http://enubet.pd.infn.it

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).

F. Pupilli
A. Longhin
(DFA-UniPD & INFN)

Workshop Excellence Project – DFA-UniPD – 28/09/2020

R&D of calorimeters and detectors for neutrino physics

in the framework of

ENUBET

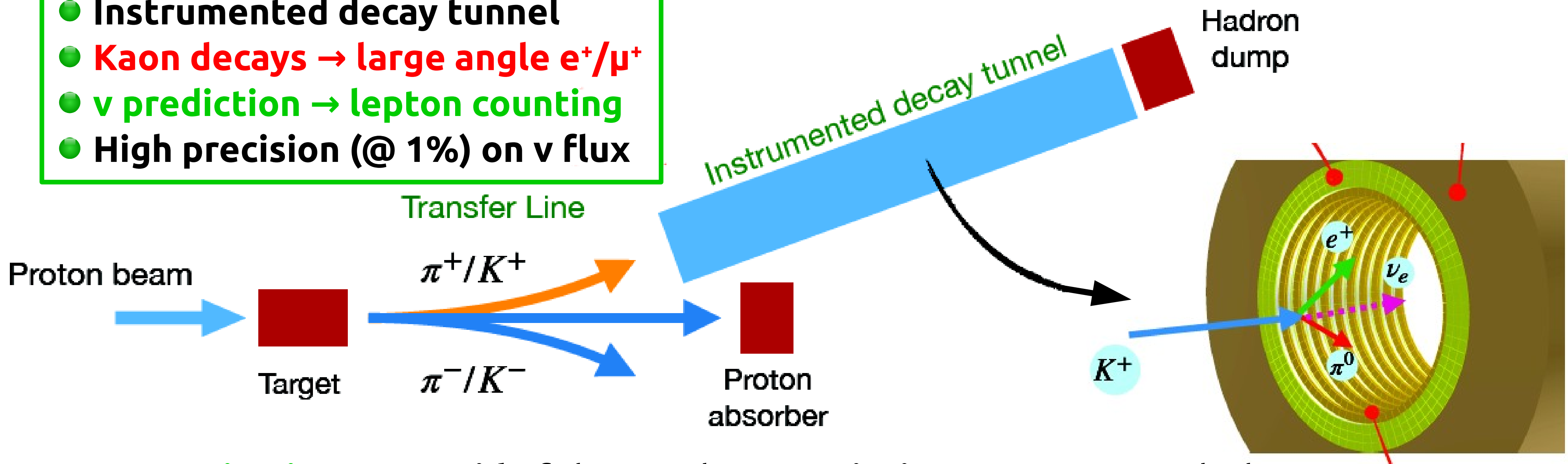
ENUBET Collaboration: 60 physicists, 12 institutions

NP06/ENUBET

A new narrow-band neutrino beam for high precision cross section measurement in the DUNE/Hyper-K era

- **ERC Cons. Grant (2016-2021)** [ENUBET, PI: A. Longhin, UniPD (host) + INFN]
- *Grant MIUR – Bando FARE (2017-2021)* [ENUBET/NUTECH]
- Since April 2019, ENUBET is also a **CERN Neutrino Platform experiment: NP06**

- **Instrumented decay tunnel**
- **Kaon decays → large angle e^+/μ^+**
- **ν prediction → lepton counting**
- **High precision (@ 1%) on ν flux**



Lepton monitoring → **Get rid** of the usual **uncertainties** in conventional ν beams (Hadro-production, protons on target, beam-line efficiency)

Main goals
1) Design/simulate the layout of the **hadronic beam-line**
2) Build/test a **demonstrator** of the **instrumented decay tunnel**

ENUBET physics programme

A narrow band beam at the GeV scale with a **superior control of the neutrino flux, flavor and energy** of the neutrinos produced at source

An ideal facility, exploiting conventional techniques, to:

- serve a new generation of short-baseline experiments in order to reach **1% precision** measurement of the **ν_e and ν_μ cross sections**
- study of neutrino interactions at the GeV scale with **"low" mass, high-granularity detectors**
- reduce below 3% the systematics of **DUNE and HyperK** and enhance their discovery reach (CP, unitarity tests, precision on angles etc.) and a natural follow-up of the Minerva and ProtoDUNE physics programme

The ENUBET research programme received an important **endorsement** in the **EU strategy**:

> To extract the most physics from DUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied. Other important

European Strategy for Particle Physics Deliberation document (pag. 5)

Explicit reference to **ENUBET** and nuSTORM

ENUBET: instrumented decay tunnel

Requirements:

- Allow **$e^+/\pi^{\pm,0}$ separation** in the GeV energy region
- **Suppress** background from **beam halo** (μ, γ, non collimated hadrons)
- Sustain O(MHz) rate and **suppress pile-up effects** (recovery time ≤ 20 ns)
- **Cost-effective** (to instrument a 40m long decay tunnel)

Calorimeter

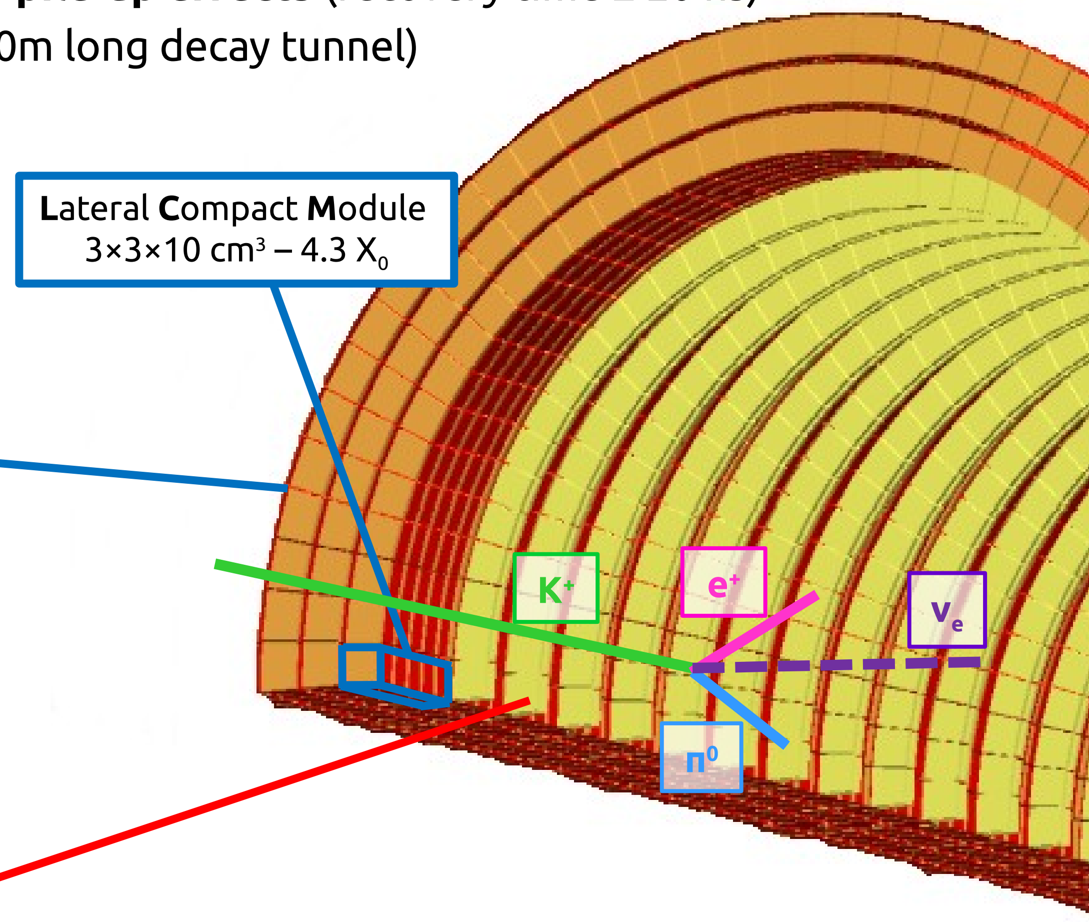
Longitudinal segmentation
Plastic scintillator + Iron absorbers
Lateral light readout with WLS+SiPM

→ $e^+/\pi^\pm/\mu$ separation

Integrated photon veto (t0-layer)

Plastic scintillators
Rings of 3×3 cm^2 pads readout by SiPM

→ π^0/γ rejection



e^+ (signal) topology

π^0 (background) topology

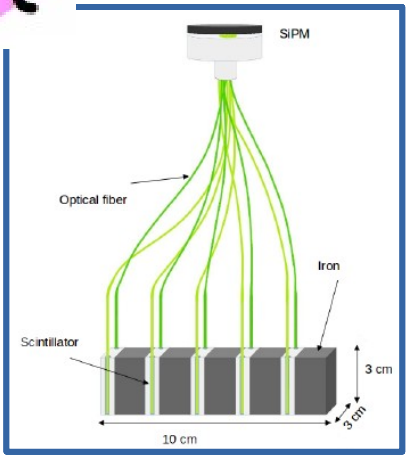
π^+ (background) topology

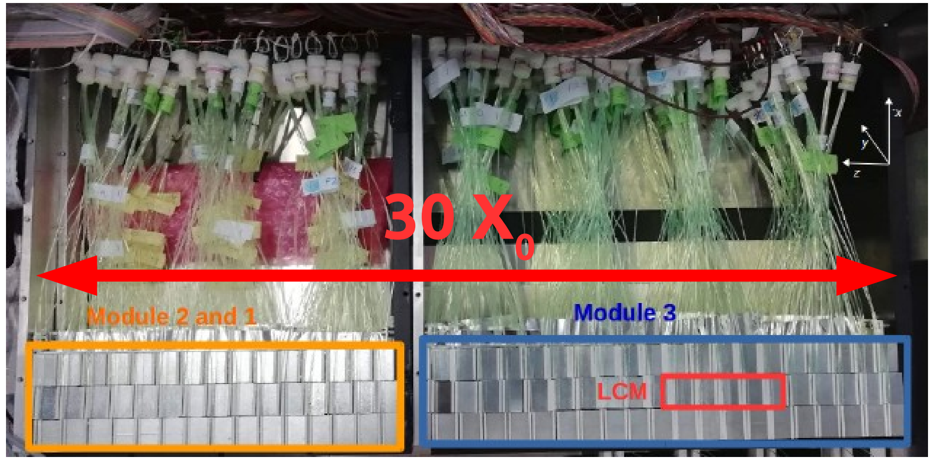
An intense testbeam activity

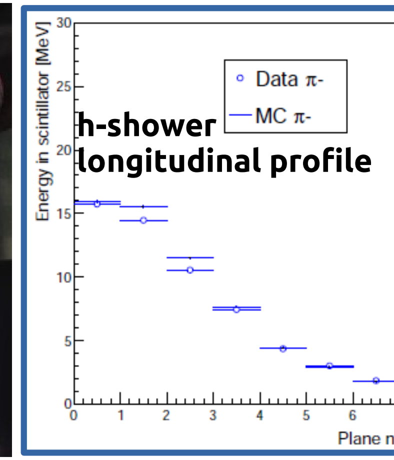
CERN-PS (x7) **INFN-LNL CN** **INFN-LNF BTF**

