ENUBET

Enhanced **N**e**U**trino **BE**ams from kaon **T**agging

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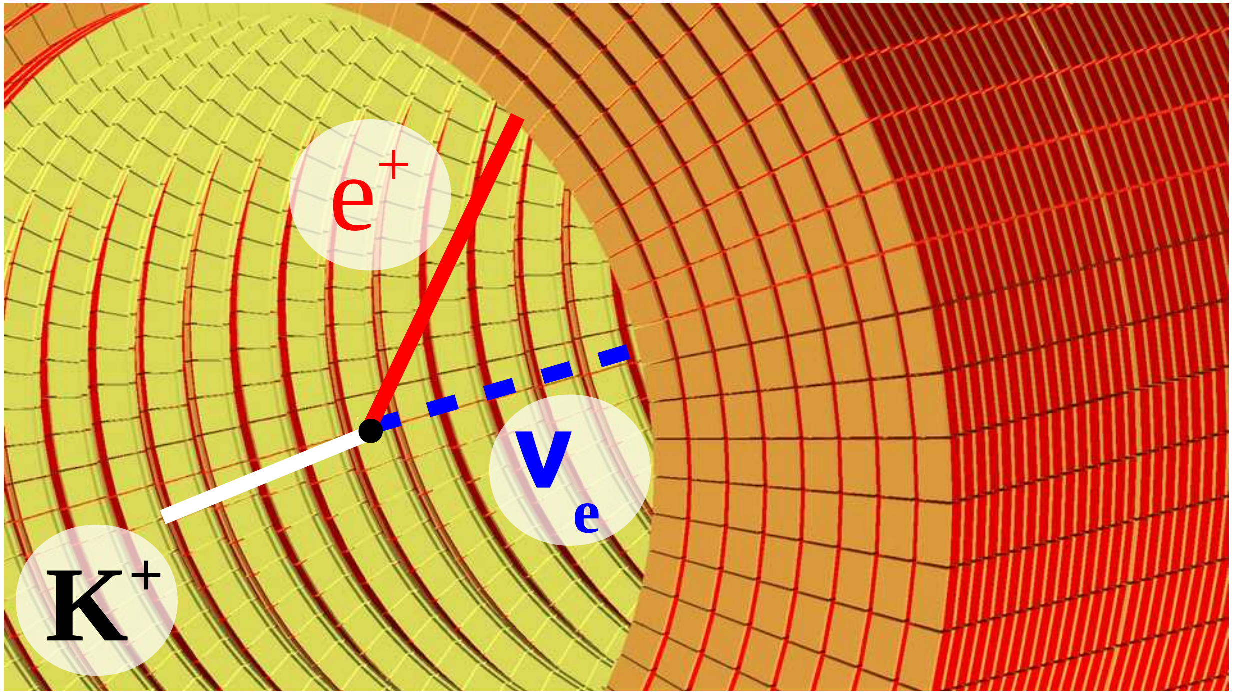
On behaf of the ENUBET Collaboration



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High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

The Idea and The Conceptual Design

- Neutrino cross sections have crucial role in the oscillation physics
  $\nu\mu \rightarrow \nu e$ experiments in appearance mode need direct νe cross section measurements
- Exact knowledge of <u>initial flux</u> is the <u>main limiting factor</u> for neutrino oscillation experiments
  - Flux estimate is an indirect procedure in conventional beams
  - Remarkable progress on neutrino cross-section measurements and hadro-production in targets but still uncertainties are at the order of ~7-10%

idea → Monitor the neutrino beam with a direct measurement of neutrino fluxes with conventional technologies by **tagging the Ke3 decays**

