Frontier Detectors for Frontier Physics
PM2018 - 14th Pisa Meeting on Advanced Detectors

MOnitor for Neutron Dose for hadrOntherapy

A new compact tracker for ultrafast secondary neutrons produced in light ions therapy

E. Gioscio, G. Battistoni, M. De Simoni, M. Fischetti, R. Mirabelli, V. Patera, A. Sarti, A. Schiavi, A. Sciubba, G. Traini, M. Marafini

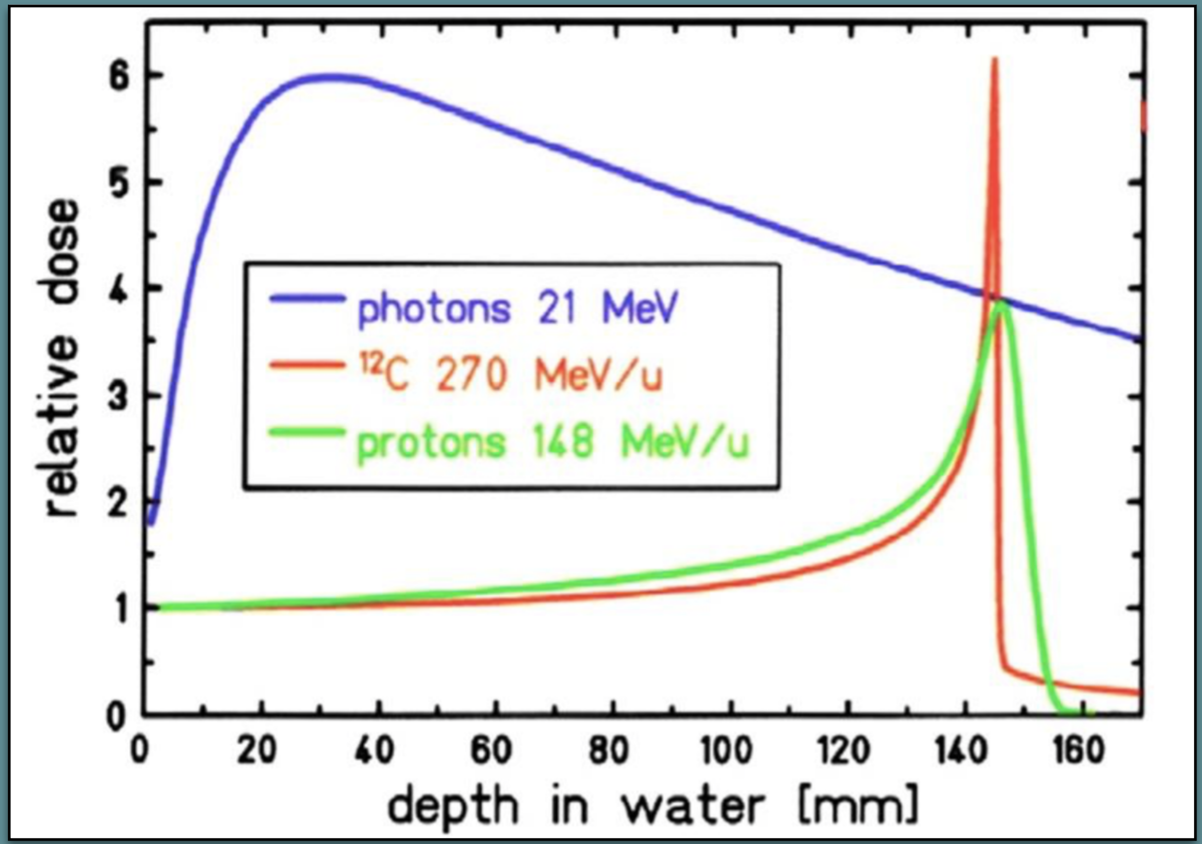
CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

INFN
Istituto Nazionale di Fisica Nucleare

SAPIENZA
UNIVERSITÀ DI ROMA

CHARGED PARTICLE THERAPY

PT is a modern technique of non-invasive radiotherapy mainly devoted to the treatment of tumours untreatable with surgery or conventional radiotherapy



Weber U., Kraft G. **Comparison of carbon ions versus protons**. Cancer J. 2009 Jul-Aug;15(4):325-32.

Light ions advantages (^{12}**C ions**):

- better spatial selectivity in dose deposition (Bragg Peak) **sparing healthy tissues** (less MS than p);
- suited for deep-seated **radio-resistant** solid tumours:
  - **relative biological effectiveness** (RBE)
  - **oxygen enhancement ratio** (OER)

Light ions disadvantages:

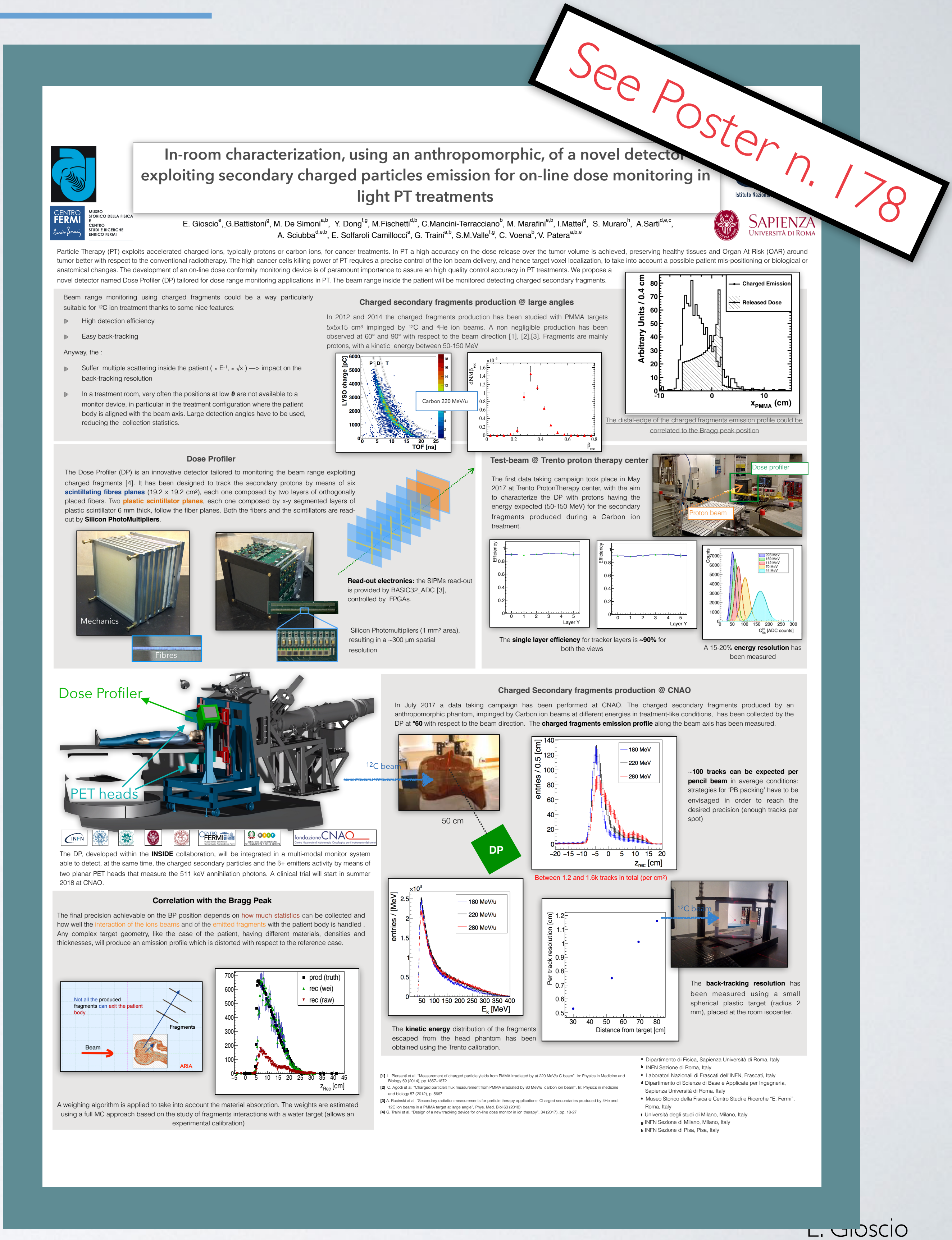
- more fragmentation (secondary products);

Increasing interest in other ions, ex. ^{4}**He** and ^{16}**O.**

SECONDARY PRODUCS IN PARTICLE THERAPY

Neutral and **charged secondary particles** are largely produced during the patient irradiation:

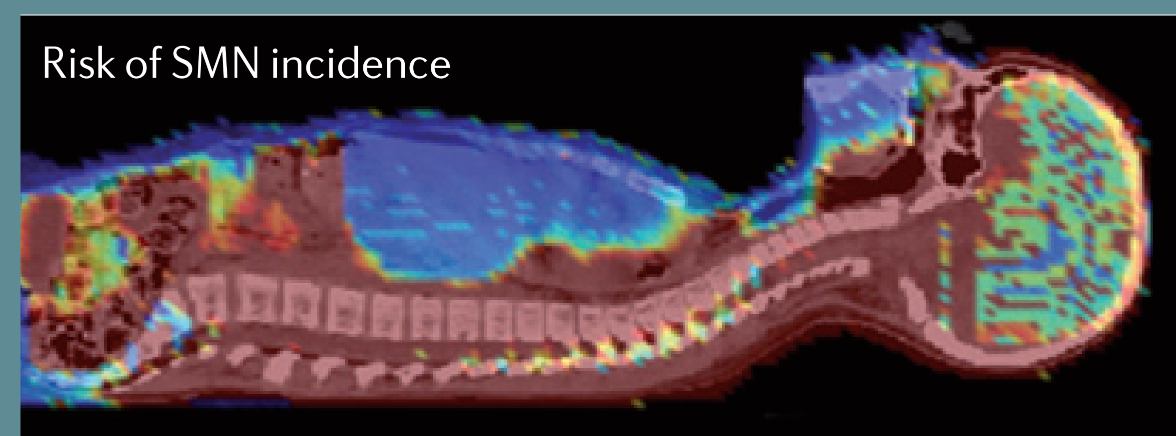
- it is crucial to characterize the secondary production in order to evaluate its contribution to the total energy deposit;
- **treatment planning system** has to take into account their contributions to the **additional dose**;
- .. but.. charged fragments can be exploited for monitoring..



SECONDARY NEUTRONS

Secondary neutrons has to be deeply investigated because they can release addition dose also **far away from the treated volume**.

Secondary malignant neoplasm (SMN): possible complication induced neutrons, one of the main concern in PT, especially in paediatric cases.



