# High precision flux measurements in conventional neutrino beams with the ENUBET ERC project

**Neutrino Telescopes**
Venice, 13-17 March 2017

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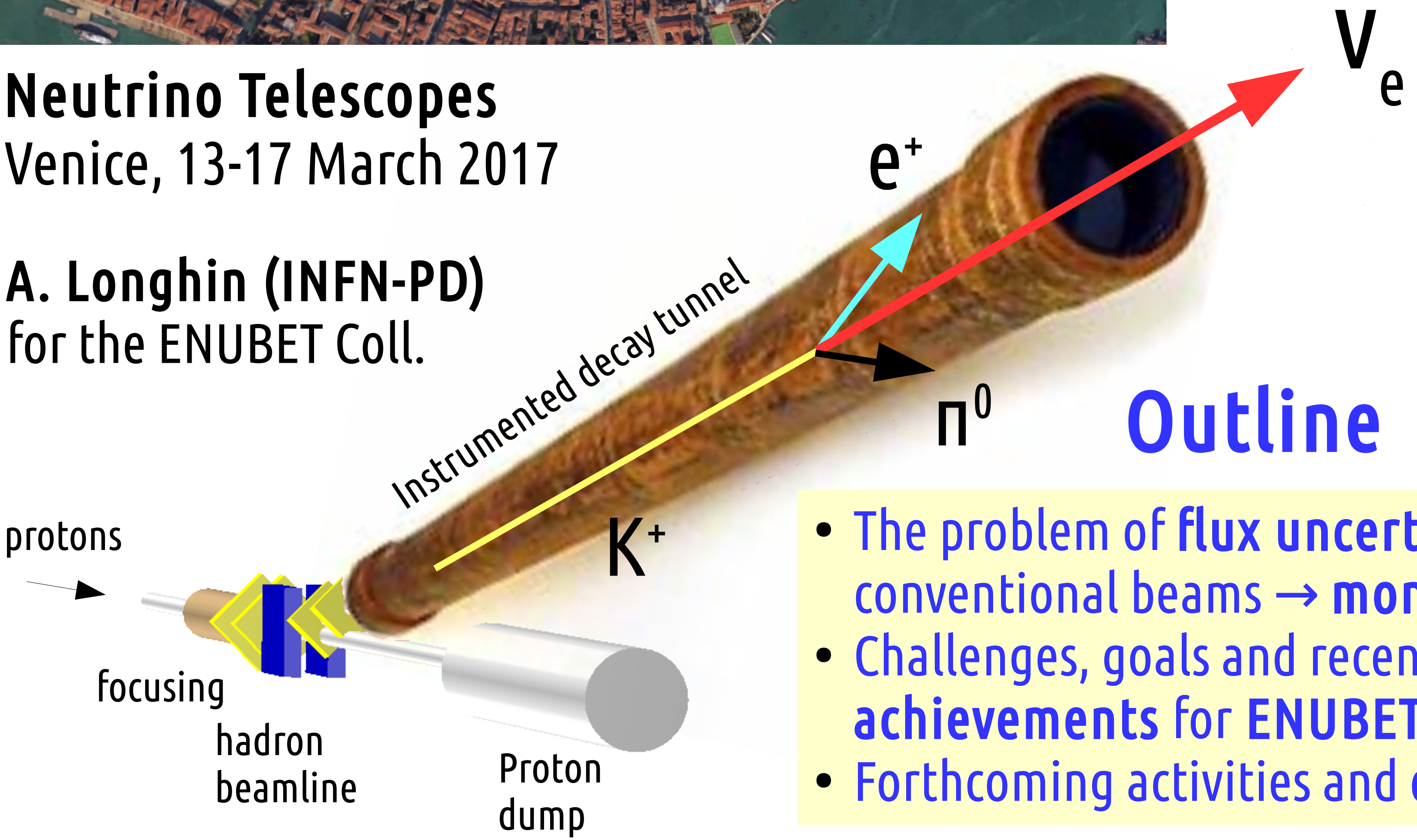
for the ENUBET Coll.

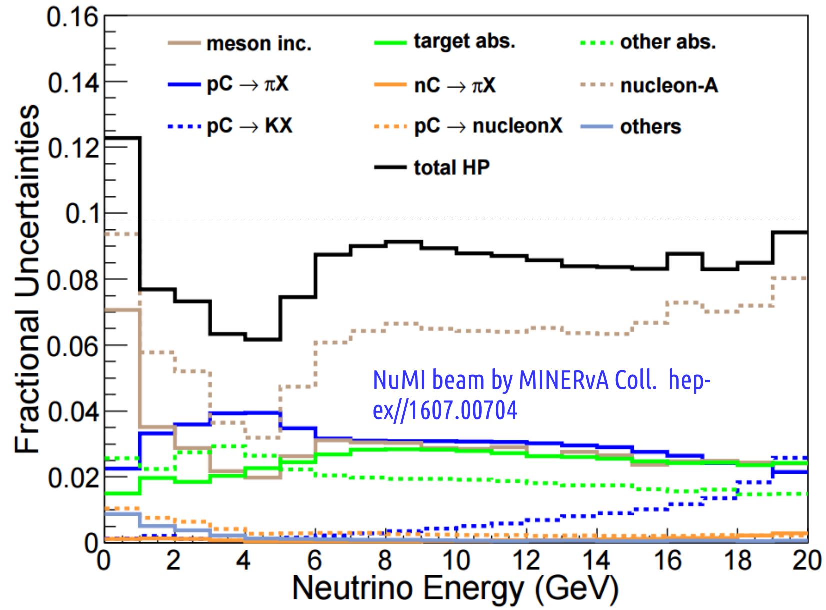



## Outline

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

# Tackling the flux uncertainty problem

Last 10 years: **knowledge of σ($\nu_\mu$) improved enormously** (SCIBooNE, MiniBooNE, T2K, MINERvA)



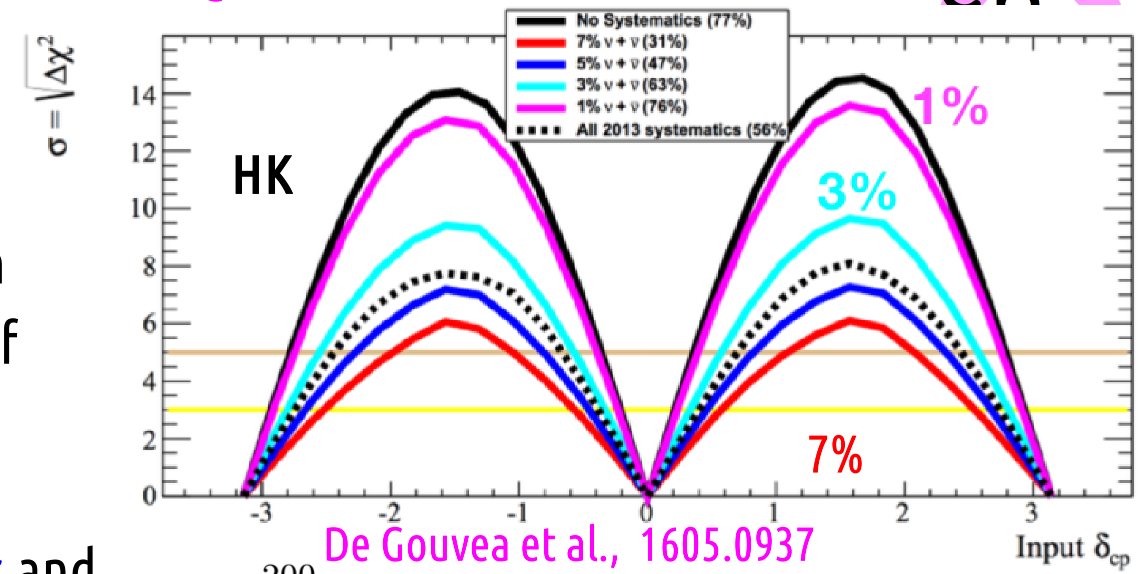

Still:

- No absolute measurement with < 10% error.
- The **flux systematics "wall"**
- **Mitigations** and flux constraints **already** in place:
  - **hadro-production experiments** (SPY, HARP, NA61)
  - **interactions on electrons** (but small rates and only useful @ high-E)
- In particular for **σ($\nu_e$)** data are **sparse/old** (Gargamelle, T2K, NOvA) being based on the beam contamination (**no intense/pure sources of GeV $\nu_e$**).

# Impact of precision on σ($\nu_e$)

**CP violation:** poor knowledge of **σ($\nu_e$)** can significantly spoil the discovery potential of future $\nu_\mu \rightarrow \nu_e$ experiments.

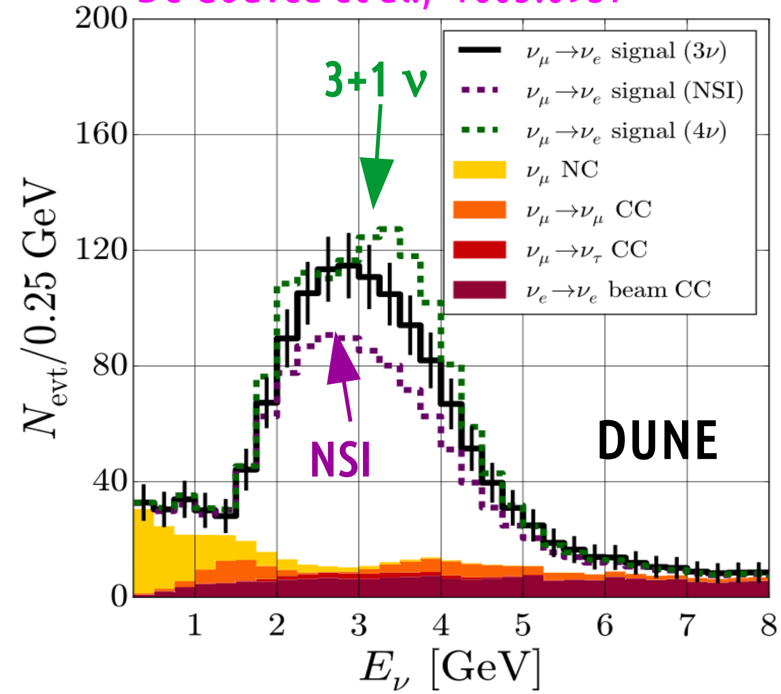
M. Hartz @ NuFact 2015




**Exotic:** sterile ν, Non-Standard Interactions and 3ν scheme have a similar phenomenology → precise knowledge of **σ($\nu_e$) vs E → a deeper insight of the underlying physics**.

- Moreover: "derivation" from **σ($\nu_\mu$)** is "delicate" expecially @ low-E (sub-GeV)
- Ideal solution? D.I.F. of stored μ as in **nuSTORM/nuPIL!** but NOT easy

De Gouvea et al., 1605.0937




**→ Monitored beams:** a **ν source** employing **conventional technologies** reaching a **precision on the initial flux < 1%**

# Monitored beams

protons → ($K^+$, $\pi^+$) → K decays → $e^+$ $\nu_e$ → neutrino detector

- Idea of existing **μ/hadron monitors** extended to the ultimate step:
  → monitoring (~ inclusively) the **decays in which ν are produced**.
- By-pass uncertainties from:
  **hadro-production**, **PoT**, **beam-line efficiency** ("before" the tagging)

## Traditional beams

- **Passive** decay region
- $\nu_e$ flux relies on **ab-initio simulations** of the full chain
- **large uncertainties**

⟷

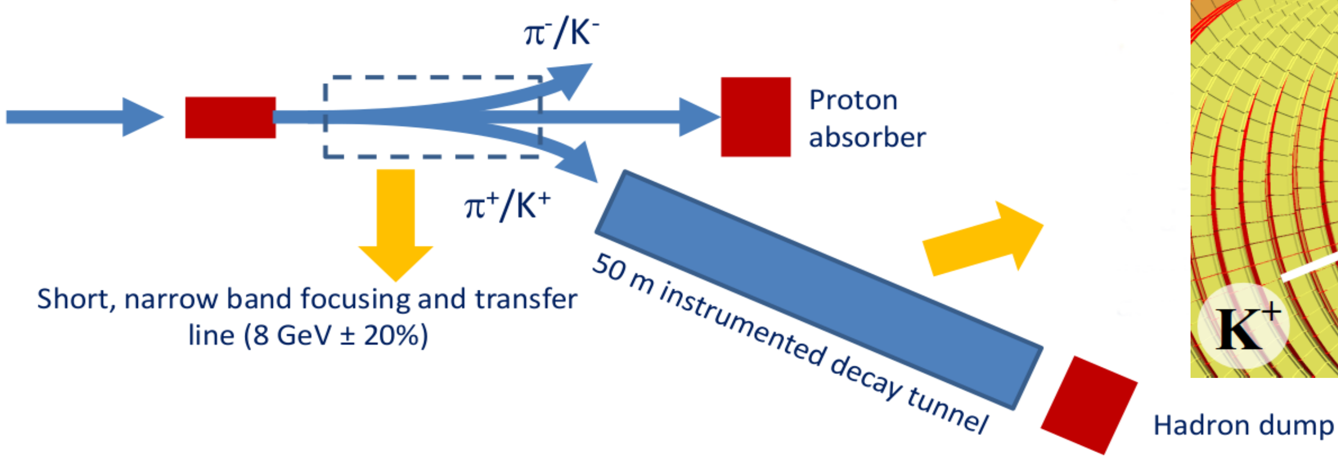
## Monitored beams

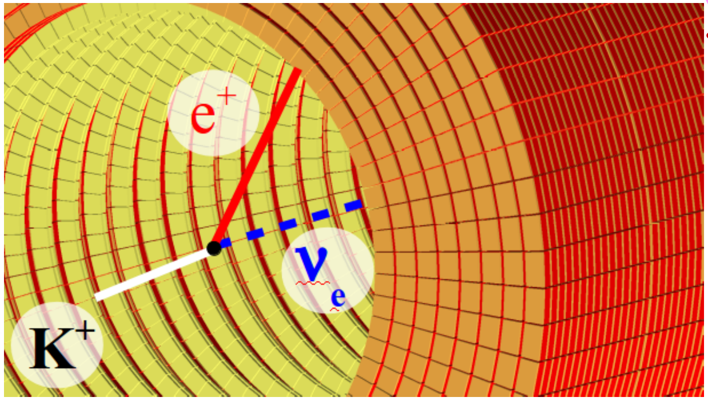
- **Fully instrumented** decay region

  $K^+ \to e^+ \nu_e \pi^0 \to$ large angle $e^+$

- **$\nu_e$ flux prediction = $e^+$ counting**

# Working principle and setup




- **1) Hadron beam-line**: charge selection, focusing, transfer of $\pi^+/K^+$ to an instrumented decay tunnel ($e^+$ tagger)
- **2) Tagger**: real-time, "inclusive" **monitoring** of K decay products

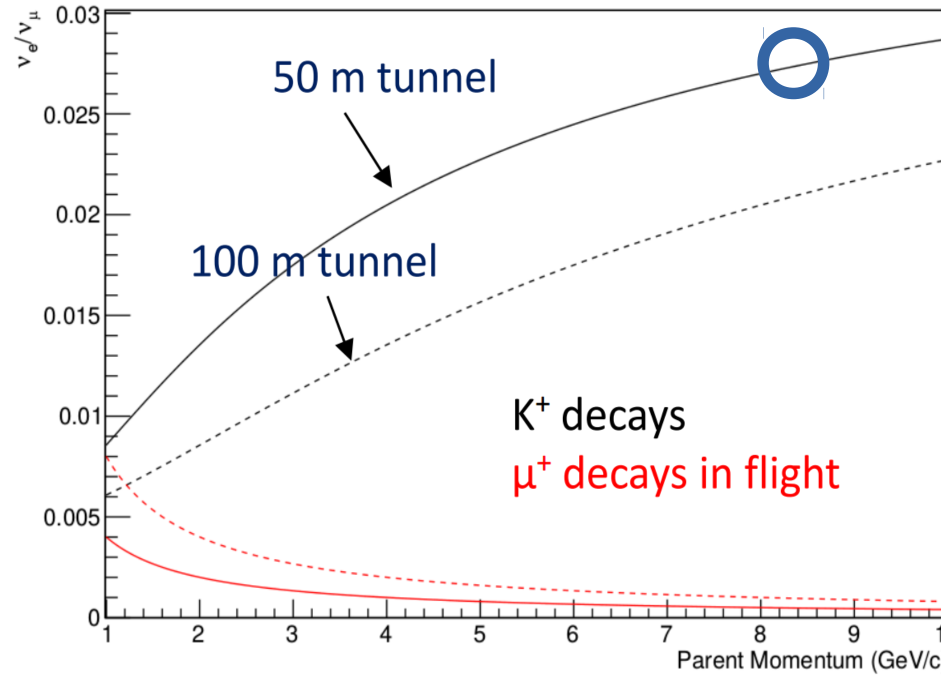
- Profiting of a **good focusing** (important!) and decay kinematics we can have:
- **only K decay products** (at large angles) being measured and **π and μ decaying** at small angles and reaching the dump **without hitting the instrumented walls**.
- This allows:
  - ✓ **tolerable rates** and **irradiation** (< 500 kHz/cm$^2$, O(1 kGy) )
  - ✓ full/continuous **control of the bulk of the produced $\nu_e$ from the $K_{e3}$ rates**
    - ✓ contribution of **$\nu_e$ from μ decays is < 2%** using a "short" decay tunnel

