MAECI
MOFFIITS

Istituto Nazionale di Fisica Nucleare
SEZIONE DI TORINO

Ideas for measuring neutron fragmentation cross sections

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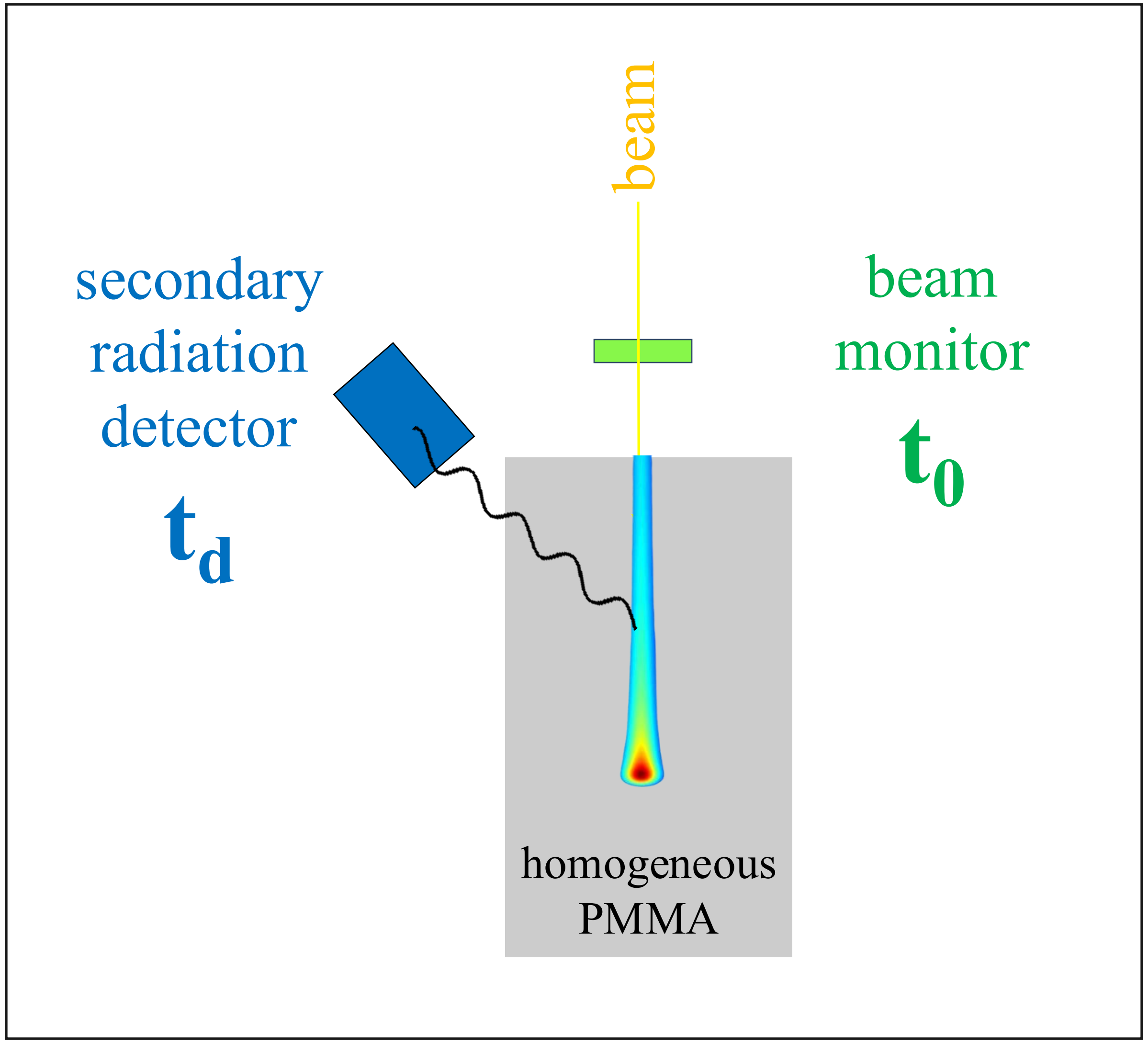
MAECI MOFFIITS Collaboration Meeting – Riccione, 26-28/05/2025

Starting point: Prompt Gamma Timing measurements



Ferrero. et al., Scientific Reports, 8:4100, 2018. DOI:10.1038/s41598-018-22325-6

$$TOF = t_d - t_0$$

The time-of-flight distribution is the difference between the photon arrival time t_d and the primary crossing time t_0

Differences in the particle range due to changes in the target density corresponds to modifications of the TOF distribution shape.

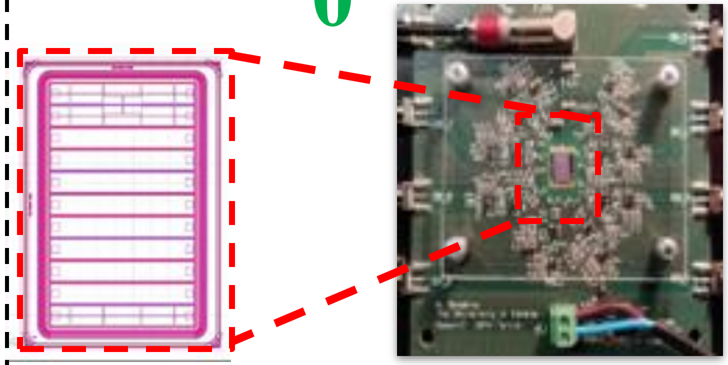
Starting point: Prompt Gamma Timing measurements

Beam Monitor Sensors

DAQ

Prompt Gamma Detectors

$\mathbf{t_0}$



8-strip silicon detector, FBK (total area of 17.6 mm^2)

Signal read-out by DT5742 digitizer (16 channels) by CAEN at a sampling frequency of 2.5 GHz