Protons → Target (K+,π+) → **Ke3** decays → νe @ neutrino detector

$K^+ \rightarrow e^+ \pi^0 \nu e$ → **e+** *3-body decay → large angle e+*

Measure positrons
in a FULLY INSTRUMENTED decay region

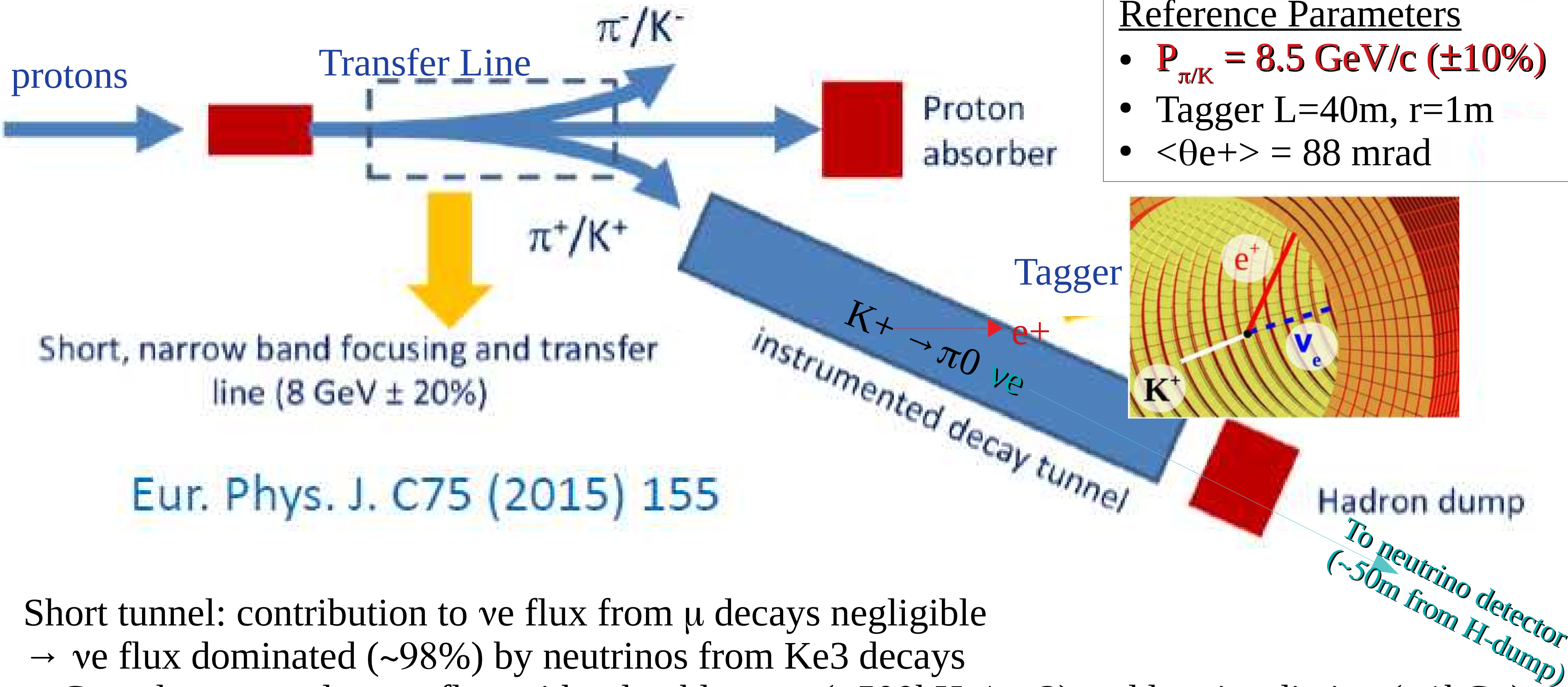
- "By-pass" uncertainties from POT,hadro-production, beamline efficiency
- **<u>νe flux prediction = e+ counting</u>**

<u>→ Improvement of one order of magnitude cross-section measurement @GeV scale =</u>
<u>Determine absolute νe flux at neutrino detector with O(1%) precision</u>

High Precision Neutrino Flux Measurements in Conventional Neutrino Beams

The Idea and The Conceptual Design

Reference Parameters
- $P_{\pi/K}$ = 8.5 GeV/c (±10%)
- Tagger L=40m, r=1m
- <θe+> = 88 mrad



- Short tunnel: contribution to νe flux from μ decays negligible
- → νe flux dominated (~98%) by neutrinos from Ke3 decays
  Complete control on νe flux with tolerable rates (<500kHz/cm2) and low irradiation (<1kGy)
- Requirements:
  - Transfer Line: as short as possible, keep contaminations low
  - Tagger:
    - e+: Longitudinal sampling + integrated light readout
    - Photon veto: photon ID + precise timing + exploit 1mip/2mip separation

The Transfer Line

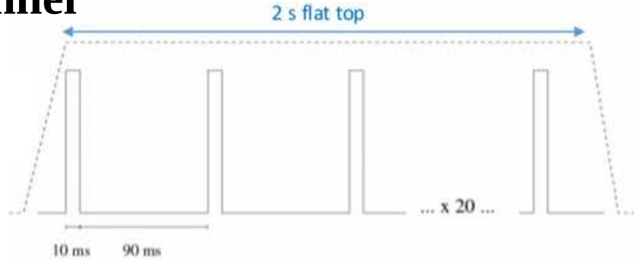
2 possibilities:

Event-count mode

- **HORN-BASED** beamline →PRO: focusing more π & K in the wanted P range before the transfer part to the decay tunnel

  Target → horn → transport → 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 → 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

  Target → transport → Tunnel

CONS:

