Advances in neutron source modelling for BNCT applications

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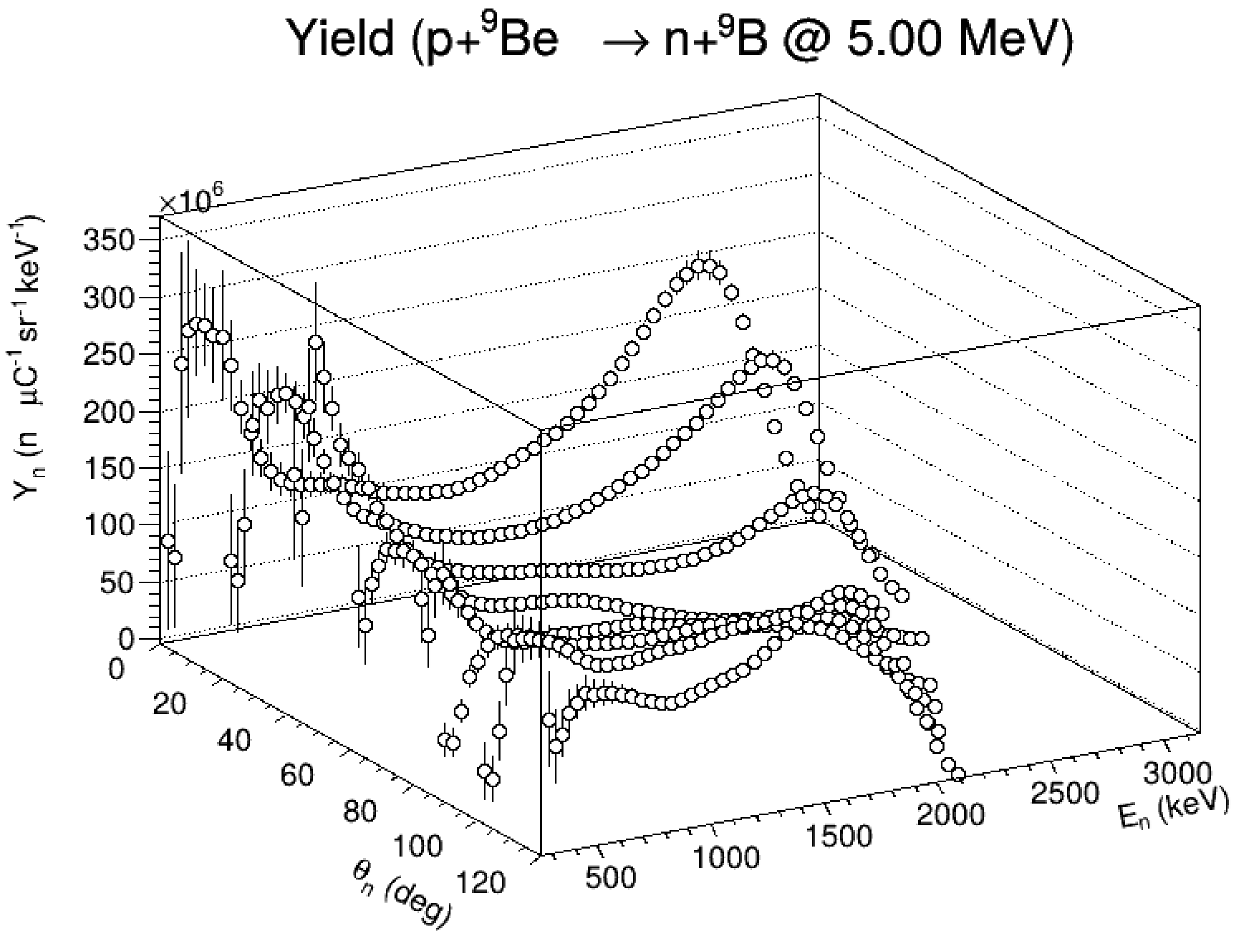
1. A new hybrid model for the accurate calculation of neutron yield for p+^{9}Be @5 MeV
2. Definition of a BNCT neutron source for p+^{9}Be in Geant4
3. Theoretical study of a composite Be+Li target for p @5 MeV

Annual bootstrap meeting Pilot 4.9 ANTHEM
Pavia, February 12, 2026

Starting point 1

- Data from Agosteo et al. (2011)

S. Agosteo et al., *Characterization of the energy distribution of neutrons generated by 5 MeV protons on a thick beryllium target at different emission angles.*, Applied Radiation and Isotopes 69.12 (2011): 1664-1667.



