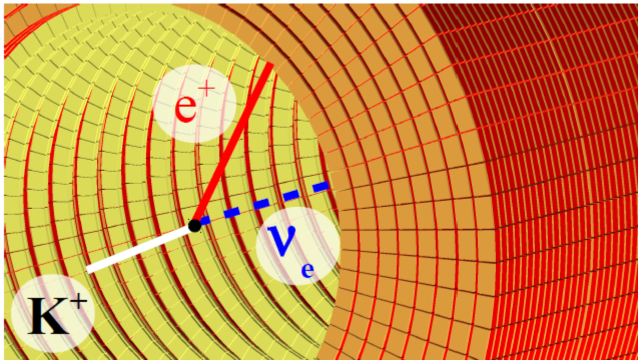
Enhanced neutrino beams from kaon tagging (ENUBET): opportunities and challenges

- Enable the technology for a new generation of neutrino beams with superior control of the ν flux and flavor composition
- The ERC ENUBET Project (2016-2021):

A pure ν_e source monitored by tagging large angle positrons in the decay tunnel originating from kaon decay $K^+ \rightarrow \pi^0 e^+ \nu_e$

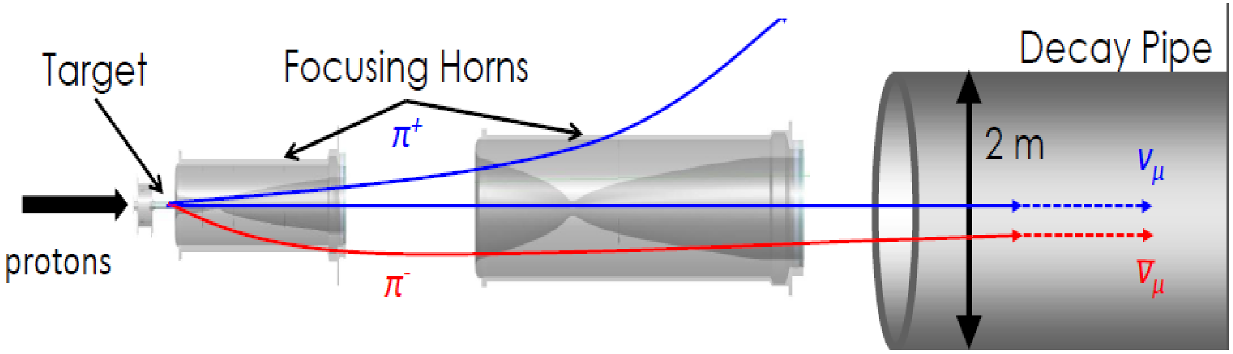


- Opportunities for a new generation of short baseline neutrino experiments
- Technical challenges:
  - Proton extraction scheme
  - Focusing system
  - Transfer line and beam dumps
  - Instrumented decay tunnel
- Conclusions

F. Terranova on behalf of the ENUBET Collaboration

European Research Council
Established by the European Commission

Accelerator neutrino beams

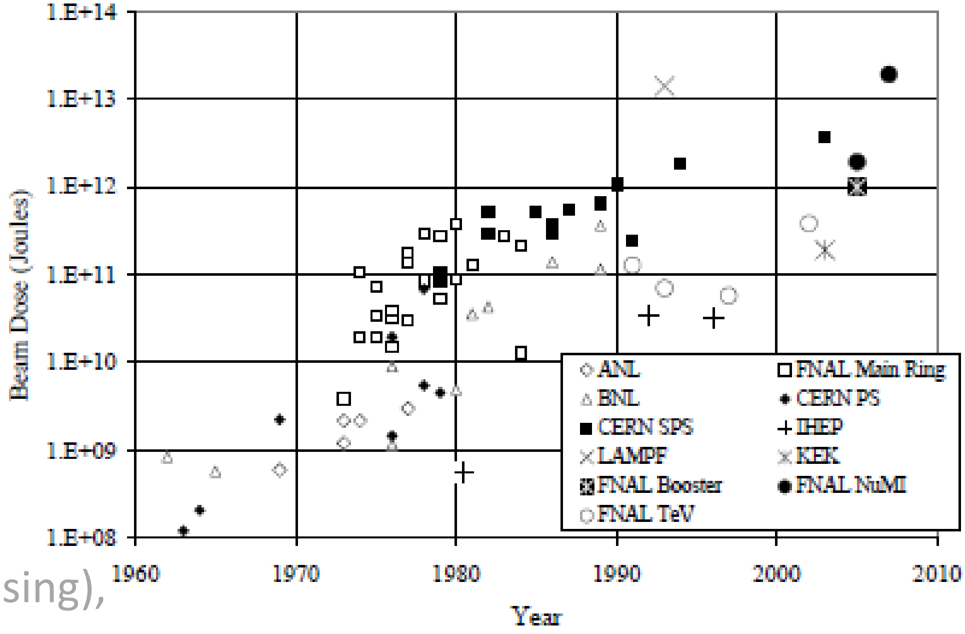


The "van Der Meer's paradigm" (A. Bross)

CERN Informal Workshop on Neutrino Physics, CERN-63-37, (1963).

S. van der Meer, "A directive device for charged particles and its use in an enhanced neutrino beam," CERN-61-07 (1961).

- Fast proton extraction (<10 ms)
- Focus of the largest amount of mesons in the forward direction
- Sign and momentum selection performed only by the horns (*)
- Decay tunnel just after the horns (**)



Notable exceptions: (*) NuTeV (static focusing), (**) Narrow Band beams (transfer line)

It has been the workhorse of major discoveries in electroweak and neutrino physics because it is scalable to very high beam power (up to MW, right now)

Limitations

In general, accelerator neutrino beams do not employ any of the beam manipulation techniques (FODO lattices, charged particle monitoring etc.) that are common in accelerator physics.

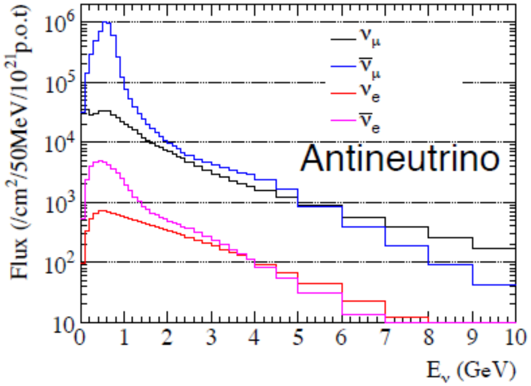
Meson selection performed only by the horns

Decay tunnel just in front of the target

No instrumentation between target and dump

[notable exception: K2K]

Large energy tails and “wrong flavor” (e.g. ν_μ in anti-ν_μ beam) contamination



D. Sgalaberna EP Seminar @ CERN, Nov 2016

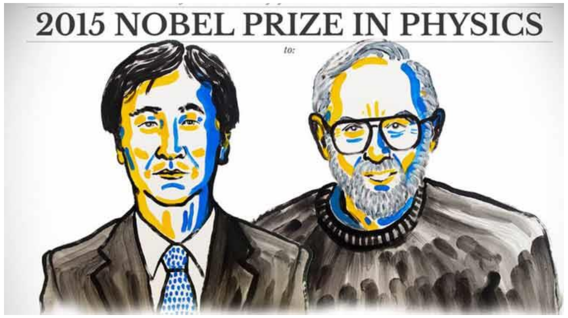
Radiation environment too hostile to directly measure the flux of decayed mesons.

Flux and flavor content estimates must resort to an ab-initio simulation of of the beamline. They are thus sensitive to secondary production yields, proton beam, target horn stability, detailed material budget etc. A tremendous task! (see e.g. L. Aliaga, Phys.Rev. D94 (2016) 092005)

An accelerator neutrino source at the GeV scale is mostly a ν_μ source whose flux is known with a precision of >8%

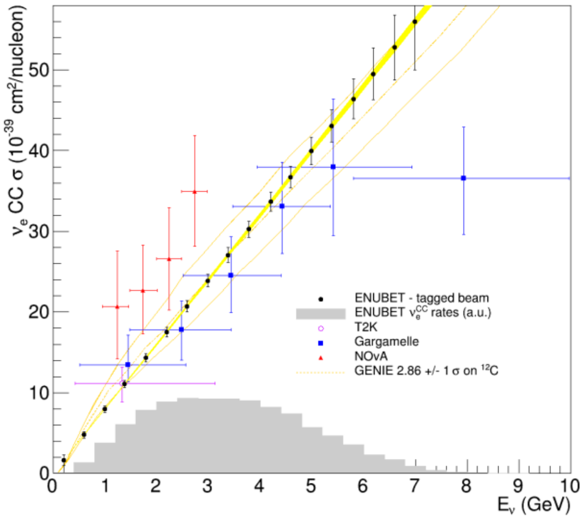
Who cares? No-one… until 2012 ☺

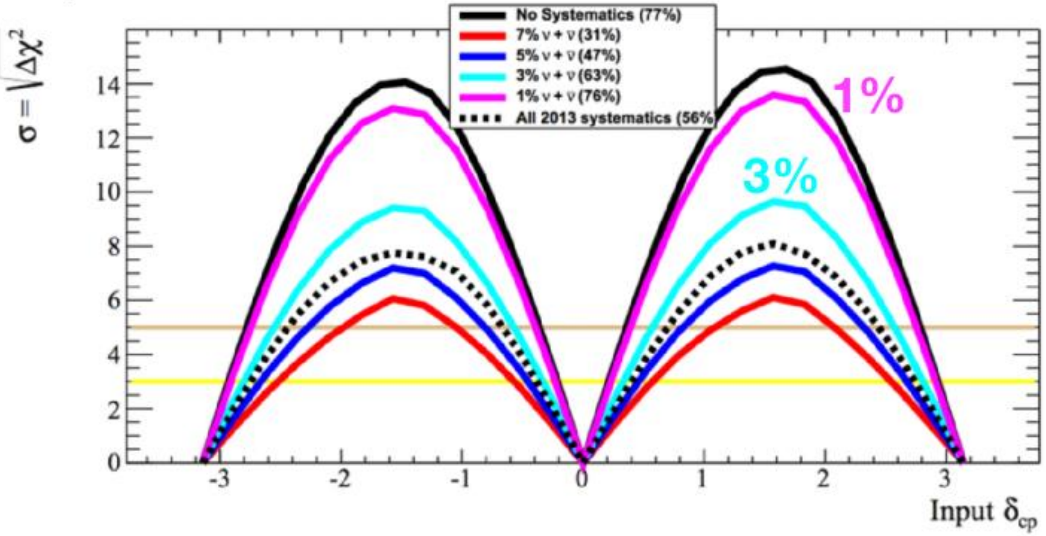
For oscillation studies this can be mitigated by comparison of events at <u>near and far detectors</u> and <u>hadro-production experiments</u>. That was enough in the discovery era of neutrino oscillation physics