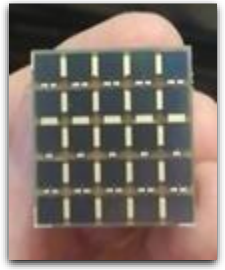
time resolution needed for the PGT

50 ps

< 200 ps

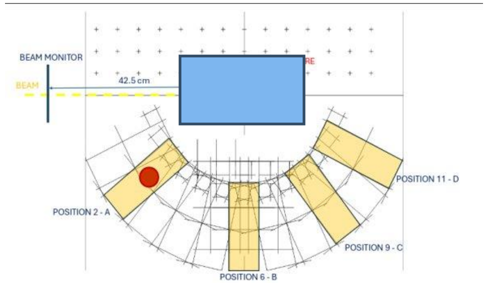
$\mathbf{t_d}$

Crystals (LaBr3:Ce) + SiPM



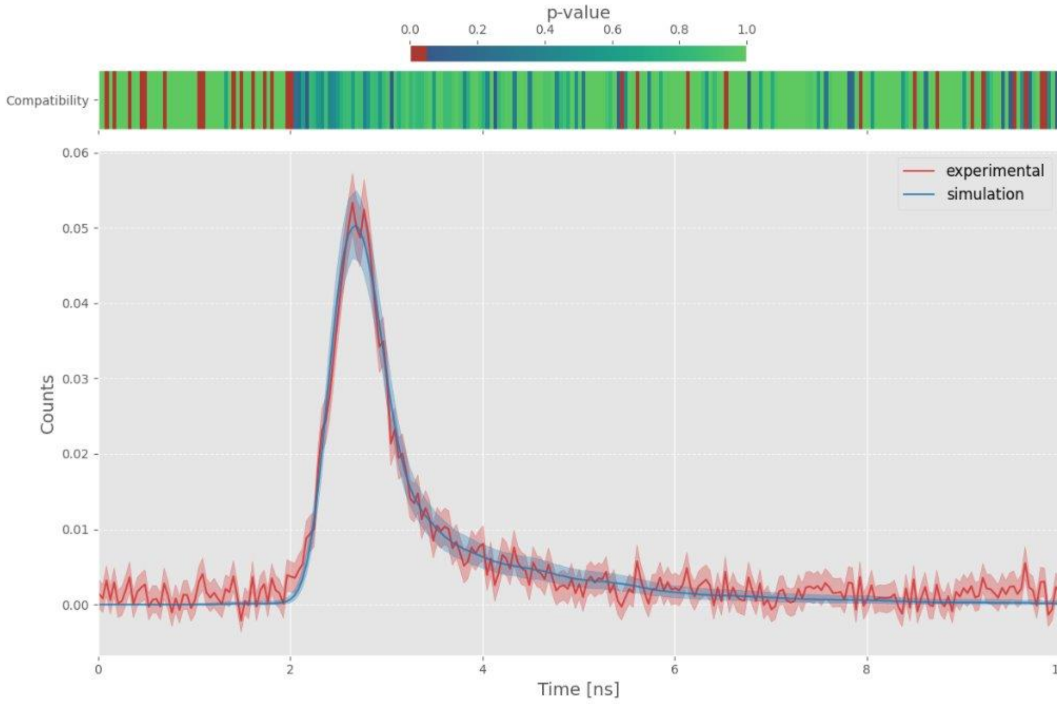
Luxium
diameter = 3.81 cm

Starting point: Prompt Gamma Timing measurements

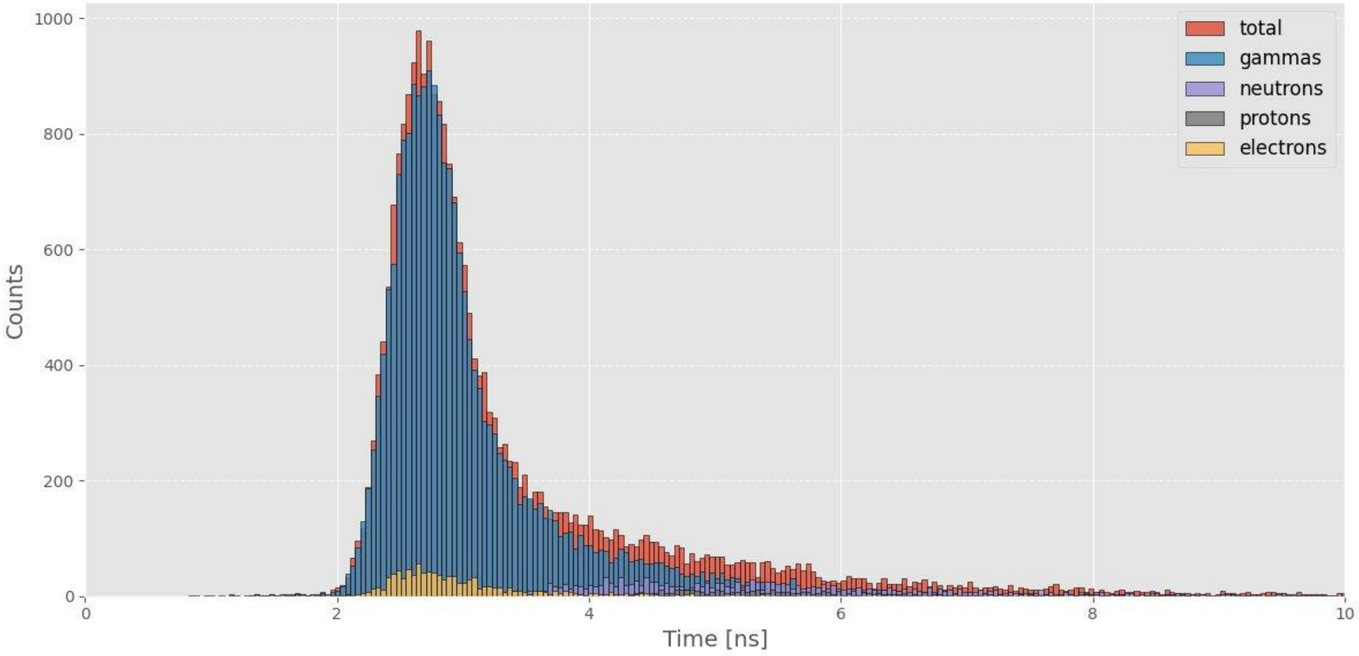


Beam: 166.41 MeV/u Carbon Ion
Target: PMMA (15x15x30 cm3)
Deposited energy : (1, 10) MeV
Sub-clinical rate: average 5e6 pps; instantaneous 2e8 pps

Experimental data VS MC simulation



MC Simulation



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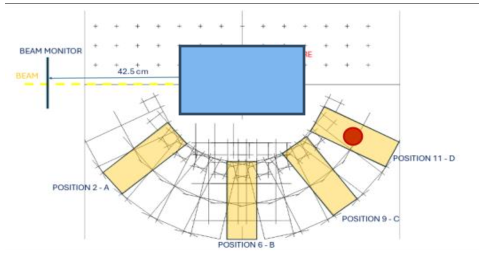

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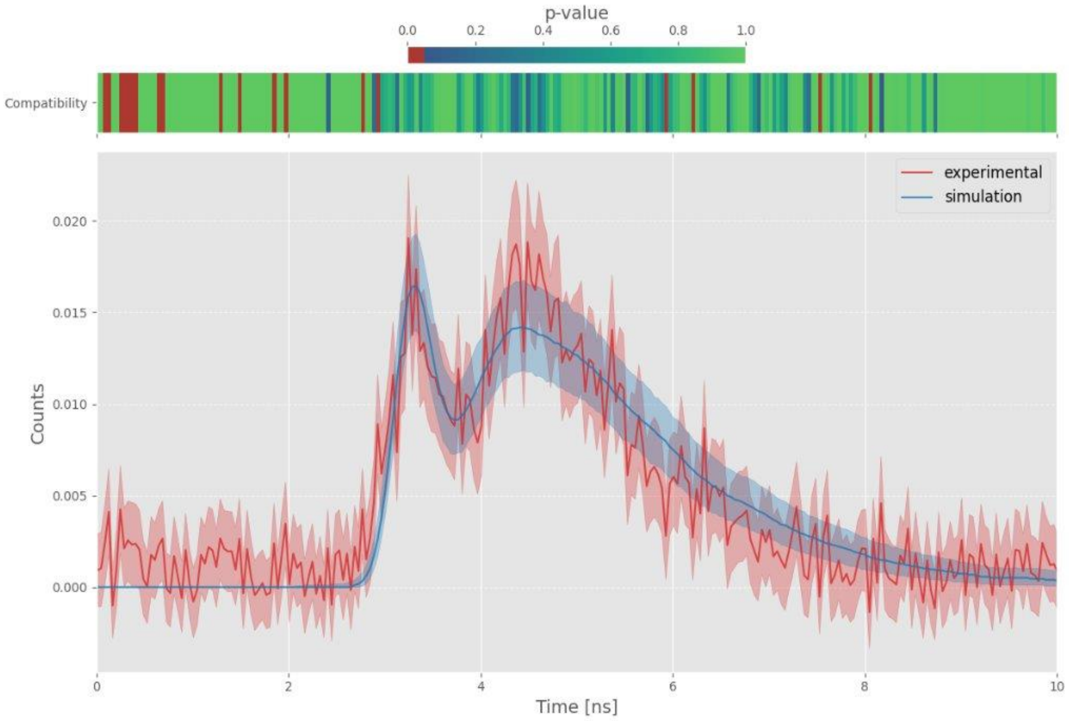
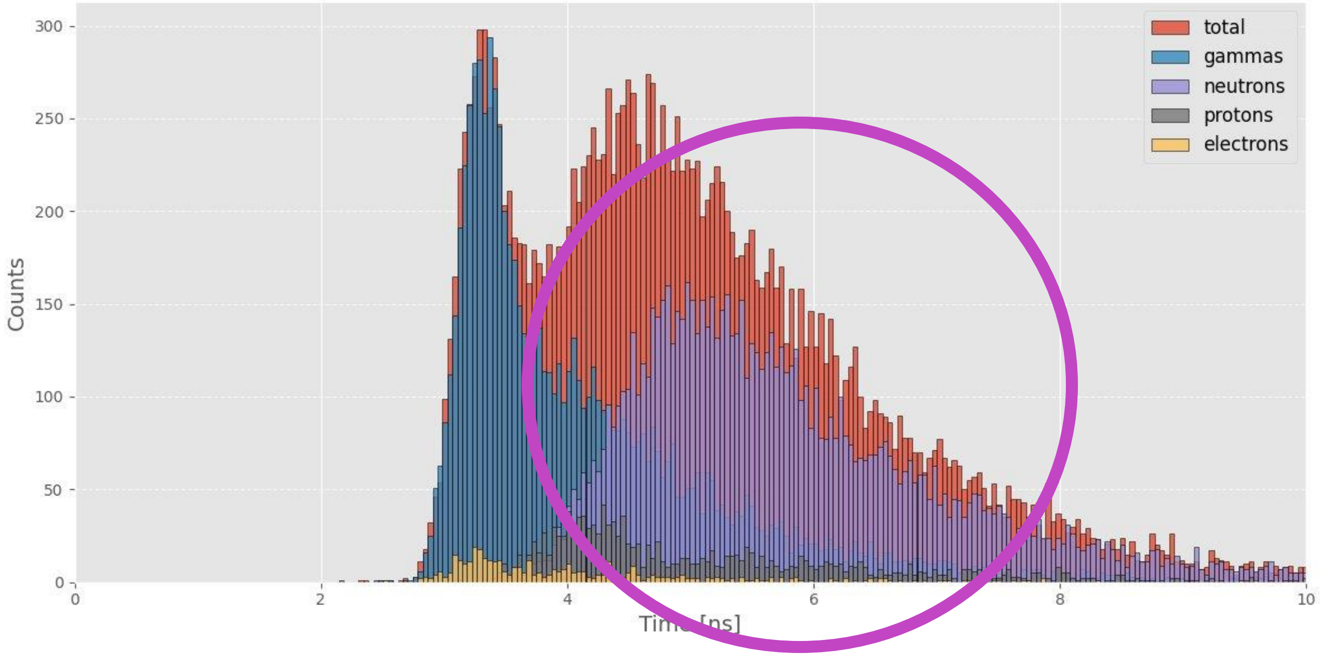


MC Simulation



Neutron related peak is visible in our experimental measurements in agreement with simulation.

Towards neutron measurements: preliminary MC simulation

Beam:
- 398 MeV/n Carbon Ion
- FWHM = 0.449442 cm

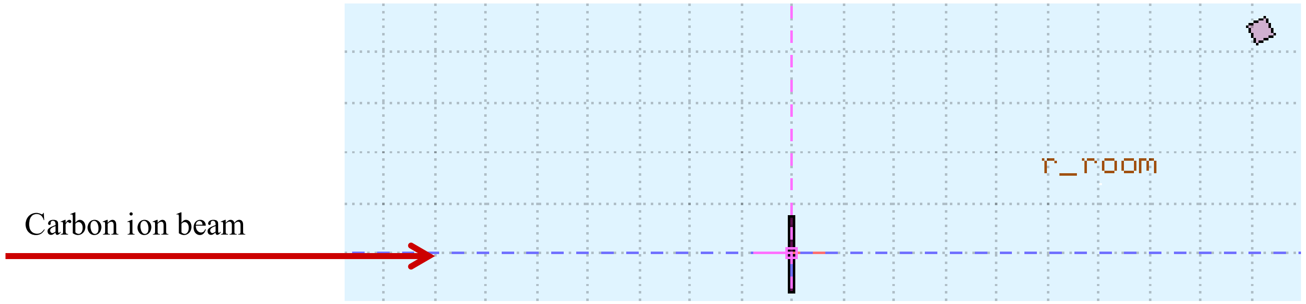
Target:
- PMMA (1 cm slab).