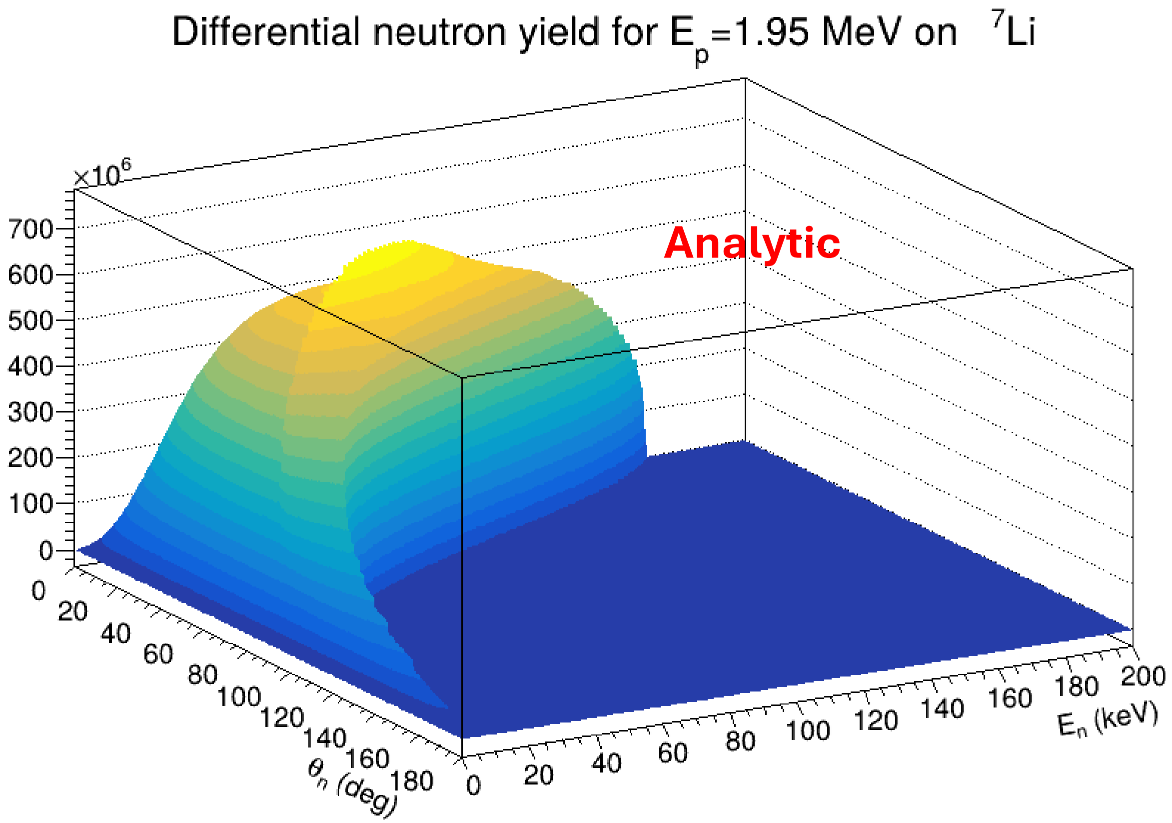
- Data only up to 120°.
- How to reproduce the spectra up to 120°?
- How to extrapolate up to 180°?