# Baseline design parameters

**Baseline design:**

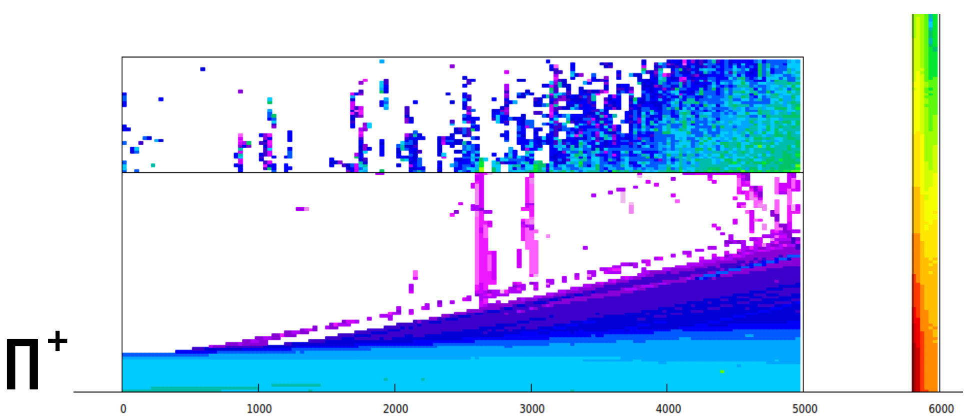
- $p_{K,\pi} = 8.5 \pm 20\%$ GeV/c
- $\theta < 3$ mrad over $10 \times 10$ cm$^2$
- Tagger: $L = 50$ m, $r = 40$ cm

$\nu_e/\nu_\mu$

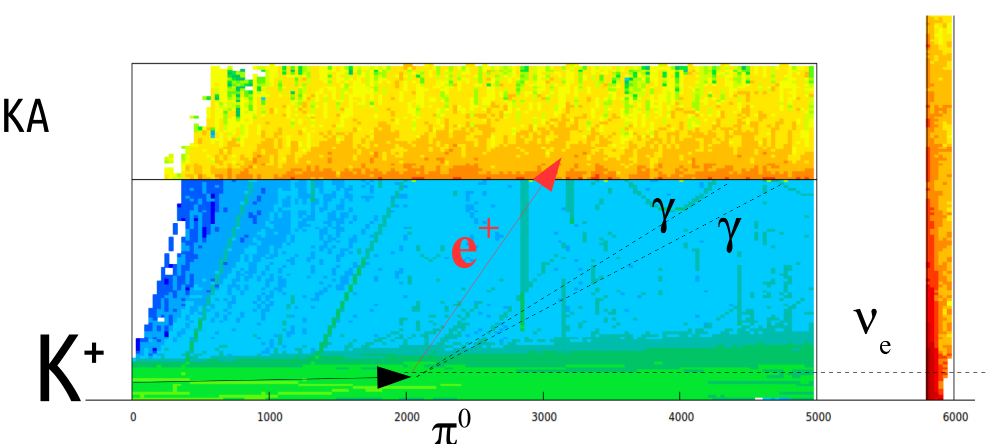



Parent momentum

- $E_\nu$ in R.O.I. with few $\nu_e$ from $\mu$ decays
- limited K losses in the beam-line
- an "easy" e/π separation at reduced costs
- Good acceptance for K decays thanks to the large emission angle (~ $m_K$)
- Positrons from $K_{e3}$ emitted at ~90 mrad




FLUKA

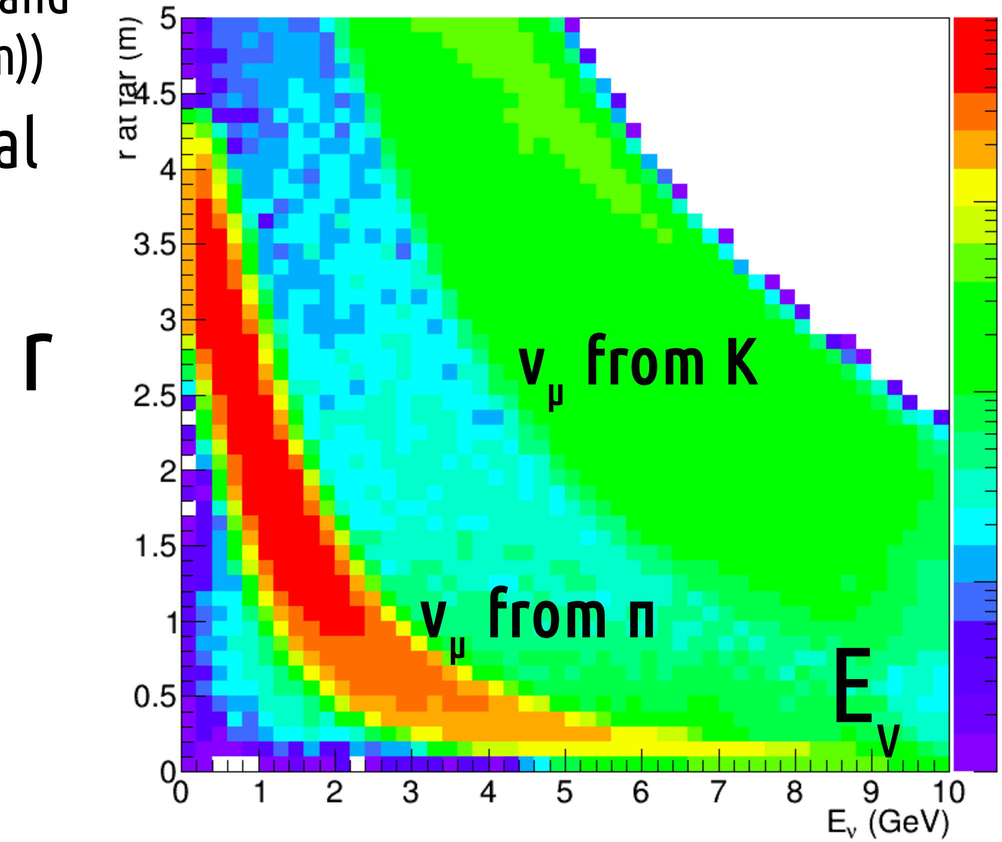


# Role of other K decays and $\nu_\mu$ flux

- **$\sigma(\nu_e)$**
  - ✓ **$K_{e3}$ (golden sample)**
    - $\pi^{+/0}$ from $K^+$ can mimic an $e^+$
      → **discriminate e/π** with:
      1) longitudinal profile of showers
      2) reconstruct vertices by timing
    - veto $e^+$ candidates if compatible with $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to \pi^+\pi^0$ vertices (needs $\sigma_t$ O(**100 ps**) ~ $\sigma_{zVTX}$ O(1m))
  - ✓ **non $K_{e3}$ (silver sample)**: only additional systematics from the $K_{e3}$ **B.R.**

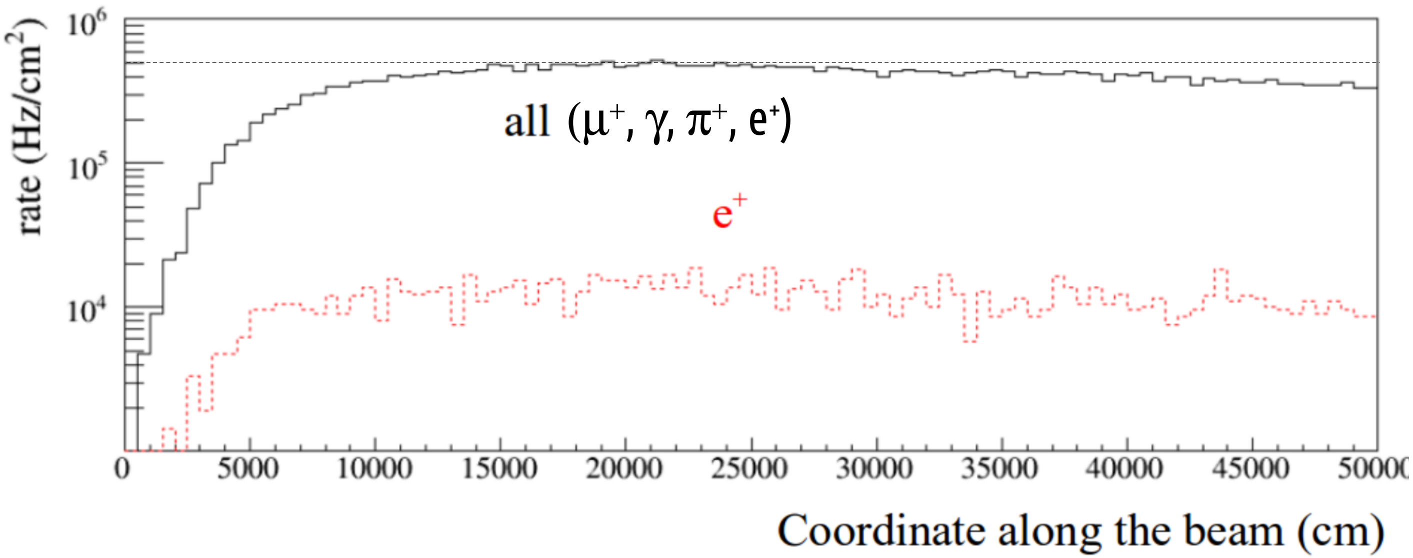
- $K^+ \to \mu^+\nu_\mu$ (63%)
- $K^+ \to \mu^+\nu_\mu\pi^0$ (3.2%)
- $K^+ \to \pi^+\pi^0$ (21%)
- $K^+ \to \pi^+\pi^-\pi^+$ (6%)
- $K^+ \to \pi^+\pi^0\pi^0$ (2%)

- **$\sigma(\nu_\mu)$**
  - μ tagging in the calorimeter
  - $\nu_\mu$ from K selected at the ν-detector with Radius-Energy correlations →



# The $e^+$ tagger challenges

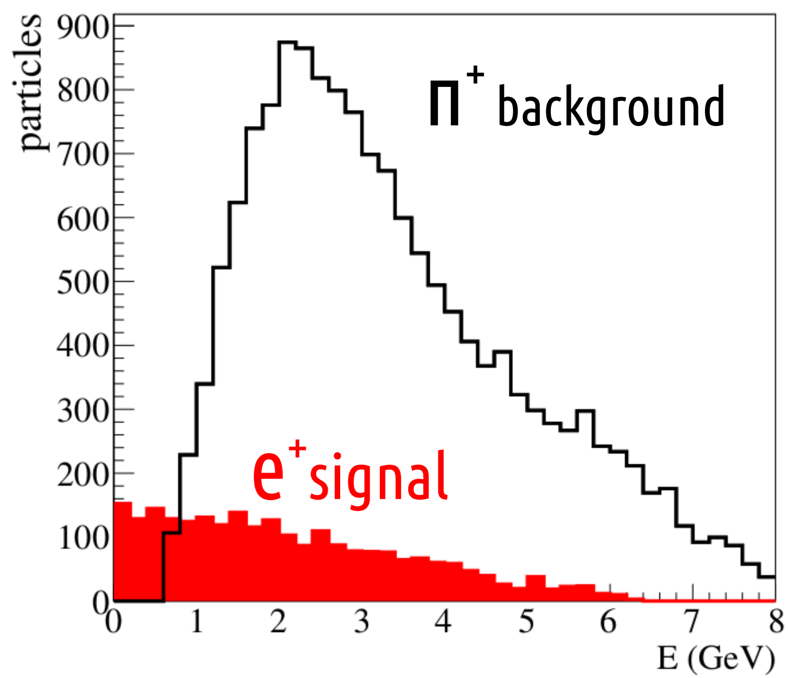
Injecting **$10^{10}$ $\pi^+$ in a 2 ms spill** →



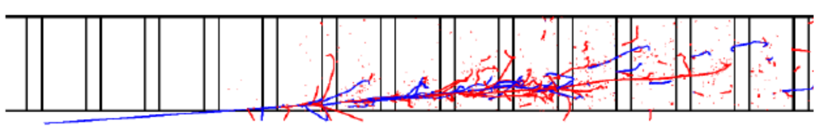

| | Max rate (kHz/cm²) |
|---|---|
| $\mu^+$ | 190 |
| $\gamma$ | 190 |
| $\pi^+$ | 100 |
| $e^+$ | 20 |
| **all** | **500** |

The decay tunnel: a **harsh environment**

- **particle rates: > 200 kHz/cm²**
- **backgrounds:** pions from $K^+$ decays →

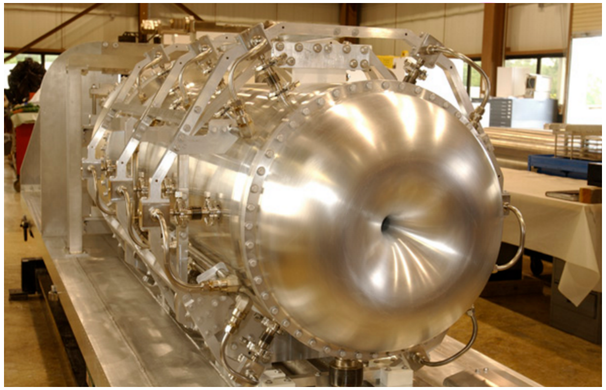



Moreover:



- **extended source of ~ 50 m**
- grazing incidence
- significant spread in the initial direction

# Hadron beam-line: scenario A

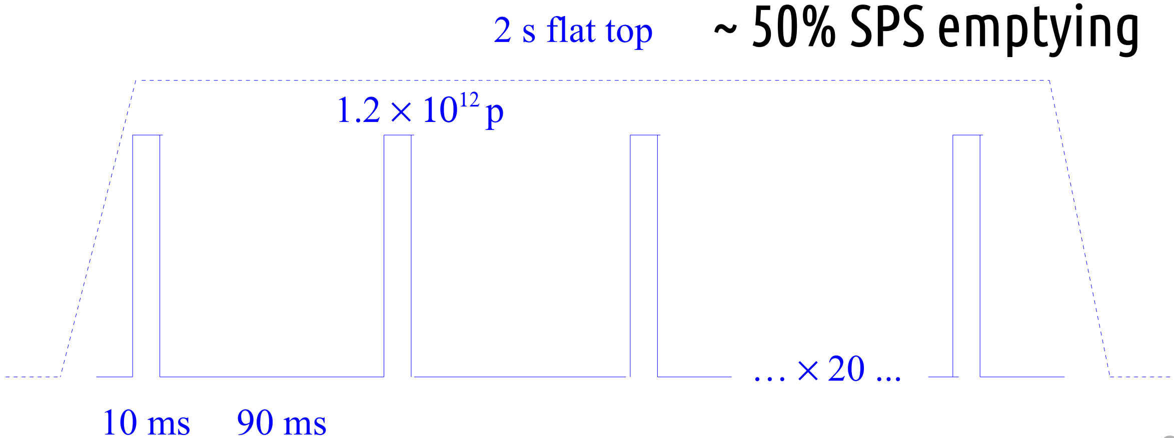


- Magnetic horns : $t_{impulse}$ < 10 ms (Joule heating, I ~ O(100) kA)
- **tagger rate limit** with **$10^{10}$ $\pi^+$ in 2 ms**
- horn collection efficiency → **0.3-2.5 × $10^{12}$ PoT/spill** depending on $E_p$
  - i.e. **(many) spills with relatively "few" protons are needed**

- Requiring **$10^4$ $\nu_e^{CC}$** in a **500 t** ν-detector **at 100 m** implies:
  - **0.5-5 × $10^{20}$ PoT** → well within present performances! A few years of run.
  - ~ **2 × $10^8$** spills. More challenging/unconventional. A possible scheme is
    - **multi-Hz slow resonant extraction** + multi-Hz horn pulsing
    - R&D and **machine studies at SPS** are planned

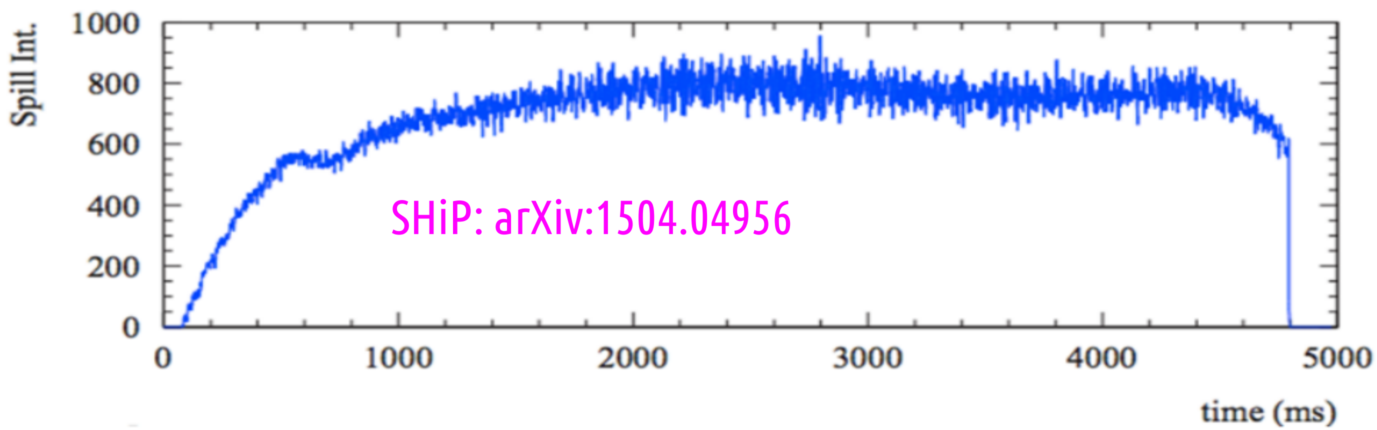
"WANF like"

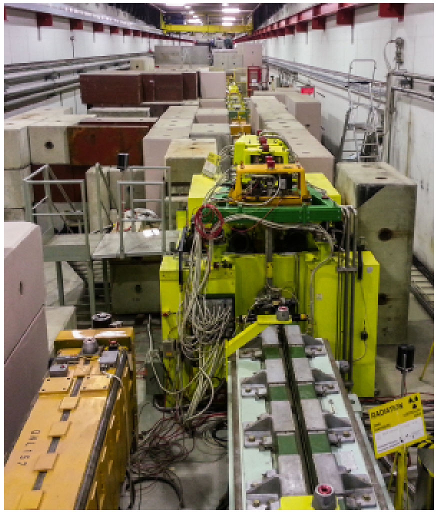
**A possible structure at the SPS:**



# Hadron beam-line: scenario B

- Static focusing: **large aperture radiation-hard quadrupoles**
- Advantage: tagger is now far from maximal tolerable rates
- Disadvantage: **loss of acceptance** w.r.t. horn-based
  - **PoT** to get **$10^4$ $\nu_e^{CC}$: 0.5-7 × $10^{21}$**
    - X10 more. Still feasible if compensated by **(run time × detector mass)**
  - R&D on static focusing beam-line:
    → maximize collection efficiency (~ “useful” hadrons/PoT)
  - Single resonant slow extraction over O(s) ← synergies with **SHiP**

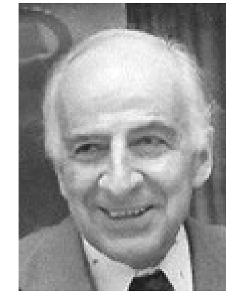


NA62 beamline

**This option offers another intriguing opportunity →**

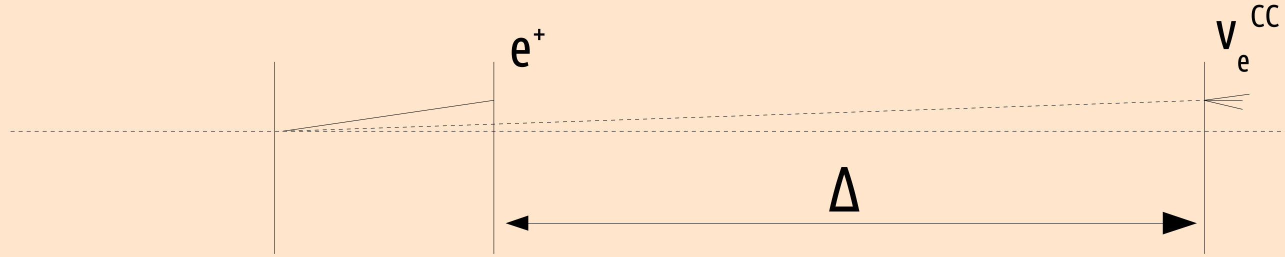
# Going beyond: "time-tagged" beams



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

Superior purity. Combine $E_\nu$ from decay with the one deduced from the interaction.