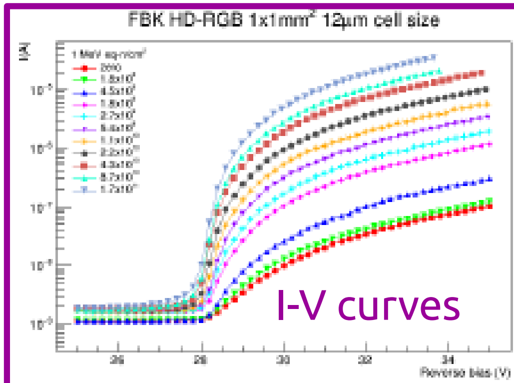
ENUBET: postcards from testbeam

Calorimeter





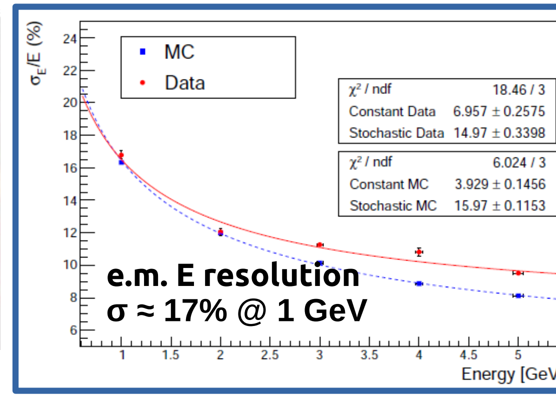




SiPM

Rad hardness test with n ($\leq 10^{11}$/cm²) @ CN-LNL

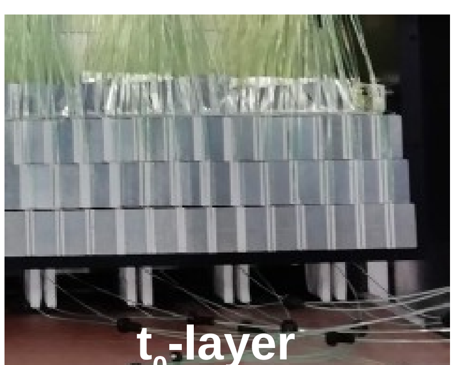
JINST14 (2020) P02029

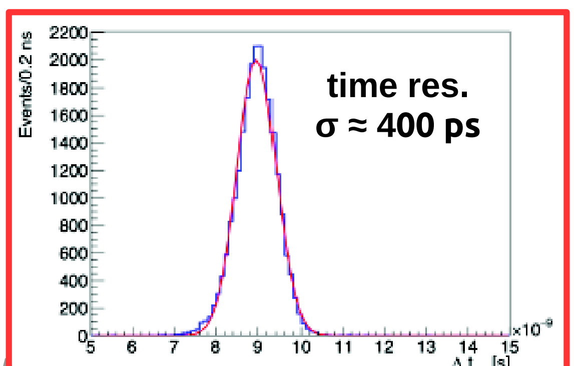


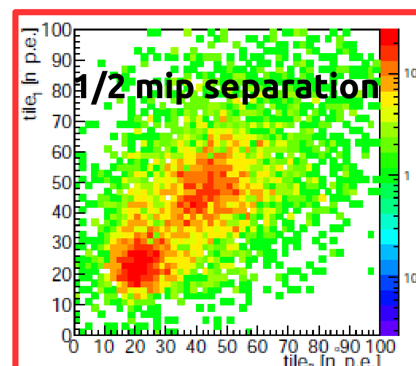
Testbeam @CERN-PS T9 beamline

JINST15 (2020) P08001

Photon veto

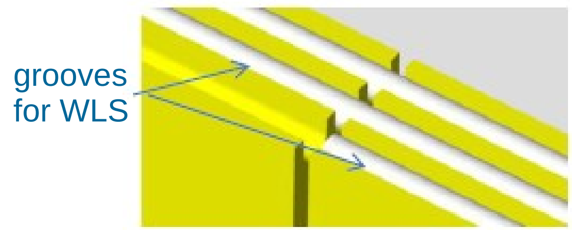


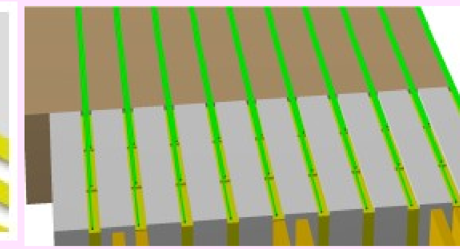




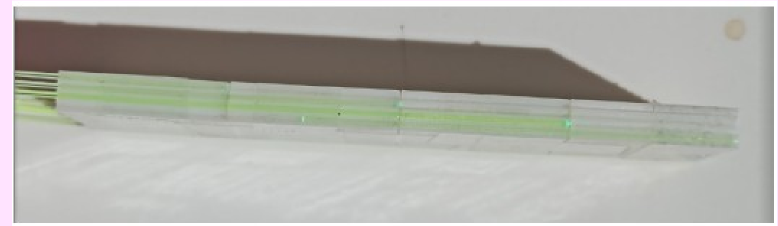
The ENUBET demonstrator

- **Large prototype** (3m length, fraction of φ) to demonstrate **performance**, **scalability** and **cost effectiveness**
- Will be **assembled** in **INFN-LNL** in 2021
- Validation in the East Area at **CERN-PS** after LS2 (2022)



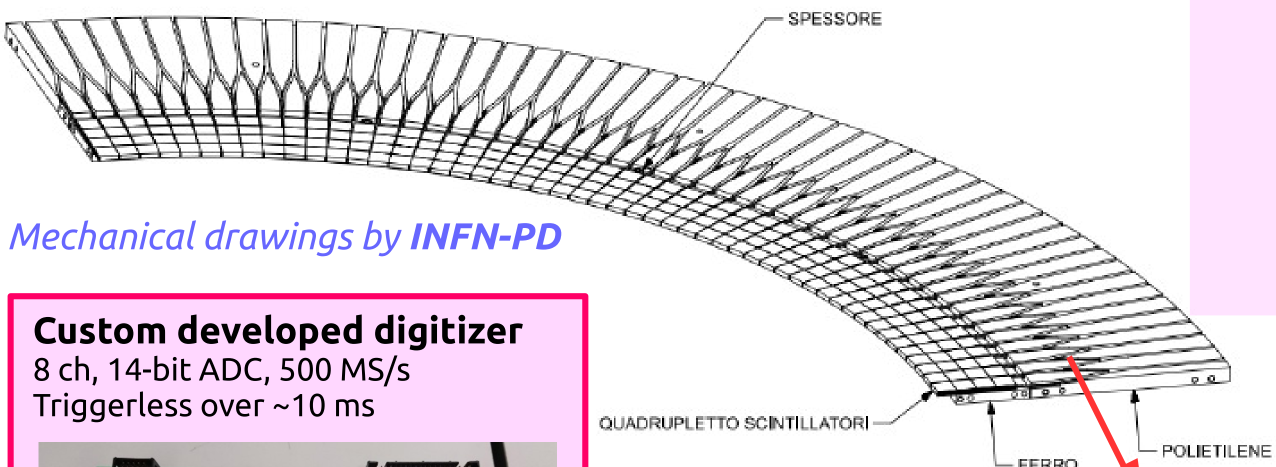


WLS will be **staggered** on the side of scint tiles to collect light from different layers



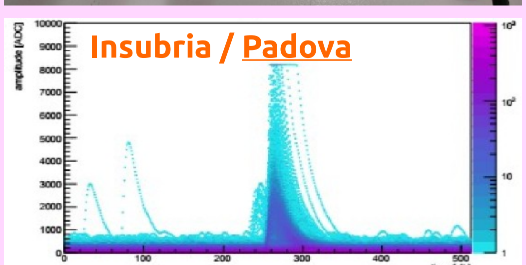
Mockup 3D printed in **INFN-PD** mech. workshop

Final tiles produced with **injection molding** by **UNIPLAST** (Russia)