The discovery of a large mixing between ν_μ and ν_e at the atmospheric neutrino scale (large θ_{13}) opened up the precision era of neutrino oscillation physics and boosted a global billion$ programme in US (DUNE, SBL), Japan (HK, T2K-II), China (JUNO) and Europe (CERN Neutrino Platform).

It comes to no surprise that the physics reach of these facilities is completely dominated by source-related systematics



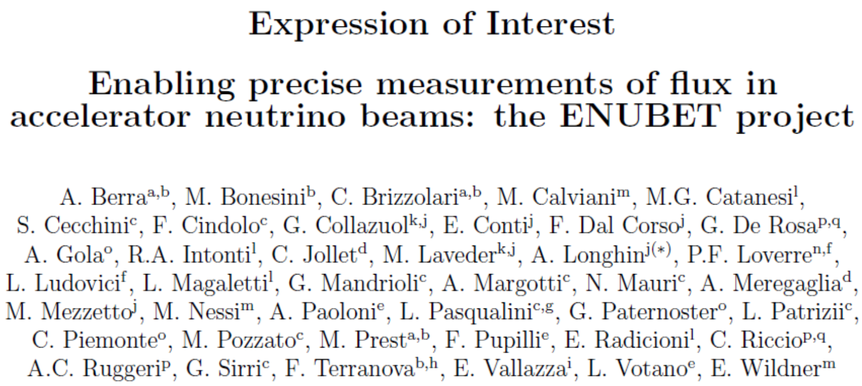


The ENUBET Project

- ✓ Enable a new technology for accelerator neutrino beams: monitor neutrino production in the decay tunnel **at the single particle level**
- ✓ In particular, monitor e^+ production in a beam where ν_e are only originated by $K^+ \to \pi^0 e^+ \nu_e$ $\Rightarrow$ **a pure ν_e source whose flux is known at the 1% level**

ENUBET is a project approved by the European Research Council (ERC) for a 5 year duration (Jun 2016 – May 2021) with an overall budget of 2 Meuro.

Grant: ERC Consolidator Grant, 2015 (PE2)
Principal Investigator: Andrea Longhin
Host Institution: INFN
Collaboration: 41 physicists from 10 institutions



Expression of Interest

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

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]

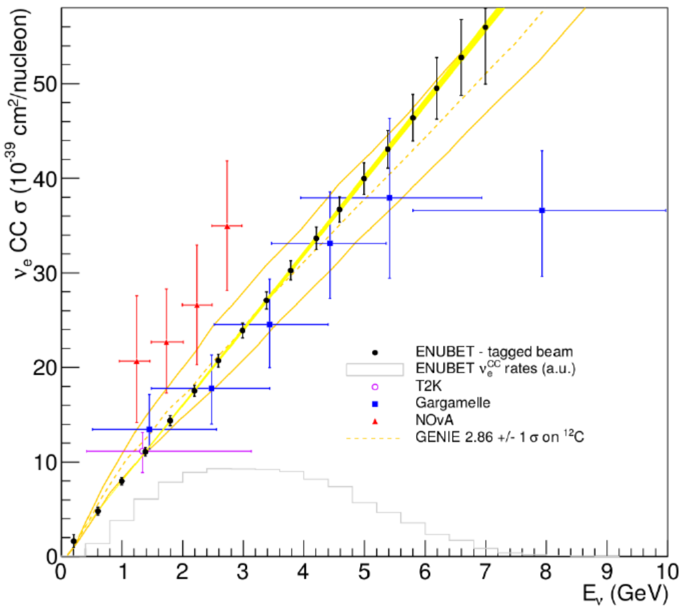
See CERN-SPSC-2016-036: SPSC-EOI-014 for details

European Research Council
Established by the European Commission

A very timely R&D

This is **just the right time** to go beyond the standard paradigm (**ENUBET, NuSTORM, NuPIL** etc.). The ENUBET technology is well suited for short baseline experiment where the intensity requirement are less stringent. There are **three major applications ENUBET can enable**:

- a new generation of cross section experiments operating with a neutrino source that is controlled at the <1% level. This is the main aim of ENUBET as funded by ERC.
- a phase II sterile neutrino search, especially in case of positive signal from the Fermilab short baseline program
- The first step toward a tagged neutrino beam where the ν_e CC interaction at the detector is time-correlated with the observation of the lepton in the decay tunnel

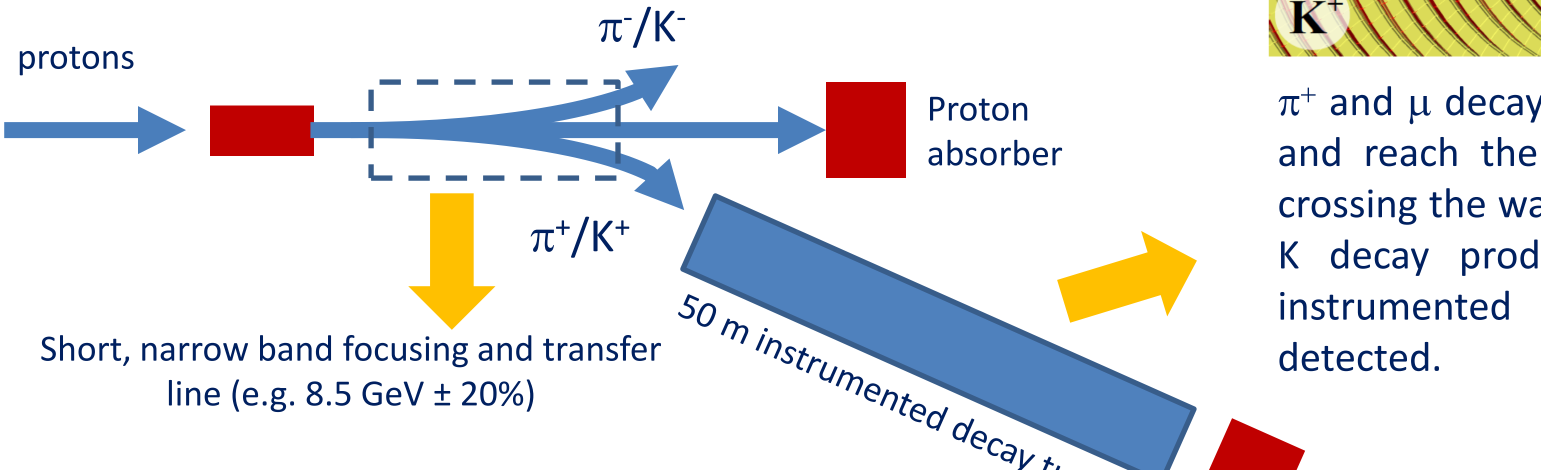


Impact on ν_e cross section measurement assuming the parameters of EPJ C75 (2015) 115 (see below)

A pure ν_e source from K decays

Enhanced NeUtrino BEams from kaon Tagging

Inspired by the “**tagged neutrino beam**” concept [Hand, 1969; Pontecorvo, 1979, Denisov, 1981; Bernstein, 1989; Ludovici, Zucchelli, 1999; Ludovici, Terranova, 2010] and by the design of **nuSTORM** and **nuPIL**



protons

π^-/K^-

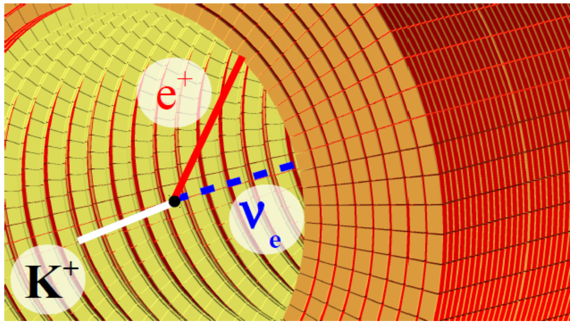
Proton absorber

π^+/K^+

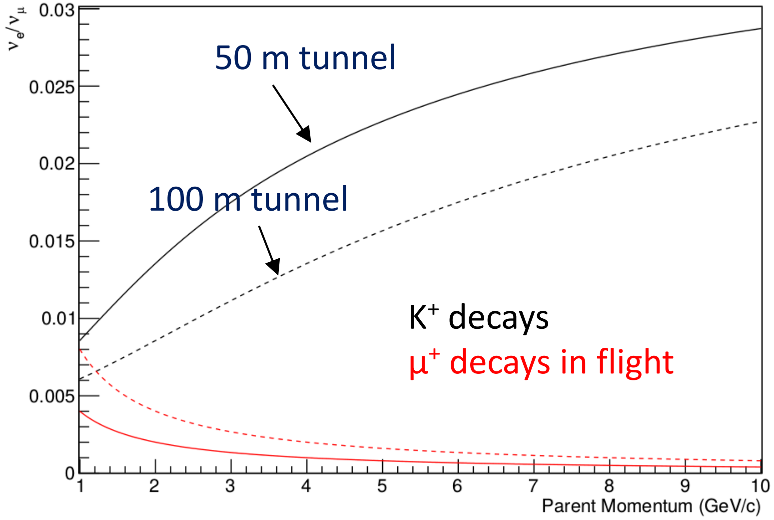
Short, narrow band focusing and transfer line (e.g. 8.5 GeV ± 20%)