D. Wayne et al., **Assessing the risk of second malignancies after modern radiotherapy**, Nat Rev Cancer (2011). doi:10.1038/nrc3069

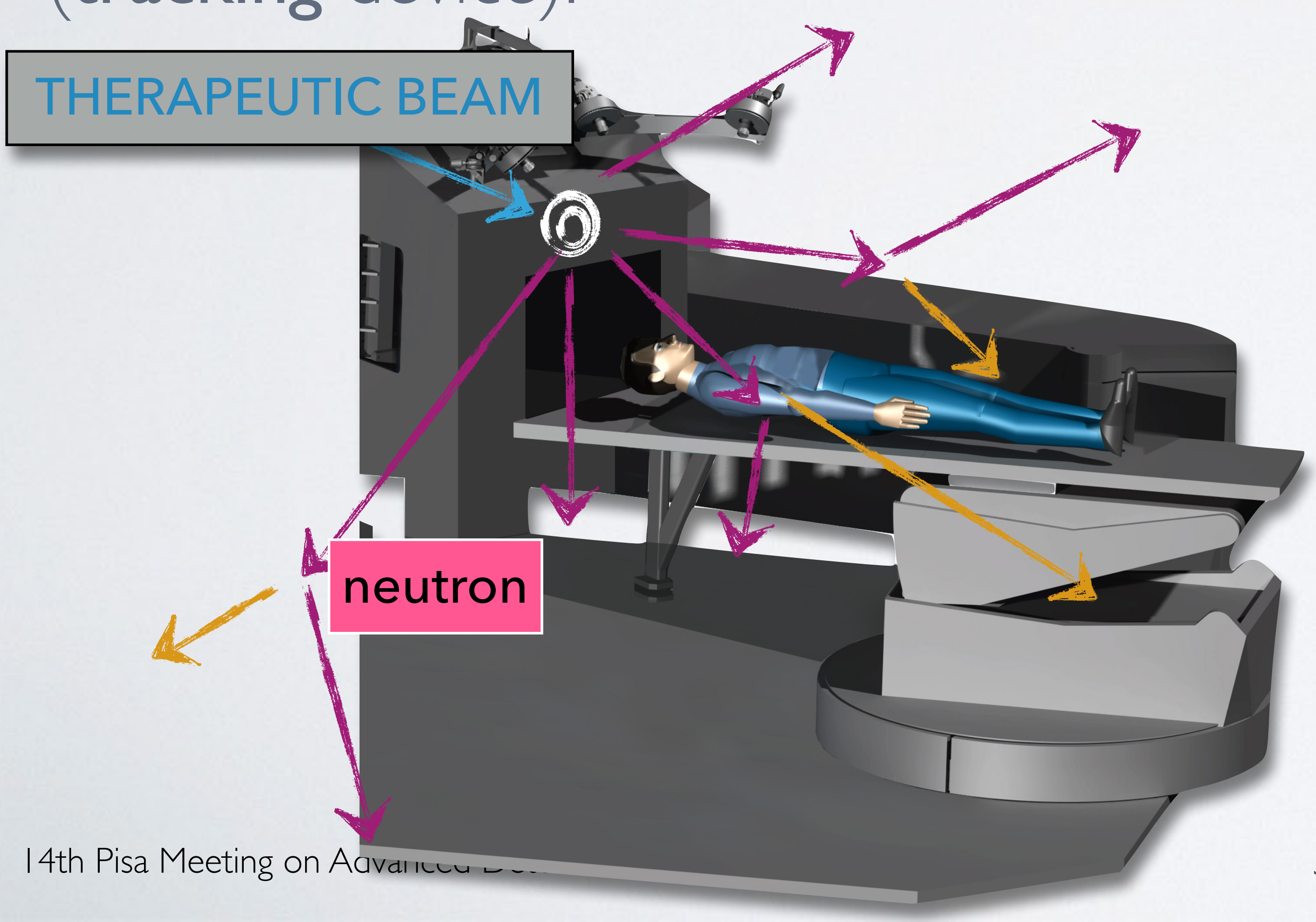
The **incidence** (also years after the treatment) of **SMNs** impacts directly in the quality and the expectation of life of the patient.

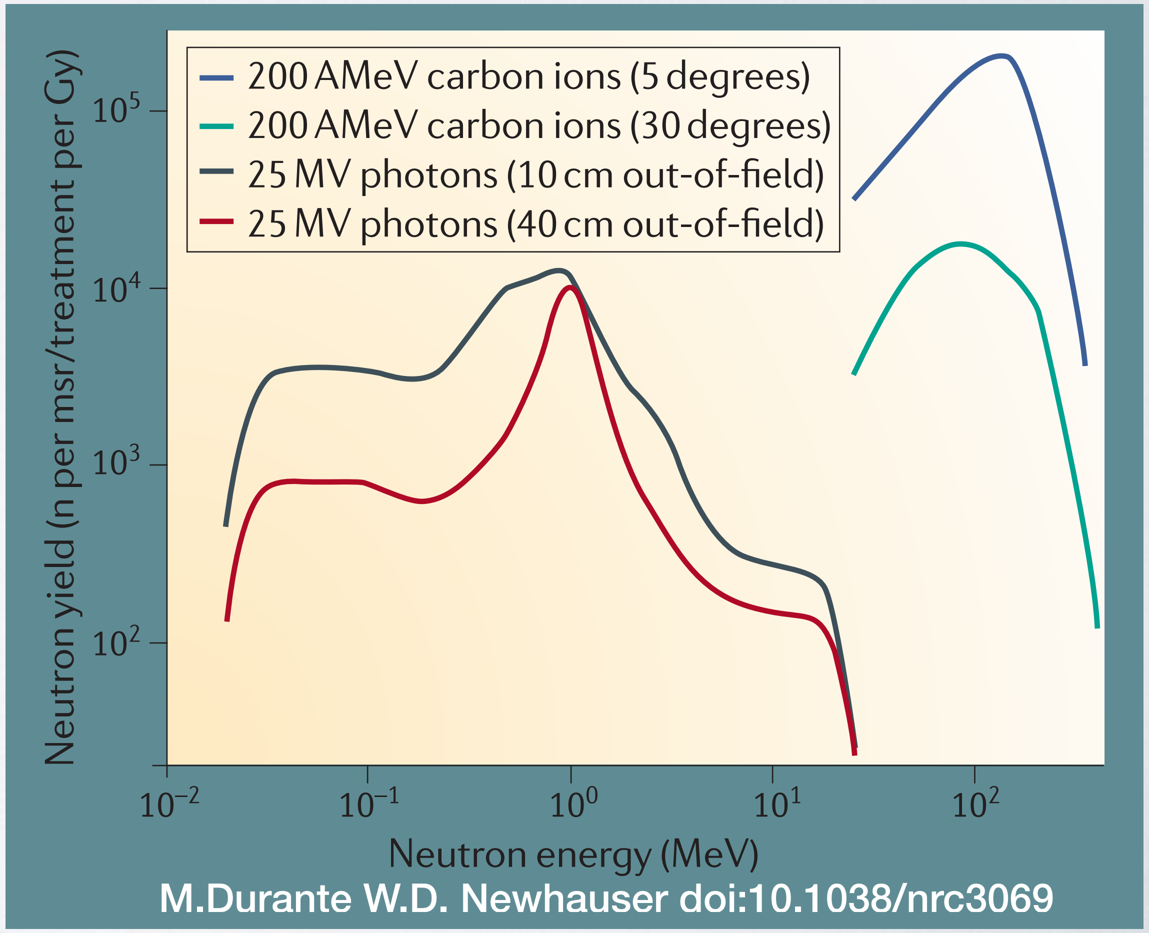
SECONDARY NEUTRONS

Neutrons are produced (as protons) in the beam nuclear interactions with the matters, in particular with the **patient tissues**.

Secondary neutrons interact also with the treatment room (and with the patient!) degrading their energy: moderation process.

It is therefore important to develop a detector capable of fully reconstruct neutrons in order to **characterize their emission profile (θ) and spectra (E_{kin})** and of rejecting the background contribution due to moderation processes (**tracking** device).

