ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

The search of the X17 boson at the n_TOF facility: demonstrator data analysis

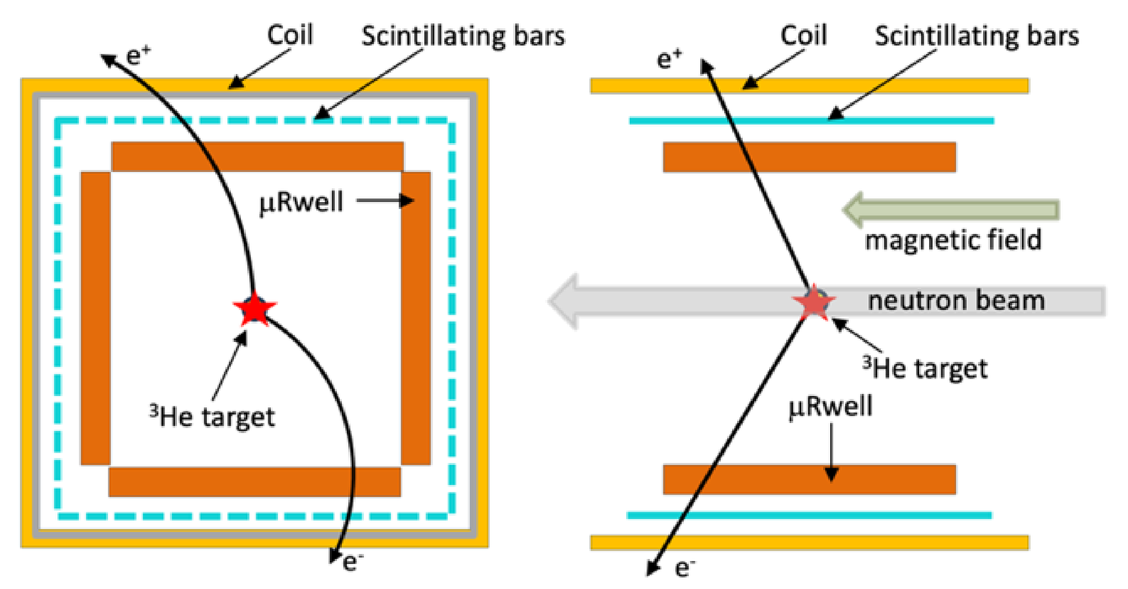
Nicholas Pieretti on behalf of the n_TOF collaboration

21 November 2024 – n_TOF collaboration national meeting

X17 at n_TOF: detector design

- **Large acceptance**
- **Tracking and PID**

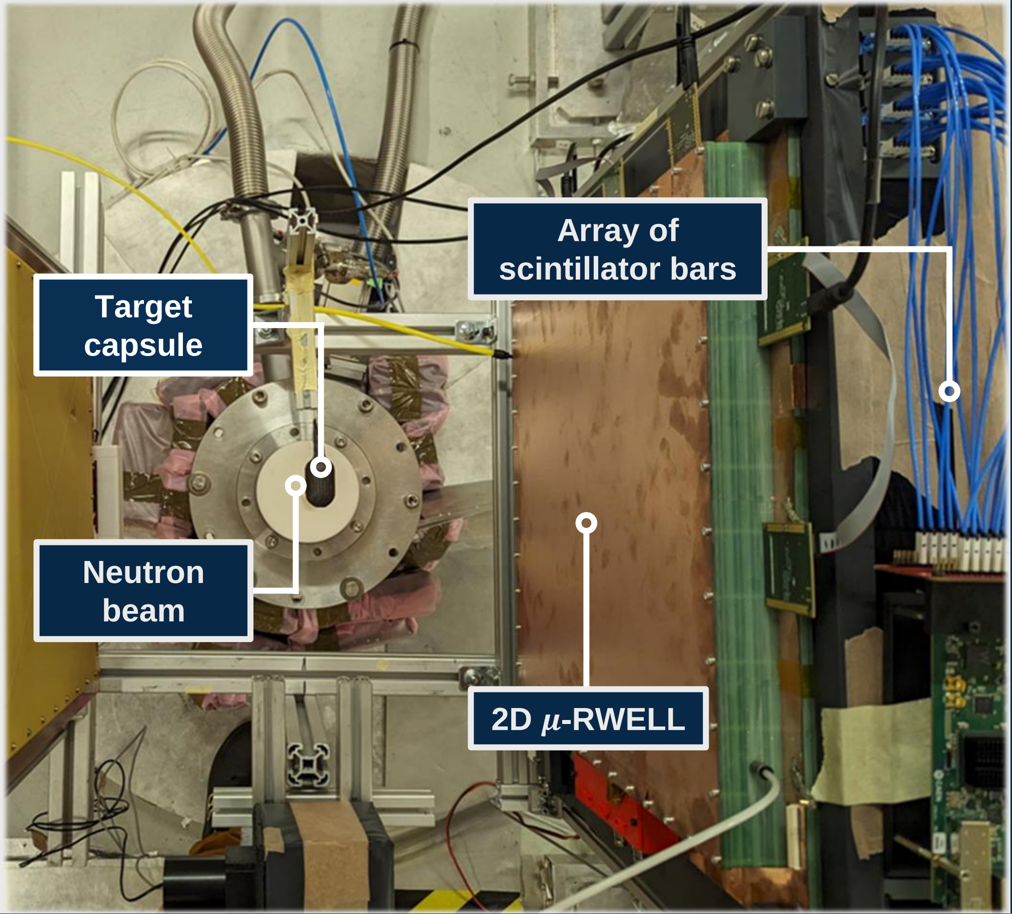
- 2D μ-RWELL
- Array of scintillator bars
- 500 Gauss magnetic field



First detector prototype test (2023)

- **Large acceptance**
- **Tracking and PID**

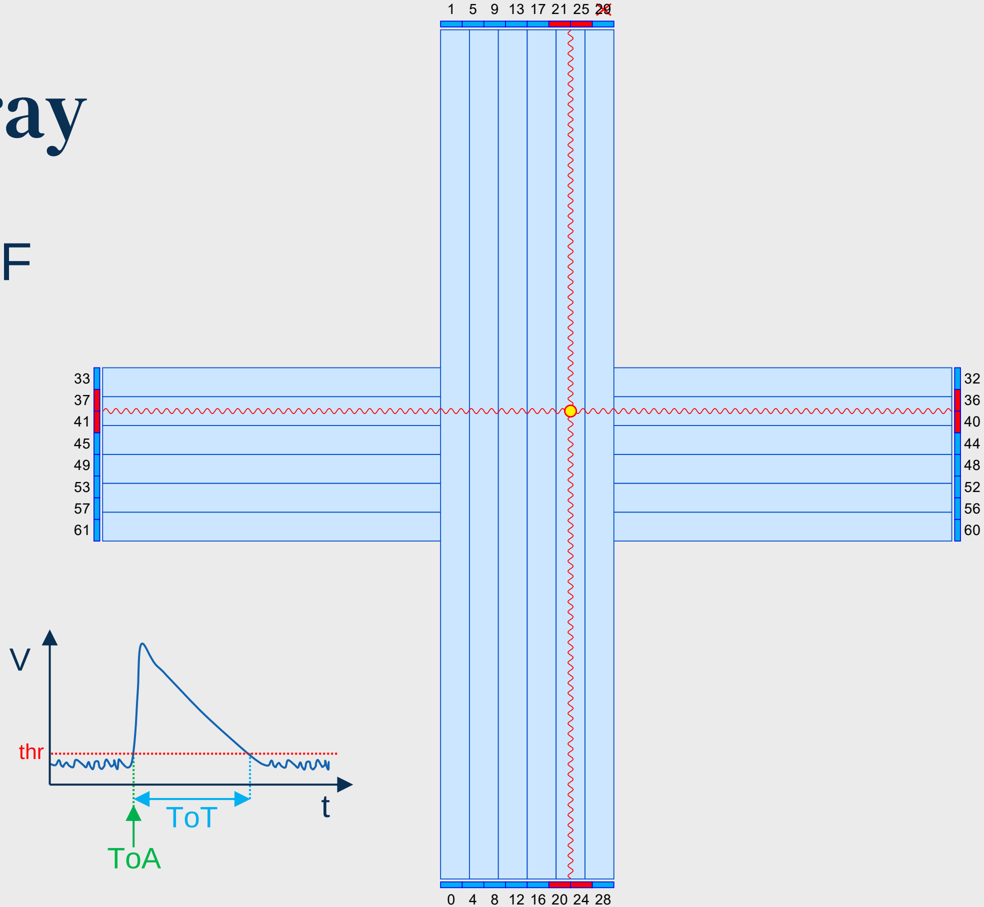
- Al and C fiber capsule
- 2D μ-RWELL
- Array of scintillator bars



The scintillator bar array

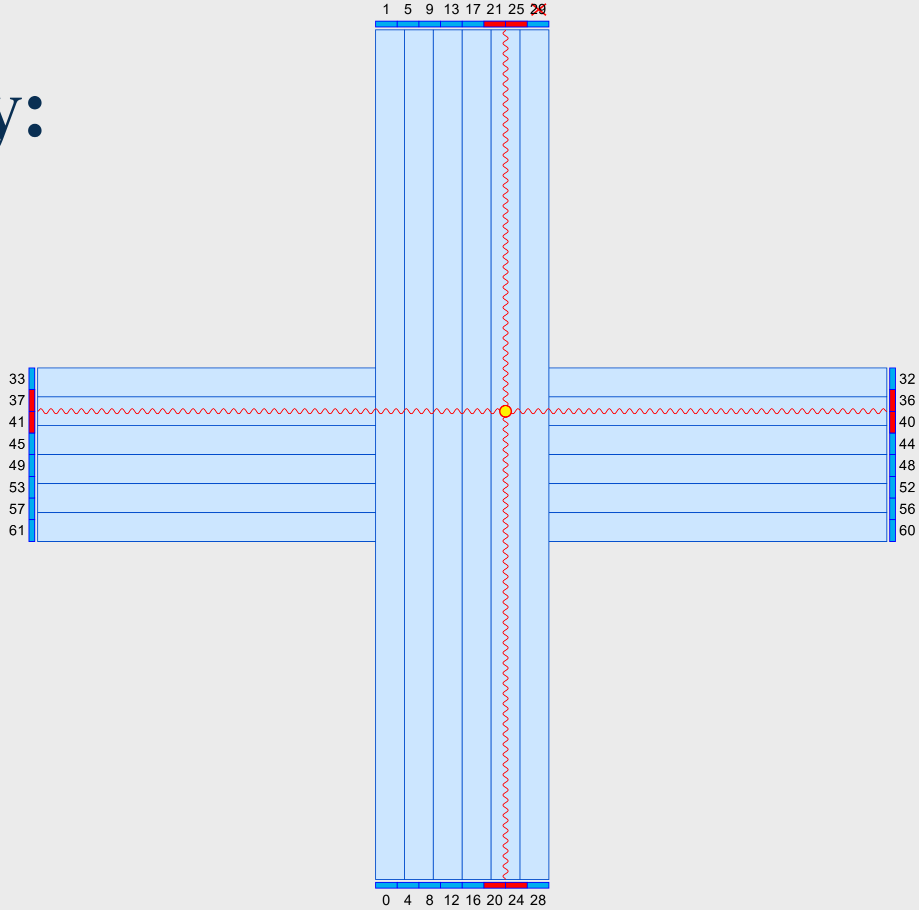
- Provide trigger and neutron TOF
- Improve spatial resolution