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




$\delta$ = combined t-resolution ($e^+$ tagger and n detector)

**Accidental tag probability using $10^{10}$ hadrons/burst: A ~ $2\times10^7$ $\delta/T_{extr}$**

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

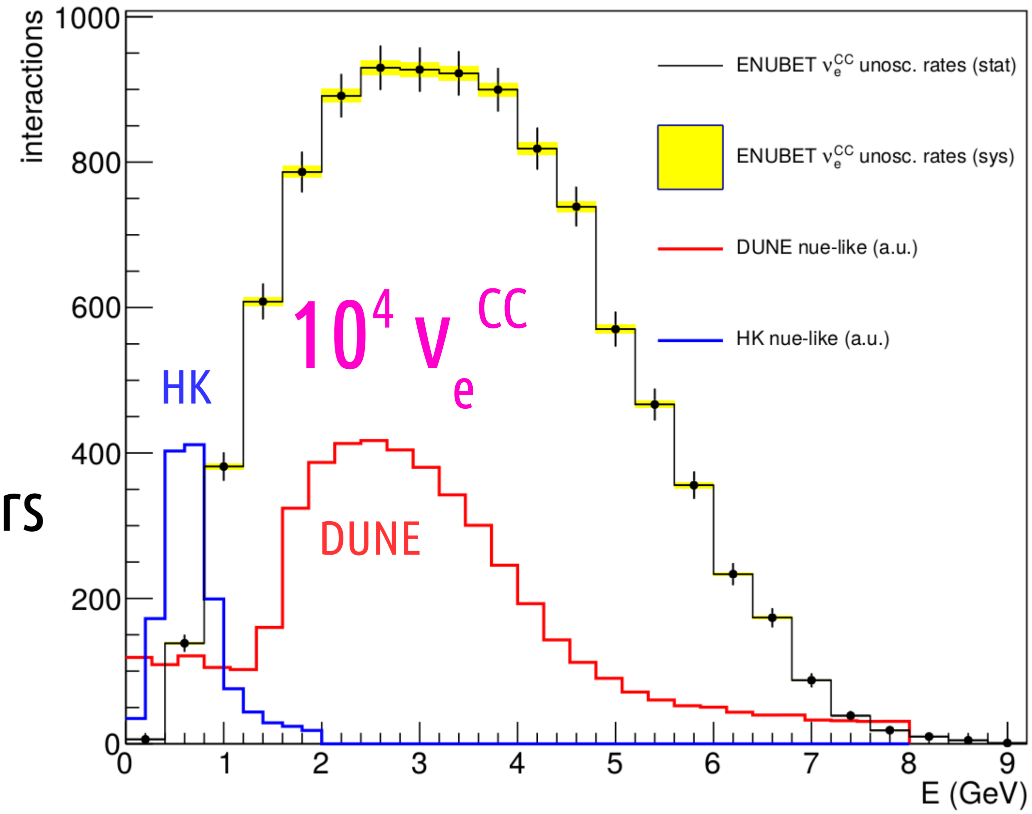
Time-tagging not possible using magnetic horns, (scenario A):

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

# ν-detector and $\nu_e^{CC}$ rates

- At ~100 m from the hadron window
- a ~500 t mass
- With good e-tagging capabilities
  - e.g. ICARUS@Fermilab
  - proto-DUNE SP/DP @CERN
  - Water Cherenkov prototypes
- $10^4$ $\nu_e^{CC}$ could be collected in a few years
- Interesting region of long baseline future projects is covered
- Extended optimization foreseen within ENUBET

<E> = 3 GeV, FWHM ~ 3.5 GeV




Eur. Phys. J. C75 (2015) 155

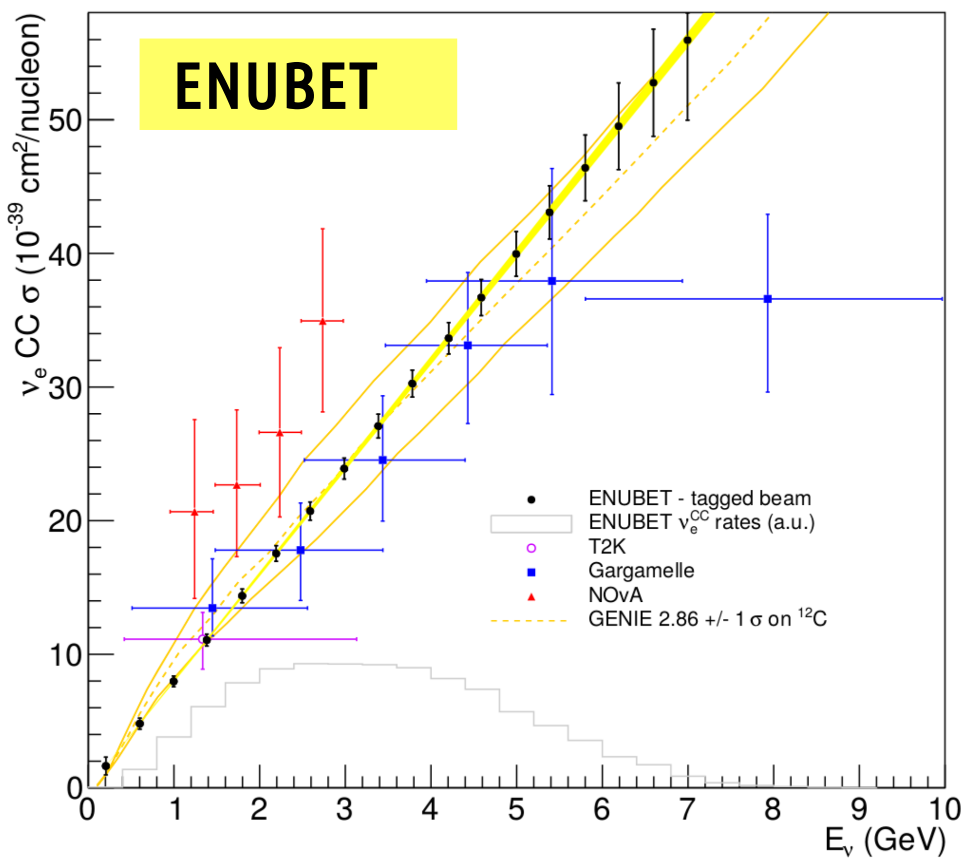
# New opportunities

The ENUBET technology is well suited for **short baseline experiment** where the intensity requirement are less stringent.

Major **applications** include:

- A new generation of **cross section experiments operating with a ν source controlled at the < 1% level**. A unique tool for precision oscillation physics and a new opportunity for the cross-section community
- A **phase II sterile neutrino search**, especially in case of positive signal from the Fermilab SBL program/reactor experiments
- The first step towards a **time-tagged ν-beam**

**$\sigma(\nu_e)$** NB. $\sigma(\bar{\nu}_e)$ is a "green field"




**1% sys.** + 1% **overall stat. errors** (10.000 $\nu_e^{CC}$) Eur. Phys. J. C75 (2015) 155

# ENUBET

http://enubet.pd.infn.it

## Enhanced NeUtrino BEams from kaon Tagging

Project approved by the European Research Council (ERC)
5 **years** (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)

CERN-SPSC-2016-036 ; SPSC-EOI-014
**Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project**

**41 physicists, 10 institutions**:
CERN, IN2P3 (Strasbourg), INFN (Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I)

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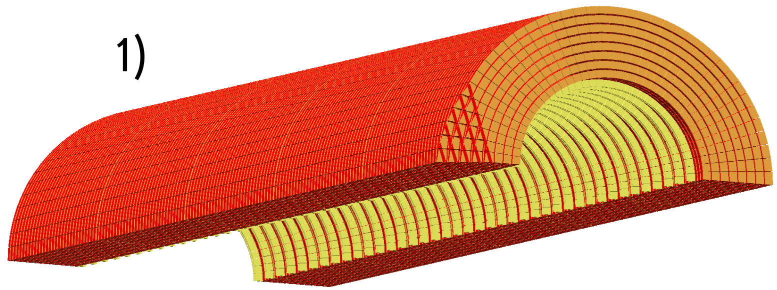
In the **CERN Neutrino Platform** (NP03, PLAFOND)

# ENUBET: the roadmap

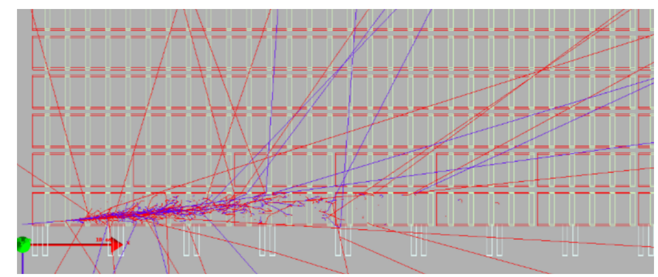
## Demonstrate the technique, prepare a "full-scale" experiment

1) Construction, tests of a **tagger demonstrator** (three m of the instrumented decay tunnel)
2) **Systematics** with full simulation supported by **test beam campaigns** at CERN-PS and INFN-LNF/LNL
3) **Design** of the hadronic **beam-line**
4) Test new **proton extraction schemes** at CERN-SPS

1)



2)



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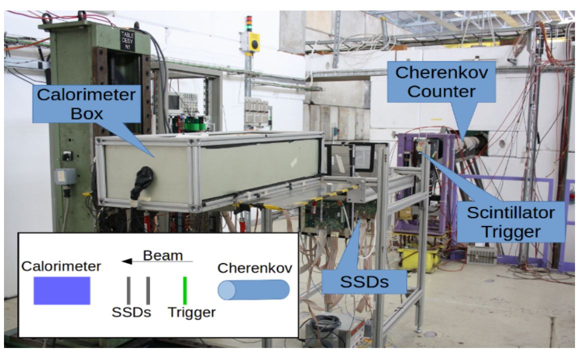
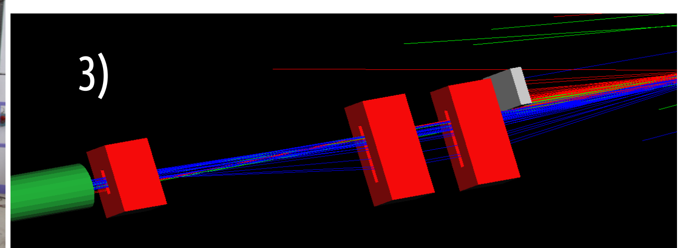
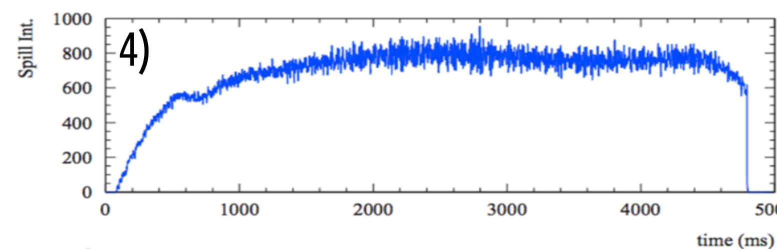



## By-products:

- **Calorimetry:** compact, modular, low-cost detectors (UCM)
- **Accelerator physics:** Multi-Hz slow resonant extraction

