ENUBET

A. Longhin, Universita` and INFN Padova

Consiglio di Sezione: preventivi 2019
Padova, 9 Luglio 2018

- Reminder: obiettivi scientifici
- Breve resoconto del 2018
- Richieste per il 2019

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 681647).

ENUBET

ENUBET Enhanced NeUtrino BEams from kaon Tagging
(ERC-CoG 2015, 2016-2021)

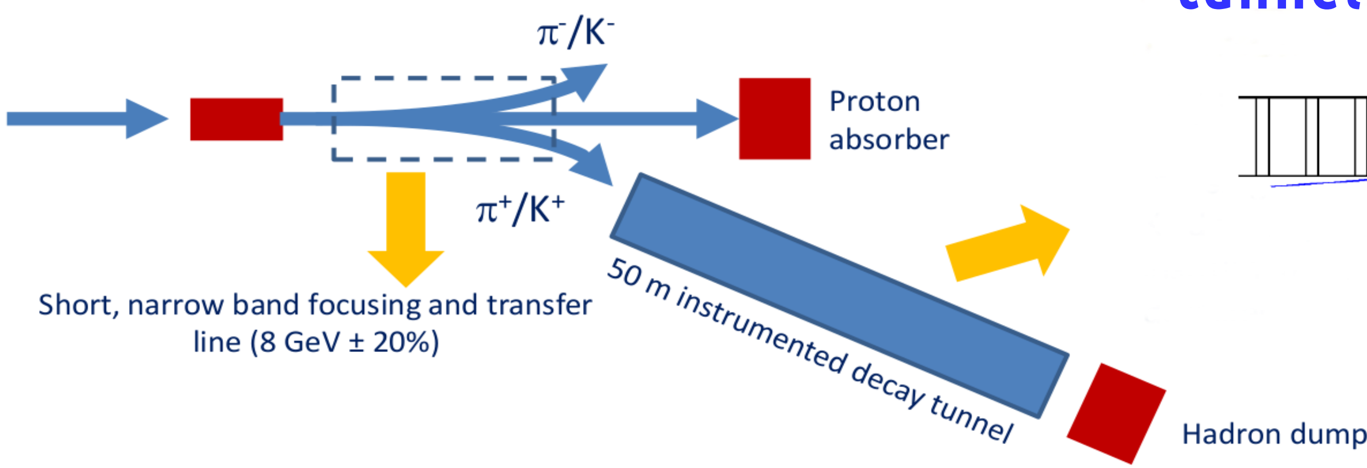
SPSC-EOI-014

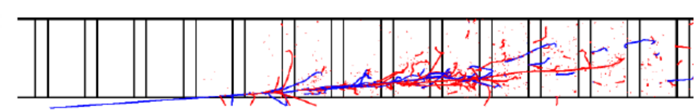
Oct 2016

- **Instrumented decay tunnel**
- **$K^+ \rightarrow e^+ \nu_e \pi^0$** → large angle e^+
- **ν_e flux prediction = e^+ counting**
- **Percent level precision**

1) Design of the hadron beamline

2) R&D for the instrumentation of the decay tunnel





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

Istituto Nazionale di Fisica Nucleare

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

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52 physicists, 11 institutions: CERN, FBK, IN2P3 (CNBG, Bordeaux), INR INFN (Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I)

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

Universita` of Padova, new host inst. since 1/3/2018.
Amendment being finalized.

Attivita` 2018

Un **anno cruciale** per ENUBET visto che è stato l'ultimo anno in cui è stato possibile fare test al CERN-PS (interruzione fino al 2021 dovuta al **Long Shutdown 2**). Prossimo test beam 5 Sett 2018.

- ✓ Full simulation e ottimizzazione della linea di estrazione (WP1)
- ✓ Full simulazione del tagger e algoritmi di ricostruzione con l'input di una linea di estrazione realistica (WP5)
- ✓ Completamento analisi performance SiPM irradiati con neutroni a LNL → ottimizzazione spessore scintillatore per autocalibrazione con mip (WP3)
- ✓ Test su calorimetro con scintillatori in polysiloxane (S. Carturan)
- ✓ Test calorimetro con lettura della luce in modalita` "non shashlik" e photon veto embedded nel calorimetro (CERN-PS Maggio e Settembre 2018) (WP5)

2019: decisione sulla tecnologia e design finale prima della **produzione di massa del rivelatore di ENUBET** (MIB-PD-BO).

ENUBET-Padova

- Il progetto e' **interamente** finanziato da **ERC**
- sigla di supporto in **CSN2 (ENUBET_2)** per piccole spese
  1) non previste nel Grant Agreement (i.e. missioni laureandi, PhD)
  2) inventariabili per cui EU rifonde una frazione del costo corretta per ammortamento a fine progetto (difficile da rendicontare).

http://enubet.pd.infn.it/team.html

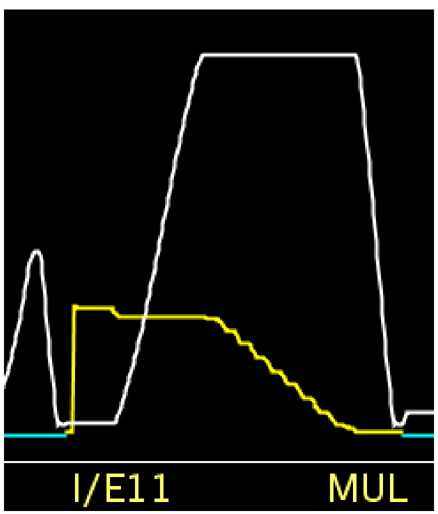
- **Gruppo e anagrafiche:**
  - **EU (time-sheets)**: A. Longhin (70%), F. Pupilli (100% art. 36 ENUBET), G. Brunetti (100% art. 36 ENUBET), G. Collazuol (10%).
  - **ENUBET_2** (% tbc): E. Conti 40%, F. Dal Corso 30%, M. Mezzetto 10%

  M. Pari (70%)
    - **Laurea magistrale** completata: *elettronica per DAQ in triggerless mode*
    - **PhD** in corso con UNIPD (1° anno). Borsa a tema **INFN**. Al CERN per sei mesi come **CERN doctoral student** nel gruppo di B. Goddard, V. Kain, F. Vellotti per approfittare del tempo macchina pre-LS2. *Estrazione dall'SPS in modalita` slow-resonant multi-Hz* (per lo schema di focusing basato su horns magnetici).
      - Primi **machine studies** con l'SPS effettuati la settimana scorsa →

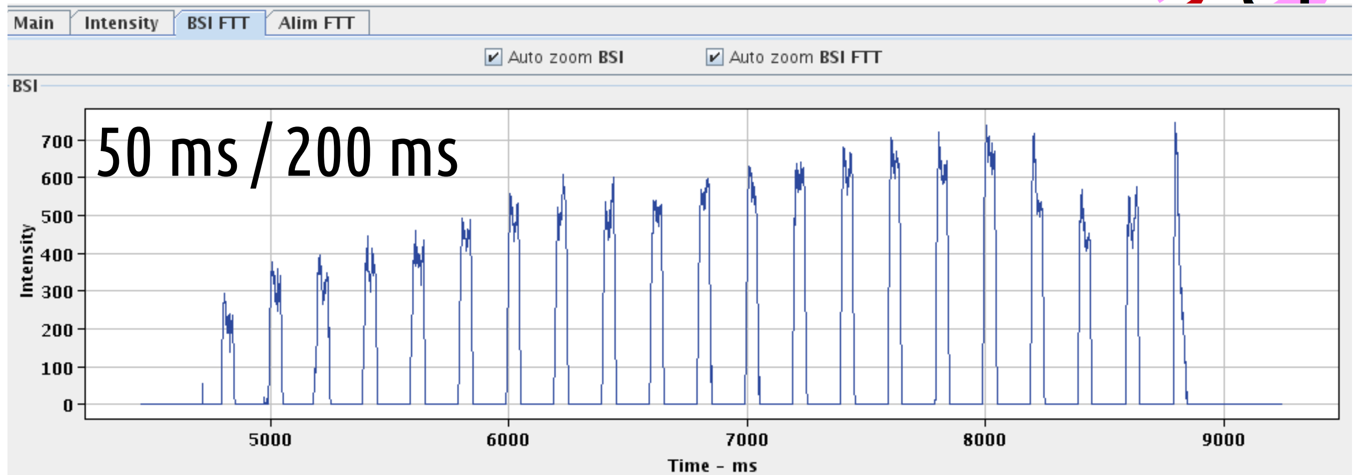
Multi-Hz resonant slow extraction with CERN-SPS

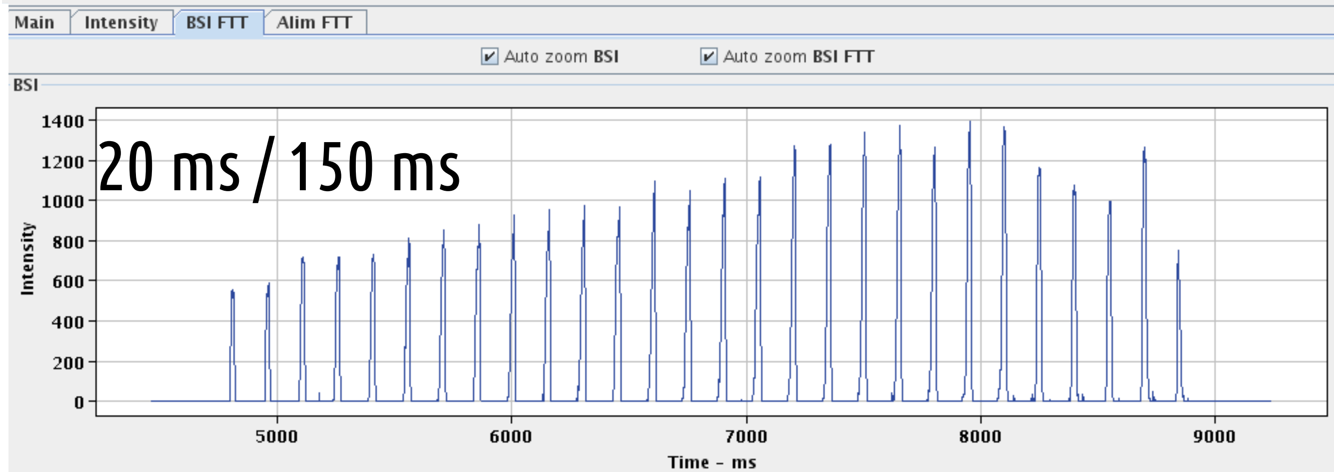
M. Pari
Machine Development of 4 July 2018

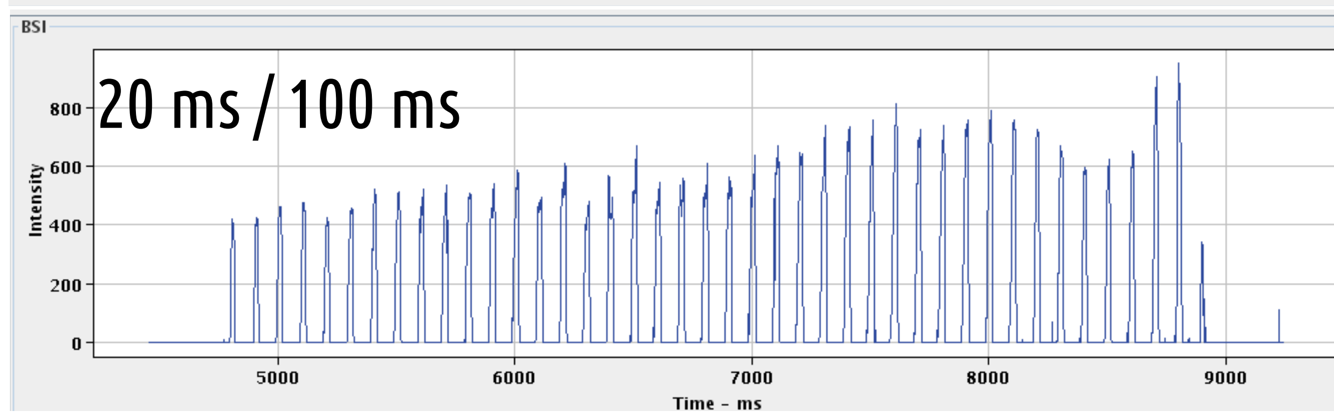
Slow extraction is induced by going to the third integer betatron resonance with a periodic pattern



Proton current

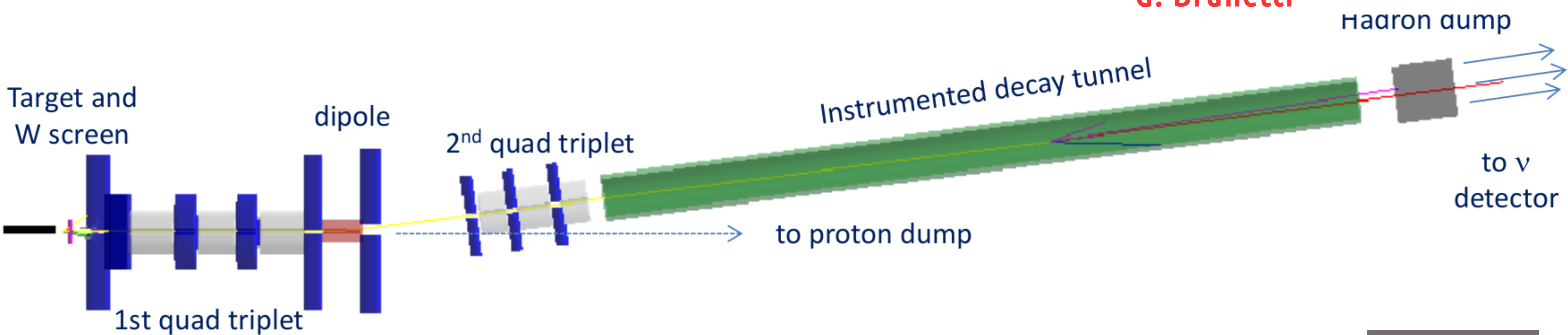






1st end-to-end simulation of the beamline

G. Brunetti



- **Proton driver**: CERN SPS (400 GeV), Fermilab Main Ring (120 GeV), JPARC (30 GeV)
- **Target**: 1 m Be, graphite target. FLUKA 2011 (+check with hadro-production data)
- **Focusing**
  - [Horn: 2 ms pulse, 180 kA, 10 Hz during the flat top] [not shown in figure]
  - Static focusing system: a quadrupole triplet before the bending magnet
- **Transfer line**:
  - Optics: optimized with TRANSPORT to a 10% momentum bite
  - Particle transport and interaction: full simulation with G4Beamline
  - All normal-conducting, numerical aperture <40 cm, Two quadrupole triplet, one bending dipole
- **Decay tunnel**
  - Radius: 1m. Length 40 m [re-optimized after beam envelope determination]
  - Low power hadron dump at the end of the decay tunnel
- **Proton dump**: position and size under optimization (in progress)

art 36 INFN-PD

Positron tagger: simulation and event reconstruction (WP5)

Instrumenting half of the decay tunnel we identify positrons from K decay at single particle level with a S/N ~ 0.5

