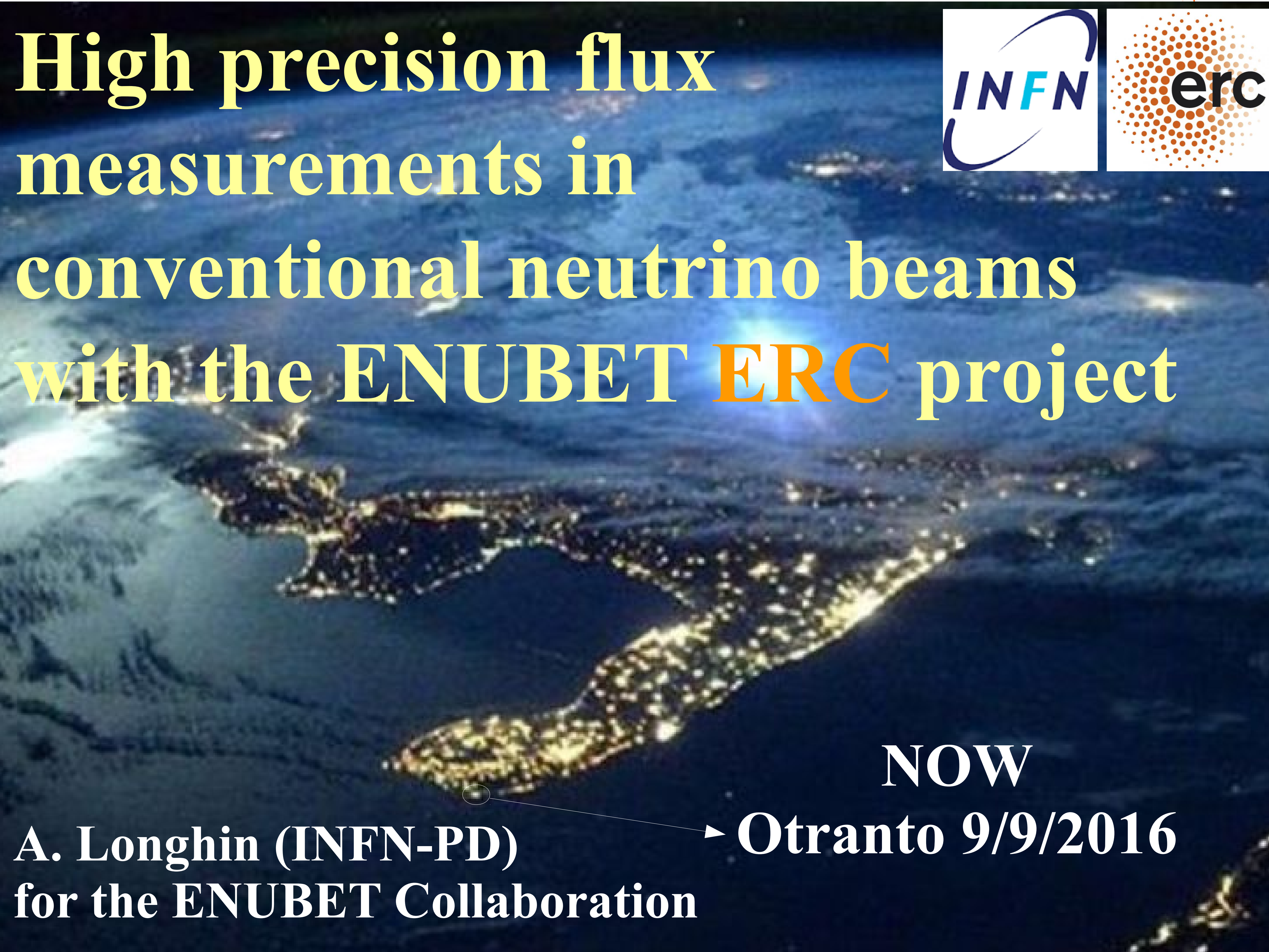
High precision flux measurements in conventional neutrino beams with the ENUBET ERC project



NOW

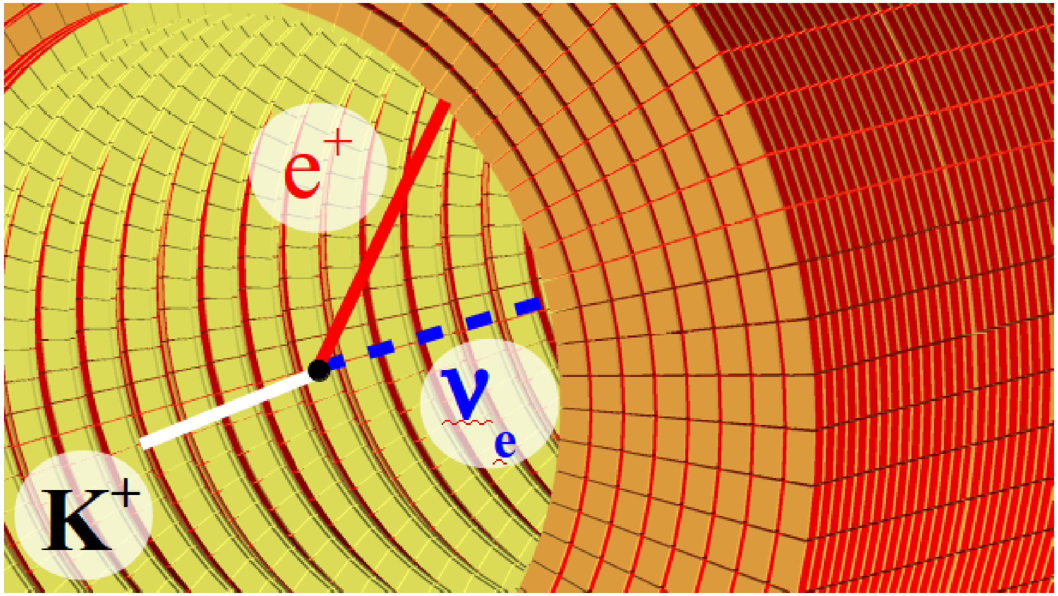
Otranto 9/9/2016

A. Longhin (INFN-PD)
for the ENUBET Collaboration

Outline

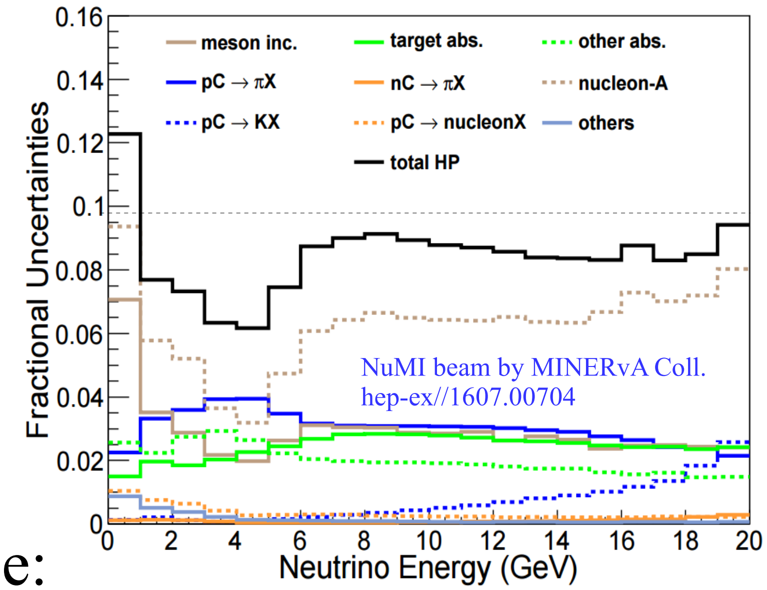
- The problem of **flux uncertainty** in conventional beams
- **Monitored beams**
- ENUBET: challenges, goals and recent **achievements**
- Forthcoming activities and **conclusions**

- 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



Tackling the flux uncertainty problem

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



NuMI beam by MINERvA Coll.
hep-ex//1607.00704

Still:

- No absolute measurement with < 10% error.
- Main contribution: 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 @ high-E)
- In particular for **$\sigma(\nu_e)$** data are **sparse/old** (Gargamelle, T2K, NOvA) being based on the beam contamination (**no intense/pure sources of GeV ν_e).** Ideal (but difficult) solution: D.I.F. of stored μ as in **nuSTORM/nuPIL**
- **$\sigma(\nu_e)$ precious for CPV!**
- "derivation" from $\sigma(\nu_\mu)$ "delicate" expecially @ low-E (sub-GeV)

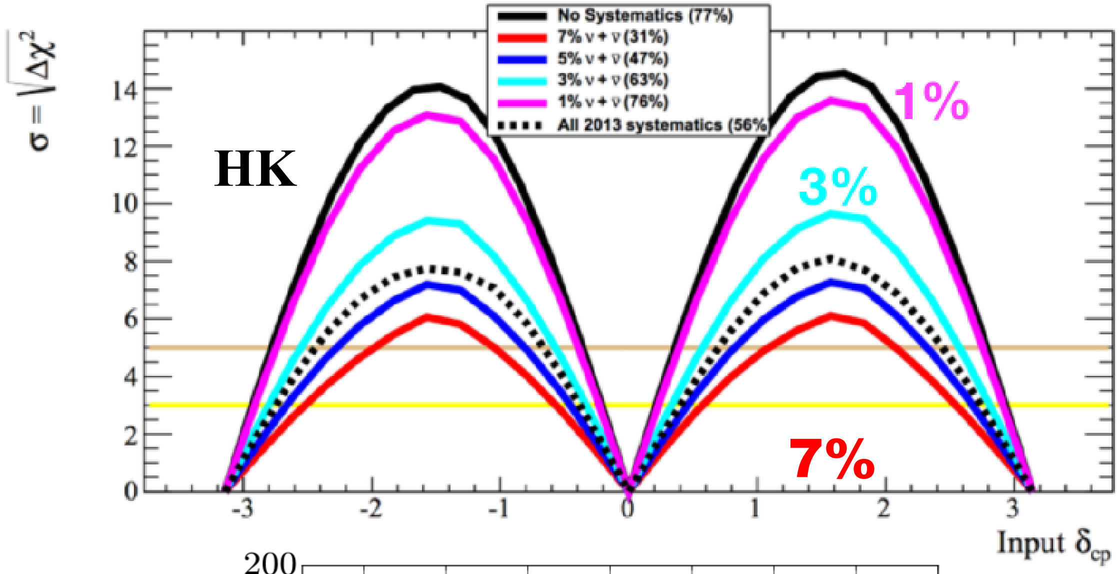
Impact of precision on σ(ν_e)

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 δ_{CP}

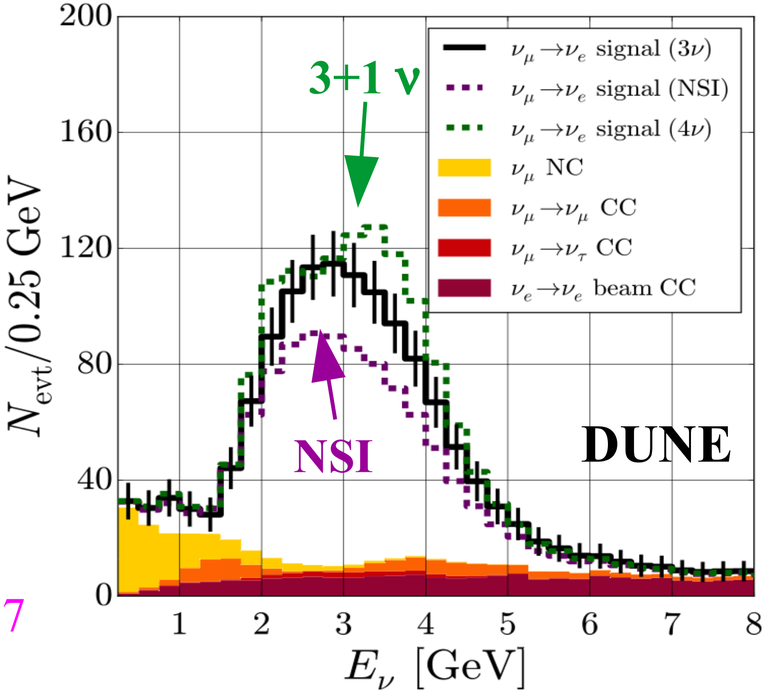
Exotic: sterile neutrinos, non-standard interactions and 3ν have a similar phenomenology →

a precise knowledge of σ(ν_e) vs E is needed to get **a deeper insight of the underlying physics**.

M. Hartz @ NuFact 2015



De Gouvea et al., 1605.0937



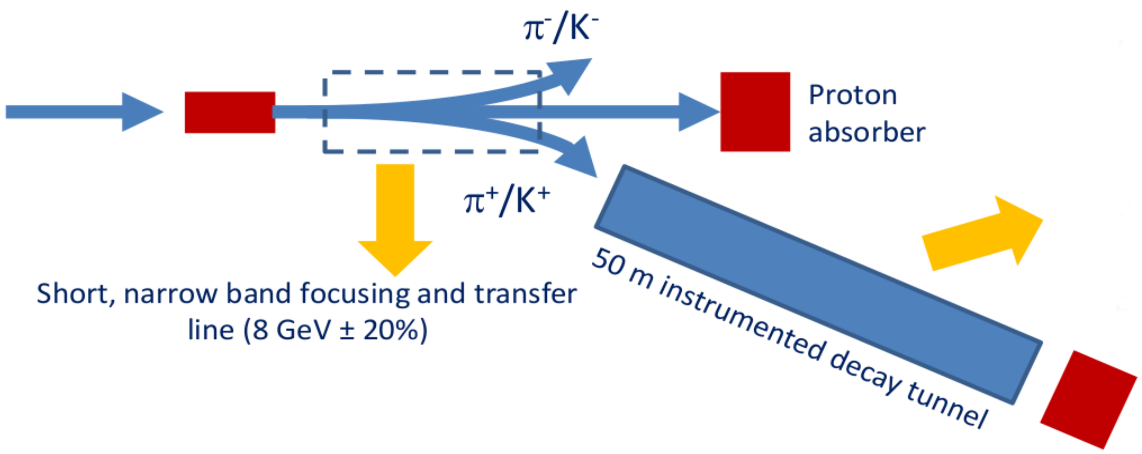
Monitored beam: build a neutrino **source** employing **conventional technologies** reaching a **precision on the initial flux** < 1%

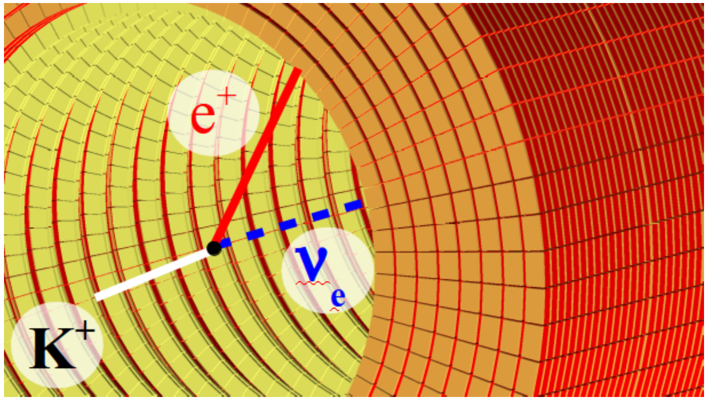
Monitored beams

- The idea behind existing **μ/hadron monitors** is extended to the ultimate step of monitoring (~ inclusively) the **decays in which ν are produced**.
- Uncertainties from **hadro-production**, **PoT**, hadron **beam-line efficiency** (happening "before" the tagging) are "by-passed" by the tagging.

