High precision flux measurements with ENUBET

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for the ENUBET Collaboration

Toronto,
25-30 July

-INT
2017

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Outline

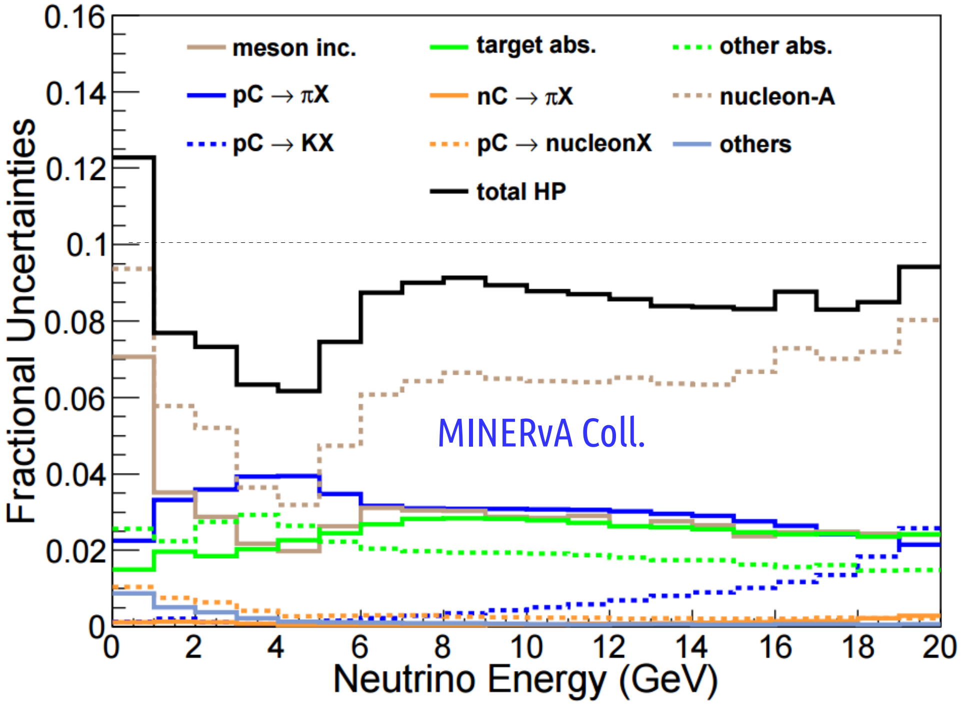
- The problem of **flux uncertainty** → **monitored beams**
- Challenges, goals and recent **achievements** for **ENUBET**
- Forthcoming activities and **conclusions**

Tackling the flux uncertainty problem

Last 10 years: **knowledge of $\sigma(\nu_\mu)$ improved enormously**

MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA ...

- **Flux** constraints **already** in place:
  - ✓ **Muon/proton monitoring**
  - ✓ **hadro-production exp.** (A. Marino, M. Hartz)
  - ✓ **interactions on electrons** (10^{-4} ν_μ^{CC})
  - ✓ **Low-ν method**



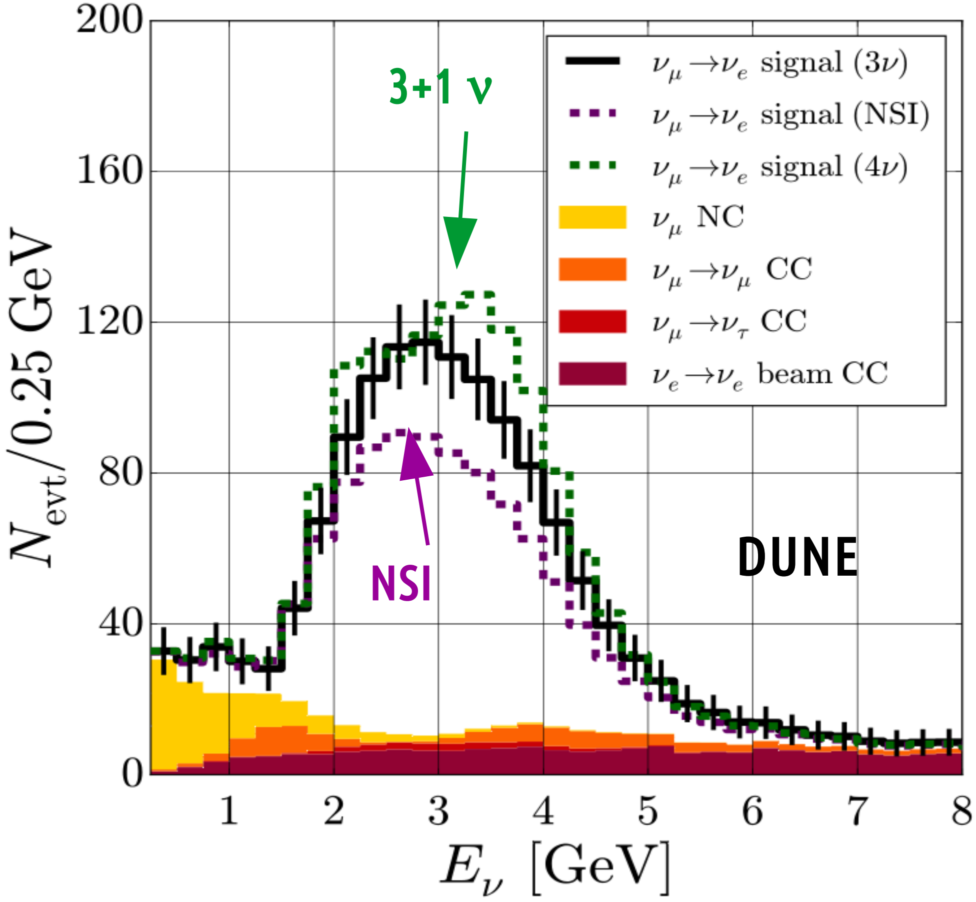
Still ...

- The **flux syst. "wall"** is "up and kicking" being typically the **dominant uncertainty** for cross section measurements
- No absolute measurements below ~7-10%

Tackling σ(ν_e)

- In addition to the flux uncertainty for **σ(ν_e)** we use the **beam contamination** (no intense/pure sources of GeV ν_e): **data still sparse** (Gargamelle, T2K, NOvA, MINERvA)
- **σ(ν_μ)↔σ(ν_e)** delicate @ low-E (Mc. Farland)
- Poor knowledge of **σ(ν_e)** can spoil :
  - ✓ the **CPV discovery potential**
  - ✓ the insight on the **underlying physics** (standard vs exotic)

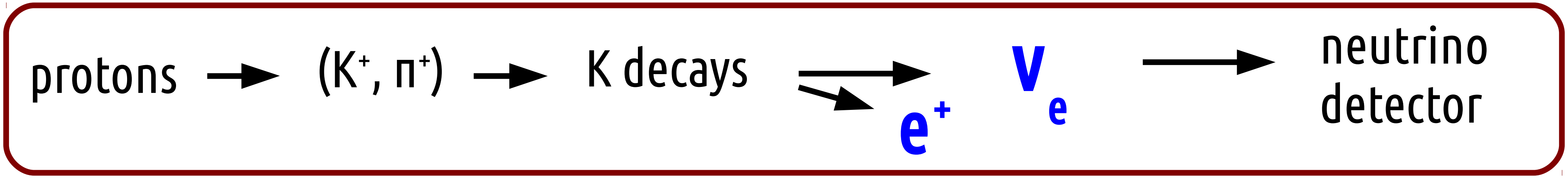
De Gouvea et al., 1605.0937



- D.I.F. of stored μ as in **nuSTORM/nuPIL** is the **ideal** solution but it is **not easy.**

Monitored beams

Based on **conventional technologies**, aiming for a **1% precision on the ν_e flux**



protons → (K^+, π^+) → K decays → e^+, ν_e → neutrino detector

- Monitor (~ inclusively) the **decays in which ν are produced**
- “By-pass” **hadro-production**, **PoT**, **beam-line efficiency** uncertainties

Traditional

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

↔

Monitored

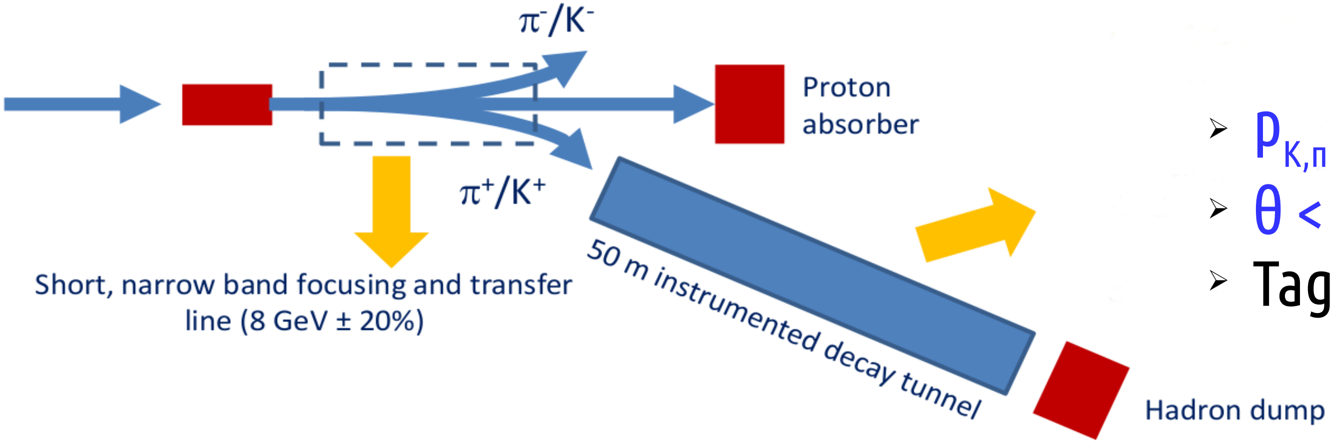
- **Fully instrumented**

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

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

The ENUBET monitored beam

- **Hadron beam-line**: charge selection, focusing, fast transfer of π^+/K^+
- **Tagger**: real-time, "inclusive" **monitoring** of K decay products

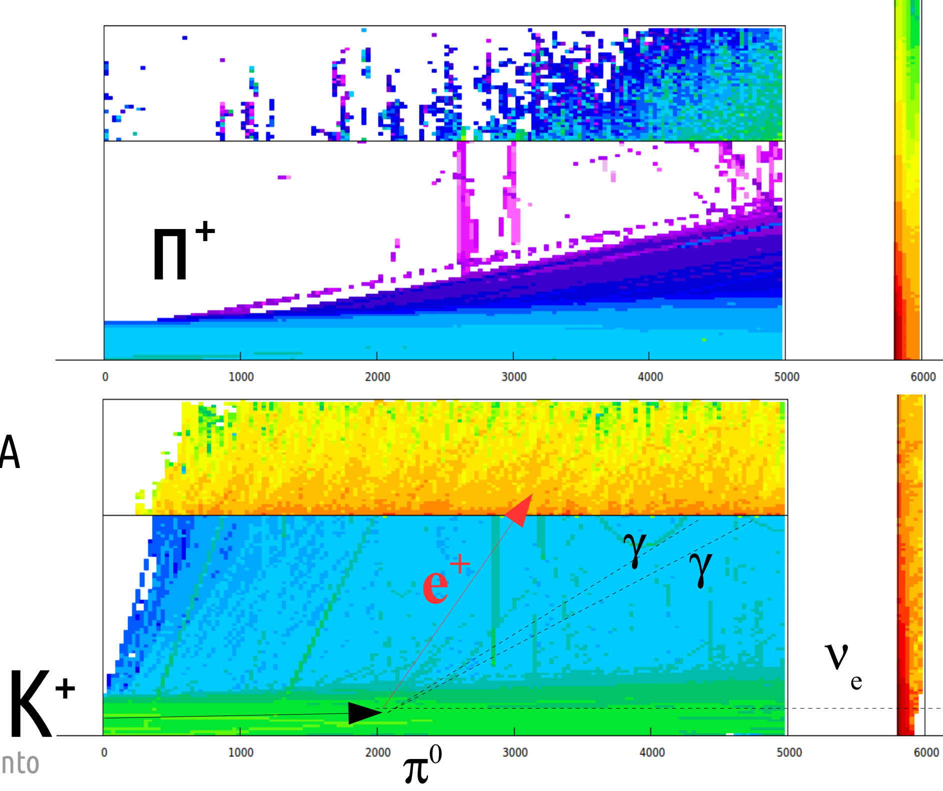


- $p_{K,\pi} = 8.5 \pm 20\%$ GeV/c
- $\theta < 3$ mrad over 10×10 cm^2
- Tagger: L = 50 m, r = 40 cm

- ✓ With proper hadron **focusing only K decay products** are measured in the tagger being emitted at **large angles** (unlike pion decay products) allowing
  - ✓ a **complete control** of produced ν_e using e^+ from K_{e3} (~98%). Muon decays gives a small contribution thanks to the short tunnel (~50 m).
  - ✓ **tolerable rates / detector irradiation**

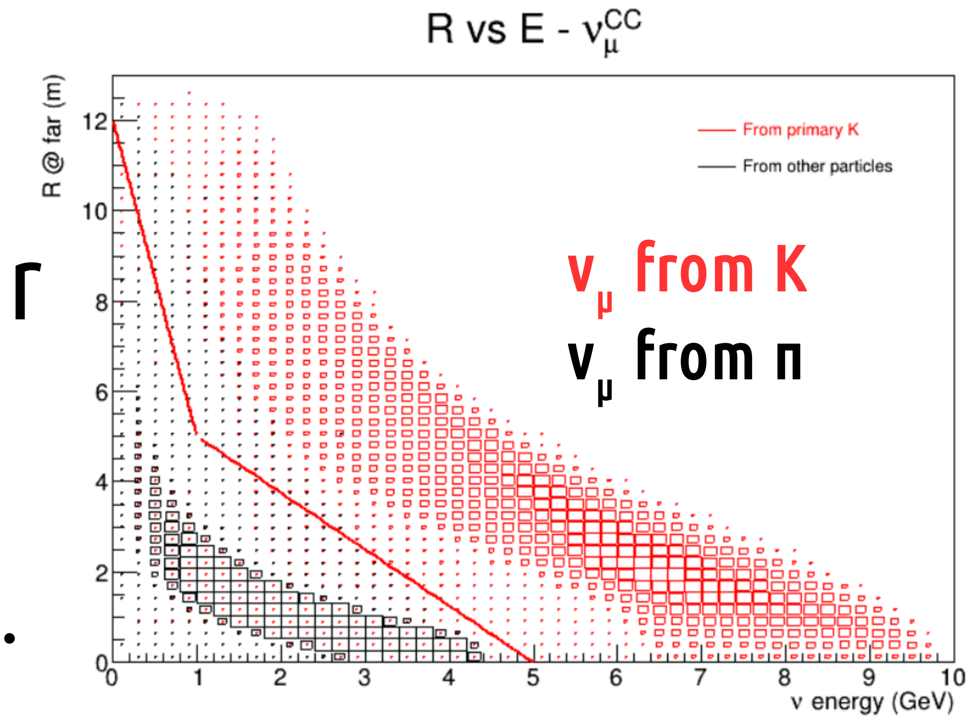
< 500 kHz/cm^2, O(~1 kGy)

FLUKA



Not only ν_e !

