Low-energy neutron cross-talk between organic scintillator detectors

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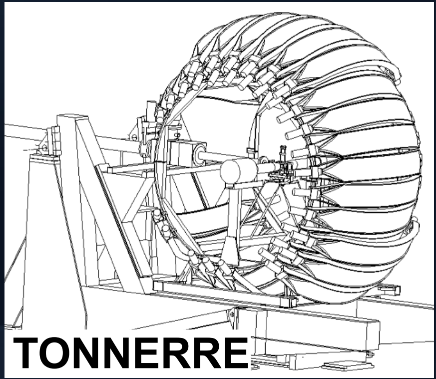
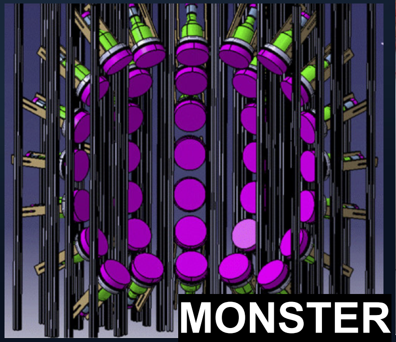
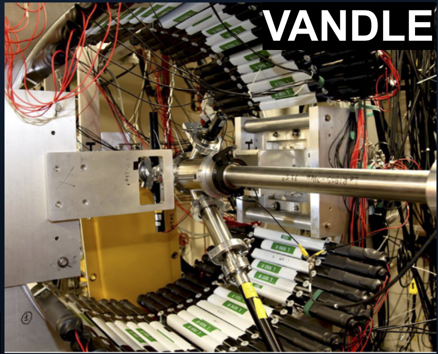
Beta-delayed neutron emission

- β-decay of neutron-rich nuclei: High Q-value, low S_n
  → Neutron emission from daughter nucleus (E_n~0-15 MeV)
  → Close to dripline: multiple neutron emission
- Measure neutron energies → decay scheme
  → Time-of-flight (TOF) spectroscopy
  → Modular arrays: thin organic scintillators (~2-5 cm)
    - Granular, efficient, good time resolution
    - Modular → Multiple neutrons







- **TONNERRE** : Buţă, NIM A 455, 412 (LPC Caen, NIPNE, GANIL...)
- **VANDLE** : Peters, NIM A 836, 122 (ORAU, ORNL, U. Tennessee, Rutgers U...)
- **MONSTER** : Garcia, JINST 7, C05012 (CIEMAT, IFIC, VECC, U. Jyvaskyla...)

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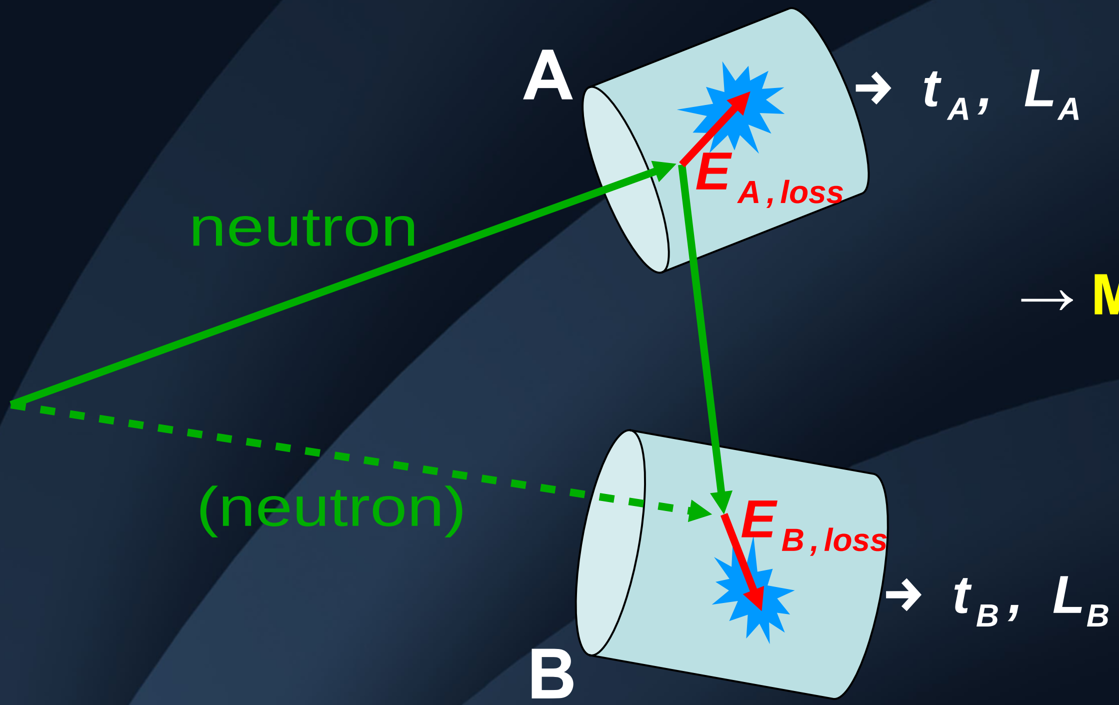
Cross-talk (CT)



→ **Mimicks direct detection of 2 neutrons**

Cross-talk characterization

- **Understanding CT is crucial to:**
  - Optimize array geometry → maximize 2n efficiency, reduce CT rate
  - Design CT identification filters used in analysis
  - Validate simulations, including effects of residual CT
- **E_n~10-300 MeV**: CT reasonably well characterized for reaction studies *
- **Below 10 MeV**: lack of data

→ **CT measurements needed to extend multi-neutron detection to β-delayed neutron emission**

* Désesquelles, NIM A 307, 366 Cronqvist, NIM A 317, 273 Edel, NIM A 332, 224 Tilquin, NIM A 365, 446 Wang, NIM A 397, 380 Kohley, NIM A 682, 59 Nakamura, NIM B 376, 156 Kondo, NIM B 463, 173

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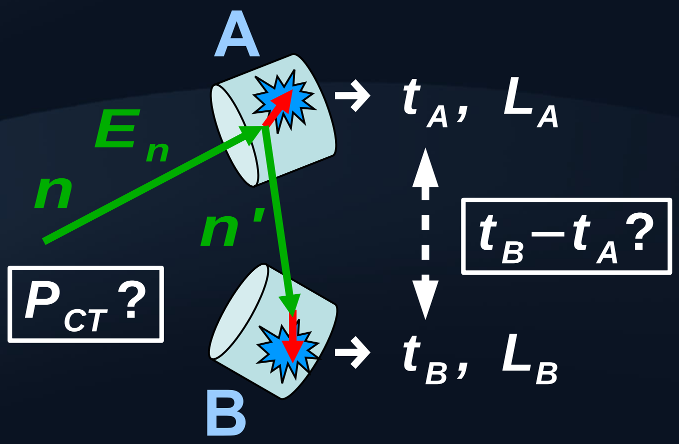
Experiment

- **Goal: CT probabilities and TOF spectra between 2 scintillator modules**
- 4-MV Van de Graaff facility, CEA/DIF, Arpajon, France
- Proton / Deuteron beams + Deuterium (TiD) / Tritium (TiT)

  → **Monoenergetic neutrons**

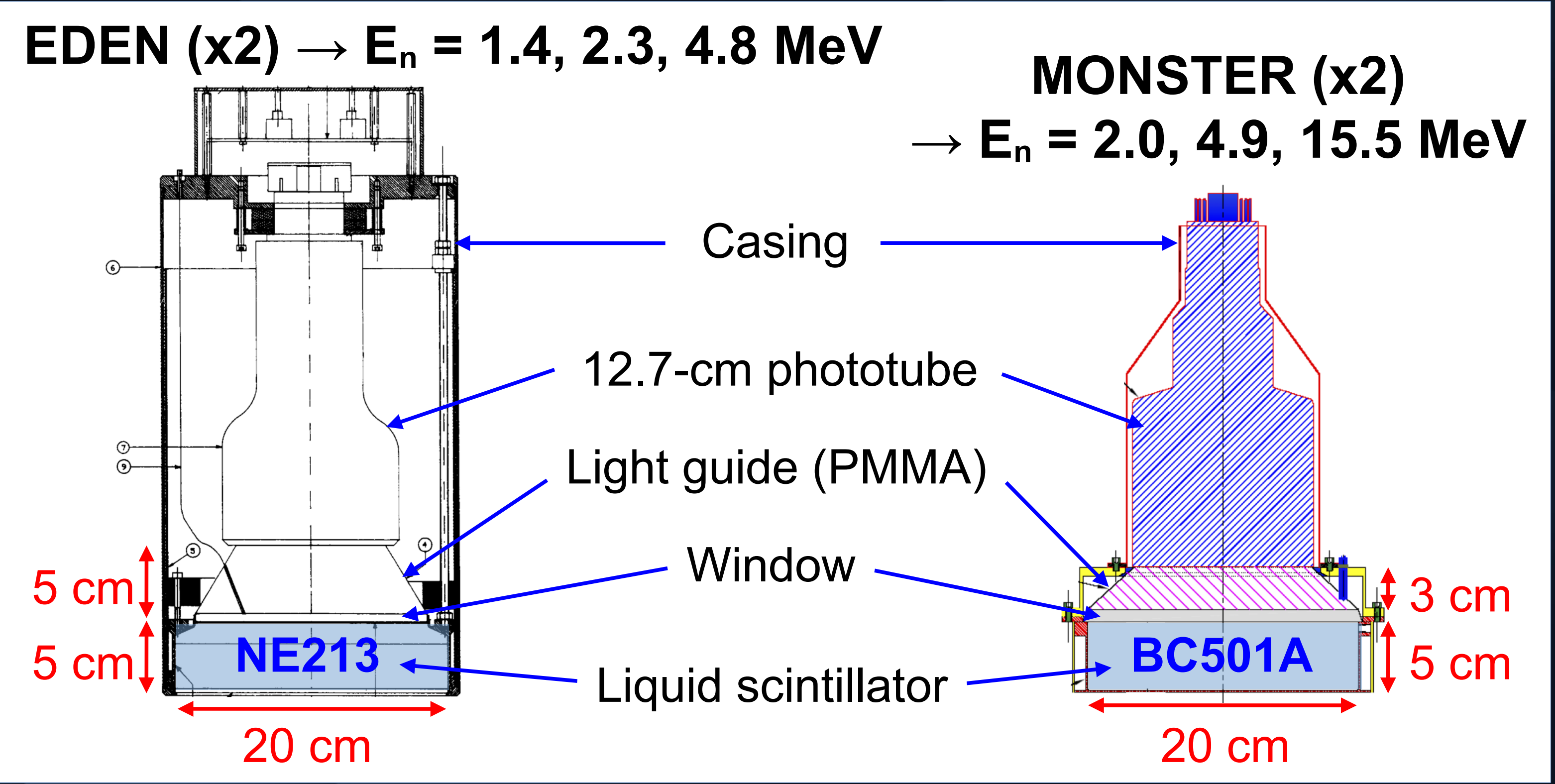
  → **E_n = 1.4, 2.0, 2.3, 4.8, 4.9, 15.5 MeV**
- Beam bunched → TOF
- FASTER digital electronics and DAQ system