Traditional beam	⟷	**Monitored beam**
• **Passive** decay region • ν_e flux relies on **ab-initio simulations** of the full chain • **large uncertainties** from hadro-production		• **Fully instrumented** decay region $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle e^+ • **ν_e flux prediction = e^+ counting**

Working principle and setup



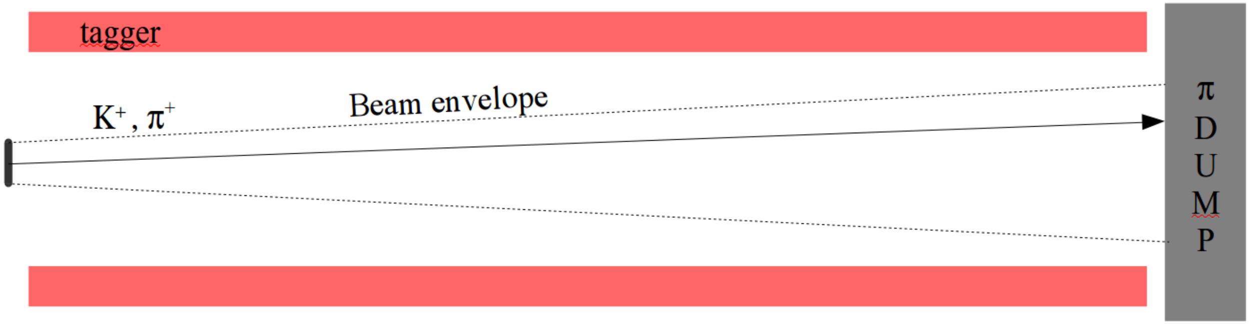


- **1) Hadron beam-line:** *q*-selection, focusing, transfer of π/K$^+$ to a **50 m long** instrumented decay tunnel (e$^+$ tagger)
- **2) e$^+$ tagger:** real-time, "inclusive" **monitoring** of decay products

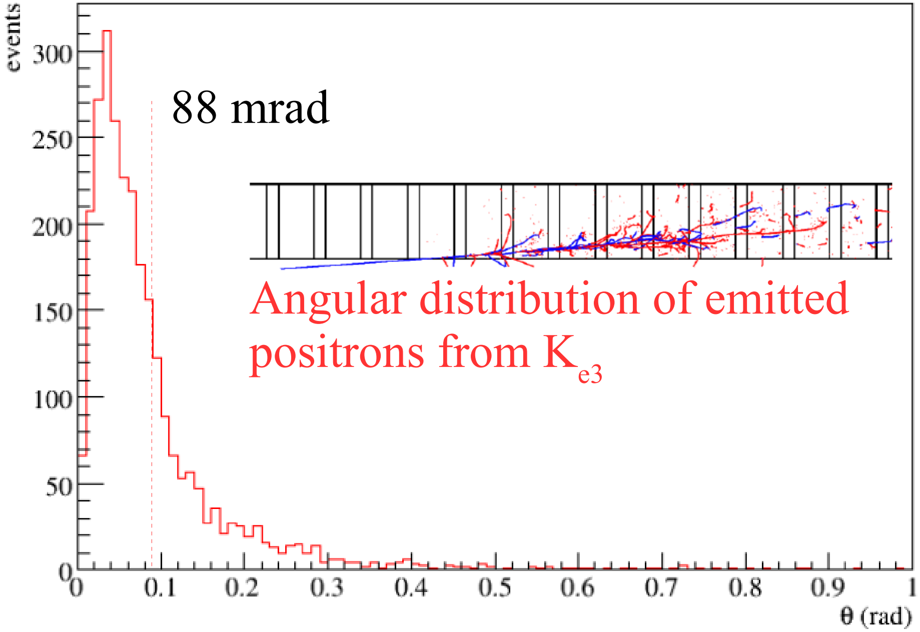
- Profiting of "kinematics" and a **good focusing** (important!) we can have: **only K decay products** (at large angles) being measured with **π^+ and μ decaying** at small angles and reaching the dump **without hitting the instrumented walls**.
- This allows:
  - ✓ **tolerable rates** and **irradiation** (< 500 kHz/cm^2, ~ 1.3 kGy)
  - ✓ full/continuous **control of all produced ν_e**
    - ✗ contribution of **ν_e from μ decays is < 2%** using a "short" decay tunnel
  - ✓ control of **ν_μ from K** (can be separated from π-ν_μ using their radial distribution)

Decay kinematics and tagger acceptance

- **Baseline design:** $p = 8.5$ GeV/c ± 20%, $\theta < 3$ mrad over 10×10 cm^2, $L = 50$ m → **trade-off** to get E_ν in R.O.I, few ν_e from μ decays, limited K loss in the beam-line, good e/π separation, reduced costs.

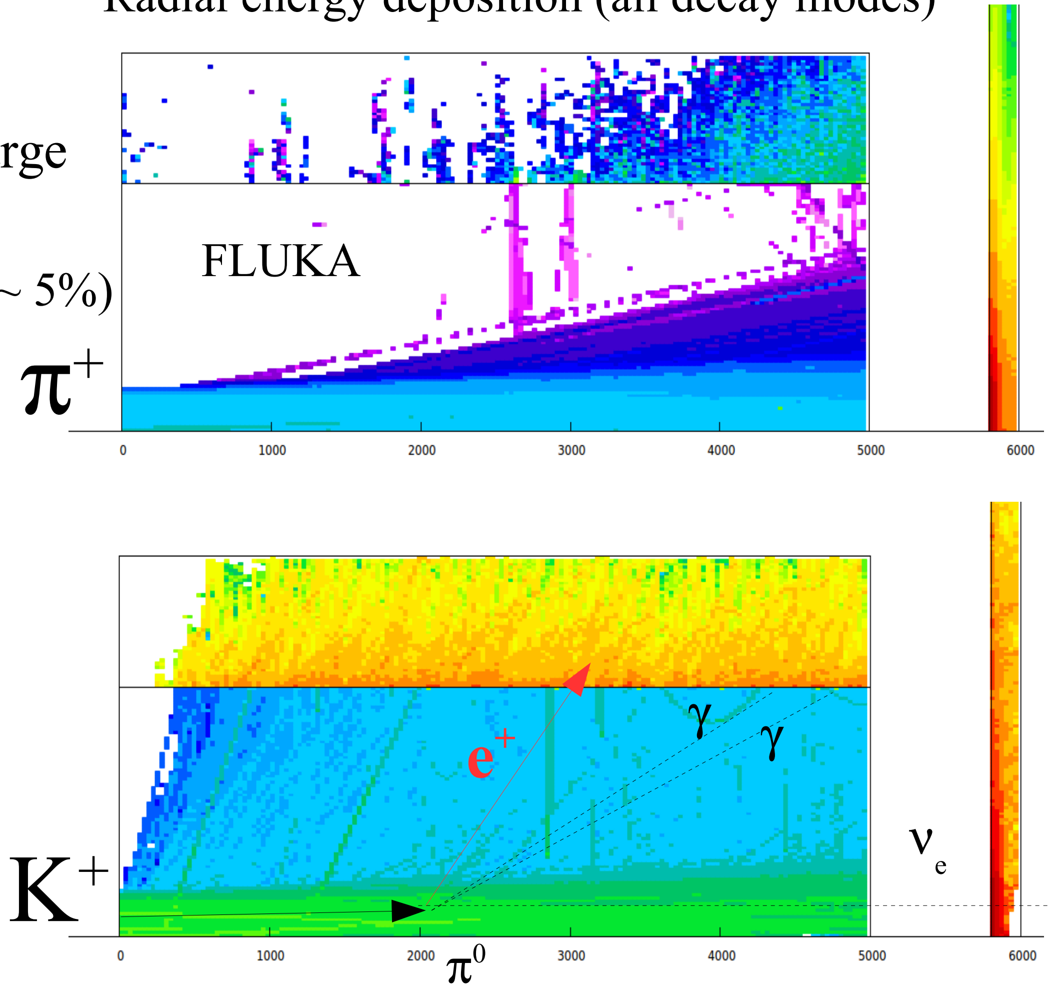


- Good acceptance for K decays thanks to the large emission angle (~ m_K)
- **Golden channel** for ν_e : $K^+ \rightarrow e^+ \nu_e \pi^0$ (**K_{e3}**, BR ~ 5%)



Angular distribution of emitted positrons from K_{e3}

Radial energy deposition (all decay modes)



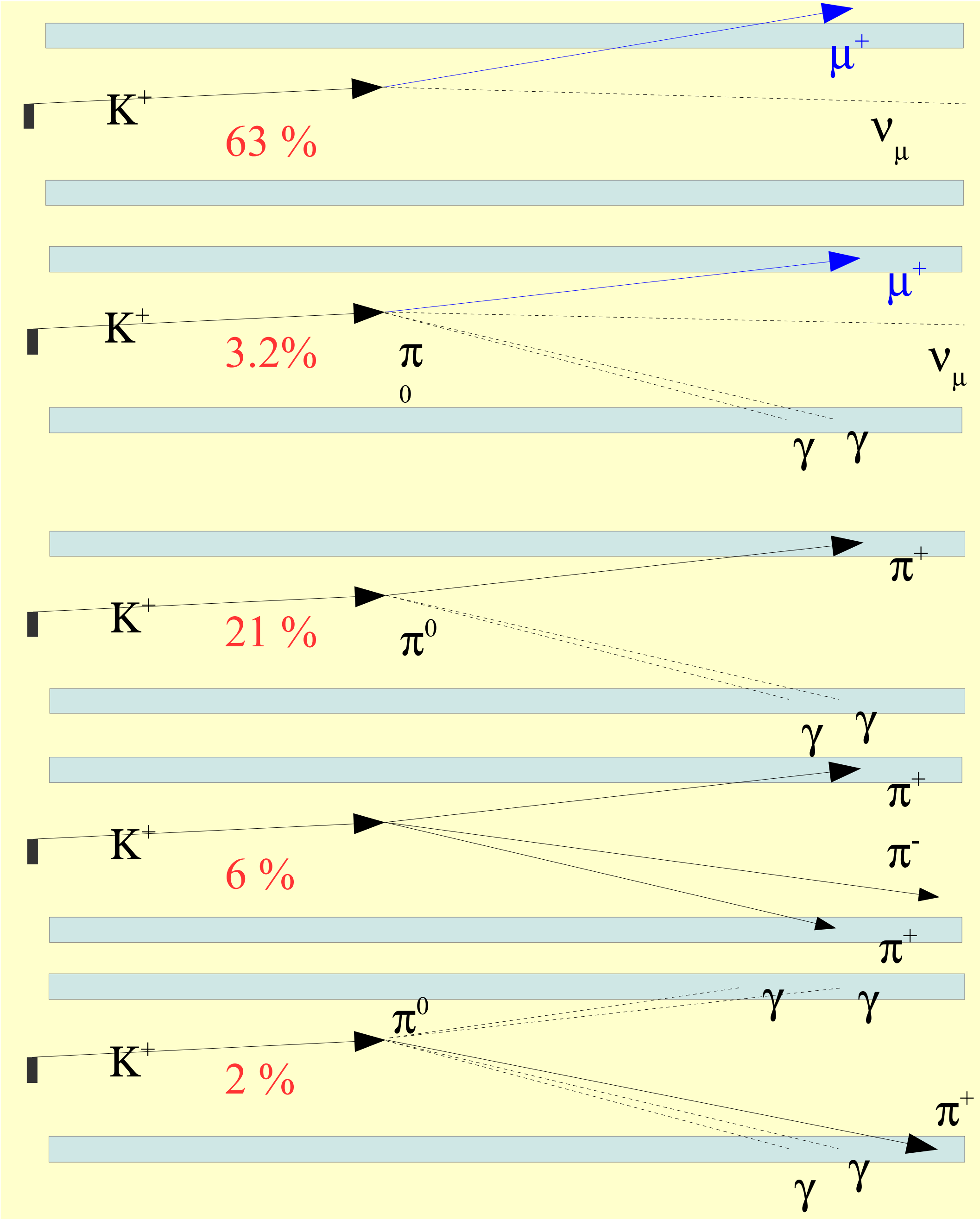
Role of other K decays

- **Hadronic K decays** (~ overall rate) can be also used to infer the $\boldsymbol{\nu_e}$ **flux** correcting for the ratio of leptonic and hadronic **branching ratios** (can be considered a "**silver sample**")

- **On the other hand** $\boldsymbol{\pi^{+/0}}$ **from** $\mathbf{K^+}$ **can mimic an** $\mathbf{e^+}$ and "pollute" the K_{e3} golden sample
  → possible to **discriminate** with:
  - **1)** calorimetric longitudinal profile of energy deposition
  - **2)** tagging vertices by timing:

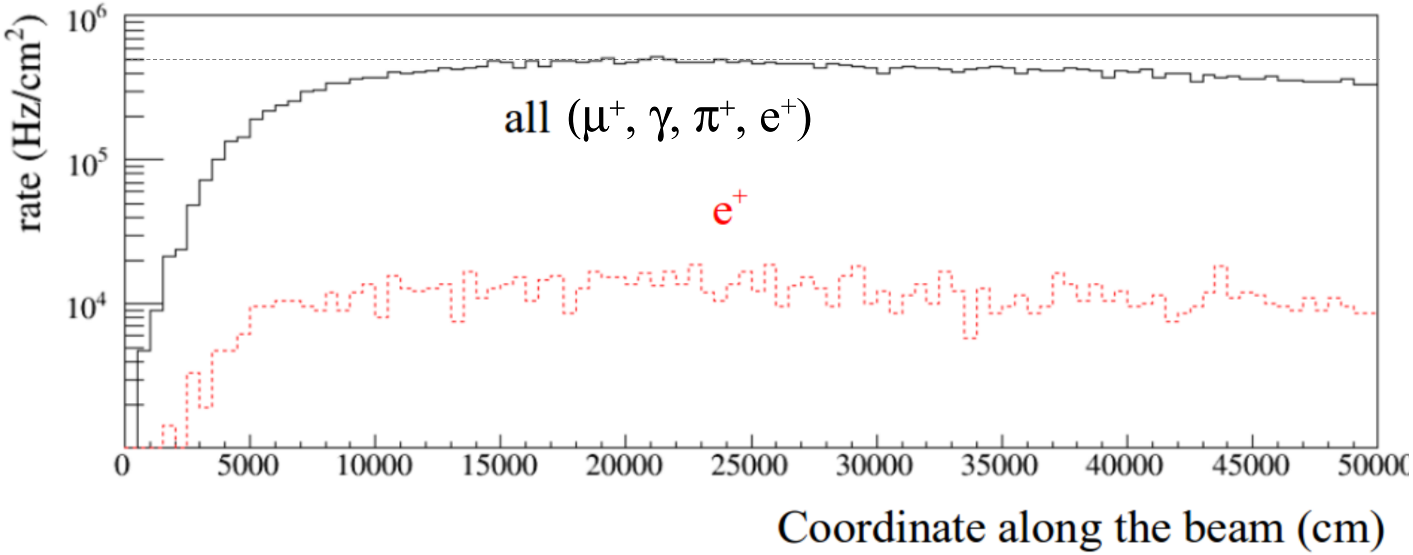
  σ_t O(**100 ps**) ~ σ_{zVTX} O(1m)

  veto fake e^+ from $K^+ \rightarrow \pi^+\pi^-\pi^+$ and $K^+ \rightarrow \pi^+\pi^0$ reconstructed vertices



The e^+ tagger challenges

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

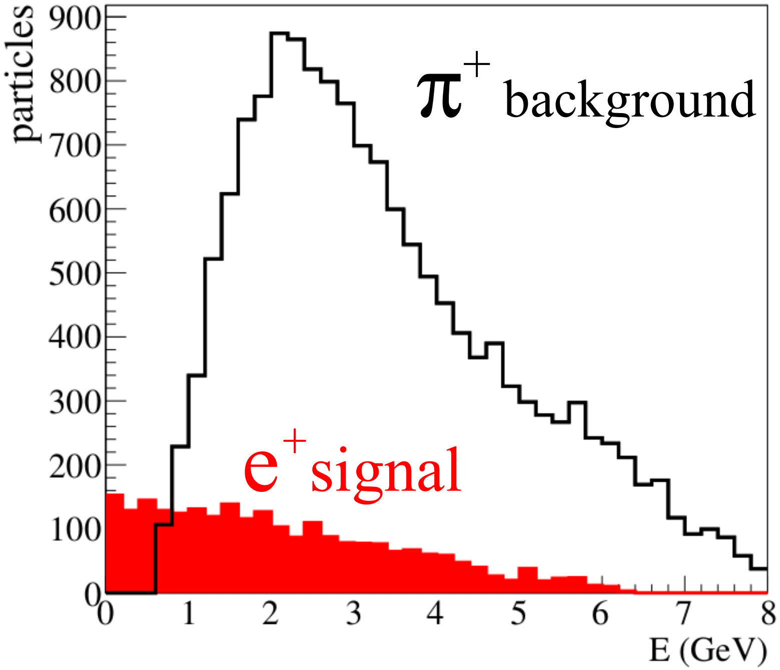


	Max rate (kHz/cm^2)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

The decay tunnel: a **harsh environment**

- **particle rates: > 200 kHz/cm^2**
- **backgrounds:** pions from K^+ decays

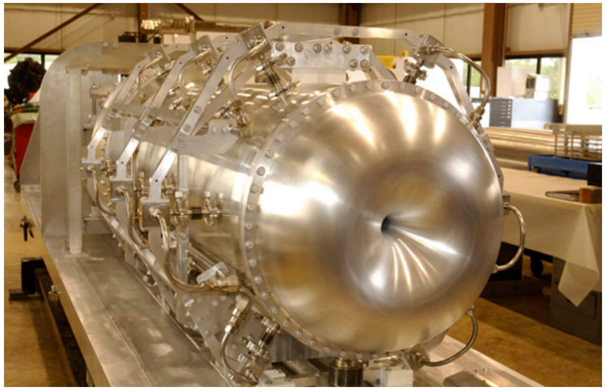
  Require to veto 98-99 % of them →



Moreover:

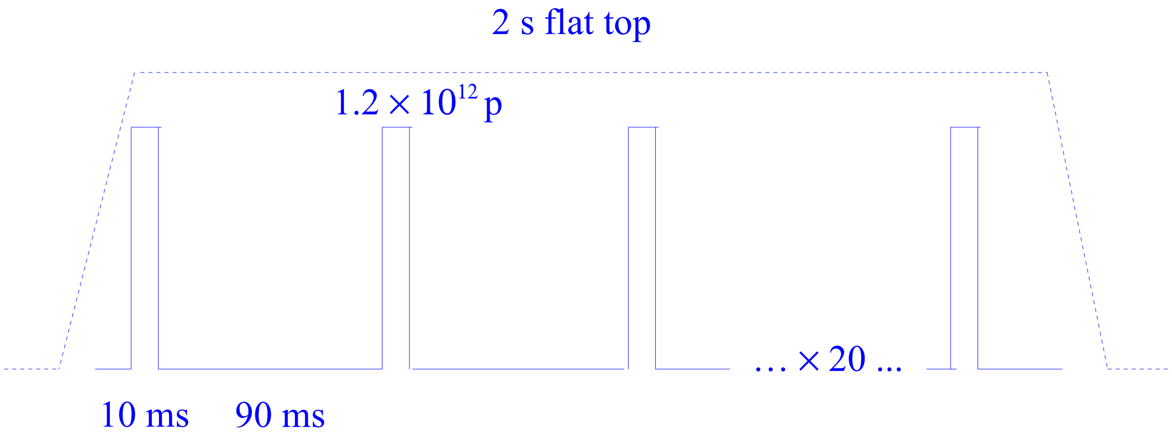
- **extended source of ~ 50 m**
- grazing incidence
- significant spread in the initial direction