- **ν_e flux constraint**
  - ✓ **K_{e3} (golden sample)**
    - $\pi^{+/0}$ from K^+ can mimic an e^+
      → **discriminate e/π** with:
      1) longitudinal profile of showers
      2) reconstruct vertices by timing
  - ✓ **non K_{e3} (silver sample):** only pay additional systematics from the K_{e3} **B.R.**



- **ν_μ flux constraint**
  - ν_μ from K are well constrained from the tagger (both from hadronic and K_{e3} rates)
    This class of neutrinos can be selected at the ν-detector using **radius-energy correlations** → high precision **$\sigma(\nu_\mu)$**

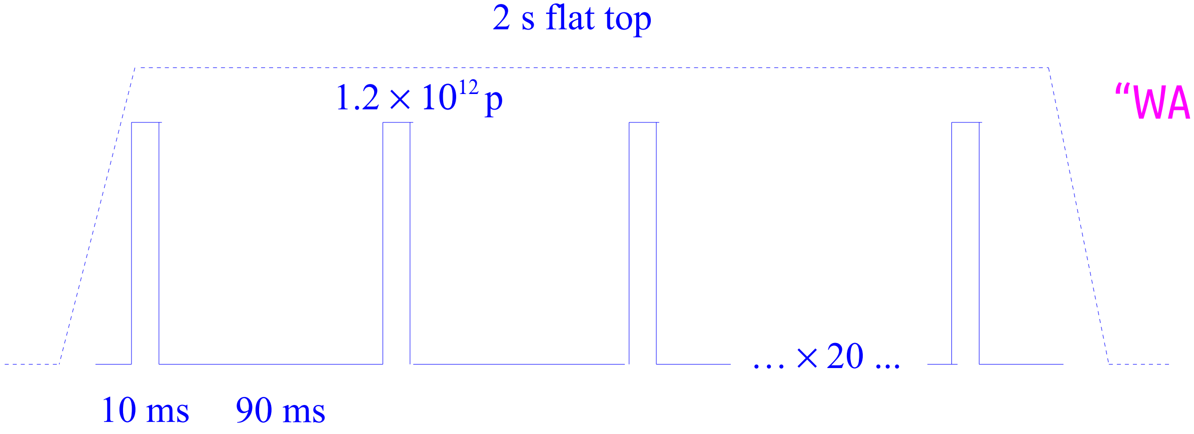
- $K^+ \rightarrow \mu^+\nu_\mu$ (63%)
- $K^+ \rightarrow \mu^+\nu_\mu\pi^0$ (3.2%)
- $K^+ \rightarrow \pi^+\pi^0$ (21%)
- $K^+ \rightarrow \pi^+\pi^-\pi^+$ (6%)
- $K^+ \rightarrow \pi^+\pi^0\pi^0$ (2%)

Hadron beam-line scenarios

- **Baseline choice:** magnetic horns focusing. $t_{impulse} < O(1\text{-}10)$ ms
- **tagger rate limit** (~200 kHz/cm^2) with ~ **10^{12} PoT/spill**
  - i.e. **(many) spills with relatively "few" protons are needed**
- Requiring **10^4 ν_e^{CC}** in a **500 t** ν-detector **at 100 m** implies:
  - **<~ 10^{20} PoT → a fraction of a year run at present proton drivers.**
  - **~ 10^8** spills. More challenging/unconventional.
- Solution: **multi-Hz (slow resonant extraction + horn pulsing)**

Possible time-structure at the CERN-SPS:

~ 50% SPS emptying



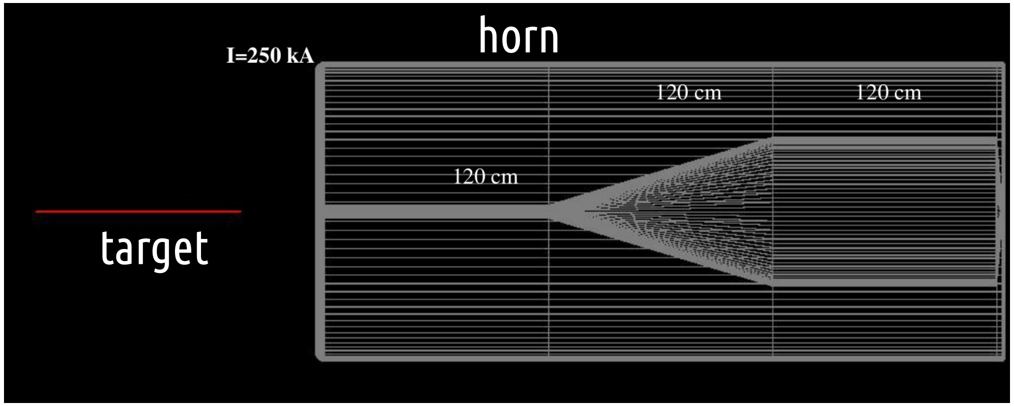
"WANF like"

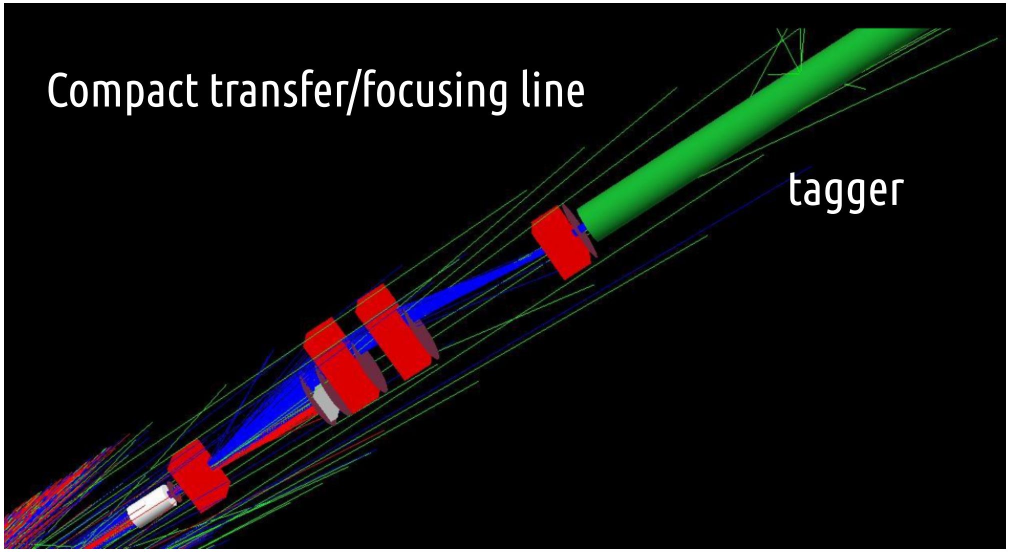
Alternative choice: static focusing devices + long extraction.

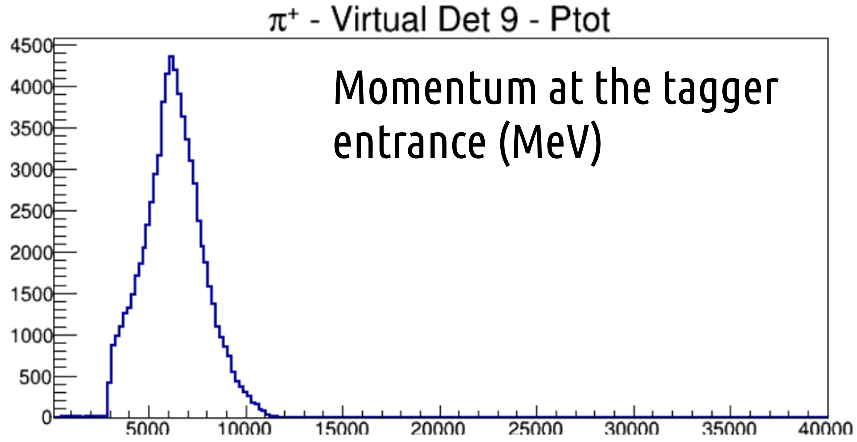
Much less efficient focusing (→ more POT) but would open the intriguing opportunity of "**time tagging**" → $T_{extr} = 1$s (~ 1 observed e^+ / 30 ns) + $\delta = 1$ ns → Accidental tag = 2 %

Hadron beam-line deliverables/progress

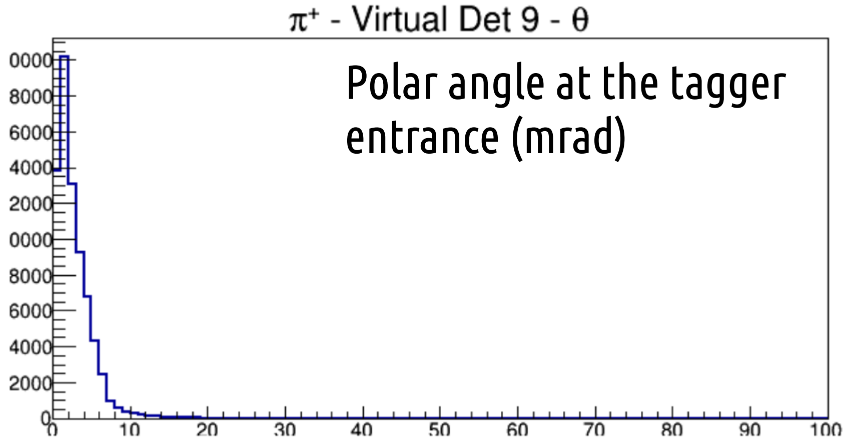
- A **realistic implementation** of the beam-line/focusing layout.
- **Site-independent**. We are considering existing proton driver energies.
- **FLUKA/G4Beamline** simulations in progress. Support early estimates.
- Assess **beam-related backgrounds**.
- **Machine studies** of multi-Hz slow resonant extraction at CERN-SPS







Momentum at the tagger entrance (MeV)



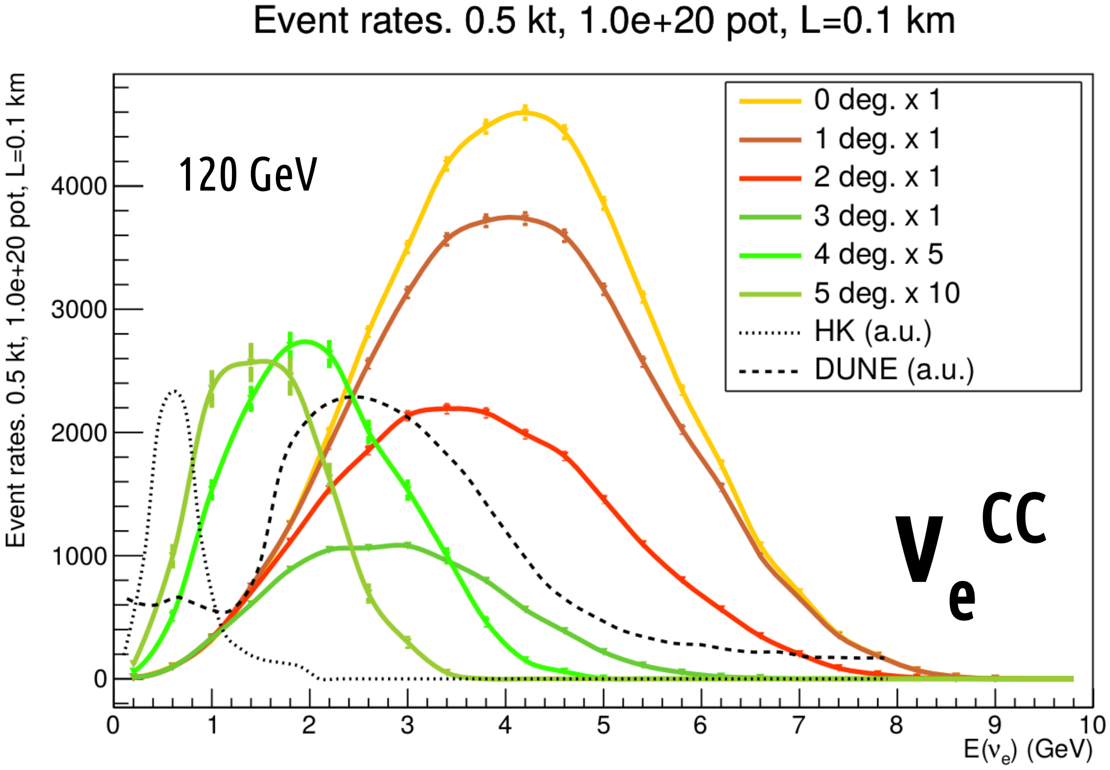
Polar angle at the tagger entrance (mrad)

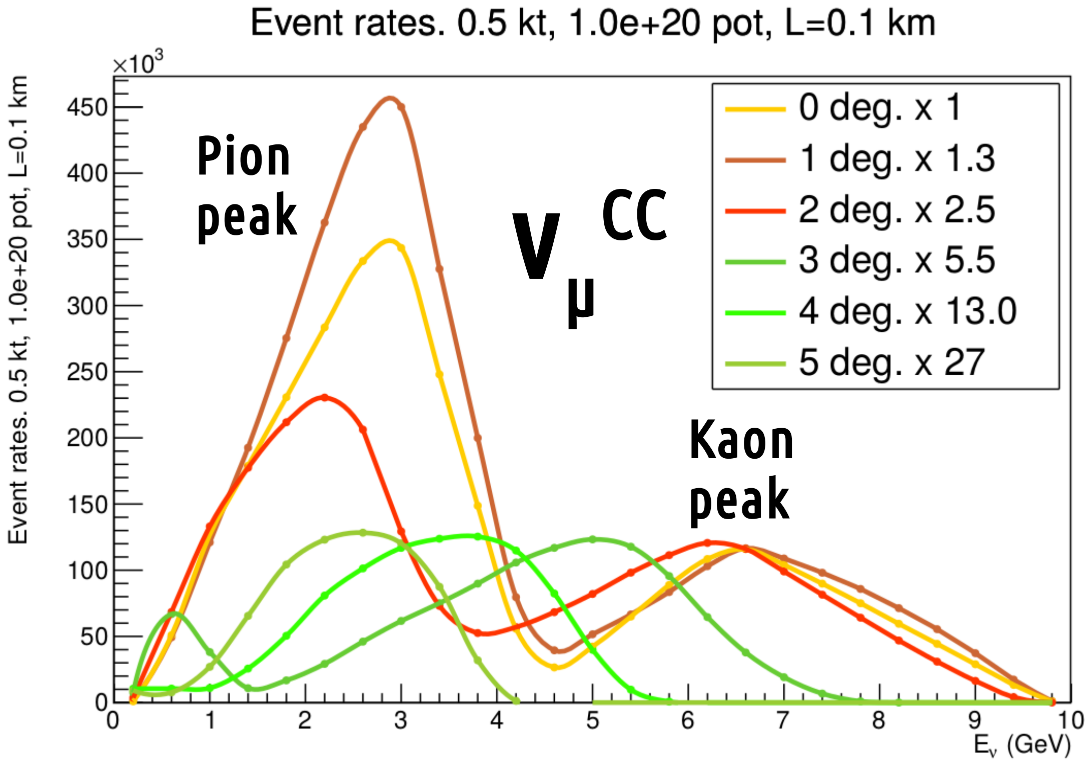
Neutrino samples

- Need good e-tagging capabilities e.g.
  - **ICARUS / μBooNE** @ FNAL
  - **proto-DUNE SP/DP** @ CERN
  - Water Cherenkov (i.e. **E61** @ J-PARC)
- ~500 t detector at 100 m (Ar:6x6x10 m^3)

E_p (GeV)	POT (10^{20}) for 10^4 ν_e^{CC} on-axis	time
30	1.03	~ 0.2 J-PARC y
120	0.24	~0.4 NuMI y
400	0.11	~0.25 CGNS y

- **Baseline design** better suited for **DUNE**.
- For **HK**, **off-axis** configurations can help at the expense of **larger exposures**.
- Further handles: **reduce the initial hadrons momentum** (in progress).
- For ν_μ in the HK region one can use **pion sample** and constrain the initial overall hadron flux with **Beam Current Transformer at low intensity** and use the K constraint from the tagger.





Systematics on the ν_e flux

Positron tagging eliminates the most important contributions. Assessing in detail the **viability of the 1% systematics** on the flux is one of the final **goals of ENUBET**. Full analysis is being setup profiting from a **detailed simulation** of the beamline, the tagger (WP5) and inputs from **test beams**.

Sources	Estimate
Overall statistical error	< 1 % (10000 ν_e^{CC})
Integrated PoT	Irrelevant (e^+ tag)
K/π production yields in the target	Irrelevant (e^+ tag)
Secondary transport efficiency	Irrelevant (e^+ tag)
Branching ratios	well known + only enter enter in π bckg estimation
3-body kinematics and mass	< 0.1%. *Chin. Phys. C38 (2014) 090001 [PDG]*
Uncertainty on phase space at entrance	can be checked with low-intensity runs
Electron/pion separation	being checked directly at test beams

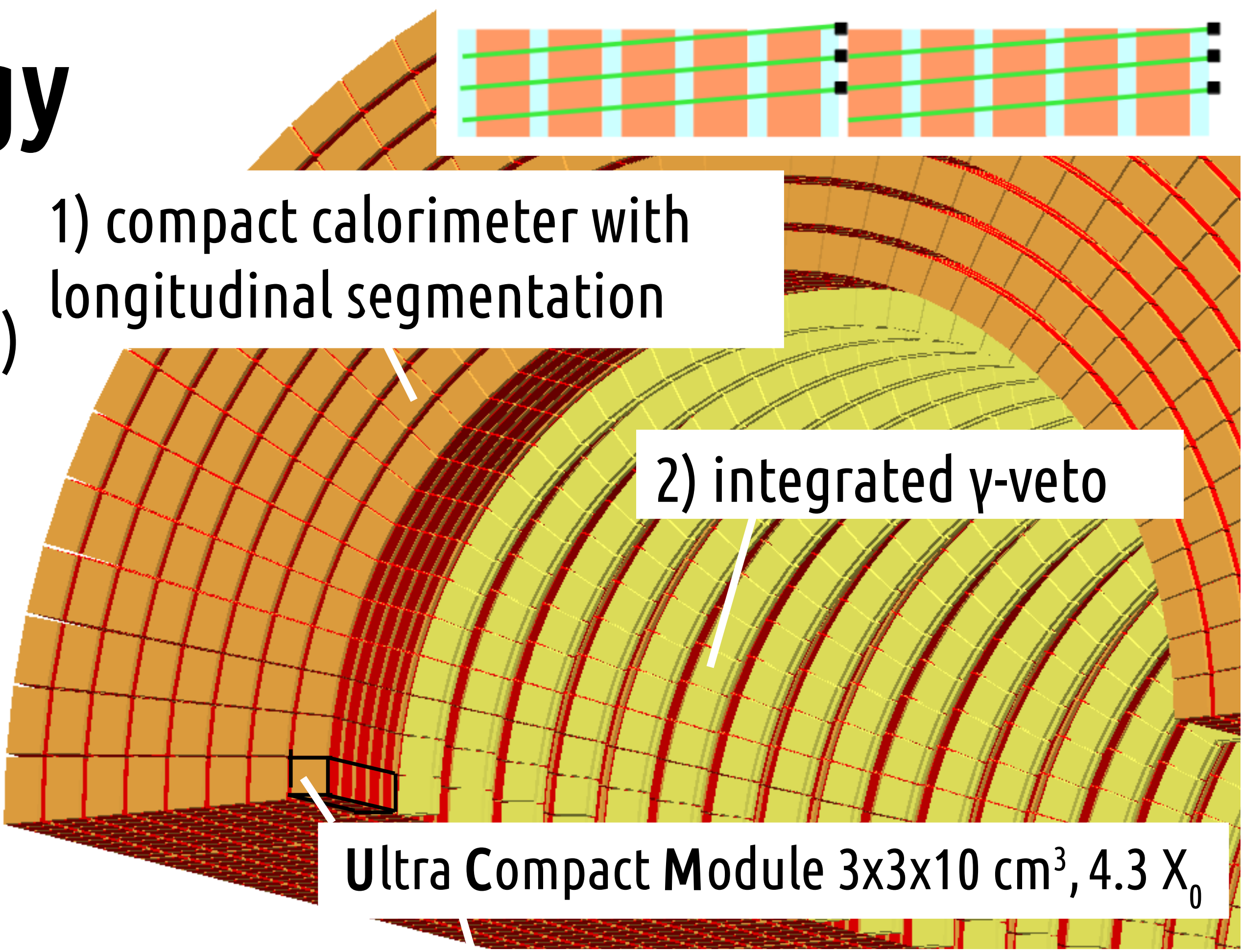
Tagger technology

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

→ π± rejection

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

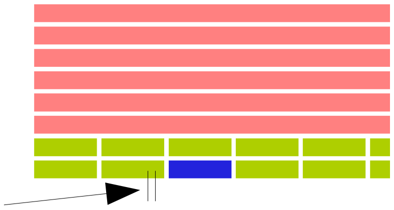
→ π⁰ rejection



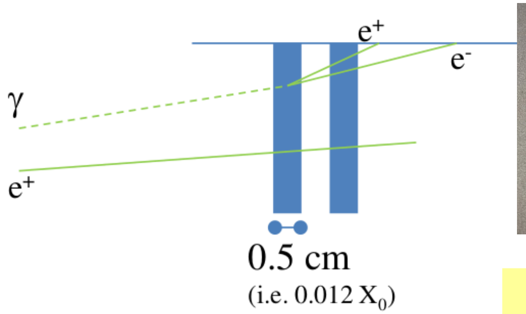
1) compact calorimeter with longitudinal segmentation

