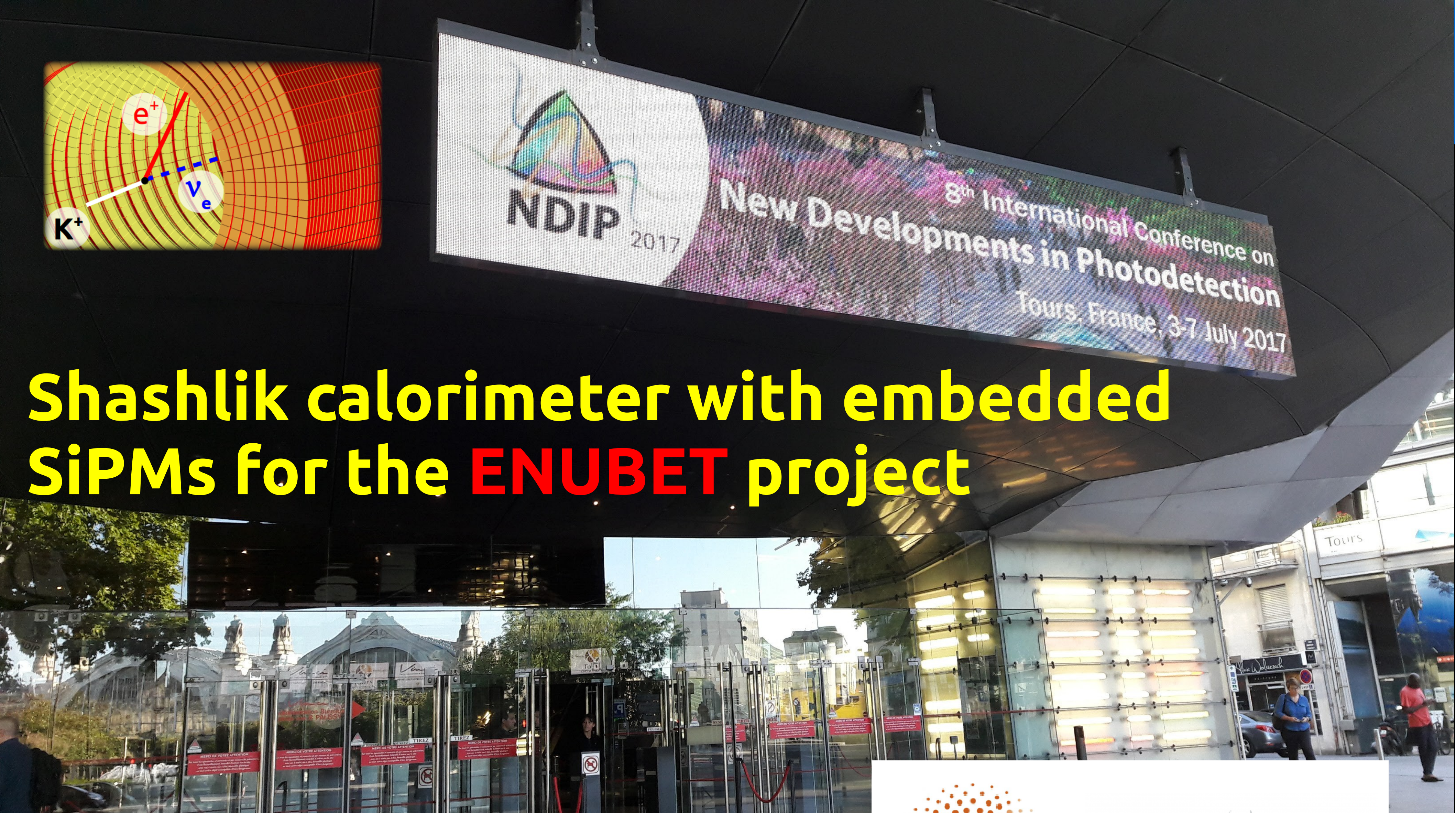


Shashlik calorimeter with embedded SiPMs for the ENUBET project

Valerio Mascagna on behalf of the ENUBET collaboration

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).

OUTLINE

- The ENUBET project
- Status of the positron tagger (shashlik calorimeter)
- Overview of the testbeam results
- Conclusions and outlooks

ENUBET

Enhanced NeUtrino BEams from kaon Tagging

http://enubet.pd.infn.it

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

ERC-Consolidator Grant-2015, no 681647 (PE2)
P.I.: **A. Longhin**
Host Institution: **INFN**

Expression of Interest (CERN-SPSC, Oct. 2016)
CERN-SPSC-2016-036; SPSC-EOI-014

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

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]

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

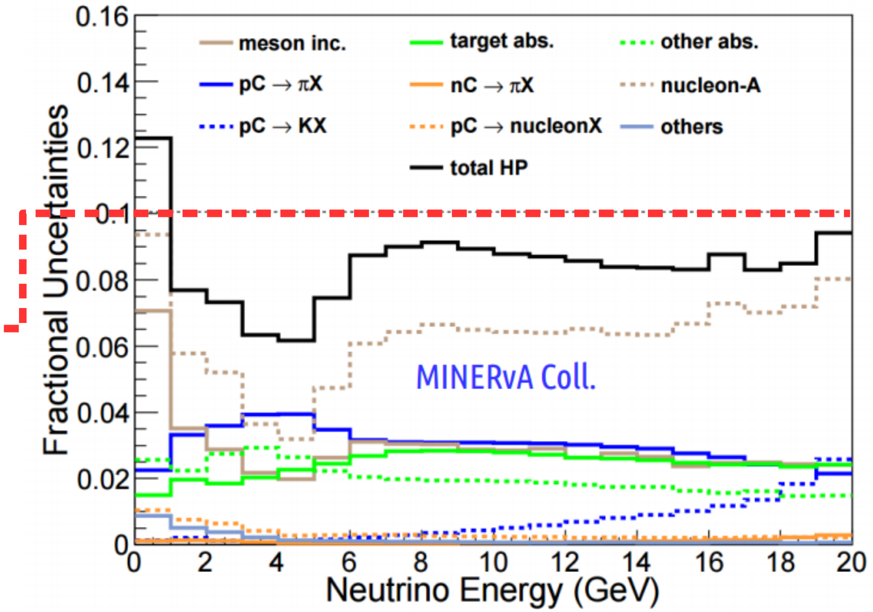
Flux uncertainty and ν_e, ν_μ cross sections

