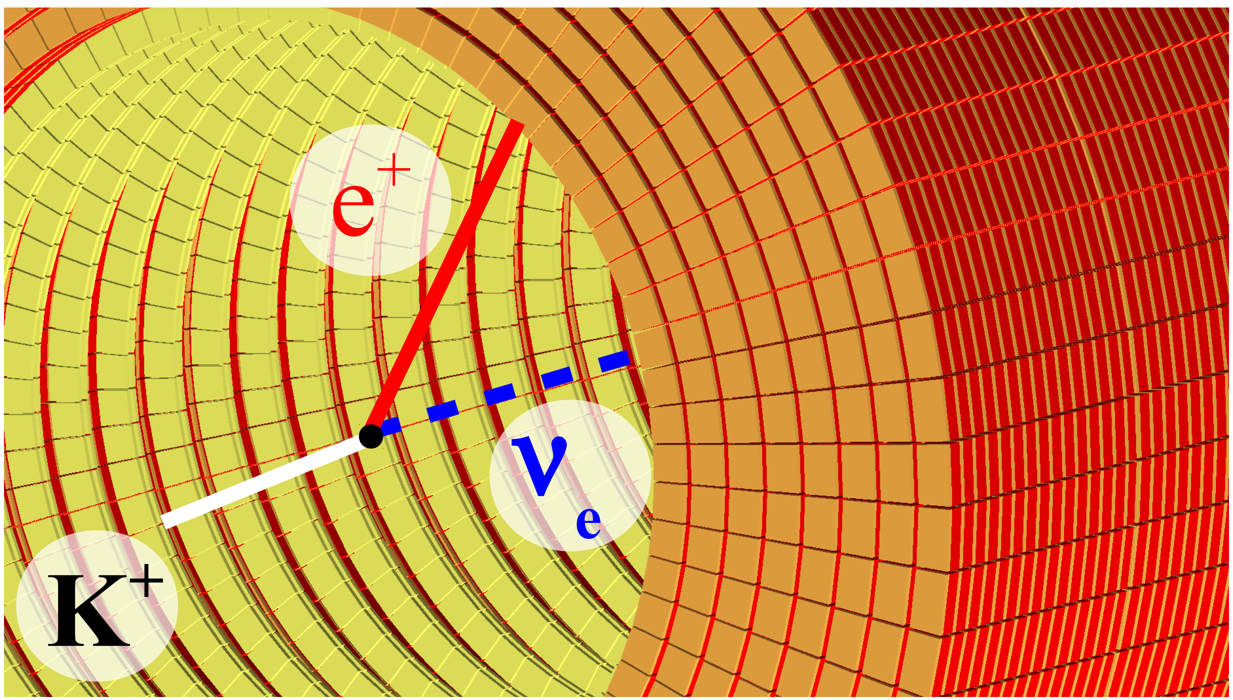
ENUBET

Enhanced NeUtrino BEams from kaon Tagging

A. Longhin (PI, INFN-PD)

Hyper-K open meeting

London, 10/07/2016

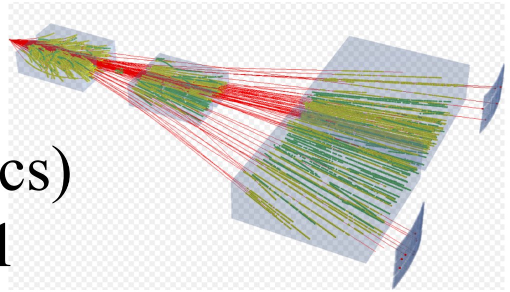


Host Institution

ERC-Consolidator Grant-2015, n° 681647 (PE2)

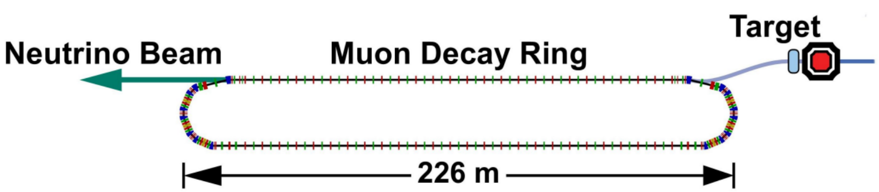
The ENUBET approach

In the last ten years, our **knowledge of ν cross sections has improved enormously**. Vigorous experimental programme (**T2K, MINERνA, SCIBooNE, MiniBooNE** etc.) motivated by the **needs of the precision oscillation physics**. Still:



- no absolute σ with precision < 10% (mainly flux systematics)
  - Mitigation: **hadro-production exp.s**. SPY, HARP, NA61
  - Mitigation: constrain flux using **interactions with e** ? small cross section

- ν_e cross sections are sparse (Gargamelle, T2K, NovA). Beam contamination.
  - **we do not have intense sources of ν_e in the GeV energy range**
  - (ideal) solution: i.e. decay in flight of stored muons (**nuSTORM**)



ENUBET: build a **pure source of ν_e** employing **conventional technologies** reaching a **precision on the initial flux < 1%**

Tagged electron neutrino beams

protons → Hadrons (K, π) → K decays → ν_e → neutrino detector

K decays → e^+

The problem of predicting the ν_e flux at the neutrino detector

A traditional beam

- **Passive** decay region
- ν_e flux relies on **ab-initio simulations** of the full chain
- **large uncertainties** from hadro-production

↔

The tagged beam

- **Fully instrumented** decay region

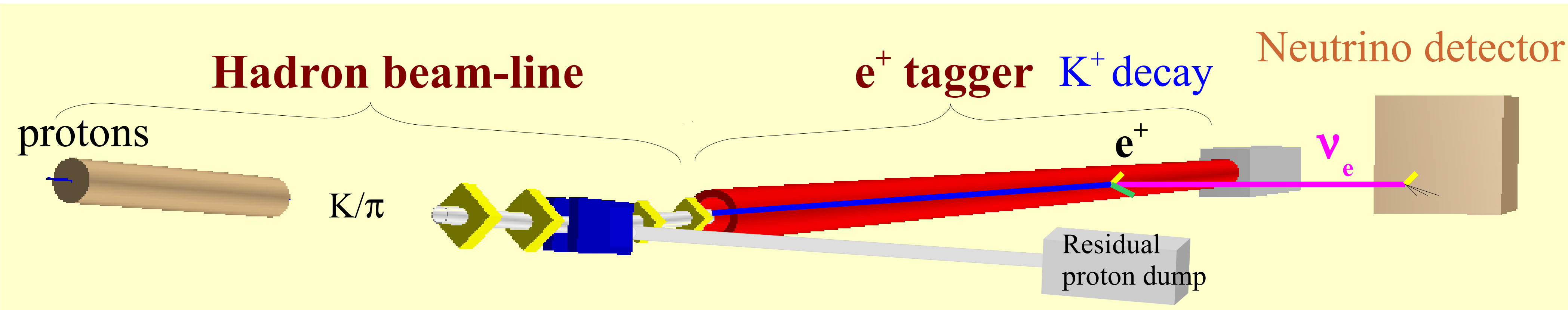
$K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle e^+

- **ν_e flux prediction = e^+ counting**

Towards the first tagged ν_e beam

A baseline setup to implement this idea proposed in:

A. Longhin, F. Terranova, L. Ludovici ***Eur. Phys. J. C (2015) 75:155***

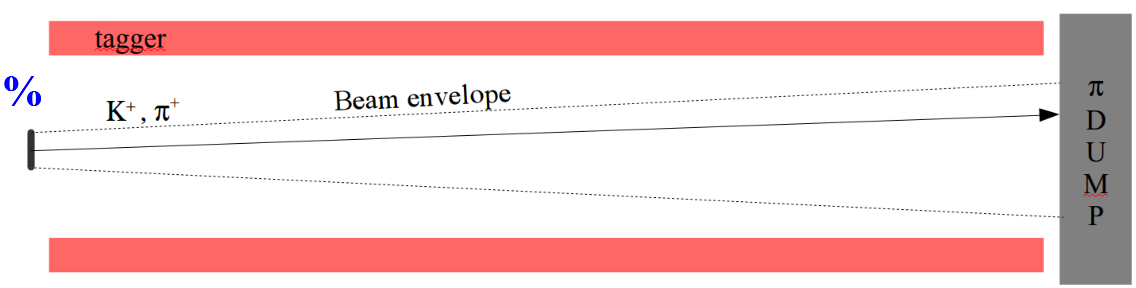


- **Hadron beam-line:** collects, focuses, transports K^+ to the e^+ tagger
- **e^+ tagger:** real-time, "inclusive" **monitoring** of produced **e^+**

Positron tagging: uncertainties from K hadro-production, PoT, hadron beam-line efficiency become irrelevant for the ν_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

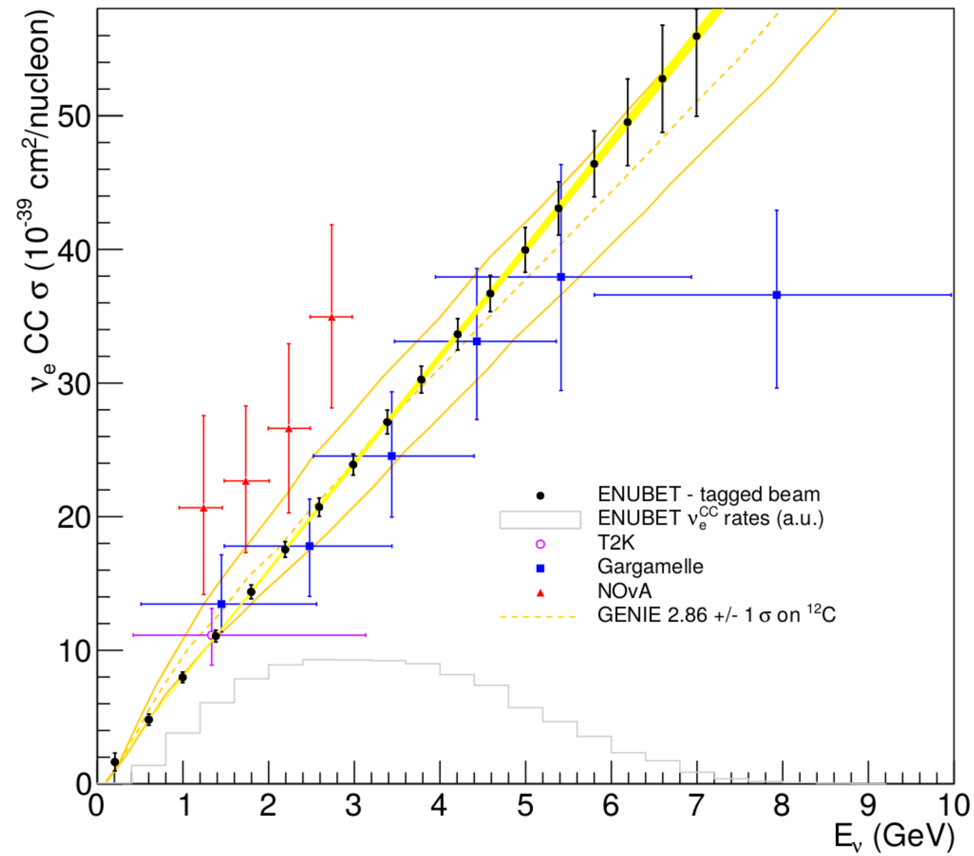


The ENUBET goals and program

Demonstrate experimentally that a new-concept ν_e **source, with × 10 better precision is feasible**

→ **σ(ν_e) 1% sys.** + 1% **overall stat. errors** (10.000 events) in realistic terms

NB. **σ($\bar{\nu}_e$)** is to date a "green field"



What's peculiar with ENUBET:

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

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

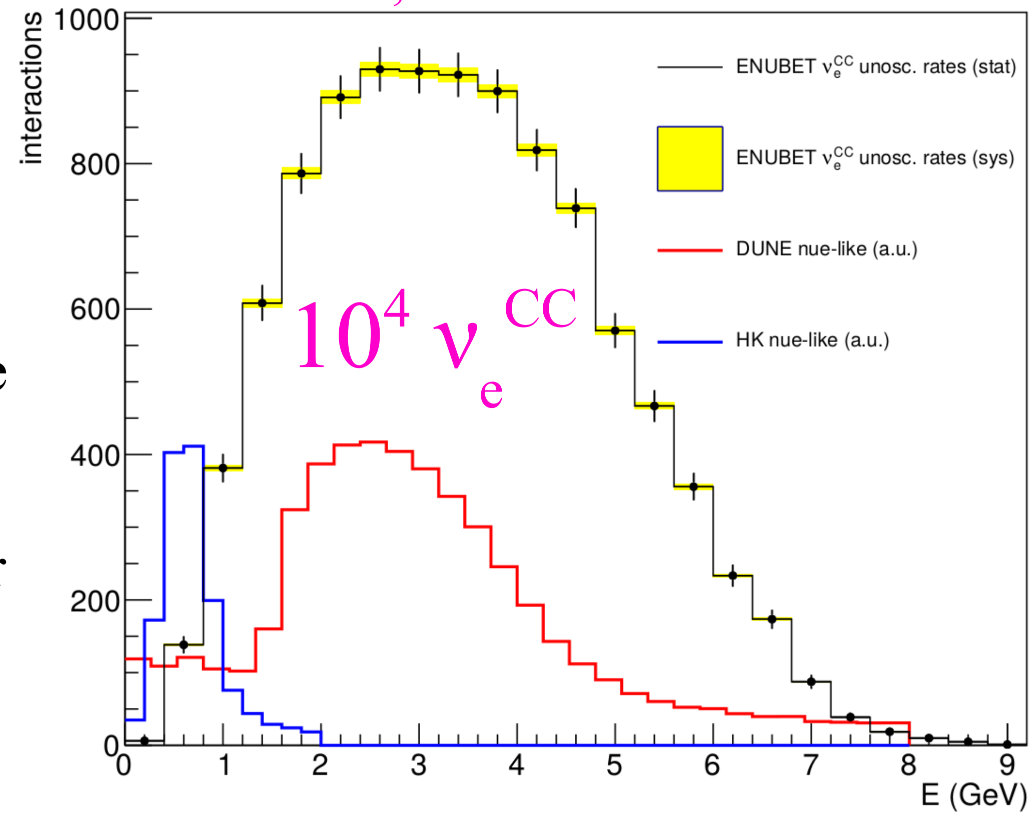
By-products

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

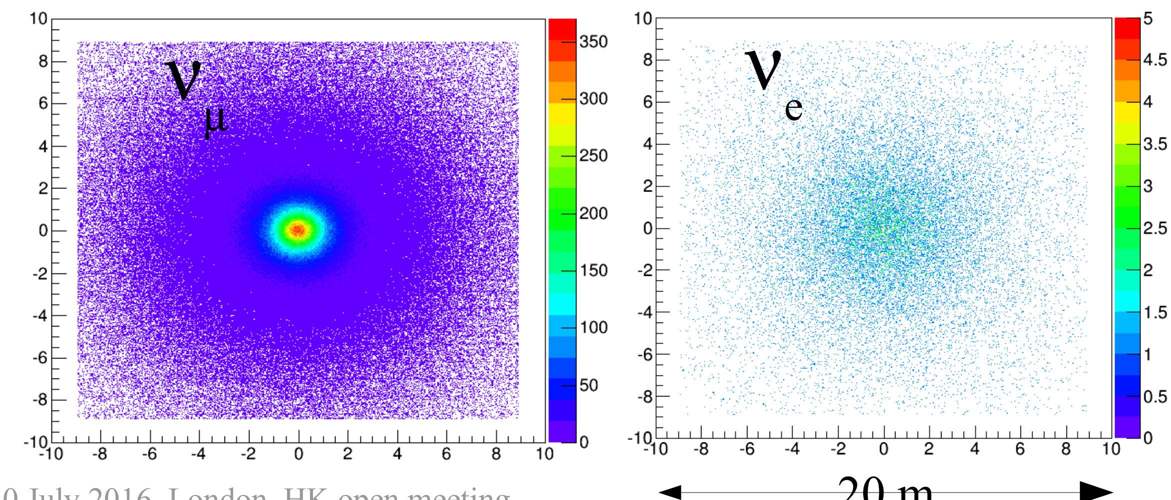
ν detector and ν_e^{CC} rates

- At 100 m from the hadron window
- A 500 t mass (< ICARUS T600)
- Interesting region of long baseline future projects is covered
- Further tuning foreseen to go even lower in energy preserving an acceptable positron purity (some ideas on the table)

<E> = 3 GeV, FWHM ~ 3.5 GeV



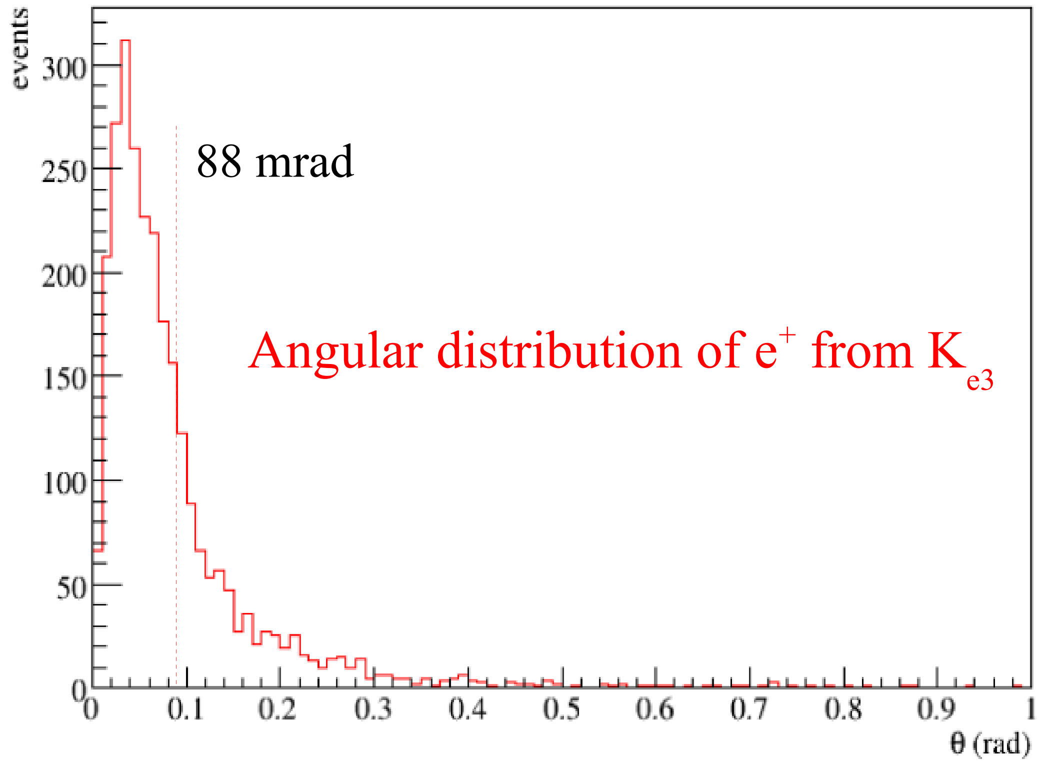
- **tagger geometrical acceptance:** 85% of ν_e^{CC} with a tagged e^+ (15 % in the forward "hole")
- $1.95 \times 10^{13}\ K^+/\nu_e^{CC}$
- Radial profiles at the ν detector

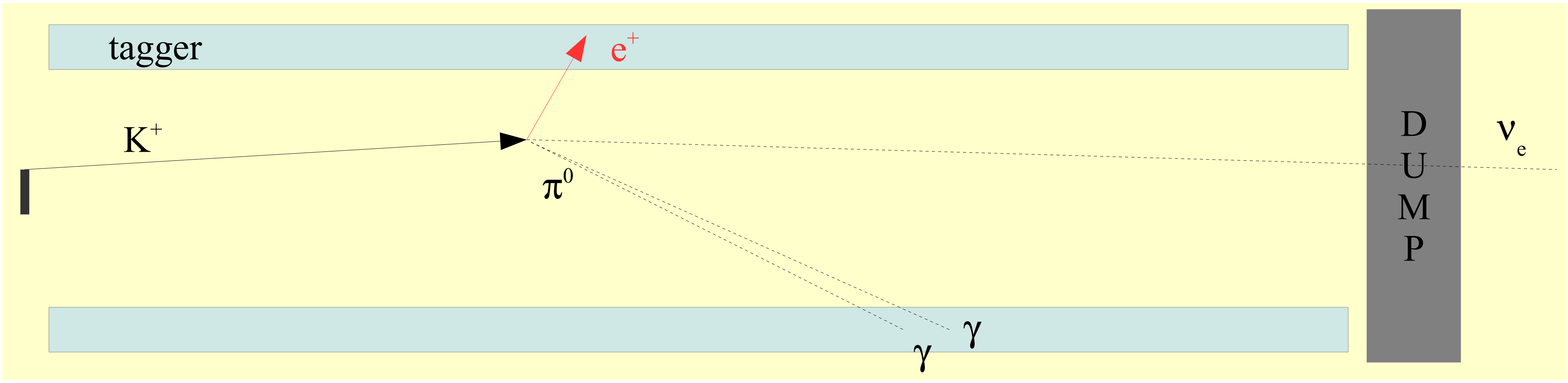


The golden channel: $K^+ \rightarrow \pi^0 e^+ \nu_e$

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

- $L_\mu >> L$(decay tunnel) ν_e ^{CC,DIF} ~ **3.3%** → **~ all ν_e are from K_{e3}**



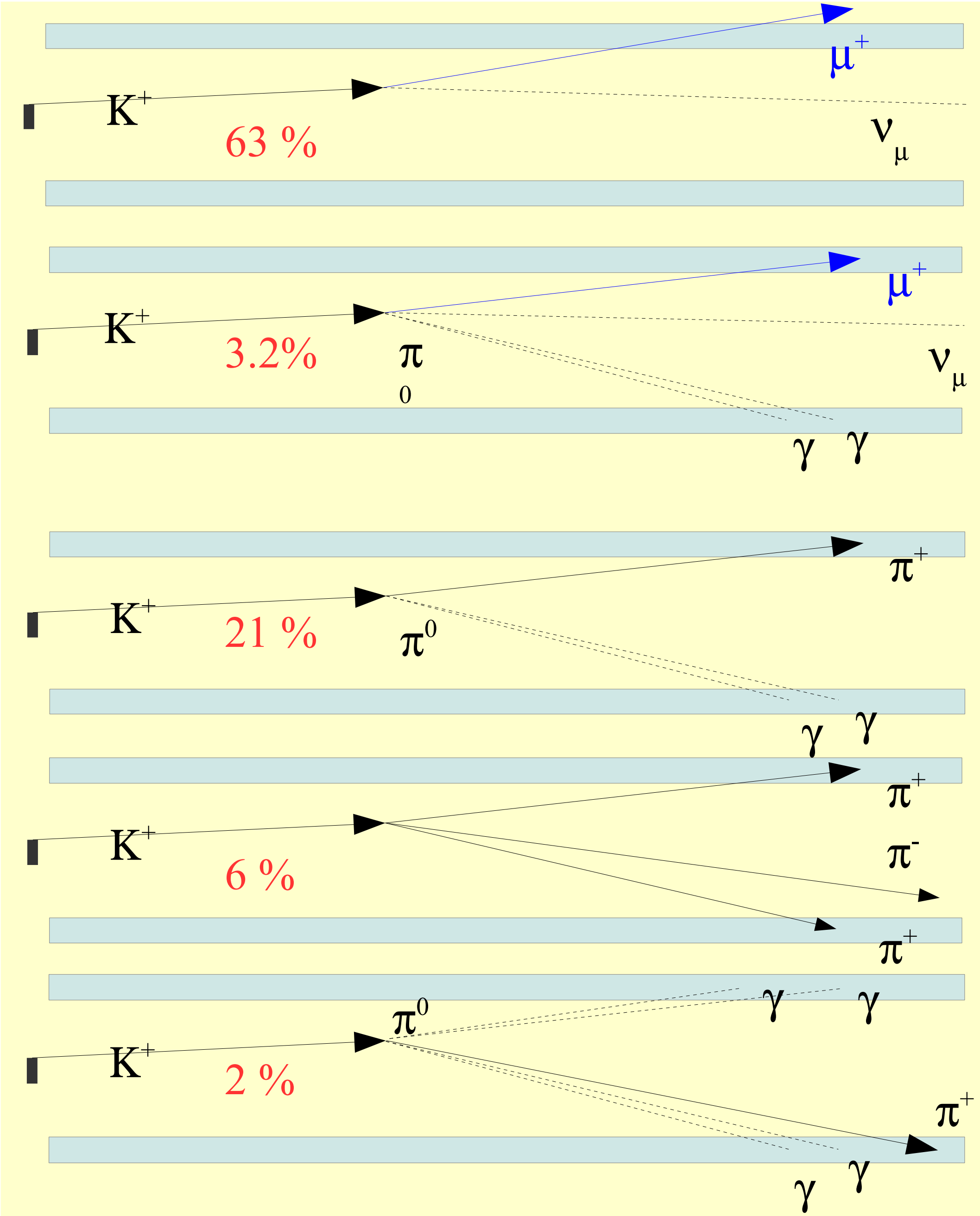


Other K decays: silver channel

- **K decays are the only π source in the tagger** $\rightarrow$ can be used with the K_{e3} **"golden sample"** to infer the ν_e **flux**

GOLDEN $\phi(\nu_e) \sim N(e^+)/BR_{Ke3}$

SILVER $\phi(\nu_e) \sim N(\pi^+)/BR_{K\rightarrow \pi X}$

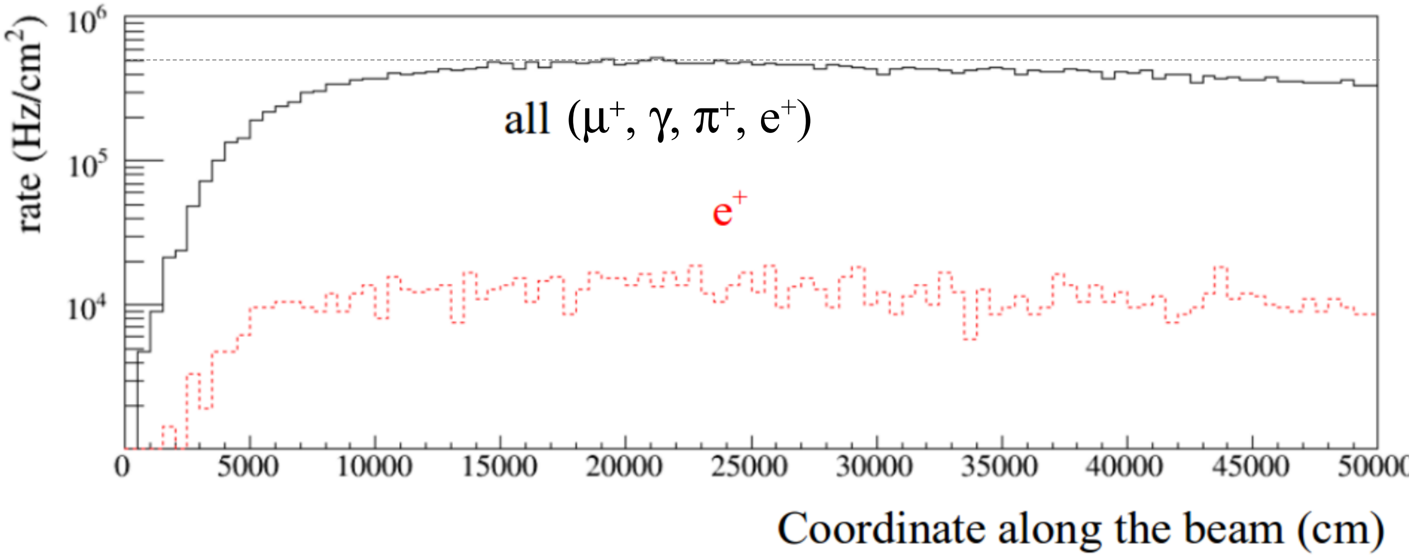


- **$\pi^{+/0}$ from K^+ can mimic an e^+** and pollute the K_{e3} golden sample $\rightarrow$ must be **discriminated**:
  - **1)** calorimetric rejection using longitudinal energy profile
  - **2)** tagging vertices w. timing:

    σ_t O(**100 ps**) ~ σ_{zVTX} O(1m) veto π^+ from the decay vertex rejects fake e^+ from $K^+ \rightarrow \pi^+\pi^-\pi^+$ and $K^+ \rightarrow \pi^+\pi^0$

The e^+ tagger challenges

Injecting **10^{10} π^+ in a 2 ms** spill →



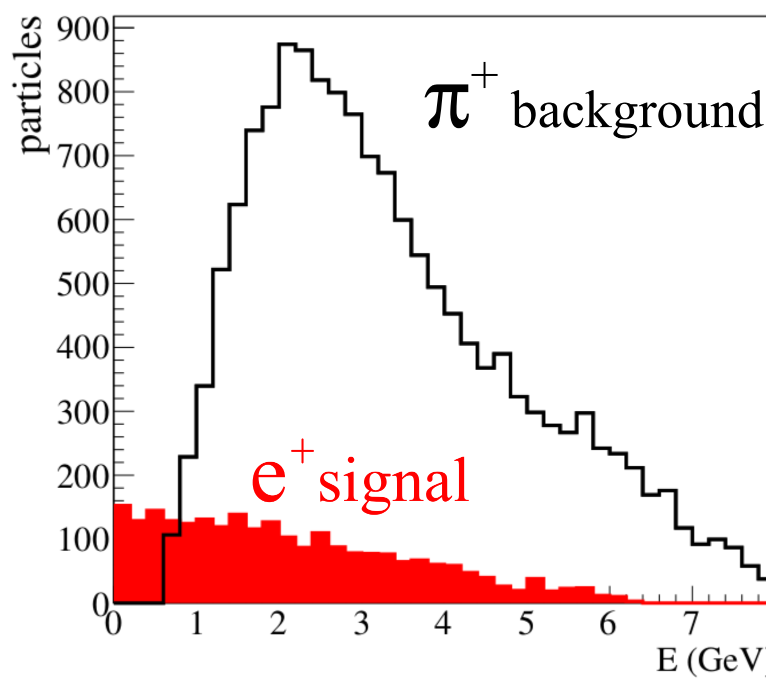
	Max rate (kHz/cm^2)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

The decay tunnel: a **harsh environment**

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

Need to veto 98-99 % of them →

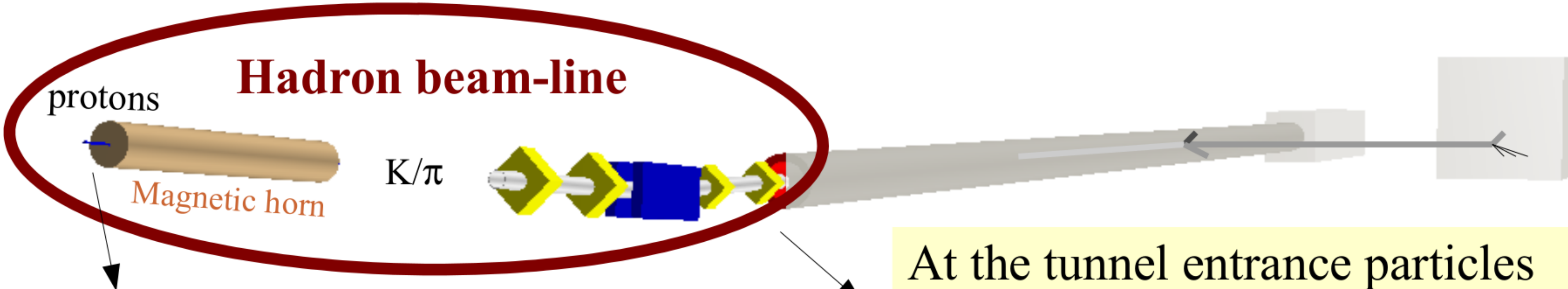
A. Longhin et al. EPJ. C (2015) 75:155



Moreover:

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

The hadron beam-line challenge



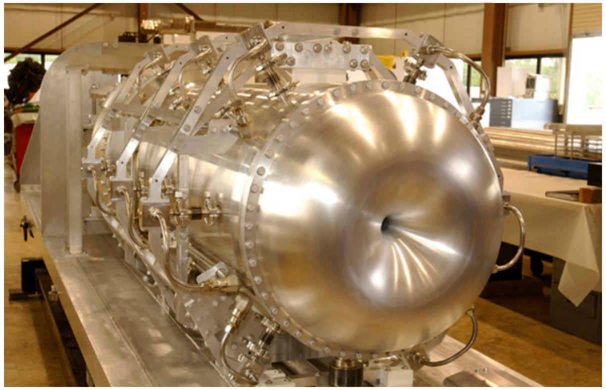
The proton extraction must be efficient and **"slow"** (saturation)

At the tunnel entrance particles must be **collimated** (< 3 mrad) and **energy selected** (20% spread)

Short transport line to prevent early decays

Scenarios	Focusing system		Proton extraction from accelerator
	A: **pulsed device** (magnetic horn)	→	**Unconventional:** many (10^8), short (2 ms) pulses with few protons ($< 3 \times 10^{11}$)
	B: **static devices** (DC magnets)	→	**O(1s) long slow extractions**

Hadron beam-line: scenario A



- Magnetic horns. Good collection. Pulsed devices.
- $t_{impulse}$ < 10 ms (Joule heating, I ~ O(100) kA)
- tagger rate limit: 10^{10} π^+ in 2 ms ~ (collection eff.) **0.3-2.5 × 10^{12} PoT/spill** depending on E_p

E (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{12})	PoT for 10^4 ν_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 → (PoT/π^+ spill)

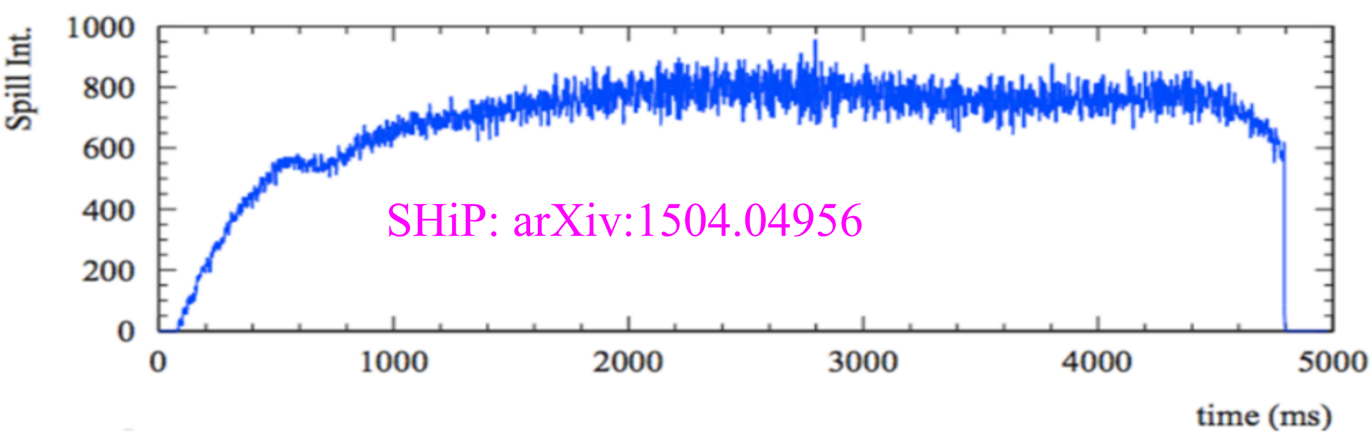
Simple conversion 1.94×10^{13} K^+ / ν_e^{CC} → (PoT for 10^4 ν_e CC)

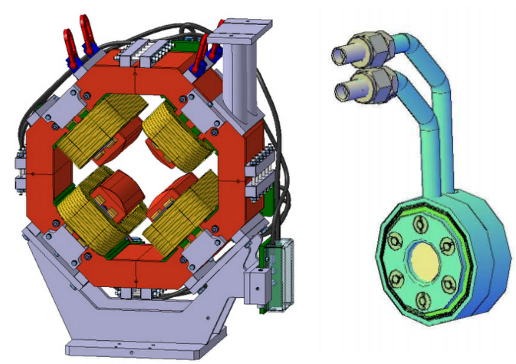
* J-PARC > 1.5 x 10^{21} PoT
CNGS = 1.8 x 10^{20} PoT
NuMI = 1.1 x 10^{21} PoT

- **PoT to get 10^4 ν_e^{CC}: 0.5-5 × 10^{20}** OK with present acc. performances!
- **Number of spills: ~ 2 × 10^8**. More challenging:
  - R&D **multi-Hz slow resonant extraction** (machine studies), horn

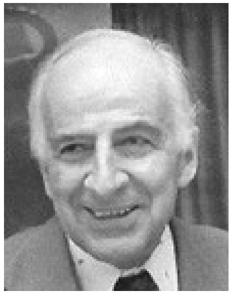
Hadron beam-line: scenario B

- Static focusing: **large aperture radiation-hard quadrupoles**.
- Disadvantage: **loss of acceptance** w.r.t. horn-based focusing.
  - **PoT to get 10^4 ν_e^{CC}: 0.5-7 × 10^{21}** O(~10 ×) more but still feasible.
    Can be compensated by **(data taking x detector mass)**
  - Far from tagger maximal rates
  - **R&D on static focusing beam-line** to maximize the collection efficiency (~ increase "useful" hadrons/PoT).
  - the single **resonant slow extraction** over O(s) times is less challenging than the multi-Hz version. Sinergies with the needs of **SHiP** proposal at CERN.





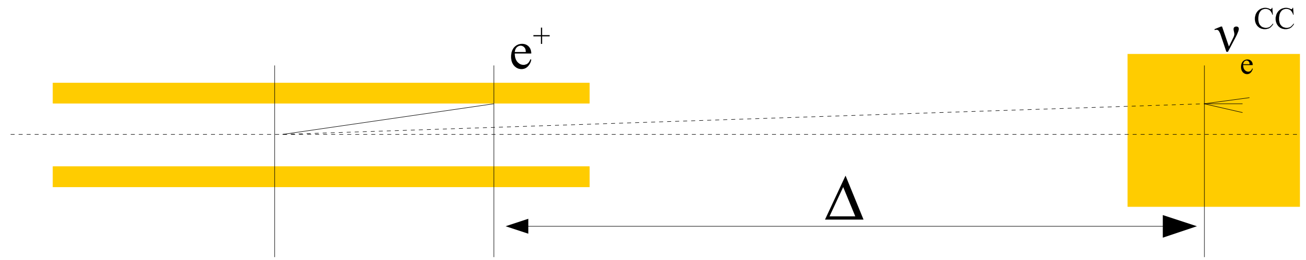
Scenario B: "time tagging" !



- Event time dilution → **Time-tagging**
- **Associating a single neutrino 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 ν detector)

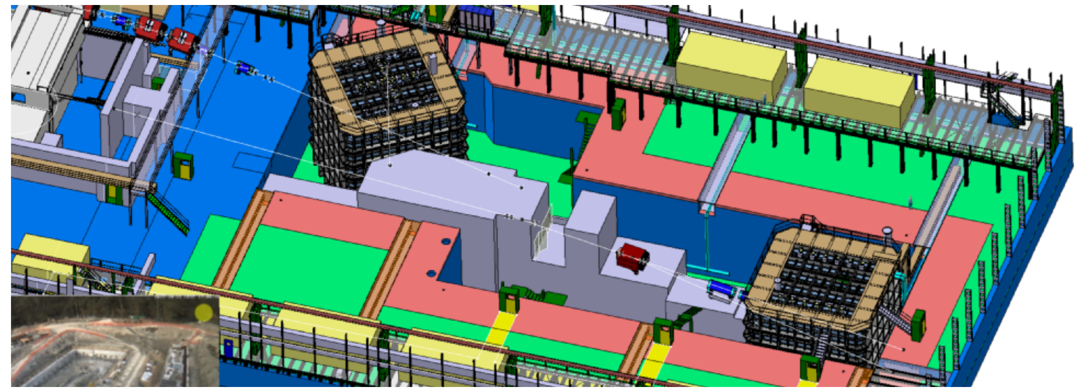
Accidental tag probability: $\mathbf{A \sim 2 \times 10^7\ \delta/T_{extr}}$

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

N.B. horn focusing (scenario A) is not viable if we are interested in time-tagging.
T_{extr} = 2 ms (1 e^+ / 70 ps) even δ = 50 ps gives A = 50%.

Beyond cross sections: time tagging

Proving a tagged neutrino beam for cross-sections is ENUBET's primary goal ("**monitored beam**"). Test beam activities based at the **CERN-PS East area**.



