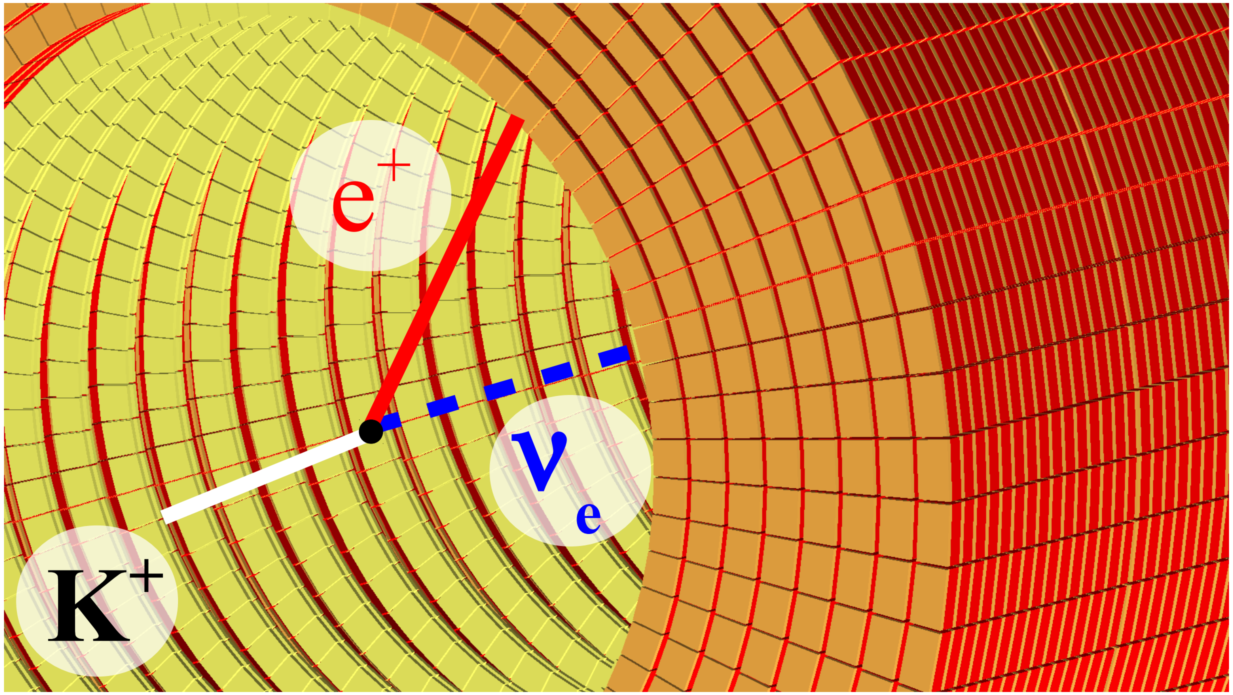
ENUBET

Enhanced NeUtrino BEams from kaon Tagging

A. Longhin (INFN-PD)

ENUBET kick-off meeting

Padova, 23 June 2016



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

The ENUBET physics case

A FUNDAMENTAL QUESTION

The role of neutrinos in the dominance of **matter over anti-matter** in our universe

THE MEASUREMENT

Find experimental evidence of **CP violation** in the leptonic sector

$$\left(\nu_\mu \rightarrow \nu_e\right) \neq \left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)\ ?$$

CP violating effects are **small**:
we need a **nearly perfect knowledge** of the **interactions of ν_e with matter**

THE OBSTACLE

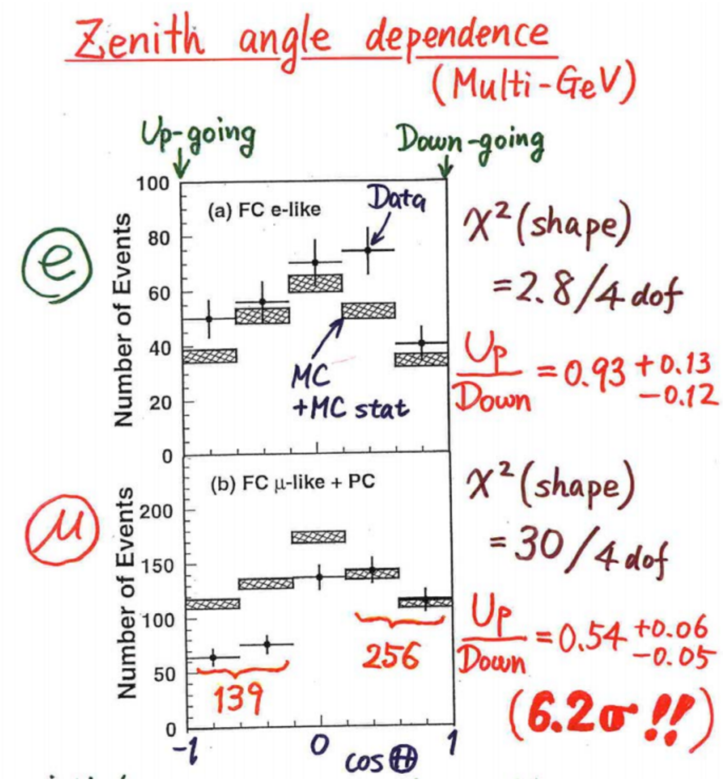
conventional ν_e beams are flawed by **O(10%) uncertainties**

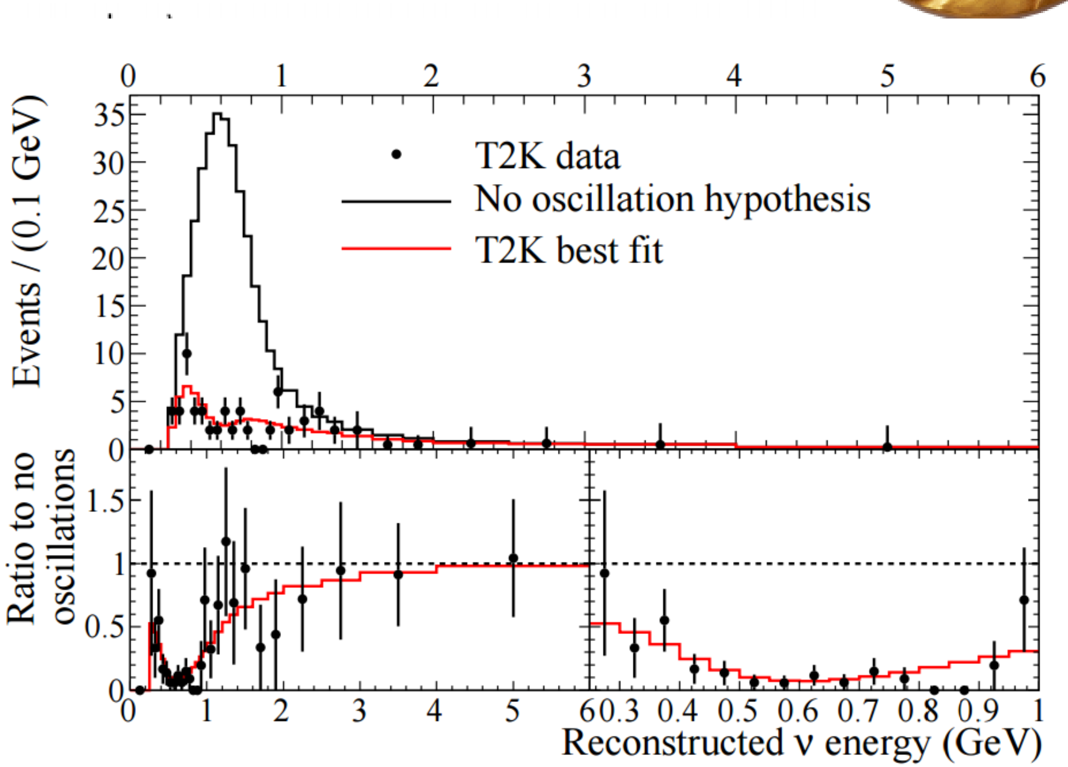
"The instrinsic limit": initial neutrino flux is not known well

Neutrino oscillations

"The discovery that neutrinos can convert from one flavour to another and therefore have nonzero masses is a major milestone for elementary particle physics. It represents compelling experimental evidence for the incompleteness of the Standard Model as a description of nature... Neutrino oscillations and the connected issues of the nature of the neutrino, neutrino masses and possible CP violation among leptons are today major research topics in particle physics."

A lot of progress and still a lot of interesting (and challenging!) physics





The “precision era” of ν physics

“atmospheric” Δm^2_{31} “solar” Δm^2_{21}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Super-K, K2K, MINOS, OPERA, T2K, NOνA

(D)CHOOZ, Daya Bay, RENO T2K, MINOS, NOνA

Super-K, SNO, GNO, Gallex, Borexino, KamLAND

$\theta_{23} = (45.8 \pm 3.2)°$
$\theta_{12} = (33.4 \pm 0.85)°$
$\theta_{13} = (8.88 \pm 0.39)°$

$\Delta m^2_{21} = (7.53 \pm 0.18)\ 10^{-5}\ eV^2$
$|\Delta m^2_{32}| = (2.44 \pm 0.06)\ 10^{-3}\ eV^2$

PDG2014

Open questions:

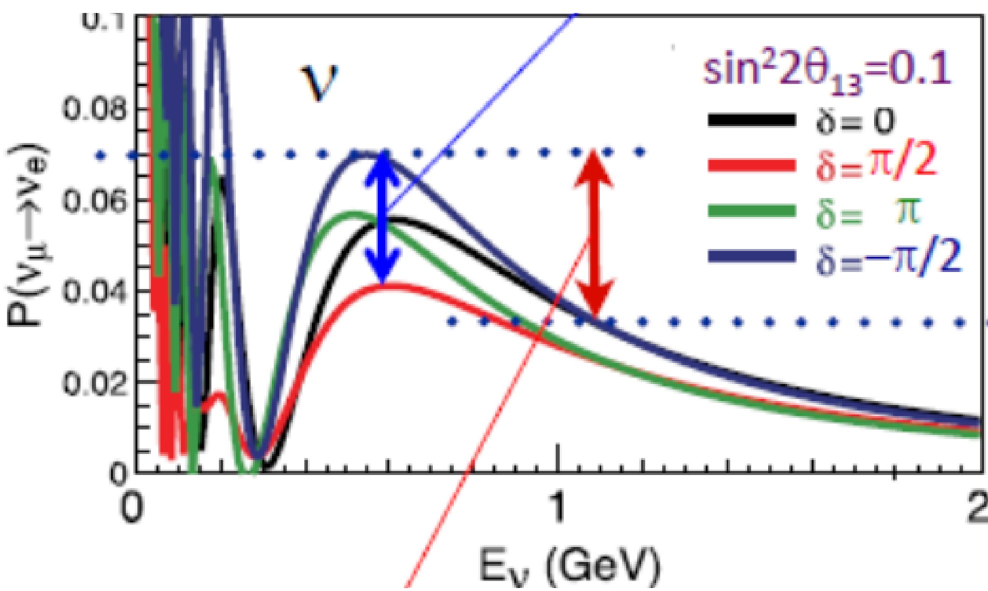
CP violation? mass hierarchy ($m_{1,2} \lessgtr m_3$)? $\theta_{23} = 45°$? Symmetries ? Relation with CKM ? Leptogenesis and BAU ? Majorana/Dirac ($0\nu\beta\beta$) ?

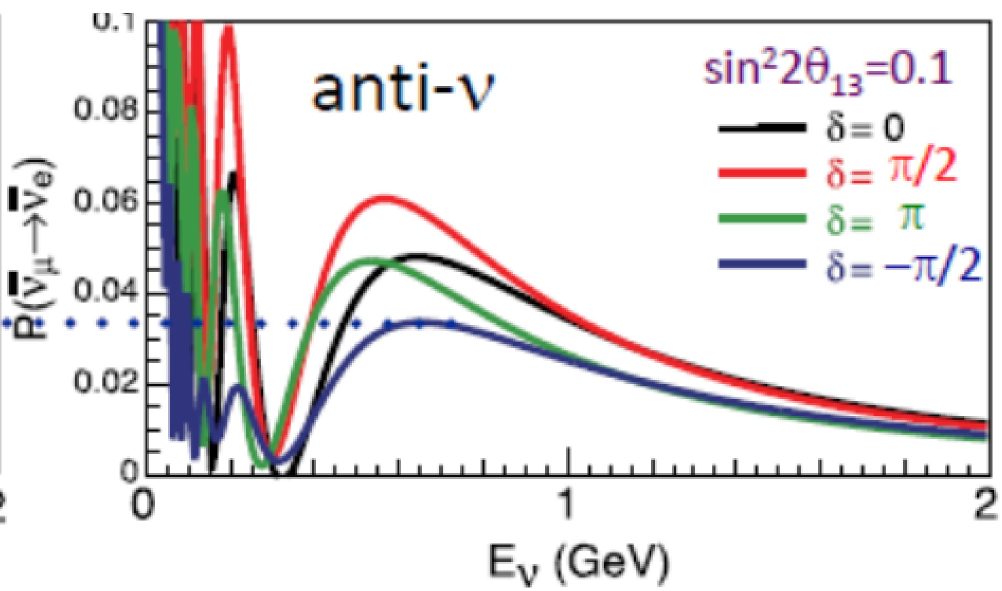
Learning a lot from (precisely!) measuring $\nu_\mu \to \nu_e$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) =& 4 c_{13}^2 \underline{s_{13}^2} s_{23}^2 \sin^2\Delta_{31} \quad \text{dominant term} \\
&+ 8 c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta_{CP} - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
&- 8 c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underline{\sin\delta_{CP}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \quad \text{CP violation} \\
&+ 4 s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta_{CP}) \sin^2\Delta_{21} \\
&- 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{aL}{4E_\nu}} (1 - 2 s_{13}^2) \cos\Delta_{32} \sin\Delta_{31} + 8 c_{13}^2 s_{13}^2 s_{23}^2 \underline{\frac{a}{\Delta m_{31}^2}} (1 - 2 s_{13}^2) \sin^2\Delta_{31} \quad \text{matter}
\end{aligned}
$$

- **θ_{13}**
- **CP violation,**
- **mass hierarchy**
  - matter effects at large L
- **the octant of θ_{23}**

- δ_{CP} affects the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation **in opposite directions**: exploit both!
- At the first oscillation maximum the effect is mainly a **change in normalization**

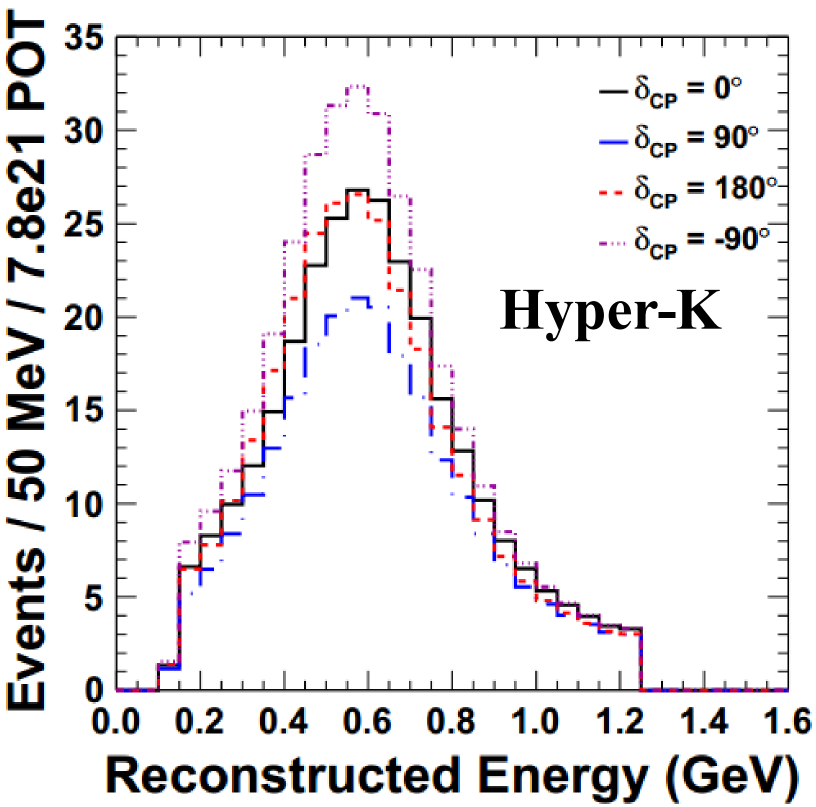


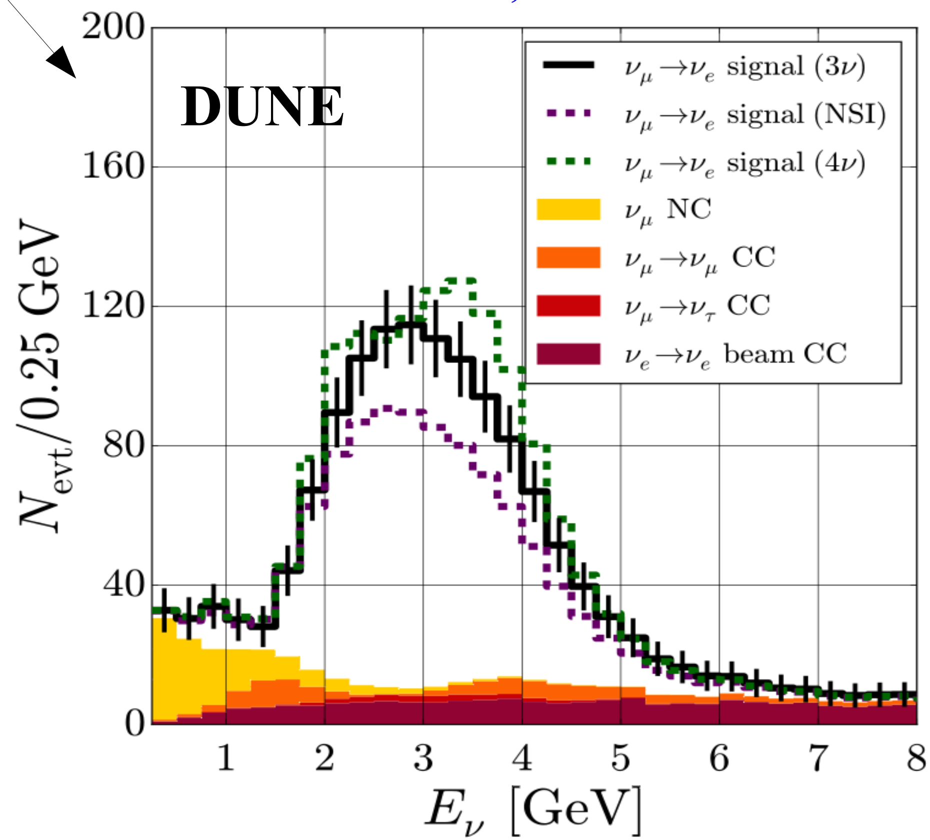


Why measuring $\sigma(\nu_e)$

- Leptonic CP violation, mass hierarchy, θ_{13}: $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- But we measure **interaction rates** of electron neutrinos
  - knowing well the ν_e cross section **crucial for future experiments** (HyperK, DUNE).
  - **Moreover** a perfect knowledge of $\sigma(\nu_e)$ vs E is a must to **unravel 3-flavour CP violation** from more **exotic scenarios** (sterile neutrinos, non-standard interaction -NSI- models). A similar phenomenology!

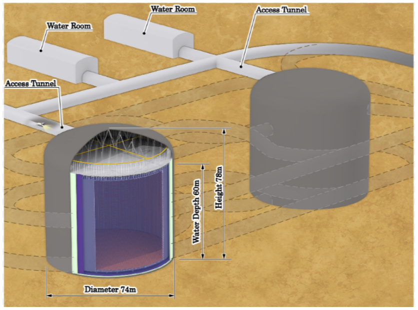
De Gouvea et al., 1605.0937





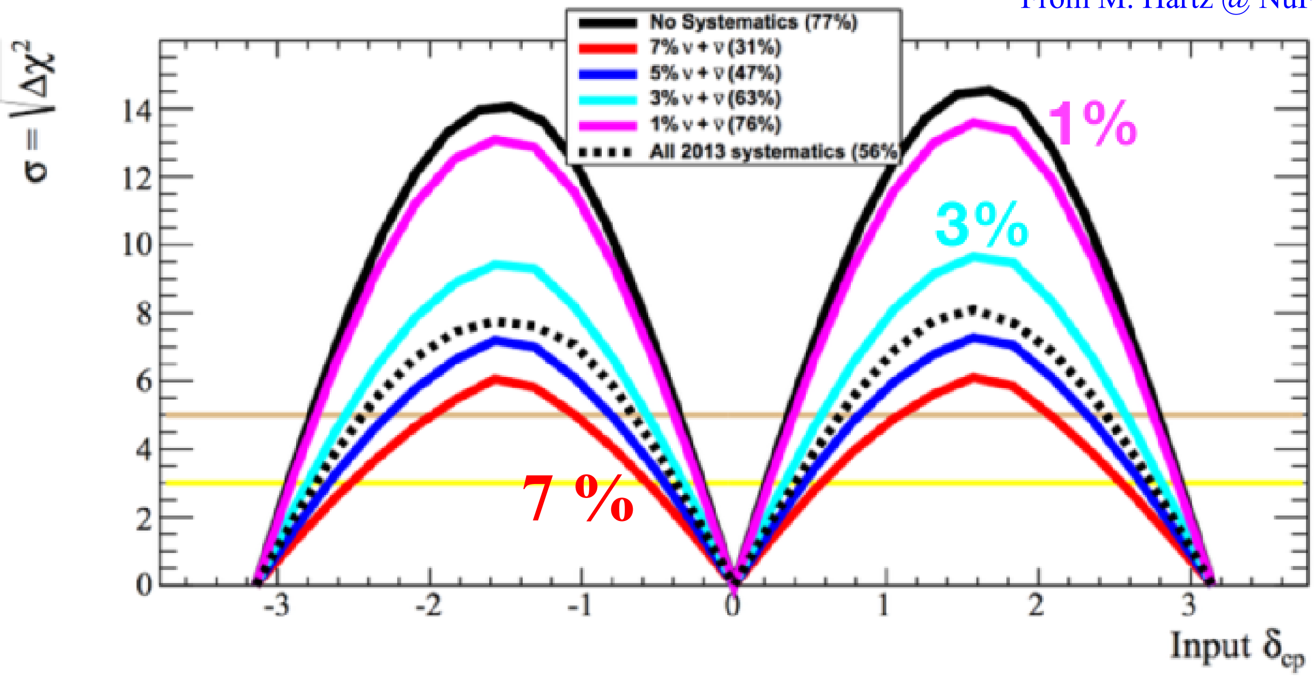
Impact of $\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$ at Hyper-K

Sensitivity study for the **discovery of CP violation**
$\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$: uncorrelated normalization systematics parameters
Uncertainty on the normalization parameters: {0, 1, 3, 5, 7 %}



From M. Hartz @ NuFact 2015

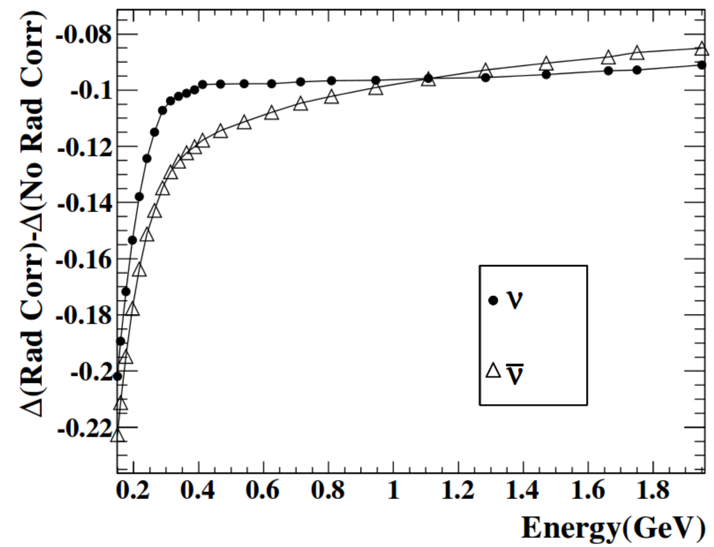
δ_{CP} values for which the curves are above N σ are those for which it is possible to discover CP violation ($\sin\delta_{CP}$!= 0) with N σ confidence.