Last 10 years: knowledge of $\boldsymbol{\sigma(\nu_\mu)}$ improved enormously

MiniBooNE, SCIBooNE, T2K, MINERvA, NOvA …

Nevertheless, the flux systematics **“wall”** is still there being typically the **dominant uncertainty** for cross section measurements

No absolute measurements below ~7-10%



In addition, for $\boldsymbol{\sigma(\nu_e)}$ we use the beam contamination (no intense/pure sources of GeV ν_e): data still sparse

Gargamelle, T2K, NOvA, MINERvA

Poor knowledge of $\boldsymbol{\sigma(\nu_e)}$ can spoil :

- the **CPV discovery potential**
- the insight on the underlying physics (standard vs exotic)

→ **Monitored beams**

Monitored (e)neutrino beams

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

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" of the hadro-production, beam-line efficiency uncertainties, ...

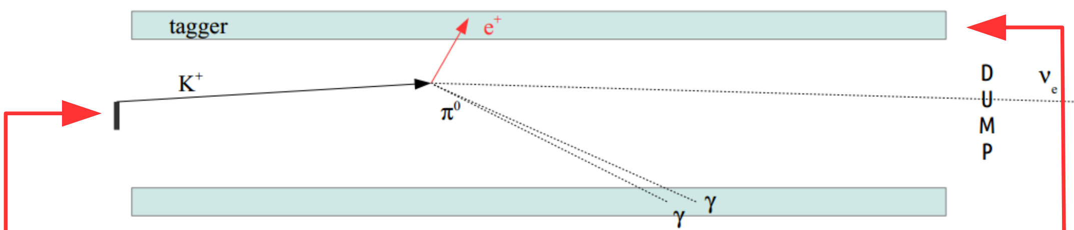
Traditional		**Monitored**
• **Passive** decay region • ν_e flux relies on **ab-initio simulations** of the full chain • **large uncertainties**	⟷	• **Fully instrumented** $K^+ \to e^+ \nu_e \pi^0 \to$ large angle e^+ • **ν_e flux prediction = e^+ counting**

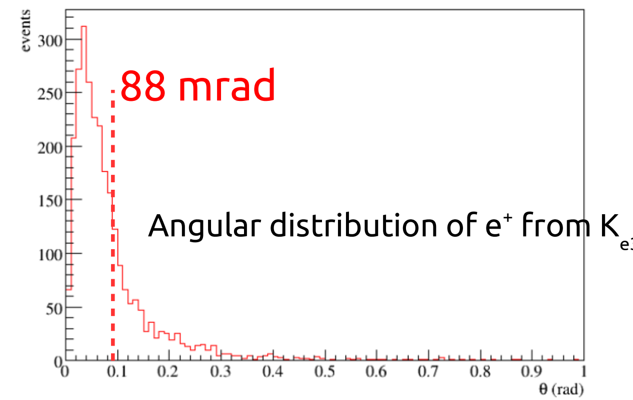
The ENUBET monitored beam

The K_{e3} channel: $K^+ \rightarrow \pi^0 e^+ \nu_e$

Good acceptance for e^+ 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}





$p_{K,n}$ = 8.55 ± 20% GeV/c

θ < 3 mrad (over 10x10cm^2)

tagger: L = 50 m, r = 40 cm

Hadron beam line: charge selection, focusing only K decay product.

→ slow resonant extraction +horn pulsing vs static focusing devices + long extraction?

→ FLUKA/G4Beamline simulation

→ assess beam-related backgrounds

→ machine studies of multi-Hz slow res. extr. at CERN-SPS

Good e-tagging capabilities needed by:

ICARUS / μ BooNE @ FNAL

proto-DUNE SP/DP @ CERN

Water Cherenkov (i.e. E61 @ J-PARC)

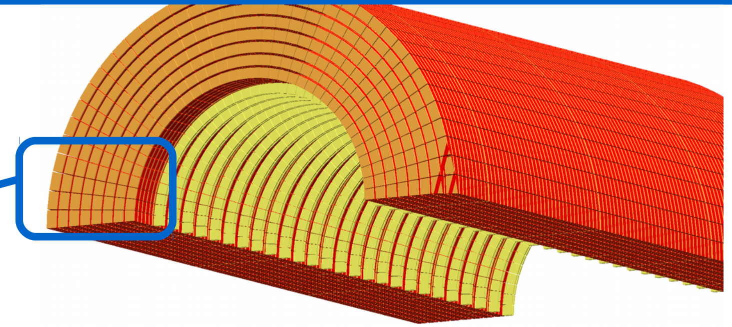
~500 t detector at 100 m (Ar:6x6x10 m3)

Positron tagger: real-time, "inclusive" monitoring of K decay products

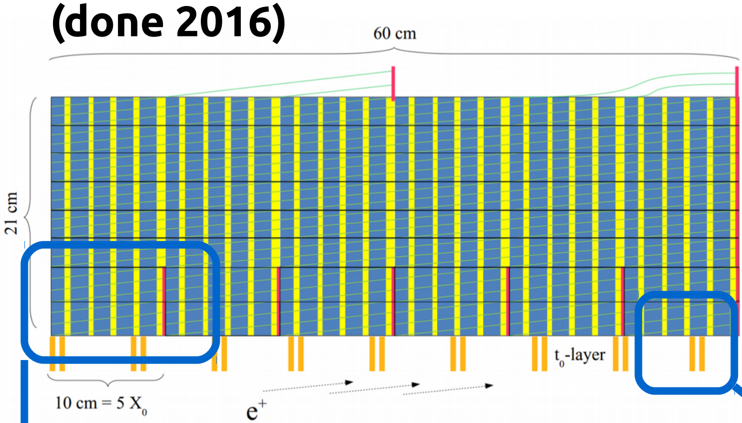
$\pi^\pm$ rejection → **CALORIMETER** ("shashlik")
compact, cost effective, integrated light readout

