VCI
VIENNA CONFERENCE ON INSTRUMENTATION

MOnitor for **N**eutron **D**ose for hadr**O**ntherapy

Development of a novel neutron tracker for the characterisation of secondary neutrons emitted in Particle Therapy

E. Gioscio, G. Battistoni, Y. Dong, M. De Simoni, M. Fischetti, I. Mattei, R. Mirabelli, V. Patera, A. Sarti, A. Schiavi, A. Sciubba, S. M. Valle, G. Traini, M. Marafini

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

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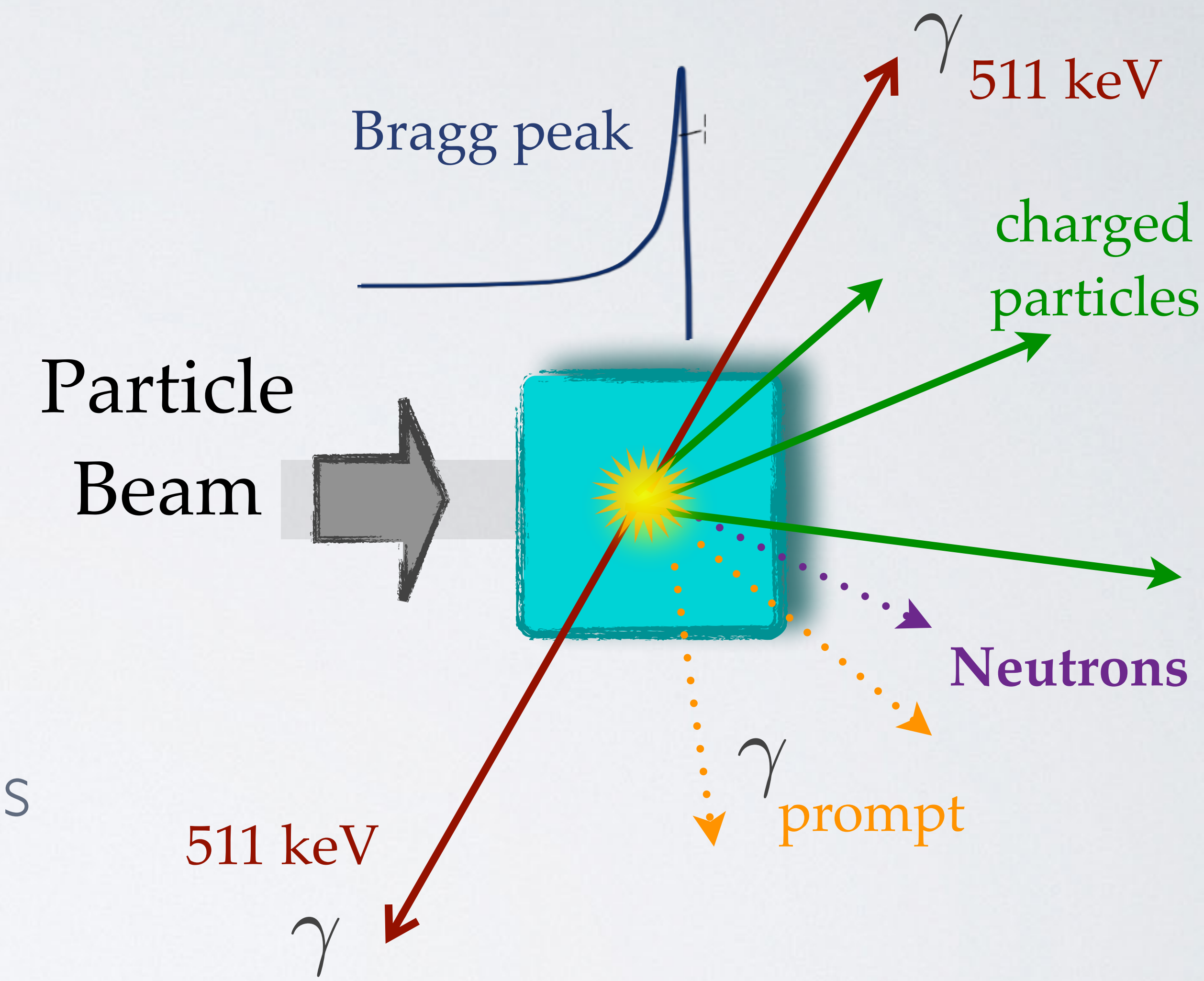
UNIVERSITÀ DI ROMA

SECONDARY PRODUCTS IN PARTICLE THERAPY

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



- it is crucial to characterize the secondary production in order to evaluate its contribution to the total energy deposition;
- **Treatment Planning System (TPS)** has to take into account their contributions to the **additional dose**;

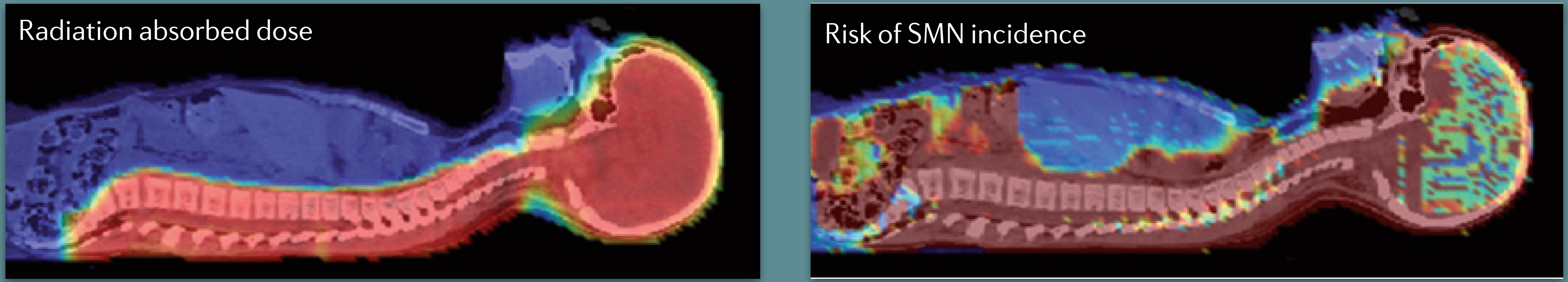
- secondary particles can be exploited for range monitoring..

"Novel charged particles monitor of light ions PT treatments: results of preliminary tests using a RANDO® phantom" (G.Traini)

SECONDARY NEUTRONS

Secondary neutrons have to be deeply investigated while they can release additional dose in- and out-of-field, thus also **far away from the treated volume**.

The insurgence of complications as Secondary Malignant Neoplasm induced by neutrons is one of the main concerns 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

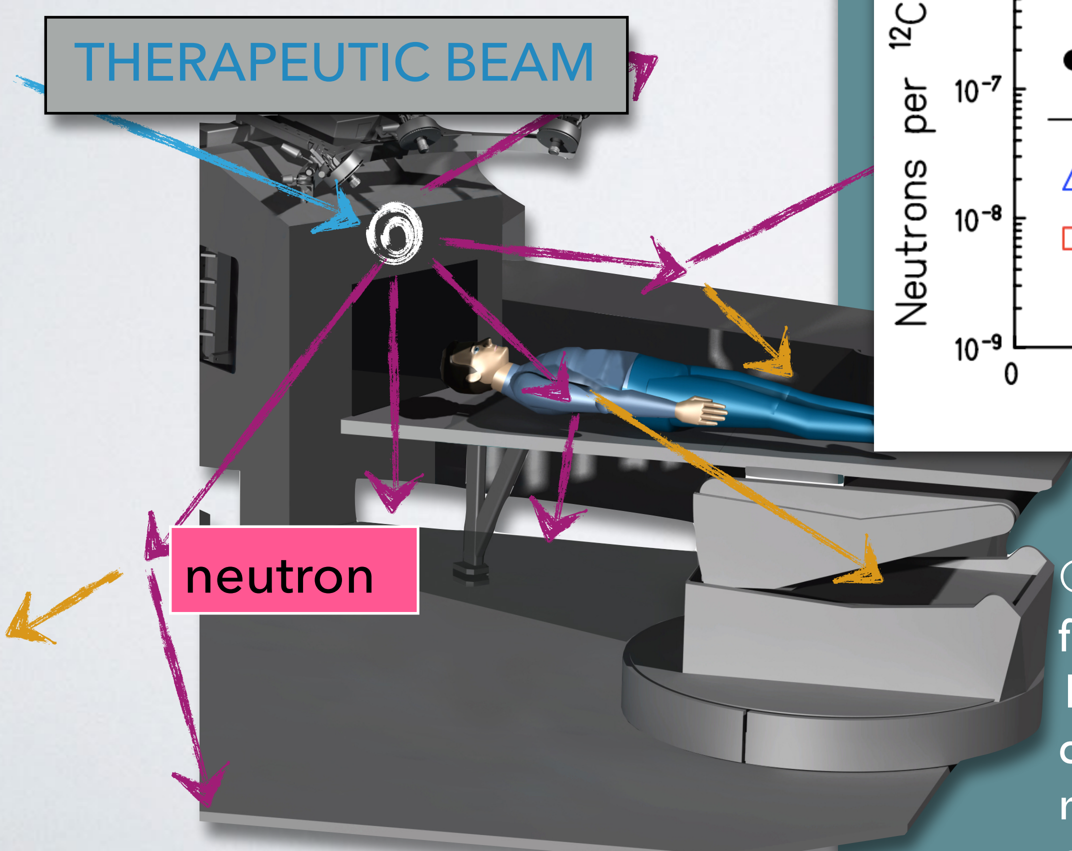
The **incidence** (also years after the treatment) of **SMNs** impacts directly in the quality and the expectation of life of the patient.

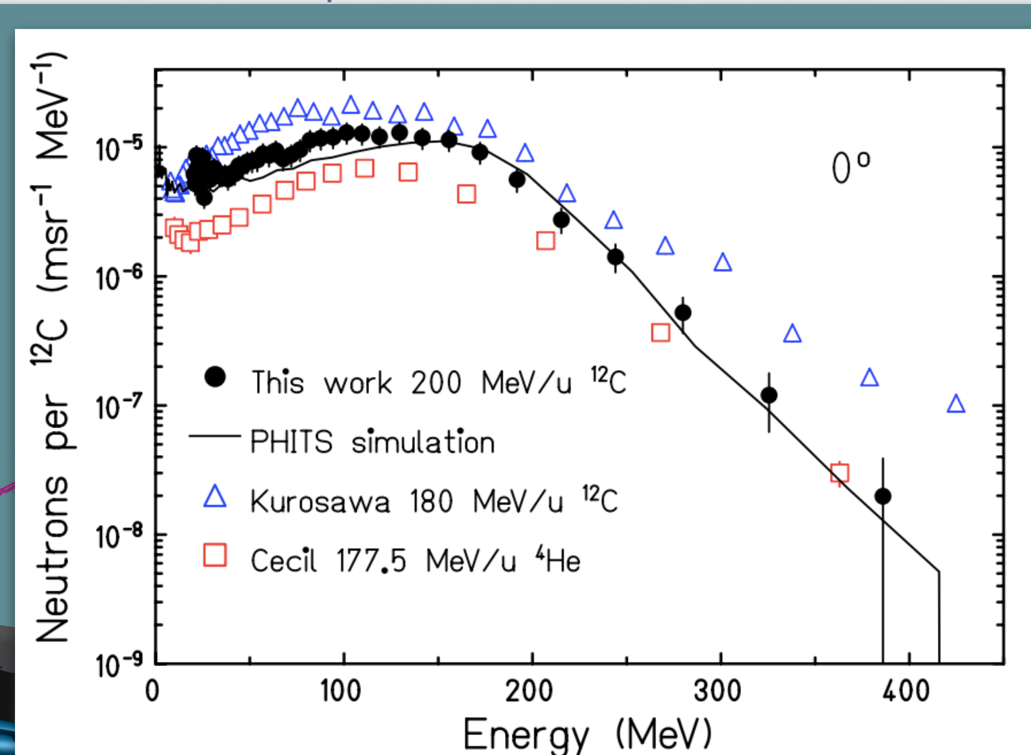
Need of new data: cross-section measurements on tissue compound elements and <u>secondary neutron production measurements from anthropomorphic phantoms</u>.

SECONDARY NEUTRONS => TRACKING DETECTOR

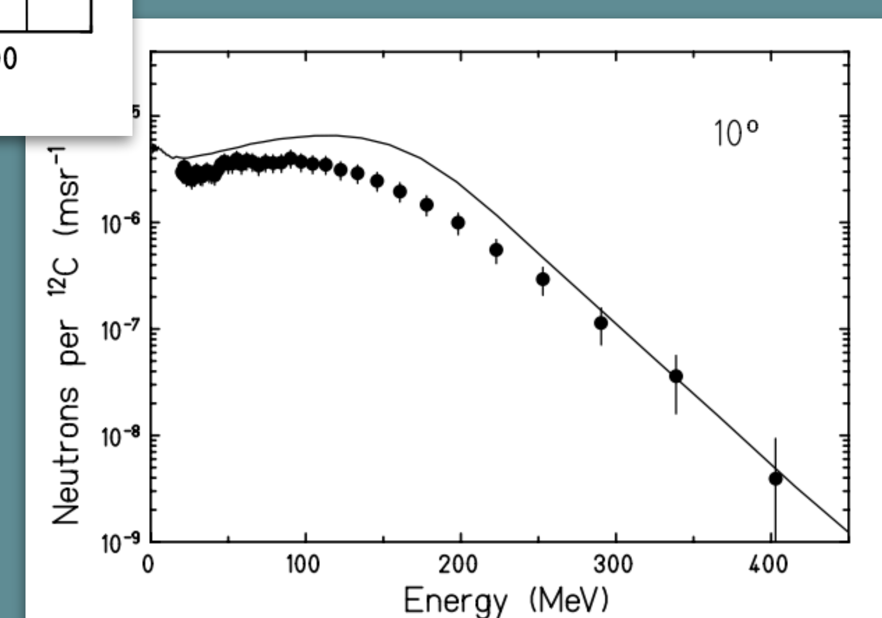
Neutrons are produced (as protons) in the beam nuclear interactions with the matters, in particular with the **patient tissues**.

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





Neutron energy spectra (treatment-like carbon beam) measured at laboratory angle at different energies and angles.



