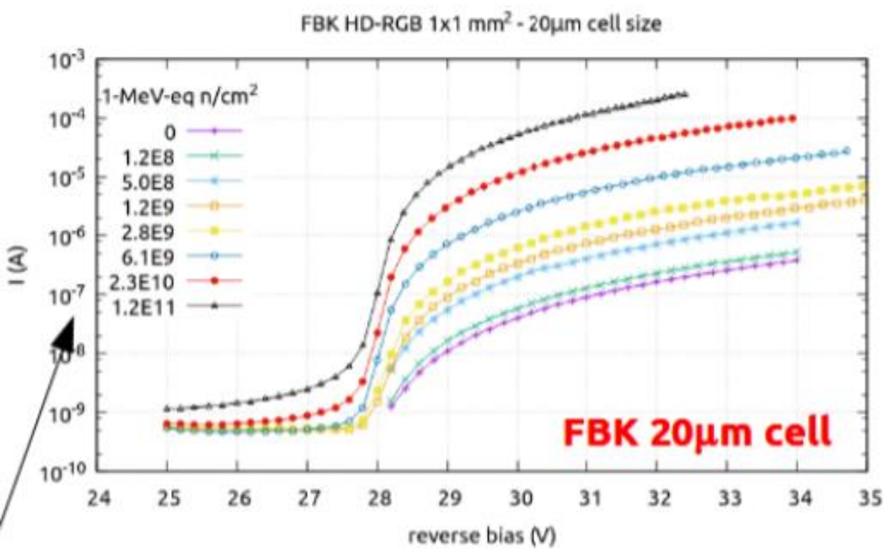


Data/MC agreement reasonably good already → **GEANT4 simulation validated**

Doses and radiation damage

- **Neutron** and **ionizing doses** have been studied for a tagger radius of 40, 80 and 100 cm with **FLUKA** and cross-checked with **GEANT4**
- Choosing 100 cm allows **~2 x 10^{11} n 1MeV-eq/cm^2** and **~0.05 kGy** in the innermost layers in the detector lifetime
- Test irradition with **1-3 MeV neutrons** performed at **INFN-LNL CN** Van de Graaff on 12-27 June 2017. Characterization of rad-hard SiPM with 12-15-20 μm cell size (FBK, SensL) through **I-V curves**

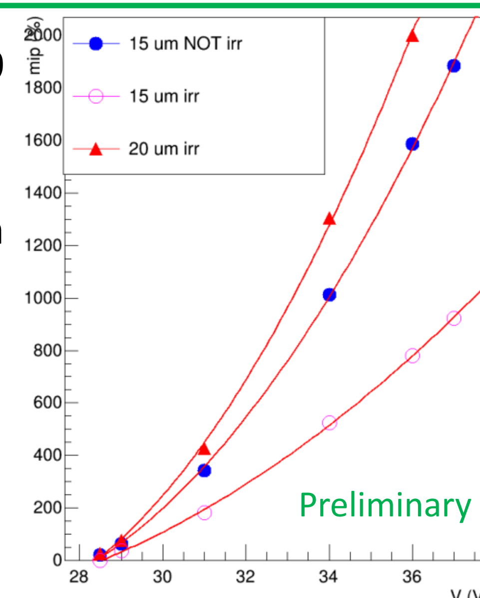




Irr. SiPM tested @ T9
(July 2017)

Reduction of the gain

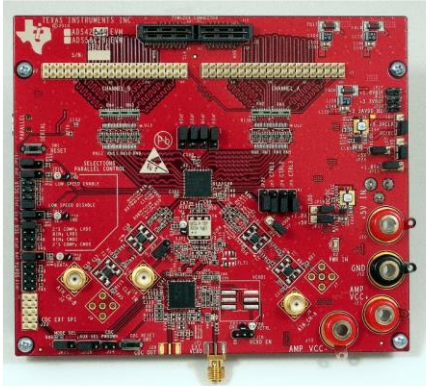
Self-calibration with m.i.p **still viable** (increasing scint. thickness)



R&D activities

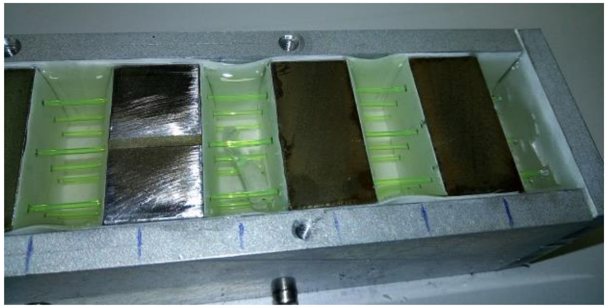
Intense test beam activity @ CERN-PS T9

- Achieve **recovery time <~10 ns** (to cope with pile-up)
- Test of **custom digitizers electronics**
- **Photon veto** prototypes with plastic scintillators