50 m instrumented decay tunnel

Hadron dump



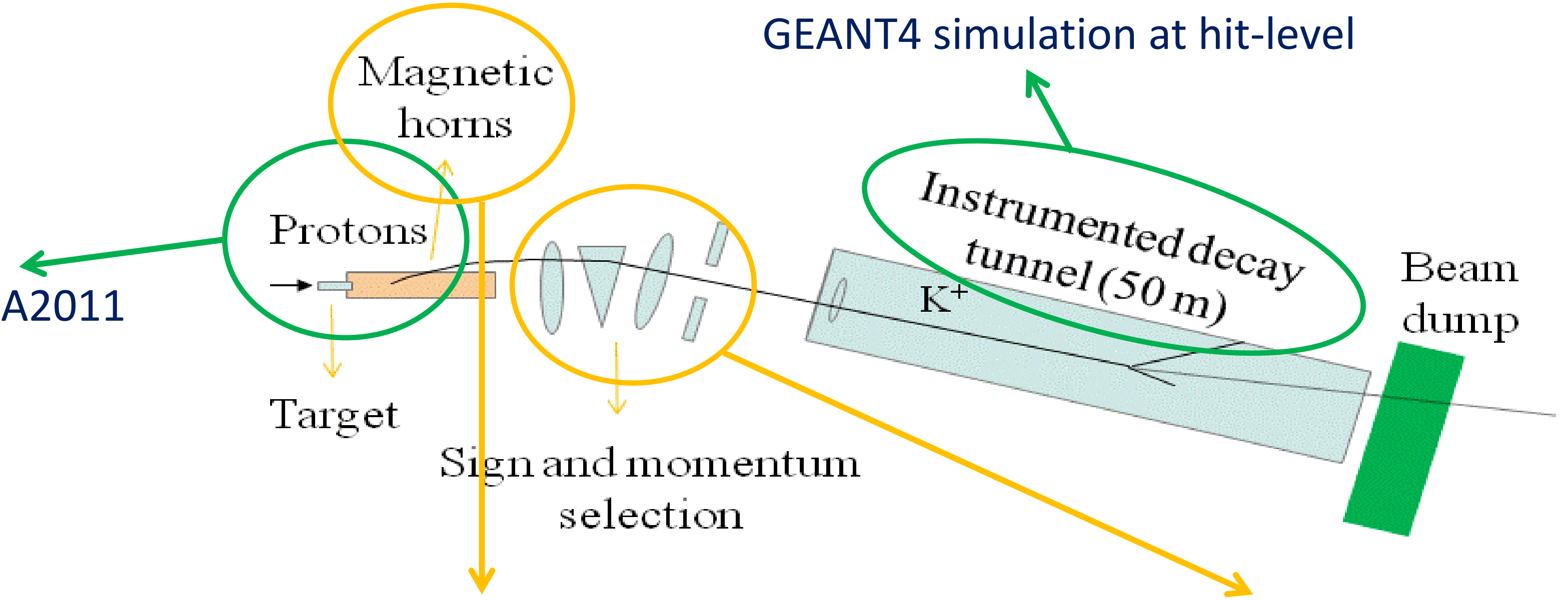
π^+ and μ decay at small angles and reach the dump without crossing the wall of the tunnel. K decay products cross the instrumented walls and are detected.



Since the decay tunnel is short and the secondary momentum is 8.5 GeV, 97% of the ν_e are from K decay.

the e^+ rate is a direct measurement of the ν_e flux

Before ENUBET: the SCENTT R&D and the Reference Design



GEANT4 simulation at hit-level

FLUKA2011

Assuming 85% efficiency for secondaries inside the ellipse $\varepsilon_{xx'}=\varepsilon_{yy'}=0.15$ mm rad in the (x,x',y,y') phase space

Assuming 20% momentum bite at 8.5 GeV and flux reduction due to decay (15 m).

Tunnel instrumentation mostly based on calorimetric techniques (SCENTT: longitudinally segmented shashlik calorimeters)

A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155, NIM A824 (2016) 693; A. Berra et al., NIM A830 (2016) 345, A. Berra et al., NuFact15 Proceedings, arXiv:1512.08202 etc.

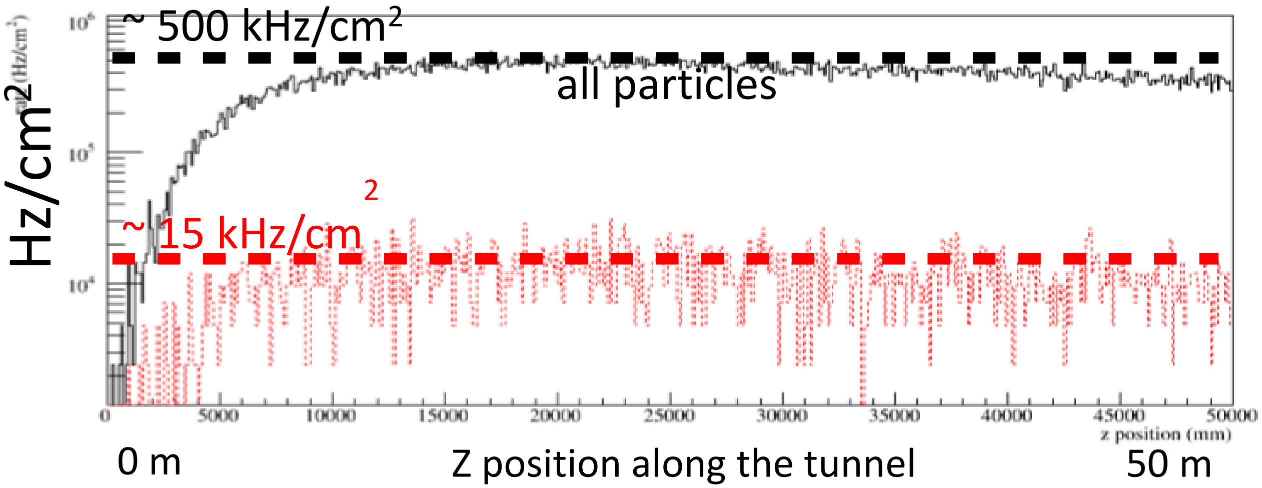
Reference parameters: **500 ton neutrino detector**(*) at 100 m from the entrance of the tunnel. How many protons-on-target are needed to observe 10^4 ν_e CC events in the detector (1% statistical uncertainty on cross section)?

(*) e.g. ICARUS@Fermilab, Protodune SP/DP @CERN

	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})
JPARC	30	4.0	0.39	2.5	5.0
Protvino	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
Fermilab	120	16.6	1.69	0.60	1.16
CERN-SPS	450	33.5	3.73	0.30	0.52

For 10^{10} π^+ in a 2 ms spill at the entrance of the tunnel **rates are well below 1 MHz/cm²**

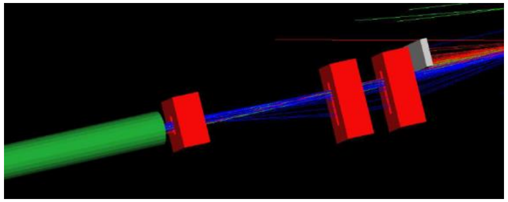
Positron identification based on calorimetric techniques S/N ratio >6



See below for details

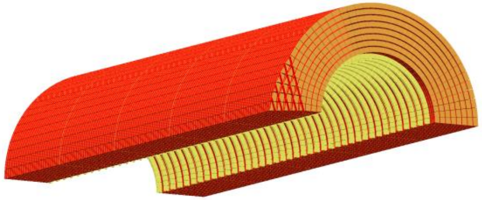
The deliverables of ENUBET

- Conceptual design of the beamline



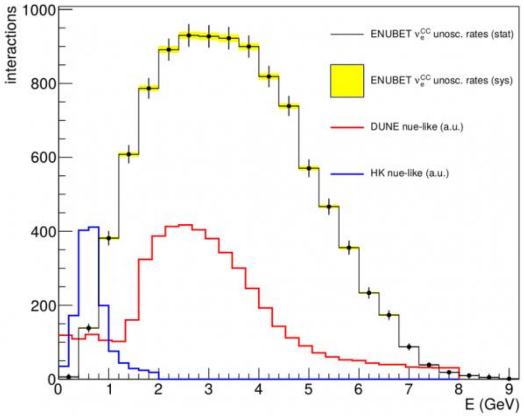
WP1,5

- Construction of a 3 m section of the instrumented decay tunnel (~10% of the actual instrumentation)