- Less efficient focusing: lower yields, more POT needed

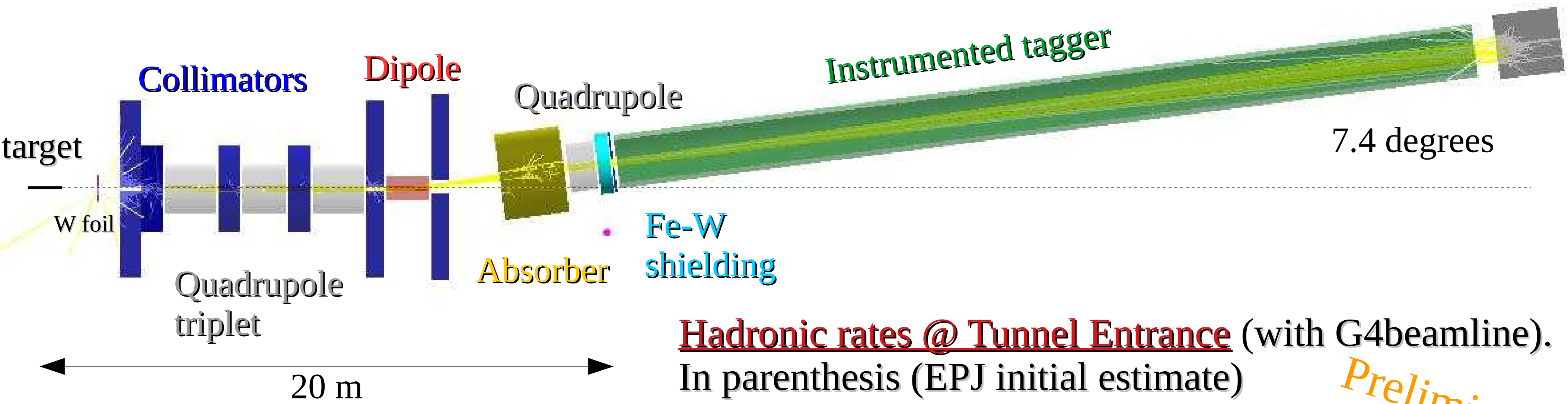
→ Single slow extraction

The Transfer Line

- Preliminary study for the Horn-based beamline completed → best configuration: Target + Horn + quad triplet + dipole + quad triplet (background studies not yet completed)
- Concentrating now on the Static beamline → looks very promising despite lower yields

Latest layout of the static transfer line option

- FLUKA for protons interactions in the target
- TRANSPORT for optic optimization + G4Beamline for complete TL simulation



Hadronic rates @ Tunnel Entrance (with G4beamline). In parenthesis (EPJ initial estimate)

Preliminary

	π^+/pot (10^{-3})	K^+/pot (10^{-3})	Increase factor wrt initial estimates
Horn-based transfer line	77.3 (33.5)	7.9 (3.7)	~2.2
Static transfer line	26.7 (3.6)	2.05 (0.43)	5-7

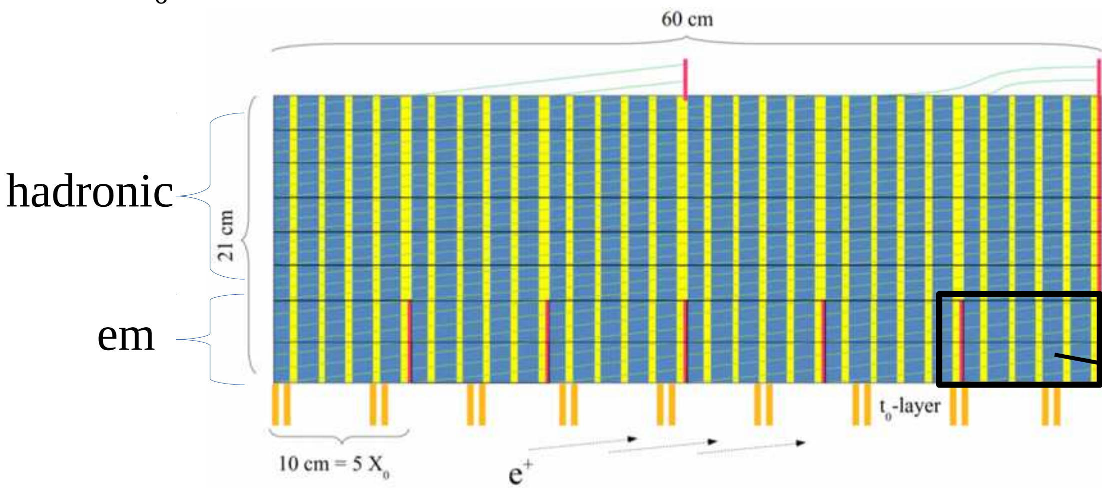
- Very promising!
- Detailed study on beam contaminations in progress