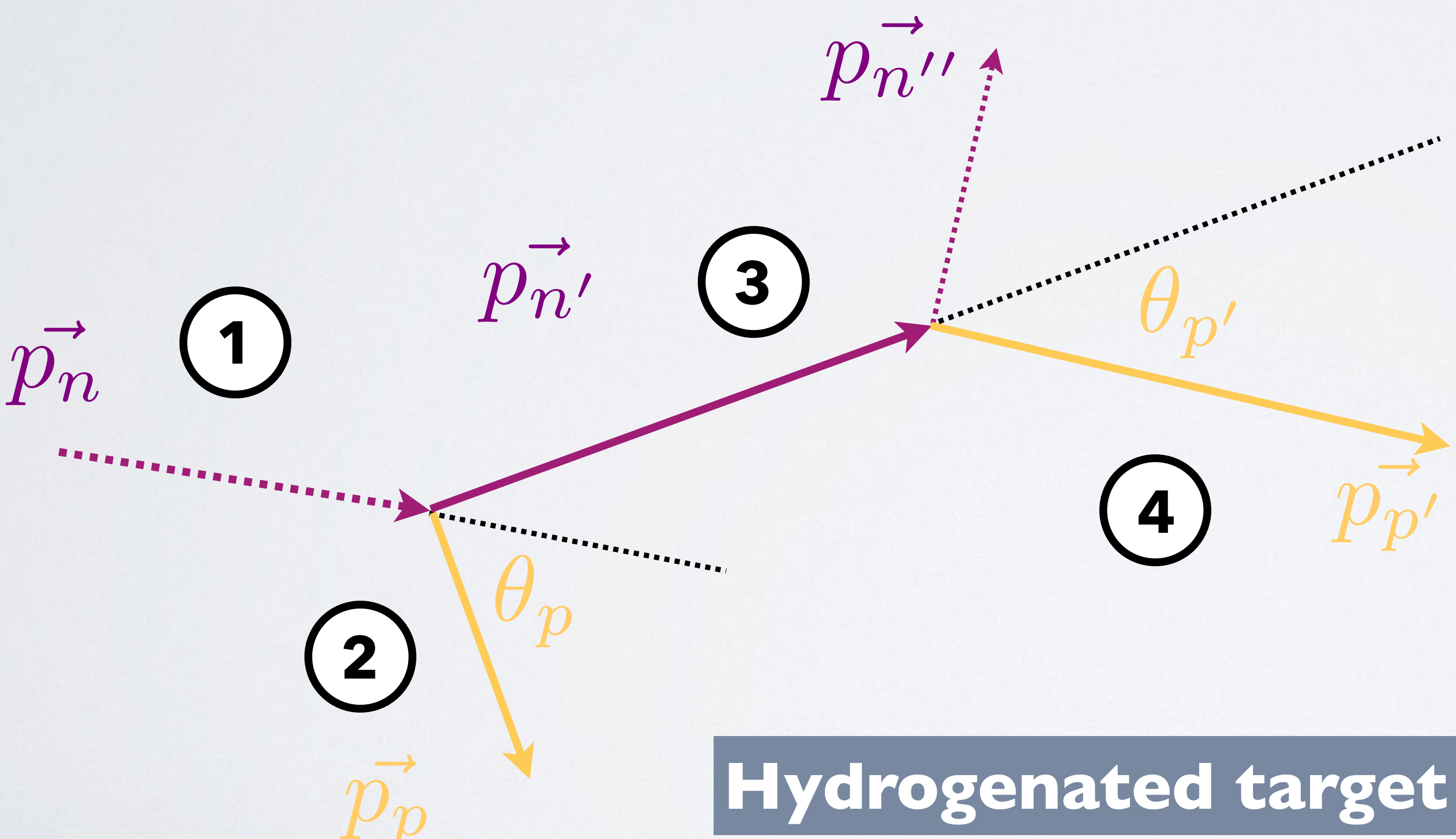




THE MONDO CHALLENGE

Tracking the neutrons with *high efficiency*

Double elastic scattering



1. First neutron interaction: elastic scattering (ES)
2. Proton recoil (E_{kin} from range)

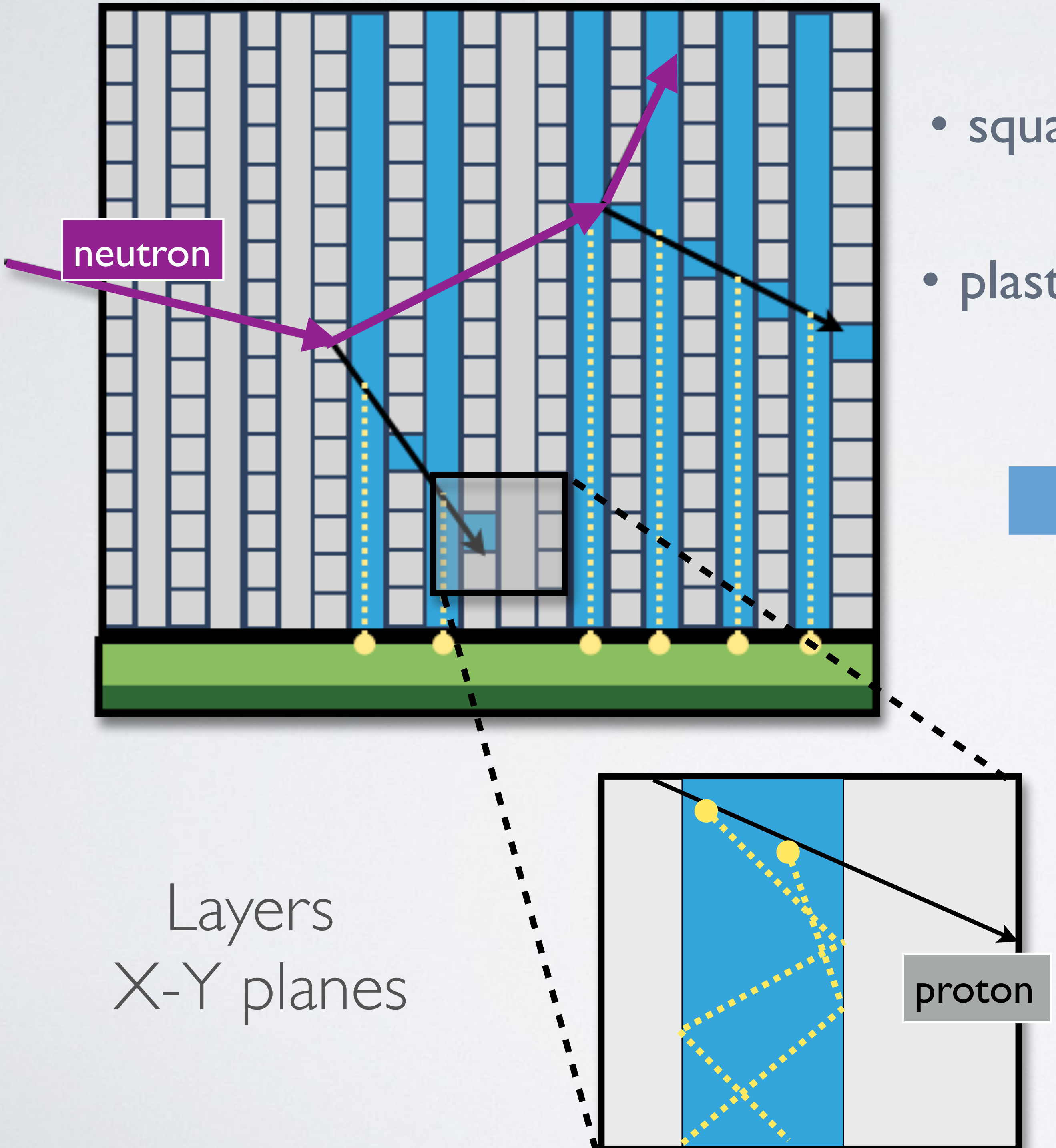
$$\vec{p_n} = \frac{p_p}{\cos\theta_p}\hat{n}$$

3. The diffused neutron interact again via ES
4. Second proton recoil

$$\vec{p_{n'}} = \frac{p_{p'}}{\cos\theta_{p'}}\hat{n}'$$

THE MONDO CHALLENGE

Double elastic scattering



Layers
X-Y planes

SCINTILLATING PLASTIC FIBRES

- squared 250 μm (to maximise the granularity)
- plastic (high neutron interaction probability on H)

layers of fibres → target and tracker

Final tracker size:
10 x 10 x 20 cm³

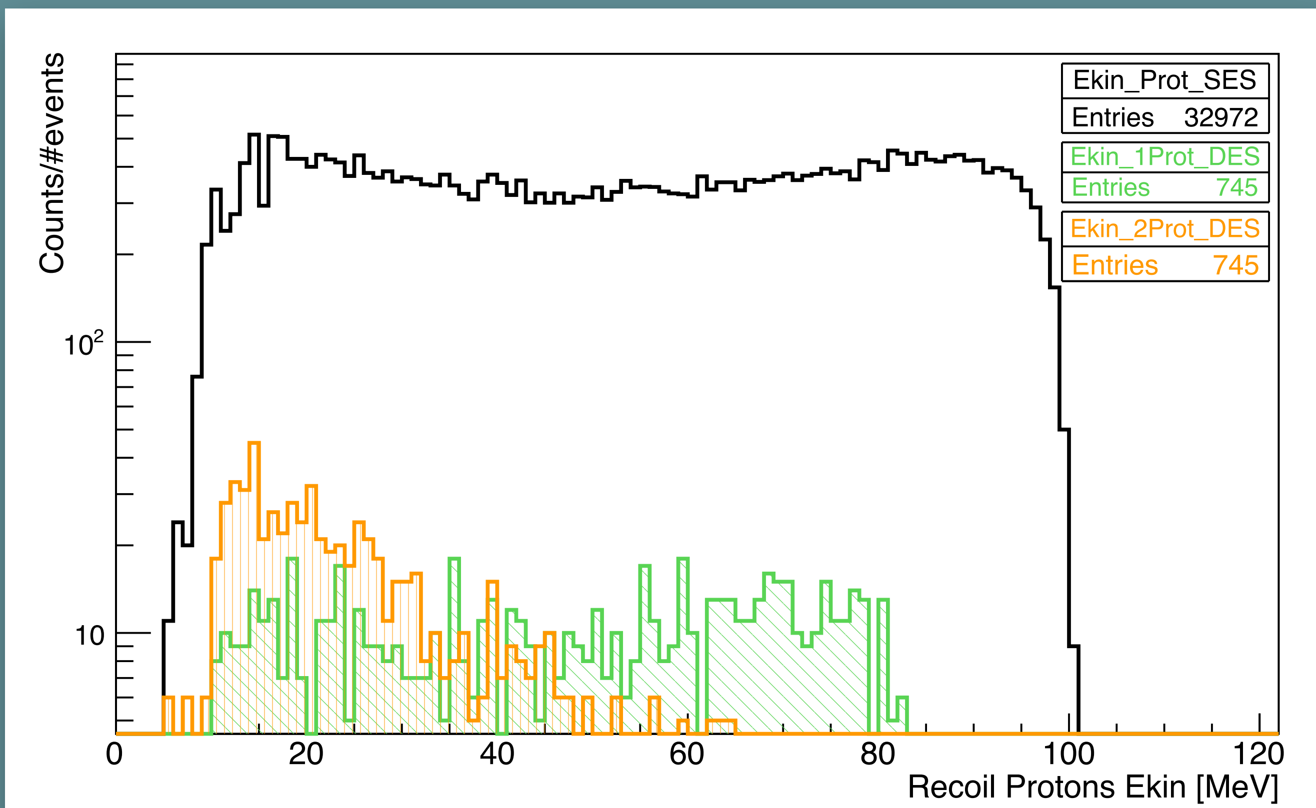
more than 6x10⁵ channels

=> **silicon readout system**

ENERGY DEPOSITED

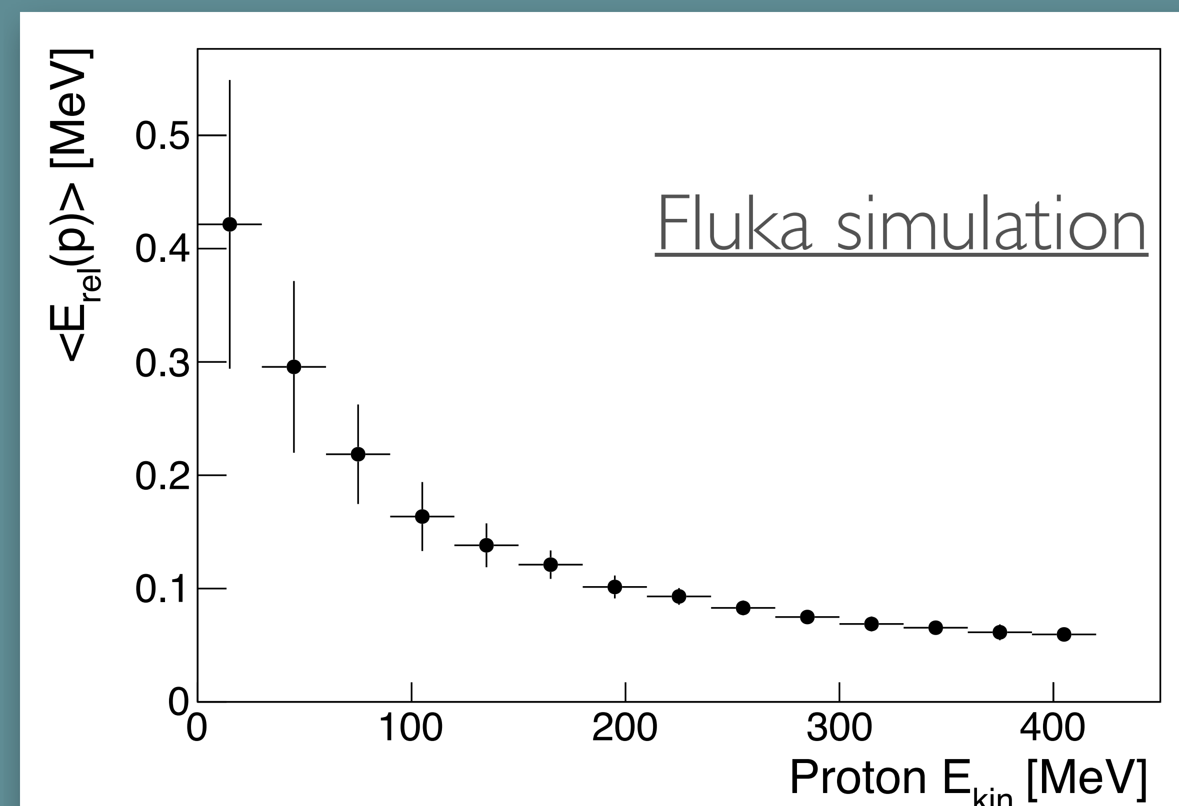
A Monte Carlo simulation has been developed using FLUKA code to optimize and study the detector. The energy release of the protons in the fibers as a function of the neutron (and proton) energy has been evaluated.