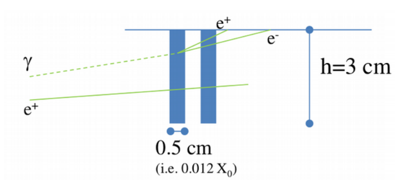
π^0 rejection → **INTEGRATED VETO**
Plastic scintillator (or large area APDs , Cherenkov radiator + LAPPD)

The TAGGER – shashlik calorimeter



PROTOTYPE SUPER-MODULE (done 2016)

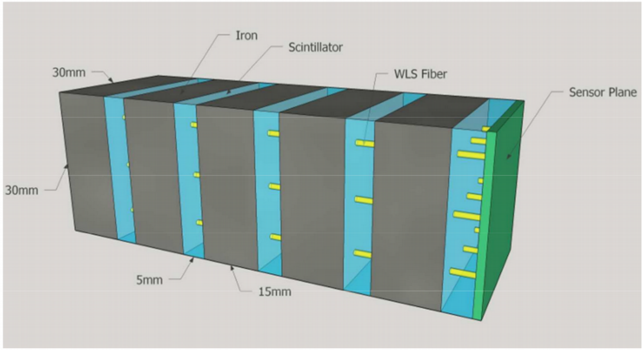




Key points:

- longitudinal sampling
- perfect homogeneity **integrated light-readout**
  WLS fibers → SiPMs

56 "UCM" (Ultra Compact Modules)

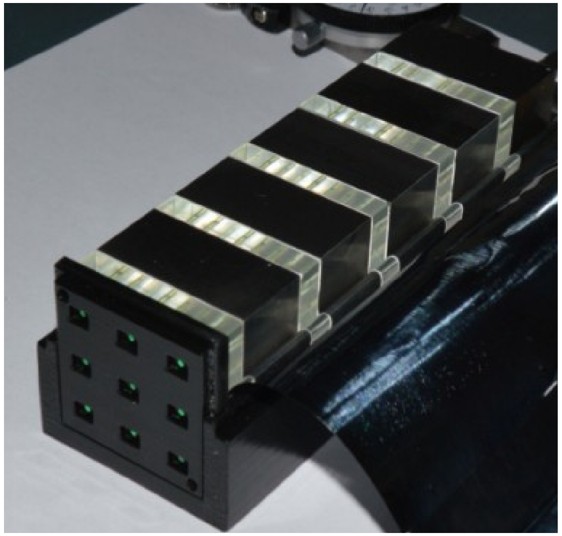


2021 goal
Building/testing a scalable demonstrator consisting of a **3 m long** section of the instrumented tunnel

5 SUPER-MODULEs

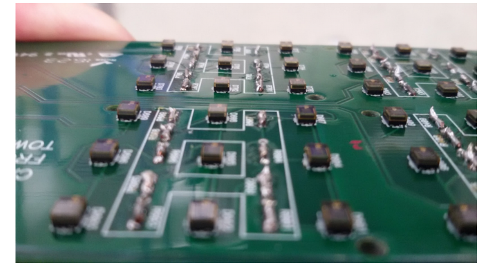
Dimensions:	3 m x π
#SiPMs:	34000
#Channels:	3800
Weight:	~ 5 t
fib length:	~10000 m
Readout:	custom waveform digitizers 2 ns granularity over ~10 ms

The TAGGER – shashlik calorimeter

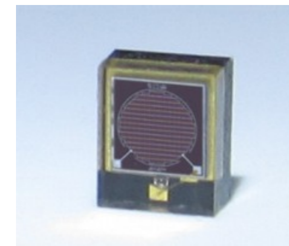


Ultra Compact Module

Dimensions 3x3x10 cm3
5 x (ABSORBER + SCINTI) → **~4 X_0**
Fe-15mm + EJ200
TiO2 painting
WLS: Kuraray Y11 double clad, 1mm diameter



9 SiPMs summed (AC coupled, 47 pF)



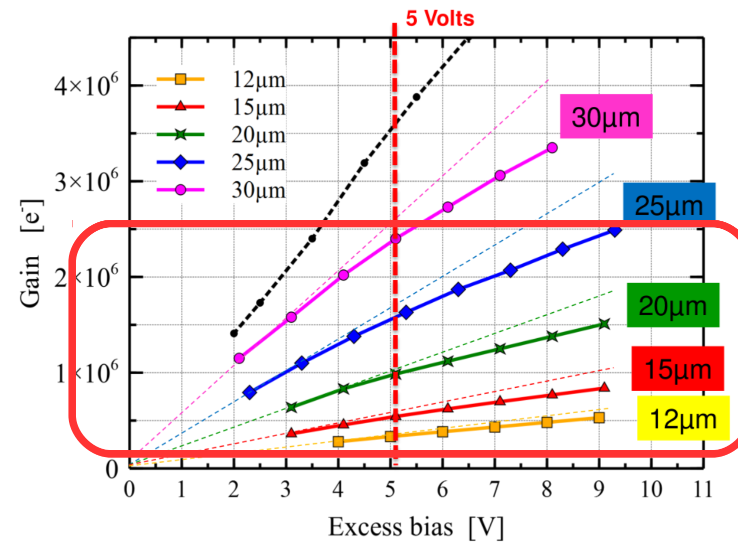
SiPMs: **FBK HD-RGB, 1mm²**

Need to be:
Fast (10ns ← avoid pileup)
Rad.hard (10^{12} n/cm²)

CS	FF	Cell Density
12 × 12 µm²	52 %	~7000 cells/mm²
15 × 15 µm²	62 %	~4444 cells/mm²
20 × 20 µm²	66 %	2500 cells/mm²
25 × 25 µm²	72 %	1600 cells/mm²
30 × 30 µm²	77 %	~1111 cells/mm²