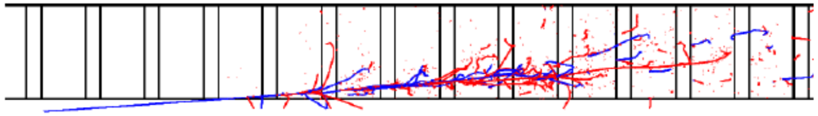
2) integrated γ-veto

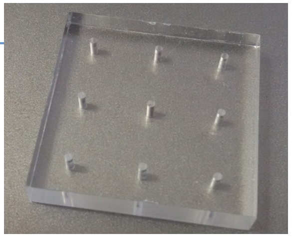
Ultra **C**ompact **M**odule 3x3x10 cm^3, 4.3 X_0

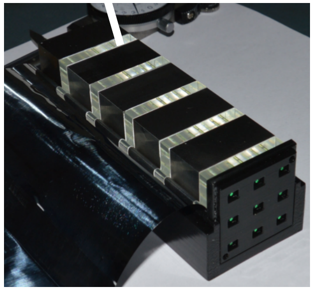


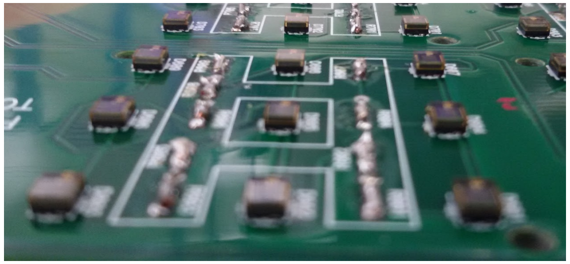
e$^+$ (signal) topolog





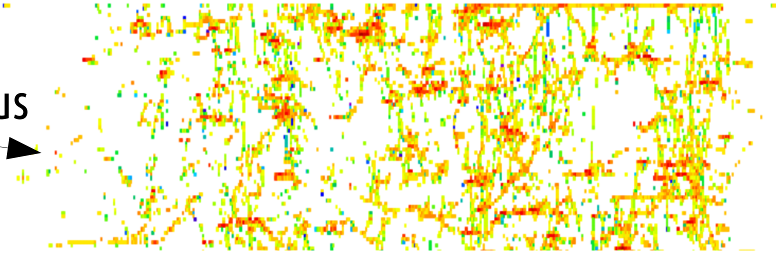






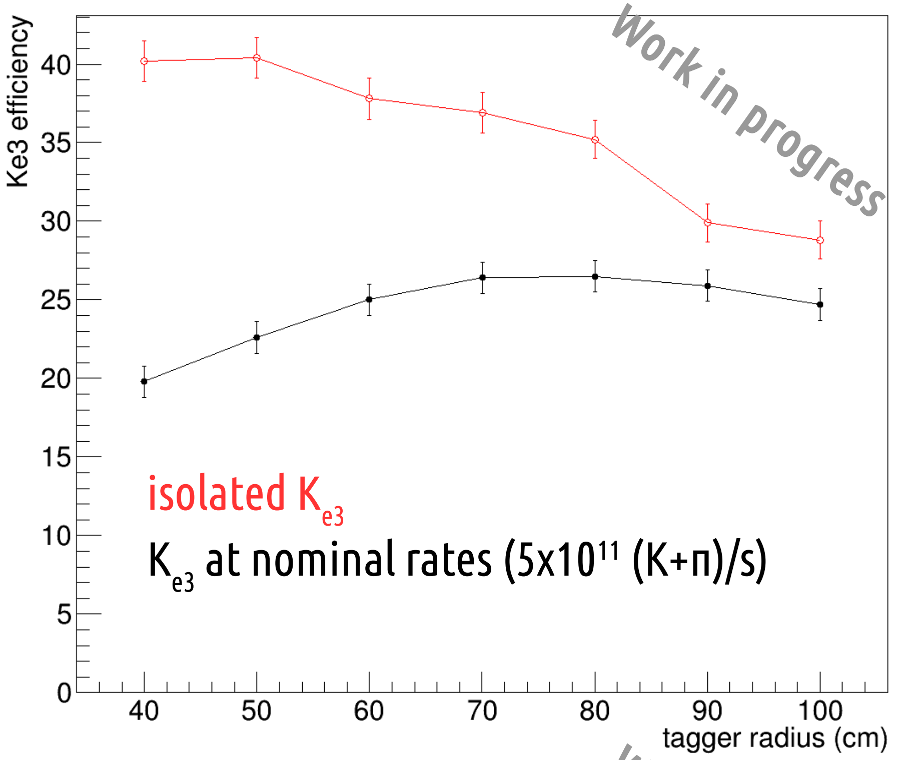
We aim at building/testing a scalable **demonstrator** consisting of a 3 m long section of the instrumented tunnel by 2021

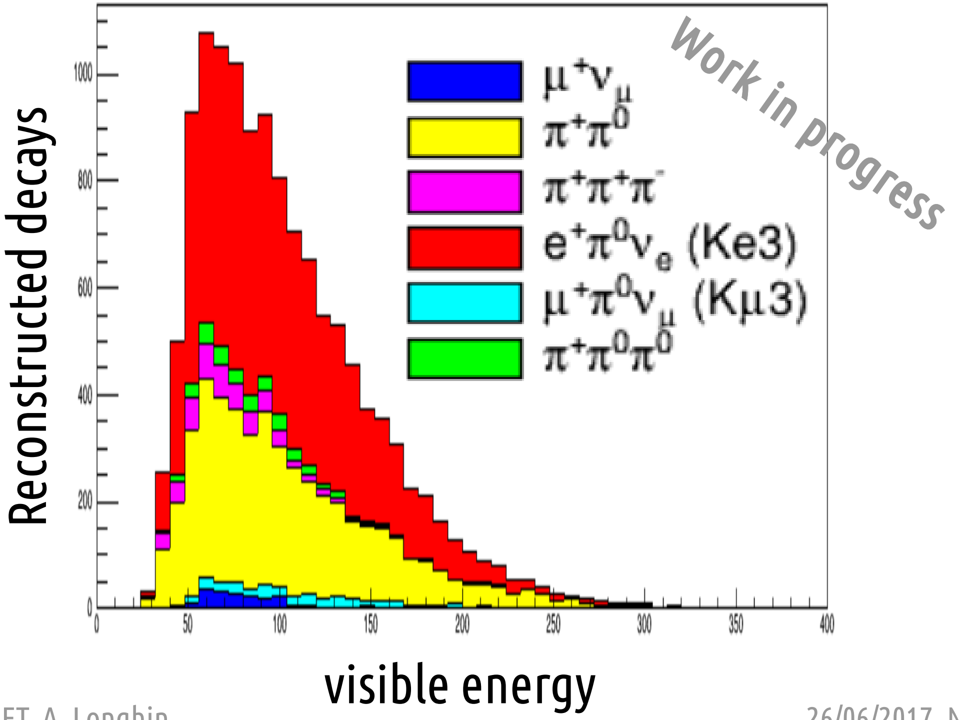
Event building, pile-up, eff., purity

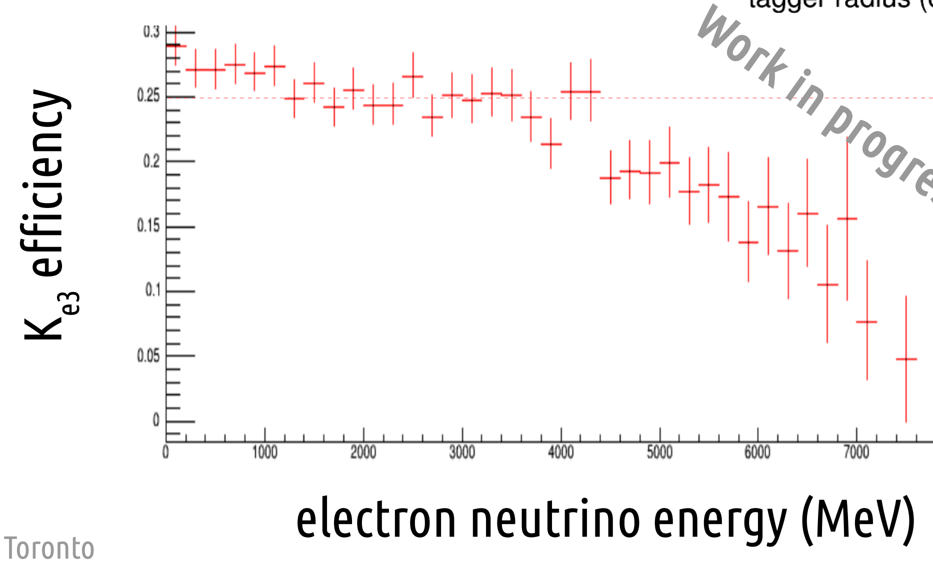

e^+ in 2 ns at nominal rates and 40 cm radius

- **Multivariate** analysis to select e^+ and reject simultaneously π^+ and π^0 using a **GEANT4** simulation of the tagger.
- **"Event-building"** : clustering based on position and timing of UCM waveforms with realistic treatment of background (up to **500 KHz/cm^2!**).
- **Pile-up** effect on **K_{e3} efficiency** seen at nominal rates.

  Mitigation enlarging the radius: **~ 25 %** (**~ 50 %** purity).

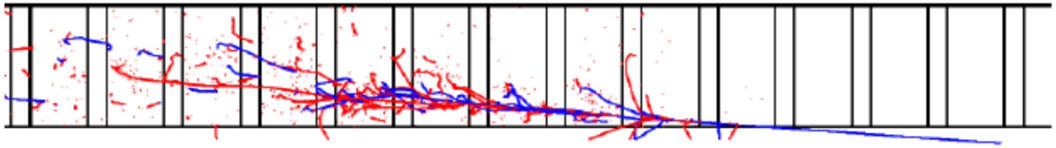


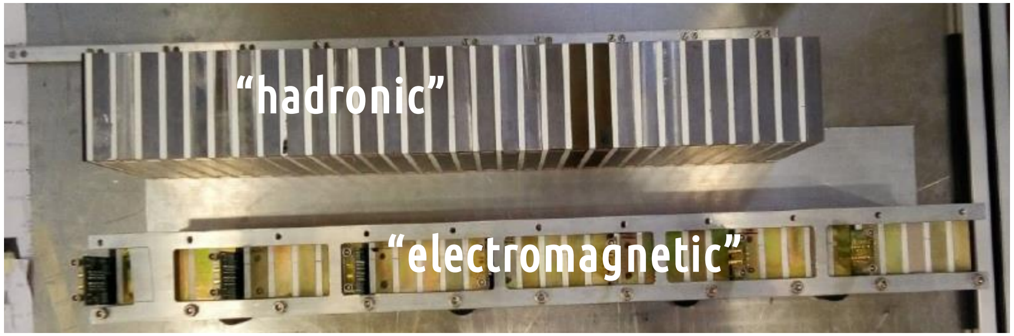


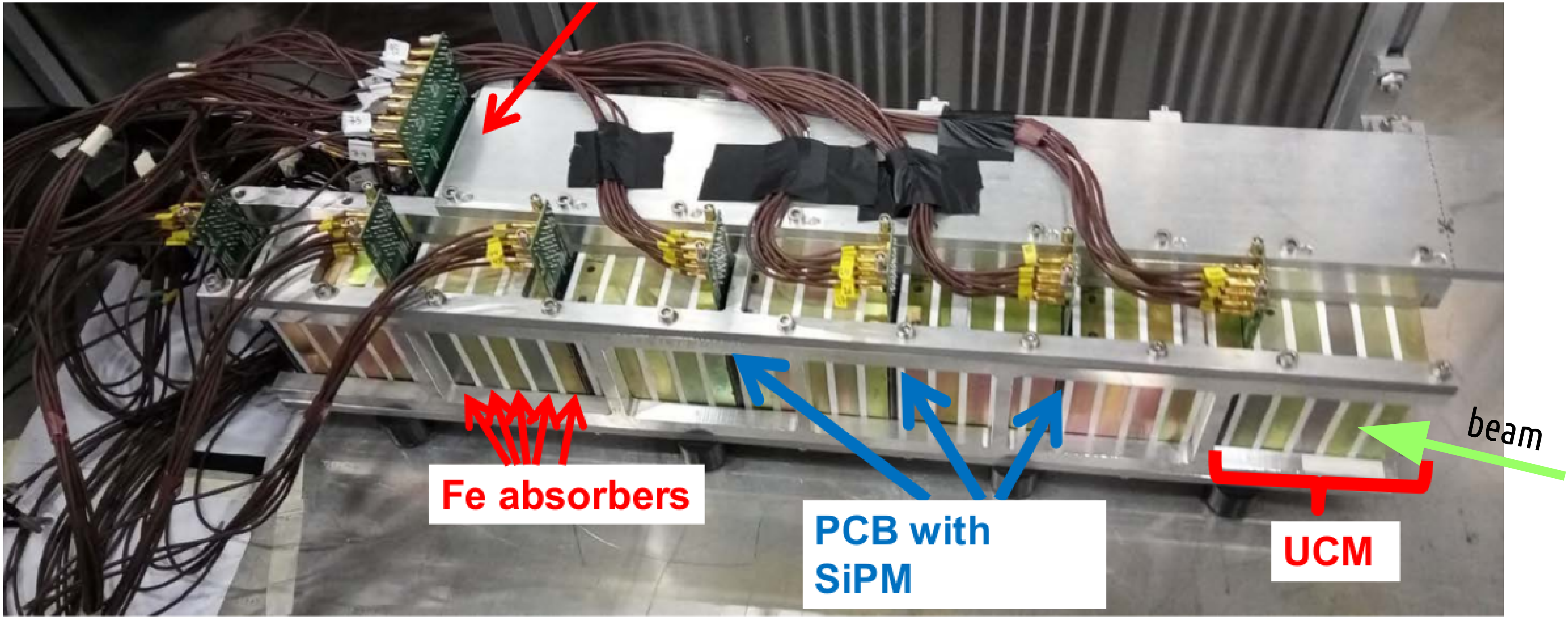


Test beam at CERN-PS T9 Nov. 2016

- Test **data/MC agreement** and **e/π separation** at grazing incidence (~ 30 X_0, orientable cradle)
- 56 (e.m.) + 18 (had.) UCM, 666 SiPM

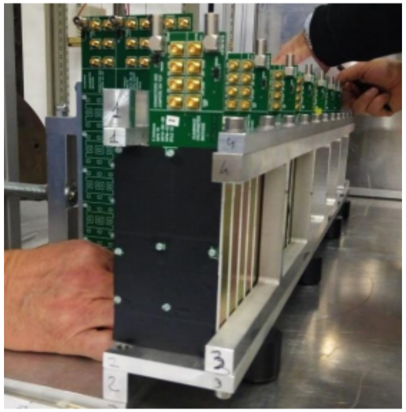


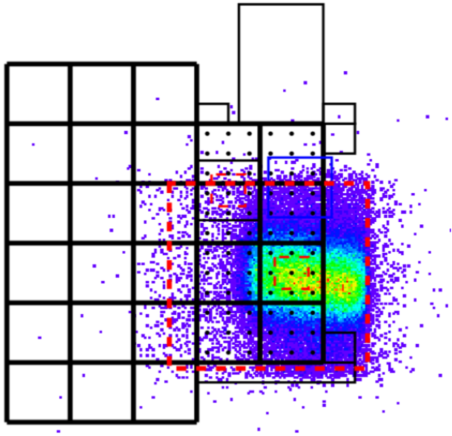




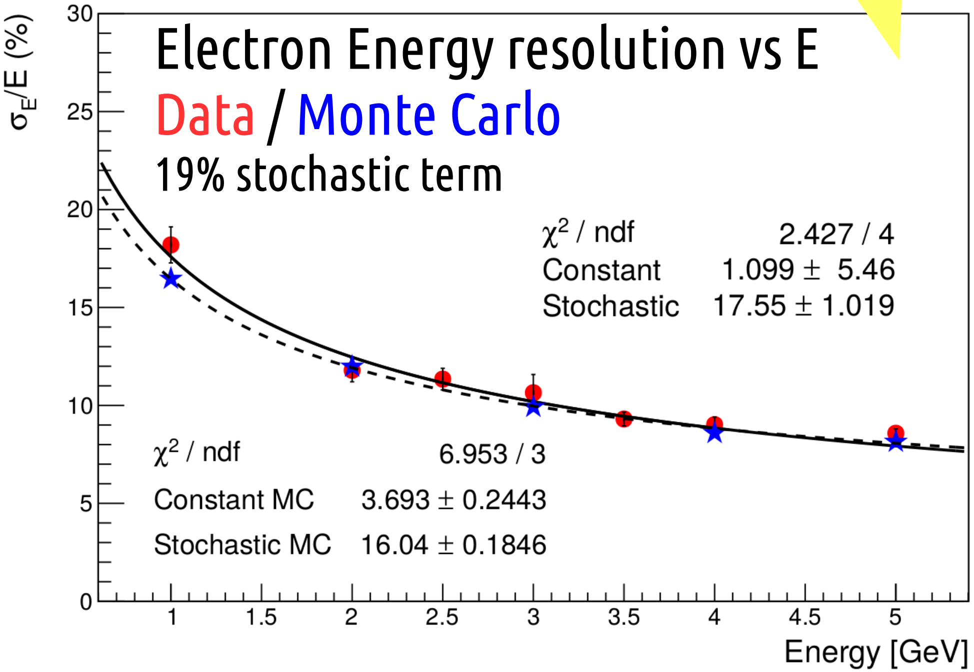
e/π separation analysis with test beam data