  (LPC Caen, faster.in2p3.fr)



Detectors

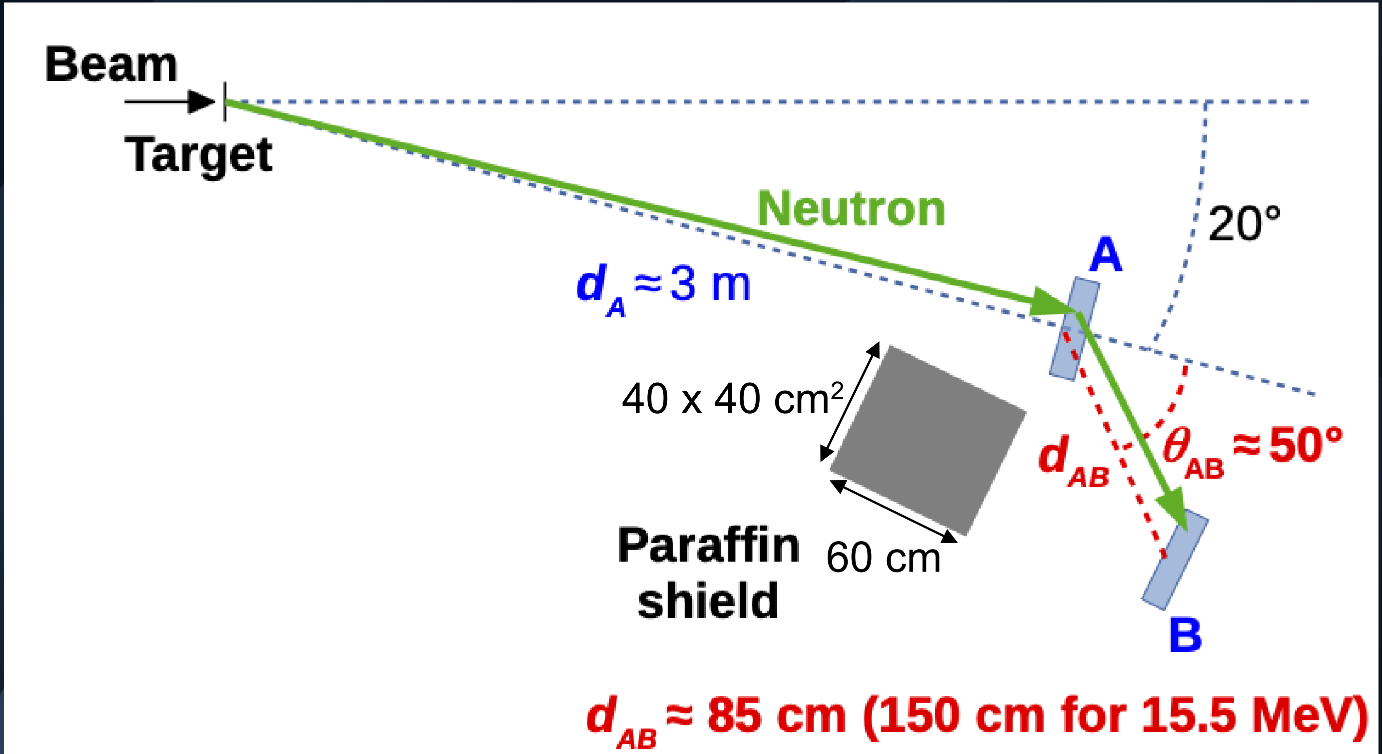
- Two series of measurements with two types of liquid scintillator modules



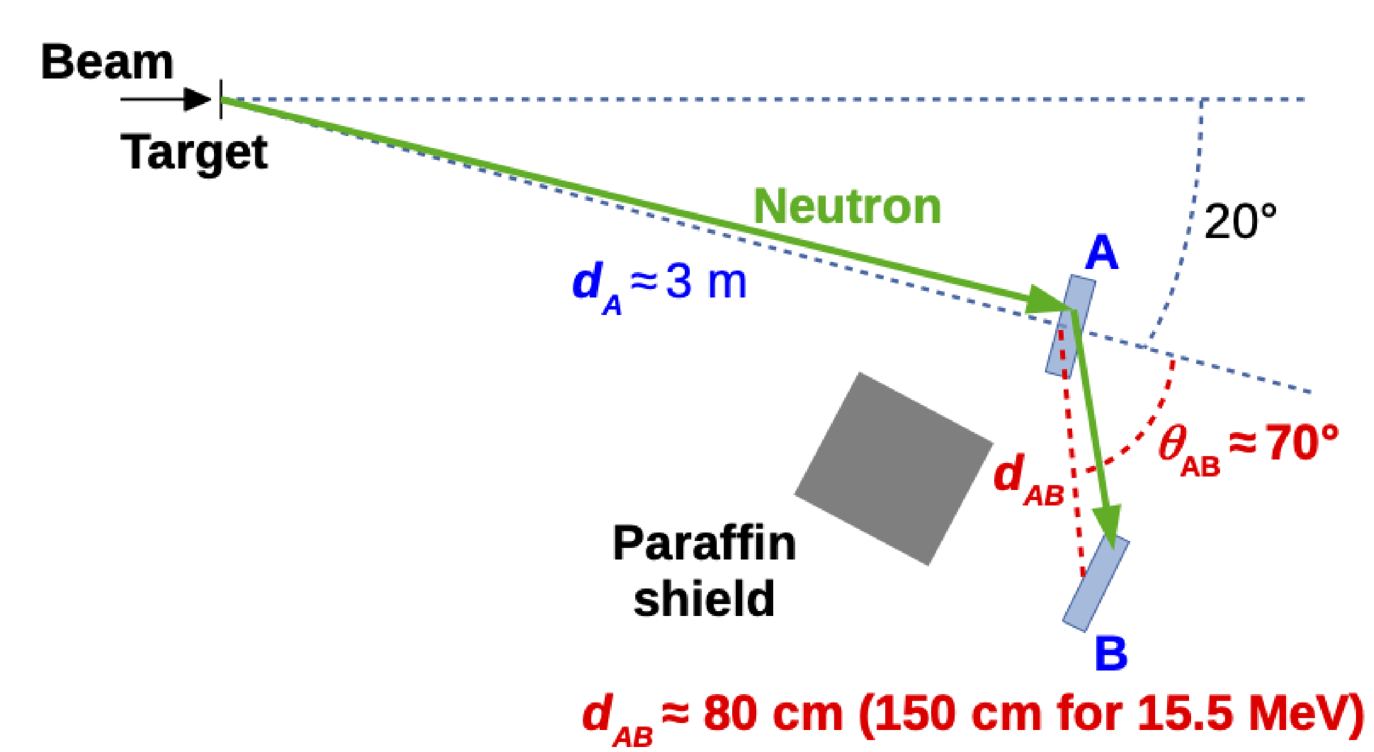
Laurent, NIM A 326, 517
(IPN Orsay, KVI)

Garcia, JINST 7 C05012
(CIEMAT, IFIC, VECC...)

