Silicon Photomultipliers for the decay tunnel instrumentation of the ENUBET neutrino beam

M. Pozzato on behalf of the ENUBET collaboration

2019/10/02

This project has received funding from
the European Research Council (ERC)
under the European Union's Horizon 2020 research and
innovation programme (G.A. n. 681647).

HORIZON 2020

European Research Council
Established by the European Commission

Istituto Nazionale di Fisica Nucleare

Neutrino beam for precision physics

The next generation of short baseline experiments should rely on:

- a direct measurement of the fluxes
- a narrow band beam → energy known a priori from beam width
- a beam covering the region of interest from sub- to multi-GeV

ENUBET project

Goal: demonstrate the technical feasibility and physics performance of a neutrino beam where lepton production at large angles is monitored at single particle level exploiting the Ke3 decay.

Two aims:

- Design/simulate the layout of the hadronic beamline
- Build/test a demonstrator of the instrumented decay tunnel

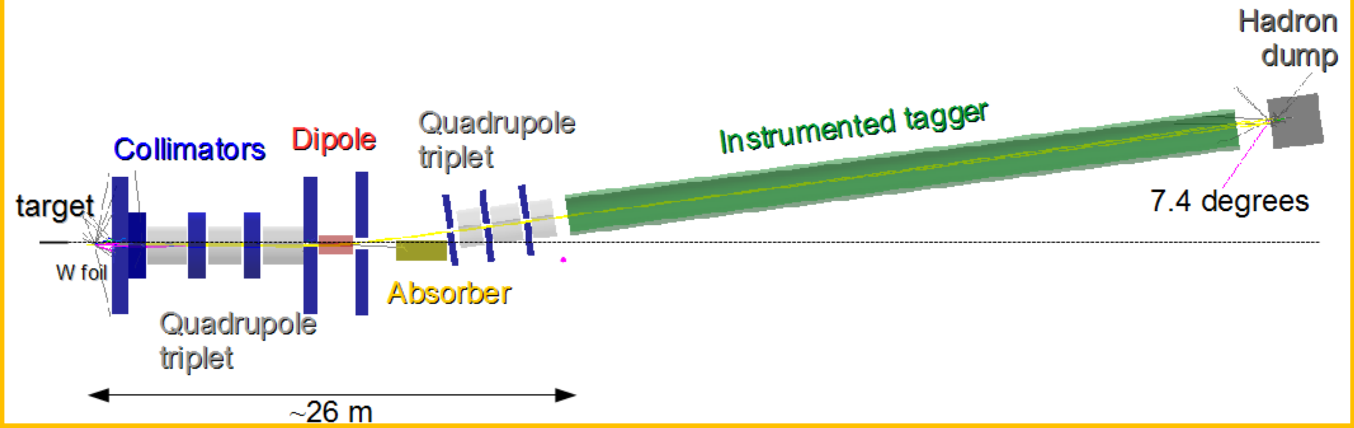
Recognized in the CERN Neutrino Platform as ENUBET/NP06

A high precision narrow band ν beam

REQUIREMENTS:

e^+ tagger:
- longitudinal sampling
- homogeneity
  → integrated light-readout
- Separate e^+, π^+, μ (PID)

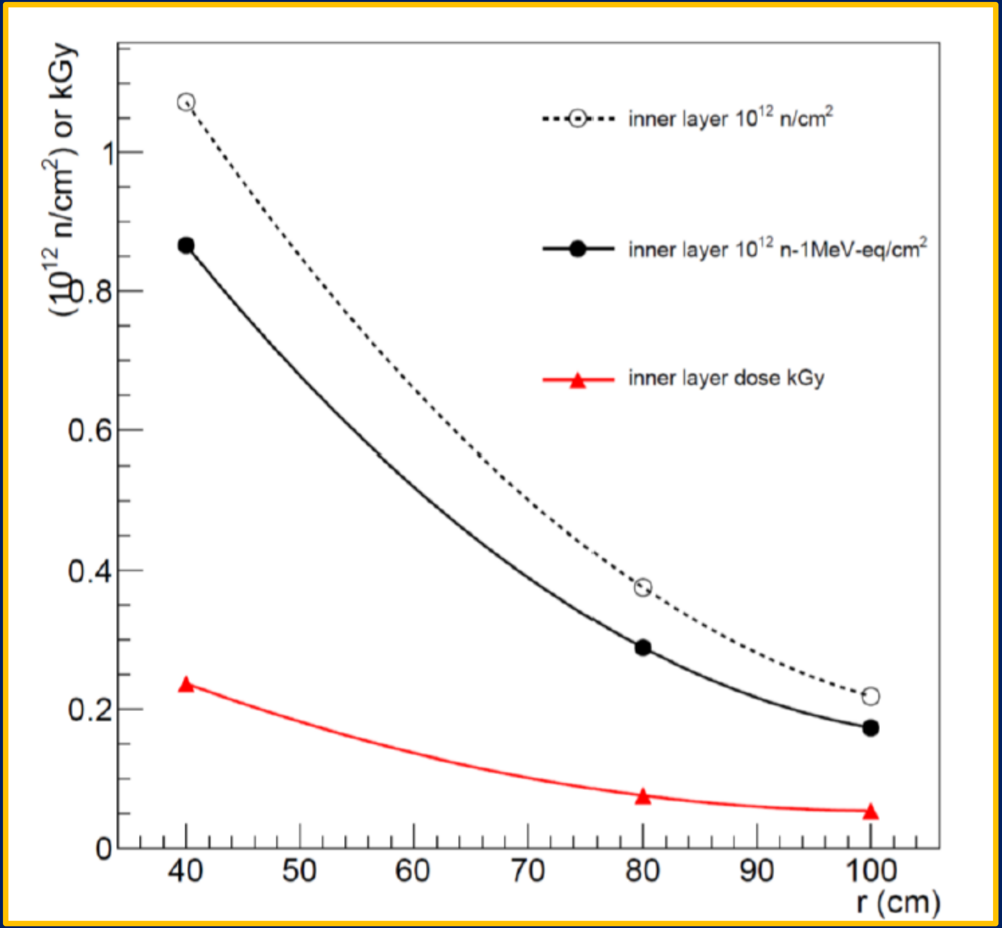
Photon veto:
- photon identification capabilities
- precise timing of the particles (< 1 ns)
- exploit 1 mip – 2 mip separation



CHALLENGES:

The decay tunnel is a harsh environment:
- particle rates: > 200 kHz/cm^2
- instrumented region: ~ 50 m
- backgrounds: pions from K^+ decays
  → need to veto 98-99 % of them
- significant spread in the initial direction

Expected doses - ENUBET lifetime

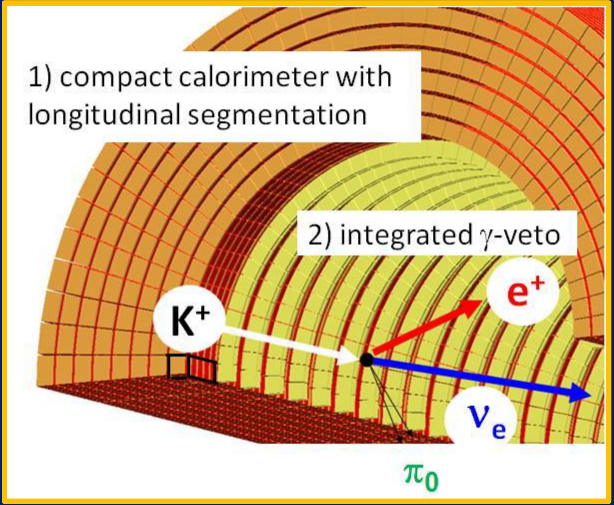


The integrated fluence to achieve 1% of statistical error on ν_e CC depends on the position of the calorimeter with respect to the axis of secondary beam at the entrance of the decay tunnel.

ENUBET @ 1 m distance (lifetime - integrated):

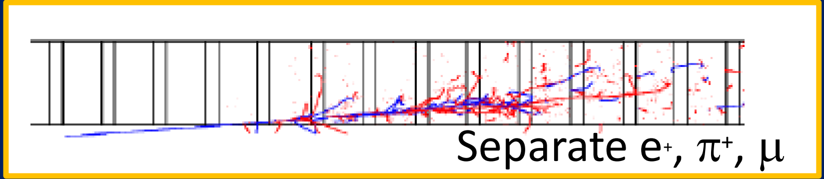
- non ionizing fluence: 1.8×10^{11} n/cm^2 1-MeV eq.
- ionizing dose: 0.06 kGy

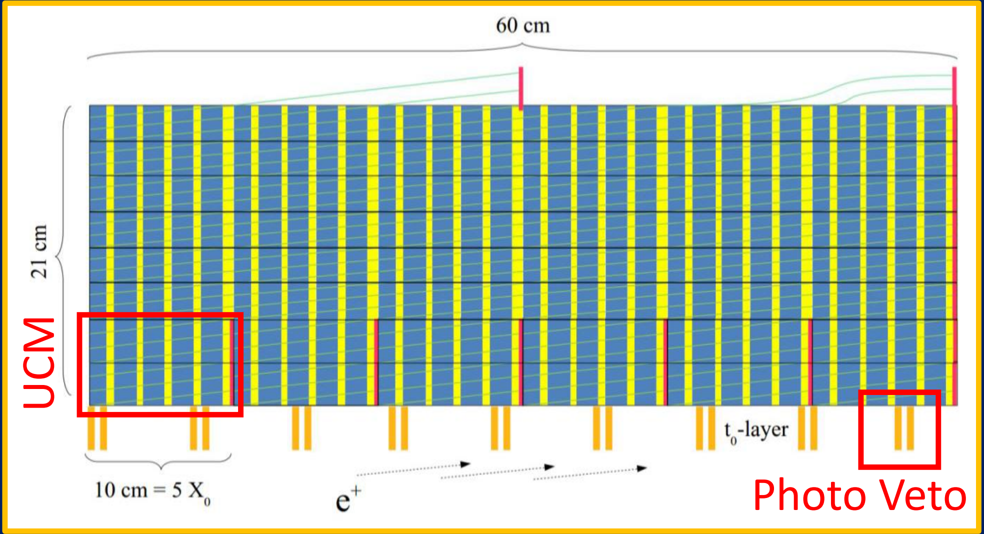
The Tagger/Photon Veto technology



Compact shashlik calorimeter
Ultra Compact Module(UCM):