Gunzert-Marx et al. **Secondary beam fragments produced by 200 MeV/ u 12C ions in water and their dose contributions in carbon ion radiotherapy,**
doi:10.1088/1367-2630/10/7/075003

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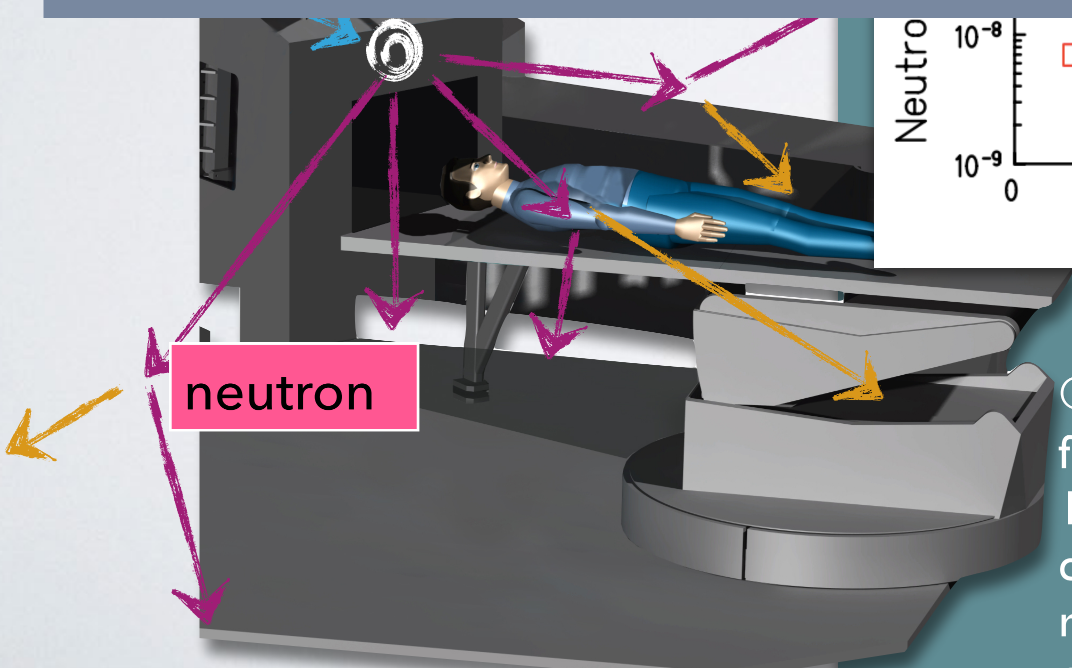
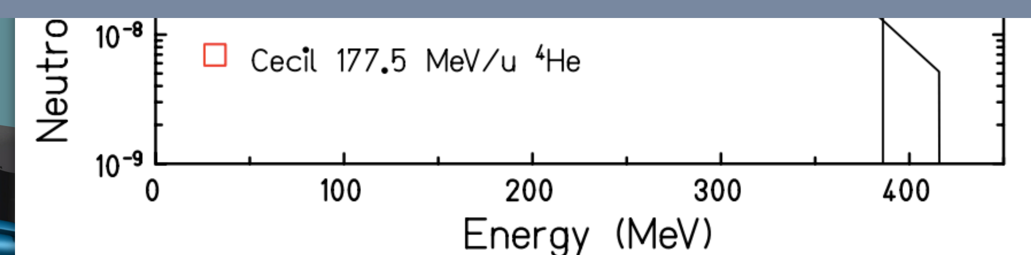
Neutrons are produced (as protons) in the beam nuclear interactions with the matters, in particular with the **patient tissues**.

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).





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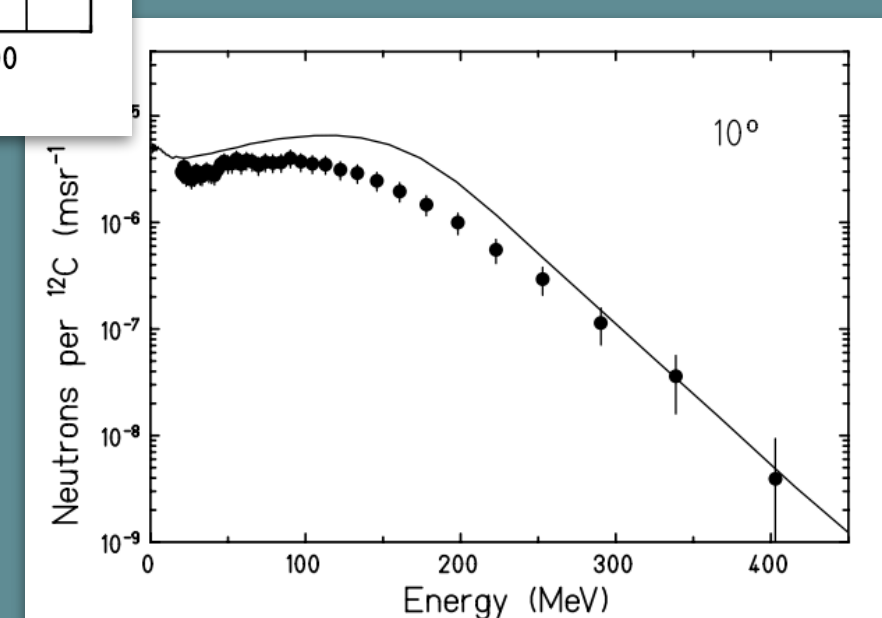
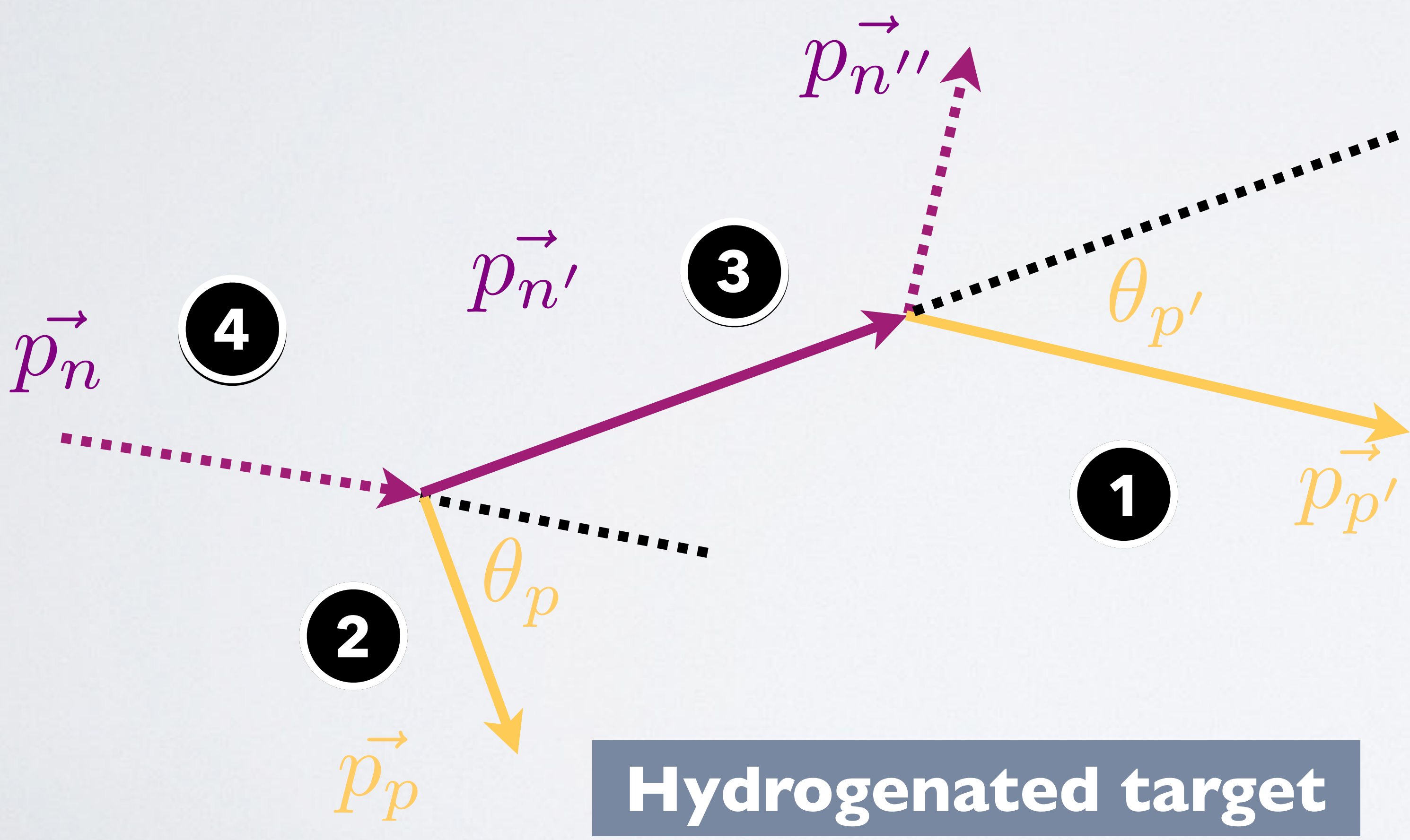


DETECTOR STRATEGY

Tracking the neutrons with *high efficiency*

Double elastic scattering



Hydrogenated target

1. Second Proton recoil measurement:
   Range => Energy
   Track => Direction
2. First Proton recoil measurement:
   Range => Energy
   Track => Direction
3. Diffused neutron reconstruction:

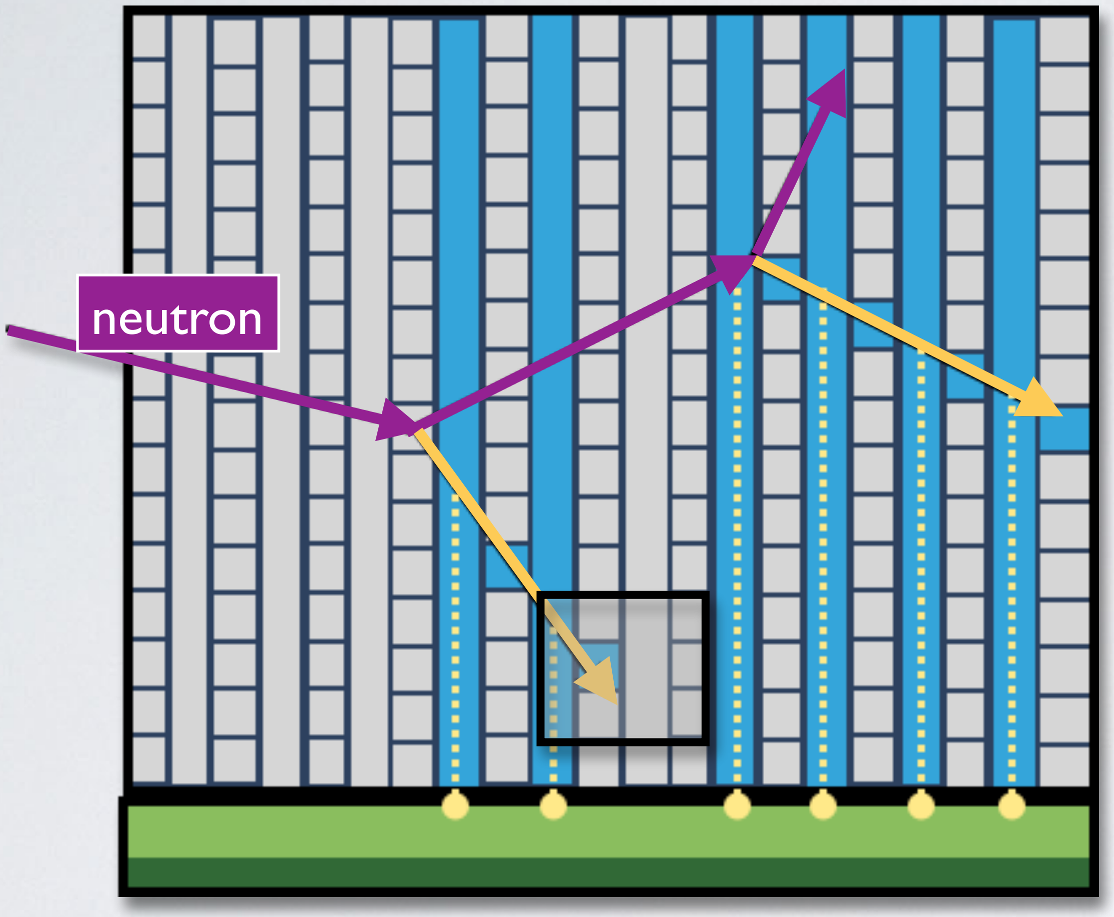
$$\vec{p_{n'}} = \frac{p_{p'}}{\cos\theta_{p'}}\hat{n}'$$

4. Emitted neutron reconstruction:

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

DETECTOR STRATEGY

Double elastic scattering



The dimensions have been chosen as a compromise between: compactness, DES interaction probability and cost.

Final tracker size: 16 x 16 x 20 cm^3

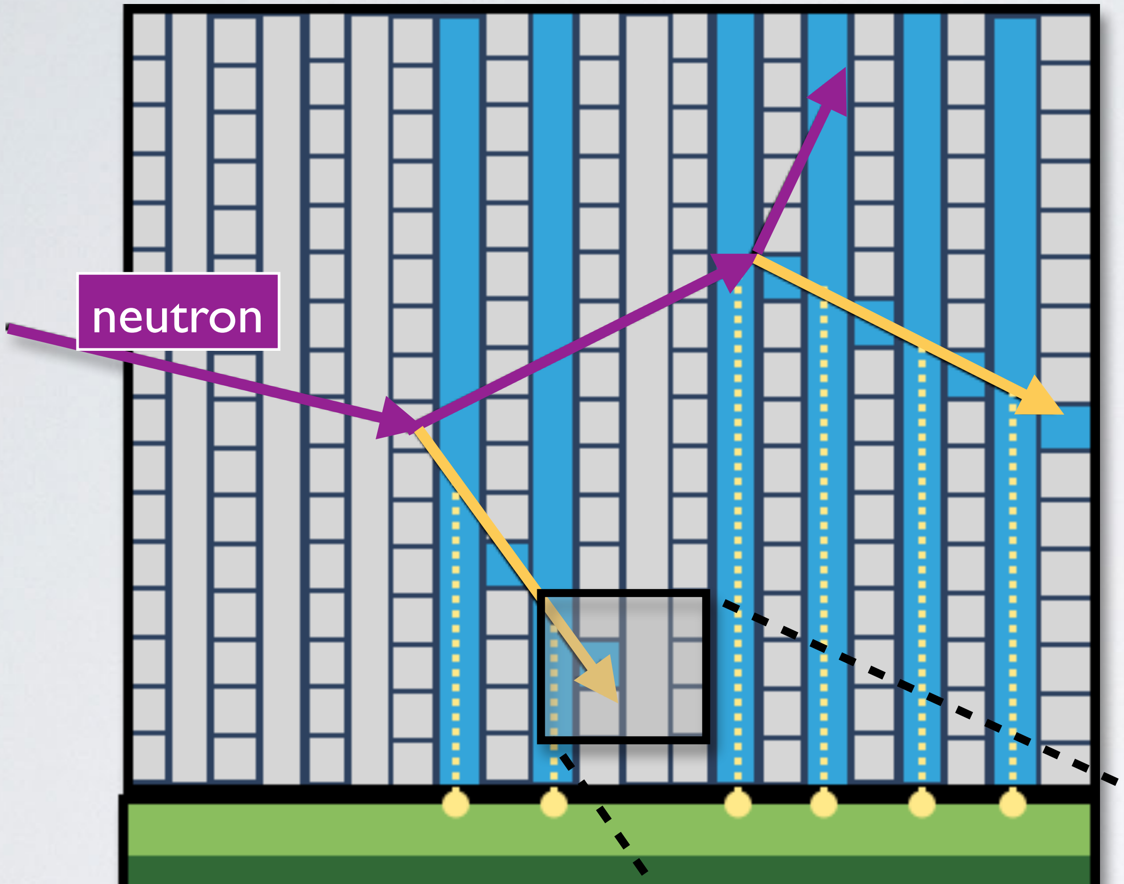
PLASTIC SCINTILLATING FIBRES

- squared 250 μm: minimal size in order to maximise the granularity on the proton tracks (proton energy is measured by range);
- plastic: increase the neutron interaction probability on light nucleus (H) to increase elastic scattering events;

layers of fibres *X-Y oriented* → **target and tracker**

DETECTOR STRATEGY

Double elastic scattering



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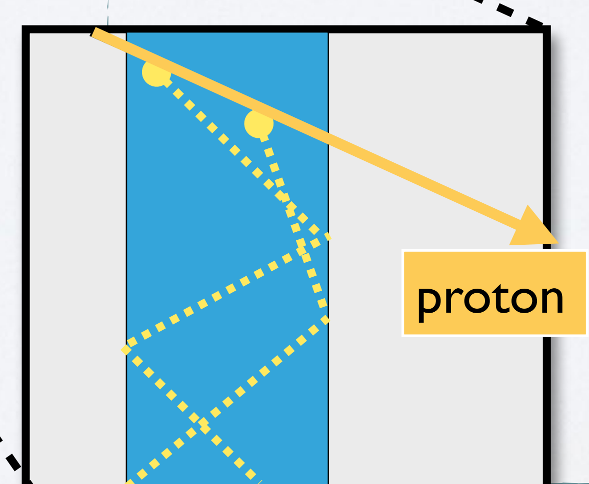


CUSTOM READOUT SYSTEM

more than 10^5 channels

=> **silicon readout system**

ENERGY DEPOSITED

A Monte Carlo simulation has been developed using FLUKA code to optimise 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.