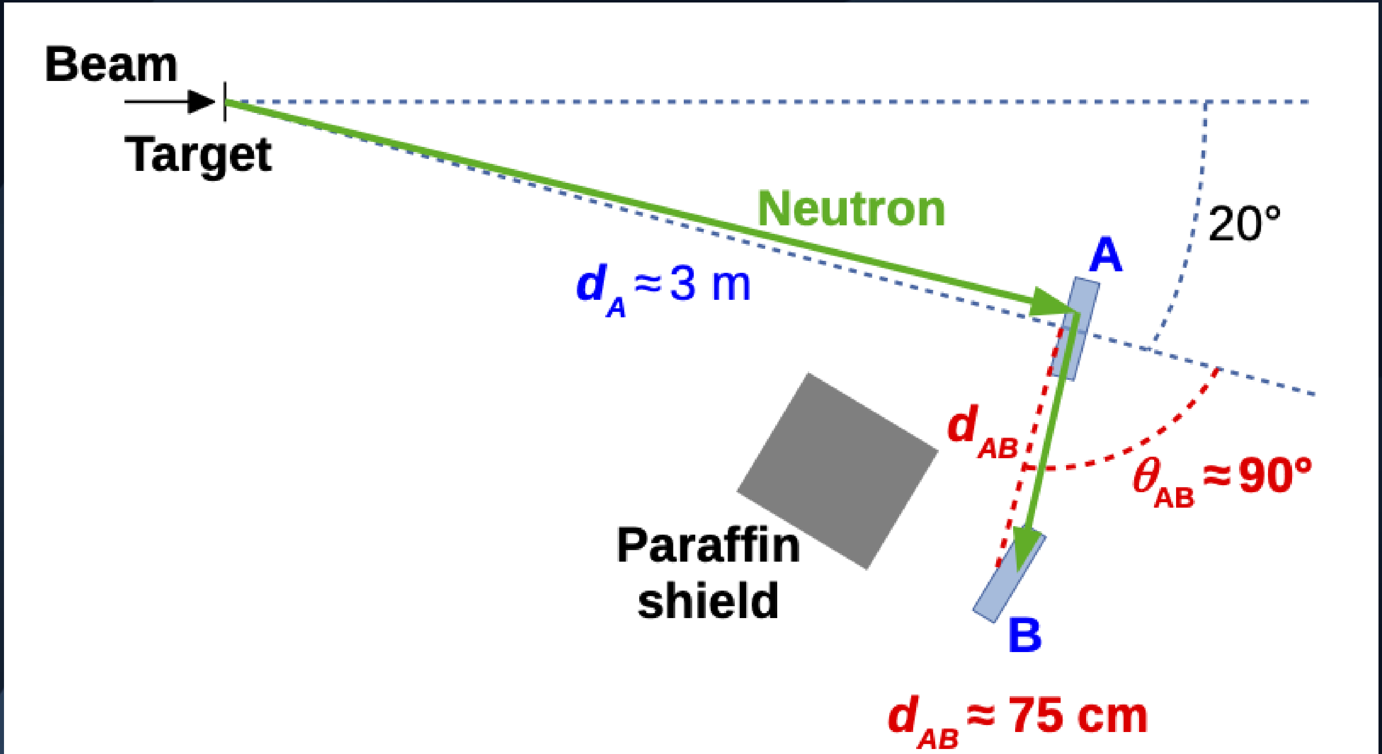
Detector placement



Detector placement



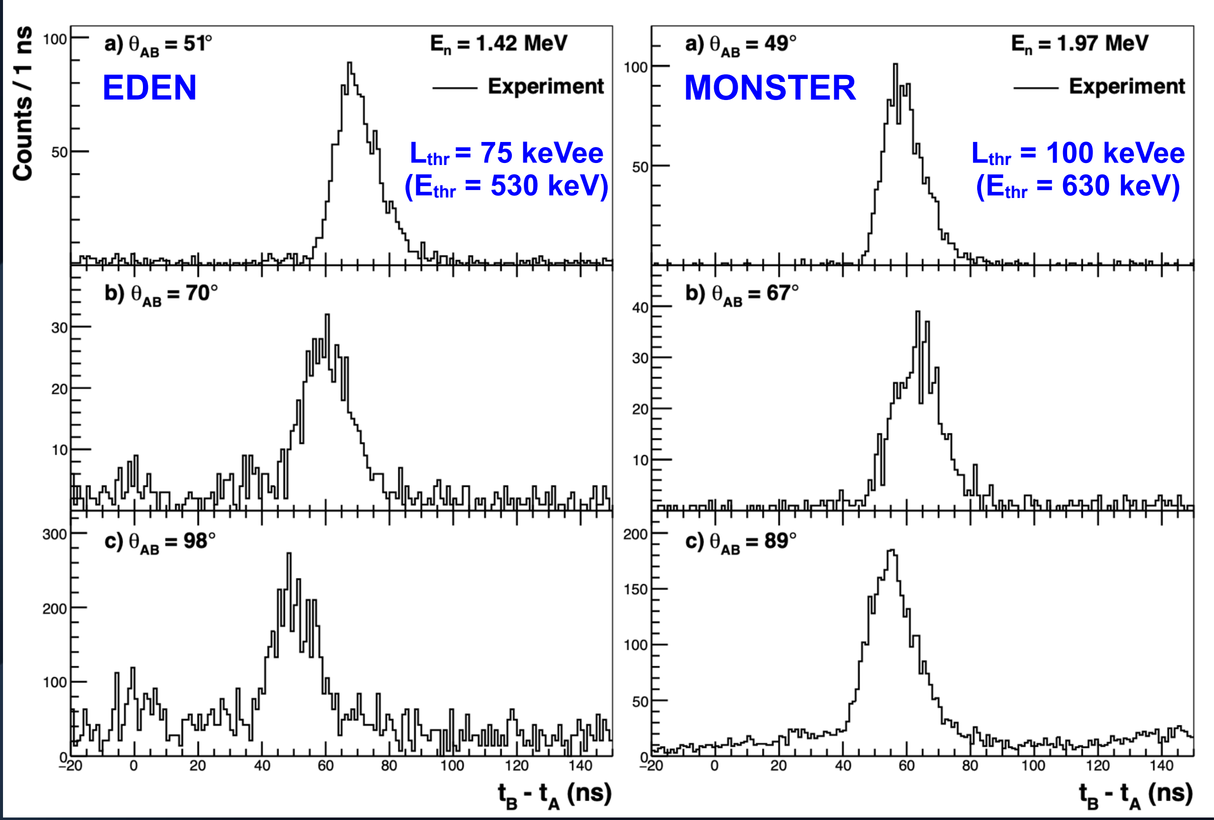
Detector placement



A→B TOF spectra : E_n = 1.4 & 2.0 MeV

- **A+B coincidence**
- **Same light output threshold L_{thr} on A and B**
- **Pulse-shape discrimination**
  → $Hit_{A,B}$ = neutron
- TOF A gate
  → **Incident E_n of interest**

➢ **Single well defined peak**



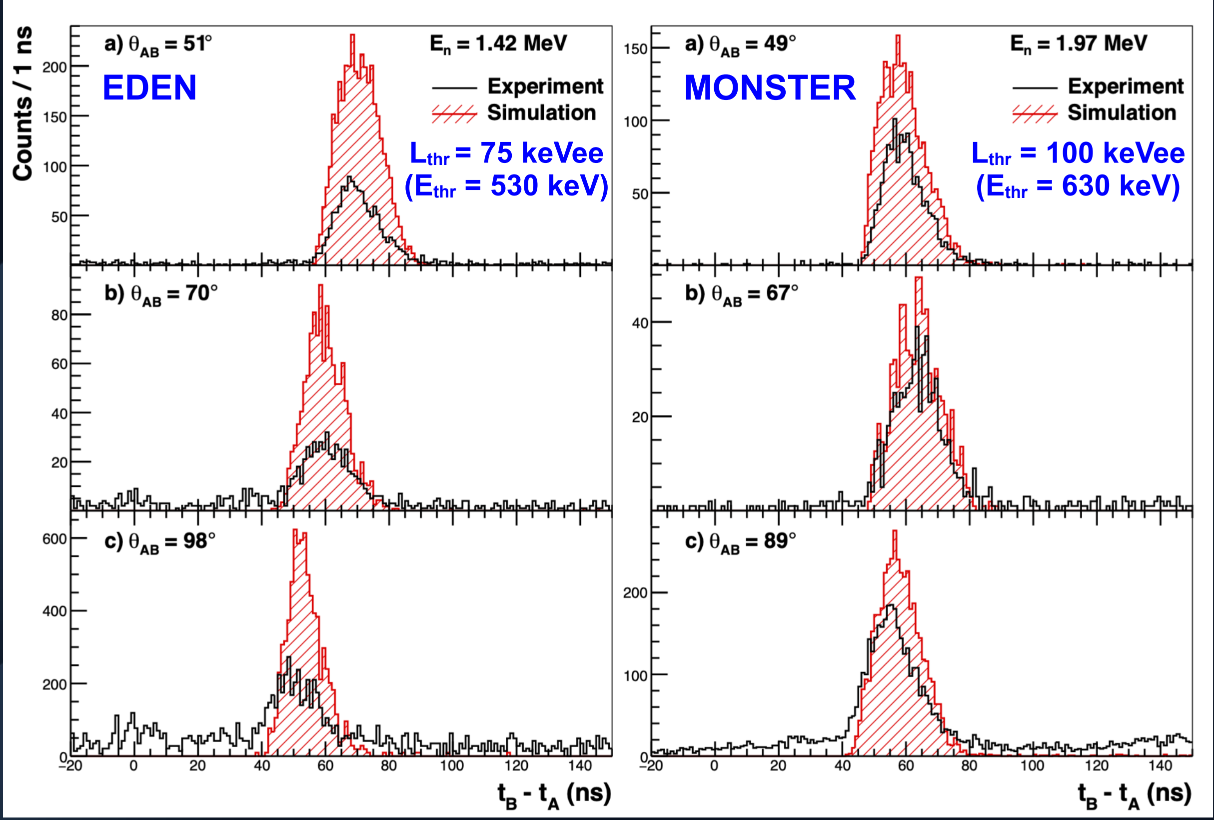
A→B TOF spectra : E_n = 1.4 & 2.0 MeV

- **GEANT4 simulations**
- Scintillator + cell walls + window + light guide + casing
- *NeutronHP* model (<20 MeV) (based on evaluated data)
- Same number of neutrons detected in A as in exp. data