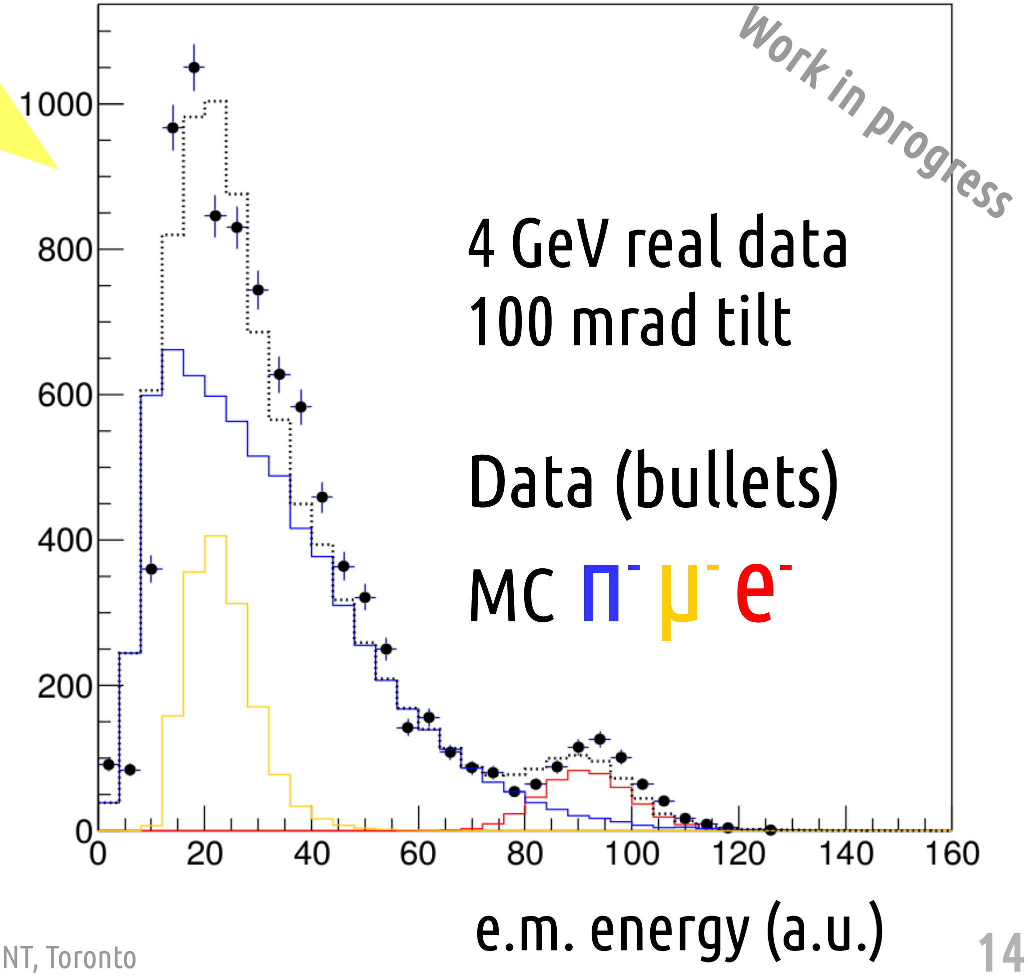
- Electrons/muons tagged by T9 Cherenkov counters and a muon catcher. Silicon strip chambers for μm tracking and fiducialization.
- Current **GEANT4 simulation is working reasonably well** already





hit map (with silicon trackers)

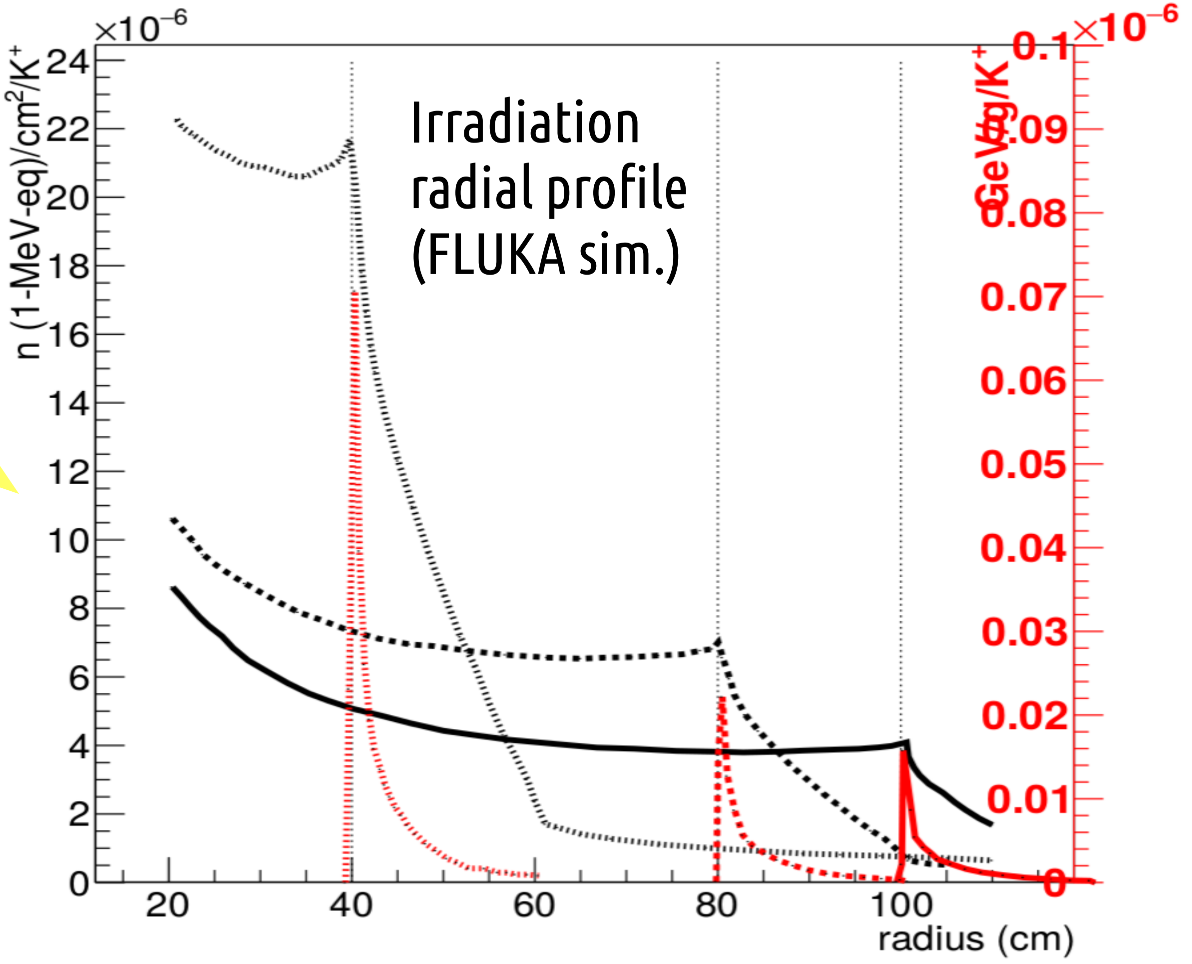


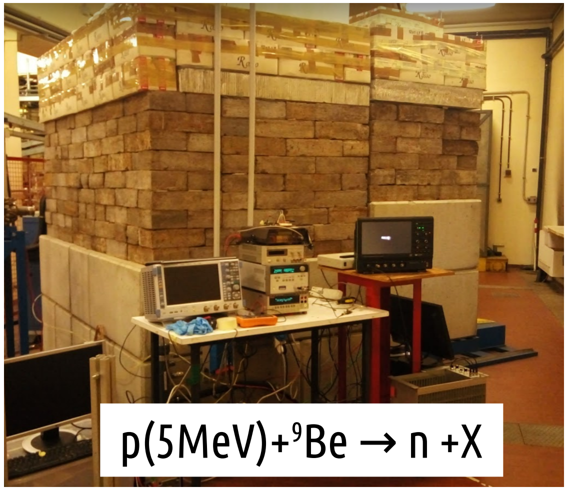


A. Berra *et al.*, IEEE Trans. Nucl. Sci, April 2017, 64 – 4 (1,6)

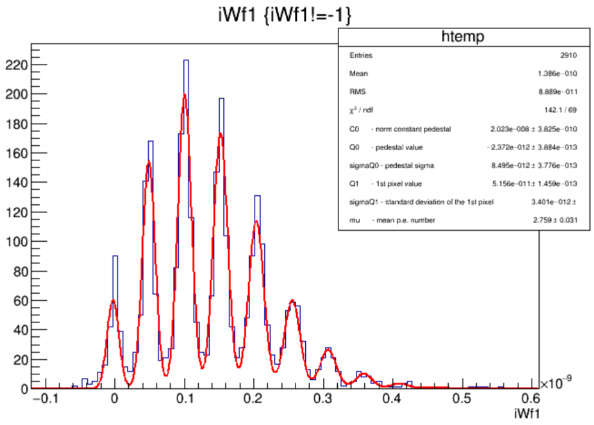
Irradiation studies

- **Neutron** and **ionizing doses** have been studied for a tagger radius of 40, 80 and 100 cm with FLUKA and cross-checked with GEANT4.
- Choosing 100 cm allows ~ **1 x 10^{12} n 1MeV-eq/cm^2** and **~0.25 kGy** in the innermost layers in the detector lifetime.
- **Test irradition with 1-3 MeV neutrons** performed at **INFN-LNL** CN Van de Graaff on **12-27 June 2017**.
- Characterise **rad-hard SiPM** with 12-15-20 μm cell size (FBK, SensL) up to **10^{11-12} 1MeV-eq n/cm^2**.
- Test viability of **self-calibration with m.i.p.**



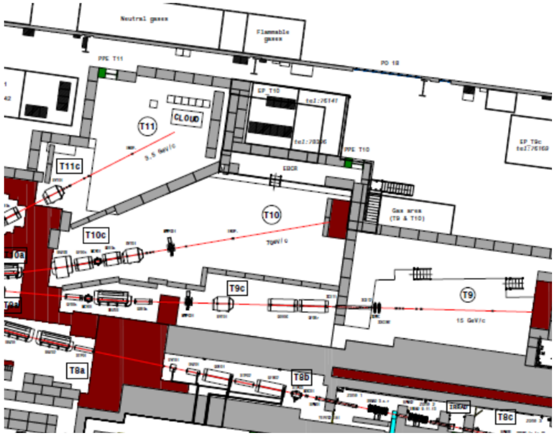


p(5MeV)+^{9}Be → n +X



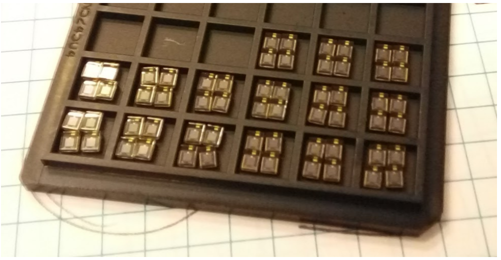
Single p.e. peaks (laser)

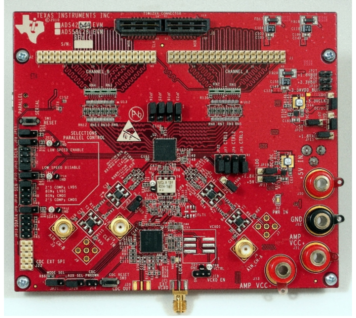
Lots of ongoing R&D activities



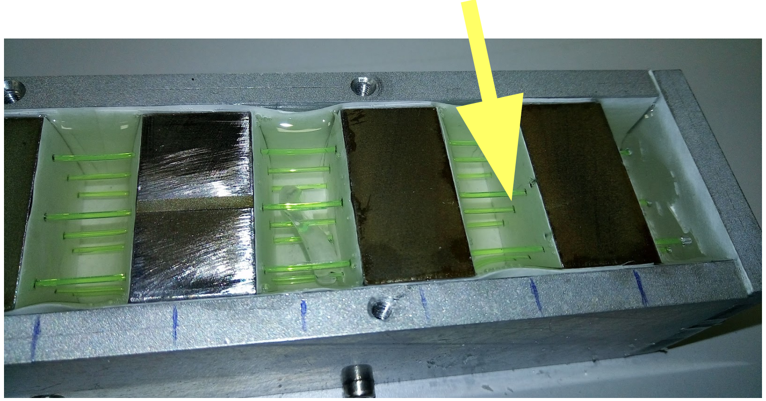
CERN-PS: **4 weeks** this year at T9 (July and Oct.)

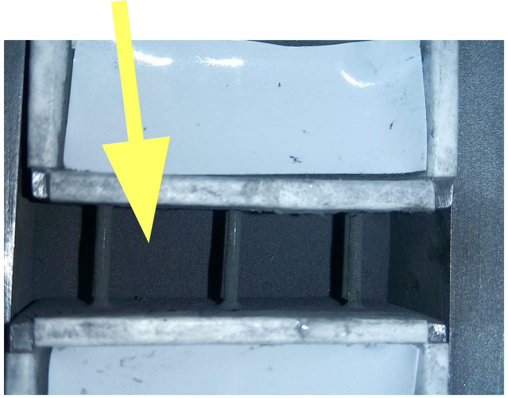
- Test response of **irradiated SiPM**
- Achieve **recovery time <~10 ns** (to cope with pile-up)
- Test of **custom digitizers electronics**
- **photon veto** prototypes with plastic scintillators

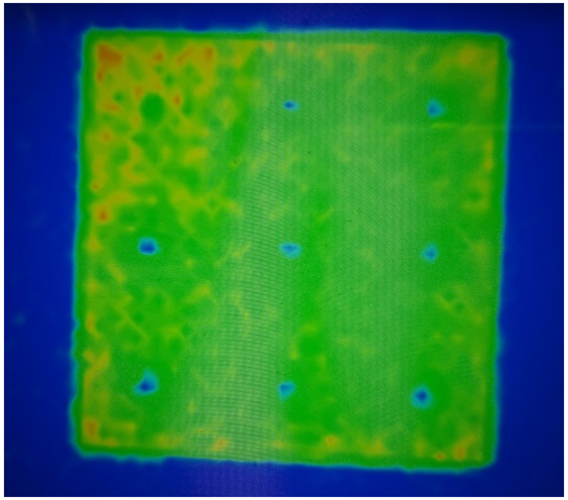




- **Scalable/reproducible technological solutions**
  - **Molded** scintillators, **water-jet holes machining** for absorbers
  - **Polysiloxane** scintillators/**powder** absorbers







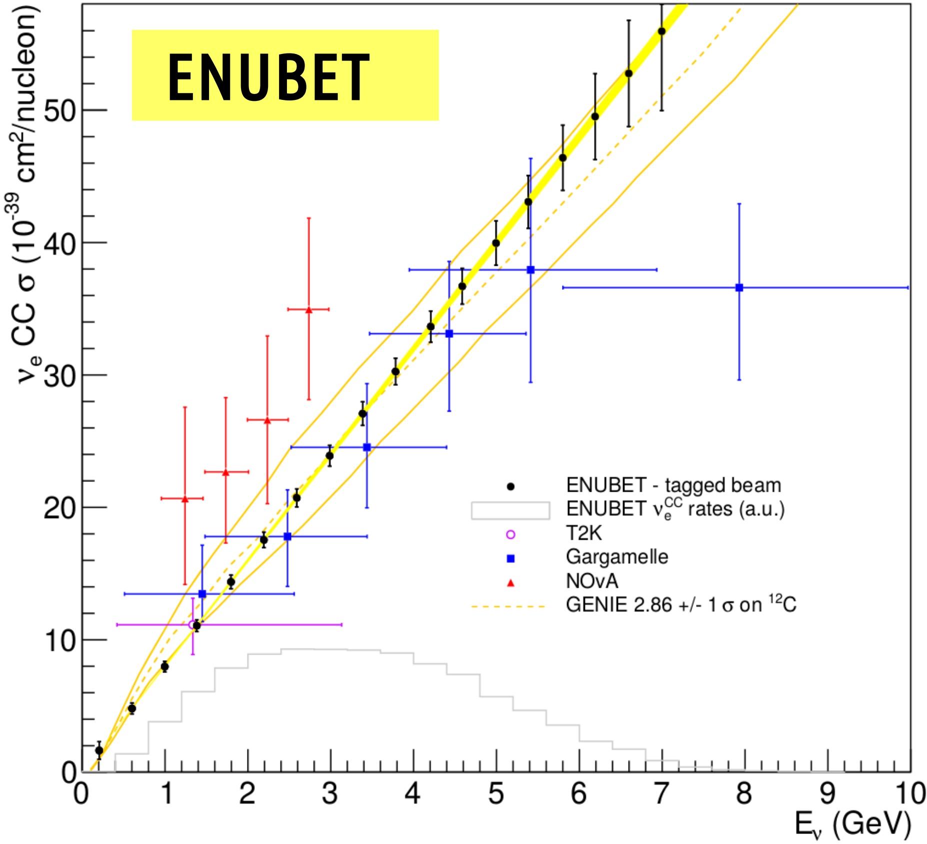
Conclusions

- Flux error limit could be **reduced by one order of magnitude** exploiting **$K^+ \rightarrow \pi^0 e^+ \nu_e$**
- In the next **4 years ENUBET** will investigate this approach and its application to a new generation of **cross section experiments** with possible extensions for a **phase-II sterile neutrino** search and a **time-tagged facility**

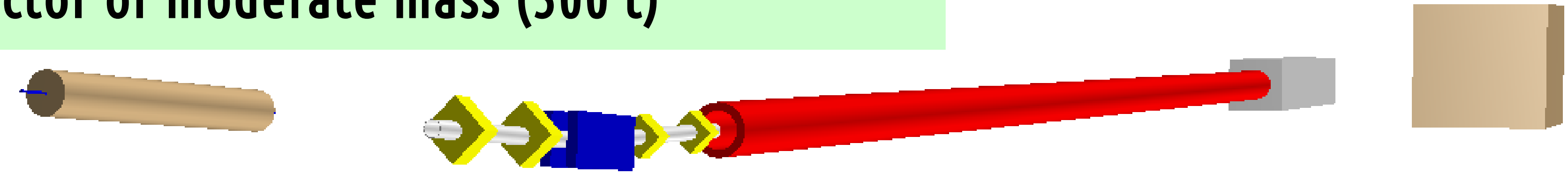
- 1st year of the project: a **rich simulation and prototyping program** is giving very **promising results**. Challenging open items ahead. No **showstoppers** so far.