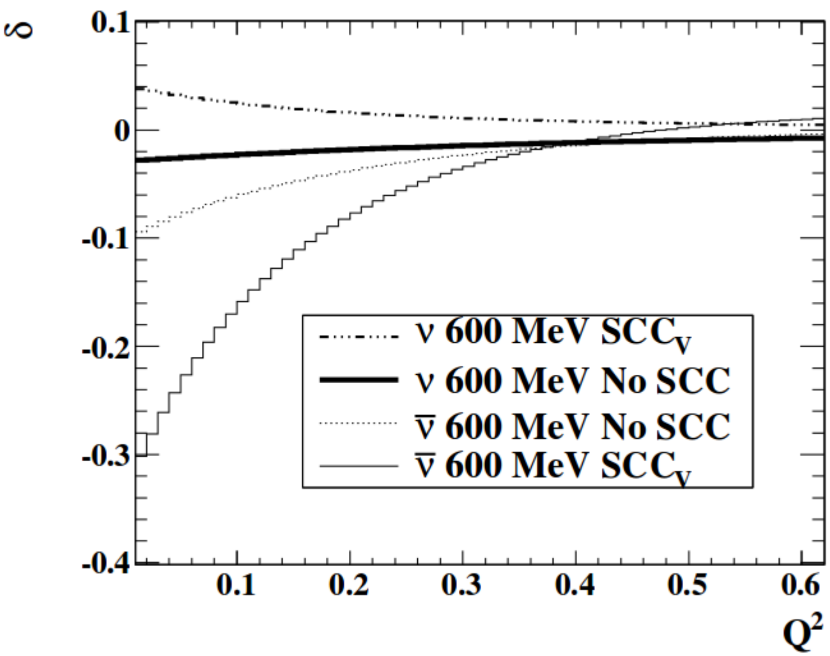


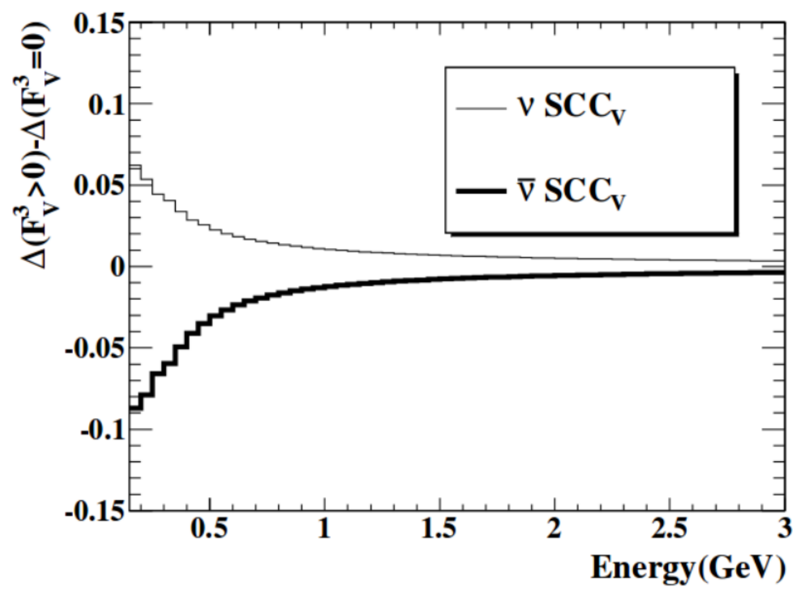
The systematic uncertainty should be controlled to < 1-2% to **minimize the impact on the CPV discovery sensitivity** → probe smaller and smaller values of $\sin\delta_{CP}$

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

- No...0) also **$\sigma(\nu_\mu)$ is poorly known** (and ENUBET will contribute also in that direction)
- 1) Differences in quasi-elastic cross sections of μ and *e* neutrinos. Phys. Rev. D86 (2012) 052003
- **Lepton universality** in weak interactions is **not the full story**:
  - ✓ Uncertainties from the **interplay** of
    - ✓ **radiative corrections**
    - ✓ uncertainties on **nucleon for factors**
      - ✓ F_P, $F_V^{1,2}$, F_A, second class currents
    - ✓ alteration of **kinematics** due to mass
- Differences (Δ, δ) can be
  - Significant (10-20%) espec. at low-E, Q^2
  - different for neutrinos and anti-neutrinos!

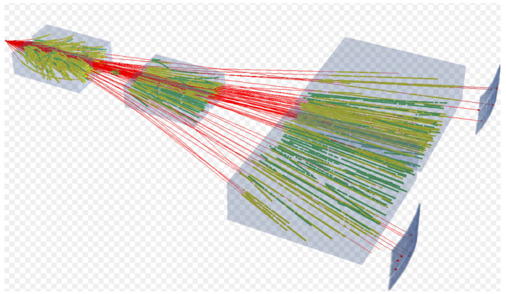




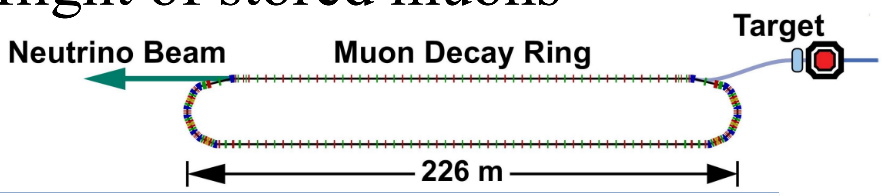


The ENUBET approach

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



- no absolute cross section with precision better than ~10%
  - Mitigation (in place): **hadro-production experiments**. (SPY, HARP, NA61)
  - Use **interactions with electrons** as a standard candle process to determine the flux ? tiny cross section
- ν_e cross sections are sparse (Gargamelle, T2K, NovA), from ν_e contamination
  - **we do not have intense sources of ν_e in the GeV energy range**
  - (ideal) solution: i.e. beams from decay in flight of stored muons (**NUSTORM**)



ENUBET approach: 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**

Tagged neutrino beams: the origins

The "forbidden dream" 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 ($\pi/K \to \nu_\mu$)
- G. Vestergombi, 1980, R. Bernstein, 1989 ($K \to \nu_e$)
- 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 $\sigma(\nu_e)$**
- taking advantage of the progress in **fast, cheap, radiation-hard detectors**
- using **$K^+ \to e^+ \pi^0 \nu_e$** (K^+_{e3} decays)

The ENUBET breakthrough

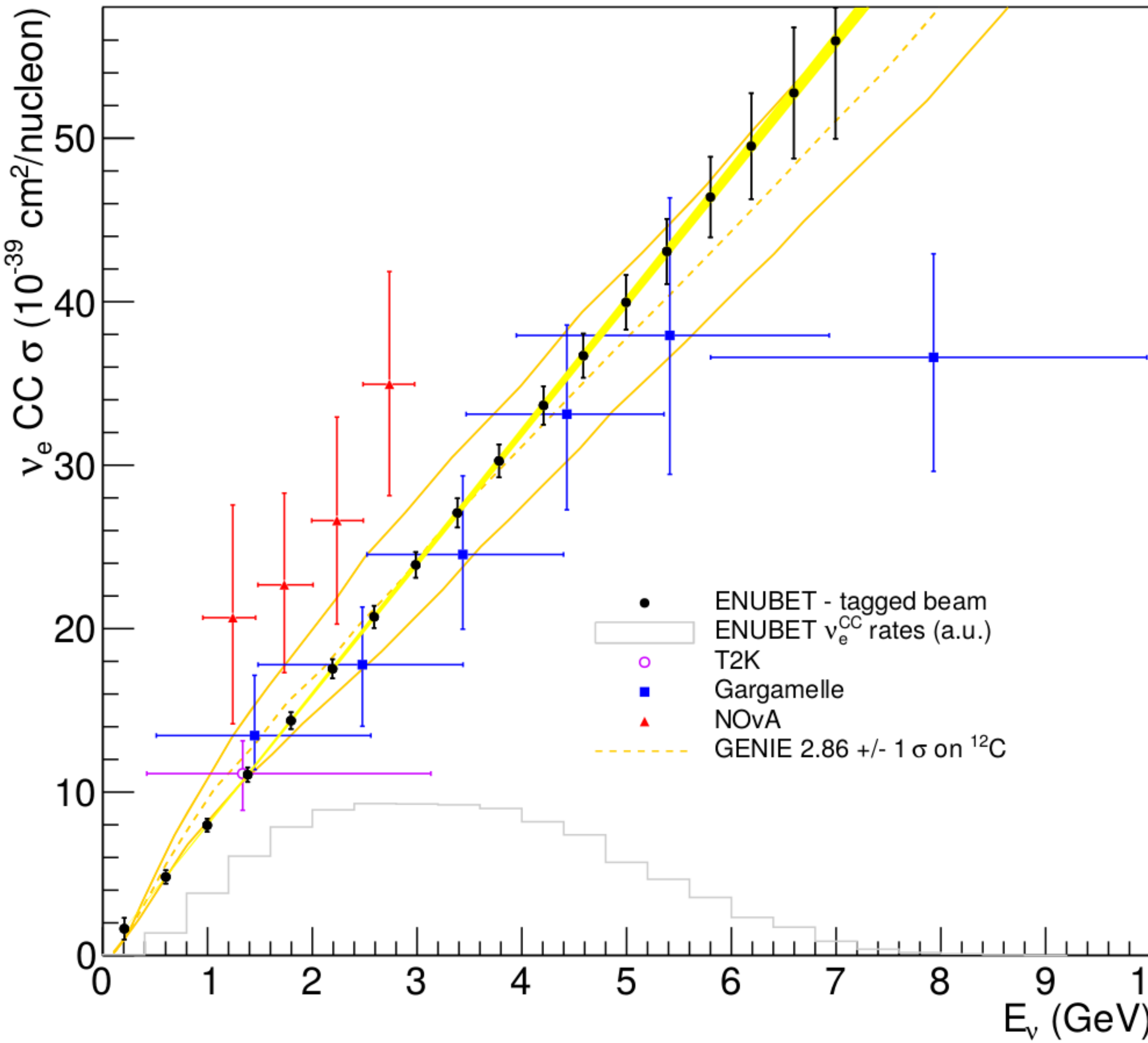
A new-concept ν_e **source.**

× 10 better precision

→

ν_e cross-section at 1% systematic error and 1% overall statistical error (10.000 events).

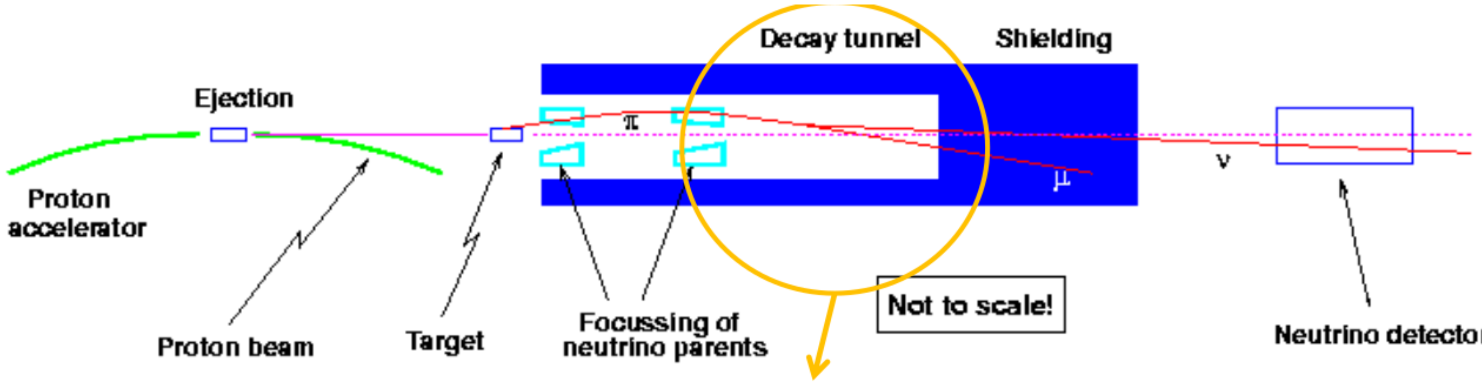
NB. no measurements for **$\sigma(\bar{\nu}_e)$** to date! Green field.



OK, but ...

Inside a neutrino beam tunnel

A traditional neutrino beam:



Consider **a beam of collimated pions and kaons selected in sign and momentum**

$p = 8.5$ GeV $\pm$ 20 %, 3 mrad in 10×10 cm^2 window [$\varepsilon_{xx'} = \varepsilon_{yy'} = 0.15$ mm $\times$ rad] (see below)

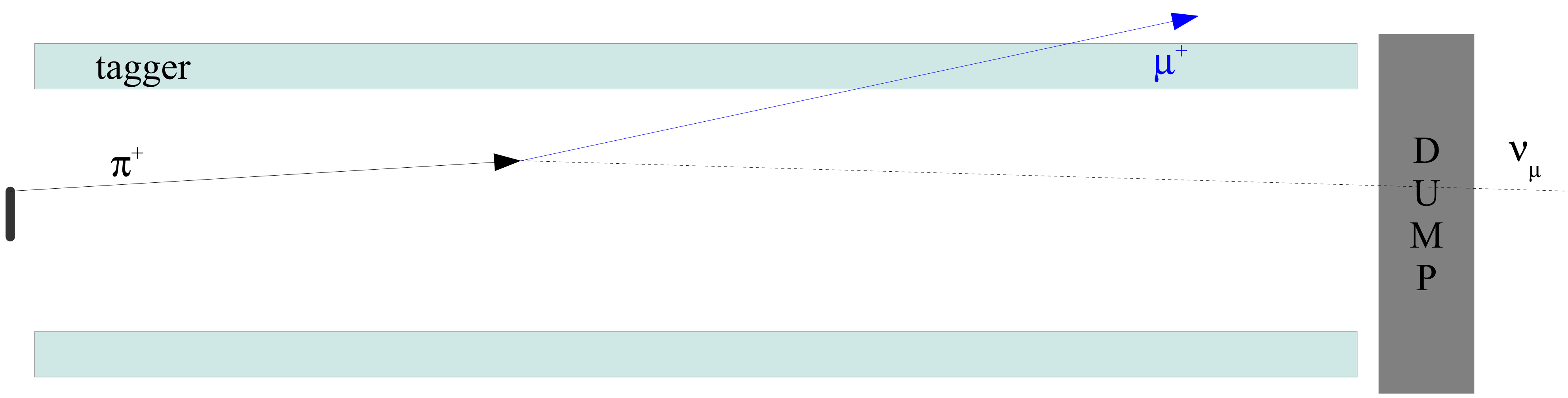
Collimation allows having only decay products in the tagger. Not decaying primaries are absorbed in the dump. This allows **tolerable rates** and good **S/N** (**not true** in conventional beams → **crucial role of the hadron beamline**)

Inside a neutrino beam tunnel: $\pi^+ \to \mu^\pm \nu_\mu$

- Mostly pions (~95% @ 400 GeV protons) with a ~100% BR to muons
- Creates the bulk of $\boldsymbol{\nu_\mu}$
  - The **neutrino detector must have good $\boldsymbol{\nu_e}$ PID** to avoid contamination of NC π^0 in the ν_e^{CC} sample

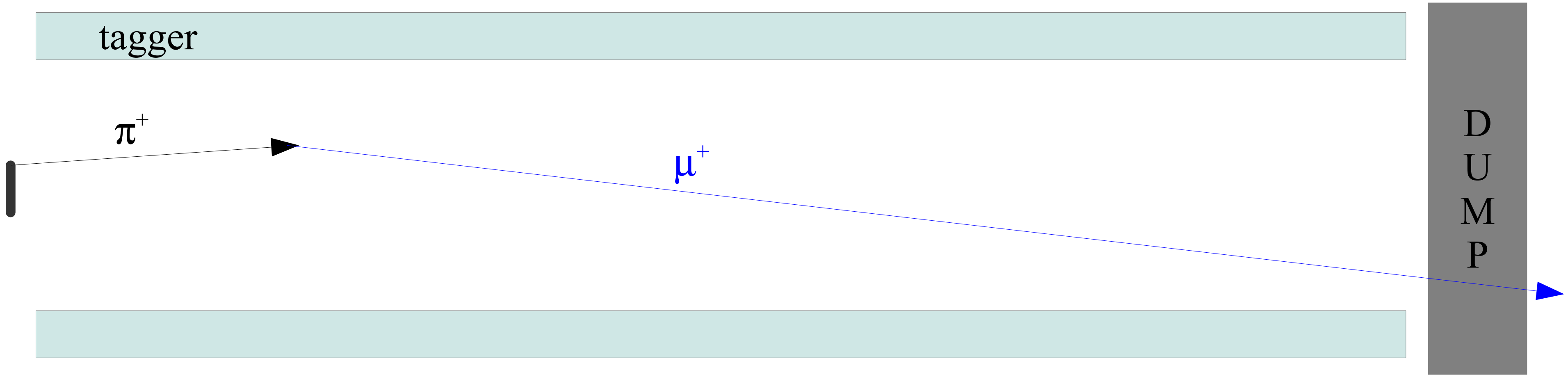
$$\frac{\Phi_{\nu_e}}{\Phi_{\nu_\mu}} = 1.8\ \%\ (\nu_e \text{ from } K_{e3})$$

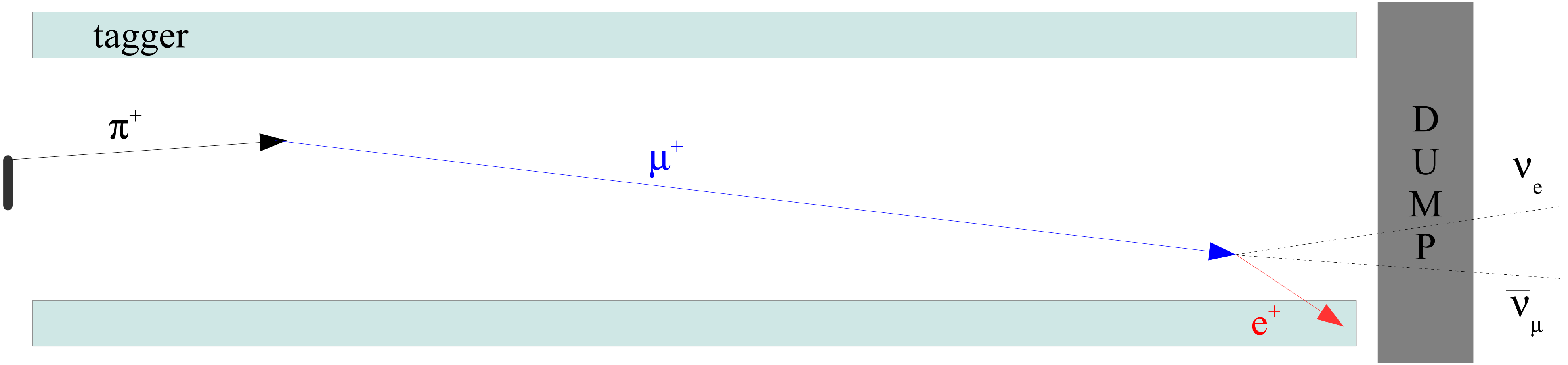
- 2-body decay kinematics, $m_\mu \sim m_\pi$
  - $\mu^+ \sim 4$ mrad (low acceptance in the tagger)
- μ^+/e^+ discrimination relatively **easy**



Inside a ν beam tunnel: decays in flight of μ

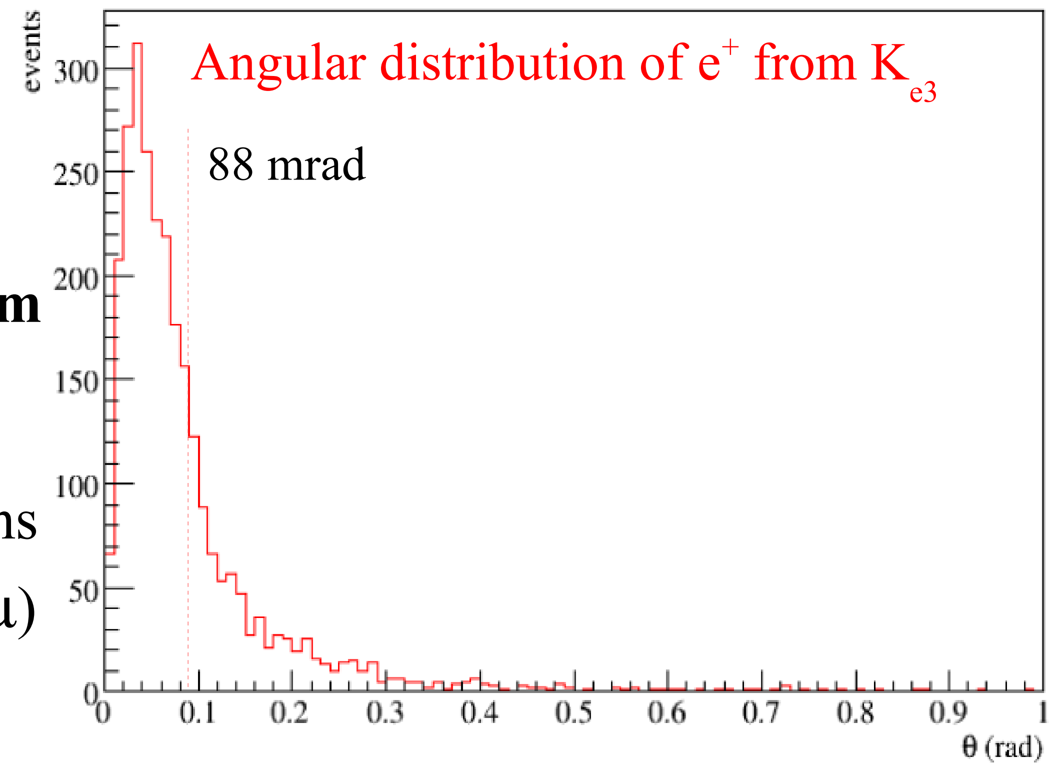
- **3-body** decay kinematics but $\mathbf{m_\mu \sim 0.2\, m_K}$
  - $e^+_{DIF} \sim 28$ mrad ($e^+_{Ke3} \sim 88$ mrad)
- Produce ν_e and anti-ν_μ in the neutrino detector
- **Suppressed by long μ decay path** (see later): $\boldsymbol{\nu_{e,}^{CC,DIF} \sim 3.3\%}$