- Readout and DAQ with SiPM + FERS (CAEN)
- Only timing data available:
  - Time of Arrival (ToA)
  - Time over Threshold (ToT)



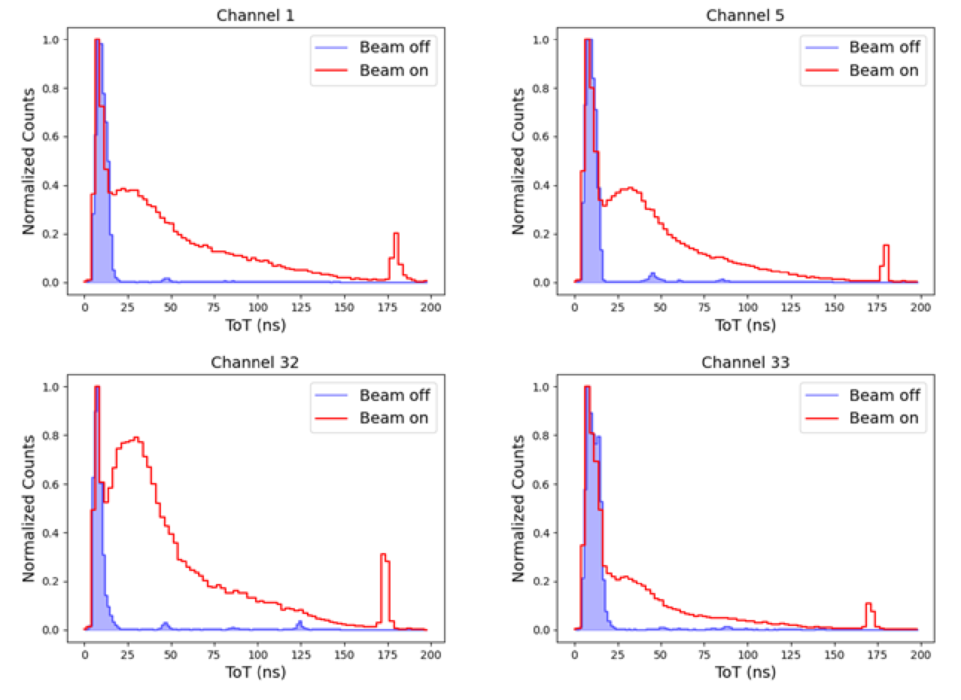
The scintillator bar array: analysis performed

- Background estimation
- Dead time estimation
- Hit map reconstruction
- Neutron energy dependence



Background estimation

- Pedestal data (beam off)
- Threshold on ToT as event selection cut ≈ 22 ns
- Mainly electronic noise
- Visible γ-flash peak at ≈ 175 ns



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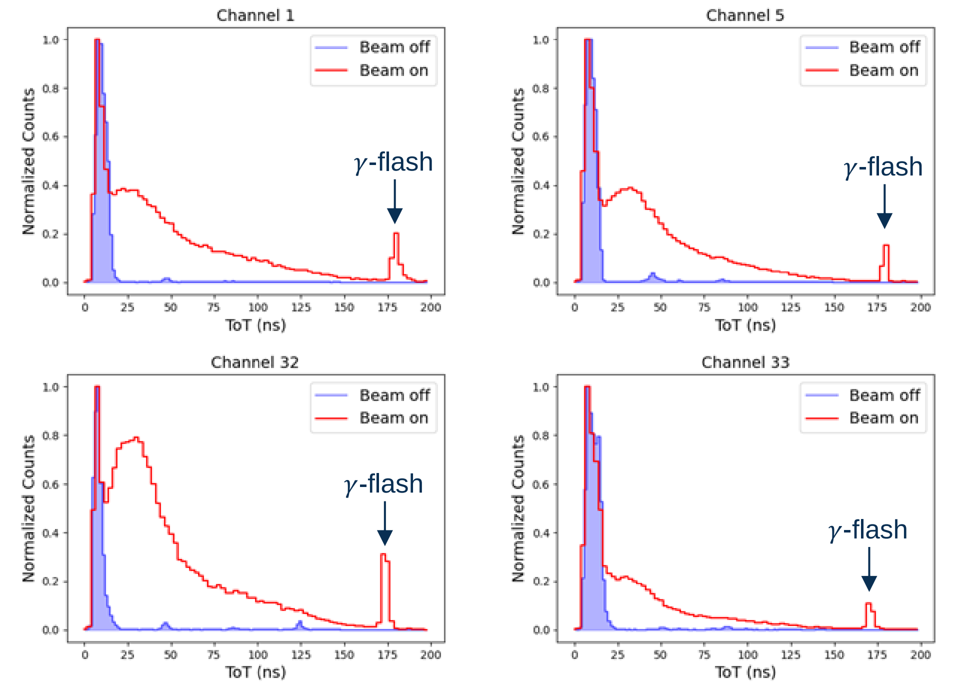
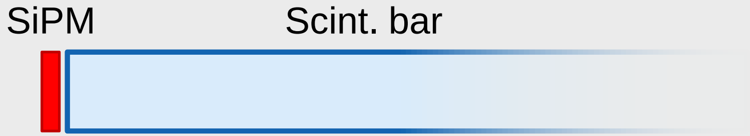
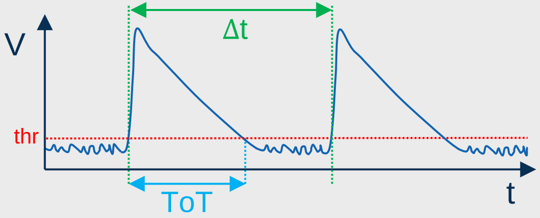
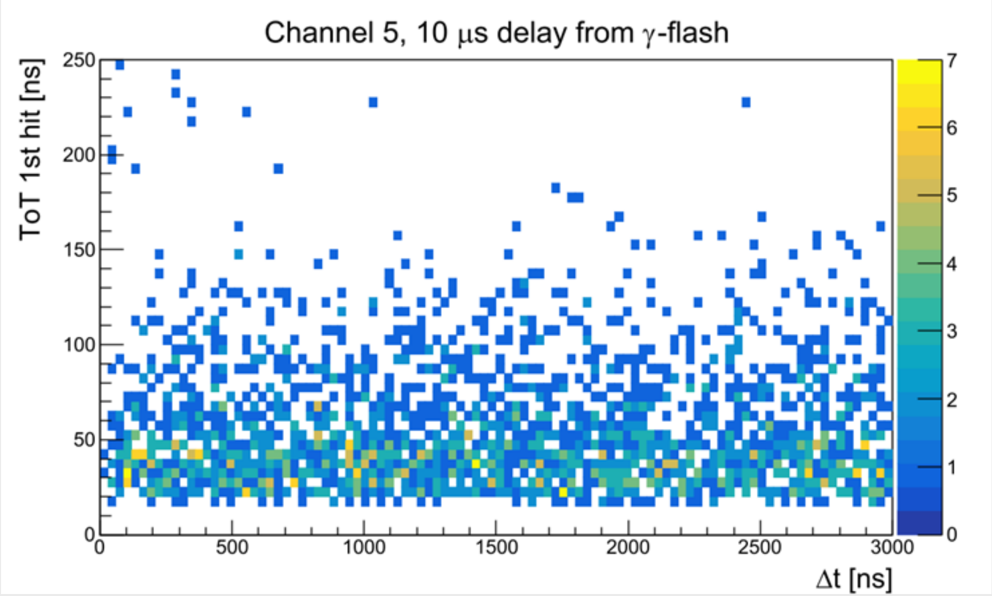




Dead time estimation

- ToT vs time difference between two consecutive events Δt





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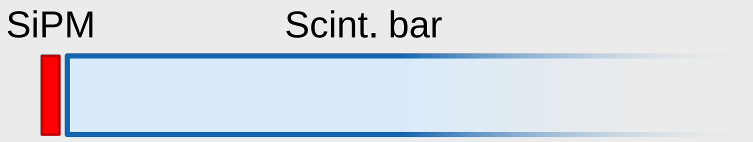

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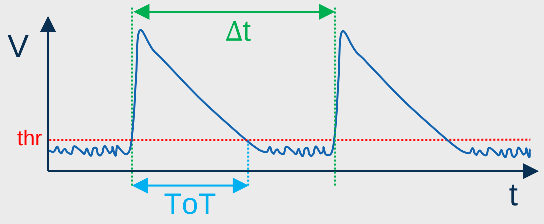
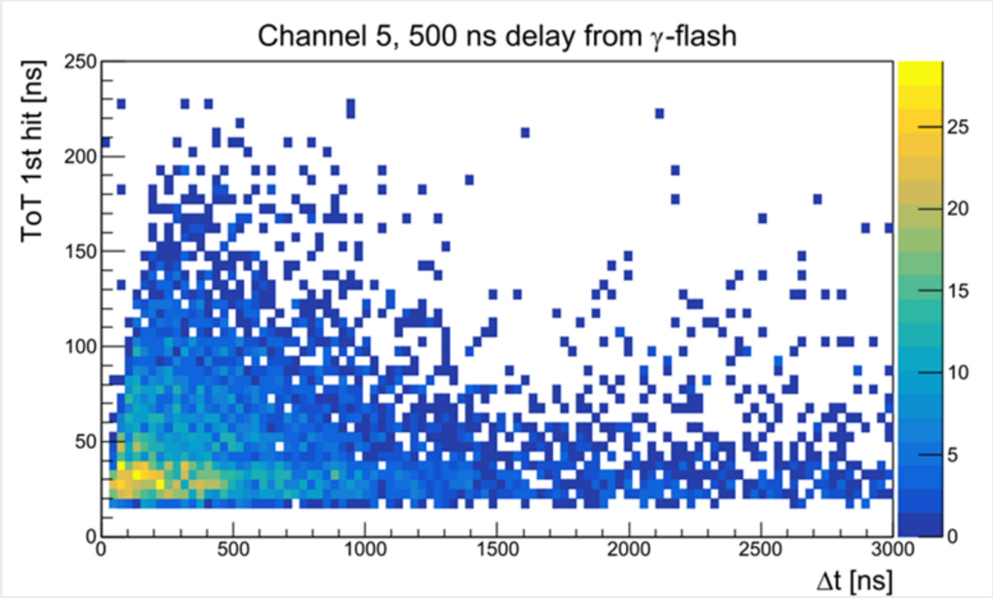