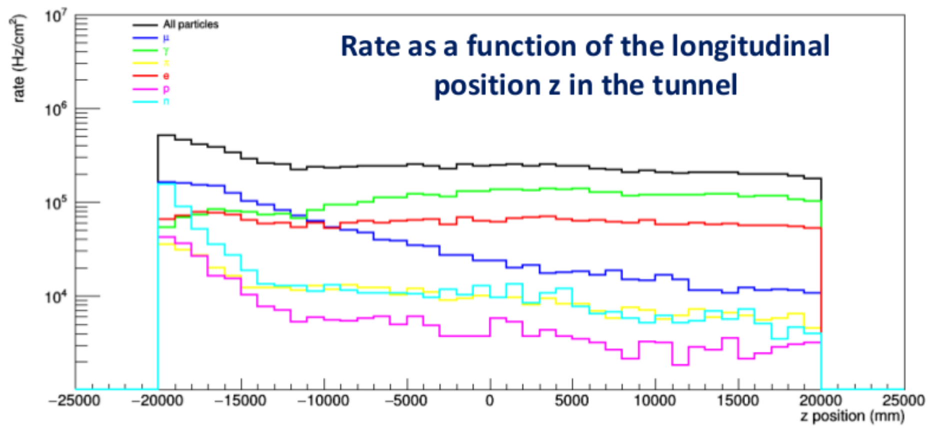
F. Pupilli

art 36 INFN-PD

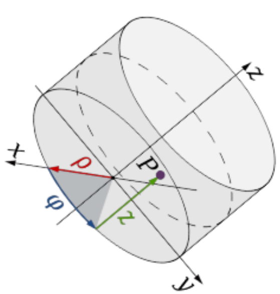
Particles in the decay tunnel

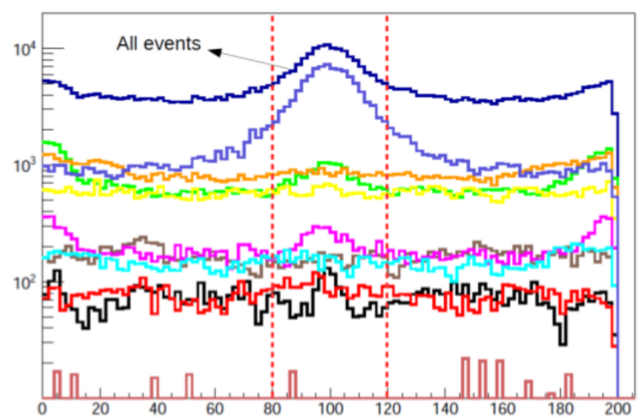
Static focusing system, 4.5 10^{13} pot in 2 s (400 GeV)

Calorimeter 1 m from the axis of the tunnel (ρ_{inner}=1.00 m)
Three radial layers of UCM (ρ_{outer}=1.09 m)

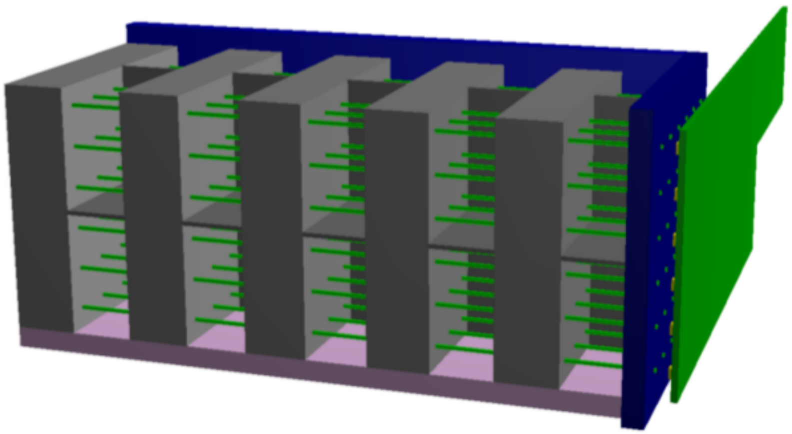


Rate as a function of the azimuthal angle φ in the tunnel

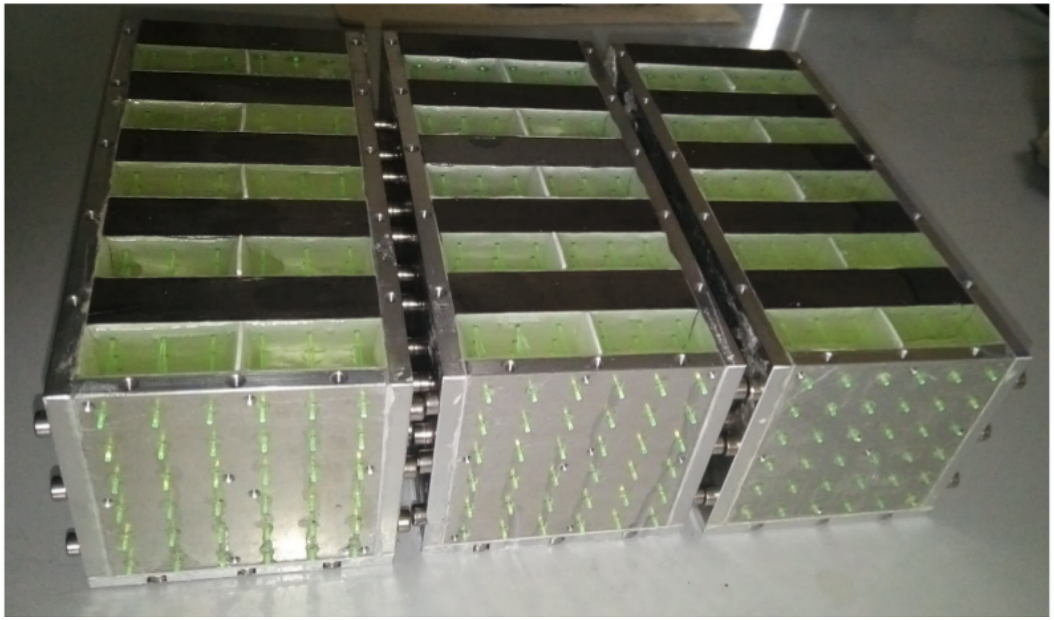


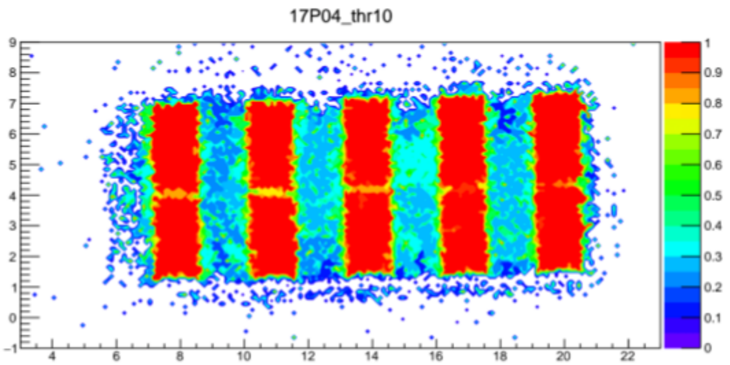


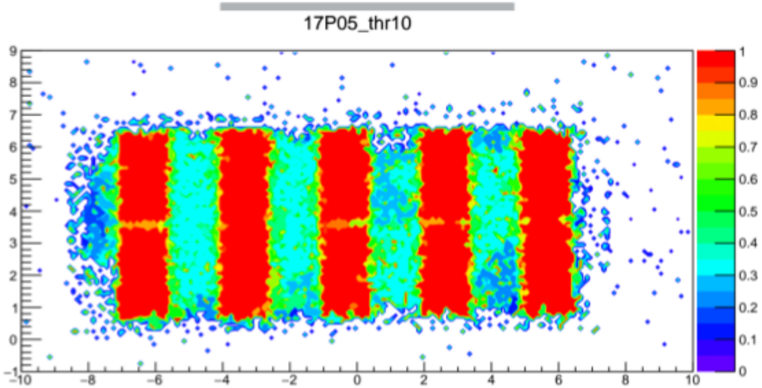
Polysiloxane shashlik (Oct 2017, CERN PS)

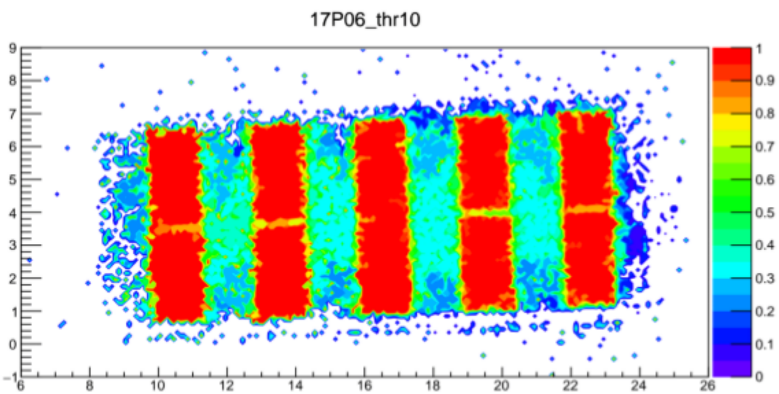


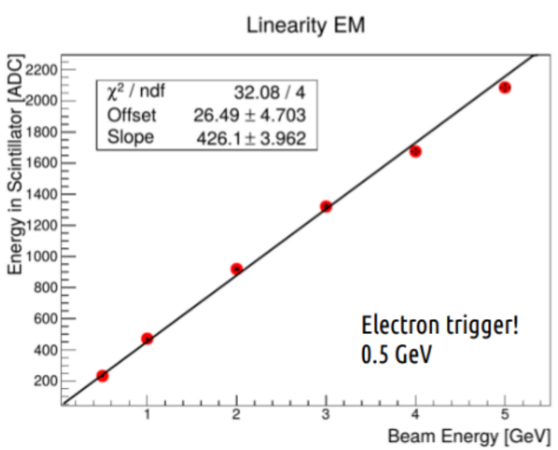
S. Carturan

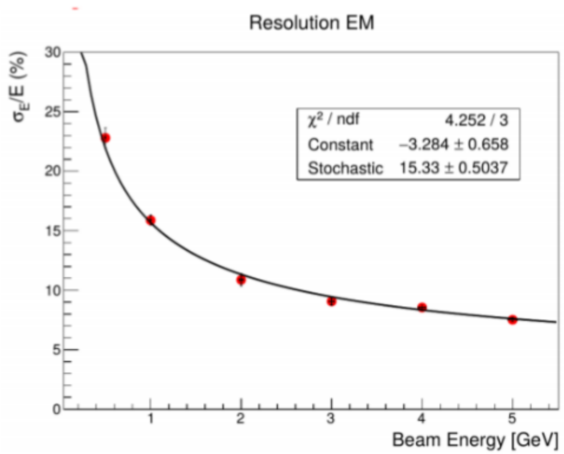






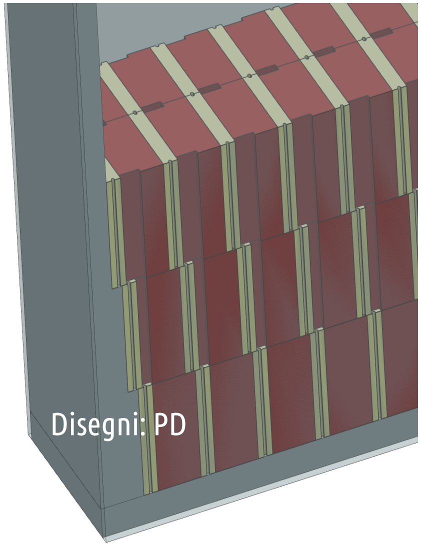


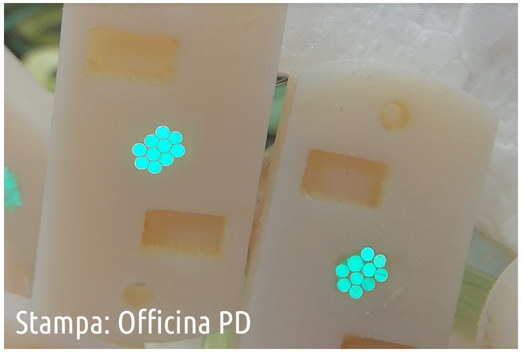


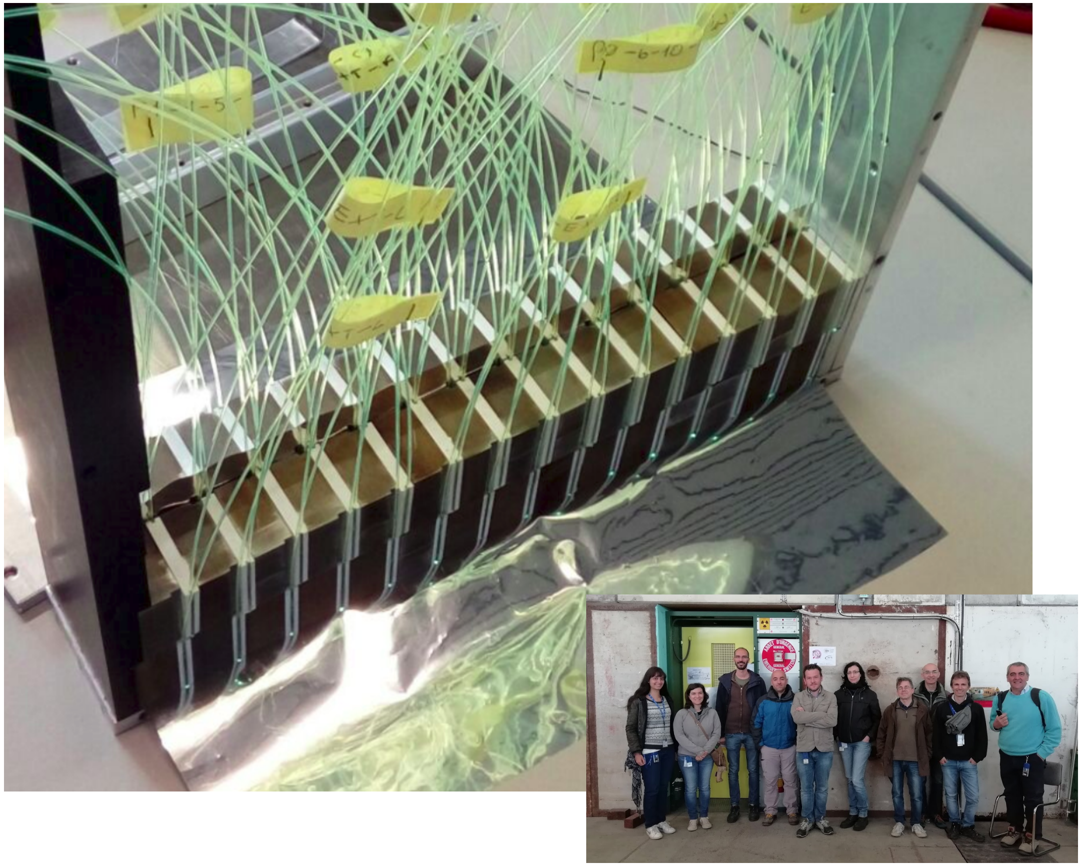


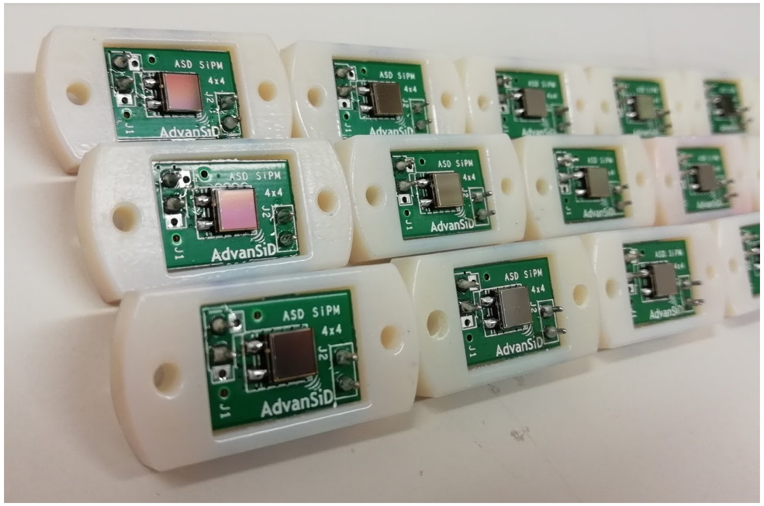
Non-shashlik May 2018

Sampling calorimeter (15 mm iron + 5 mm EJ204 tiles) with lateral WLS light collection. Test of Light yield, uniformity, resolution, optical coupling to photosensors (FBK Advansid 3x3 mm^2)