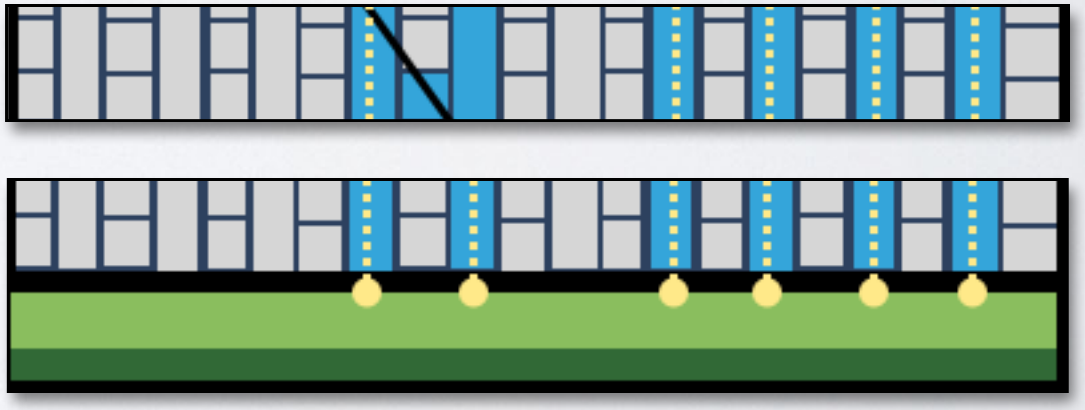
The average energy protons is between 10-300 MeV

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

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

Silicon Detector for READOUT

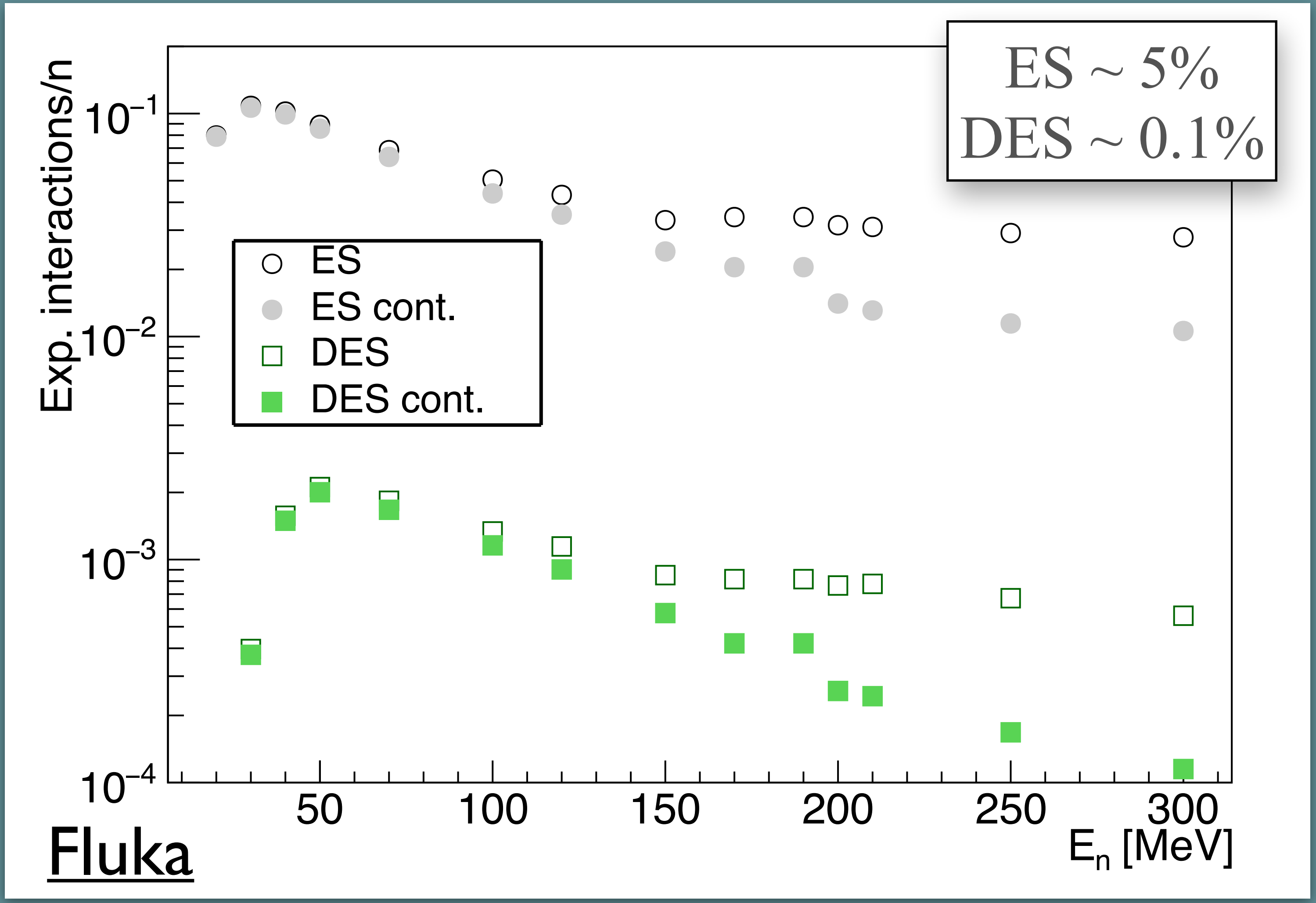
- Need to keep the space granularity of the fibres (~250μm)
- many channels!
- Few photons (few ph. electrons)
- Fast signals: typically ~5ns



1-4 ph. electrons

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.** https://doi.org/10.1016/j.radmeas.2018.10.006

MONDO 10x10x20 cm³

Constraints:

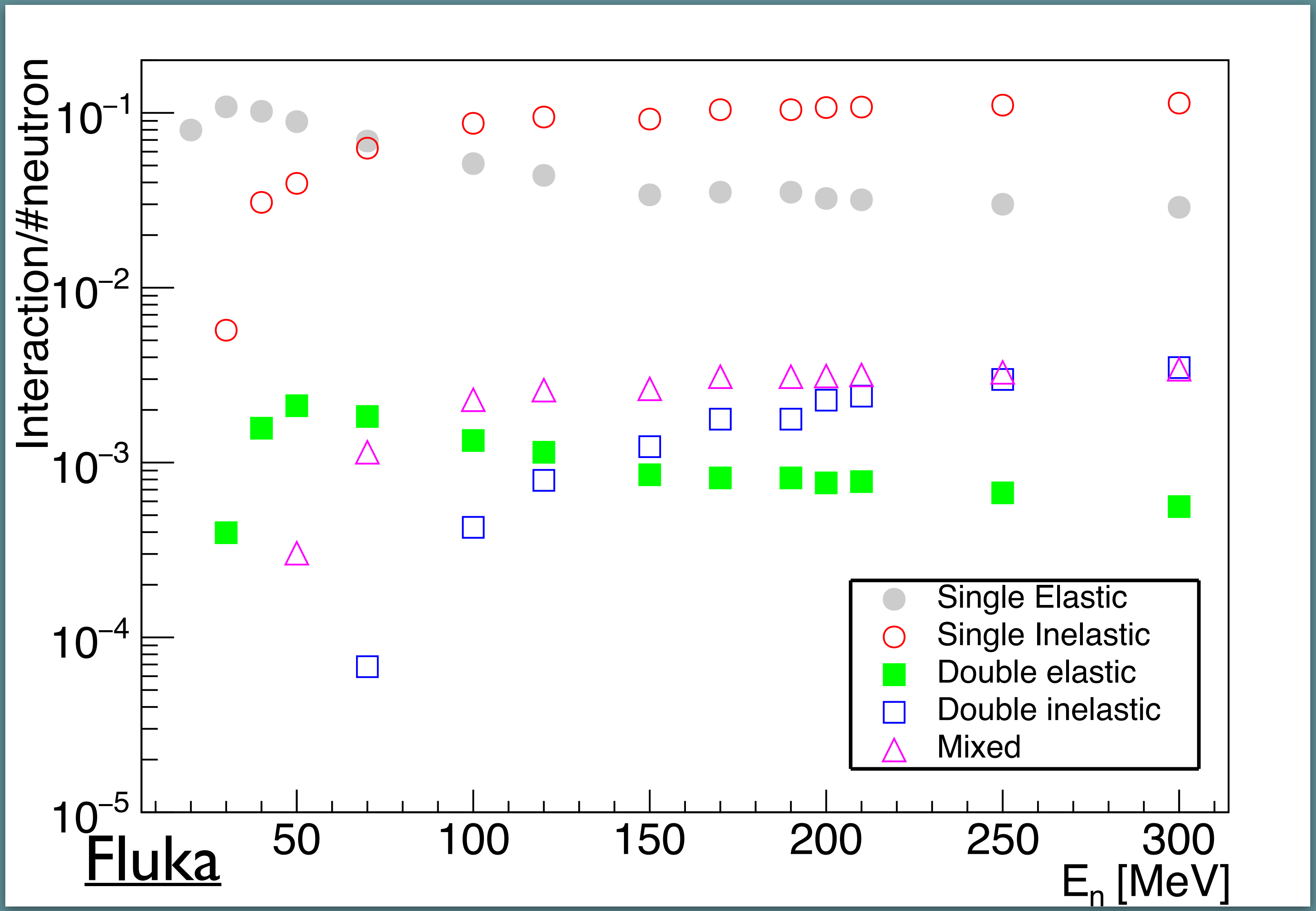
- request of full protons containment;
- at least 3 layers crossed (about 12 MeV)

for En>200 MeV containment decreases of an order of magnitude the detection efficiency => under evaluation other proton kinetic energy measurements strategies (i.e. **energy loss along the track**, etc, ..)

only statistical uncertainty

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.



Backgrounds have been studied with the MC-simulation. The main background is composed by the inelastic scattering.

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.** https://doi.org/10.1016/j.radmeas.2018.10.006

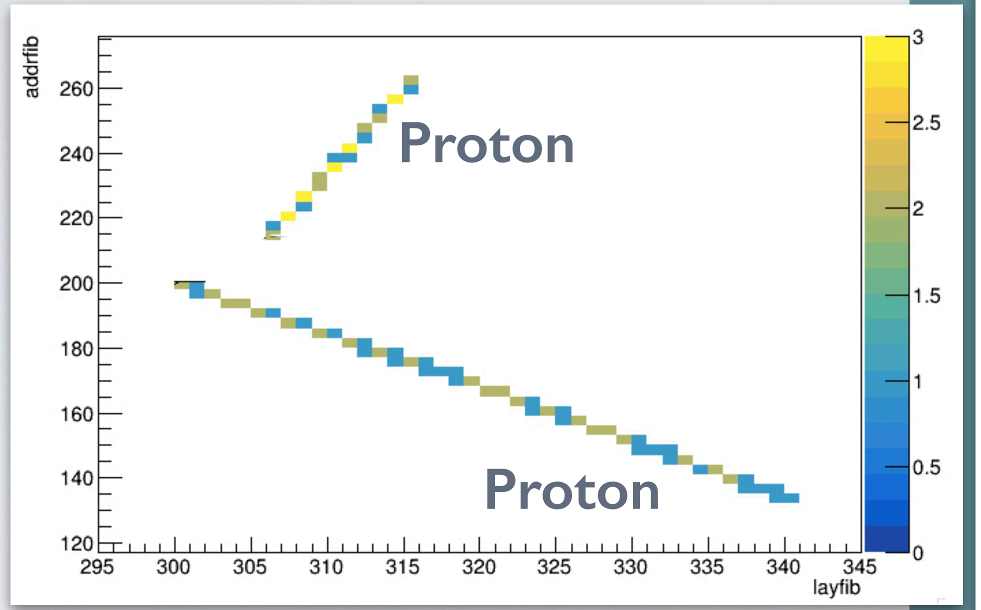
MONDO 10x10x20 cm^3

only statistical uncertainty

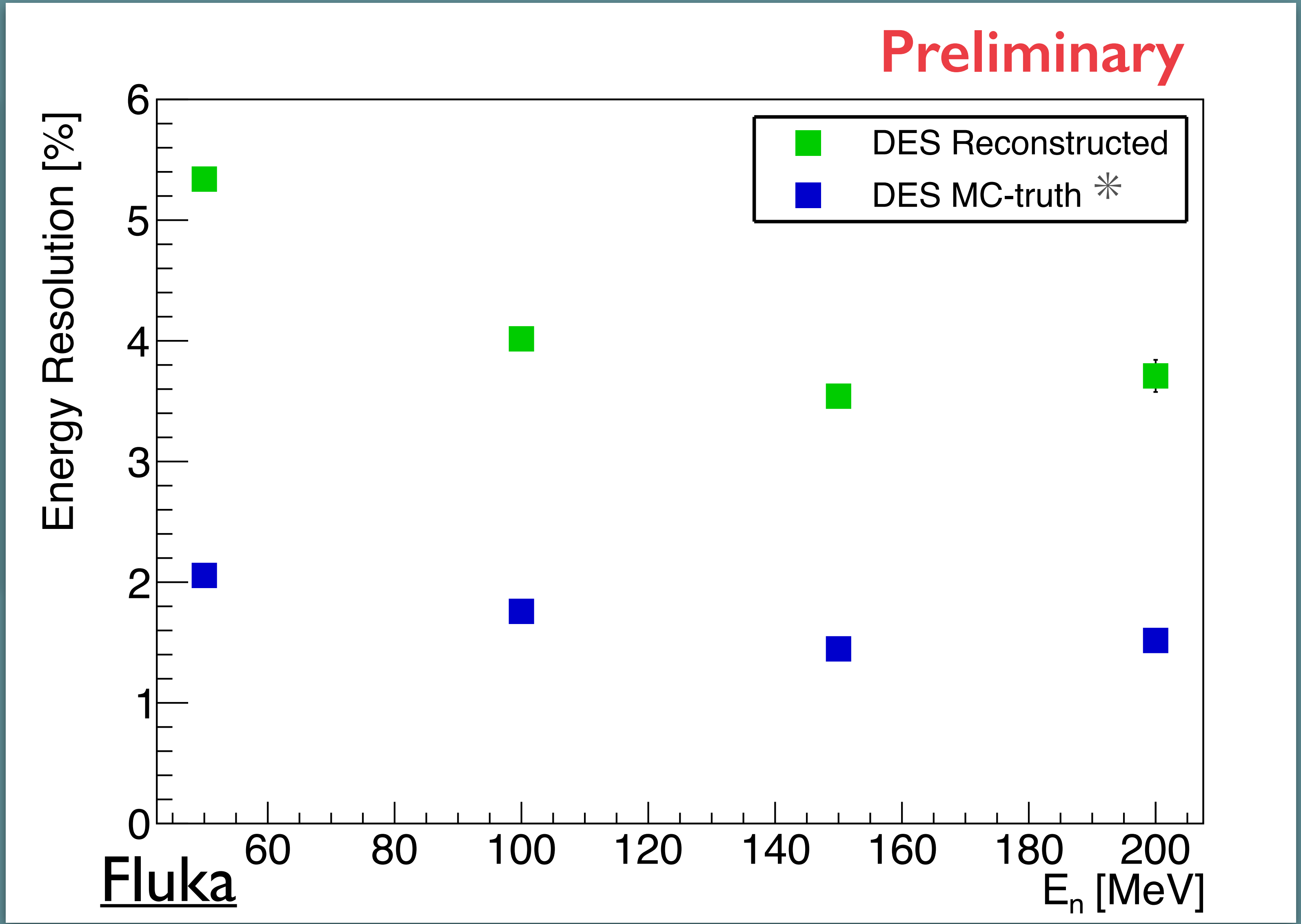
SIMULATION: DES ENERGY RESOLUTION

The neutron energy is reconstructed via DES with a resolution that is shown as a function of the neutrons kinetic energy. The protons kinetic energy has been calculated using the length of the particle track with NIST range-energy values. The protons angles is computed by means of a linear fit to the proton track.