In the last phase of the project time synchronization could be tested at the **EHN1 CERN neutrino platform:**

beam halo μ / cosmic rays

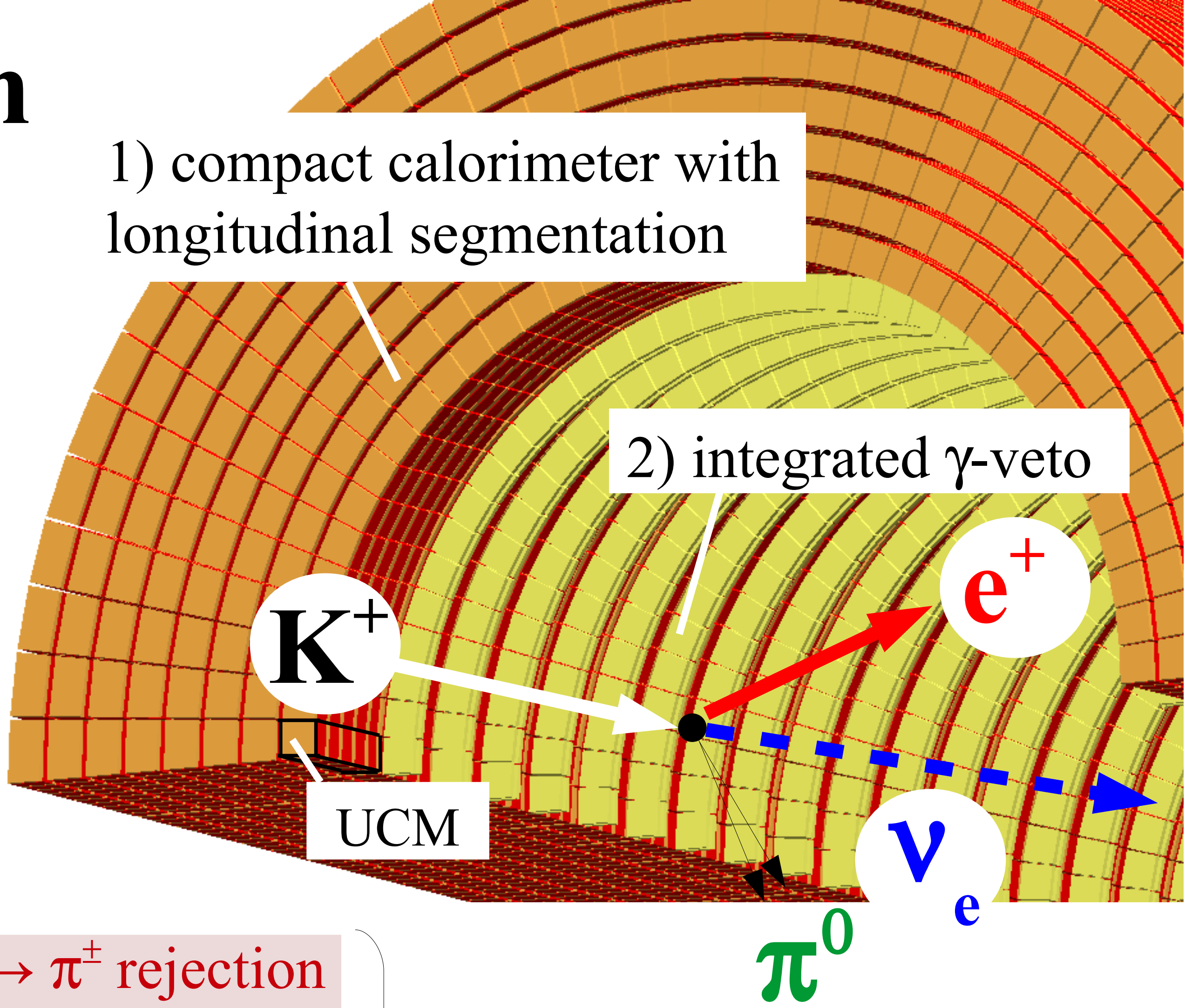
ENUBET tagger prototype ↔ **LAr** (WA105, proto-DUNE w. scint. light) or **WCh** prototypes

For a final experiment

- Tagger-detector sync. << ns → OK (direct optical links)
- σ_t of the tagger < 1 ns → OK
- σ_t of the ν detector < 1 ns → **at the limit of present technology**
- Cosmic background ×10 → Foresee overburdens
- small K^+ momentum bite small → **can imply flux reduction** (not to spoil the ν_e energy reco.)

e⁺ tagger design

Conventional beam-pipe replaced by **active instrumentation** →



1) Calorimeter ("shashlik") → $\pi^{\pm}$ rejection

- Ultra-Compact Module (UCM)

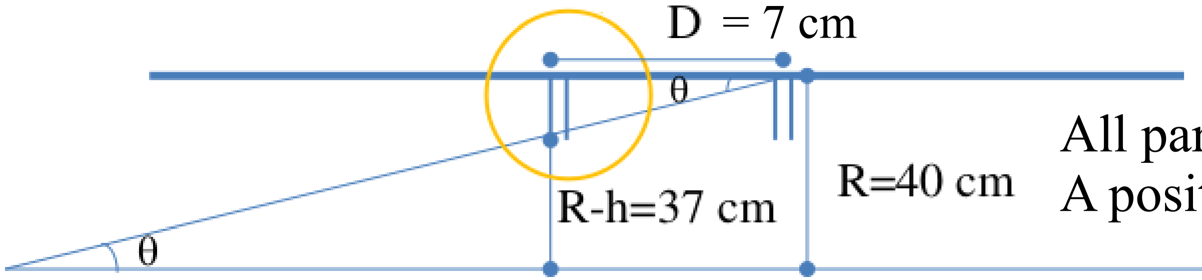
2) Integrated γ -veto → π^{0} rejection

- plastic scintillators or
- large-area fast avalanche photodiodes
- other fast detectors options

Detector **R&D activities**

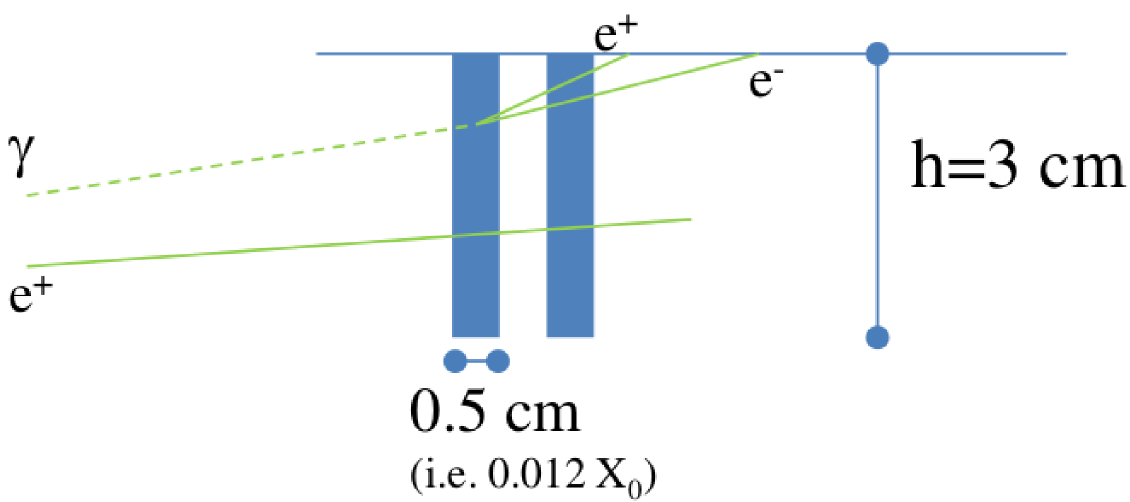
The photon-veto baseline option

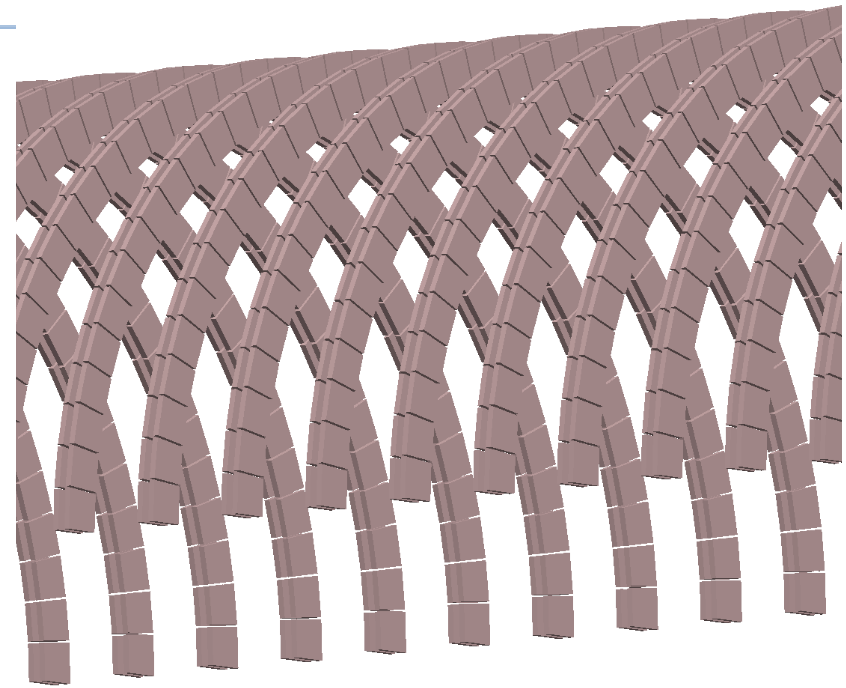
Background from γ conversions from π^0 emitted mainly in K_{e2} decays ($K^+ \rightarrow \pi^+ \pi^0$)



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

e/π separation studies

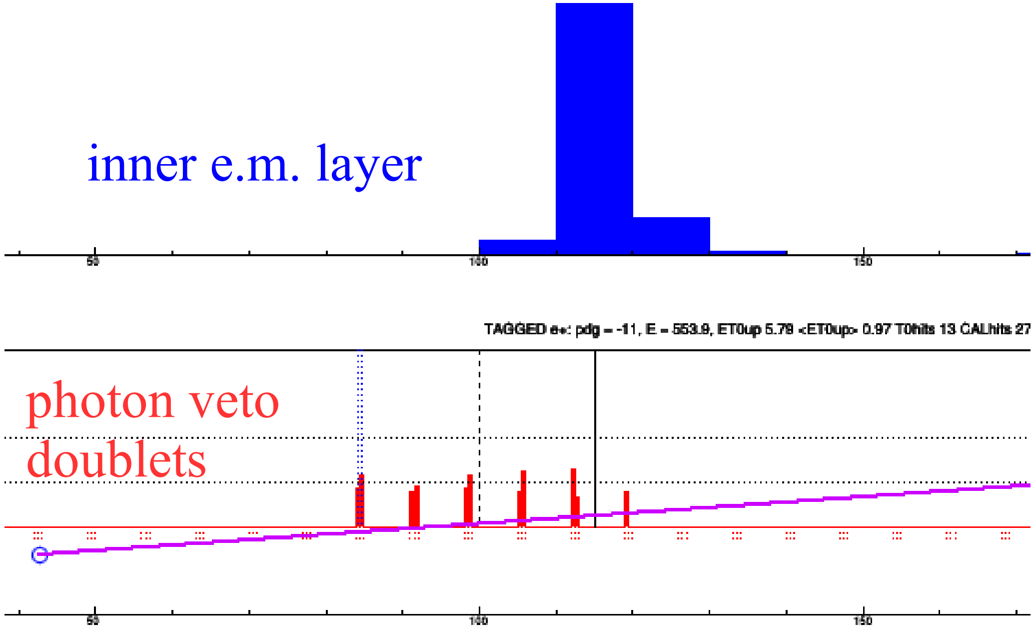
GEANT4 simulation.
Reject **simultaneously π^+ and π^0**

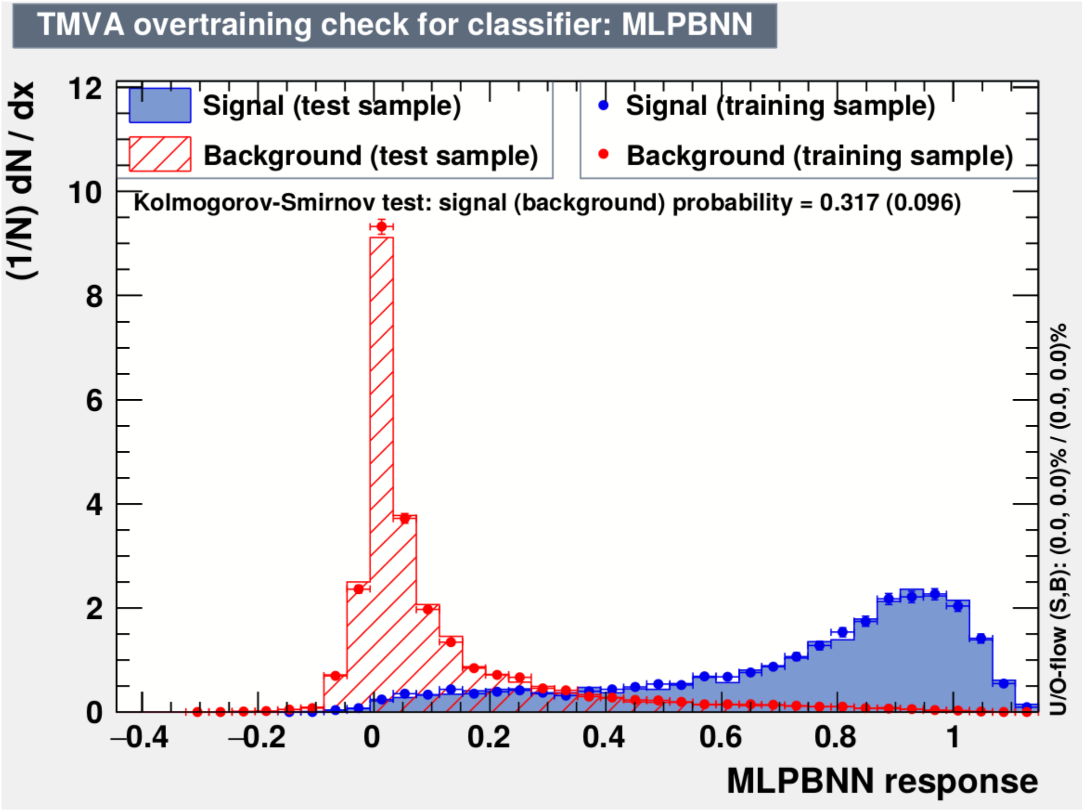
Takes into account **pile-up** related restrictions in the event building.