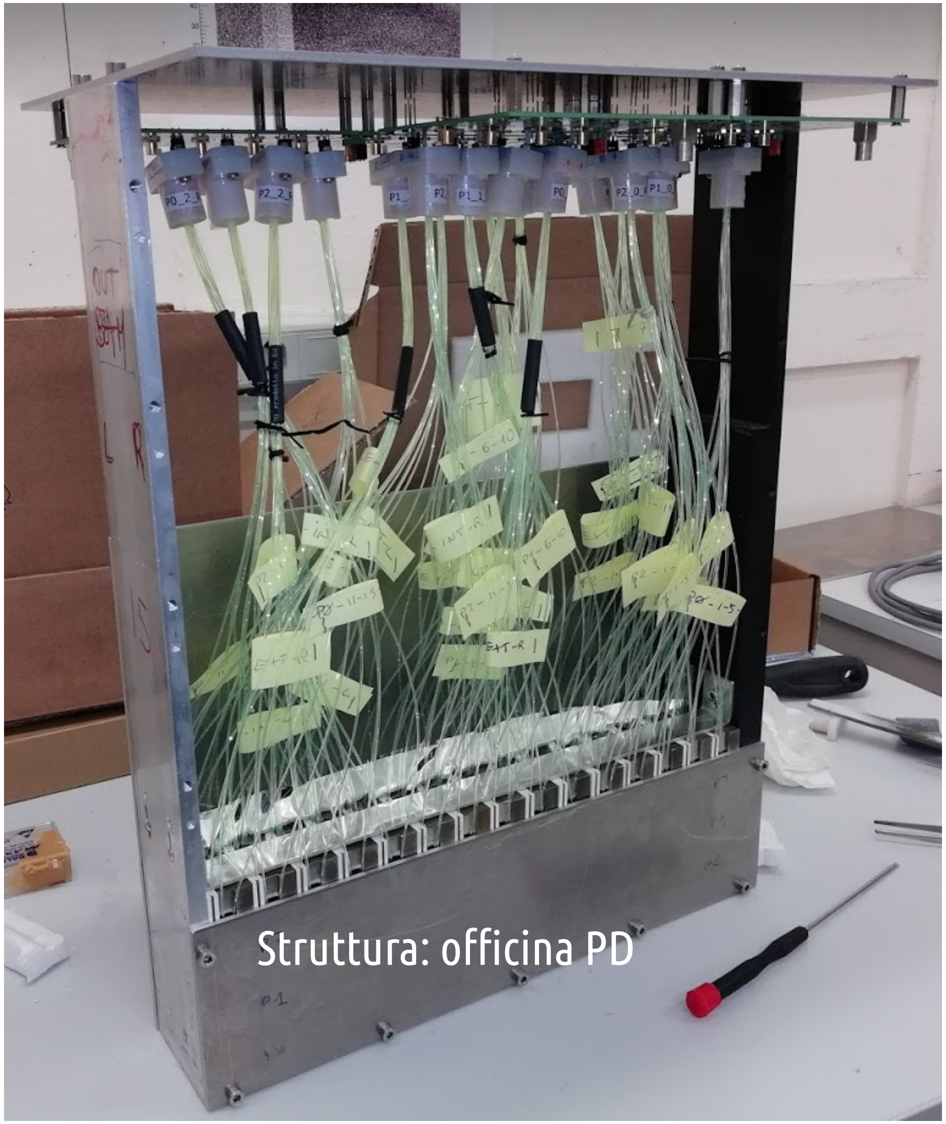


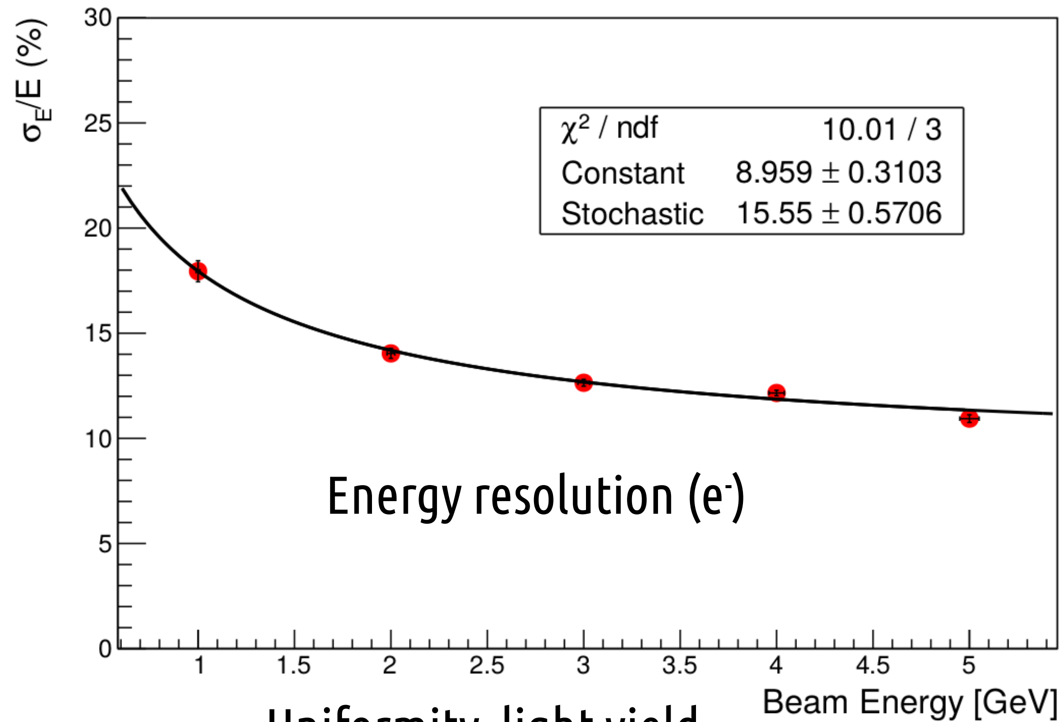




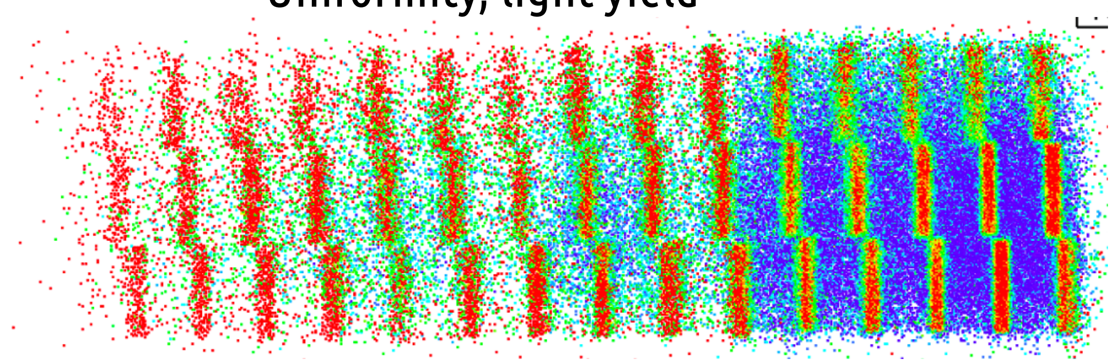
Non-shashlik May 2018

- **Calorimeter with lateral light readout**

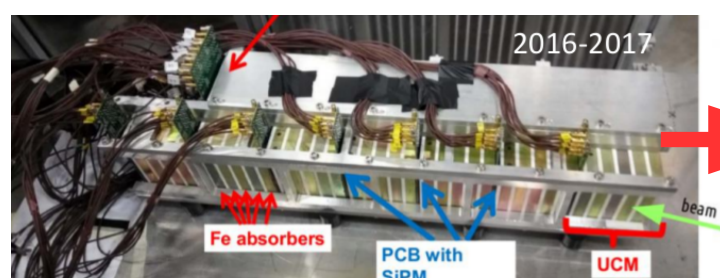


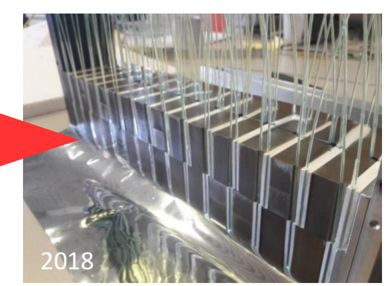


Uniformity, light yield



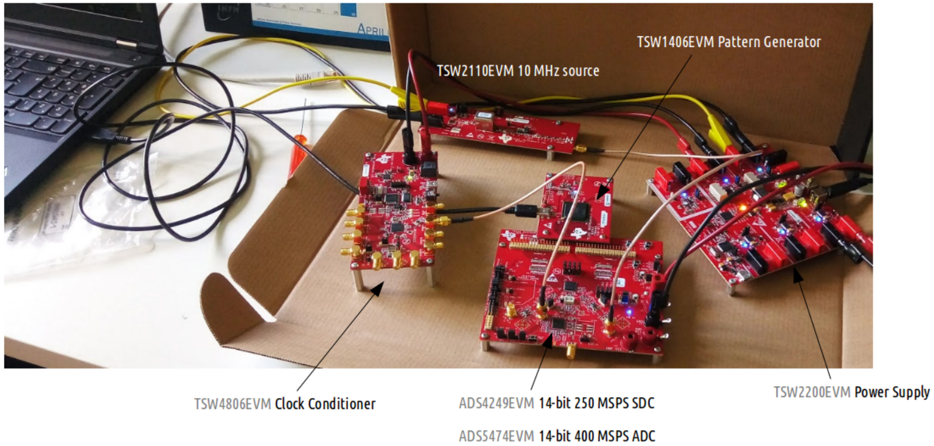
09/18 test: we are building a larger setup with this technology allowing pion containment similar to the 2016-2017 shashlik prototype:



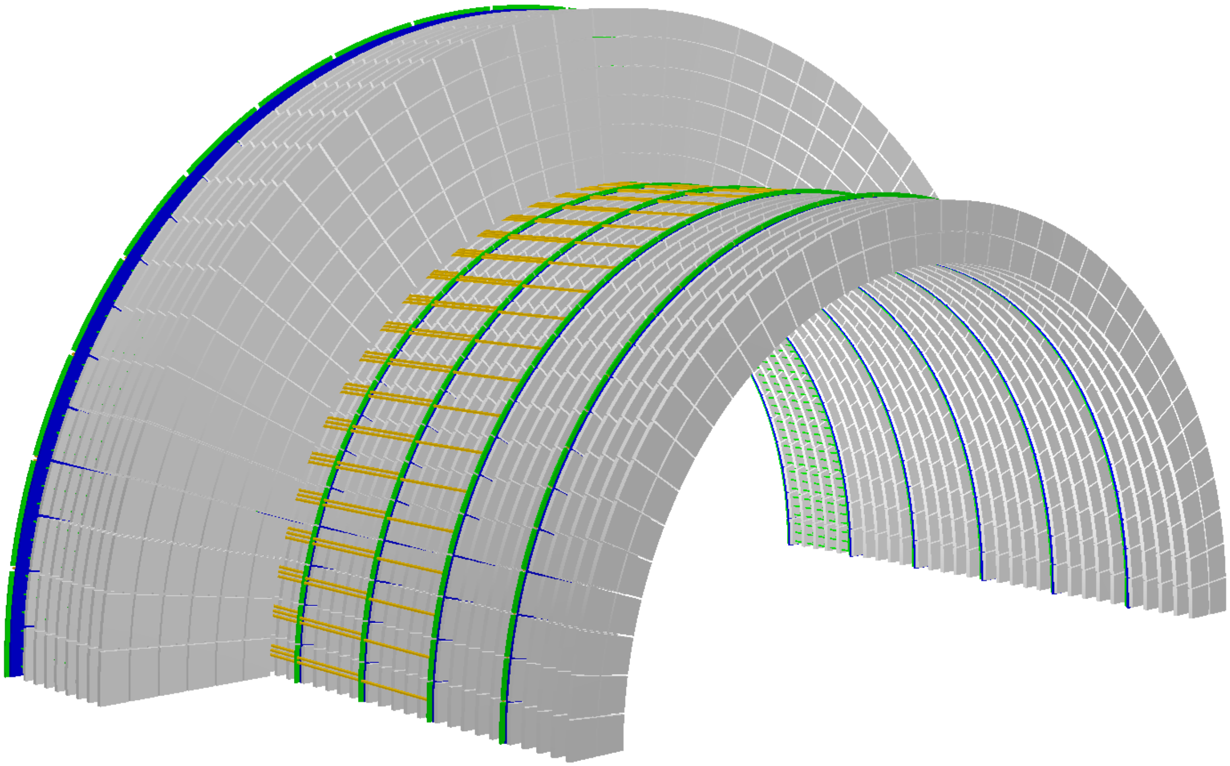


Richieste 2019

- **Preventivi CSN-II 2019**
  Missioni: 3 kEUR (PhD)



- **Servizi**
  - **Elettronica:** realizzazione prototipo scheda digitizer (2 mu)
  - **Uff. Tecnico/officina meccanica** impostare disegni del prototipo tagger e ingegnerizzazione (2 mu)