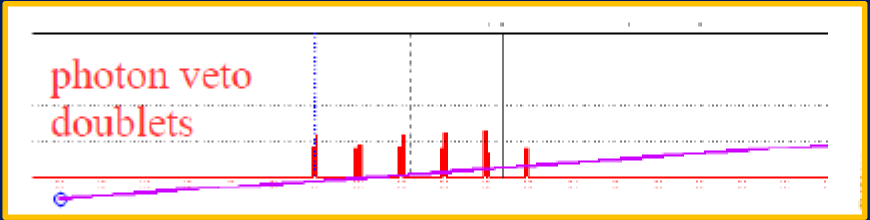
- longitudinal (~4 X_0) segmentation.
- 3x3x1.5 cm^3 Fe + 3x3x0.5 cm^3 scint. modules
- SiPM embedded in the bulk of the calorimeter





Photon Veto Rings (t_0 layer):

3 x 3 cm^2 pads of plastic scintillator readout by SiPM



UCM SiPM - FBK RGB - HD

Factory Parameters:

- Active Area: 1 x 1 mm^2 (match with WLS fiber ∅ = 1 mm^2)
- Cell pitch: < 25 μm
- Breakdown Voltage @T_{ROOM}: ~ 28V

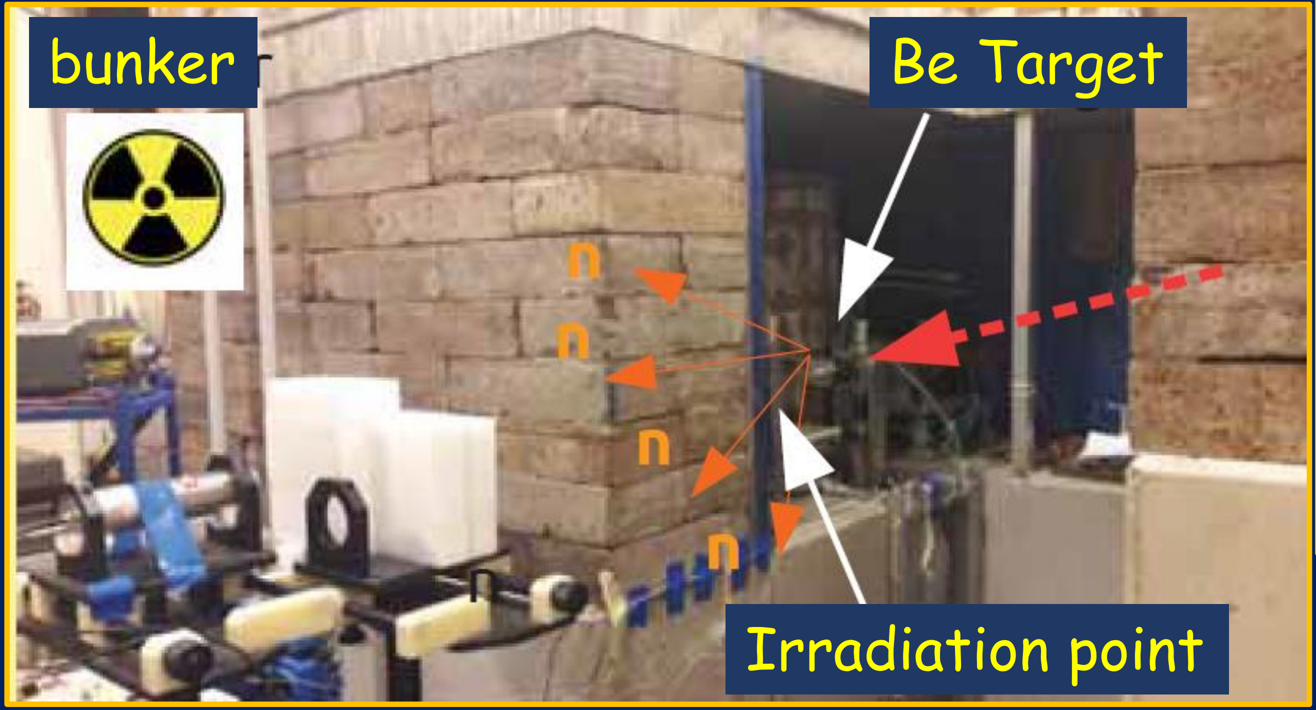
Tests:

- Exposure to fast neutrons @ Irradiation Test Facility of Laboratori Nazionali di Legnaro (LNL)
- Measure the response to MIP and eletrons @ CERN T9 beamline

Irradiation tests @ LNL

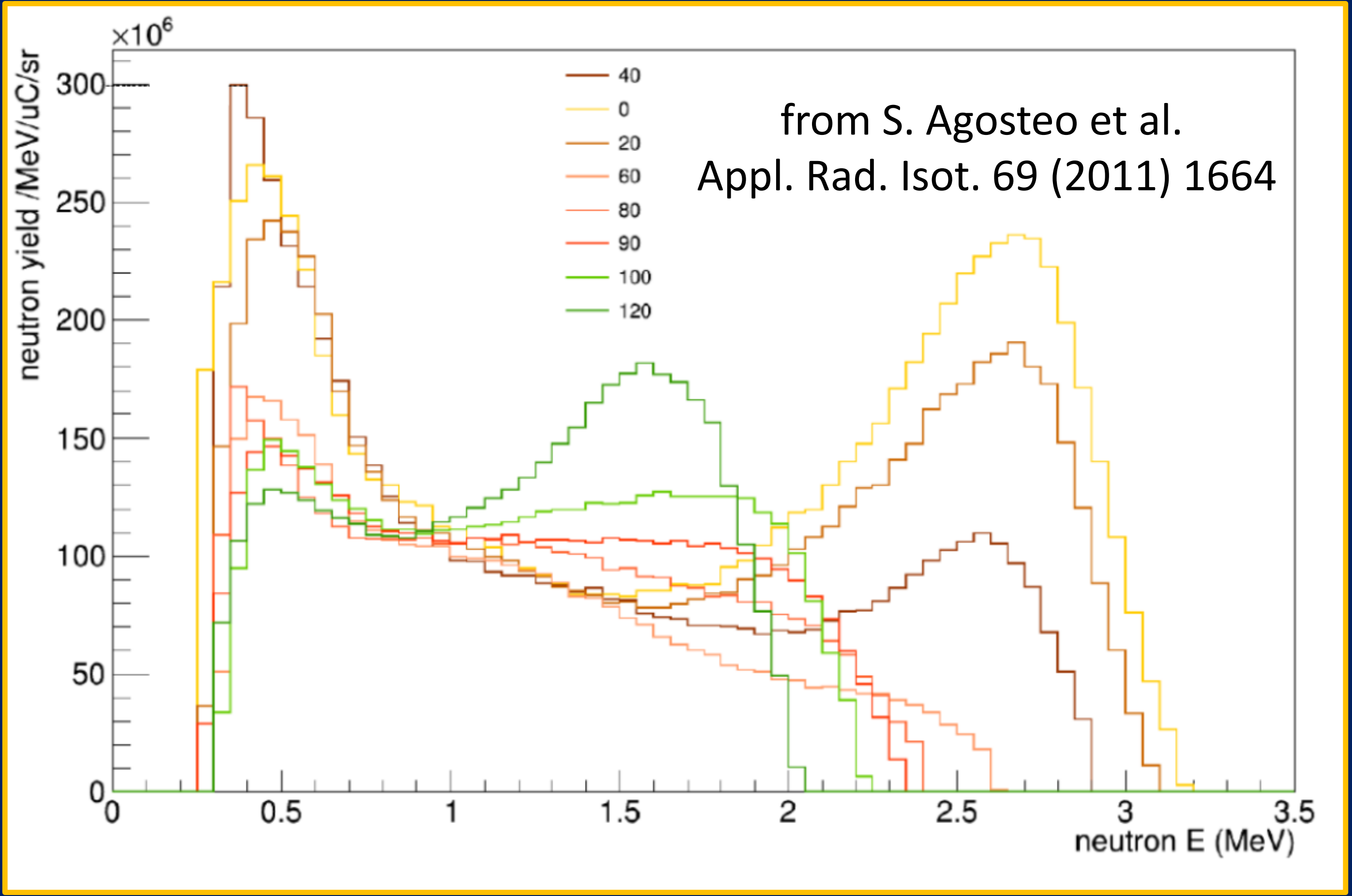
Van der Graaf accelerator (Vmax = 7 MV)

Protons on Beryllium target: p (5 MeV) + ^{9}Be → n + X



Irradiated sample inside an experimental area: external shield of concrete inner layer of water as neutron moderator

Neutron Yeld assessment



Expected fluxes on irradiated samples evaluated from:

- S. Agosteo et al. Appl. Rad. Isot. 69 (2011) 1664
- real time monitoring of proton current to the target (current integrator)
- Neutron backscattering on the shielding estimated with FLUKA 2011 → negligible contribution