- Dead time ≈ 100 ns
- Possible pileup events



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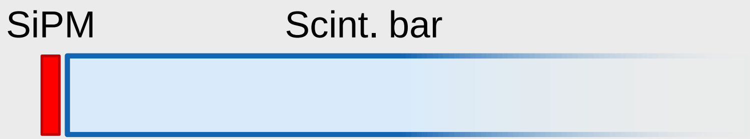

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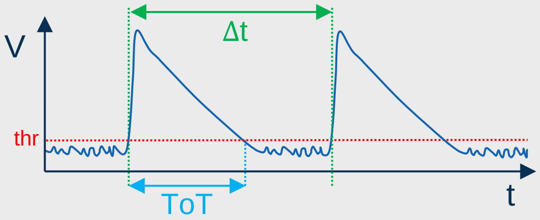
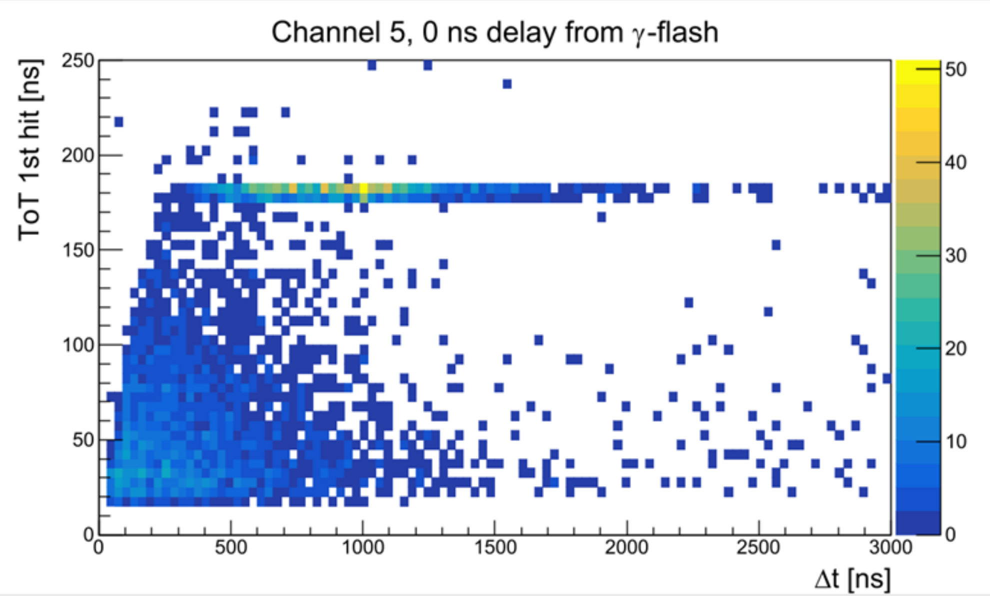
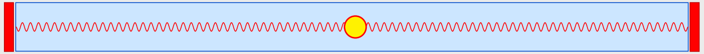


- Dead time ≈ 100 ns
- Possible pileup events
- γ-flash saturates the detector

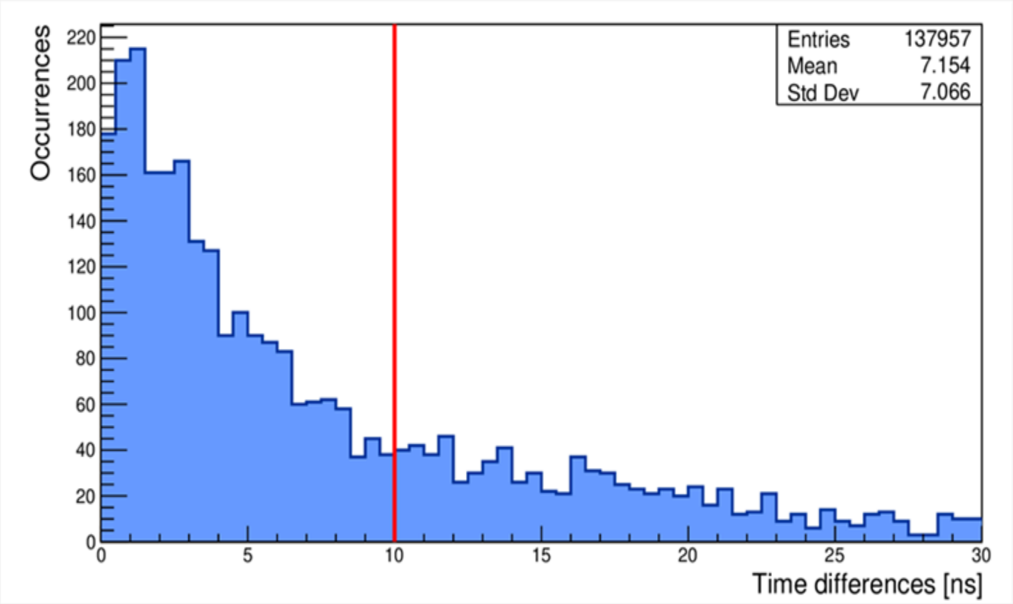


Hit map reconstruction

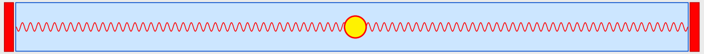
Time window estimation



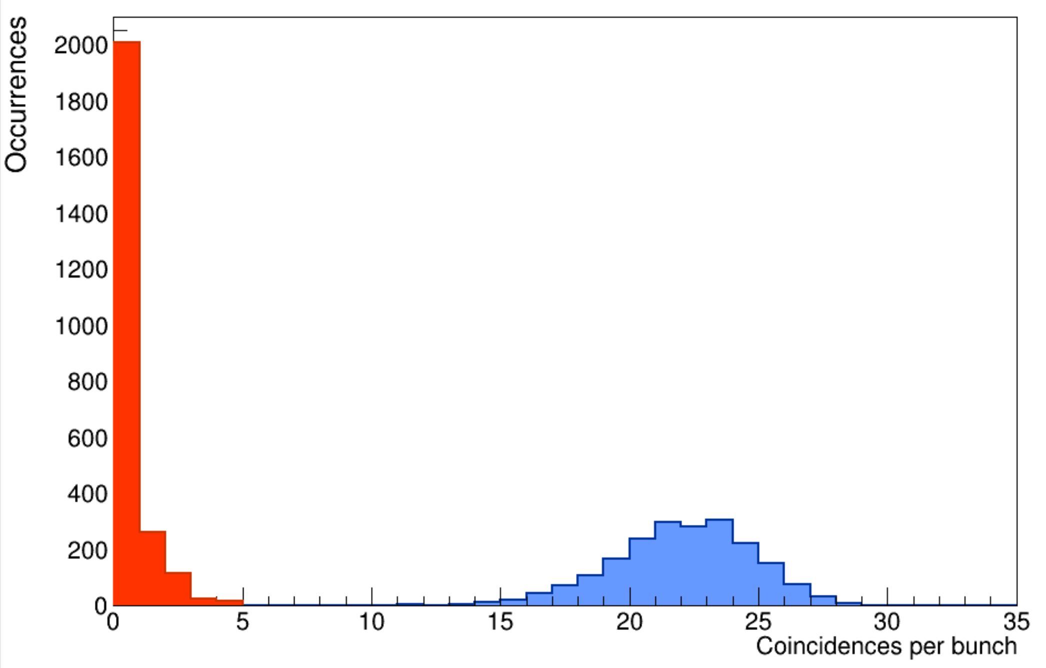
- Coincidences between signals at opposite ends of a bar
- First estimation $Ln/c \approx 2.5$ ns
- Account for several delays $\rightarrow \Delta t_c = 10$ ns



Hit map reconstruction
Coincidence rate



- Low coincidence rate, except for γ-flash
- Very low single bar coincidence rate
- Noisy bars flagged in the analysis



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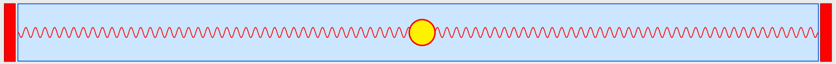
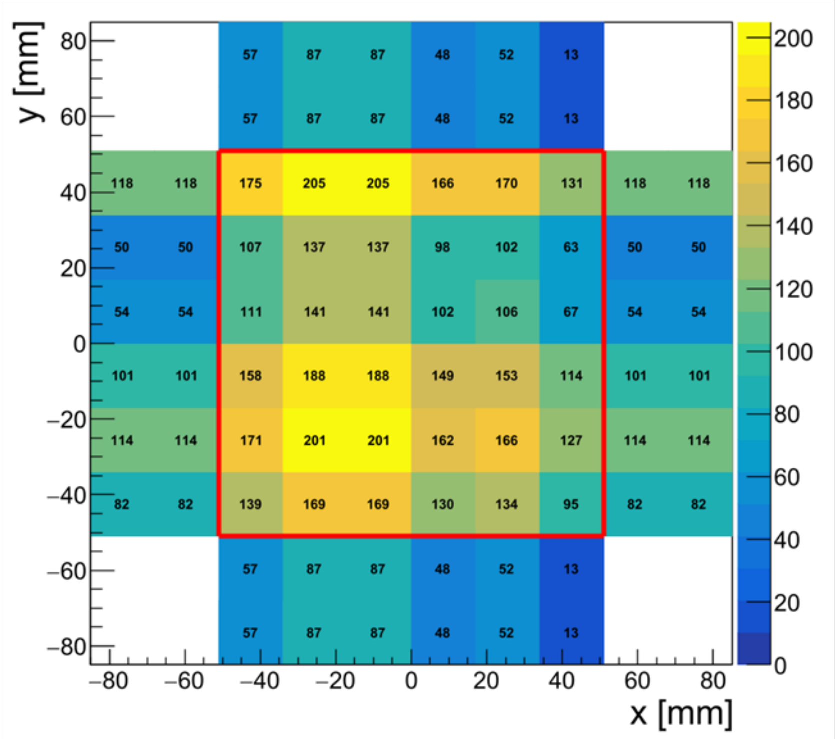