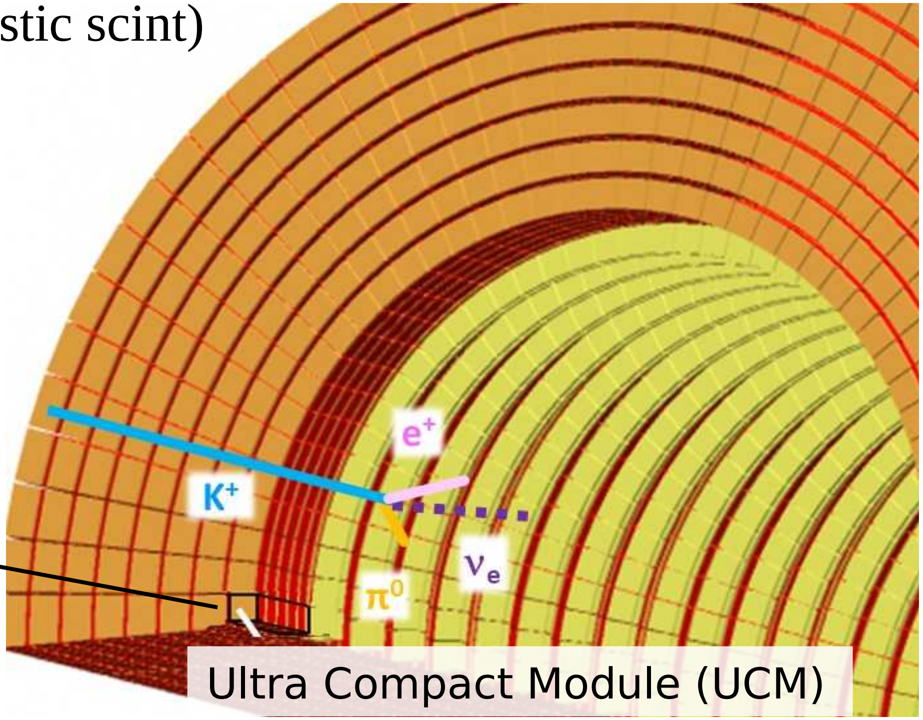
The Tagger

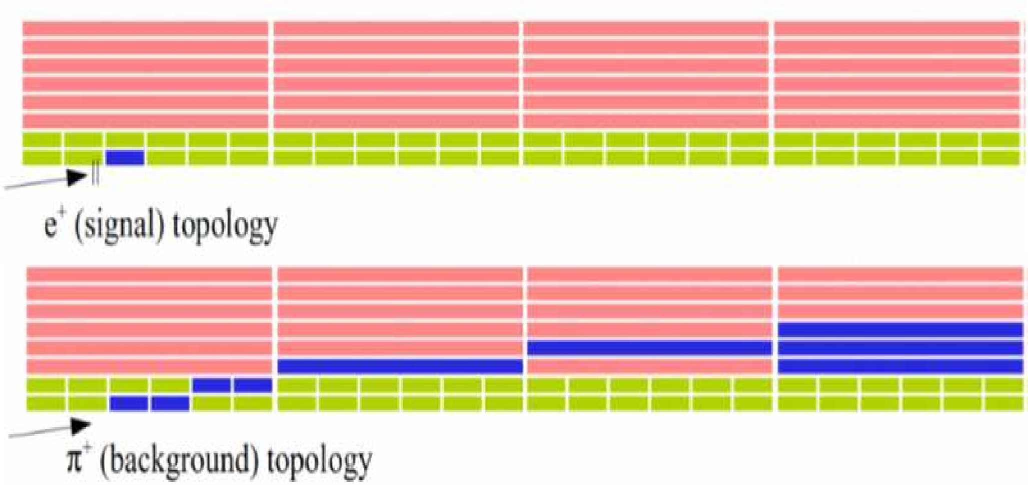
1) Shashlik Calorimeter

- Ultra Compact Module (UCM) (Fe absorber+Plastic scint)
- Light Readout with SiPM