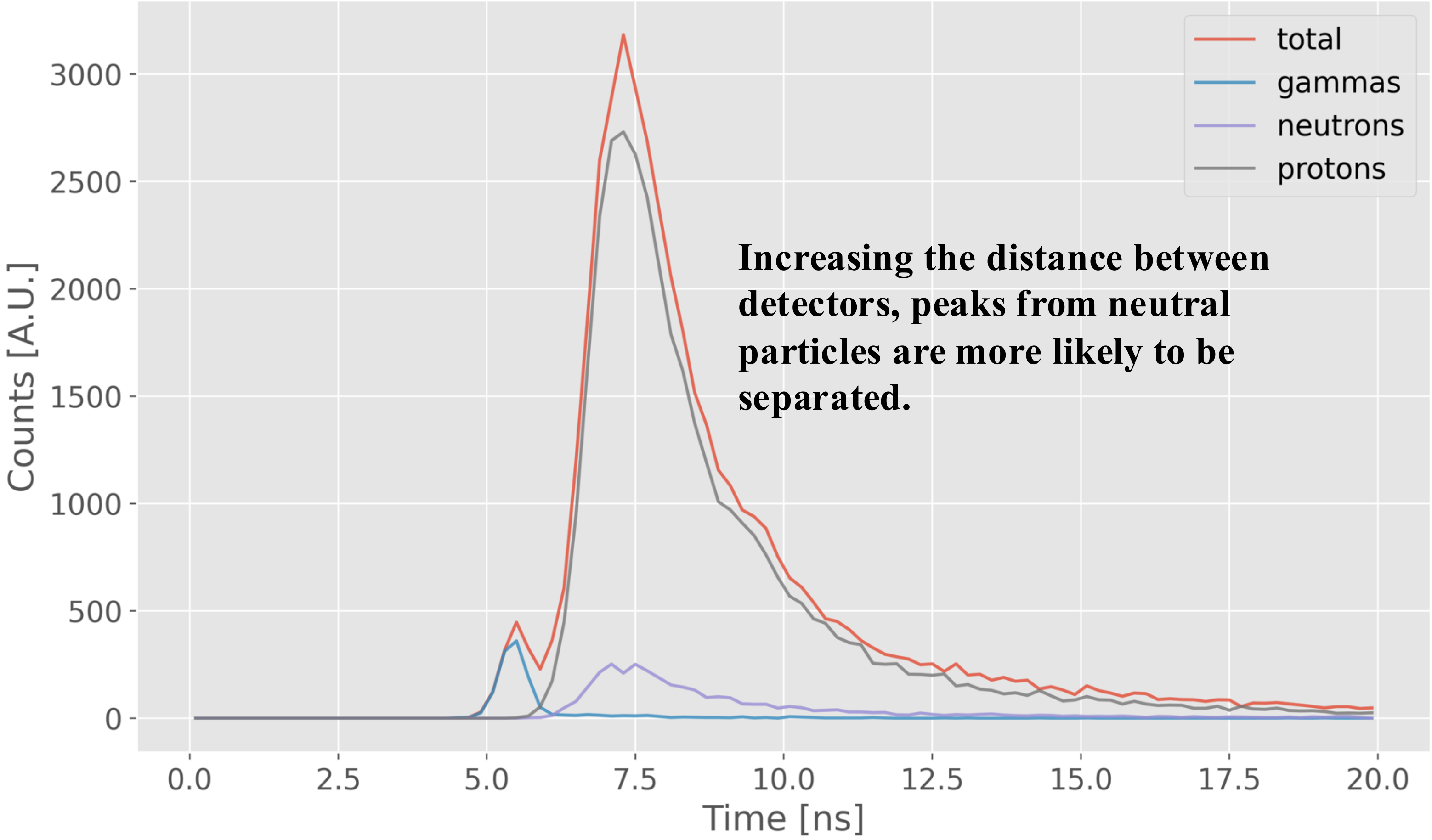
Scintillator:
- LaBr3:Ce (cylindrical shape)
- r = 1.905 cm
- h = 3.81 cm
- **1 m away from target**

Smearing = 200 ps.

Deposited energy: >1 MeV

5E8 primaries





Towards neutron measurements

- Charged particle filtering
- Combinatorial background rejection
- Neutron time distribution from TOF distributions
- Neutron kinetic energies from neutron time distributions
- Number of incoming neutrons in the secondary detector

Very (very) preliminary test @ CNAO

Experimental setup for the beam test carried out at CNAO in April 2025

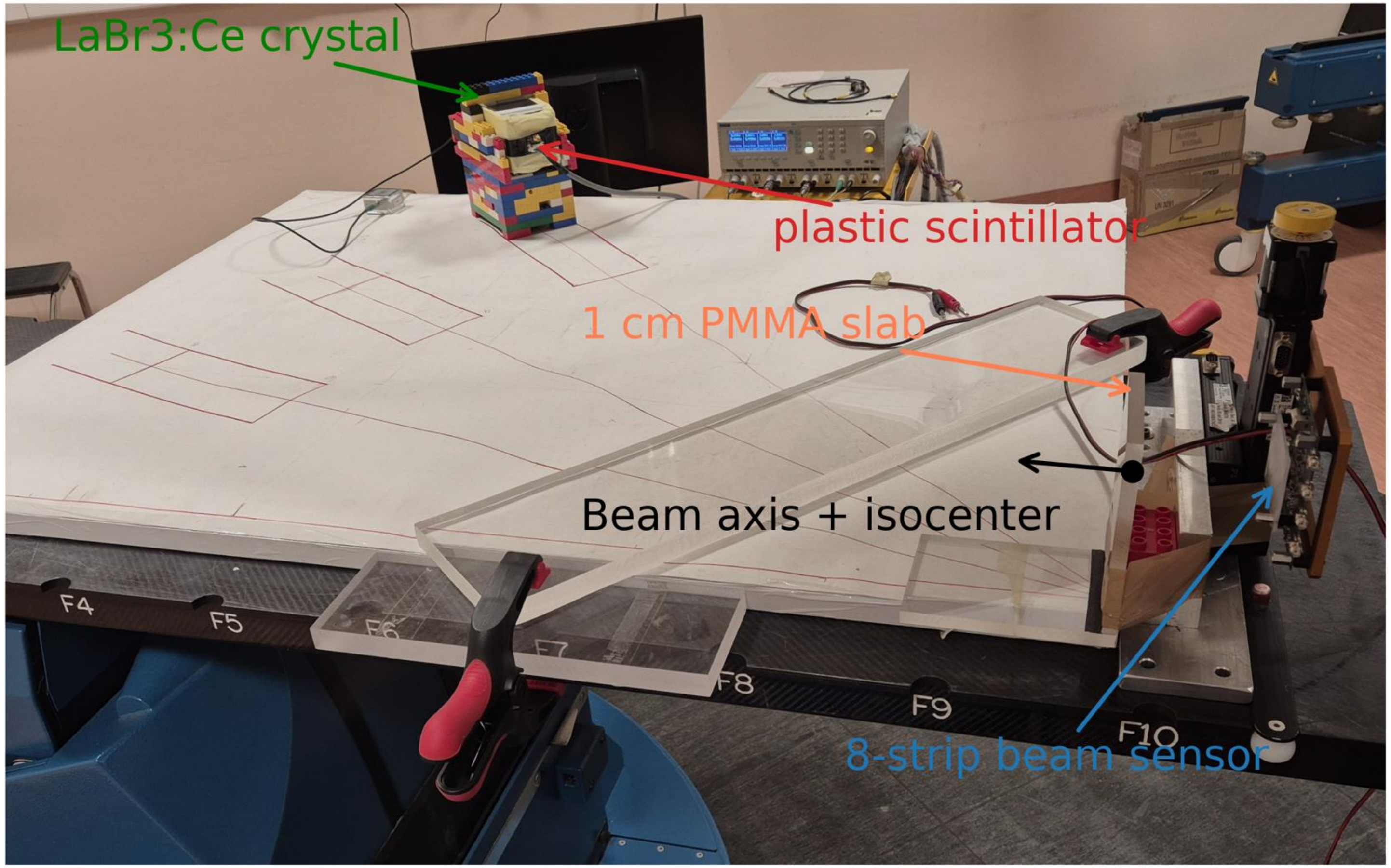
- **398.84 MeV/u carbon ion beam, clinical intensity,** irradiate **PMMA target** (1.00 cm thickness).

- Carbon ion signals monitored with using an **8-strip silicon sensor.**

- **Lanthanum Bromide (LaBr3:Ce)** crystal with 5x5 SiPM array.

- **Plastic scintillator** in front of LaBr3:Ce crystal with 5x5 SiPM array.

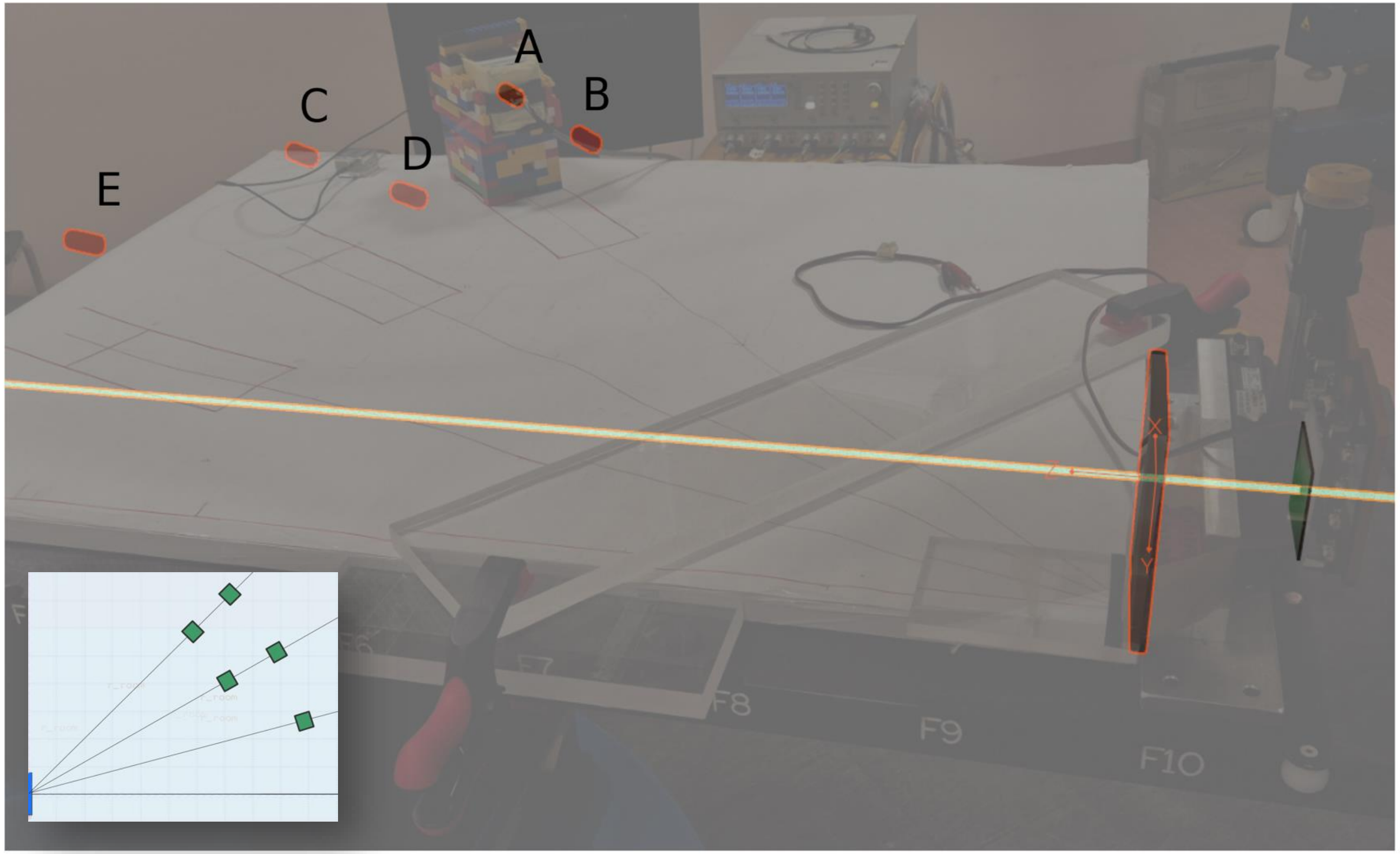
- CAEN DT5742 digitizer operating at 2.5 GHz