F. Acerbi (FBK) SPW2015

Cell size:
Investigating
tagger prototype



F. Acerbi (FBK) SPW2015

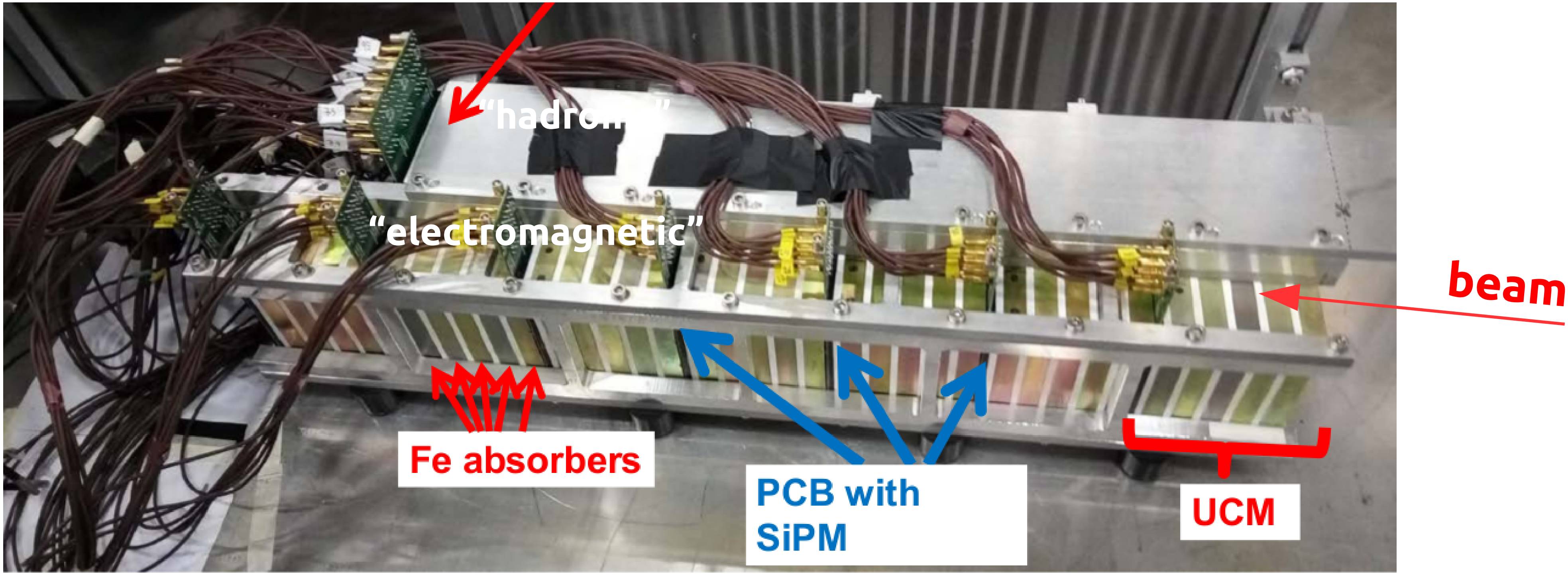
The TAGGER – prototype validation

Test beam at CERN-PS T9 Nov. 2016

1-5 GeV/c e^-,μ^-,π^- PS extracted beam

Test **data/MC agreement** and **e/π separation** at grazing incidence (~ 30 X_0, orientable cradle)

56 (e.m.) + 18 (had.) UCM, 666 SiPM



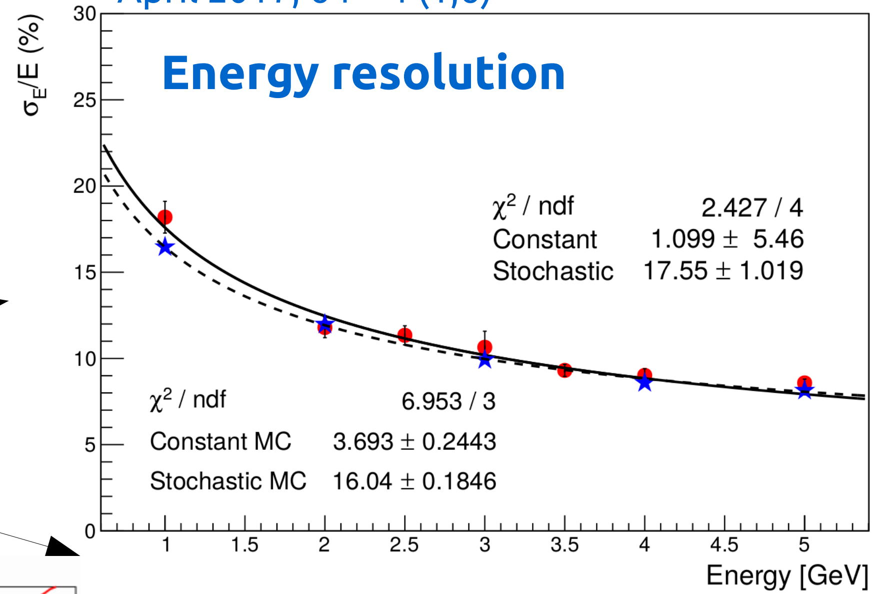
The TAGGER – prototype validation

Test beam at CERN-PS T9 Nov. 2016

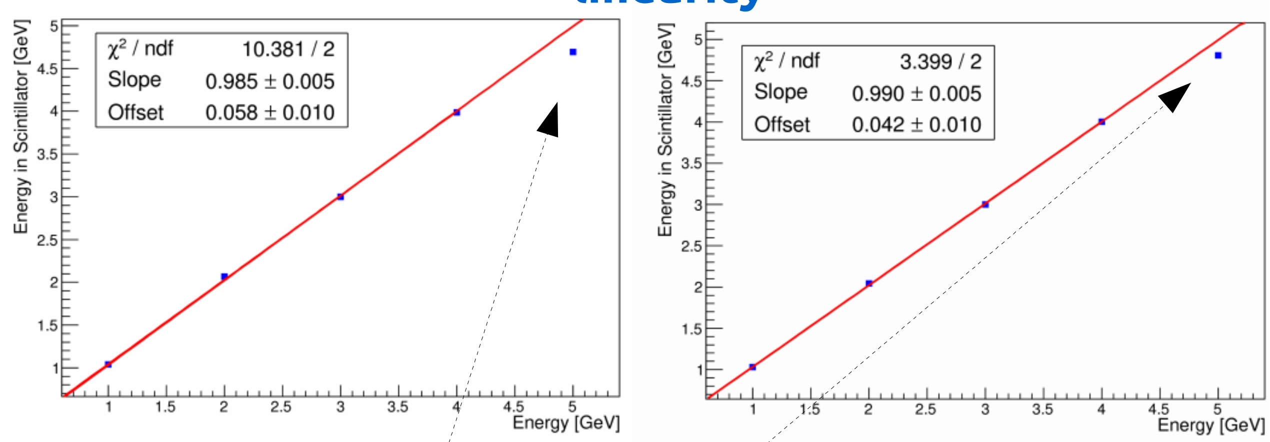
A. Berra et al., IEEE Trans. Nucl. Sci April 2017, 64 – 4 (1,6)