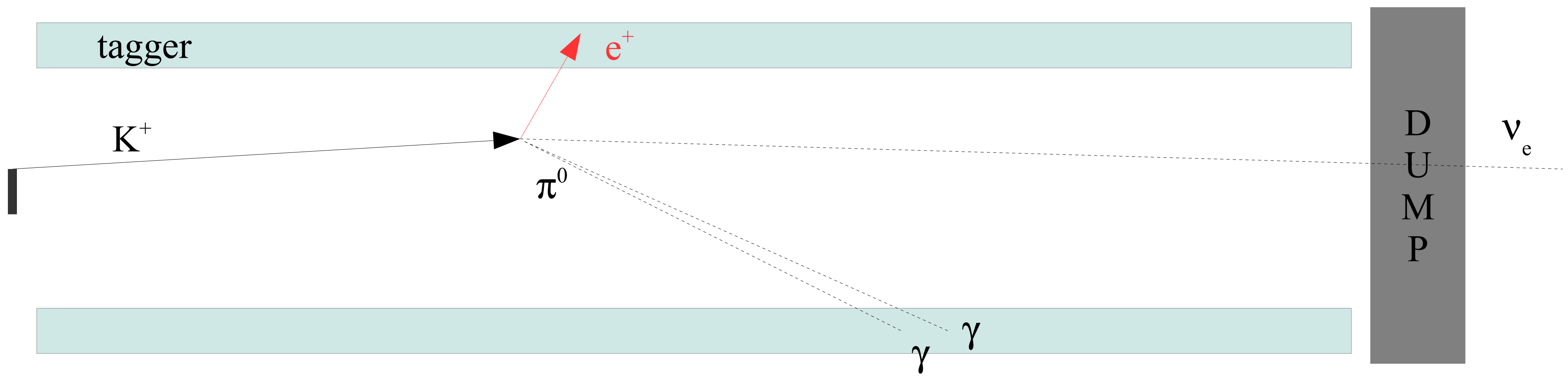




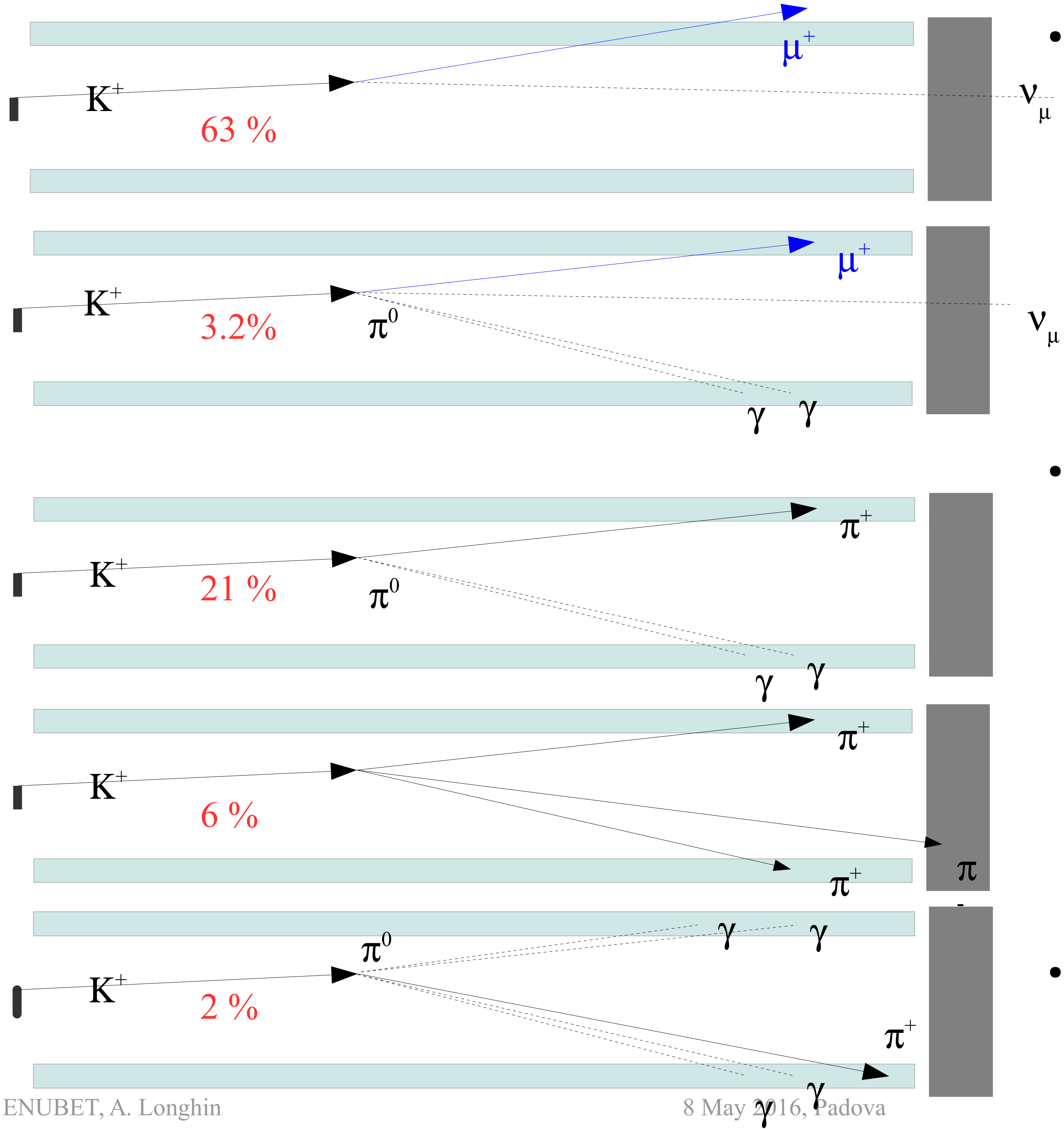
A ν_e source based on $K^+ \to \pi^0 e^+ \nu_e$

- Good tagging efficiency for e^+ from K_{e3} thanks to the **large emission angle**
- Practically **all electron neutrinos are from K_{e3}** (only a minor contamination from muon deays in flight)
- On the contrary ν_μ come mainly from pions which are not directly tagged (low-angle μ)





Inside a ν beam tunnel: other K decays



- $\pi^{+/0}$ can mimic an e^+ signal → must be **discriminated** !
  - **1)** rejection in the tagger +
  - **2)** vertexing with timing σ_t O(100 ps) ~ σ_{zVTX} O(1m) vetoing π^+ from the decay vertex rejects fake e^+ from $K^+ \to \pi^+\pi^-\pi^+$ and $K^+ \to \pi^+\pi^0$
- NB. **K decays are the only pion source in the tagger →** not simply a "background": a **π "control sample"** can be used with the **K_{e3} "golden sample"** to infer the **ν_e flux**

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

  2) $\phi(\nu_e) \sim N(\pi^+)/BR_{K\to\pi X}$
- Will be fully investigated **in ENUBET WP5**

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

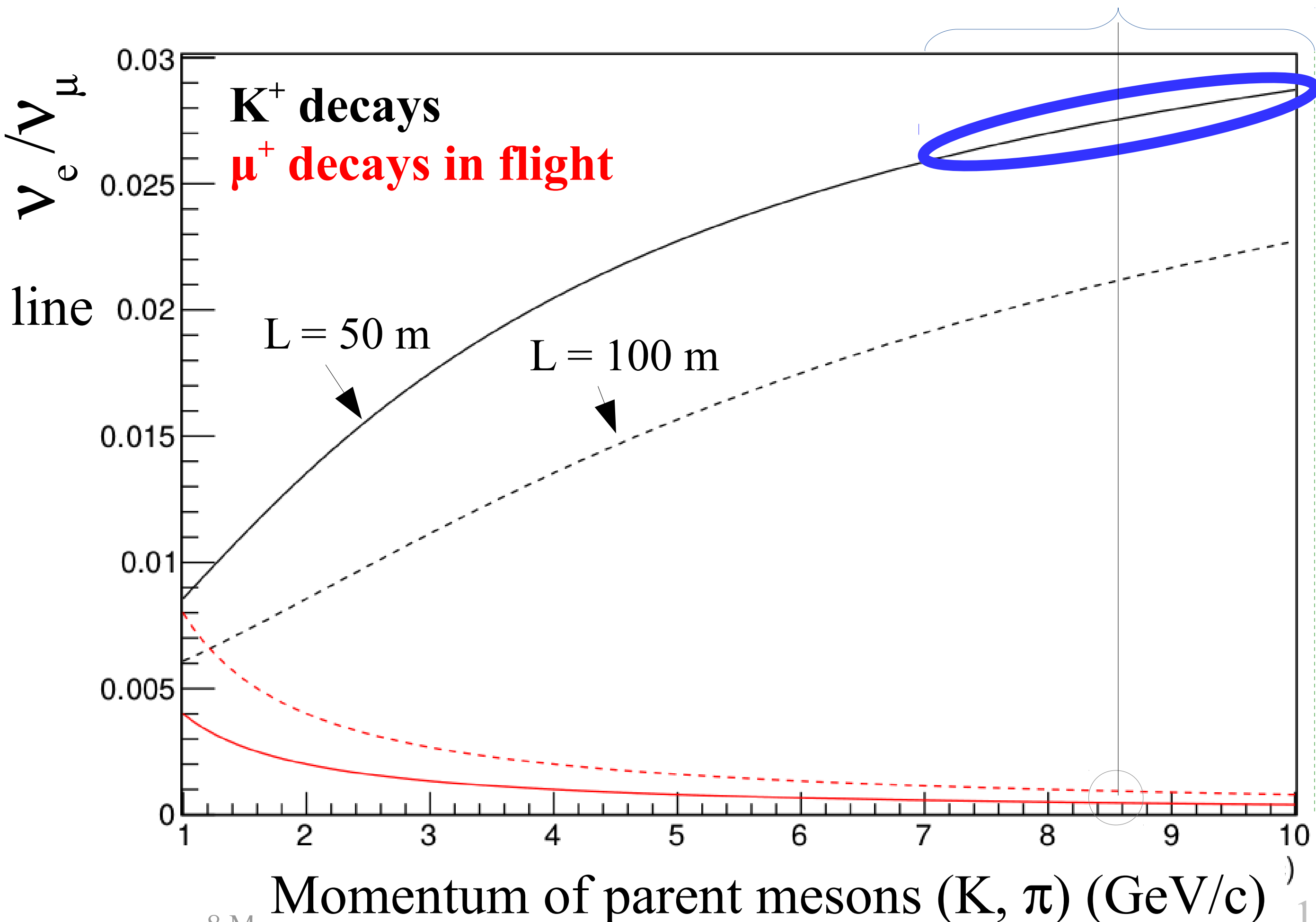
$p = 8.5$ GeV/c $\pm$ 20%
$L = 50$ m

High momentum

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

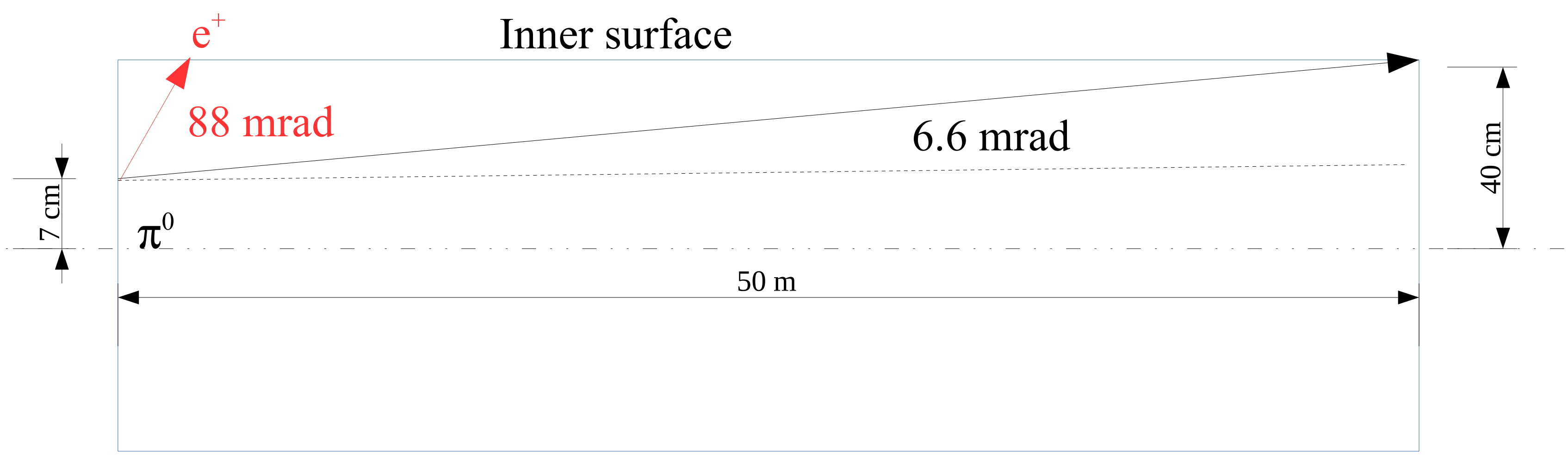
Costs:
- $E(\nu_e)$ above the R.O.I.
- longer decay region

A trade-off: further optimization in ENUBET

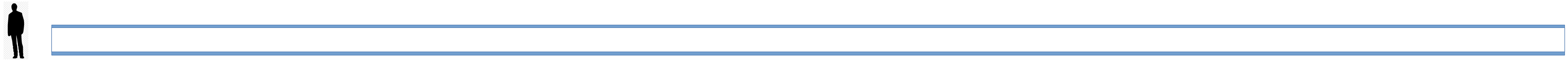


Final dimensioning of the tagger

- Determined by **realistic requirements in the hadron beam emittance** combined with the **need to keep primary mesons away from the tagger**

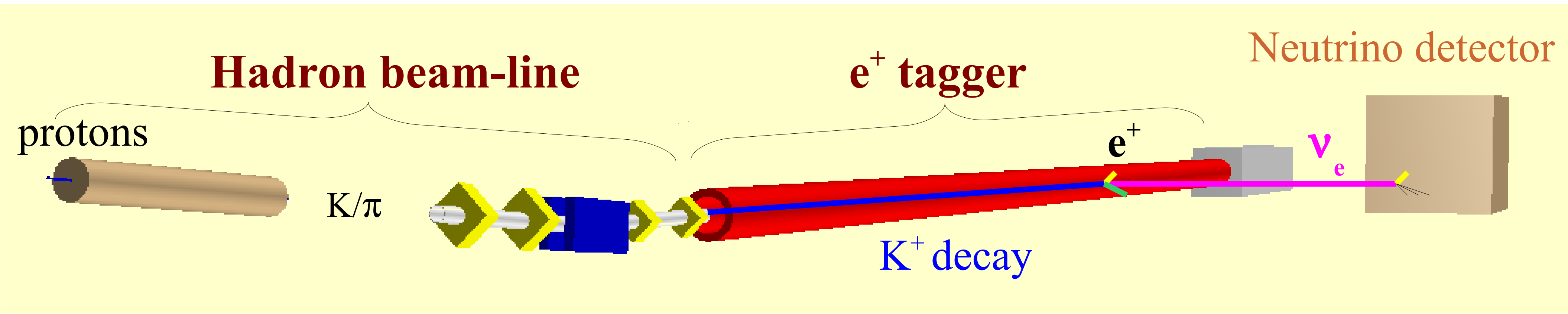


- The radial depth (~ 20 cm) is determined by requiring full hadronic containment of the highly "inclined" pions



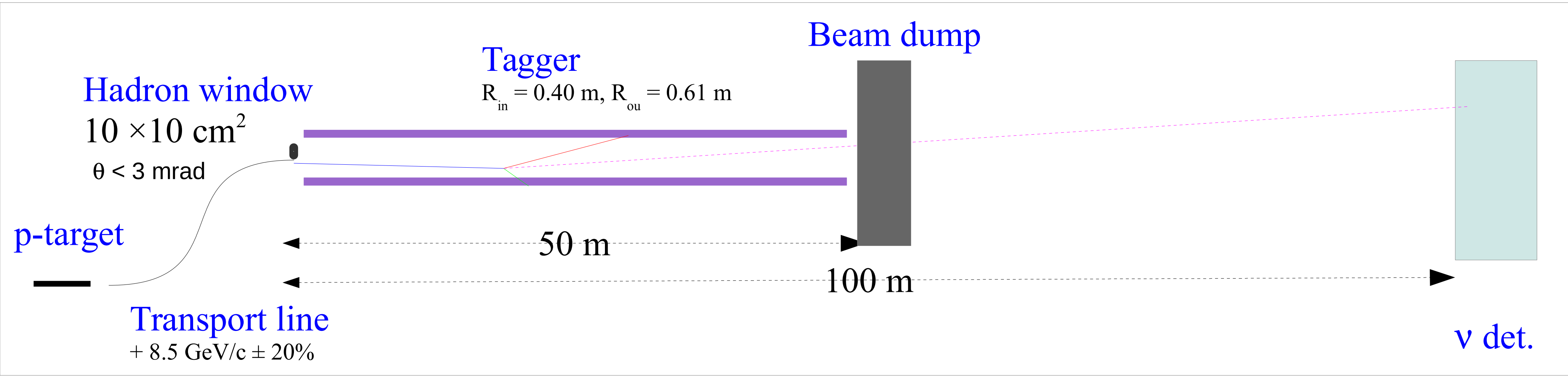
Towards the first tagged ν_e beam

A specific setup to implement this idea proposed in:
A. Longhin, F. Terranova, L. Ludovici ***Eur. Phys. J. C (2015) 75:155***

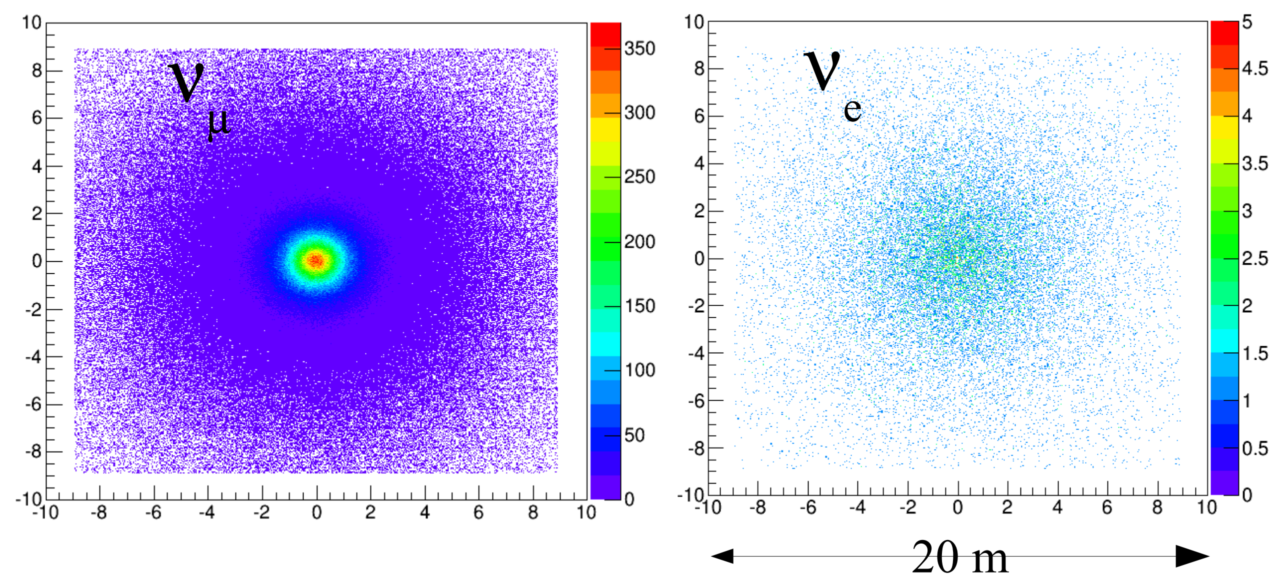


- **Hadron beam-line:** collects, focuses, transports K^+ to the e^+ tagger
- **e^+ tagger:** real-time, "inclusive" **monitoring** of produced **e^+**

Full layout and neutrino yield



Radial profiles at the ν detector (z = 100 m)



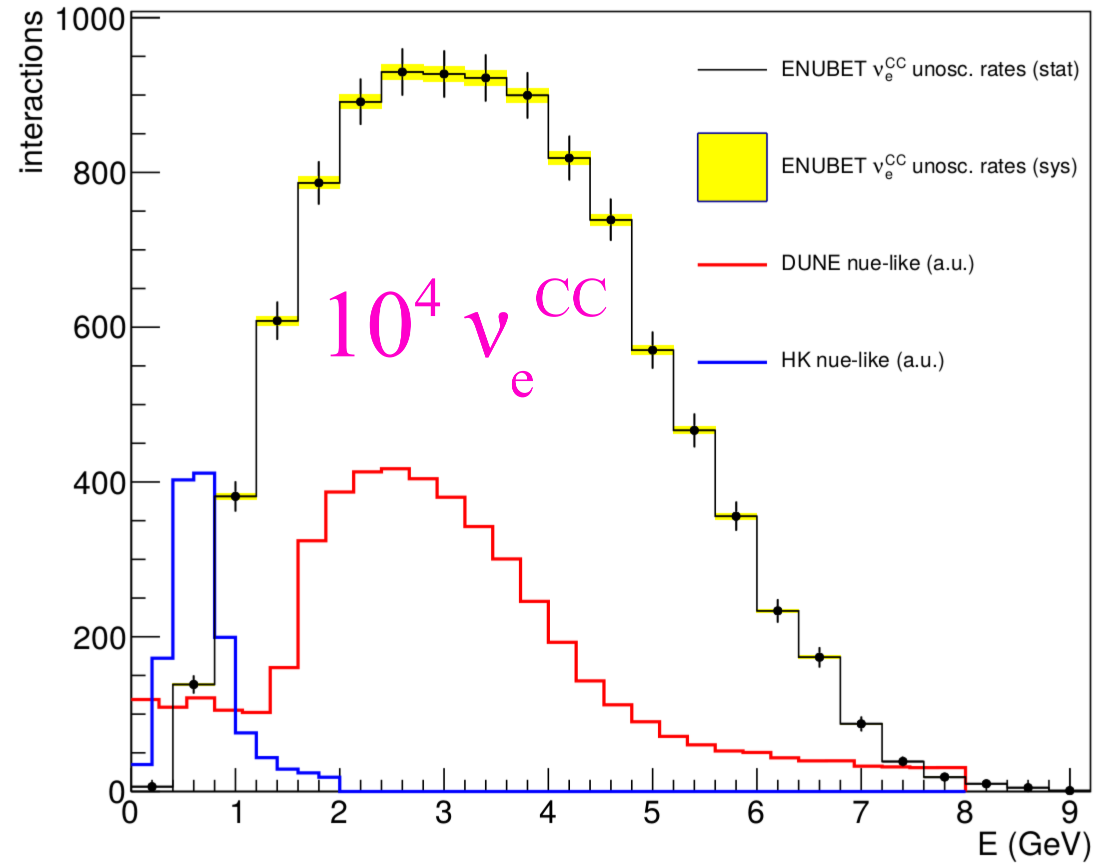
- **tagger geometrical acceptance:** 85% of ν_e at detector with a tagged e^+ (forward "hole")
- M = 500 t →

$1.95 \times 10^{13}\ K^+/\nu_e^{CC}$

ν detector and ν_e^{CC} rates

- At 100 m from the hadron window
- A 500 t mass (< ICARUS T600)

<E> = 3 GeV, FWHM ~ 3.5 GeV



- Interesting region of long baseline future projects is covered
- Further tuning foreseen within ENUBET to go even lower in energy preserving an acceptable positron purity

Calorimetric e^+/π^+ separation

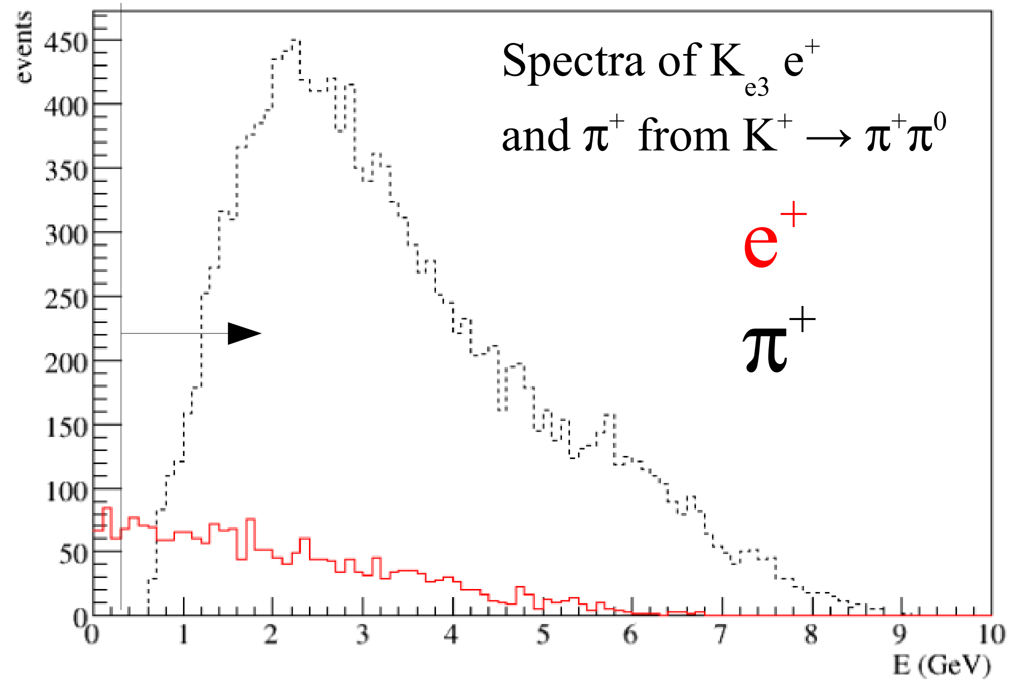
Defining $E_{1,2}$ as the E deposited in a cylinder w.