WP2,3,4

- Assessment of physics potential (systematics reduction)



WP5

Tests at PS-T9, LNL

Tests at LNL, LNF

Tests at PS-T9, EHN1

LHC LS2

Jun 2016

Prototyping (WG2,3,4)

SPS-based Design (WG1,5)

Dec 2018

Review of the Design

Jun 2021

Demonstrator (WG2,2,4)

FInal Design (WG1-5)

Work Packages (WP)

PI A. Longhin

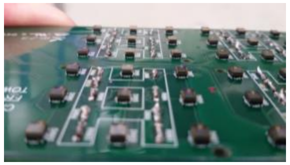
WP1 **Conceptual design of the beamline** see below

WP2 **Design and prototyping of the positron taggers**

WP coordinator: M. Pozzato

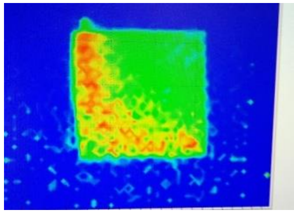
WP3 **SiPM and front-end electronics for the instrumented decay tunnel**

WP coordinator: V. Mascagna



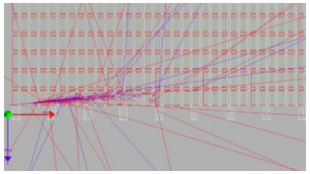
WP4 **Design and prototyping of the photon veto (e/γ separation)**

WP coordinator: G. Sirri

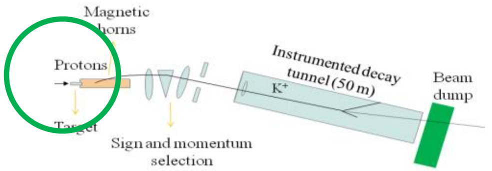


WP5 **Simulation and assessment of the systematics**

WP coordinator: A. Meregaglia

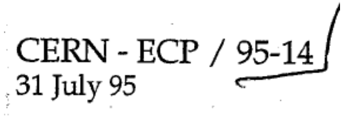


Proton extraction schemes



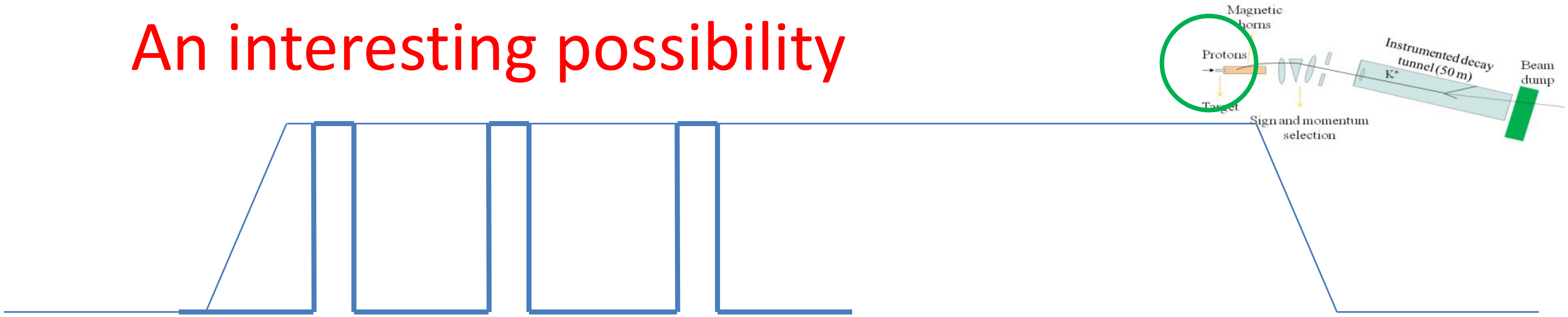
At SPS, 5 10^{19} pot must be accumulated to perform a ν_e cross section measurement at 1% (about 1 year of CNGS) but the extraction scheme must be compatible with the maximum sustainable rates in the tunnel:

$\boxed{\approx 1.5\ 10^{11}\ \text{pot/ms}}$

Fast extractions (few μs) [e.g. CNGS]	**Not compatible** (rates at GHz/cm^2)	Interesting for options like NuPIL(*) (BCT in the transfer line) but, currently, not in the ENUBET scope
WANF-like extractions (few ms)  CERN - ECP / 95-14 31 July 95	**Compatible** with both rates and the use of horns	Baseline option for ENUBET
Slow extractions (>100 ms) [e.g. SHIP]	**Excellent** for rates but **not compatible** with horns	Very interesting option for ENUBET if a **static focusing system** can be devised

(*) J.B. Lagrange et al., FERMILAB-CONF-16-160-AD

An interesting possibility

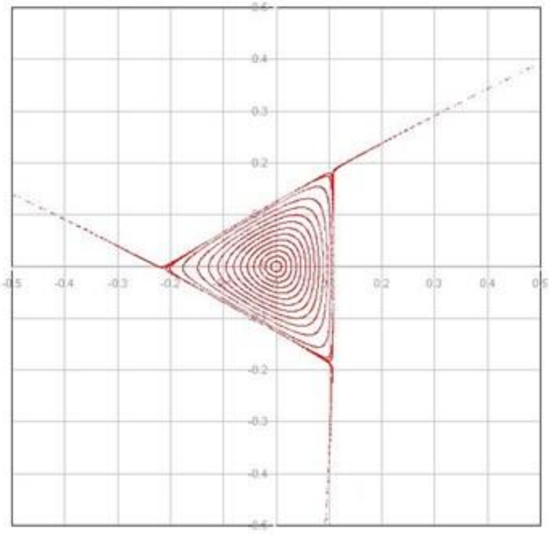


Deplete the SPS using “slow” (2-10 ms) resonant extractions repeated at multi-Hz rate during the flat top.

Example: 6 ms (WANF) extractions (9 10^{11} pot/6 ms) at 10 Hz provide about 1.8 10^{13} per supercycle for a 2s flat top. It completely depletes the SPS (4 10^{13} pot per supercycle) for a 4.4 s flat top.

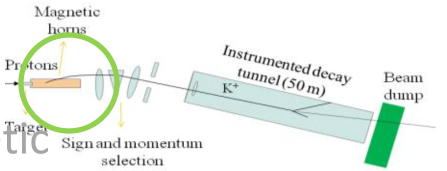
Interesting (not only for ENUBET) but non conventional:

- ✓ Can we extract these protons employing a slow (thousand turns) resonant extraction?
- ✓ Can we cross the 3rd order resonance at the sought-for rate (multi-Hz)
- ✓ Are losses tolerable?



This is a possibility that we’d like to investigate in collaboration with CERN (TE-ABT)

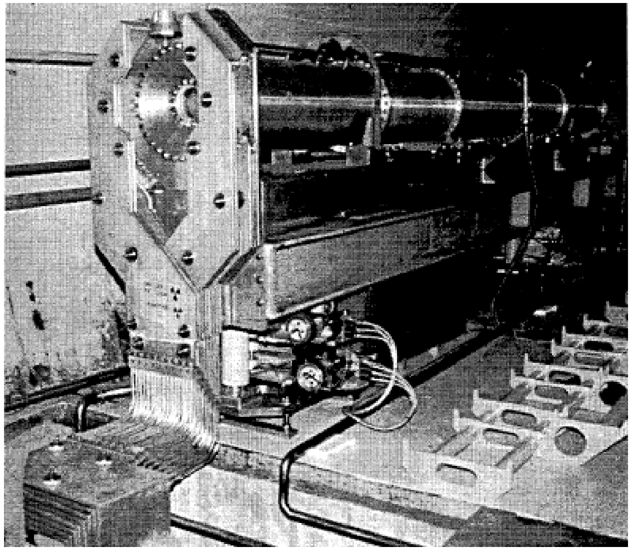
Horn



The main advantage of ms extraction is the possibility to employ magnetic horns in the beamline as envisaged in projects that employ sign selection and transfer lines similar to the one of ENUBET (NuSTORM and NuPIL).

Again, there are specific issues that have to be investigated:

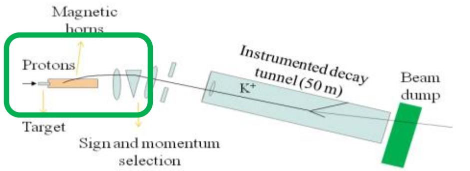
- ✓ What it is optimal pulse length and rep. rate at the flat top accounting both for the engineering constraints (mostly Joule heating) and the maximum tolerable rate at the instrumented decay tunnel?
- ✓ Compatibility between the proton extraction scheme and the thermo-mechanical properties of the horns



WANF horn
(max 0.4 Hz, 120 kA, 6 ms proton pulse)

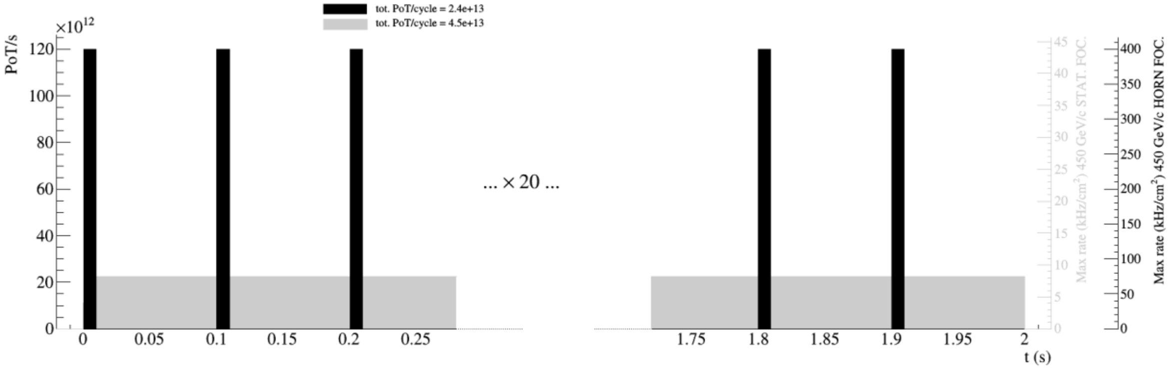
MiniBooNE horn
(max 15 Hz, 170 kA, 0.2ms proton pulse)