Hadron beam-line: scenario A



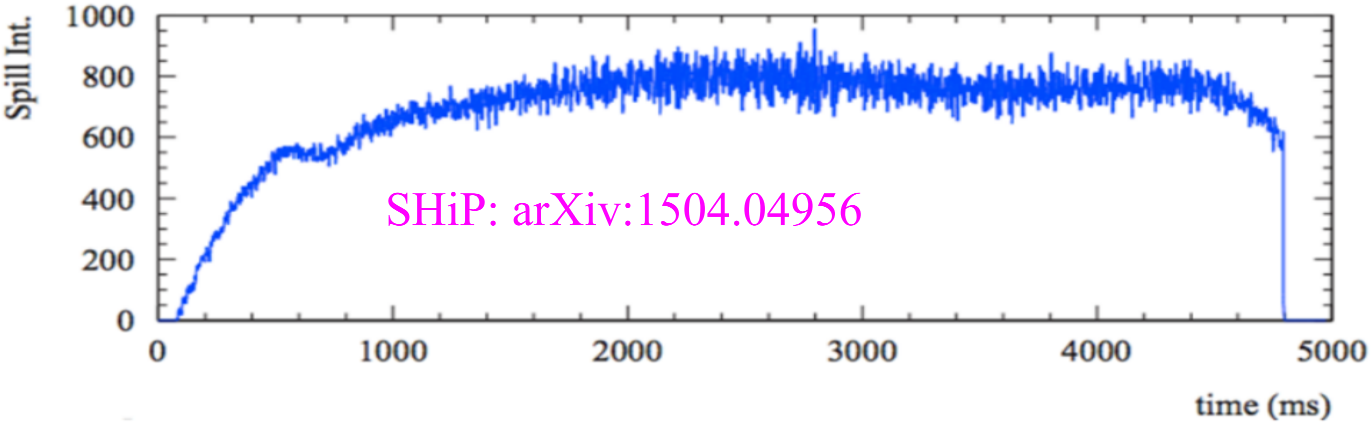
- Magnetic horns. Good collection. Pulsed devices.
- $t_{\text{impulse}} < 10$ ms (Joule heating, I ~ O(100) kA)
- **tagger rate limit** is hit injecting **10^{10} π^+ in 2 ms**
- Considering typical horn collection efficiencies this corresponds to **0.3-2.5 × 10^{12} PoT/spill** depending on E_p (spills with relatively "few" protons)
- Considering we need 1.94 × 10^{13} K^+ for ν_e^{CC} with a **500 t ν** detector **at 100 m** asking for **10^4 ν_e^{CC} 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
  - R&D and machine studies are planned

A possible structure at the SPS: a train of twenty10 ms long spills with 1.2 × 10^{12} protons each spanning 2 s of the flat top (=50% SPS emptying).

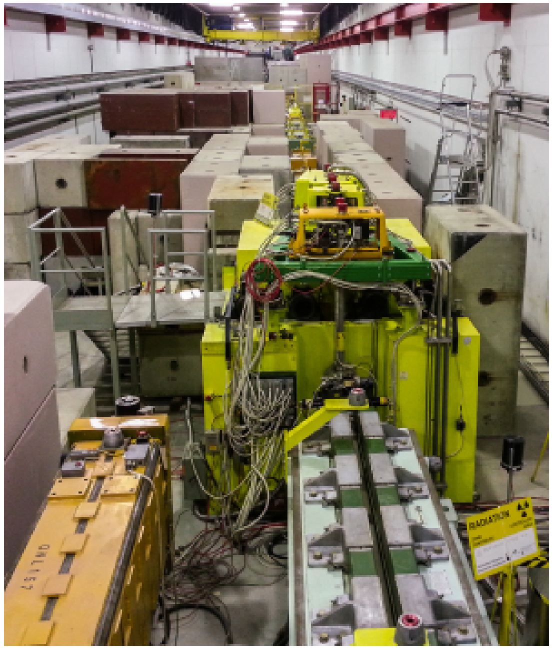


Hadron beam-line: scenario B

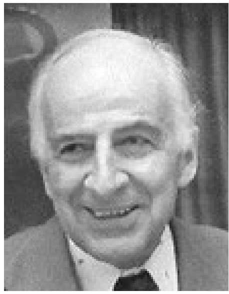
- Static focusing: **large aperture radiation-hard quadrupoles**.
- Disadvantage: **loss of acceptance** w.r.t. horn-based focusing.
  - **PoT to get 10^4 ν_e^{CC}: 0.5-7 × 10^{21}** O(~10 ×) more but still feasible.
    Can be compensated by **(data taking × detector mass)**
  - Far from tagger maximal 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. Synergies with the needs of **SHiP** proposal at CERN.



SHiP: arXiv:1504.04956



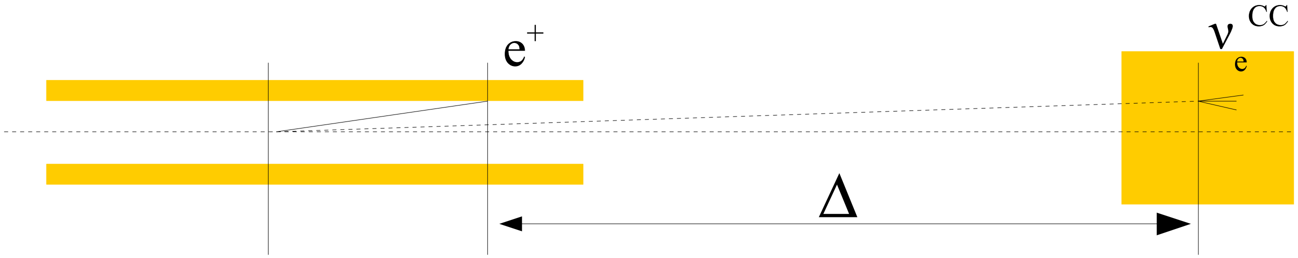
Going beyond: "time tagged" beams



- Event time dilution → **Time-tagging**
- **Associating a single ν interaction to a tagged e^+ with a** small "accidental coincidence" probability through **time coincidences**
- **E_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 using 10^{10} hadrons/burst: $\mathbf{A \sim 2 \times 10^7\ \delta/T_{extr}}$

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

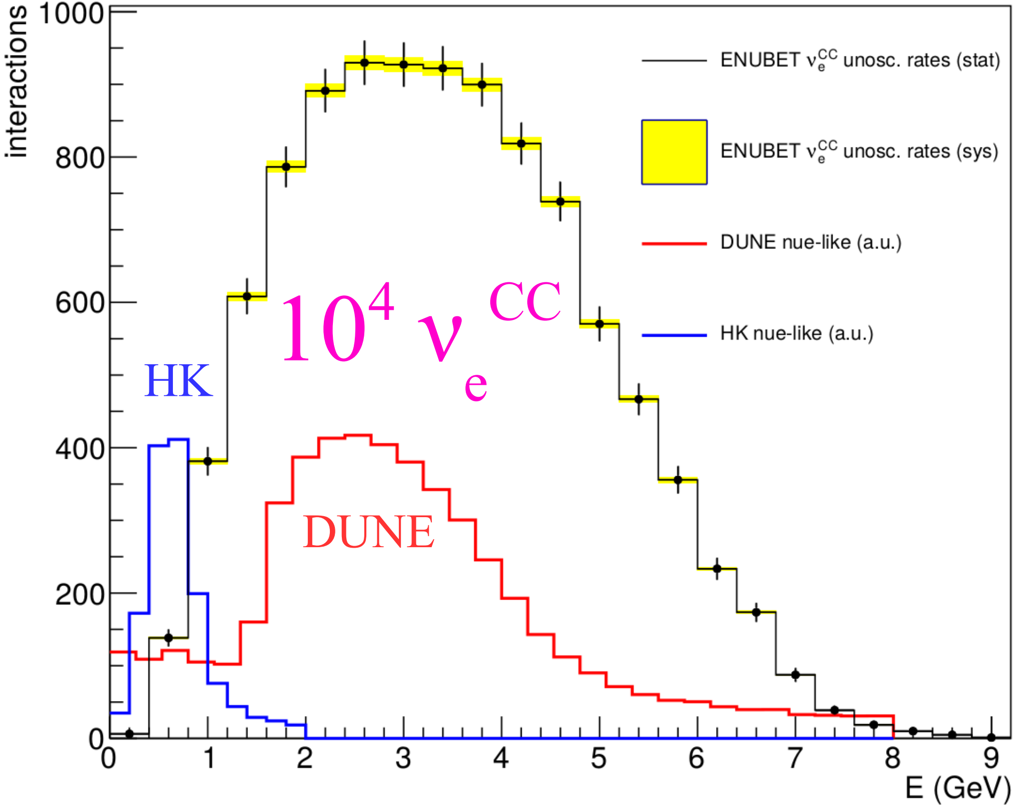
Using such long extractions prevents* using O(ms) **pulsed focusing devices** (horns, scenario A) but could be feasible with a **static based focusing with DC elements** (quadrupole triplets, bending magnets, scenario B)

*T_{extr} = 2 ms (1 e^+ / 70 ps) even δ = 50 ps gives A = 50%.

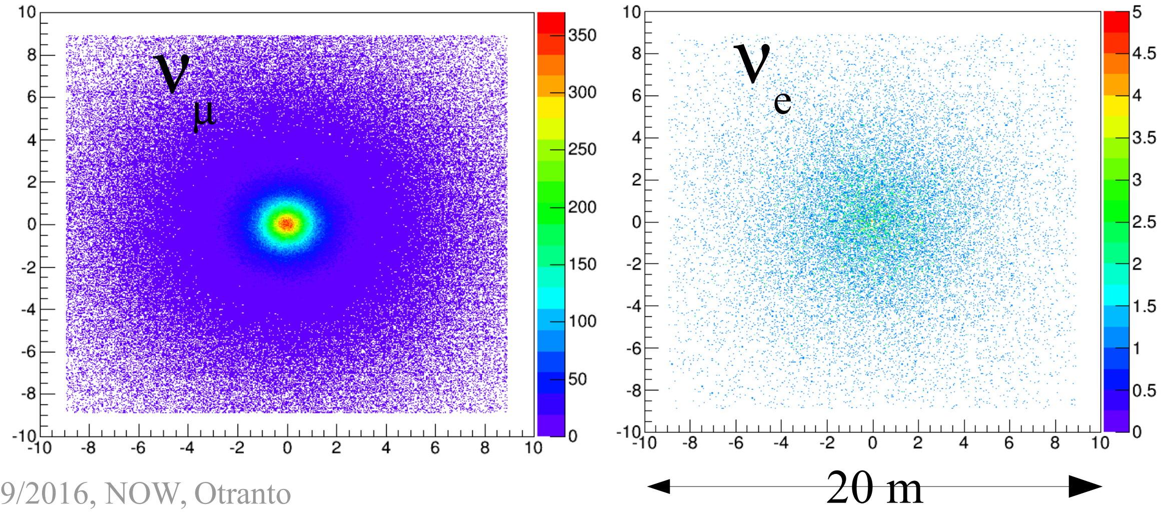
ν detector and ν_e^{CC} rates

- At 100 m from the hadron window
- A 500 t mass (e.g. ICARUS@Fermilab , Protodune SP/DP @CERN)
- Interesting region of long baseline future projects is covered
- Further tuning foreseen to go even lower in energy preserving an acceptable positron purity

<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



New opportunities

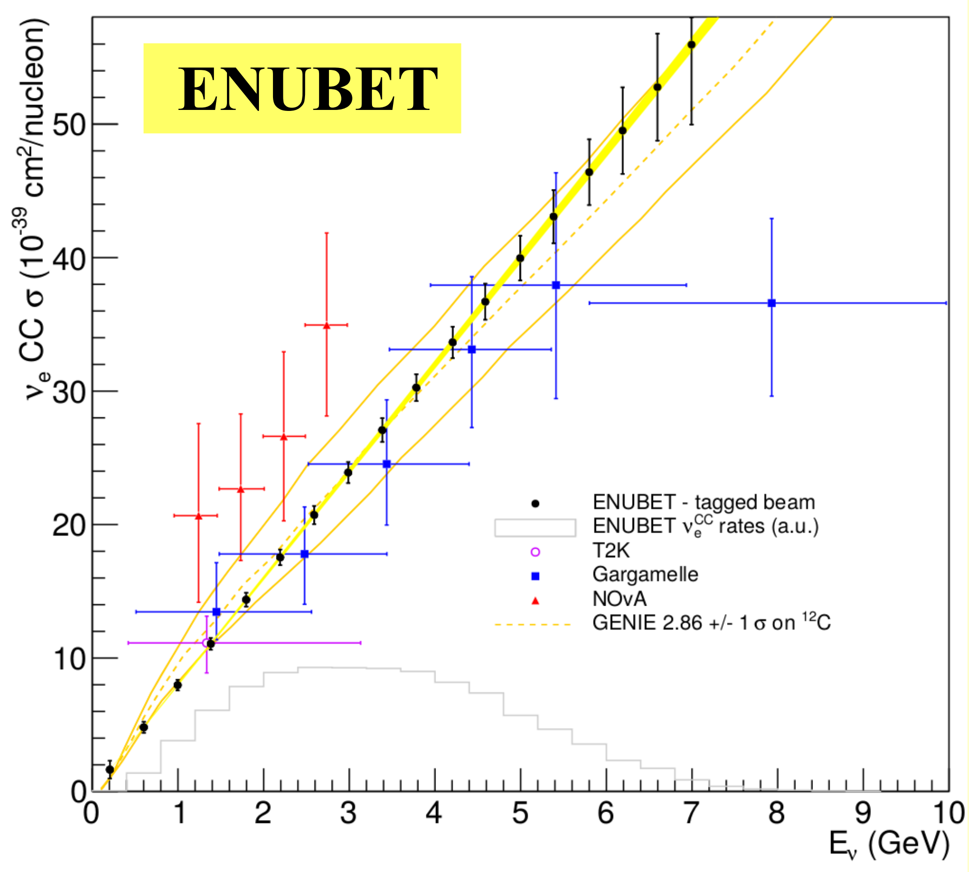
The ENUBET technology is well suited for **short baseline experiment** where the intensity requirement are less stringent. Major applications include:

- 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”

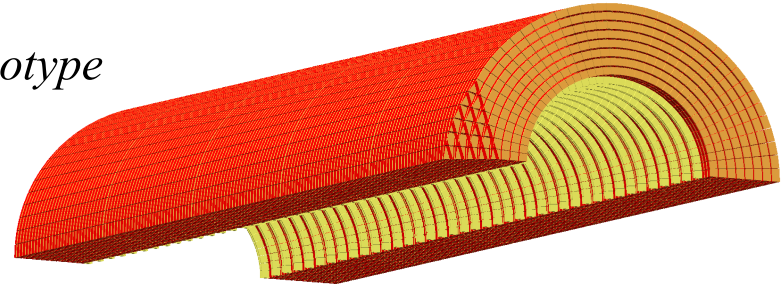


1% sys. + 1% **overall stat. errors**
(10.000 ν_e^{CC}) Eur. Phys. J. C75 (2015) 155

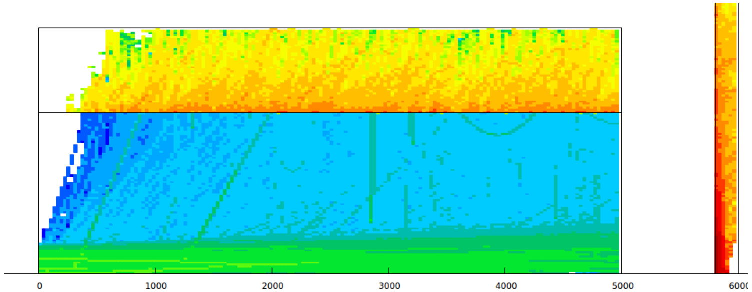
The ENUBET roadmap

- Construction of a **3 m section of the instrumented decay tunnel** (tagger prototype)
- **Test beams** at CERN-PS T9 and INFN-LNF
- Assessment of **systematics with a full simulation** supported by test beam results
- **Design of the beam-line** for collection/transport/focusing of hadrons in the tagger
- Design and test of suitable **proton extraction schemes** (CERN-SPS)

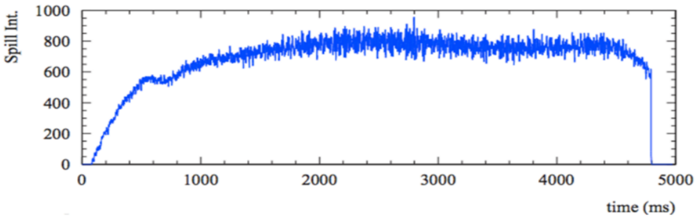
Tagger prototype



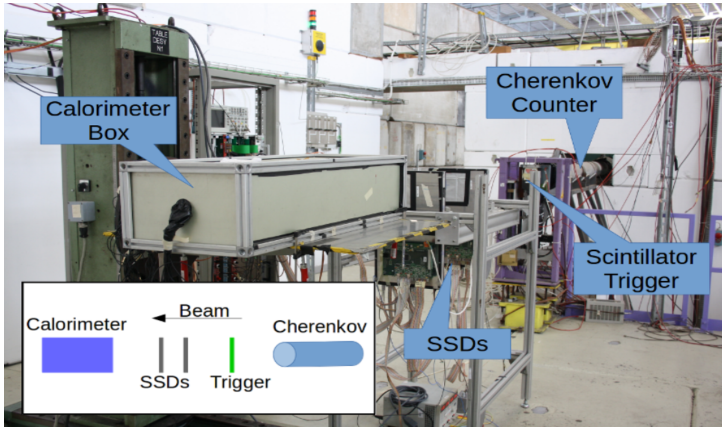
Tagger simulation example (FLUKA)