Electrons/muons tagged by T9 Cherenkov counters and a muon catcher. Silicon strip chambers for μ m tracking and fiducialization.
→ linearity, energy resolution, e/π separation

Current **GEANT4** simulation is working reasonably **well already**

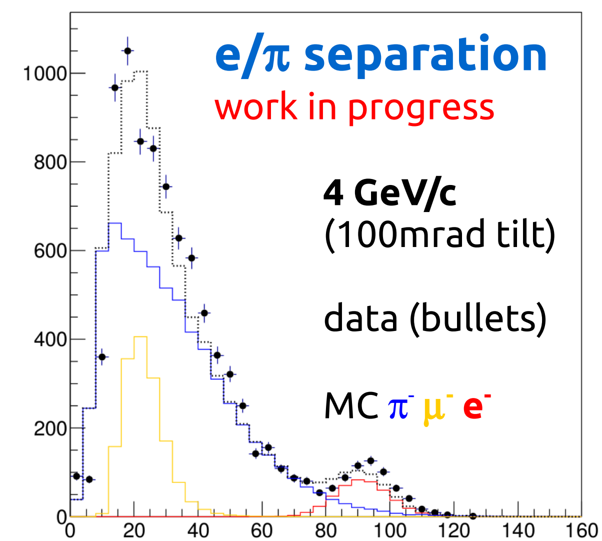


linearity



EMcal EMcal+HADcal

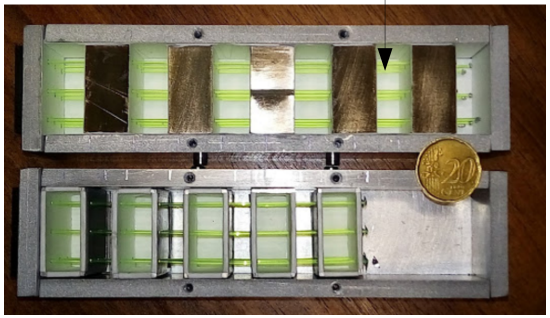
~3% "saturation" at 5 GeV ← investigating

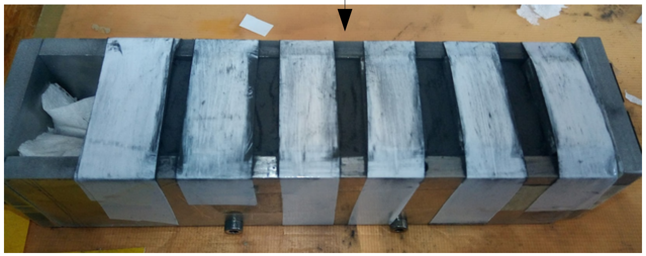


The TAGGER – scinti/absorber variants

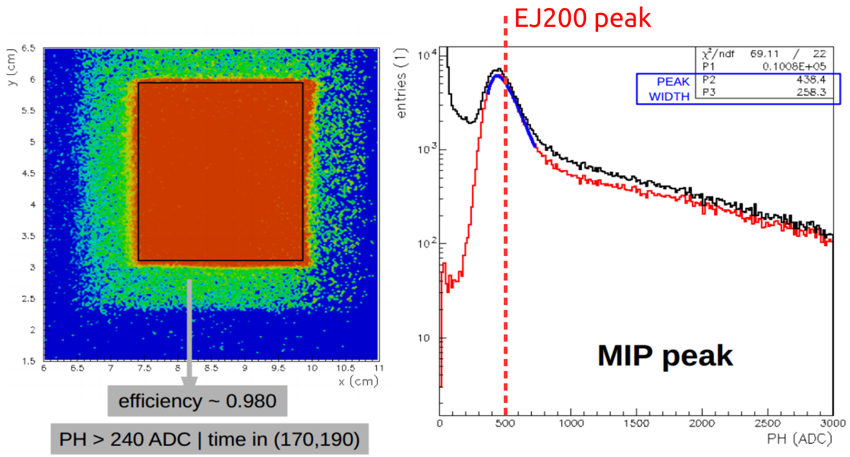
Test beam at CERN-PS T9 May 2017

Polisyloxane scintillators (liquid) + powder absorbers (no drilling!)