Very (very) preliminary test @ CNAO

Data acquisition was carried out at five detector position (15 minutes each):

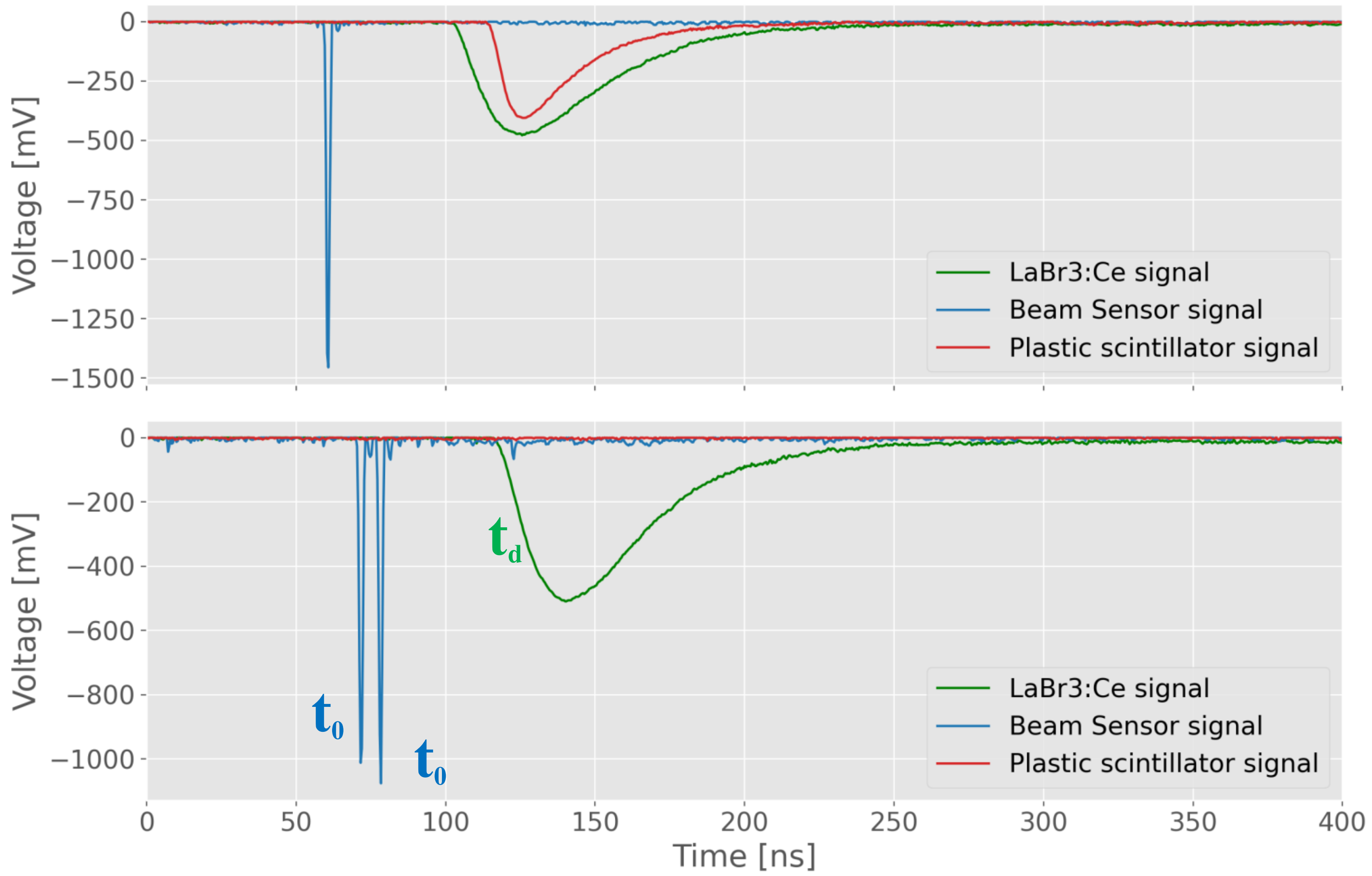
- **A** (distance: 100 cm, polar angle: 45°)
- **B** (distance: 80 cm, polar angle: 45°)
- **C** (distance: 100 cm, polar angle: 30°)
- **D** (distance: 80 cm, polar angle: 30°)
- **E** (distance: 100 cm, polar angle: 15°)



FLUKA version 2024.1 was used for the simulations. Only the LaBr3:Ce crystals were modeled

Charged particles filtering

Charged particle filtering at the waveform level using the LaBr3:Ce and the plastic scintillator signals.



Charged Particle Event:
Signals recorded by the plastic scintillator allow us to identify charged secondaries at the early post processing stage .

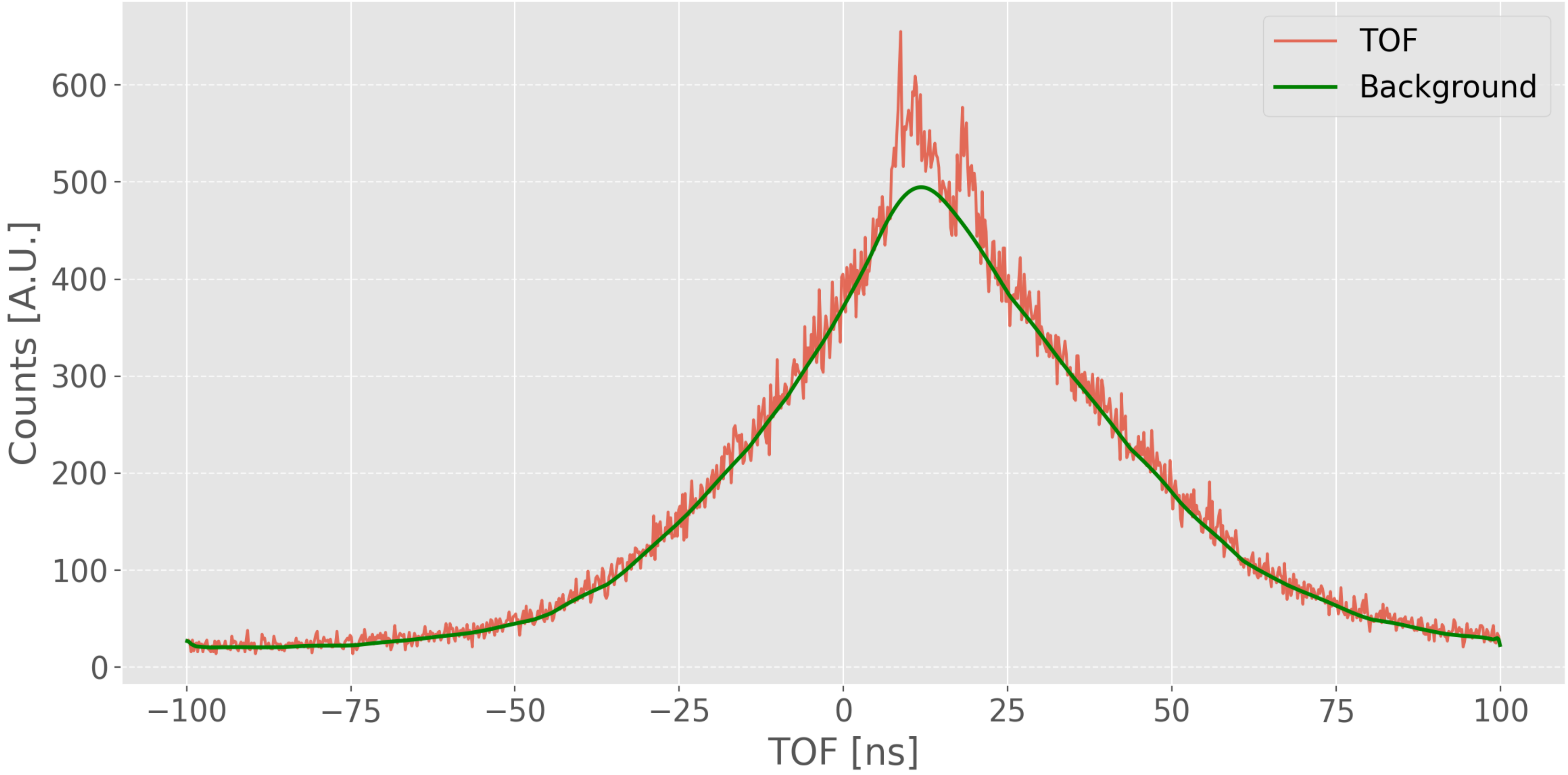
Neutral Particle Event: No charged from the plastic scintillator indicates the detection of a neutral particle.

$$TOF = t_d - t_0$$

Carbon ion timing: Gaussian fit. Secondary particle timing: Linear fit on rising edge.