- **ENUBET** is working to demonstrate that a "positron monitored" ν_e source can be built using existing technologies at **CERN, FNAL or J-PARC** giving a **measurement of $\sigma(\nu_e)$ at 1%** with a **detector of moderate mass (500 t)**

$\sigma(\nu_e)$



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



ENUBET

http://enubet.pd.infn.it

Enhanced NeUtrino BEams from kaon Tagging

Project approved by the European Research Council (ERC)
5 **years** (06/2016 – 06/2021)
overall budget: **2 MEUR**

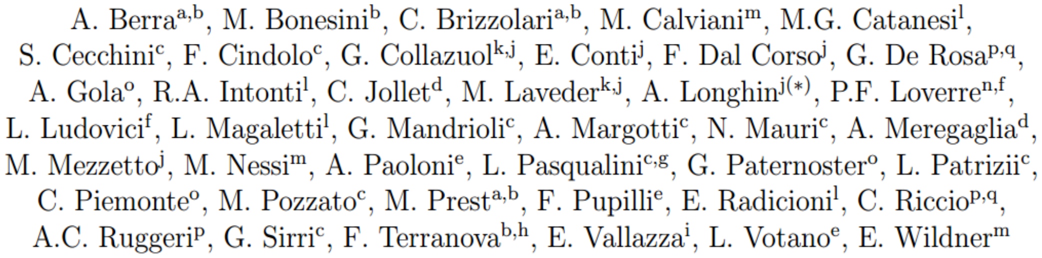
ERC-Consolidator Grant-2015, n° 681647 (PE2)
P.I.: A. Longhin
Host Institution: INFN

Expression of Interest
(CERN-SPSC, Oct. 2016)

CERN-SPSC-2016-036 ; SPSC-EOI-014

Enabling precise measurements of flux in accelerator neutrino beams: the ENUBET project

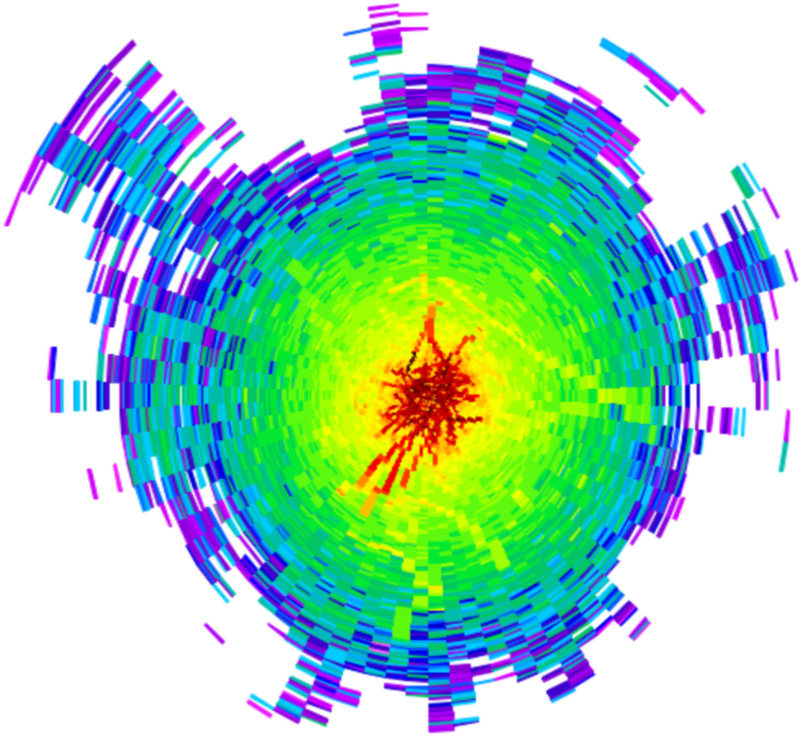
41 physicists, 10 institutions:
CERN, IN2P3 (Strasbourg), INFN (Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I)

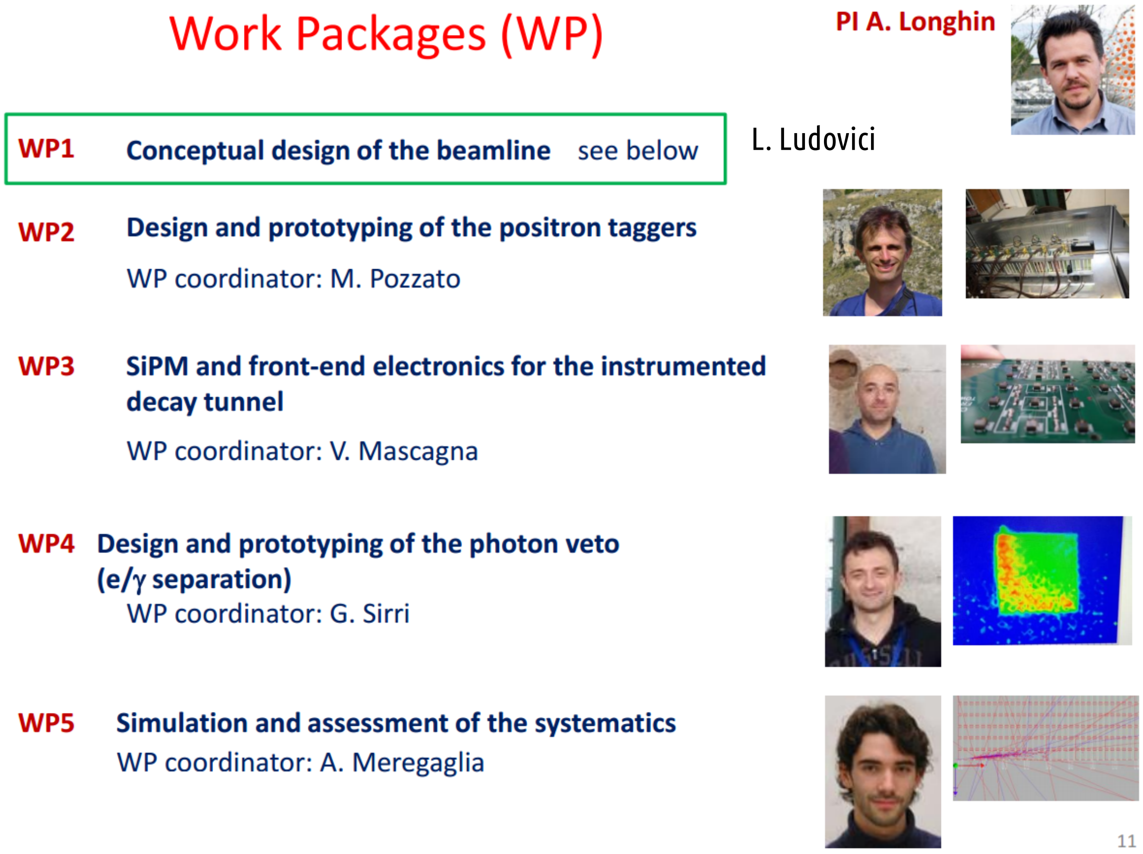


A. Berra[a,b], M. Bonesini[b], C. Brizzolari[a,b], M. Calviani[m], M.G. Catanesi[l],
S. Cecchini[c], F. Cindolo[c], G. Collazuol[k,j], E. Conti[j], F. Dal Corso[j], G. De Rosa[p,q],
A. Gola[o], R.A. Intonti[l], C. Jollet[d], M. Laveder[k,j], A. Longhin[j](*), P.F. Loverre[n,f],
L. Ludovici[f], L. Magaletti[l], G. Mandrioli[c], A. Margotti[c], N. Mauri[c], A. Meregaglia[d],
M. Mezzetto[j], M. Nessi[m], A. Paoloni[e], L. Pasqualini[c,g], G. Paternoster[o], L. Patrizii[c],
C. Piemonte[o], M. Pozzato[c], M. Prest[a,b], F. Pupilli[e], E. Radicioni[l], C. Riccio[p,q],
A.C. Ruggeri[p], G. Sirri[c], F. Terranova[b,h], E. Vallazza[i], L. Votano[e], E. Wildner[m]

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

Thank you!





Work Packages (WP)

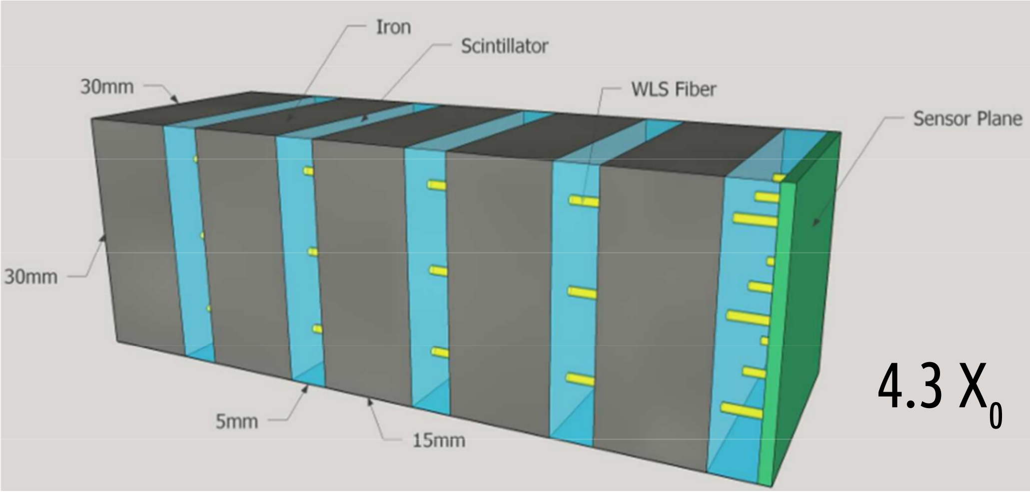
PI A. Longhin

WP1	**Conceptual design of the beamline** see below	L. Ludovici
WP2	**Design and prototyping of the positron taggers** WP coordinator: M. Pozzato	
WP3	**SiPM and front-end electronics for the instrumented decay tunnel** WP coordinator: V. Mascagna	
WP4	**Design and prototyping of the photon veto (e/γ separation)** WP coordinator: G. Sirri	
WP5	**Simulation and assessment of the systematics** WP coordinator: A. Meregaglia	

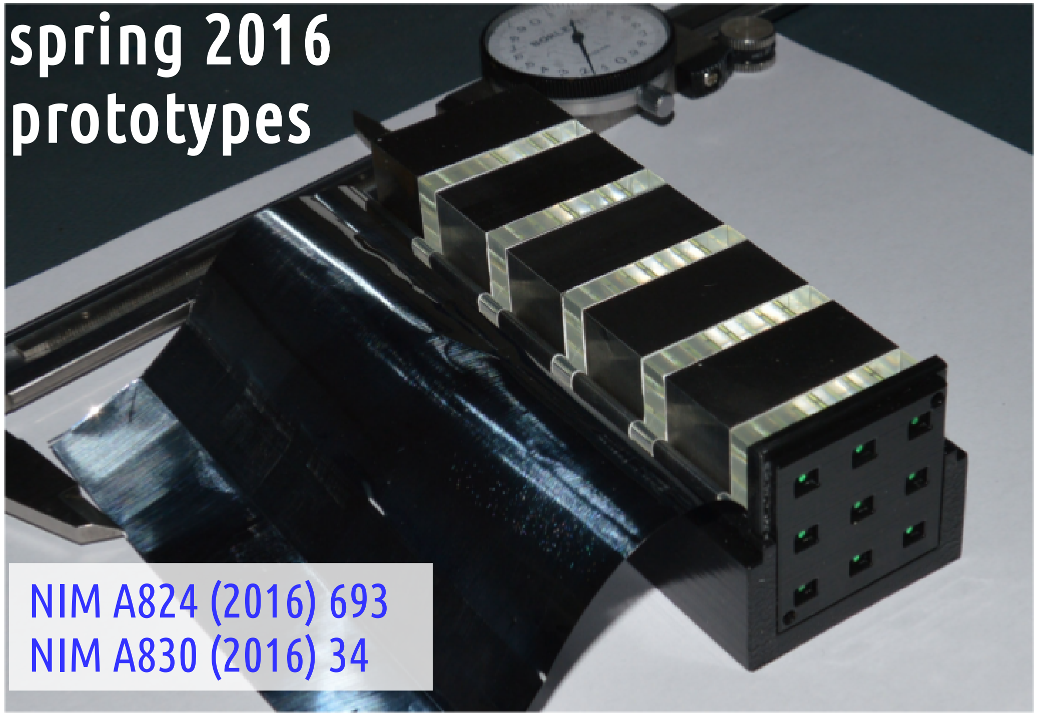
11

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

The Ultra Compact Module (UCM)

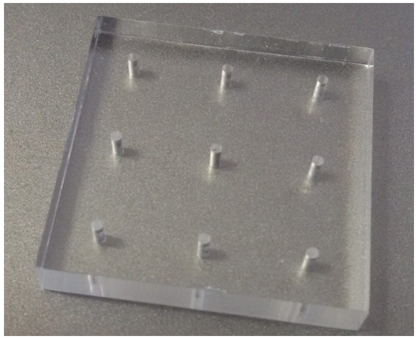


4.3 X_0

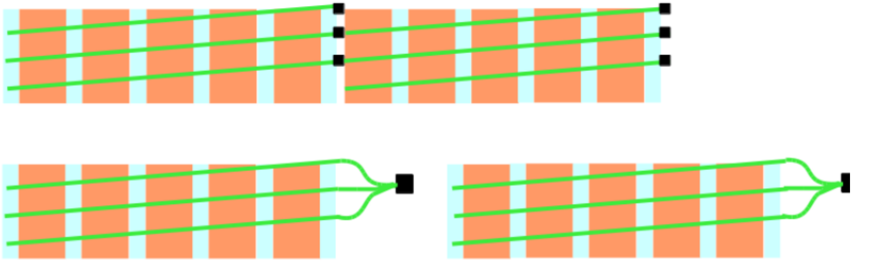


spring 2016 prototypes

NIM A824 (2016) 693
NIM A830 (2016) 34



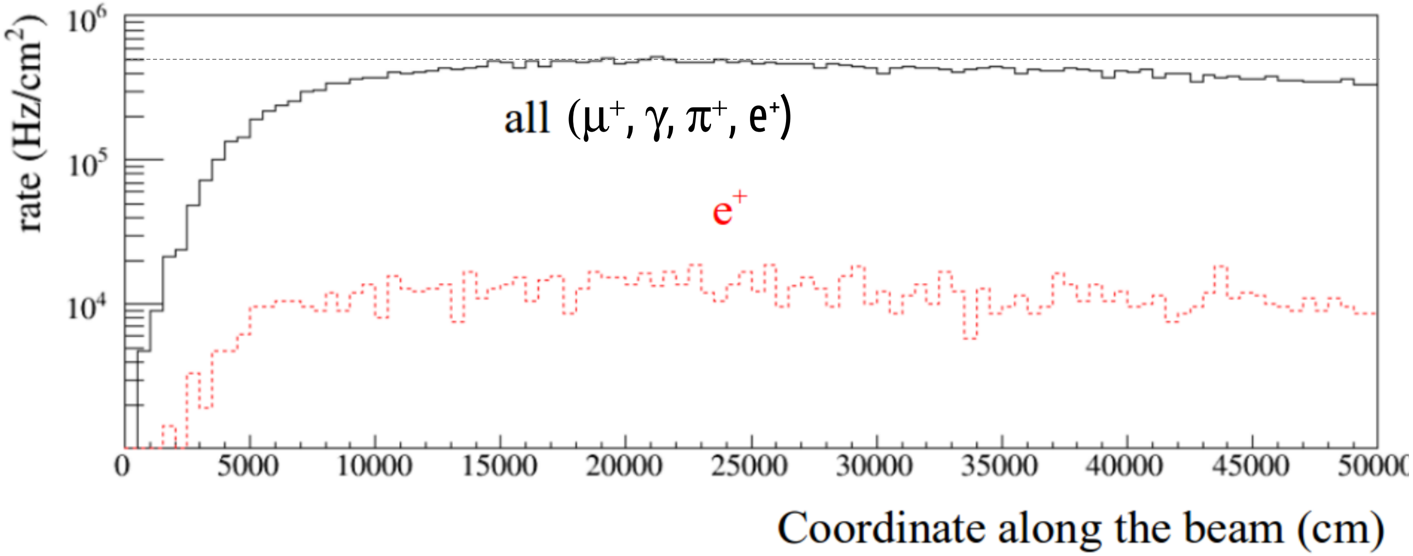
- 1 SiPM ↔ 1 WLS fiber
- 9 SiPM signals are added (reduce R/O costs)
- Add SiPM signals in place of light → **no WLS bundling = optimal homogenity in longitudinal sampling (UCM)**