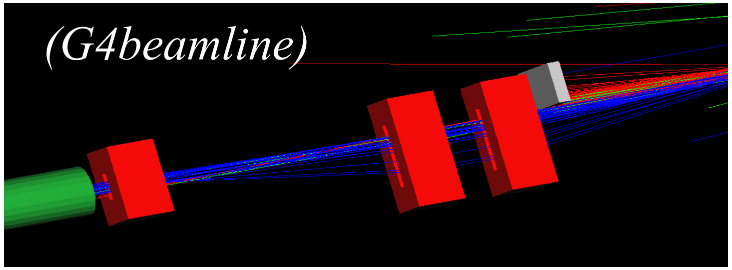
SPS resonant slow extraction



PS-T9 test beam (2015)



Beamline design early studies



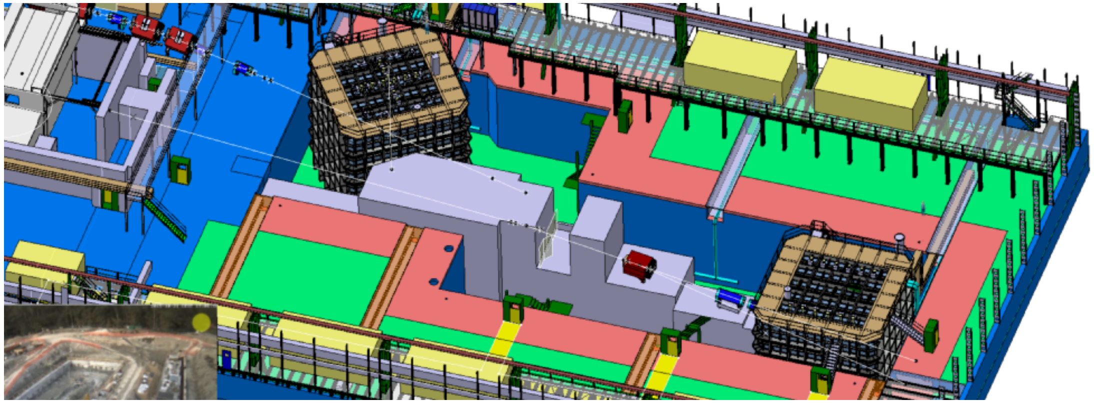
→ The complete picture to move forward to a full scale experiment

By-products in calorimetry (new low-cost, ultra-compact detectors) **and accelerator physics** (novel extraction schemes for fixed-target, beam-dump experiments)

The ENUBET roadmap (contd.)

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:**

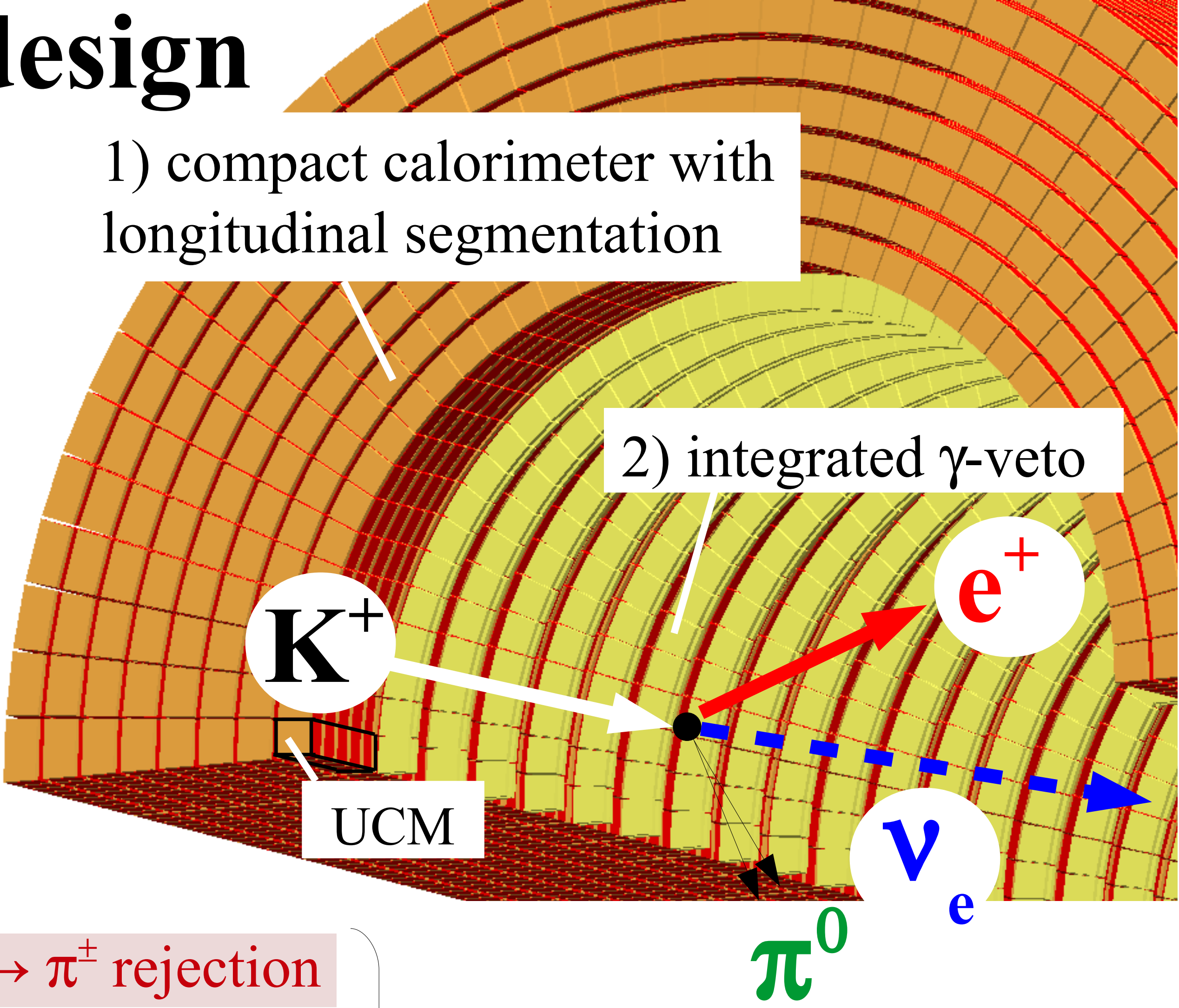


with **beam halo μ** and low-angle **cosmic rays**

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

Tagger current 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**

Full simulation: e/π separation

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

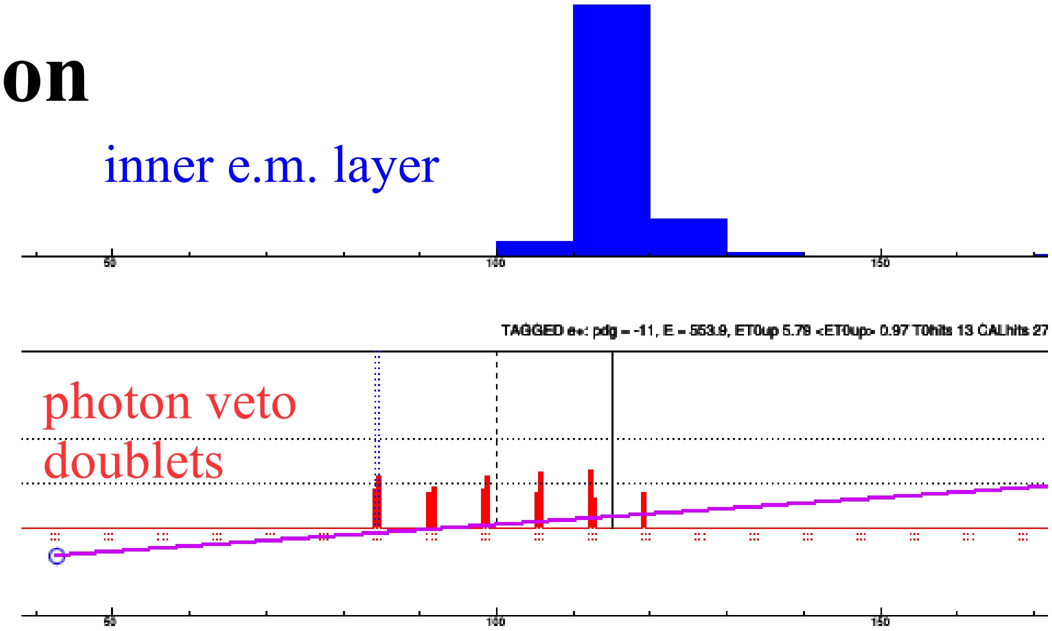
Takes into account **pile-up** related restrictions in the event building.

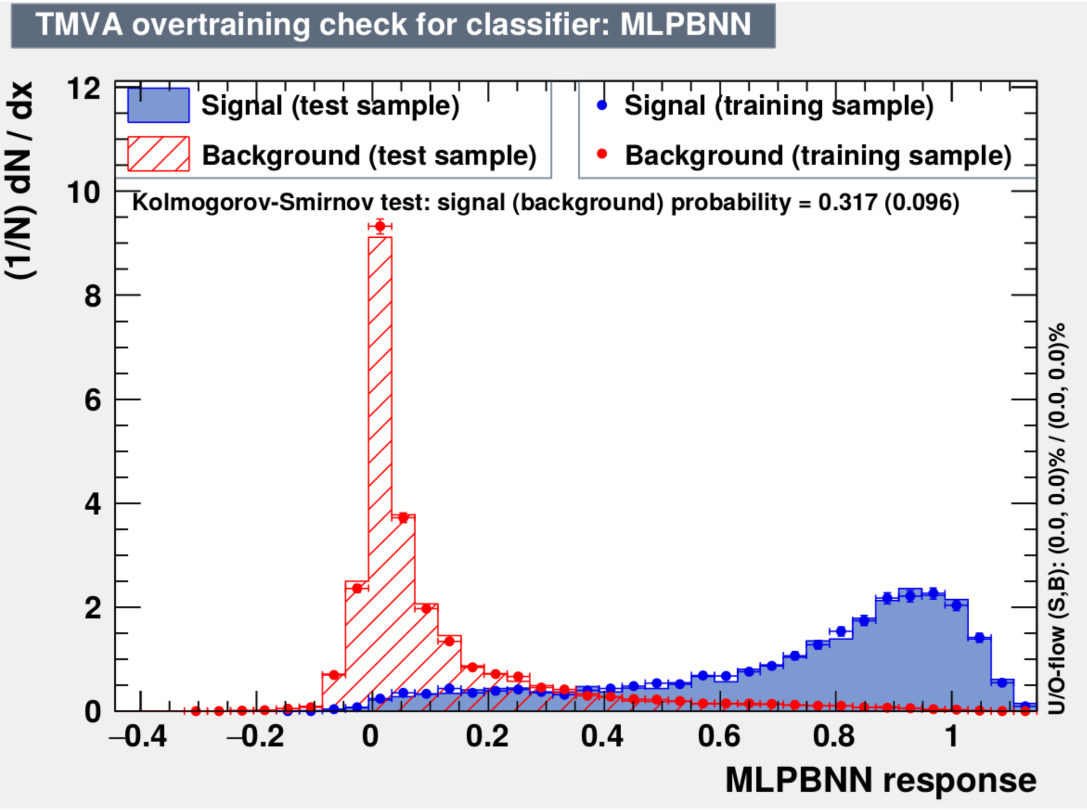
TMVA **multivariate** analysis:

- 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

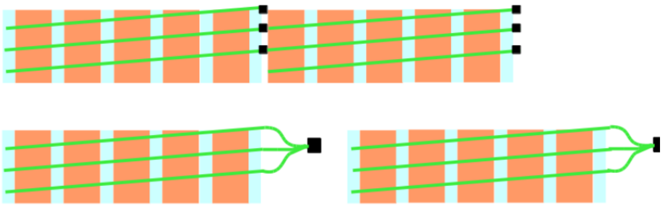
	ε_{geom}	ε_{sel}
e^+	90.7 %	49.0 %
π^+	85.7 %	2.9 %
π^0	95.1 %	1.2 %

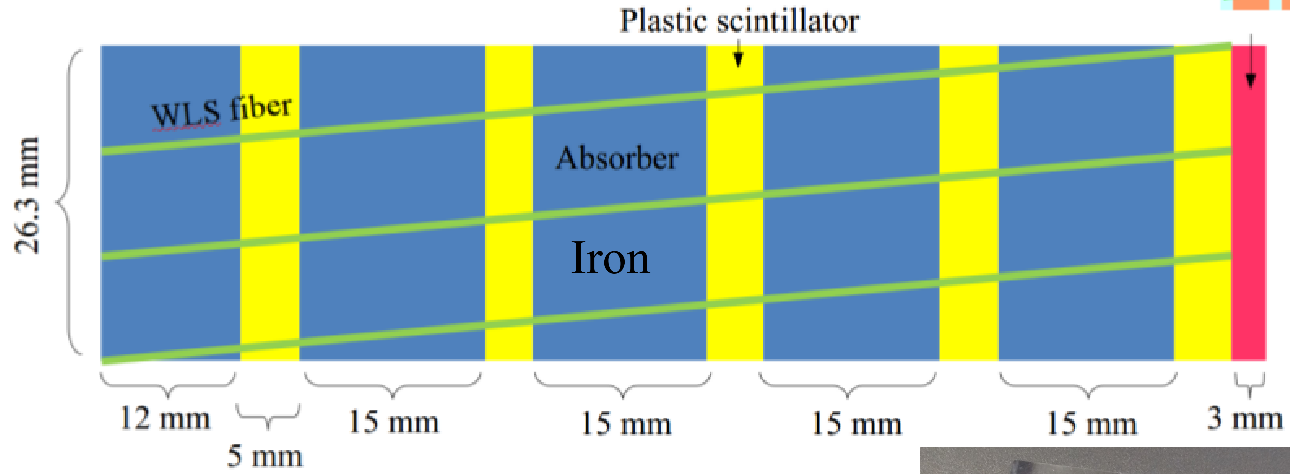
Former estimates from parametrizations confirmed with a **realistic** and **cost-effective** setup.