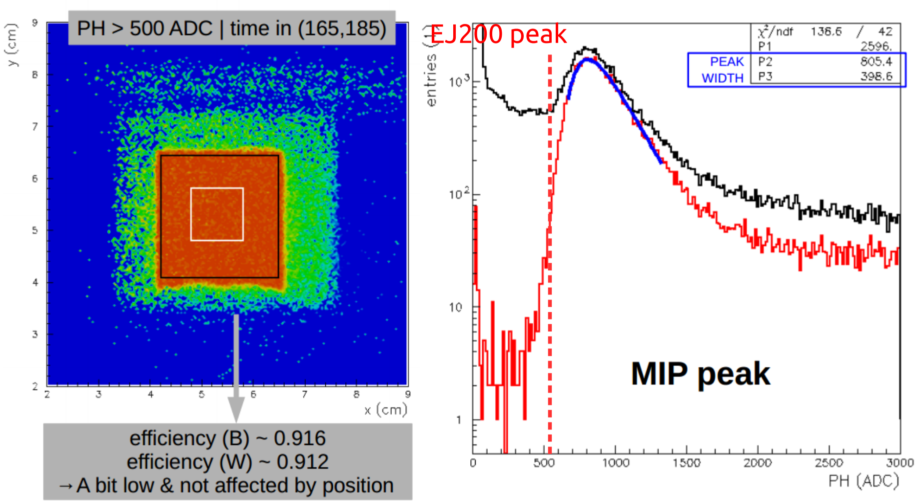




15mm Polisyloxane scintillator



15 Polisyloxane scintillator + 5mm Pb-powder



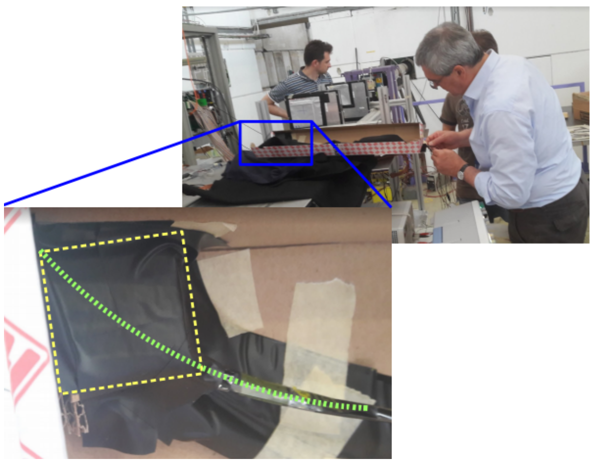
High efficiency, uniformity, light yeld >~ typical organic scinti (with triple thickness wrt EJ200)
→ promising results

The TAGGER – tentative t0-layer

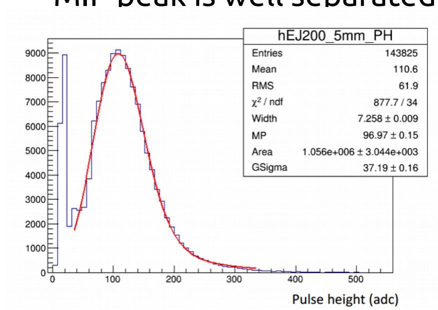
Test beam at CERN-PS T9 May 2017

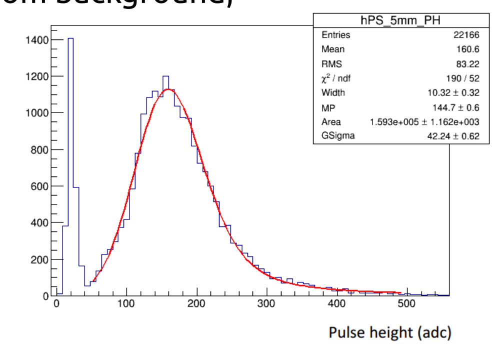
Scintillator Code	Scintillator Type	Thickness (mm)	Wrapping
SC1	EJ200	5.0	Tyvek
SC3	PS (*)	5.0	Tyvek
SC4	PS (*)	8.0	Tyvek
SC5	EJ200	5.0	EJ-510 paint (TiO_2)

4 x detectors :
tile 29.5x29.5 mm², different thickness, type and wrapping
fiber Y11, single cladding, 2.2 mm diameter, ~ 40 cm, glued in a groove along the diagonal, mirrored with mylar

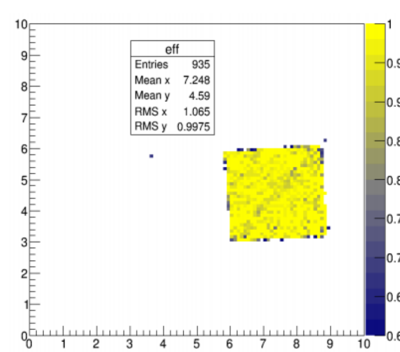


MIP peak is well separated from background;

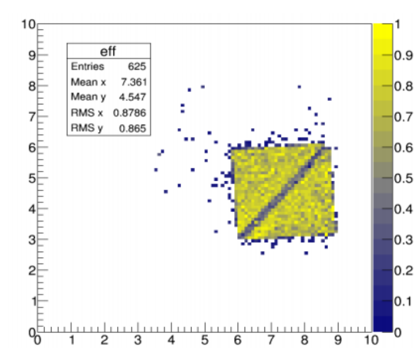




Selection: Pulse Height > 40 ADC counts



Selection: Pulse Height > 140 ADC counts



Uniformity and **efficiency** is good (reduction only on the fiber groove);

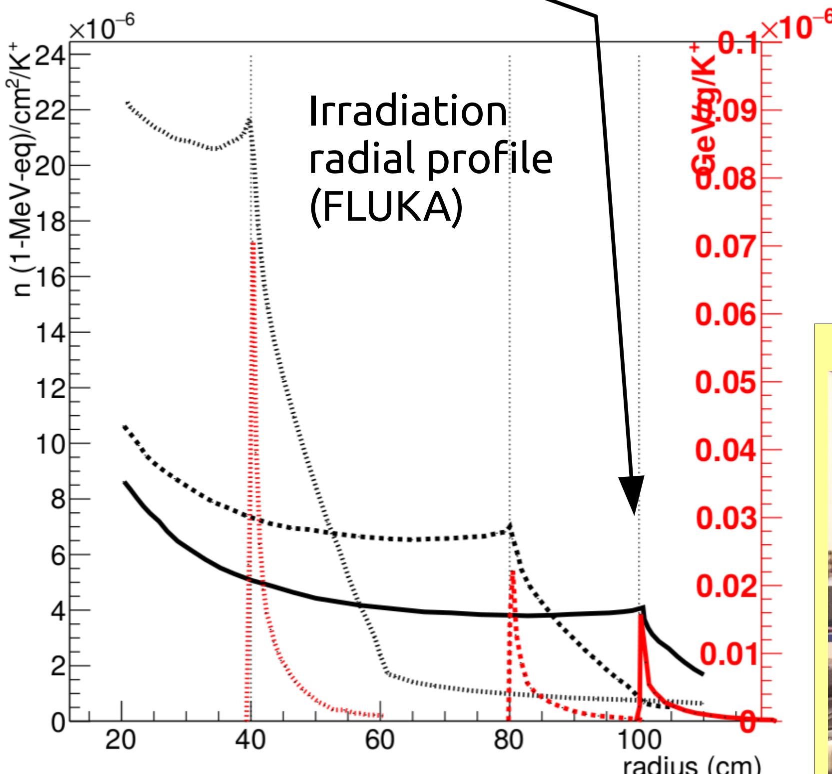
Tyvek seems **better** then paint (comparing 5 mm tile)

Noise issues (← 500MHz/1GHz amplif!)