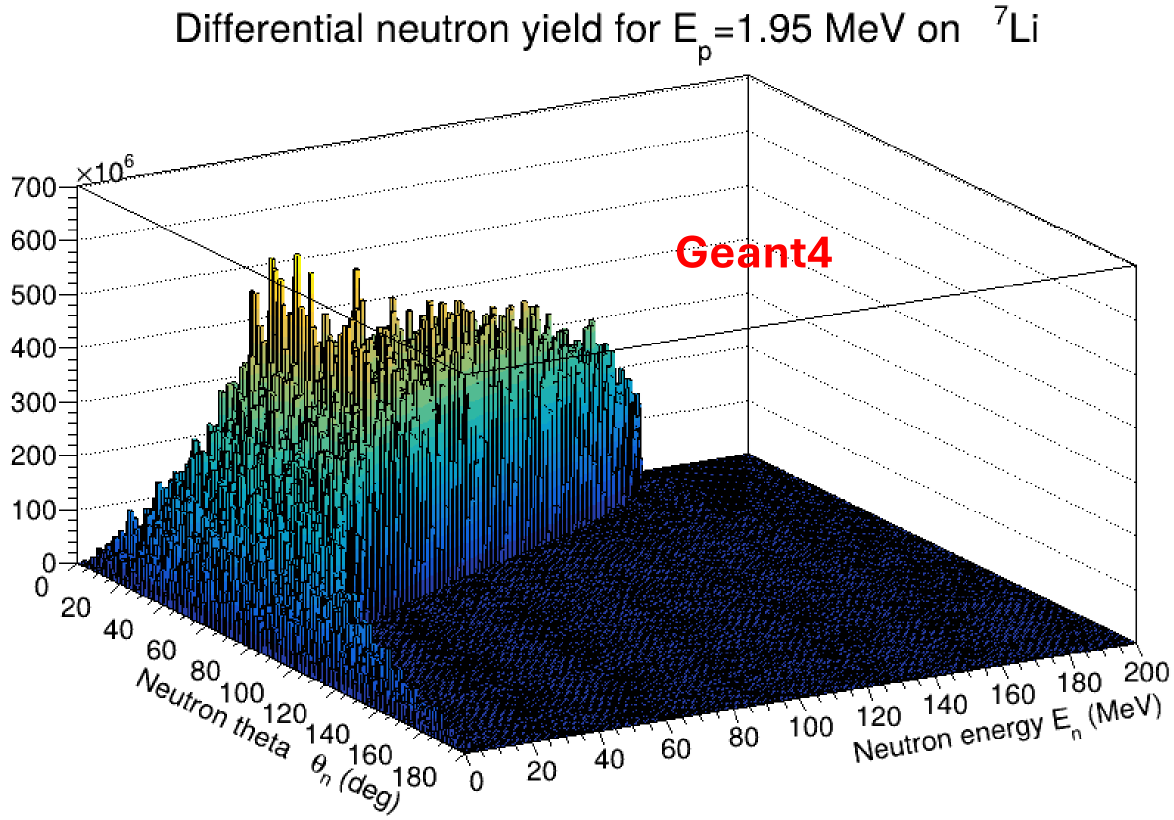
Starting point 2

- Reaction: p + ^{7}Li (solved analytically and with Geant4 with QGSP_BIC_AllHP)
- Only 1 reaction channel (p + ^{7}Li → ^{7}Be + n)

C.L. Lee, X.-L. Zhou, NIMB 152 (1999)

Energy (MeV)	Analytic yield (n/mC)	MC yield (n/mC)
1.95	6.29×10^{10}	5.94×10^{10}
2.00	1.10×10^{11}	1.08×10^{11}
2.30	5.86×10^{11}	5.67×10^{11}





p + ^{9}Be reaction

- Reaction channels at 5 MeV:

channel	products	Q-value (keV)	Threshold (keV)
(p, n)	$^9B + n_0$	-1850.4	2057.4
	$^9B^* + n_1$	-3529.96	3924.62
	$^9B^* + n_2$	-4194.96	4663.97
(p, p'n)	$^8Be + p + n$	-1664.54	1850.77
(p, p'αn)	$2\alpha + p + n$	-1572.70	1748.65
(p, αn)	$^5Li + \alpha + n$	-3540	3930

Many open channels!

They all involve the same final state:

$2\alpha + p + n$

$$p + {}^9Be \rightarrow \begin{cases} {}^9B + n \rightarrow {}^8Be + p + n \\ {}^8Be + p + n \rightarrow 2\alpha + p + n \\ {}^5Li + \alpha + n \rightarrow \alpha + p + \alpha + n \\ \alpha + p + \alpha + n \end{cases}$$

^{9}B	$T_{1/2} = 0.8$ as $= 0.8 \times 10^{-18}$ s
^{8}Be	$T_{1/2} = 81.9$ as $= 81.9 \times 10^{-18}$ s
^{5}Li	$T_{1/2} = 0.37$ zs $= 0.37 \times 10^{-21}$ s