- Scalable/reproducible technological solutions
  - ✓ **water-jet holes** machining for absorbers
  - ✓ **Molded scintillators** (a prototype calorimeter tested in July 17 @ T9, analysis on-going)
  - ✓ Polysiloxane scintillators (a 12 X_0 calorimeter will be tested @ **T9 in october**)

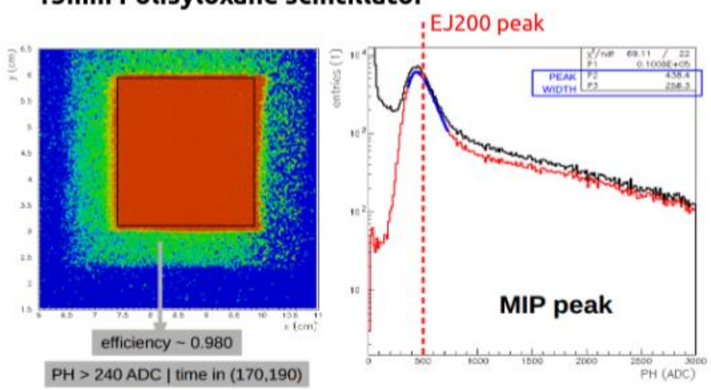
First application in HEP!



High rad. hardness

No drilling!

15mm Polisyloxane scintillator



Promising results:
- High efficiency
- Light yield comparable to plastic scint.

(w/ ×3 thickness wrt to EJ200)

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

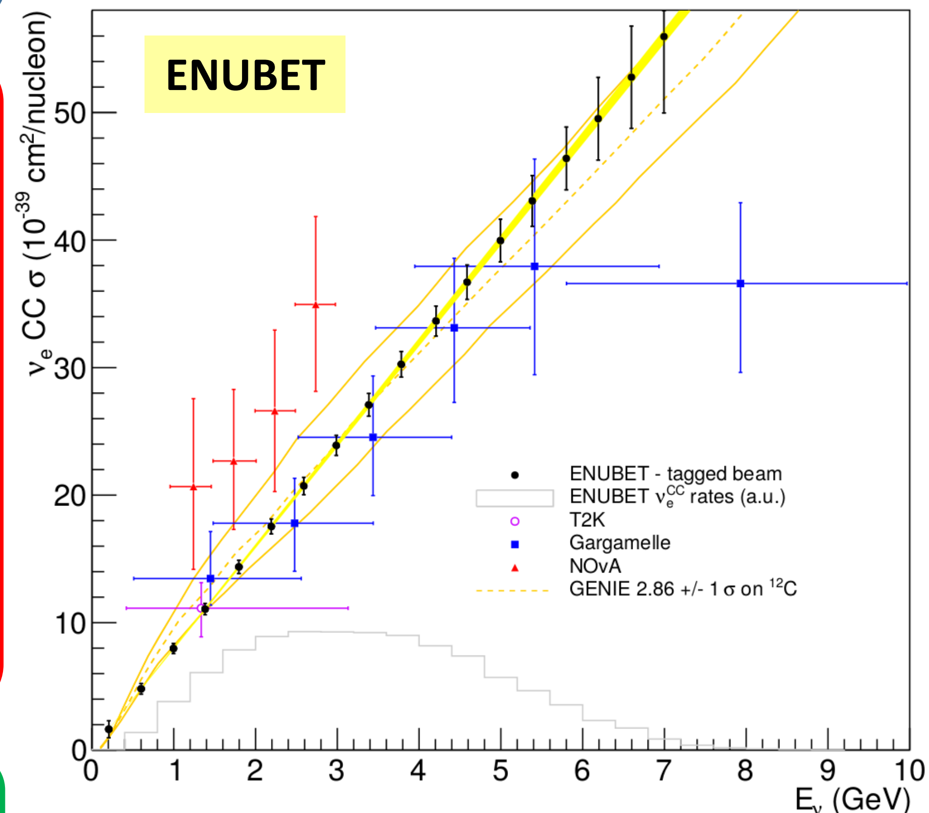
- **Flux systematics** could be **reduced by one order of magnitude** exploiting $K \rightarrow e^+ \nu_e \pi^0$

- In the next 4 years ENUBET will investigate the **feasibility** of this approach and of its application to a new generation of **cross section experiments** at **CERN, FNAL or JPARC** providing **$\sigma(\nu_e)$** at **1%** with a detector of **moderate mass (500 t)**

- The intriguing possibility of a **time-tagged facility** will be also studied

- 1st year of project: a **rich simulation and prototyping program** is giving very **promising results**. Challenging open items ahead. But **no showstoppers** so far

$\sigma(\nu_e)$



1% syst. + 1% stat. (10^4 ν_e^{CC}) **errors**

Eur. Phys. J. C75 (2015) 155

A major breakthrough in experimental neutrino physics