



# MOonitor for Neutron Dose for hadrOntherapy

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

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# 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

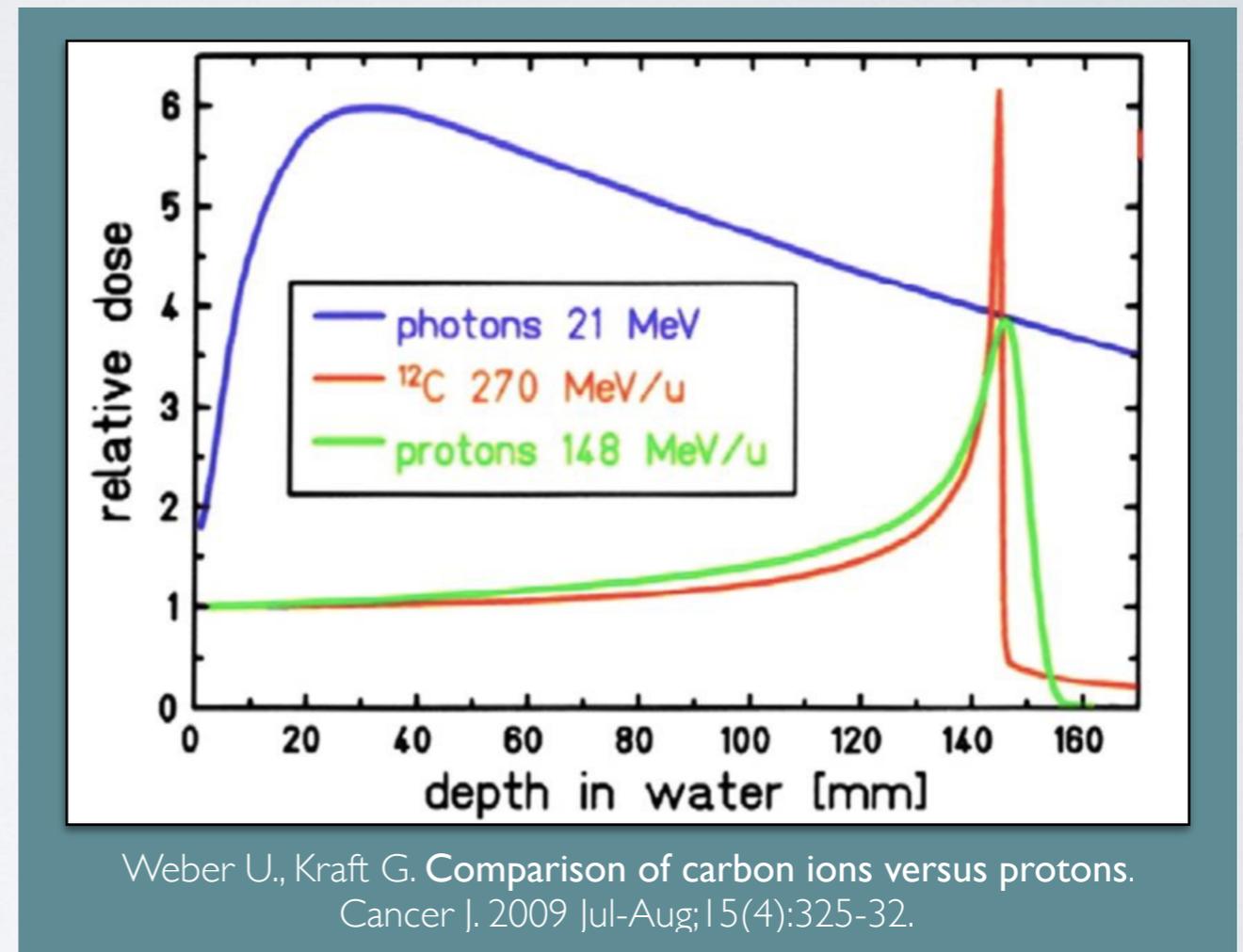
Light ions advantages ( $^{12}\text{C}$  ions):

- 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.  $^4\text{He}$  and  $^{16}\text{O}$ .



# SECONDARY PRODUCTS 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..

See Poster n. 178

**In-room characterization, using an anthropomorphic, of a novel detector exploiting secondary charged particles emission for on-line dose monitoring in light PT treatments**

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Particle Therapy (PT) exploits accelerated charged ions, typically protons or carbon ions, for cancer treatments. In PT a high accuracy on the dose release over the tumor volume is achieved, preserving healthy tissues and Organ At Risk (OAR) around tumor better with respect to the conventional radiotherapy. The high cancer cells killing power of PT requires a precise control of the ion beam delivery, and hence target voxel localization, to take into account a possible patient mis-positioning or biological or anatomical changes. The development of an on-line dose conformity monitoring device is of paramount importance to assure an high quality control accuracy in PT treatments. We propose a novel detector named Dose Profiler (DP) tailored for dose range monitoring applications in PT. The beam range inside the patient will be monitored detecting charged secondary fragments.

Beam range monitoring using charged fragments could be a way particularly suitable for <sup>12</sup>C ion treatment thanks to some nice features:

- ▶ High detection efficiency
- ▶ Easy back-tracking

Anyway, the:

- ▶ Suffer multiple scattering inside the patient ( $\sim E^{-1} \cdot \sqrt{x}$ )  $\rightarrow$  impact on the back-tracking resolution
- ▶ In a treatment room, very often the positions at large  $\theta$  are not available to a monitor device, in particular in the treatment configuration where the patient body is aligned with the beam axis. Large detection angles have to be used, reducing the collection statistics.

**Charged secondary fragments production @ large angles**

In 2012 and 2014 the charged fragments production has been studied with PMMA targets 5x5x15 cm<sup>3</sup> impinged by <sup>12</sup>C and <sup>4</sup>He ion beams. A non negligible production has been observed at 60° and 90° with respect to the beam direction [1], [2],[3]. Fragments are mainly protons, with a kinetic energy between 50-150 MeV

The distal-edge of the charged fragments emission profile could be correlated to the Bragg peak position

**Dose Profiler**

The Dose Profiler (DP) is an innovative detector tailored to monitor the beam range exploiting charged fragments [4]. It has been designed to track the secondary protons by means of six scintillating fibres planes (19.2 x 19.2 cm<sup>2</sup>), each one composed by two layers of orthogonally placed fibres. Two plastic scintillator planes, each one composed by 19 segmented layers of plastic scintillator 6 mm thick, follow the fiber planes. Both the fibers and the scintillators are read-out by Silicon PhotoMultipliers.

Read-out electronics: the SiPMs read-out is provided by BASIC32\_ADC [3], controlled by FPGAs.

Silicon PhotoMultipliers (1 mm<sup>2</sup> area), resulting in a ~300  $\mu$ m spatial resolution

**Test-beam @ Trento proton therapy center**

The first data taking campaign took place in May 2017 at Trento Proton Therapy center, with the aim to characterize the DP with protons having the energy expected (50-150 MeV) for the secondary fragments produced during a Carbon ion treatment.

The **single layer efficiency** for tracker layers is ~90% for both the views

A 15-20% energy resolution has been measured

**Charged Secondary fragments production @ CNAO**

In July 2017 a data taking campaign has been performed at CNAO. The charged secondary fragments produced by an anthropomorphic phantom, impinged by Carbon ion beams at different energies in treatment-like conditions, has been collected by the DP at 90° with respect to the beam direction. The **charged fragments emission profile** along the beam axis has been measured.

~100 tracks can be expected per pencil beam in average conditions: strategies for "PB" packing have to be envisaged in order to reach the desired precision (dose tracks per spot)

Between 1.2 and 1.6 tracks in total (per cm<sup>2</sup>)

The **back-tracking resolution** has been measured using a small spherical plastic target (radius 2 mm), placed at the room isocenter.

**Correlation with the Bragg Peak**

The final precision achievable on the BP position depends on how much statistics can be collected and how well the interaction of the ions beams and of the emitted fragments with the patient body is handled. Any complex target geometry, like the case of the patient, having different materials, densities and thicknesses, will produce an emission profile which is distorted with respect to the reference case.

Not all the produced fragments can exit the patient body

A weighing algorithm is applied to take into account the material absorption. The weights are estimated using a full MC approach based on the study of fragments interactions with a water target (allows an experimental calibration)

**References:**

- [1] P. Ferrari et al., "Measurement of charged particle tracks from PMMA irradiated by 200 MeV/u C beam", In: Physics in Medicine and Biology 59(2014), pp. 1807-1823
- [2] E. Gioscio et al., "Charged particles fluence measurement from PMMA (carbon ion beam)", In: Physics in Medicine and Biology 57(2012), p. 5967
- [3] A. Sarti et al., "Secondary electron measurements for particle therapy applications: Charged electron production by the 12C ion beams in a PMMA target at large angle", Phys. Med. Biol. 63(2018)
- [4] G. Traini et al., "Design of a new tracking device for on-line dose monitor in ion therapy", J. Phys.: Conf. Ser. 1017(2017), pp. 10-27

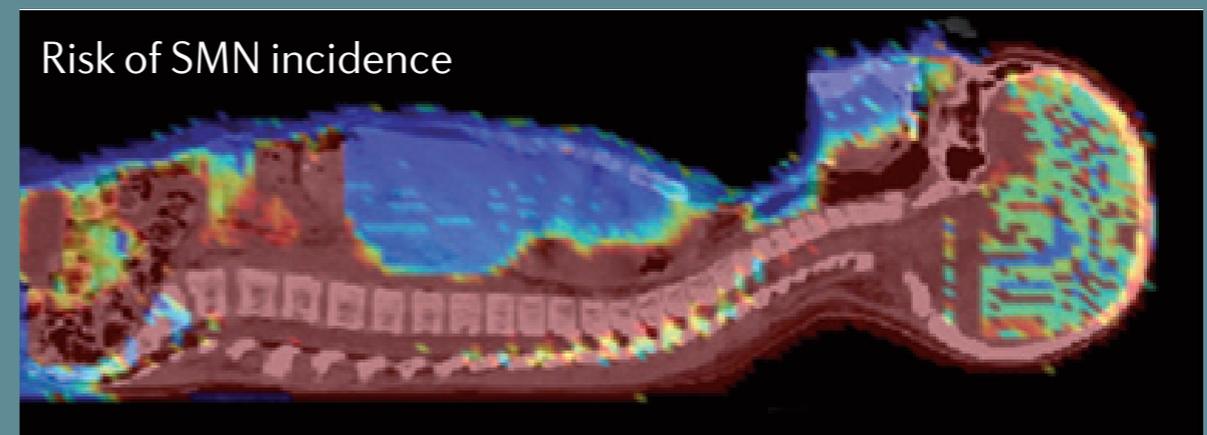
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## SECONDARY NEUTRONS