Ex. Neutron track~100 MeV



Energetic secondary protons (straighter and longer tracks) lead to a better achievable precision, as expected.

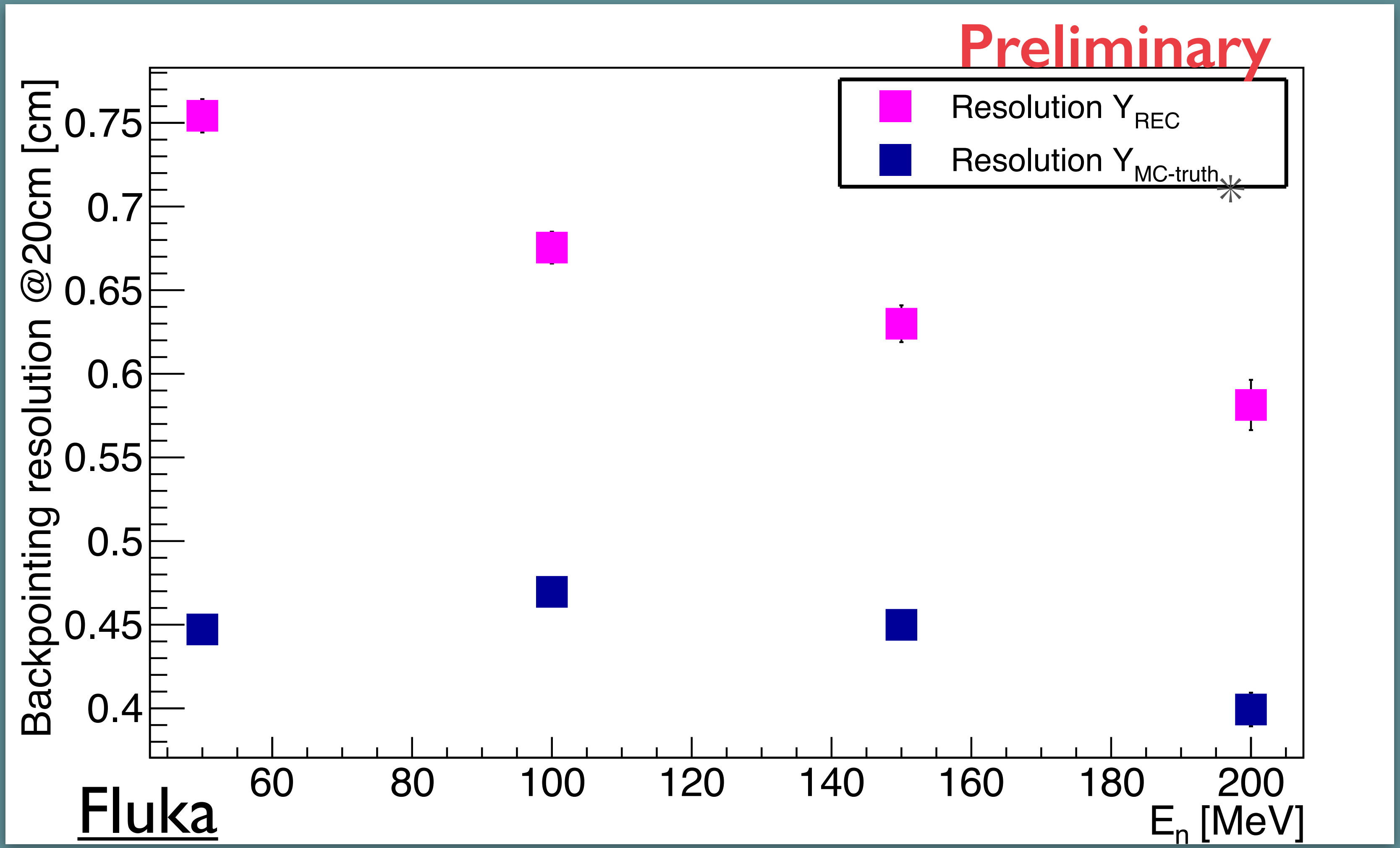


✳ **deposit energy proton in the fibre by range MC-truth, the directional cosines by MC-truth**

only statistical uncertainty

SIMULATION: BACKPOINTING

The backpointing resolution @20cm is reported as a function of the neutrons initial kinetic energy.



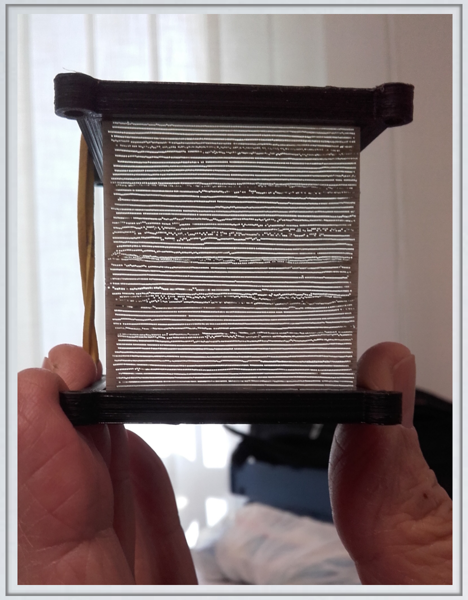
* deposit energy proton in the fibre by range MC-truth, the directional cosines by MC-truth

The aim is to discriminate the scattered neutrons coming from each side from those coming from the patient…so it's not necessary a millimetric precision.

The tracking with centimeter resolution allows to measure neutron flux in function of the emission angle.

only statistical uncertainty

NEUTRONS TRACKER

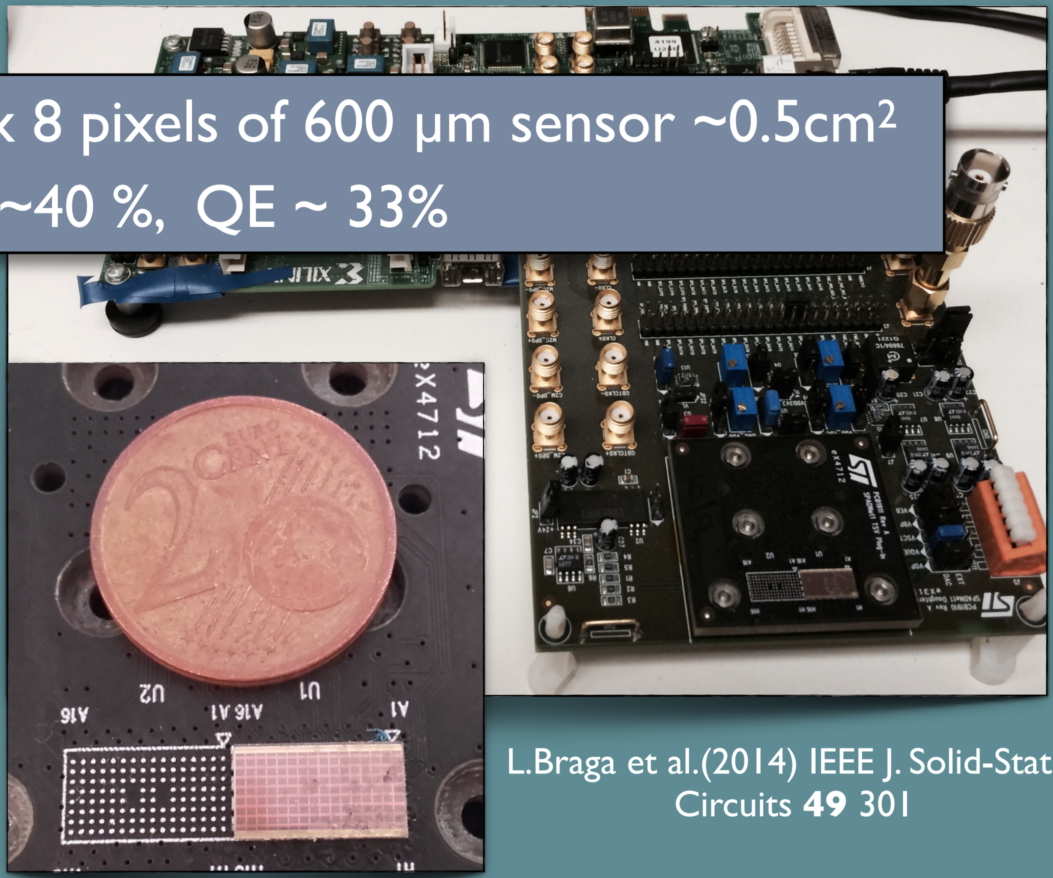


A tracker prototype (4 x 4 x 4.8 cm^3) has been realized as a proof of principle for proton trading and in order to test the assembling procedure.

Practicing with a **sensor prototype, SPAD-net**, allowed us to point out the critical issues to be addressed in our sensor development phase. A new custom sensor has been developed starting from the experience gained using spad-net.

Test PENELOPE prototype:

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

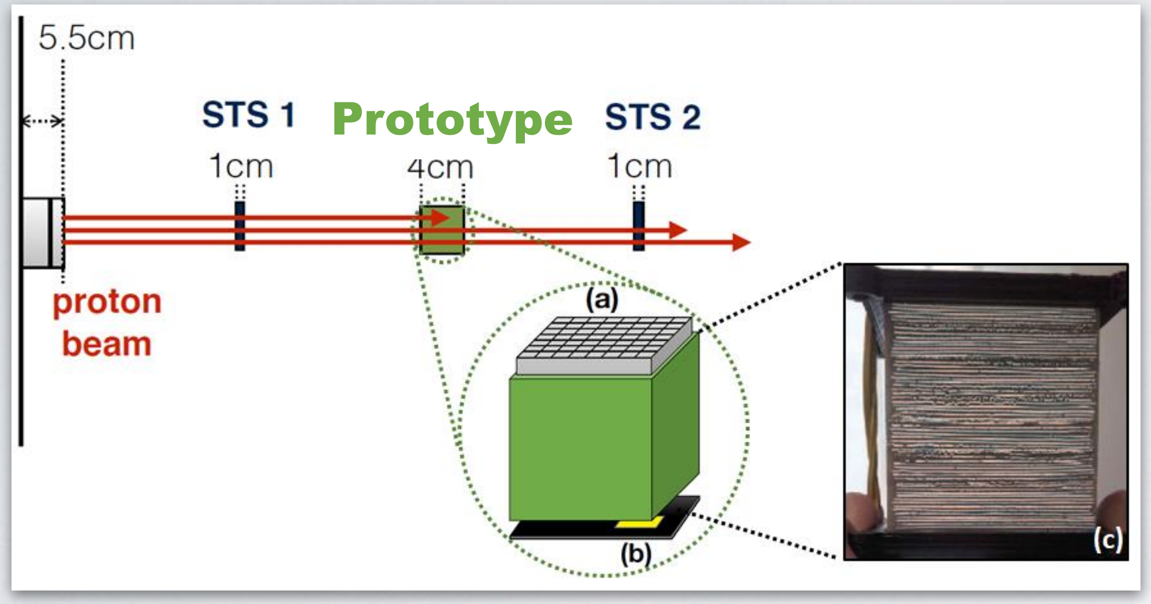


L.Braga et al.(2014) IEEE J. Solid-State Circuits **49** 301

* 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

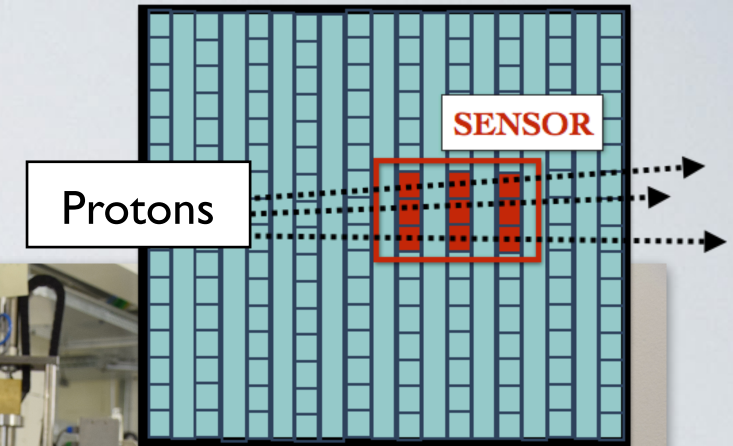
** R. Mirabelli et al, The MONDO detector prototype development and test: steps towards a SPAD-CMOS based integrated readout (SBAM sensor) doi:10.1109/TNS.2017.2785768