Irradiated samples

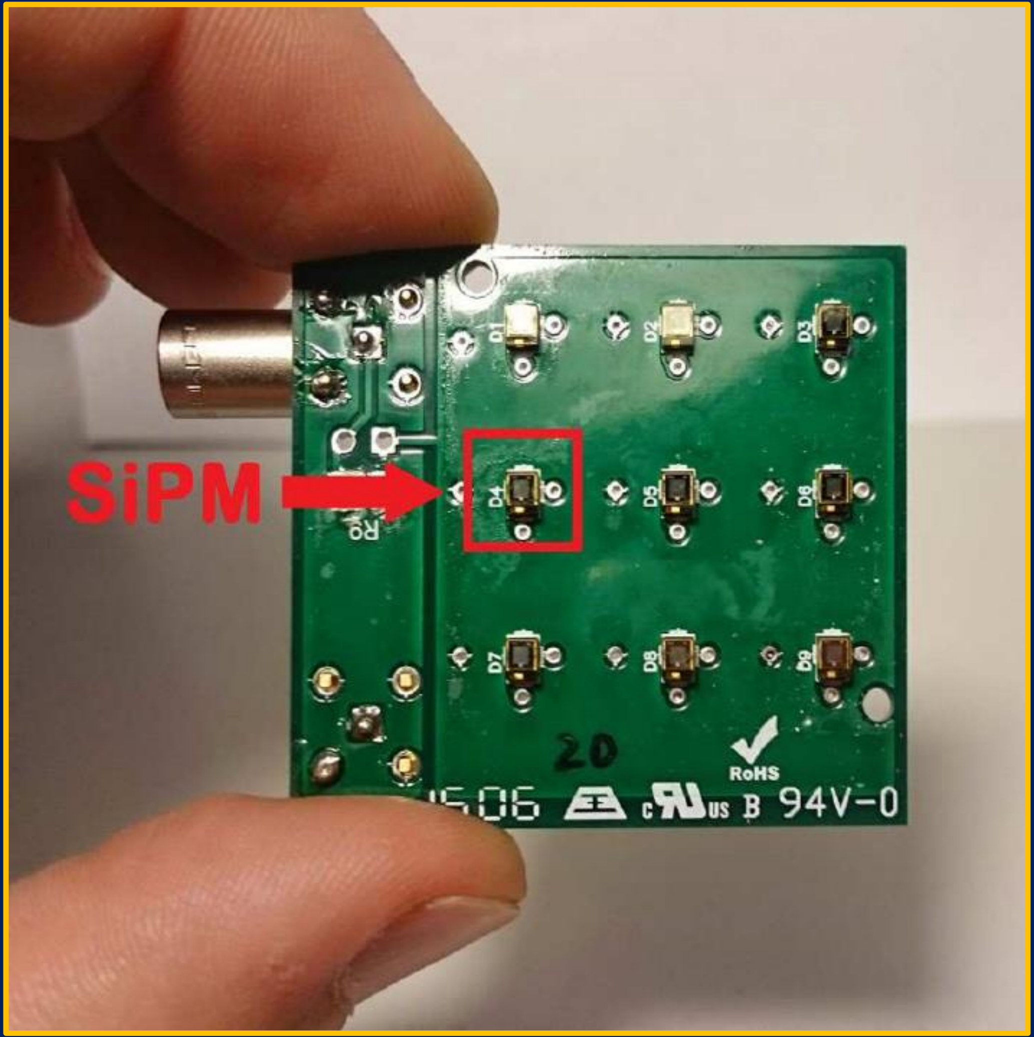
3 PCB Boards - Each Board hosts:

- 9 SiPM – parallel connection
- Passive components
- Signal routing to front-end
- Readout through a decoupling capacitor no amplification

SiPM tested: cell pitch 12, 15, 20 μm

1 PCB Board equipped with:

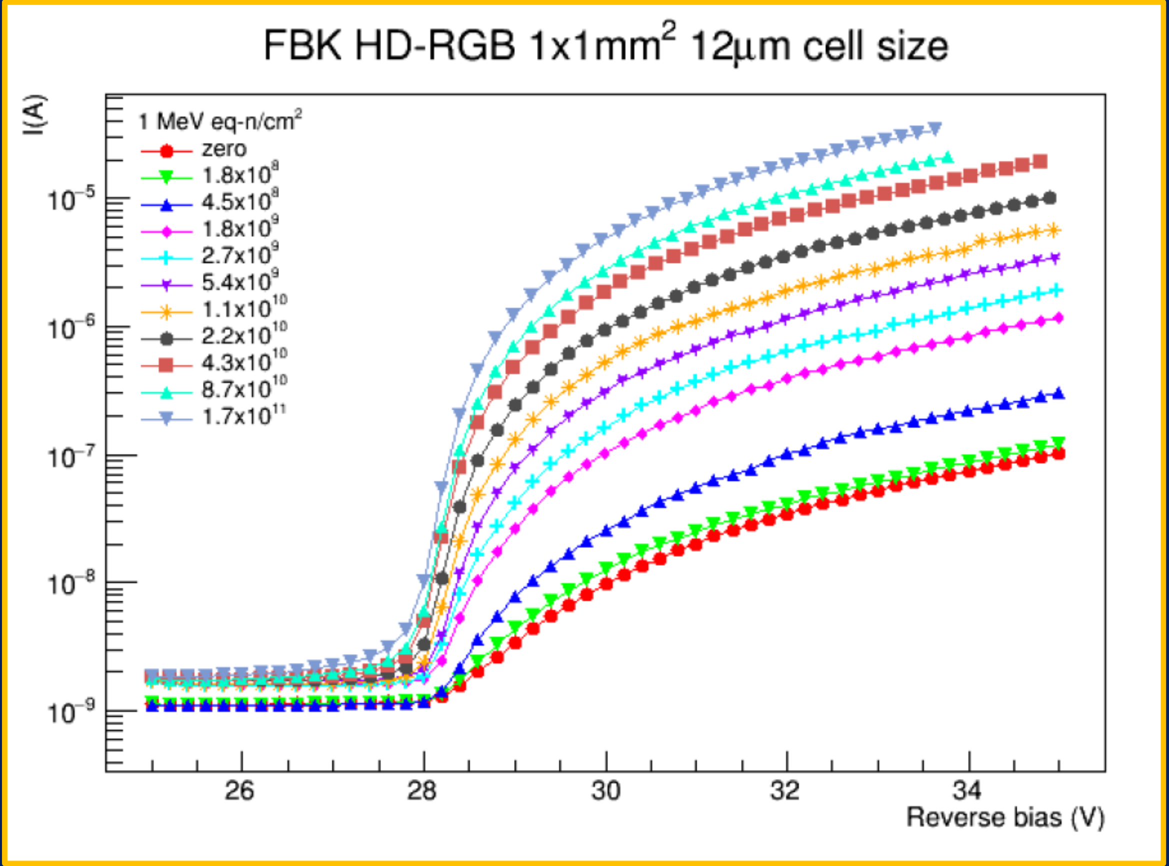
- 1 SiPM – 12 μm cell pitch
- Readout with Advansid amplifier (ASD-EP-EB-N) removed during exposure time

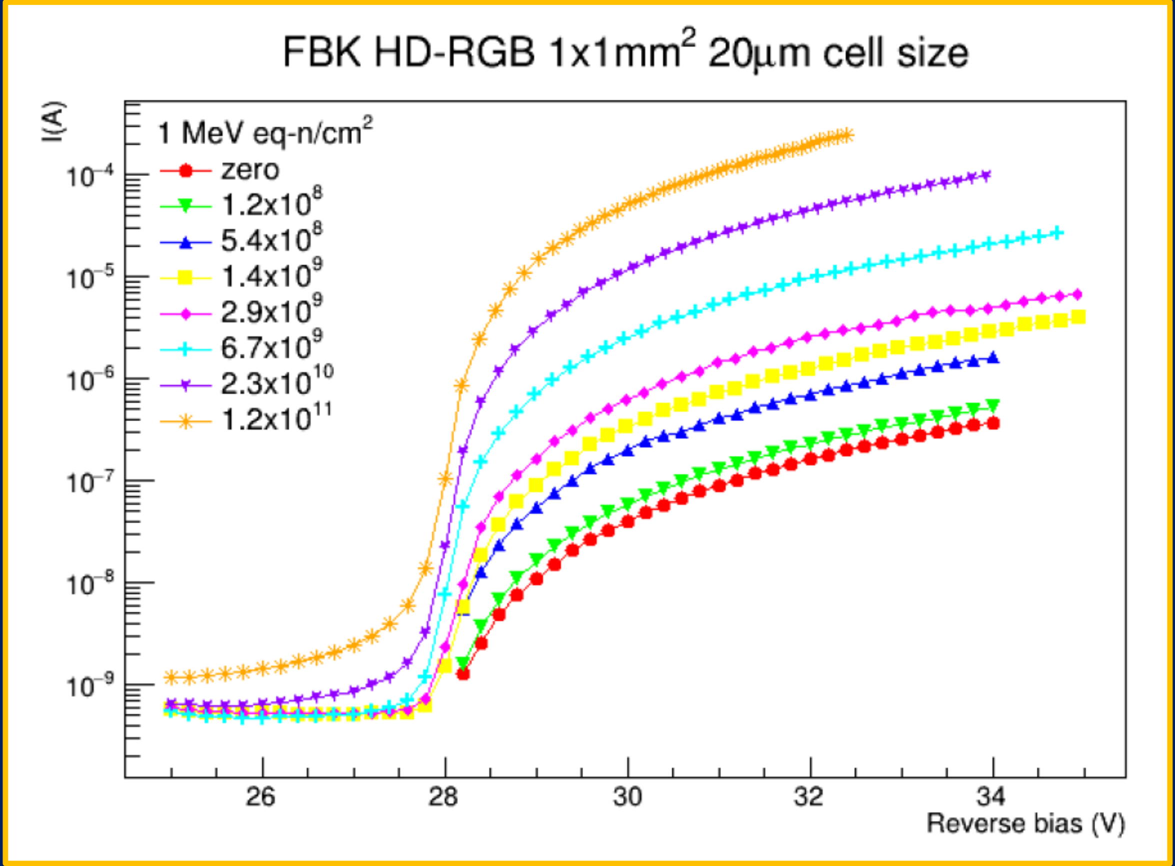


Irradiation Procedure

- All PCB boards irradiated with:
  - minimum dose: 1.8×10^{6} n/cm^2;
  - maximum dose: 1.7×10^{11} n/cm^2;
- During irradiation SiPM are:
  - not biased
  - temperature monitored (two LM 35 sensors – Arduino One board)
    - maximum increase + 10 °C w.r.t T_{Env}
    - time to reach room temperature after irradiation: 15-30 min.
- After each irradiation run:
  - I-V curve recorded (Keythley 485 Picoammeter);
  - darkCurrent and p.e. sensitivity measured (Rohde & Schwarz RTO 1024 oscilloscope).