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



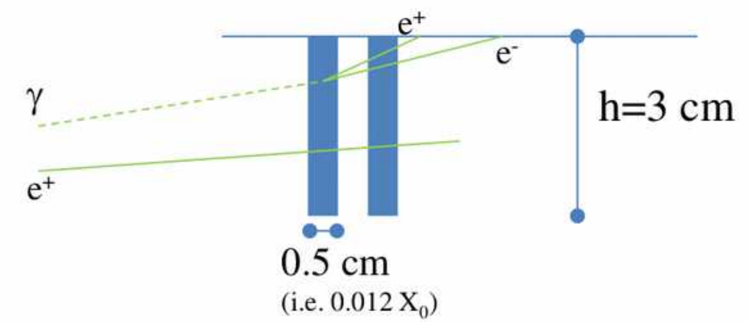




2) Integrated Photon-veto

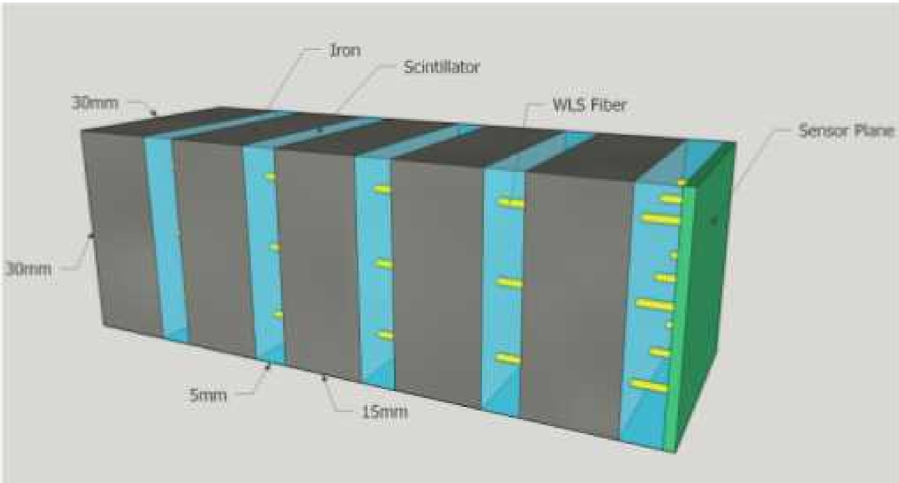
3)3x3 cm2 plastic scintillator pads

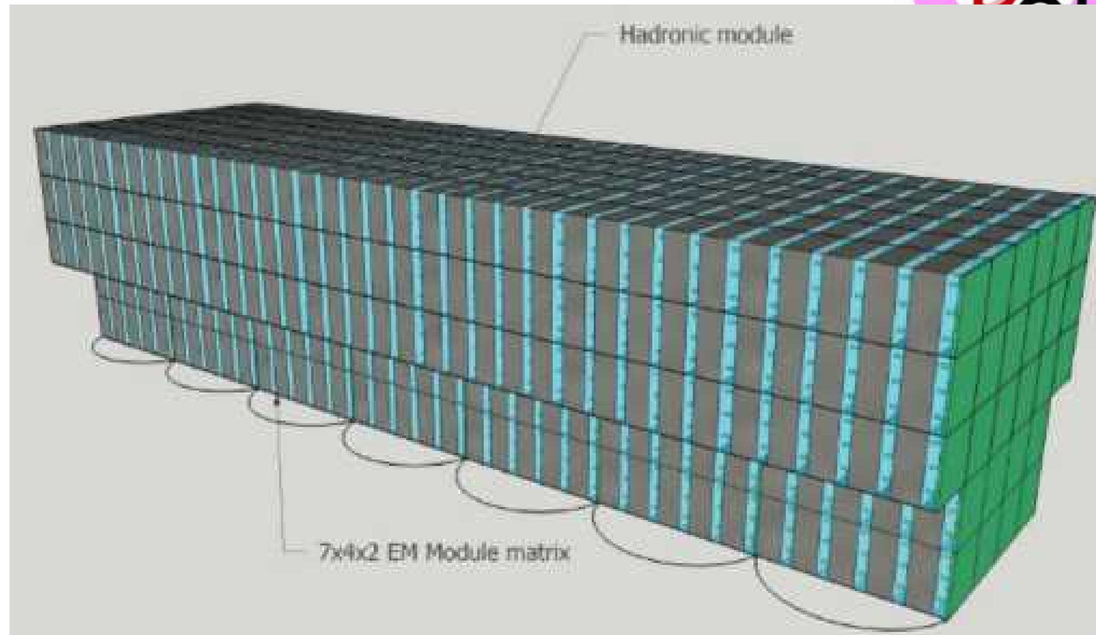
→ **e+/π0 separation (π0 rejection)**



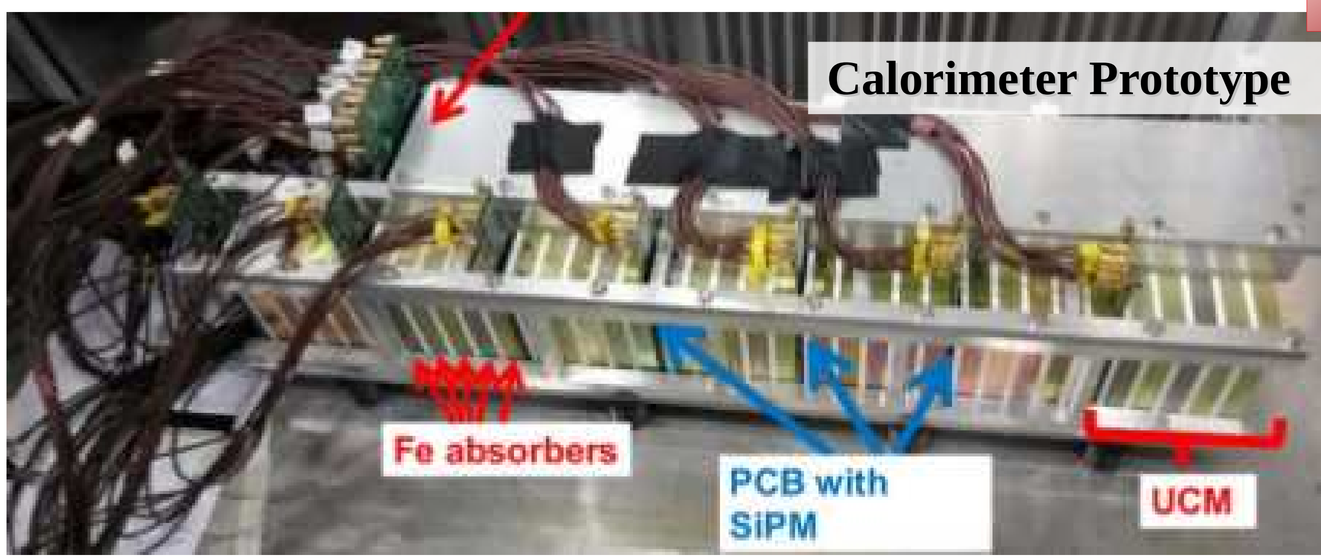
The Tagger

Shashlik Calorimeter





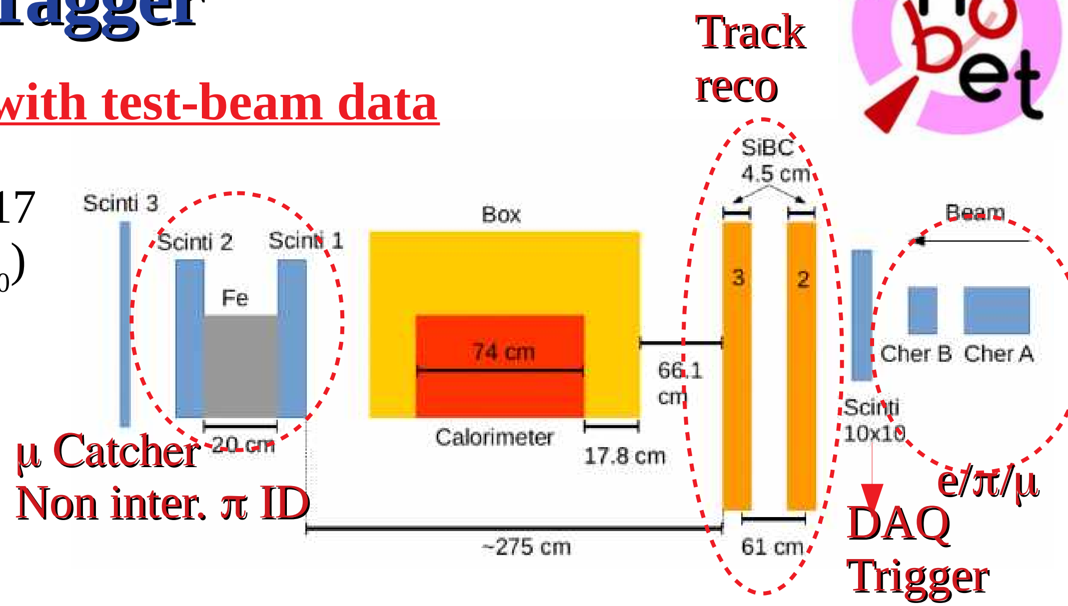
Calorimeter prototype performance with test-beam data