Early concept with ROOT 3D graphics

backup

Monitored beams

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

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

- 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

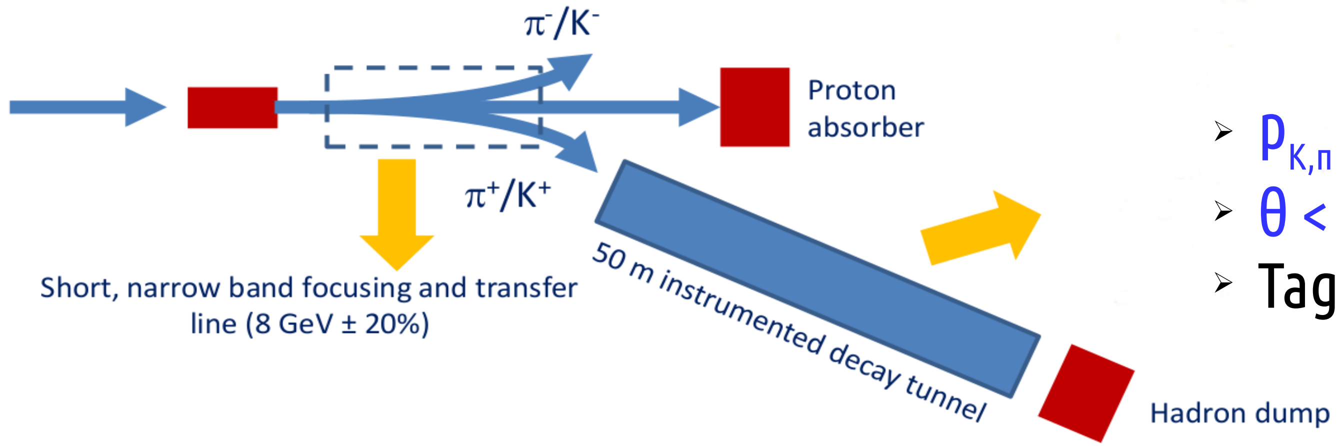
- **Fully instrumented**

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

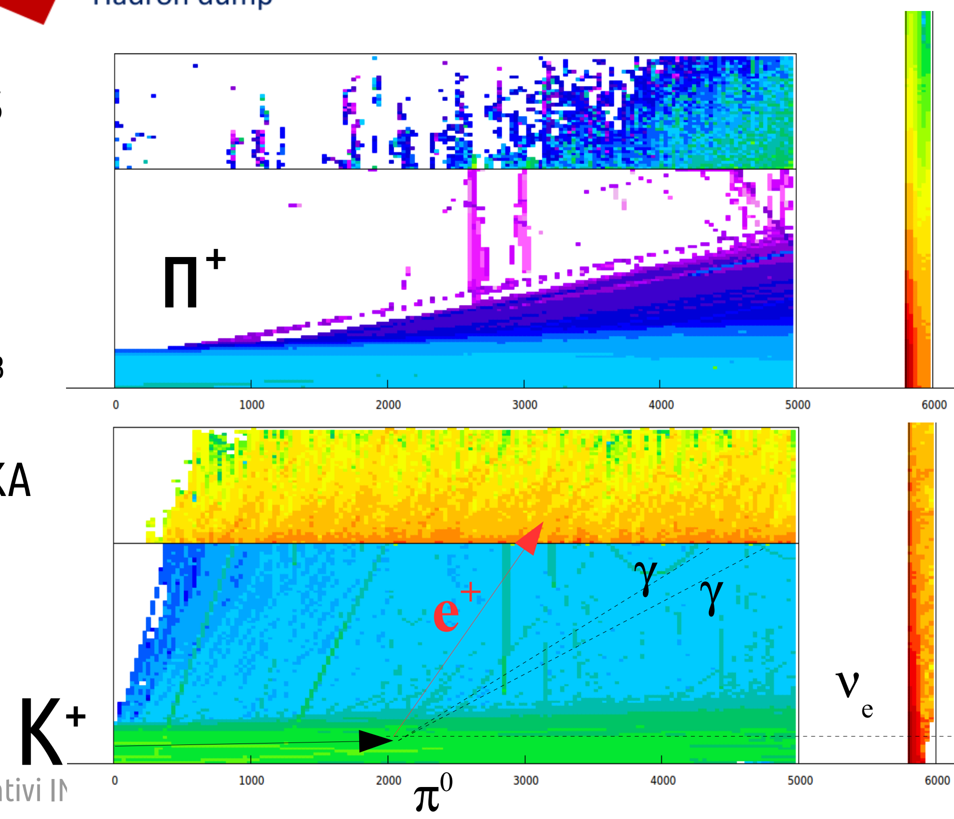


- $p_{K,\pi} = 8.5 \pm 20\%$ GeV/c
- $\theta < 3$ mrad over 10×10 cm^2
- Tagger: L = 50 m, r = 40 cm

- 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



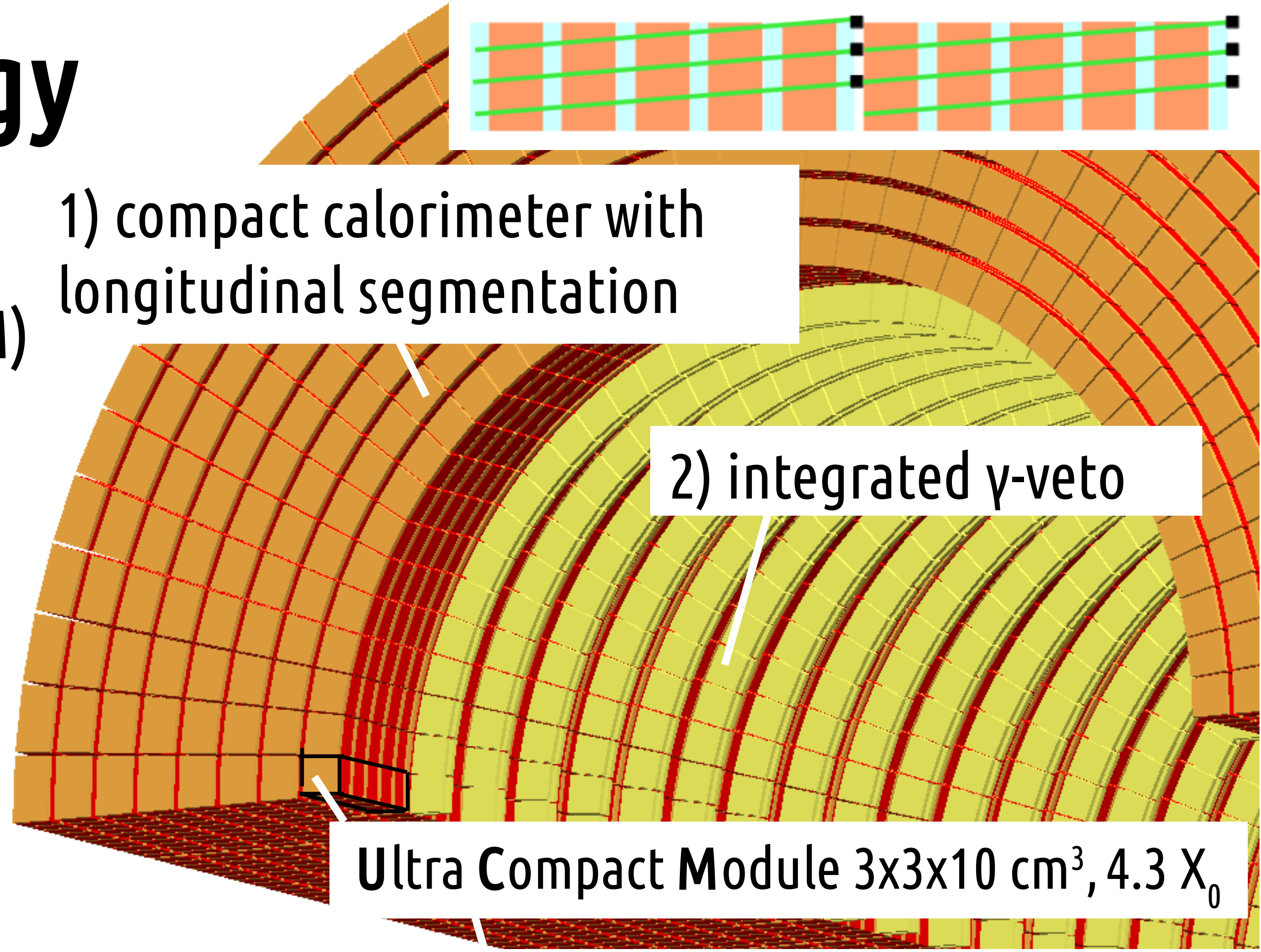
Tagger technology

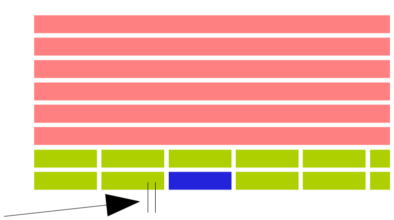
1) Calorimeter (“shashlik”)
- Ultra-Compact Module (UCM)
- Integrated light readout

→ $\pi^{\pm}$ rejection

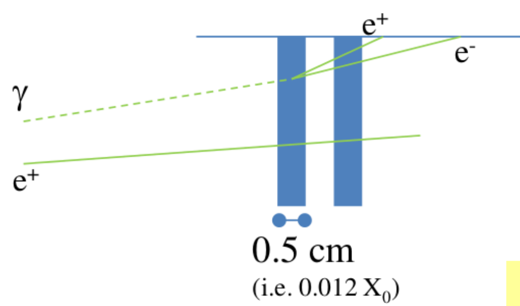
2) Integrated γ-veto
- plastic scintillators or
- large-area fast APDs
- Cherenkov radiator + LAPPD

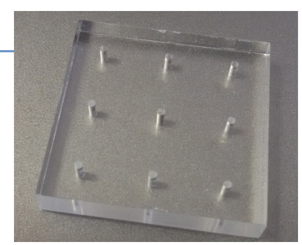
→ π^{0} rejection

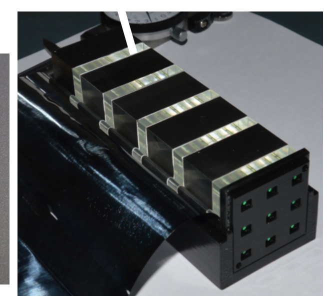


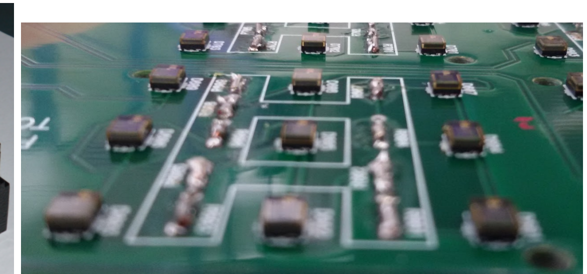


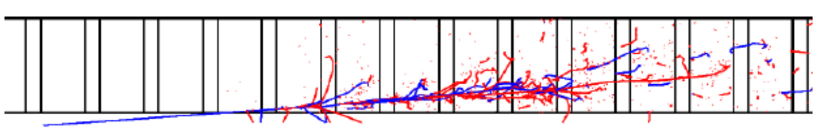
e$^+$ (signal) topolog







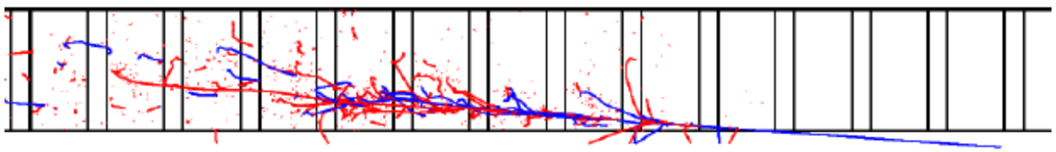


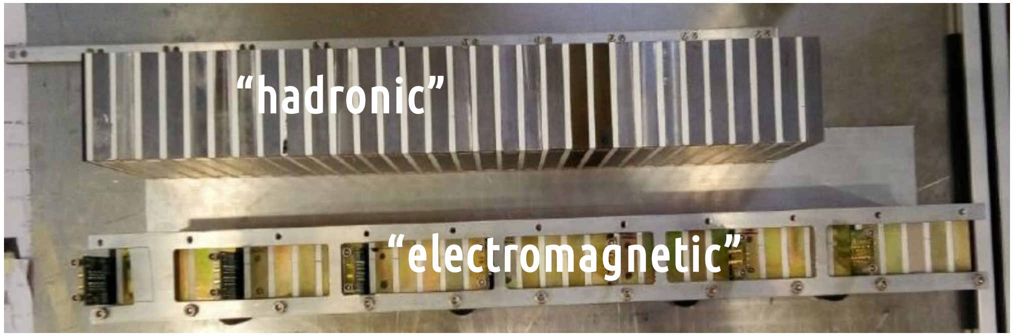


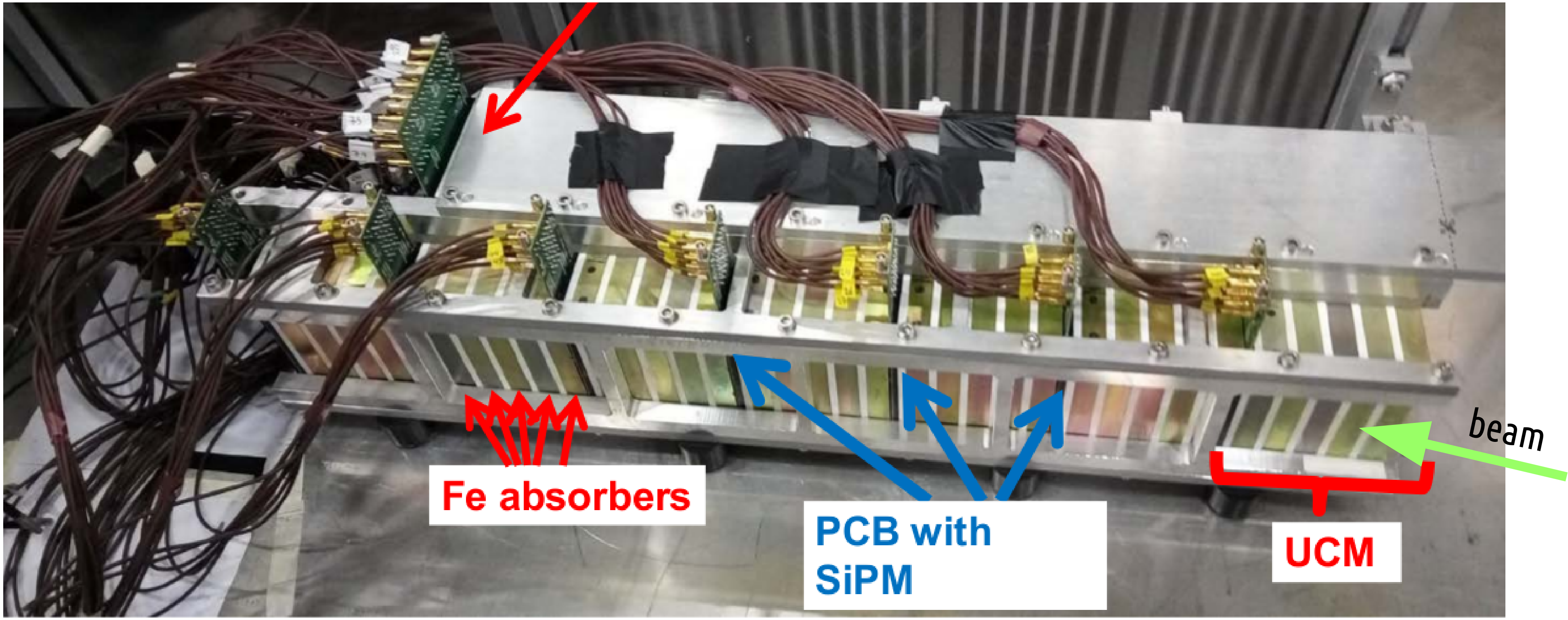
We aim at building/testing a scalable **demonstrator** consisting of a 3 m long section of the instrumented tunnel by 2021

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

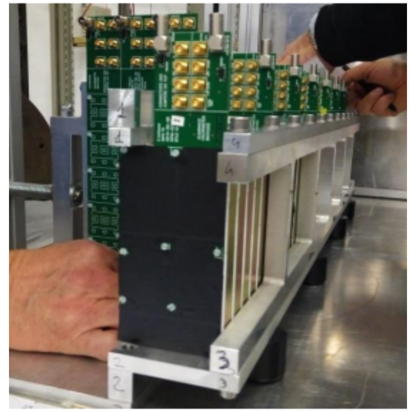


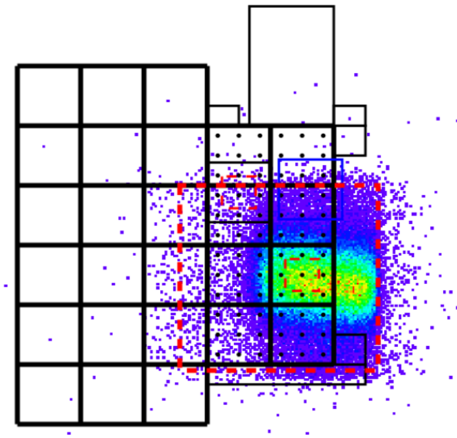




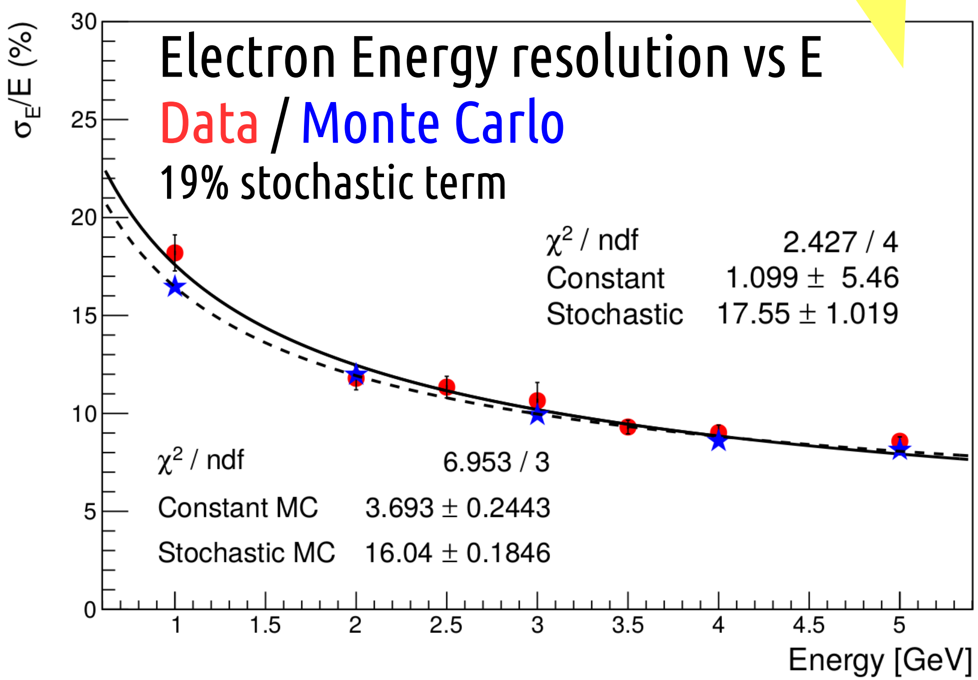
e/π separation analysis with test beam data