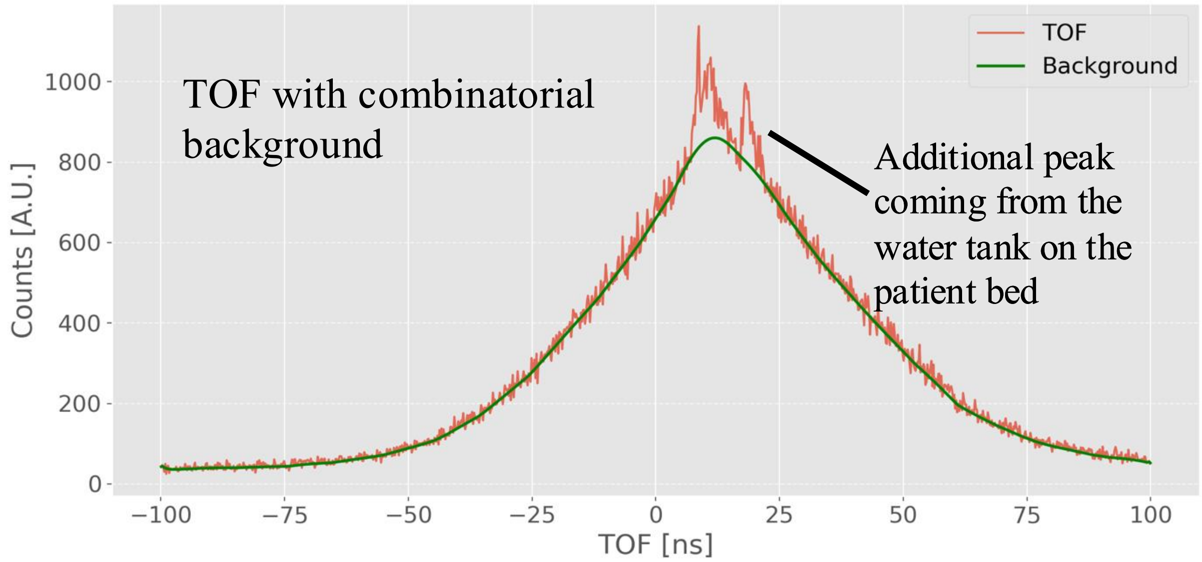
Combinatorial background rejection

TOF distributions composed by real and fake coincidences. Fake coincidences contribute to a large **combinatorial background** estimated by the SNIP algorithm (Ryan et al. 1988).



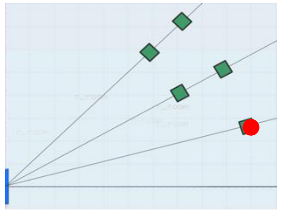
Ryan et al., Nucl. Instr. Meth. Phys. Res. Sec. B., 34(3), 1988, doi: 10.1016/0168-583X(88)90063-8

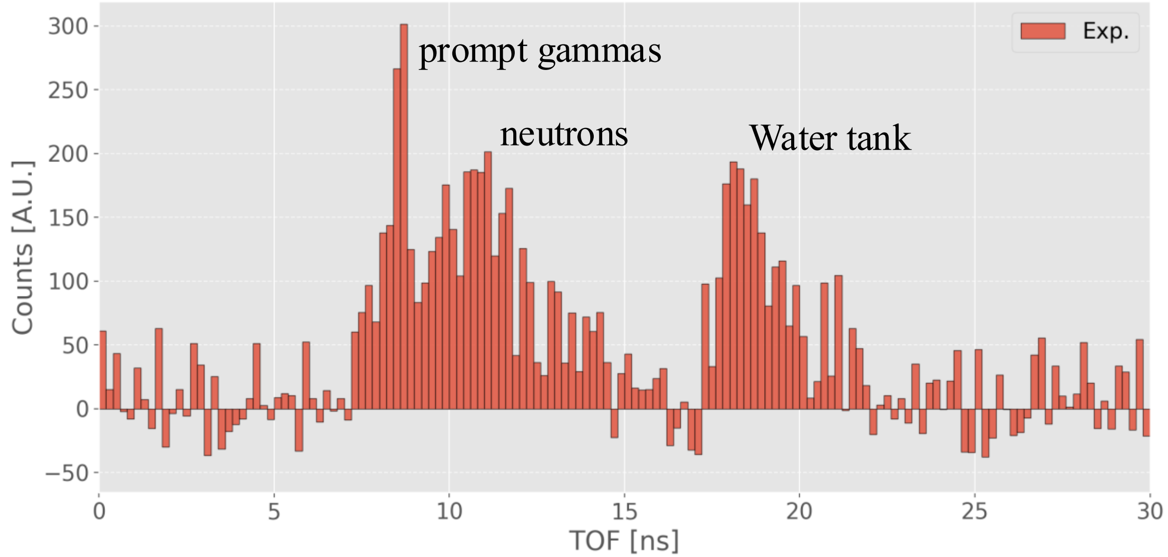
Gammas + Neutrons TOF distributions

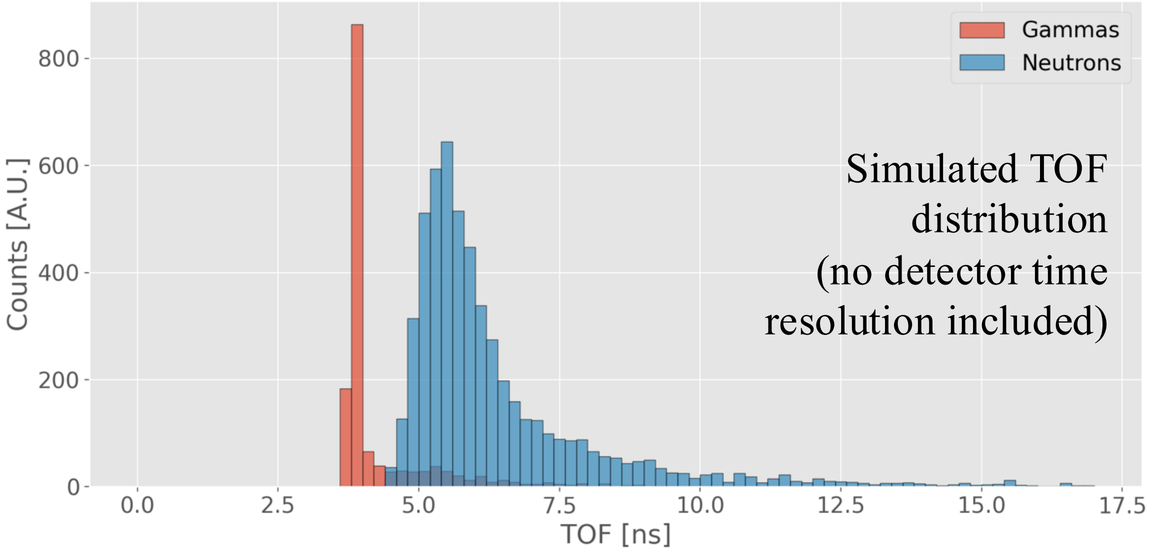


Low statistics but promising results at clinical rate.

Gammas + neutrons TOF distribution
for detector position E (100 cm, 15 degrees)