The Tagger

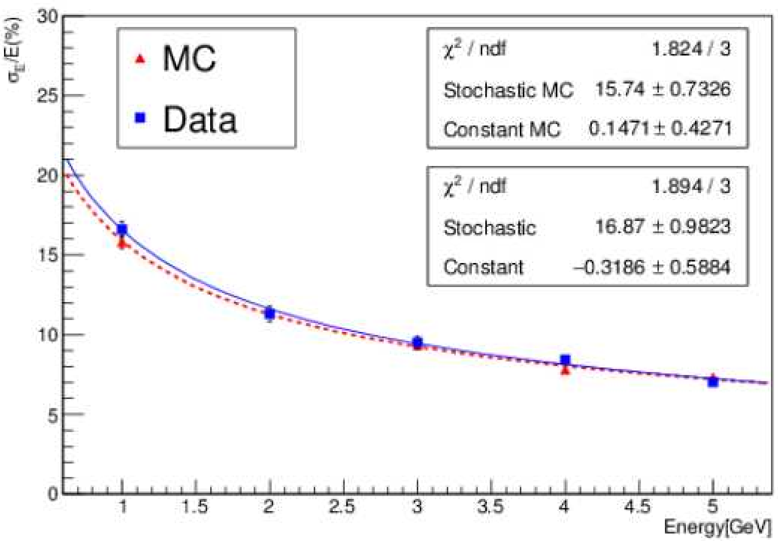
Calorimeter prototype performance with test-beam data

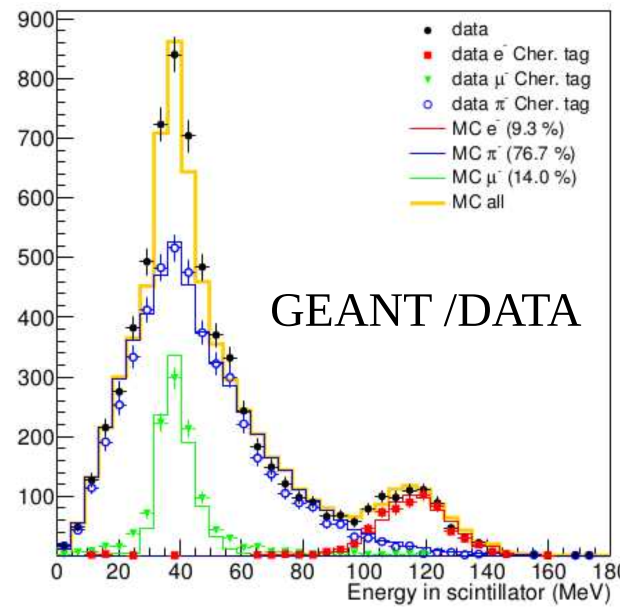
- Test Beam @ CERN-PS T9 beamline in Nov 2017
- 56 UCM arranged in 7 longitudinal block (~30X_0) + hadr. Layer (coarse sampling)
- e/μ tagged with Cherenkov counters and muon catacher
- Beam Composition @ 3GeV:
  9% e-, 14% μ , 77% hadrons



- Tested response to MIP, electrons and charge pions

Ballerini et al., JINST 13 (2018) P01028



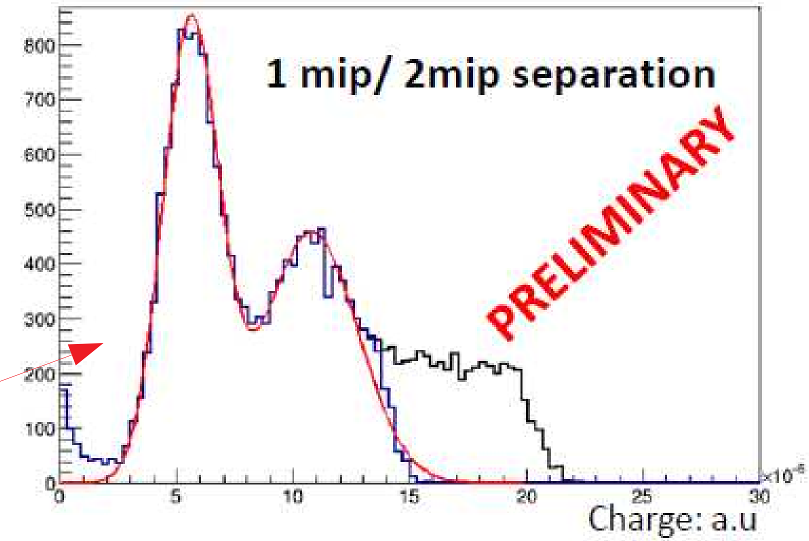


- em energy res 17%/√E(GeV)
- Linearity <3% in 1-5 GeV
- From 0 to 200mrad tilts tested → no significant differences
- Work to be done on the fiber-to-SiPM mechanical coupling → dominates the non-uniformities (effect corrected equilizing UCM response to mip)
- MC/data already in good agreement, longitudinal profiles of partially contained π reproduced by MC @ 10% precision