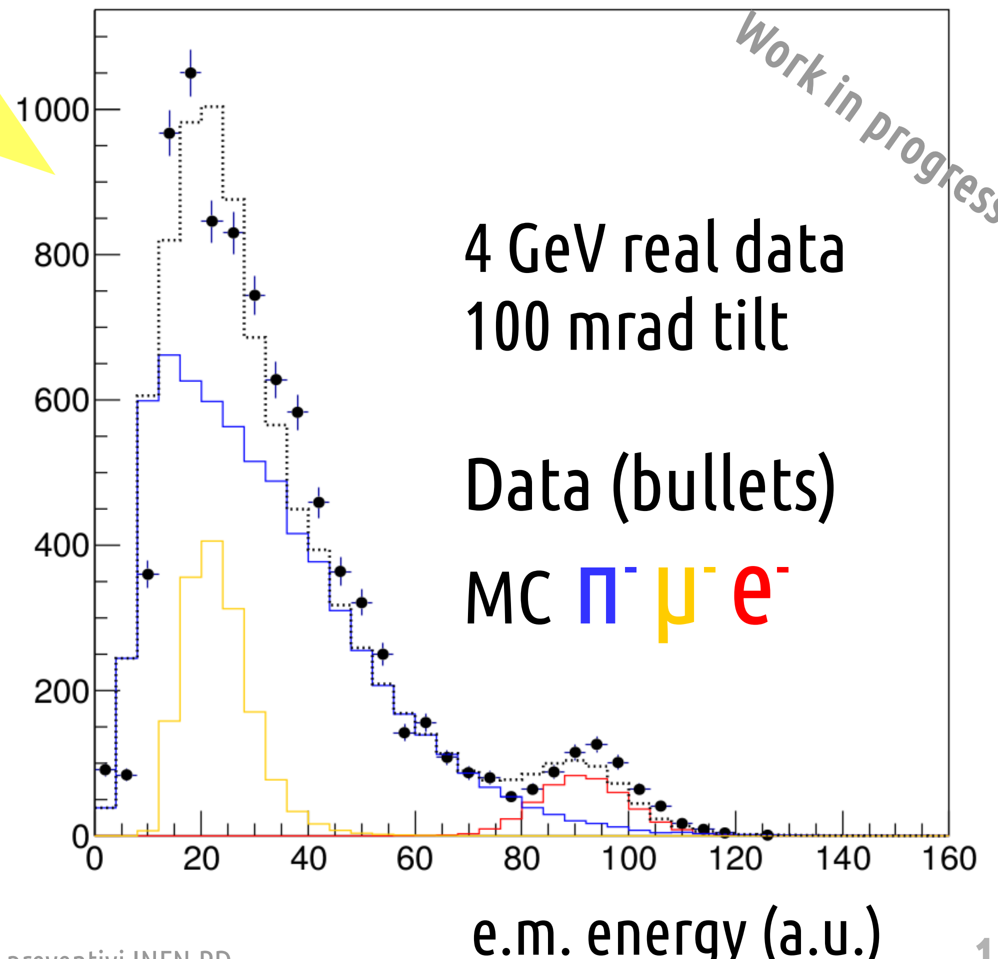
- Electrons/muons tagged by T9 Cherenkov counters and a muon catcher. Silicon strip chambers for μm tracking and fiducialization.
- Current **GEANT4 simulation is working reasonably well** already





hit map (with silicon trackers)

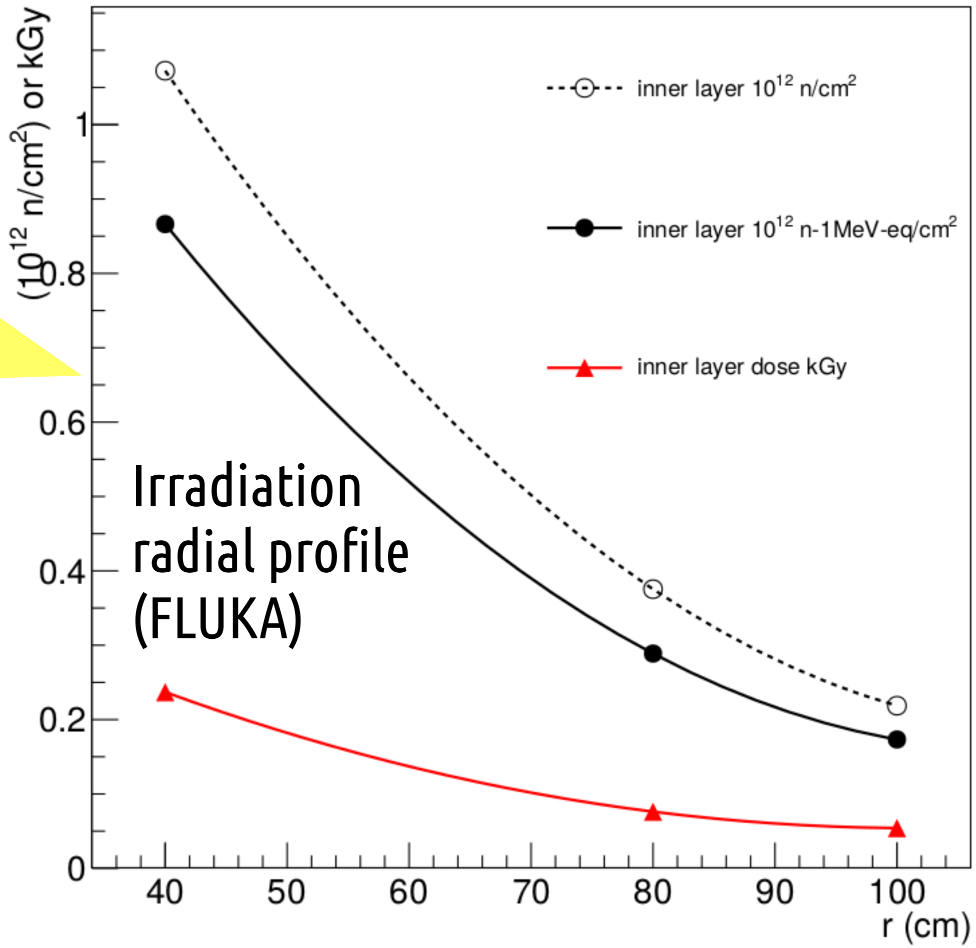




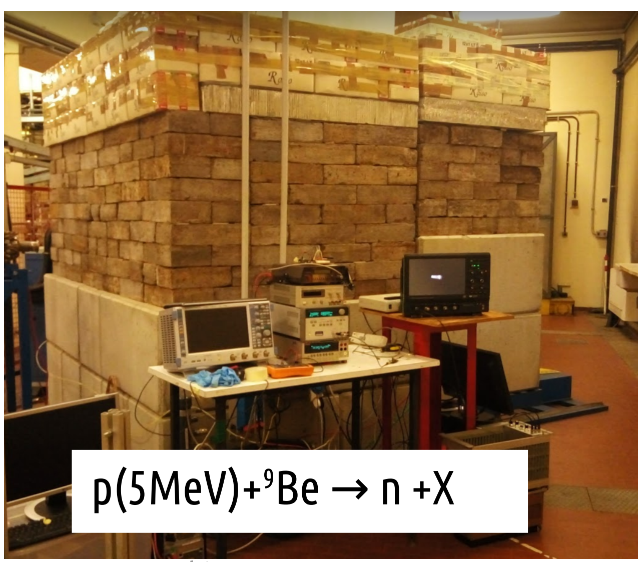
A. Berra *et al.*, IEEE Trans. Nucl. Sci, April 2017, 64 – 4 (1,6)

Irradiation studies

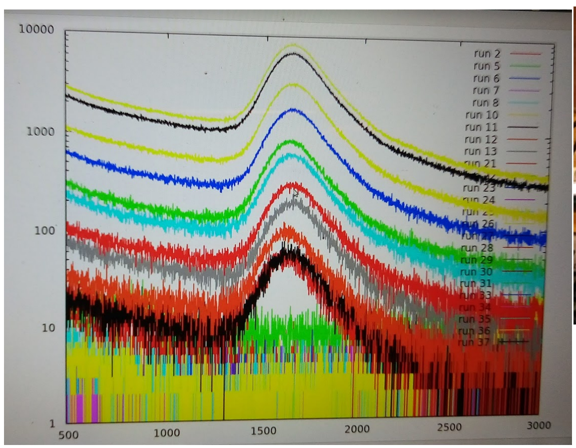
- **Neutron** and **ionizing doses** have been studied for a tagger radius of 40, 80 and 100 cm with FLUKA and cross-checked with GEANT4.
- With 100 cm ~ **2 x 10^{11} n 1MeV-eq/cm^2** and **~0.05 kGy** in the innermost layers (for 10^4 ν_e^{CC}).
- **Test irradition with 1-3 MeV neutrons** performed at **INFN-LNL** CN Van de Graaff on **12-27 June 2017**.
- Test viability of **self-calibration with m.i.p.**

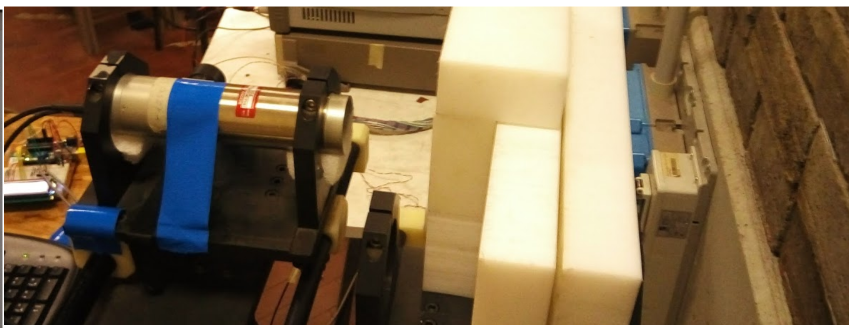


Irradiation radial profile (FLUKA)



p(5MeV)+^{9}Be → n +X





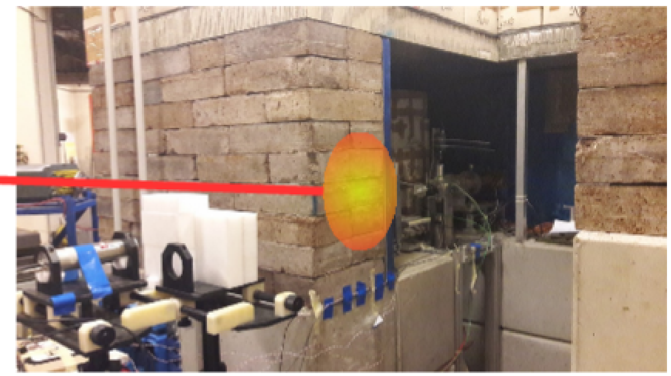
Proton and neutron monitors (thanks P. Mastinu)

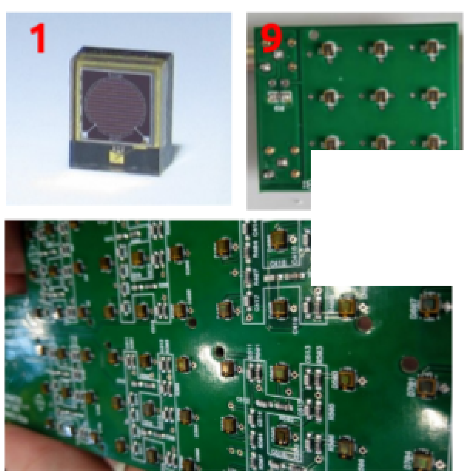
NEUTRON IRRADIATION - INFN-LNL

12-16 Giugno 2017, LNL

SiPMs irradiated up to 1MeV-eq n/cm^2 :

- FBK – HD-RGB – 1x1mm^2 - 12µm cell size
- FBK – HD-RGB - 1x1mm^2 - 15µm cell size
- FBK – HD-RGB - 1x1mm^2 - 20µm cell size
- SensL – J-series 3mm^2 - 20µm cell size
- PCB with 9 SiPMs (UCM), all cell sizes
- PCB with 56 SiPMs (tagger prototype layer)



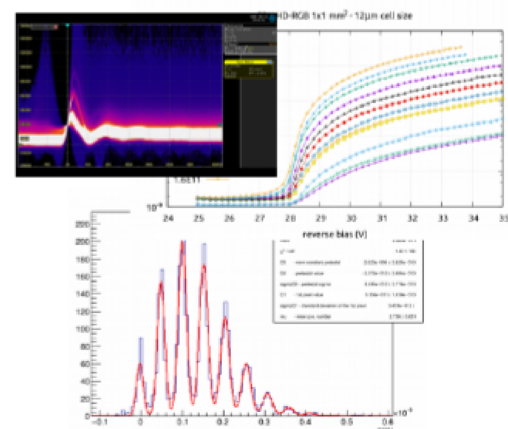


Monitoring of:

- I-V curves (live)

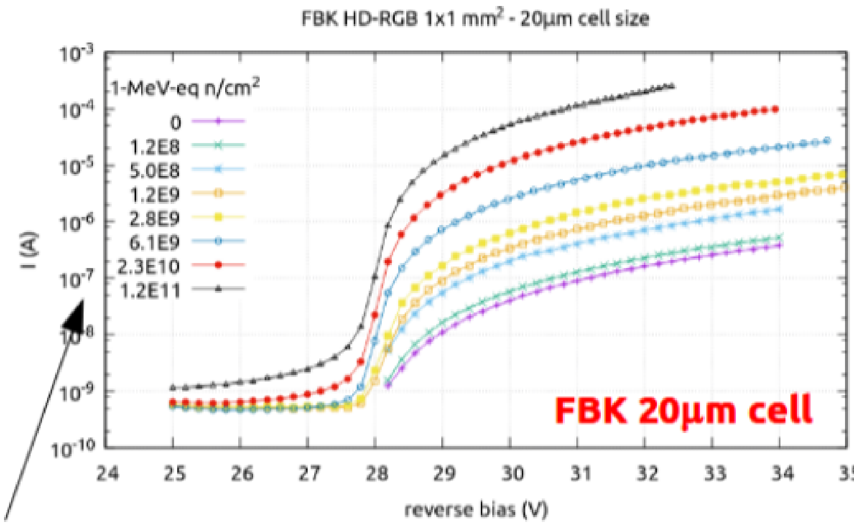
rum)

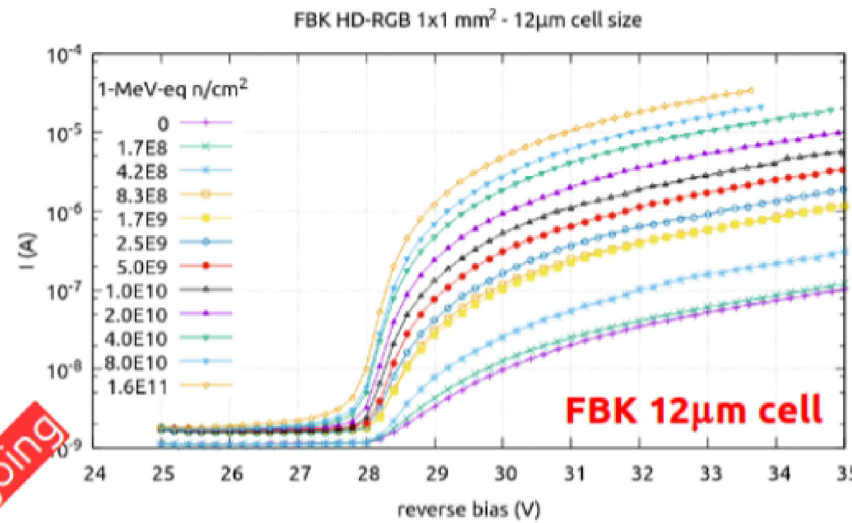
Analysis is ongoing
(sorry! ended last week...)