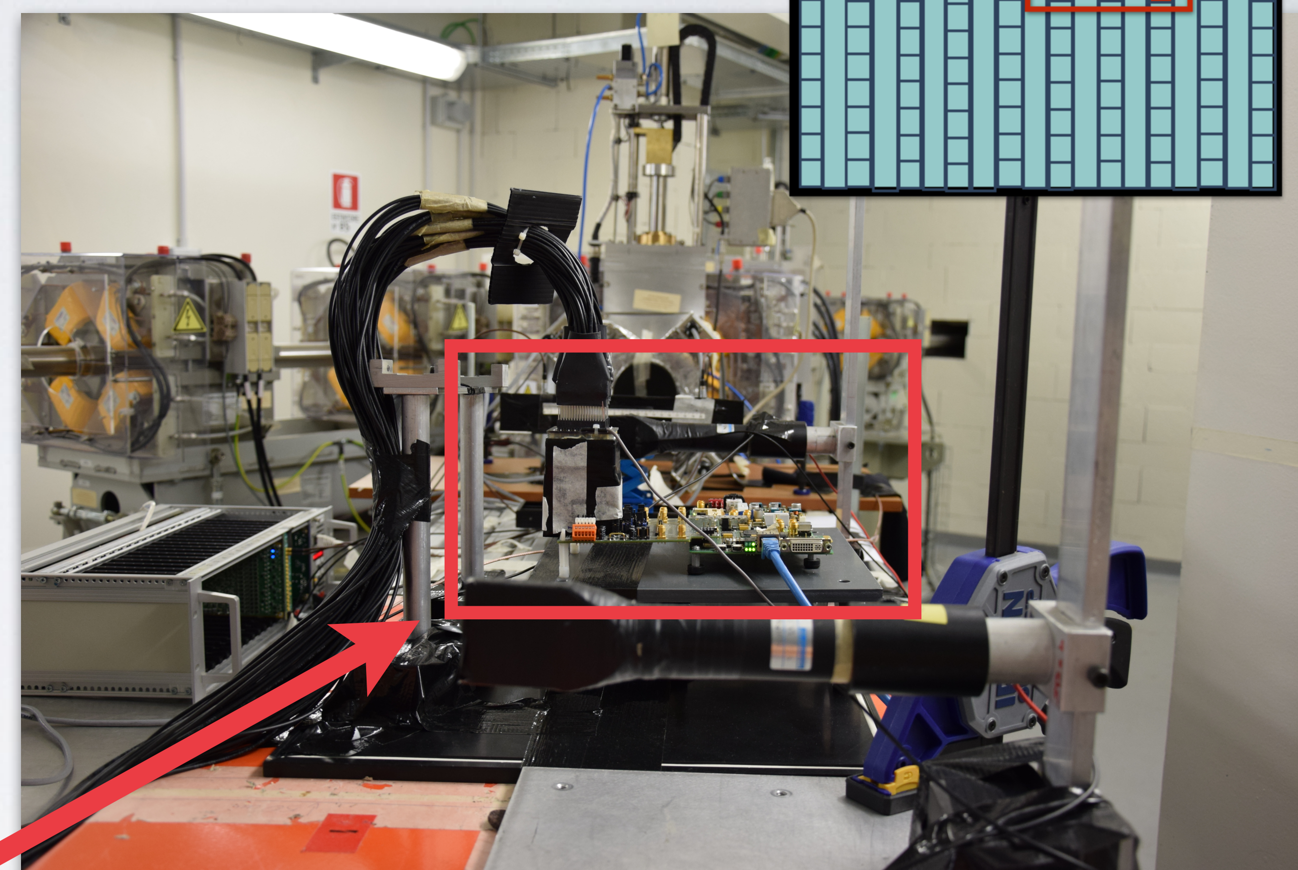
PROTONS @TRENTO

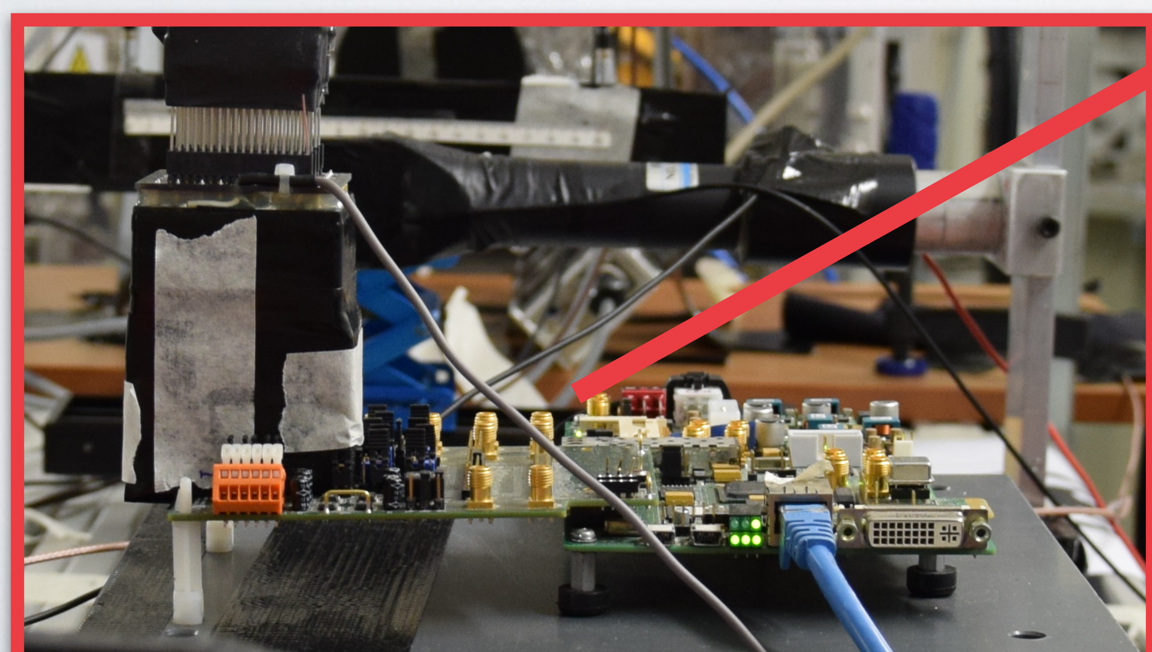


Beam energy: [70-240] MeV protons

Beam size (σ): [3-7] mm



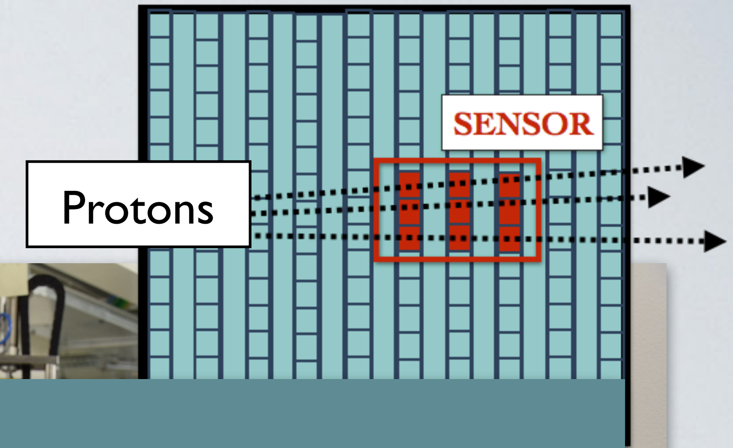


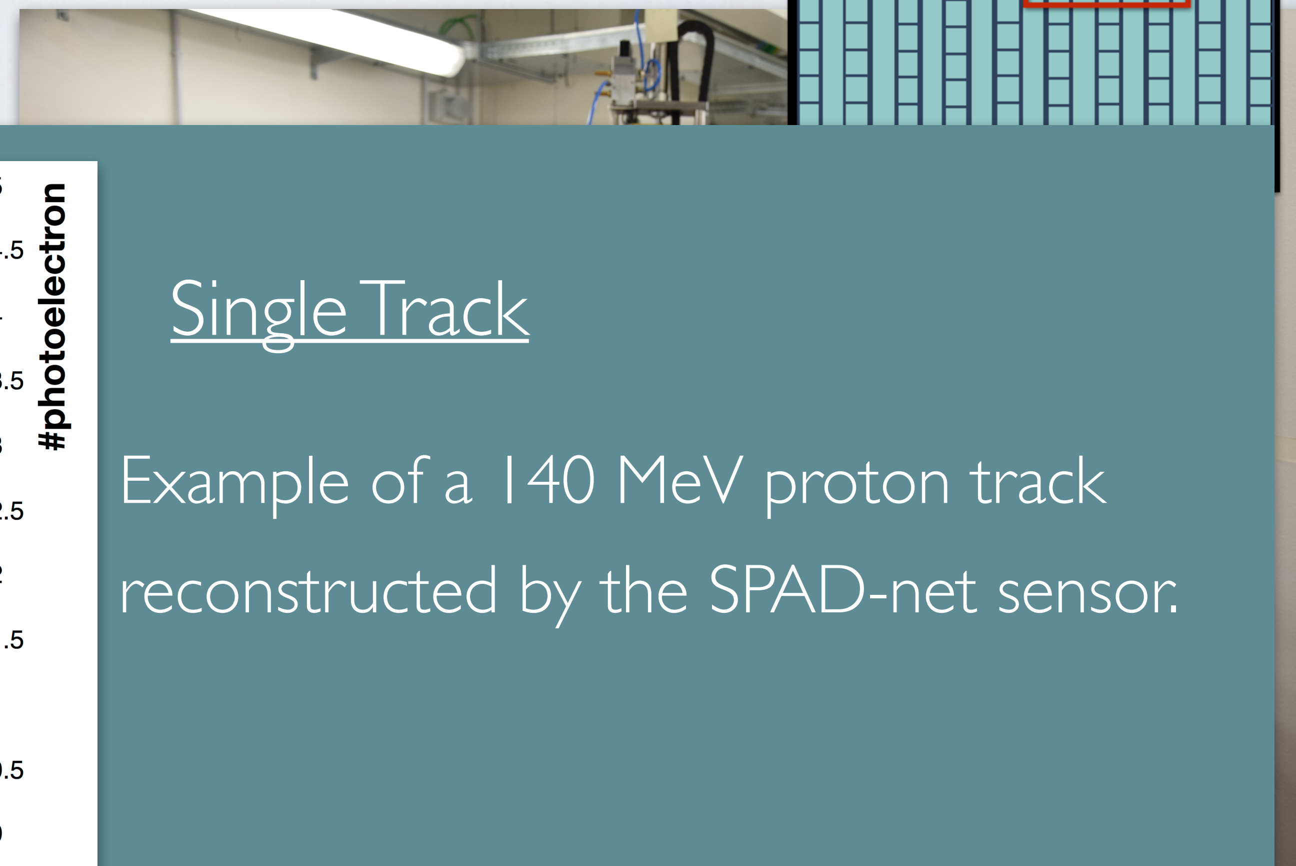


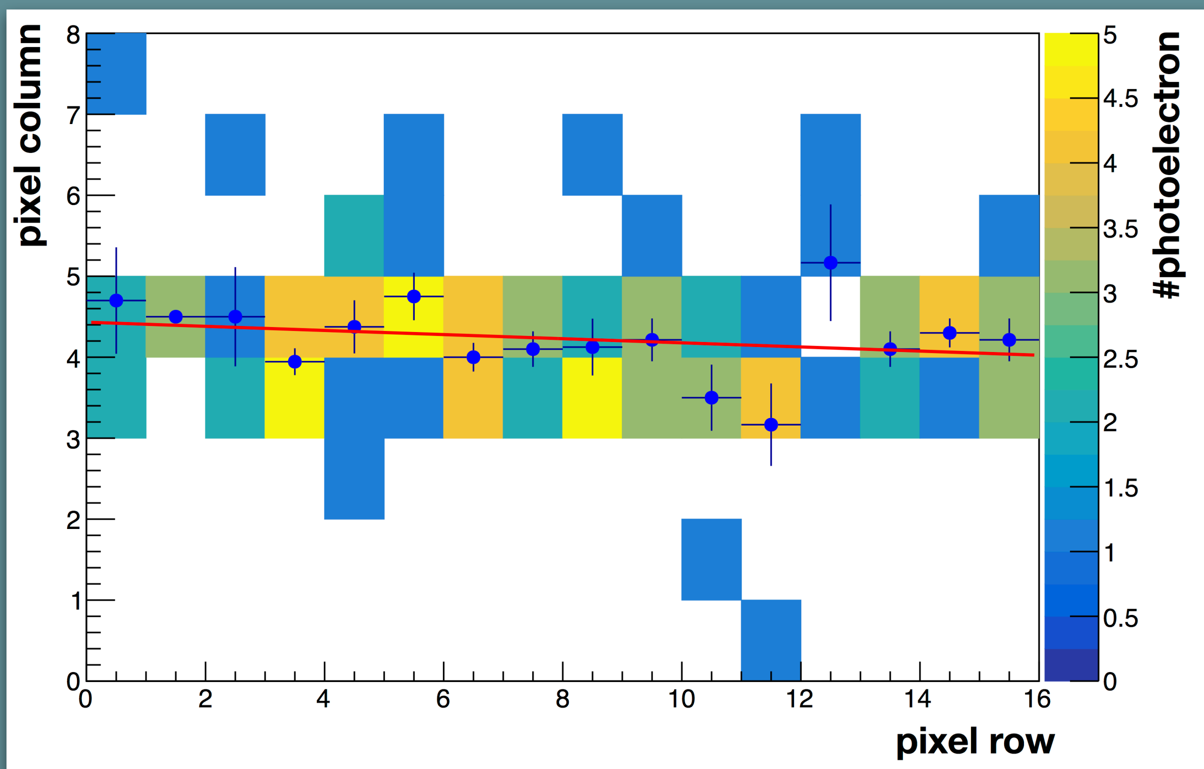
Prototype readout FBK spad-net sensor (128 ch., 600 μm per pixel)

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

PROTONS @ TRENTO







Single Track

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

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

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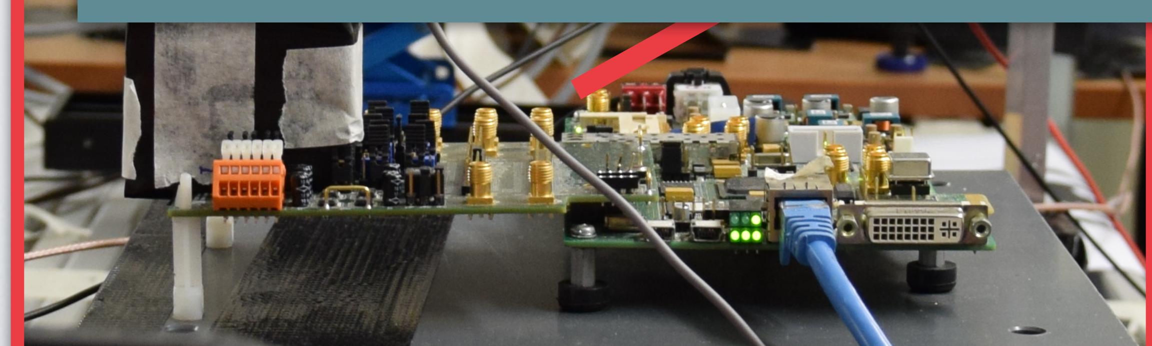
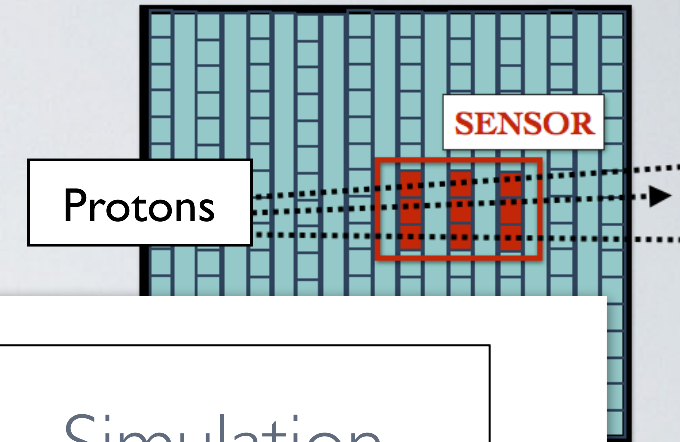
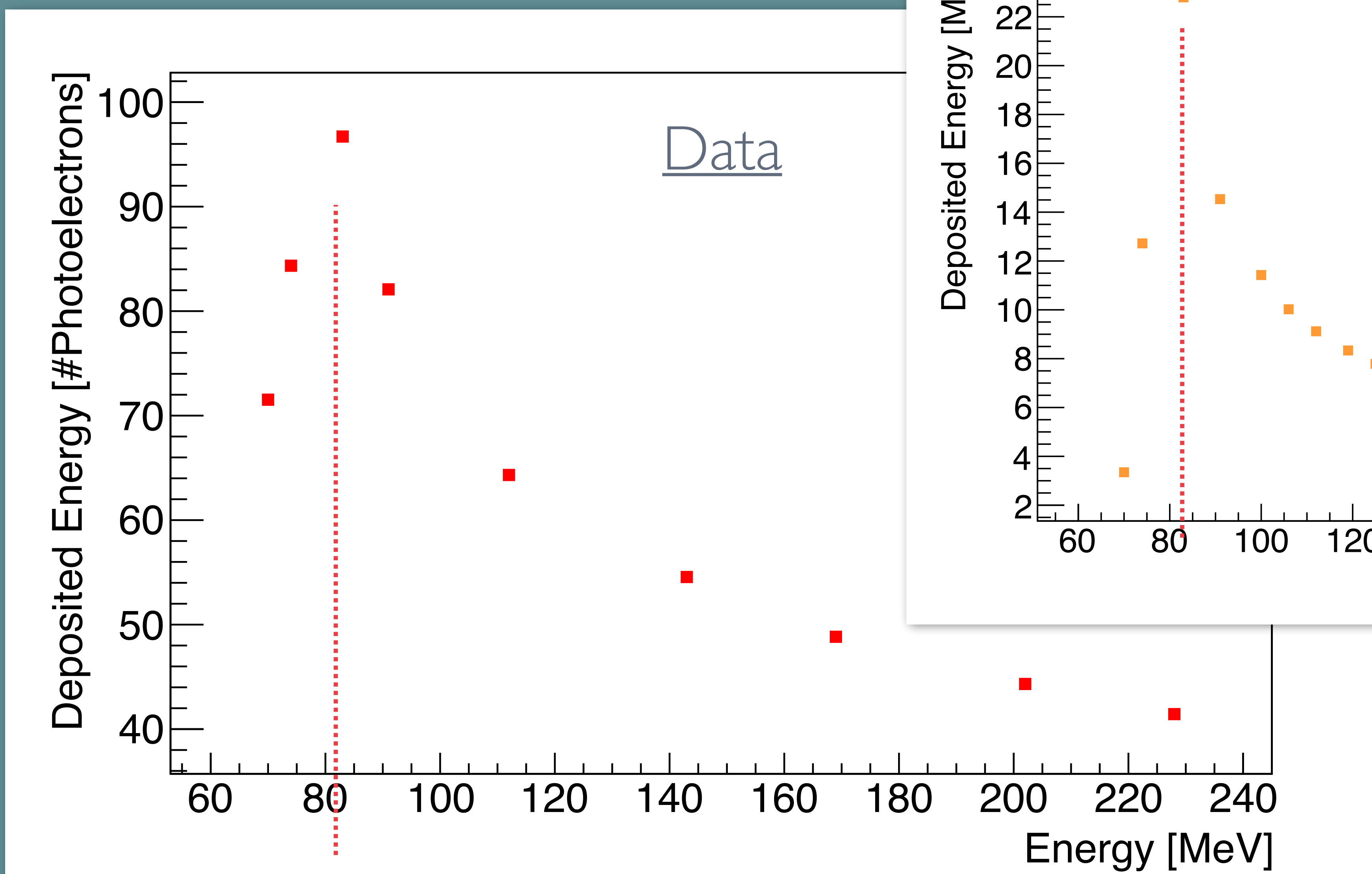