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

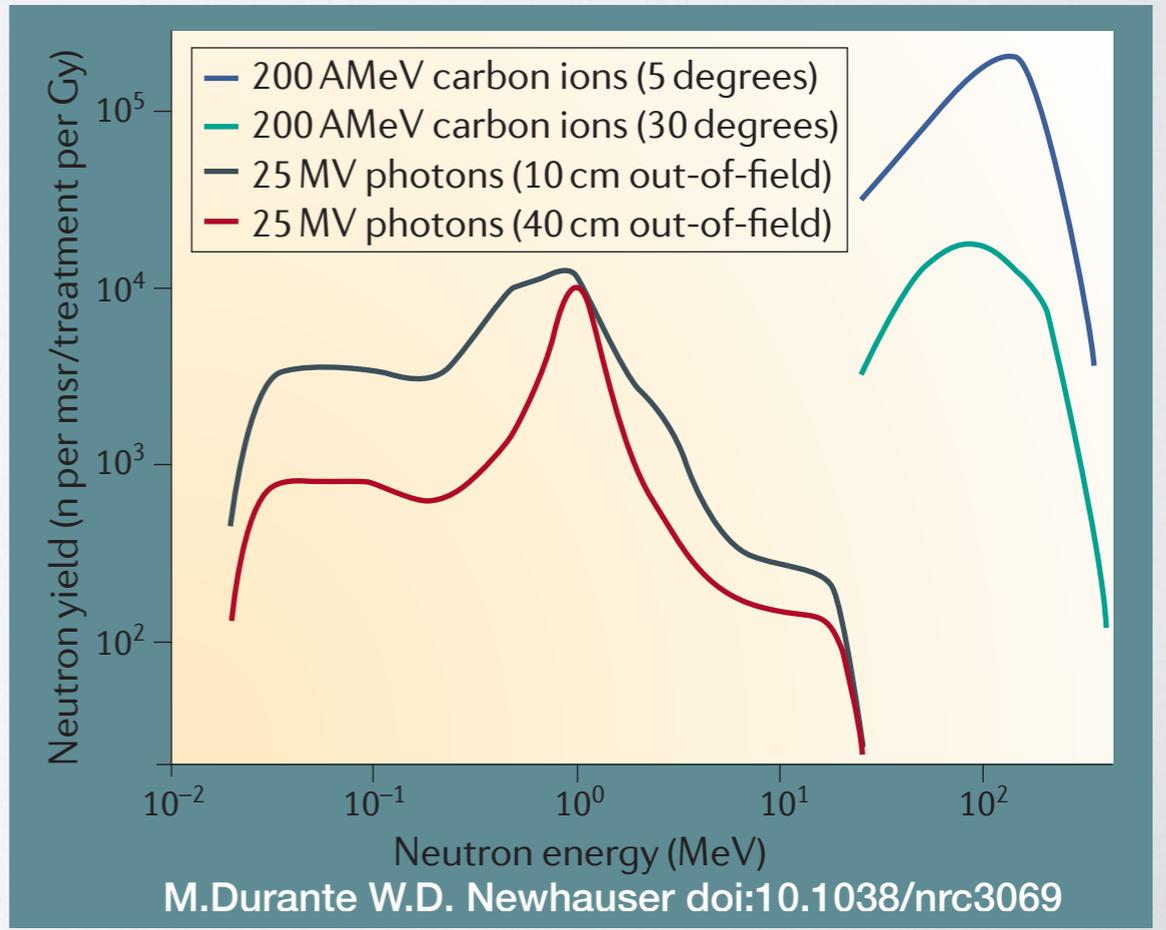
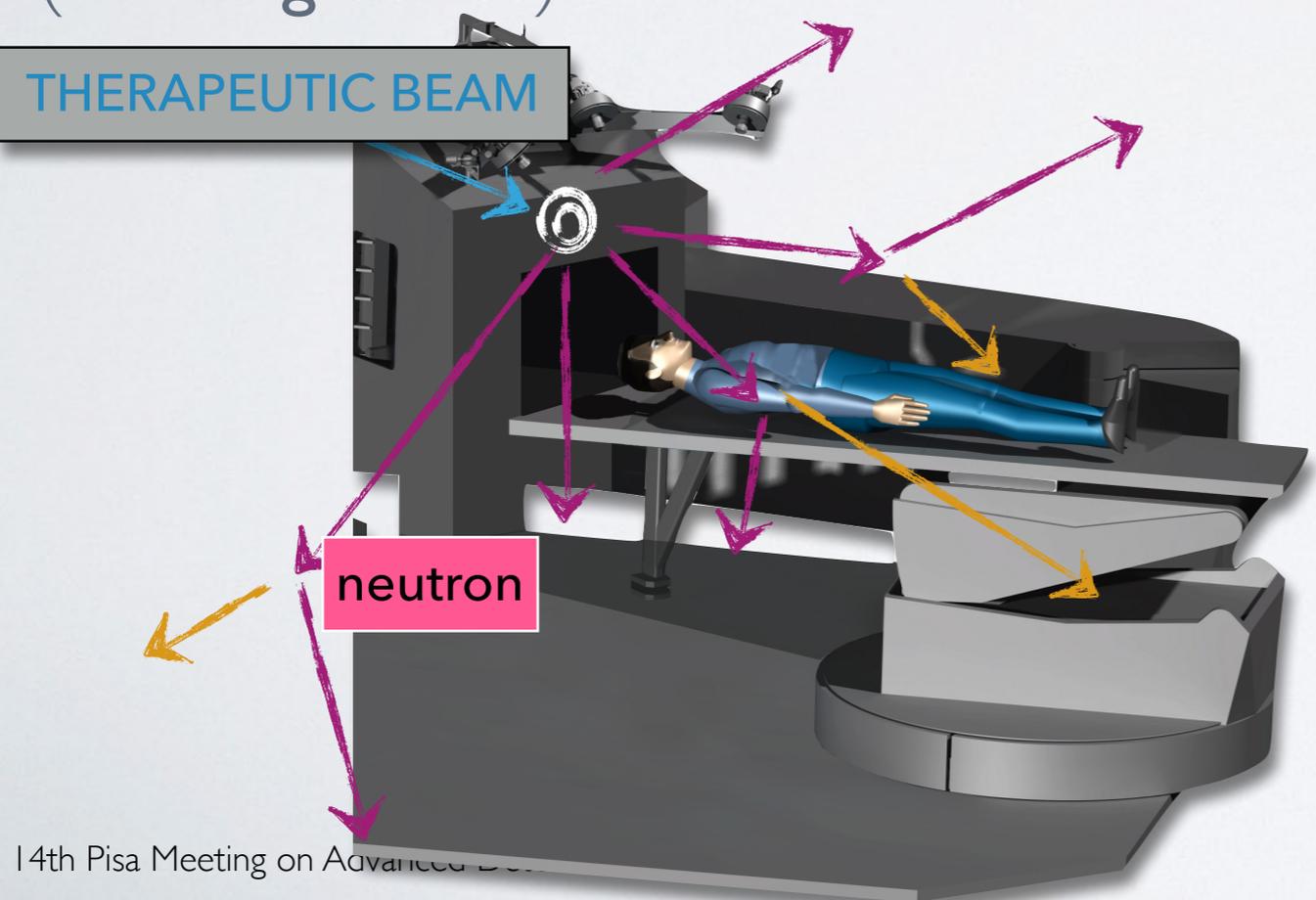
The **incidence** (also years after the treatment) of **SMNs** impacts directly in the quality and the expectation of life of the patient.

# 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 ( $\theta$ ) and spectra ( $E_{kin}$ )** and of rejecting the background contribution due to moderation processes (**tracking device**).