Post irradiation:
(No annealing)
→ CERN **test beam incoming** (end of July)

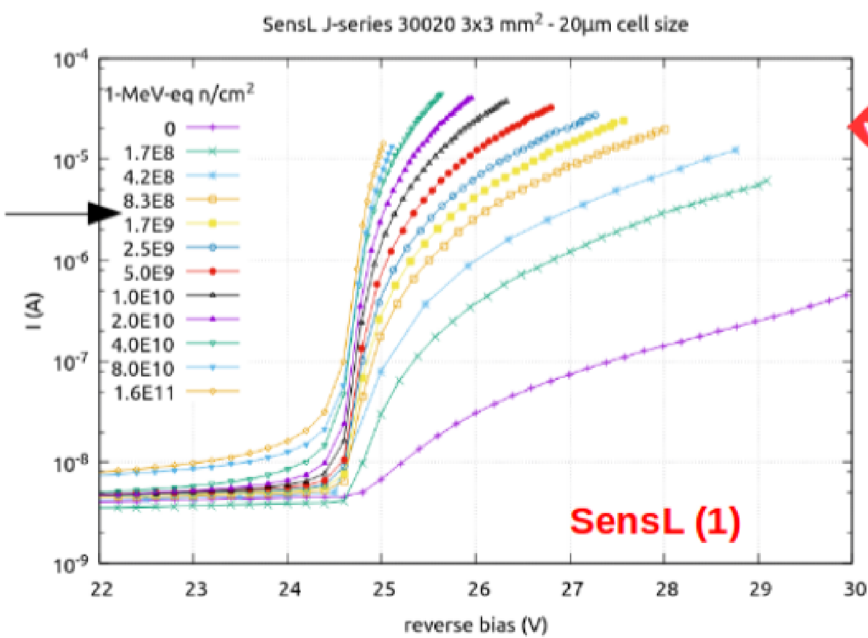
Irradiation studies: iV curves

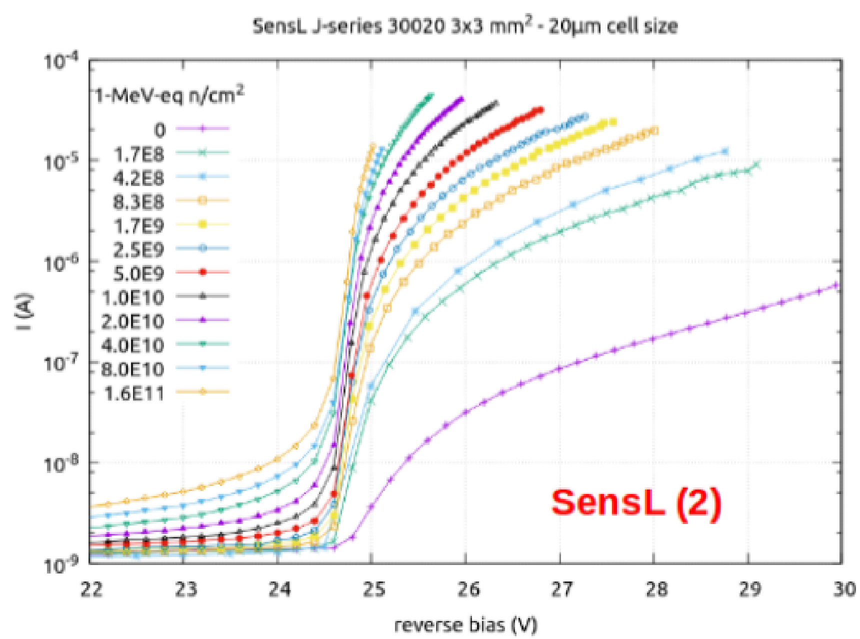




fluence calculation to be refined!

Analysis is ongoing



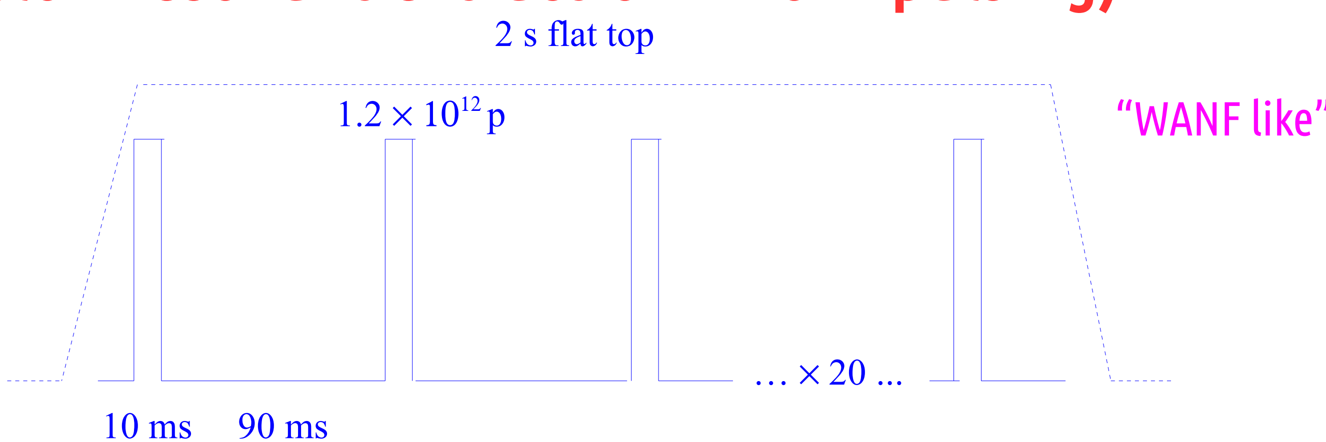


Hadron beam-line scenarios

- **Baseline choice:** magnetic horns focusing. $t_{impulse}$ < O(1-10) 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



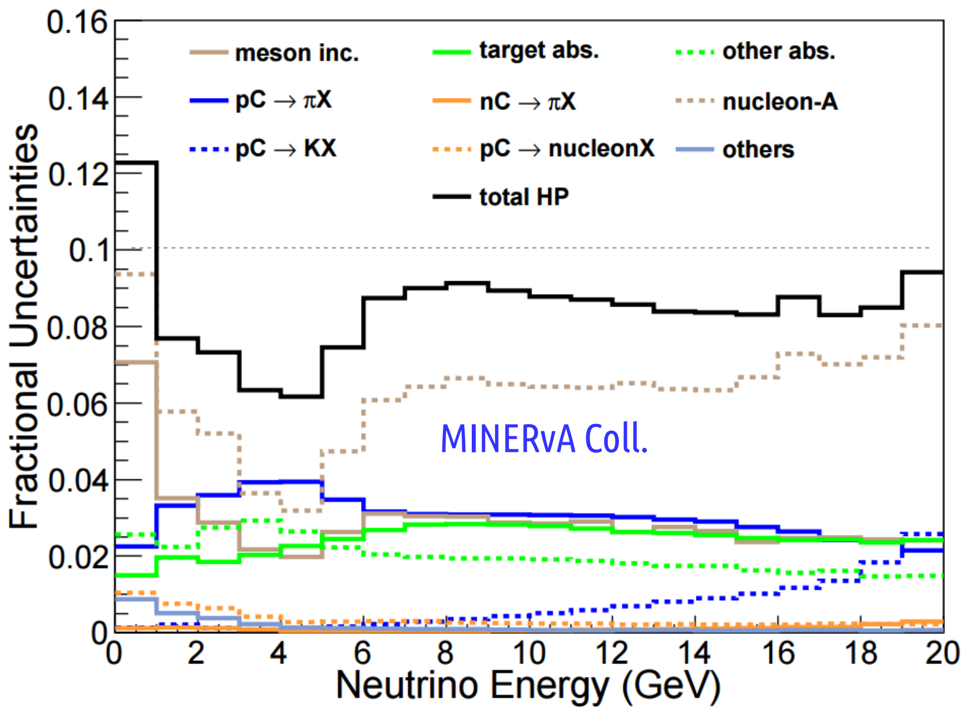
Alternative choice: static focusing devices + long extraction.
Much less efficient focusing (→ more POT) but would open the intriguing opportunity of "**time tagging**" → T_{extr} = 1s (~ 1 observed e$^+$ / 30 ns) + δ = 1 ns → Accidental tag = 2 %

Tackling the flux uncertainty problem

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

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

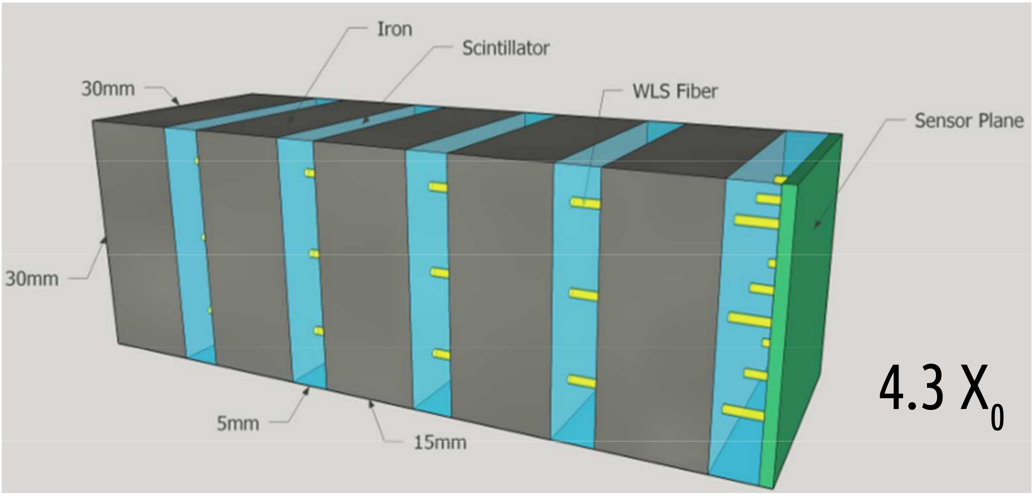
- **Flux** constraints **already** in place:
  - ✓ **Muon/proton monitoring**
  - ✓ **hadro-production exp.** (A. Marino, M. Hartz)
  - ✓ **interactions on electrons** (10^{-4} ν_μ^{CC})
  - ✓ **Low-ν method**

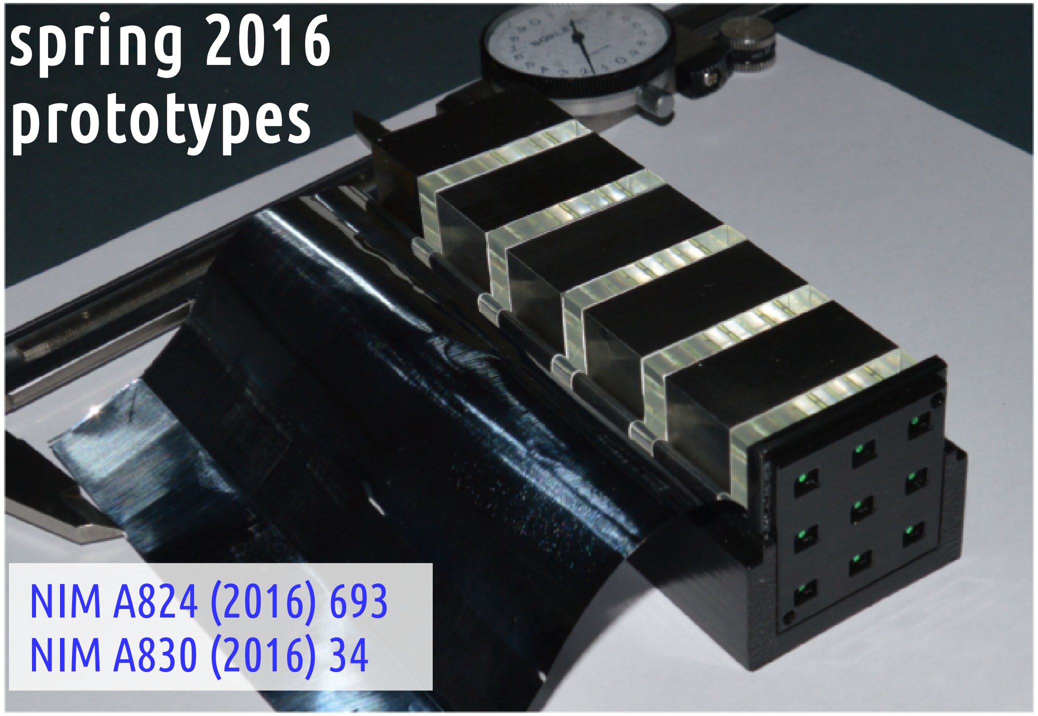


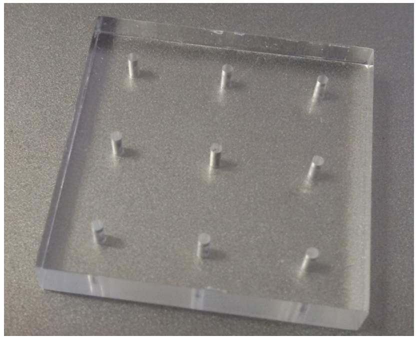
Still ...