Slow extraction schemes and static focusing systems

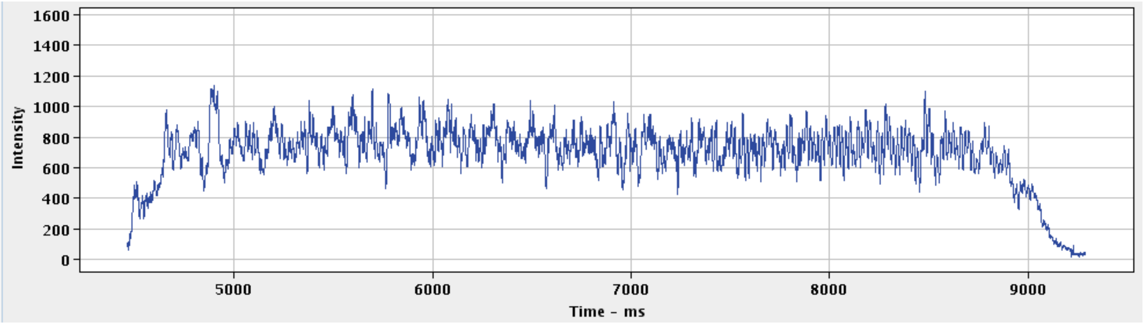


Quad-based focusing systems come to the expense of a strong flux reduction, especially for low energy, high intensity beams. For short-baseline experiments (ENUBET) this is still tolerable (up to a factor 2-3) and bring major advantages:

Decrease by one order of magnitude the particle rate in the instrumented tunnel



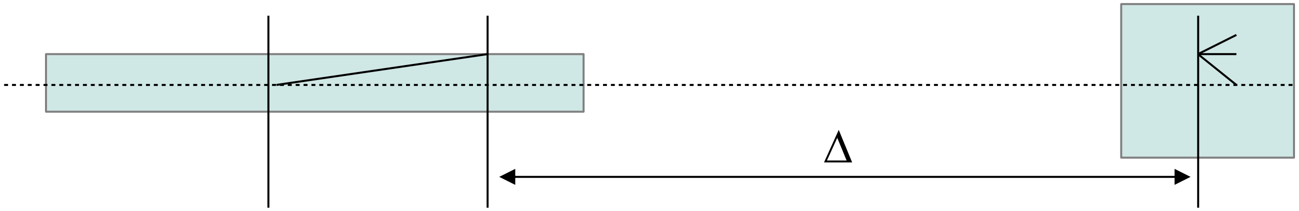
Allows for the implementation of more conventional slow resonant extraction schemes (1-4 s)



This is an option that will be investigated with great care in ENUBET because…

Tagged neutrino beams

Time coincidence between the ν_e CC and the positron: $|\delta t-\Delta/c| < \delta$



δt is the difference between the e^+ and the ν_e CC time (≈100 ns).

δ is the linear sum of the timing resolutions of the e^+ tagger and neutrino detector

Time correlation between can work **if we can beat the number of accidentals:**

$$\mathcal{A} \equiv \left[N_K \cdot \mathrm{BR}(K_{e3})(1-e^{-\frac{\gamma_K c\tau_K}{L}})\epsilon + \mathrm{bkg} \right] \cdot \delta \simeq 2\times 10^7 \frac{\delta}{T_{extr}}$$

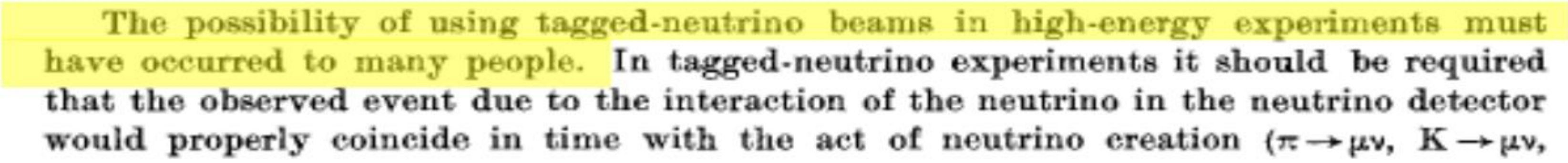
positron rate per extraction

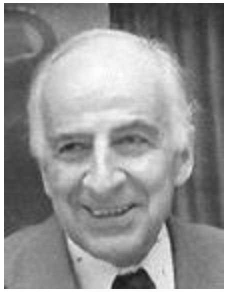
fake e^+ per extraction

extraction time

If T_{extr} = 2 ms we have one positron every 70 ps. δ is unrealistically small. As a consequence, a double tag facility must be operated with **long extraction (1 s)** as it was the "Tagged Neutrino facility" developed in USSR in the 80's.

For T_{extr}= 1s (1 observed e^+ every 30 ns) and δ = 1 ns → A = 2%


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 ($\pi\to\mu\nu$, $K\to\mu\nu$,



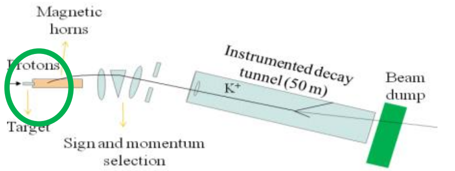
B. Pontecorvo, Lett. Nuovo Cimento, 25 (1979) 257

Tagged beams: the holy grail of ν physics

- Know the flavor of the observed neutrino before it changes due to oscillation
- Reconstruct the energy of every single neutrino by the kinematics reconstruction in the decay tunnel

The proton extraction time must be ~1s	Cannot use any more the horns. Must rely on static systems → reduction of acceptance
The time resolution of the tag must be <1 ns	OK
The time resolution of the neutrino detector must be ~1 ns	Feasible and strongly synergic with current R&D's
The cosmic background increases by x10 [i.e. by $A \times$ (1s)/(2 ms)]	Comparable to what have to be dealt by ICARUS@Fermilab
The momentum bite of the K^+ must be small enough not to limit the ν_e energy reconstruction	A 20% energy resolution for ν on event by event basis would be a major breakthrough
Time synchronization between the tagger and the detector $\ll$1 ns	OK [direct optical link at short baselines]

Target



Formally, the ENUBET beamline is a O(100 kW) mean power conventional narrow-band neutrino beam.

Maximum conceivable	at SPS
Proton energy:	400 GeV
Nominal flat top:	4.8 s
Repetition rate:	15 s (0.07 Hz)
Protons per cycle:	4.5 10^{13}
Average beam power	192 kW
Power during flat top	600 kW
Pot/y (200 day livetime)	5.2 10^{19} pot/y

(physics programme in 1 y of data taking)

CNGS target
design average beam power: 750 kW

ENUBET early calculations

Be target, 110 cm length, 3 mm diameter

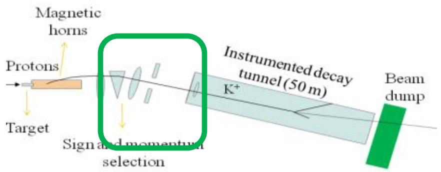
In progress

Graphite target (NuMI-like)

Other options

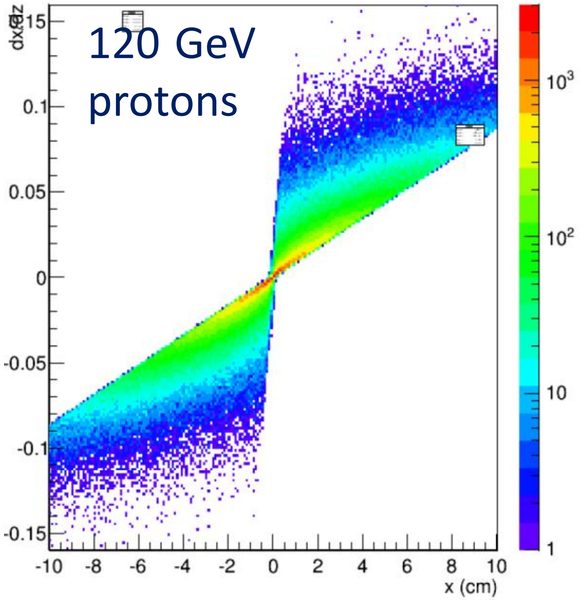
CNGS-like; INCONEL

Transfer line



This is a **key part of the Project** because the transfer line determines:

Source	Expectation
The K yield at the entrance of the tunnel	20% reduction for 15 m
The contamination due to neutral and off momentum particles	Bending >5deg
The quality of the beam at the entrance of the tunnel	10x10 cm^2 with angle <3 mrad
The beam related background	Halo muons (not critical) and debris from collimators