➢ **Peak shape well described**

➢ **Cross-talk**

➢ **CT rates overestimated**



A→B TOF spectra : E_n = 1.4 & 2.0 MeV

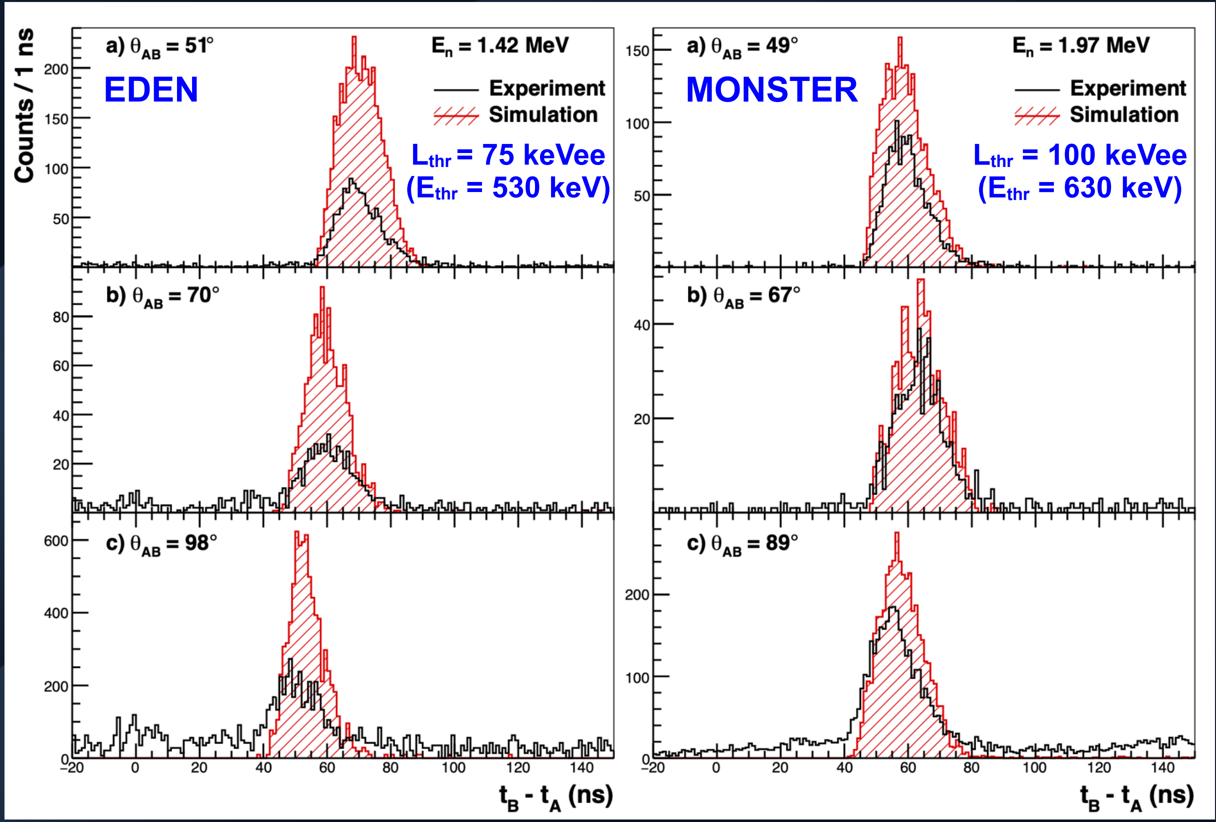
- **Background subtraction**
- **Peak integration**

  → N_{CT} cross-talk events

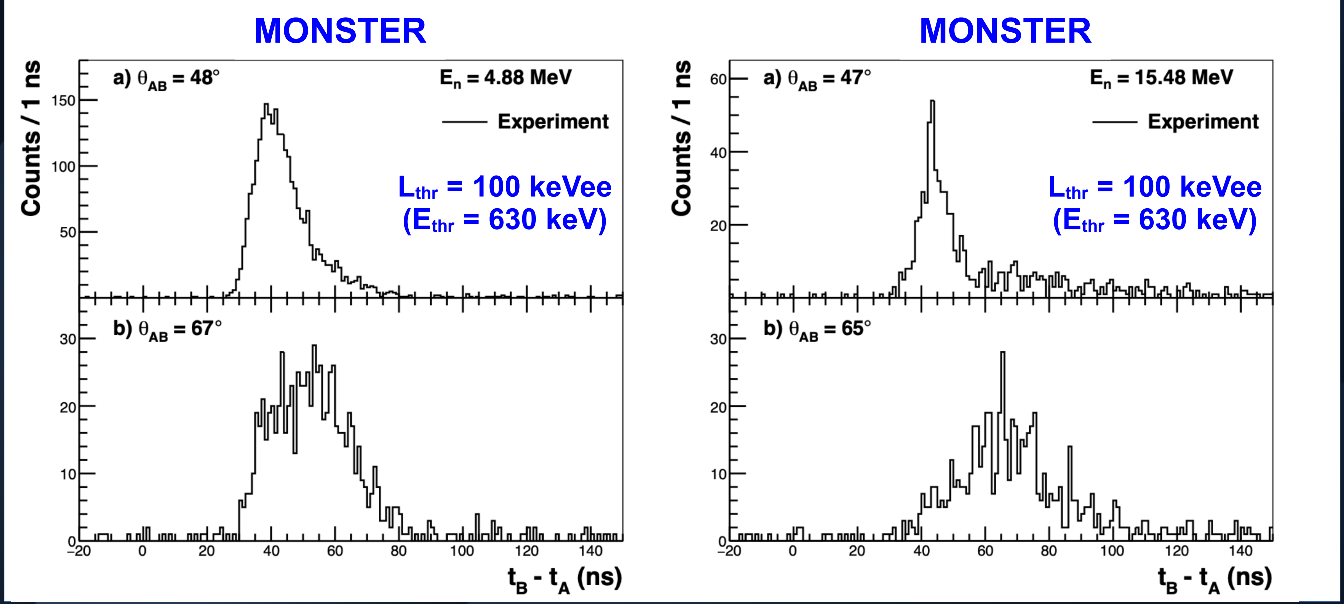
- **Cross-talk probability**:

$$P_{CT} = \frac{N_{CT}}{N_A}$$

N_A = number of neutrons detected in A with E_n of interest

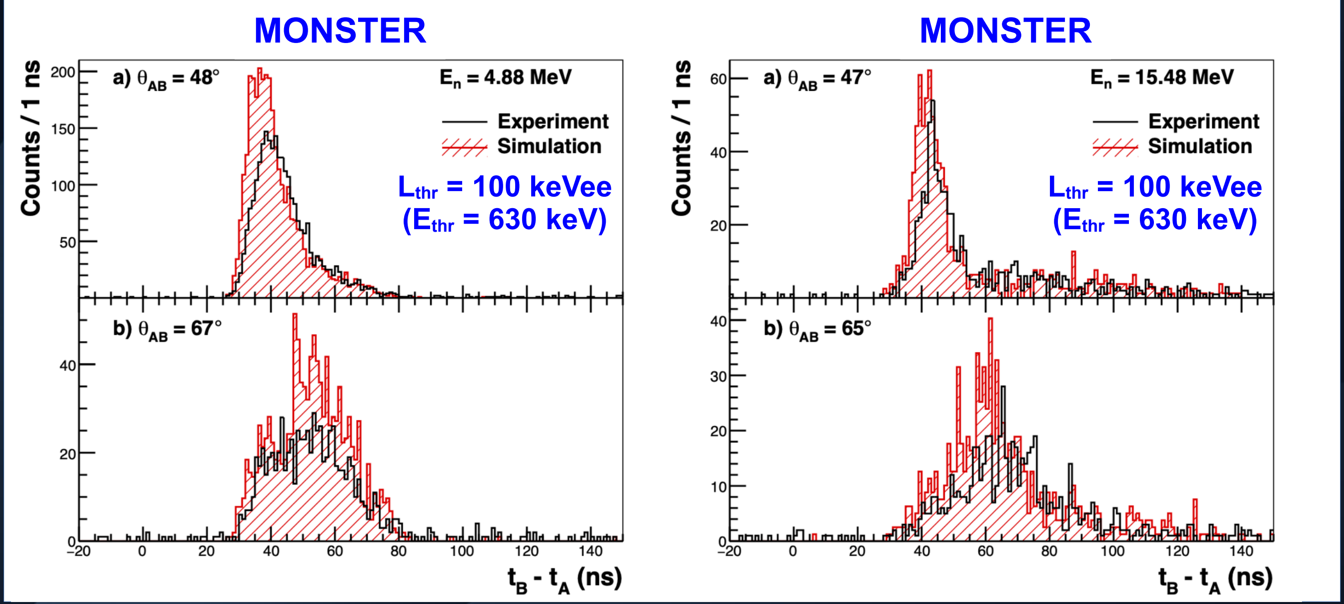


A→B TOF spectra : E_n = 4.9 & 15.5 MeV



- Broader, asymmetric peak

A→B TOF spectra : E_n = 4.9 & 15.5 MeV

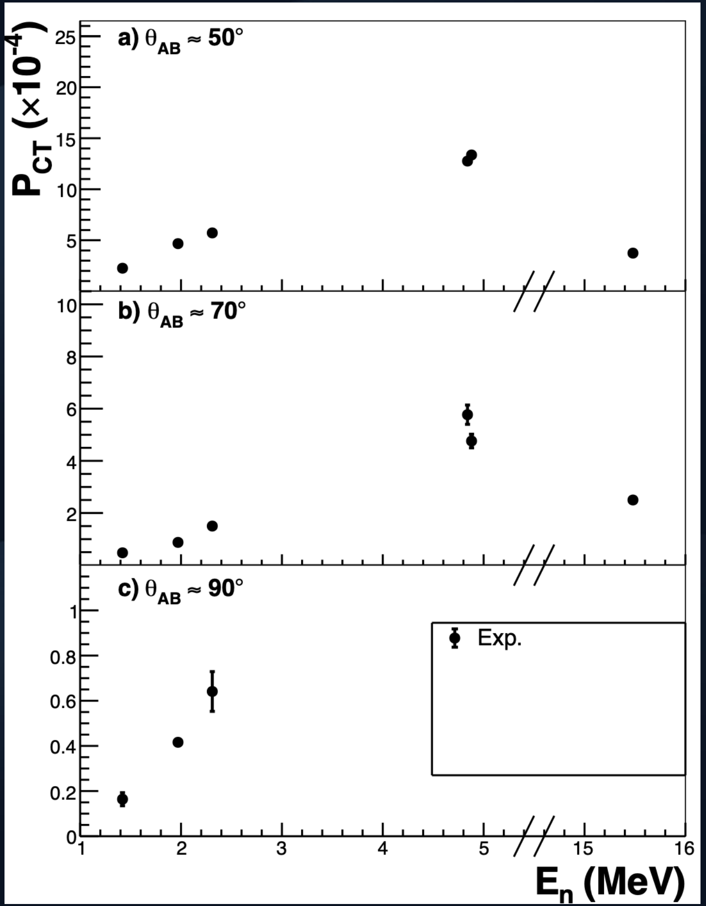


- Broader, asymmetric peak → well described by simulations

Cross-talk probabilities

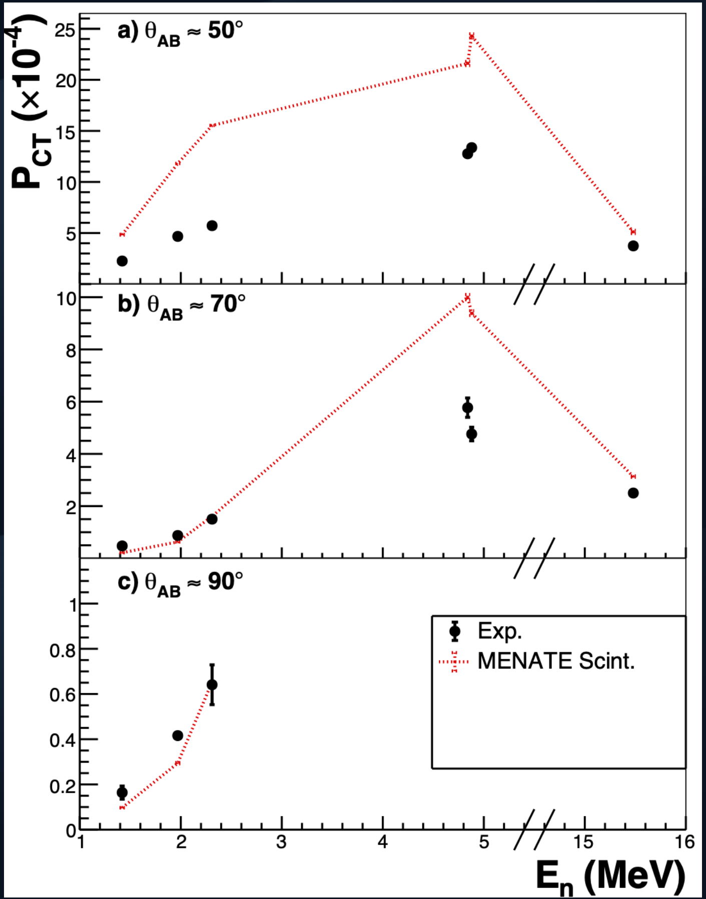
$$P_{CT} = \frac{N_{CT}}{N_A}$$

- **Experiment**:
  - $P_{CT,exp}$ increases with E_n, then decreases above E_n~5 MeV
  - Factor ~10 decrease from ~50° to ~90°



Cross-talk probabilities

- **MENATE * simulations**
  - n+p and n+^{12}C elastic scattering, n+^{12}C reactions
    → scintillator only



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* Désesquelles, NIM A 307, 366

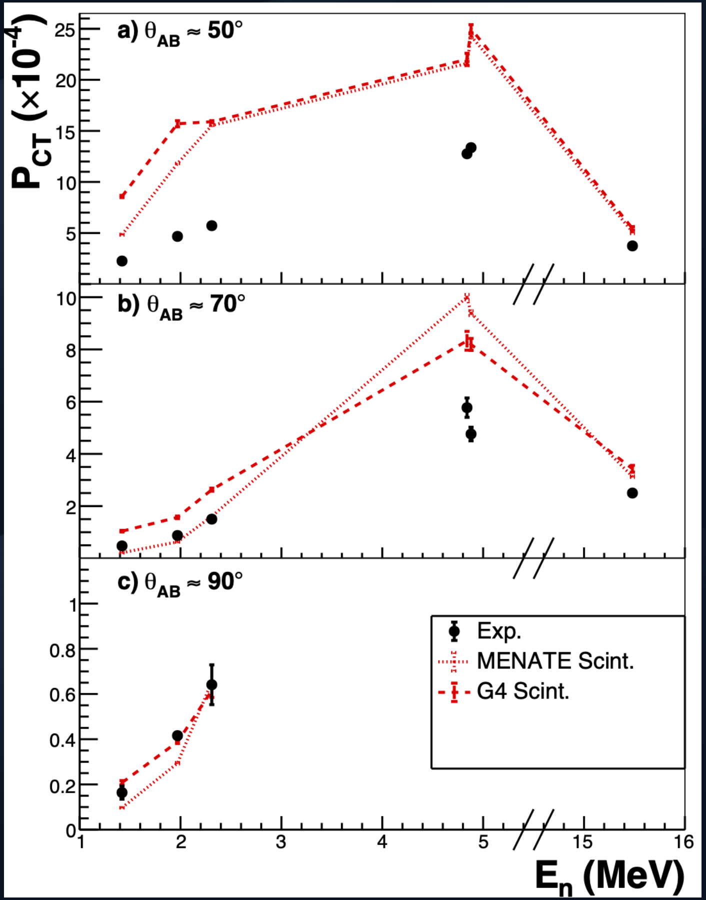
Cross-talk probabilities

- **MENATE * simulations**
  - n+p and n+^{12}C elastic scattering, n+^{12}C reactions
    → scintillator only

- **GEANT4 simulations** (scintillator only)

→ MENATE & GEANT4 agree for E_n>2-3 MeV

→ P_{CT} overestimated, except at ~90°



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* Désesquelles, NIM A 307, 366

Cross-talk probabilities

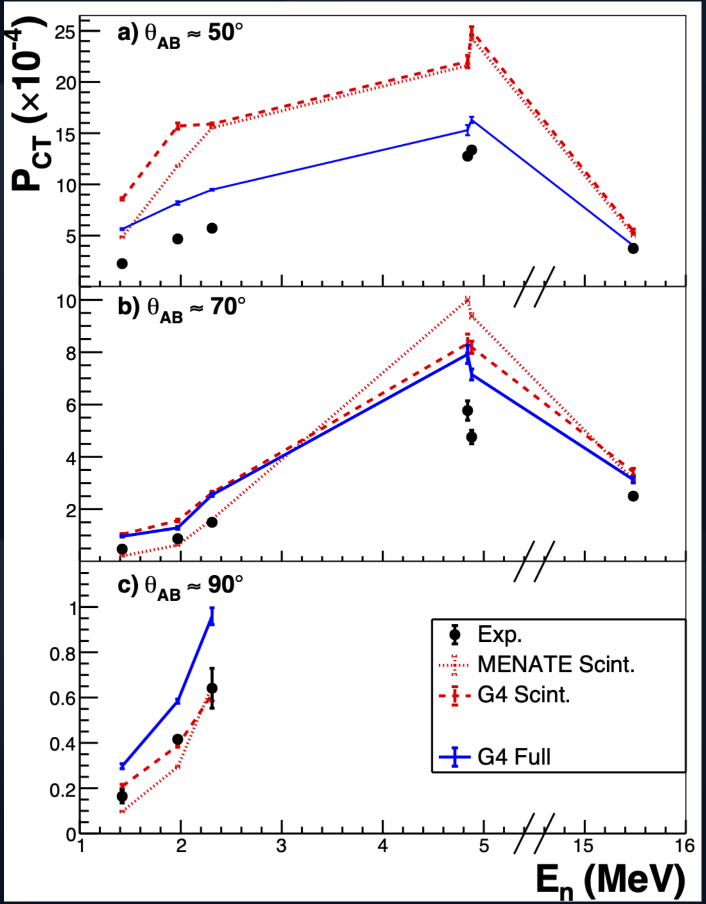
- “Full” GEANT4 simulations
  - Scintillator + inactive materials

    (cell walls + light guide + window + casing)

    → Strong improvement at ~50°

    → Smaller improvement at ~70°

    → Degradation at ~90°



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Cross-talk probabilities

- **"Full" GEANT4 simulations**
  - **Scintillator + inactive materials**

    (cell walls + light guide + window + casing)

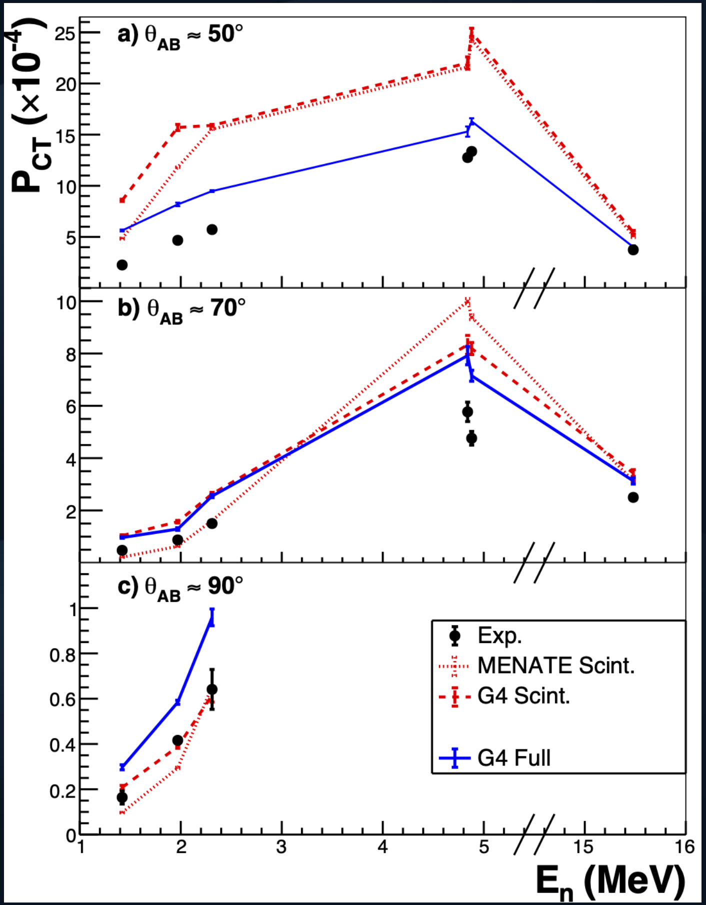
    → Strong improvement at ~50°

    → Smaller improvement at ~70°

    → Degradation at ~90°

    → Evolution with angle and incident E_n reasonably well described

    → P_{CT} overestimated, typically <40%, factor ~2 at lowest E_n



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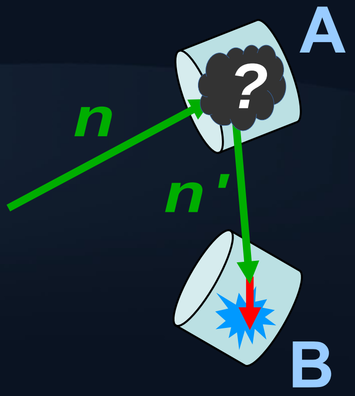
Cross-talk mechanisms