- Reconstruction on channels and bars
- Different response and non-uniform background



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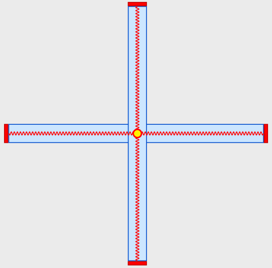

- Reconstruction on channels and bars
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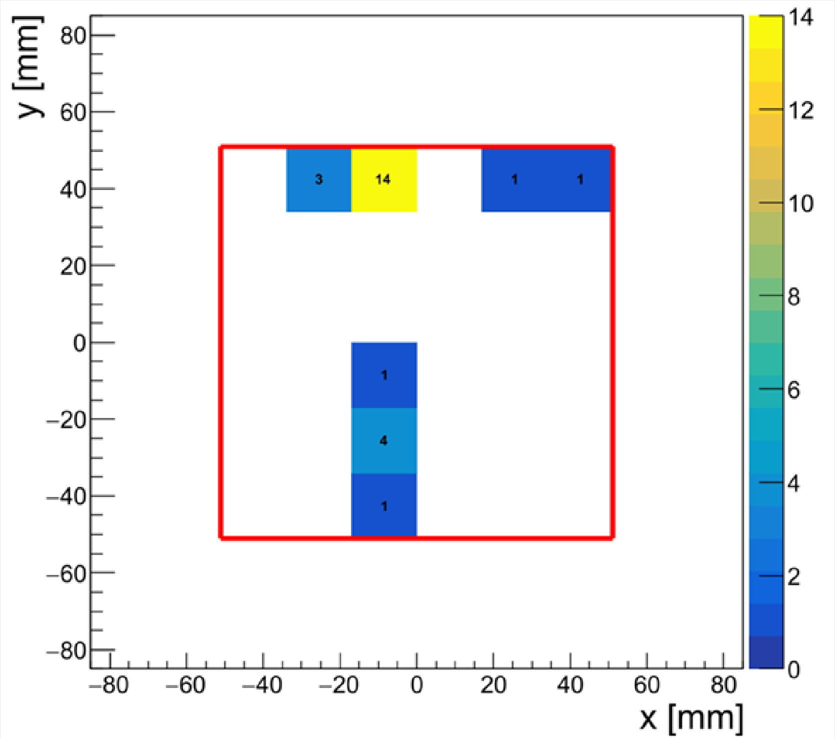

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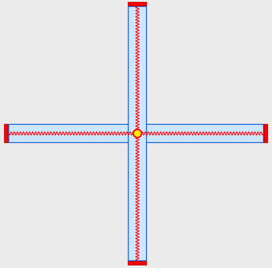
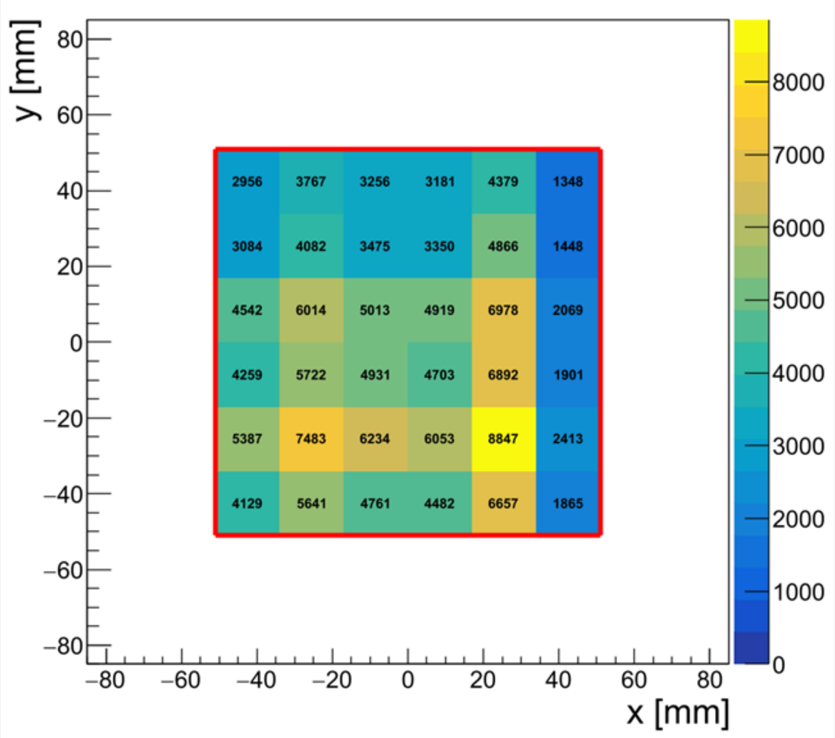
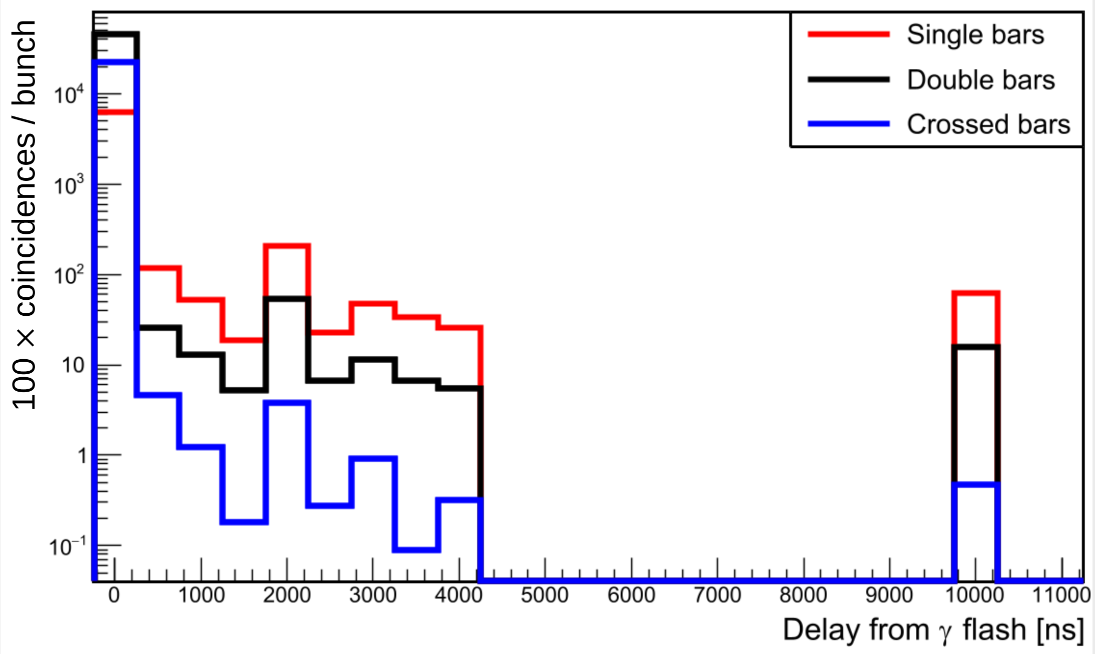


- Reconstruction on channels and bars
- Different response and non-uniform background
- Very few crossed coincidences (except for γ-flash)



Neutron energy dependence

- Main background: elastically scattered neutrons
- Other channels open from 1500 ns (1 MeV)
- Relevant γ-flash tail



Conclusions

- Performance evaluation of scintillator bar array
- Detector suitable for neutron energies of interest
- γ-flash sensitivity, but short dead time
- Different DAQ system for extended acquisition time window and amplitude information

Thank you for your attention!

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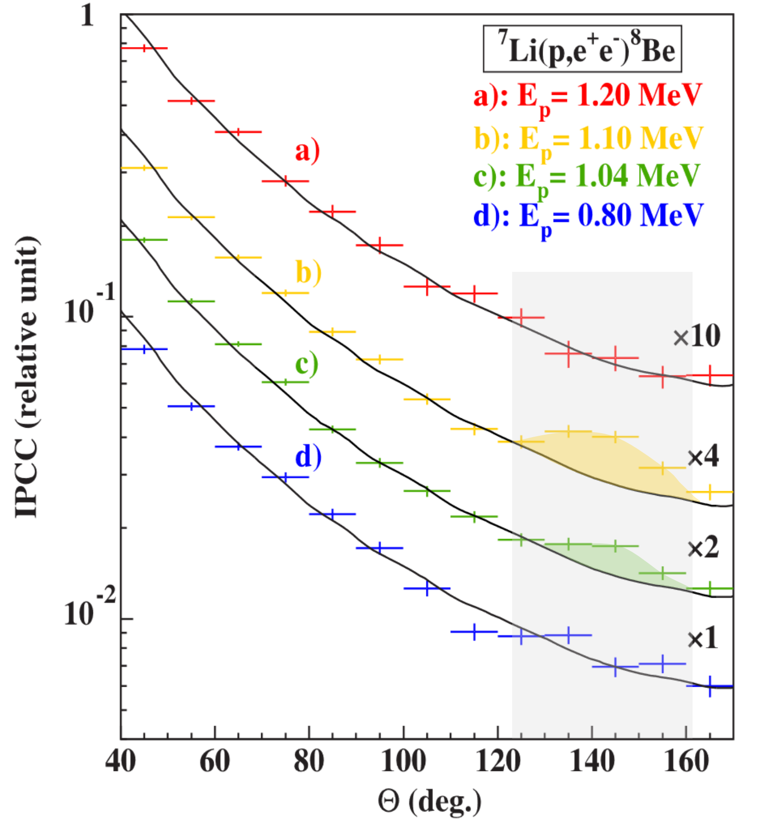
nTOF