IV Curves

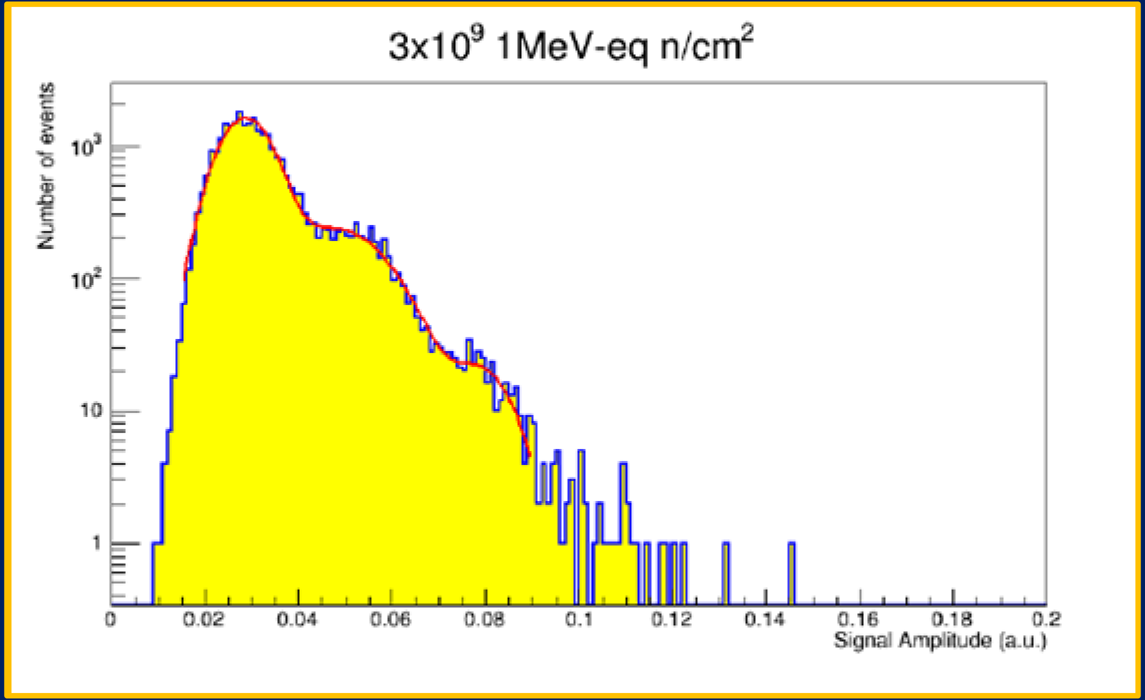


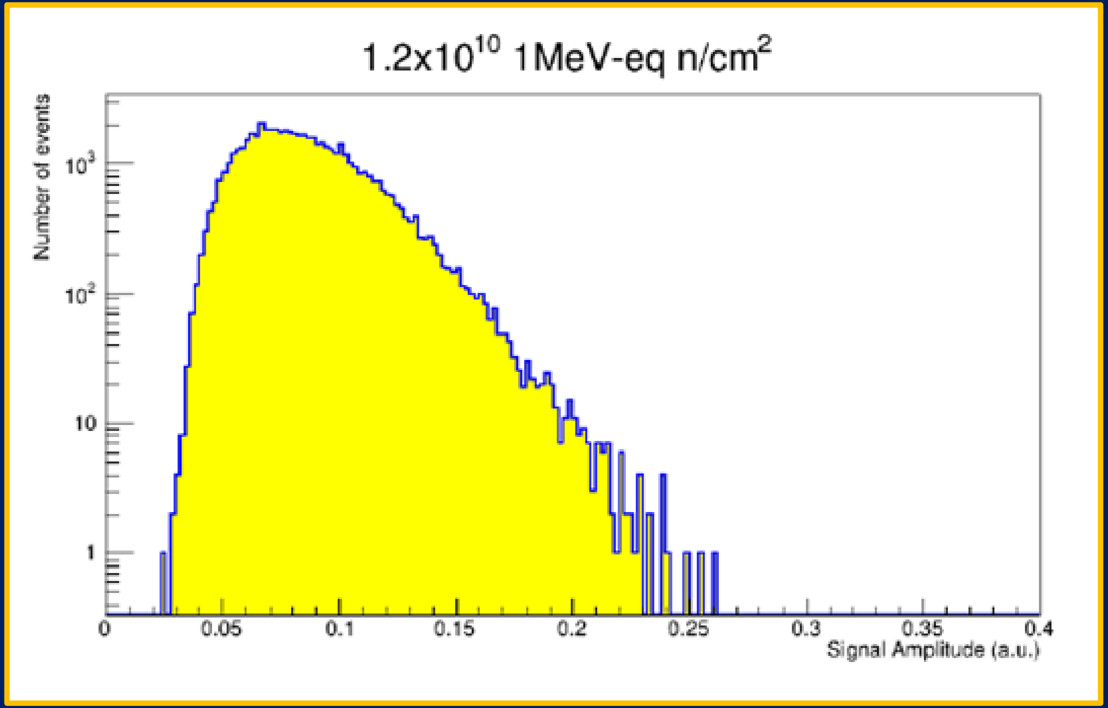


FBK - RGB-HD sensors shows after irradiation:

- minor changes in the breakdown voltage
- dark current increases by more than two orders of magnitude

Sensitivity to single photo electron





Single SiPM PCB 12 μm cell, 1 mm^2

sensitivity lost at fluence >= 3×10^9 n/cm^2

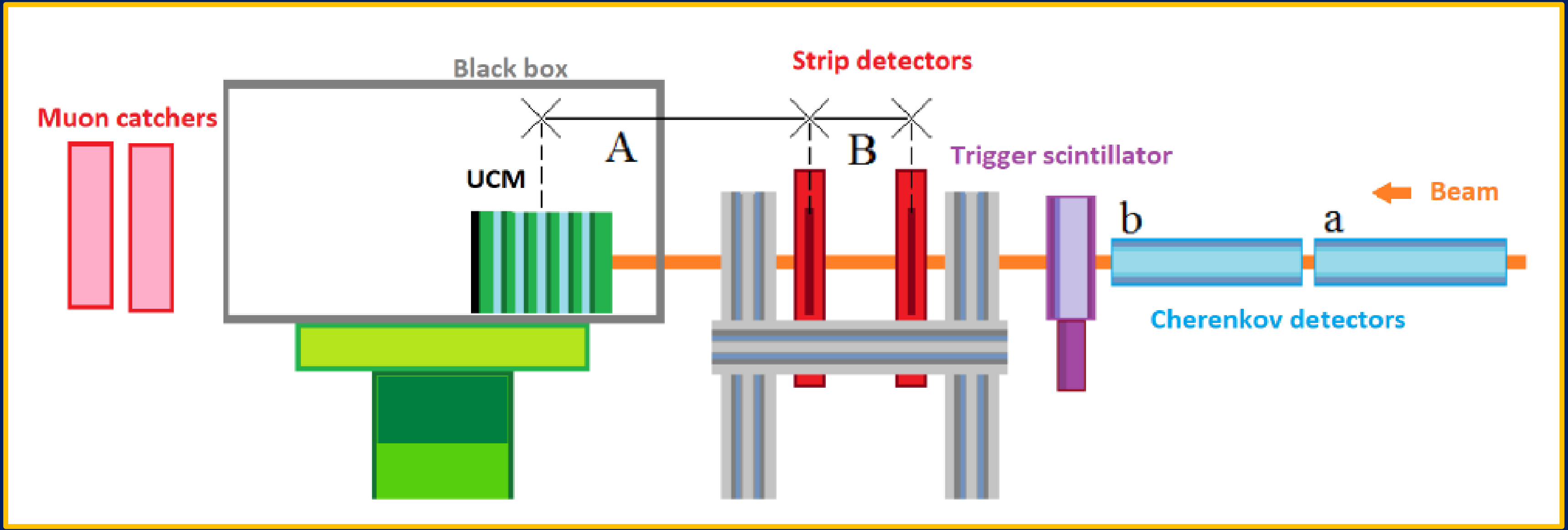
TB @ CERN – T9 beamline

- Particle beam composition:
  - Electrons;
  - Muons;
  - Pions;

- Momentum selected in the range 1 -5 GeV → covering the whole ENUBET energy range;

SiPM after irradiation were stored @ 25 °C for three months

Test beam setup



Strip detectors used to select particles hitting the UCM front face (fiducial area 2x2 cm^2) and crossing it.

Electrons selection:

- Signals required in both Cherenkov Couters;

MIP – like particle (muons and not interaction pions) selection:

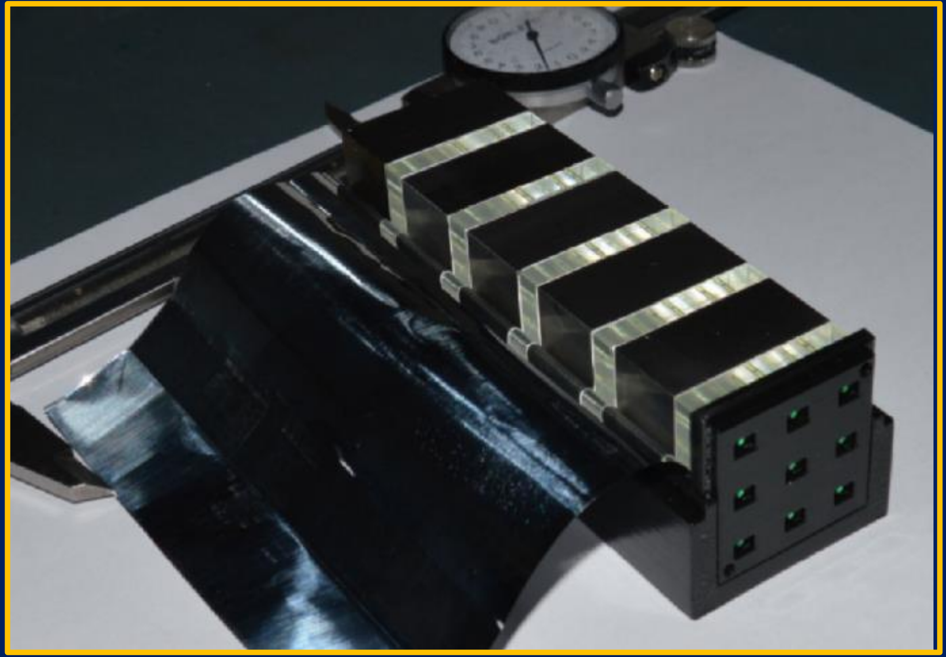
- No signals in Cherenkov counters and signals in muon catchers;