Analytical approach

- The basis is the **Lee and Zhou formalism**:

$$\frac{d^2N}{dE_n d\Omega} = \frac{f_{Be} N_0}{eA} \cdot \frac{\frac{d\sigma}{d\Omega_{cm}} \cdot \frac{d\Omega_{cm}}{d\Omega} \frac{dE_p}{dE_n}}{-\frac{1}{\rho}\frac{dE_p}{dx}} \quad \Longleftrightarrow \quad Y'' = k \cdot \frac{X' \cdot J}{S}$$

With the four channels →

$$Y''_{tot} = Y''_{p,n} + Y''_{p,p'n} + Y''_{p,p'\alpha n} + Y''_{p,\alpha n}$$

***k*, *J* and *S* can be evaluated** (J with MC methods for many particles final states).

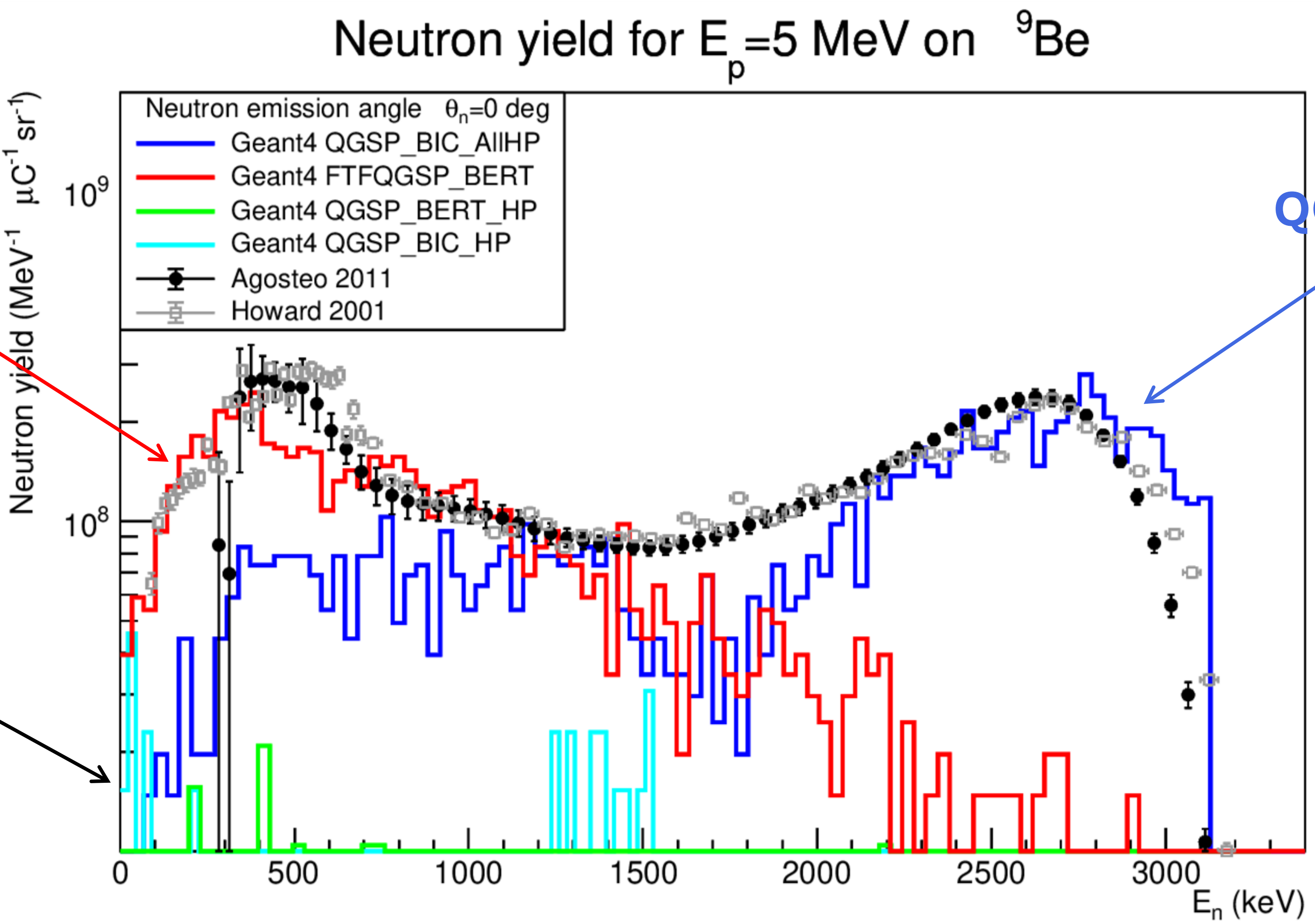
The differential cross sections are not known for each individual reaction channel.