Phys. Rev. Lett. 116 (2016) 042501

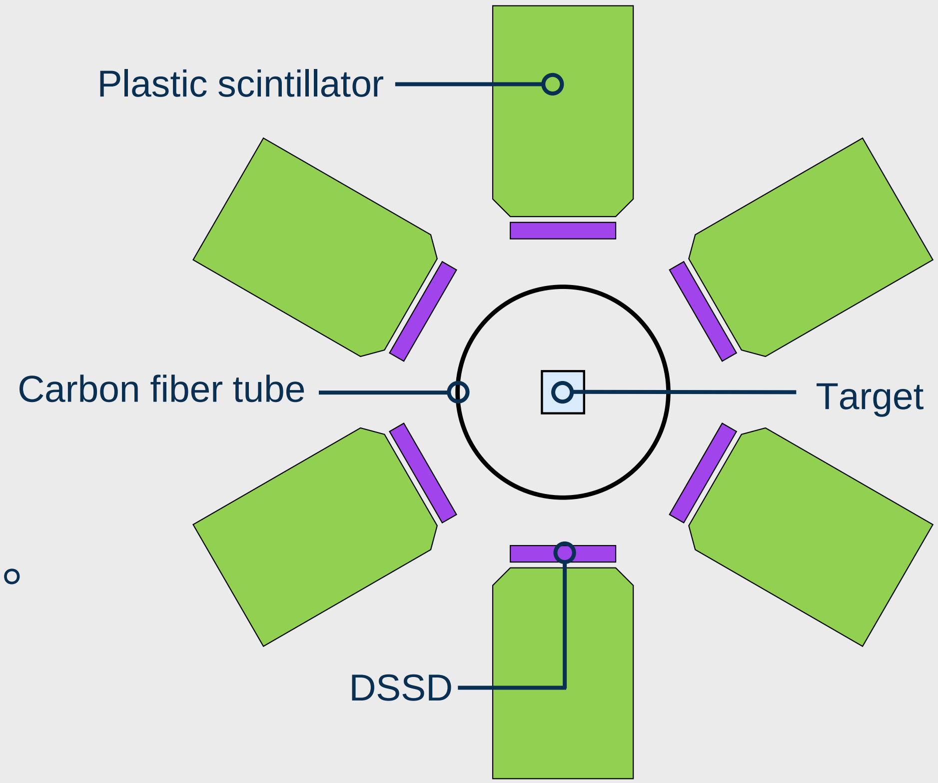
The X17 anomaly

- Significant anomalies observed at ATOMKI, Hungary, in:
  - $^{7}\mathrm{Li}(p, e^{+}e^{-})^{8}\mathrm{Be}$
  - $^{3}\mathrm{H}(p, e^{+}e^{-})^{4}\mathrm{He}$
  - $^{11}\mathrm{B}(p, e^{+}e^{-})^{12}\mathrm{C}$
- Excess of $e^{+}e^{-}$ pairs emitted at large relative angle



The ATOMKI setup

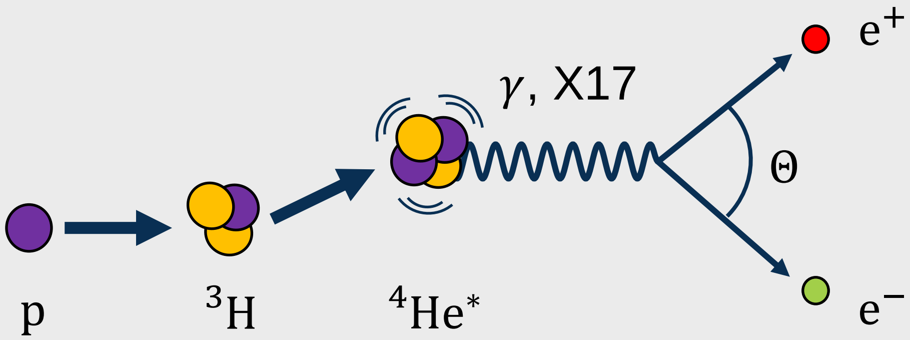
- ^{3}H on Ti layer
- 6 plastic scintillators
- 6 double-sided silicon strip detectors
- 1 mm thick carbon fiber tube

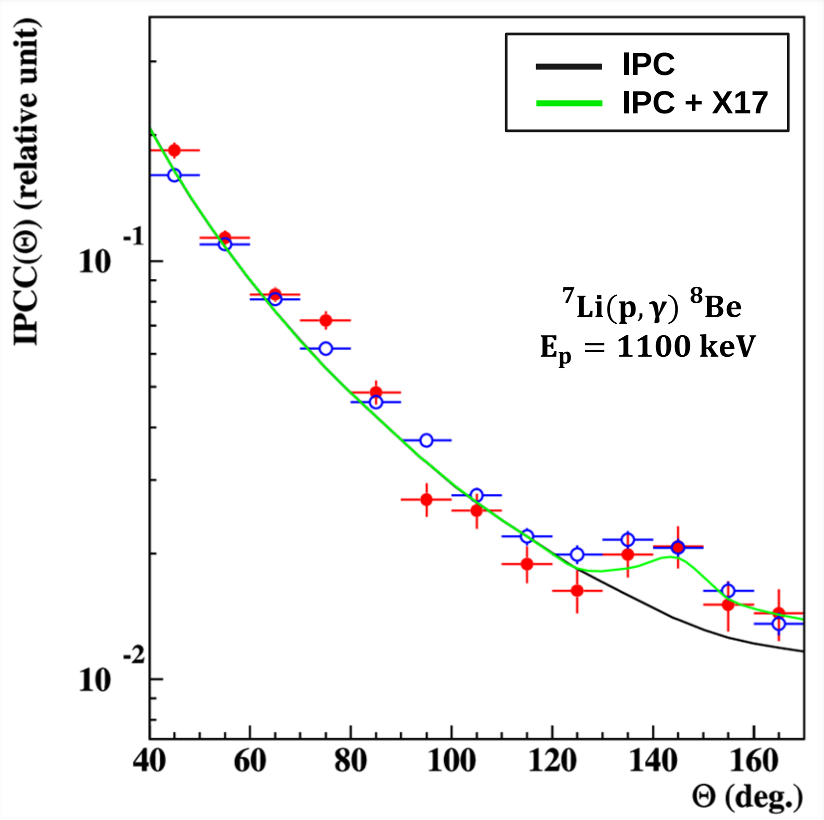


❖ **Detector acceptance only ~ 90° with respect to the beam axis**
❖ **No tracking or PID**

The X17 anomaly

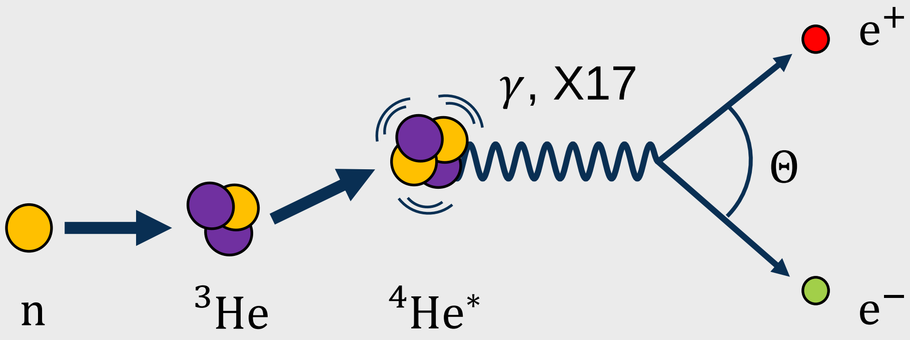
- A new particle with mass ≈ 17 MeV/c² ?
- Not confirmed or refuted by independent experiments

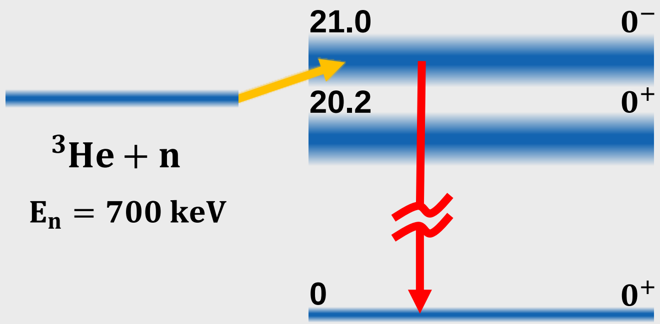




X17 at n_TOF

- Study of the conjugate reaction $^{3}\mathrm{He}(\mathrm{n},\mathrm{e}^{+}\mathrm{e}^{-})^{4}\mathrm{He}$
- Wide energy range $\rightarrow$ explore different J^{π}
- Large detector acceptance $\rightarrow$ statistics and kinematics





The X17 anomaly: a genuine effect?

- The statistical significance of the observations is always >6 standard deviations.
- The anomaly has been observed in ^{8}Be using two different experimental setups: 5 and 6 arms spectrometers.
- The anomaly has been observed using different position sensitive detectors: multiwire chambers and silicon strip detectors.
- The anomaly has been observed in two different target nuclei ^{8}Be and ^{4}He and shows up at different value of the angle.
- The anomaly has been observed with different proton beam energies.
- The anomaly has not been observed in calibration atoms i.e. ^{16}O during the same data taking period.
- The anomaly has not been observed in events with asymmetric momentum e^+e^- pairs

The X17 anomaly: new physics?

- The anomalies are statistically significant. They are both roughly 7σ excesses and are unlikely to disappear with more data.
- The excesses are bumps. They are localized in opening angle Θ and invariant mass $m_{e^+e^-}$. Diffuse excesses or excesses that appear at an experiment's kinematic limit are much more likely to have mundane explanations.
- The excess rises and falls as one scans through the resonance by varying the proton beam energy
- There are no compelling SM or experimental explanations
- The fit improves drastically with the introduction of a single new particle. A priori the excess need not have a shape consistent with the simplest new physics explanations.
- The ^{8}Be and 4 He results support each other. In particular, the excess shifts from Θ ≈ 140° for ^{8}Be to 115° for ^{4}He. Such a shift excludes many experimental systematic error explanations, but it is exactly what is expected for all of the simplest new particle explanations. Additionally, the size of the ^{4}He excess is consistent with the prediction of the protophobic gauge boson explanation of the ^{8}Be anomaly.