NEUTRON IRRADIATION - INFN-LNL

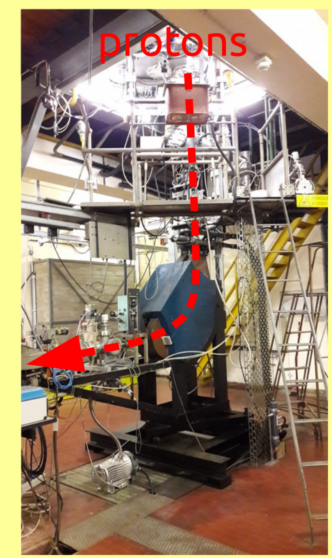
Neutron and ionizing doses have been studied for a tagger radius of **40**, **80** and **100 cm** with **FLUKA** and cross-checked with **GEANT4**.

Choosing **100 cm** allows ~ **10^{12} 1MeV-eq/cm^2 n** and **~0.25 kGy** in the innermost layers in the detector Lifetime (~10y)



Van de Graff CN accelerator
@ **L**aboratori **N**azionali di **L**egnaro

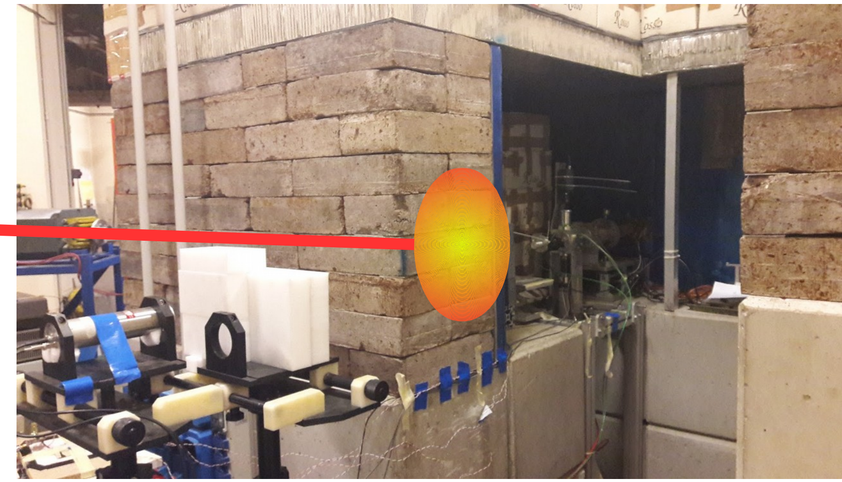
p (5MeV)+^{9}Be → n + X
p currents ~< 1uA
n spectrum ~1-3 MeV

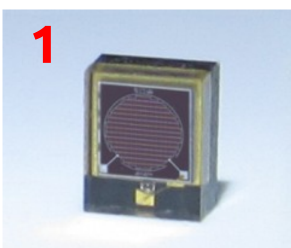


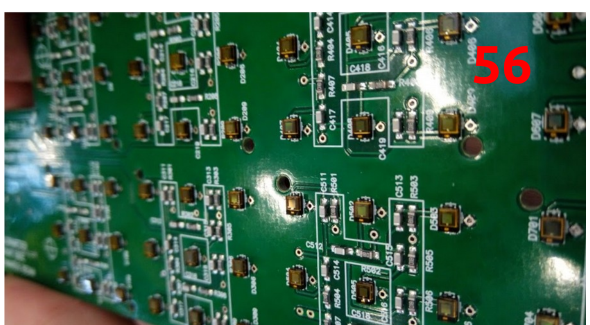
NEUTRON IRRADIATION - INFN-LNL

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)





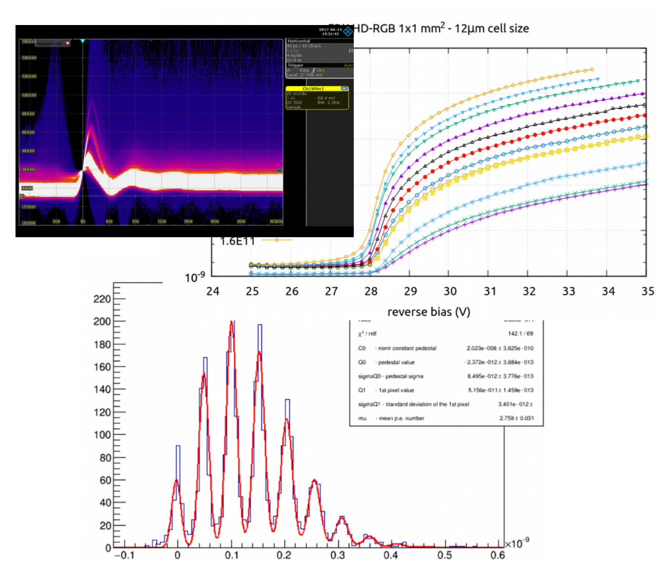


Monitoring of:

- I-V curves (live)
- Waveforms
- Gain (p.e. spectrum)

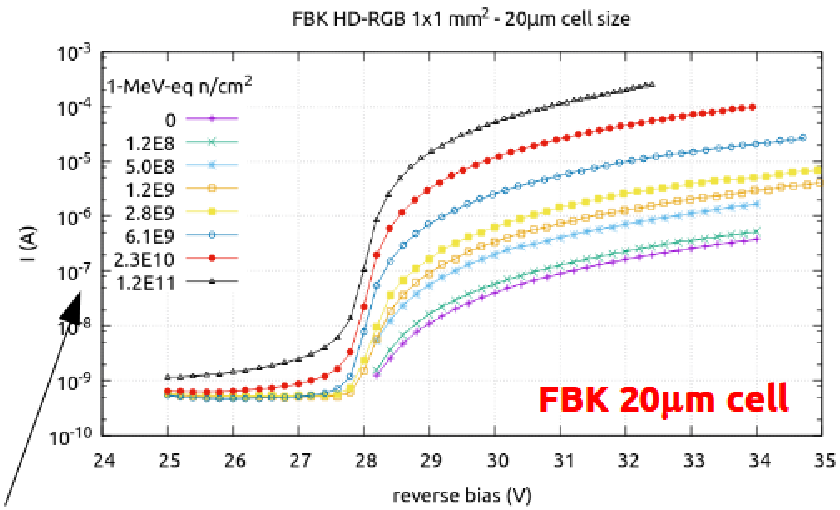
Analysis is ongoing
(sorry! ended last week…)