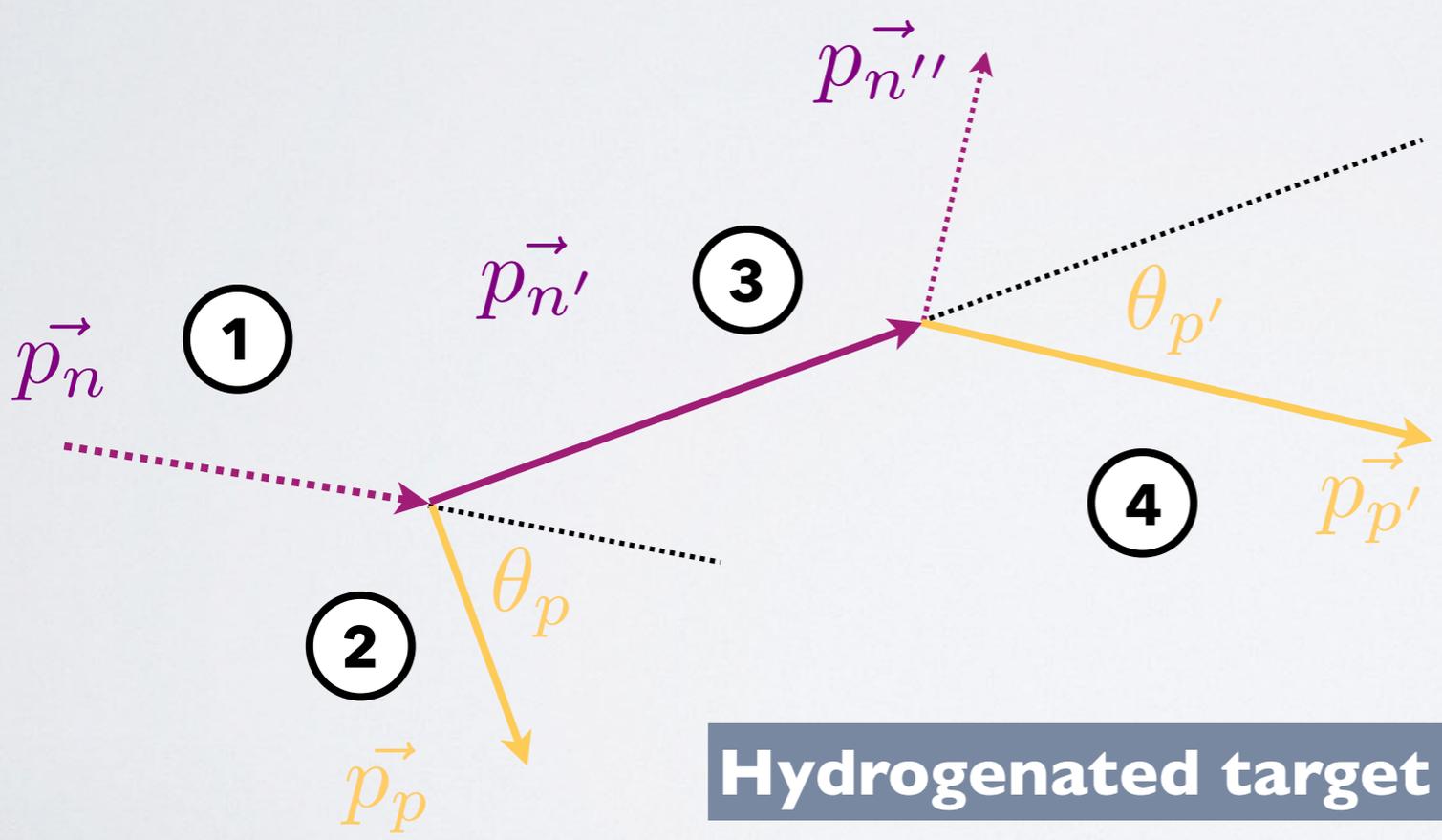




# THE MONDO CHALLENGE

Tracking the neutrons with *high efficiency*

## ➔ Double elastic scattering



**Hydrogenated target**

- 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

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

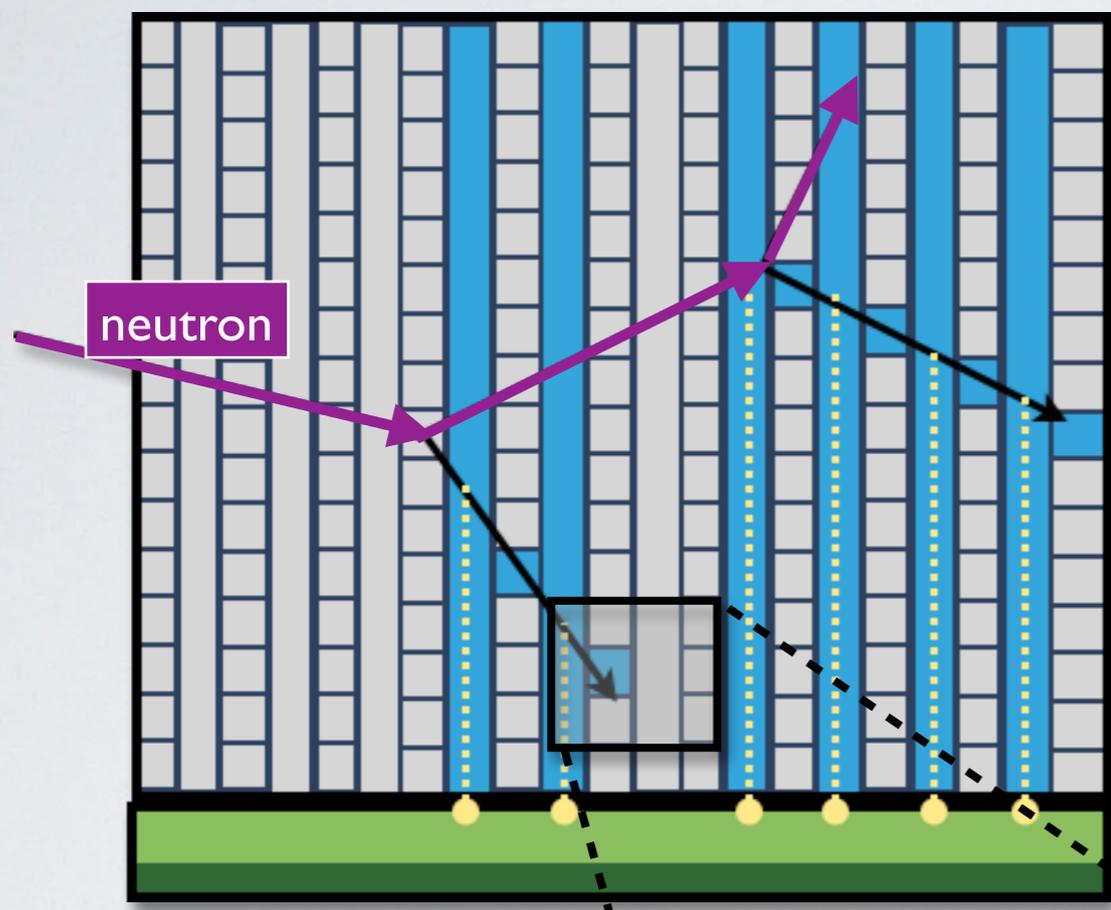


# THE MONDO CHALLENGE

➔ Double elastic scattering

## SCINTILLATING PLASTIC FIBRES

- squared 250  $\mu\text{m}$  (to maximise the granularity)
- plastic (high neutron interaction probability on H)