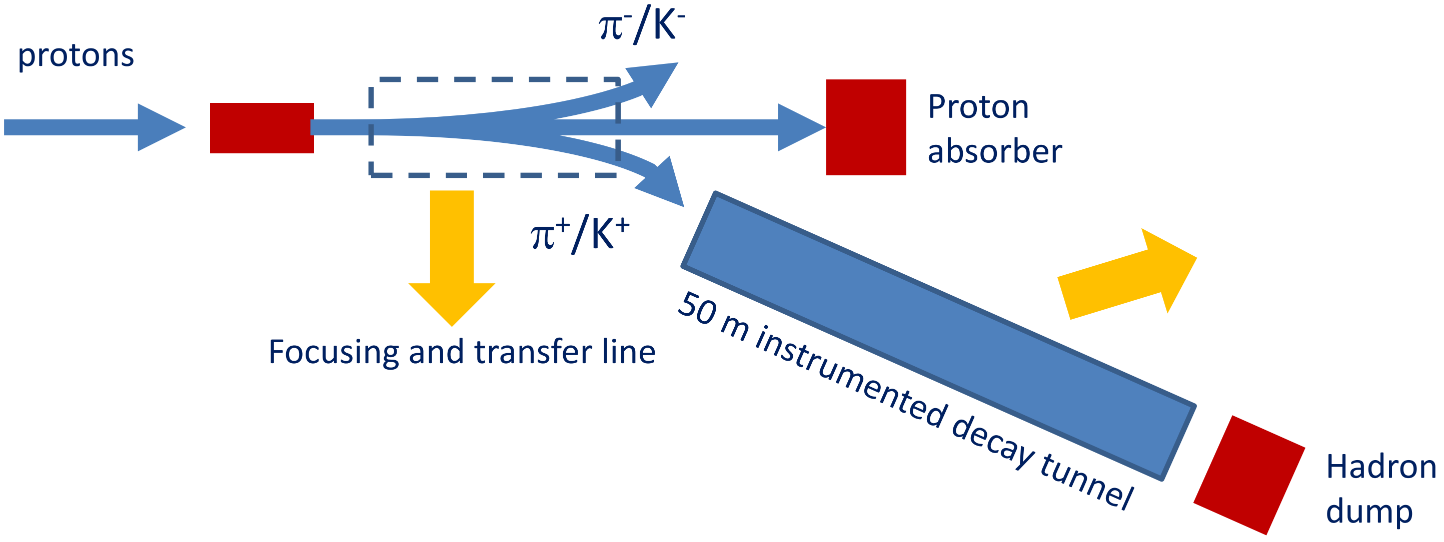
Acceptance of the transfer line matched with the geometry of the decay tunnel

$$A = 4 \times (5\,\mathrm{cm}) \times (3\,\mathrm{mrad}) =$$
$$4\epsilon_{xx'} = 4\epsilon_{yy'} = 0.60\,\mathrm{mm\,rad}$$
$$\epsilon_{xx'} = \epsilon_{yy'} = 0.15\,\mathrm{mm\,rad}$$

$\Rightarrow$a narrow band beam configuration

Full simulation (G4beamline) is ongoing

Proton absorber and hadron dumps



Both are necessary in a narrow band beam configuration. These are conventional facilities but relevant for ENUBET for the following reasons:

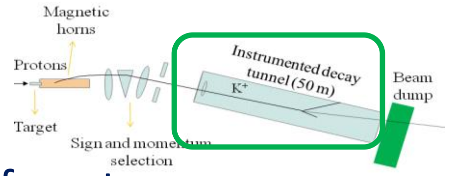
Proton absorber:

Large power (tens of kW)
Shielding and hence, cost assessment of the implementations

Hadron dump:

Low power (<0.5 kW)
Activation and thermal behaviour of the tunnel (relevant for instrumentation)

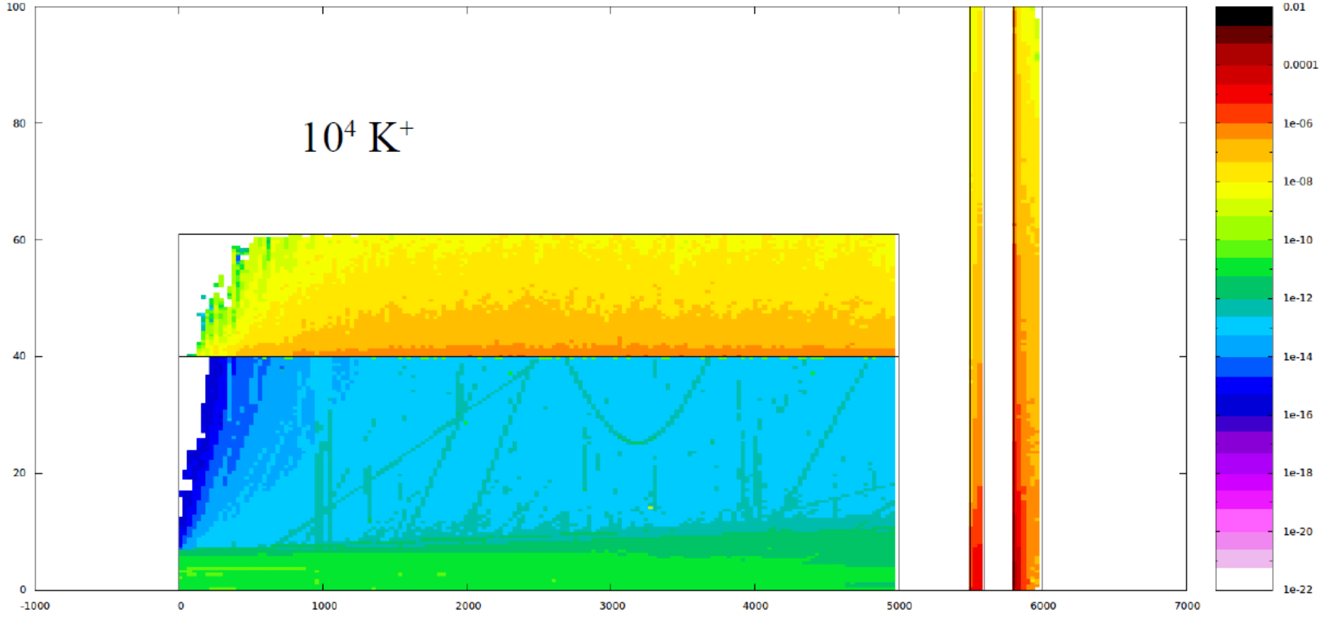
Instrumented decay tunnel



A too harsh environment in conventional wide band beam. Here it is different:

- the tunnel is located after a narrow band transfer line
- the instrumentation is located in the peripheral area of the tunnel

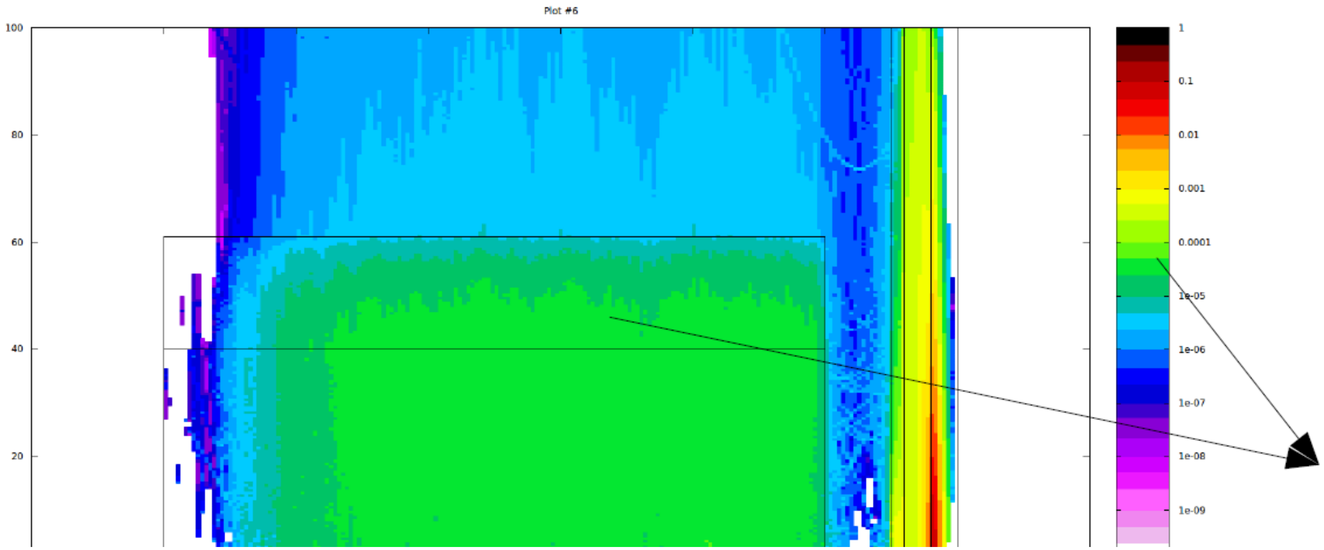
Ionizing and non-ionizin doses evaluated with Fluka2011 assuming instrumentation located at 40 cm from the tunnel axis. Entrance windows 10x10 cm^2, <1 mbar pressure in the tunnel.