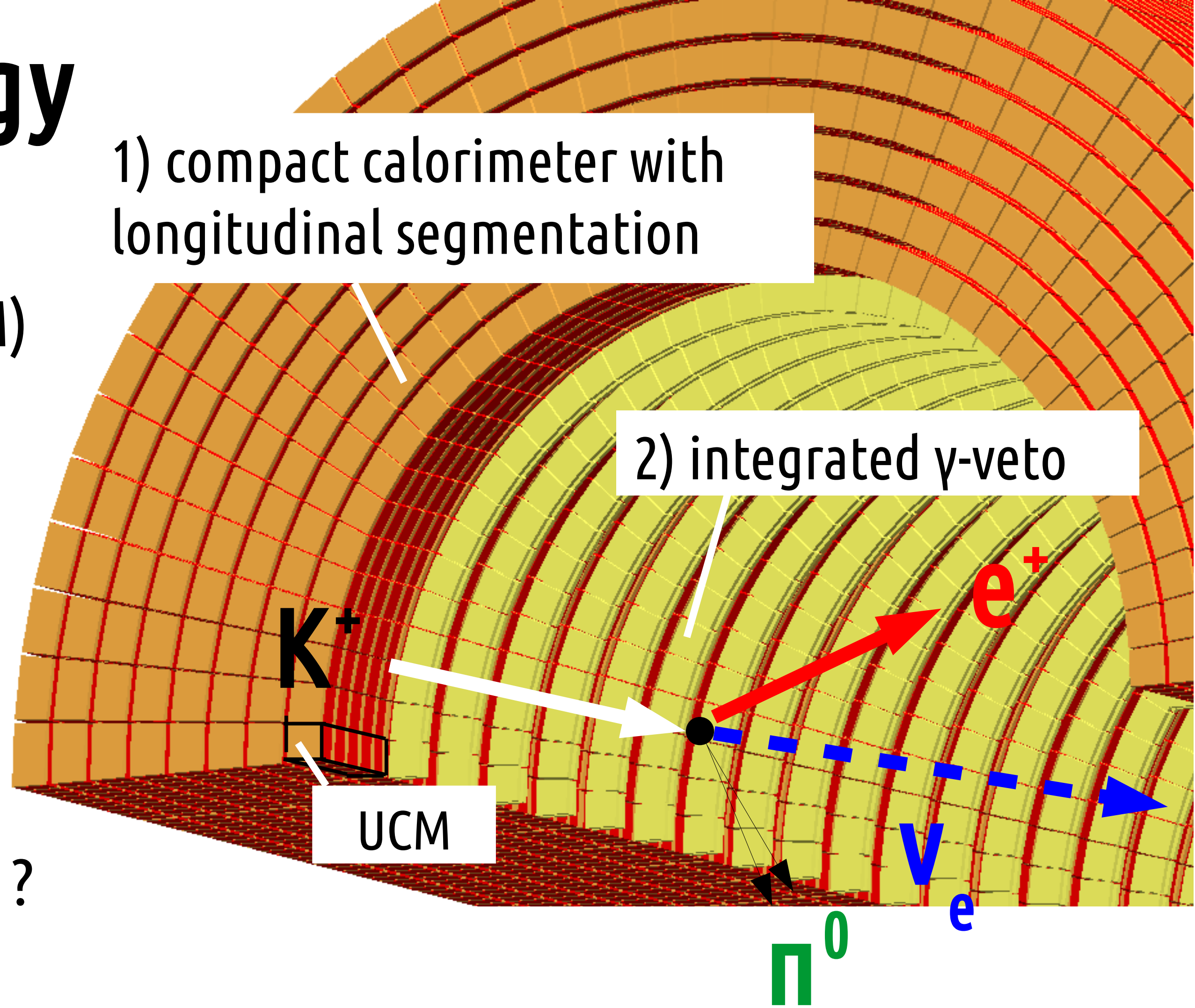
# Tagger technology

**1) Calorimeter** ("shashlik")
- Ultra-Compact Module (UCM)
- Integrated light readout

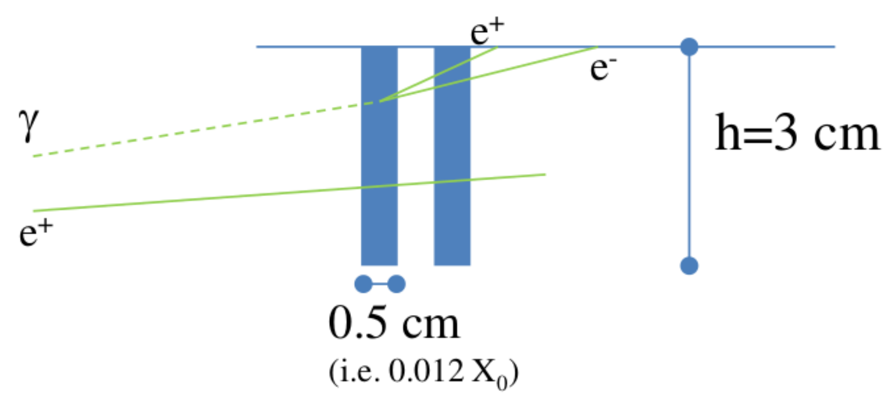
→ $\pi^{\pm}$ rejection

**2) Integrated γ-veto**
- plastic scintillators or
- large-area fast APDs ?
- Cherenkov radiator + LAPPD ?

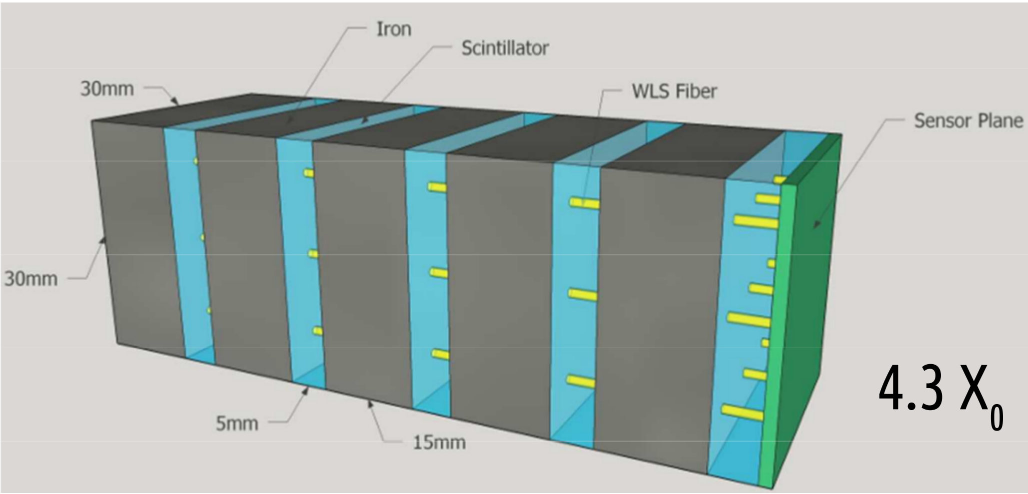
→ $\pi^{0}$ rejection

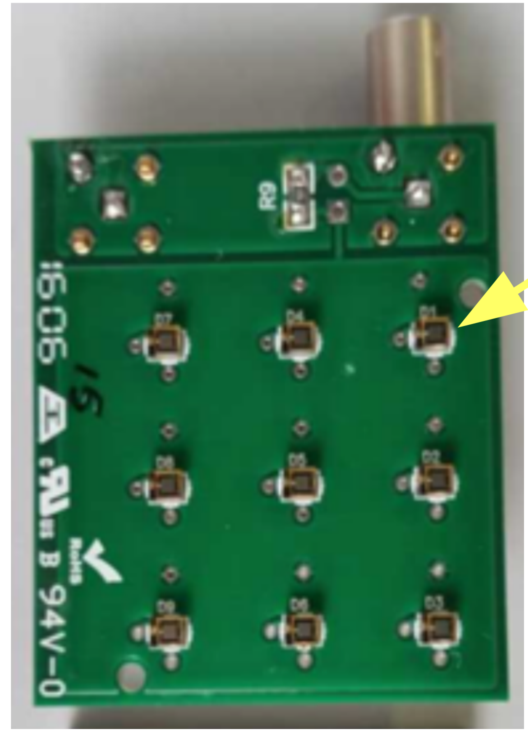


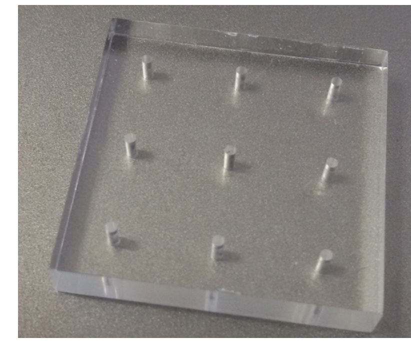

e+ (signal) topology

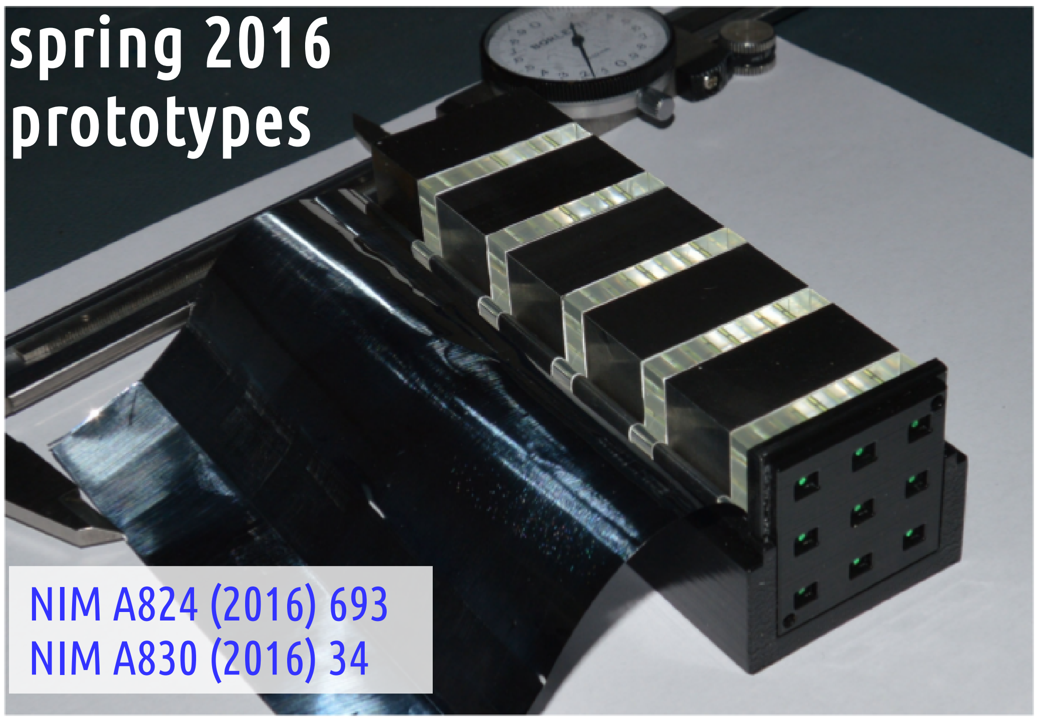


# The Ultra Compact Module (UCM)

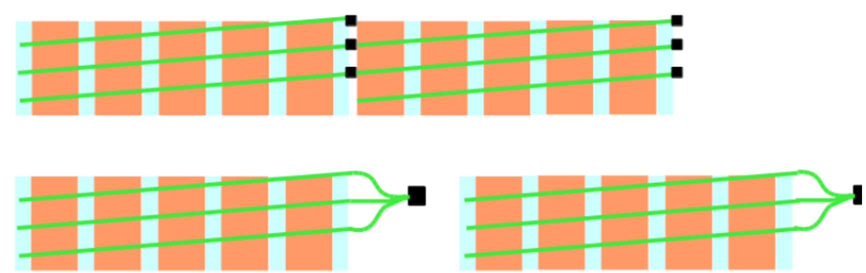







- 1 SiPM ↔ 1 WLS fiber
- 9 SiPM signals are added (reduce R/O costs)
- Add SiPM signals in place of light → **no WLS bundling = optimal homogenity in longitudinal sampling (UCM)**

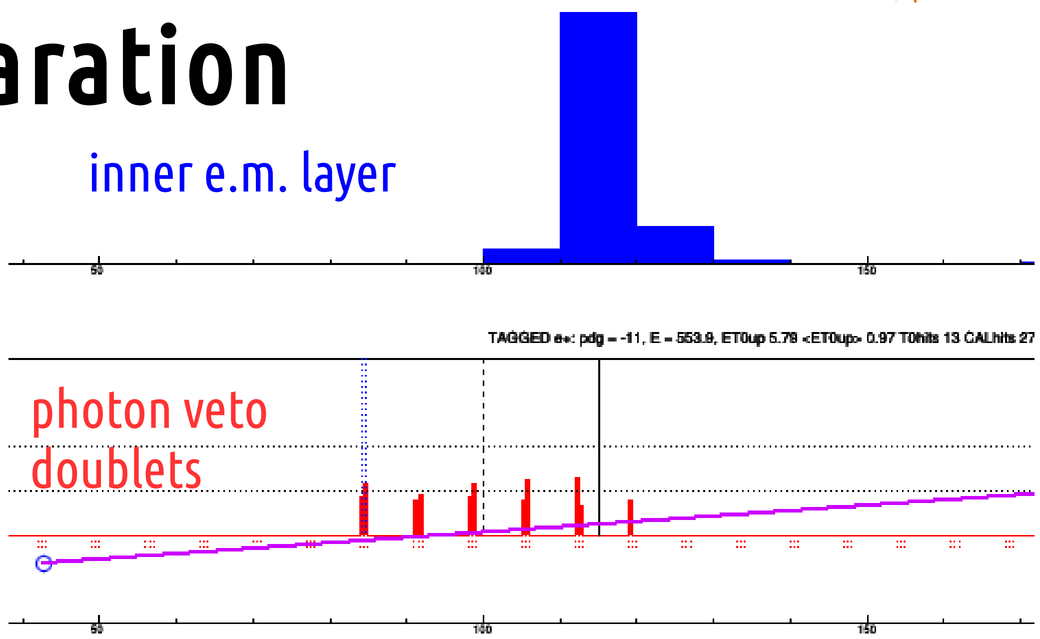


Concept validated by **SCENTT** R&D within INFN Gruppo 5 (2016-17)

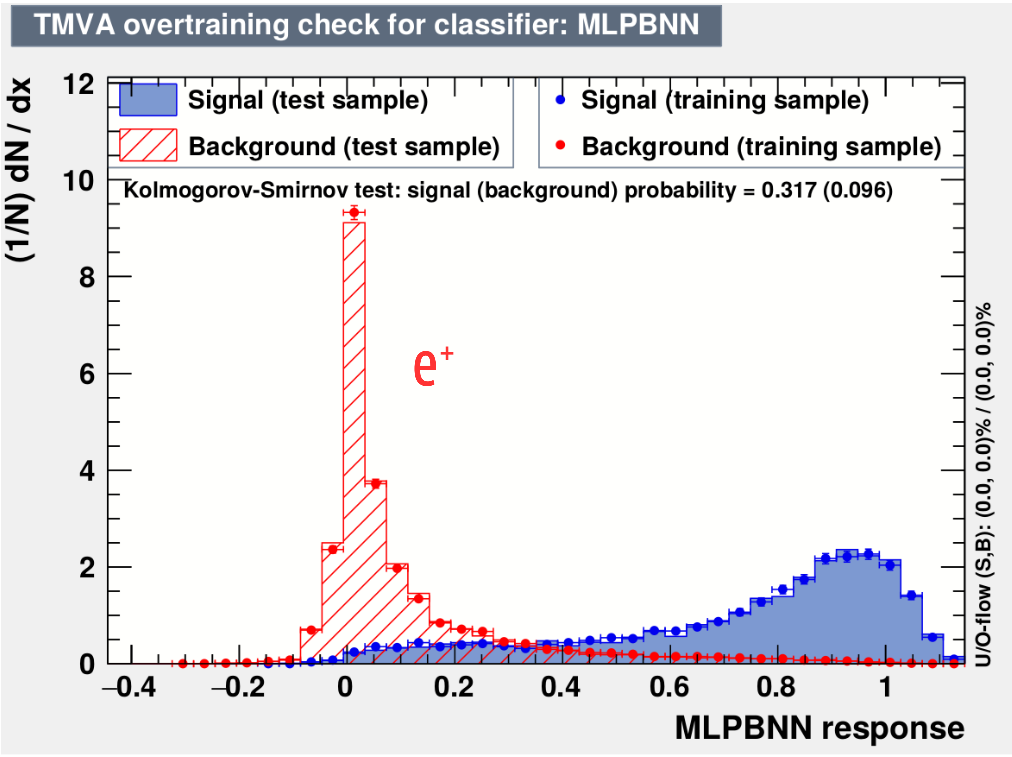
# Full simulation: e/π separation

**GEANT4** simulation. TMVA **multivariate** analysis: rejects simultaneously π+ and $\pi^0$.

| | $\varepsilon_{geom}$ | $\varepsilon_{sel}$ |
|---|---|---|
| $e^+$ | 90.7 % | 49.0 % |
| $\pi^+$ | 85.7 % | 2.9 % |
| $\pi^0$ | 95.1 % | 1.2 % |

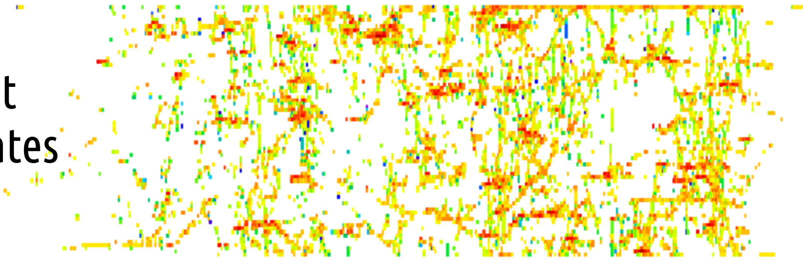



Former estimates from parametrizations confirmed with a **realistic** and **cost-effective** setup.



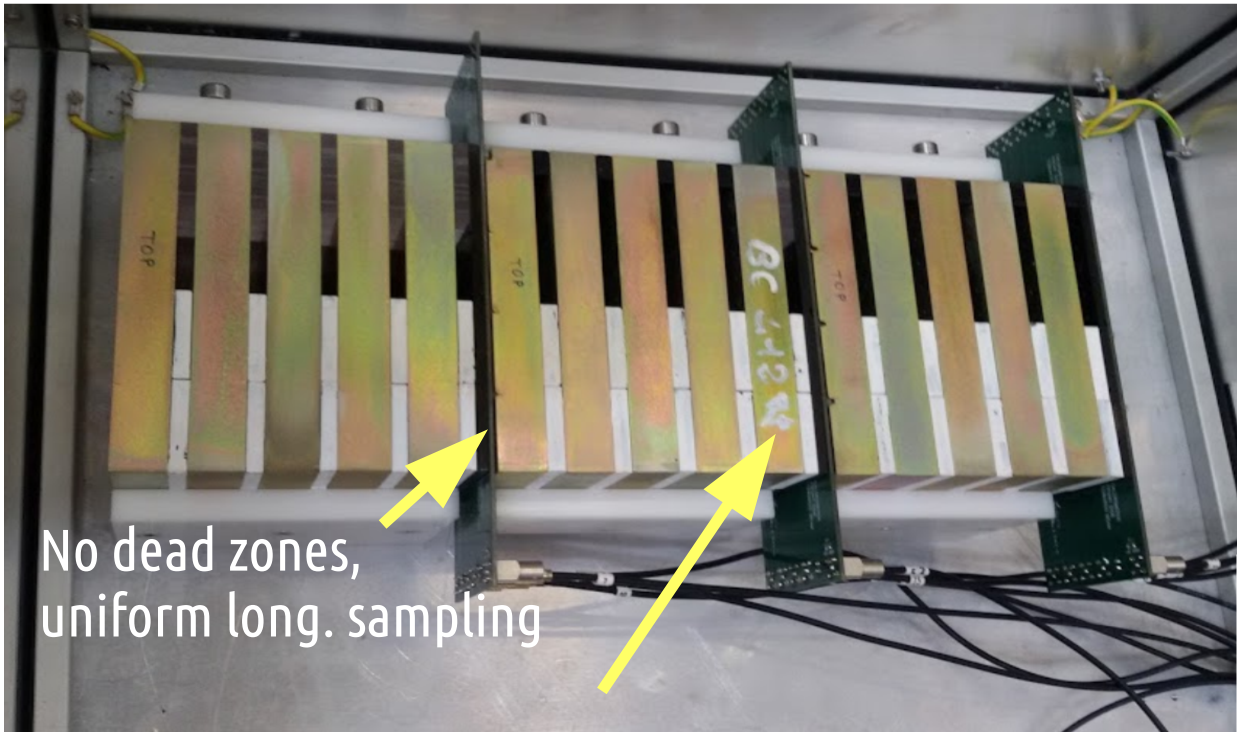

**Current efforts (ENUBET-WP5):** understand the maximum rate at which the separation of **e** and **$\pi^+$ and $\pi^0$** topologies works before being spoiled by **pile-up**. **Event-building algorithm** using full information from digitized UCMs (clustering based on cell position and timing)