TMVA **multivariate** analysis:
- E released in calorimeter
- E in photon-veto doublets (3 layers).
- ΔZ between inner e.m. layer peak and the 1st photon-veto doublet.
- N. photon veto doublets upstream of the inner e.m. layer peak

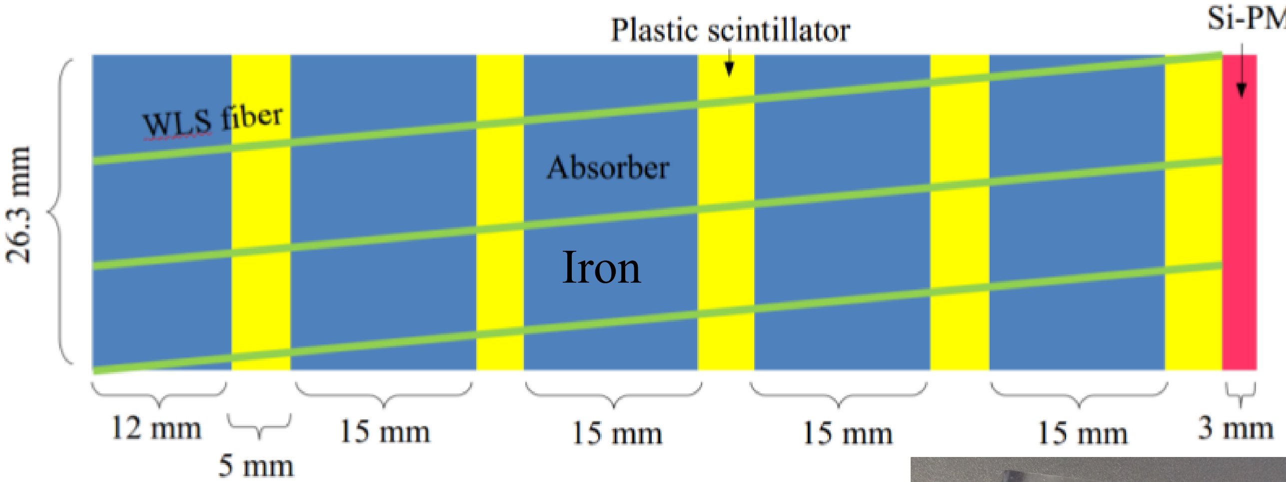
	ε_{geom}	ε_{sel}
e^+	90.7 %	49.0 %
π^+	85.7 %	2.9 %
π^0	95.1 %	1.2 %

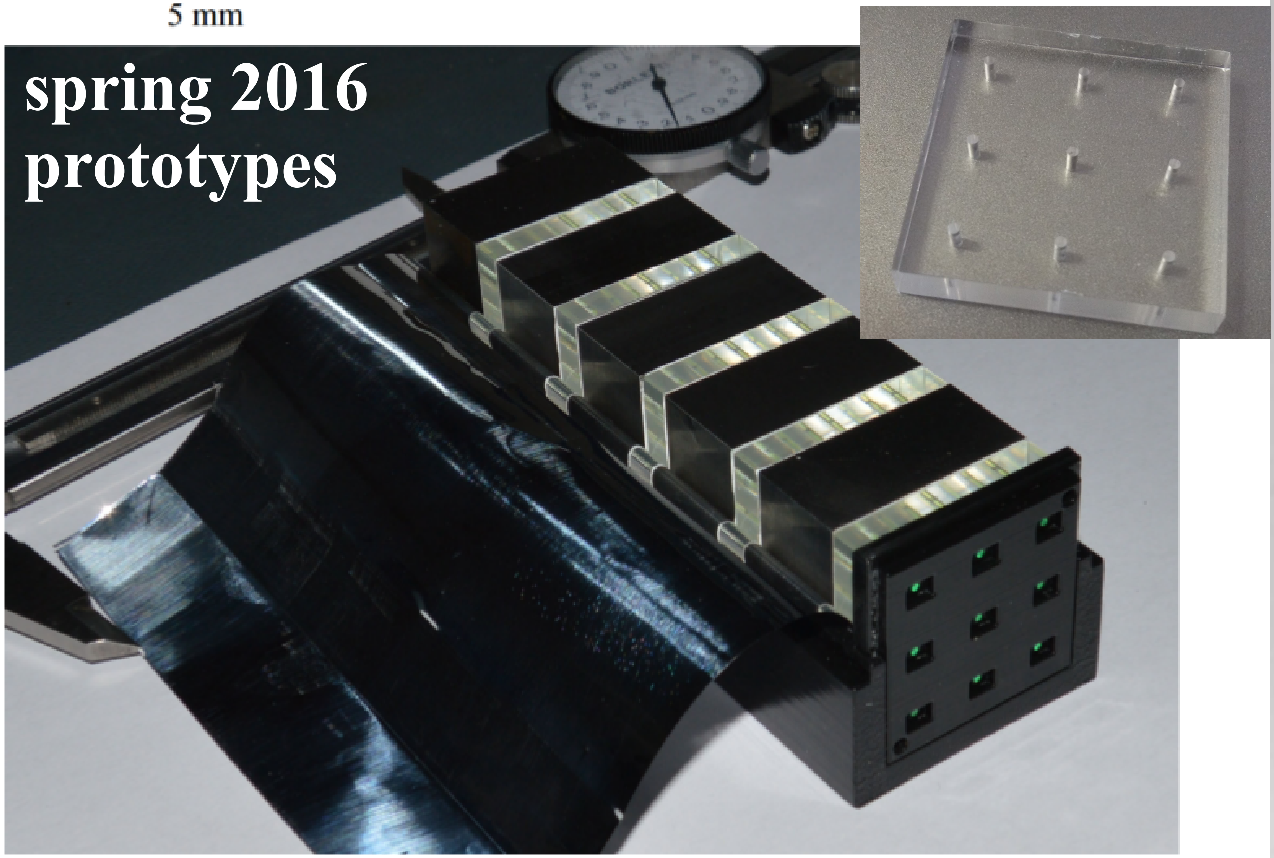
Early results confirm previous estimates from parametrizations

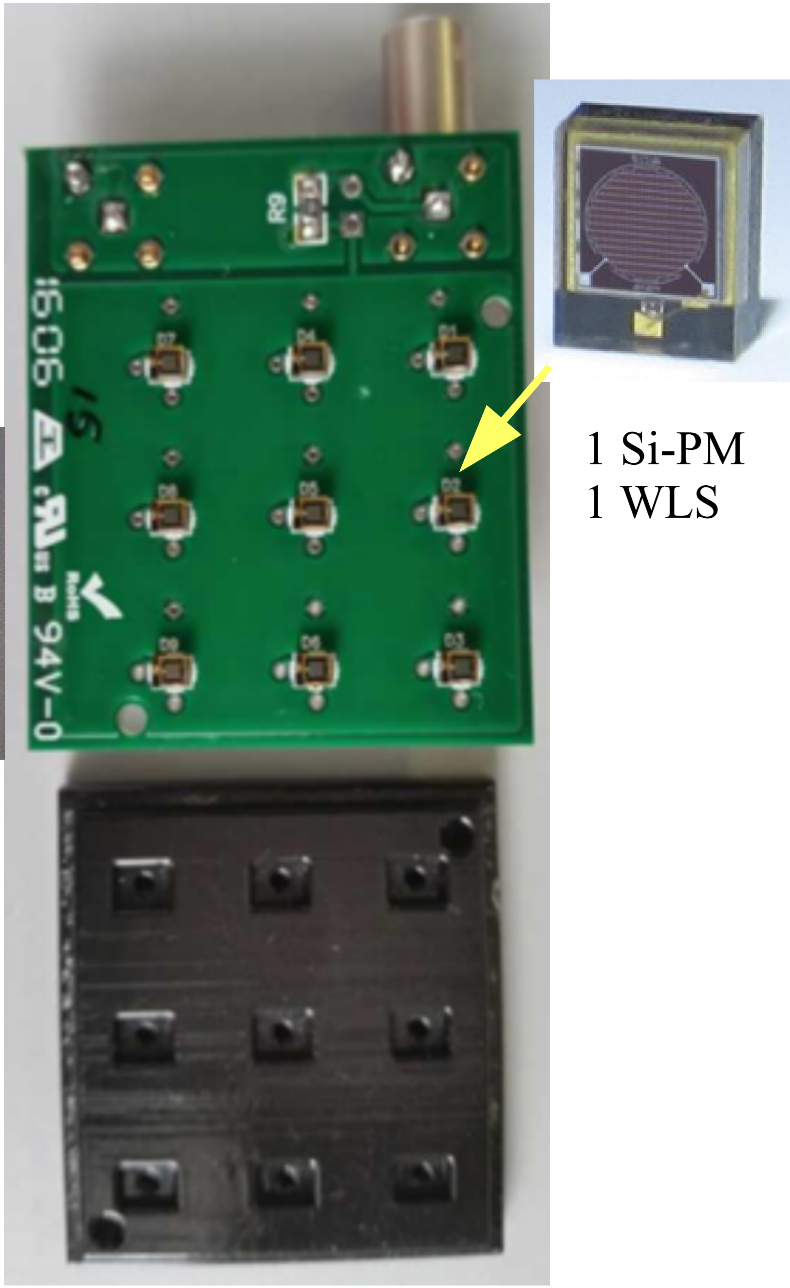




The Ultra Compact Module (UCM)







1 Si-PM
1 WLS

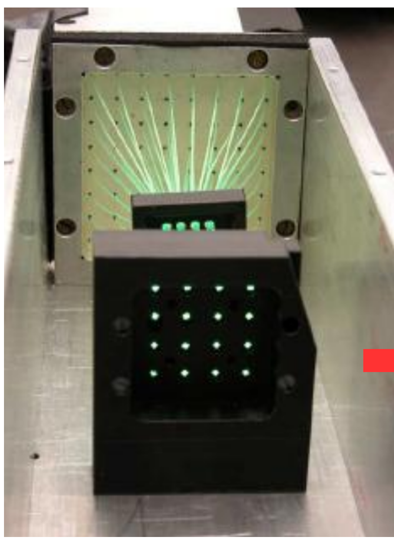
Tagger detector R&D: SCENTT

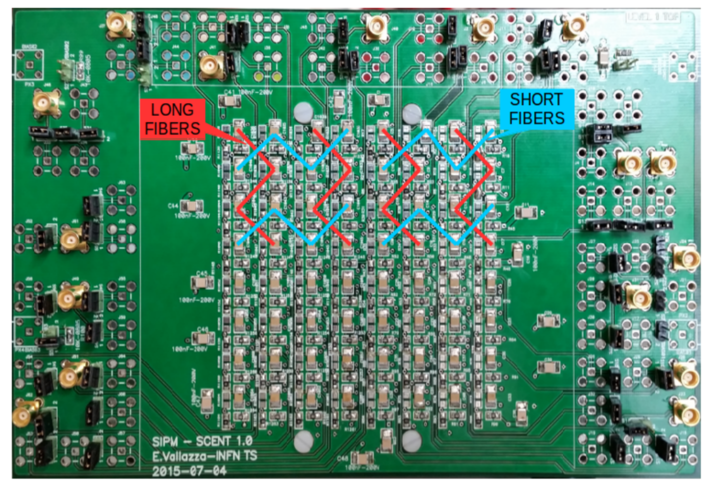
Shashlik Calorimeters for Electron Neutrino Tagging and Tracing

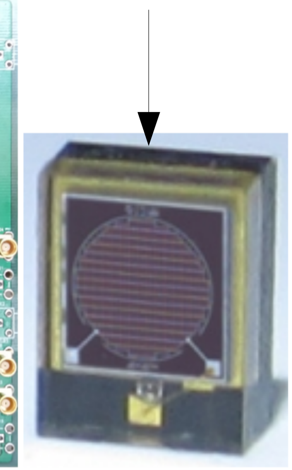
A. Berra, C. Jollet, A. Longhin, L. Ludovici, L. Patrizii, M. Prest, A. Meregaglia, G. Sirri, F. Terranova, E. Vallazza

- 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**

Model	V_{BD} (V)	# of cells	Cell area (μm^2)	Active Area (mm^2)	Fill factor	PDE
ASD-RGB1C-P	~28	673	40×40	1.13	~60%	32.5%







Results recently published in **N.I.M. A**

Resolution vs E and e/π separation in line with simulation. Done both using TDC or digitizers. No nuclear counter effects.

A compact light readout system for longitudinally segmented shashlik calorimeters

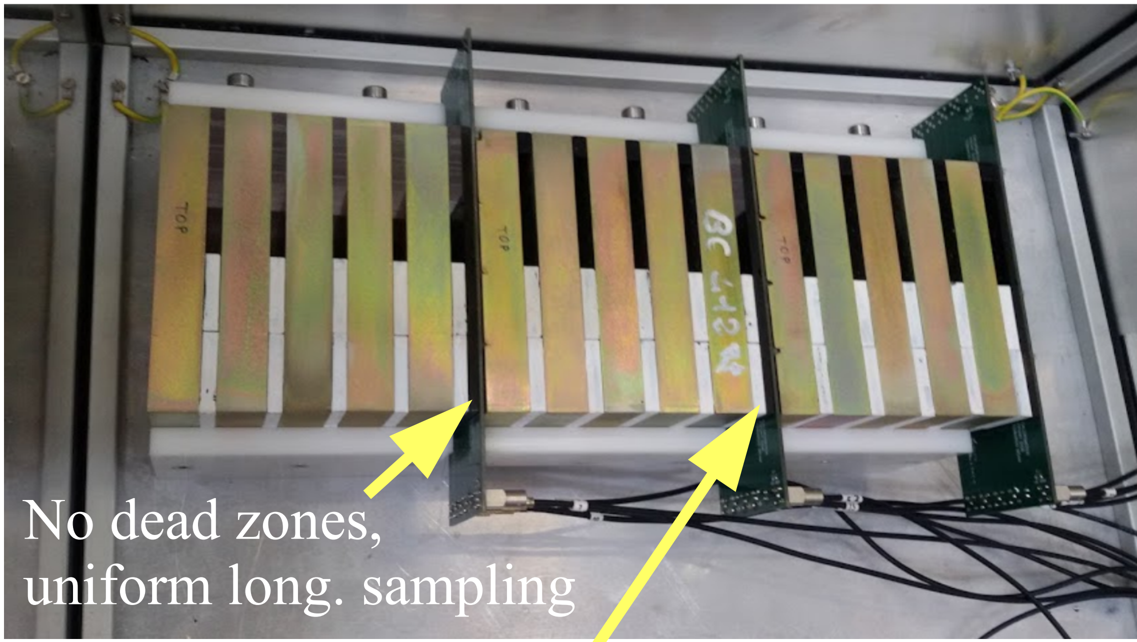
http://dx.doi.org/10.1016/j.nima.2016.05.123 ArXiv:1605:09630