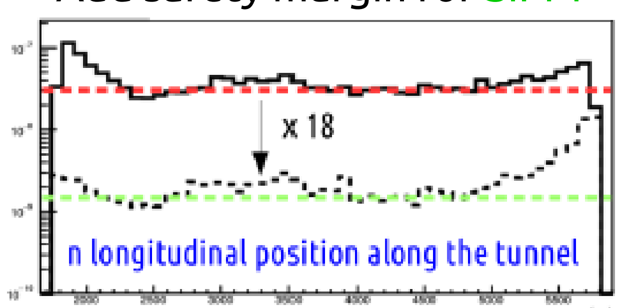


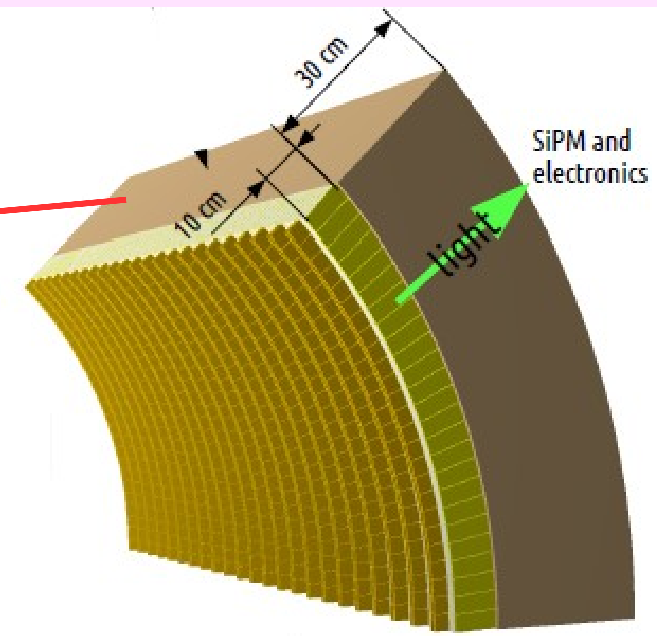
*Mechanical drawings by **INFN-PD***

Custom developed digitizer
8 ch, 14-bit ADC, 500 MS/s
Triggerless over ~10 ms

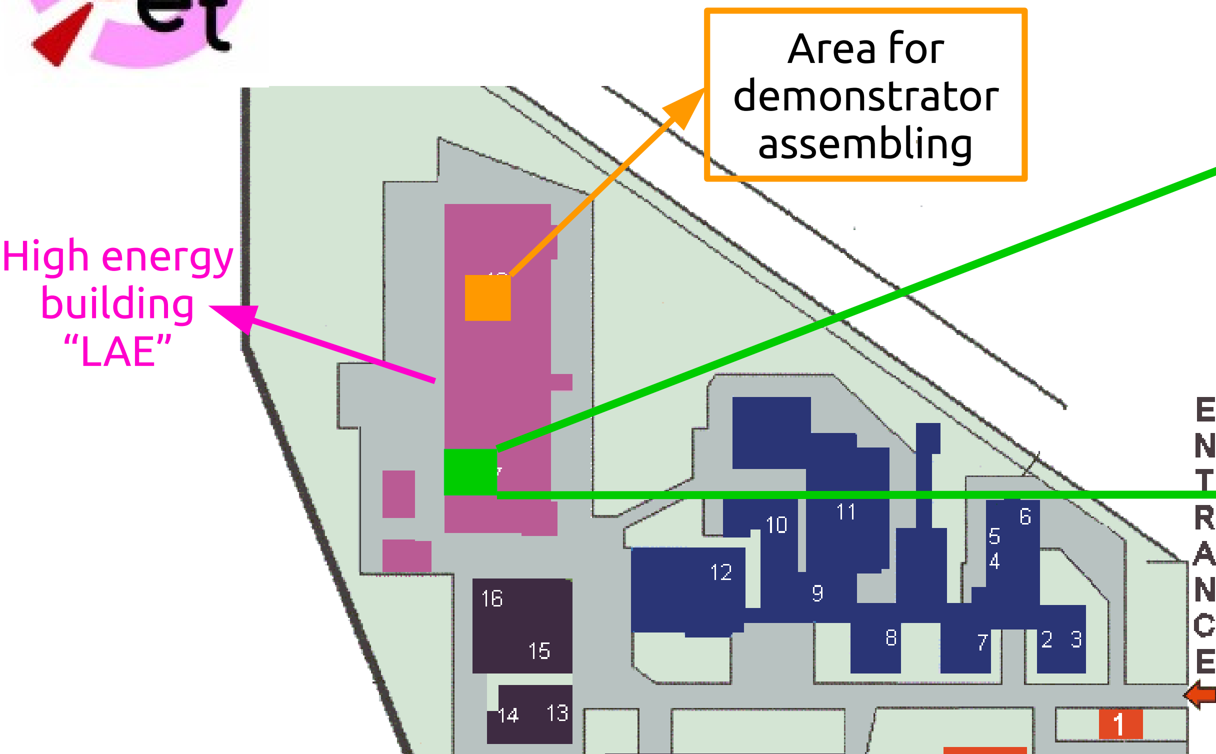


30 cm borated polyethylene
→ ~ **x18 neutron reduction**
Add safety margin for SiPM



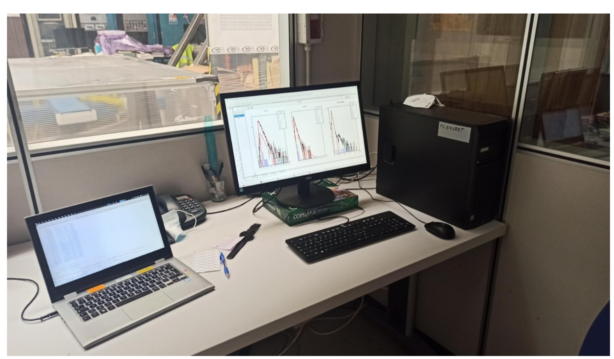


The ENUBET lab @ INFN-LNL



Team

- A. Longhin
- G. Collazuol
- F. Pupilli (AdR)
- M. Pari (PhD)
- C. Delogu (PhD)
- S. Capelli (borsa)



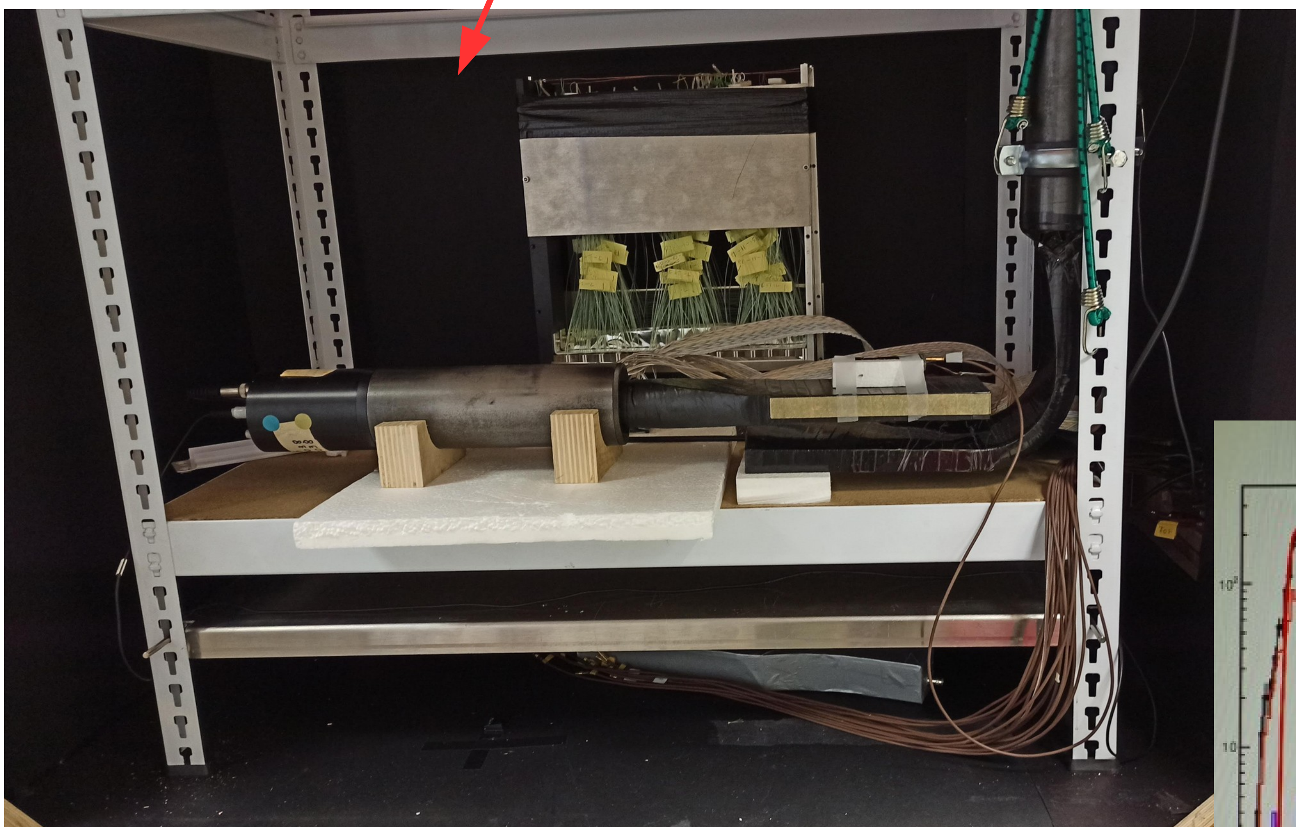
Office/DAQ

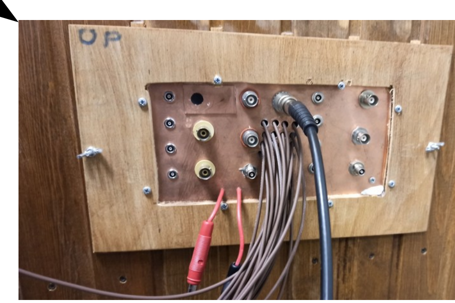
Lab space

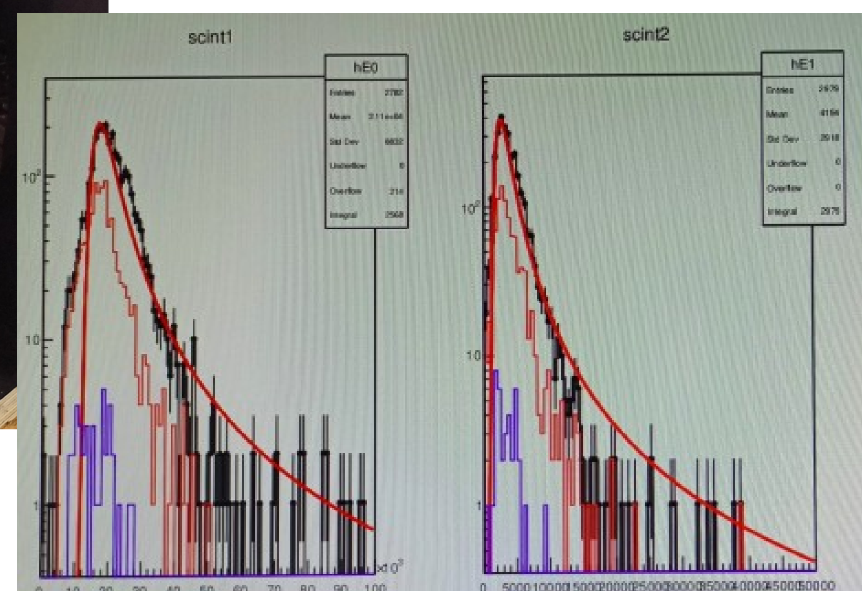
Cosmic ray teststand @ LNL (I)