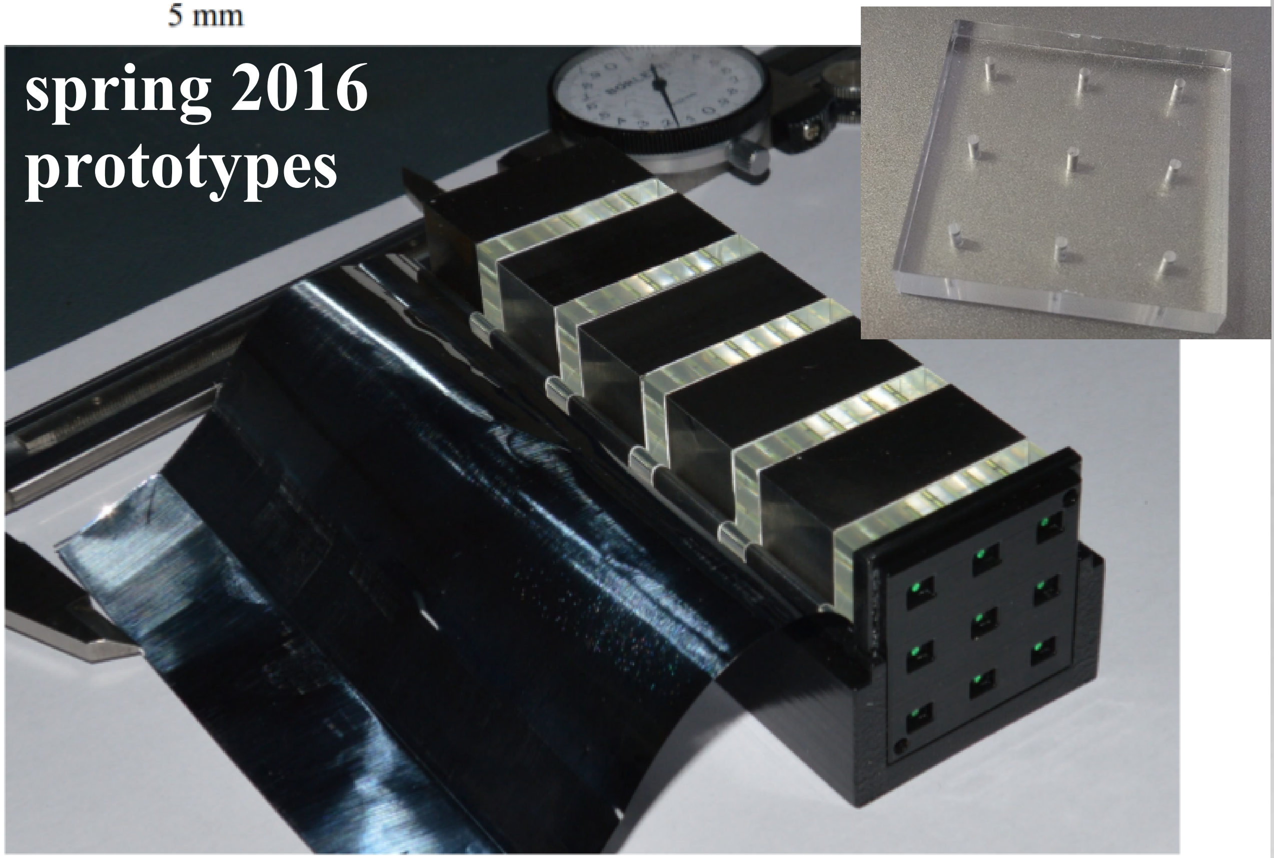




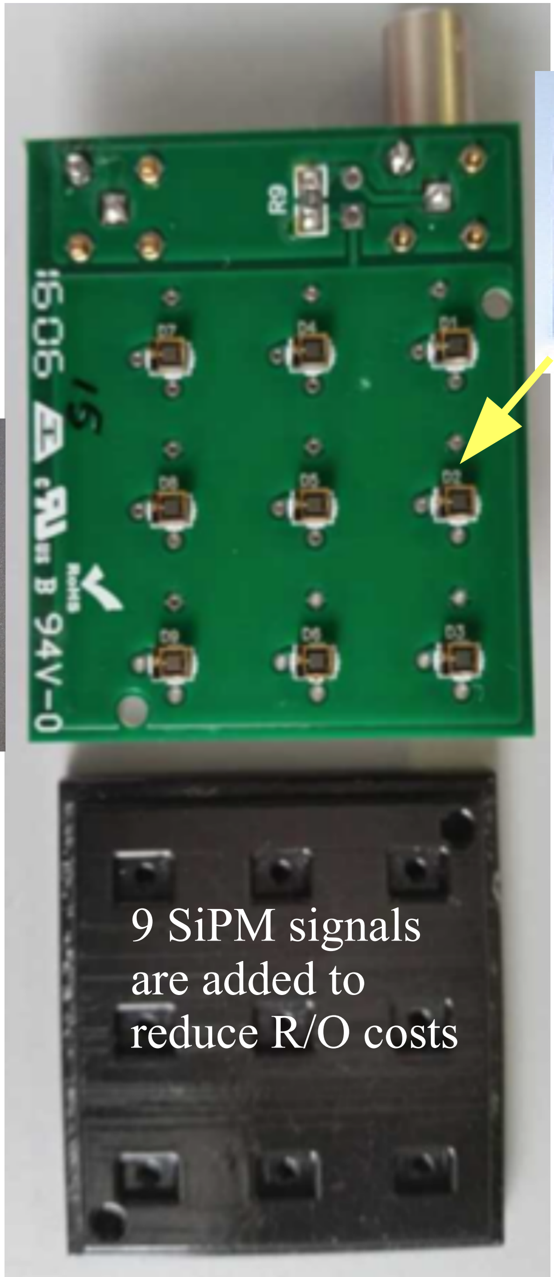
The Ultra Compact Module



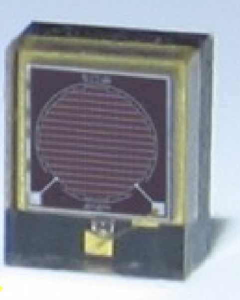




spring 2016 prototypes



9 SiPM signals are added to reduce R/O costs

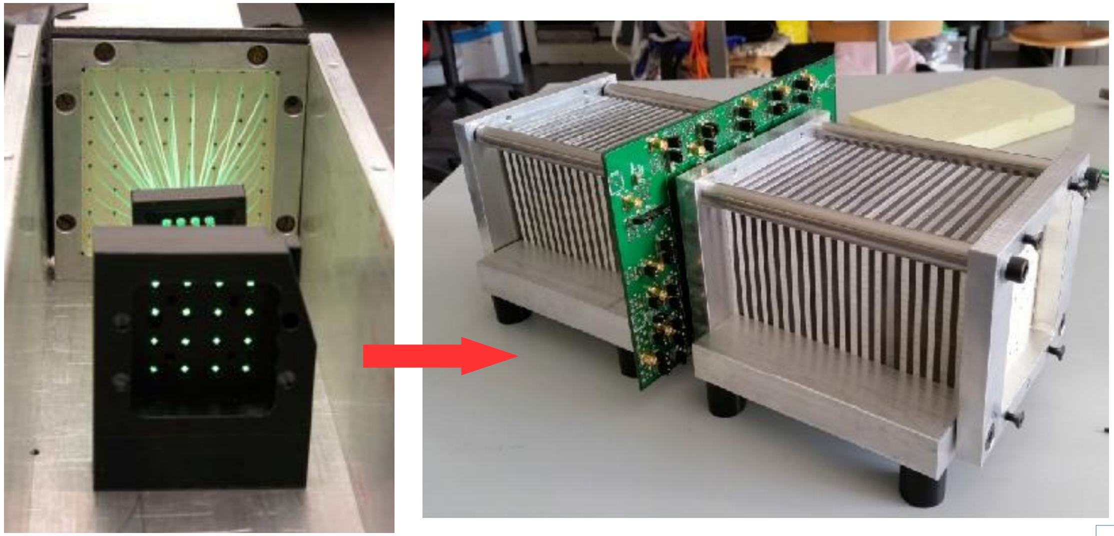


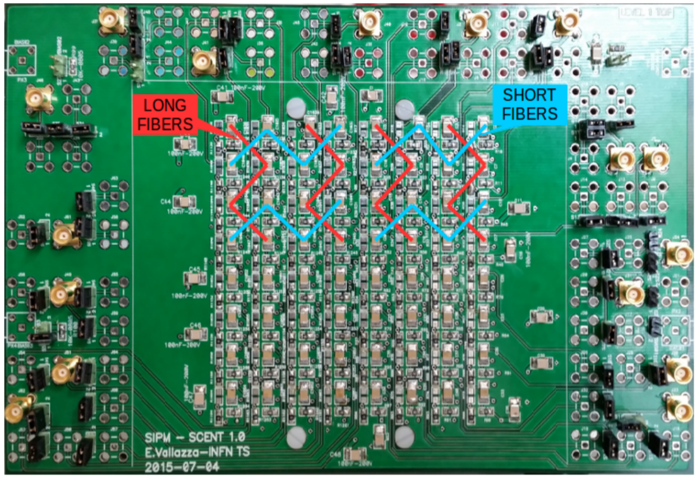
1 Si-PM
1 WLS

Tagger detector R&D: SCENTT

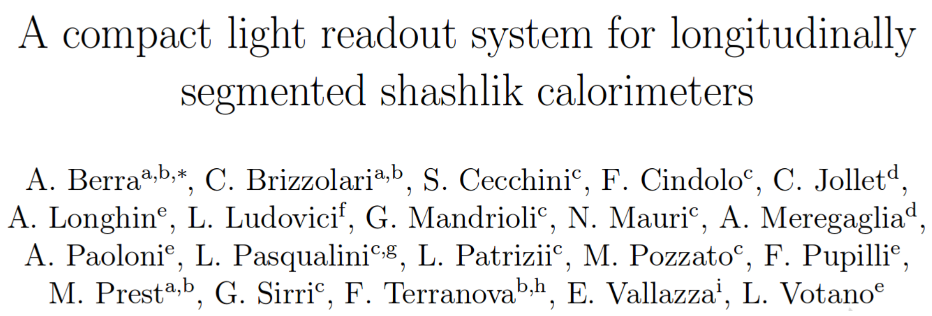
Shashlik Calorimeters for Electron Neutrino Tagging and Tracing

- 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]

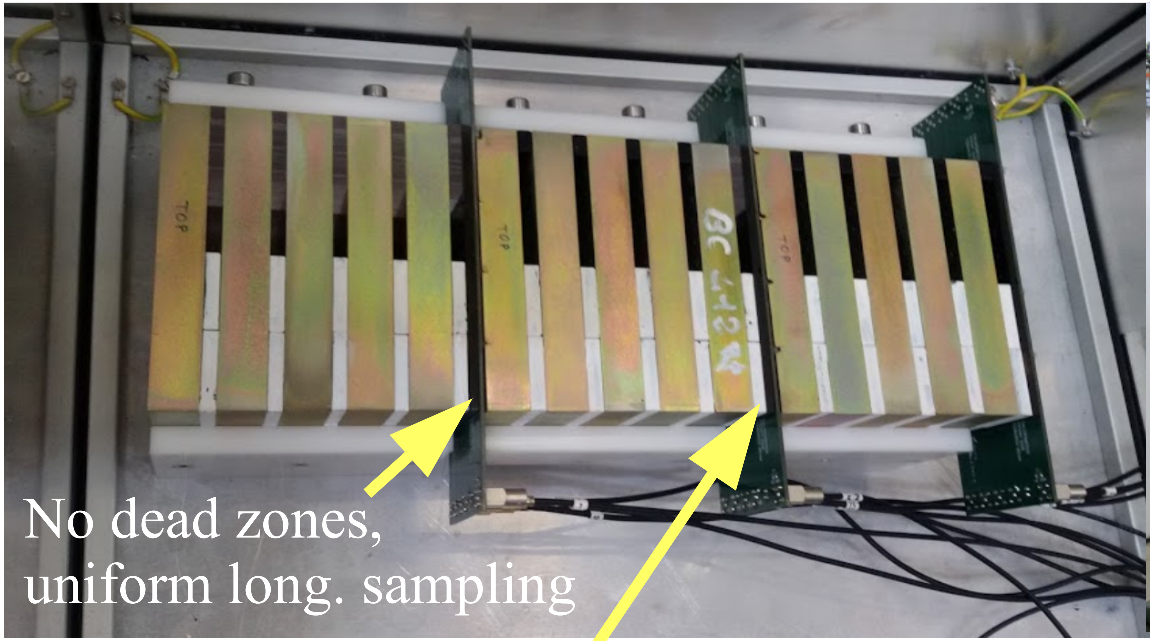
A. Berra et al., NIM A824 (2016) 693

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

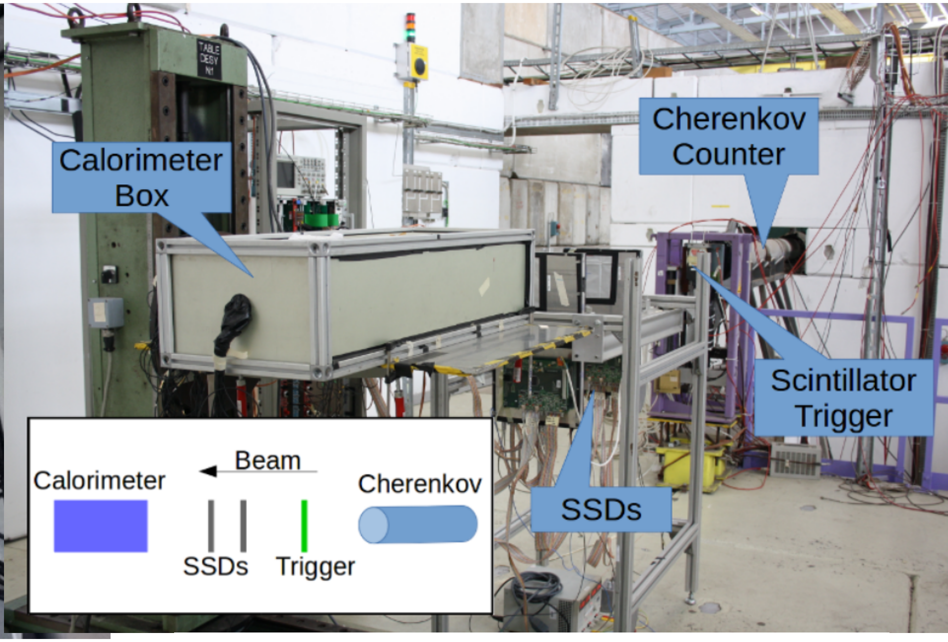
http://dx.doi.org/10.1016/j.nima.2016.05.123 arXiv:1605:09630

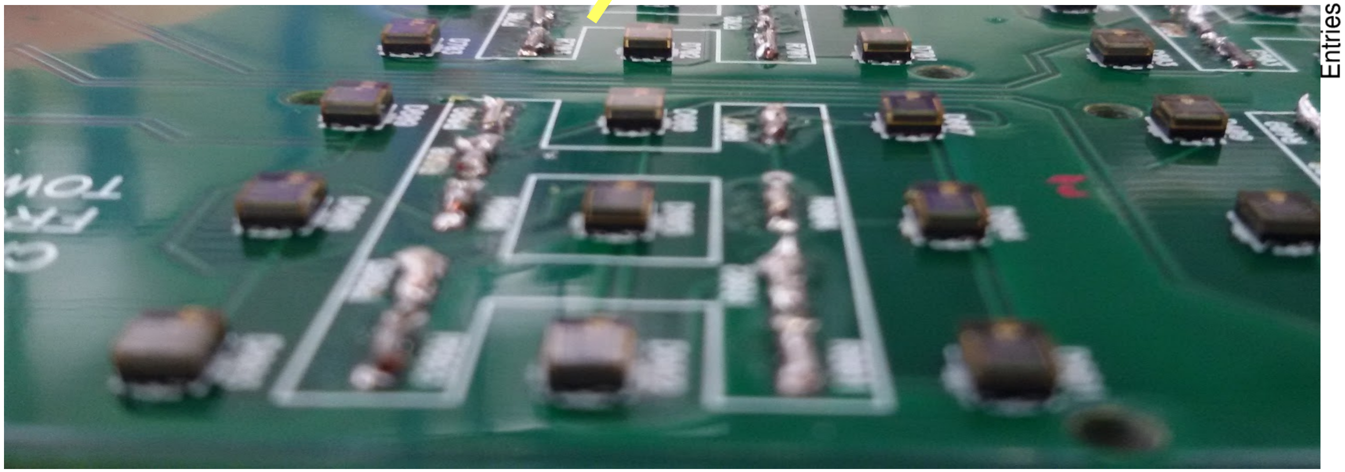
First test beam validation of UCM

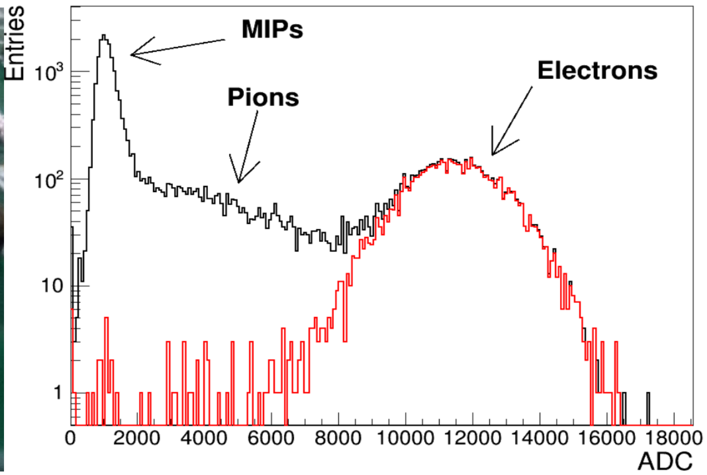
CERN-PS T9 test beam (July 2016). 12 ENUBET UCM modules (12 X_0) exposed to pions and electrons from 1-5 GeV. HD Si-PM with 20 μm cell size.