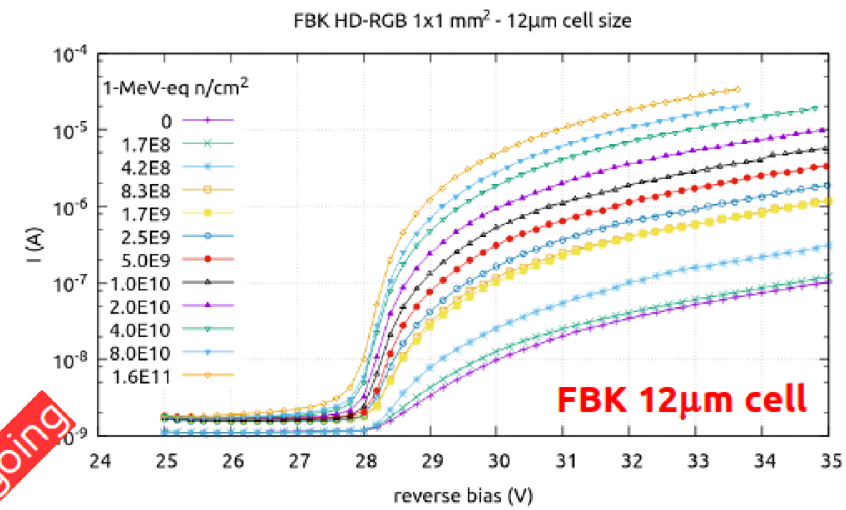
Post irradiation:
(No annealing)
→ CERN **test beam incoming** (end of July)



NEUTRON IRRADIATION – data

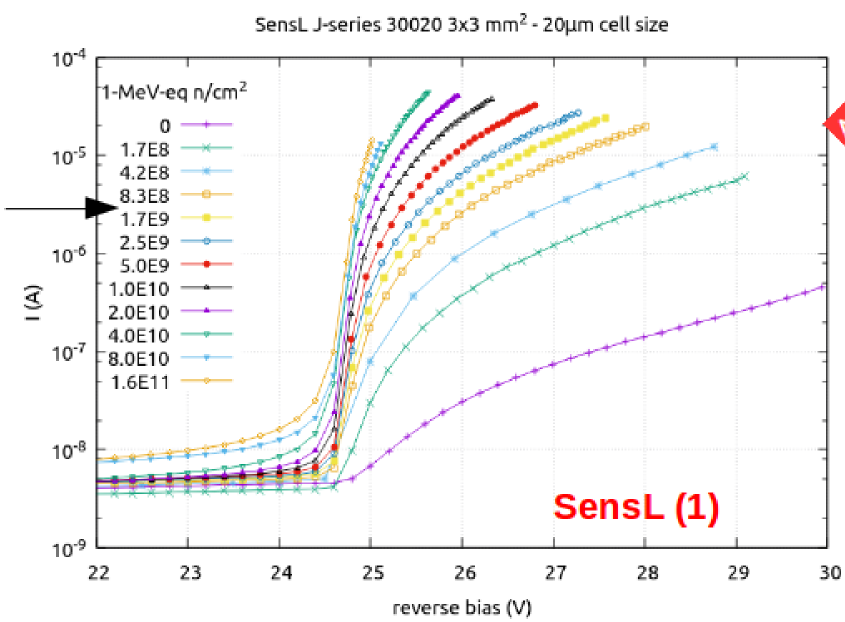
VERY PRELIMINARY (analysis and fluence calc.+simul. in progress) – data taking ended last week!

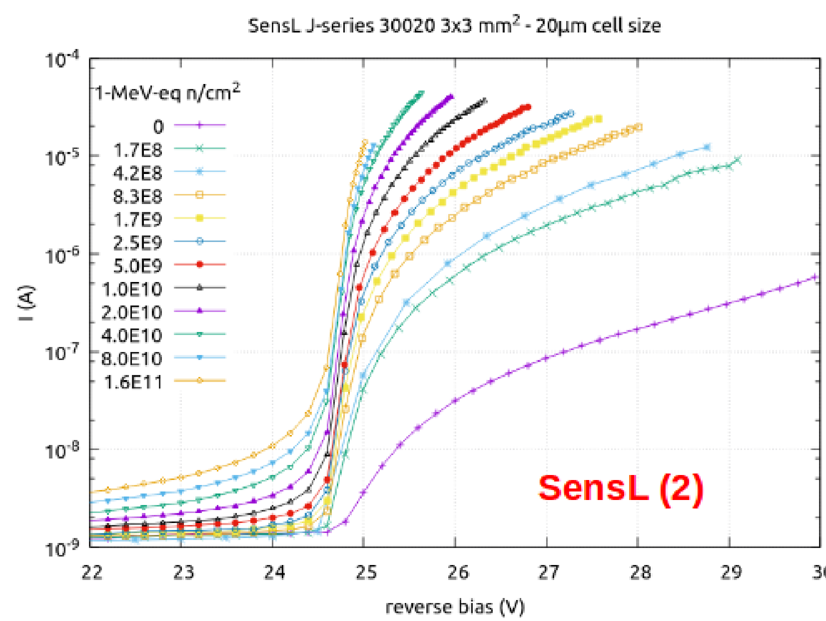




fluence calculation to be refined!

Analysis is ongoing





CONCLUSIONS & OUTLOOKS

- Neutrino flux error limit could be reduced by 1 order of magnitude exploting $\mathbf{K^+ \rightarrow \pi^0 e^+ \nu_e}$
- In the **next 4 years** **ENUBET** will investigate this approach and its application to a **new generation of cross section experiments**

- In the **1st year of the project** a rich simulation (beam & tagger) and prototyping program (**tagger**) is giving very promising results

- Challenging open items ahead, lots of ongoing R&D activities (**2017/2018**):

  test of irradiated SiPMs
  achieve recovery time of ~10ns (to cope with pile up, now 50ns)
  test of custom digitizers electronics
  photon veto prototypes with plastic scintillators
  Scalable/reproducible technological solutions like molded scintillators, water-jet holes machining for absorbers, polysiloxane scintillators, powder absorbers

THANK YOU!

ENUBET info/wiki

http://enubet.pd.infn.it

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