Cosmic ray test facility

- Generic tools for **detector R&D** are in place
- Used so far for the characterization of **calorimeter modules**, tests of **SiPMs** in support of the test beam campaigns (similar setups for ENUBET at Bologna, UNINSUBRIA and Milano Bicocca). Key role for **testing** before the **demonstrator** assembling
- Wide lightproof box (1 x 1.5 x 1 m^3) with *patch panel*







> 2 trigger scintillators + PMTs
R/O: CAEN V1743 (custom digitizers in the future)

Cosmic ray teststand @ LNL (II)

Silicon strip detectors

for particle tracking

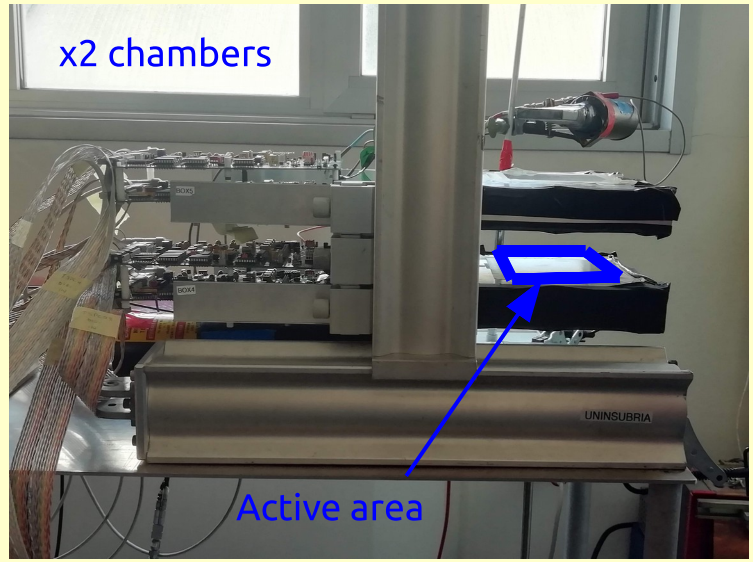
and high resolution

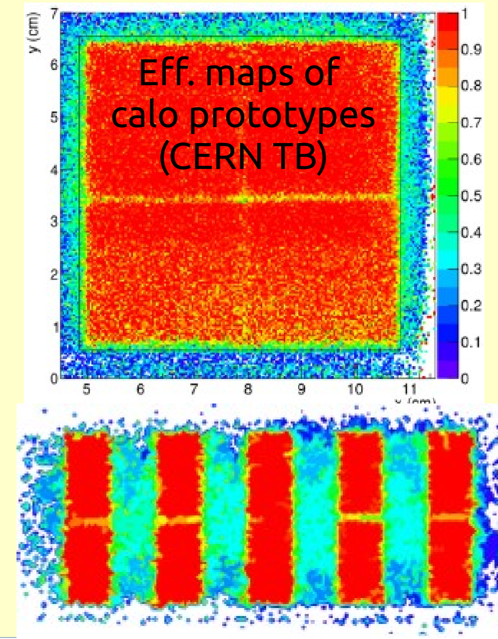
efficiency maps

Developed for AGILE

NIMA 501 (2003) 280

- **Active area**: 10x10 cm^2
- **σ ≈ 30 μm**

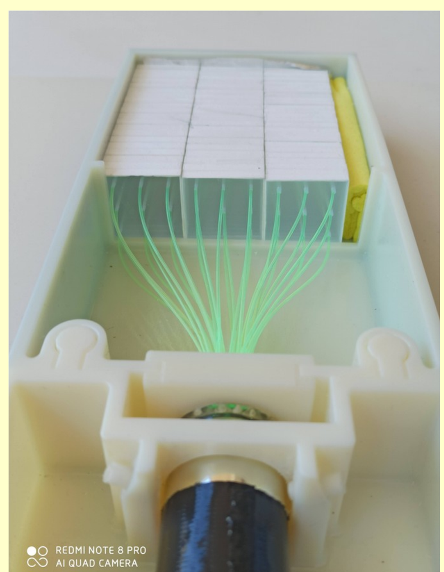


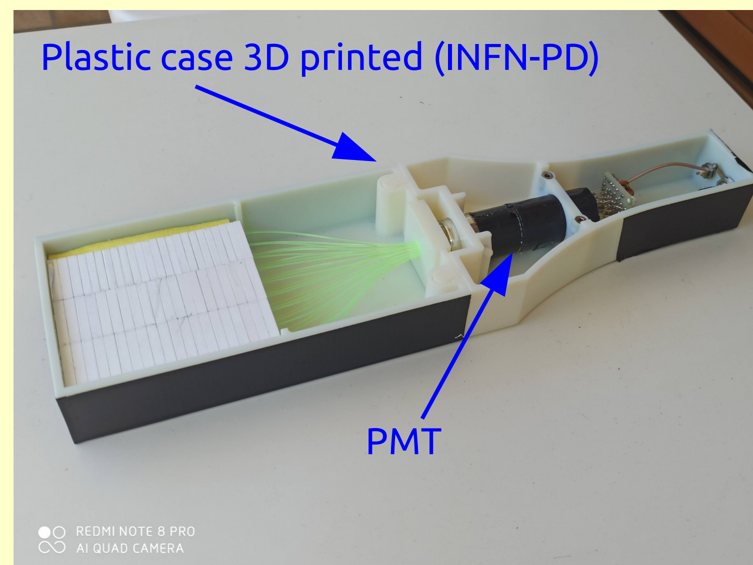


Trigger scintillator

3D printed at INFN mech. Workshop. Uses tiles developed for shashlik calorimeters R&D in collaboration with INR Moskow

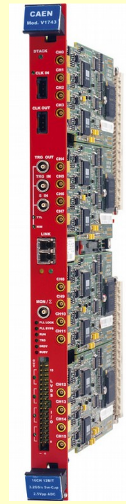
- **Active area**: ~10x10 cm^2

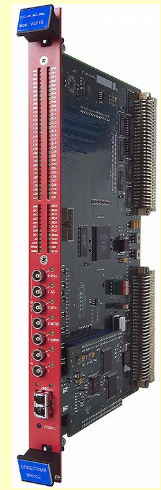


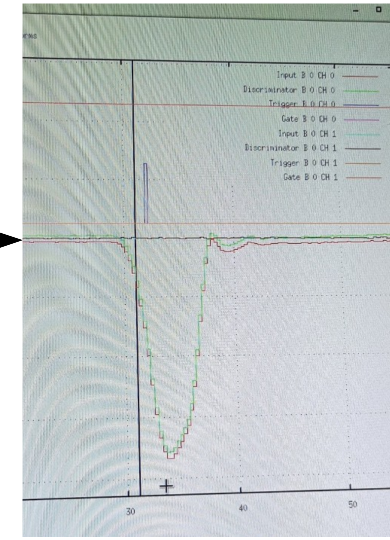


Readout & Instrumentation

Digitizer

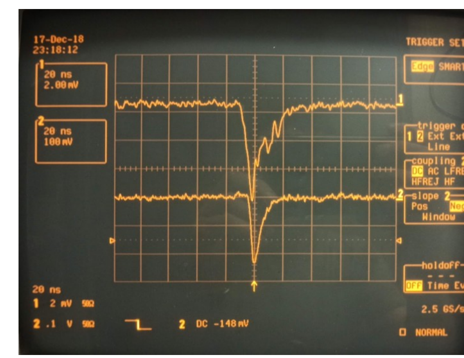






CAEN V1743
- 16 ch
- 12 bit
- 3.2 GS/s
- 2.5 Vpp dynamic range

CAEN V2718 VME-PCI Optical link bridge + **A3818** PCI controller



Lecroy oscill.