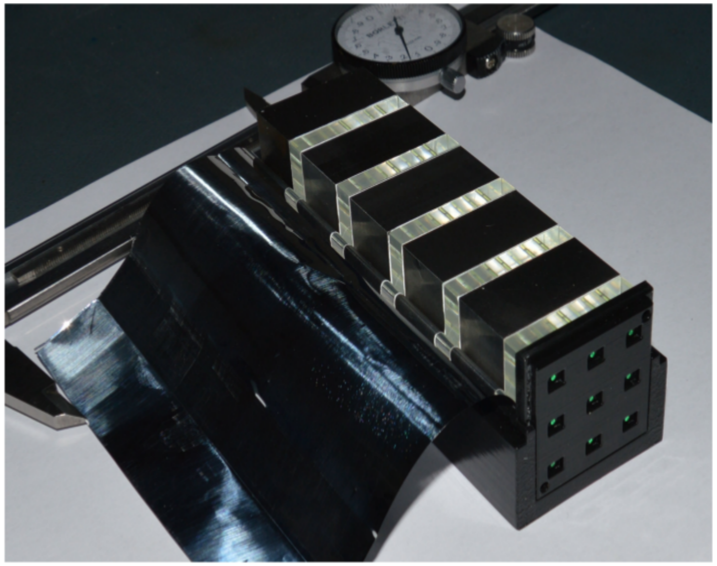
No dead zones,
uniform long. sampling



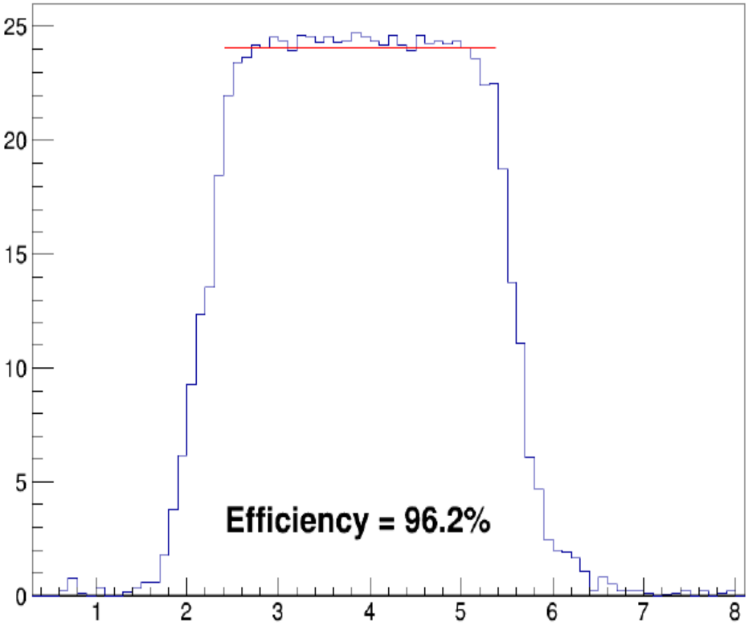




Results from UCM prototypes

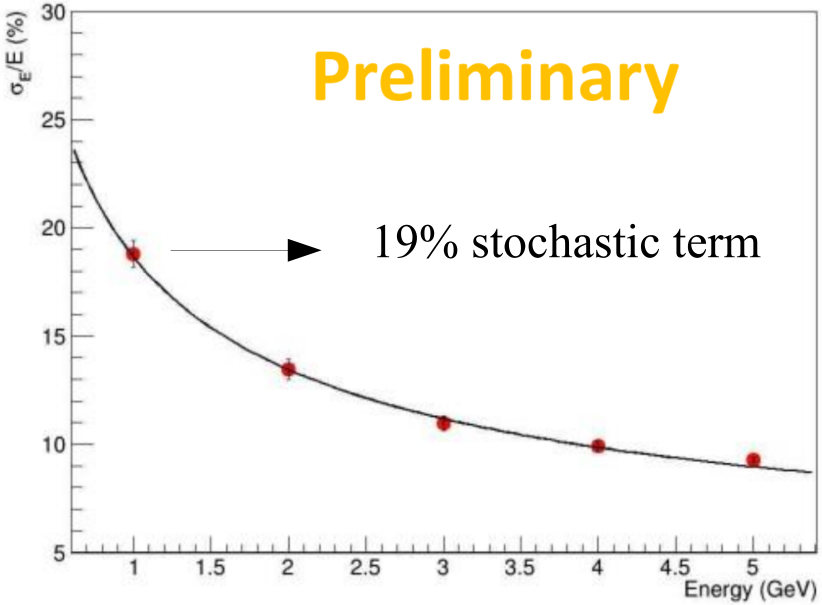


Cheap, fast (<10 ns), Rad-hard technological solution



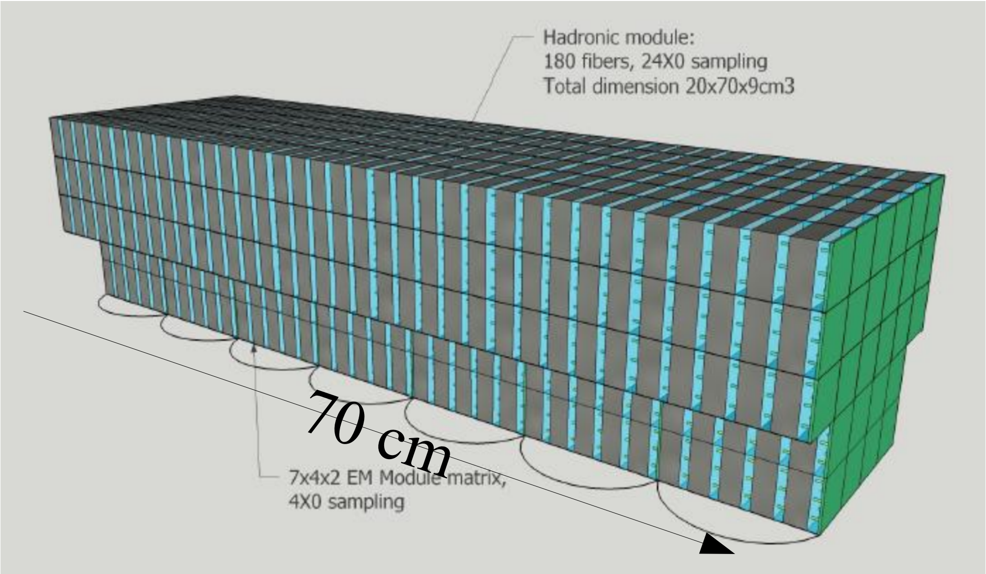
Requirements for ENUBET:

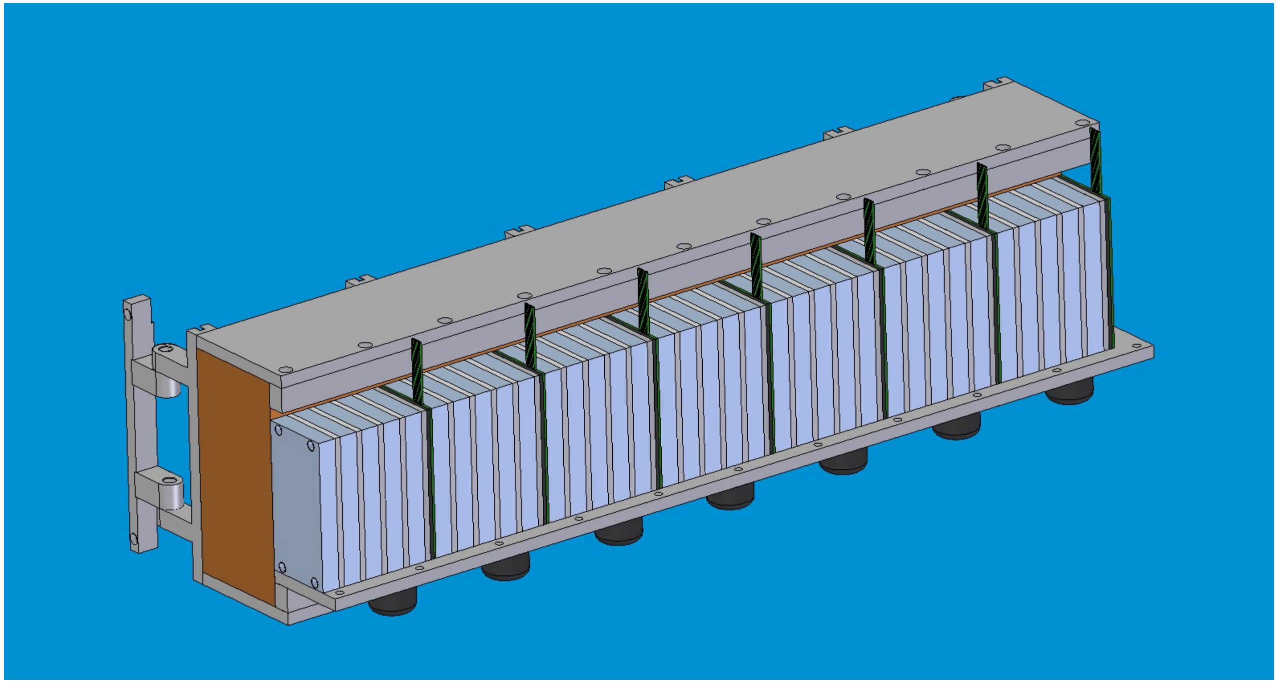
- m.i.p. sensitivity w/o saturation for e.m. showers up to 4 GeV **DONE**
- E resolution < 25% / $E^{1/2}$ **DONE**
- No role for "nuclear counter" effects (direct ionization of SiPM in the e.m. shower) **DONE**
- recovery time ~10 ns (sufficient to cope with pile-up) → **NOV 2016**
- validation of MC for e/π separation → **NOV 2016**

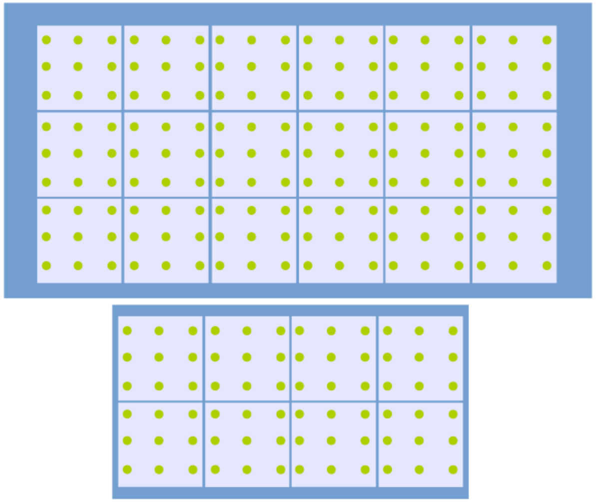


Next test beam at CERN-PS T9

- Sufficient length and presence of outer modules (hadron catcher) allows for e/π validation thanks to hadronic containment (56+18 UCM, 666 SiPM)
- Orientable cradle to study the effect of **grazing incidence.**
- Test final readout with **prototype custom fast digitizers**
- Starting 2 November 2016







Conclusions

- The precision era of neutrino oscillation physics requires **better control of its artificial sources**. At the GeV scale the limited knowledge on the **initial flux is the dominant contribution to cross section uncertainties**
- Such limit can be **reduced by one order of magnitude** exploiting $\mathbf{K^+ \rightarrow \pi^0 e^+ \nu_e}$
- 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 in 2015-2016 are very promising:
  - **Full simulation** of the decay tunnel supports the effectiveness of the calorimetric approach for large angle lepton identification
  - **First prototypes** demonstrate that shashlik calorimeters with longitudinal segmentation can be built without compromising energy resolution (19% at 1 GeV) and provide the requested performance

- The final goal of the **ENUBET Collaboration** is to demonstrate that:
  - a "positron monitored" ν_e source based on K_{e3} can be constructed using existing beam technologies and can be implemented at **CERN, Fermilab or JPARC**
  - a 1% measurement of the **absolute ν_e cross section** can be achieved with **detector of moderate mass (500 ton)**

ENUBET

http://enubet.pd.infn.it

Enhanced NeUtrino BEams from kaon Tagging

ENUBET is a project approved by the European Research Council (ERC) for a 5 **years** (06/2016 – 06/2021) with an overall budget of **2 MEUR**

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

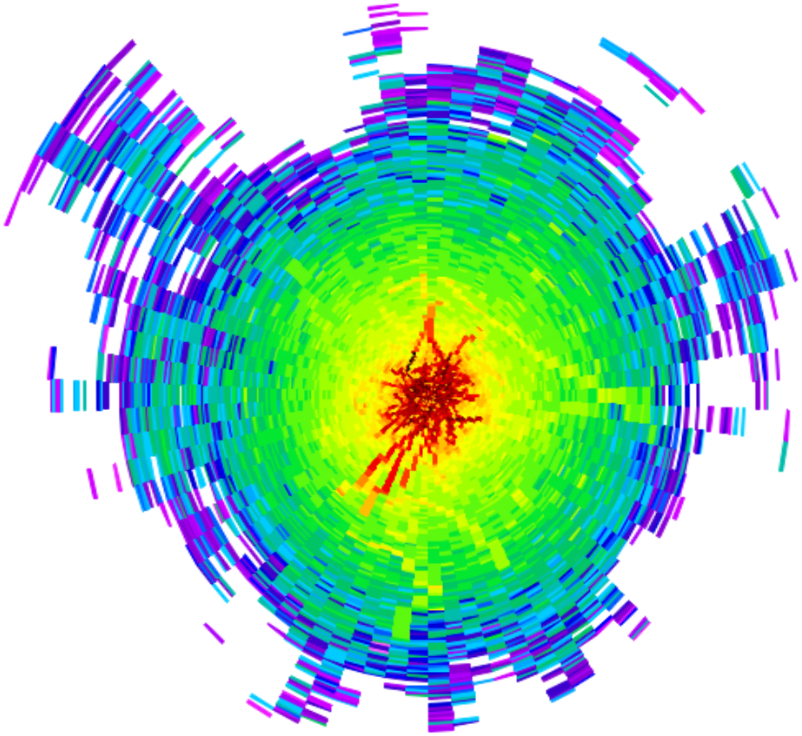
Collaboration (as for Sep. 2016):
~ **40 physicists from 10 institutions**: INFN, CERN, IN2P3, Univ. of Bologna, Insubria, MI-Bicocca, Napoli, Padova, Roma, Strasbourg

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**.

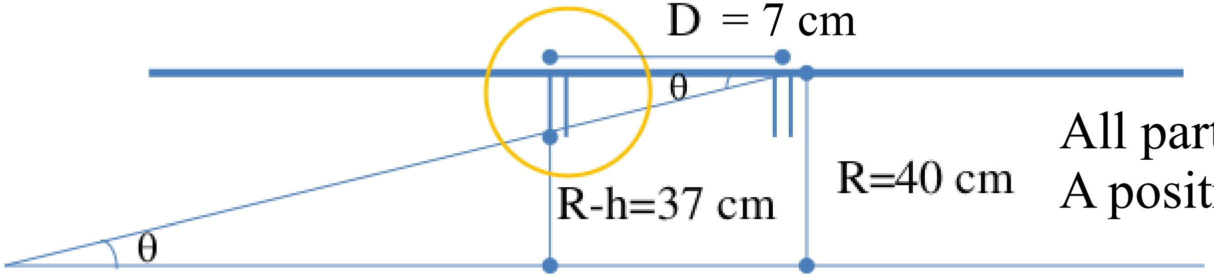
- Kick-off meeting in Padova, 23-24 June 2016
  https://agenda.infn.it/conferenceDisplay.py?confId=11574

Thank you!



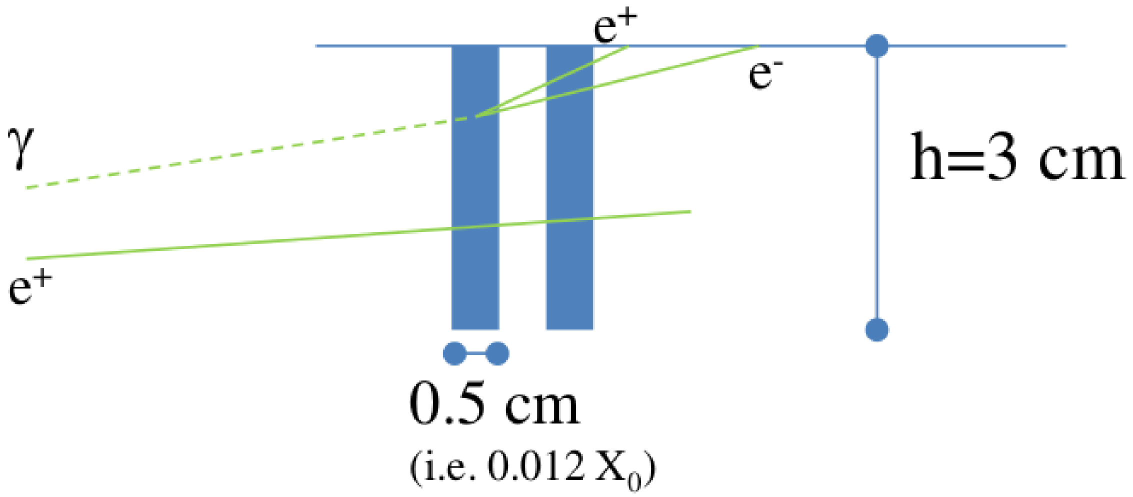
The photon-veto baseline option

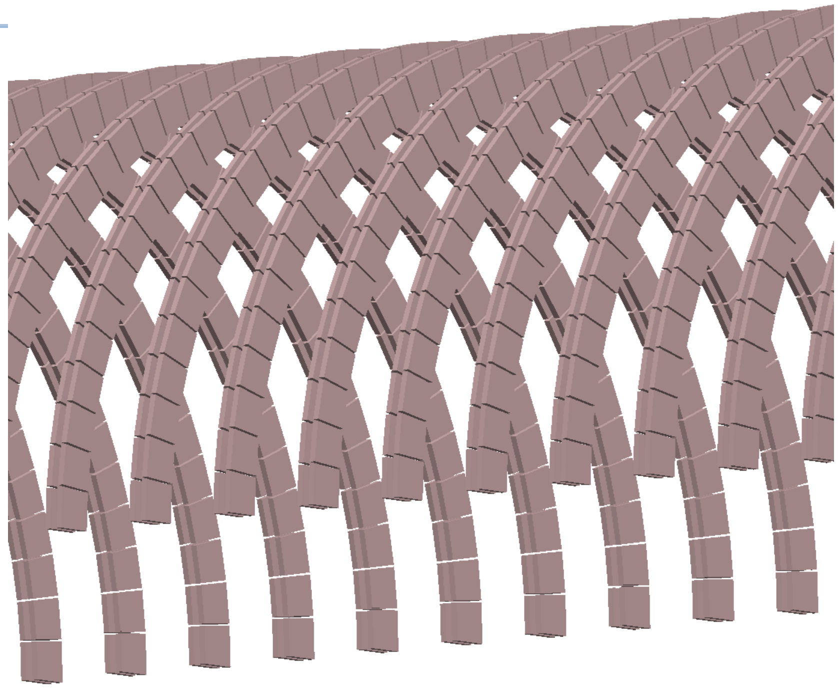
Background from γ conversions from π^0 emitted mainly in K_{e2} decays ($K^+ \rightarrow \pi^+ \pi^0$)