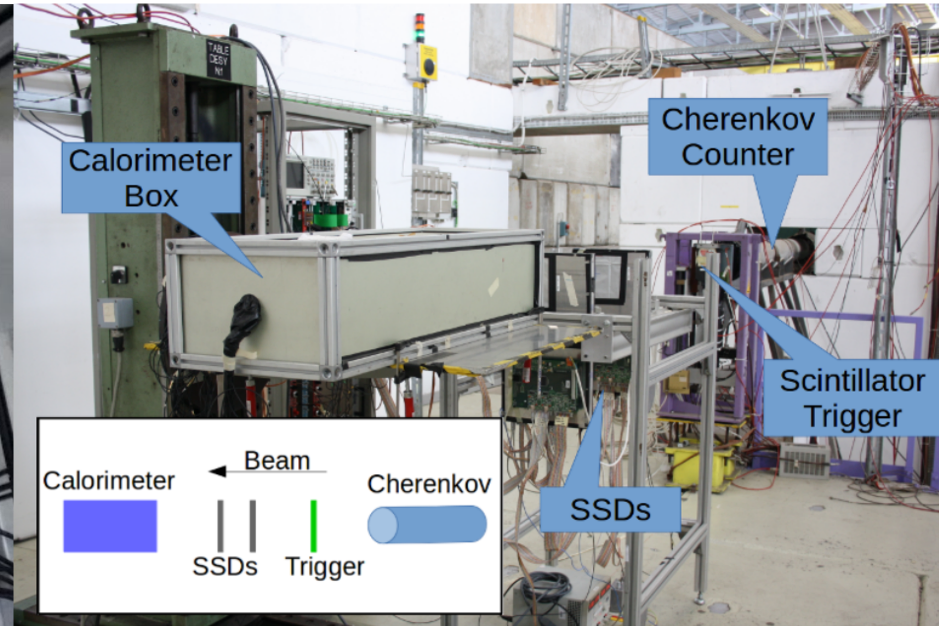
A. Berra[a,b,*], C. Brizzolari[a,b], S. Cecchini[c], F. Cindolo[c], C. Jollet[d], A. Longhin[e], L. Ludovici[f], G. Mandrioli[c], N. Mauri[c], A. Meregaglia[d], A. Paoloni[e], L. Pasqualini[c,g], L. Patrizii[c], M. Pozzato[c], F. Pupilli[e], M. Prest[a,b], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i],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

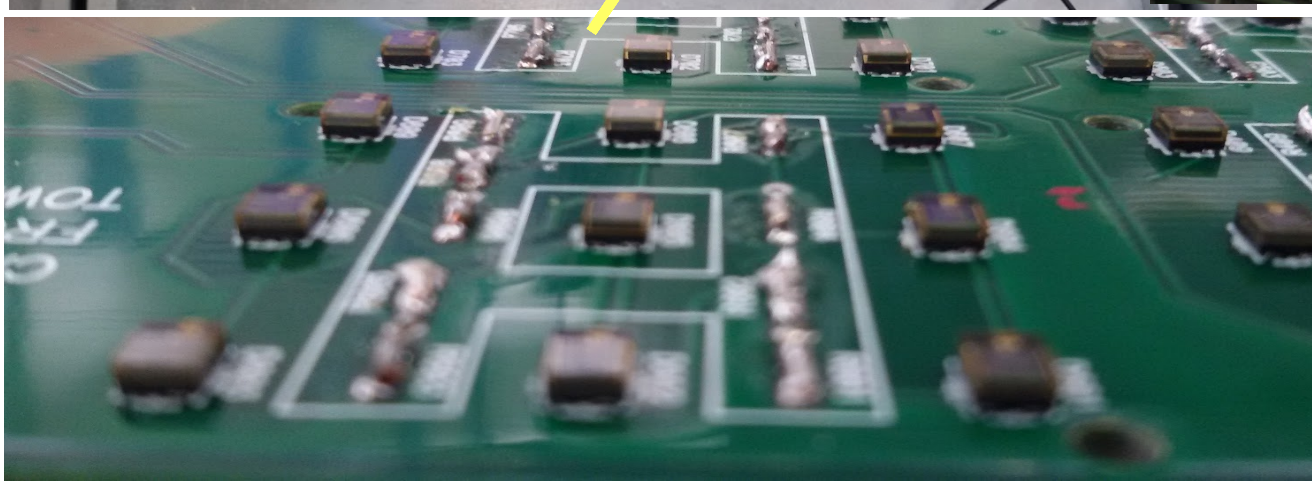
July 2016 CERN-PS T9 test beam

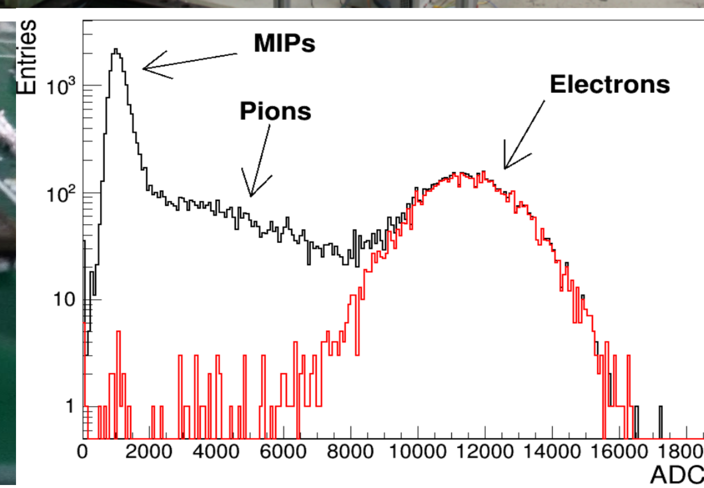
29-06 → 12/07/2016

First (successful) tests of 12 ENUBET UCM modules (12 X_0) with pions and electron beams from 1-5 GeV. HD Si-PM with 20 μm cell size.





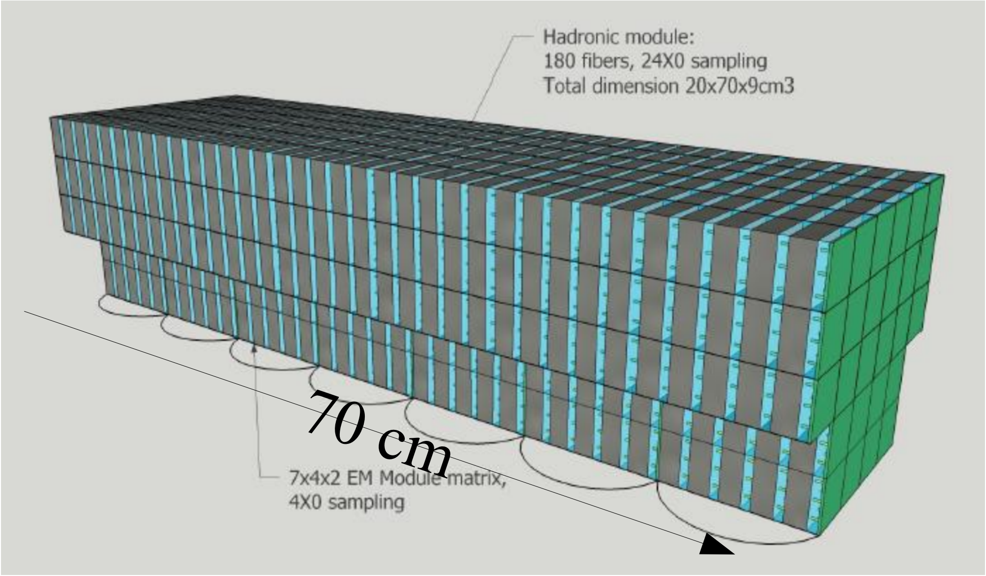


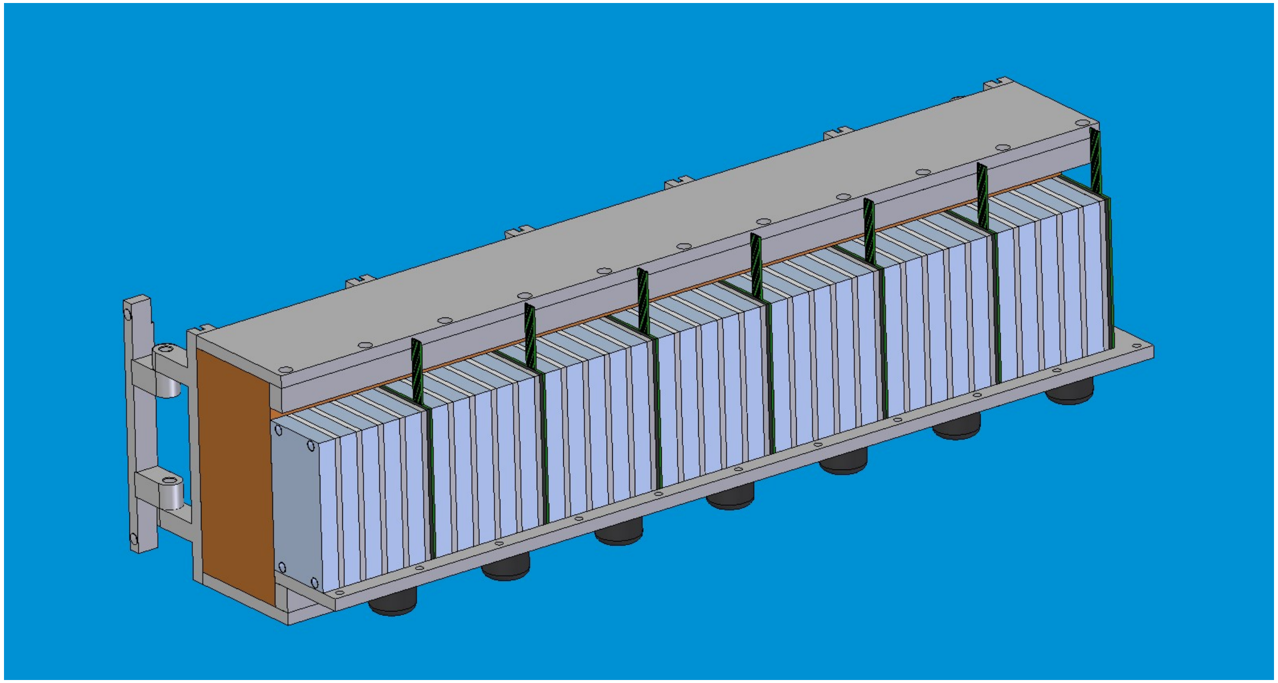


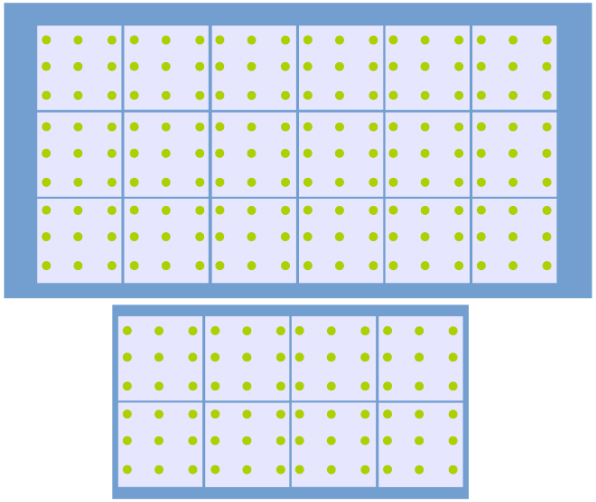
Next test beam at CERN-PS T9

Planned for November 2016:

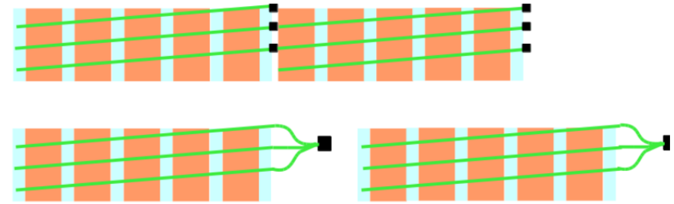
Inner + outer modules → readout **w. custom fast digitizers**
Orientable cradle to study **grazing Incidence.**