The differential and total cross sections are available only for (p,n_0) and (p,xn).

Geant4 yield at 0°: physics lists comparison

FTFQGSP_BERT

All the other hadronic physics lists



QGSP_BIC_AllHP

Results obtained with 10^{10} primaries on a 3 mm thick ^{9}Be target with a 3 mm radius

QGSP_BIC_AllHP and FTFQGSP_BERT provide partial description

Hybrid model

We used QGSP_BIC_AllHP for the (p, n_0) channel. How to calculate the yield of (p,p'n)?

Idea: with the hypothesis of 2 dominant channels, **cross section of (p, p'n) can be derived from the cross sections of (p, xn) and (p,n_0)**

assuming isotropic emission

$$X_{p,p'n} = X_{tot} - X_{p,n}$$

$$X'_{p,p'n} = \frac{X_{p,p'n}}{4\pi}$$

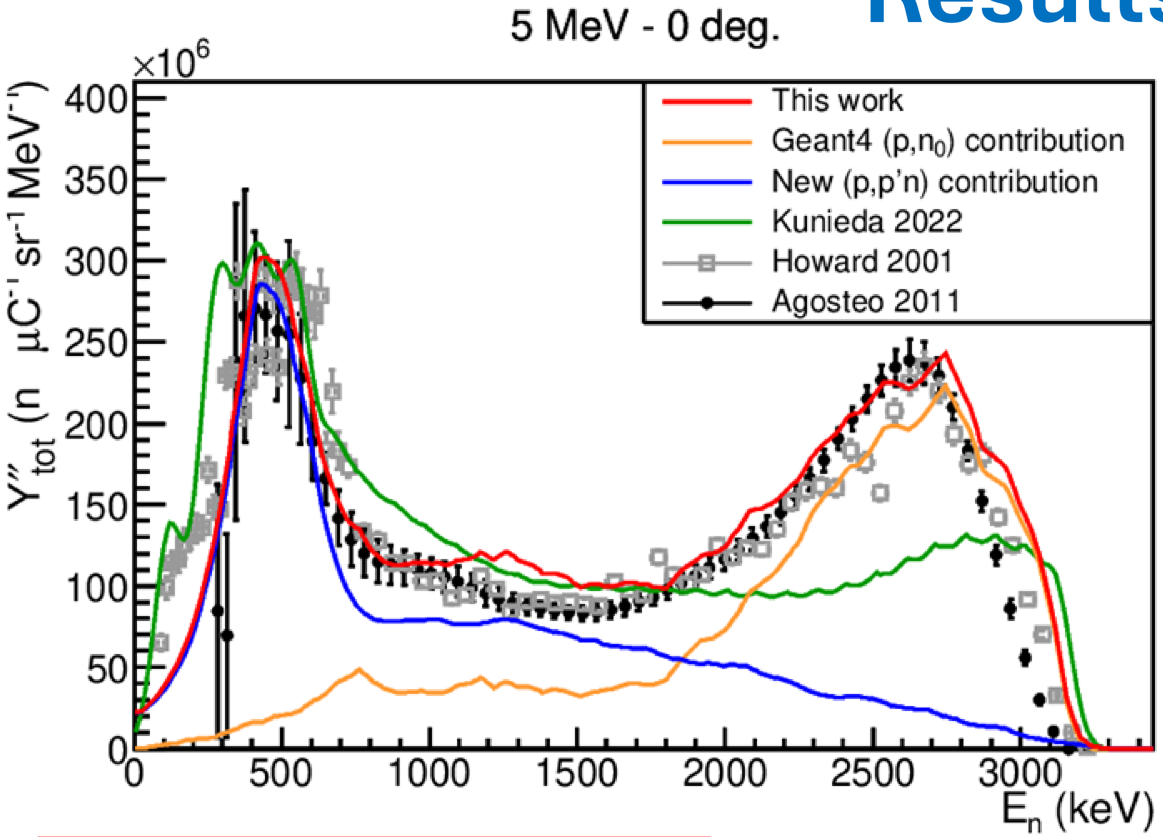
$$Y''_{p,p'n} = k \cdot \frac{X'_{p,p'n} J_{p,p'n}}{S}$$