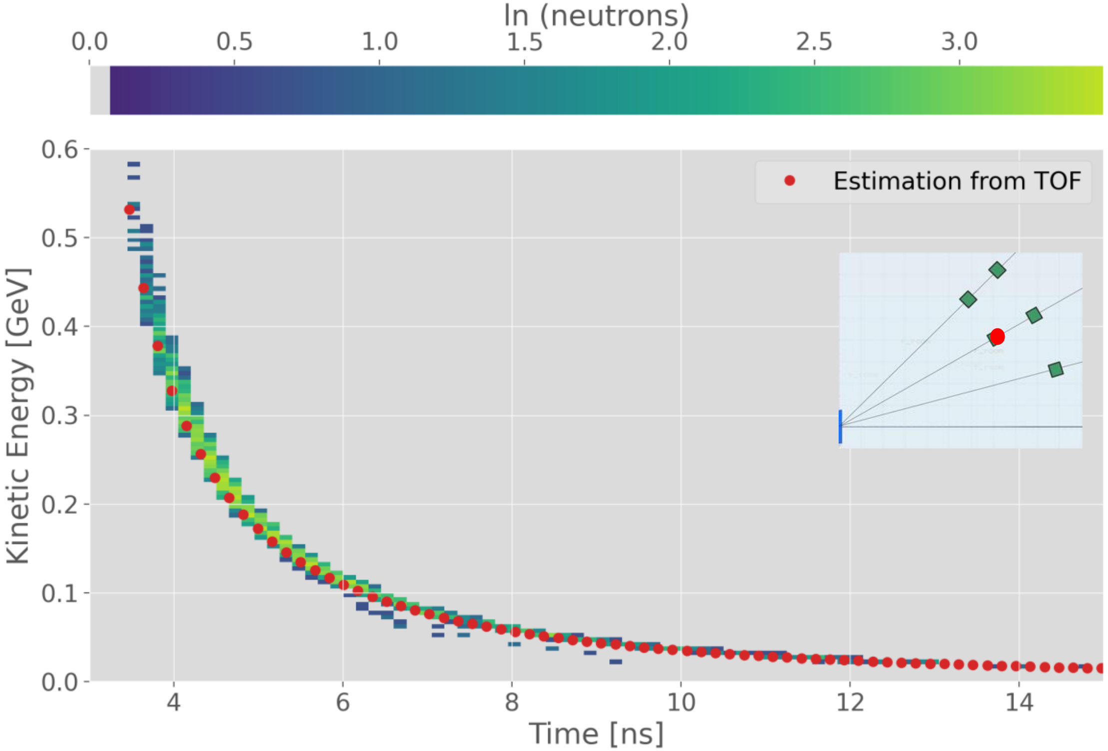


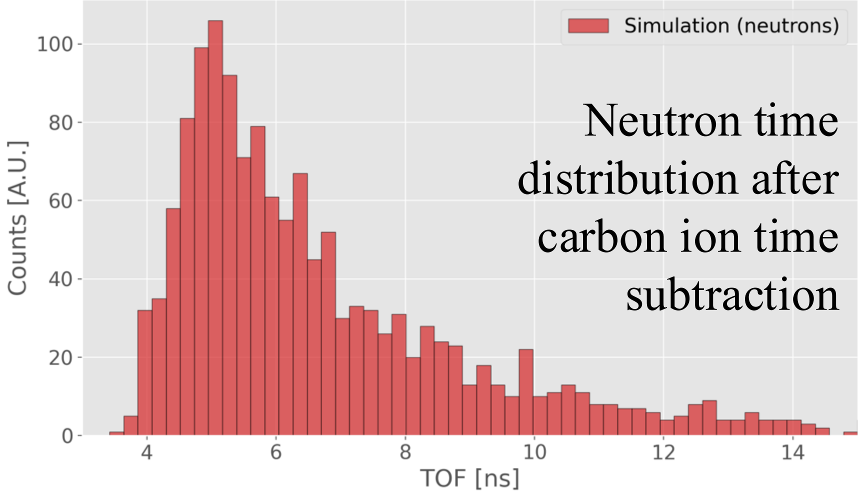


Neutron kinetic energy

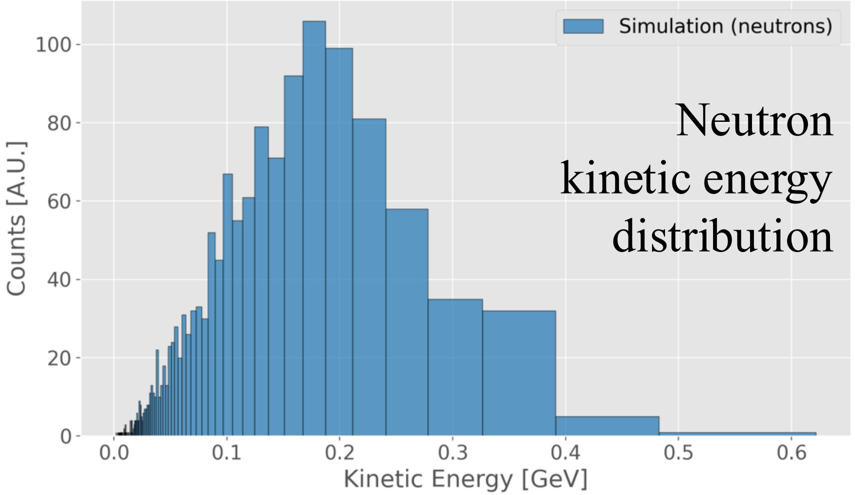
The neutron kinetic energies are estimated using the relativistic formula:

$$K = mc^2\left(\frac{1}{\sqrt{1-v^2/c^2}} - 1\right)$$





Neutron time distribution after carbon ion time subtraction



Neutron kinetic energy distribution

Neutron Cross section measurements

- Combinatorial background subtraction
- Neutron identification
- Neutron kinetic energy
- Number of primaries
- Number of neutrons incoming on secondary detectors
- DAQ time for a full angular scan
- Designing the optimal setup

Number of primaries & neutrons/primary

Beam Intensity: 3.0E+07 pps

Acquisition Rate: 1.5 - 2 kHz during spill, 0.5 kHz averaged

Delivered Particles (150 spills / detector position): 4.5E+09

Detector position (distance, angle)	Detected signals (counts)	Detected neutral signals (counts)	Detected Neutrons (After bkg subtraction) (counts)
100 cm, 45 deg	181571	93873	682
80 cm, 45 deg	226051	98660	902
100 cm, 30 deg	295536	116453	956
80 cm, 30 deg	365717	116708	1078
100 cm, 15 deg	352408	86891	1449

Number of incoming neutrons in the secondary detector

Different detector depths were investigated:

- 3.81 cm

- 7.62 cm (2x),

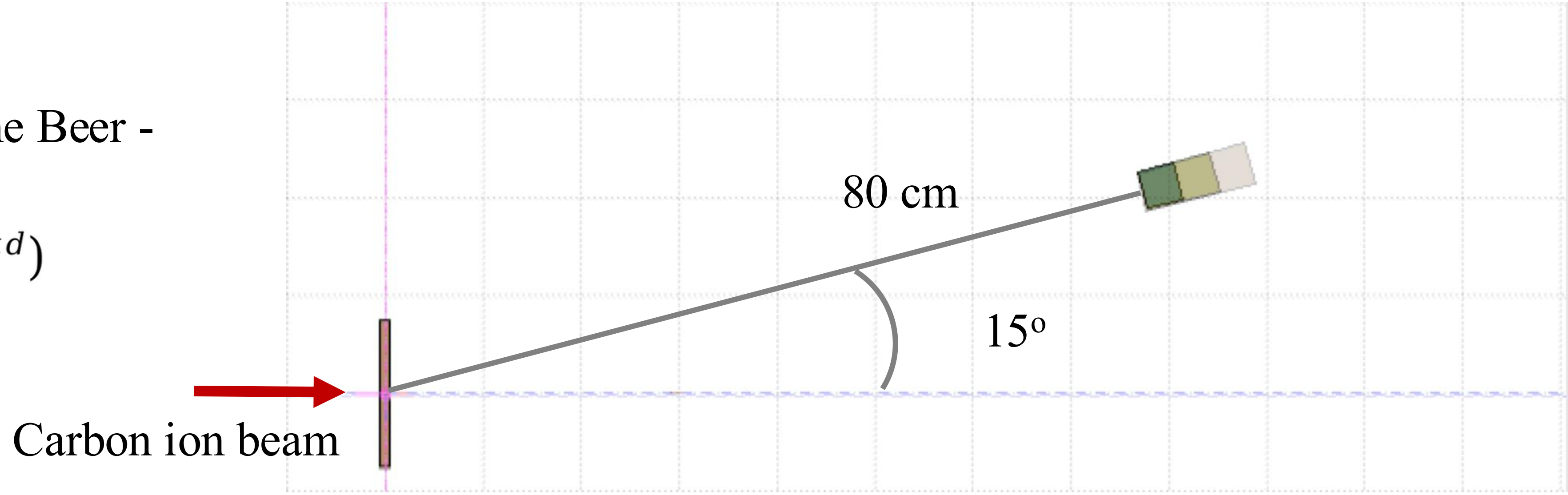
- 11.43 cm (3x)

Curve fitting following the Beer - Lambert law:

$$N(d) = N_0(1 - e^{-\alpha d})$$

MC Setup:

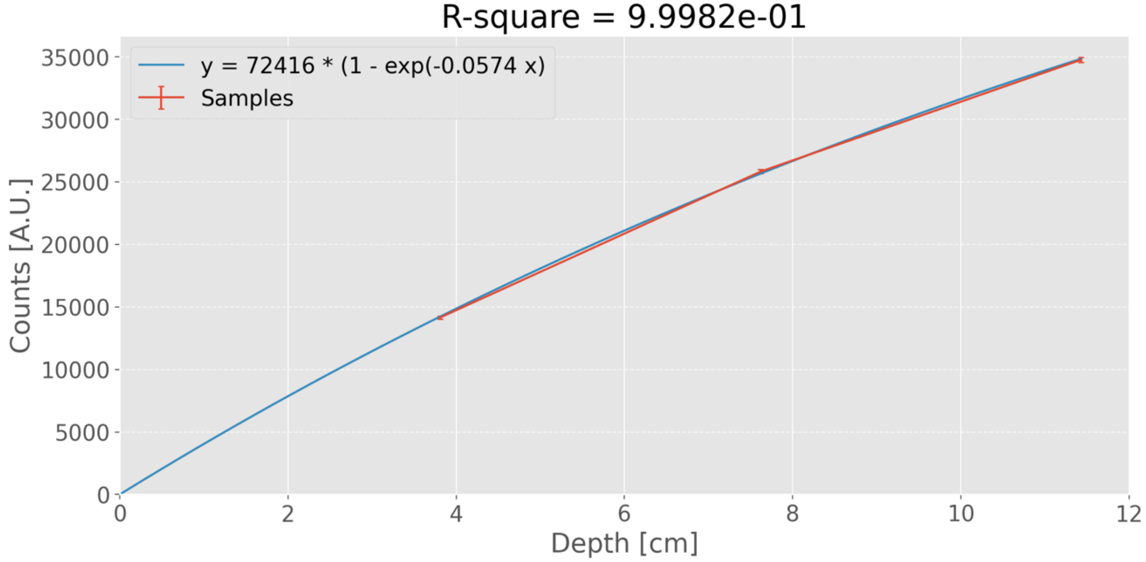
- Carbon ion pencil beam (398.84 MeV/u)
- Cone shape detector (equal solid angle along depth)
- Vacuum surroundings



Estimation of incoming neutrons in the secondary detector

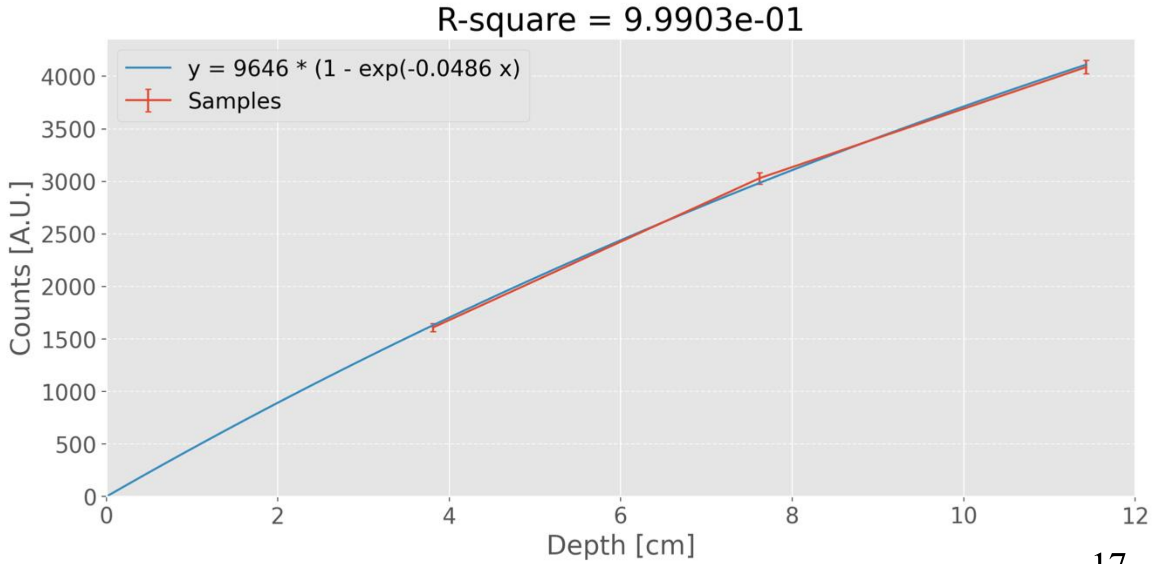
MC (neutron kinetic energy > 100 MeV)

Detector Depth (cm)	No interaction (counts)	Absorption (counts)	Scattering (counts)
3.81	60648	2556	11596
7.62	48978	4983	20839
11.43	40035	6754	28011
Incoming neutrons (MC truth)	**74801**	**Estimation of incoming neutrons**	**72416 ± 3676**



MC (490 MeV < neutron kinetic energy < 510 MeV)