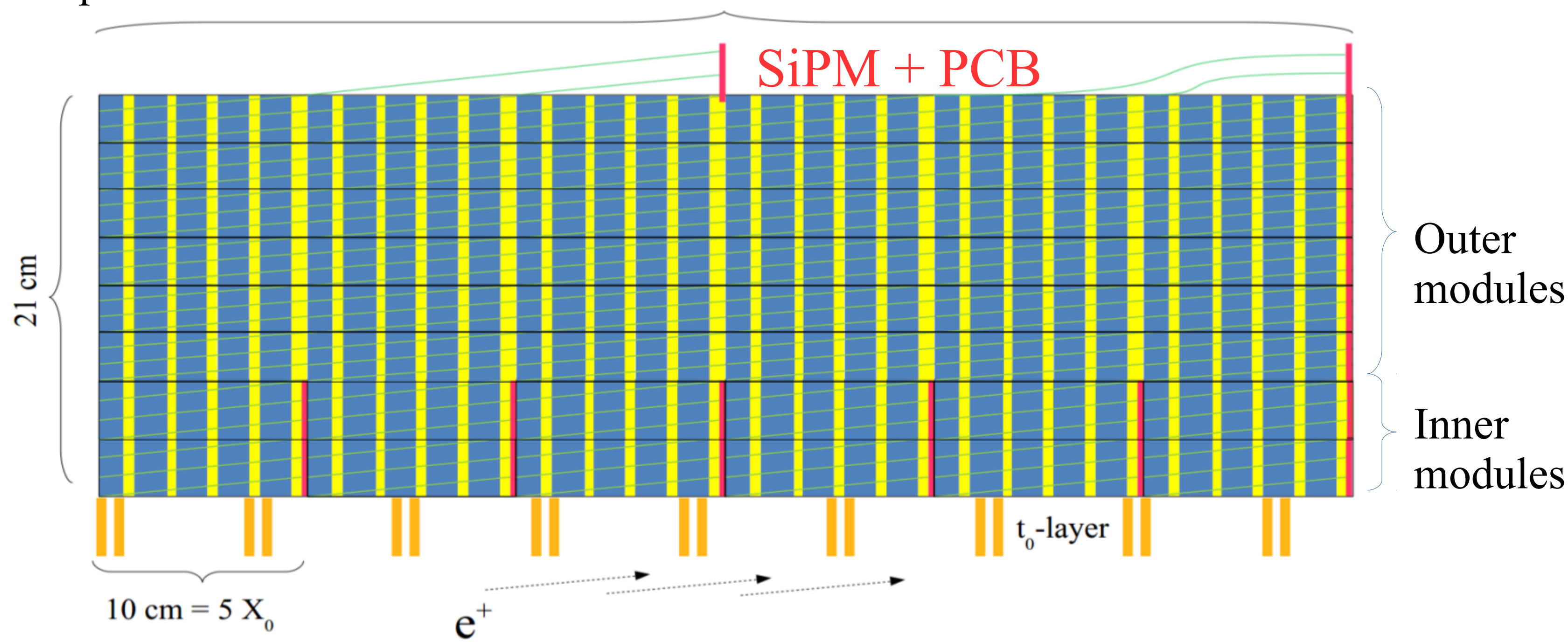




The final prototype

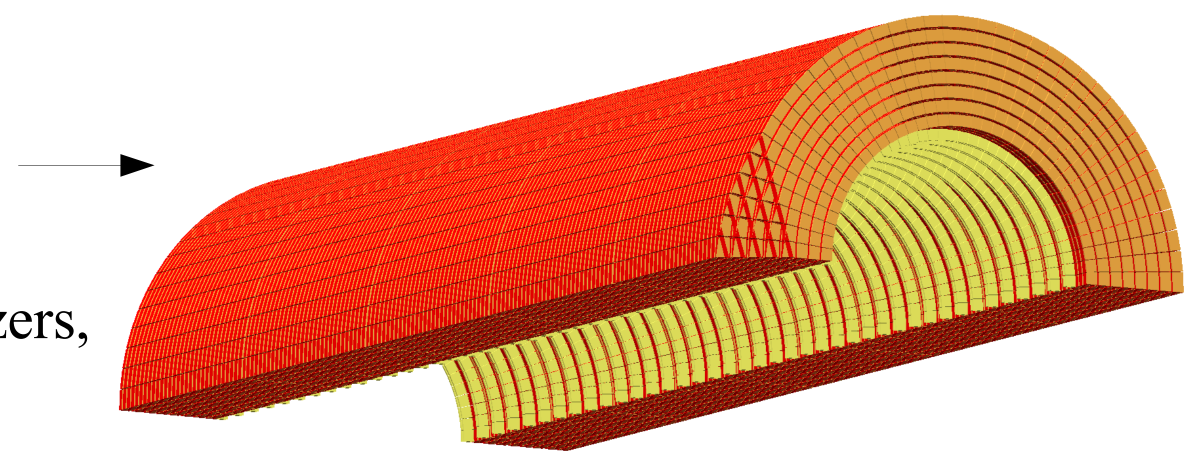


1 super-module



- 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**



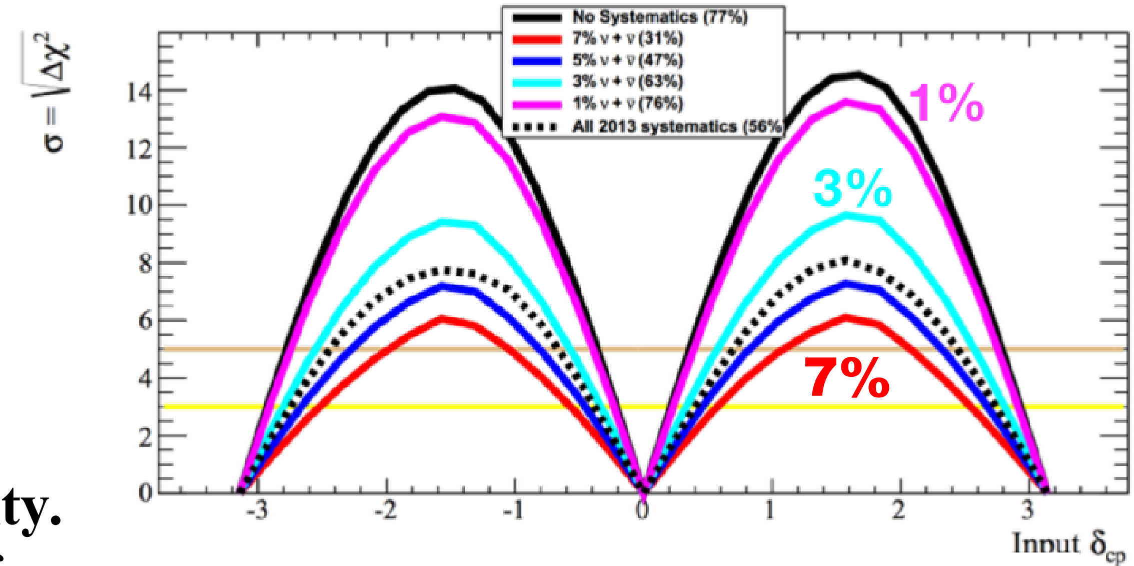
Possible sinergies of our programs (I)

The "natural" one:

HK

Sensitivity study for **CPV for HK**
$\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$: uncorrelated normalizations parameters with {0, 1, 3, 5, 7 %} uncertainties

M. Hartz @ NuFact 2015

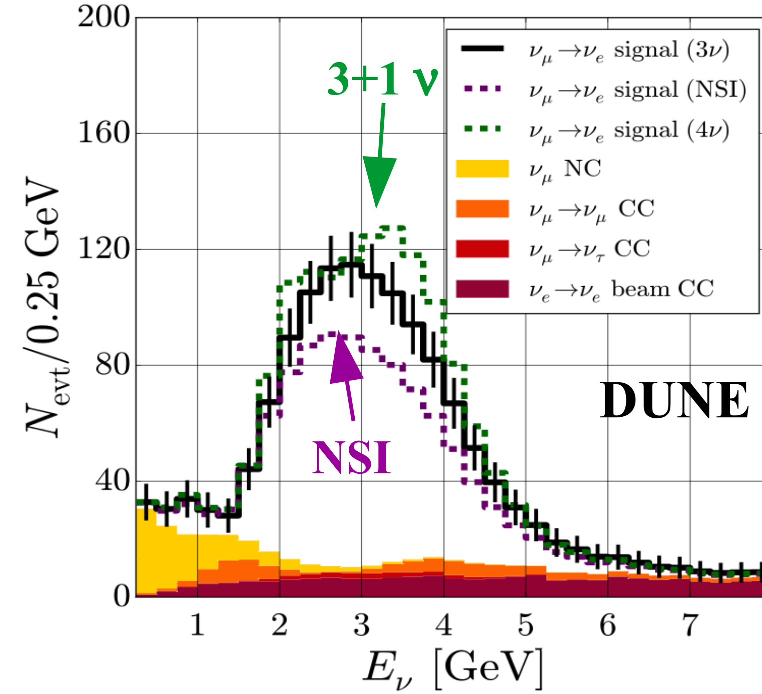


The systematic uncertainty should be controlled to < 1-2% to **minimize the impact on the CPV discovery sensitivity.**
Probe smaller and smaller values of $\sin\delta_{CP}$

De Gouvea et al., 1605.0937

Exotic (sterile neutrinos, non-standard interactions): a similar phenomenology

→ a precise knowledge of $\sigma(\nu_e)$ vs E is needed to get **a deeper insight of the underlying physics**.



Possible sinergies of our programs (II)

The ENUBET tagger could be coupled with a **WCh detector** (time coincidences tests with prototypes or even eventually for the final experiment).

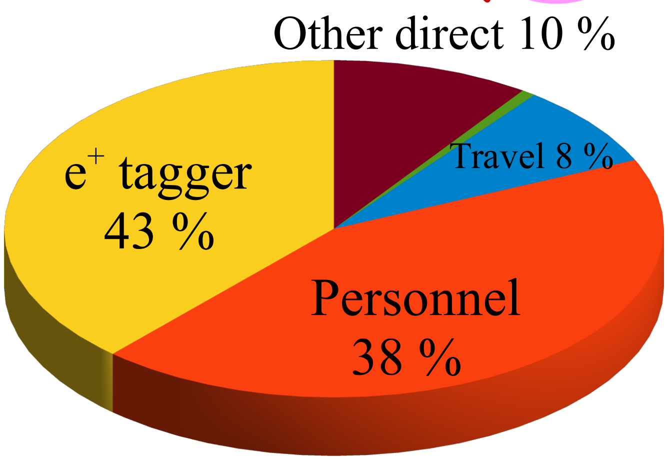
The ENUBET beam-line study is intended to be **site-independent**. → study extraction schemes opportunities at J-PARC (fast rep. rate!) and proton economics.

Large area fast ps detectors for Cherenkov light detection for the **photon veto** would allow **superior timing** and improve π rejection at low energies (relevant for Hyper-K) using **timing-based vertexing**. → To be studied!

Large area fast ps detectors also for the neutrino detector (+ **static focusing**) would open the doors to real **time tagging.**

Resources, institutions

- Project started on 1 June 2016 (5 y duration)
- Kick-off meeting (Padova, 23-24 June 2016): https://agenda.infn.it/conferenceDisplay.py?confId=11574
- **2 MEUR budget**



- **Team:**

  expertise in **calorimetry, accelerator** and **ν physics**.

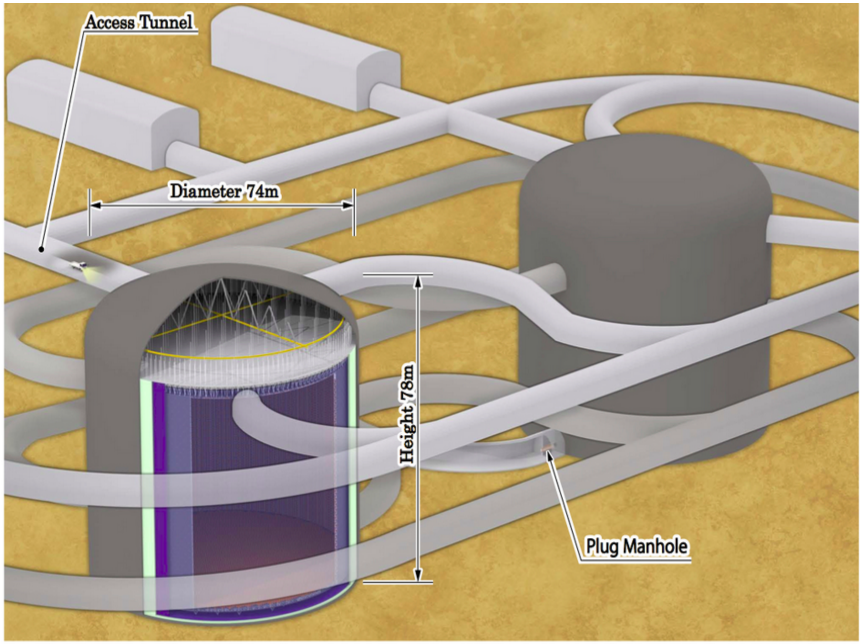
- **INFN** Padova, Mi-Bicocca-Insubria, Rome1, LNF, Trieste, Bologna, Bari, Naples.
- **CERN-**ABT (beam extraction)/STI (targetry, focusing), **IN2P3** Strasbourg.
- Interest from **FBK,** Trento (Si-PM R&D).

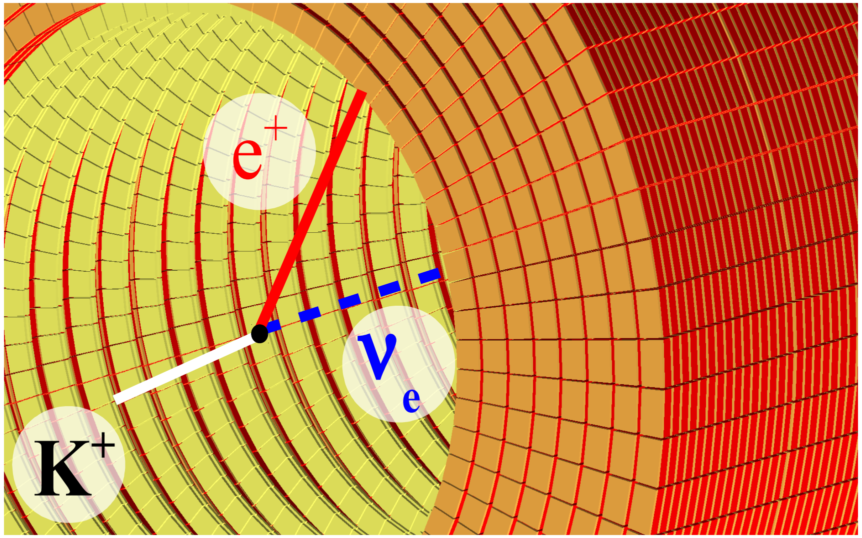
~ **35** people currently interested to an **Expression of Interest** planned for submission to CERN-SPSC this autumn. Allow official commitment of CERN collaborators, support for beam test campaigns. Visibility. Possibility for CERN NP.

Available upon request for **interested colleagues**!