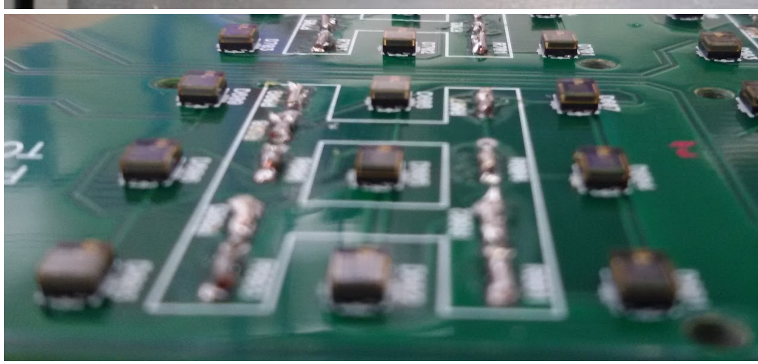
$e^+$ in 2 ns at nominal rates

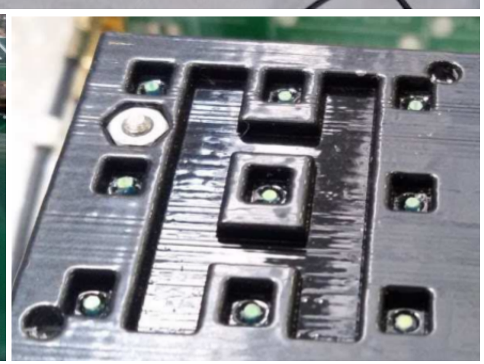


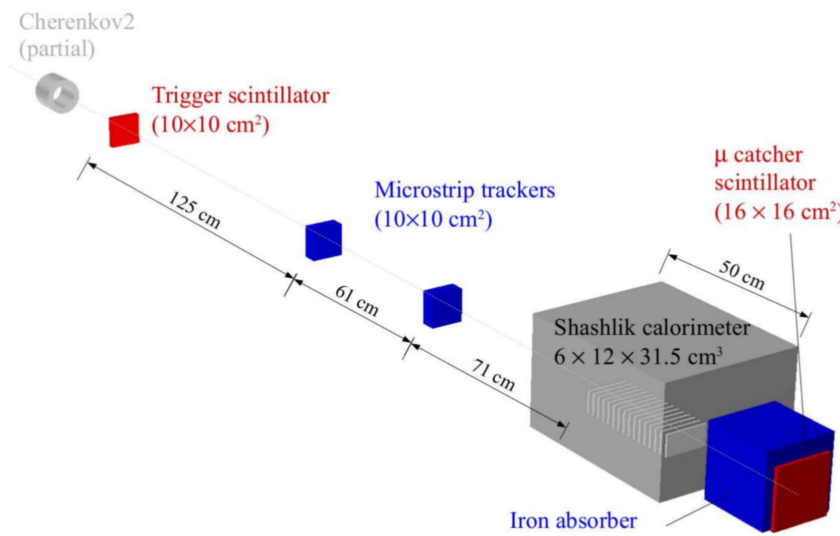
# First test beam validation of UCM

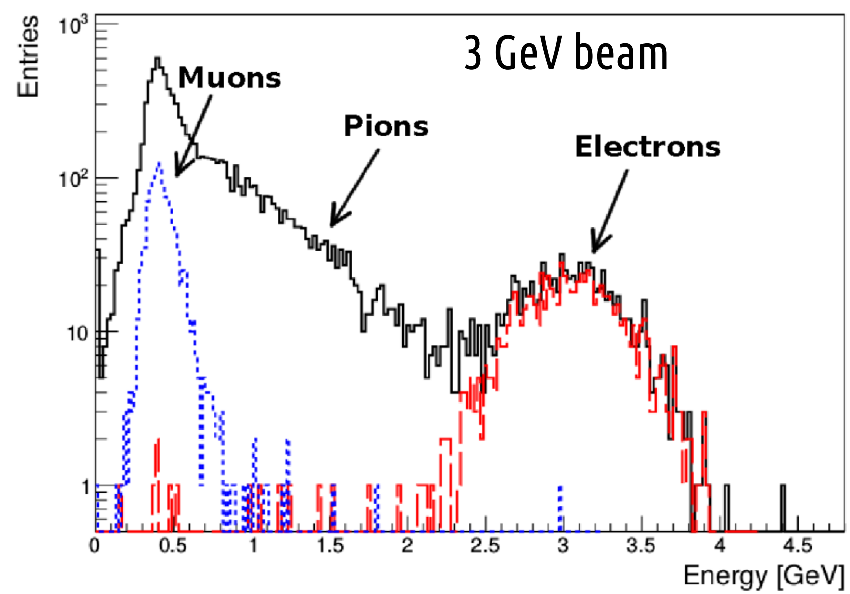
CERN-PS T9 test beam (July 2016). Beam: π, e, μ from 1-5 GeV.
12 ENUBET UCM modules (~13 $X_0$). 1 $mm^2$ HD Si-PM with 20 μm cell size (FBK).







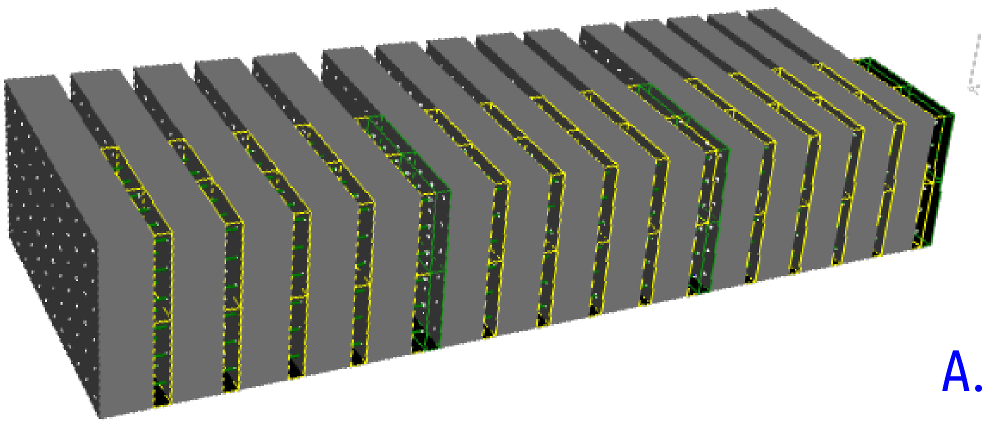



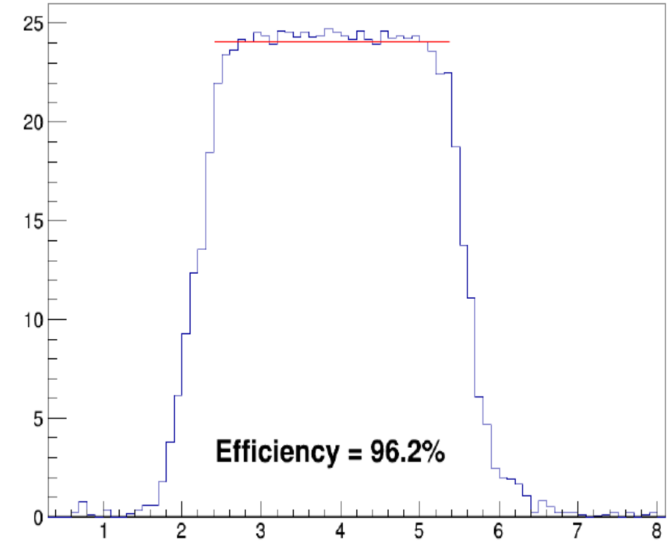

A. Berra *et al.*, IEEE Trans. Nucl. Sci., in press.

# Results from UCM prototypes

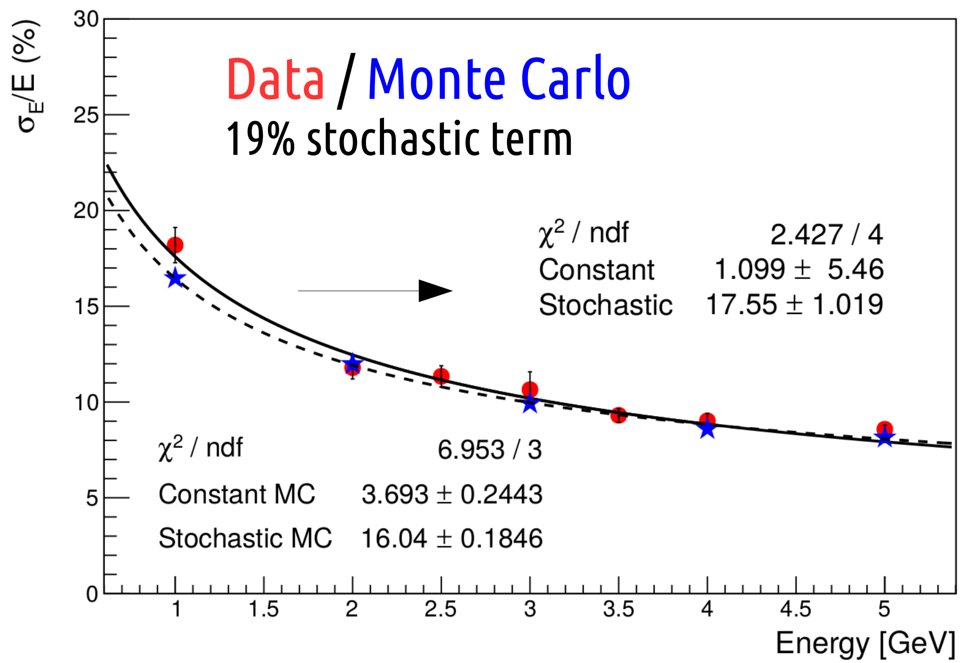
Cheap, fast (<10 ns),
Rad-hard technological solution

Geant4






A. Berra *et al.*, IEEE Trans. Nucl. Sci., in press.

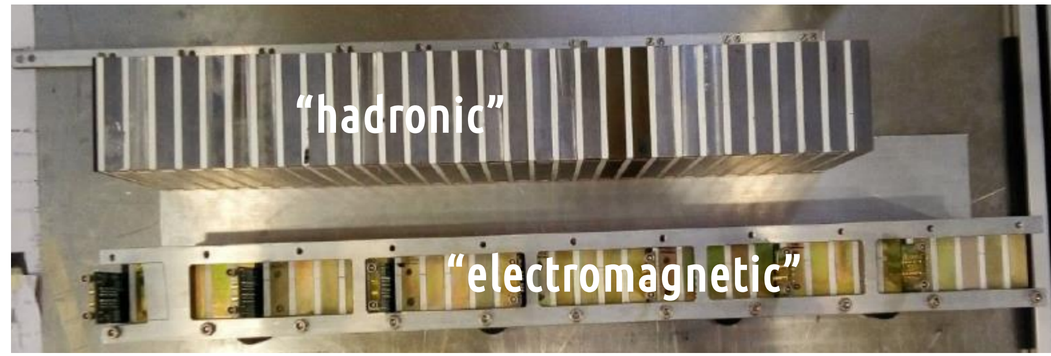


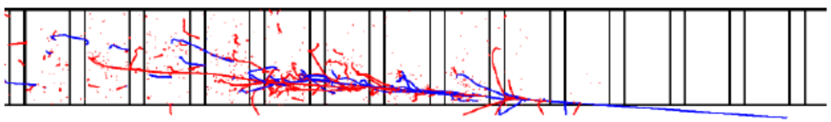

**Requirements for ENUBET**:

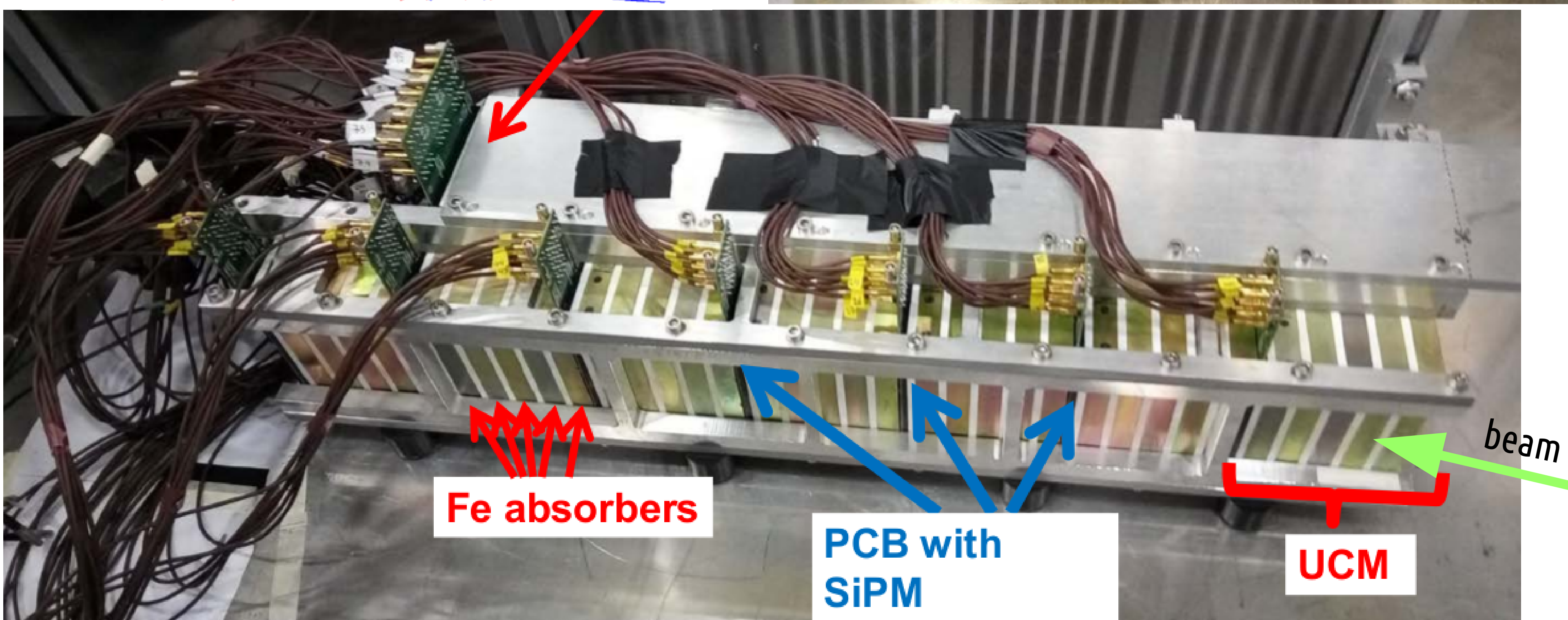
- m.i.p. sensitivity w/o saturation for e.m. showers up to 4 GeV **DONE**
- E resolution < 25% / $E^{½}$ **DONE**
- No role for "nuclear counter" effects (direct ionization of SiPM in the e.m. shower) **DONE**

# Second test beam at CERN-PS T9 Nov. 2016

- 56 (e.m.) + 18 (had.) UCM modules, 666 SiPM
- ~ 30 $X_0$ → test e/π separation
- Orientable cradle → study **grazing incidence at various angles**





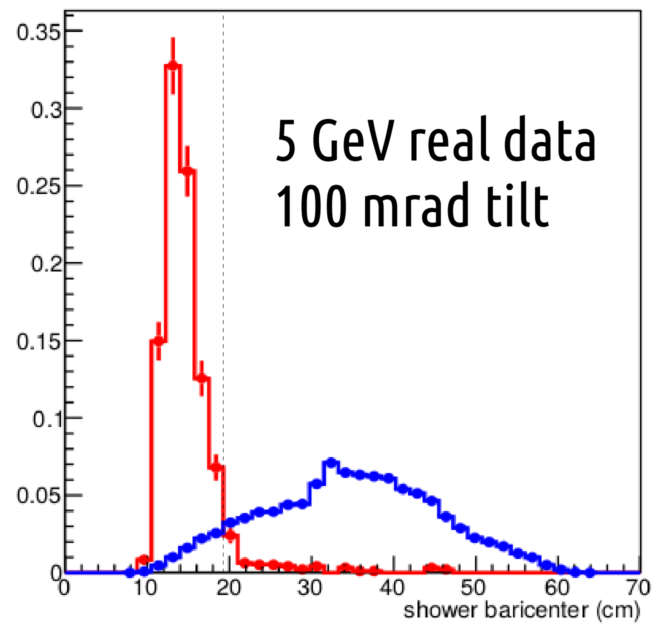
# Test beam at CERN-PS T9: work in progress

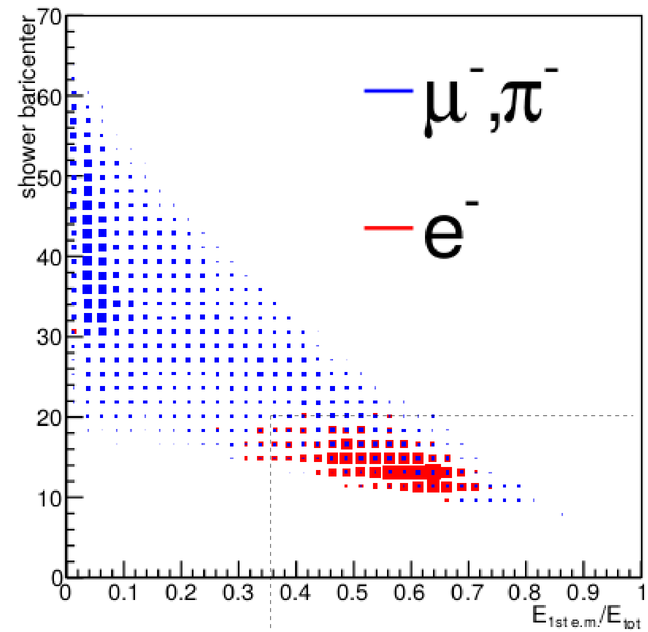
e/π separation with tilted incidence

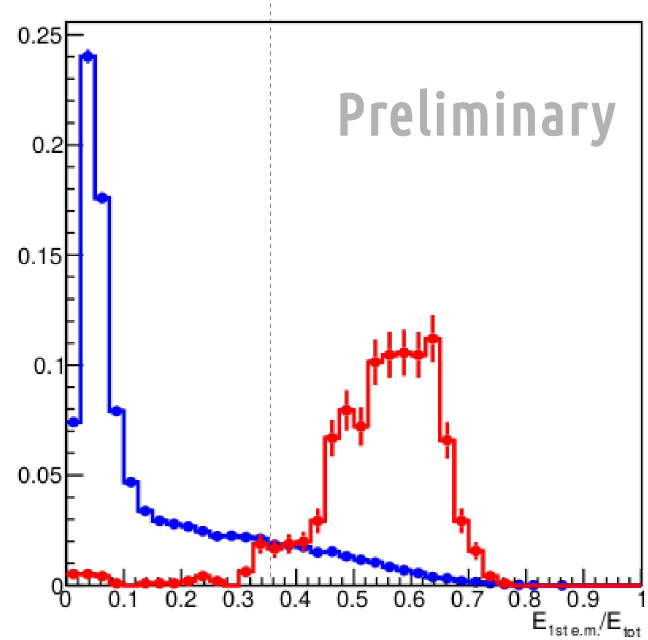
Cut-based analysis

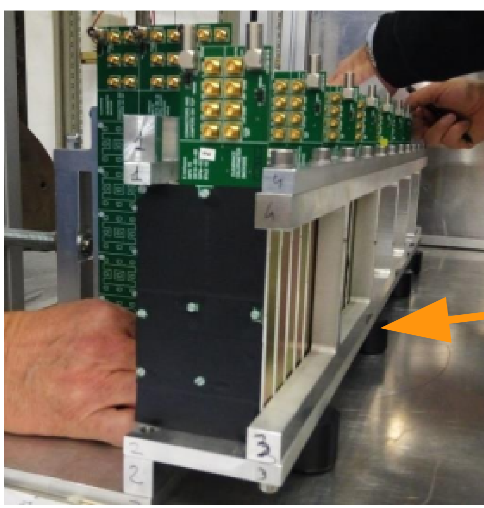
Electrons tagged by Cherenkov counters

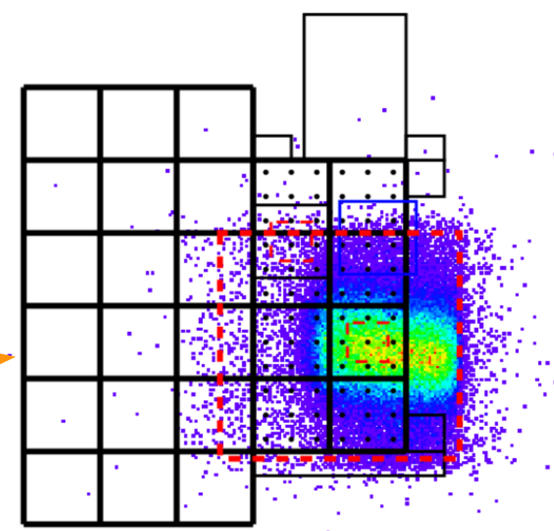
In progress:
- multivariate analysis
- stringent comparison with GEANT4 simulation





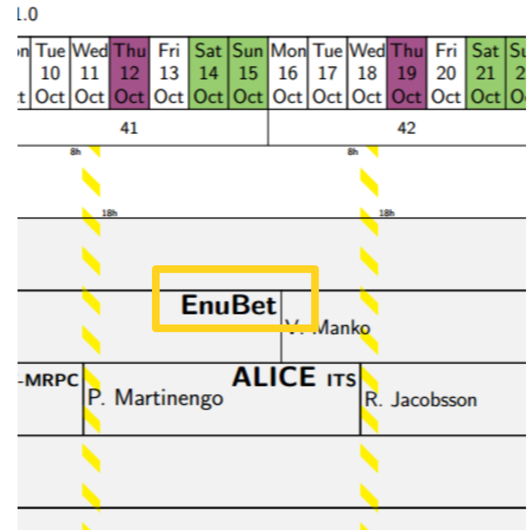
Particles hit map

# More ongoing R&D activities

**CERN-PS**: **4 weeks** this year (July and Oct.). Will test:

- **rad-hard components**: SiPM (HD, 15 μm cells)
  - neutron irradition at **INFN-LNL** CN in spring 2016
- **scalable/reproducible technological solutions**
- **recovery times ~10 ns** (sufficient to cope with pile-up)
- **custom digitizers electronics**
- **photon veto** prototypes with plastic scintillators
- **polysiloxane-based scintillators** (avoid drilling/molding!)