Ex. of the proton spectrum for 100MeV neutrons



V. Giacometti et al. **Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation** (in press).

Deposited energy per fibre	100 keV in 250 μm
Light yield (BCF-12)	8000 ph. MeV^{-1}
Trapping eff. (double clad.)	7%
$N_{\mathrm{Ph.}}^{\mathrm{prod}}$	60 ph.

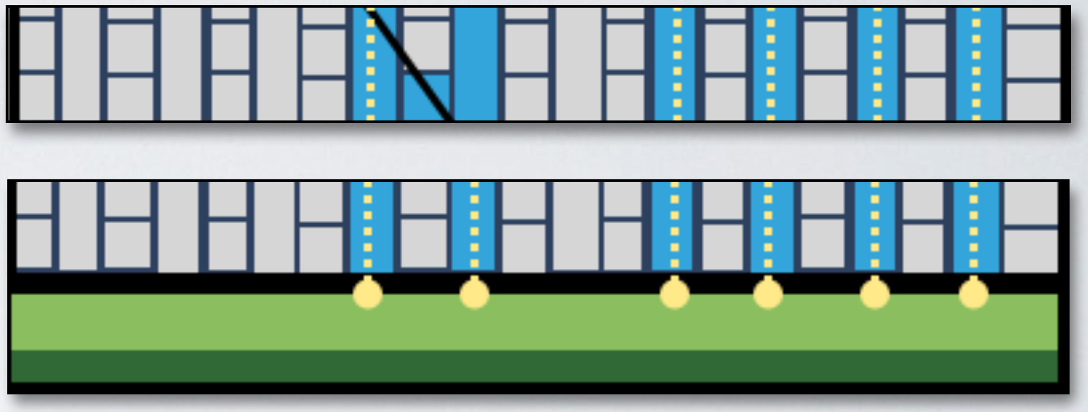


M. Marafini et al., PMB (2017) doi: 10.1088/1361-6560/aa623a

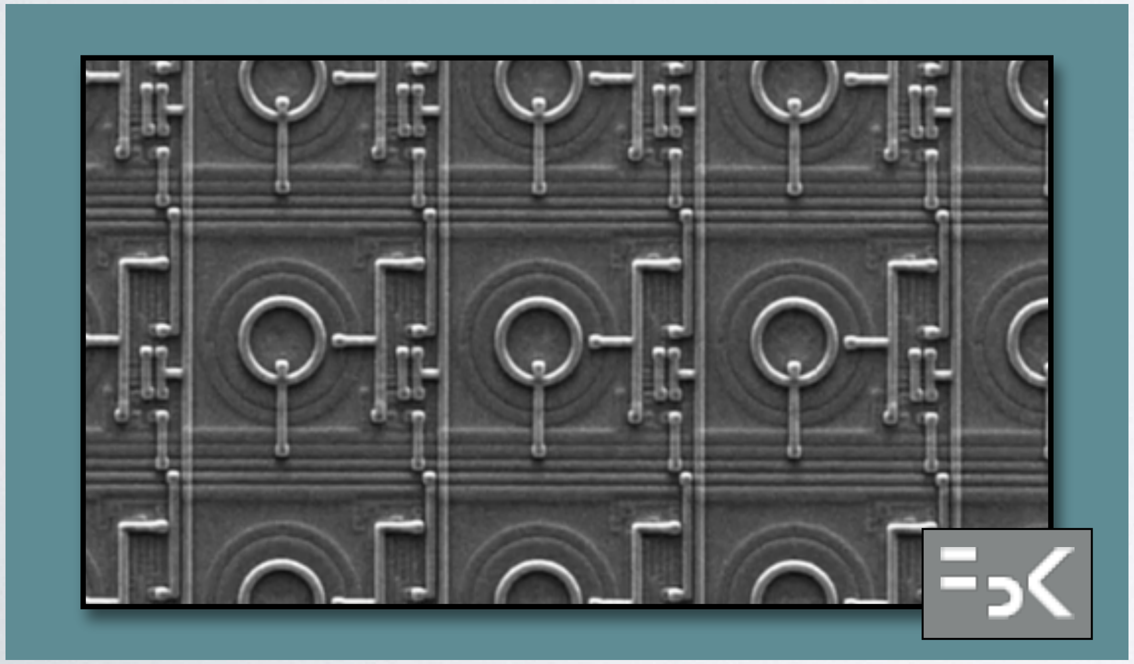
NEUTRONS TRACKER

Silicon Detector for READOUT

- Need to keep the space granularity of the fibres
- Few photons (few ph. electrons)
- Fast signals: typically ~5ns



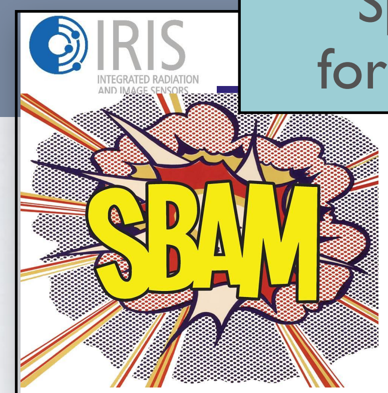
Digital silicon diode (Silicon Photon Avalanche Diode -SPAD) allows to build a sensor with customized pixel size. An internal smart trigger logic allows to discriminate the scintillation light signals from the background due to the dark count rate.



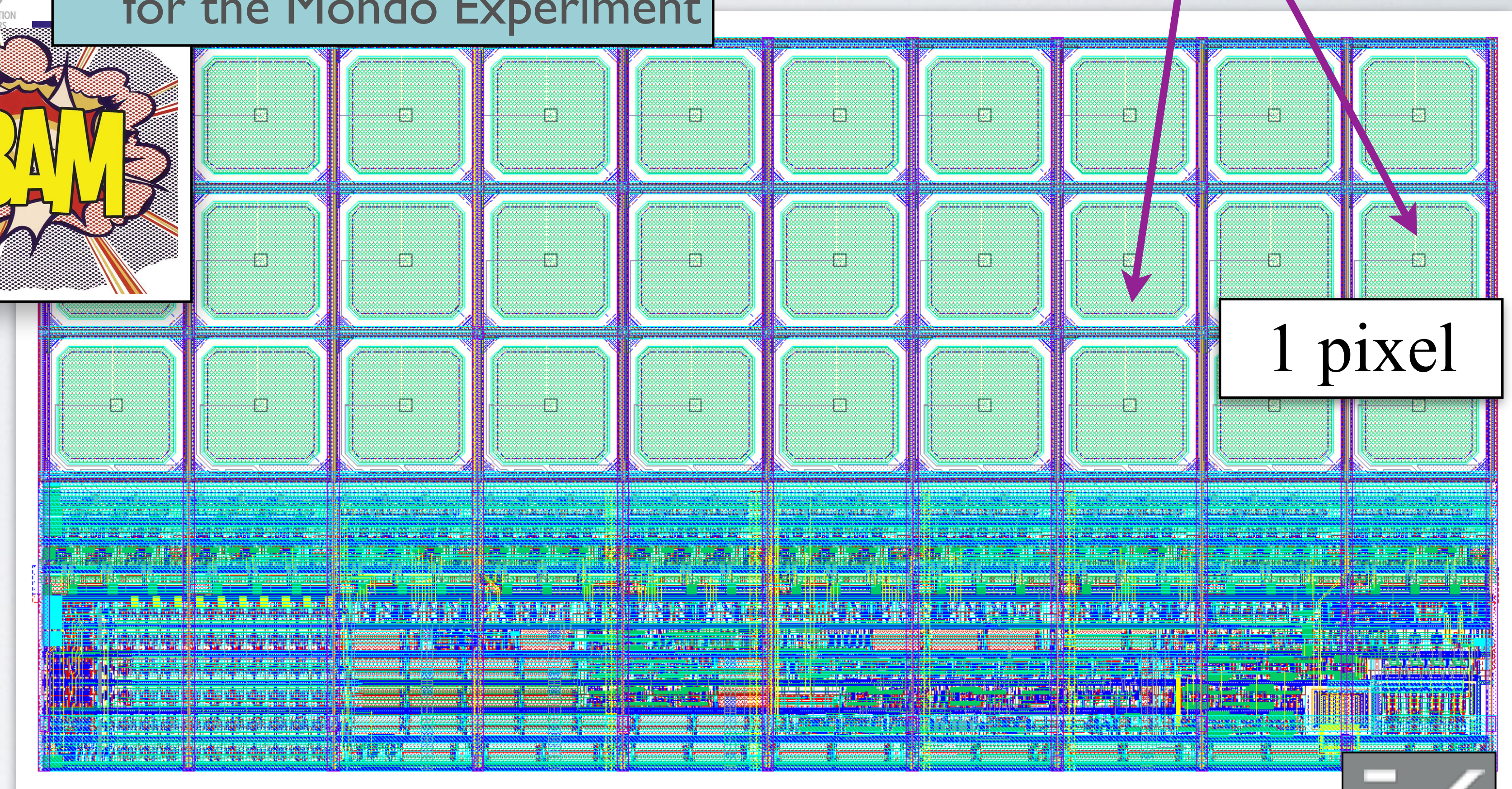
We choose to develop a new SPAD array sensor - in collaboration FBK (SBAM sensor) - tailored for the MONDO needs

NEUTRONS TRACKER

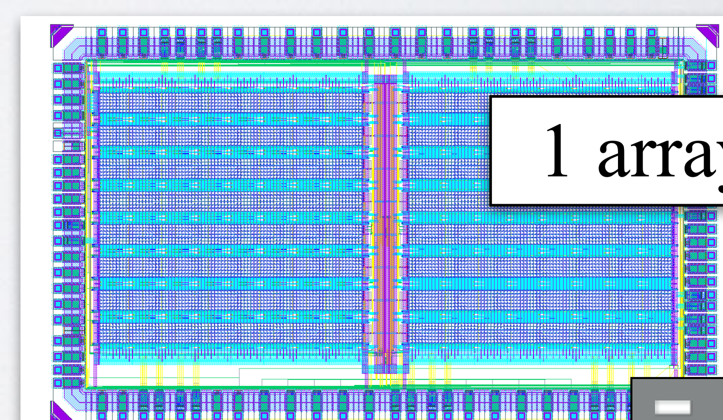
Main characteristics of the new sensor



- Pixel 125x250 μm
- side-by-side sensors
- Fill Factor ~33%
- Trigger logic tuned for plastic scintillation signals
- Quantum efficiency ~40%
- Possibility to turn-off noisy SPAD (Dark Current reduction)
- Possible EXT. Trigger