Detector Depth (cm)	No interaction (counts)	Absorption (counts)	Scattering (counts)
3.81	7818	299	1309
7.62	6397	566	2464
11.43	5339	780	3308
Incoming neutrons (MC truth)	**9428**	**Estimation of incoming neutrons**	**9646 ± 1401**



DAQ time for a full angular scan*

Position E (d = 1m)
Duration: 6E+02 s (10 mins)
Neutrons: 1.4E+03 = 2.3 n/s
Triggers: 4.4E+05
Delivered Particles: 4.5E+09

n/shift: 6.6 E+04 -> if 5 detectors: 3.3 E+05 n/shift
if 25 Energy bins (20 MeV bins up to 1 GeV): 1.3E+04 n/energy bin
if 5 angles: ~ 2600 n/E_bin/angle

if 18 angular bins (5 degrees / bin): **about 4* shifts/beam energy**

***delivery not optimised, a factor ~ 2 could be gained**
1 cm PMMA target
events at different angles can be summed for absorption coefficient evaluation

Designing the optimal setup

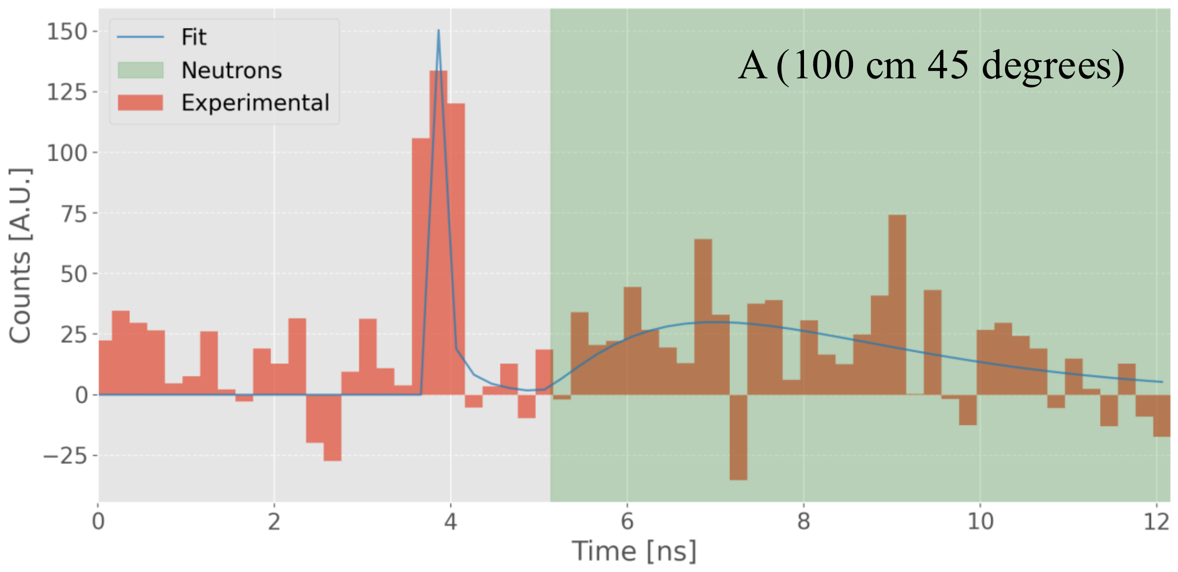
- What crystals? How many? How many depths? What distance from the target?
- What primary detector? Are silicon strips the best? Plastic scintillator?
- What mechanical structure to minimise physics background?
- Targets: C, Polyethylene, PMMA
- Energies
  - Up to 400 MeV C at CNAO (+ O, sometime in the future)
  - GSI for higher energies?

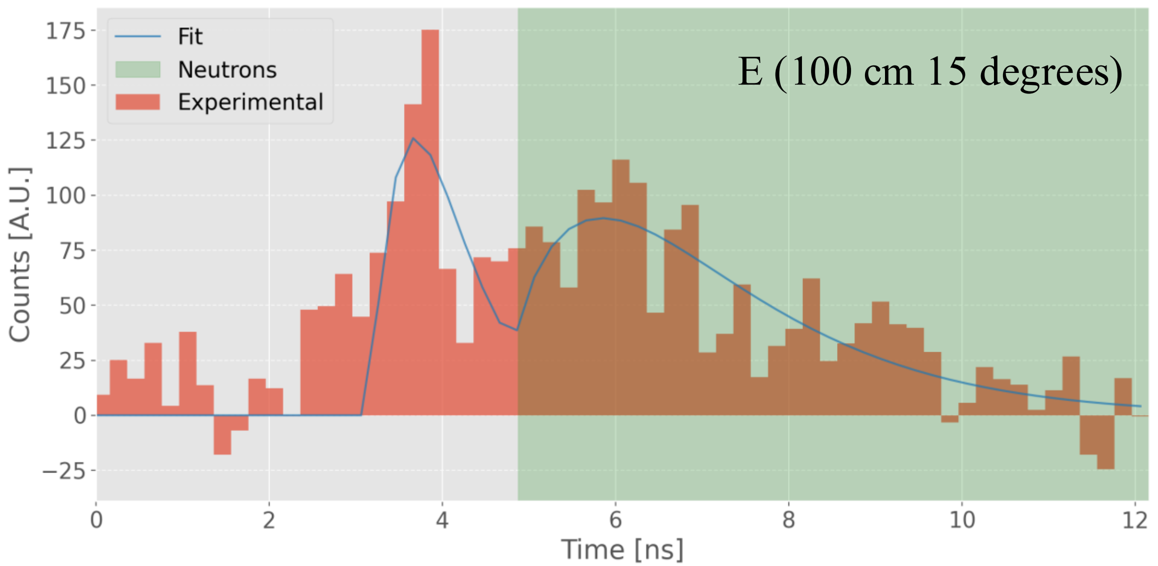
Backup Slides

Backup: Experimental TOF distribution to neutron time distribution

Neutron estimation from experimental TOF distributions at different detector positions.

Detector Position	Gammas + Neutrons)	Estimation (N2)
A	1422	682 ± 261
B	1793	902 ± 262
C	2127	956 ± 248
D	2772	1078 ± 371
E	2837	1449 ± 252



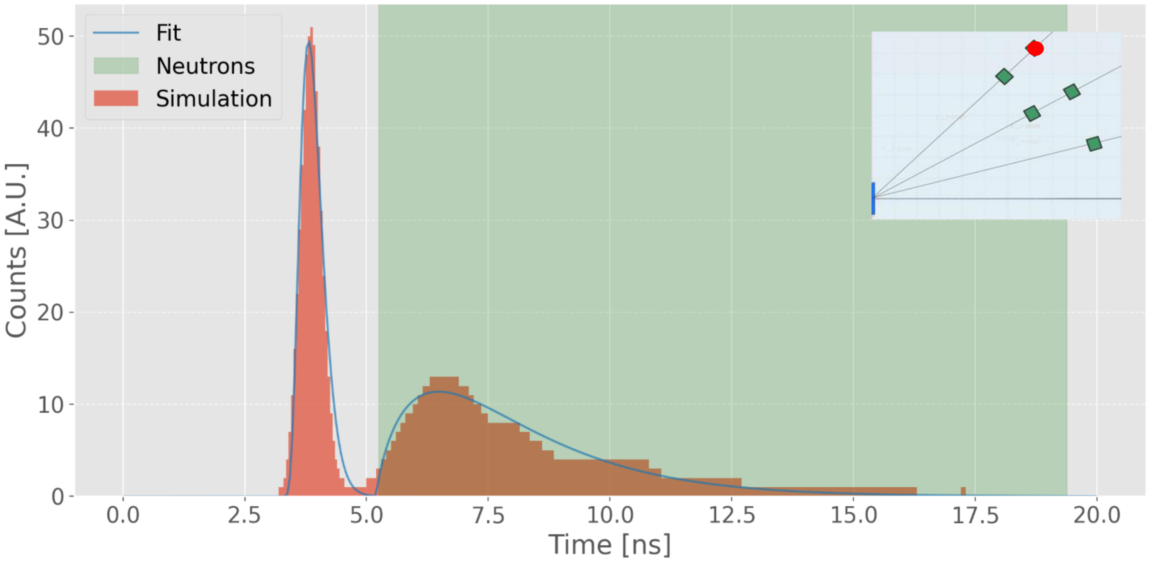


TOF distribution to neutron time distribution

Linear combination of two Γ distributions:

$$f(t; N_1, \alpha_1, \beta_1, N_2, \alpha_2, \beta_2) = N_1 \frac{t^{\alpha_1 - 1} e^{-t/\beta_1}}{\Gamma(\alpha_1)\beta_1^{\alpha_1}} + N_2 \frac{t^{\alpha_2 - 1} e^{-t/\beta_2}}{\Gamma(\alpha_2)\beta_2^{\alpha_2}}$$

α1, **β1 [0, 1]** and α2, **β2 (1, ∞)**: Shape parameters. N1 and **N2**: Weighting coefficients that can be interpreted as the contribution of gamma rays and neutrons to the overall TOF distribution.