Multichannel Analyzer

CAEN DT5781
- 2 channels

Laser

ALPHALAS Picosecond Pulse Laser Diode
- 405 nm
- <40 ps pulse width

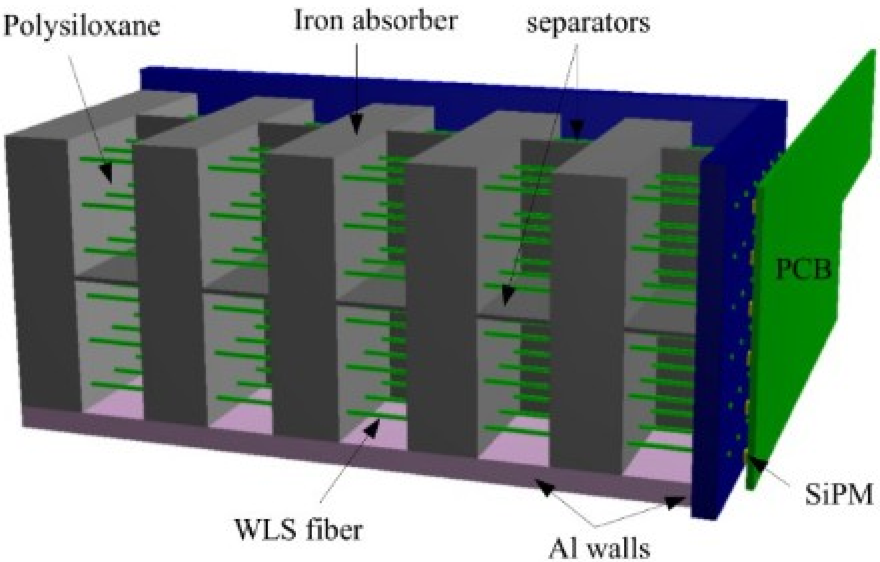
Picommeter for SiPM i-V curves

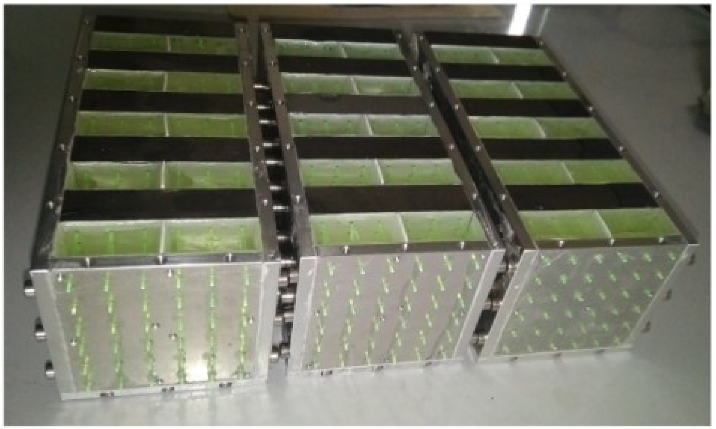
Polysiloxane-based scintillators

NIMA 956 (2020) 163379

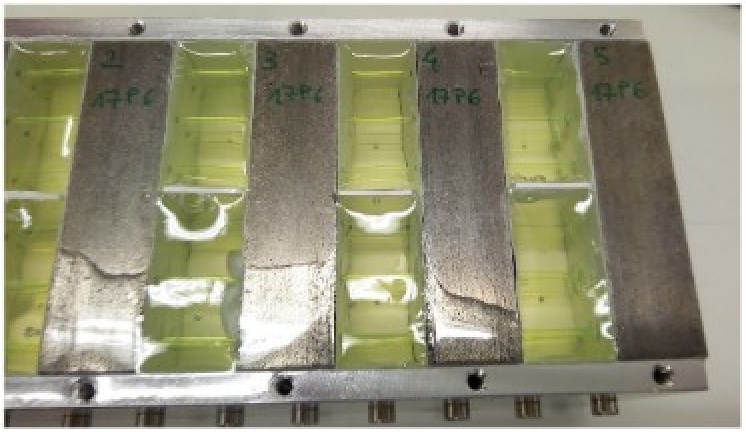
Polysiloxane resin instead of plastic with suitable dyes for scintillation

- A 13X_0 shashlik calorimeter prototype tested in 2017-18 @ CERN (**first application** in HEP!)
- **Pros:** increased **radiation hardness** (no yellowing), **simpler** (just pouring+reticulation)

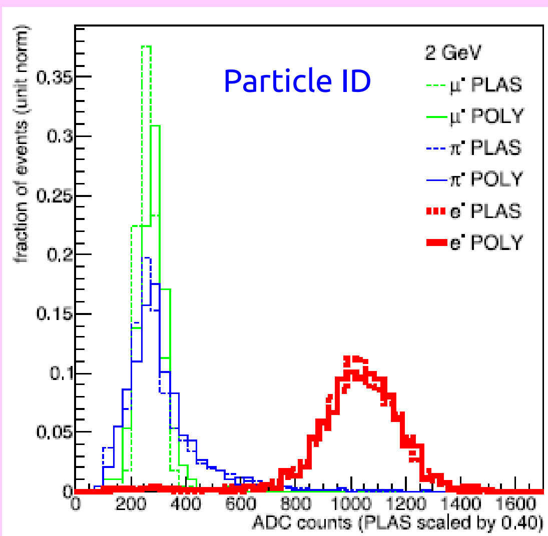


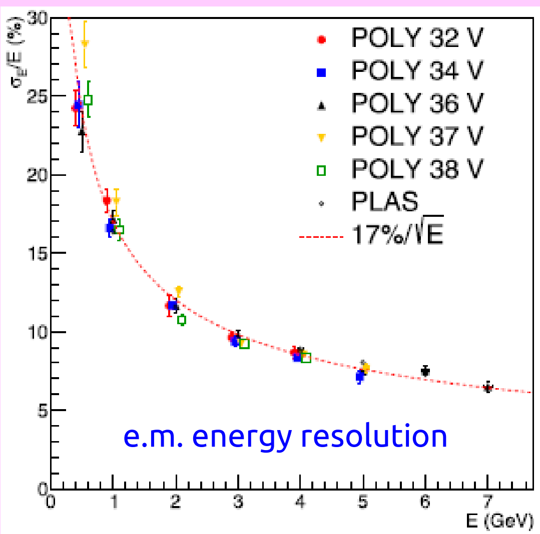


Scintillator prepared by **S. Carturan** (INFN-LNL)



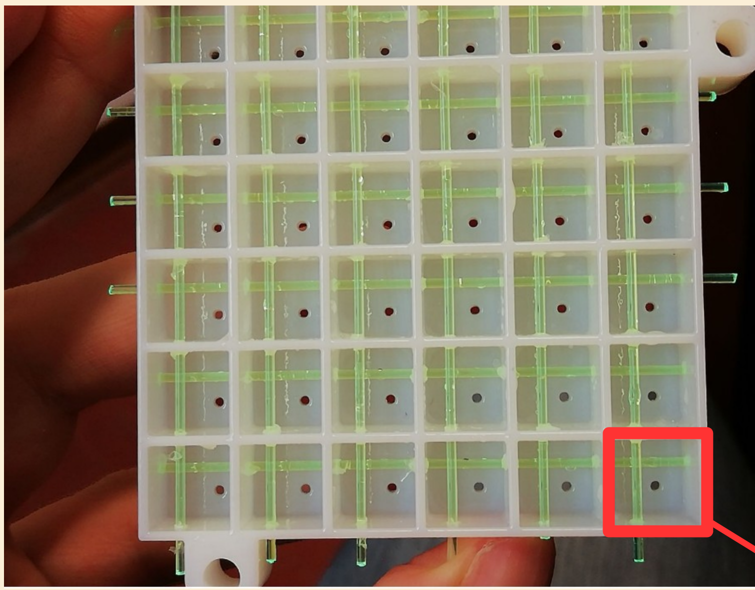
Light yield ~1/3 wrt plastic, but similar calorimetric performance



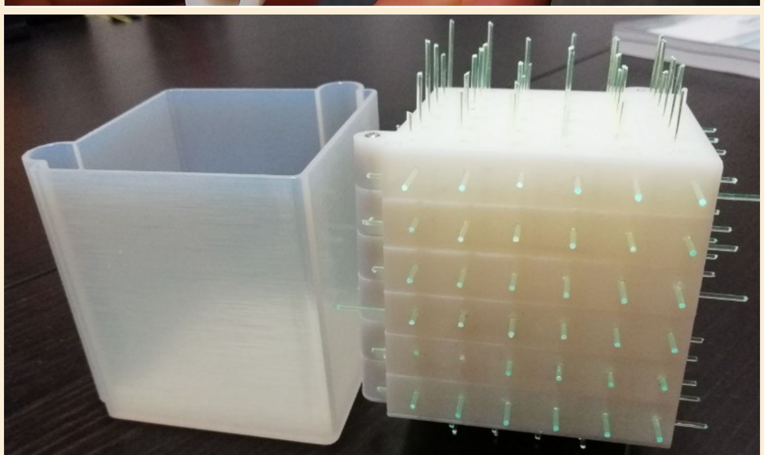


More collateral detector R&D
(work in progress)

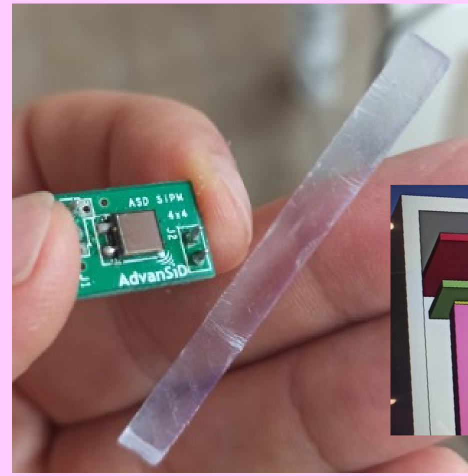
Polysiloxane-based high granularity neutrino targets. 3 views. Same idea of the new T2K near detector (SuperFGD) but without the need of assemblying millions of mechanically independent cubes → pouring into a frame.

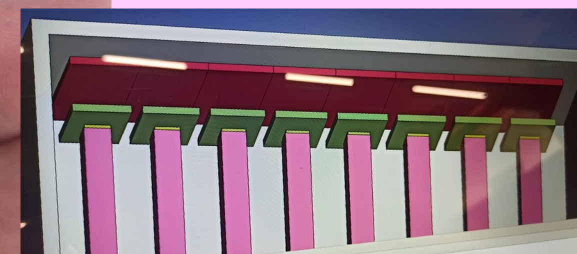


1x1x1 cm^3



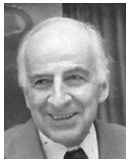
Tracker with scintillator bars readout with a delay line. Hit strip is determined by the delay of the signal → good granularity with just a single channel per view in place of N (G. Collazuol).