Detectors R&D

- **γ/e+ discrimination (Photon-Veto)**
  t0 layer scintillator (3x3x0.5 cm^3) + WLS Fiber + SiPM
  Tested @ CERN T9 in July+October
  → 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)

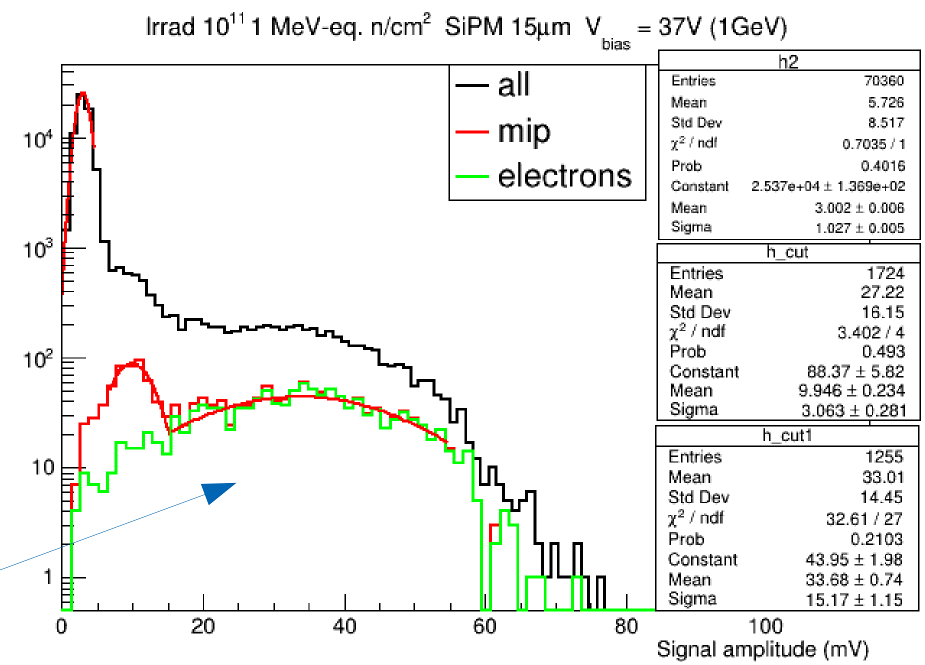
We are able to discriminate γ from Ke3 e+



- **Irradiation Studies**
  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)

  irradiated SiPM tested at CERN in October 2017

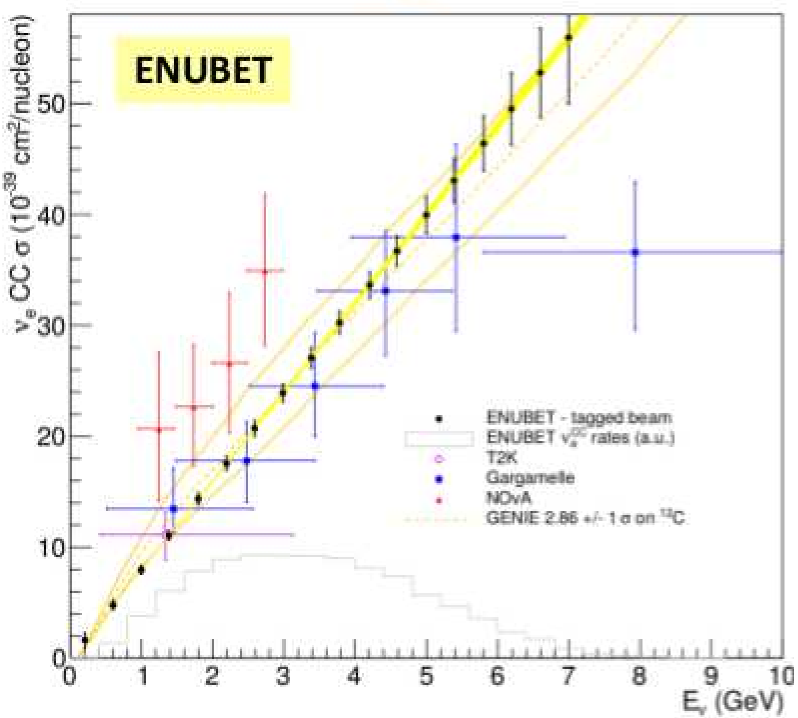
Detectors are radiation hard, we see mip & electrons



Conclusions

- Results of ENUBET studies coming faster than expected and very promising
- Many R&D activities currently on-going and another year of test-beams @ CERN ahead→
  - Achieve recovery time <10ns (to cope with pile-up)
  - Test of custom digitizer electronics
  - Photon veto prototypes with plastic scintillators
  - Scalable/reproducible technological solutions (water-jet holes machining for absorbers, molded scintillators, *polysiloxane scintillators → First application in HEP! No drilling&high rad. hard*)
- Static beam line looks very promising, would avoid the problem of pulsing a horn + *event-by-event tagged beam!*
  Work in progress to have precise estimation of expected beam backgrounds

$\sigma(\nu_e)$



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

Eur. Phys. J. C75 (2015) 155

- By The end of the year we expect to complete the **Reference Design**:
  Complete simulation end-to-end of the beamline +
  Final configuration of the calorimeter +
  (will test a non-shaslik configuration as well)
  Updated physics performance
  (monitor of major BR of K+, neutrinos flux determination at 1%, possibility of a tagged beam)

Thank you!