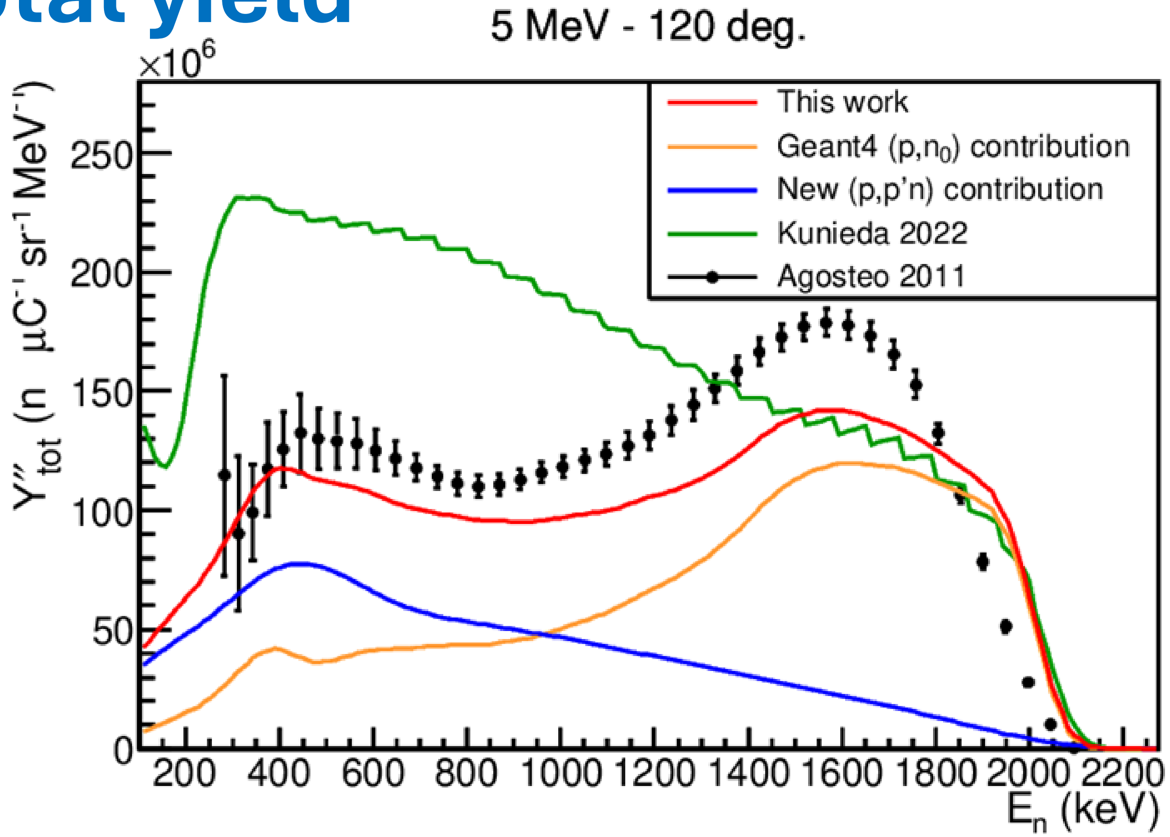
$$Y''_{tot} \approx Y''_{p,n} + \hat{Y}''_{p,p'n} = Y''_{p,n} + Y''_{p,p'n} f_{p,p'n}(\theta_n, E_n)$$

Correction factor to reproduce the realistic angular distribution of (p, p'n): parameters from yield data fitting

$$f_{p,p'n}(\theta_n, E_n) = p_0 + \frac{p_1}{1 + \exp(p_2\,\theta_n)} \exp\left[-\frac{(E_n - p_3 - p_4 \sin(\theta_n/2))^2}{p_5}\right]$$