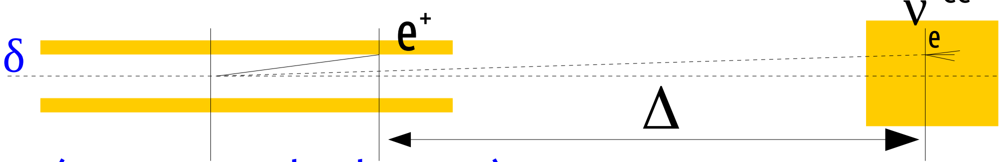
NUTECH: high res timing detectors

Side project (funded by MIUR) to investigate the feasibility of a **time-tagged neutrino beam** based on the ENUBET technology


Pontecorvo

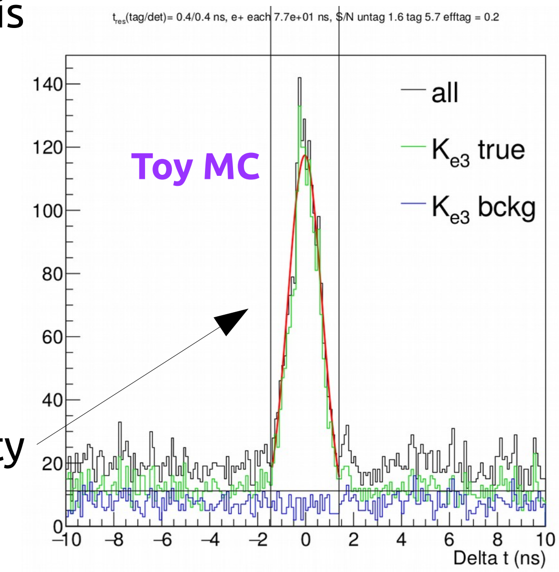
Time coincidence among **neutrino interaction** at the detector and **e⁺** at production
→ E_ν and flavor of the interacting ν measured a priori on a event by event basis

Time coincidence of ν_e^{CC} and e^+ $|\delta t - \Delta/c| < \delta$



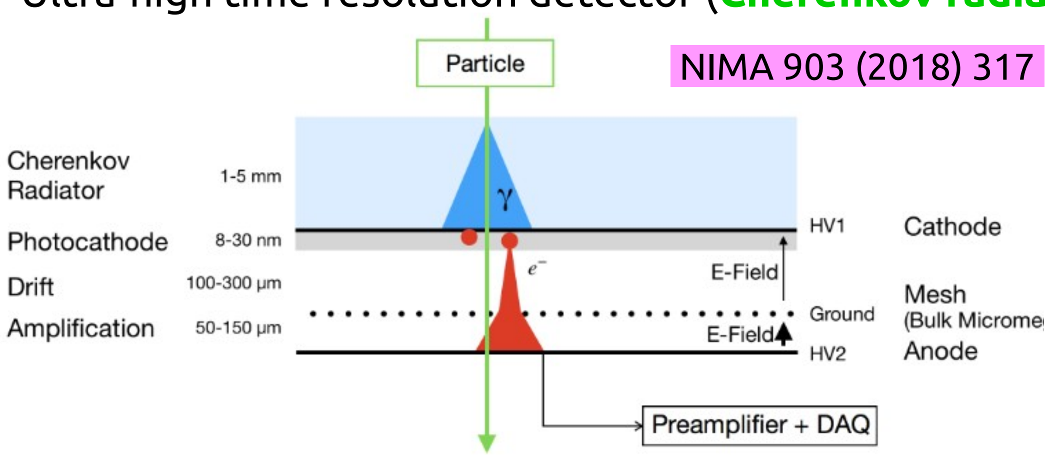
δ = combined t-resolution (e⁺ tagger and ν detector)

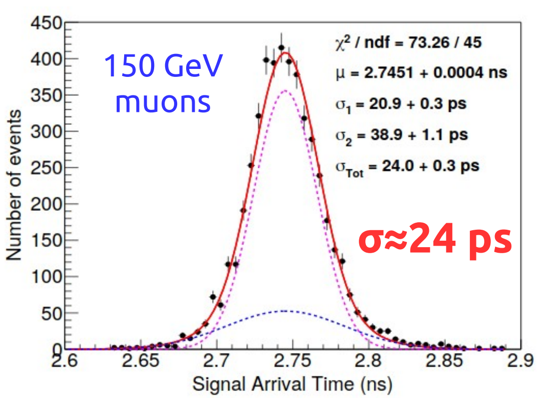
Already with δ=0.4 + 0.4 ns results in a correct association with interesting purity



Recent discussions with the **PICOSEC collaboration**
Ultra-high time resolution detector (**Cherenkov radiator+MicroMegas**) to improve the tagger timing

NIMA 903 (2018) 317





Possible implementations:

- as t_0-layer
- in the bulk of the calorimeter

Summary

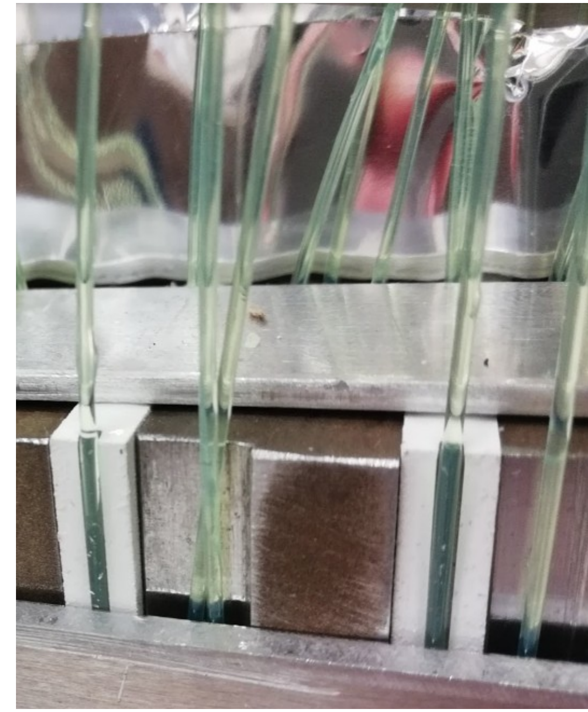
ENUBET+NUTECH: calorimetry and timing for instrumented decay tunnels for particle monitoring and PID at extreme rates and doses

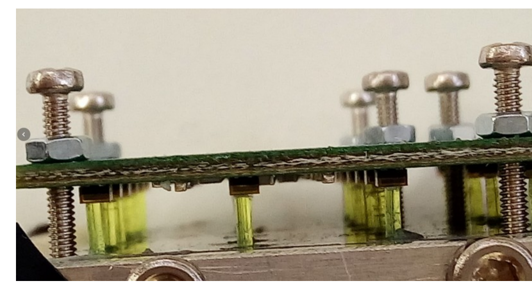
- New **light readout schemes**
  - shashlik → lateral readout with neutron shielding
- **Irradiation tests** for SiPM at INFN-LNL (CN)
- Large **demonstrator** will be soon be assembled @ LNL
- Development of **custom digitizers** for triggerless read-out

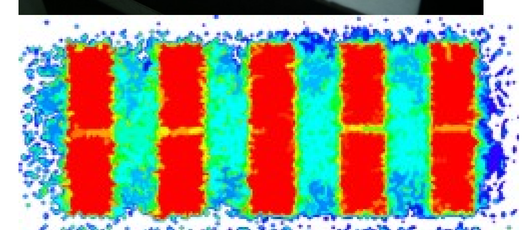
- "colletaral" new ideas:
  - **polysiloxane shashlik calorimeters**
  - polysiloxane **highly granular neutrino targets**

Bulk of R&D at **test beams** but we have a **running cosmic ray test stand setup** for generic future detector R&D studies with:

- A **30 um Si tracker** → high resolution efficiency maps
- **3.2 GS/s digitizer + ps laser**
  - R&D with PICOSEC MICROMEGAS technology
  - More future ideas