Back-ups

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 (next slide) possibility of complete K-decay kinematic reconstruction → νe energy event-by-event (“**tagged neutrino beam**”)

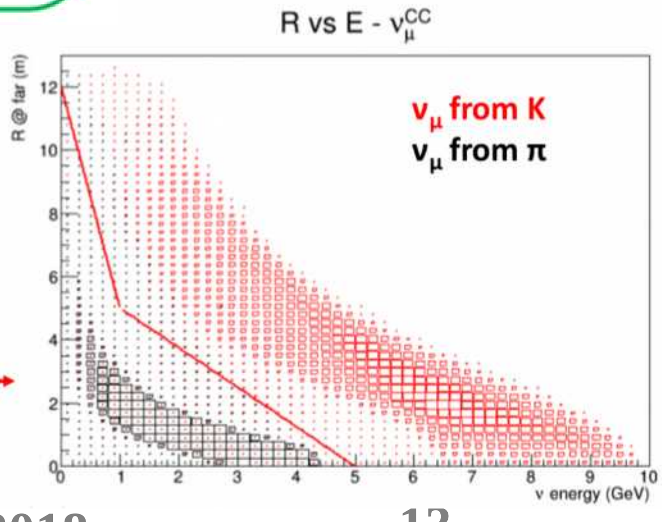
νe Flux

- **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)

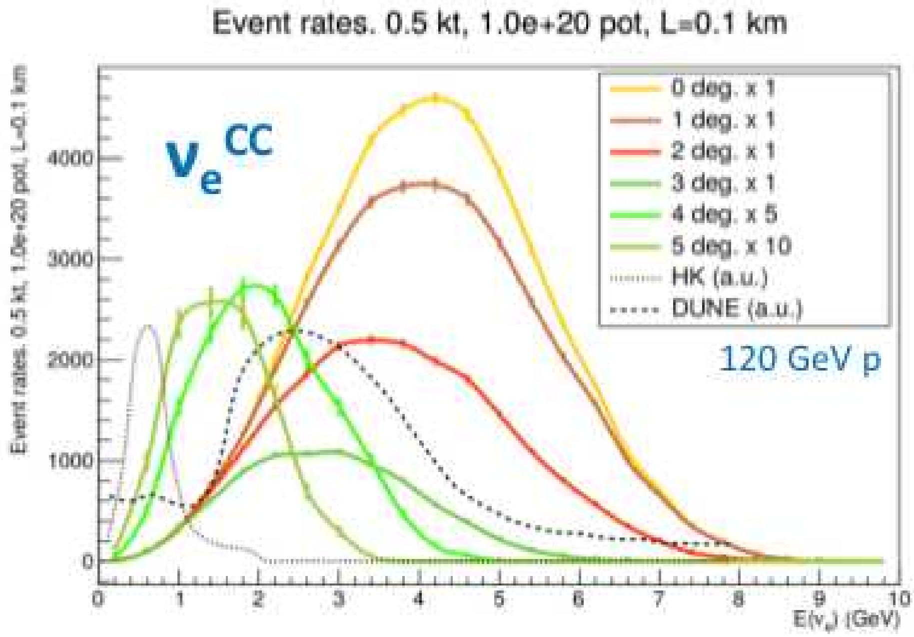


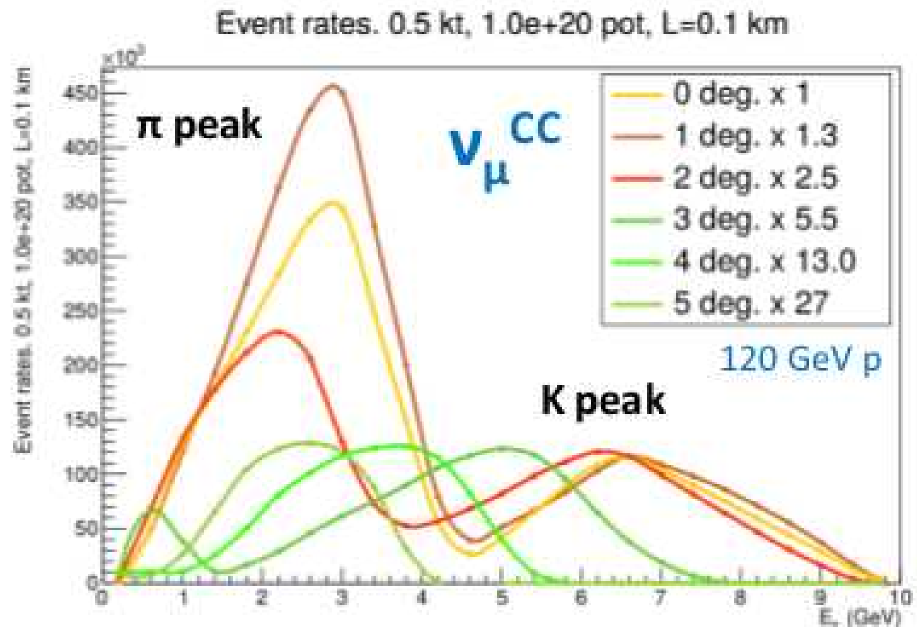
Neutrino Samples

- 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 ($6\times6\times10$ 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