- E_n<30 MeV: Main interaction for neutron detection = np scattering
- E_n~1-2 MeV, ~90° : CT from single np scattering in A kinematically impossible
- **Interactions in A inducing CT?** → GEANT4 “full” simulations
  - E_n~1-2 MeV, ~90°: multiple scattering
  - Other (E_n, angle) configurations:

    → Single np scattering can induce CT → dominates CT

    → Other processes (multiple scattering...) → >20 % of CT



Conclusion & Outlook

- Cross-talk probabilities and TOF spectra measured between organic scintillators, for scattering angles from ~50° to ~90°, at low E_n (1.4 – 15.5 MeV)
- Monoenergetic neutrons
- GEANT4 simulations (scintillator volumes + inactive materials)
  - Shape of CT TOF spectra well reproduced
  - Evolution of P_{CT} with E_n and angle reasonably well reproduced
  - CT probabilities overestimated
- Whenever single np scattering in A can induce CT → dominates CT events
- But other processes (multiple scattering) → >20 % of CT, become dominant ~90°

→ Must be taken into account in simulations and CT identification filters

Thank you for your attention

Back up

Beams, targets and reactions

E_n (MeV) (20°, det. A)	Reaction	Beam energy (MeV)	Target	Impregnation ratio x	Thickness (mg/cm^2)
1.42	$T(p,n)^3He$	2.37	TiT_x	1.59	0.608
1.97	$T(p,n)^3He$	3.00	TiT_x	1.52	0.956
2.31	$T(p,n)^3He$	3.30	TiT_x	1.59	0.608
4.84	$D(d,n)^3He$	1.93	TiD_x	1.76	0.964
4.88	$D(d,n)^3He$	1.93	TiD_x	1.55	0.929
15.48	$T(d,n)^4He$	0.70	TiT_x	1.52	0.956

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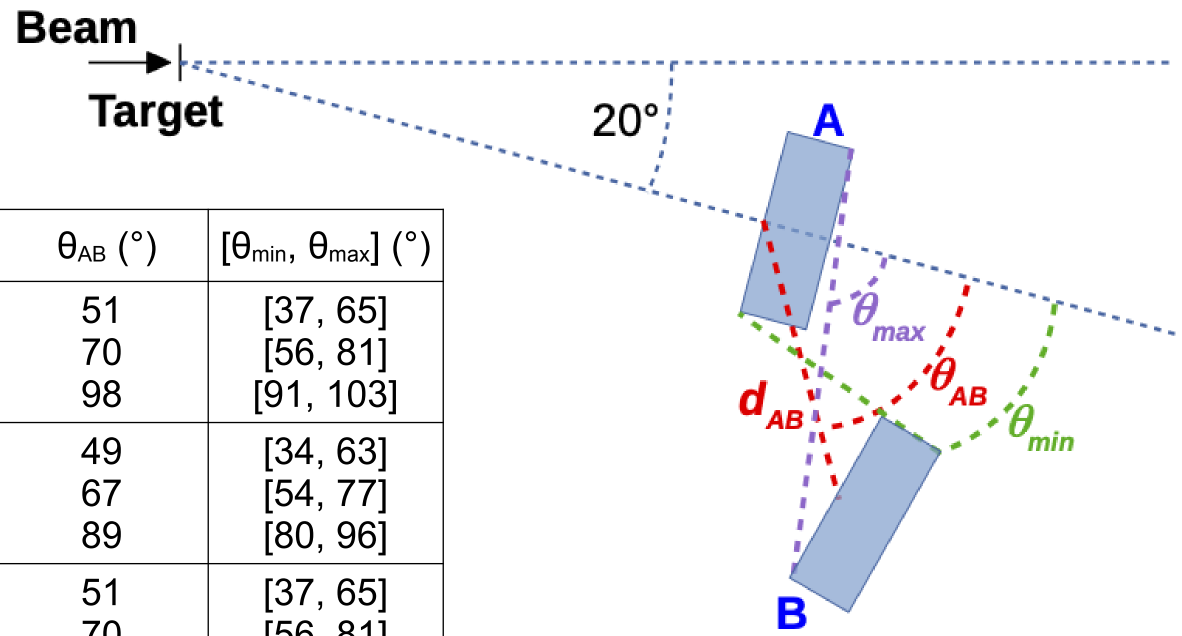
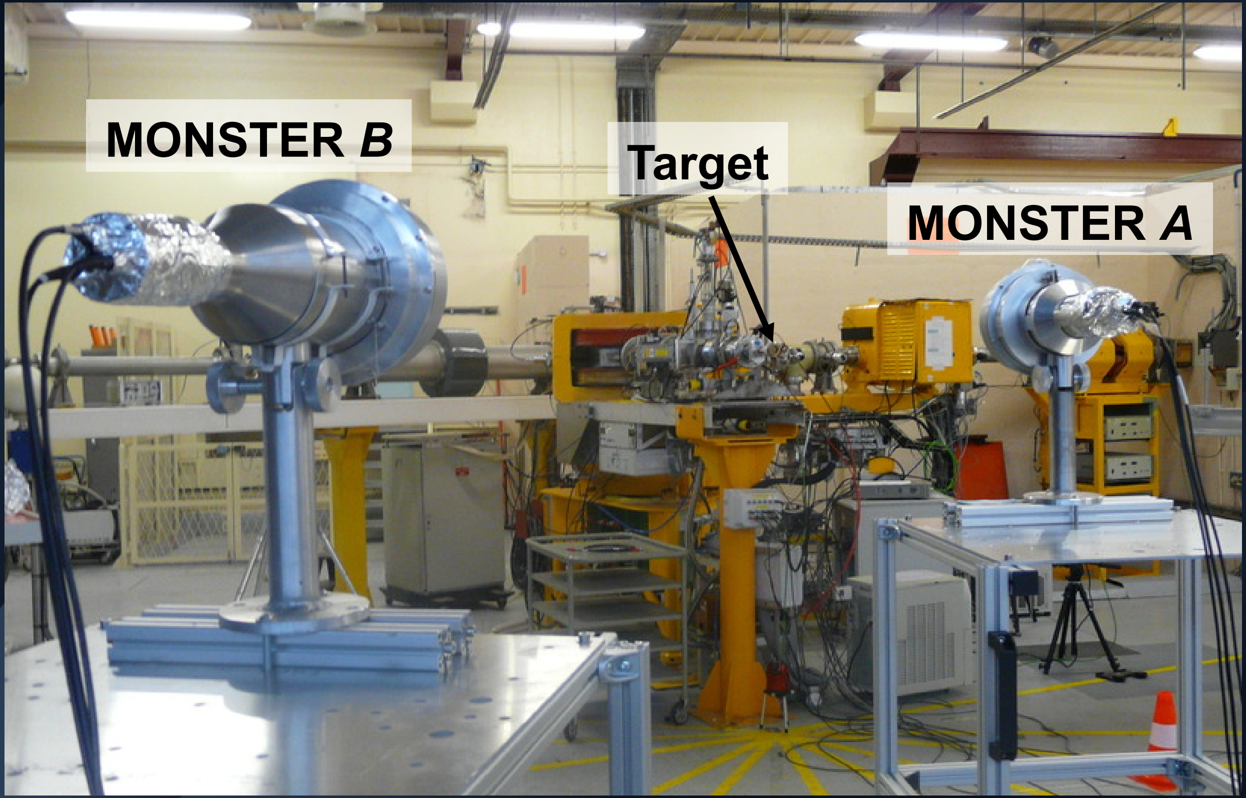
Detector placement

E_n (MeV)	Detectors	d_{AB} (cm)	θ_{AB} (°)	[θ_{min}, θ_{max}] (°)
1.42	EDEN	86 73 67	51 70 98	[37, 65] [56, 81] [91, 103]
1.97	MONSTER	84 87 81	49 67 89	[34, 63] [54, 77] [80, 96]
2.31	EDEN	86 73 67	51 70 98	[37, 65] [56, 81] [91, 103]
4.84	EDEN	86 73	51 70	[37, 65] [56, 81]
4.88	MONSTER	84 87	48 67	[34, 63] [54, 77]
15.48	MONSTER	156 153	47 65	[38, 57] [57, 73]



Detector placement



Paraffin shield

- Cross section = 40 x 40 cm^2, thickness = 60 cm
- Reduce rate of real 2n coincidences from 2 reactions in the same beam pulse
- Simulations with MCNP (v4C2)