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

The e⁺ tagger challenges

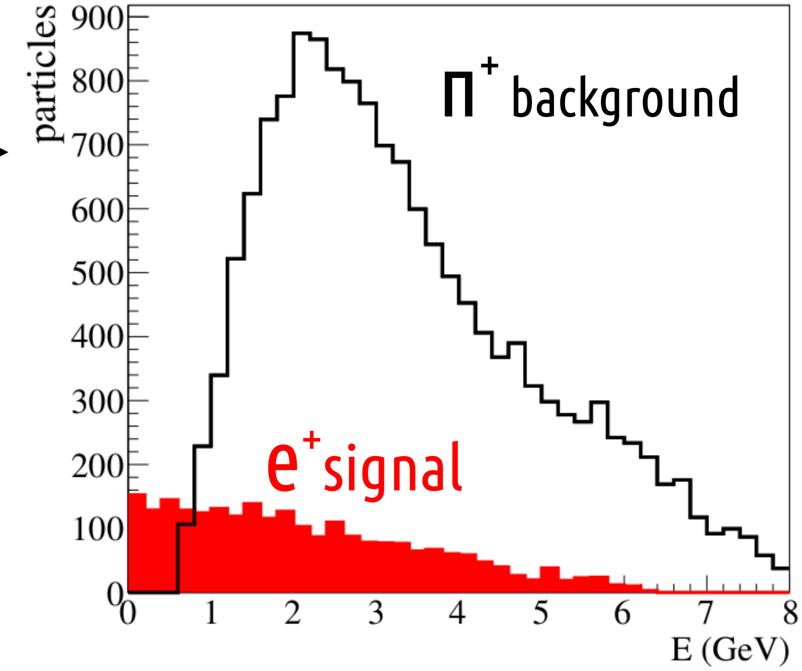
Injecting **10^{10} π^+ in a 2 ms spill** →



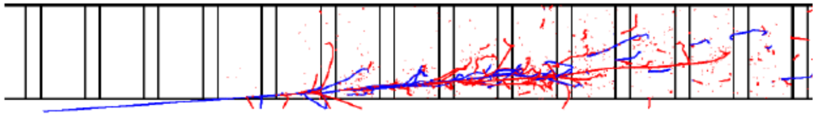
	Max rate (kHz/cm²)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

The decay tunnel: a **harsh environment**

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



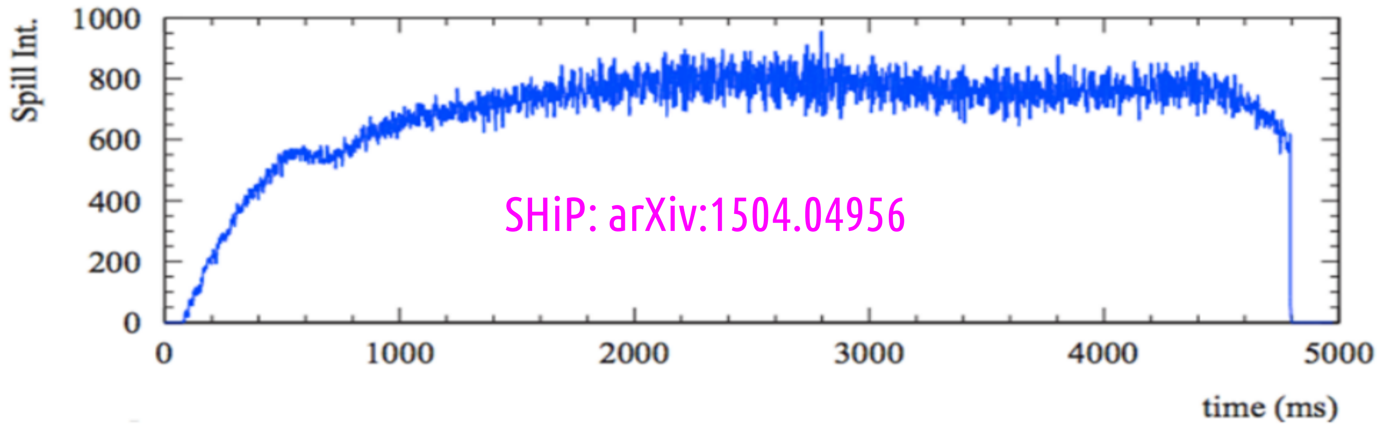
Moreover:



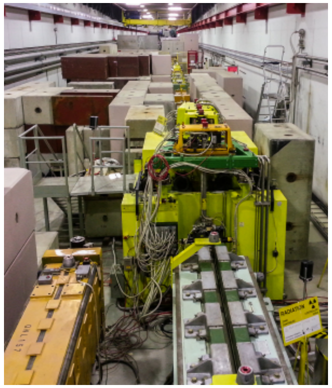
- **extended source of ~ 50 m**
- grazing incidence
- significant spread in the initial direction

Hadron beam-line: “static” scenario

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



SHiP: arXiv:1504.04956



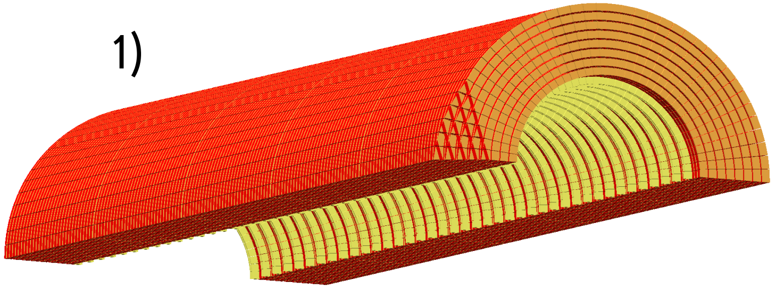
Intriguing opportunity: “time tagging” →
T_{extr} = 1s (~ 1 observed e^+ / 30 ns) + **δ = 1 ns** → **Accidental tag = 2 %**

ENUBET: the roadmap

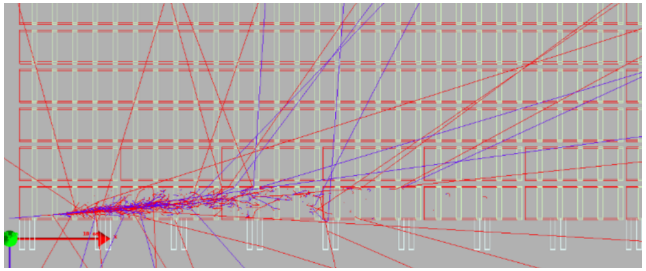
Demonstrate the technique, prepare a “full-scale” experiment

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

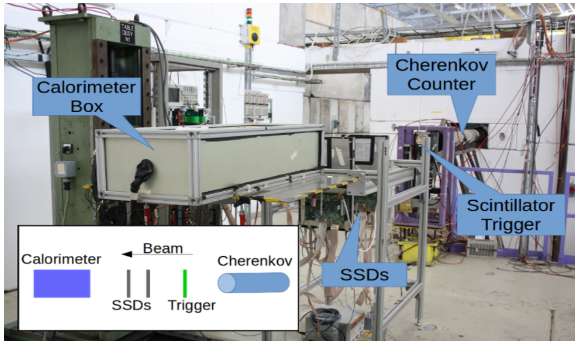
1)

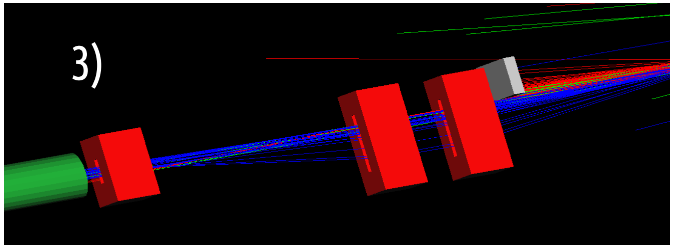


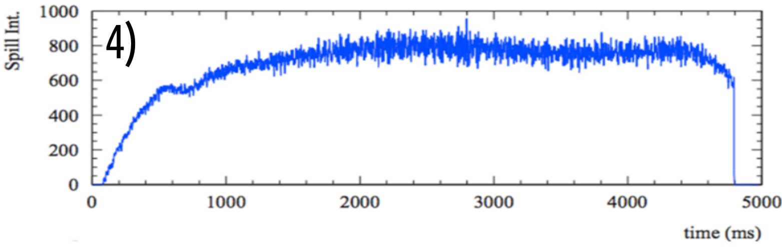
2)



2)







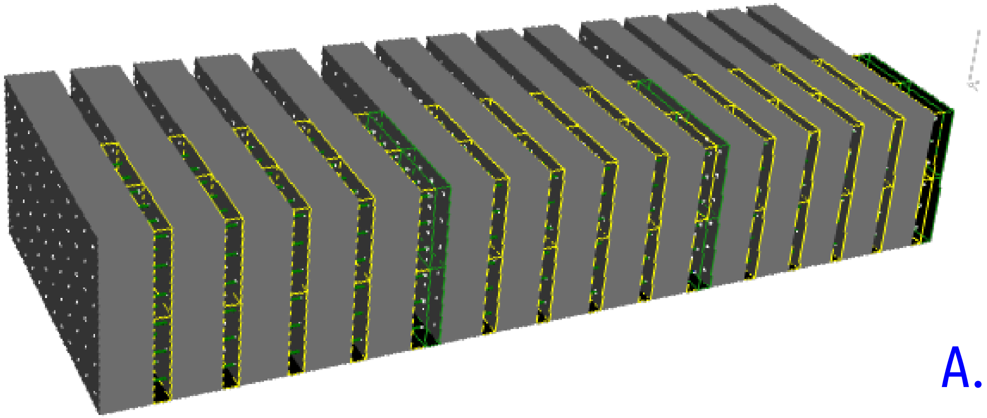
By-products:

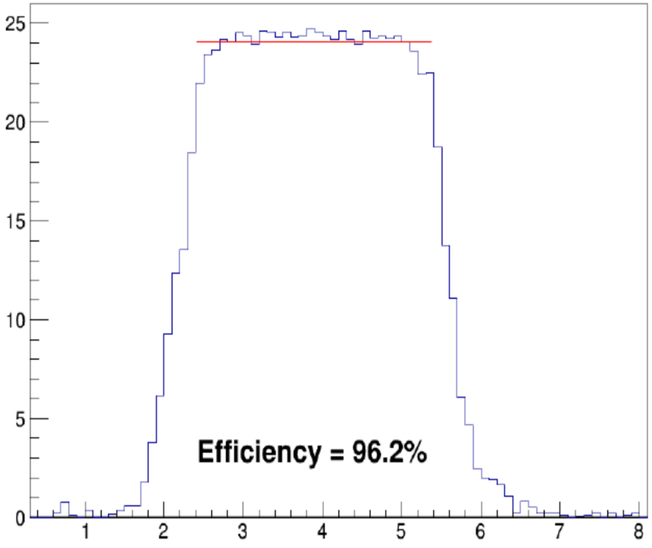
- **Calorimetry:** compact, modular, low-cost detectors (UCM)
- **Accelerator physics:** Multi-Hz slow resonant extraction

Results from UCM prototypes

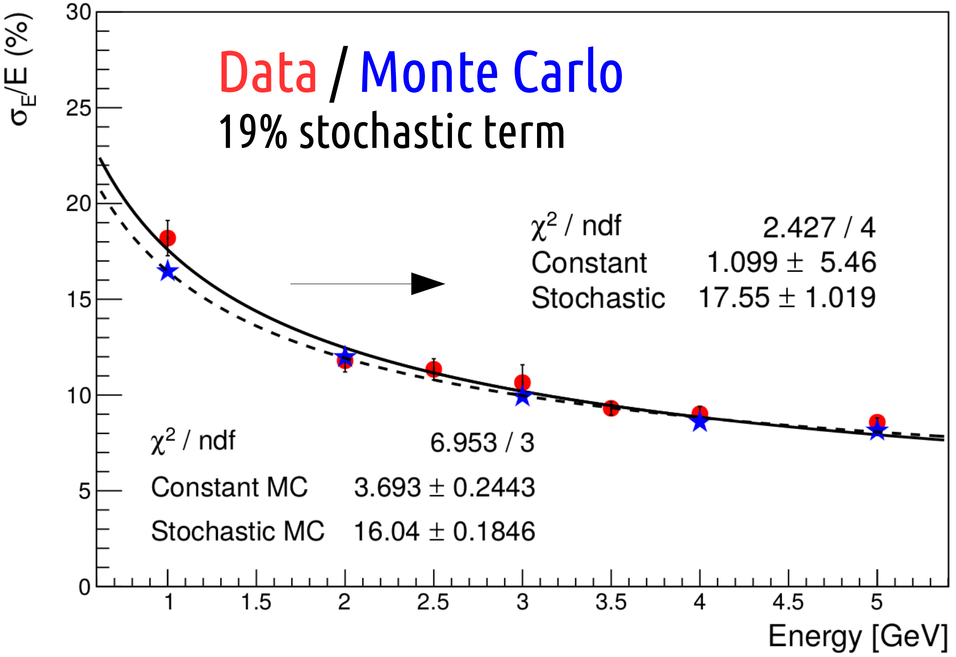
Cheap, fast (<10 ns),
Rad-hard technological solution

Geant4





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

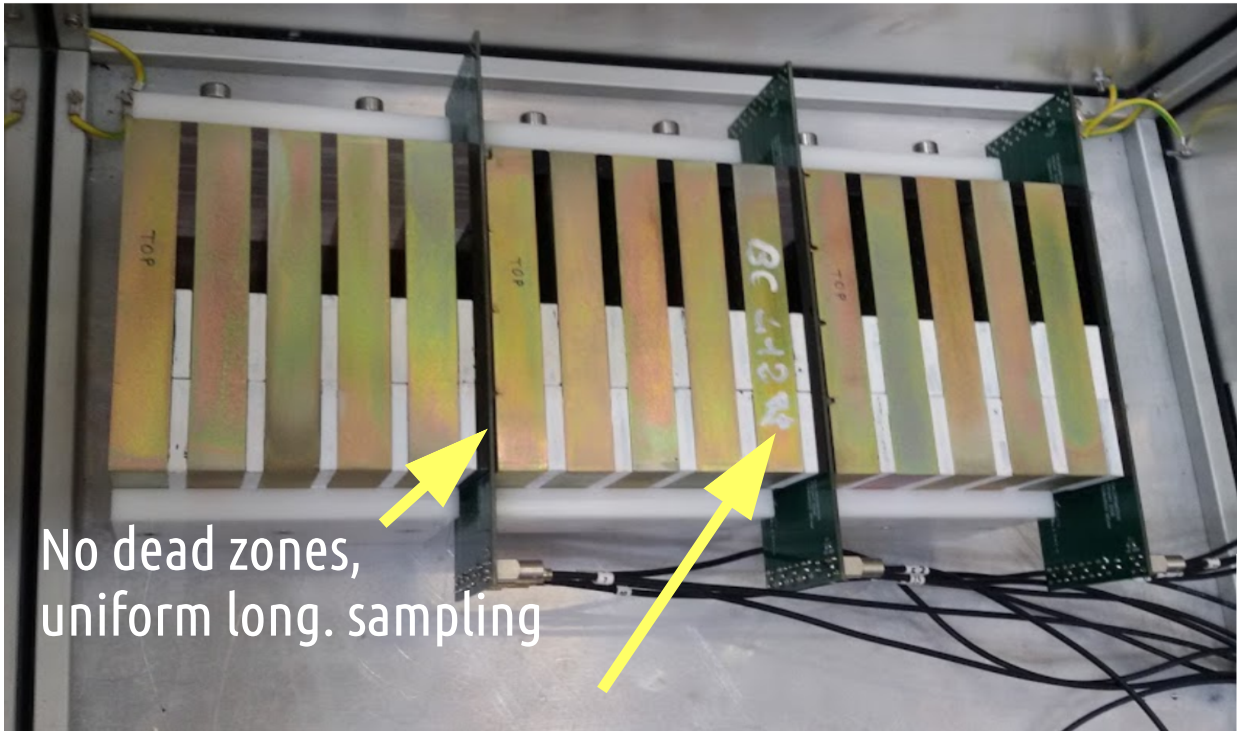


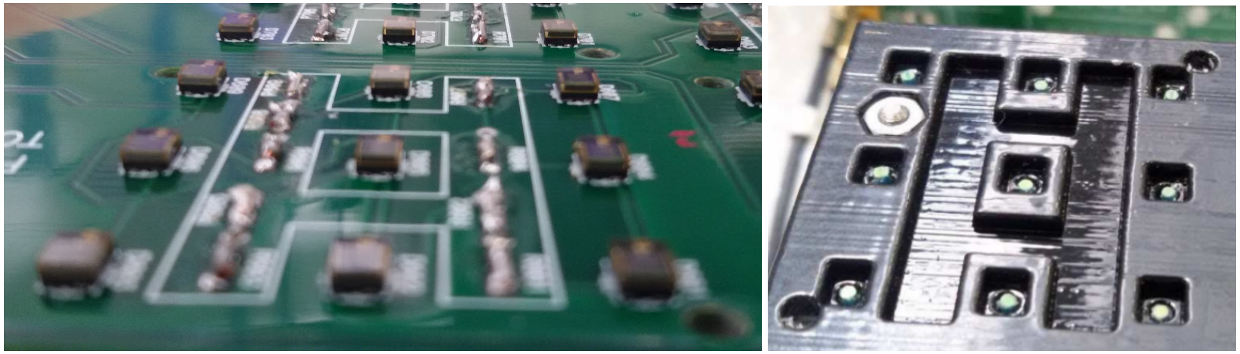
Requirements for ENUBET:

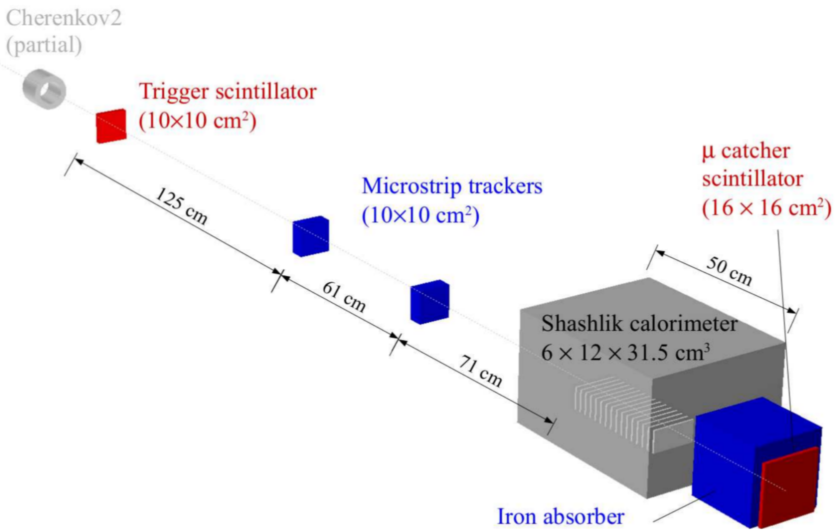
- m.i.p. sensitivity w/o saturation for e.m. showers up to 4 GeV **DONE**
- E resolution < 25% / $E^{1/2}$ **DONE**
- No role for "nuclear counter" effects (direct ionization of SiPM in the e.m. shower) **DONE**

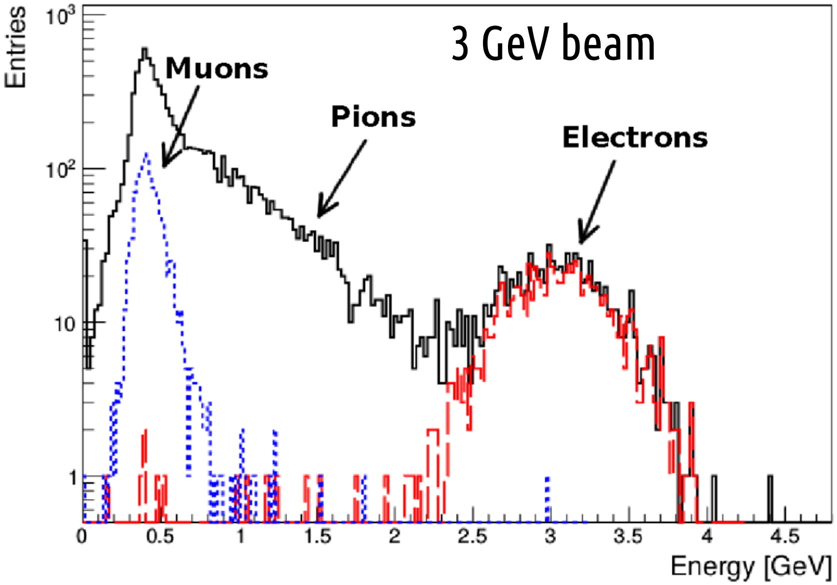
First test beam validation of UCM

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


No dead zones,
uniform long. sampling

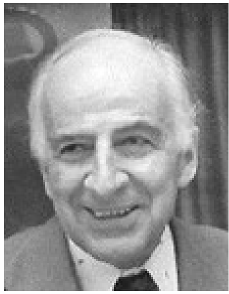






A. Berra *et al.*, IEEE Trans. Nucl. Sci., in press.

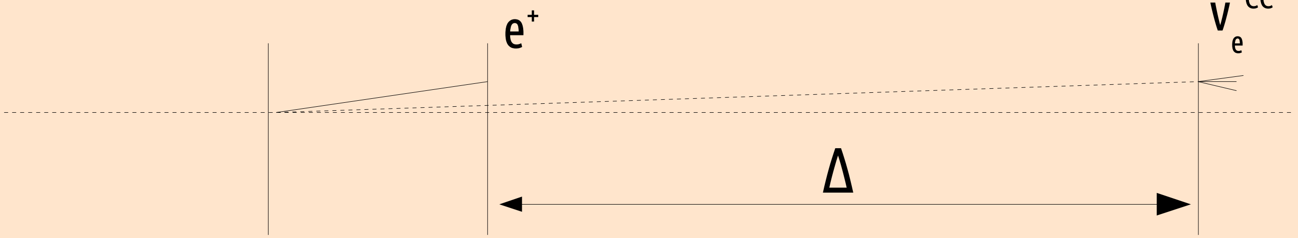
Going beyond: "time-tagged" beams



- 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 n detector)

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

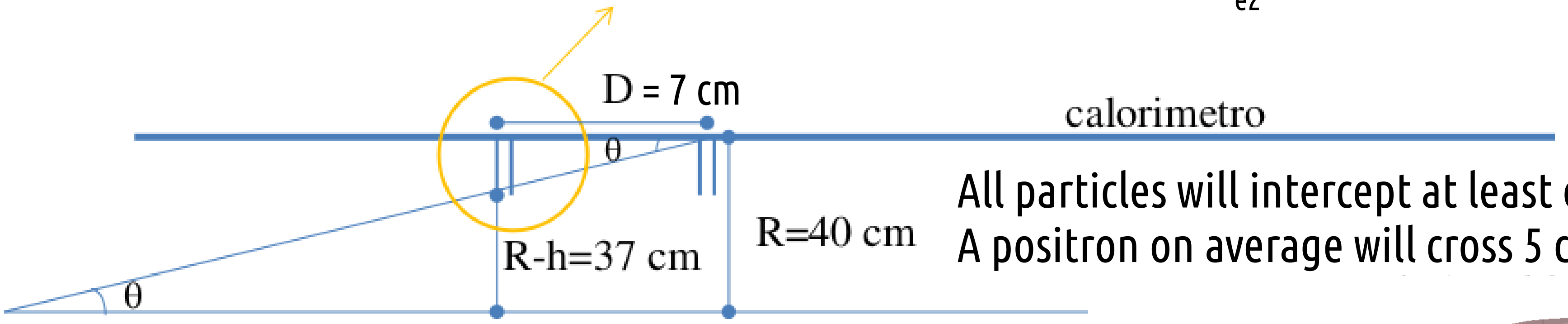
T_{extr} = 1s (~ 1 observed e^+ / 30 ns) + **δ = 1 ns** → **A = 2 %** **OK !**

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

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

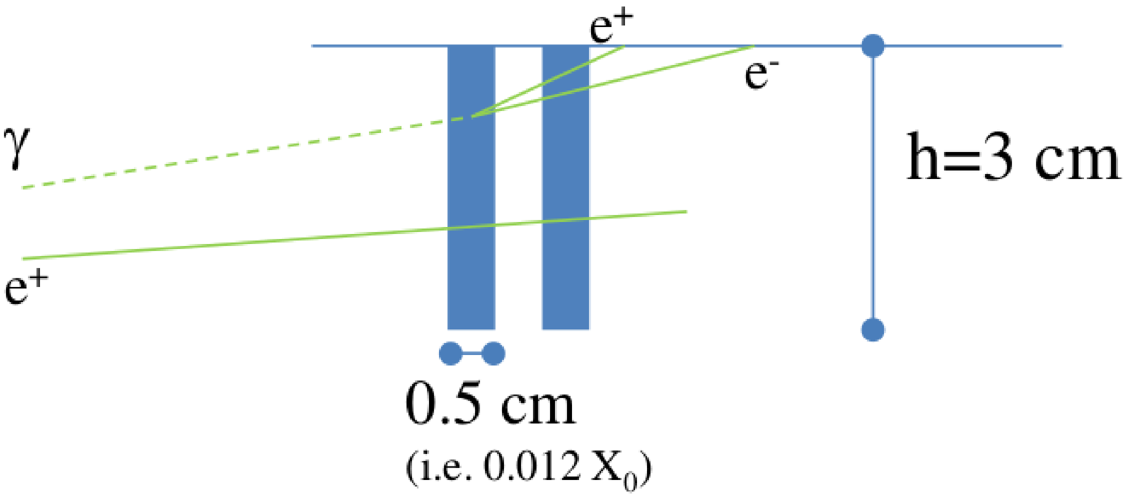
The photon-veto baseline option

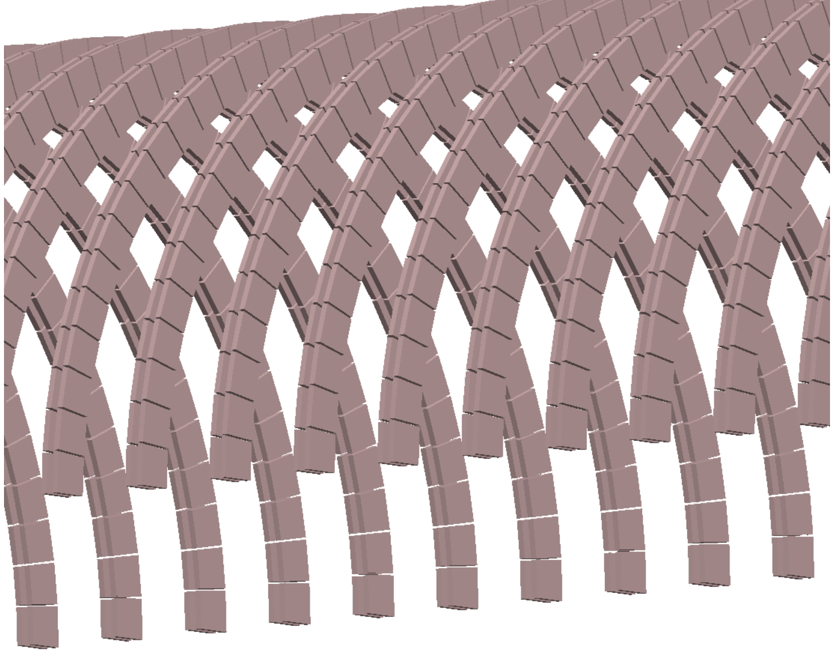
Background from γ conversions from π^0 emitted mainly in K_{e2} decays ($K^+ \rightarrow \pi^+ \pi^0$)



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

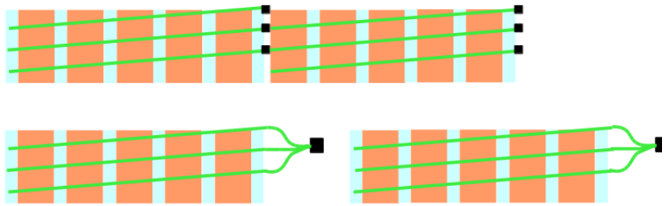
Exploit **1 mip – 2 mip separation**



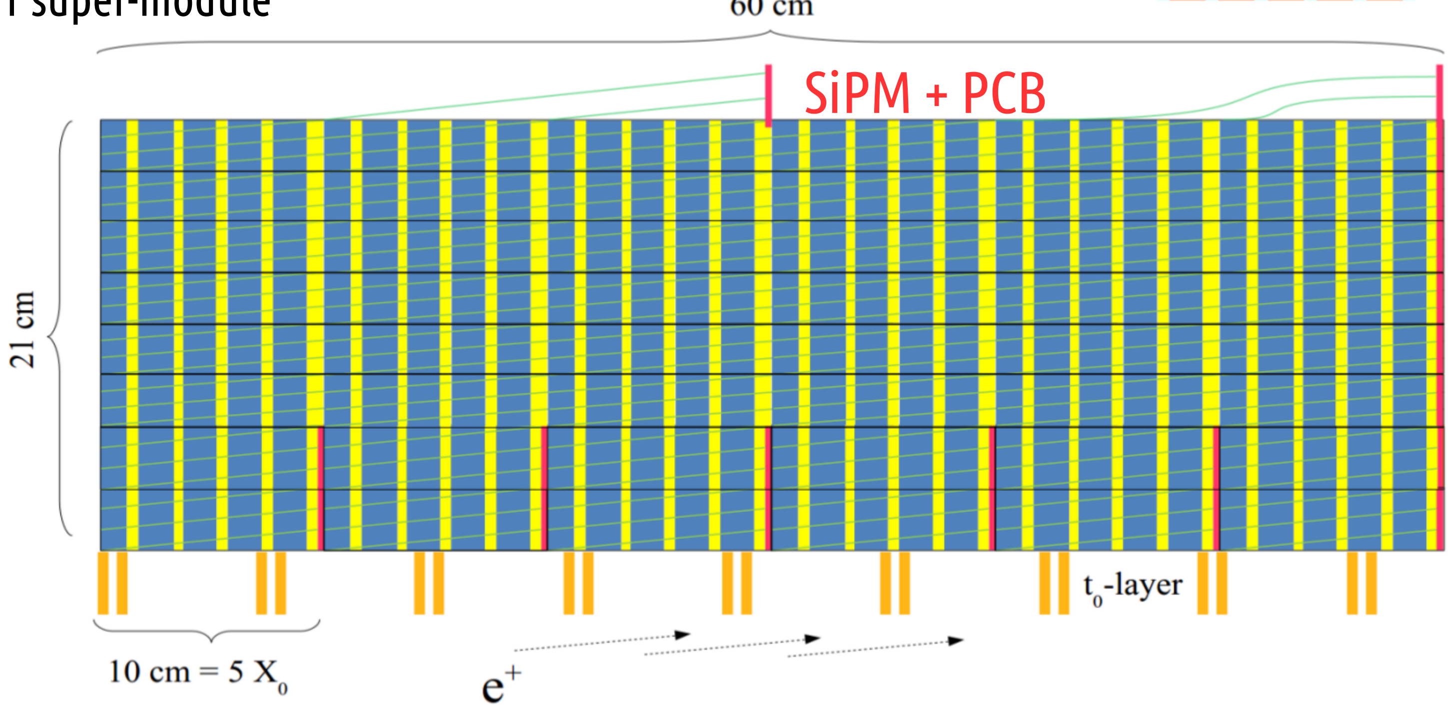


- Possible **alternative/attractive solutions** under scrutiny allowing a reduced **material budget and superior timing**.
- Test beams at Frascati: **electronics response** at high rates and low-E e^+,1 mip/2 mip

The final prototype



1 super-module

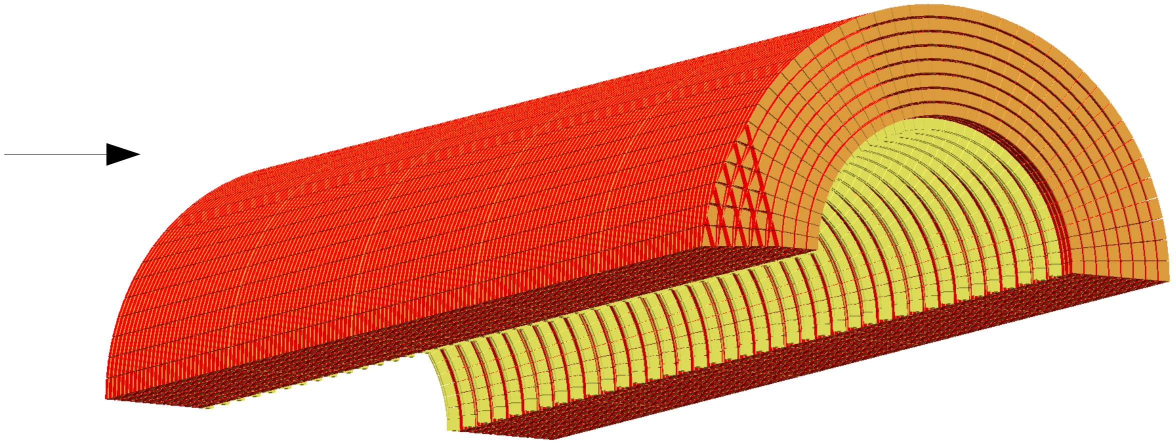


Outer modules

Inner modules

- 5 **super-modules**

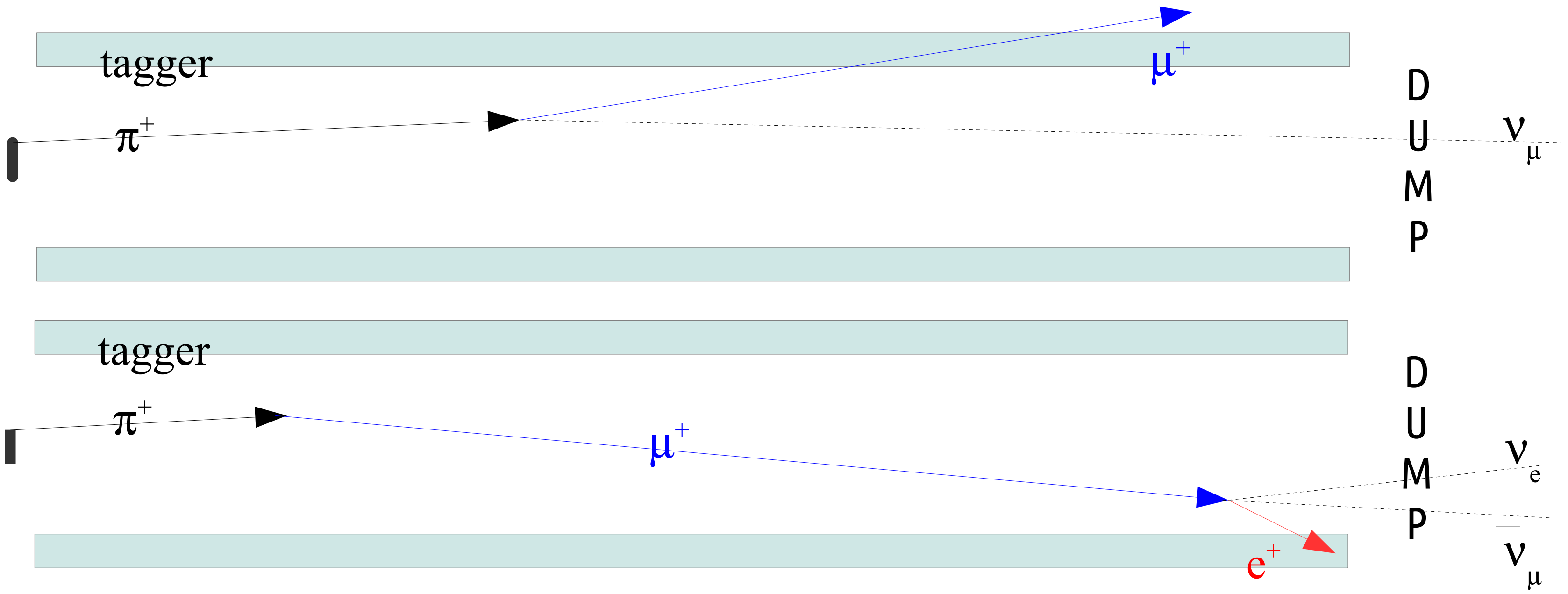
- Dimensions: **3 m × π**
- # SiPM: **34000**
- Channels: **3800**
- Weight: **~ 5 t**
- WLS fiber length: ~**10000 m**
- **Readout:** custom waveform digitizers, **2 ns** granularity over **~10 ms**