PS: October 2017

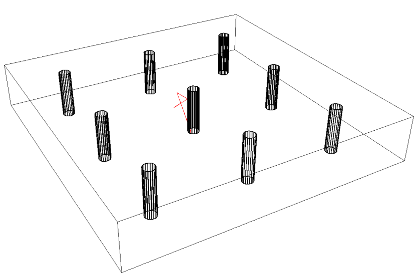


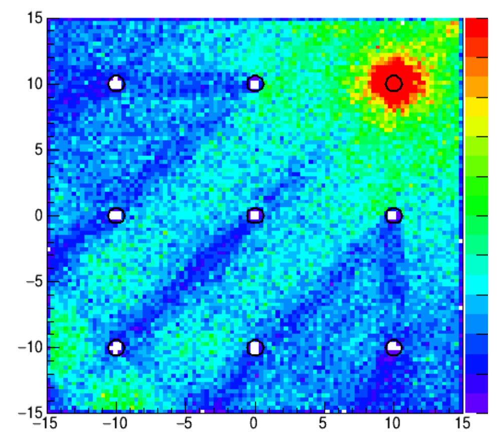


Polysiloxane shashlik UCM

In parallel a **full characterization of UCM** with **cosmics** and **radioactive sources** ongoing at **several INFN labs**

- tests of **WLS** (Y11, BCF92) and **scintillators** (EJ200,204)
- **light collection efficiency maps** (data vs MC)
- guide the **choice of optical parameters**
  - tyvek, reflective mylar, TiO painting, n. of fibers, Ø





# Conclusions

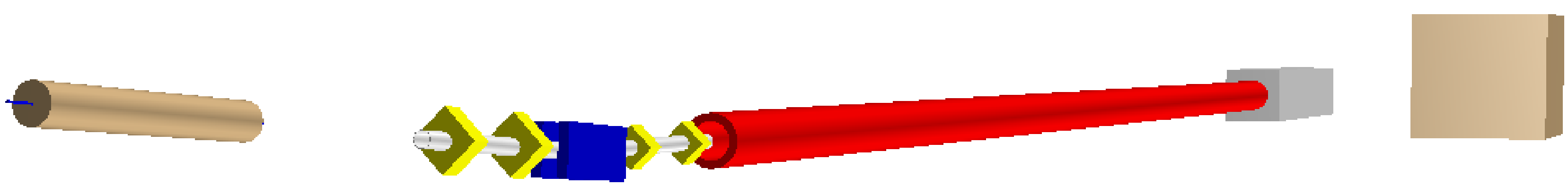
- GeV neutrino physics requires a **better control of its artificial sources**
- The **initial flux is the dominant contribution to cross section uncertainties**
- Such a limit can be **reduced by one order of magnitude** exploiting $\mathbf{K^+ \to \pi^0 e^+ \nu_e}$
- In the next **5 years ENUBET** will investigate this approach and its application to **a new generation of cross section, sterile and time-tagged neutrino experiments**

The results obtained up to now are very promising:

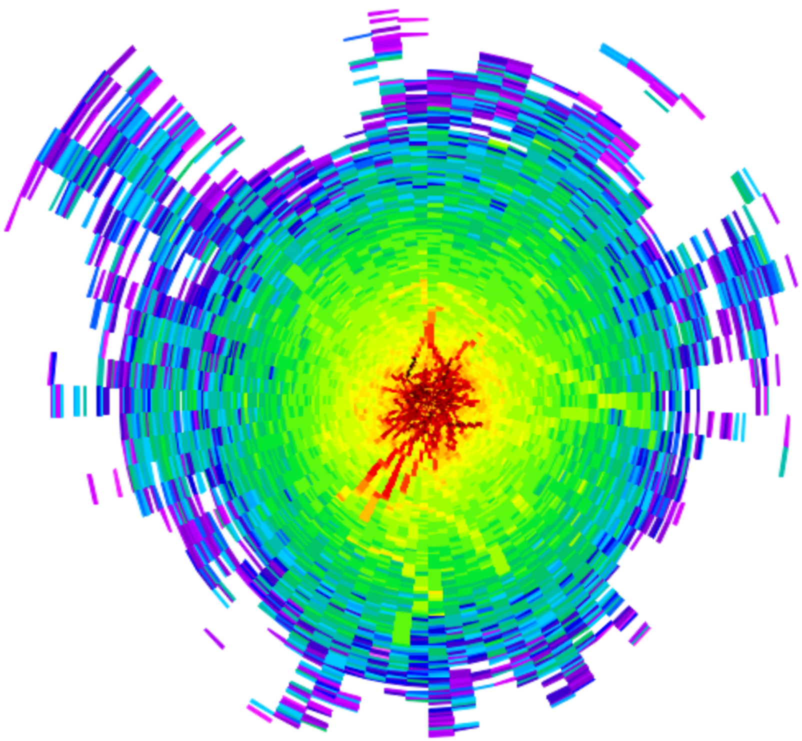
- **Full simulation of the decay tunnel**
  - effectiveness of the calorimetric approach for large-angle lepton identification
- **Prototypes of ultra compact shashlik calorimeters** with longitudinal segmentation
  - used without compromising E resolution (19% at 1 GeV) with requested performance

The final goal of **ENUBET** is to demonstrate that:

- a “positron monitored” $\nu_e$ source based on $K_{e3}$ can be built using existing beam technologies at **CERN, Fermilab or J-PARC**
- giving a **measurement of $\sigma(\nu_e)$ at 1%** with a **detector of moderate mass (500 t)**



# Thank you!



## Work Packages (WP)

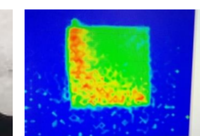
PI A. Longhin

**WP1** **Conceptual design of the beamline** see below

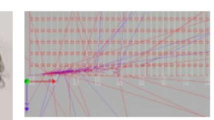
**WP2** **Design and prototyping of the positron taggers**
WP coordinator: M. Pozzato


**WP3** **SiPM and front-end electronics for the instrumented decay tunnel**
WP coordinator: V. Mascagna


**WP4** **Design and prototyping of the photon veto (e/γ separation)**
WP coordinator: G. Sirri

**WP5** **Simulation and assessment of the systematics**
WP coordinator: A. Meregaglia

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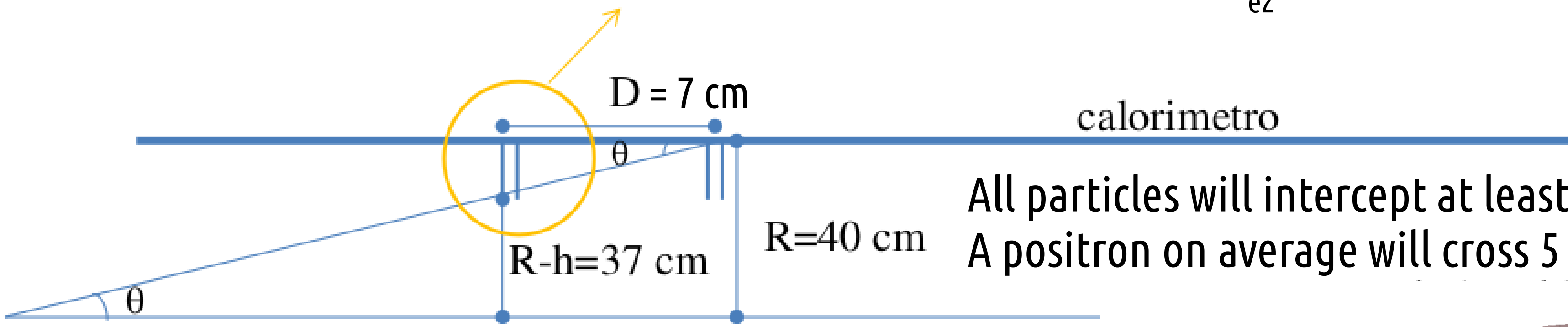
- A. Longhin, L. Ludovici, F. Terranova, Eur. Phys. J. C75 (2015) 155
- A. Berra et al., NIM A824 (2016) 693
- A. Berra et al., NIM A830 (2016) 345
- CERN-SPSC-2016-036 ; SPSC-EOI-014

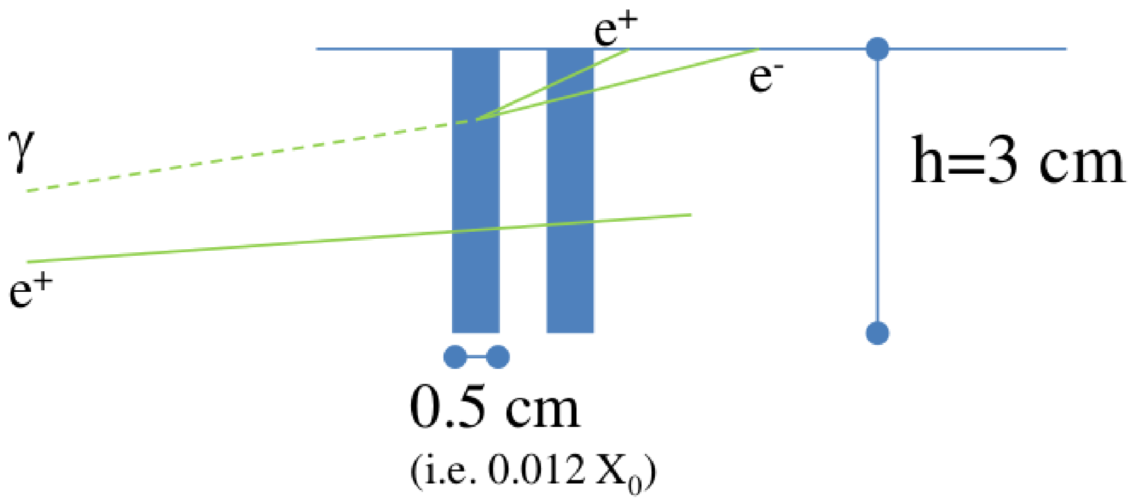
# The photon-veto baseline option

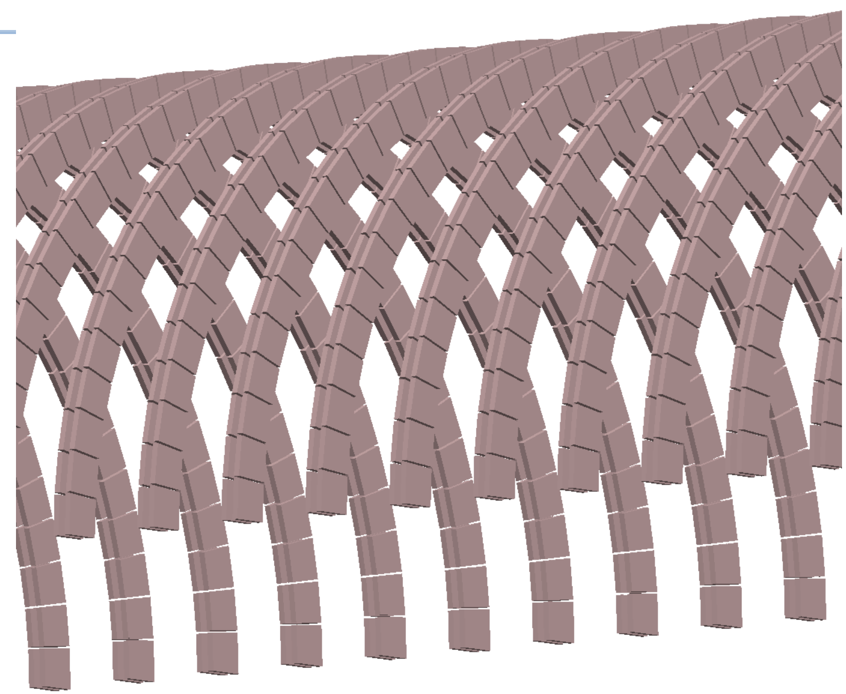
Background from γ conversions from $\pi^0$ emitted mainly in $K_{e2}$ decays ($K^+ \rightarrow \pi^+ \pi^0$)




All particles will intercept at least one doublet
A positron on average will cross 5 doublets

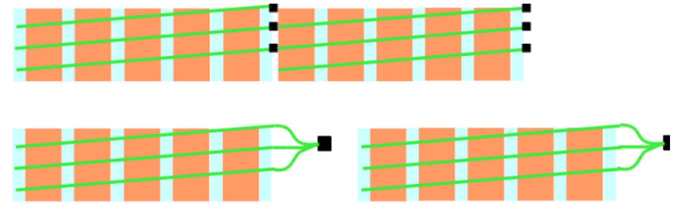
Exploit **1 mip – 2 mip separation**



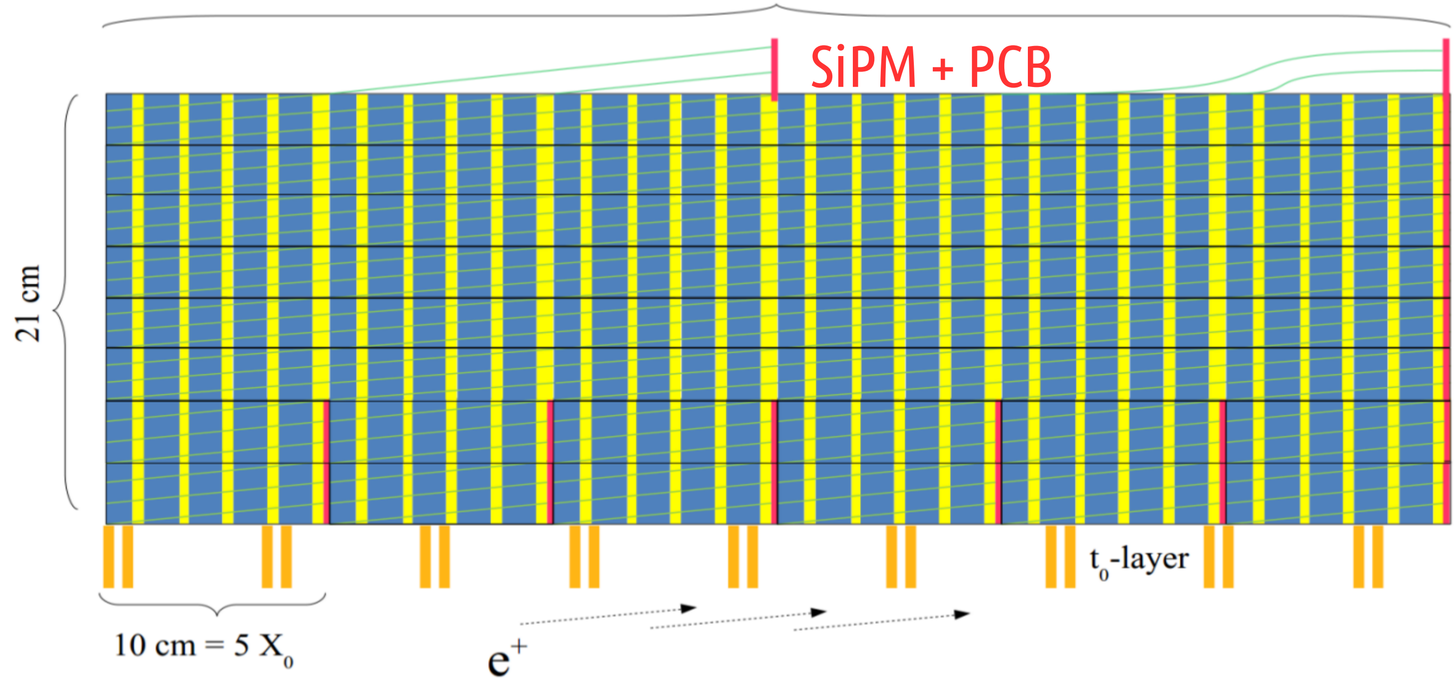



- Possible **alternative/attractive solutions** under scrutiny allowing a reduced **material budget and superior timing**.
- Test beams at Frascati: **electronics response** at high rates and low-E $e^+$,1 mip/2 mip