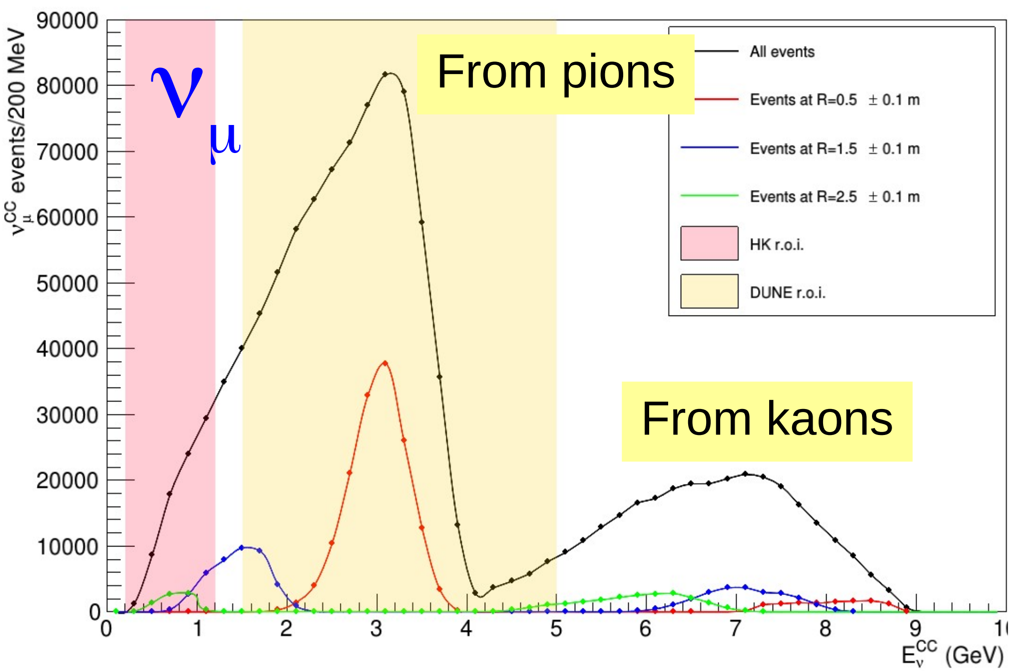
Backup slides

Neutrino events per year at the detector

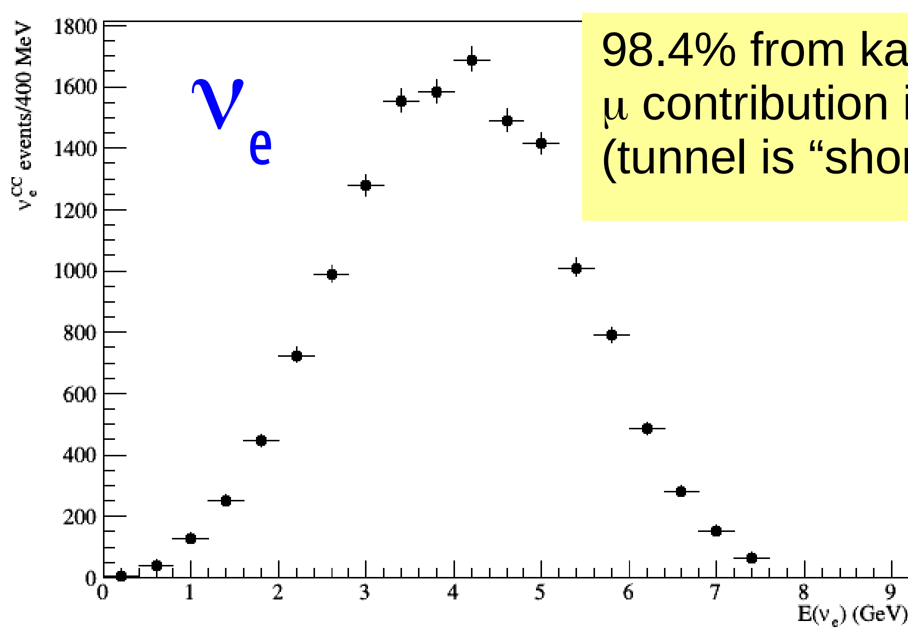
- **Detector mass**: 500 t (e.g. Protodune-SP or DP @ CERN, ICARUS @ Fermilab, WC at J-PARC)
- **Baseline** (i.e. distance between the detector and the beam dump) : 50 m
- 4.5 x 10^{19} pot at SPS (0.5 / 1 y in dedicated/shared mode) or 1.5 x 10^{20} pot at FNAL

- **ν_μ from K and π** are **well separated** in energy (narrow band)
- **ν_e and ν_μ from K** are constrained by the tagger measurement (K_{e3}, mainly $K_{\mu2}$)
- **ν_μ from π**: could be constrained by m detectors downstream of hadron - dump

1.2 million ν_μ Charged Current per year



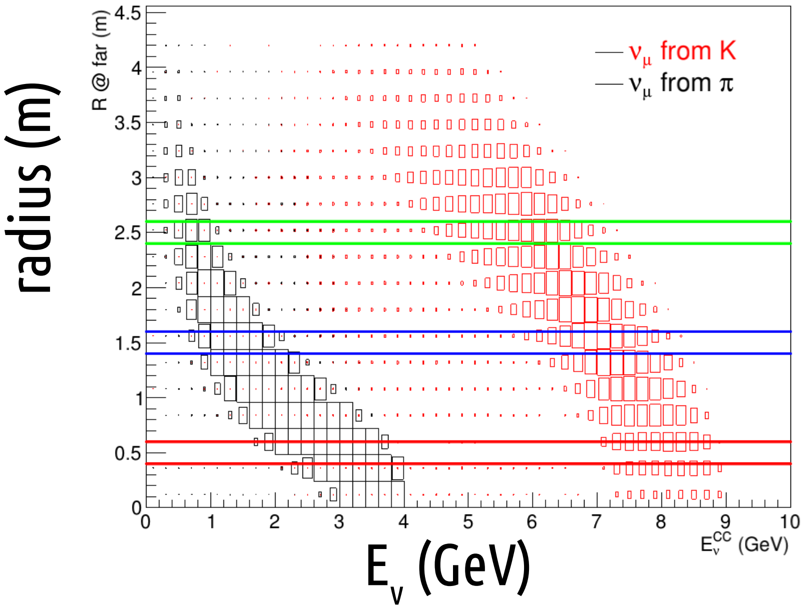
14000 ν_e Charged Current per year



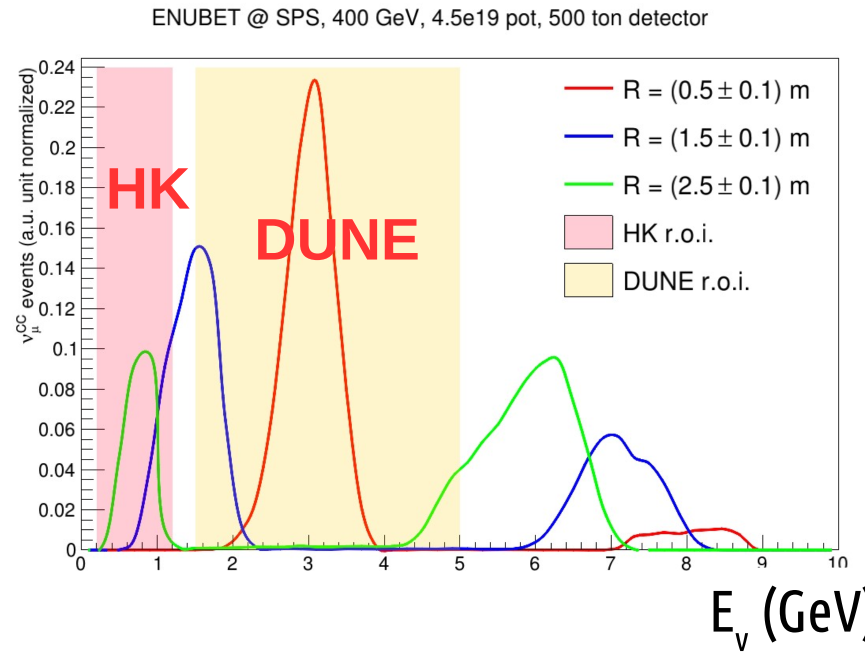
98.4% from kaons
μ contribution is small
(tunnel is “short”)

ν_μ CC events at the ENUBET narrow band beam

The neutrino energy is a function of the distance of the neutrino vertex from the beam axis.



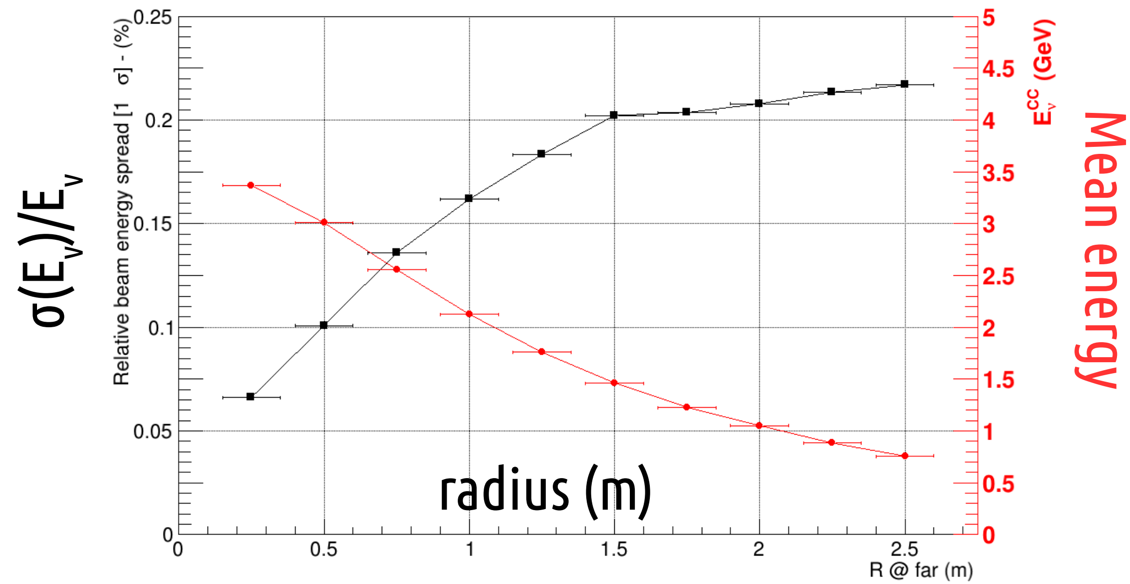
ν_μ ^{CC} in radial bins (1 norm.)



The beam width at fixed R
(≡ ν energy resolution)
for π component is:

- 8 % for r ~ 50 cm, $<E_\nu>$~ 3 GeV
- 22% for r ~ 250 cm, $<E_\nu>$ ~ 0.7 GeV

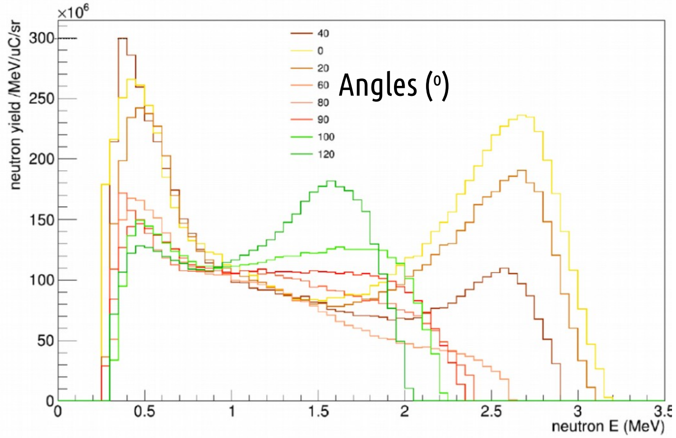
+ Binning in R allows to explore the energy domains of **DUNE/HK** and enrich samples in specific processes (quasi-elastic, resonances, DIS) for **cross section** measurements

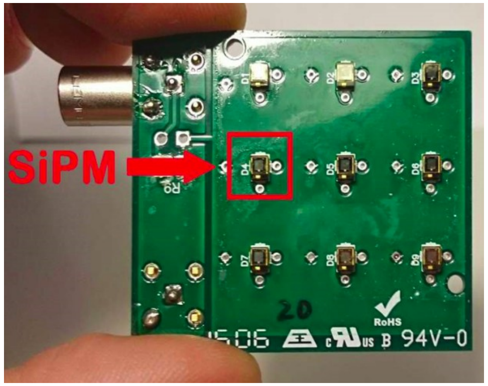


SiPM irradiation @ INFN-LNL (Legnaro)