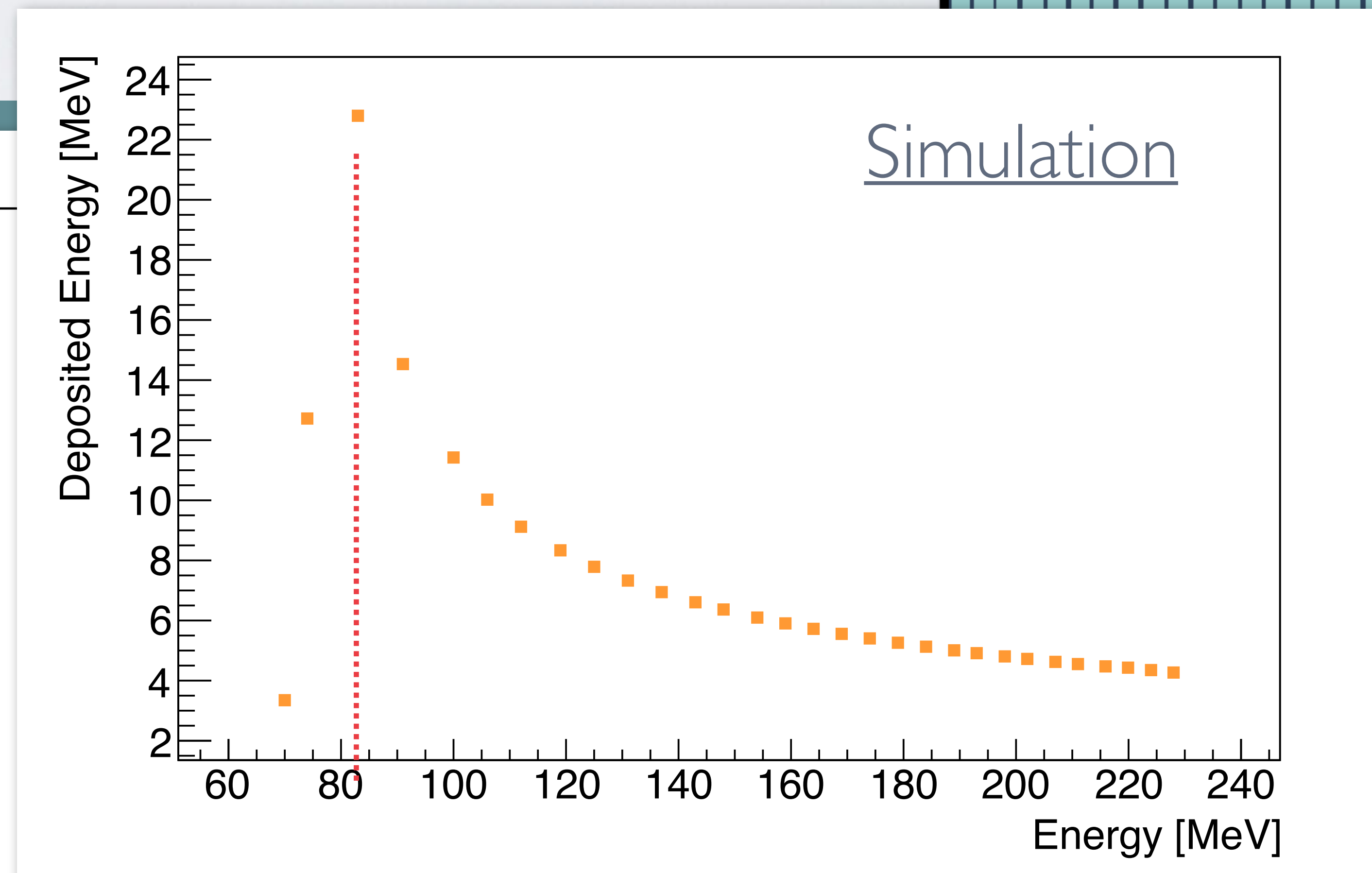
A second readout with a commercial multi-anode PMT has been used to cross-check the tracking efficiency.

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).





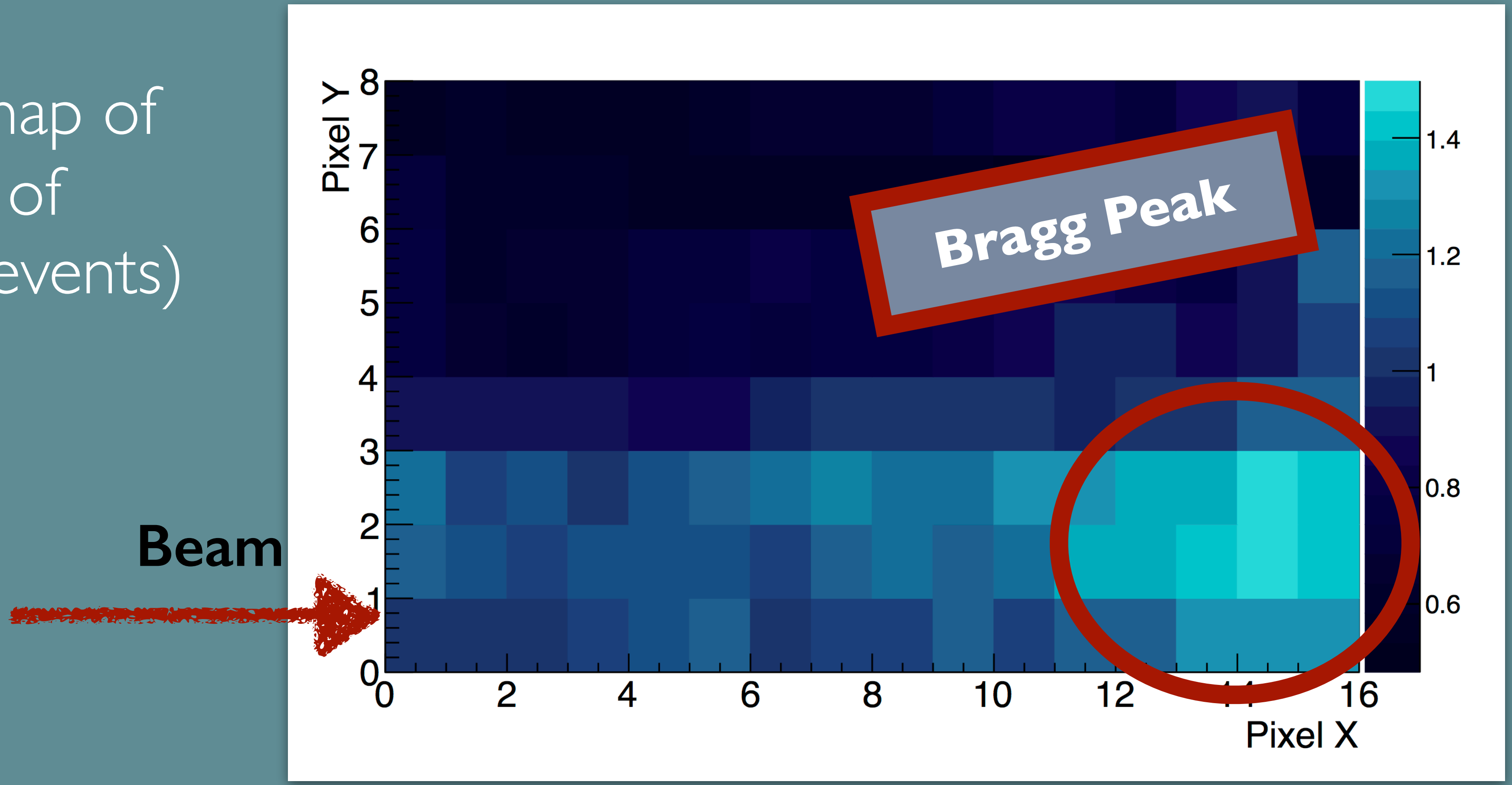
G.Traini et al, **Preliminary test of the MONDO project secondary fast and ultrafast neutrons tracker response using protons and MIP particles** doi:10.1088/1748-0221/13/04/C04014

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

only statistical uncertainty

PROTONS @ TRENTO PROTON THERAPY

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



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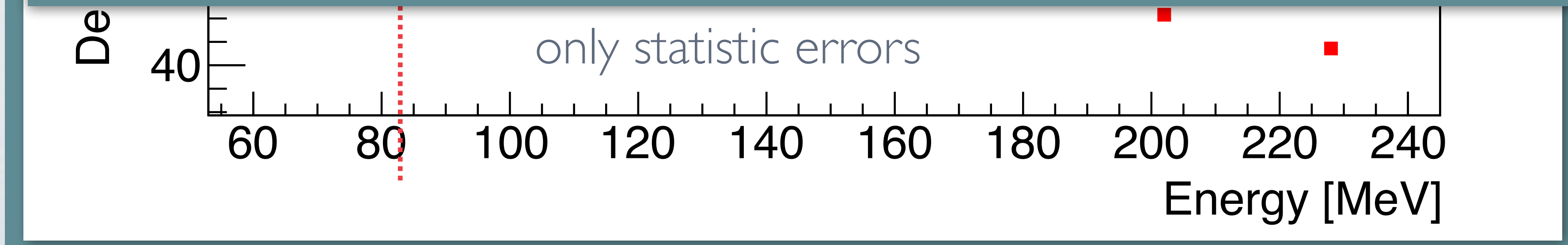

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Bragg Peak is clearly visible for 83 MeV protons.

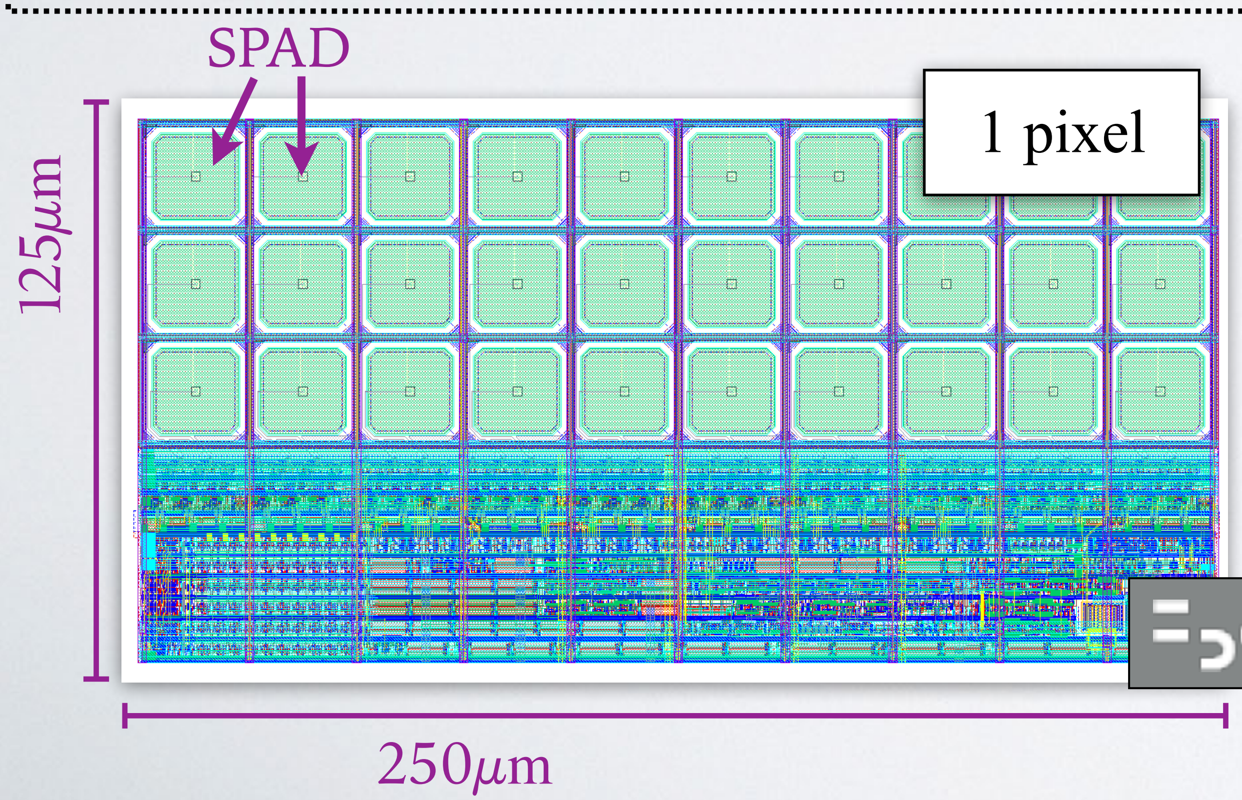
READOUT SYSTEM

We choose to develop a new SPAD array - Silicon Photon Avalanche Diode - sensor in collaboration FBK (SBAM sensor) => tailored for the MONDO needs.

- side-by-side sensors
- Sensors designed to be implemented in Tiles ("large" area, final detector ~400cm^2)

- ☑ Photon dynamic range per pixel [0-30]
- ☑ TDC per pixel 100 ps;
- ☑ Two level Trigger logic tuned for fast scintillation signals

- Fill Factor ~33%
- Quantum efficiency ~40%
- Possibility to turn-off noisy SPAD (Dark Current reduction)



Optimised to be highly efficient to proton tracks

The intellectual property of the SBAM sensor is shared by the two parts(FBK-CF).