Pion decays induced backgrounds

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

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



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

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

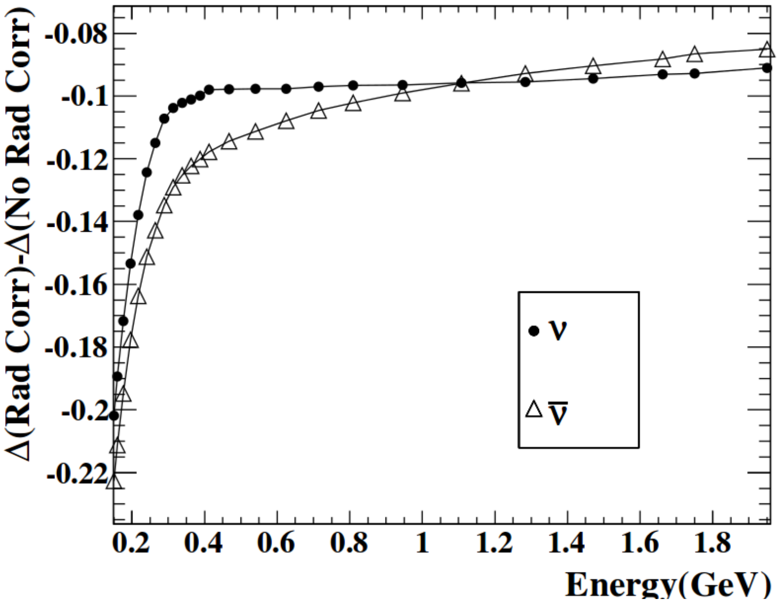
1) **Lepton universality** in weak interactions is **not the full story**:

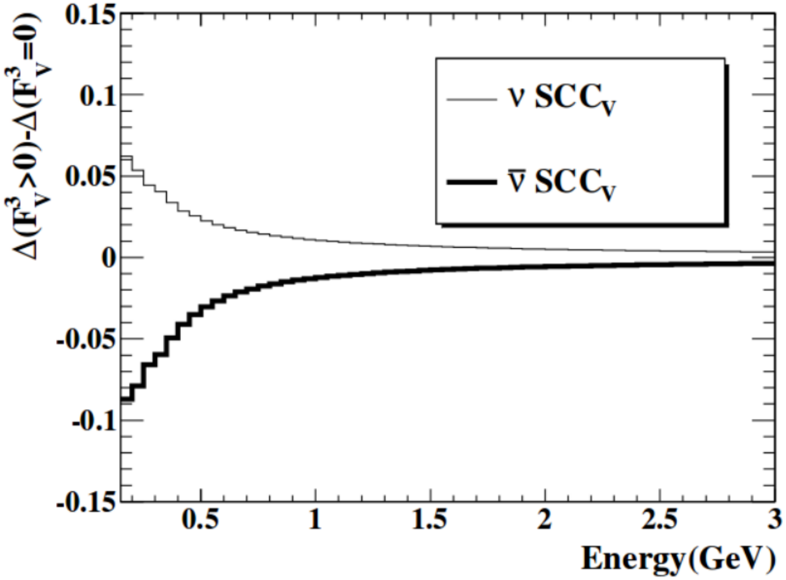
- ✓ Uncertainties from the **interplay** of
  - **radiative corrections**
  - **nucleon form factors**
    - F_P, $F_V^{1,2}$, F_A, second class currents
  - alteration of **kinematics** due to mass

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

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

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





Choosing the K±/π± momentum and tunnel length

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

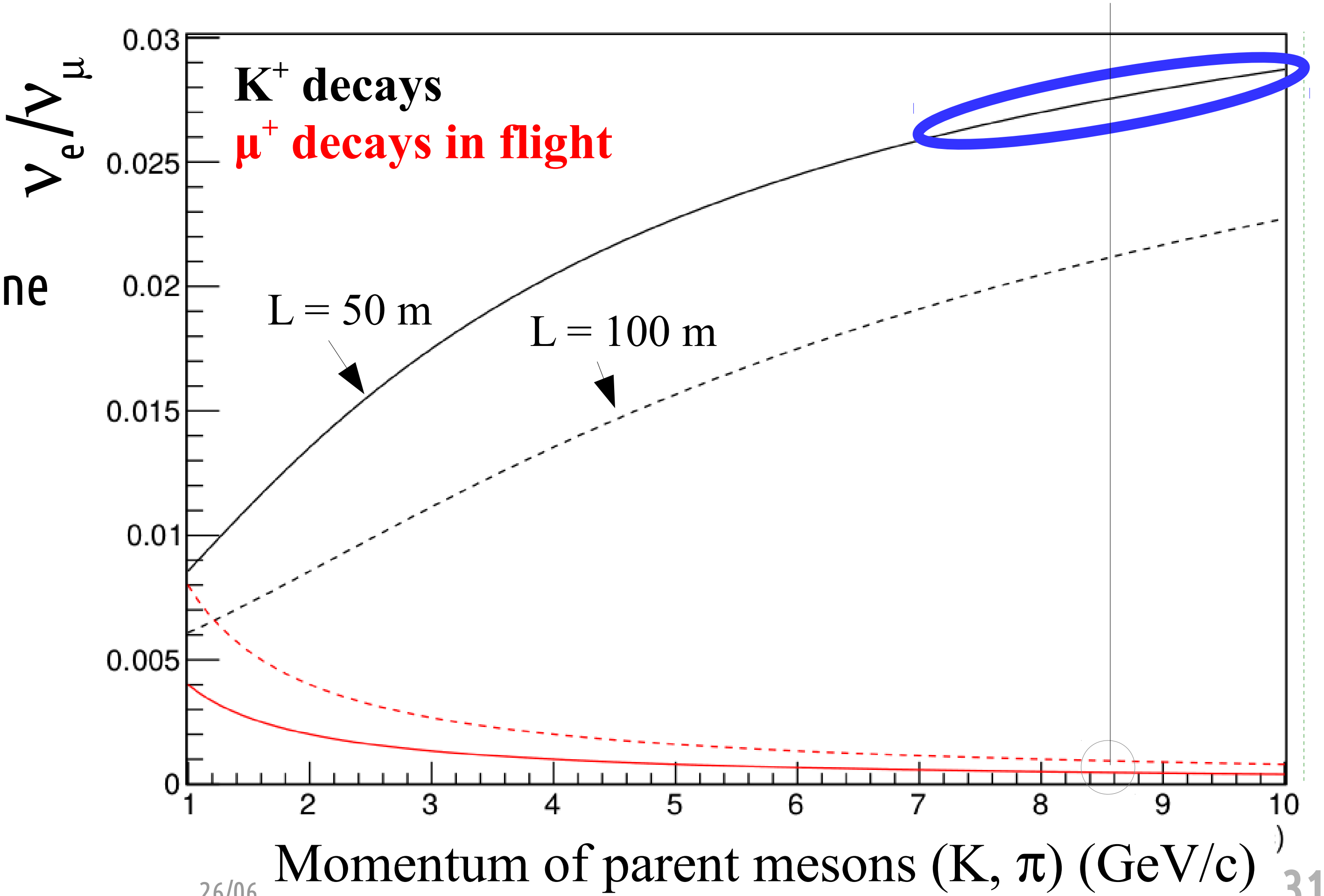
Benefits:

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

Costs:

- E(ν_e) above the R.O.I.
- longer decay region

A trade-off: further optimization in ENUBET



e^+ tagger: background rejection

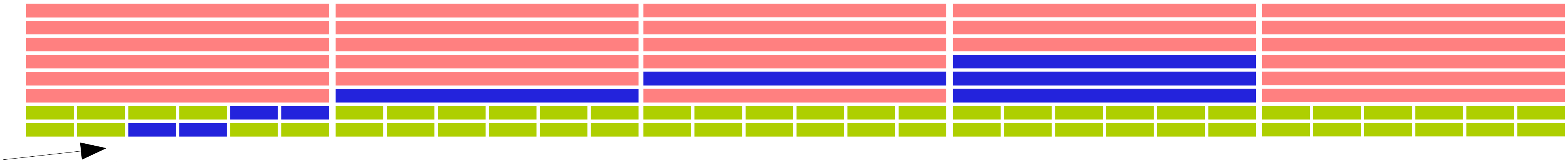
Hadronic modules
Electro-magnetic modules
Hit modules

Key point:

- longitudinal sampling
- perfect homogeneity → integrated light-readout

e^+ (signal) topology

π^0 (background) topology



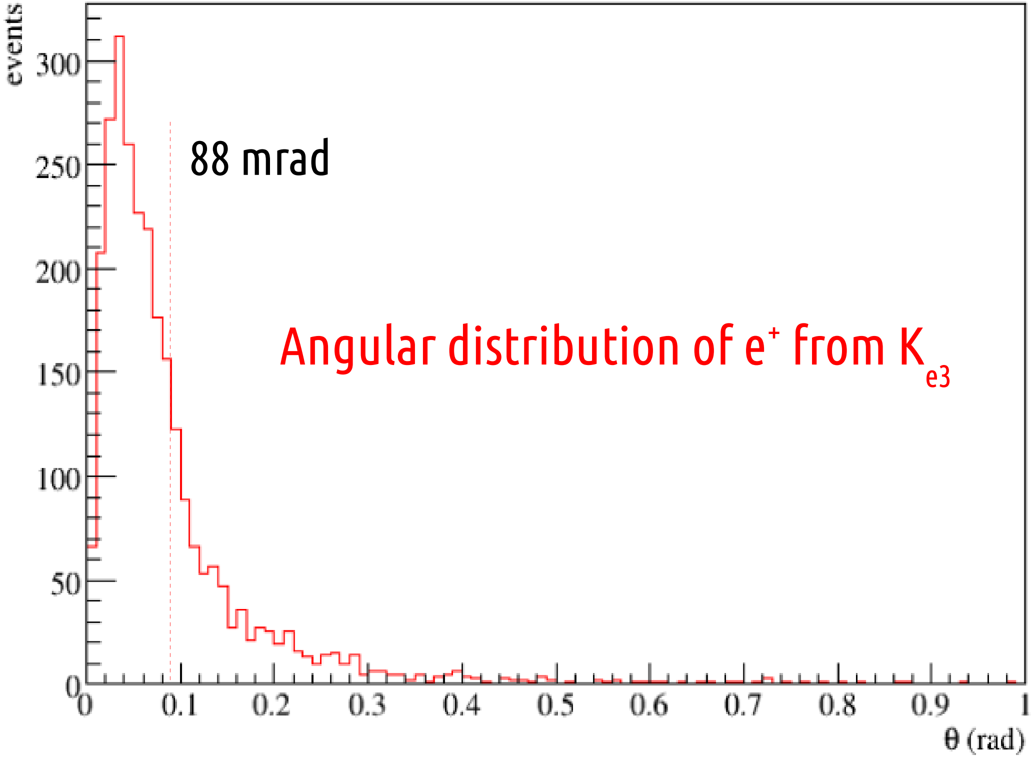
π^+ (background) topology

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

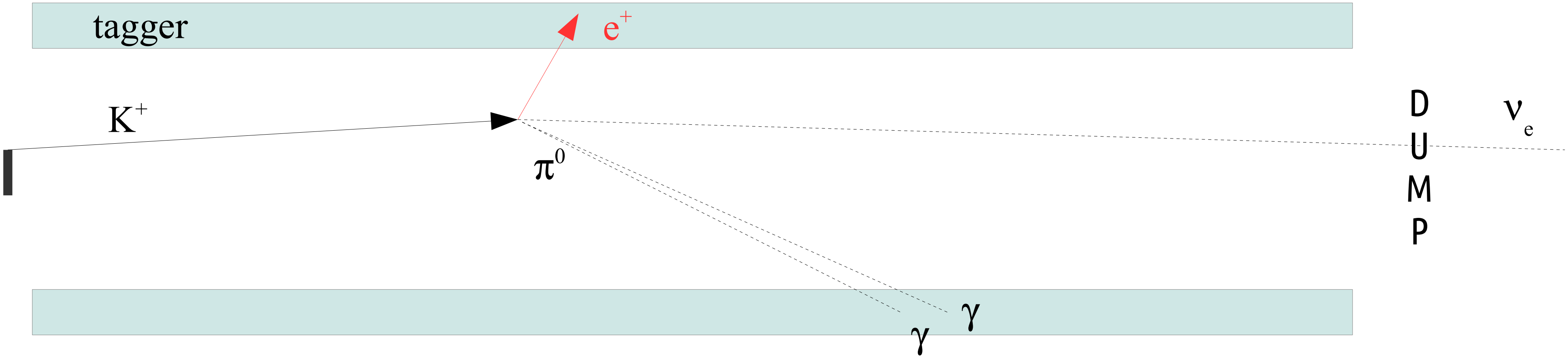
- Golden sample: good acceptance for e^+ from K_{e3} thanks to the **large emission angle** (~ K mass)

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

→ ~ all ν_e are from K_{e3}



Angular distribution of e^+ 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

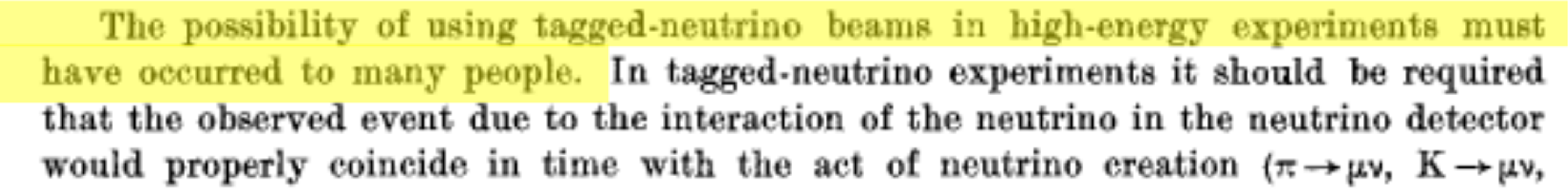
→ Simple conversion

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

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

Tagged neutrino beams: the origins

The "holy grail" of neutrino physicists:



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

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

Literature:

- L. Hand, 1969, V. Kaftanov, 1979 (p/K → n_m)
- G. Vestergombi, 1980, R. Bernstein, 1989 (K →n_e)
- S. Denisov, 1981, R. Bernstein, 1989 (K_{e3})

- L. Ludovici, P. Zucchelli, hep-ex/9701007 (K_{e3})
- L. Ludovici, F. Terranova, EPJC 69 (2010) 331 (K_{e3})

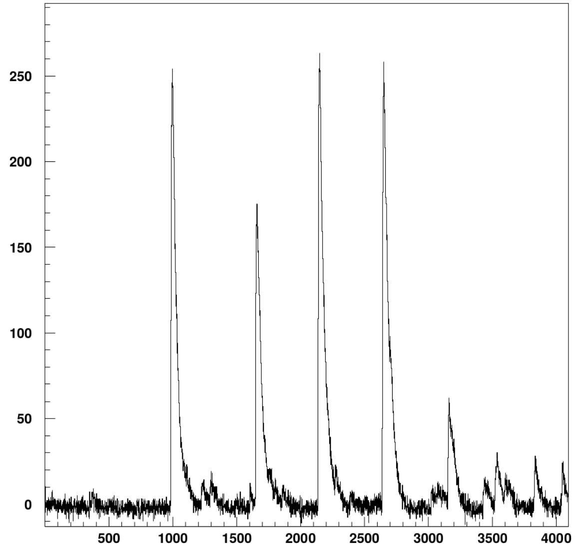
What's new with ENUBET:

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

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 $K_{\mu2}$ 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 O (1 kGy) (~100 kGy for CMS forward ECAL)