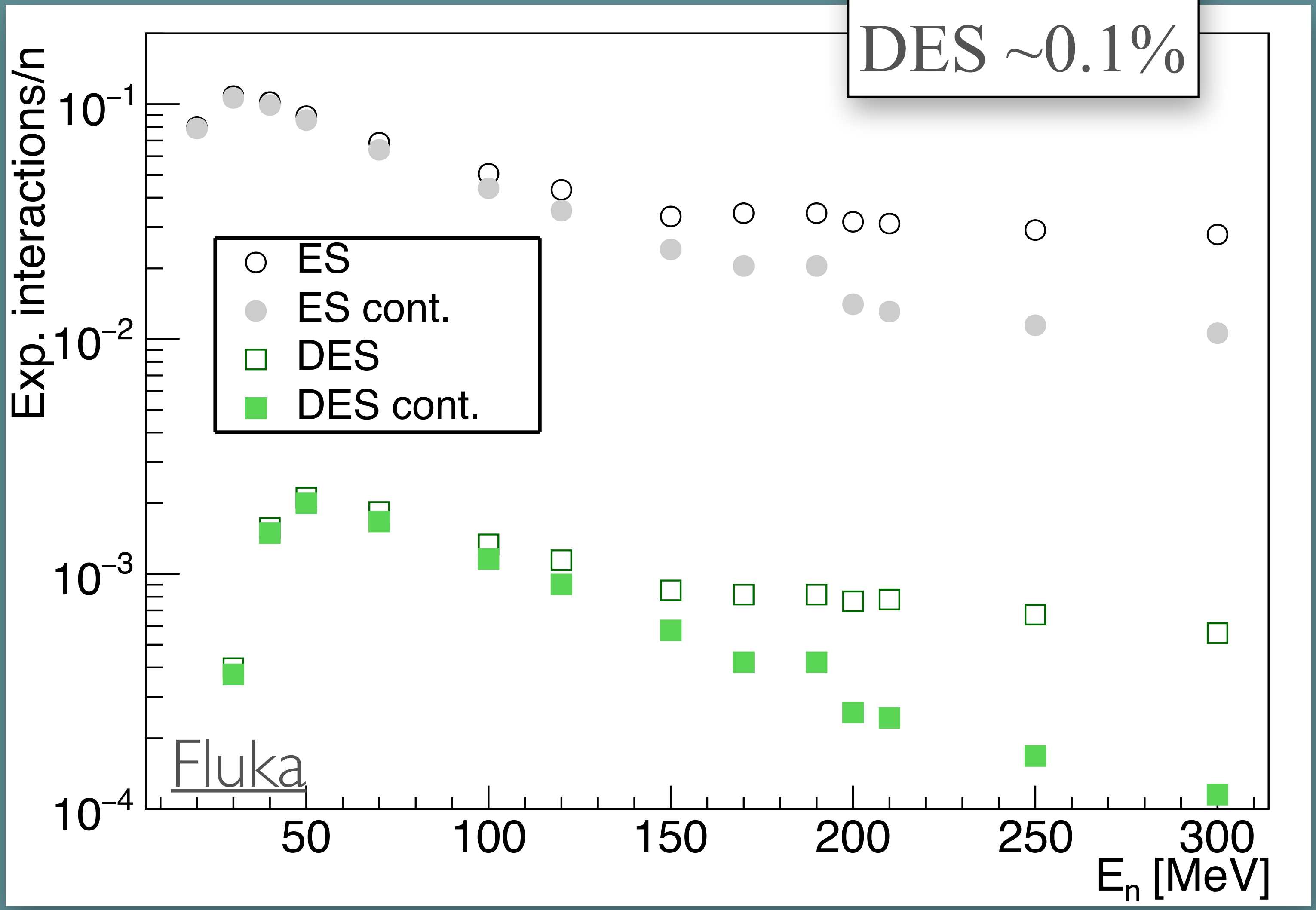


First chip run may 2018



INTERACTION PROBABILITY STUDY

Comparison of the expected number of interactions per incident neutron for single and double elastic scattering as a function of the neutrons initial kinetic energy.



ES ~ 5%
DES ~0.1%

V. Giacometti et al. **Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation** (in press)

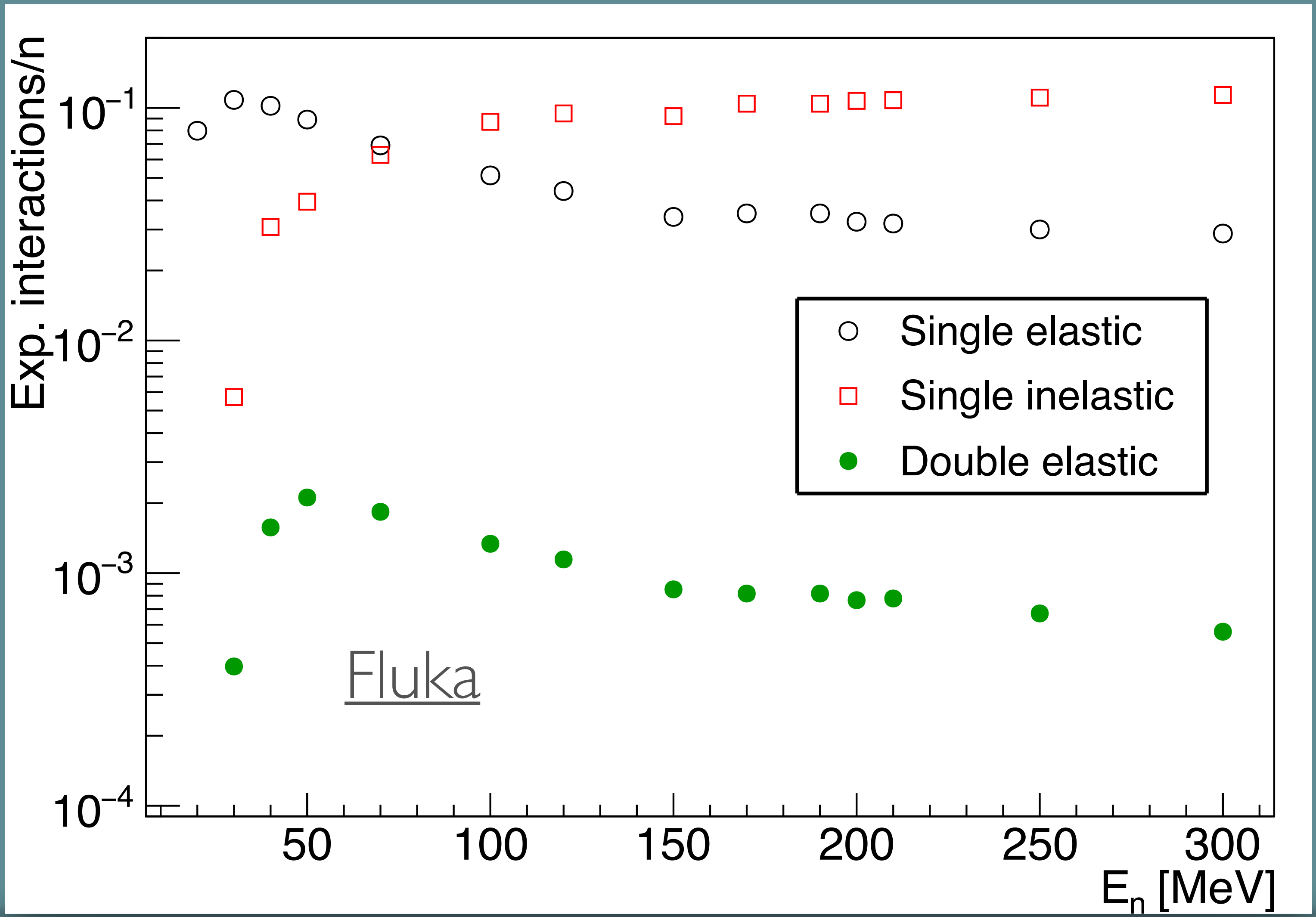
Constraints:

- full containment request of the protons;
- at least 3 layers crossed (about 12 MeV)

containment decreases of one order of magnitude the detection efficiency => under evaluation other proton kinetic energy measurements strategies (i.e. energy loss along the track, ToF, etc, ..)

BACKGROUND STUDY

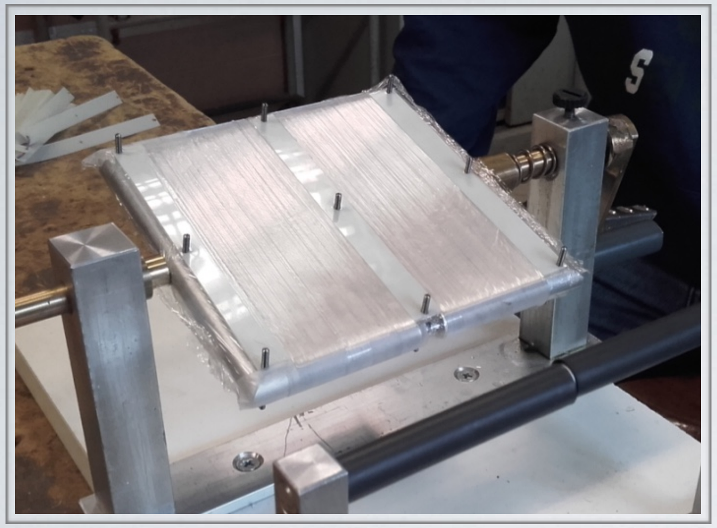
Inelastic interactions (IS) are the main intrinsic background for the elastic events (ES). ES are dominant below100 MeV, while IS are not negligible for higher energies.



V. Giacometti et al. **Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation** (in press)

- The probability of mixed elastic and inelastic interactions could have a non-negligible impact on the detector performances and it has to be taken into account when calculating the intrinsic background.

Track multiplicity at the interaction vertex will be used to reduce the background contamination and reject inelastic events.