Results: total yield





Based on (p,n_0) and $(p,p'n)$

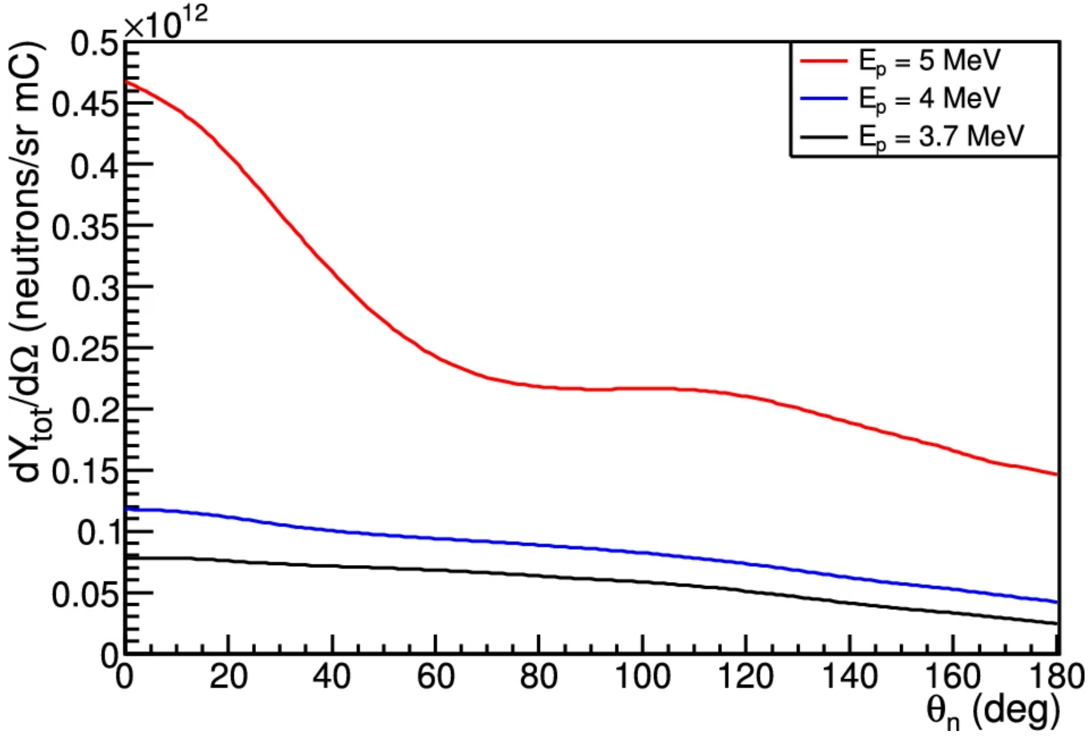
Reference	Y_{tot} (n/mC)
This work	**2.96×10^{12}**
Data from Agosteo *	**$3.3 – 3.5 \times 10^{12}$**
DROSG2000	1.55×10^{12}
Kunieda 2022	4.21×10^{12}