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

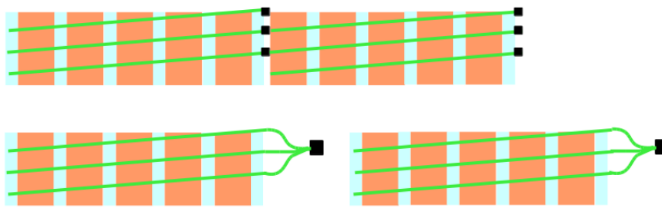
Exploit **1 mip – 2 mip separation**



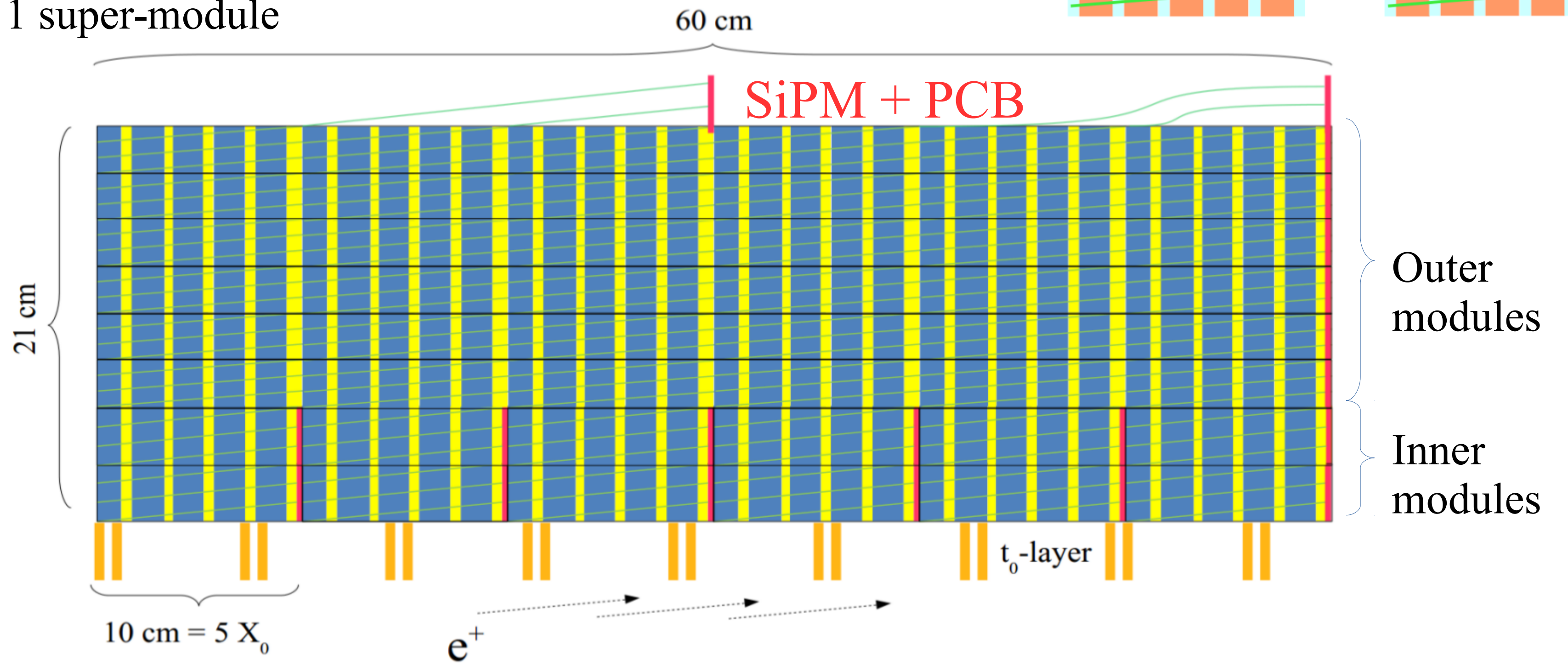


- Possible **alternative/attractive solutions** under scrutiny allowing a reduced **material budget and superior timing**.
- Test beams at Frascati: **electronics response** at high rates and low-E e^+,1 mip/2 mip

The final prototype

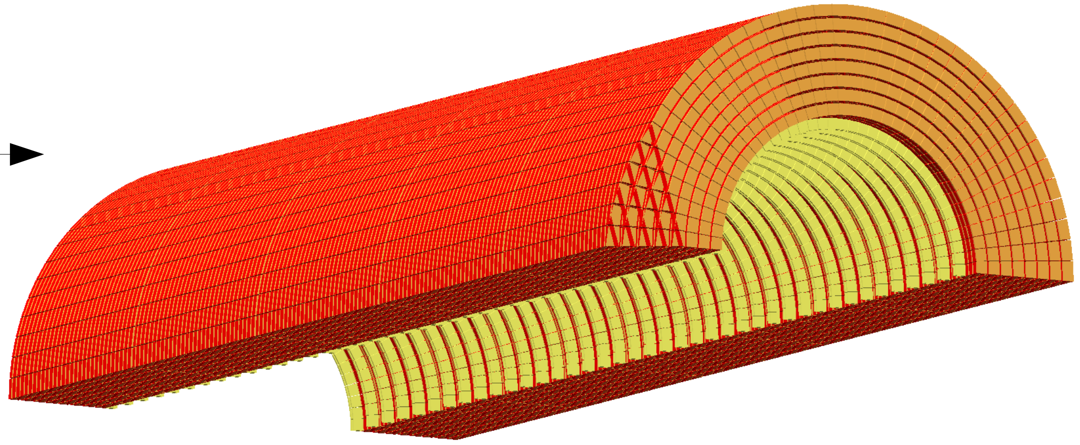


1 super-module



- 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**

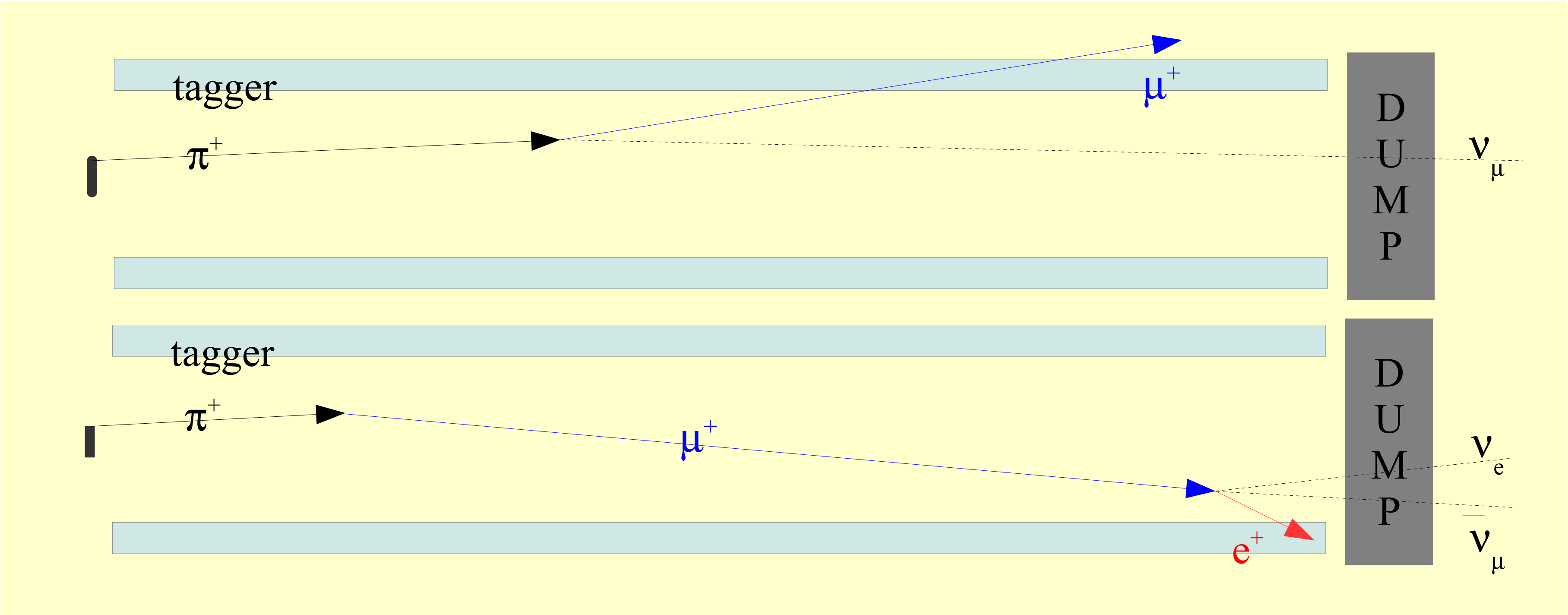
- **5 super-modules**



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)
  - $\boldsymbol{\nu_{e,}{}^{CC,DIF} \sim 3.3\%}$ → **~ 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

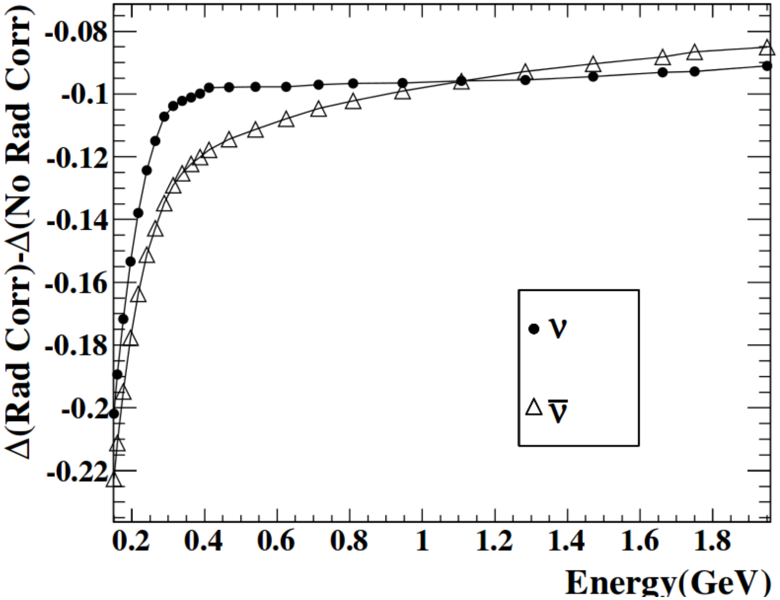
1) **Lepton universality** in weak interactions is **not the full story**:

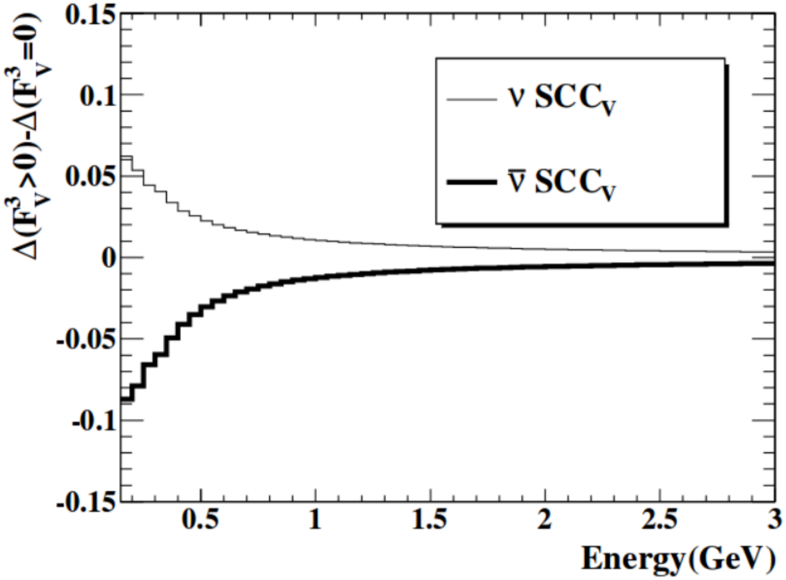
- ✓ Uncertainties from the **interplay** of
  - **radiative corrections**
  - **nucleon form factors**
    - F_P, $F_V^{1,2}$, F_A, second class currents
  - alteration of **kinematics** due to mass

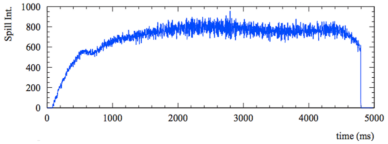
Day, McFarland, Phys. Rev. D86 (2012) 052003

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

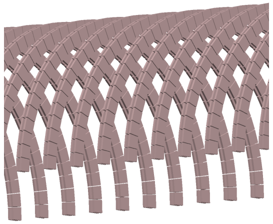
- can be **significant (10-20%) espec. at low-E**
- with **different energy trends for ν and $\bar{\nu}$**

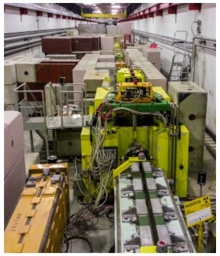


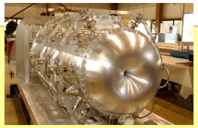




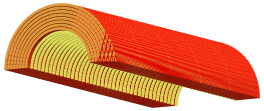
Working packages



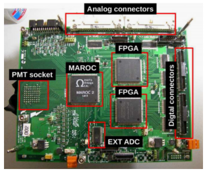


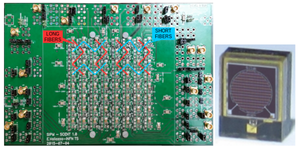


WP1: beam-line
Precise layout of the hadron beam. Study of the injection schemes.

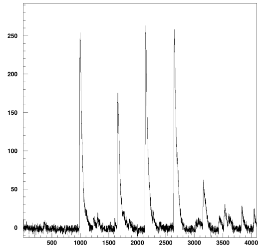


WP2: tagger prototype
Feasibility of tagging under realistic conditions with the desired background and systematics suppression. Radiation hardness.

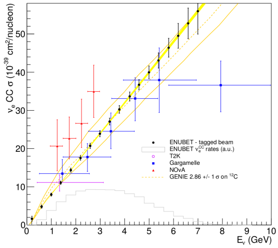




WP3: electronics and readout
testing the readout performances of the front-end electronics for horn-based (< 10 ms proton extraction) or static (1s proton extraction) focusing systems.



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).



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

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

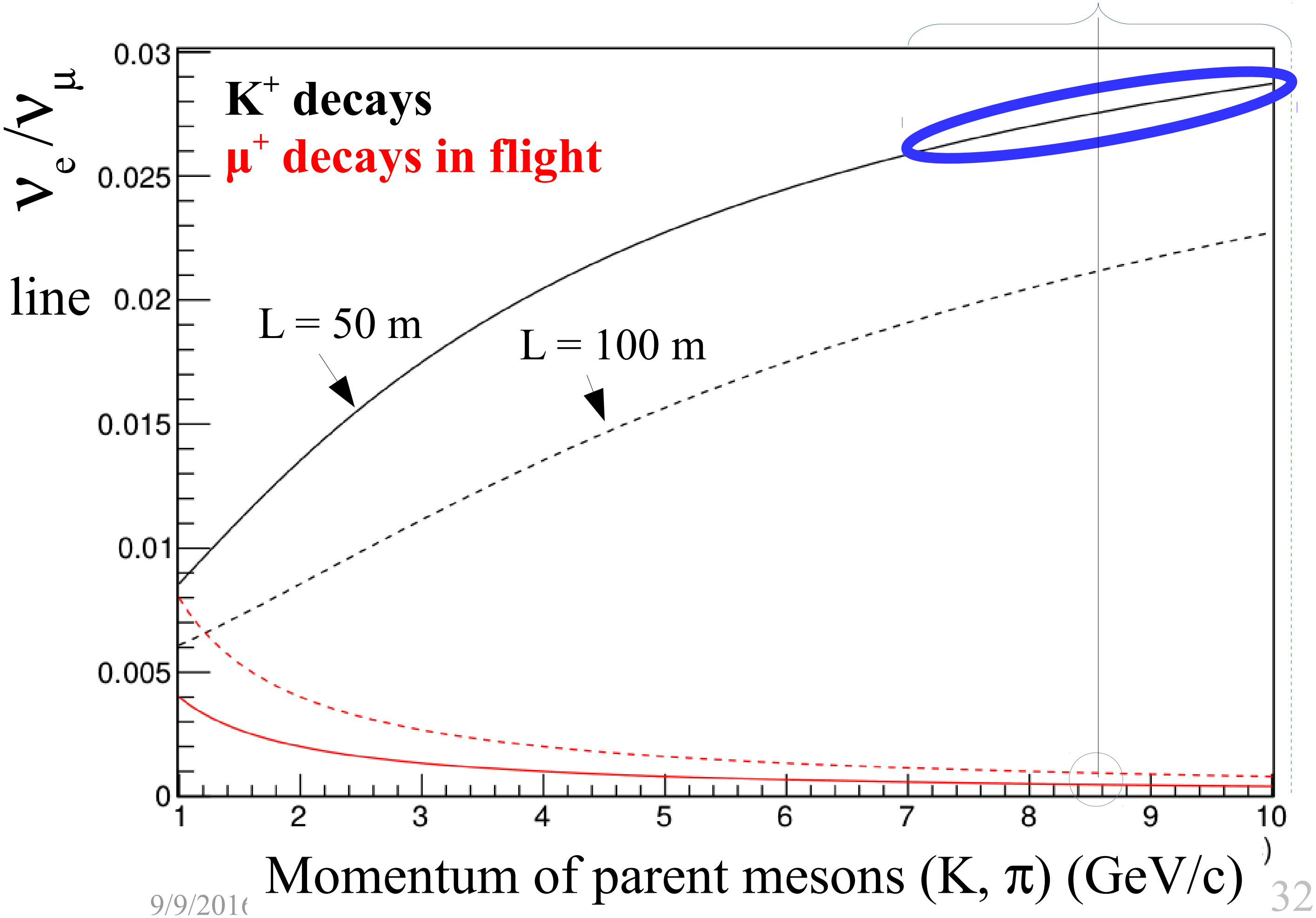
Benefits:

- 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

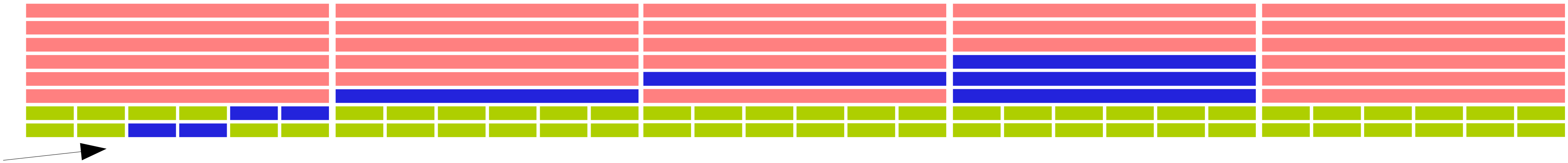
Hadronic modules
Electro-magnetic modules
Hit modules