- SiPM were irradiated at the CN Van de Graaf on July 2017
- 7MV and 5 mA proton currents on a Be target
- $^{9}Be(p,n)^{9}B$, $^{9}Be(p,np)2\alpha$, $^{9}Be(p,np)^{8}Be$ and $^{9}Be(p,n\alpha)^{5}Li$
- → 1-3 MeV n with fluences up to $10^{12}/cm^2$ in a few hours

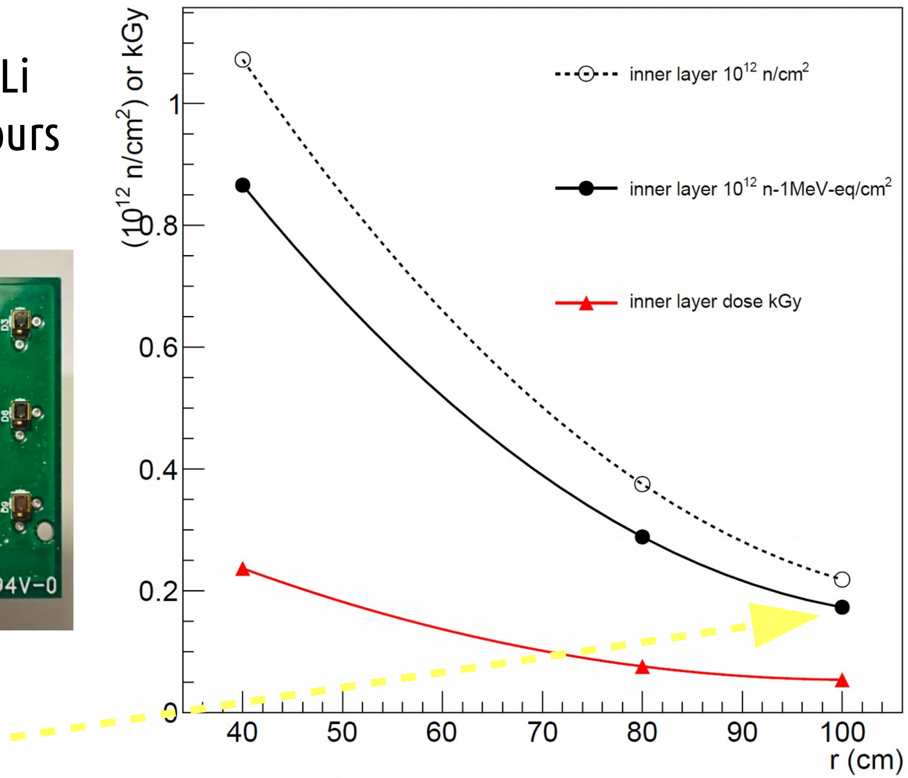
n spectra (from previous works at the same facility)

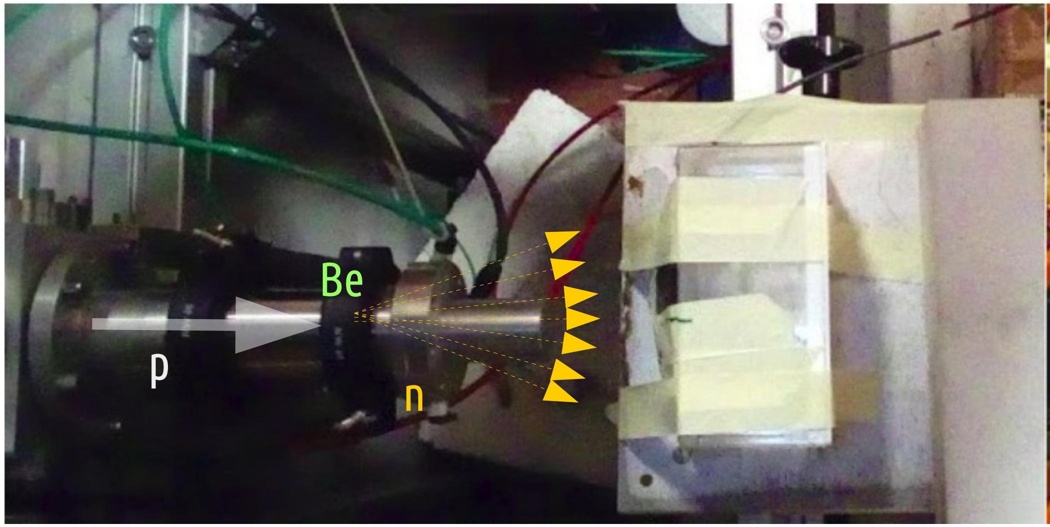




→ Tested 12,15 and 20 μm SiPM cells up to ~ **2 x 10^{11} n/cm²** 1 MeV-eq
(max non ionizing dose for 10^4 ν_e^{CC} at a 500 t ν detector at r = 1 m)

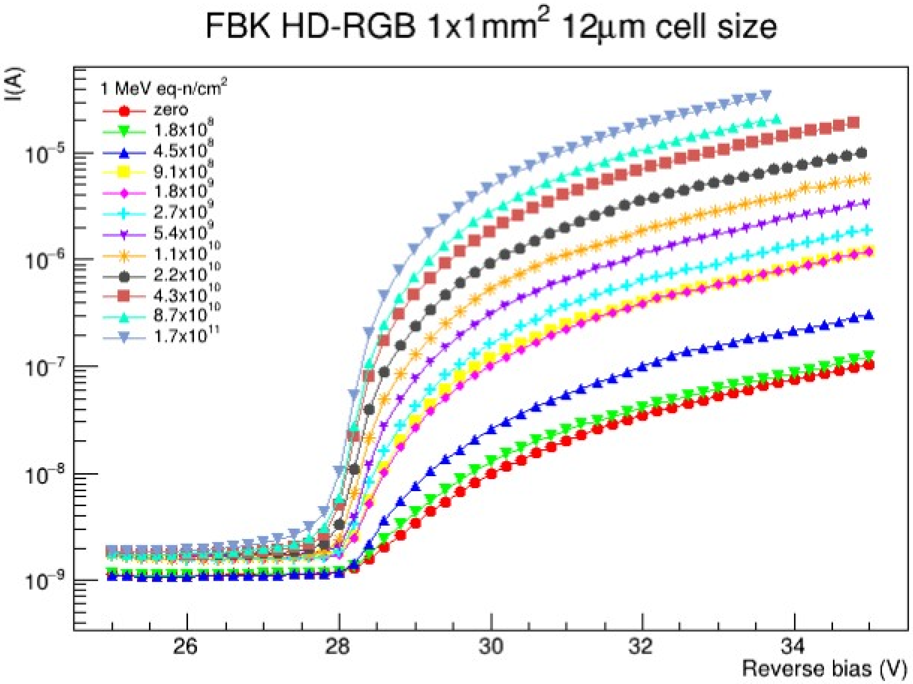
Expected n doses from K decays (FLUKA)





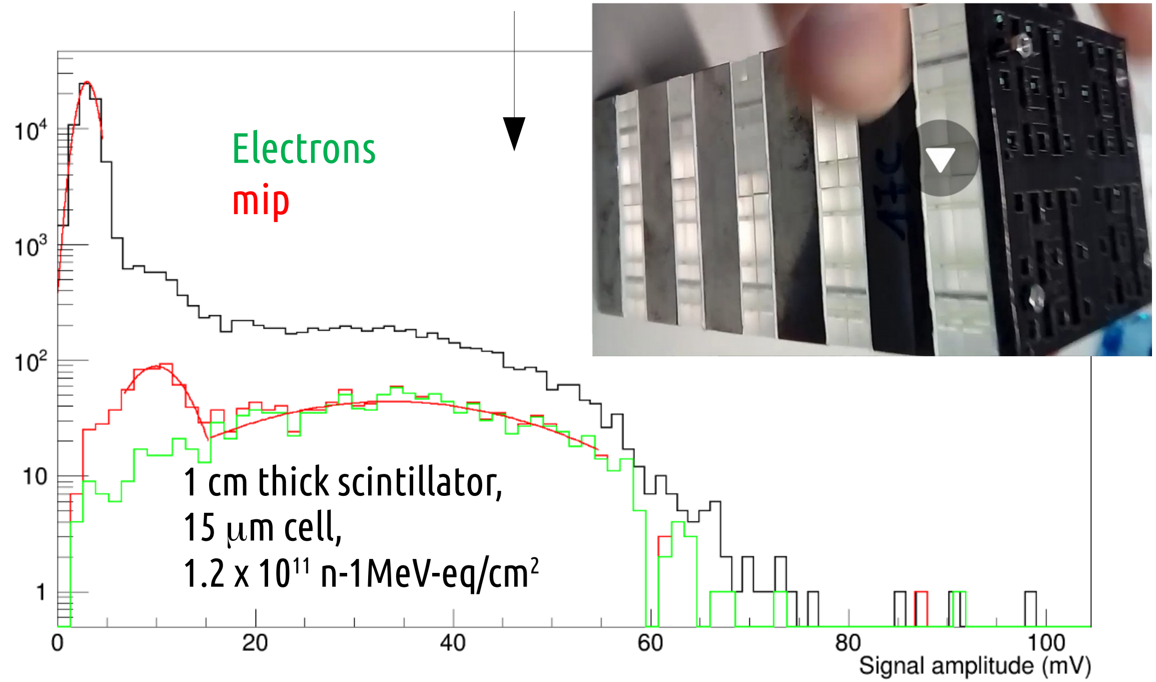
SiPM irradiation measurements at INFN-LNL and CERN

Dark current vs bias at increasing n fluences



F. Acerbi et al., Irradiation and performance of RGB-HD SiliconPhotomultipliers for calorimetric applications , JINST 14 (2019) P02029

A shashlik calorimeter equipped with irradiated SiPMs later tested at CERN-PS T9 in Oct 2017



(FBK-HD-RB Advansid)

- By choosing SiPM cell size and scintillator thickness (~light yield) properly **mip signals remain well separated from the noise even after typical expected irradiation levels**
- Mips can be used for **channel-to-channel intercalibration** even after maximum irradiation.