The X17 anomaly: features and constraints

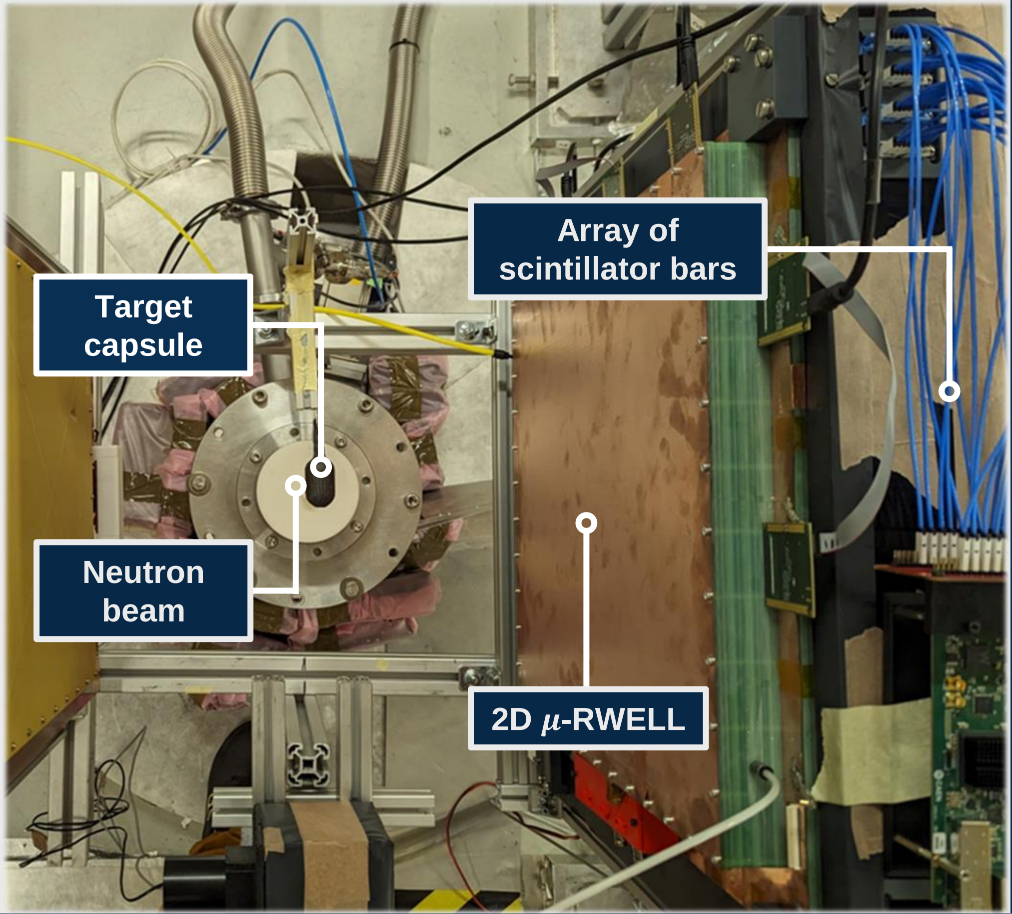
- X17 is produced through its nuclear (quark) couplings and decays through its electron coupling.
- The bumps at $\Theta \approx 140°$ for ^{8}Be and 115° for ^{4}He imply that the X17 has a two-decay X17 → e^+e^- and $m_{X17} \approx 17$ MeV.
- X17 is therefore a neutral boson, and the discovery of X17 implies the discovery of a fifth force with a characteristic range of 12 fm.
- The signal rate is determined by σ (8 Be$*$ → 8 Be X17) × BR(X17 → e^+e^-).
- Other decay modes are possible (X17 → $\bar{\nu}\nu$, DM, . . .), but to maintain the signal rate, these would require larger nuclear couplings, which are more prone to exclusion. One can assume BR(X → e+e−) = 1.
- With this assumption, X's nuclear couplings are completely determined by the signal rate.
- X17's electron coupling cannot be too small, since the X cannot travel too far before decaying.
- The quantum numbers of the reactions and symmetries of the physics models impose theoretical constraints on possible explanations.
- All experiments that have probed the 10 MeV-scale since the early days of nuclear and particle physics impose additional experimental constraints on possible explanations.

First detector prototype test (2023)

- **Large acceptance**
- **Tracking**

Assess noise and saturation effects as a function of:

- Target type
- Demonstrator distance from the beam
- Time after γ-flash

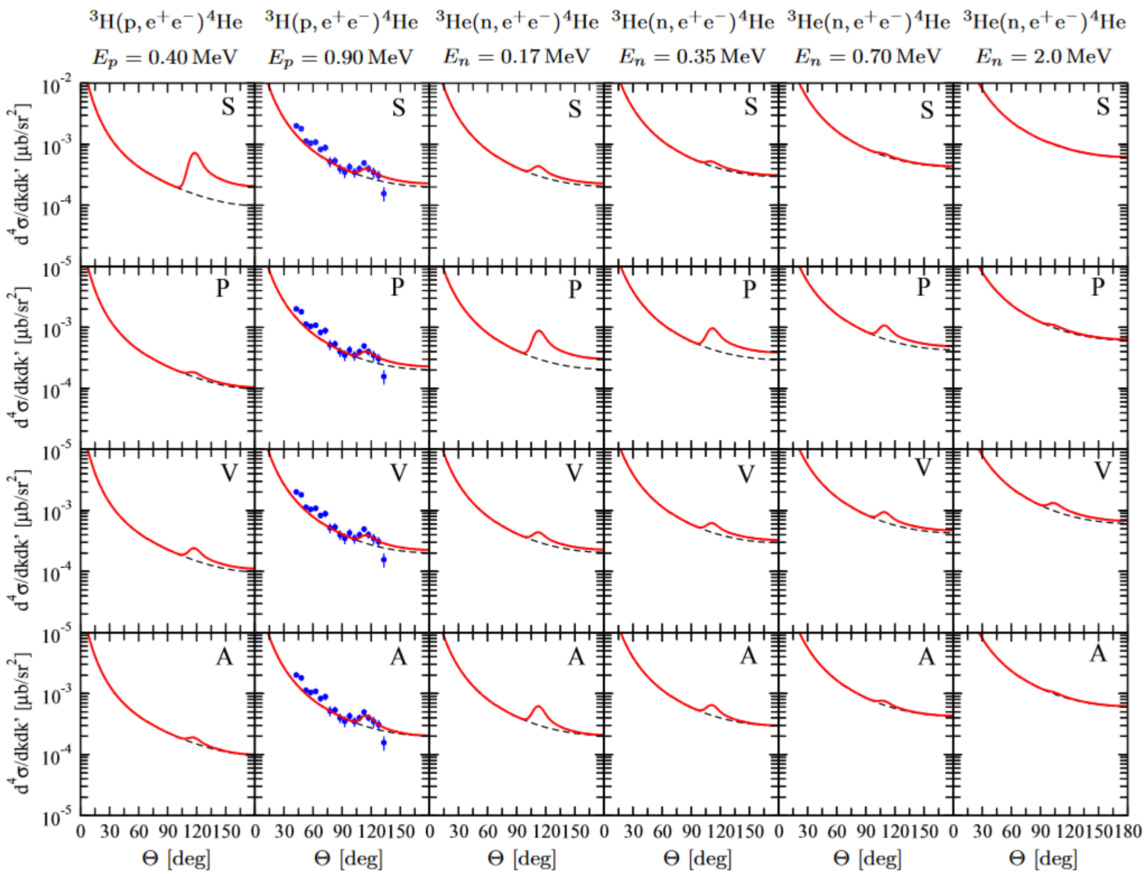


X17 at n_TOF

Neutron energy	ToF (μs)	neutrons/pulse	γ's/pulse	IPC/day	X17/day
1 – 10 eV	411 – 1300	3.0×10^5	2(1)	5569(17)	1(0)
10 – 100 eV	130 – 411	3.3×10^5	2(1)	61(18)	2(0)
0.1 – 1 keV	41 – 130	3.7×10^5	2(1)	69(21)	2(1)
1 – 10 keV	13 – 41	5.8×10^5	3(1)	83(33)	2(1)
10 – 100 keV	4 – 13	2.8×10^6	5(7)	148(208)	4(5)
0.1 – 1 MeV	1.3 – 4	1.5×10^7	36(93)	1154(3003)	29(75)
1 – 10 MeV	0.41 – 1.3	7.8×10^6	26(44)	831(1412)	21(35)
Total		1.9×10^7	66(147)	2402(4710)	60(118)

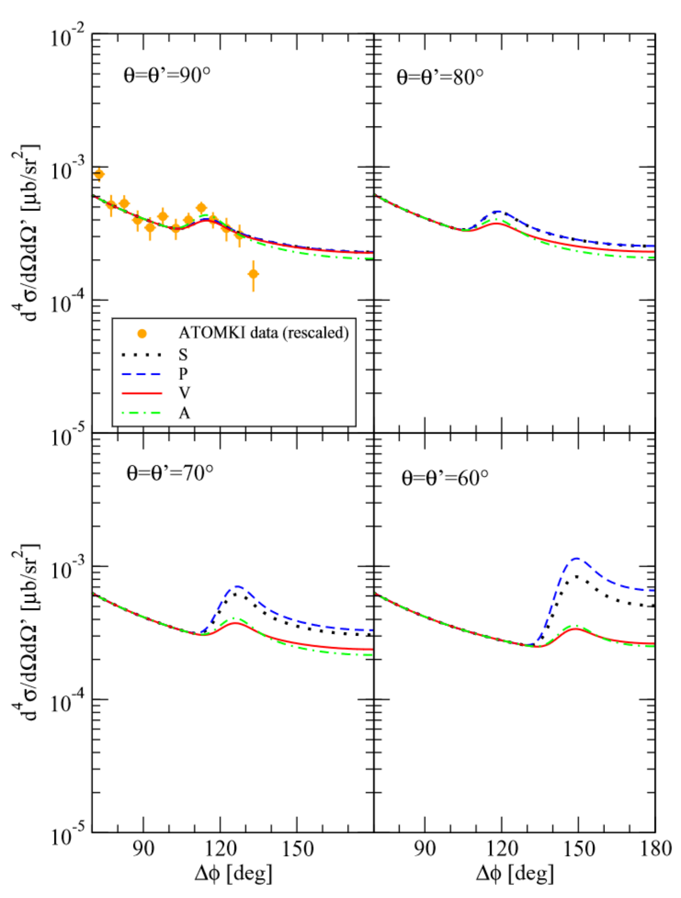
X17 at n_TOF

Differential cross sections for the $^3He(n, e^+ e^-)\,^4He$ and $^3H(p, e^+ e^-)\,^4He$ processes at θk = 90◦ and six different incident nucleon energies as a function of the correlation angle Θ. The panels labeled S, P, V, and A show the results obtained by assuming a scalar, pseudoscalar, vector, and axial X17, respectively. The dashed (black) and solid (red) curves represent the theoretical results obtained by including the electromagnetic interaction only or both the electromagnetic and X17 amplitudes. The coupling constants have been adjusted to reproduce the ATOMKI $^3H(p, e^+ e^-)\,^4He$ cross section data at Ep = 0.90 MeV (blue dots)