Dose at the tagger at the end of the experiment: 7 kGy (0.7 Mrad)
It allows even use of Fe-plastic calorimeters (Compass – SHIP)

Neutron fluence and non-ionizing doses

10^4 K^+



~5e-5 n/cm^2/primary

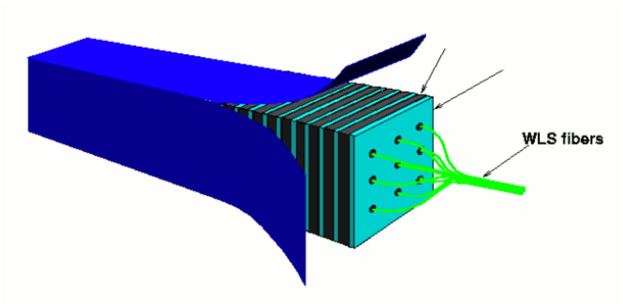
Non ionizing dose at the end of the experiment: ≈ 3 10^{12} 1-MeV-equivalent n/cm^2

Not critical for sampling calorimeter but significant for solid-state photosensors (e.g. SiPM). Two options:

- Scintillation light transported in the proximity of the photosensors with WLS fibers: safe but rather cumbersome
- Use SiPM developed e.g. for CMS hadron calorimeter upgrade (fluence >10^{12} n/cm2)

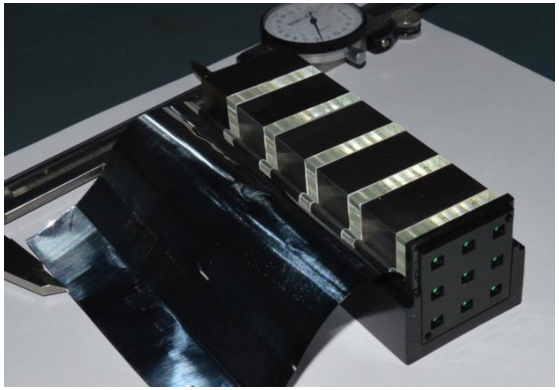
The most elegant solution

Longitudinally segmented shashlik calorimeter with embedded SiPM
INFN SCENTT R&D



Cheap, fast (<10 ns), rad-hard

e^+/π^+ separation needs longitudinal segmentation

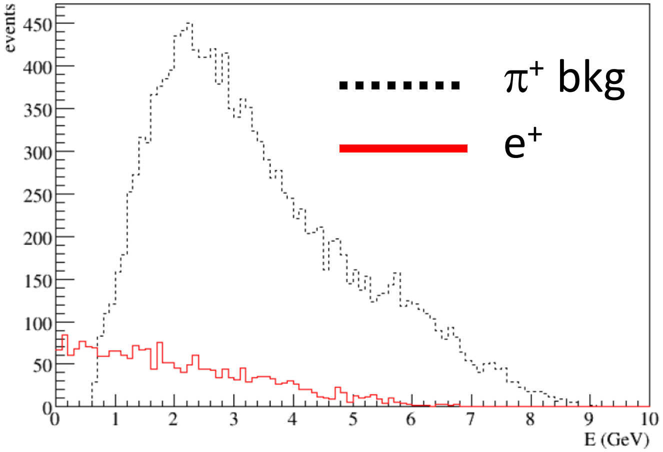


One SiPM for each fiber in the back of each module. Summed signals (9 SiPM per ADC) to reduce cost

Requirements for ENUBET:

- mip sensitivity but no saturation for e.m. showers up to 4 GeV — done
- energy resolution <25%/$E^{1/2}$ — done
- recovery time ~10 ns
- validation of MC for e/π separation

→ nov 2016



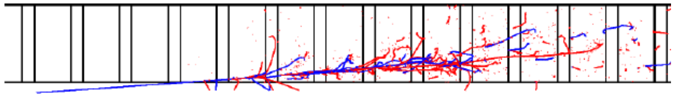
Particle identification in the decay tunnel

Within WP5 activities.

Full GEANT4 simulation of the baseline detector of choice for the instrumented tunnel

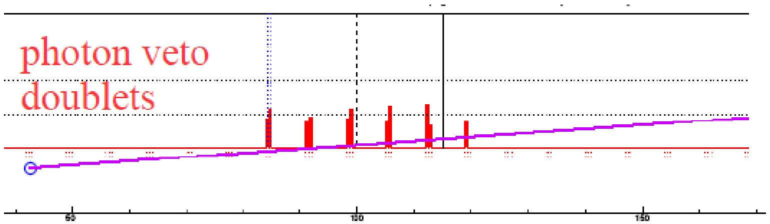
$e^+/\pi^+/\mu$ separation

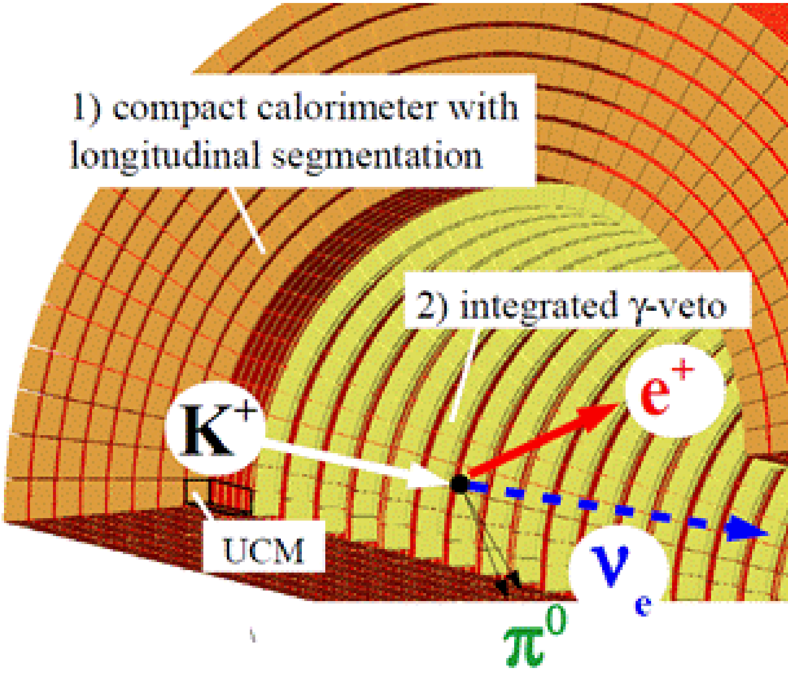
(1) Compact shashlik calorimeter (3x3x10 cm^2 Fe+scint. modules + energy catcher) with longitudinal (4 X_0) segmentation and SiPM embedded in the bulk of the calorimeter (see below)



e^+/γ separation

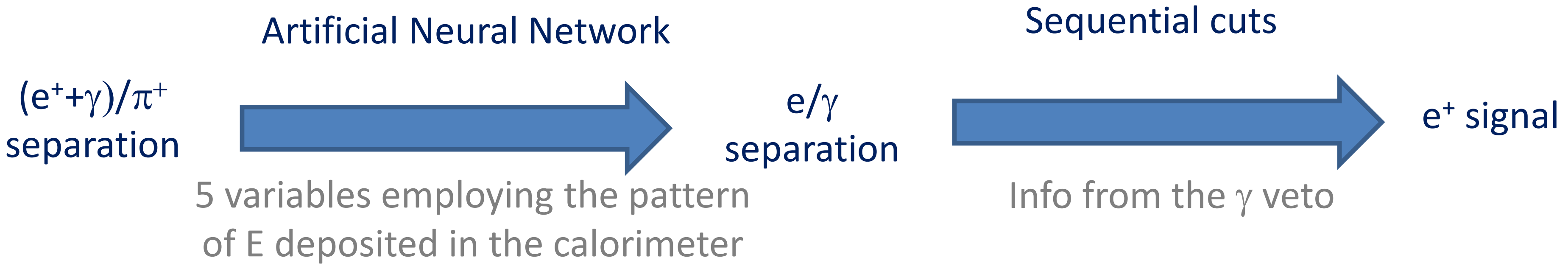
(2) Rings of 3 x 3 cm^2 pads of plastic scintillator





WP5 new results (summer 2016)

The identification algorithms separate positrons from charged and neutral pions combining info from the calorimeter modules and γ veto. Clustering and event building is limited to neighboring modules to avoid pile-up effects and mismatch due to time resolution