UCM Under Test

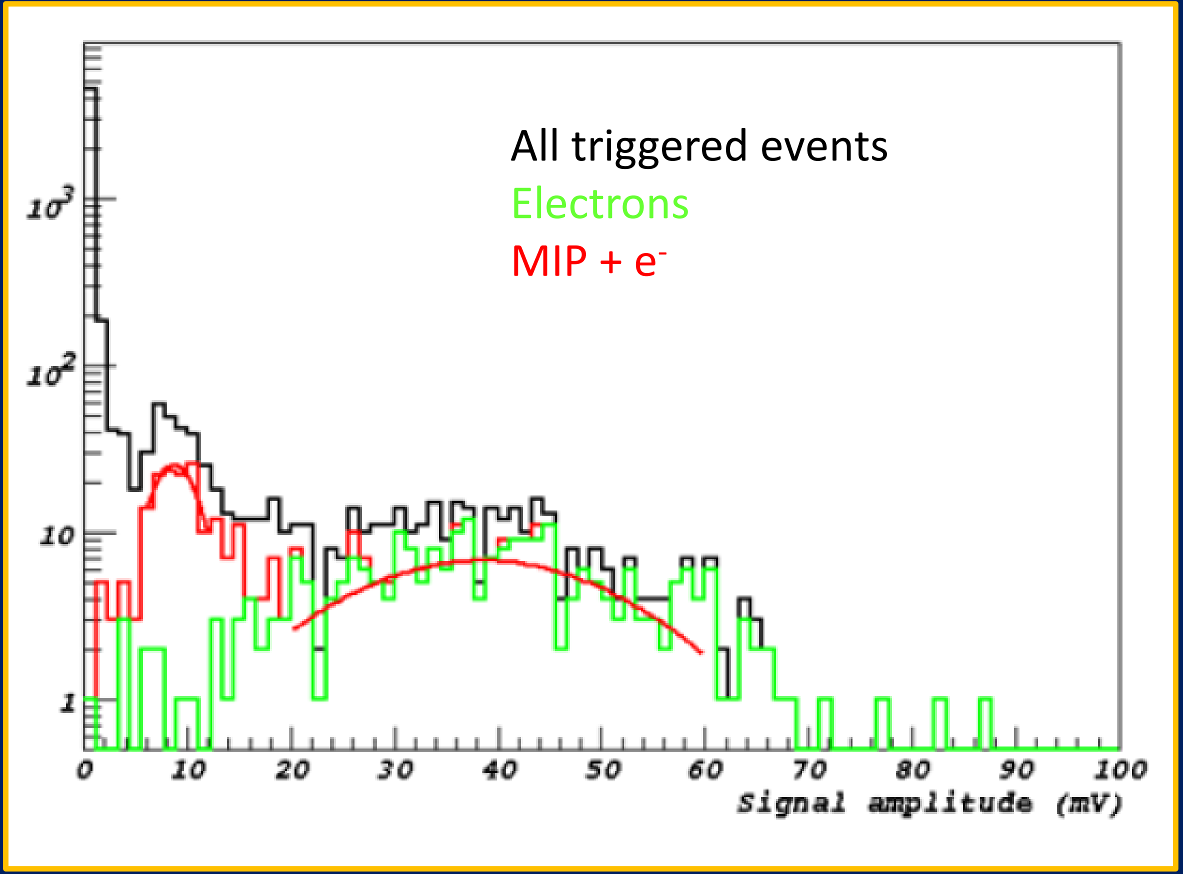
2 UCMs equipped with both irradiated and not irradiated boards:

- Prototype 16B:
  - 5 iron slabs (3x3x1.5 cm^3) interleaved with 5 scintillator tiles (3x3x0.5 cm^3) EJ-200 + WLS Kuraray Y11
  - ~ 50 p.e. for a MIP crossing the unit (from lab. Test with C.R.)

- Prototype 17UA:
  - 5 iron slabs (3x3x1.5 cm^3) interleaved with 5 scintillator tiles (3x3x1.35 cm^3) Uniplast Injeciton Molded + WLS Kuraray Y11
  - ~ 85 p.e. for a MIP crossing the unit (from lab. Test with C.R.)

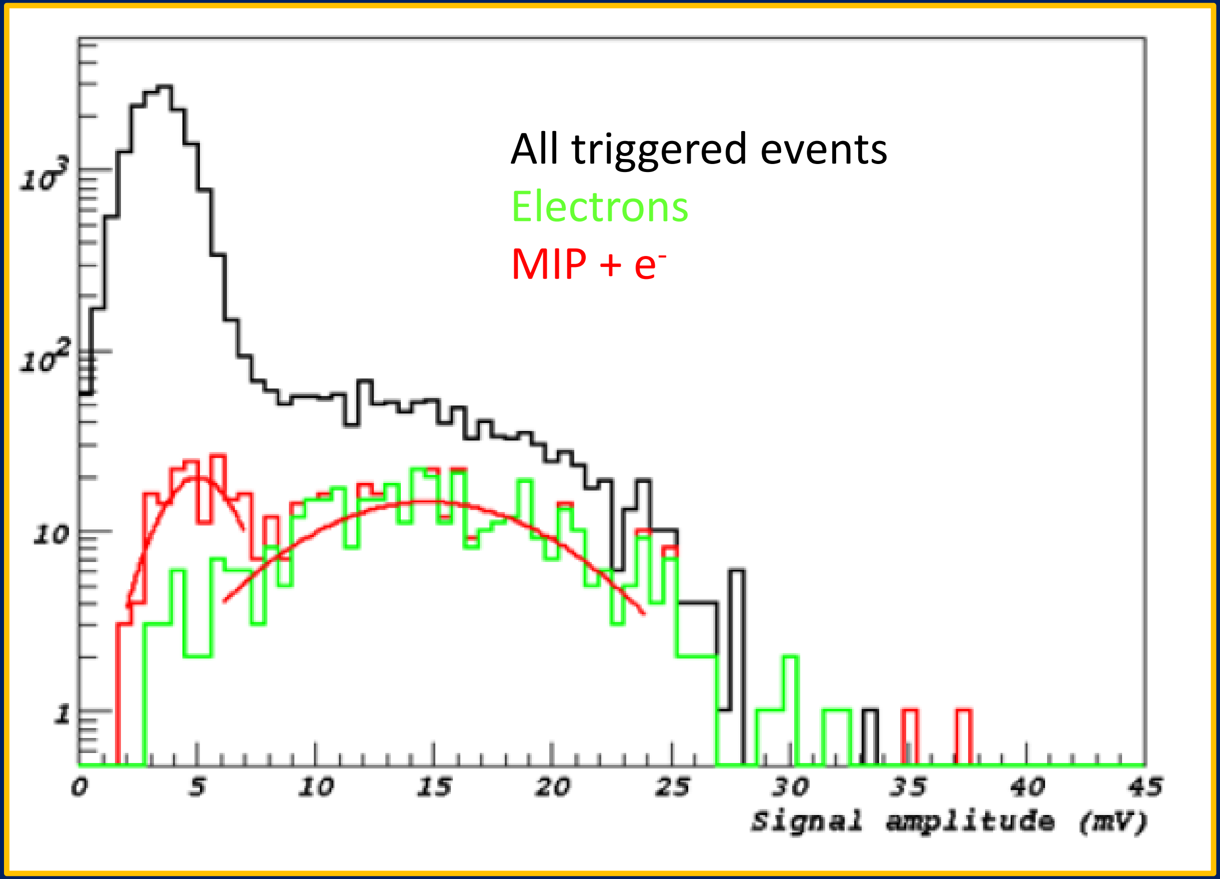


UCM 16B – Not Irradiated PCB



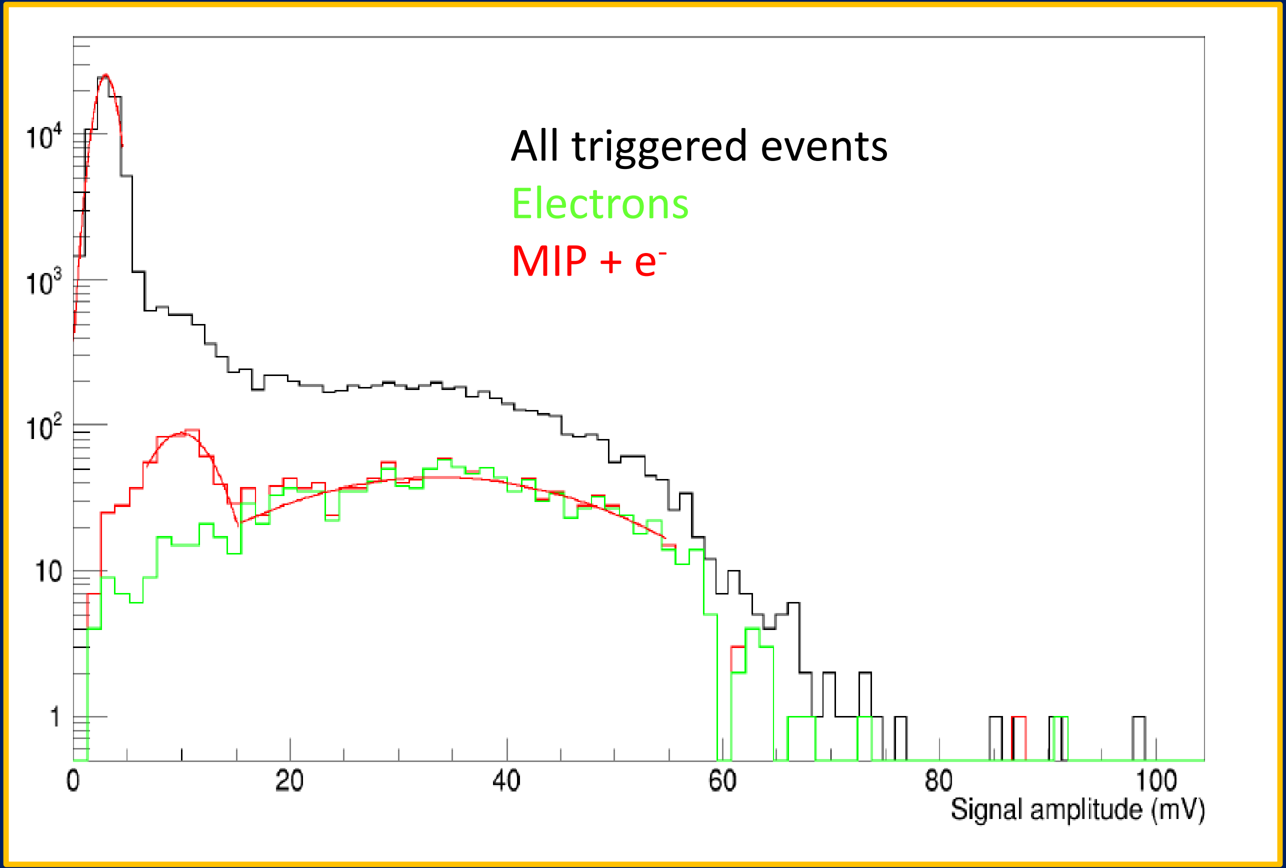
- SiPM overvoltage: ~ 9 V
- *MIP signal is separated from dark noise*
  - it can be employed to monitor changes in UCM response over time and equalize the response
- Electrons well separated from MIP particles