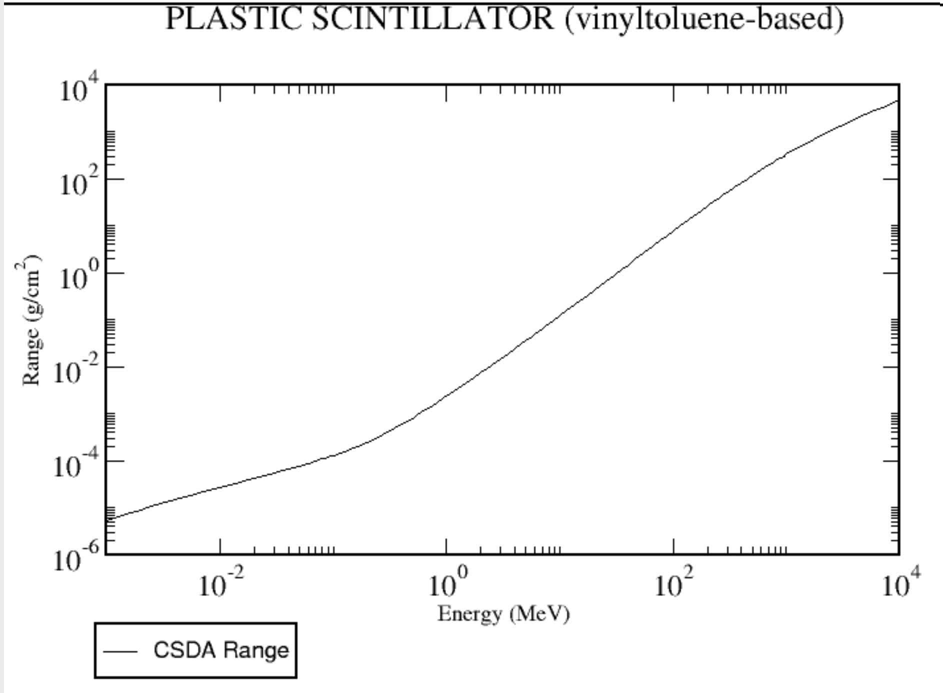
X17 at n_TOF

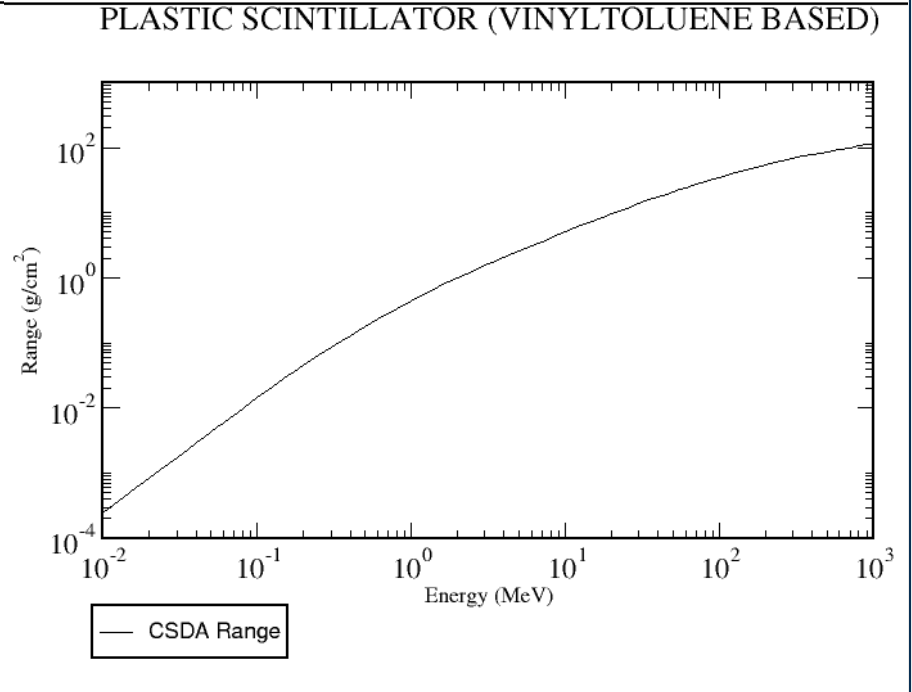
Differential cross sections for the 3H(p, e+ e–)4He processes at Ep = 0.90 MeV and different emission angle θ = θ′ = θk with respect to the beamline, as a function of the difference in azimuthal coordinate Δϕ = ϕ′ − ϕ of the positron and electron. The curves labeled S, P, V, and A show the results obtained by including the exchange of a scalar, pseudoscalar, vector, and axial X17, respectively. The coupling constants have been adjusted to reproduce the ATOMKI data at θk = 90◦ (orange dots)



Protons

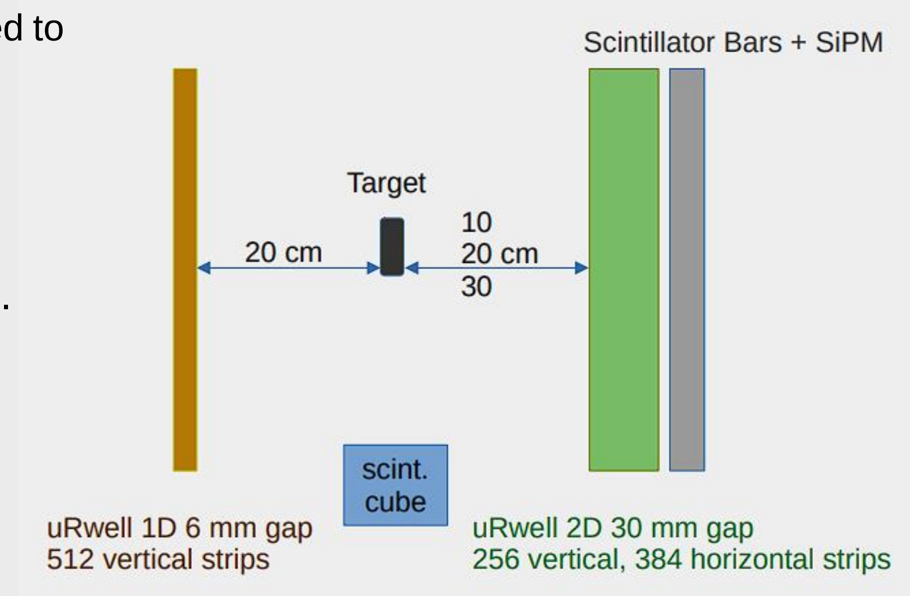
Electrons





First detector prototype test (2023)

- A target of Al and Carbon_fibre capsule projected to contain ˠl Ţ at high pressure llğɱ g lʼ ă′)
- A large μ-Rwell and an array of scintillator bars
- A small μ-Rwell
- A cubic scintillator



Each detector has a specific readout and DAQ chain. The goal of the demonstrator is to assess noise and saturation effects as a function of:

- Target type
- Demonstrator distance from the beam $(10, 20, 30\ \mathrm{cm})$:
- Time after γ-flash $(0, 500, \ldots \rightarrow\ 10000\ \mathrm{ns})$

The scintillator bar array

- Provide trigger and neutron TOF
- Improve spatial resolution

- Readout and DAQ with SiPM + FERS (CAEN)
- Only timing data available:
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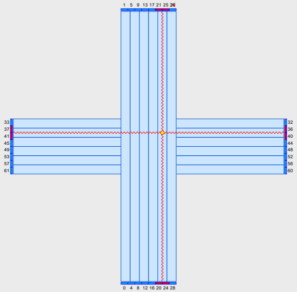
Hit map reconstruction

Time window estimation



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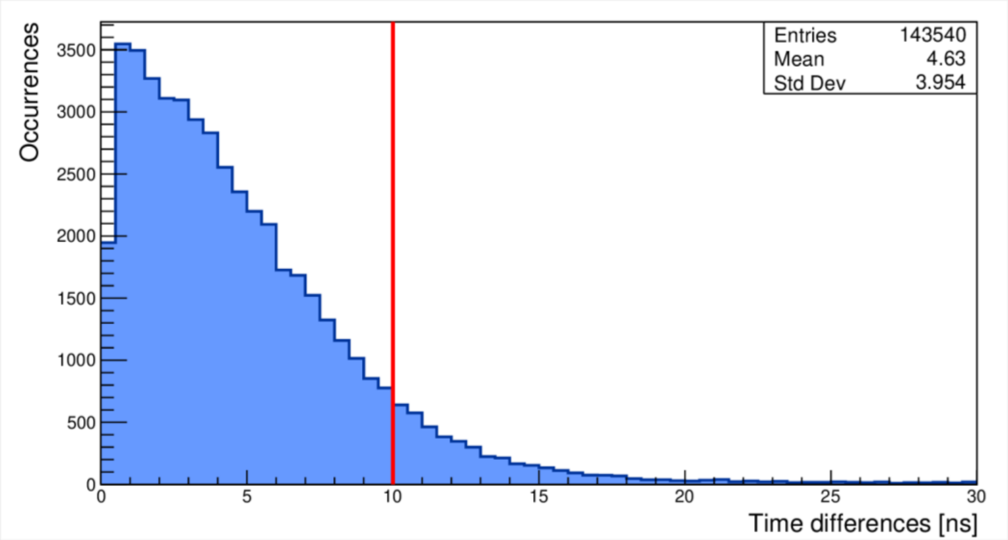