# The final prototype



1 super-module

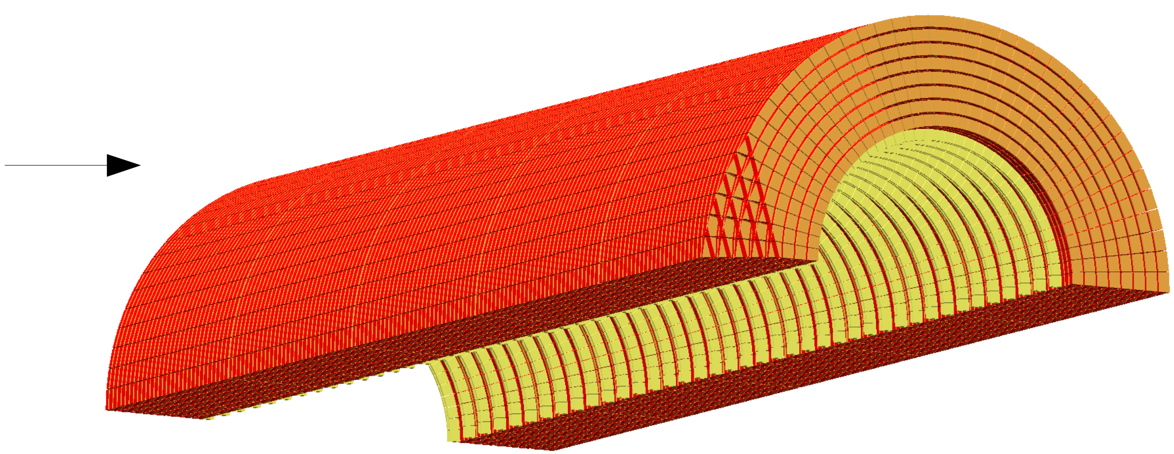



Outer modules

Inner modules

- Dimensions: **3 m × π**
- # SiPM: **34000**
- Channels: **3800**
- Weight: **~ 5 t**
- WLS fiber length: ~**10000 m**
- **Readout:** custom waveform digitizers, **2 ns** granularity over **~10 ms**

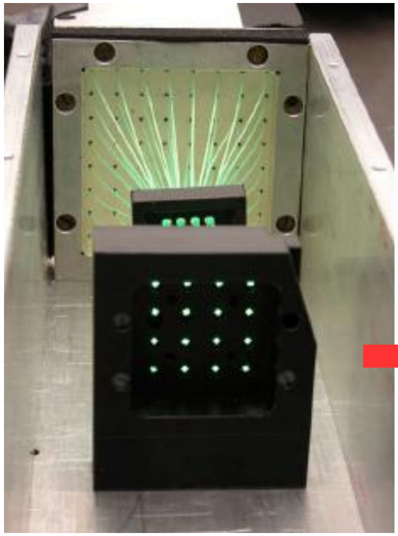
- 5 **super-modules**

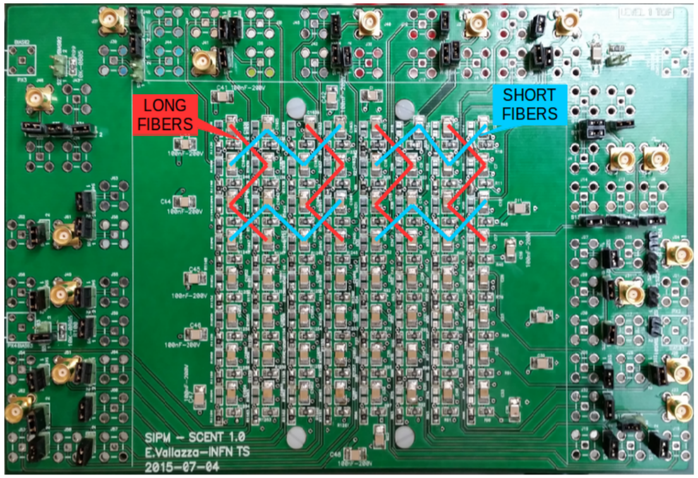


# Tagger detector R&D: SCENTT

**Shashlik Calorimeters for Electron Neutrino Tagging and Tracing**

- INFN (CSN5) activity on **shashlik calorimetry for neutrino applications** started last year (MiB-Insubria, TS, BO, LNF. R.N. **F. Terranova**)
- First tests at **CERN PS-T9 (Aug. 2015)** of a shashlik calorimeter with **WLS fibers coupled directly to individual SiPMs**






- Working well!
- Energy resolution and e/π separation in line with simulations
- achieved both with custom QDC electronics or sampling waveforms with commercial digitizers

A compact light readout system for longitudinally segmented shashlik calorimeters

A. Berra[a,b,*], C. Brizzolari[a,b], S. Cecchini[c], F. Cindolo[c], C. Jollet[d], A. Longhin[e], L. Ludovici[f], G. Mandrioli[c], N. Mauri[c], A. Meregaglia[d], A. Paoloni[e], L. Pasqualini[c,g], L. Patrizii[c], M. Pozzato[c], F. Pupilli[e], M. Prest[a,b], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i], L. Votano[e]

A. Berra et al., NIM A824 (2016) 693

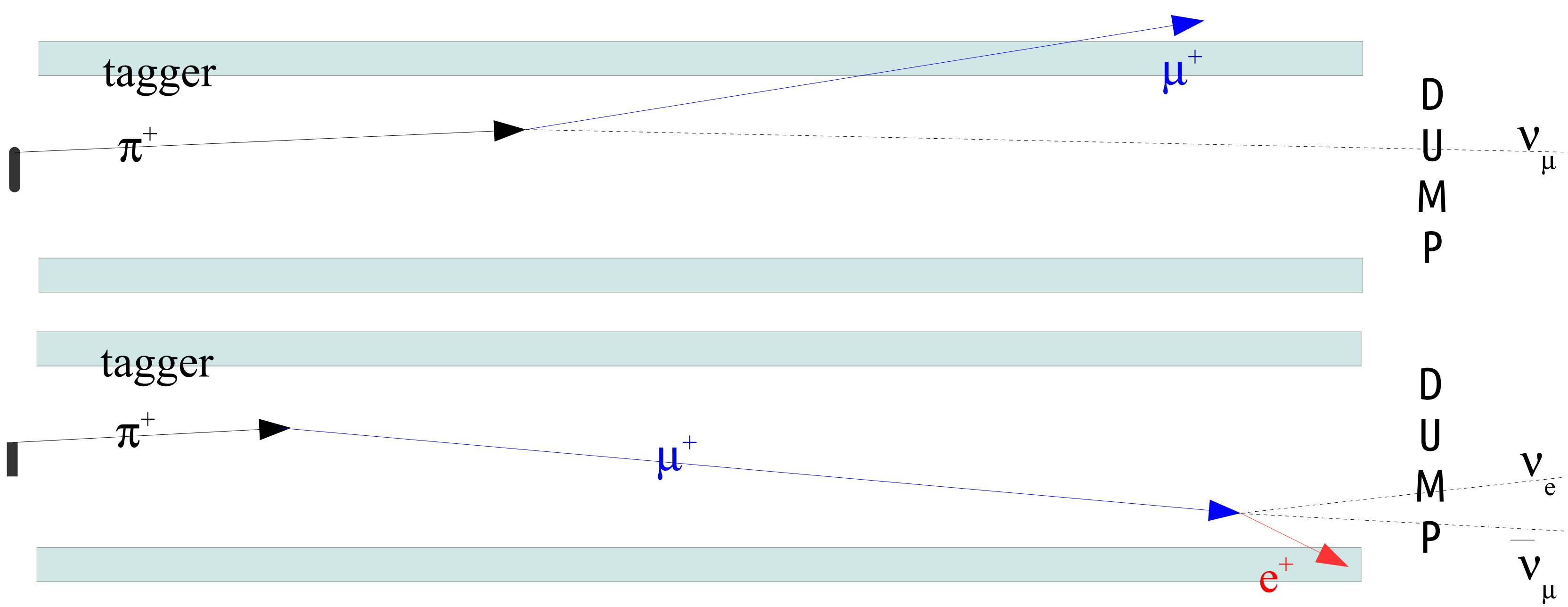
A. Berra et al., NIM A830 (2016) 345

http://dx.doi.org/10.1016/j.nima.2016.05.123 arXiv:1605:09630

# Pion decays induced backgrounds

- $p^+ \rightarrow m^\pm n_m$ creates the bulk of $\mathbf{n_m}$ (~ 95% p @ 400 GeV)
  - **n detector must have good $n_e$ PID**: reject NC $p^0$ in the $n_e^{CC}$ sample
- 2-body decay, $m_m \sim m_p$ : $m^+ \sim 4$ mrad → few in the tagger, easy to reject
- **m D.I.F : suppressed** $L_m$ >> L(decay tunnel)
- **3-body** but **$m_m$ ~ 0.2 $m_K$** ➞ $e^+_{DIF}$ ~ 28 mrad ($e^+_{Ke3}$ ~ 88 mrad)
  - **$n_{e,}^{CC,DIF}$ ~ 3.3% ➞ ~ all $n_e$ are from $K_{e3}$**

$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})$$



# Inferring $\sigma(\nu_e)$ from $\sigma(\nu_\mu)$ ?

0) **$\sigma(\nu_\mu)$ is also poorly known** due to flux systematics

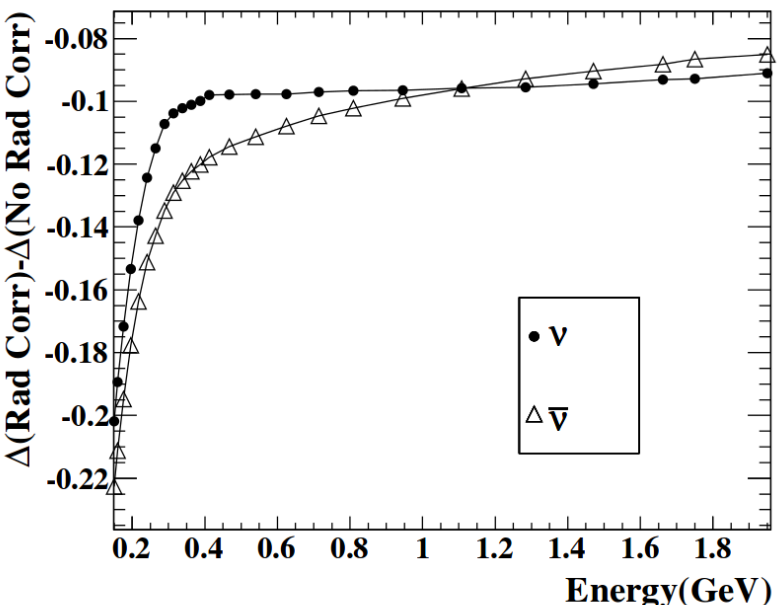
1) **Lepton universality** in weak interactions is **not the full story**:

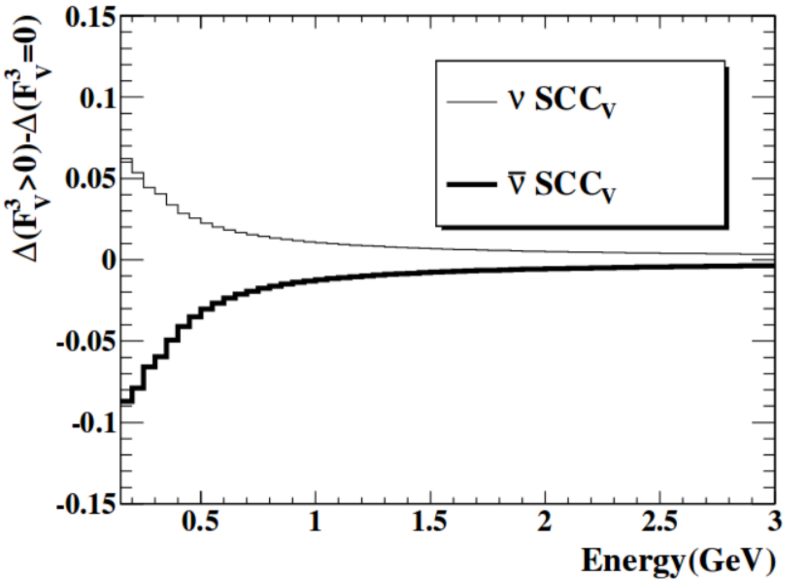
- ✓ Uncertainties from the **interplay** of
  - **radiative corrections**
  - **nucleon form factors**
    - $F_P$, $F_V^{1,2}$, $F_A$, second class currents
  - alteration of **kinematics** due to mass

→ Differences between **$\sigma(\nu_\mu)$** and **$\sigma(\nu_e)$** ($\Delta$)

- can be **significant (10-20%) espec. at low-E**
- with **different energy trends for $\nu$ and $\bar{\nu}$**

Day, McFarland, Phys. Rev. D86 (2012) 052003



# Choosing the K±/π± momentum and tunnel length

1) keeping the tunnel "short"
2) increasing the K±/π± energy

increases $\nu_e$ from $K_{e3}$ with few $\nu_e$ from μ D.I.F.

Current scenario

p = 8.5 GeV/c ± 20%
L = 50 m

**High momentum**

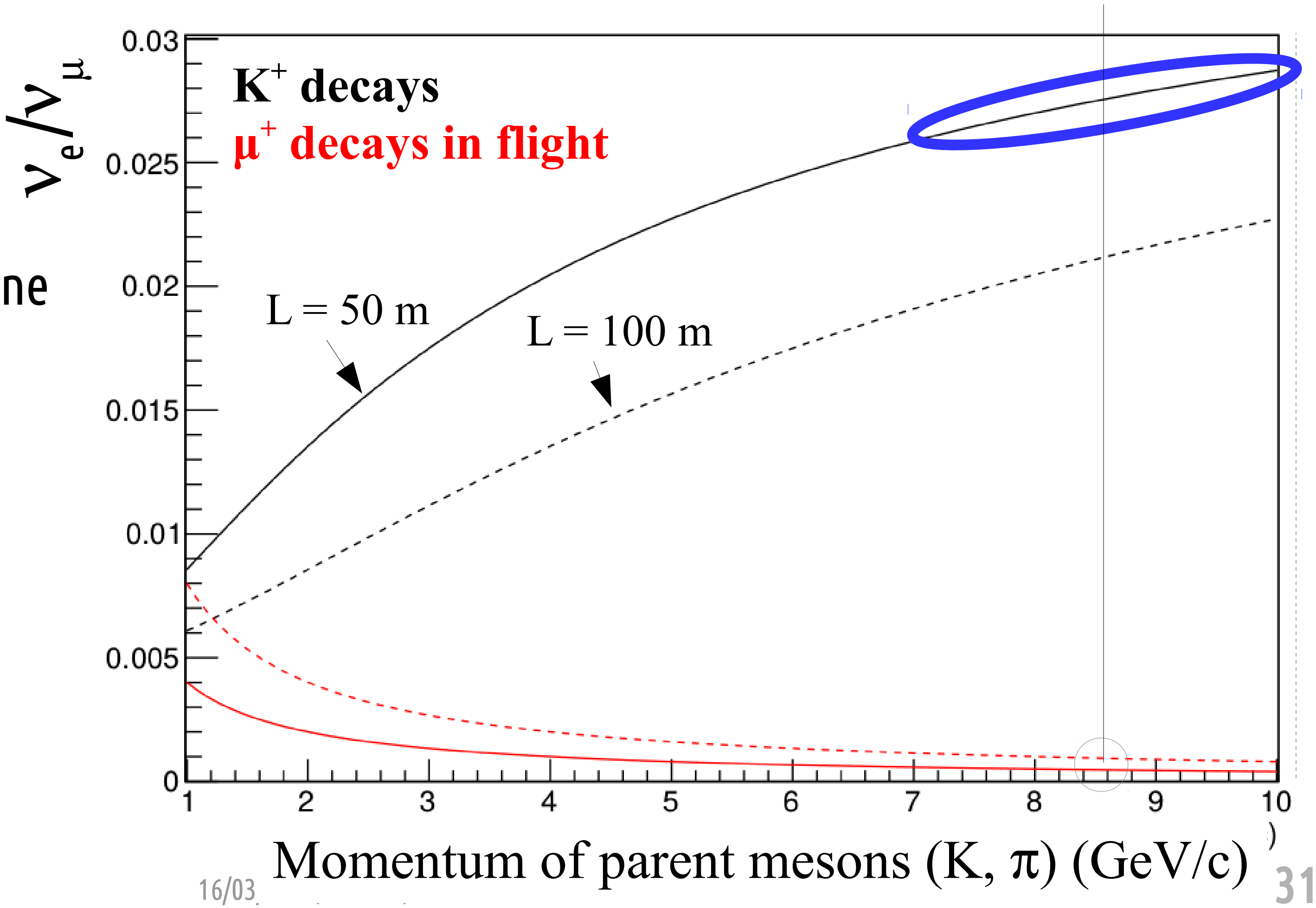
**Benefits:**

- small loss in the transport line
- improved e/π separation

**Costs:**

- E($\nu_e$) above the R.O.I.
- longer decay region

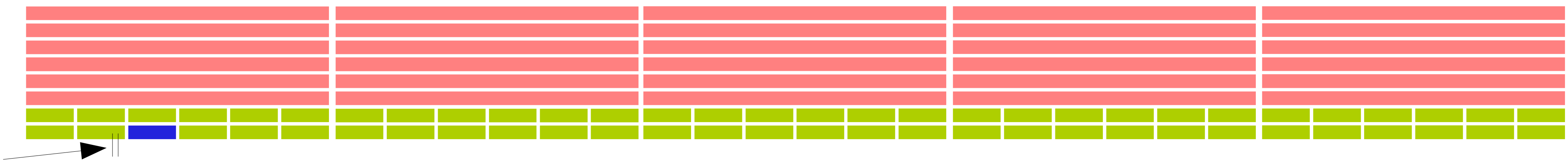
A trade-off: further optimization in ENUBET