READ

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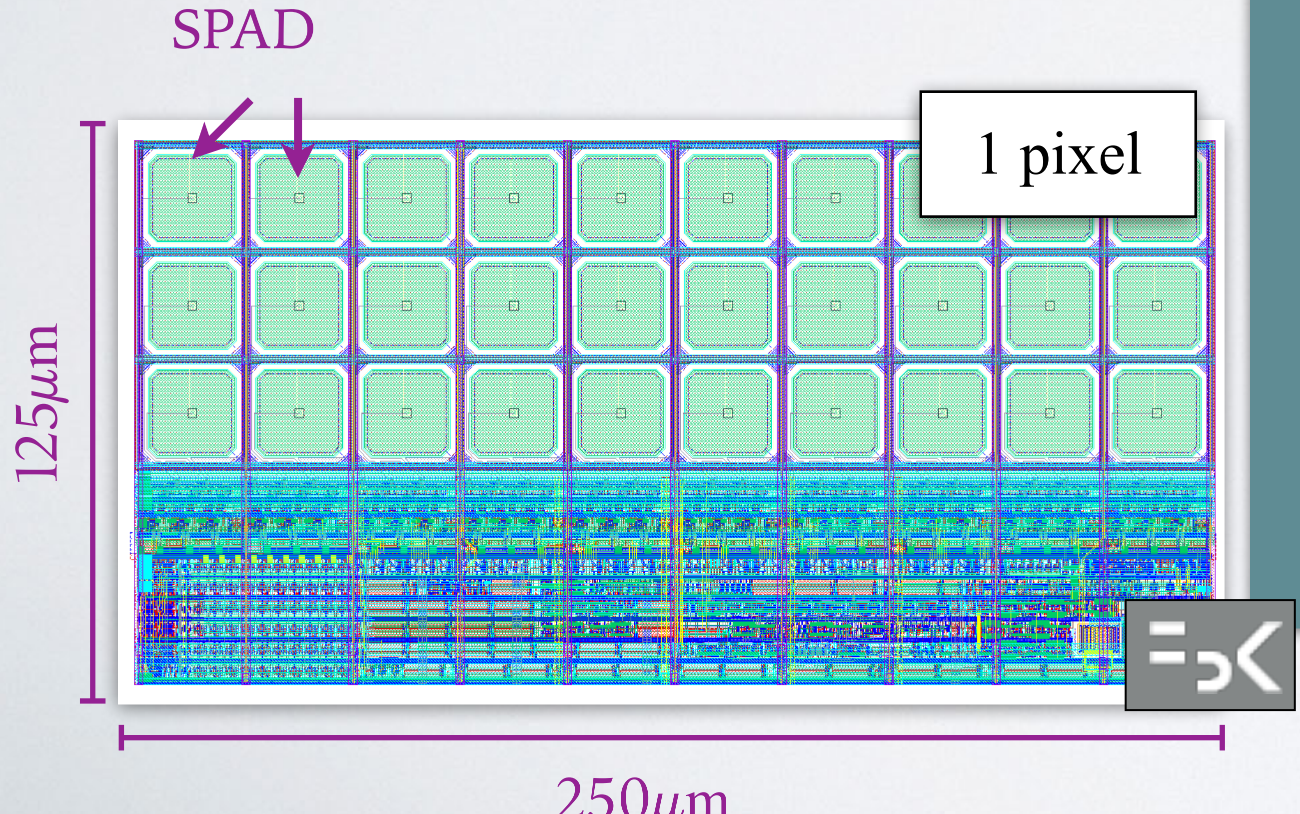
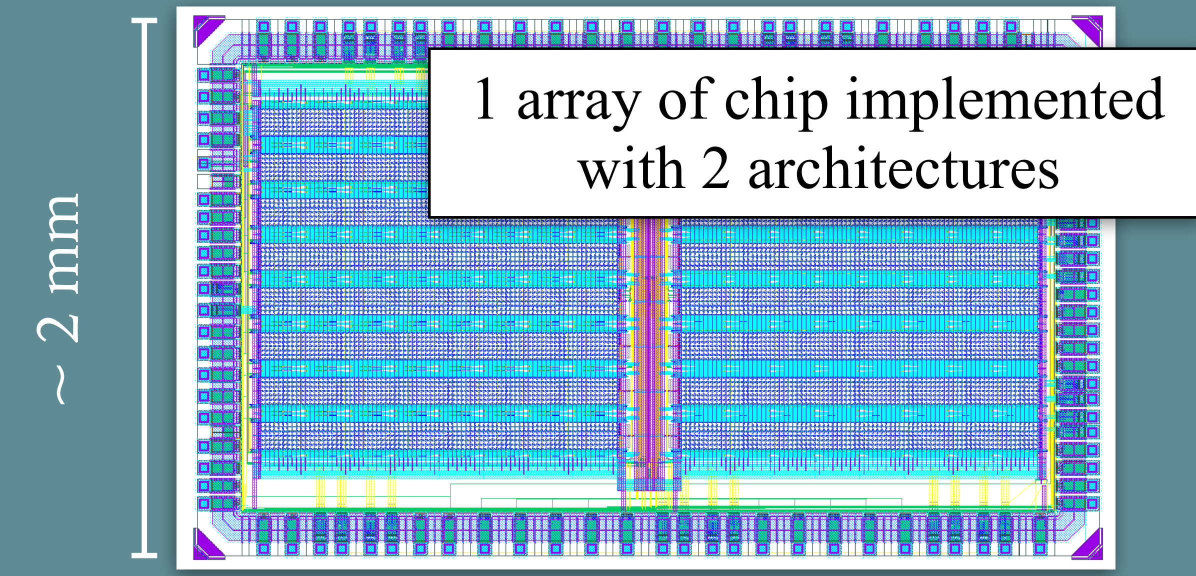
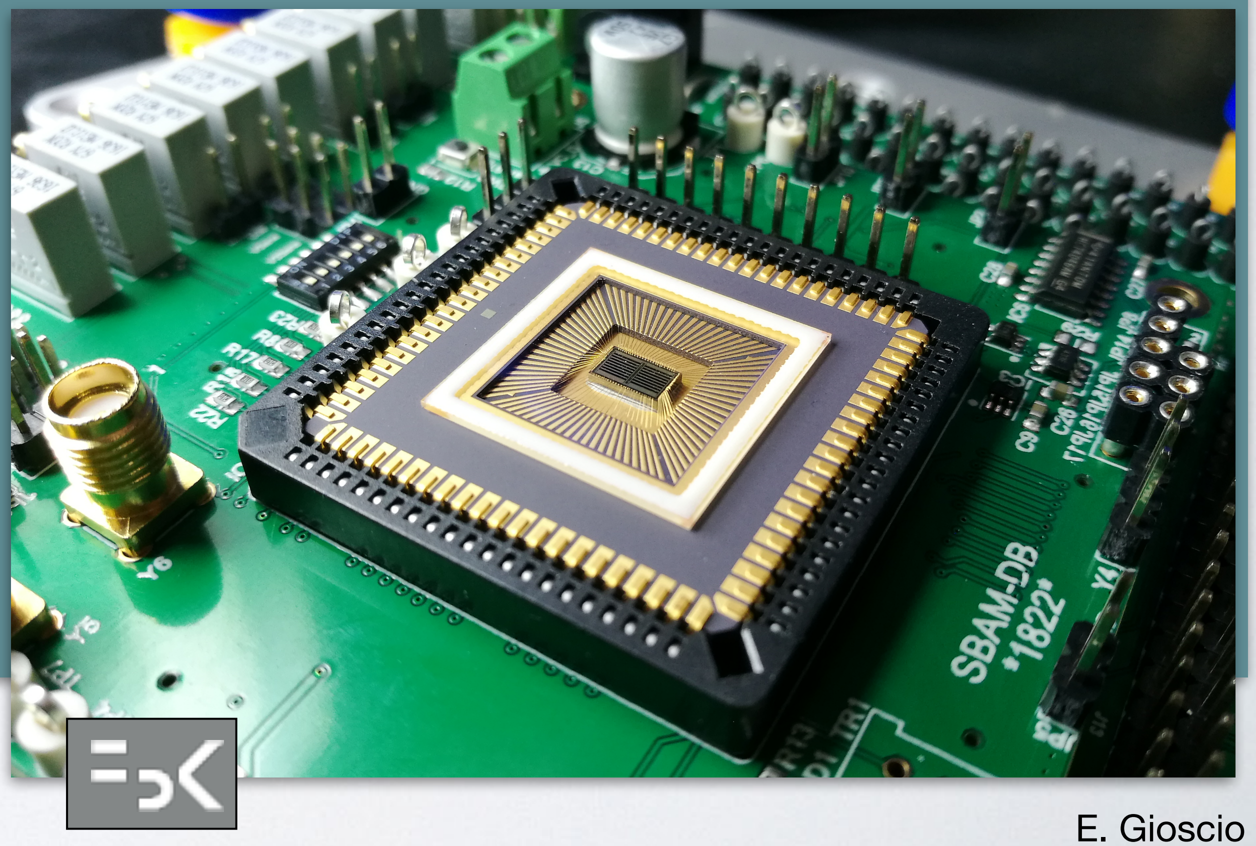


First chip september 2018

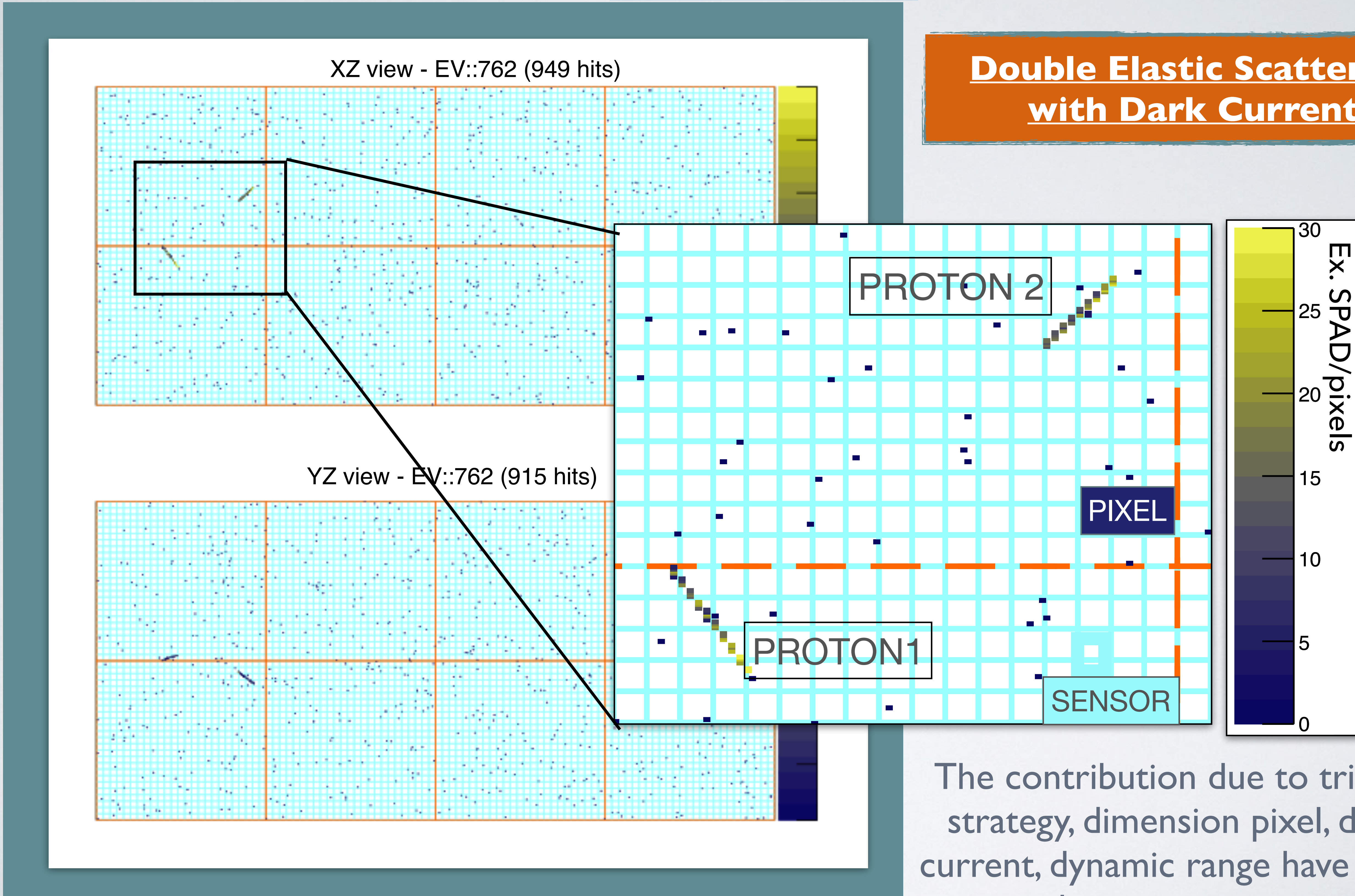
The first chip **SBAM_1** has been produced at LFoundry and tested at FBK.



8 x 16 pixel



SIMULATION: DARK COUNT RATE



Double Elastic Scattering with Dark Current

The contribution due to trigger strategy, dimension pixel, dark current, dynamic range have been taken into account.

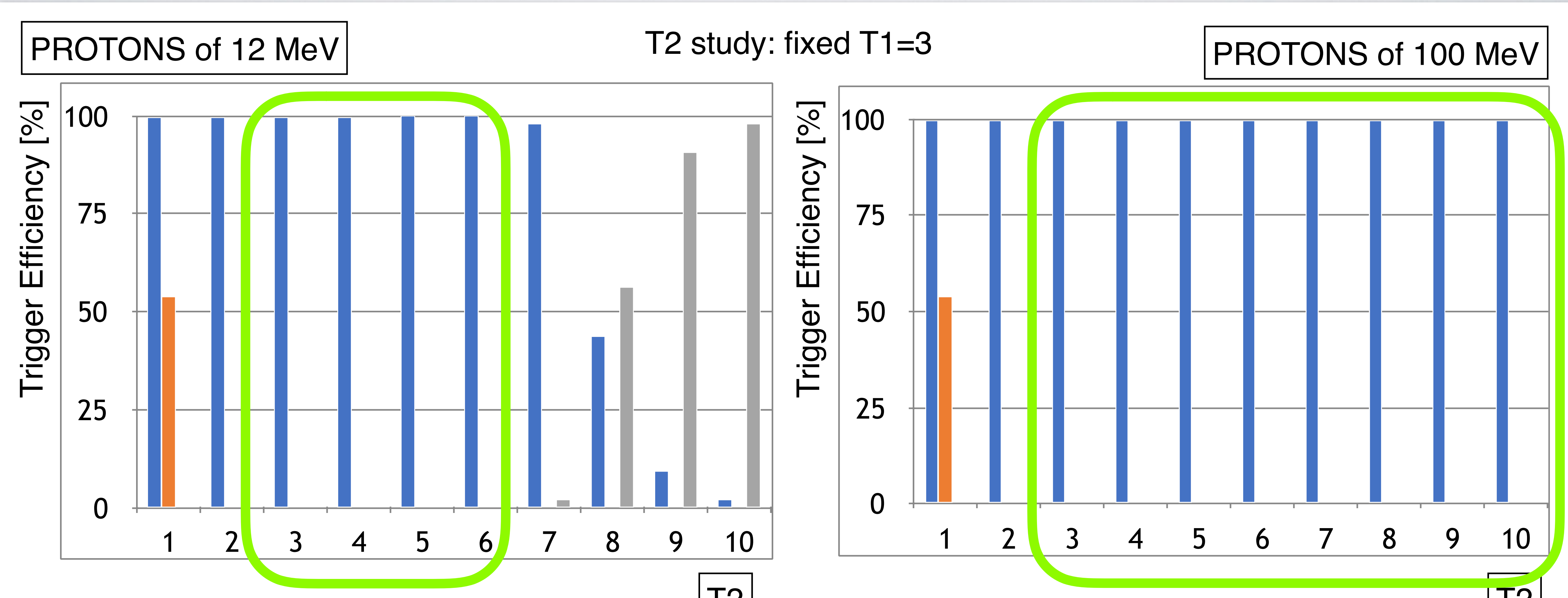
DOUBLE THRESHOLD TRIGGER STUDY

In order to optimise the double trigger strategy a dedicated data taking will be performed with protons of known energies. The implementation of the sensor details in the MC allows to start studying the expected performances of the detector and to point out eventual critical aspects before the final chip foundry run.