NEUTRONS TRACKER

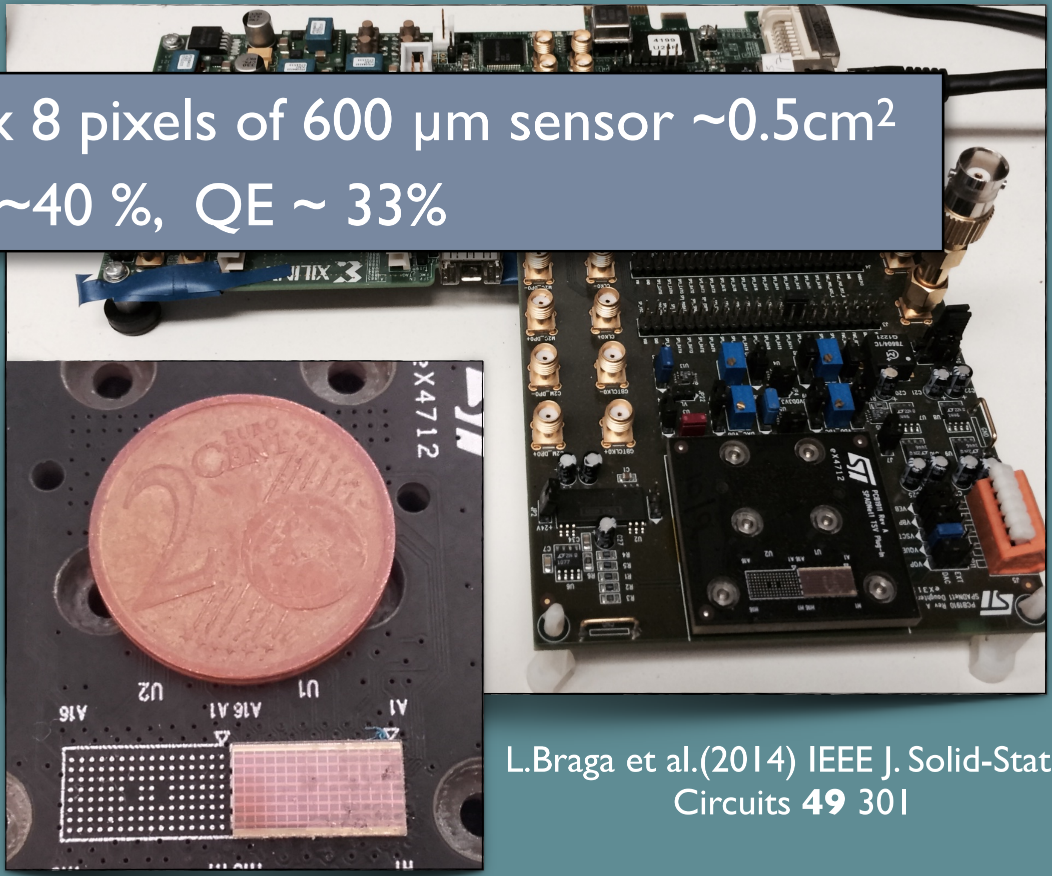
A tracker prototipe (4 x 4 x 4.8 cm^3) has been realized as a proof of principle for proton trading and in order to test the assembling procedure.

The new sensor SBAM has been developed starting from the experience gained using an other **sensor prototype: spad-net.** Practicing with spad-net allowed us to point out the critical issues to be addressed in the SBAM development phase.

Test PENELOPE prototype:

- ^{90}Sr (electrons ~2 MeV)*
- cosmics rays (mip)
- electrons@BTF (30-510 MeV) (~mip)**
- **protons@Trento (60-230MeV)**

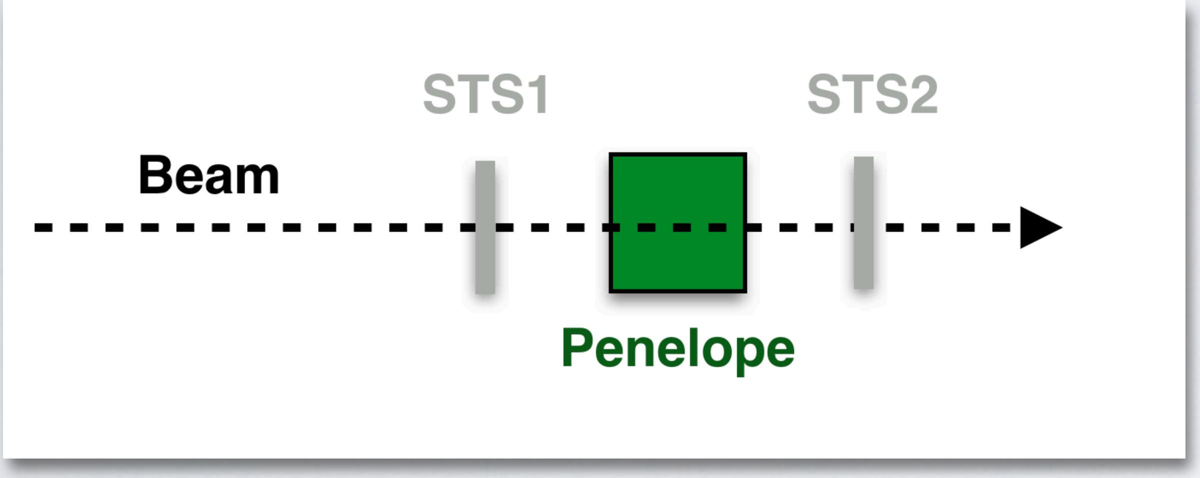
16 x 8 pixels of 600 μm sensor ~0.5cm^2
FF ~40 %, QE ~ 33%



L.Braga et al.(2014) IEEE J. Solid-State Circuits **49** 301

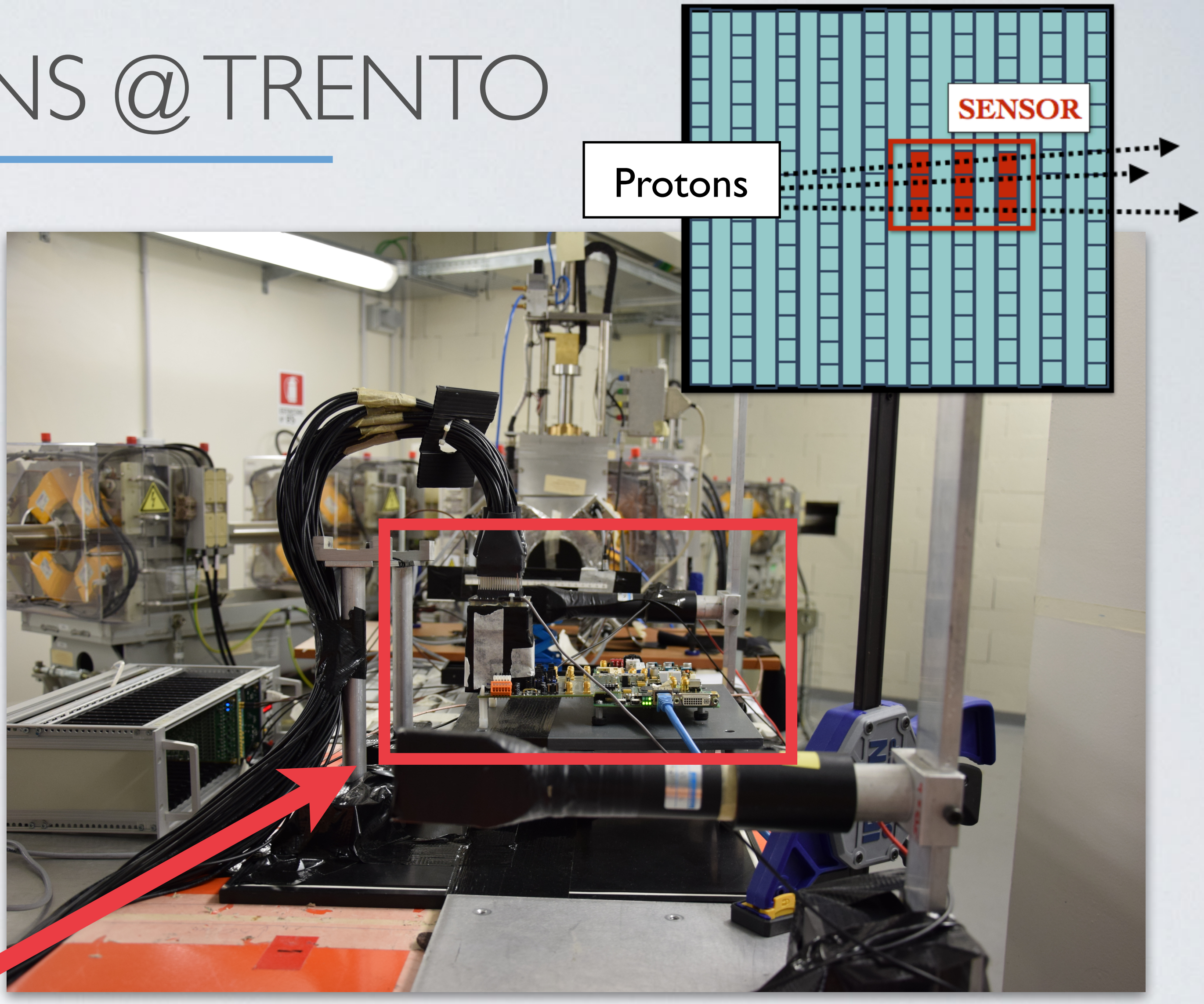
* S.M. Valle et al., The MONDO project: A secondary neutron tracker detector for particle therapy, doi: doi:10.1016/j.nima.2016.05.001
** R. Mirabelli et al, The MONDO detector prototype development and test: steps towards a SPAD-CMOS based integrated readout (SBAM sensor) doi:10.1109/TNS.2017.2785768