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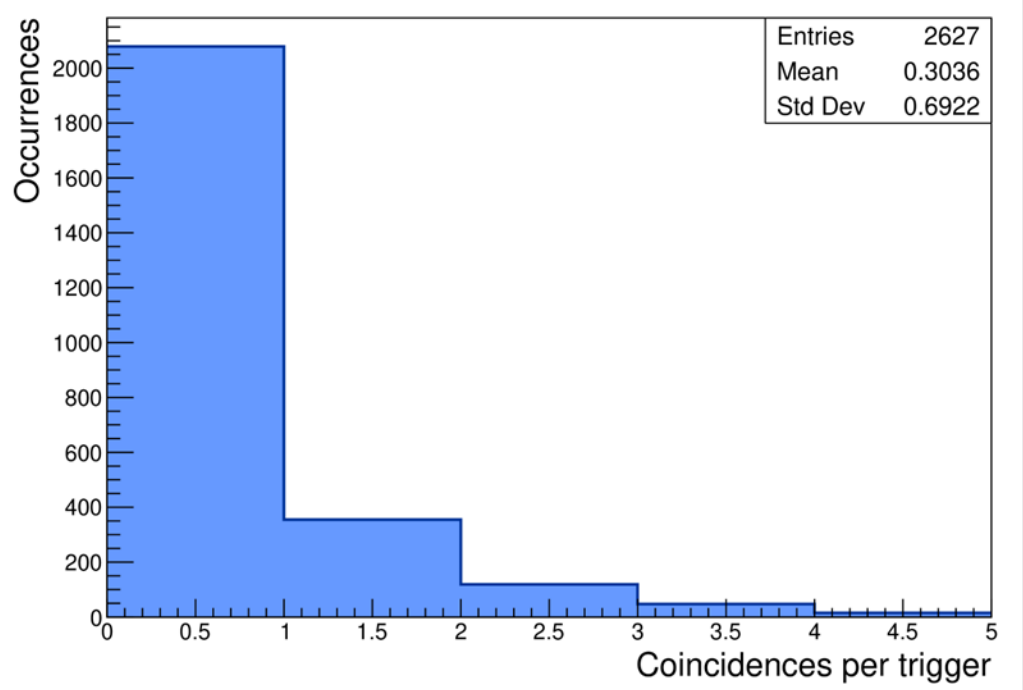
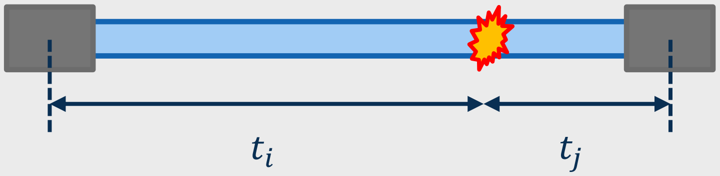
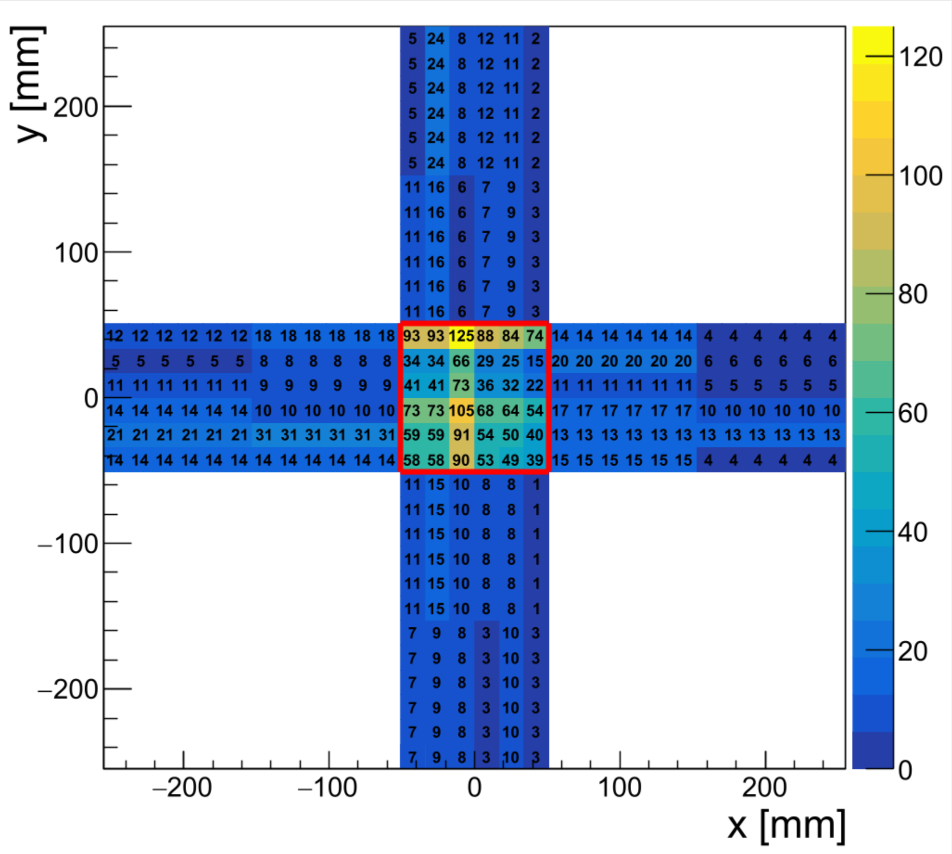
- Low coincidence rate, except for γ-flash
- Very low single bar coincidence rate
- Noisy bars flagged in the analysis



ToA information

Time of Arrival (ToA) of signal on the channels can be used to map the hit position on the scintillator bars





Neutron energy dependence

- Main background: elastically scattered neutrons
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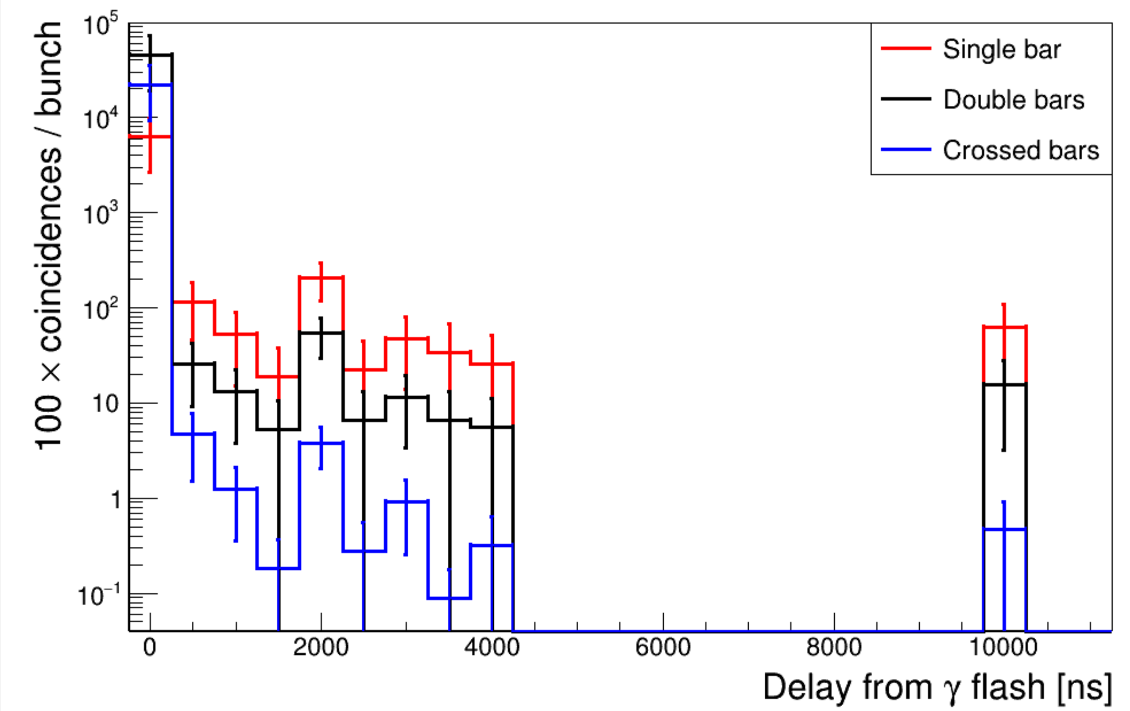
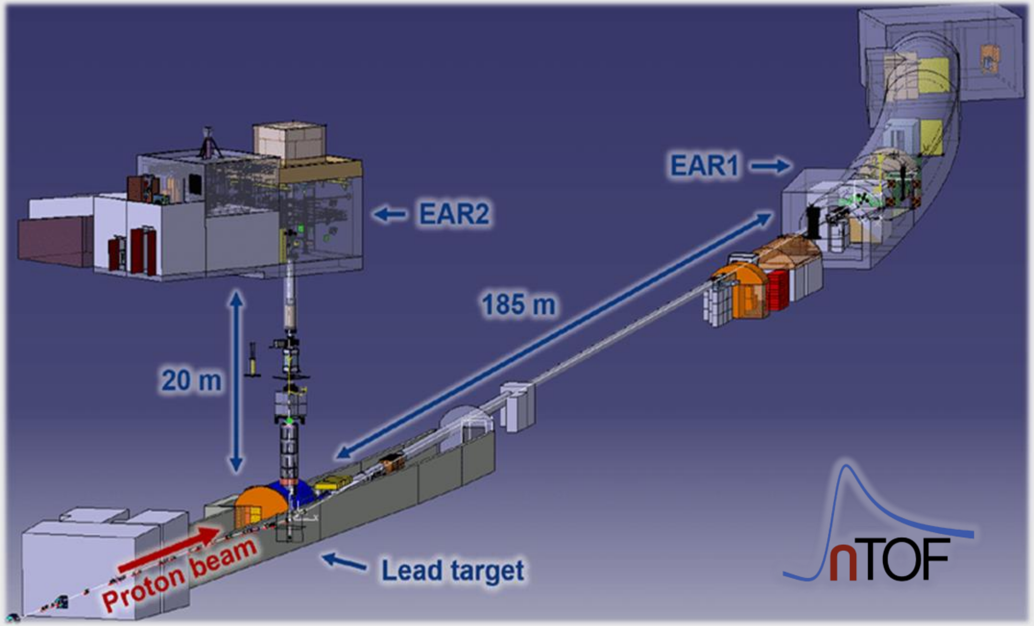
- Relevant γ-flash tail



X17 at n_TOF

- Neutrons produced through spallation of 20 GeV/c protons from PS → γ-flash

- Time of Flight technique
  - EAR1: Best energy resolution
  - **EAR2: high n flux**



X17 at n_TOF

- Wide energy range:
  $10 \text{ meV} \leq E_n \leq 1 \text{ GeV}$
- High PS current
  $\sim 10^{13}$ p/bunch
  $\Longrightarrow 10^7$ n/pulse
- Energy resolution $\frac{\Delta E}{E}$:
  - $\approx 10^{-4}$ in EAR1
  - $\approx 10^{-3}$ in EAR2