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

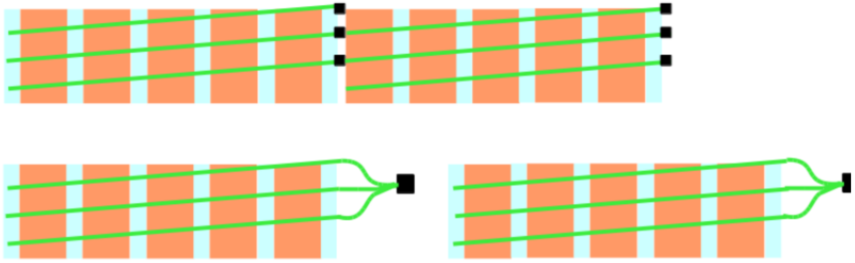
The Ultra Compact Module (UCM)







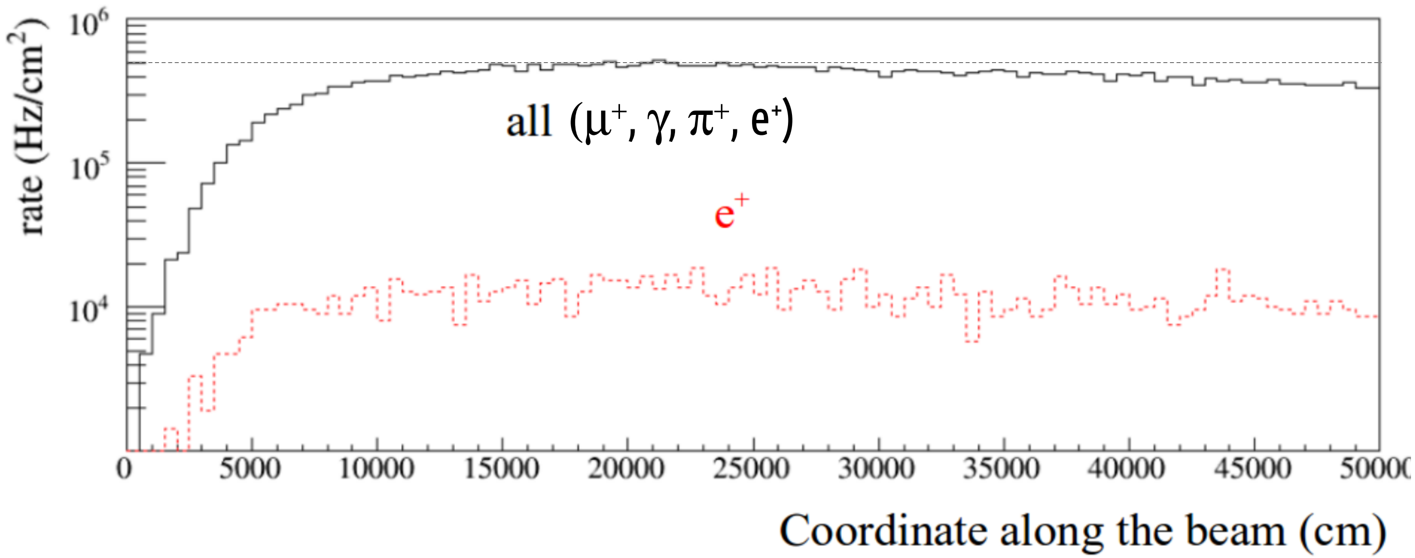
- 1 SiPM ↔ 1 WLS fiber
- 9 SiPM signals are added (reduce R/O costs)
- Add SiPM signals in place of light → **no WLS bundling = optimal homogenity in longitudinal sampling (UCM)**



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

The e^+ tagger challenges

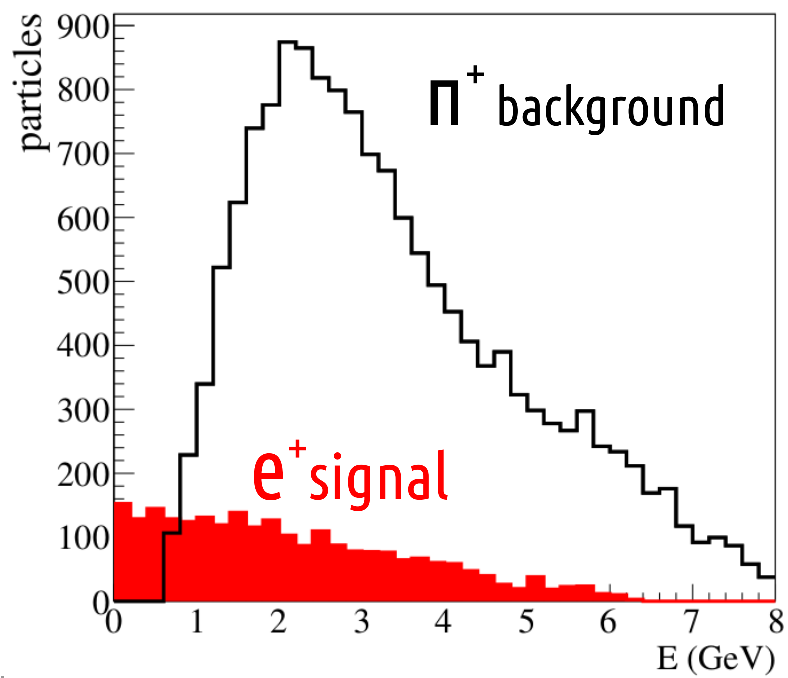
Injecting **10^{10} π^+ in a 2 ms** spill →



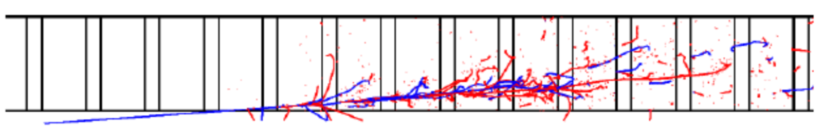
	Max rate (kHz/cm²)
μ^+	190
γ	190
π^+	100
e^+	20
all	**500**

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

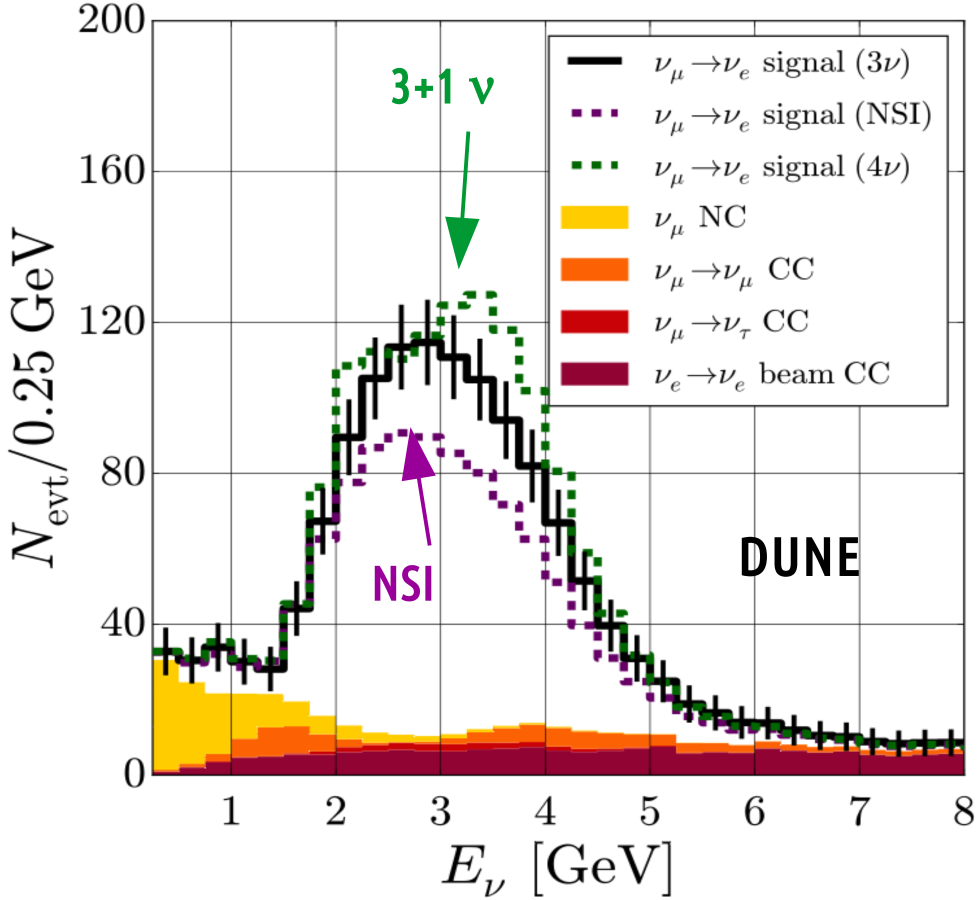
Tackling σ(ν_e)

- 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



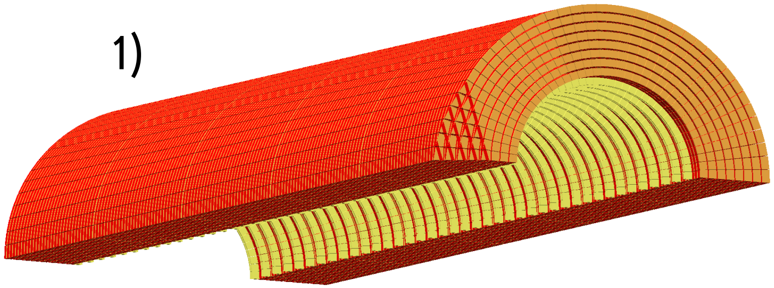
- D.I.F. of stored μ as in **nuSTORM/nuPIL** is the **ideal** solution but it is **not easy.**

ENUBET: the roadmap

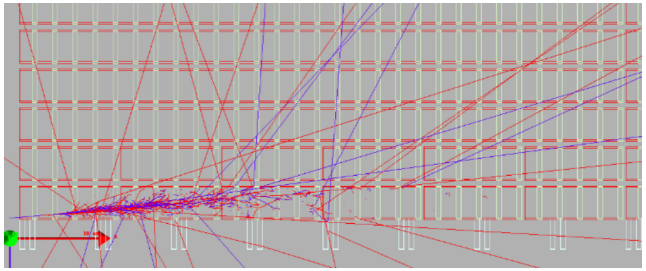
Demonstrate the technique, prepare a "full-scale" experiment

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

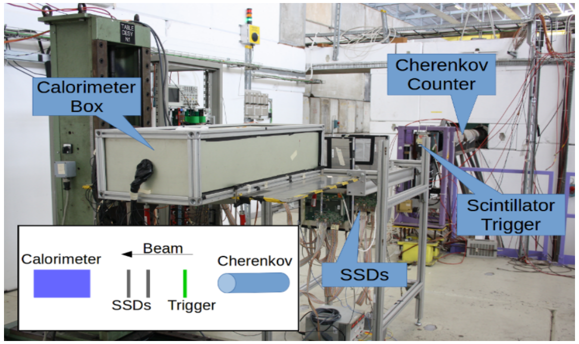
1)



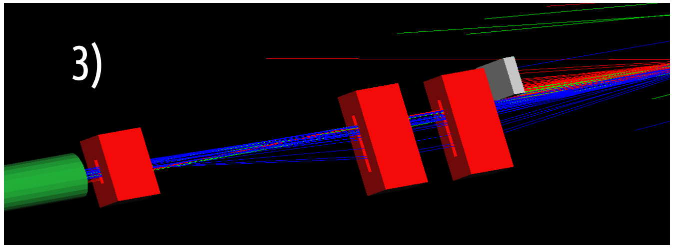
2)



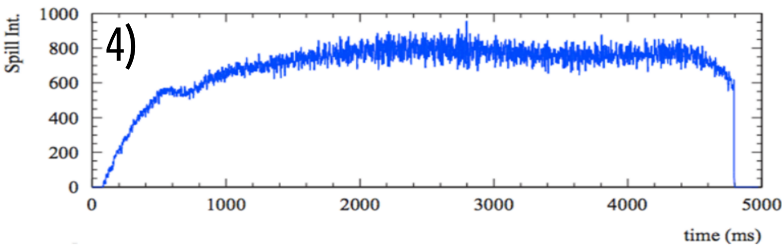
2)



3)



4)

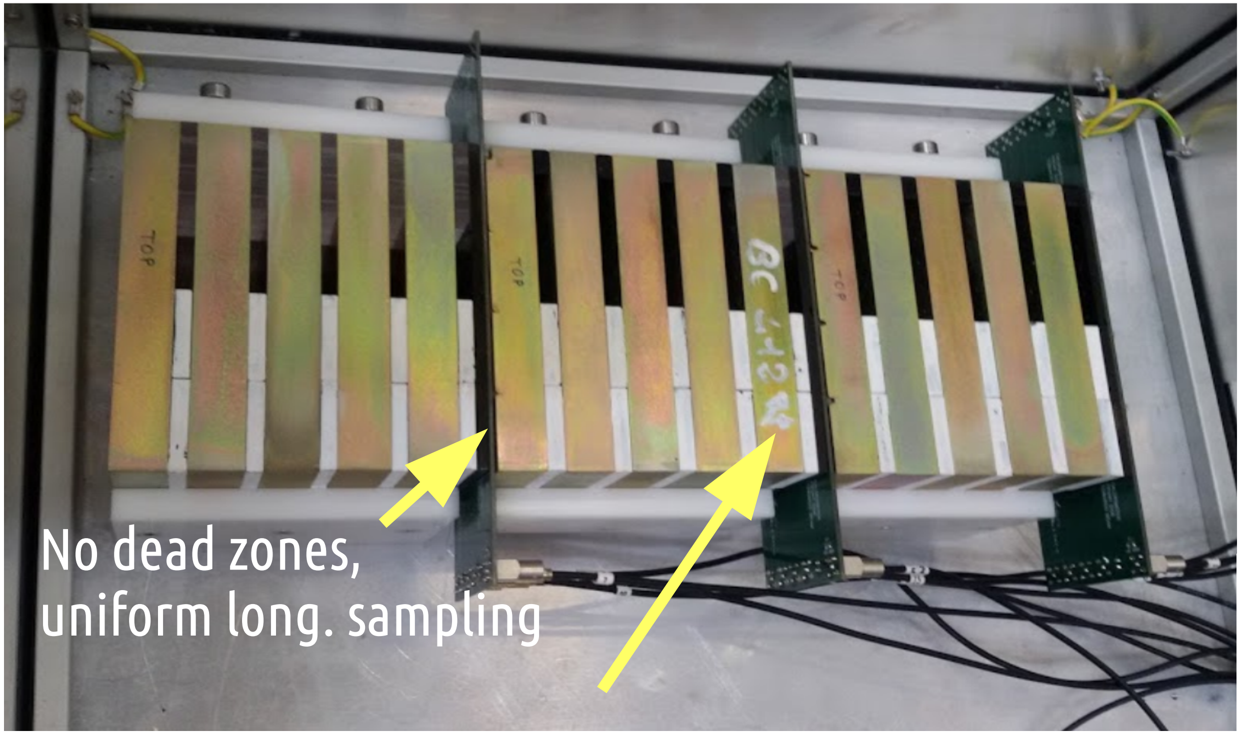


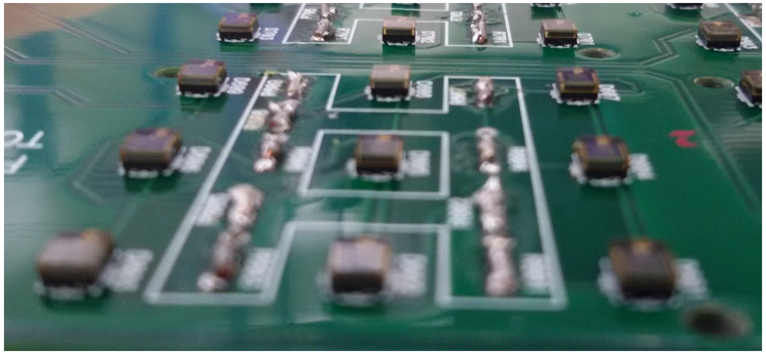
By-products:

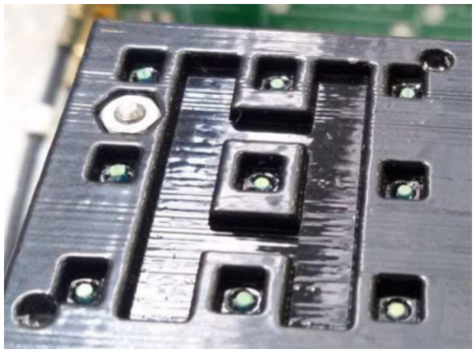
- **Calorimetry:** compact, modular, low-cost detectors (UCM)
- **Accelerator physics:** Multi-Hz slow resonant extraction