→ Transmission factor of neutrons with E_n'>600 keV (~threshold):

- E_n = 6 MeV : ~6 x 10^{-5}
- E_n = 16 MeV : ~5 x 10^{-3}

→ Given the beam intensities, the reaction cross sections, Poisson's statistics, detector solid angles, neutron efficiencies:

- P_{2n}/P_{CT} < 0.4 %

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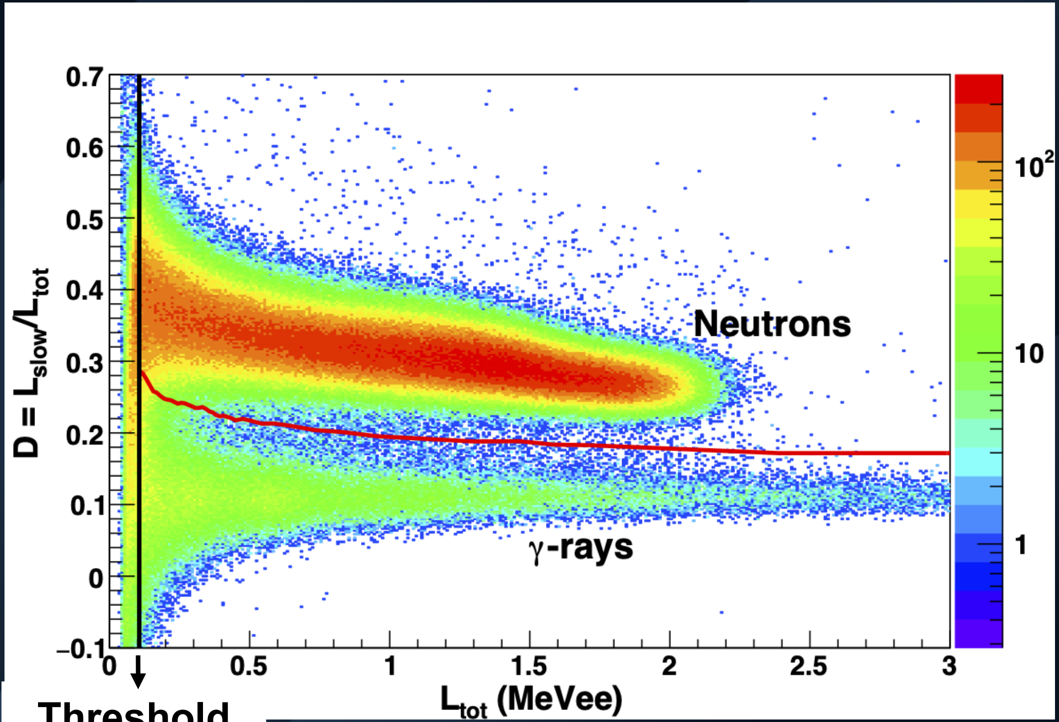
Setup – Electronics

- FASTER digital electronics and DAQ system (LPC Caen)
- 100-MHz input bandwidth
- Digitizer : 500 MS/s, 12 bit, input range 2 V
- Triggerless, no common dead time
- FPGA
  - Base line subtraction
  - Time stamping (CFD) → TOF
  - Pulse integration → Total light output L_{tot} , slow light output L_{slow}
    → Neutron-gamma pulse-shape discrimination

Pulse shape-discrimination

- E_n = 4.84 MeV, detector A (EDEN)



Threshold
= 100 keVee

Integration windows:

- L_{tot} : 250 ns
- L_{slow} : delay = 40 ns

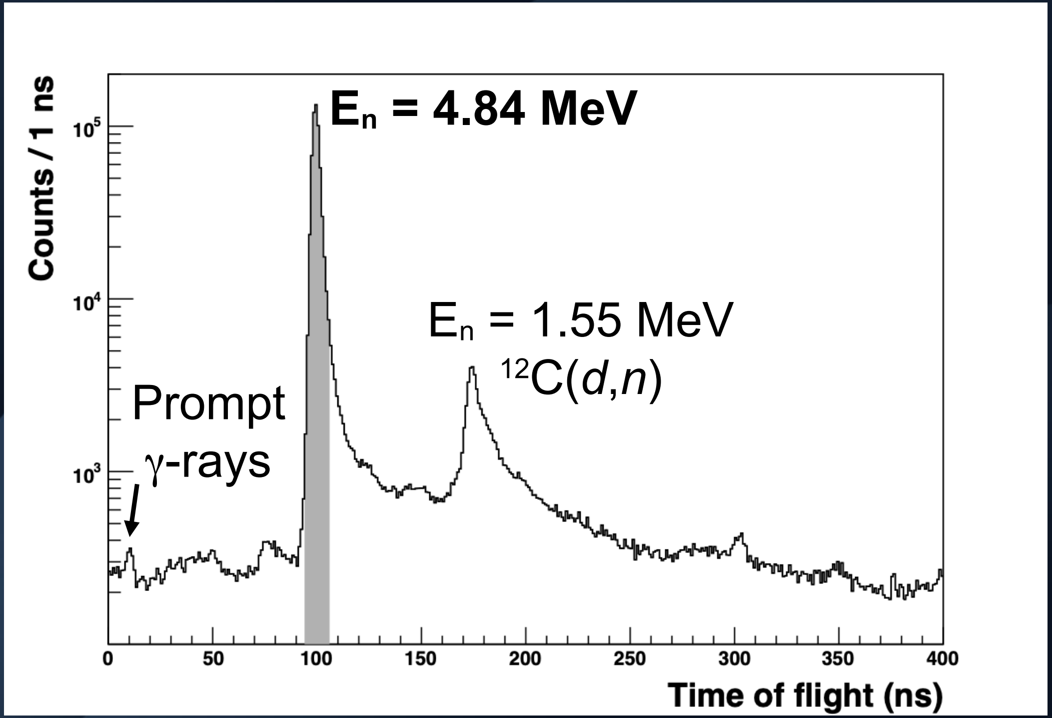
Figure of merit:

$$M = \frac{W_n - W_\gamma}{\overline{D_n} - \overline{D_\gamma}}$$

- M = 1.65 @ 1.0 MeVee
- M = 1.0 @ 0.23 MeVee

Detector A time-of-flight

- E_n = 4.84 MeV, detector A (EDEN)



Simulations

- GEANT4 v4.10.06
  - "Shielding" physics list: includes "NeutronHP" model for E_n<20 MeV → based on evaluated data (cross-section, energy-angle distributions)
  - Improved description of $^{12}C(n,\alpha)$ (E_n>6.2 MeV) and $^{12}C(n,n'3\alpha)$ (E_n>8.3 MeV) *
  - Light output response function for each charged particle type **
  - Same threshold on L_{tot} as in experimental data analysis
  - "Pulse shape discrimination" : if $L_{HCP} > 0.5 \times L_{tot}$ → neutron
- MENATE
  - n+p and n+^{12}C elastic scattering + important n+^{12}C reactions
  - Scintillator only

* Garcia, NIM A 868, 73

** Cecil, NIM 161, 439

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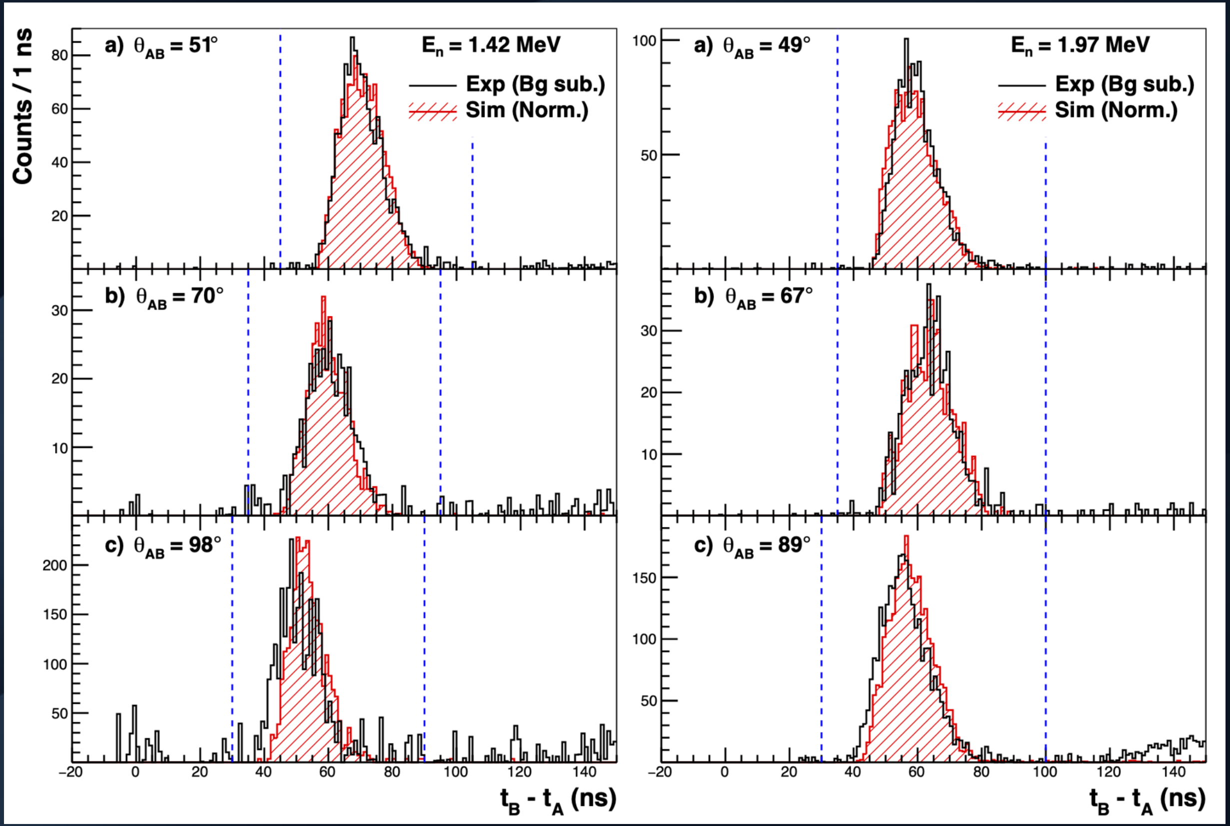
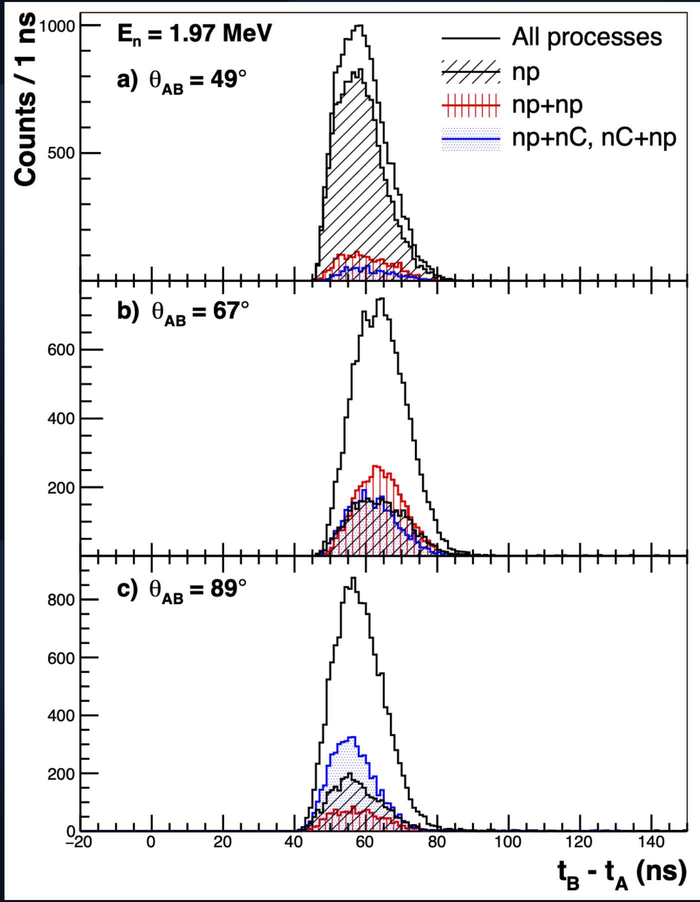
A→B TOF spectra : E_n = 1.4 & 2.0 MeV