UCM 16B Irradiated board



- SiPM overvoltage: ~ 9 V
- MIP is NOT separated from dark noise <u>after irradiation</u>
- Electrons separated from dark noise

UCM 17UA Irradiated PCB



- SiPM overvoltage: ~ 9 V
- MIP is still visible after irradiation
- Electrons separated from dark noise

Phothon Veto SiPM - SenSL 30020 J

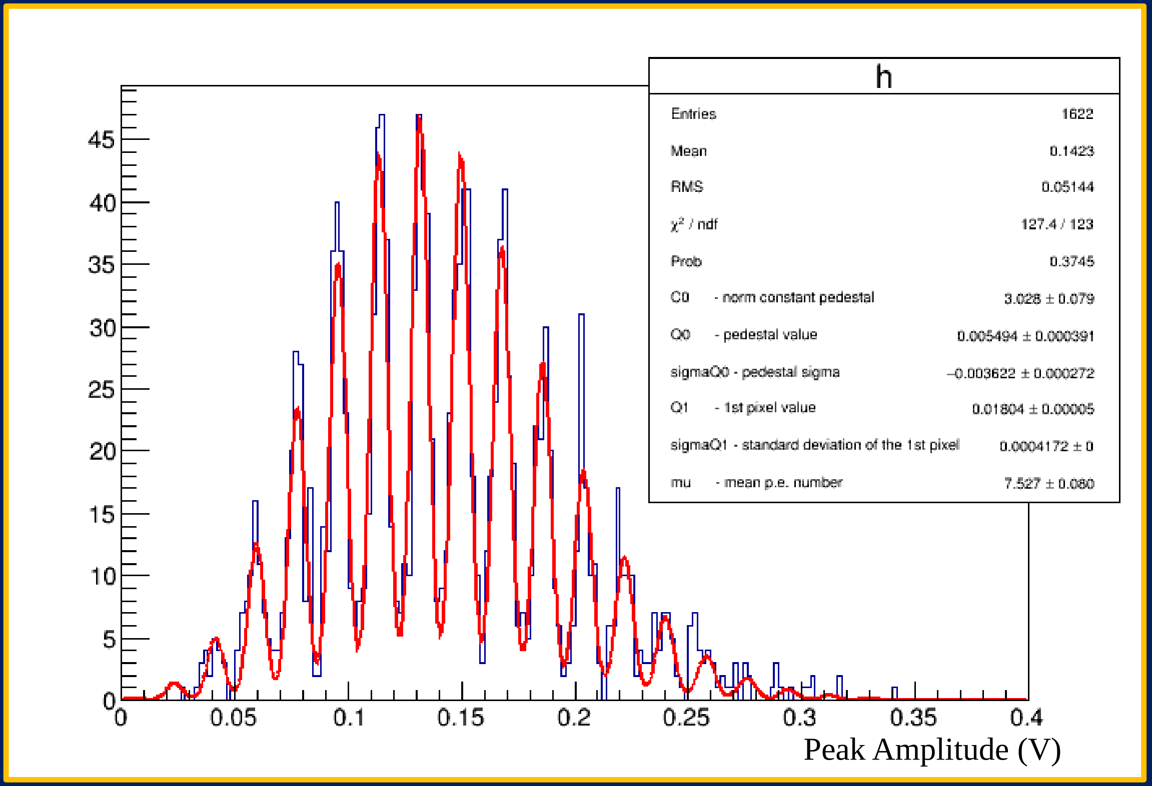
Factory Parameters:

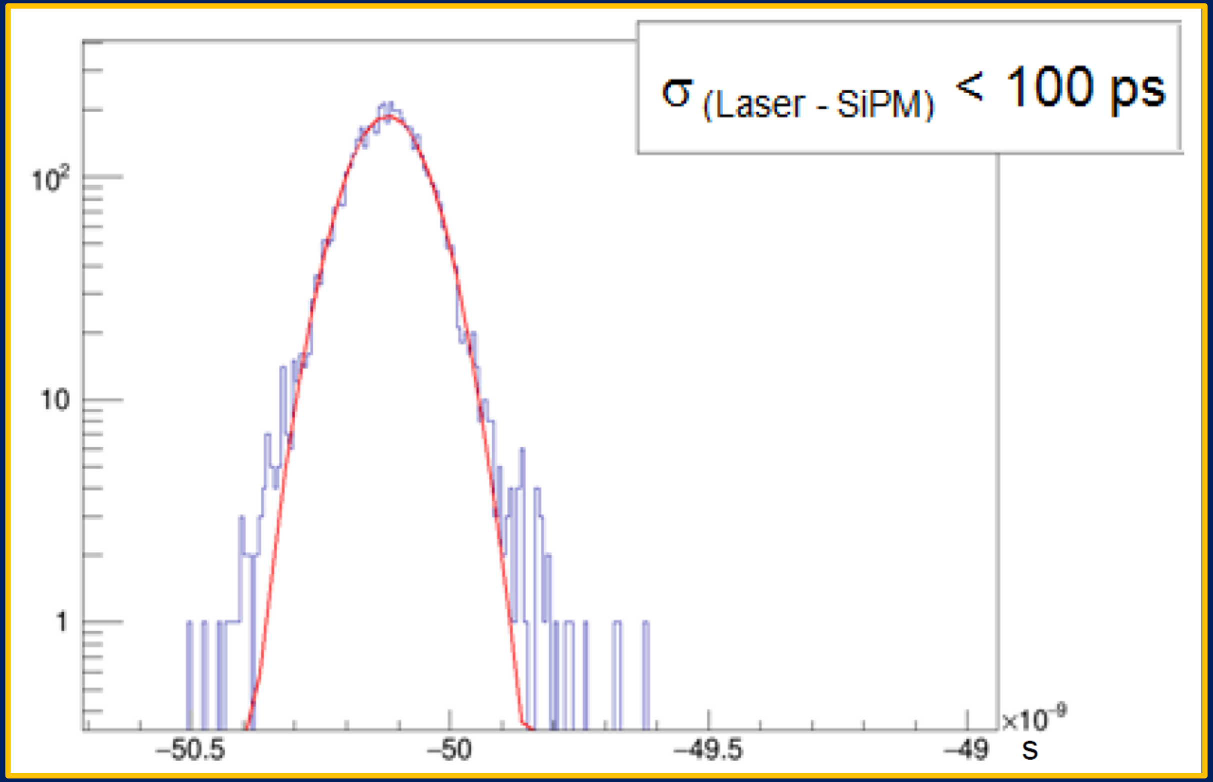
- Active Area: 3 x 3 mm^2 (match with 2 WLS fibers ∅ = 1 mm^2)
- Cell pitch: 20 μm
- Breakdown Voltage @T_{ROOM}: ~ 24V

Tests:

- SiPM characterization with laser pulses (Picosecond Laser λ = 405 nm)
- Measure the response to MIP an exploit 1-2 mip separation @ CERN T9 beamline

Laser test $V_{overvoltage}$ = +3 V

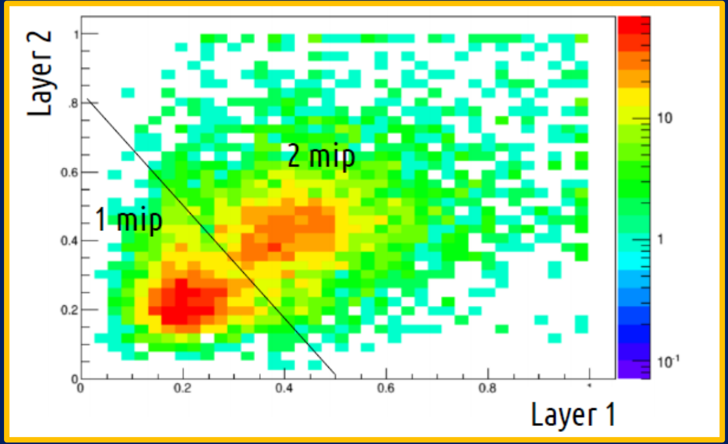


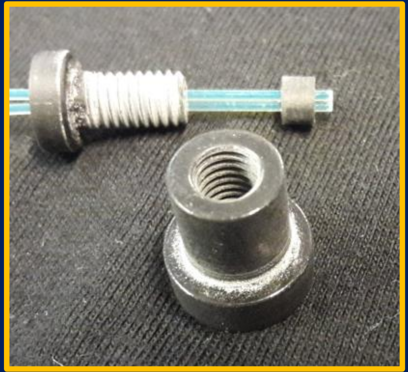


TB @ CERN – T9 beamline

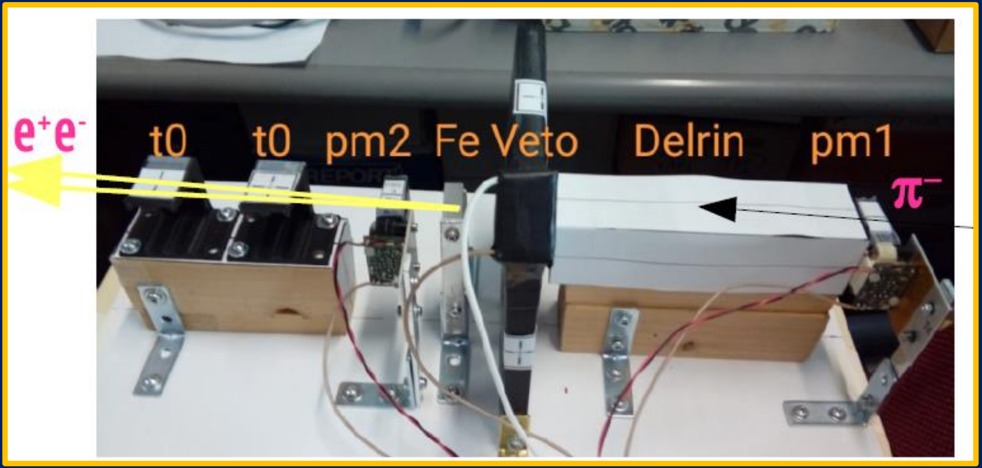
Material:
- Scintillator: EJ 204 3x3x0.5 cm^3
- TiO_2 painting: EJ / 510 reflective coating
- 2 WLS fibers – BCF 92 – 40 cm
- Optical Glue: EJ – 500