- ☑ Two level Trigger logic tuned for fast scintillation signals

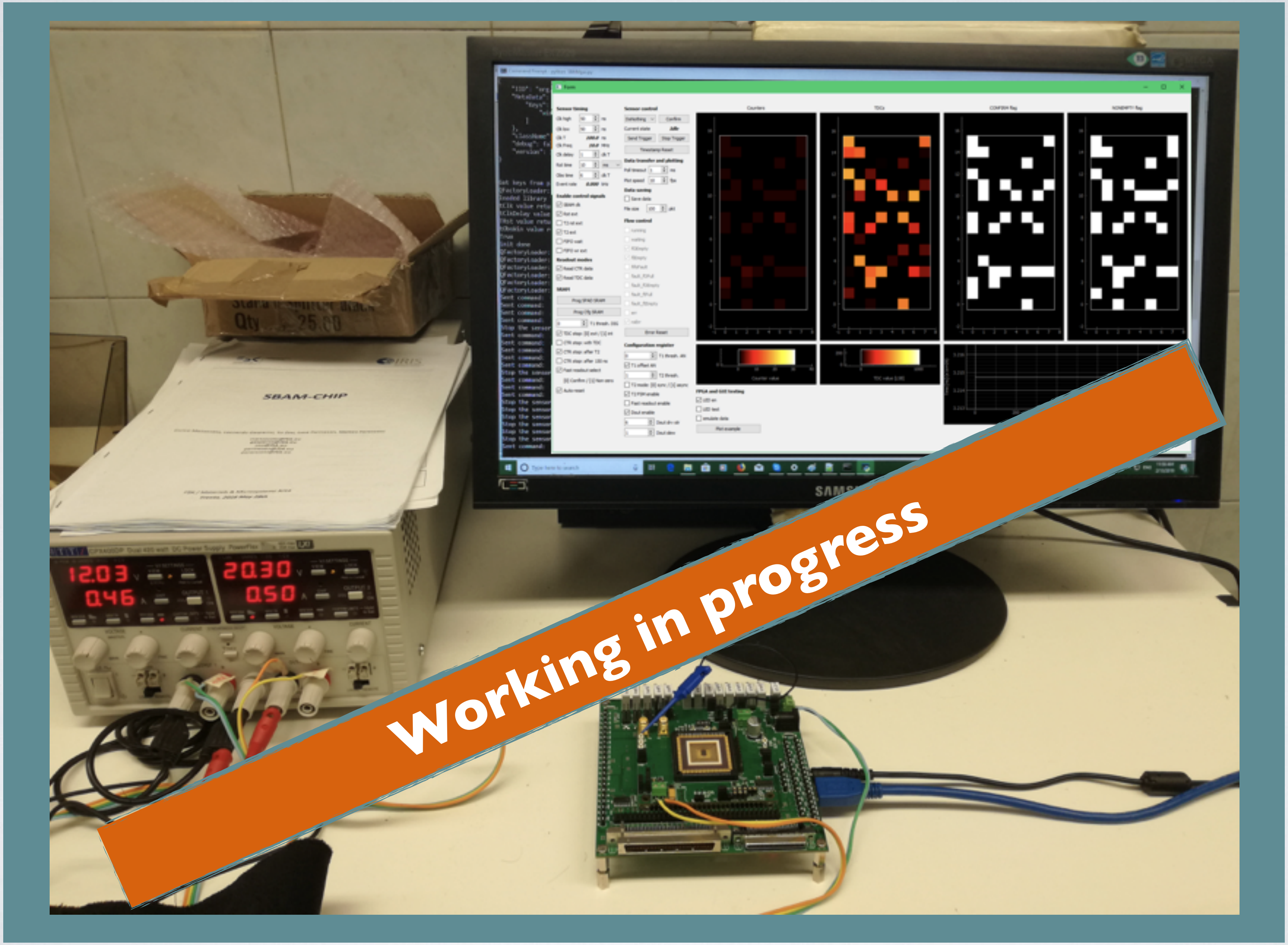
T1 => pixel threshold
T2 => chip threshold

True Positive
False Positive
False Negative



Dark Current 10 kHz, 80% hit SPAD

NEUTRONS SBAM I



CONCLUSION

- Detector and SBAM design have been developed;
- First detector prototype has been tested with protons at energies of interest allowing an optimisation of the crucial readout parameters and trigger strategy of the final SBAM sensor;
- Background and interaction probability studies have been realized with a FLUKA simulation;

NEXT FUTURE:

- The test of the first chip is undergoing;
- Next autumn: first Tile prototype;
- From 2020 Detector Calibration with protons and neutrons;
- From 2021 secondary neutrons measurements.

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http://arpg-serv.ing2.uniroma1.it/arpg-site/mondo

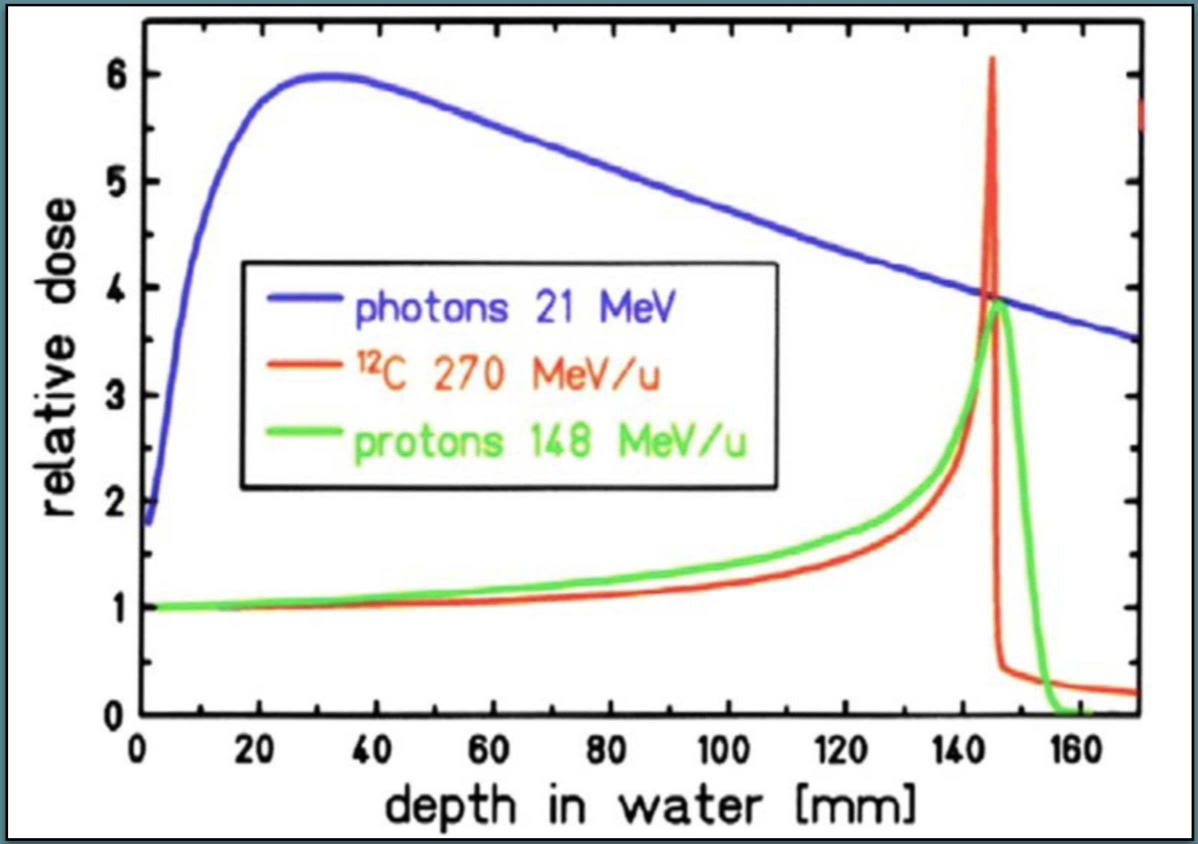
BACK UP SLIDE

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}**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)



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

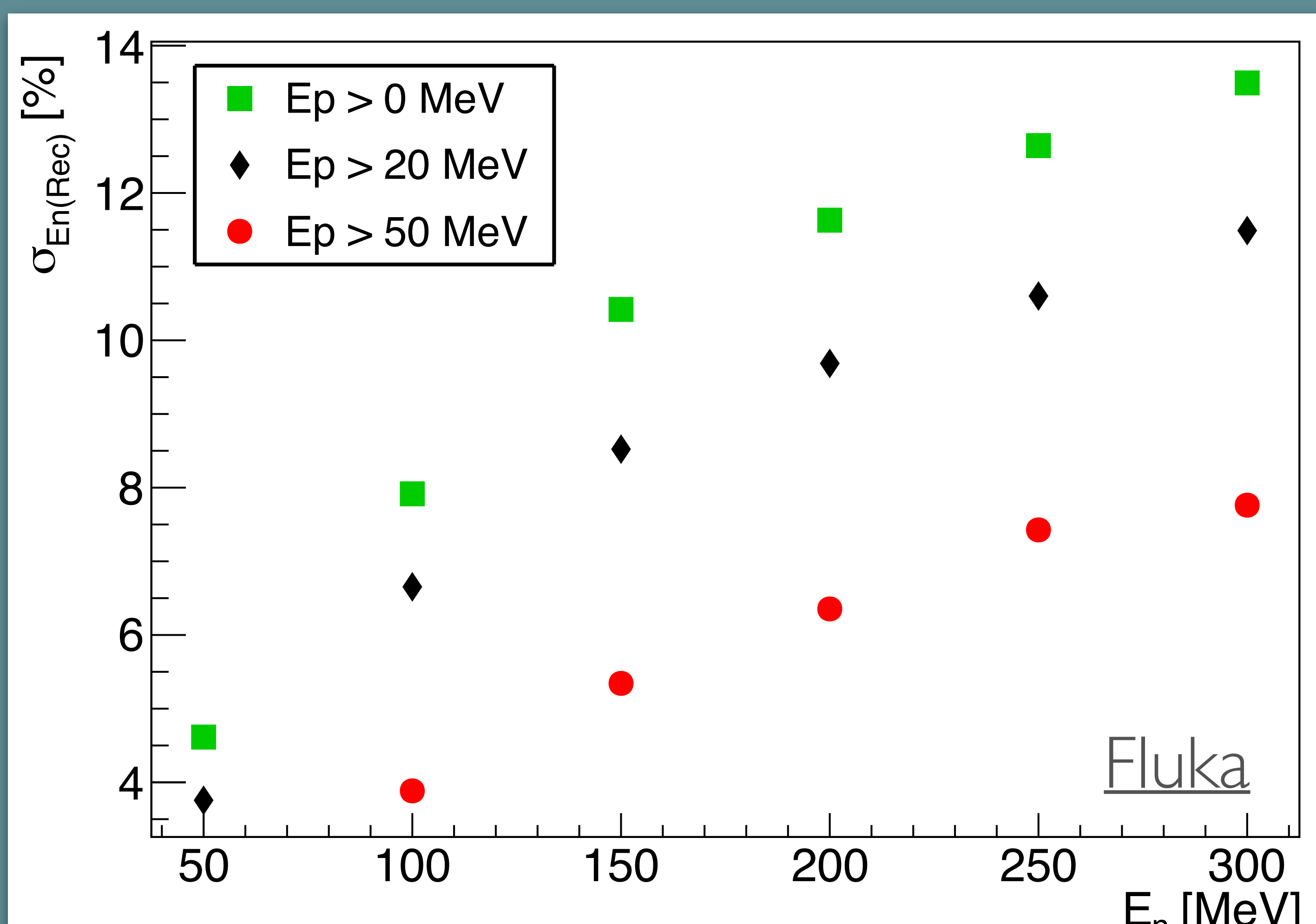
Light ions disadvantages:

- more fragmentation (secondary products);

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

SIMULATION: ENERGY RESOLUTION SES

The kinetic energy of primary neutrons coming from a known direction has been reconstructed from the detection of the secondary proton.
The proton kinetic energy has been calculated using the length of the particle track with NIST range-energy values. The proton angle is computed by means of a linear fit to the proton track.



V. Giacometti et al. **Characterisation of the MONDO detector response to neutrons by means of a FLUKA Monte Carlo simulation.** RM (2018)
doi:10.1016/j.radmeas.2018.10.006

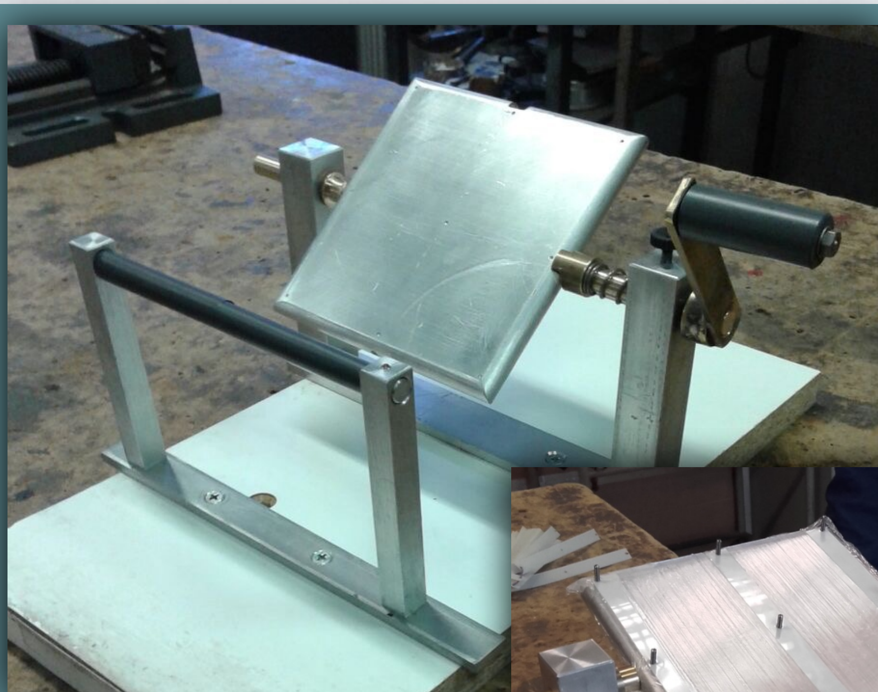
MONDO 10x10x20 cm³

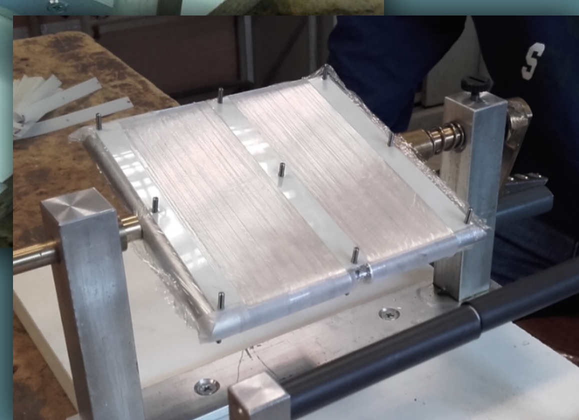
The resolution is reported as a function of the energy applying three different cut on proton energy:

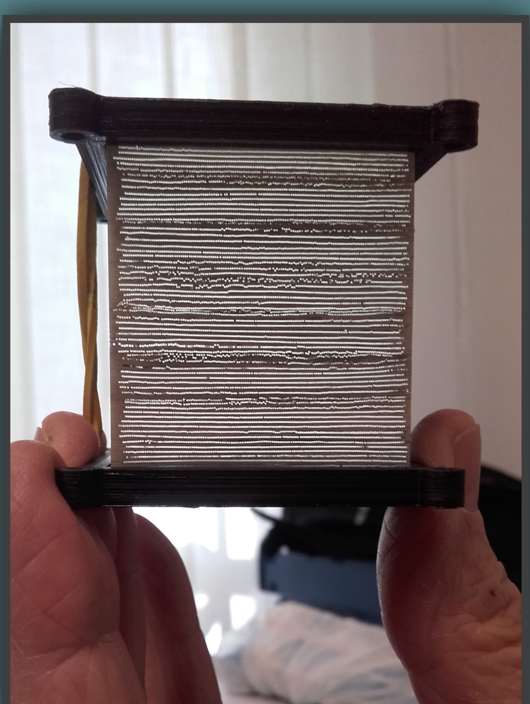
- Secondary protons with $E_k > 50$ MeV;
- Secondary protons with $E_k > 20$ MeV;
- Secondary protons without cuts in E_k

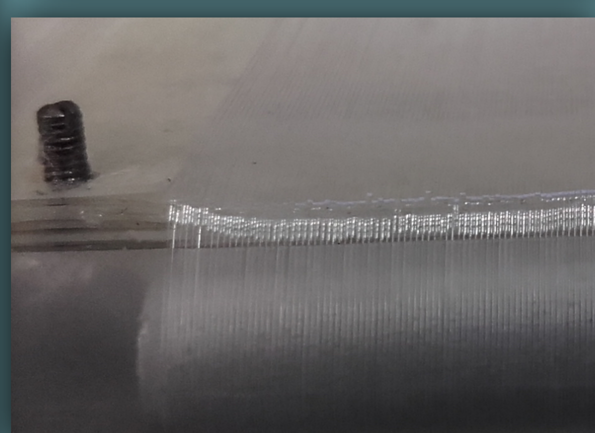
NEUTRONS TRACKER PROTOTYPE

The construction of the fibers matrix is a crucial point in the detector development: mechanics has a direct impact on space resolution and detector dimensions.









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

ARGO: 2x2x1 cm^3

New weaving methods (with a motorized part)