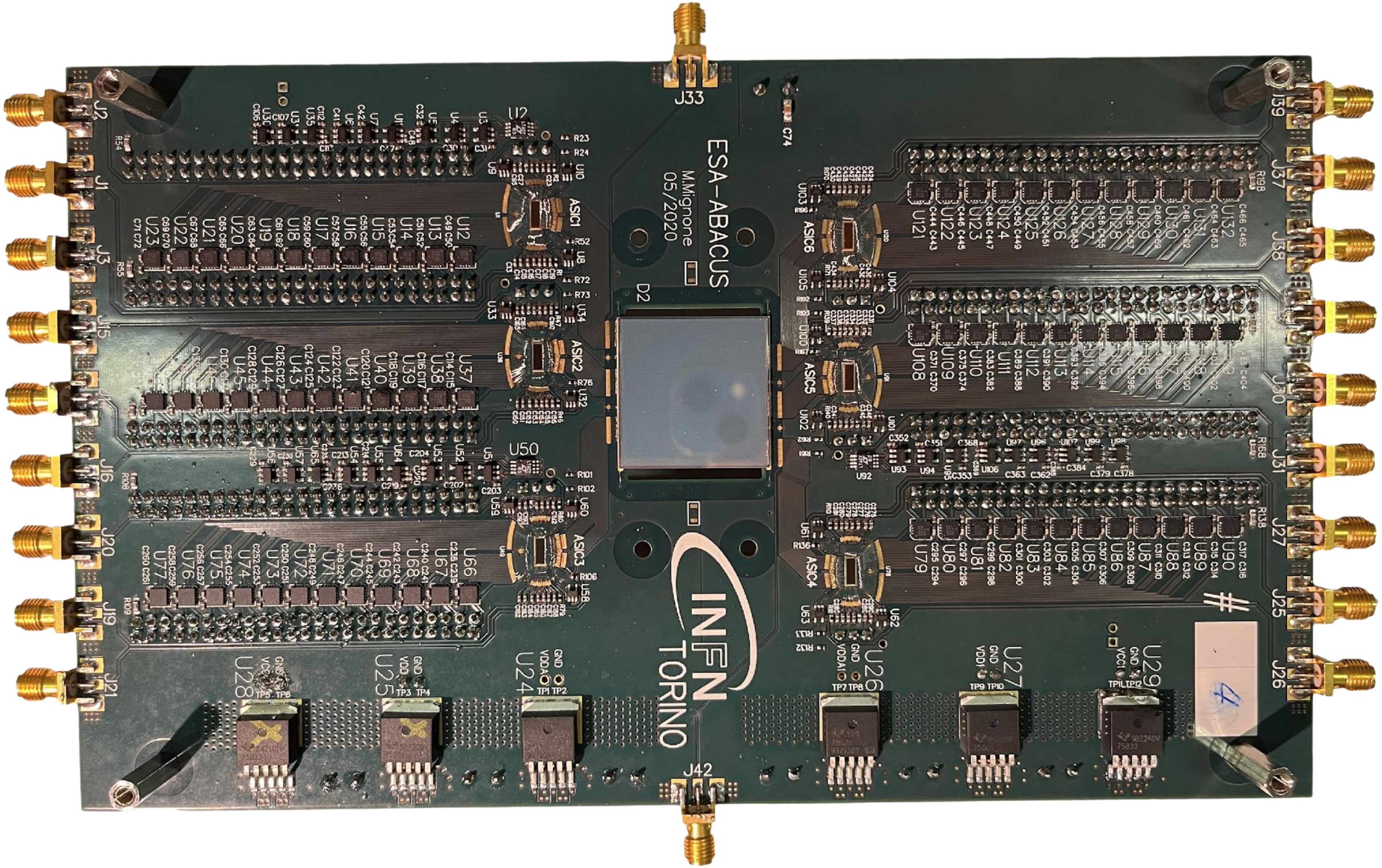


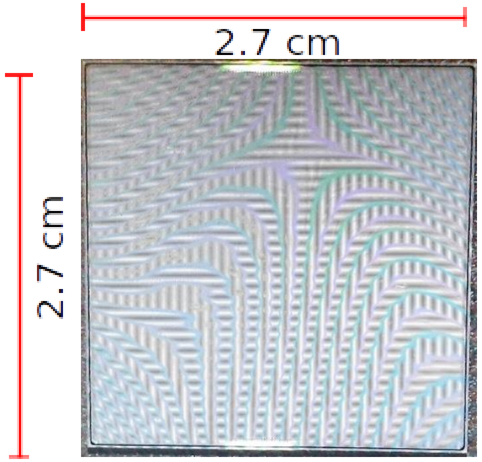
Double gamma fitting applied to the simulated TOF distribution (gammas + neutrons) at detector position A (100 cm 45 degrees).

Neutron estimation from simulated TOF distributions at different detector positions.

Detector Position (distance, angle)	Gammas + Neutrons (MC truth)	Neutrons (MC truth)	Neutron Estimation (N2 parameter)
100 cm 45 deg	1528	906	901 ± 15
80 cm 45 deg	2320	1372	1343 ± 19
100 cm 30 deg	2837	1940	1852 ± 17
80 cm 30 deg	4296	2941	2756 ± 31
100 cm 15 deg	6940	5474	5035 ± 38

Backup: silicon strip sensor



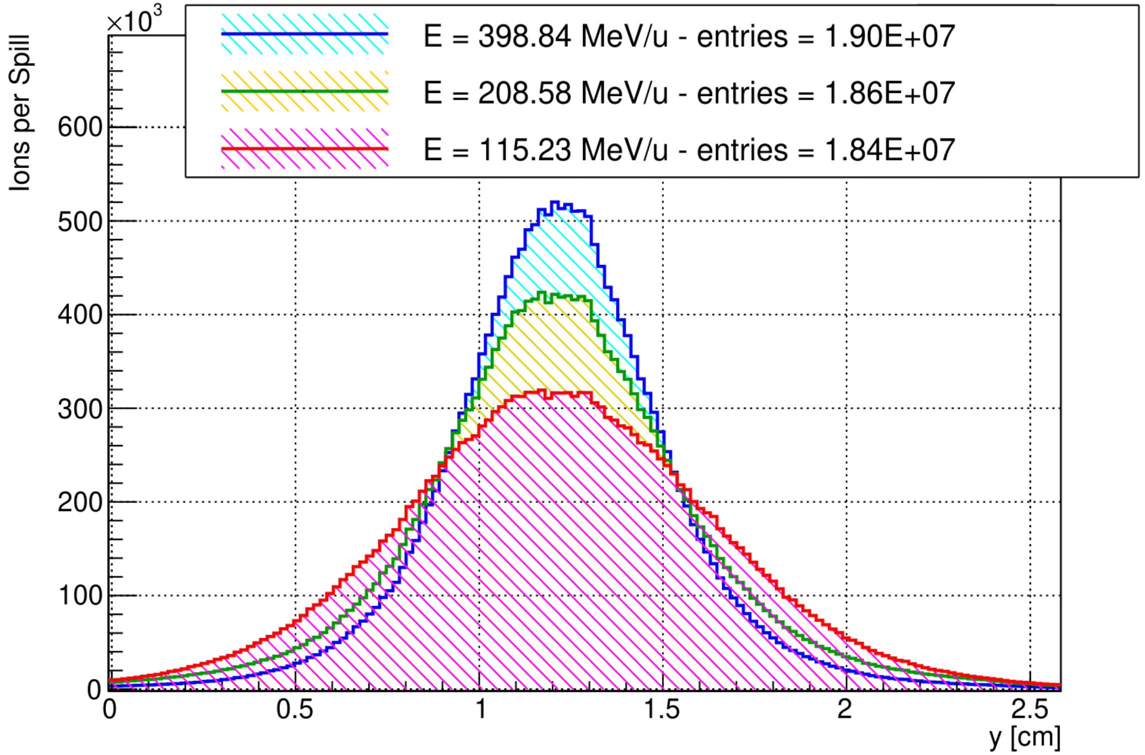


Strips with:
Width → 114 μm
Length → 26214 μm
Pitch → 180 μm
Active thickness → ~50 μm
Capacitance → ~7 pF

Courtesy of Emanuele Maria Data

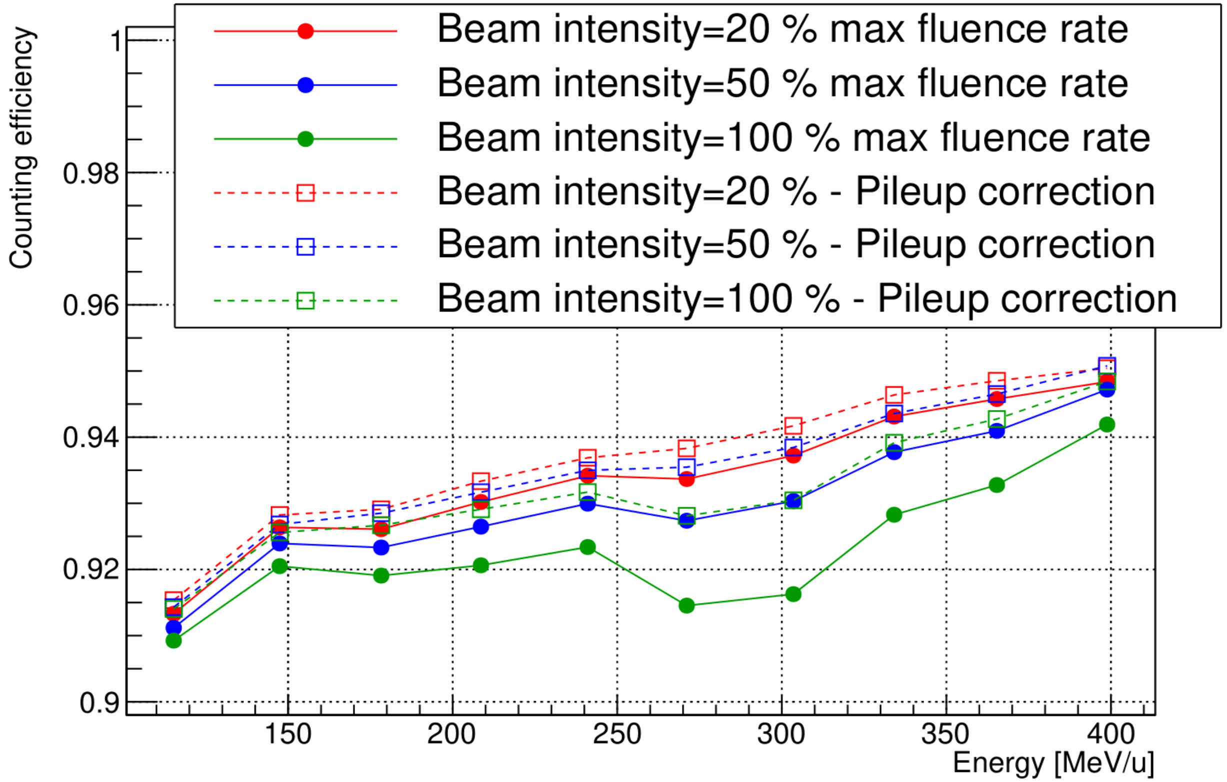
Backup: silicon strip sensor

Beam projection along the axis perpendicular to the strips



- **FWHM in agreement with values measured with gafchromic films**

Counting efficiency vs energy



Pile up correction: (10.1016/j.nima.2022.167195) based on time duration of digital pulses and combinations between adjacent strips

- **Efficiency larger than 90 %**
- No dead region between strips
- Charge sharing between strips under study

Courtesy of Emanuele Maria Data

Data, E. M., et al. "A novel detector for 4D tracking in particle therapy." *NIM A* (2024), doi: 10.1016/j.nima.2024.169690