Artificial Neural Network

$(e^+ + \gamma)/\pi^+$ separation

5 variables employing the pattern of E deposited in the calorimeter

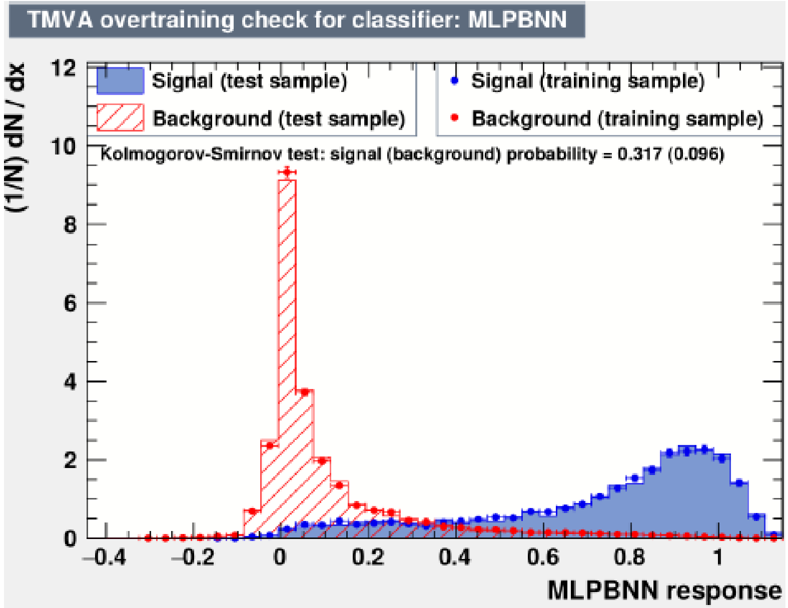
e/γ separation

Sequential cuts

Info from the γ veto

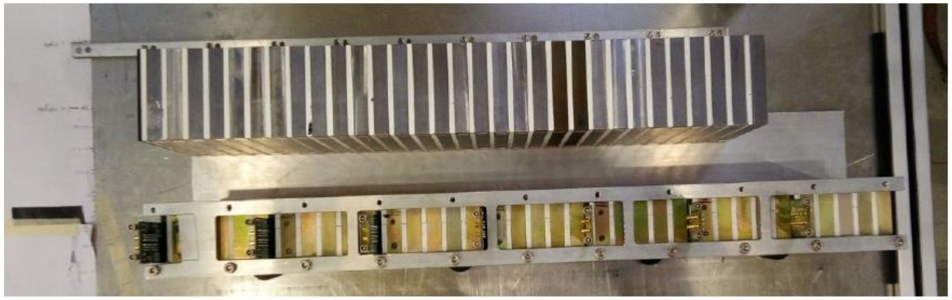
e^+ signal

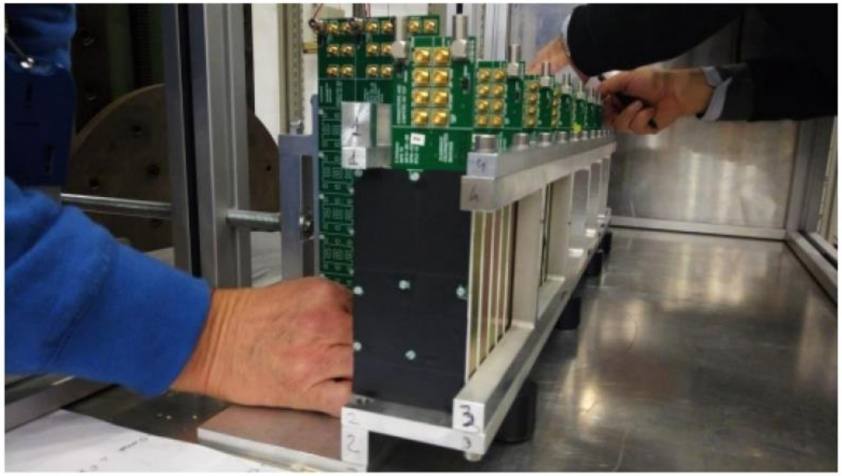
	ε_{geom}	ε_{sel}
e^+	90.7 %	49.0 %
π^+	85.7 %	2.9 %
π^0	95.1 %	1.2 %

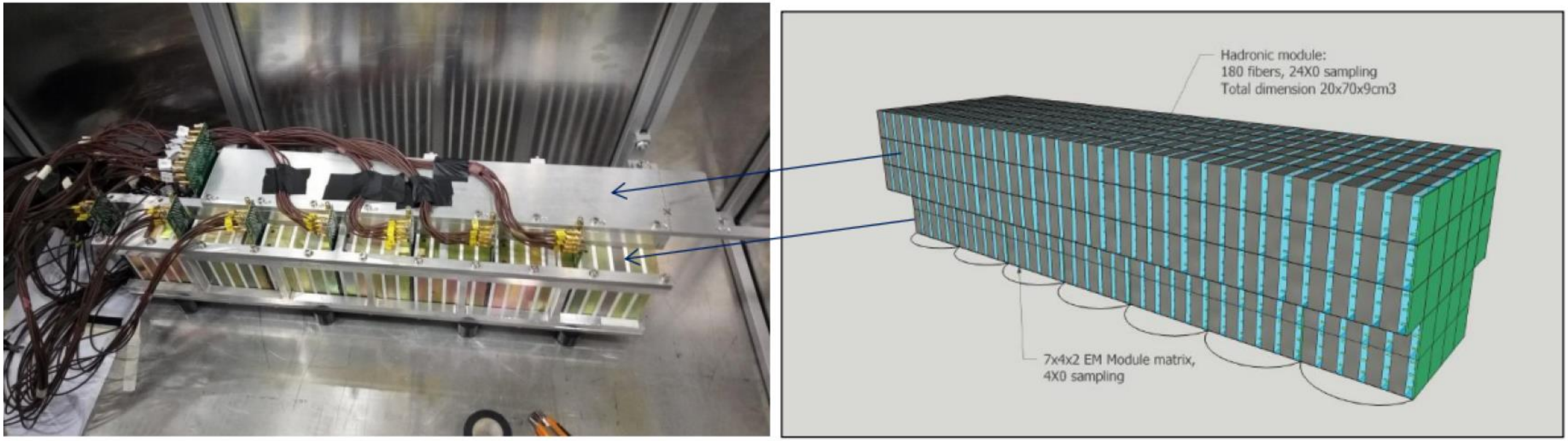


Confirm early results from fast simulation but with a **realistic** and **very cost-effective** setup!

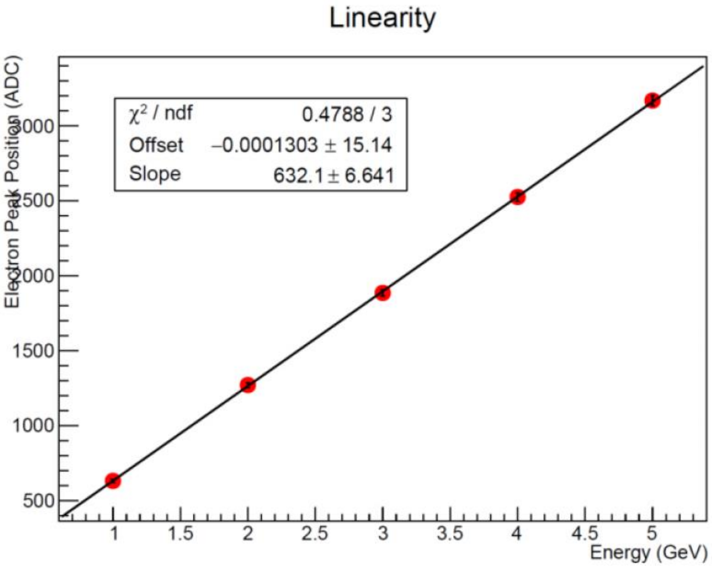
Validation at CERN East Area (T9)

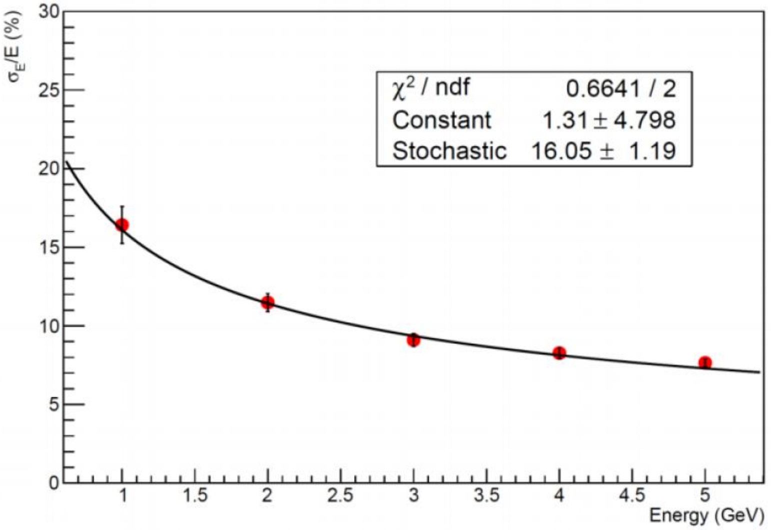






Preliminary results





Data analysis is ongoing (final results in Spring 2017)

Testbeam programme before LS2

Jan 2017

Irradiation at LNL

Hard-rad SiPM modules at T10

Jan 2018

Physics performance with custom digitizers

Ultra compact module

Dec 2018

Demonstrator design validation

Systematics on the flux

Source of uncertainties	**Size and mitigation**
Statistical error	<1%
kaon production yield	**irrelevant (positron tag)**
uncertainty on integrated pot	**irrelevant (positron tag)**
geometrical efficiency	<0.5%
uncertainty on 3-body kinematics and mass	<0.1%
uncertainty on the ν_e contam. from μ DIF	<0.5%
secondary beam phase space at the entrance of decay tunnel	**can be checked directly with low intensity pion runs**
uncertainty on Branching Ratios	**irrelevant (positron tag)** except for background estimation (<0.1%)
e/π^+ separation and detector stability	**can be checked directly at test-beams**

WP1,5

WP2,5

The claim of <1% uncertainty is very likely but has to be firmly grounded if ENUBET has to become the standard flux monitoring technique for short baseline neutrino beams.

Conclusions

- The precision era of neutrino oscillation physics requires better control of its artificial sources. At the GeV scale the limited knowledge of the initial flux is **the dominant contribution to cross section uncertainties**
- Such limit **can be reduced by one order of magnitude exploiting the $K^+ \rightarrow \pi^0 e^+ \nu_e$ channel (K_{e3})**
- 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 technological challenges of this approach are very interesting for accelerator and detector science. For instance:
  - Non conventional extraction schemes (CERN TE-ABT)
  - Focusing, target and beam dump (CERN EN-STI)
  - Transfer Line (CERN EN-EA)
  - Photosensors and instrumentation development (NP3-Plafond)
  - Neutrino physics applications (CERN-EP)

- We hope to enable this technology by 2021 for the next generation of short baseline experiments and – my two cents ☺ - take a step forward beyond the van Der Meer's paradigm.