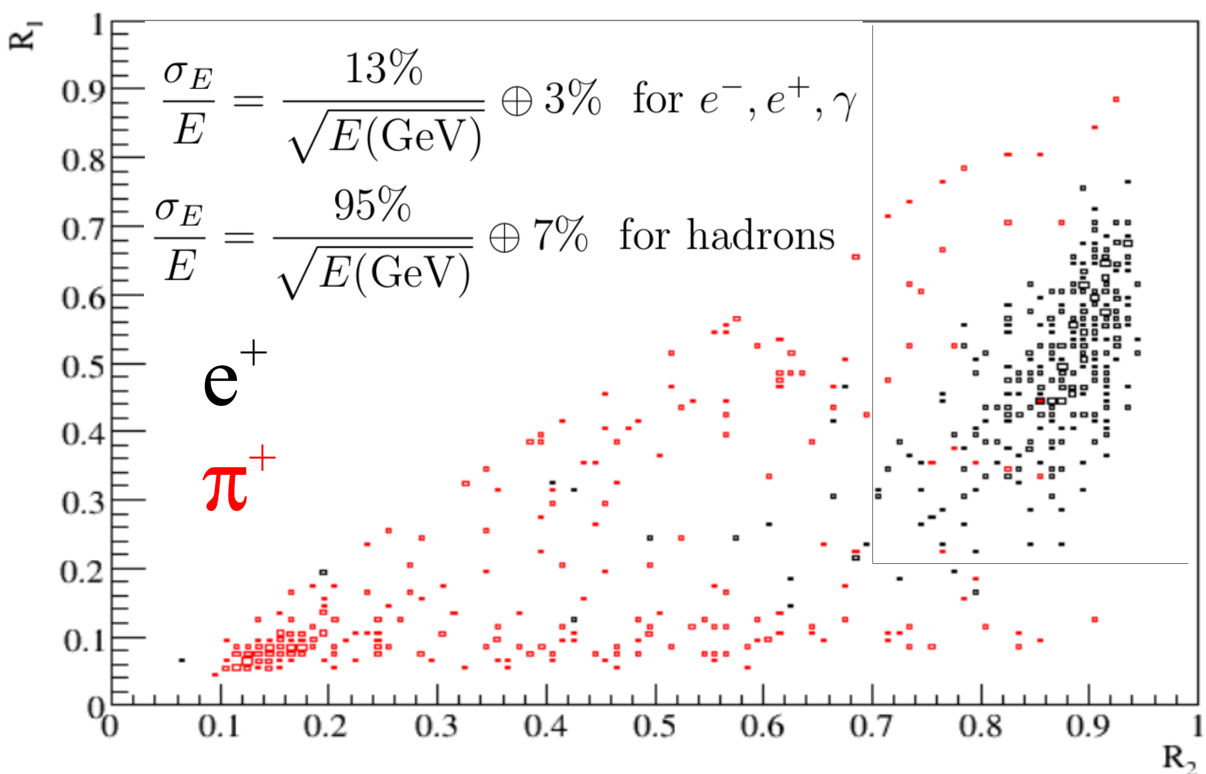
- $r = 2R_{Moliere}$ (3.2 cm for Cu)
- $h = 5$ and $10\ X_0$ (7.2 and 14.4 cm)

Selection:

- **$E_{tot} > 300$ MeV**
- **$R_1 = E_1 / E_{tot} > 0.2$**
- **$R_2 = E_2 / E_{tot} > 0.7$**

Cut	Efficiency
K_{e3} decay	100%
e^+ in calorimeter	85%
R_1,R_2 cuts	67%
$E_{tot} > 300$ MeV	59%





Preliminary background budget

- $\varepsilon(\mu^+ \to e^+) \sim 10^{-3}$
- $\varepsilon(\pi^+ \to e^+) = 2.2$ % → 18 % of fake e^+
- $\varepsilon(\pi^0 \to e^+)$ tagger in vacuum (as for NA62 LAV). Conversions in the γ veto.

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

Additional improvements from exploitation of vertexing with timing not included

Systematics on the ν_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 beams**
Detector backg. From NC π^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

The ENUBET program

ENUBET aims at demonstrating that the outlined program is feasible in practical terms

Two pillars:

- 1) e^+ **tagger** proto. validated with **particle beams**
- 2) a detailed design for the **hadron beam-line**

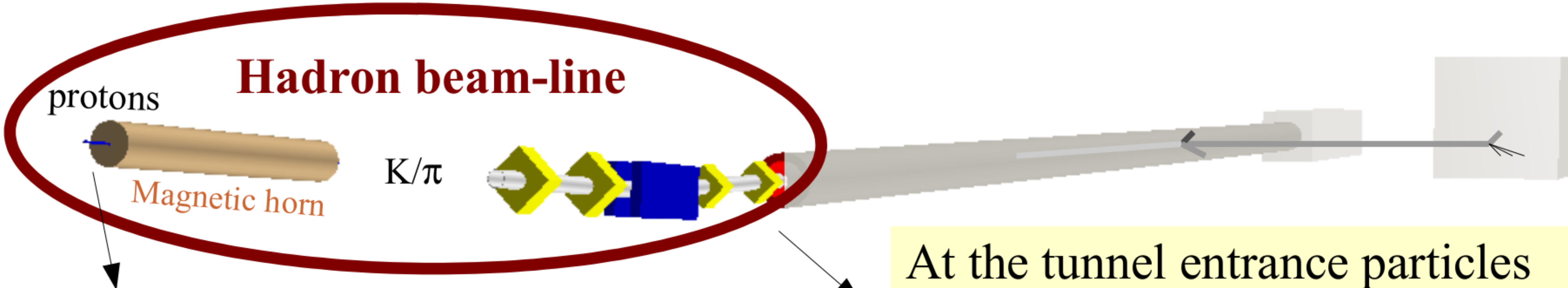
The complete picture to move forward

By-products:

- **calorimetry** → new low-cost, ultra-compact detectors
- **accelerator physics solutions** → novel proton extraction schemes for fixed-target and beam-dump experiments

1) The hadron beam-line

The hadron beam-line challenge



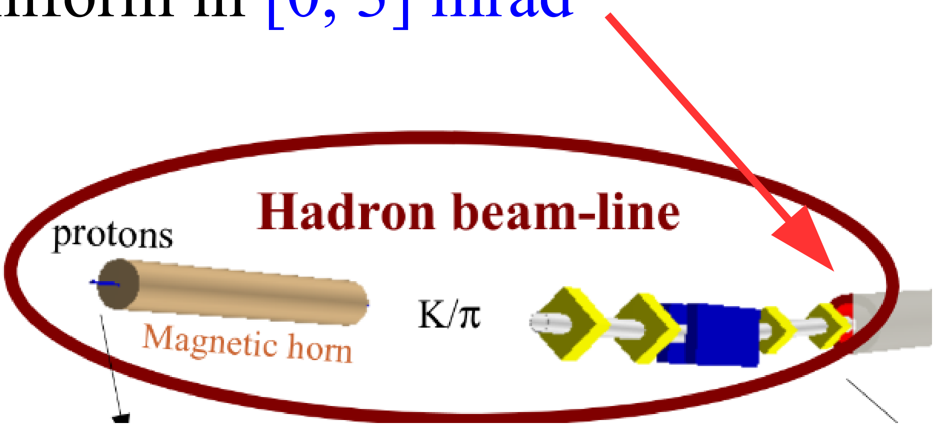
The proton extraction must be efficient and **“slow”** (saturation)

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

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**

Requirements in terms of collimation and momentum selection

- Secondary K^+ and π^+ have to be captured, sign-selected and ("quickly") transported into the e^+ tagger
  - Beam-line length: ~10 m induces a 16% loss from early decays
  - 8.5 GeV/c ± 20 % momentum bite (previous slide)
- We want only decay products in the tagger (to cope with tagger rates)
  - particles distributed over a 10×10 cm^2 window
  - $dN/d\theta$ uniform in [0, 3] mrad

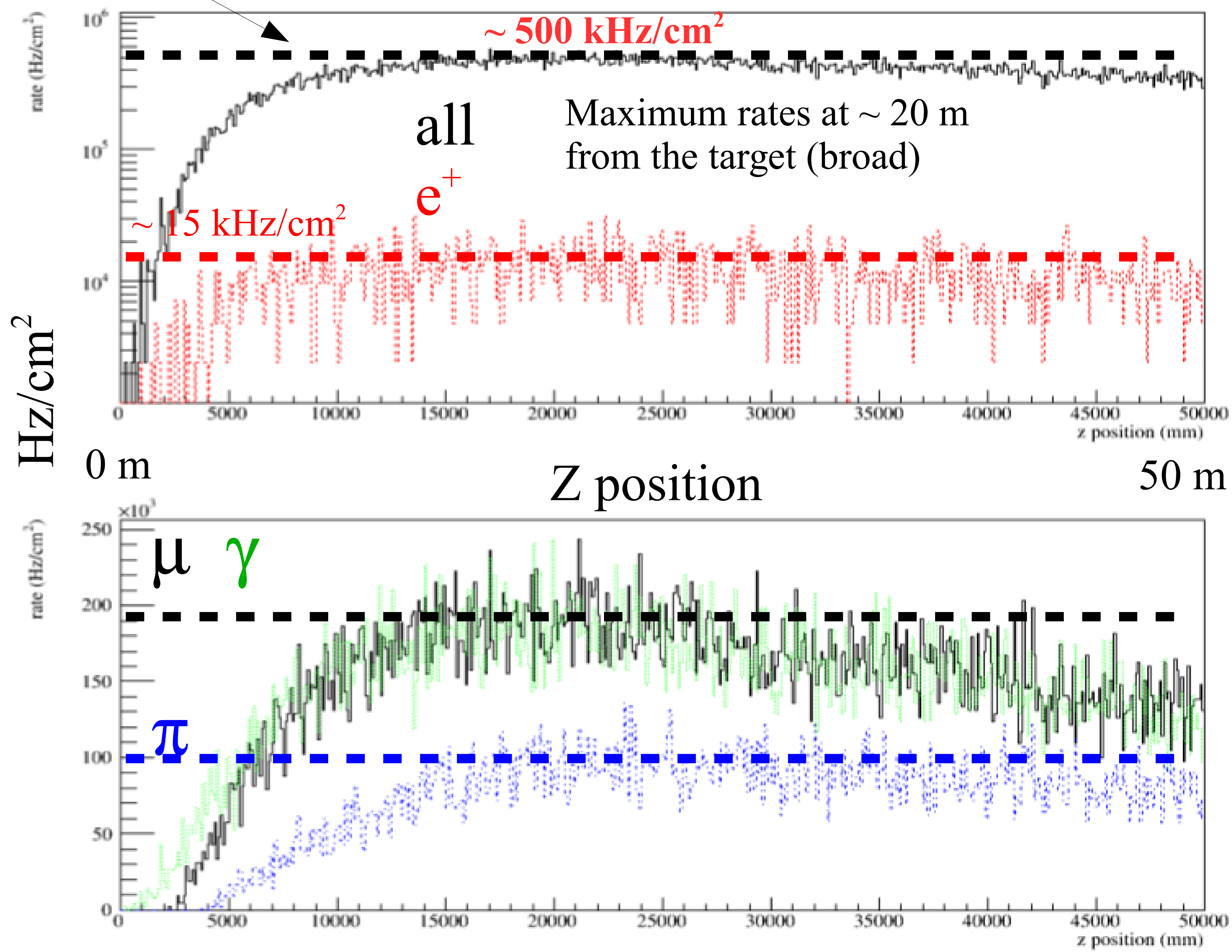


Particle rates in the tagger

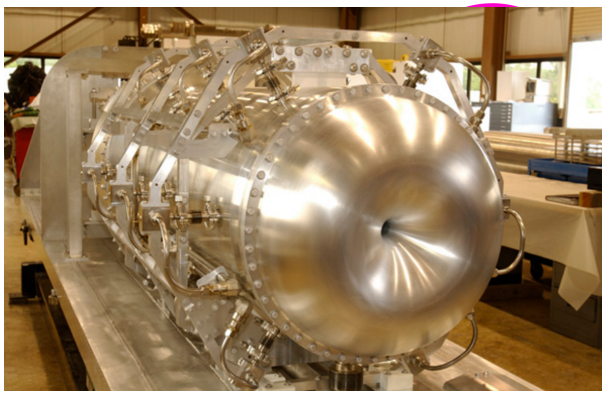
Injecting **10^{10} π^+ in a 2 ms** spill at the tunnel entrance (hadron window) the peak rate hits 500 kHz/cm²

	Max rate (kHz/cm²)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

Manageable with a proper choice of the detector technology



Hadron beam-line: scenario A



- Magnetic horns. Good collection. Pulsed devices.
- $T_{impulse} < 10$ ms (Joule heating, I ~ O(100) kA)
- Can give 10^{10} π^+ in 2 ms (~ tagger rate limit) →
- Given the horn efficiency → how many PoT/spill does it correspond to?
- Given 1.94×10^{13} K^+ / ν_e^{CC} → How many spills to get 10^4 ν_e^{CC} (= 1% stat.)?

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 →

Simple conversion → 1.94×10^{13} K^+ / ν_e^{CC}

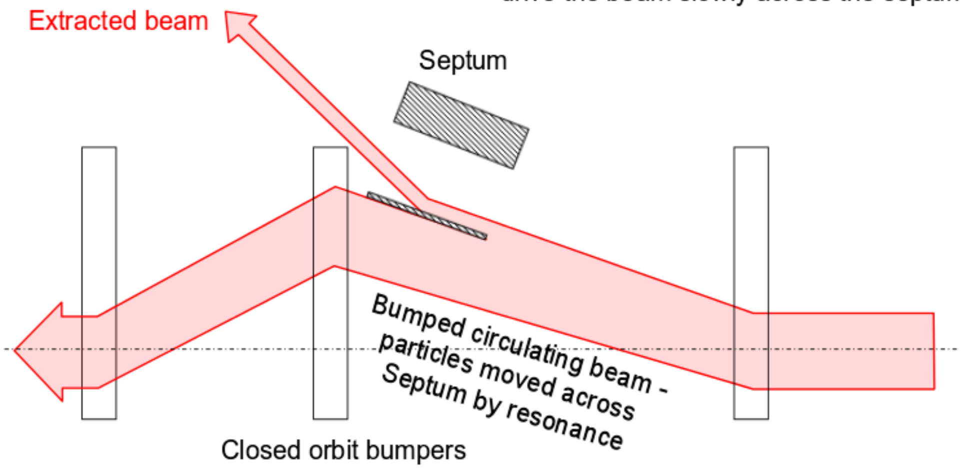
- **Needed integrated PoT:** in the range of present acc. performances*
- **Number of needed spills: ~ 2 × 10^8**. More challenging:
  - needs R&D on **multi-Hz slow resonant extraction** →

* JPARC > 1.2 x 10^{21} PoT
CNGS = 1.8 x 10^{20} PoT
2.4x10^{13} pot/spill every 6s
NuMI = 10.7 x 10^{20} PoT

Scenario A: multi-Hz resonant multi-turn extraction

Resonant multi-turn extraction

Non-linear fields excite resonances which drive the beam slowly across the septum.

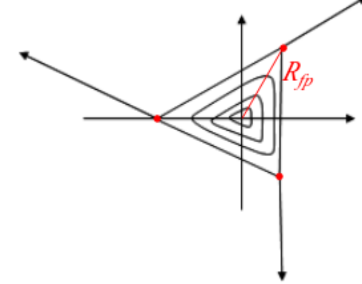


- Slow bumpers move the beam near the septum
- Tune adjusted close to n[th] order betatron resonance
- Multipole magnets excited to define stable area in phase space, size depends on $\Delta Q = Q - Q_r$

Resonant multi-turn extraction

- 3[rd] order resonances – Lecture from O.B.
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

$$R_{fp}^{\;1/2} \propto \Delta Q \cdot \frac{1}{k_2}$$



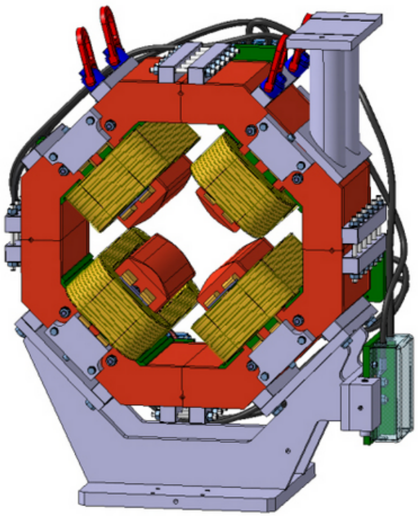
  - Sextupoles families arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
  - Stable area can be reduced by increasing the sextupole strength, or (easier) by approaching machine tune Q_h to resonant 1/3 integer tune
  - Reducing ΔQ with main machine quadrupoles can be augmented with a 'servo' quadrupole, which can modulate ΔQ in a servo loop, acting on a measurement of the spill intensity

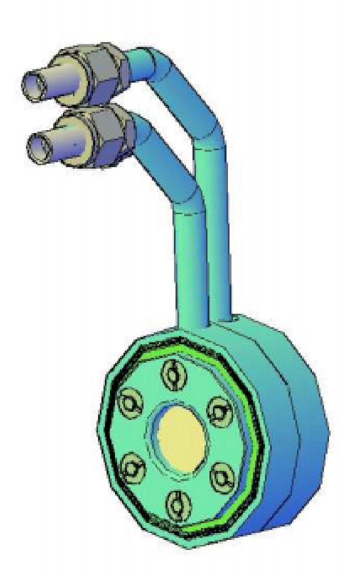
Within ENUBET the possibility to **excite the resonance with a multi-Hz frequency** will be studied and tested in **cooperation with CERN collaborators**. Machine studies with the CERN-SPS.

This **would allow having an efficient horn-based focusing** with **tolerable event rates** and enough ν_e^{CC} (thanks to multi-Hz repetition)

Hadron beam-line: scenario B

- Static focusing: **large aperture rad-hard quadrupoles**.
- Disadvantage: **loss of acceptance**. Assume focusing π, K in the p-bite and a 80 mSr forward cone → need × **10 (more PoT/ν_e)** resulting in **longer data taking or larger detectors** wrt the baseline (500 t + 5 years)
- **needs R&D on focusing beam-line**





E (GeV)	π^+/PoT (10^{-3})	K^+/PoT (10^{-3})	PoT for a 10^{10} π^+ spill (10^{13})	PoT for 10^4 ν_e CC (10^{21}) ←
30	0.24	0.027	4.2	7.2
50	0.58	0.069	1.7	2.8
60	0.73	0.091	1.4	2.2
70	0.80	0.095	1.3	2.0
120	1.25	0.16	0.80	1.22
450	3.65	0.43	0.27	0.46

Scenario B: resonant slow extraction

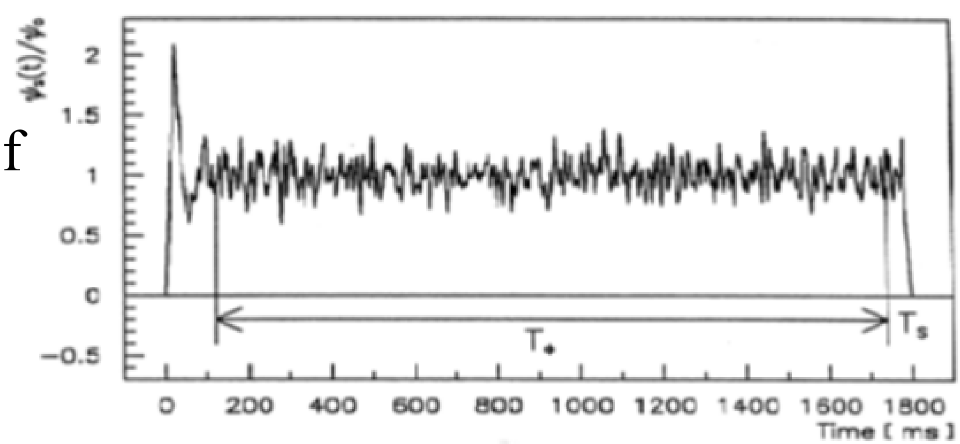
Third-order resonant extraction

Example – SPS slow extraction at 450 GeV/c.
~3 x 10^{13} p+ extracted in a 2-4 second long spill (~200,000 turns)

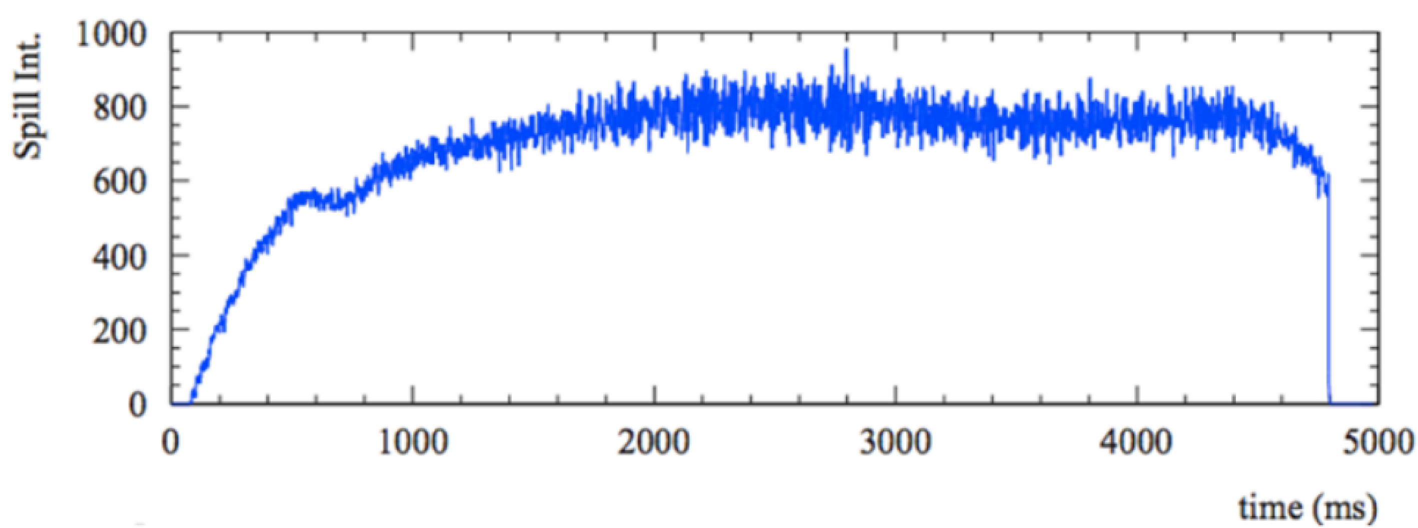
From B. Goddard

“More established” in comparison to multi-Hz mode.