Key point:

- longitudinal sampling
- perfect homogeneity → integrated light-readout

e^+ (signal) topology

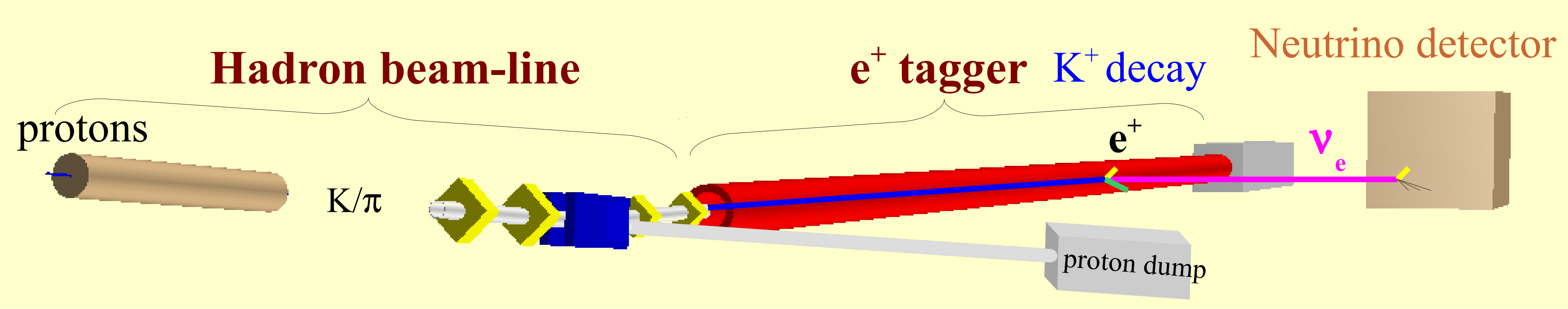
π^0 (background) topology



π^+ (background) topology

Towards the first tagged ν_e beam

A schematic setup to implement this idea:

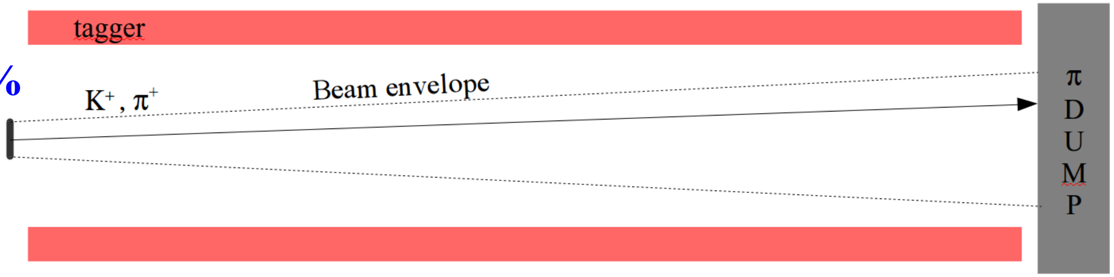


- **Hadron beam-line:** collects, focuses, transports K^+ to the e^+ tagger
- **e^+ tagger:** real-time, "inclusive" **monitoring** of produced **e^+**

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

Hadron collimation:
allows having only decay products in the tagger.
→ **tolerable rates**
→ good **S/N**

$p = 8.5$ GeV ± 20%
$\theta < 3$ mrad



The ENUBET goals and program

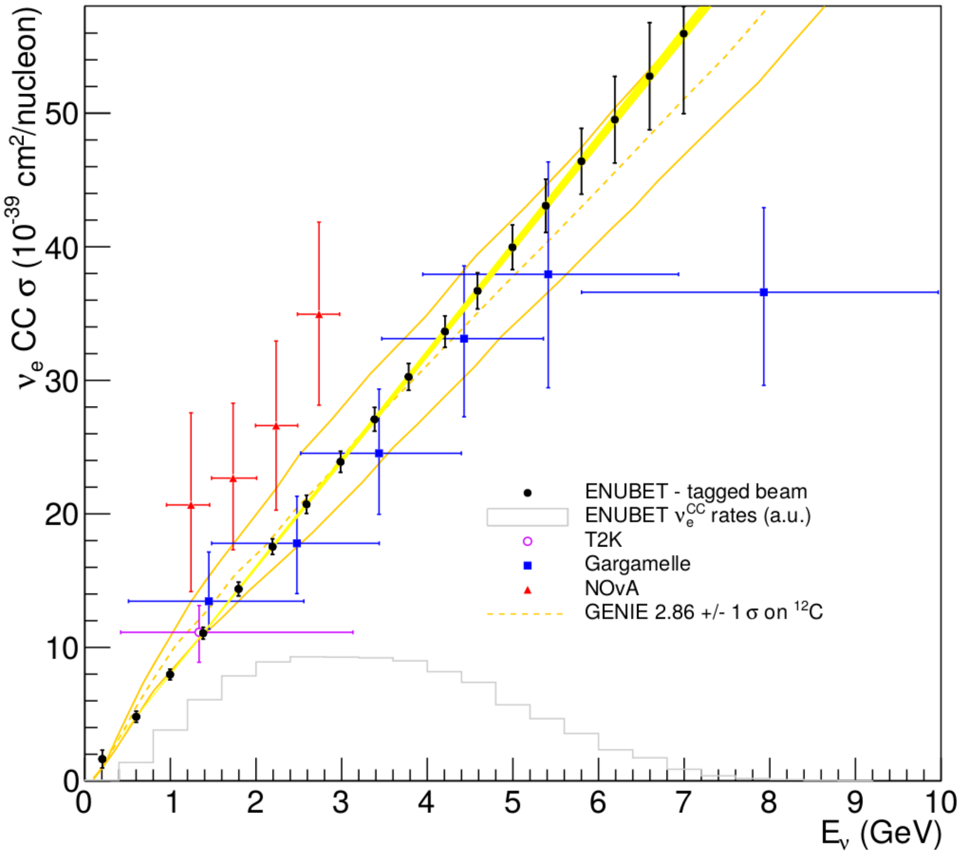
Demonstrate experimentally that a new-concept ν_e **source, with × 10 better precision is feasible**

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

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**

NB. **σ($\bar{\nu}_e$)** 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

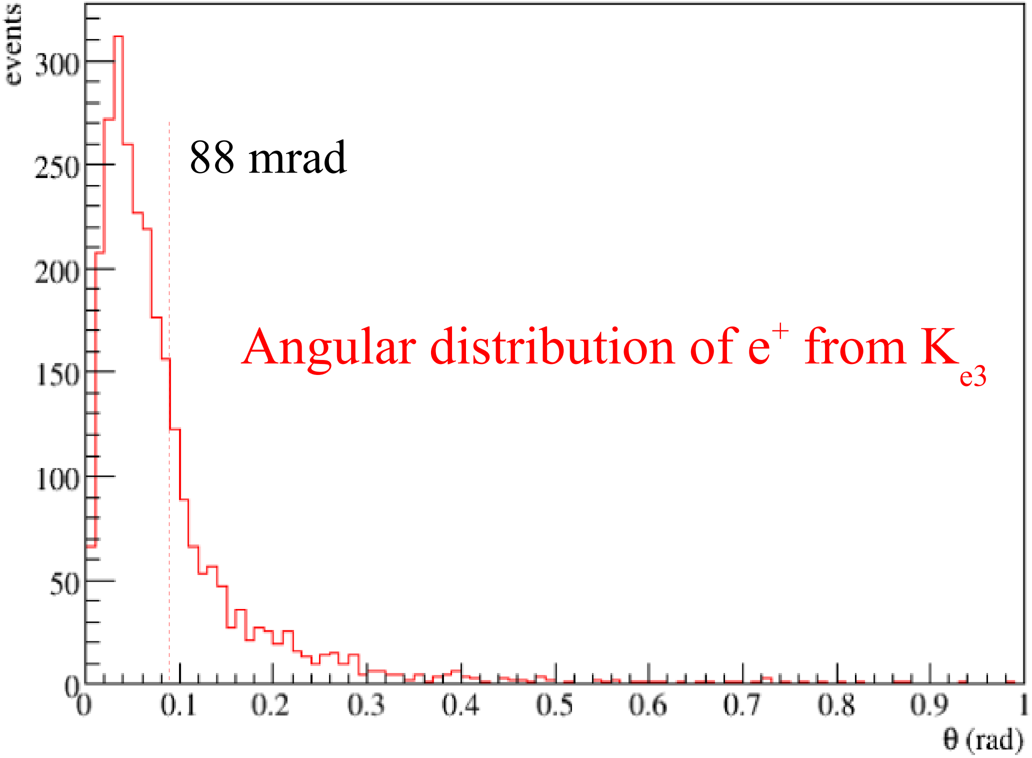
- **calorimetry** → new low-cost, ultra-compact detectors
- **accelerator physics** → novel extraction schemes for fixed-target, beam-dump exp.

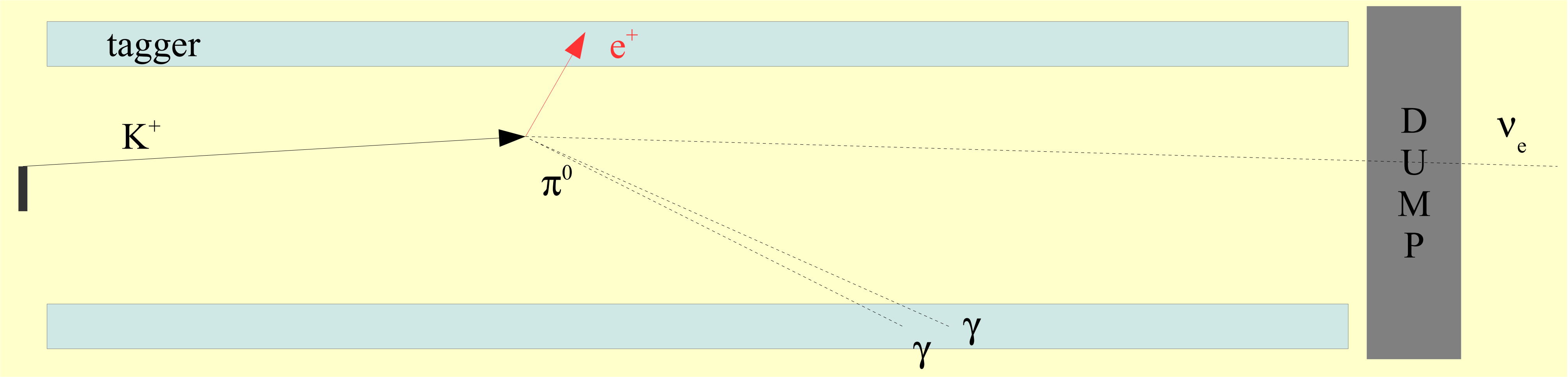
The golden channel: $K^+ \rightarrow \pi^0 e^+ \nu_e$

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

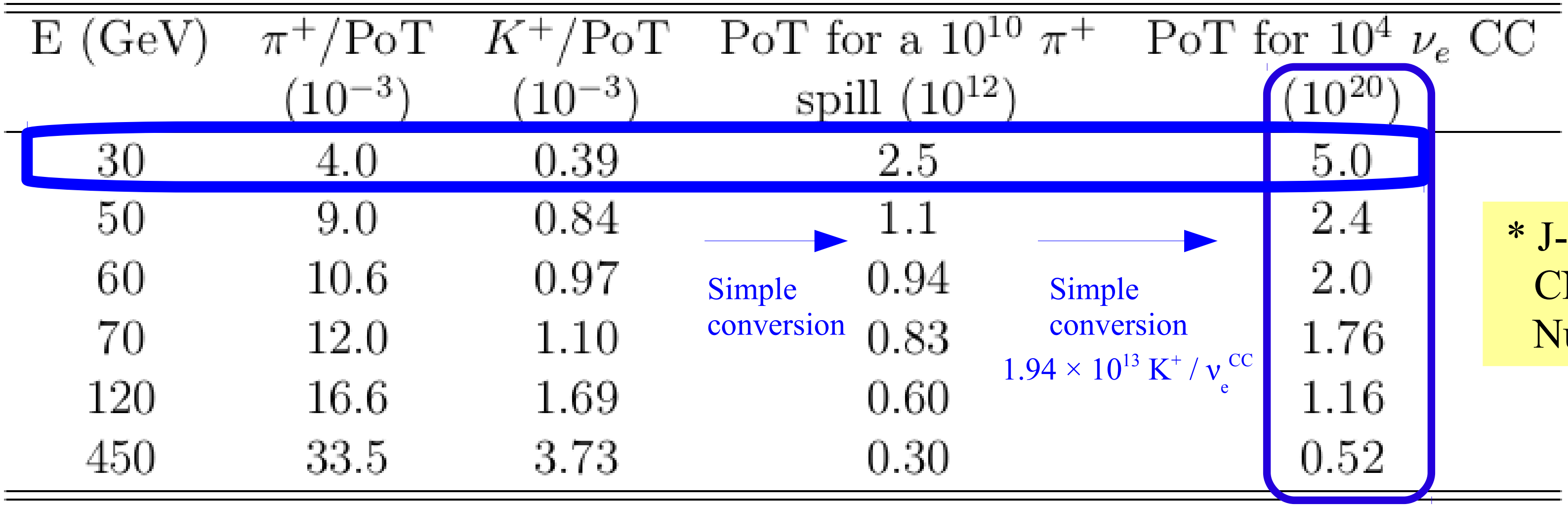
- L_μ >> L(decay tunnel) $\nu_{e,}^{CC,DIF}$ ~ **3.3%**

→ **~ all ν_e are from K_{e3}**





Hadron beamline with horn focusing



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

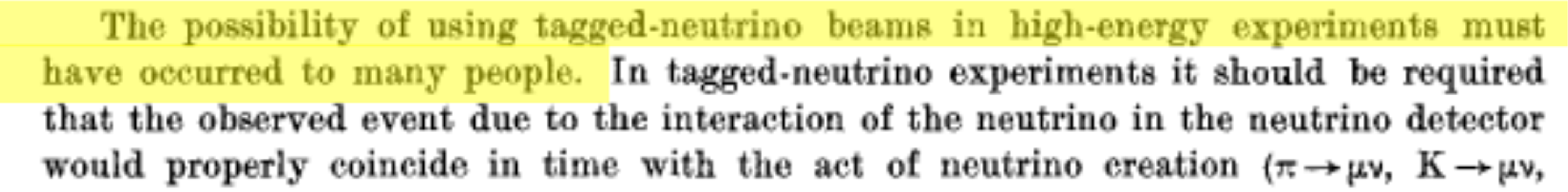
Simple conversion

1.94×10^{13} K^+ / ν_e^{CC}

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

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)

Systematics on the ν_e flux

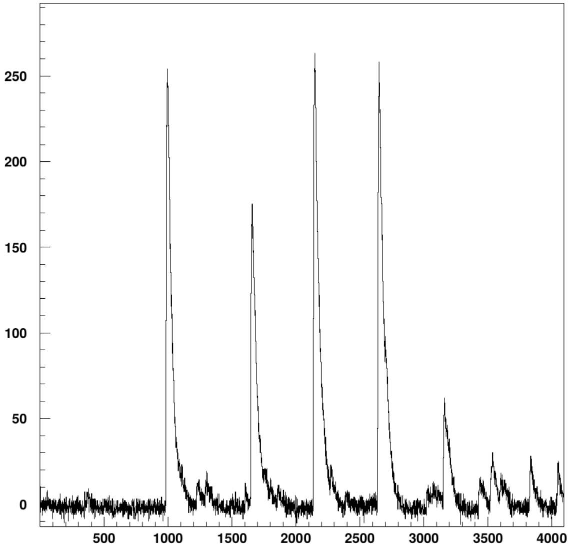
The positron tagging eliminates the most important source of systematics but **can we get to 1%**? Very likely, **to be demonstrated by ENUBET**

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 beam
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

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

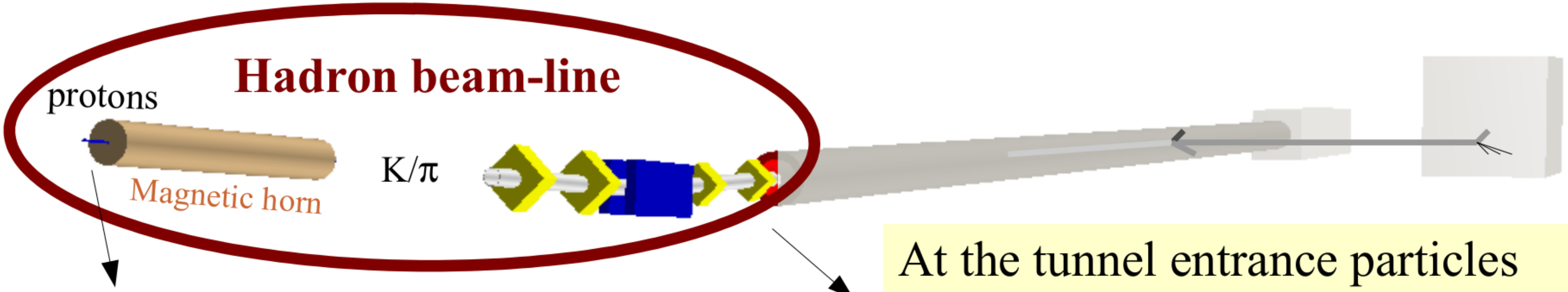
Radiation

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

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

	Focusing system		Proton extraction from accelerator
Scenarios	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**