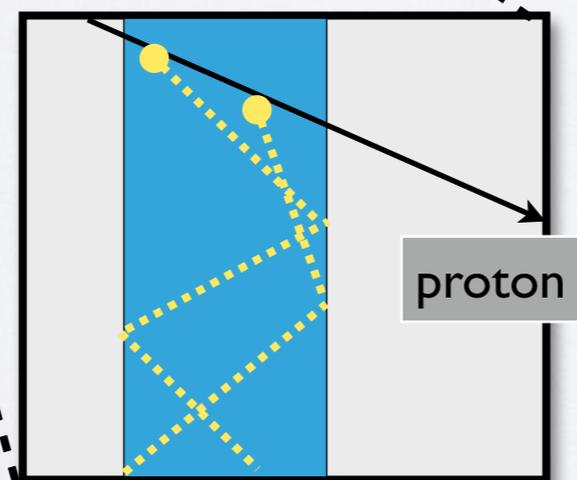


➔ layers of fibres → target and tracker

**Final tracker size:**  
**10 x 10 x 20 cm<sup>3</sup>**

more than  $6 \times 10^5$  channels  
=> **silicon readout system**

Layers  
X-Y planes

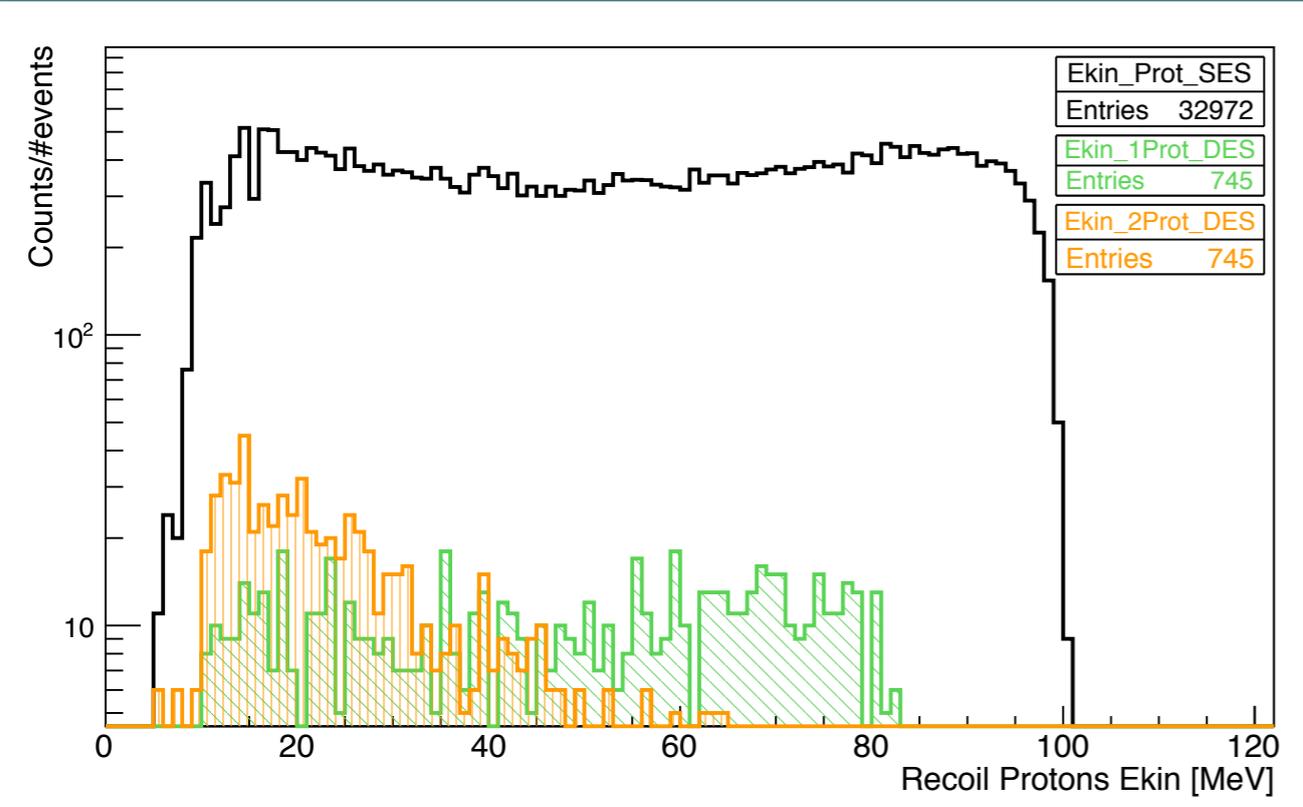




# ENERGY DEPOSITED

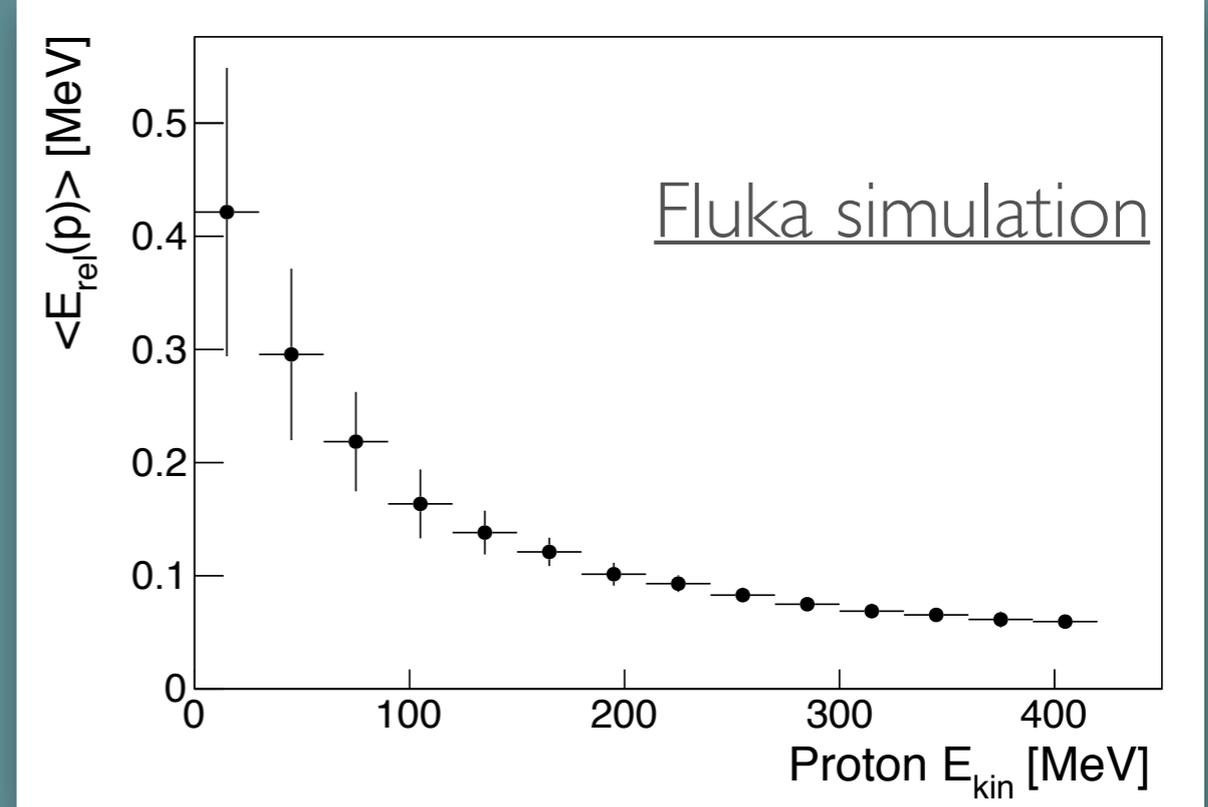
A Monte Carlo simulation has been developed using FLUKA code to optimize and study the detector. The energy release of the protons in the fibers as a function of the neutron (and proton) energy has been evaluated.

## 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).

<b>Deposited energy per fibre</b>	100keV in 250 $\mu\text{m}$
<b>Light yield (BCF-12)</b>	8000 ph. $\text{MeV}^{-1}$
<b>Trapping eff. (double clad.)</b>	7%
<b><math>N_{\text{Ph.}}^{\text{prod}}</math></b>	60 ph.



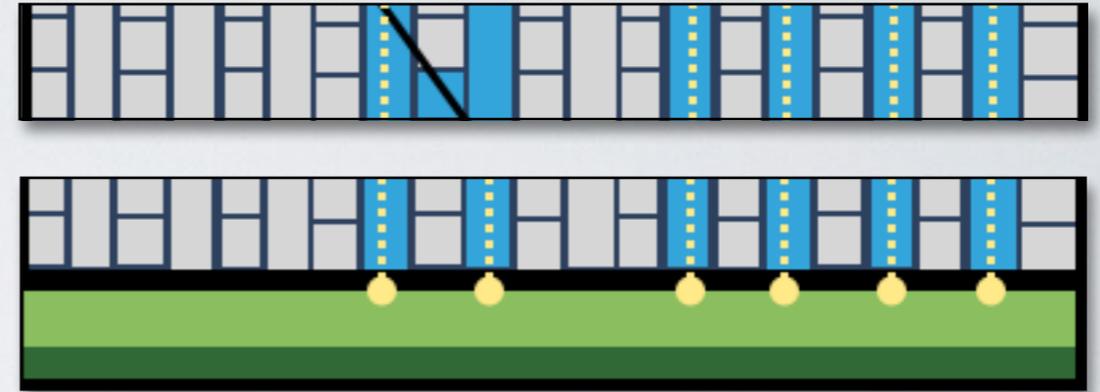
M. Marafini et al., PMB (2017) doi: 10.1088/1361-6560/aa623a



# NEUTRONS TRACKER

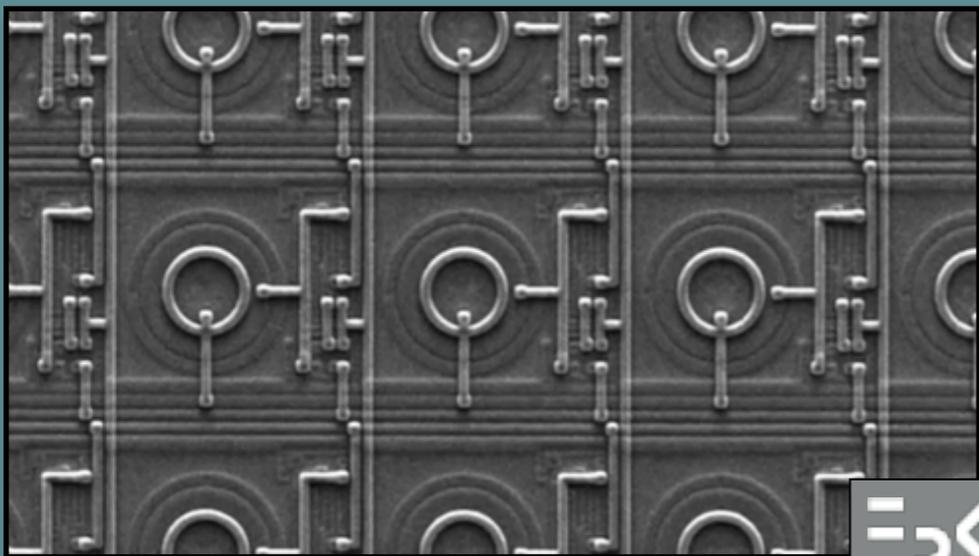
## ➔ Silicon Detector for READOUT

- Need to keep the space granularity of the fibres
- Few photons (few ph. electrons)
- Fast signals: typically  $\sim 5\text{ns}$



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



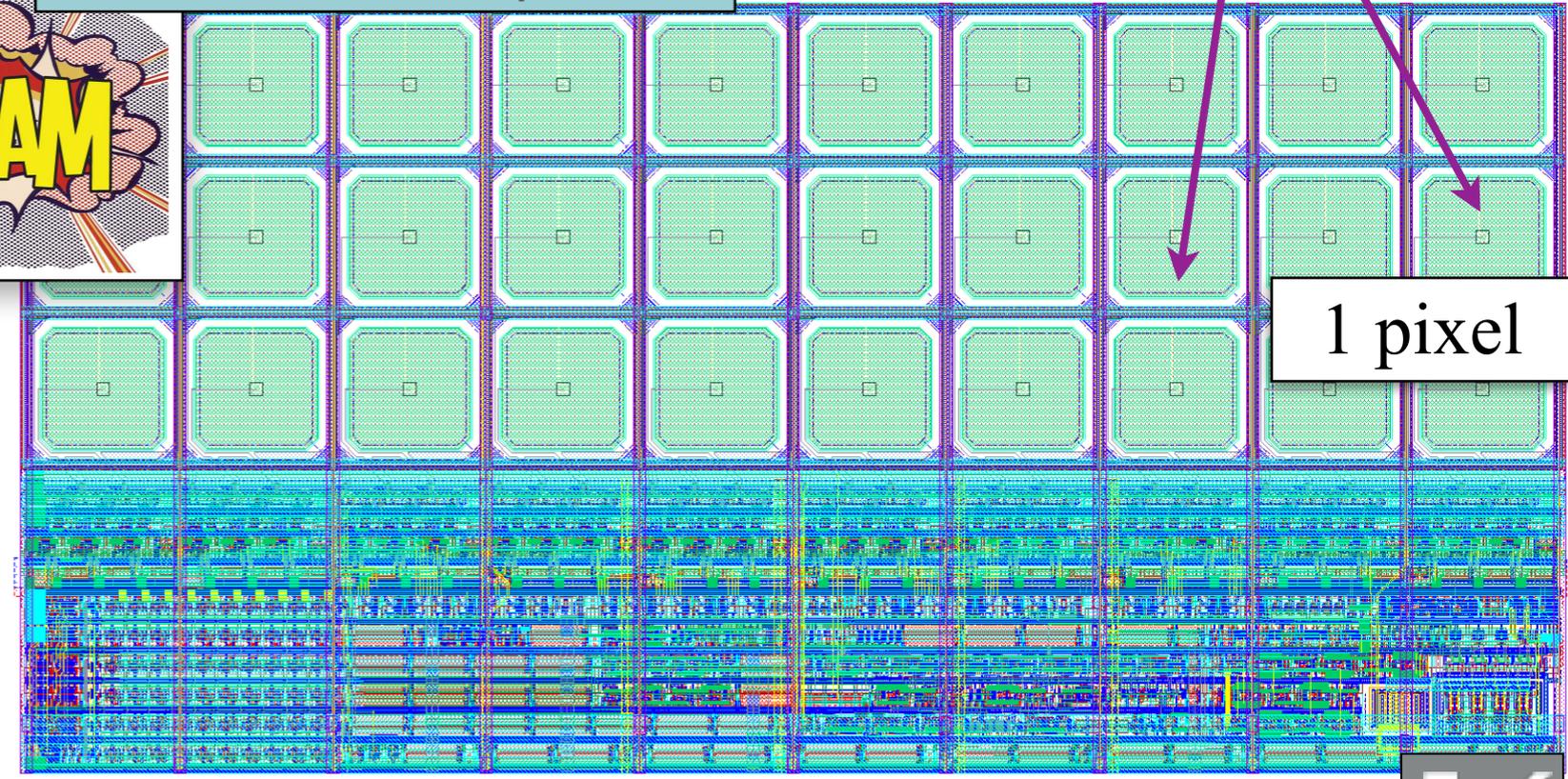


# NEUTRONS TRACKER

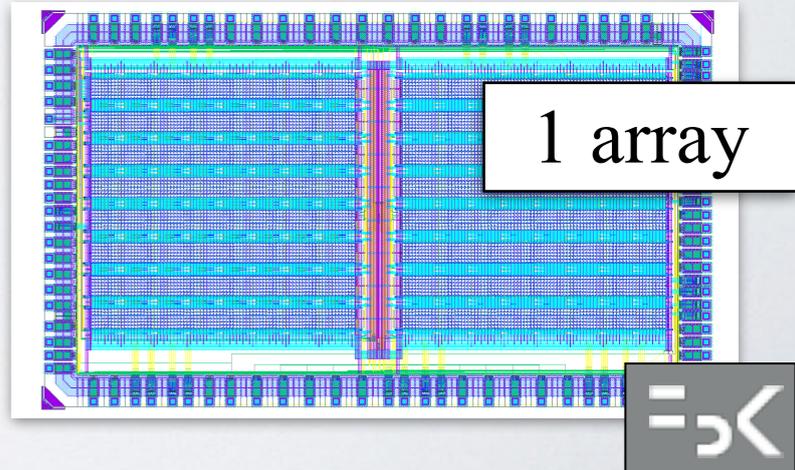
## Main characteristics of the new sensor