Conclusions

- ENUBET, HK: many potential **synergies**:
  - **systematics reduction** for precision oscillation physics:
    - ✓ **CP violation** and standard parameters
    - ✓ **non-standard scenarios** (NSI, sterile neutrino searches)
  - R&D for **large area ps detectors**
    - ✓ fast timing in **the decay tunnel** (background reduction)
    - ✓ fast **neutrino detectors** (**time tagged** neutrino beams)





- Fore more information a draft for an **Expression of Interest for CERN SPSC** is available (longhin@pd.infn.it)
- Some T2K colleagues already in the business

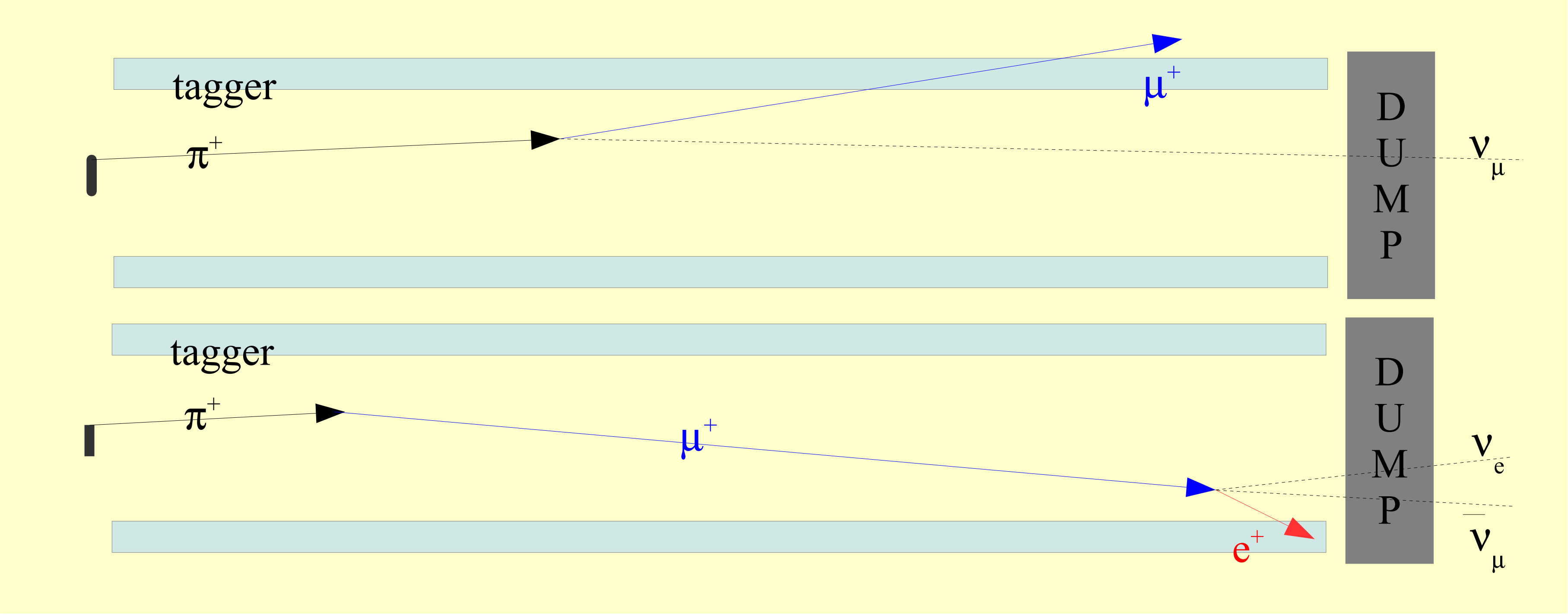
- **Thank you** for the invitation !

Thank you!

Pion decays induced backgrounds

- $\pi^+ \to \mu^\pm \nu_\mu$ creates the bulk of $\boldsymbol{\nu_\mu}$ (~ 95% π @ 400 GeV)
  - **ν detector must have good ν_e PID**: reject NC π^0 in the ν_e^{CC} sample
- 2-body decay, $m_\mu \sim m_\pi$: $\mu^+ \sim$ 4 mrad → few in the tagger, easy to reject
- **μ D.I.F : suppressed** $L_\mu >> L$(decay tunnel)
- **3-body** but $\mathbf{m_\mu \sim 0.2\, m_K}$ → $e^+_{DIF} \sim$ 28 mrad ($e^+_{Ke3} \sim$ 88 mrad)
  - $\boldsymbol{\nu_{e,}}^{\mathbf{CC,DIF}}$ **~ 3.3%** → **~ all ν_e are from K_{e3}**

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



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

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

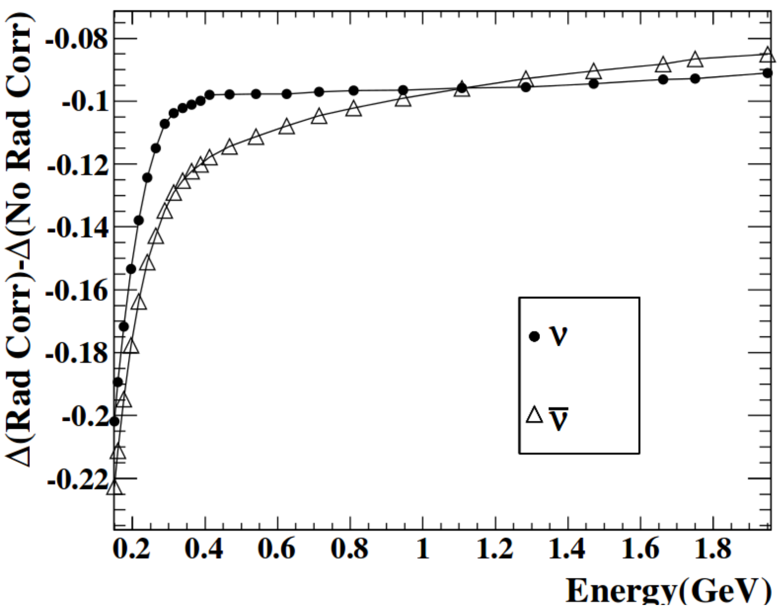
1) **Lepton universality** in weak interactions is **not the full story**:

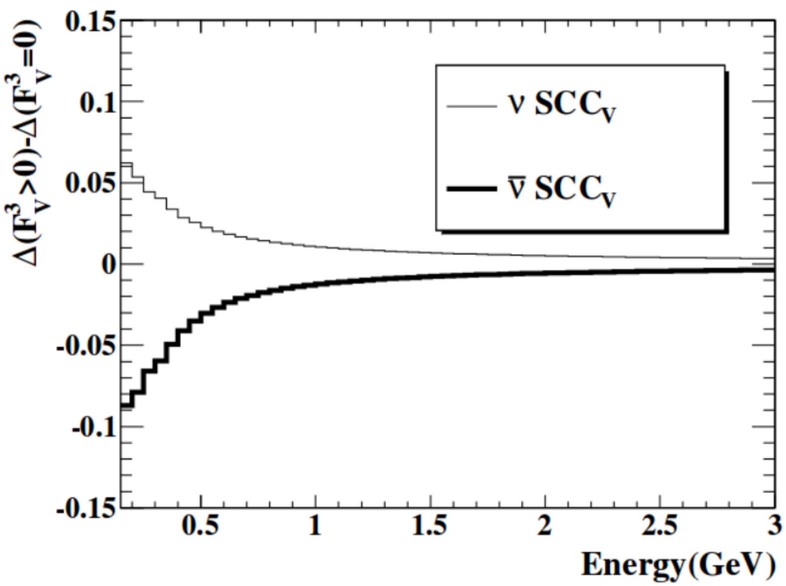
- ✓ Uncertainties from the **interplay** of
  - **radiative corrections**
  - **nucleon form factors**
    - F_P, $F_V^{1,2}$, F_A, second class currents
  - alteration of **kinematics** due to mass

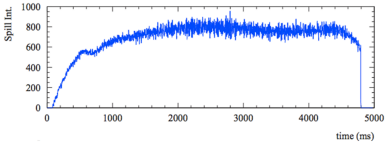
Day, McFarland, Phys. Rev. D86 (2012) 052003

→ Differences between $\sigma(\nu_\mu)$ and $\sigma(\nu_e)$ (Δ, δ)

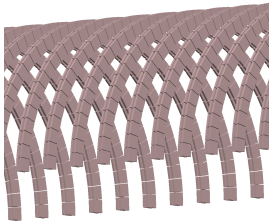
- can be **significant (10-20%) espec. at low-E**
- with **different energy trends for ν and $\bar{\nu}$**

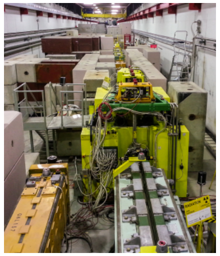




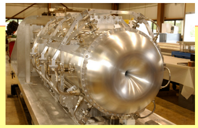


Working packages

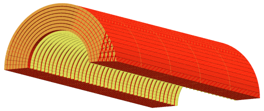




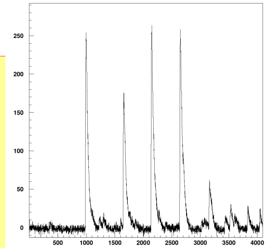
WP1: beam-line



Precise layout of the hadron beam. Study of the injection schemes.



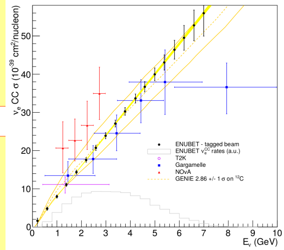
WP4: photon veto and timing system

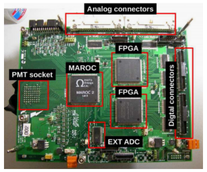


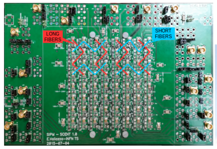
validating the timing accuracy of the tagger and the photon veto e^+/π^0 separation. Vertex reconstruction inside the tunnel. Pave the way to "tagged neutrino beams" (time synchronization studies with existing LAr or water Cherenkov prototypes).

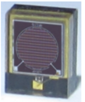
WP2: tagger prototype

Feasibility of tagging under realistic conditions with the desired background and systematics suppression. Radiation hardness.









WP5: systematic assessment

assessment. Overall flux systematics reachable by the exploiting the e^+ rate and the impact on a direct measurement of the $\sigma(\nu_e^{CC})$. Tagger simulation.

WP3: electronics and readout

testing the readout performances of the front-end electronics for horn-based (< 10 ms proton extraction) or static (1s proton extraction) focusing systems.

Choosing the $K^{\pm}/\pi^{\pm}$ momentum and tunnel length

1) keeping the tunnel "short"
2) increasing the $K^{\pm}/\pi^{\pm}$ energy

increases ν_e from K_{e3} with few ν_e from μ D.I.F.

Current scenario

p = 8.5 GeV/c ± 20%
L = 50 m

High momentum

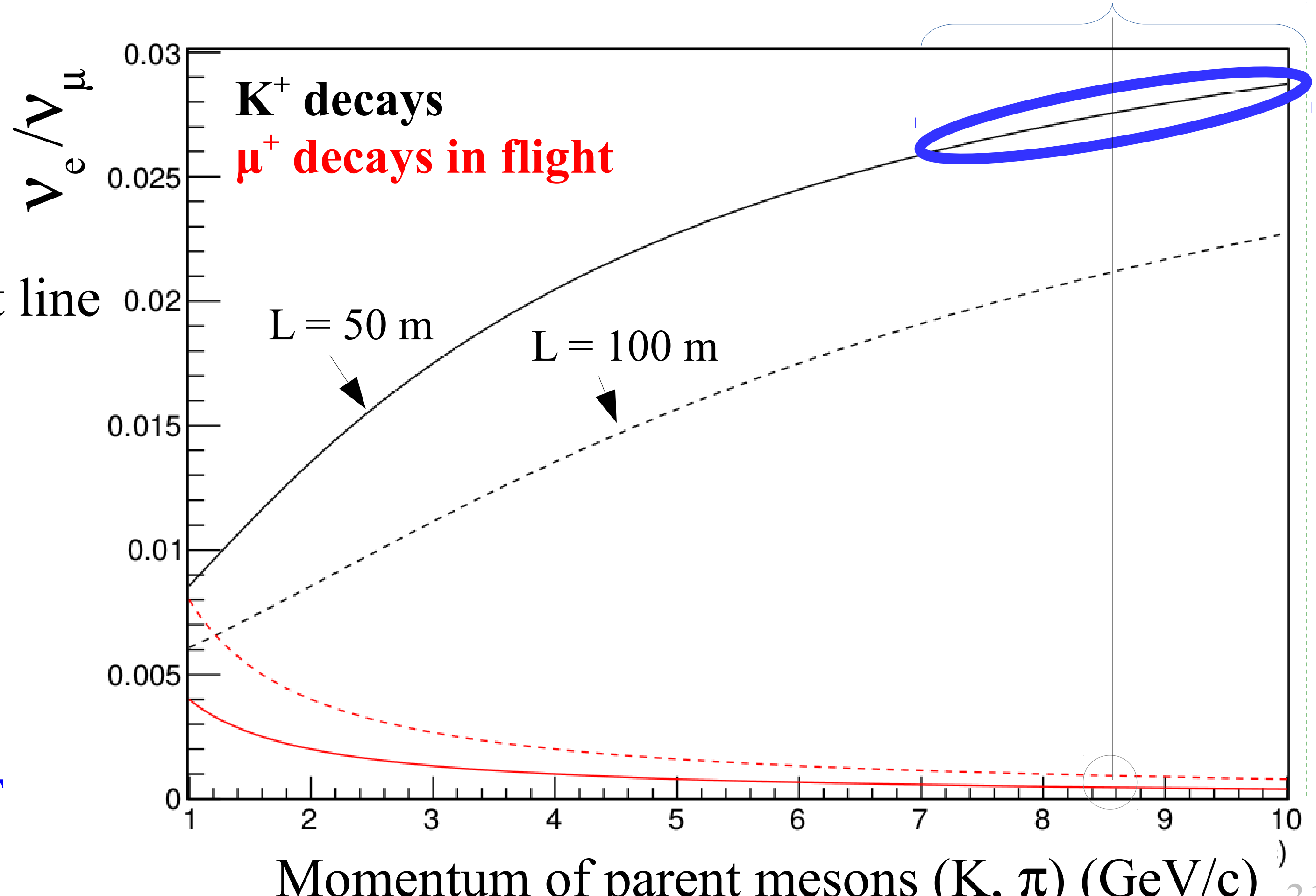
Benefits:

- 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

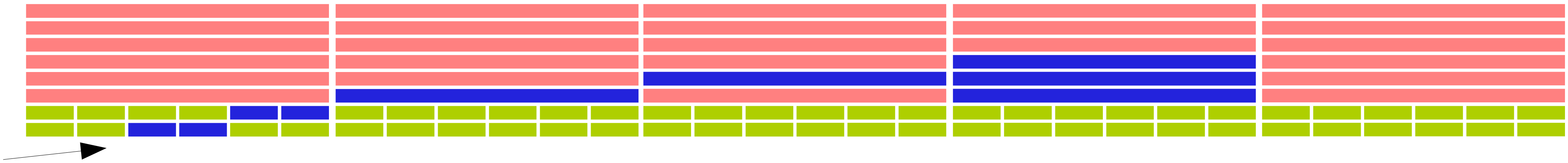
Hadronic modules
Electro-magnetic modules
Hit modules

Key point:

- longitudinal sampling
- perfect homogeneity → integrated light-readout

e^+ (signal) topology

π^0 (background) topology



π^+ (background) topology