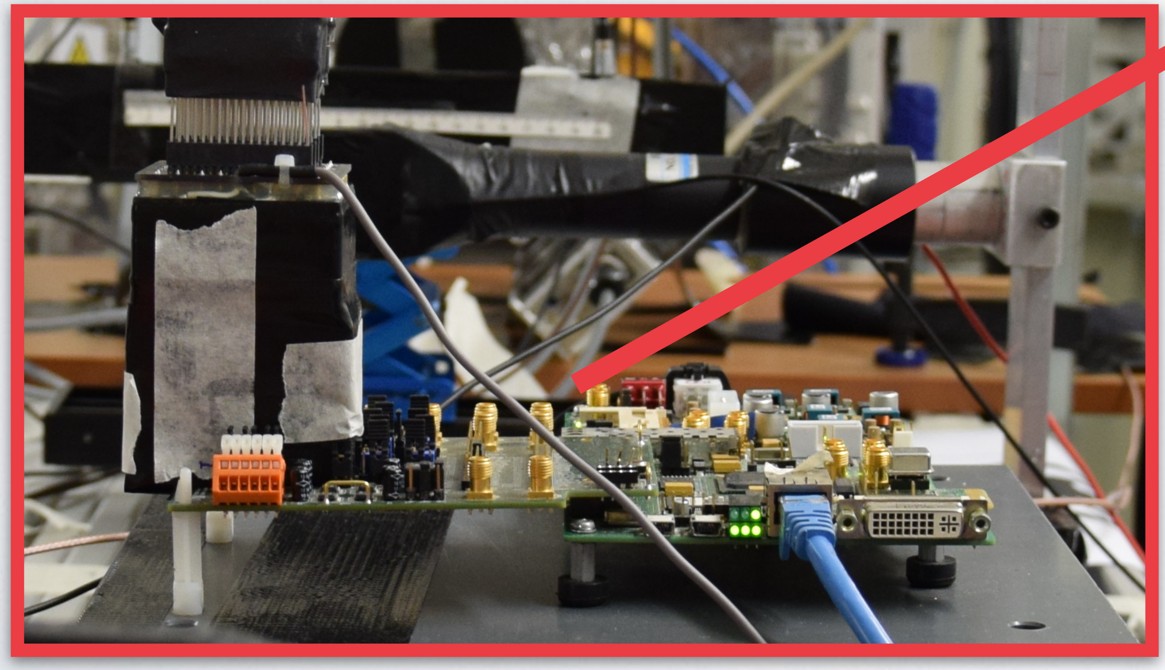
PROTONS @TRENTO



Beam energy: [70-140] MeV protons

Beam size (σ): [3-7] mm



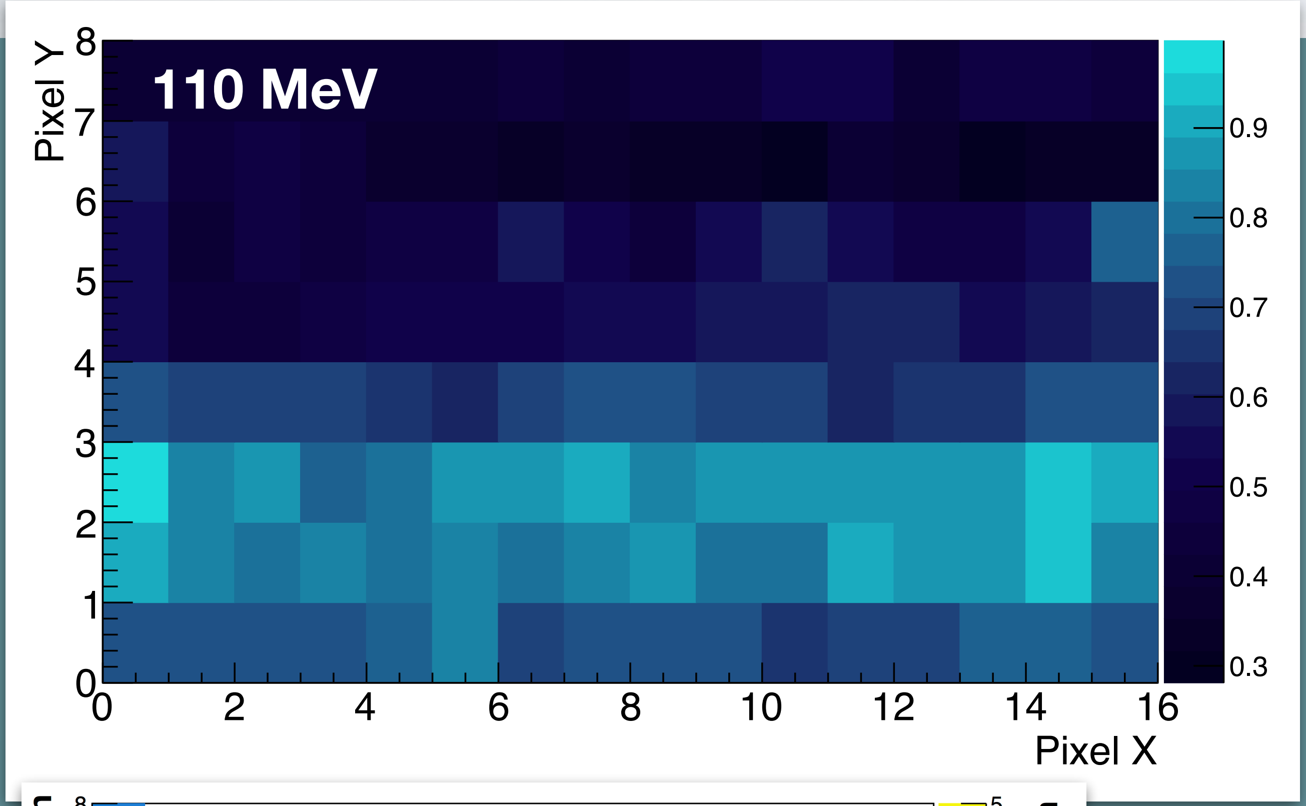


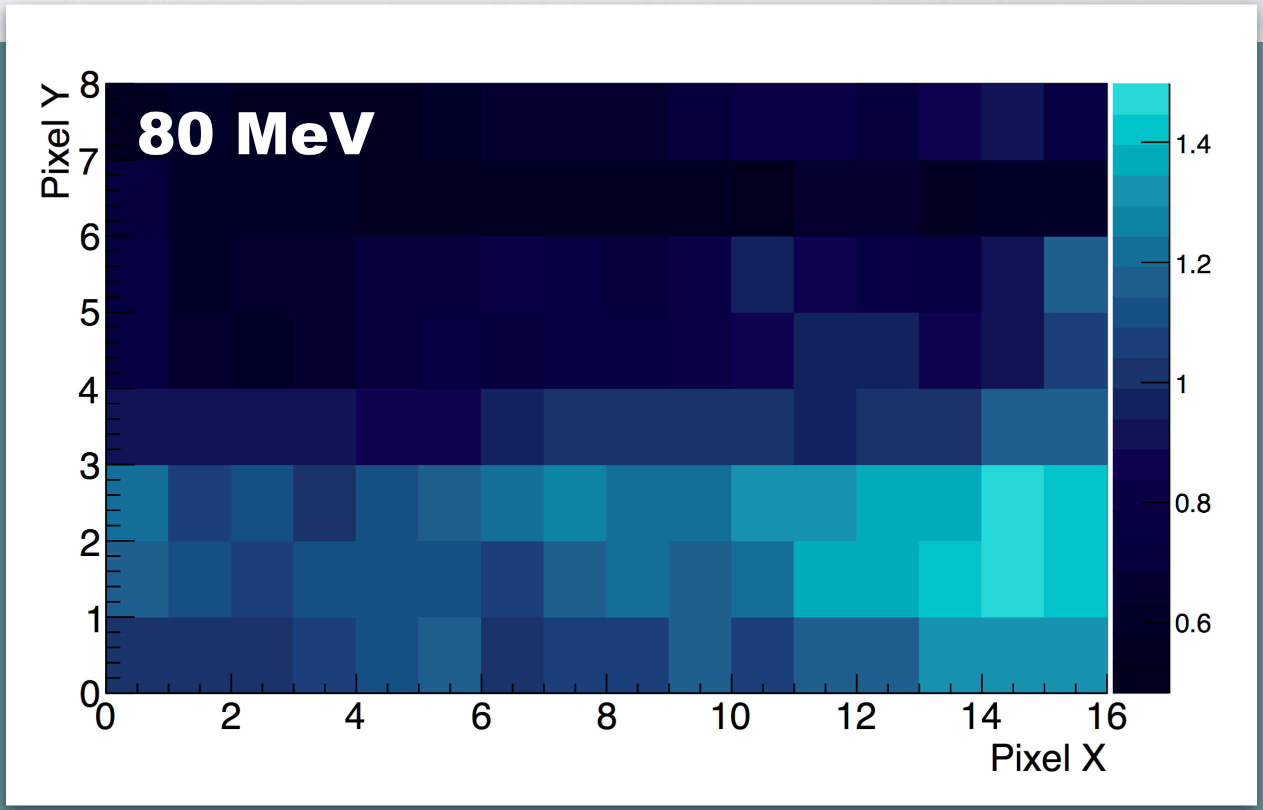
PENELOPE readout FBK spad-net sensor (128 ch., 600 μm per pixel)

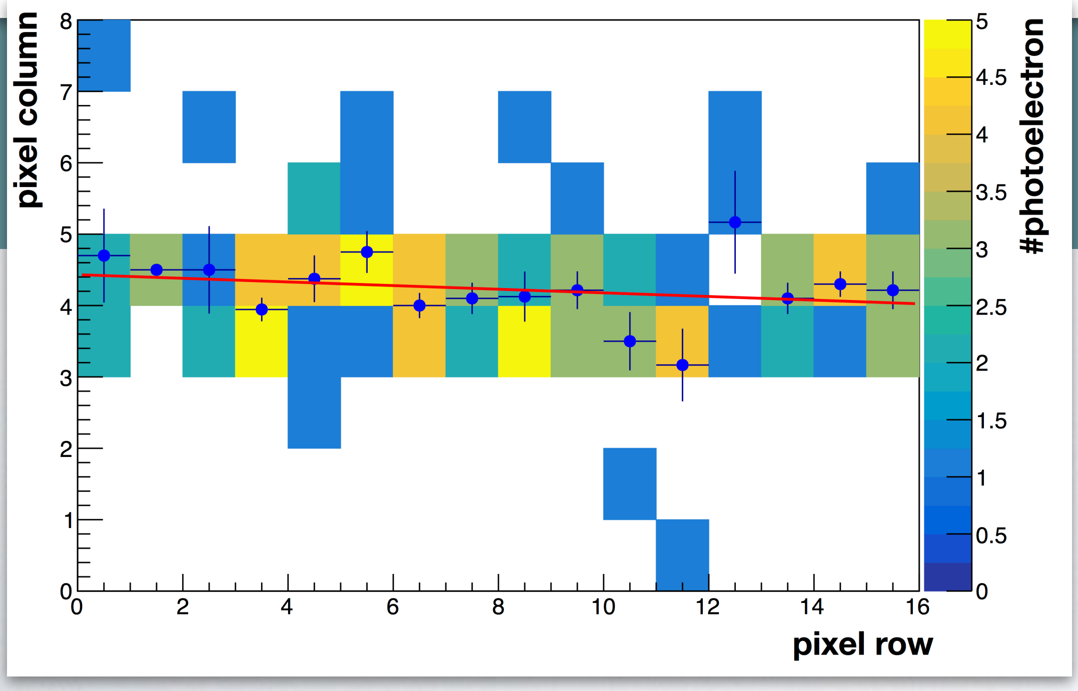
A second readout with a commercial multi-anode PMT has been used to cross-check the tracking efficiency.

PROTONS @ TRENTO PROTON THERAPY

Sensor response: map of the average number of ph.el per pixel (75k events)





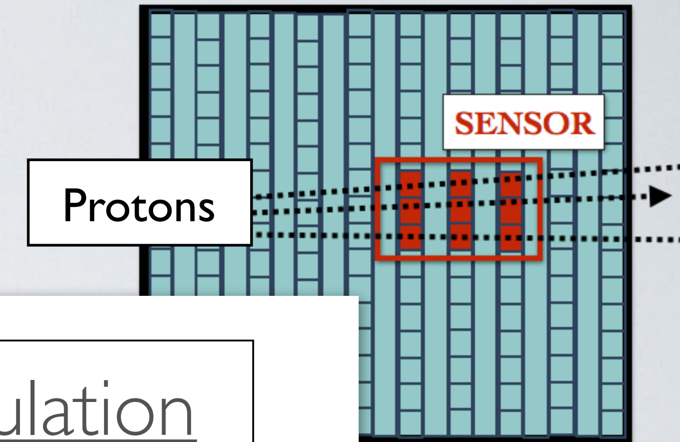


G. Traini et al, **Preliminary test of the MONDO project secondary fast and ultrafast neutrons tracker response using protons and MIP particles** doi:10.1088/1748-0221/13/04/C04014