# e⁺ tagger: background rejection

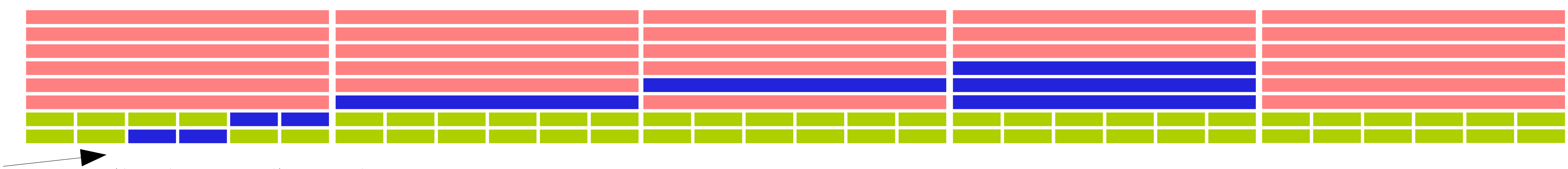
Hadronic modules
Electro-magnetic modules
Hit modules

**Key point:**
- longitudinal sampling
- perfect homogeneity → integrated light-readout



$e^+$ (signal) topology

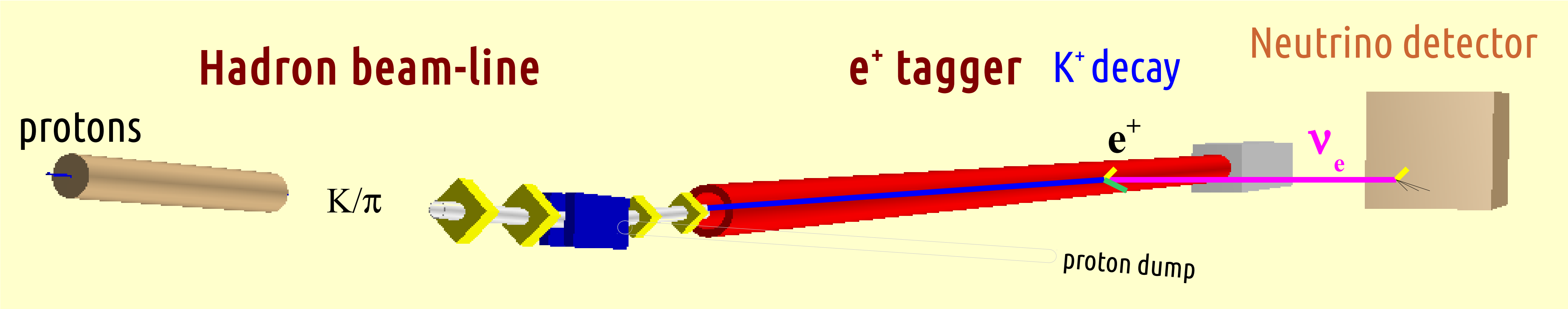
$\pi^0$ (background) topology



$\pi^+$ (background) topology

# Towards the first tagged $\nu_e$ beam

A schematic setup to implement this idea:




- **Hadron beam-line**: collects, focuses, transports $K^+$ to the $e^+$ tagger
- **$e^+$ tagger**: real-time, "inclusive" **monitoring** of produced **$e^+$**

**Positron tagging:** uncertainties from K hadro-production, PoT, hadron beam-line efficiency become irrelevant for the $\nu_e$ flux prediction

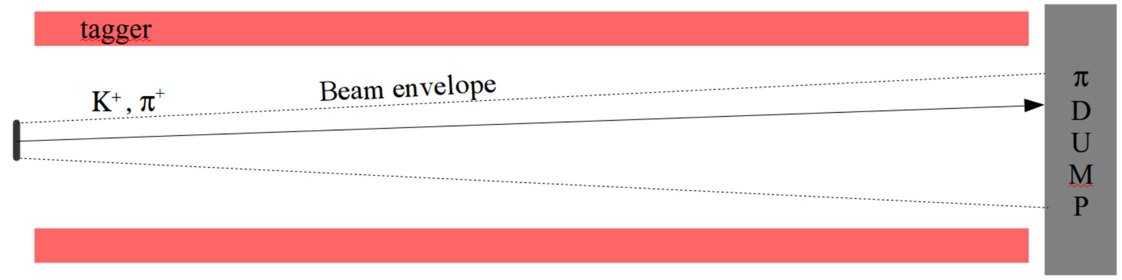
**Hadron collimation:** allows having only decay products in the tagger.

→ **tolerable rates**

→ good **S/N**

$p = 8.5$ GeV $\pm$ 20%

$\theta < 3$ mrad



# The ENUBET goals and program

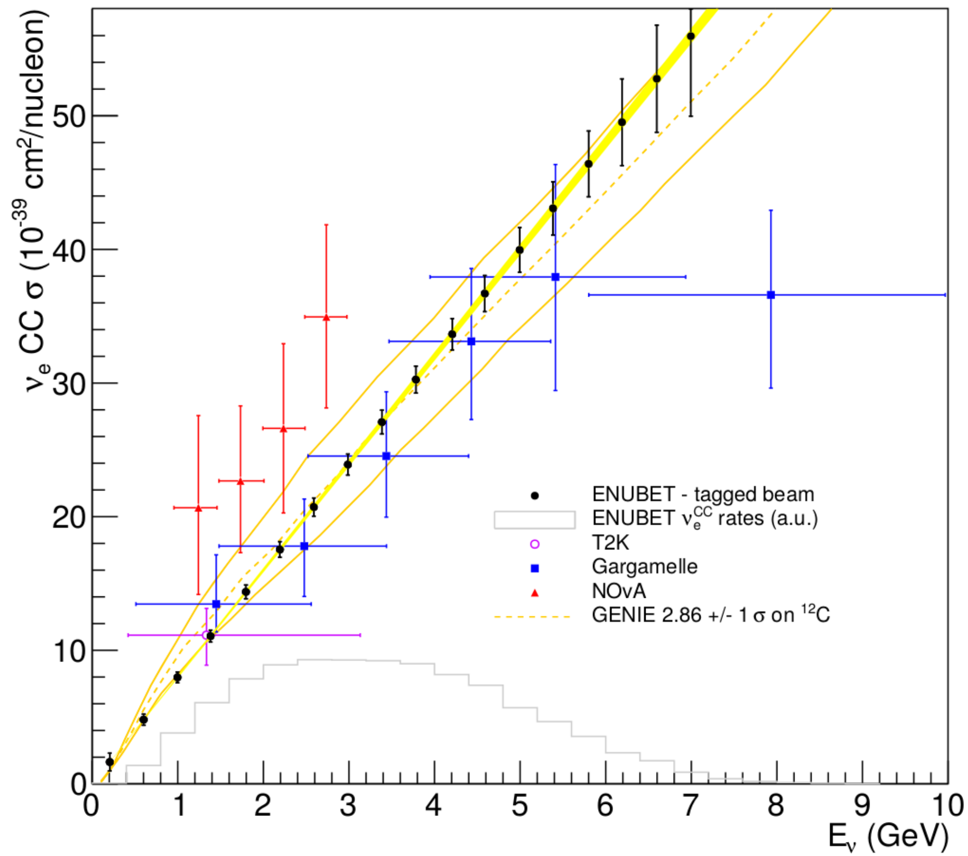
Demonstrate experimentally that a new-concept $n_e$ **source, with x 10 better precision is feasible**

→ $s(n_e)$ **1% sys.** + 1% **overall stat. errors** (10.000 events) in realistic terms

**What's peculiar with ENUBET**:

- a compelling, new physics case: a beam design **optimized for $s(n_e)$**
- taking advantage of the progress in **fast, cheap, radiation-hard detectors**

NB. $\mathbf{s(\bar{n}_e)}$ is to date a "green field"




**ERC program: 2 pillars**

- $e^+$ **tagger** prototype validated at test **beams**
- **a detailed design** for the **hadron beam-line**

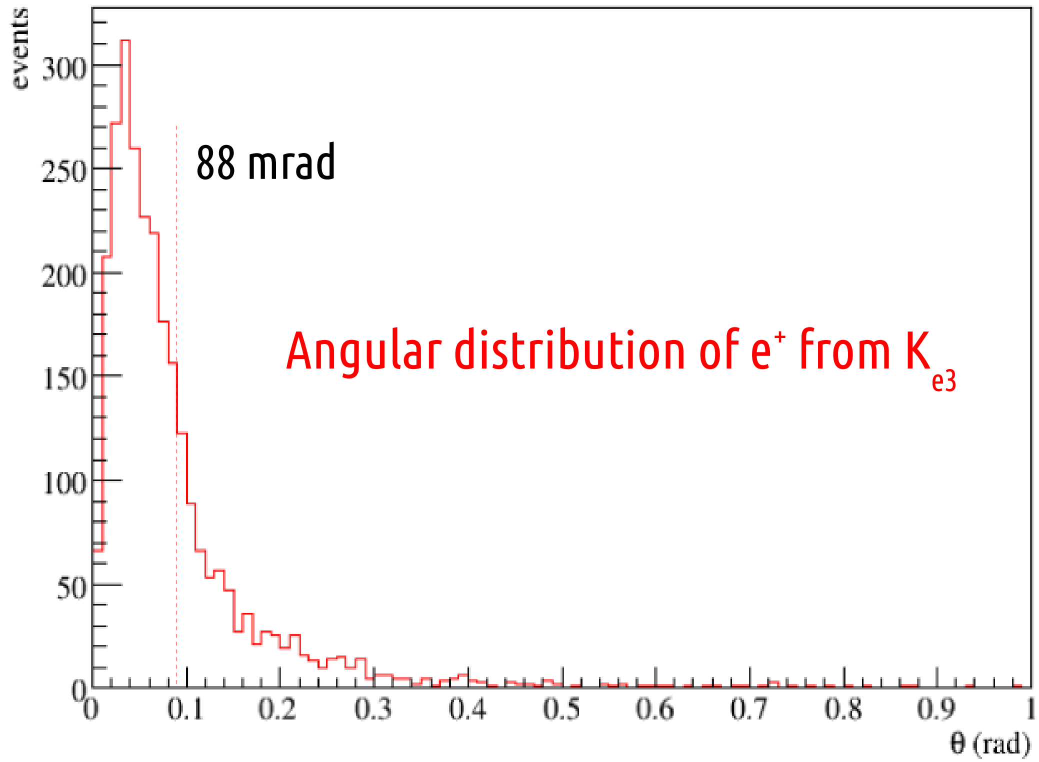
**The complete picture to move to a full experiment**

**By-products**

- **calorimetry** → new low-cost, ultra-compact detectors
- **accelerator physics** → novel extraction schemes for fixed-target, beam-dump exp.

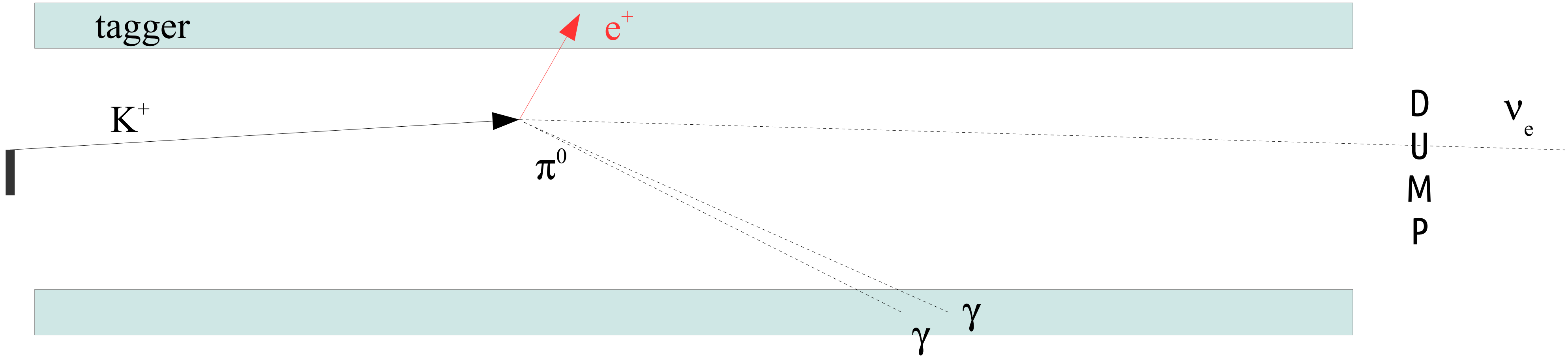
# The golden channel: $K^+ \rightarrow \pi^0 e^+ \nu_e$

- **Golden sample:** good acceptance for $e^+$ from $K_{e3}$ thanks to the **large emission angle** (~ K mass)




- $L_m >> L(\text{decay tunnel})$ $\nu_{e,}$ $^{CC,DIF}$ **~ 3.3%**

**→ ~ all $\nu_e$ are from $K_{e3}$**



# Hadron beamline with horn focusing

| 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 ($10^{20}$) |
|---|---|---|---|---|
| 30 | 4.0 | 0.39 | 2.5 | 5.0 |
| 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 |
| 120 | 16.6 | 1.69 | 0.60 | 1.16 |
| 450 | 33.5 | 3.73 | 0.30 | 0.52 |

Simple conversion

Simple conversion

$1.94 \times 10^{13}$ $K^+$ / $\nu_e^{CC}$

* J-PARC > 2 x $10^{21}$ PoT
CNGS = 0.18 x $10^{21}$ PoT
NuMI = 1.1 x $10^{21}$ PoT

# Tagged neutrino beams: the origins

The "holy grail" of neutrino physicists:

The possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people. In tagged-neutrino experiments it should be required that the observed event due to the interaction of the neutrino in the neutrino detector would properly coincide in time with the act of neutrino creation ($\pi \to \mu\nu$, $K \to \mu\nu$,

*B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257*

Literature:

- L. Hand, 1969, V. Kaftanov, 1979 (p/K → $n_m$)
- G. Vestergombi, 1980, R. Bernstein, 1989 (K →$n_e$)
- S. Denisov, 1981, R. Bernstein, 1989 ($K_{e3}$)
- L. Ludovici, P. Zucchelli, hep-ex/9701007 ($K_{e3}$)
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 ($K_{e3}$)

**What's new with ENUBET**:

- a compelling and new physics case: a beam design **optimized for σ($\nu_e$)**
- taking advantage of the progress in **fast, cheap, radiation-hard detectors**
- using **$K^+ \to e^+ \pi^0 \nu_e$** ($K^+_{e3}$ decays)

# Systematics on the $\nu_e$ flux

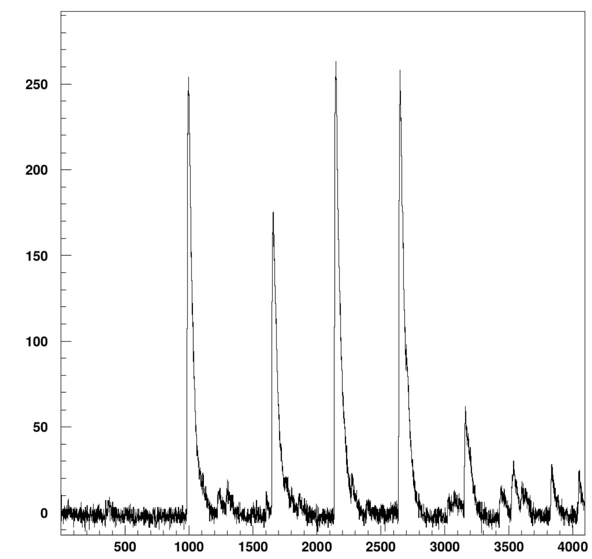
The positron tagging eliminates the most important source of systematics but **can we get to 1%**? Very likely, **to be demonstrated by ENUBET**

| Sources | Size |
|---|---|
| Statistical error | < 1 % |
| K production yield | Irrelevant ($e^+$ tag) |
| Secondary transport efficiency | Irrelevant ($e^+$ tag) |
| Integrated PoT | Irrelevant ($e^+$ tag) |
| Geometrical efficiency and fiducial mass | < 0.5%. *PRL 108 (2012) 171803 [Daya Bay]* |
| 3-body kinematics and mass | < 0.1%. *Chin. Phys. C38 (2014) 090001 [PDG]* |
| Branching ratios | < 0.1%. Irrelevant ($e^+$ tag) except for bckg. estim. |
| e/π separation | To be checked directly at test beam |
| Detector backg. From NC $\pi^0$ events | < 1%. *EPJ C73 (2013) 2345 [ICARUS]* |
| Detector efficiency | < 1%. Irrelevant for CPV if the target is the same as for the long baseline experiment |

# $e^+$ tagger: pile-up and radiation

## Pile-up

Not decayed π, K do not intercept the tagger "by construction". Pile-up mostly from overlap between a $K_{\mu 2}$ and a candidate $e^+$




Recovery time, $\Delta t_{tag}$ = 10 ns
Rate, R = 0.5 MHz/cm$^2$
Tile surface, S ~ 10 cm$^2$

→ 5% pile-up probability (= $RS\Delta t_{tag}$)

**Possible mitigation**: veto (also offline) mip-like and punch-through particles using the longitudinal segmentation of the tagger + eventually a μ catcher

## Radiation

Only contribution comes from K/π decay products. Thanks to bending of the secondaries, non-interacting protons or neutrons are not dumped in the tagger.

Livetime integrated dose O (1 kGy) (~100 kGy for CMS forward ECAL)

- **tagger geometrical acceptance:** 85% of $\nu_e^{CC}$ with a tagged $e^+$ (15 % in the forward "hole")
- $1.95 \times 10^{13}$ $K^+/\nu_e^{CC}$
- Radial profiles at the ν-detector