- Experimental spectra:
  Background subtraction
- Simulations:
  Normalized to the same number of CT events as in the experiment



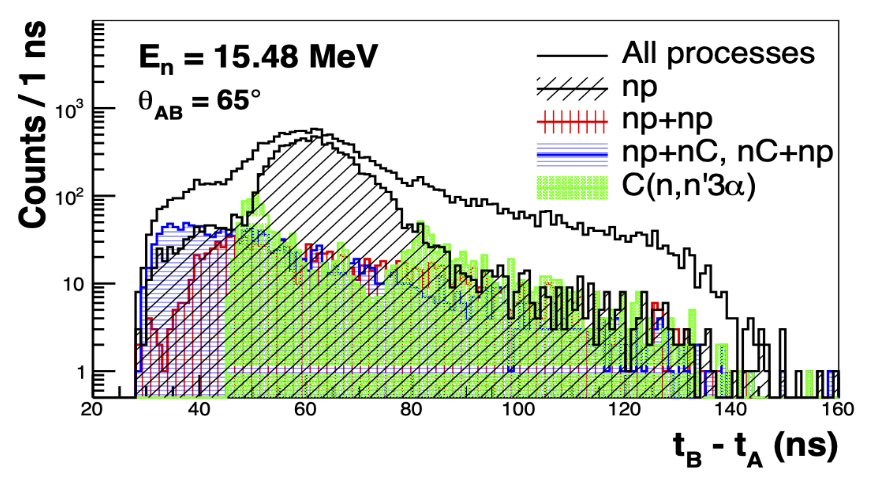
Cross-talk mechanisms

- np scattering = main *detection* process
- For ~90° and (1.42 MeV, ~70°):
  CT from single np scattering in A impossible
  → CT from multiple scattering in A
  or in A + light guide
- If CT from np scattering possible
  → Dominates CT
  → But other processes >20 % of CT
- CT identification algorithms for E_n<30 MeV:
  → often assume np scattering in A
  → limited efficiency, need other criteria



Cross-talk mechanisms – E_n = 15.48 MeV

- When CT from single np kinematically possible → Dominates CT
- But other processes = significant source of CT (> 25 %)



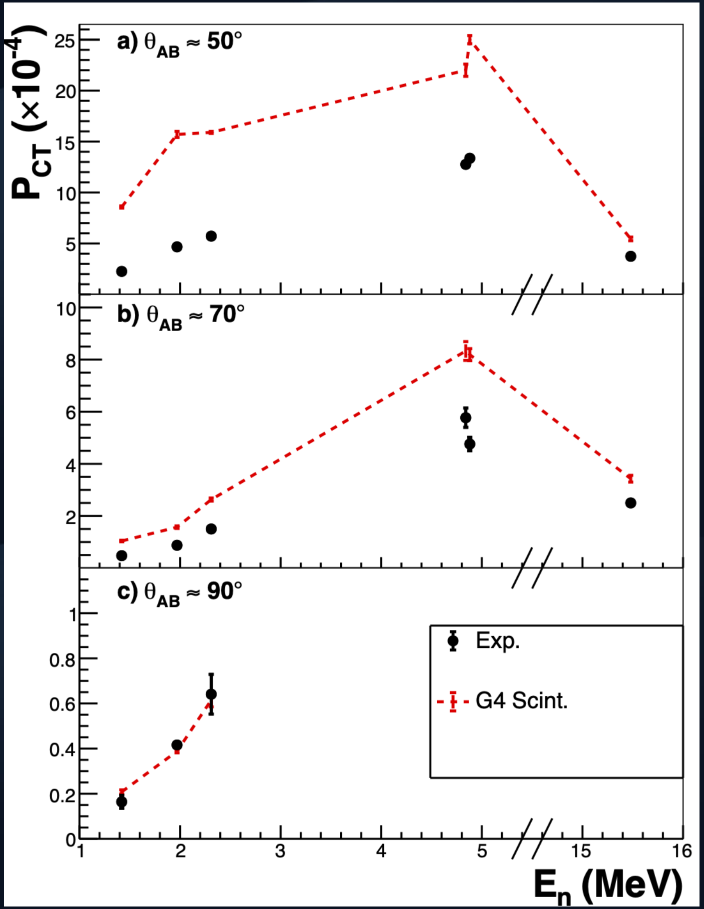
- Single np scattering → 50-60 % of CT
- Double scattering → 17 % of CT
- $^{12}C(n,n'3\alpha)$ → 10 % of CT
- $^{12}C(n,\alpha)^9Be$, $^{12}C(n,p)^{12}B$, $^{12}C(n,d)^{11}B$ → no CT

- $t_B - t_A$ peak : single np scattering
- $^{12}C(n,n'3\alpha)$, double scattering → broader TOF distribution

Cross-talk probabilities

- **GEANT4 simulations**
  - Scintillator only

    → P_{CT} overestimated at ~50° and ~70°



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Cross-talk probabilities

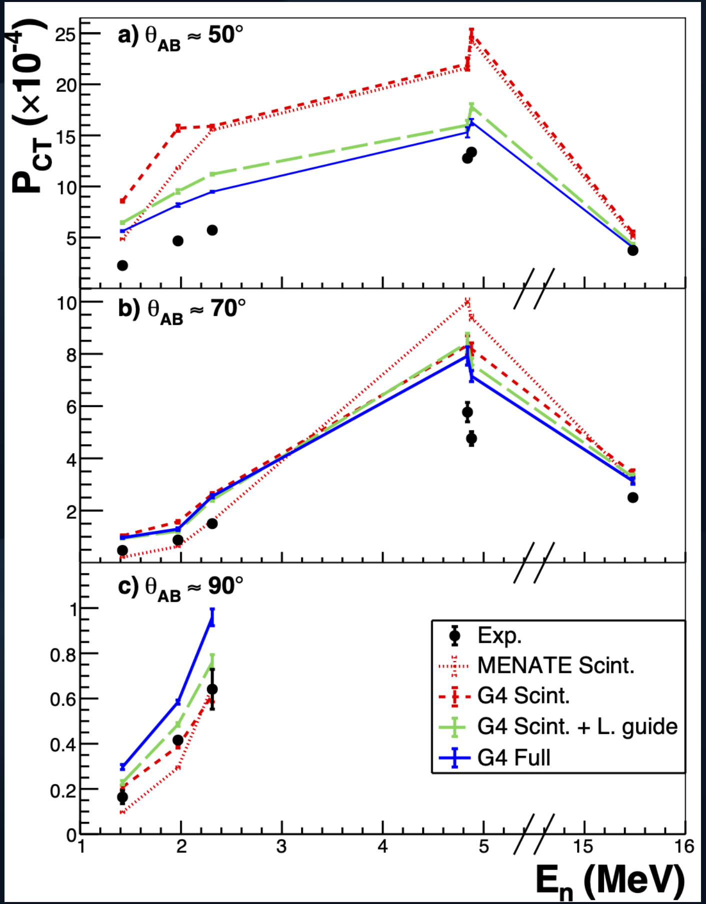
- GEANT4 simulations
  - Inclusion of light guide

    → Crucial at ~50°, small effects at ~70° and ~90°
  - Inclusion of other inactive materials (“Full”)

    (cell walls + window + casing)

    → Improvement at ~50° (and ~70°)

    → Degradation at ~90°



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