- 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

Spad Based Acquisition for the Mondo Experiment



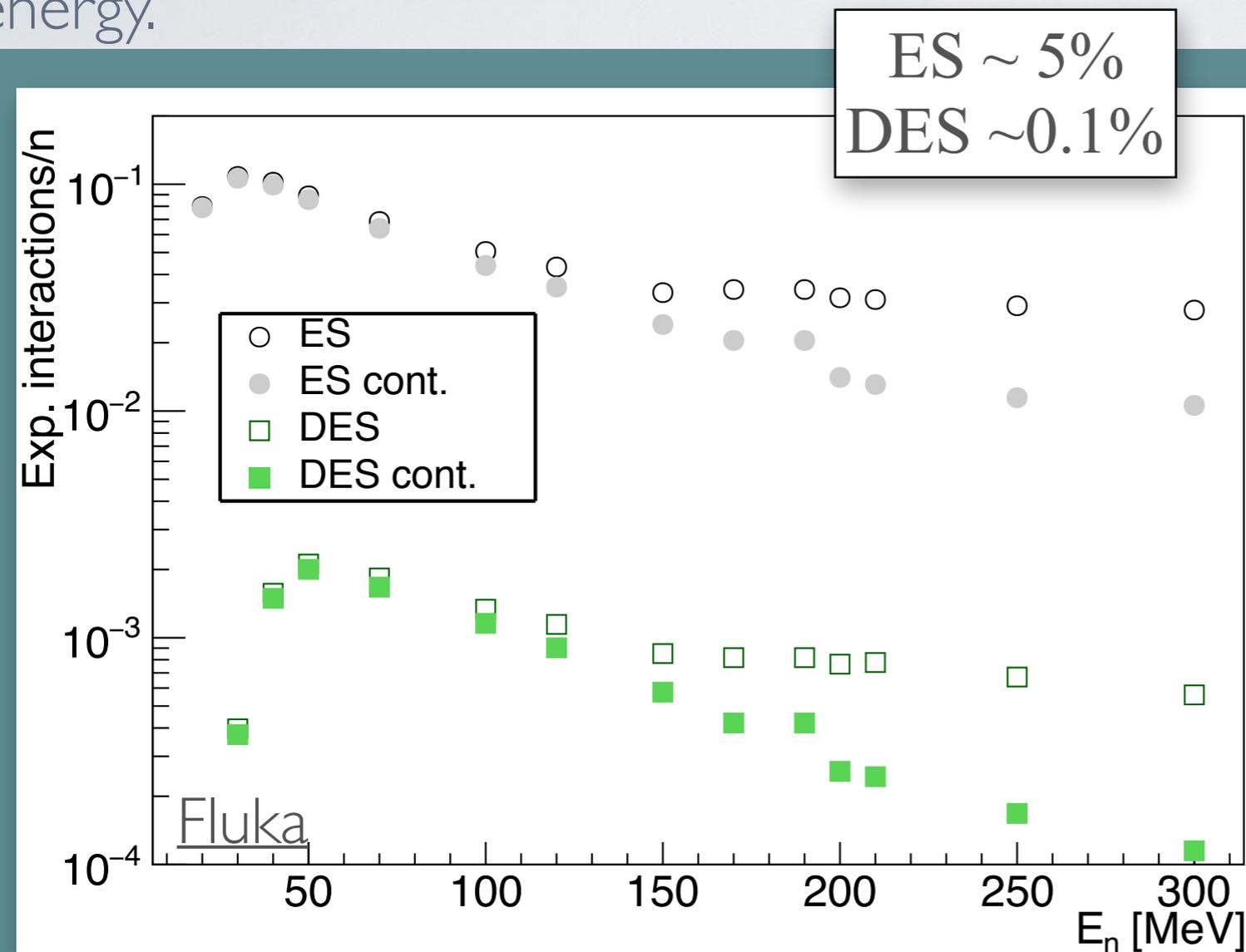
First chip run  
may 2018





# 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.



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

## Constraints:

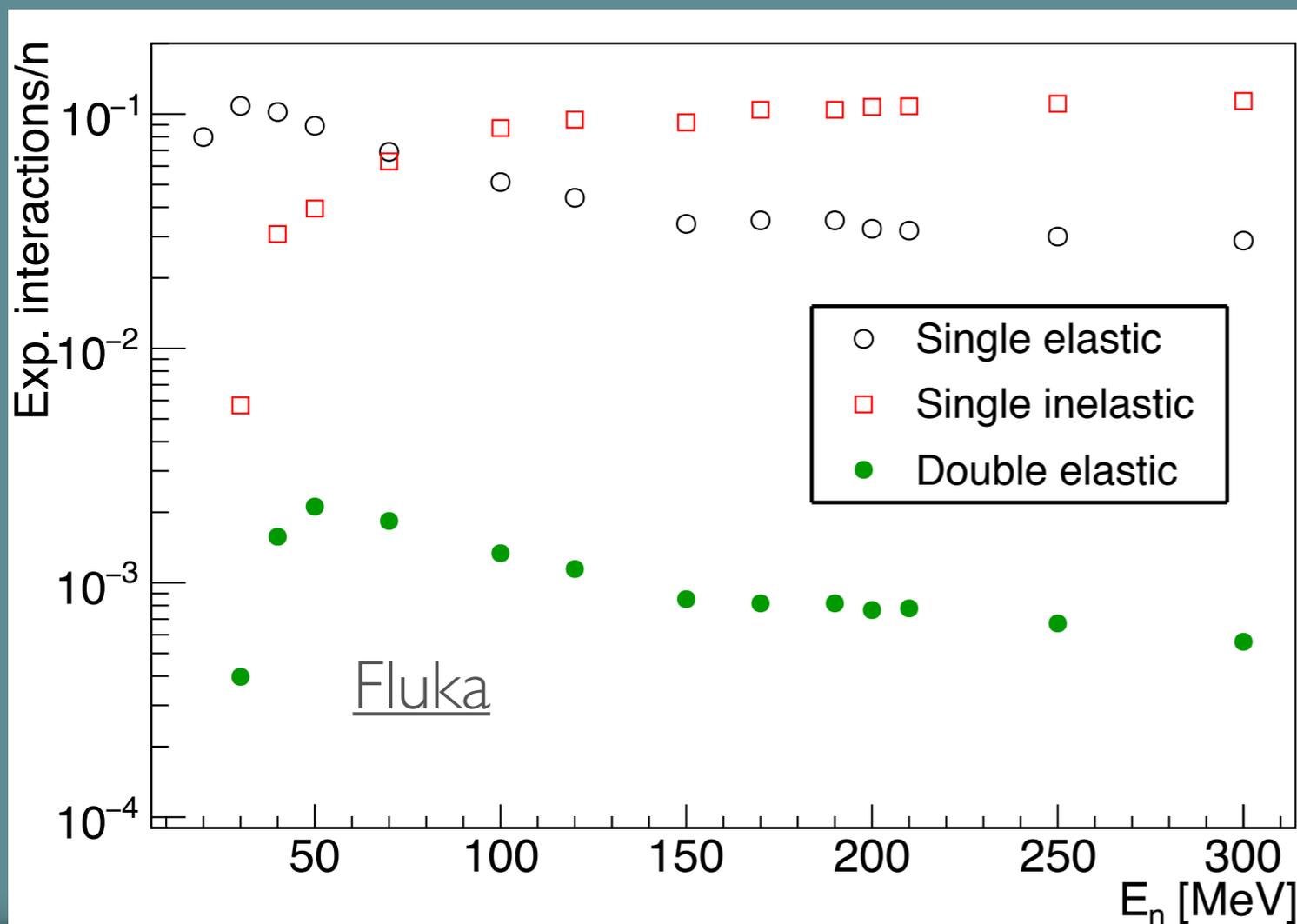
- full containment request of the protons;
- at least 3 layers crossed (about 12 MeV)

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

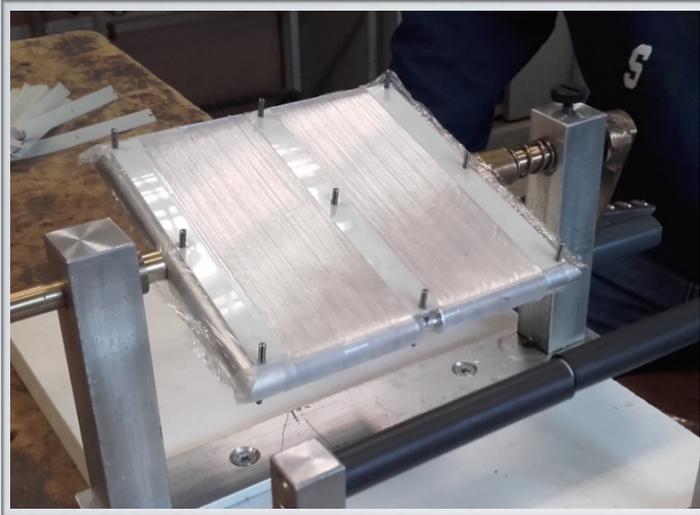
Inelastic interactions (IS) are the main intrinsic background for the elastic events (ES). ES are dominant below 100 MeV, while IS are not negligible for higher energies.



- 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.

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



## NEUTRONS TRACKER

A tracker prototype ( $4 \times 4 \times 4.8 \text{ cm}^3$ ) has been realized as a proof of principle for proton tracking and in order to test the assembling procedure.

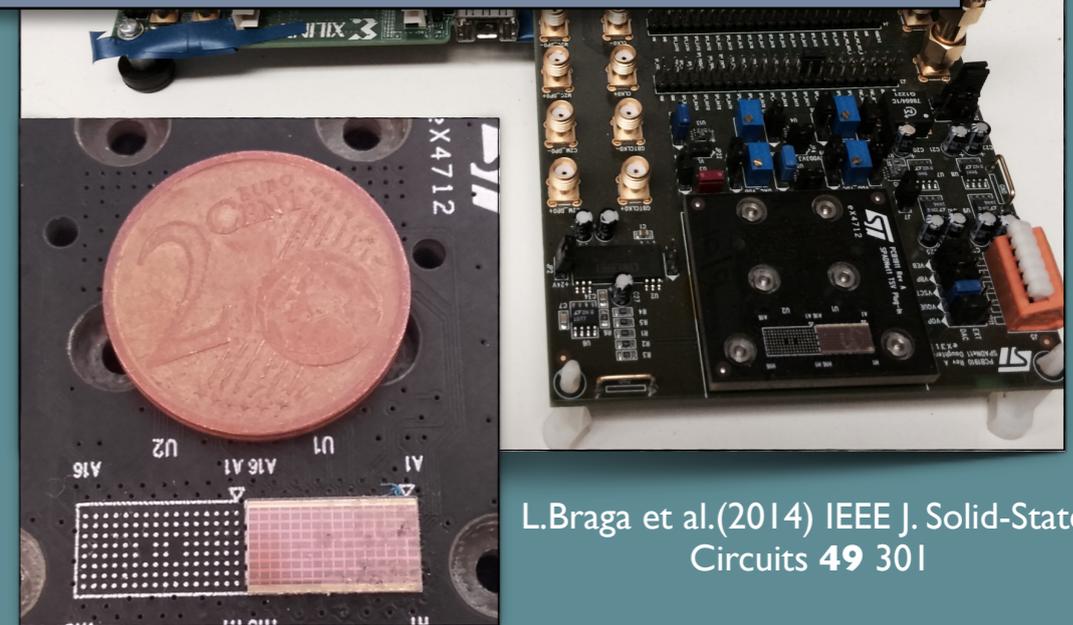


The new sensor SBAM has been developed starting from the experience gained using an other **sensor prototype: spad-net**. Practicing with spad-net allowed us to point out the critical issues to be addressed in the SBAM development phase.