Synergy with R&D in the context of the **SHiP** proposal at CERN for the search of heavy leptons



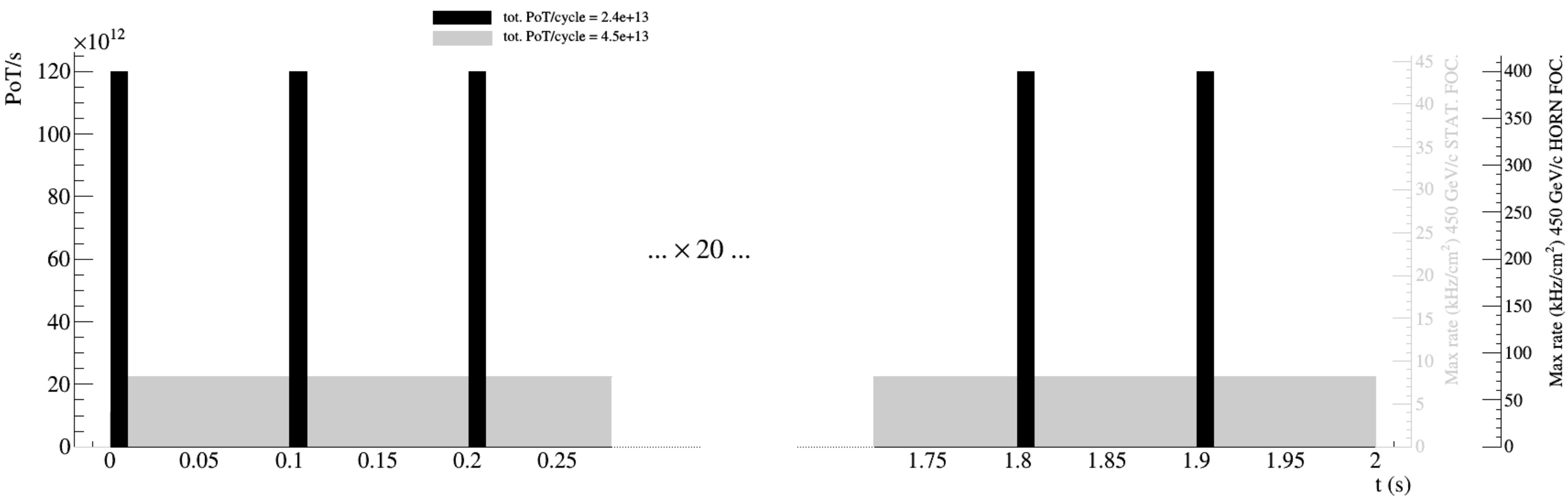
arXiv:1504.04956



Intensity vs time:
~10^8 p+ extracted per turn

Baseline options for the extraction

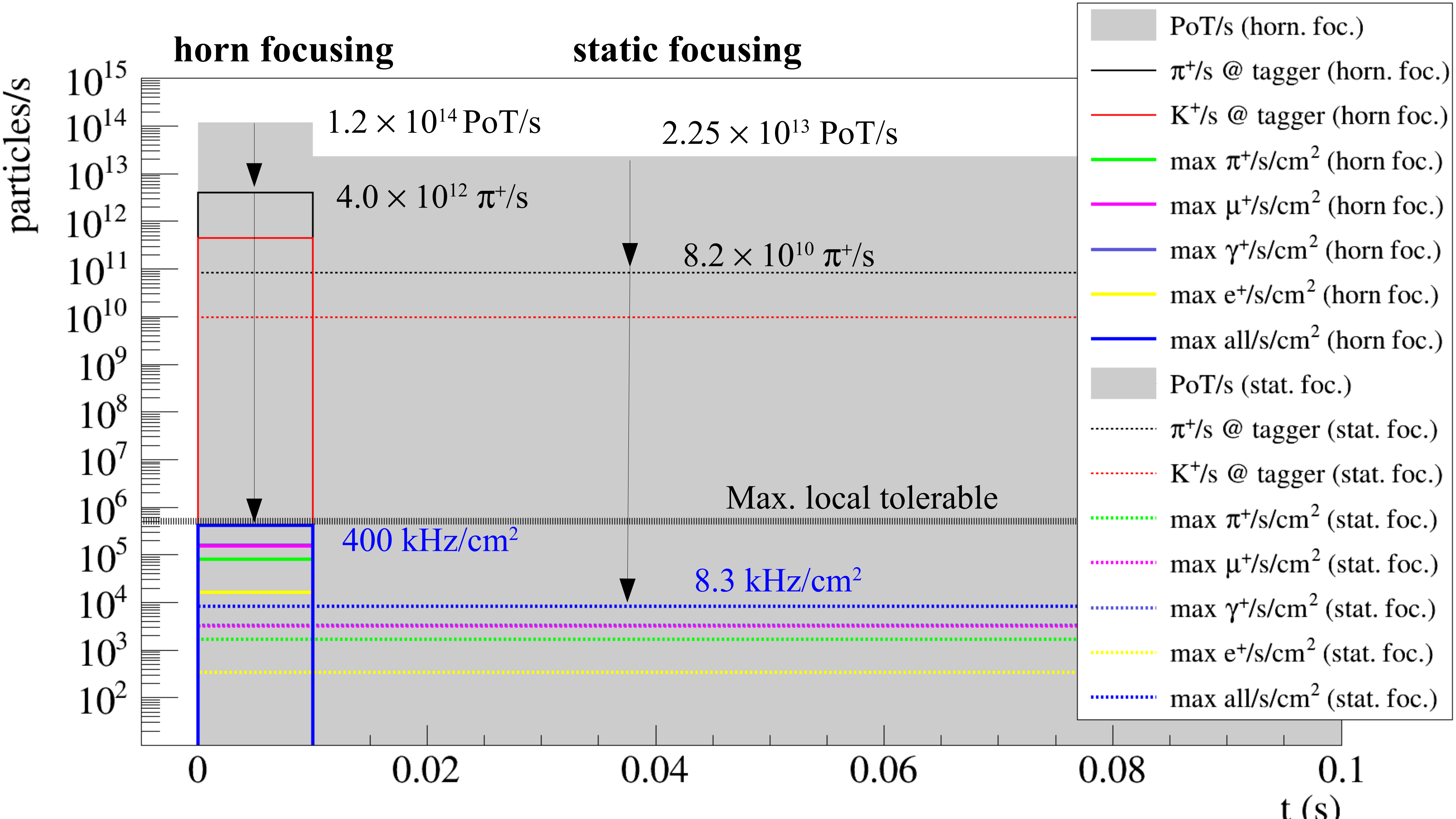
A specific example of a concrete realisation of the two schemes:



Take 2s out of the 15 s SPS super-cycle (4.5×10^{13} protons at 400 GeV).
Slow resonant extraction on the third integer.

Scenario A: Multi-Hz. 10 Hz switch of the lattice resonance for 10 ms every 100 ms for 20 times. 1.2×10^{12} protons/cycle (50% of SPS emptied).
Scenario B: continuous. Could use 4.5×10^{13} protons/super-cycle (full SPS) in 2 s without hitting rate contraints. See more →

Proton injection schemes and peak particle rates



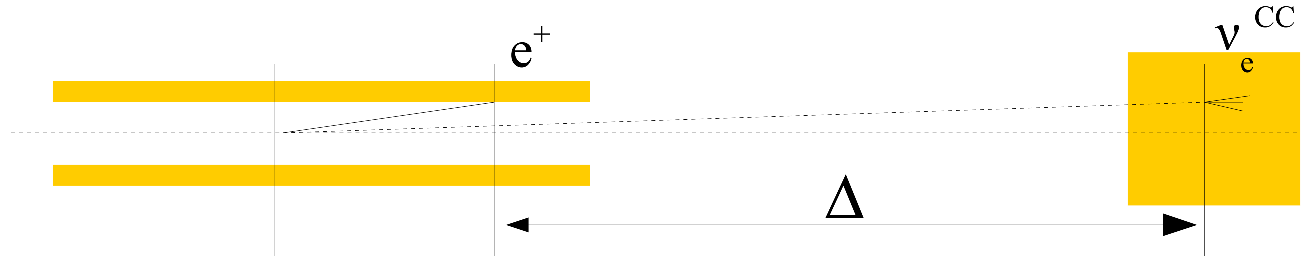
Static focusing solves completely any issue with maximal rate constraints

But this would not be the only advantage … →

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**

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



δ = combined t-resolution (e^+ tagger and ν detector)

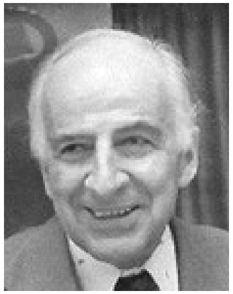
Accidental tag probability:

$$A \sim 2 \times 10^7 \, \delta / T_{extr}$$

T_{extr} **= 1s** (~ 1 obs. e^+ / 30 ns), **δ = 1 ns gives A = 2 %** → **OK !!!**

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

Time-tagging: beyond cross section measurements



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.

- Proton **extraction ~ 1s** → Must rely on static systems: reduction of acceptance (flux) by x 10
- σ_t of the tagger < 1 ns → OK
- σ_t of the ν detector < 1 ns → **Feasible but at the limit of present tech.**
- Cosmic background × 10 → Foresee overburdens
- small K^+ momentum bite small (**not to spoil the ν_e energy reco.**) → **Feasible but can imply flux reduction**
- Tagger-detector time sync. << 1 ns → OK (direct optical links)

Proving a tagged neutrino beam for cross-sections is ENUBET primary goal (“**monitored beam**”)

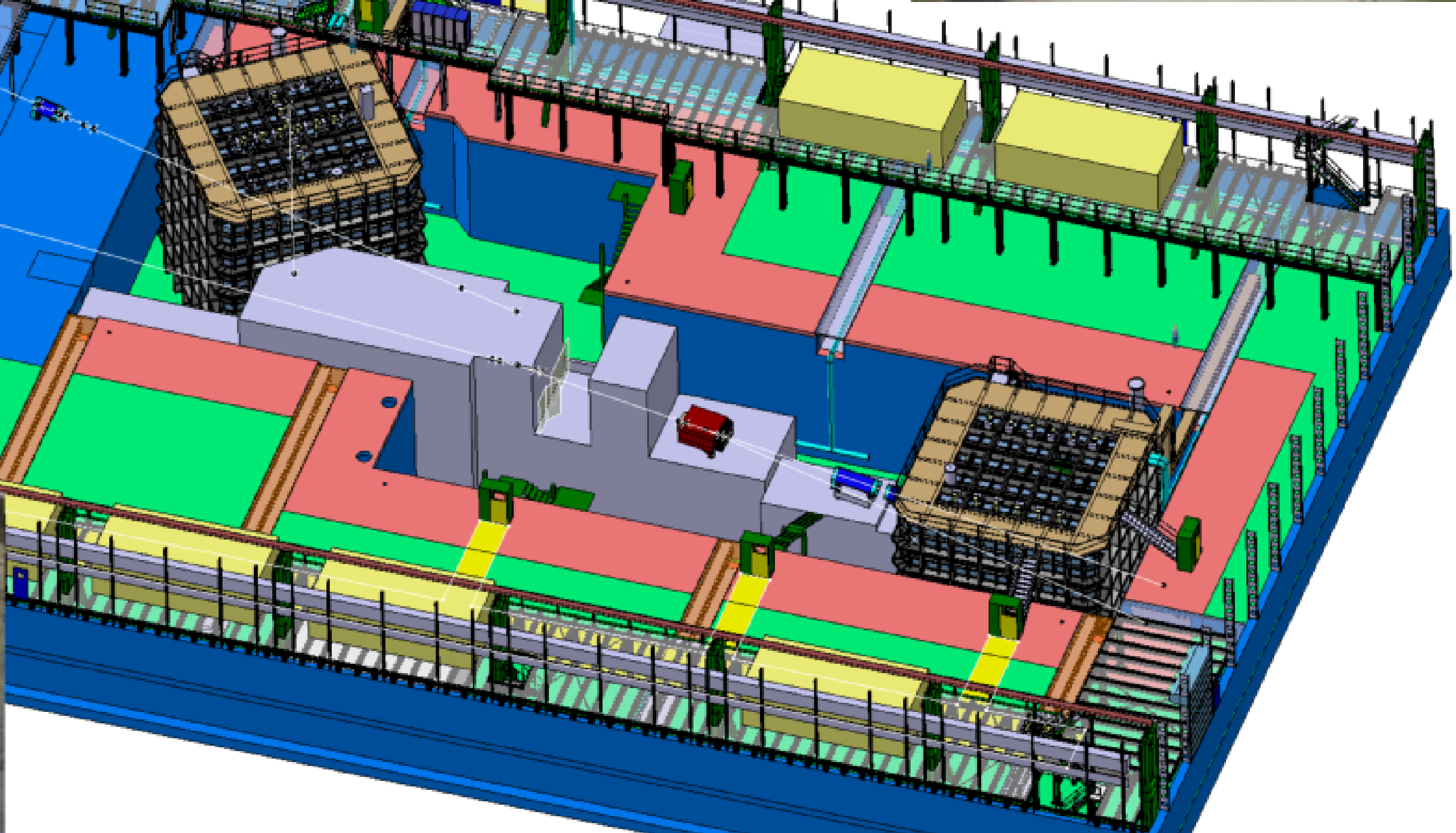
… **but in the last phase** time synchronization for the “time-tagged beam” could be tested at the **EHN1 CERN neutrino platform** building linking the ENUBET tagger prototype signals from halo muons with **scintillation signals** of **LAr** prototypes (WA105, proto-DUNE) or **Water Cherenkov** detectors. NB. Other test beam activities are based at the CERN-PS East area

The CERN neutrino platform @ EHN1

- ✓ *PLAFOND : an generic R&D framework*
- ✓ *WA104 : ICARUS as far detector for SBN*
- ✓ *WA105 : demonstrator + engineering prototype for a double ph. TPC*
- ✓ *ProtoDUNE : engineering prototype for a single phase TPC*
- ✓ *Baby MIND : a muon spectrometer for the WAGASCI experiment*
- ✓ *ArgonCube : a modular TPC R&D*

From S. Bertolucci @ INFN CSN2

EHN1 extension in Prevessin



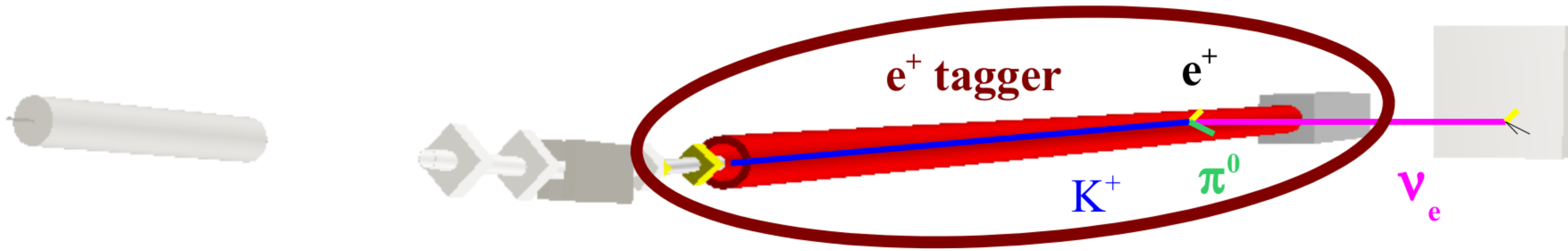
- ✓ *HKK detector components R&D*
- ✓ *Darkside 20K*
- ✓ *ARIADNE*

- ✓ *LBNF cryostat and LAr cryogenics*
- ✓ *SBND cryostat and LAr cryogenics*
- ✓ *CERN member of DUNE and SBN*

- ✓ The CERN Neutrino Platform represents a gateway for the European Neutrino Community towards a global, organized accelerator neutrino program
- ✓ In the short- and medium-term, Europe is helping in getting a Short Baseline operational at FNAL with an agreed physics program … and later a Long Baseline

2) The positron tagger

The e^+ tagger challenges

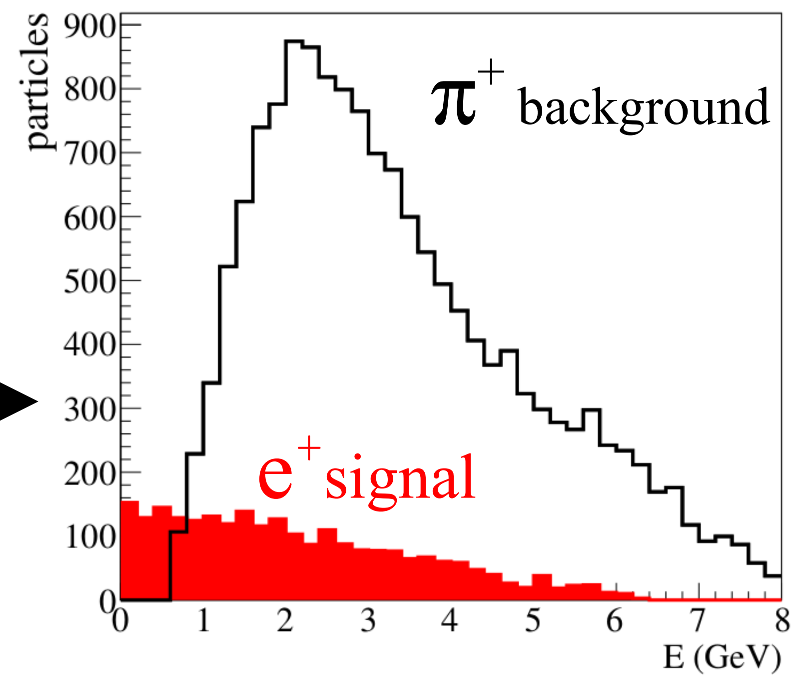


A. Longhin et al. ***EPJ. C (2015) 75:155***

The decay tunnel: a **harsh environment**

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

  Need to veto 98-99 % of them



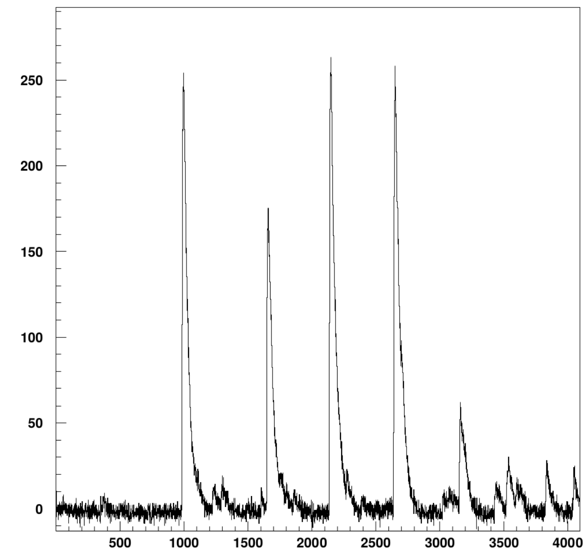
Moreover:

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

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, Δt_{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 < 1.3 kGy (~100 kGy for CMS forward ECAL)

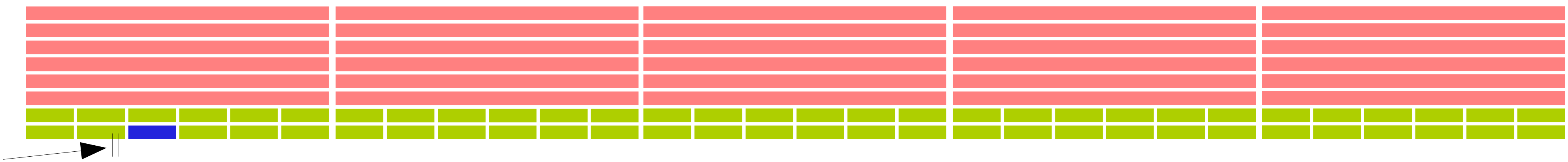
Both issues not critical

e^+ tagger: background rejection

Hadronic modules
Electro-magnetic modules
Hit modules

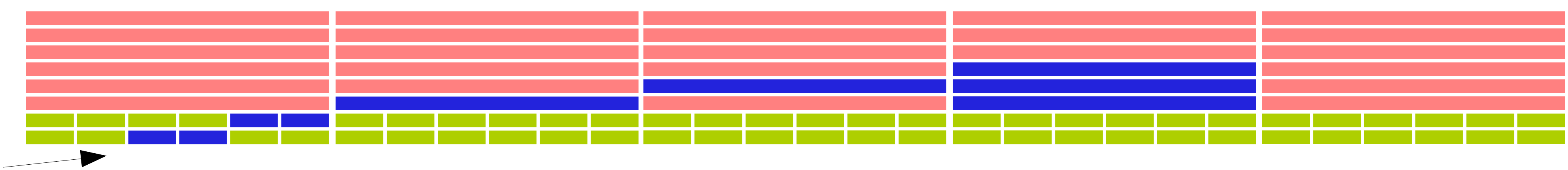
Key point:

- longitudinal sampling
- perfect homogeneity → integrated light-readout



e^+ (signal) topology

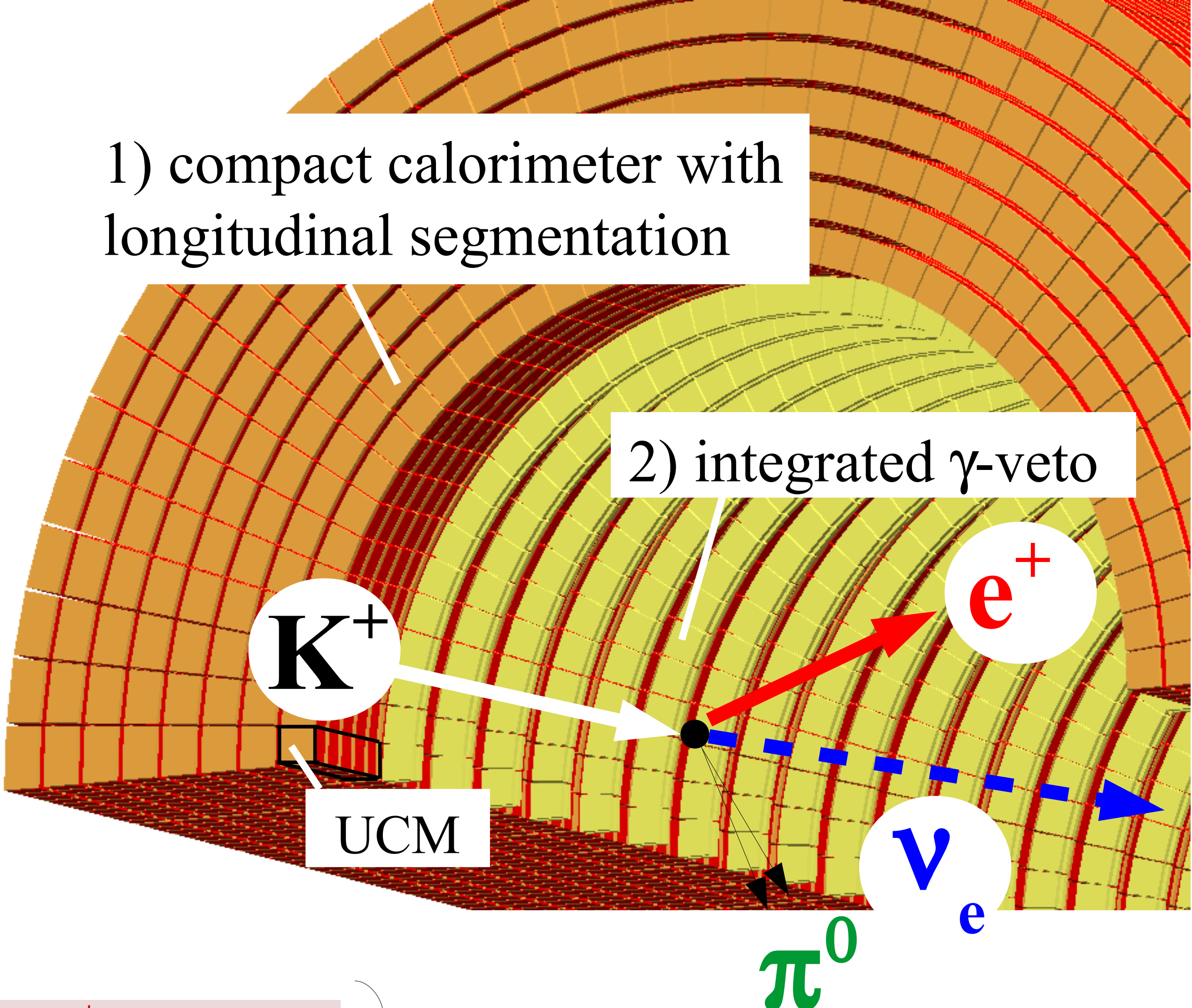
π^0 (background) topology



π^+ (background) topology

e^+ tagger design

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



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

- Ultra-Compact Module (UCM)

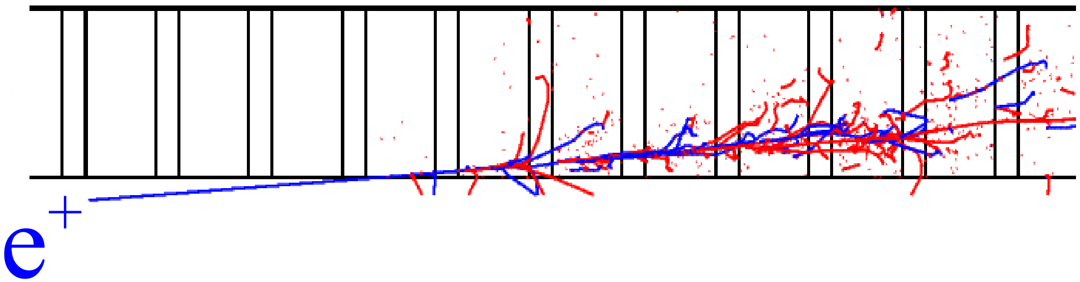
2) Integrated γ -veto → π^0 rejection

- plastic scintillators or
- large-area fast avalanche photodiodes

Detector **R&D activities**

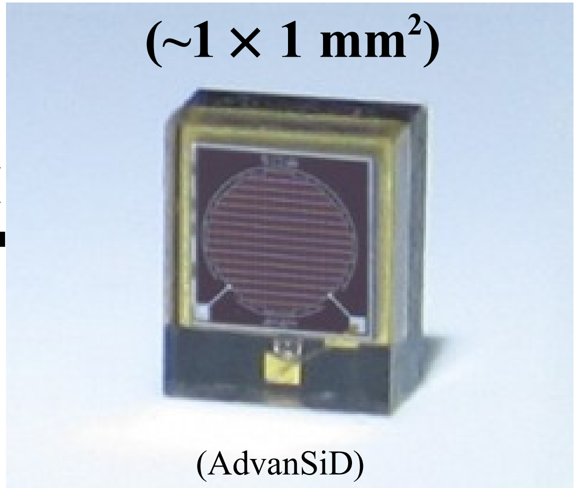
The Ultra Compact Module (UCM)

electromagnetic shower



Scintillation light:

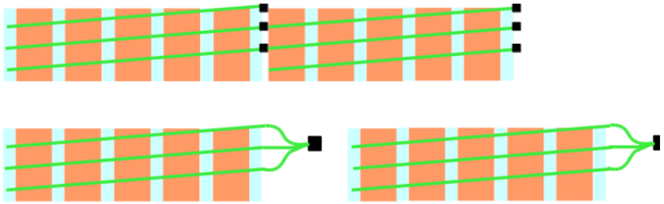
- Collection: **Wave-Length-Shifting fibers**
- Read-out: **Silicon-PhotoMultipliers**

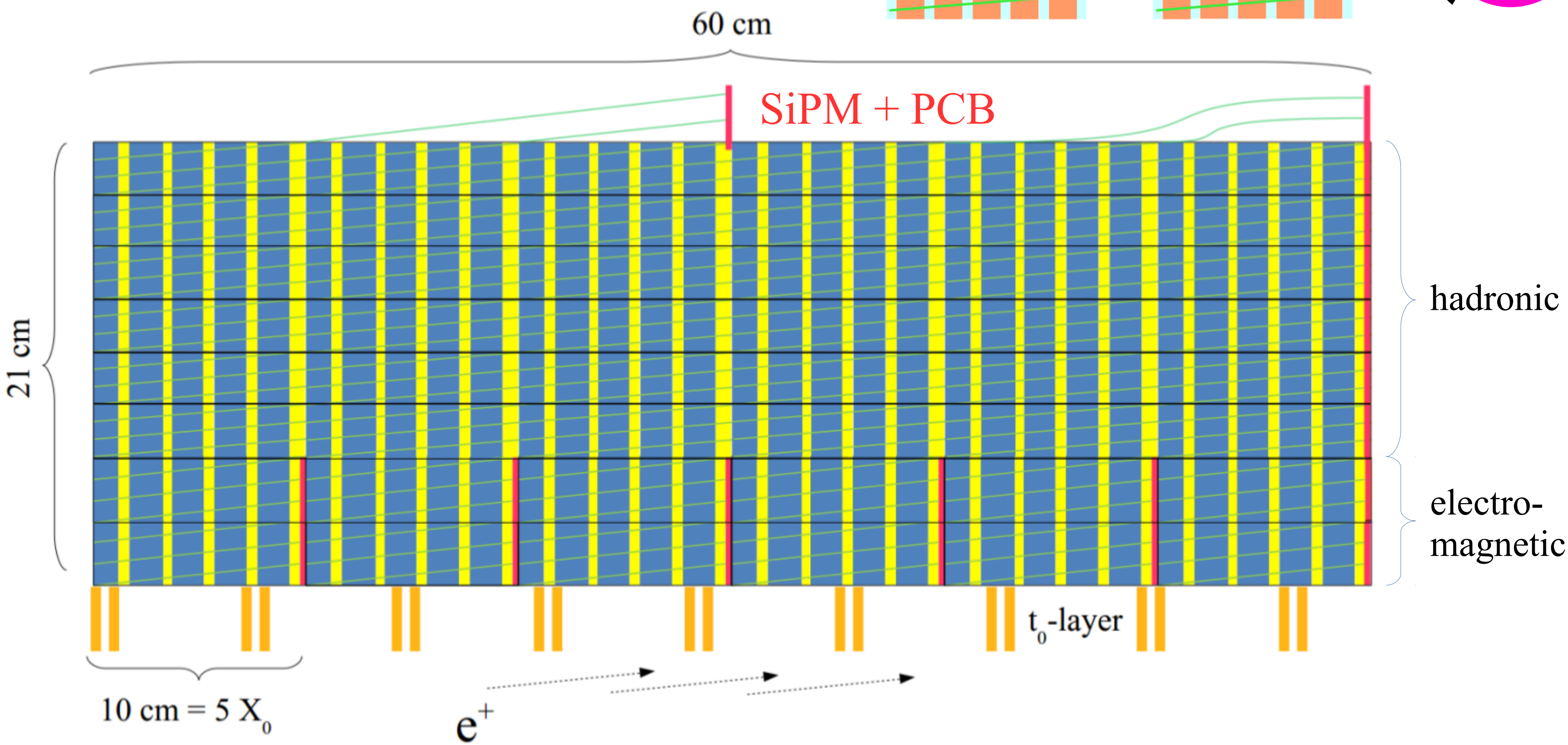


~ 10 × 3 × 3 cm

SiPM coupled to individual fibers.
Stand-alone module with embedded readout
→ no limitations in the **homogeneity of the longitudinal sampling**

The supermodule





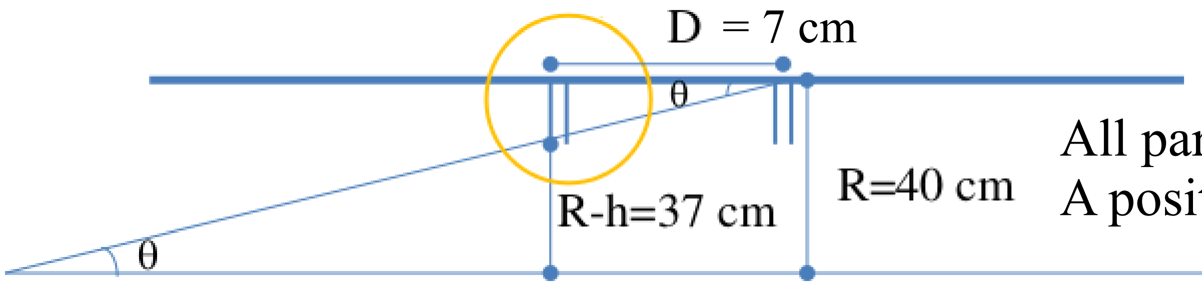
The two innermost layers ("electromagnetic" are readout every ~10 cm = 4-5 X_0)

The six outer layers ("hadronic") are readout with a 60 cm segmentation.

SiPM signals are summed in place of light signals → very compact longitudinally (no dead regions introduced by WLS fiber bundling)

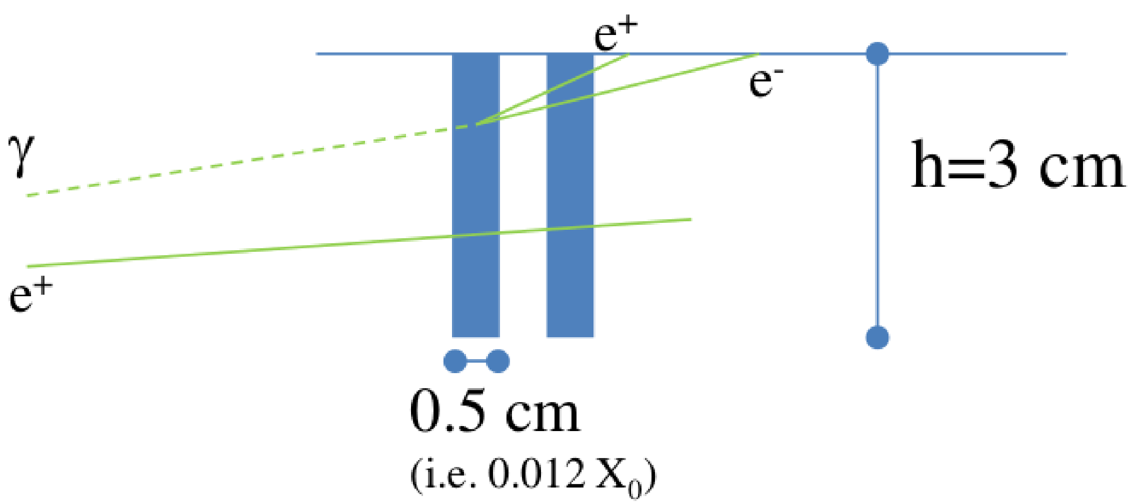
The photon-veto design

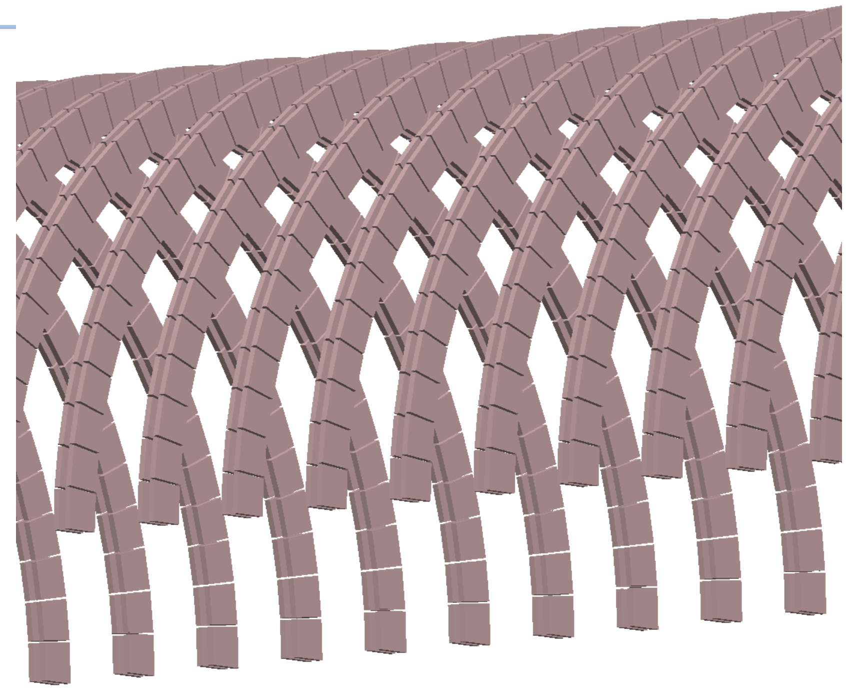
Background from γ conversions from π^0 emitted mainly in K_{e2} decays ($K^+ \rightarrow \pi^+ \pi^0$)



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 solution** using **fast avalanche photodiode detectors** allowing smaller **material budget and superior timing**.
- Test beam at Frascati BTF: **electronics response** at high rates and low-E e^+
- **1 mip – 2 mip separation** using conversions of bremmstrahlung photons

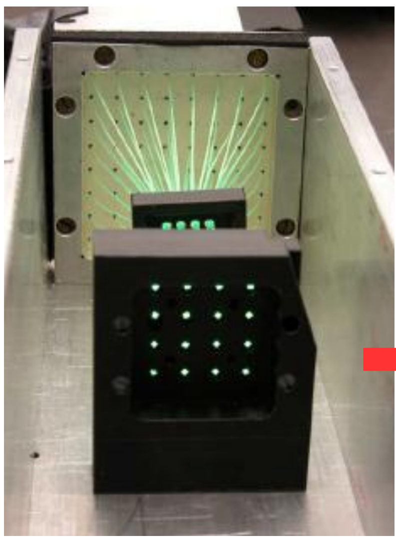
Tagger detector R&D: SCENTT

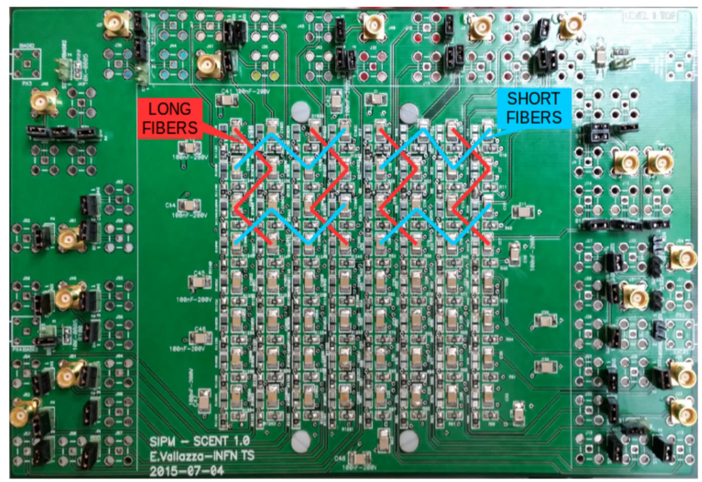
Shashlik Calorimeters for Electron Neutrino Tagging and Tracing

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%





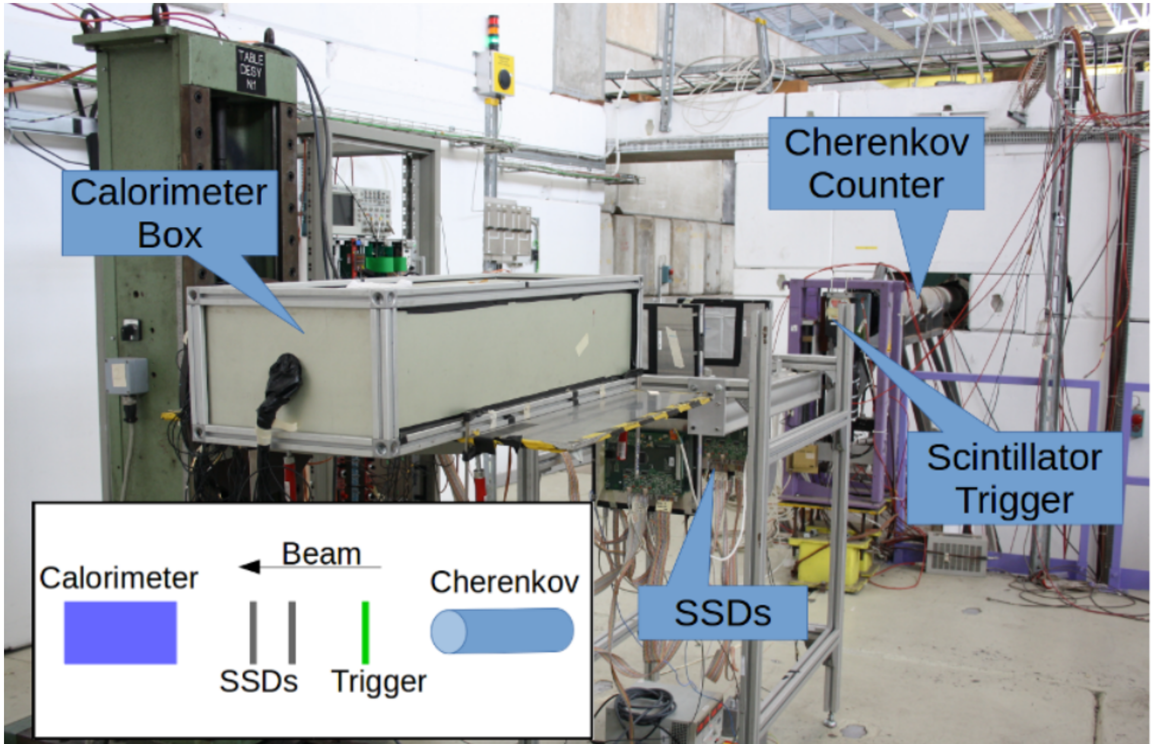
Results recently published in **N.I.M. A**

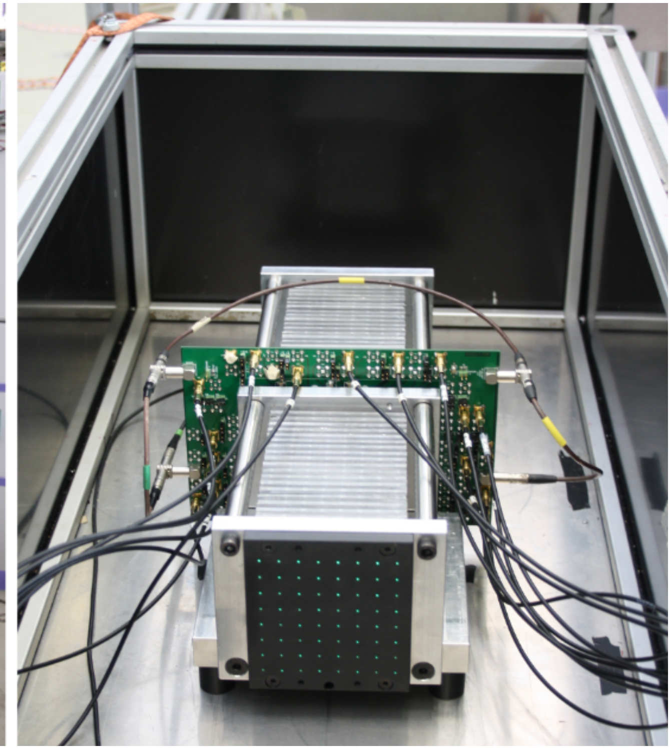
A compact light readout system for longitudinally segmented shashlik calorimeters

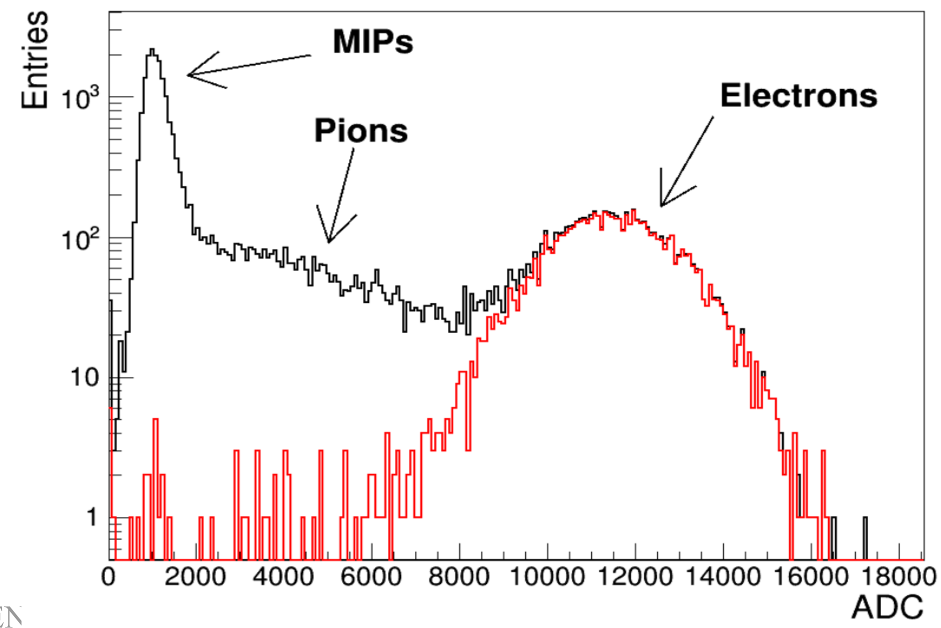
http://dx.doi.org/10.1016/j.nima.2016.05.123 ArXiv:1605:09630