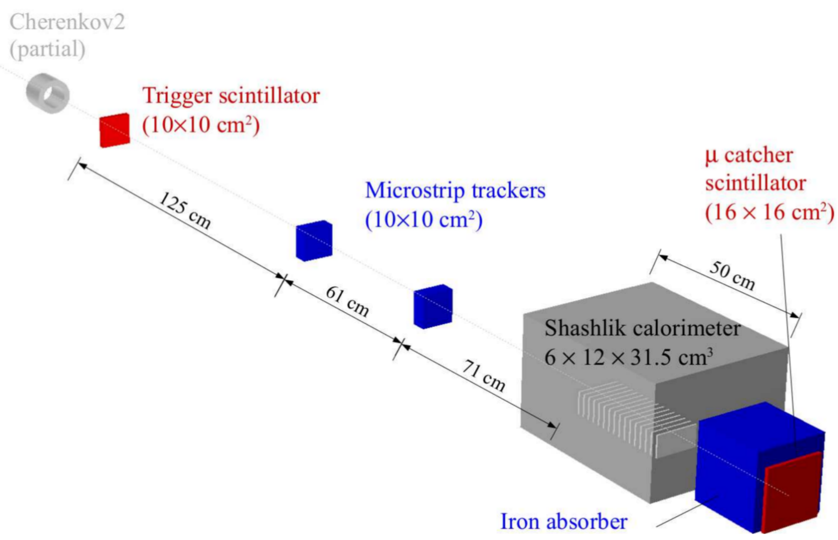
First test beam validation of UCM

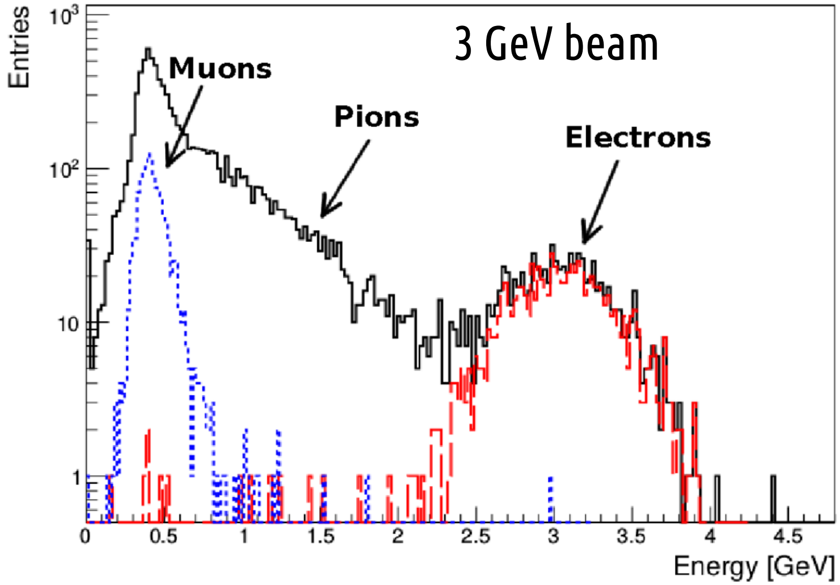
CERN-PS T9 test beam (July 2016). Beam: π, e, μ from 1-5 GeV.
12 ENUBET UCM modules (~13 X_0). 1 mm² HD Si-PM with 20 μm cell size (FBK).





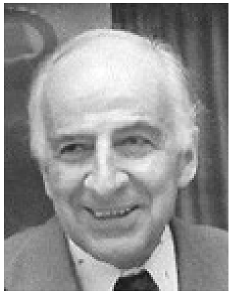






A. Berra *et al.*, IEEE Trans. Nucl. Sci., in press.

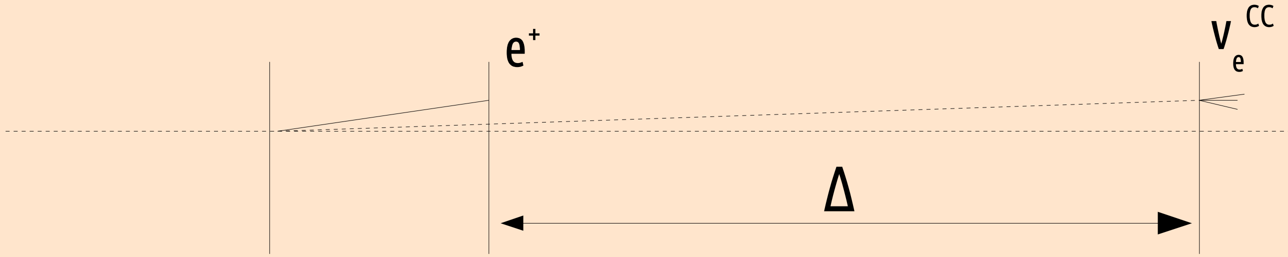
Going beyond: "time-tagged" beams



- 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: **$A \sim 2{\times}10^{7}\ \delta/T_{extr}$**

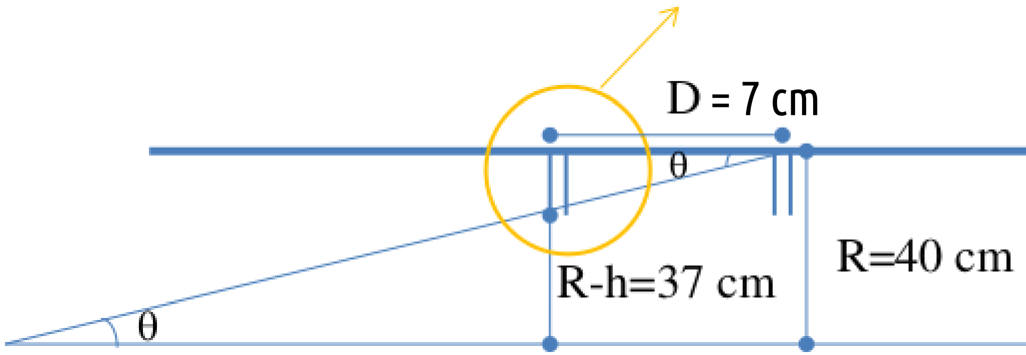
T_{extr} = 1s (~ 1 observed e^+ / 30 ns) + **δ = 1 ns** → **A = 2 % OK !**

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

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

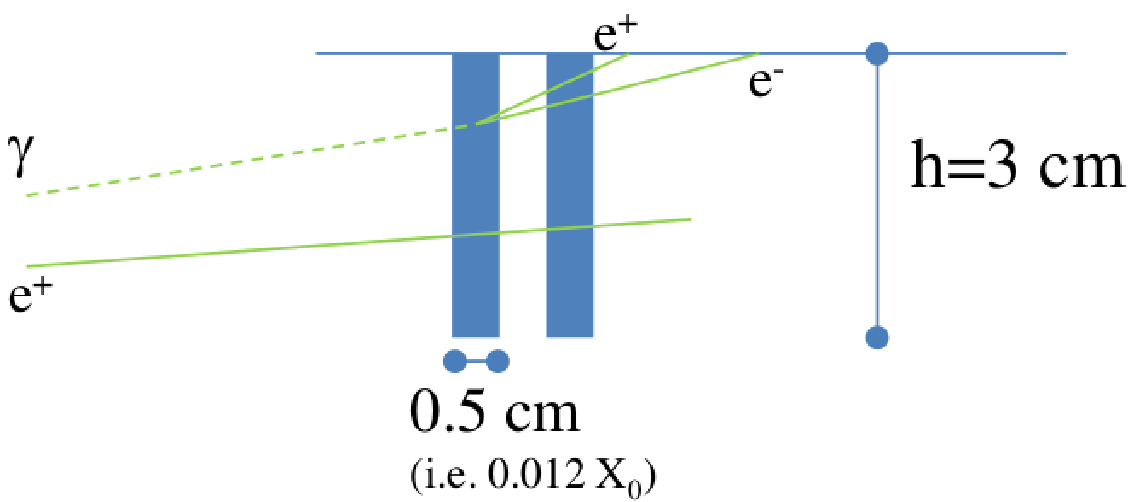
The photon-veto baseline option

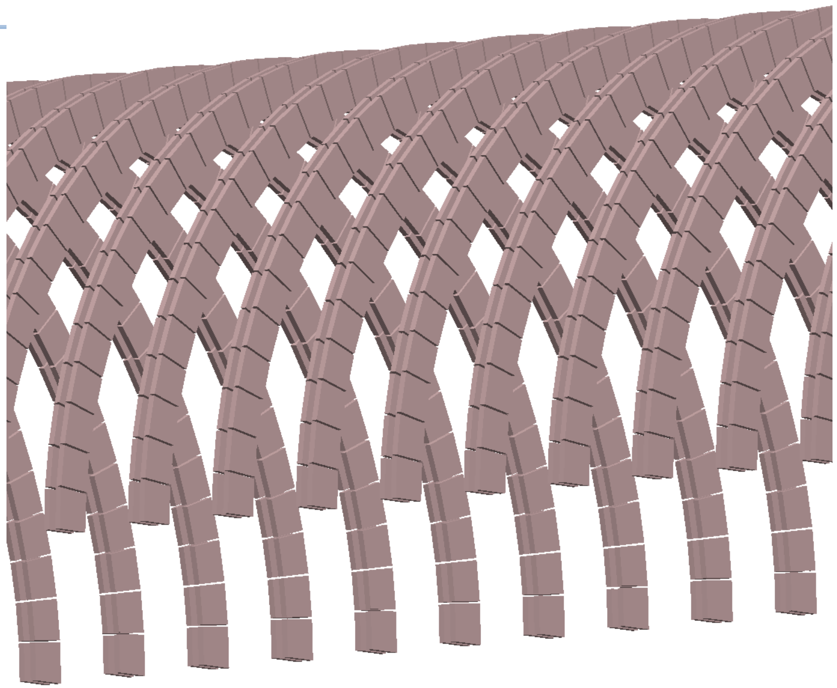
Background from γ conversions from π^0 emitted mainly in K_{e2} decays ($K^+ \rightarrow \pi^+ \pi^0$)



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

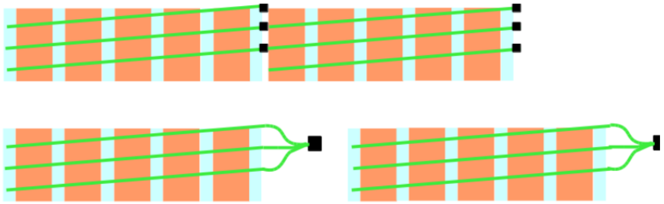
Exploit **1 mip – 2 mip separation**

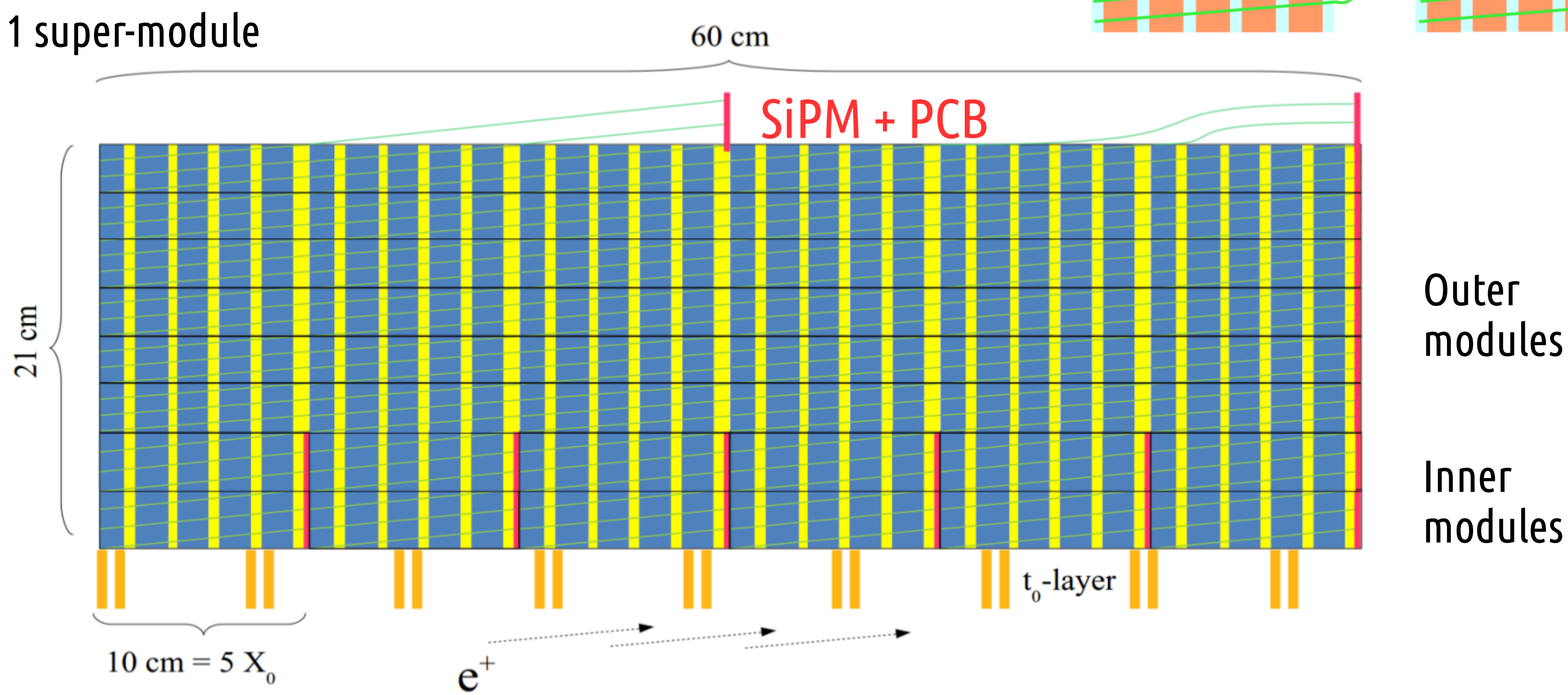




- Possible **alternative/attractive solutions** under scrutiny allowing a reduced **material budget and superior timing**.
- Test beams at Frascati: **electronics response** at high rates and low-E e^+,1 mip/2 mip

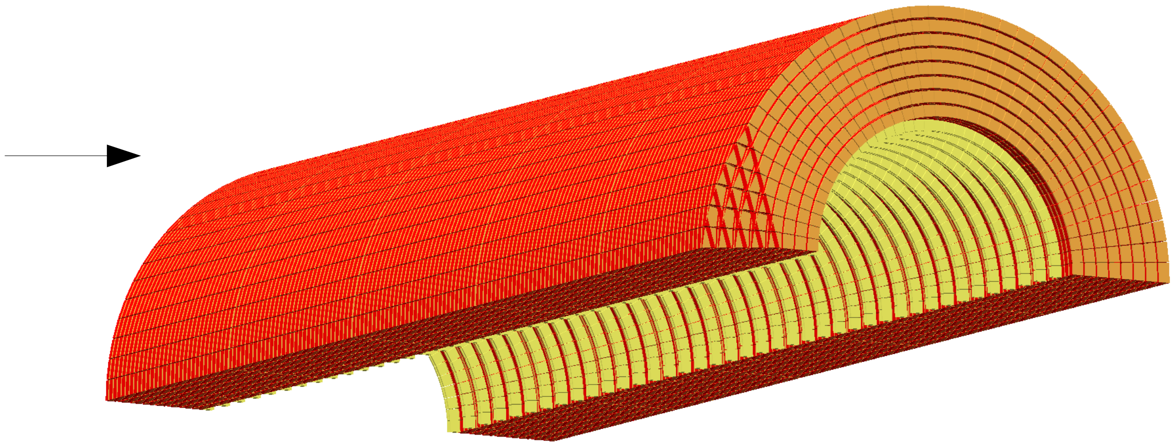
The final prototype





- 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**



e^+ tagger: background rejection

Hadronic modules
Electro-magnetic modules
Hit modules

Key point:

- longitudinal sampling
- perfect homogeneity → integrated light-readout