### Test **PENELOPE** prototype:

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

16 x 8 pixels of 600  $\mu\text{m}$  sensor  $\sim 0.5 \text{ cm}^2$   
FF  $\sim 40\%$ , QE  $\sim 33\%$



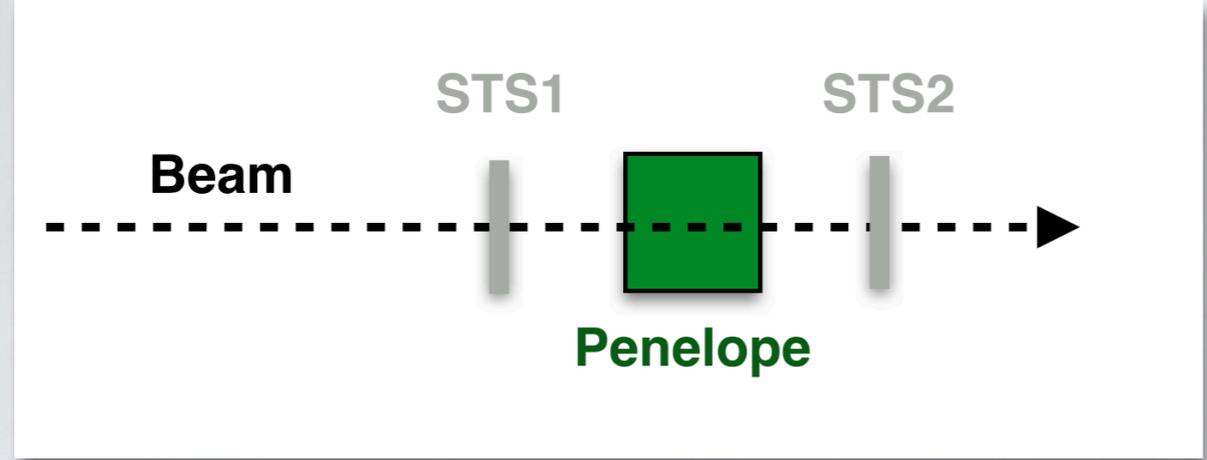
L.Braga et al.(2014) IEEE J. Solid-State Circuits **49** 301

\* 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

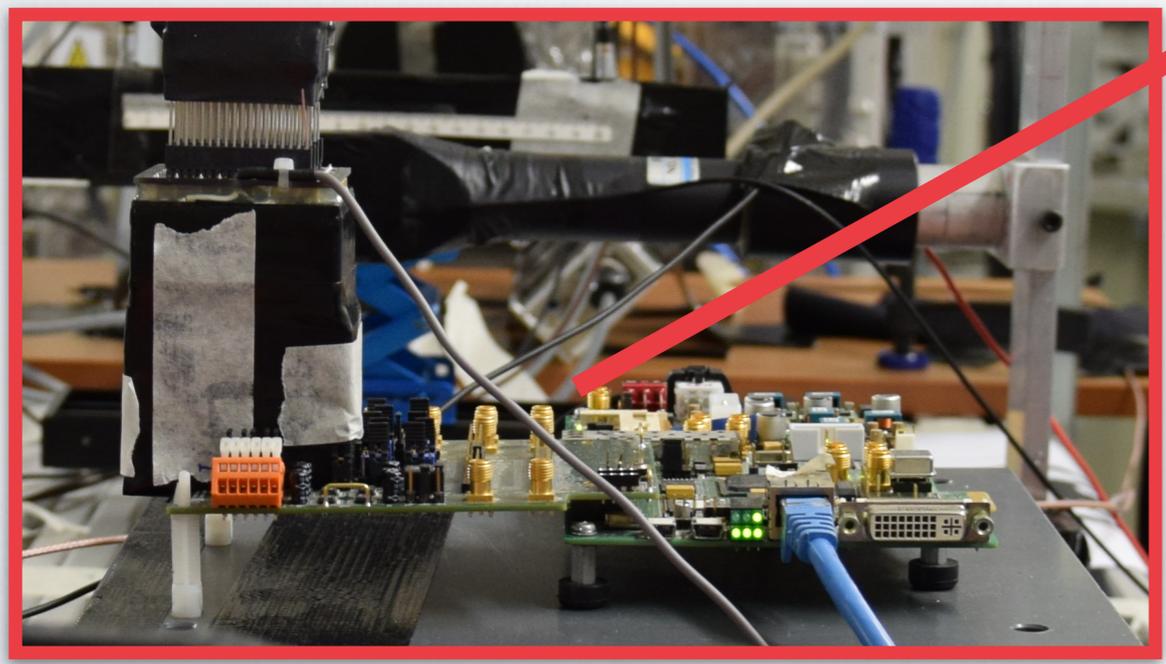
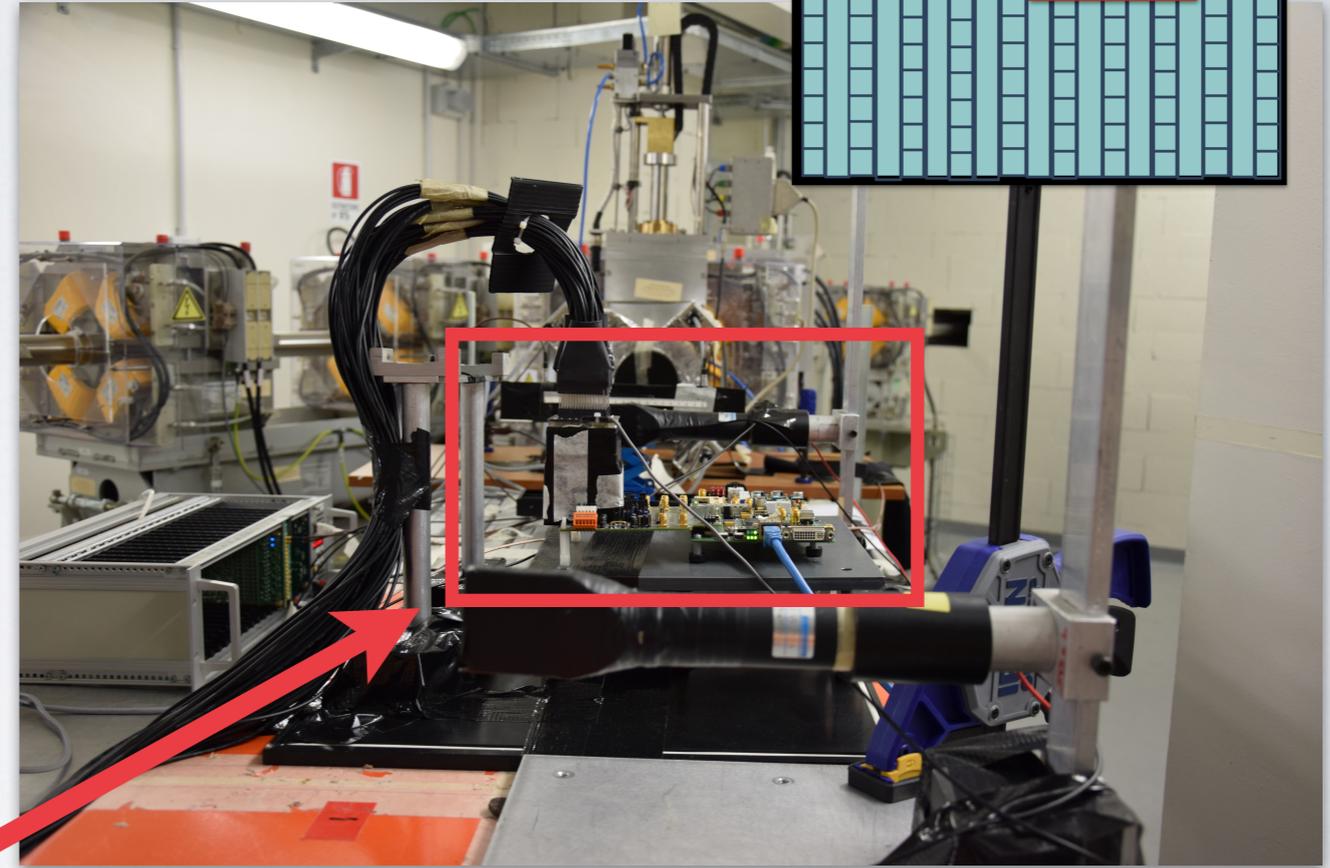
\*\* R. Mirabelli et al, The MONDO detector prototype development and test: steps towards a SPAD-CMOS based integrated readout (SBAM sensor) doi:10.1109/TNS.2017.2785768