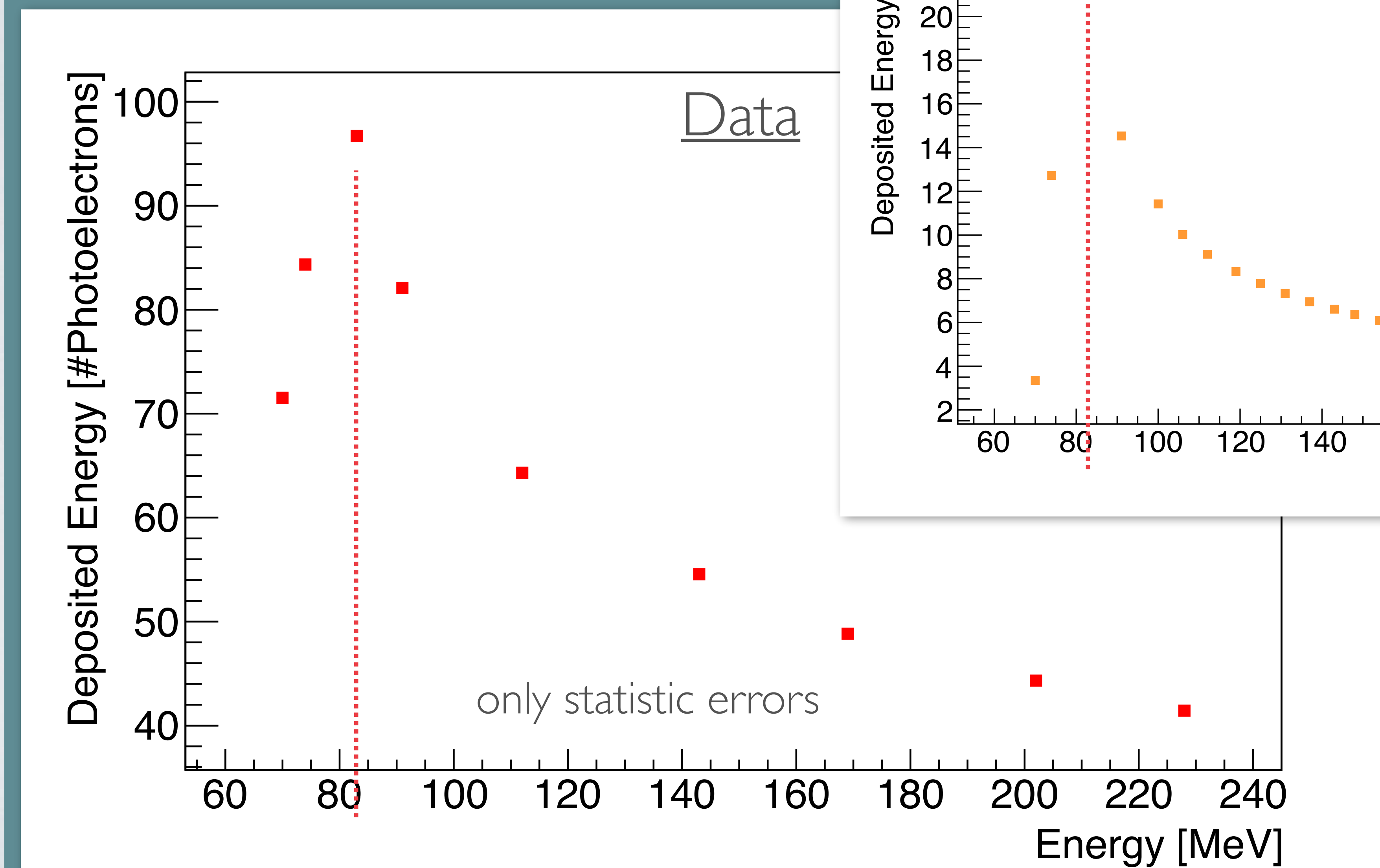
Single Track

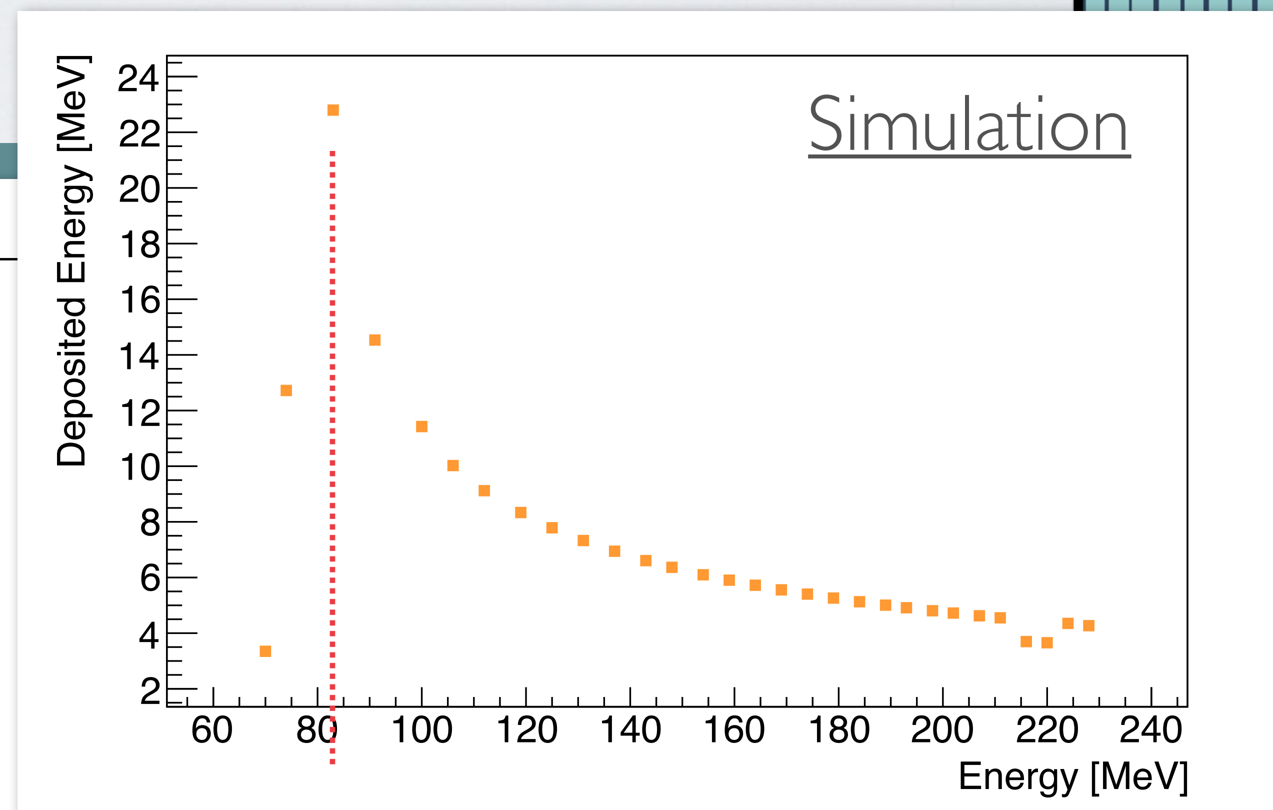
Example of a 140 MeV proton track reconstructed by the SPAD-net sensor.

PROTONS @ TRENTO PROTON THERAPY



Simulated energy deposited in the fibres as a function of the primary proton kinetic energy (only the volume covered by the SPAD-net sensor was considered).





G. Traini et al, **Preliminary test of the MONDO project secondary fast and ultrafast neutrons tracker response using protons and MIP particles** doi:10.1088/1748-0221/13/04/C04014

As expected, the Bragg Peak is clearly visible for 83 MeV protons.

E. Gioscio

CONCLUSION

NEXT FUTURE:

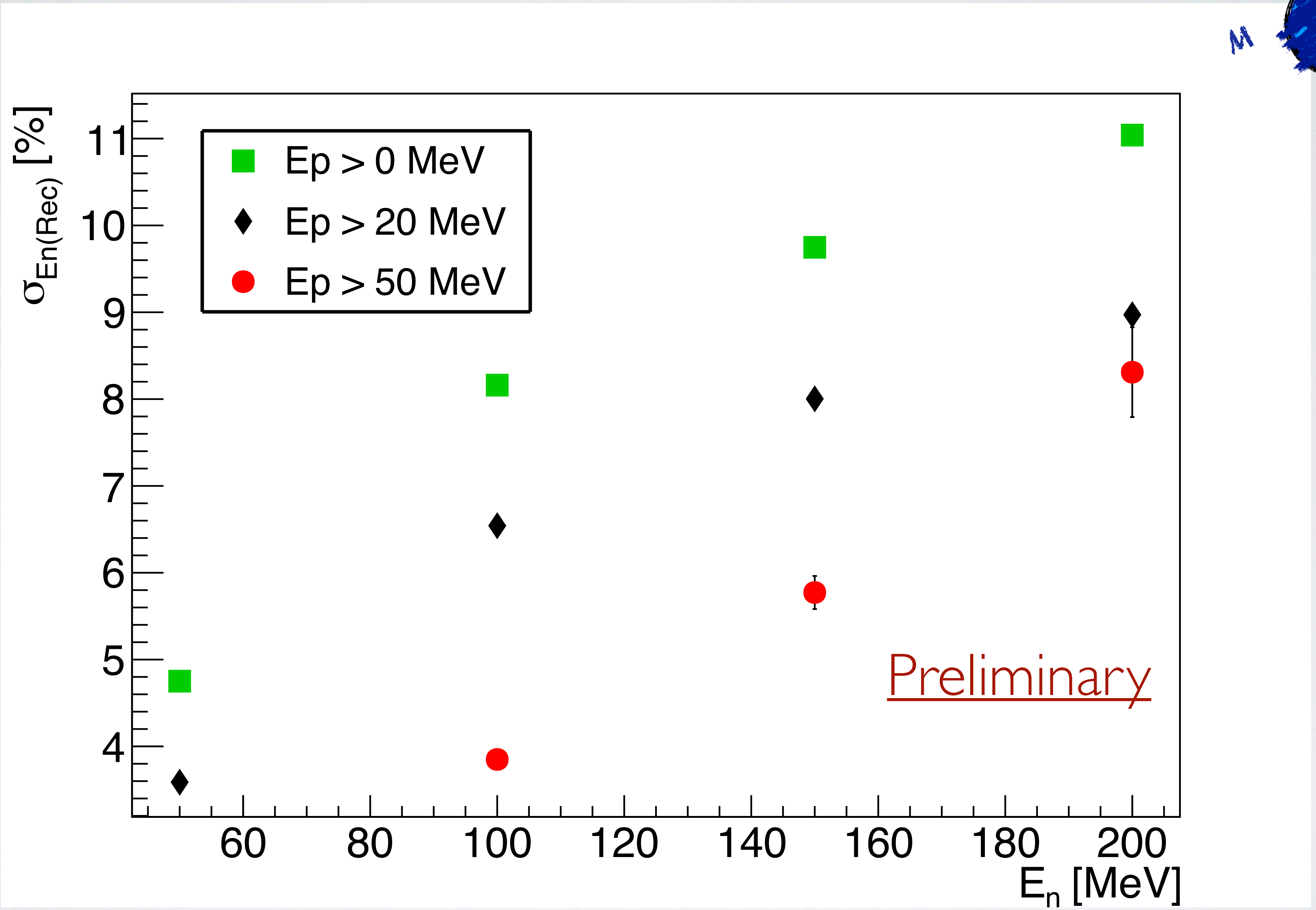
1. New sensor SBAM:
    1. test chip (may 2018 @LFoundery, under test @FBK summer 2018)
    2. full run (2019);
2. Full matrix assembling and instrumentation;
3. Calibration and test beam (protons at TIFPA, neutrons ?);

Measurements with secondary neutrons produced by Carbon ions (CNAO) beams on different targets;

Evaluation of the impact of the secondary neutron emissions in TPS, in particular for Paediatric Particle Therapy.

BACK UP SLIDE

RESOLUTION



For single elastic scattering