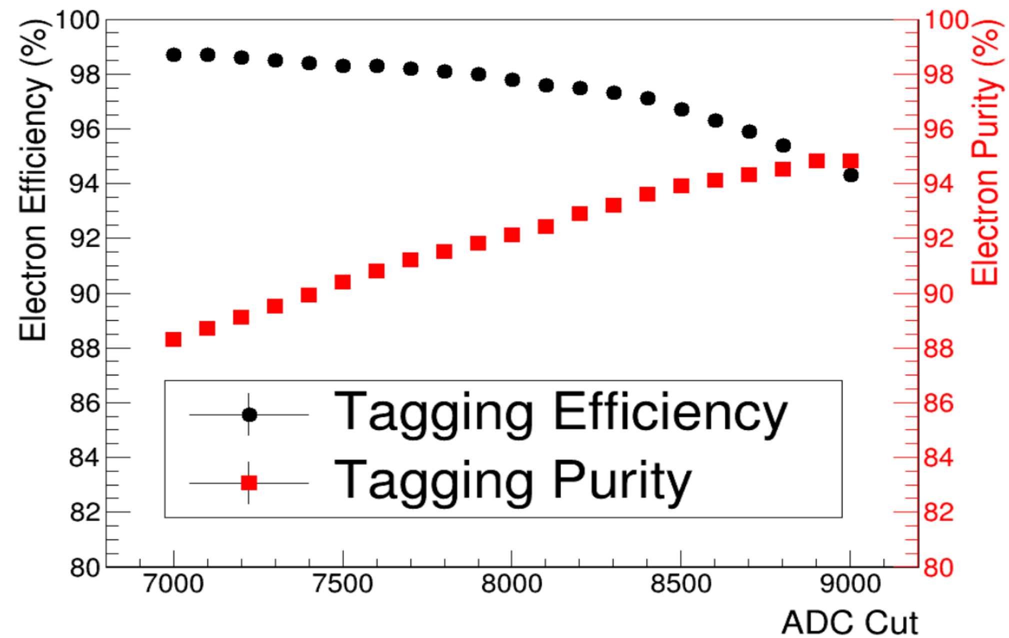
A. Berra[a,b,*], C. Brizzolari[a,b], S. Cecchini[c], F. Cindolo[c], C. Jollet[d], A. Longhin[e], L. Ludovici[f], G. Mandrioli[c], N. Mauri[c], A. Meregaglia[d], A. Paoloni[e], L. Pasqualini[c,g], L. Patrizii[c], M. Pozzato[c], F. Pupilli[e], M. Prest[a,b], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i],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

SCENTT, Aug. 2015, PS test beam





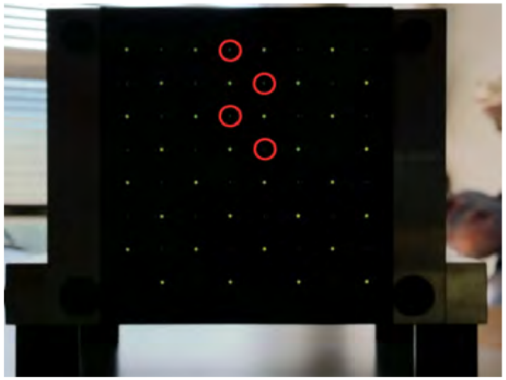


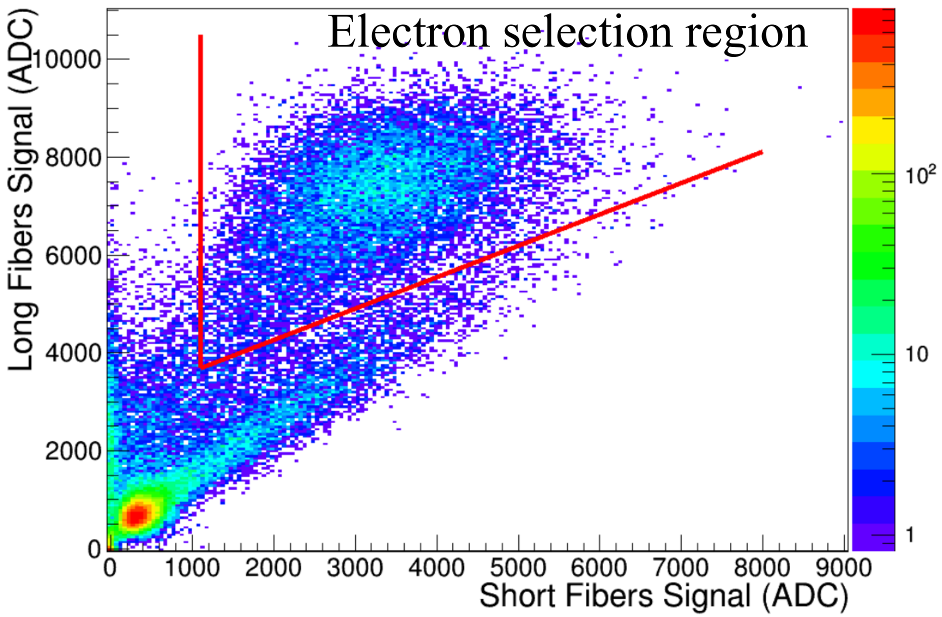


August test beam results

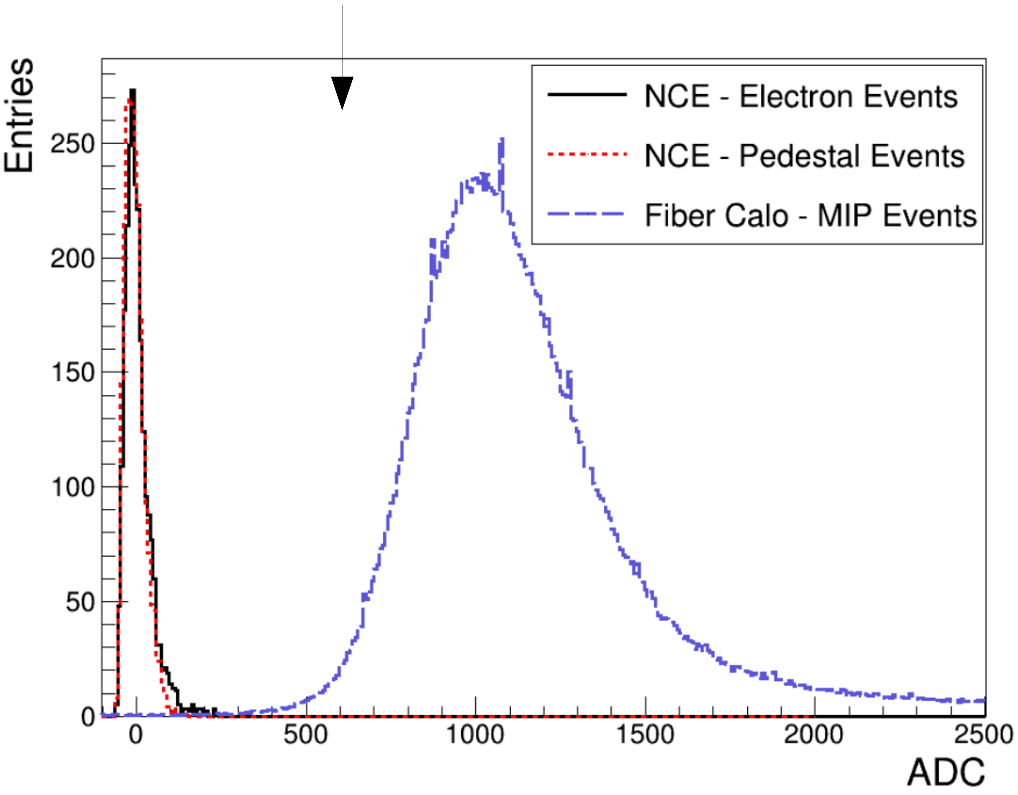
- A possible additional handle for e/π separation from using **long/ short fibers alternately** (different sampling of the longitudinal shower profile)

Long/short fibers pattern. Circles: short fibers (dimmer)



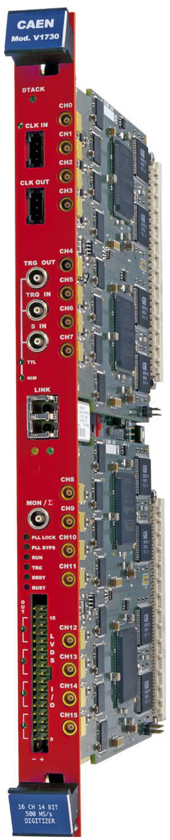


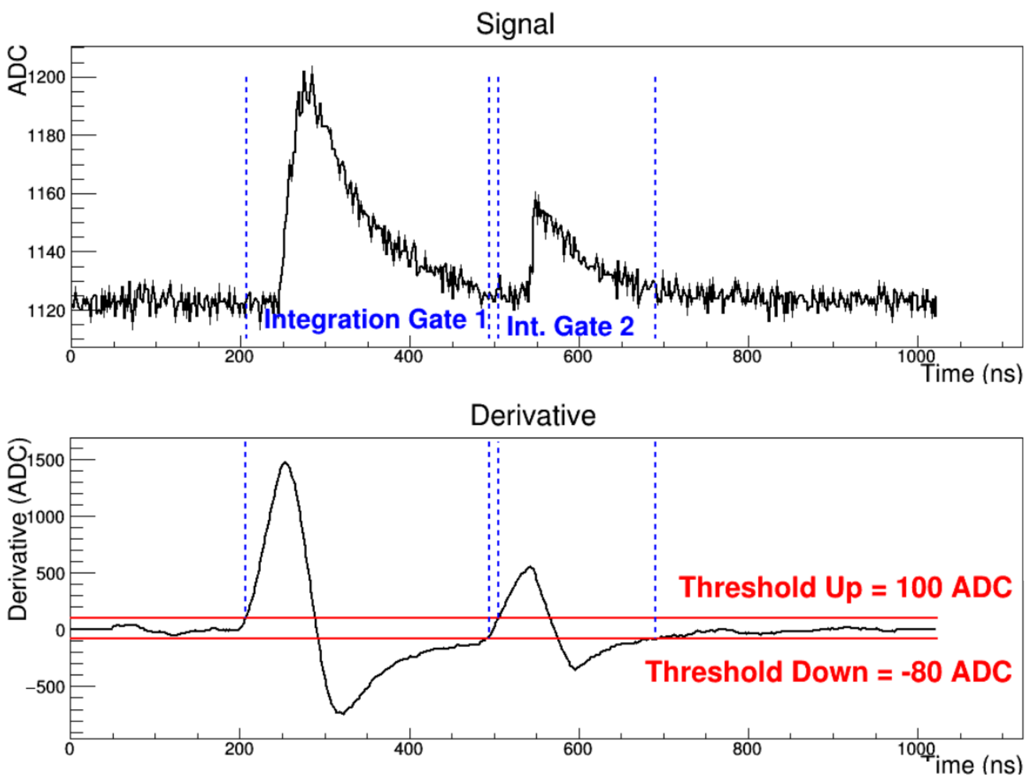
- An important test to operate the SiPM directly inside the calorimeter: when WLS fibers are removed the signal in the SiPM is compatible with the pedestal. **Nuclear counter effects** (direct ionization on SiPM) are negligible (pixelization+Geiger mode).

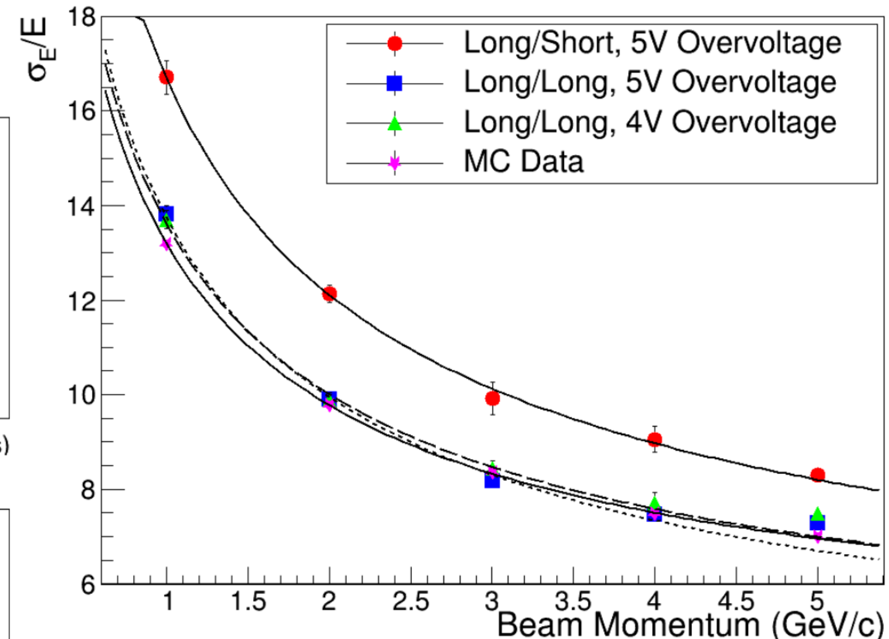


Results with signal sampling

Energy resolution obtained with signal sampling at 500 MS/s (12 or 14 bit) is comparable with the one obtained with QCD electronics (and consistent with GEANT4 MC simulations)







Smoothed derivative

$$\delta_i(N) = \sum_{k=1}^{N} s_{i+k} - \sum_{k=1}^{N} s_{i-k}$$

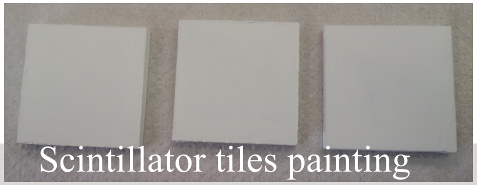
Energy resolution:

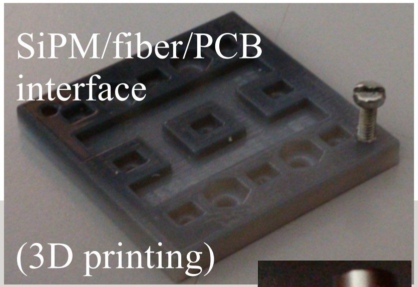
Beam Momentum	500 MS/s 14-bit	250 MS/s 12-bit	QDC (5 V OV)	QDC (4 V OV, 90 mrad Tilt)
1 GeV/c	17.0%	17.2%	16.7%	17.3%
2 GeV/c	13.4%	13.3%	12.1%	12.6%
3 GeV/c	10.8%	10.8%	9.9%	10.4%

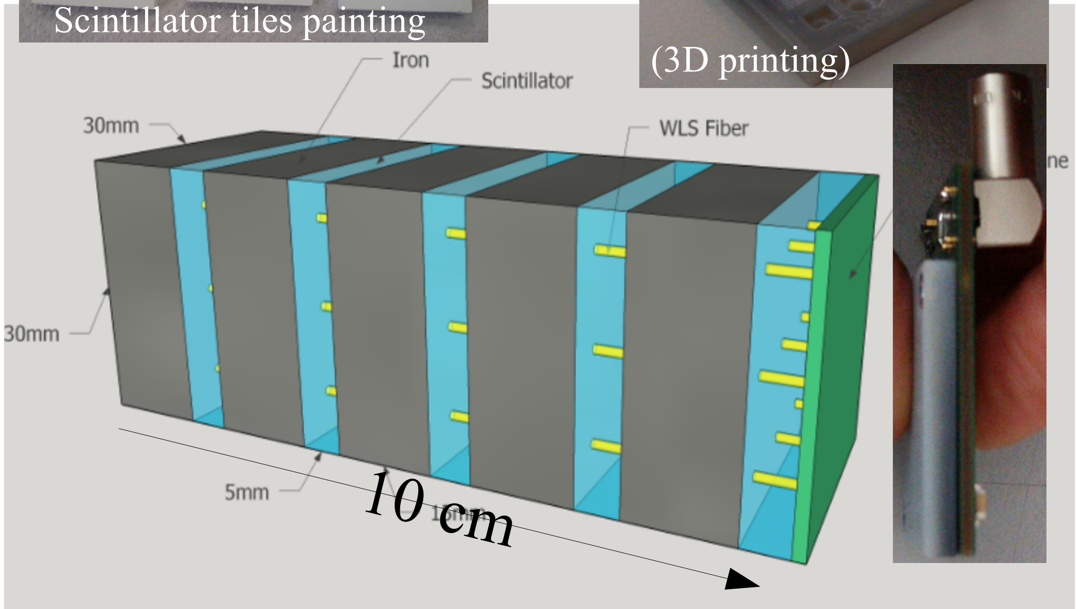
ENUBET: develop **custom waveform digitizers** in place of commercial products sampling the signal every 2 ns for 10 ms (= 5 MS/ch/spill). First tests this Fall.

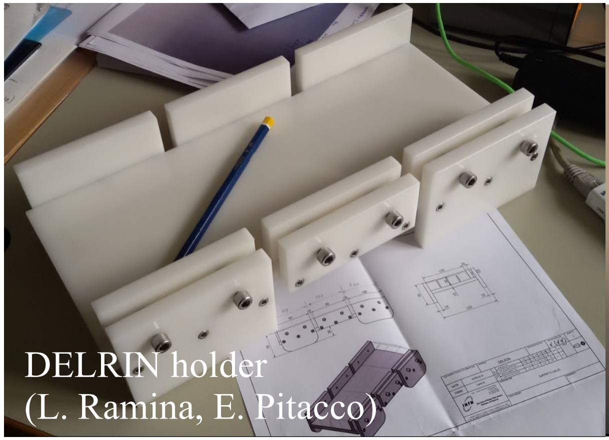
Upcoming test beams at CERN-PS (T9)

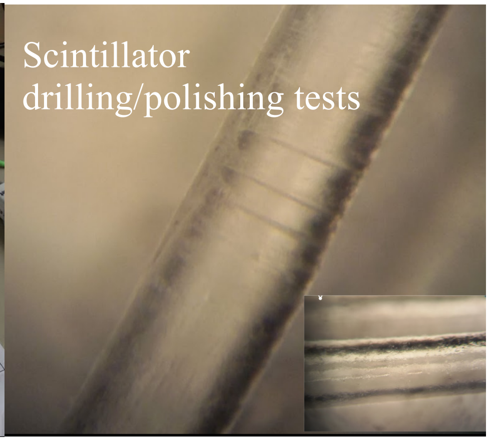
July 2016: first tests of tagged beam UCM setup (e.m. component, ~ 12 modules)



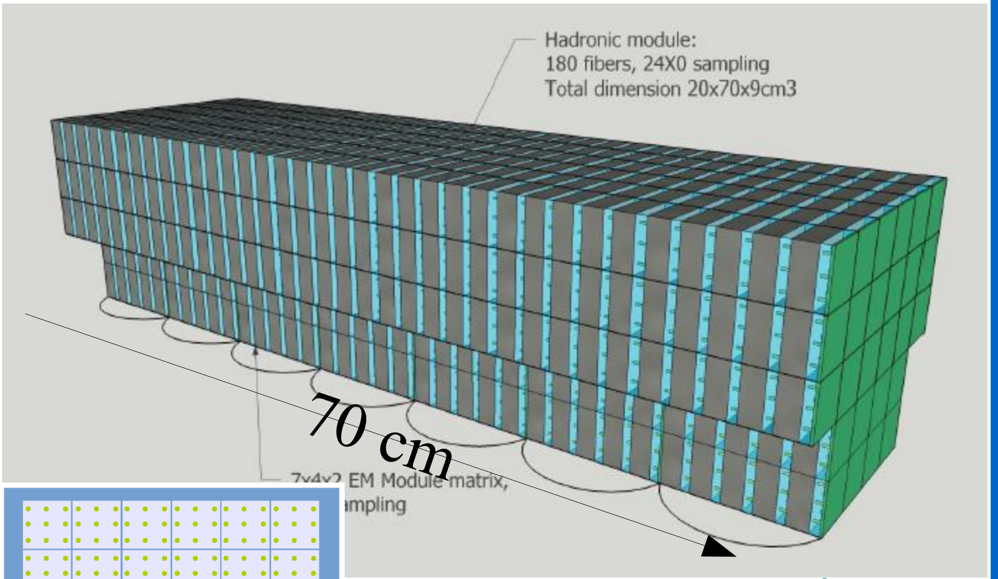


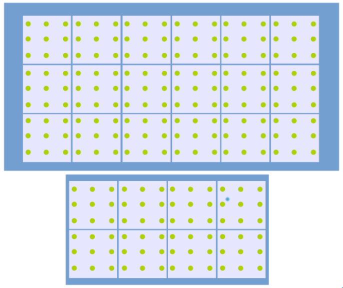


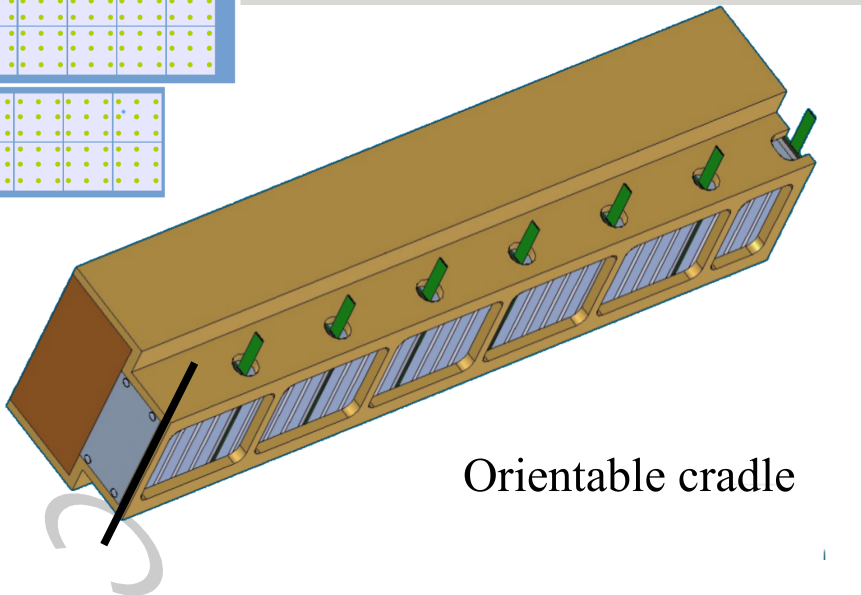




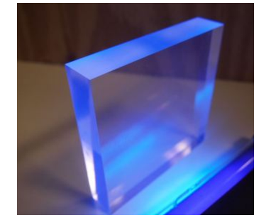
November 2016: hadronic + e.m. modules
→ readout w. custom fast digitizers