# PROTONS @ TRENTO



Beam energy: [70-140] MeV protons  
 Beam size ( $\sigma$ ): [3-7] mm



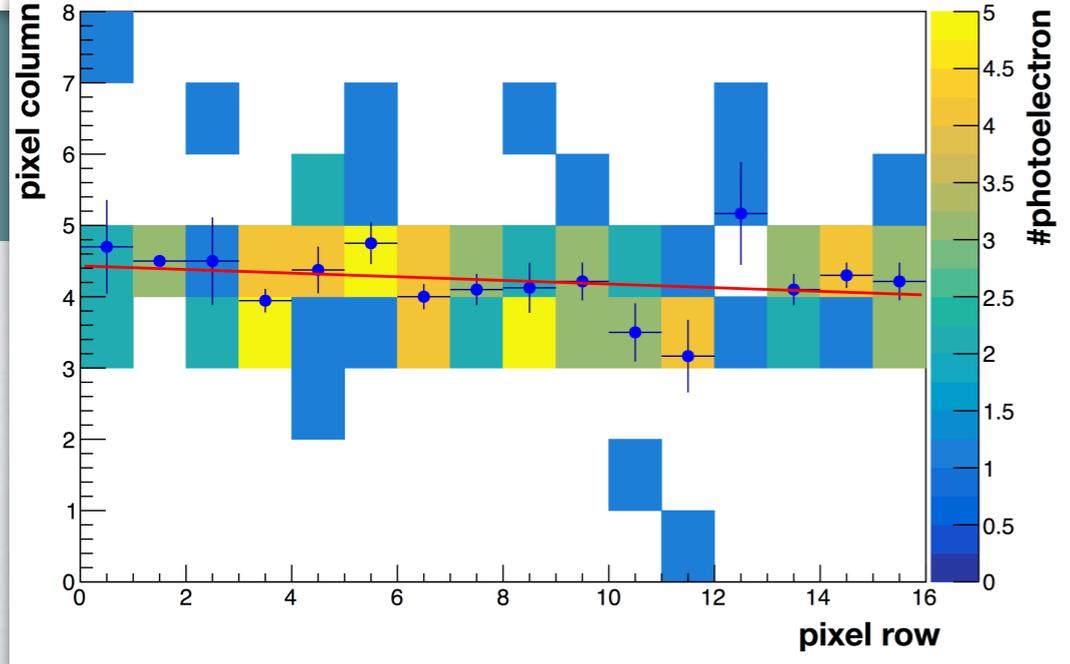
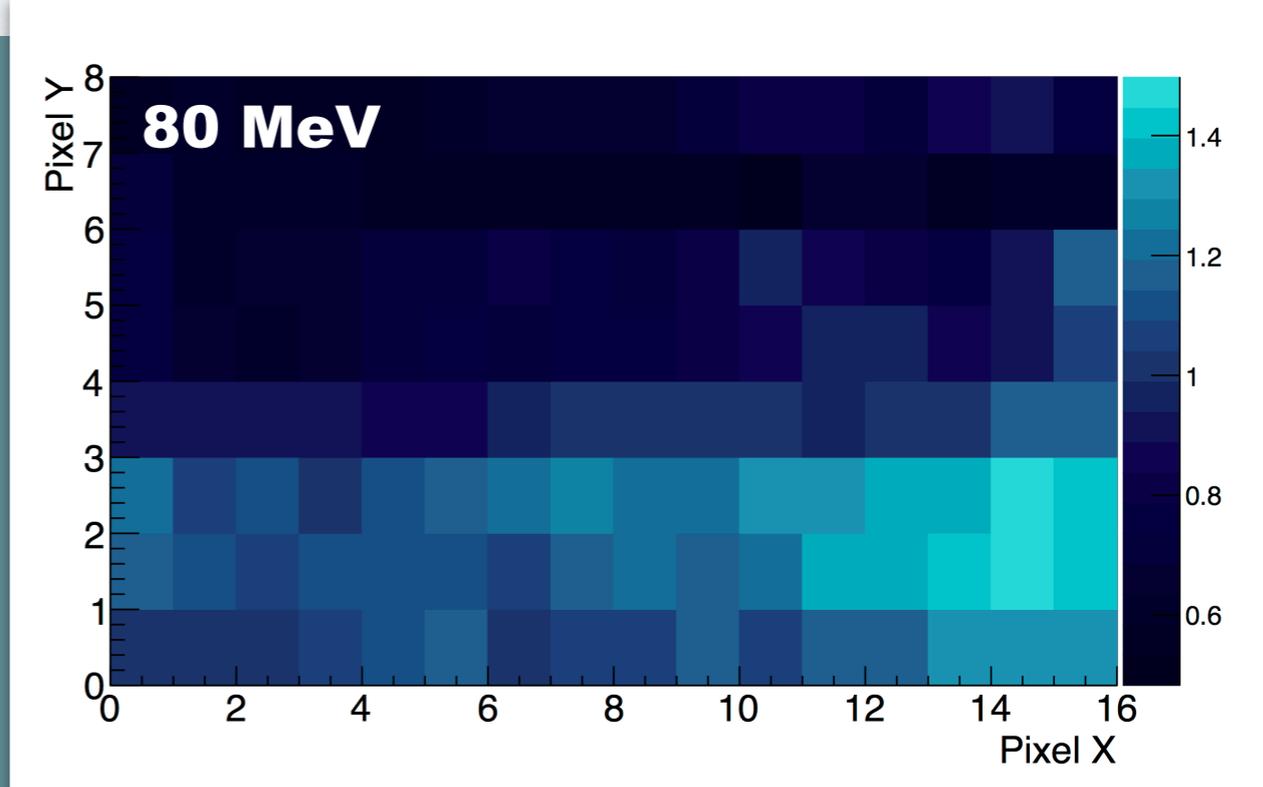
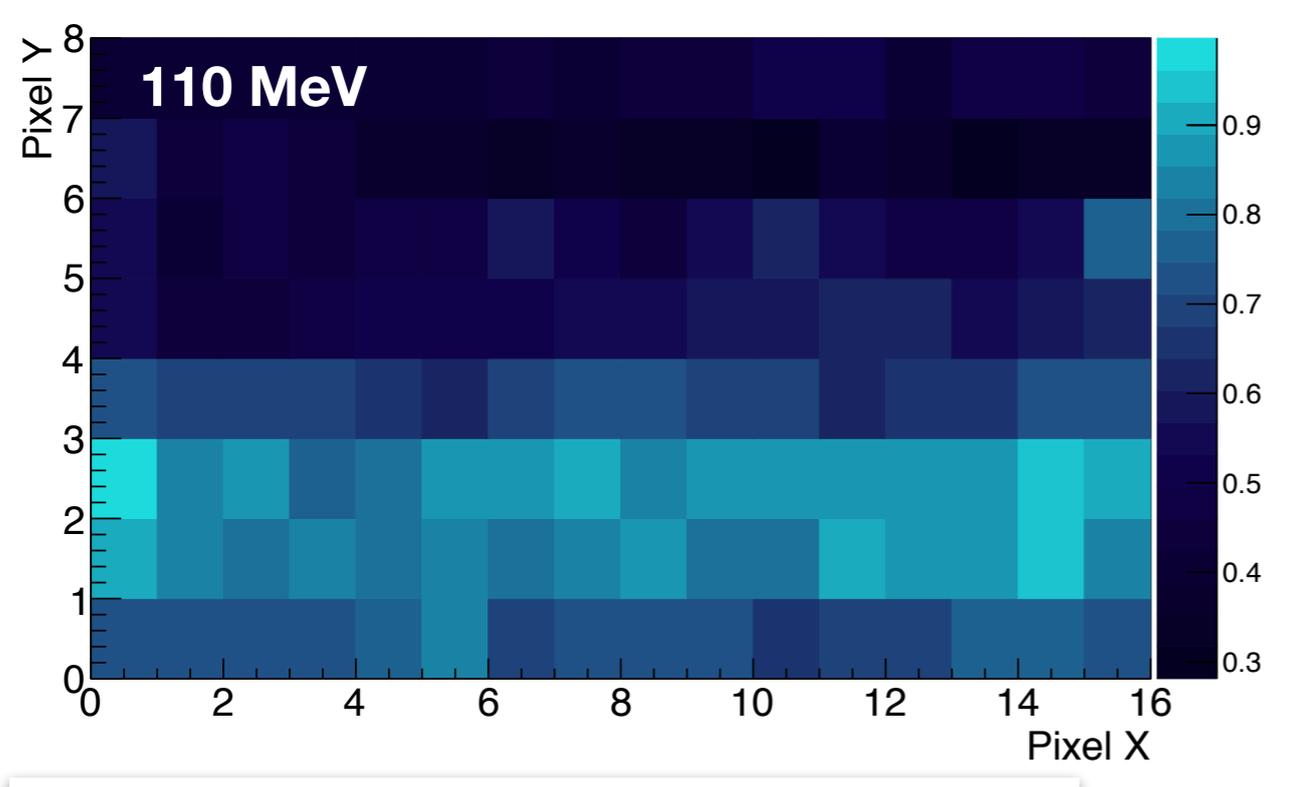
**PENELOPE readout FBK spad-net sensor (128 ch., 600  $\mu\text{m}$  per pixel)**