Results:
- Collection efficiency: > 95%
- Time resolution: ~400 ps
- 1 mip / 2 mip separation

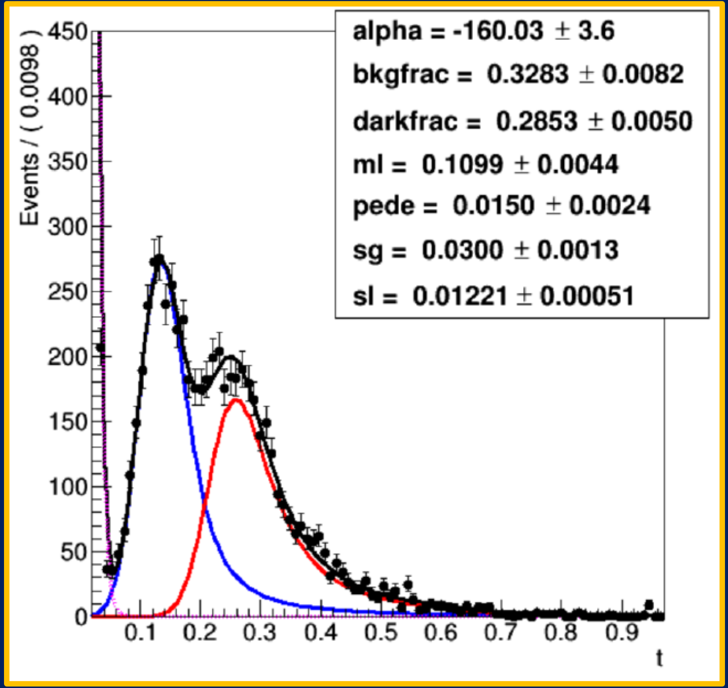




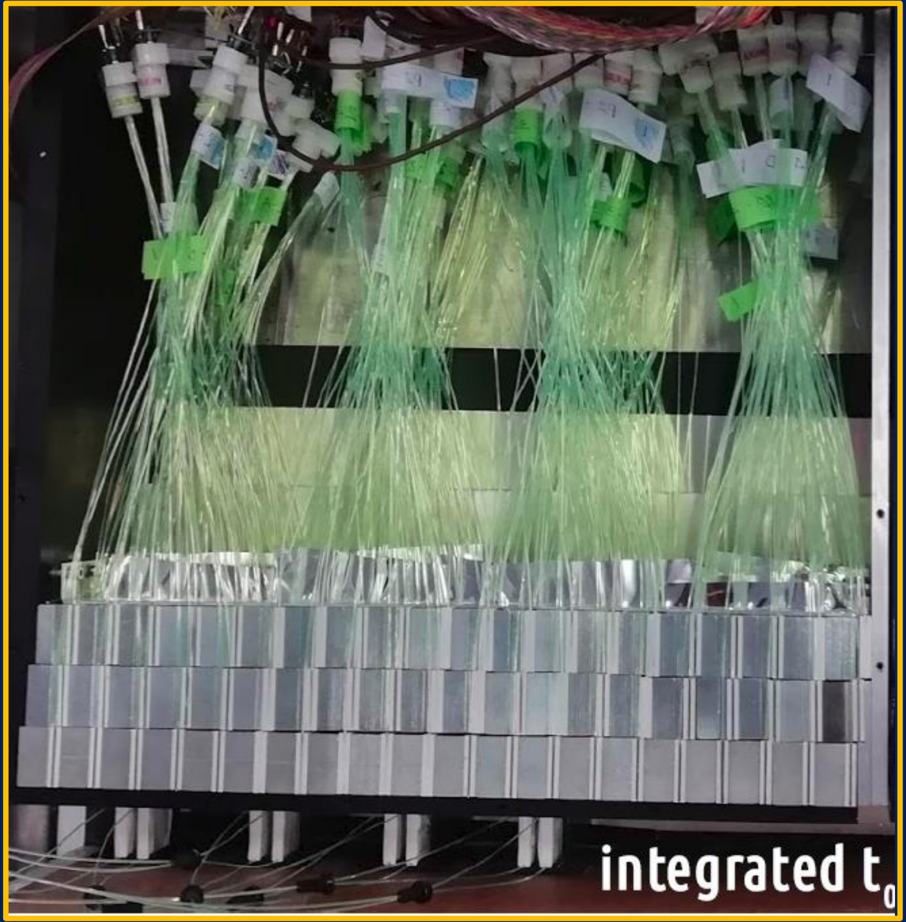
Custom Optical Connector



$\pi^- p \rightarrow n \pi^0 (\rightarrow \gamma \gamma)$

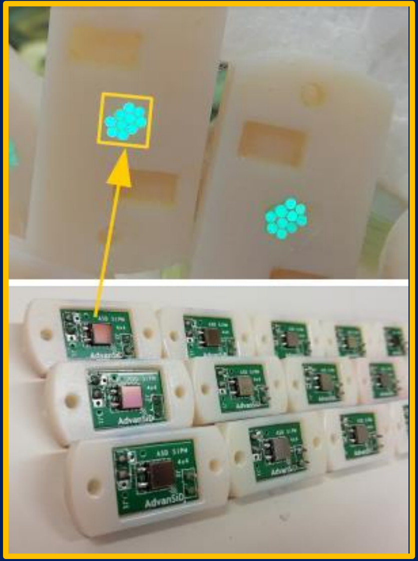


UCM modified - photon veto design

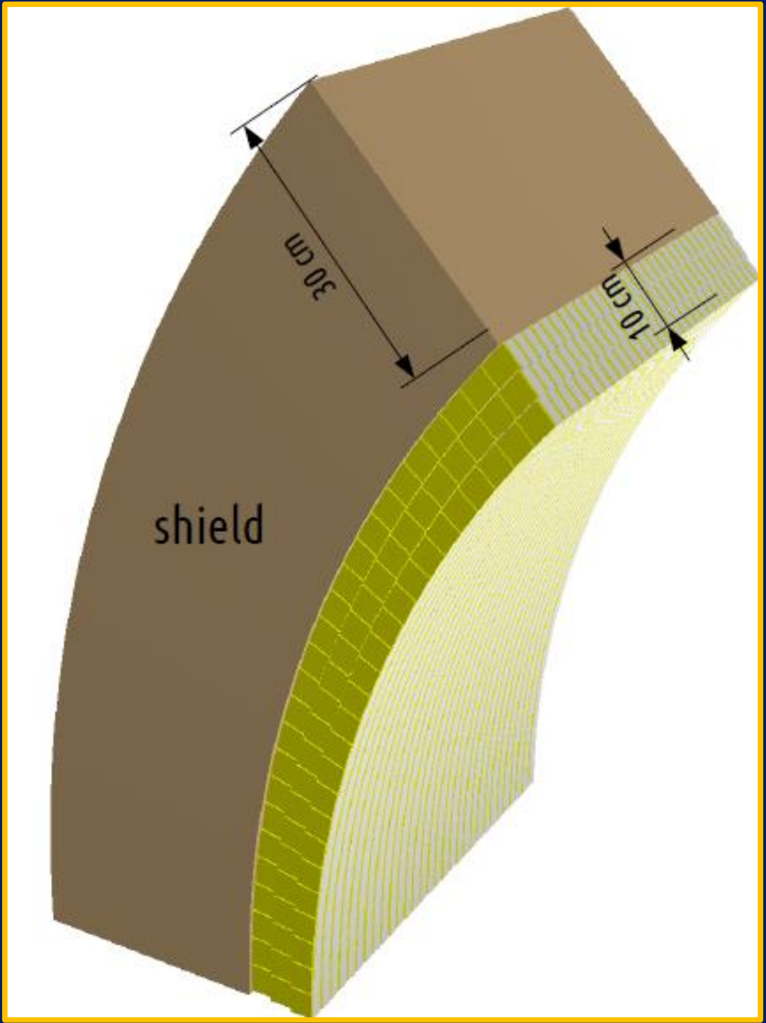


Profiting of t0 design new UCM configuration is under investigation:

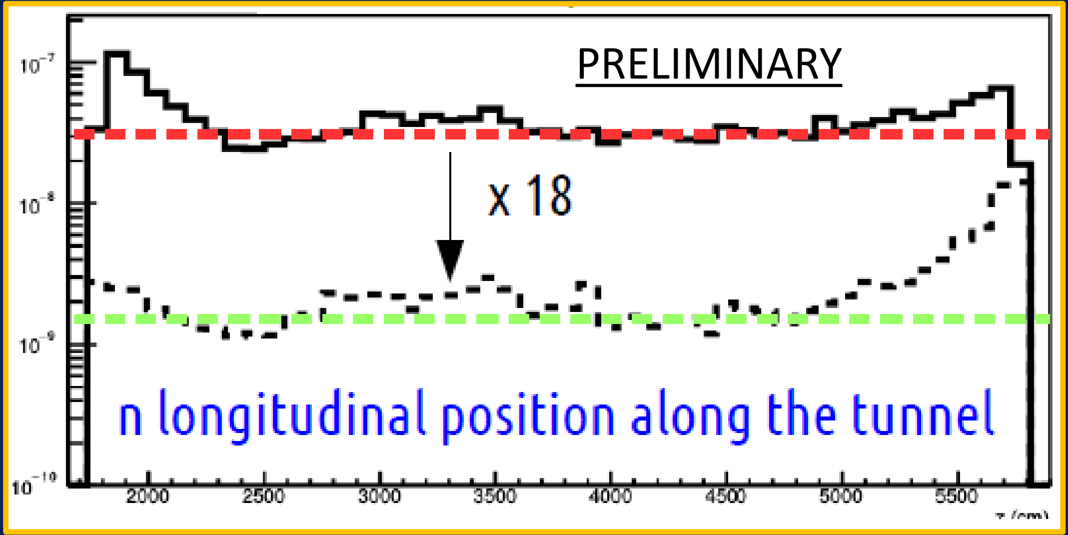
- WLS fibers from scintillator sides are bundled to single SiPM reading 10 fibers (1 UVC)
- Fibers are connected with a custom optical connector;
- 40 cm WLS fibers allow for
  - reducing neutron flux impinging on SiPM MIP signal preserverd for entire life-time of ENUBET
  - better accessibility (replacement is possible)
  - reproducibility in WLS-SiPM connection;



Neutron reduction lateral readout



- 30 cm of borathed polyethylene in front of SiPM
- FLUKA Simulation (proton 400 GeV)
- Reduction Factor ~18 averaging over the spectrum



Conclusions (1/2)

ENUBET aims:

- at monitoring lepton production at large angles (single particle level).

CHALLENGE

the decay tunnel is a harsh environment (particle rate > 200 kHz /cm^2)
→ lifetime integrate non ionizing fluence 1.8×10^{11} n/cm^2 1-MeV eq.

FBK – SiPM + UCM integration:

- Irradiation tests @ LNL → RGB-HD sensors shows after irradiation:
  - minor changes in the breakdown voltage
  - dark Current increases by more than two orders of magnitude
- Test @ T9 – CERN beamline:
  - MIP is NOT separated from dark noise after irradiation for standard UCM
    → it can be preserved by increasing the scintillator thickness

Conclusions (2/2)

Photon Veto:

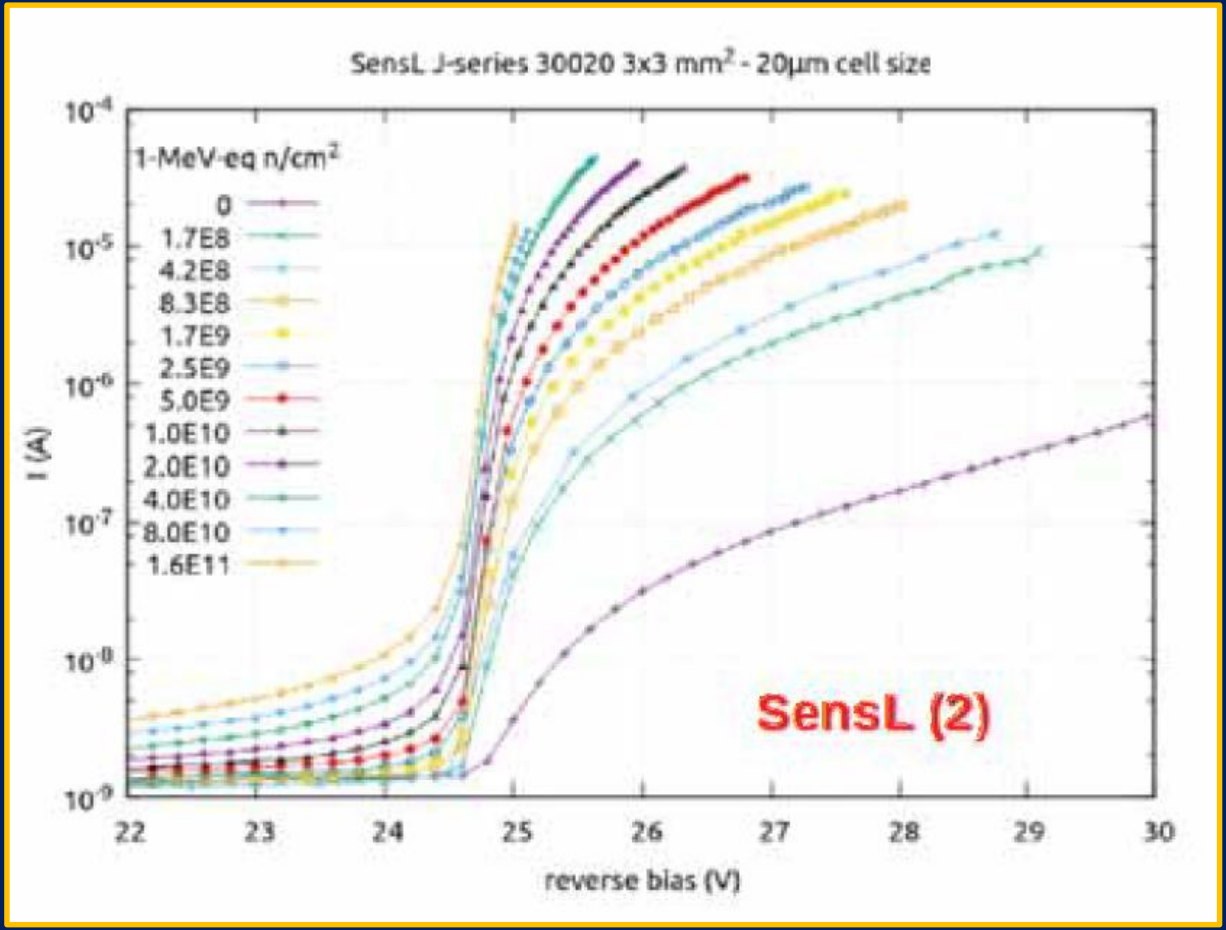
- SiPM SenSL 30020J → $\sigma_t \sim 70$ ps with laser $\lambda \sim 400$ nm
- Test @ T9 – CERN beamline
  → $\sigma_t \sim 400$ ps (matching requirement < 1 ns)
  → 1 mip / 2 mip separation (matching requirement e+ / e^-e^+ separation)

UCM modified with t_0 – like design allow for:

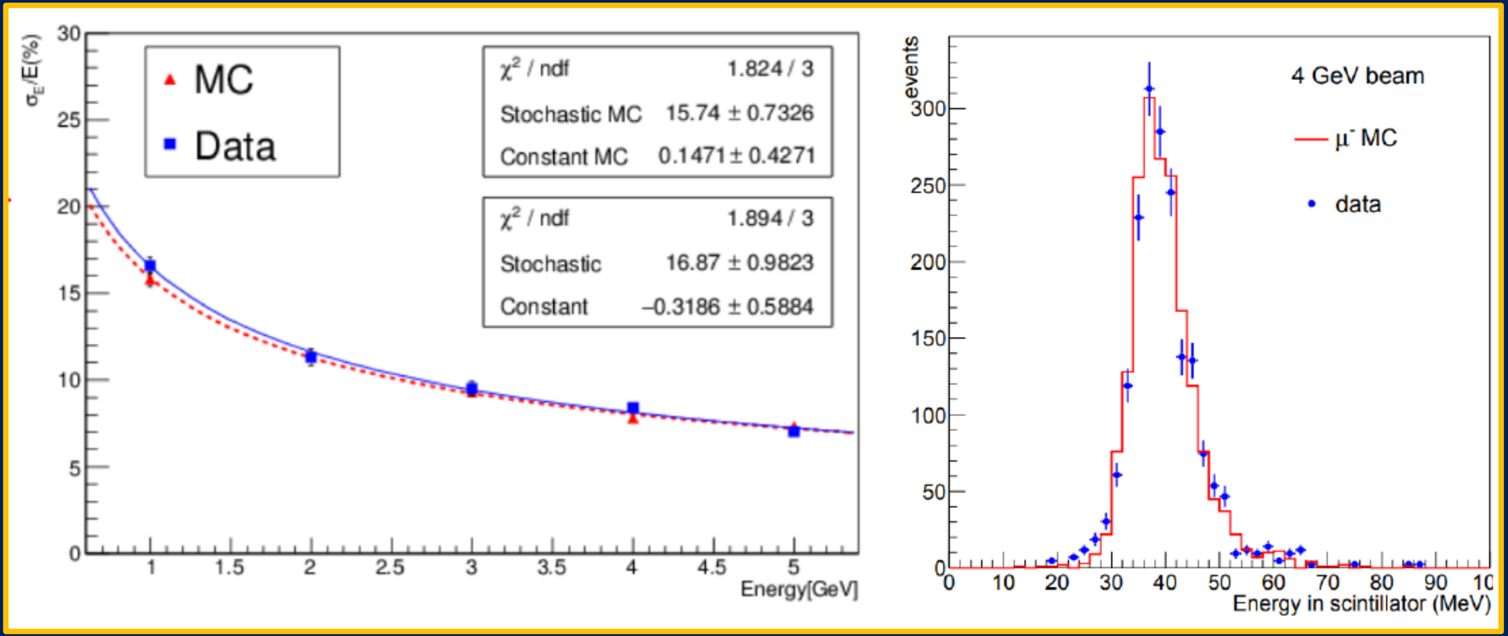
- reducing neutron flux impinging on SiPM → MIP signal preserved for entire life-time of ENUBET
- better accessibility (replacement is possible)
- reproducibility in WLS-SiPM connection

F. Acerbi et al., Irradiation and performance of RGB-HD Silicon Photomultipliers for calorimetric applications, JINST 14 (20 19) P02029

Backup slides



Standard UCM



The tagger demonstrator

- Length ~3m → allow the containment of shallow angle particles in realistic conditions
- Fraction of ϕ
- Due by 2021