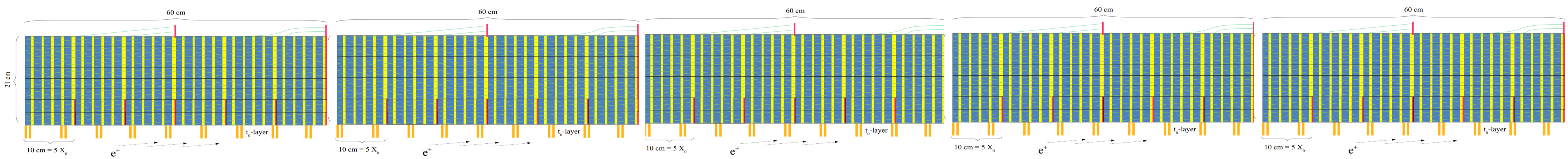




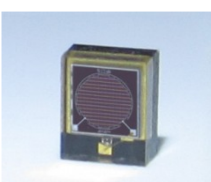
The full prototype

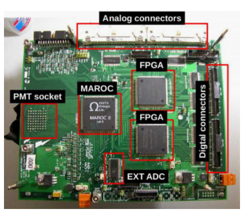


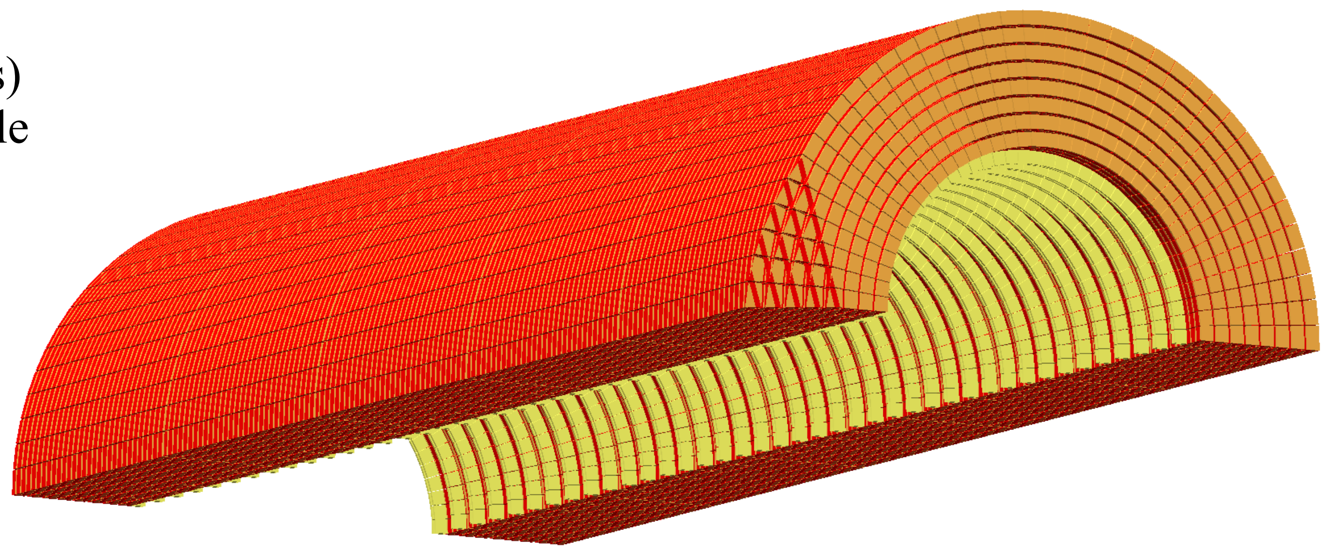
- Dimensions: **3 m × π**
- Material: **steel, organic scint., fibers, SiPM**
- # SiPM: **34000**
- Channels: **3800**
- Weight: **~ 5 t**
- WLS fiber length: ~**10000 m**



This length (3 m = 5 super-modules) allows the containment of high angle particles in realistic conditions

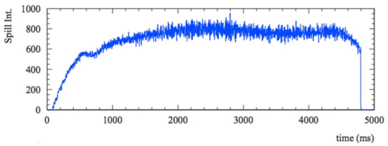




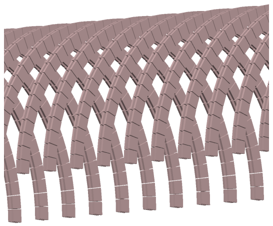


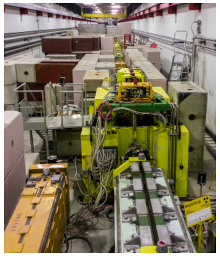
ENUBET prototype

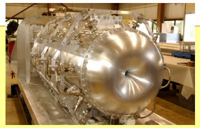
Final experiment (in its original layout)



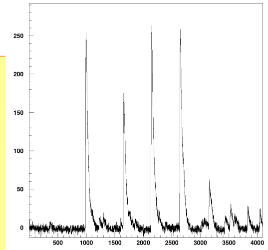
Working packages



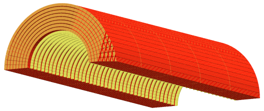




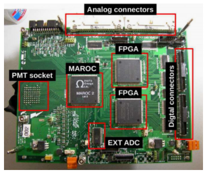
WP1: beam-line
Precise layout of the hadron beam. Study of the injection schemes.

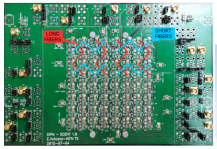


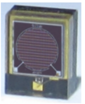
WP4: photon veto and timing system
validating the timing accuracy of the tagger and the photon veto e^+/π^0 separation. Vertex reconstruction inside the tunnel. Pave the way to "tagged neutrino beams" (time synchronization studies with existing LAr or water Cherenkov prototypes).



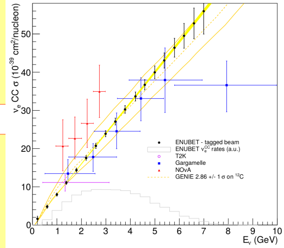
WP2: tagger prototype
Feasibility of tagging under realistic conditions with the desired background and systematics suppression. Radiation hardness.







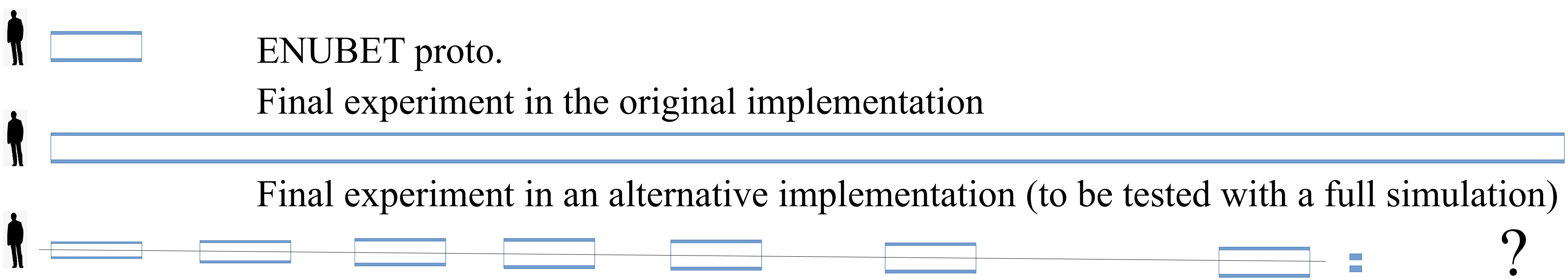
WP3: electronics and readout
testing the readout performances of the front-end electronics for horn-based (< 10 ms proton extraction) or static (1s proton extraction) focusing systems.



WP5: systematic assessment. Overall flux systematics reachable by the exploiting the e^+ rate and the impact on a direct measurement of the $\sigma(\nu_e^{CC})$.

ENUBET-WP5: tagger design and reconstruction

- First year will also look for **alternative approaches** in the design developing a solid and parametric simulation of the detector
  - i.e. multiple-stations? How crucial is inclusive monitoring for reducing the systematics ? Needs full simulation/reconstruction/treatment of systematics on the ν_e flux



  - Explore different **detector technologies** (i.e. for photon veto)?
  - Powerful multi-variate techniques for e/π separation
    - this activity has already started →

Ongoing reconstruction studies

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

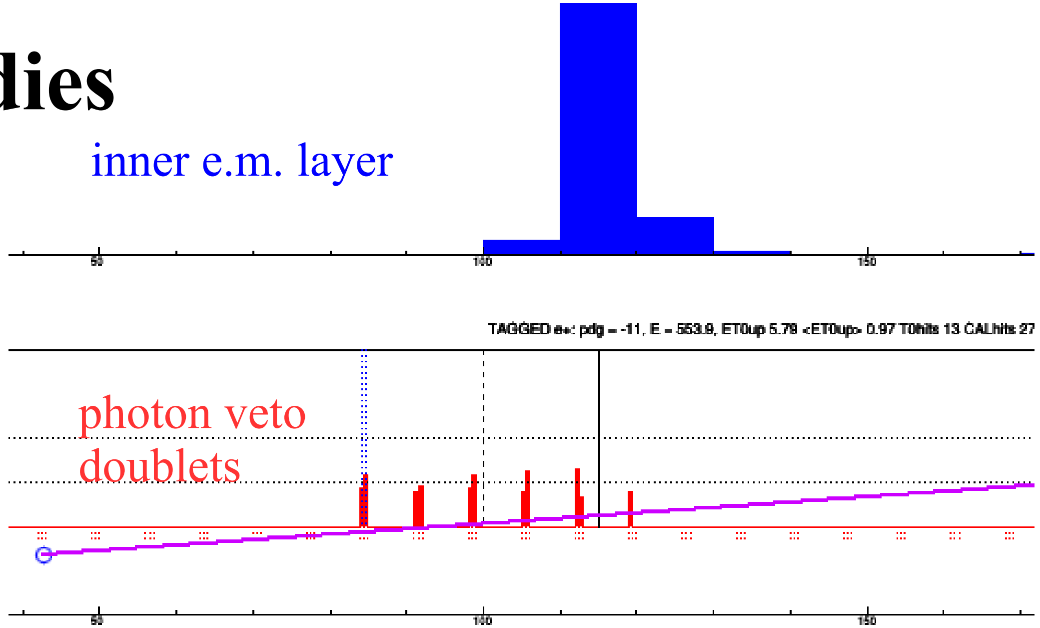
Takes into account **pile-up** related restrictions in the event building.

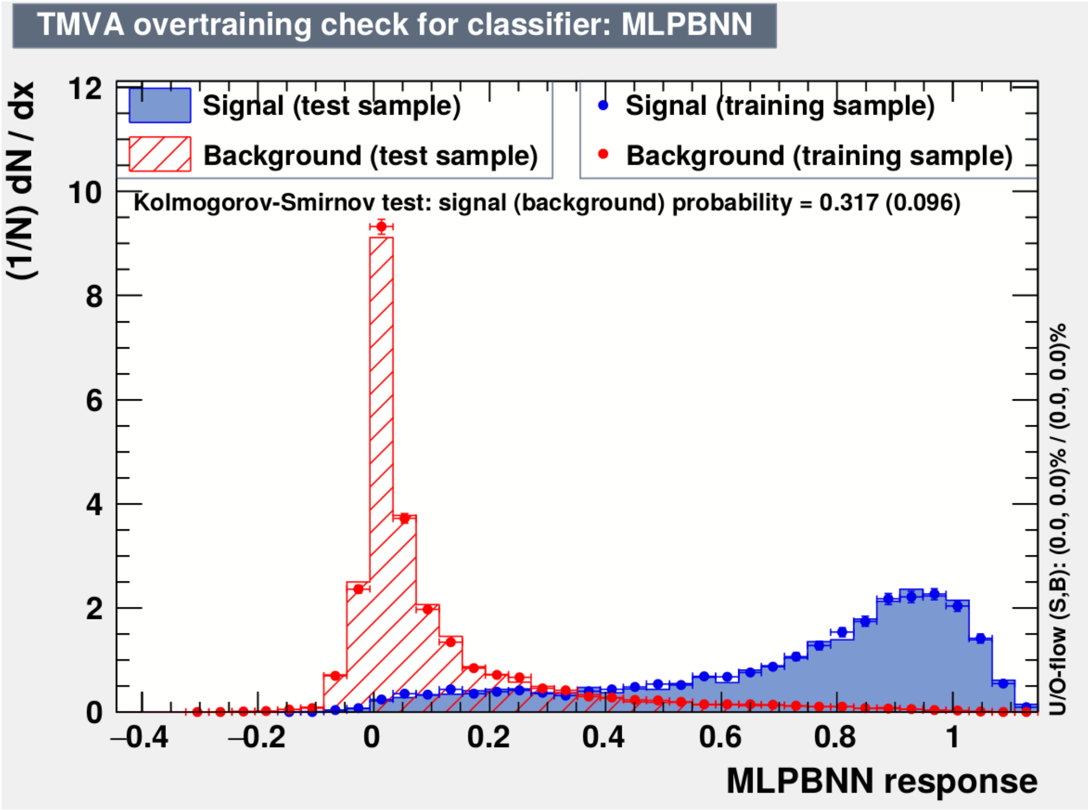
TMVA **multivariate** analysis:

- 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

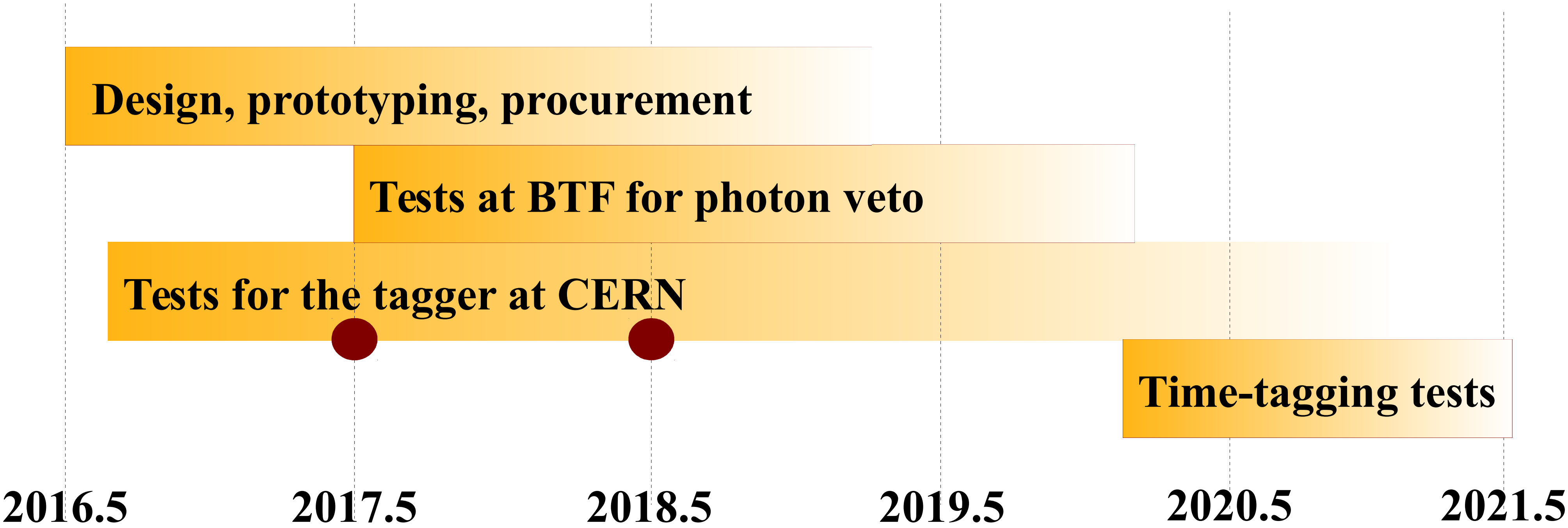
	ε_{geom}	ε_{sel}
e^+	90.7 %	49.0 %
π^+	85.7 %	2.9 %
π^0	95.1 %	1.2 %

Early results confirm previous estimates from parametrizations





Simplified work plan



Critical decisions (●): γ-veto technology (Y1), front-end electronics (Y2)

→ after moderate investments with laboratory-based prototyping

Flexibility and redundancy

- many handles to promptly react against possible critical issues
  - detector granularity, technology options
- base-line/alternative solutions (i.e. hadron beam-line, γ-veto technology)
- complementary beam-lines for tests (Frascati, CERN)

Resources, institutions

Team

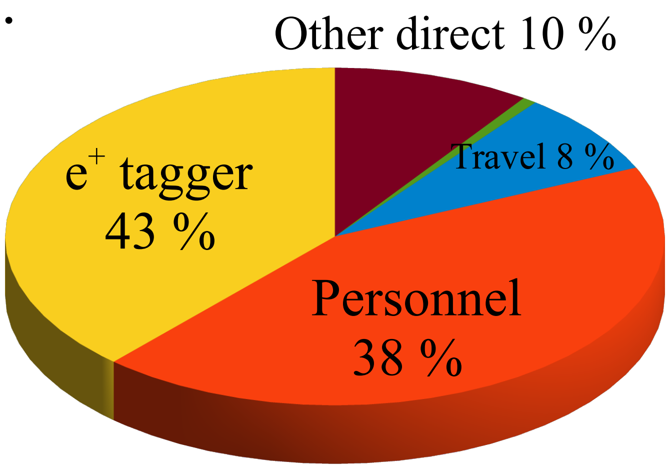
- Expertise in **calorimetry, accelerator** and **ν physics**.

- **INFN**: PD, MIB-Insubria, RM1, LNF, TS, BO, BA.
- **CERN**-ABT (beam extraction)/STI (targetry, focusing), IN2P3 Strasbourg.
- Contacts with **Protvino** for scintillators.
- Interest from **FBK** for Si-PM R&D.
- INFN administration: L. Iacono, A. Lombardo

- About **35** people for an EoI, expected to increase.

Budget

- Grant Agreement finalised by end of March
- **2 MEUR** assigned



ENUBET is taking off!

- **T_0: 1st June** 2016 (3 weeks-old, for 5 years)

- **Kick-off meeting**: today

- **Expression of interest to SPSC** in preparation. Enlarge the community, give visibility, allow official commitment of CERN collaborators, support for beam test campaign.

- **First year tasks**: complete the design of the tagger. Full simulation of detector and systematics. Study of beam-line and photon veto detector options. Test beam activities.

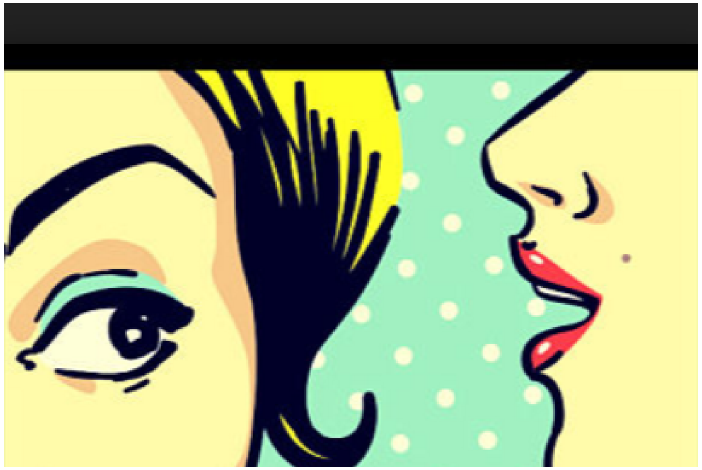
- **Outreach and dissemination** started: INFN-LNF news, INFN News, INFN focus in monthly newsletter, Frascati Scienza, Radio24. Conferences.

- **INFN-CSN2**: “sigla tecnica” to cope with specific items not covered by EU

ENUBET opportunities

A very diversified program involving:

- Accelerator physics
- Electronics (design and tests)
- Mechanics
- Reconstruction/simulation
- Advanced high-level analysis
- Test beams at CERN, Frascati.
- Visibility in the neutrino community.
- Possibility of **thesis work**.



http://enubet.pd.infn.it

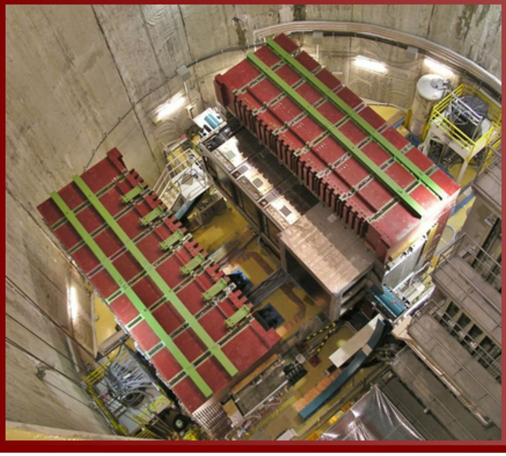
A good time to join the "adventure" !

ENUBET

Why ERC A break-through in ν physics — e^+ monitoring in a decay tunnel is the right tool for **ν_e cross-section at O(1%)**

Why NOW
- **readiness** of detector technology
- **timeliness** with respect to the needs of the field

1^{st} gen. experiments: "the basic picture"



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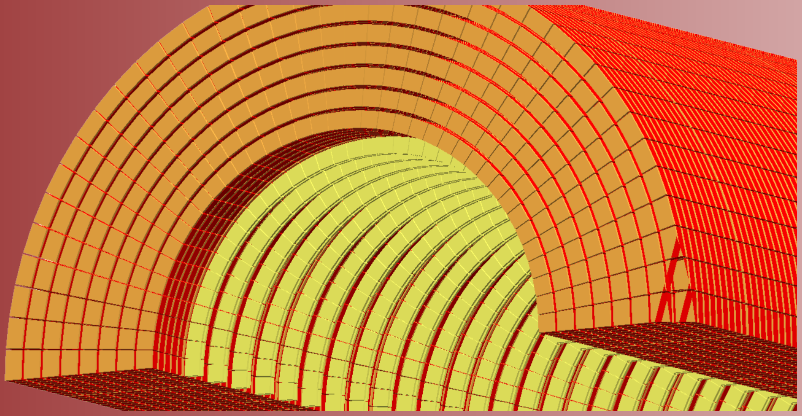
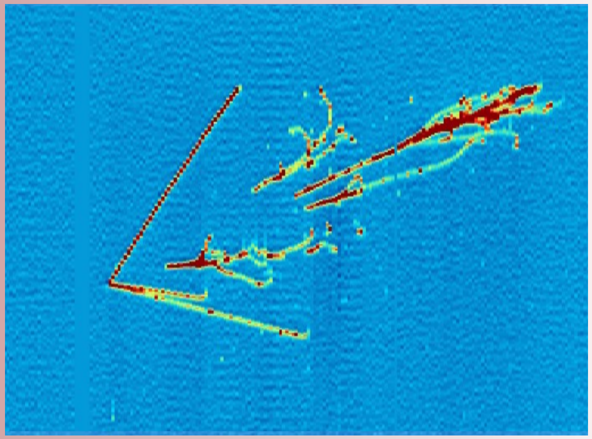


The precision era

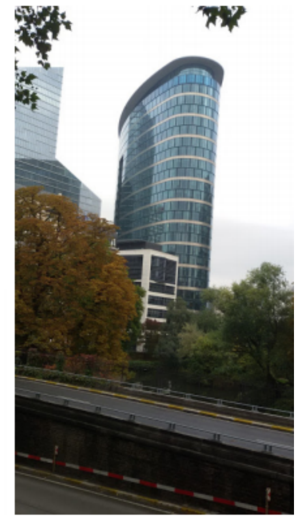


A ground-breaking opportunity for ν science is within reach

Experience with the ERC

Will be covered in the second part. Some material here:
https://agenda.infn.it/getFile.py/access?subContId=2&contribId=3&resId=0&materialId=slides&confId=11394

La mia esperienza con l'ERC-Consolidator Grant 2015 con ENUBET (G.A. 681647)



A. Longhin (INFN-PD)
LNF, Giornata sui progetti H2020
25 Maggio 2016