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

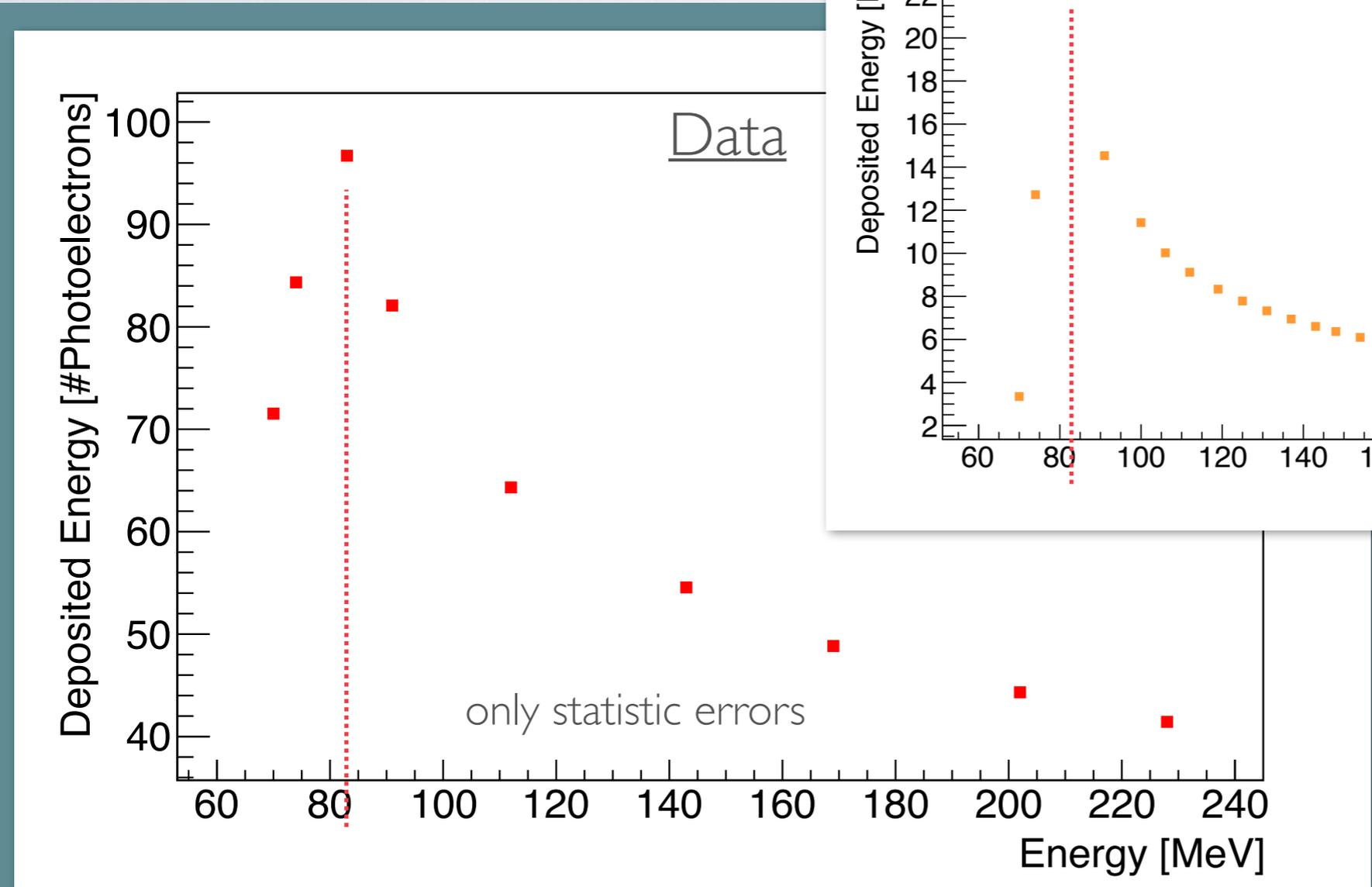
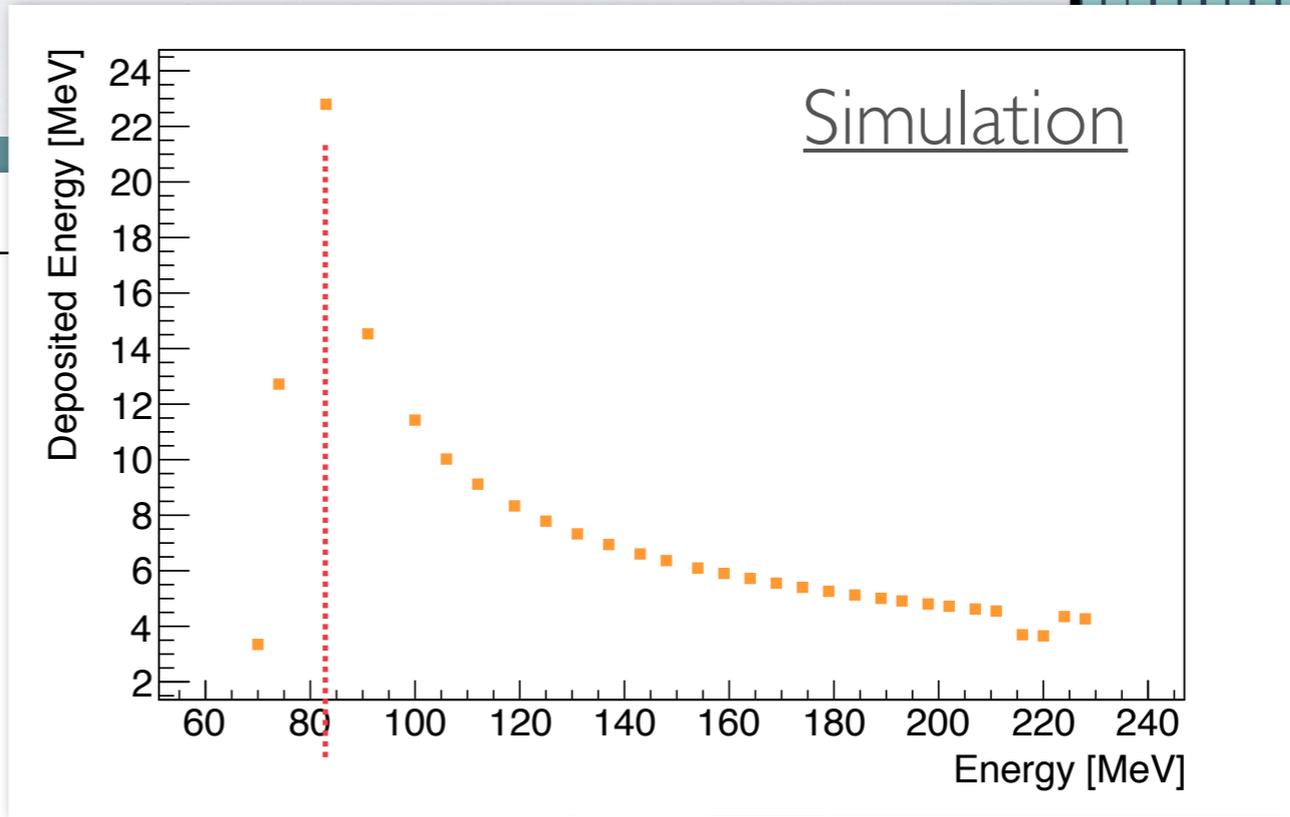
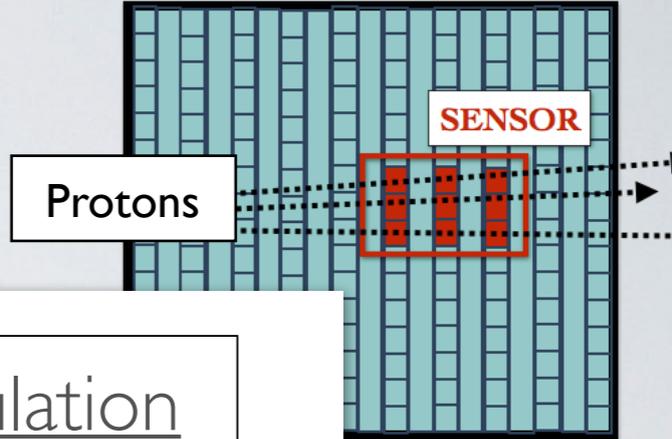
## Single Track

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

# PROTONS @ TRENTO PROTON THERAPY

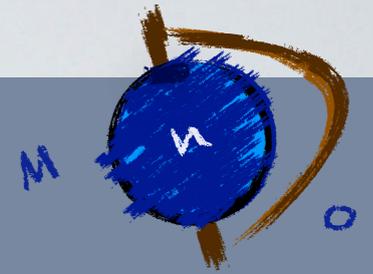


Simulated energy deposited in the fibres as a function of the primary proton kinetic energy (only the volume covered by the SPAD-net sensor was considered).



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

# 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 ?);

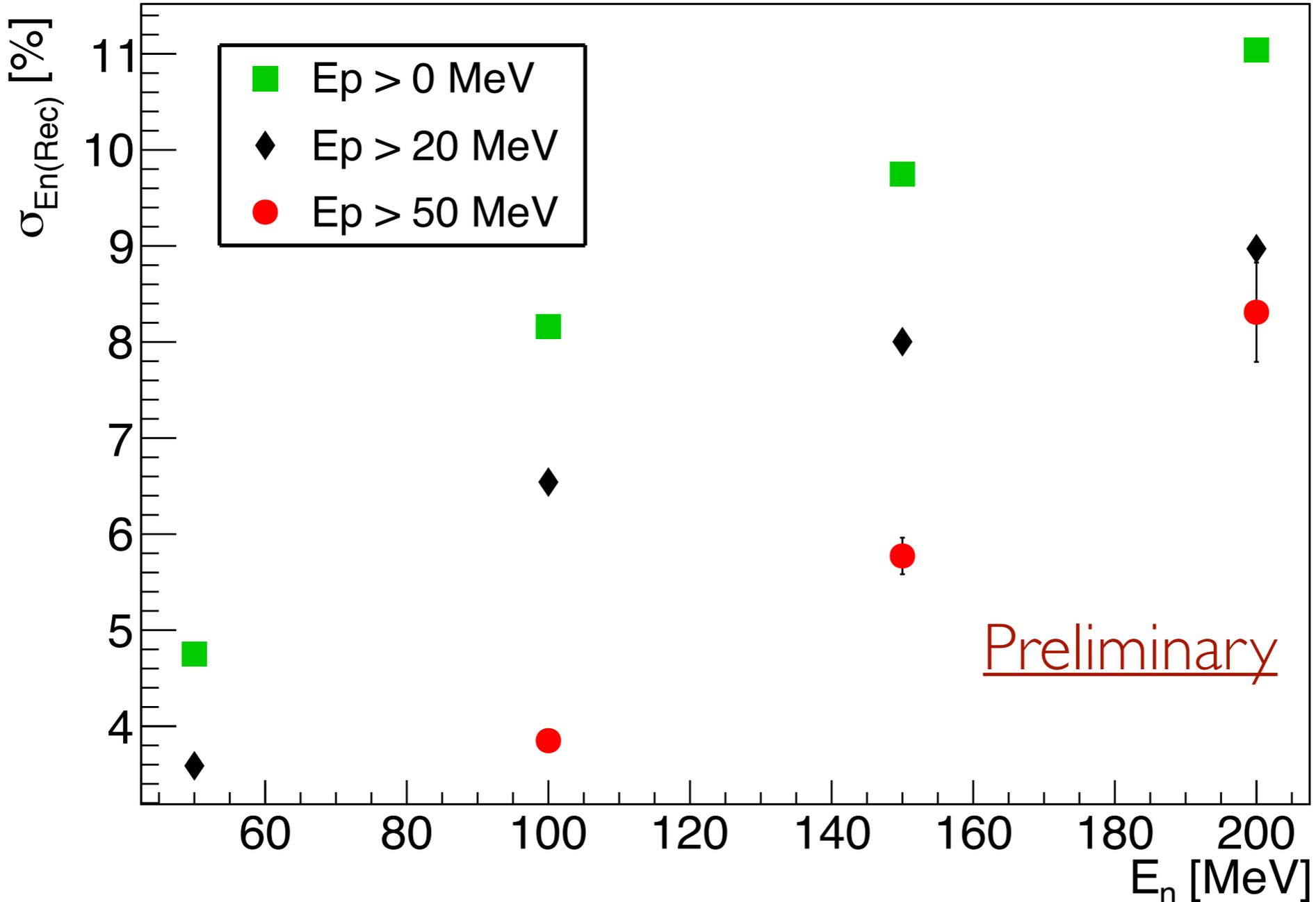
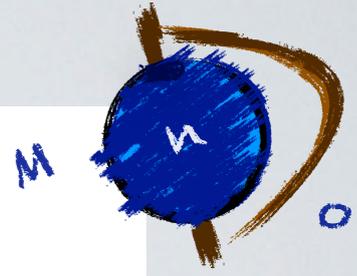
Measurements with secondary neutrons produced by Carbon ions (CNAO) beams on different targets;

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