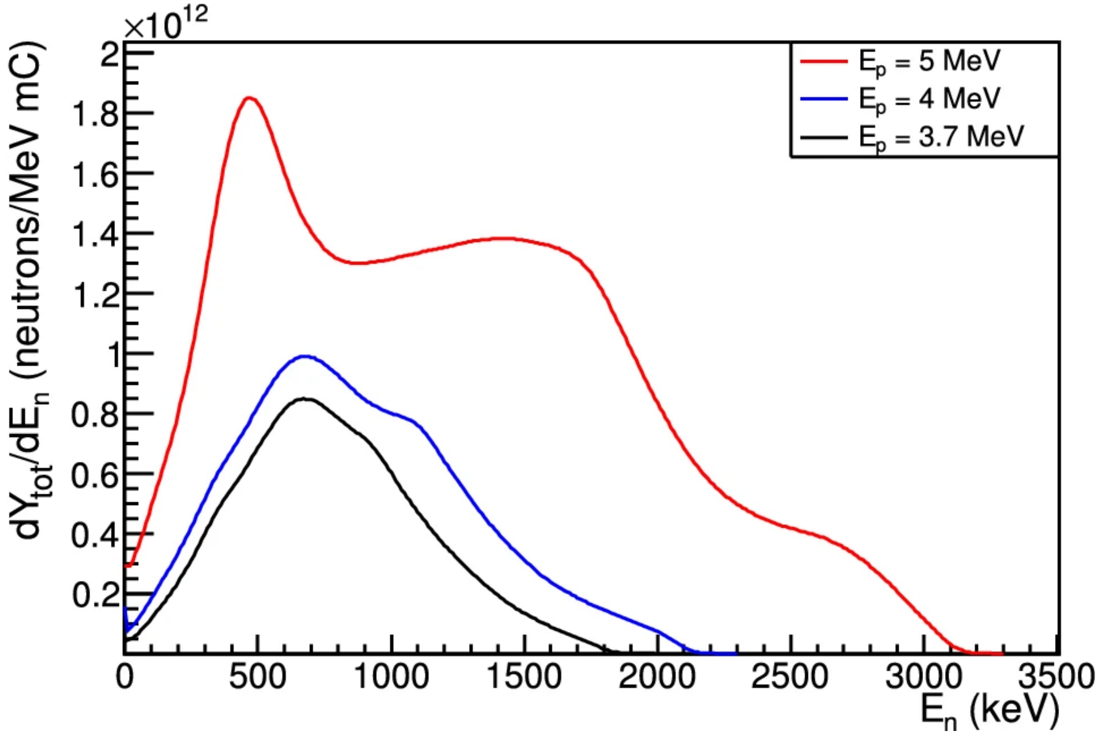
Distributed by IAEA
Based only on (p,n_0)

*** explicit integration of data gives 2.84×10^{12} n/mC**

Implemented in JENDL5
Based on (p,n_0), (p,n_2) and (p,n_4)

Results: angle and energy distributions





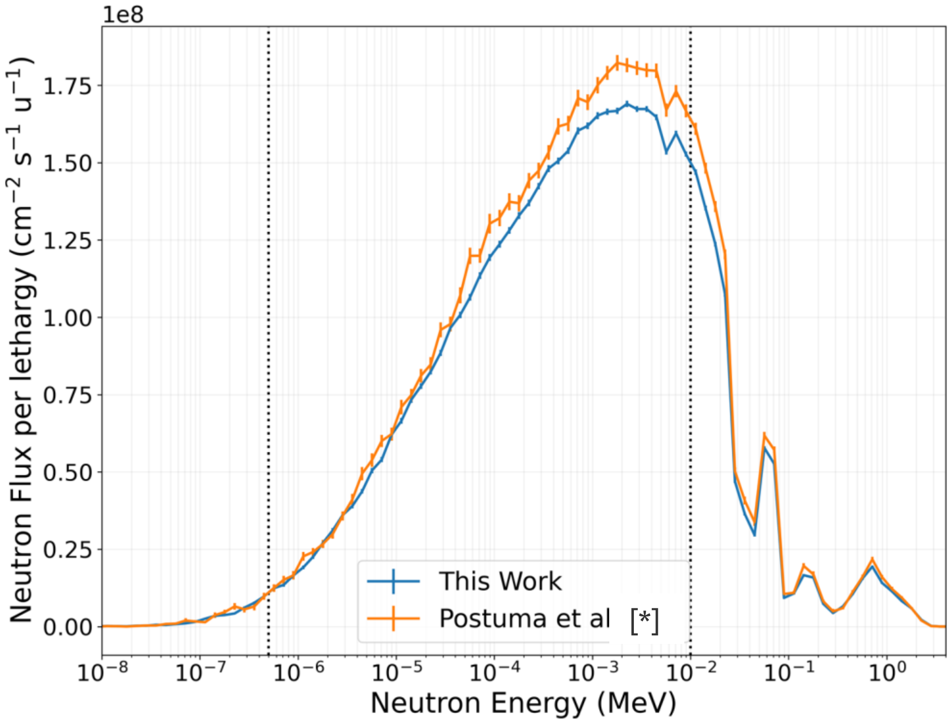
Maximum and average values of the energies and angles of the emitted neutrons

E (MeV)	E_n max (keV)	E_n avg (keV)	θ_n max (deg)	θ_n avg (deg)
3.70	1998.	791.73	180.	76.01
4.00	2300.	894.59	180.	76.96
5.00	3303.	1299.08	180.	73.38

BSA study refinement

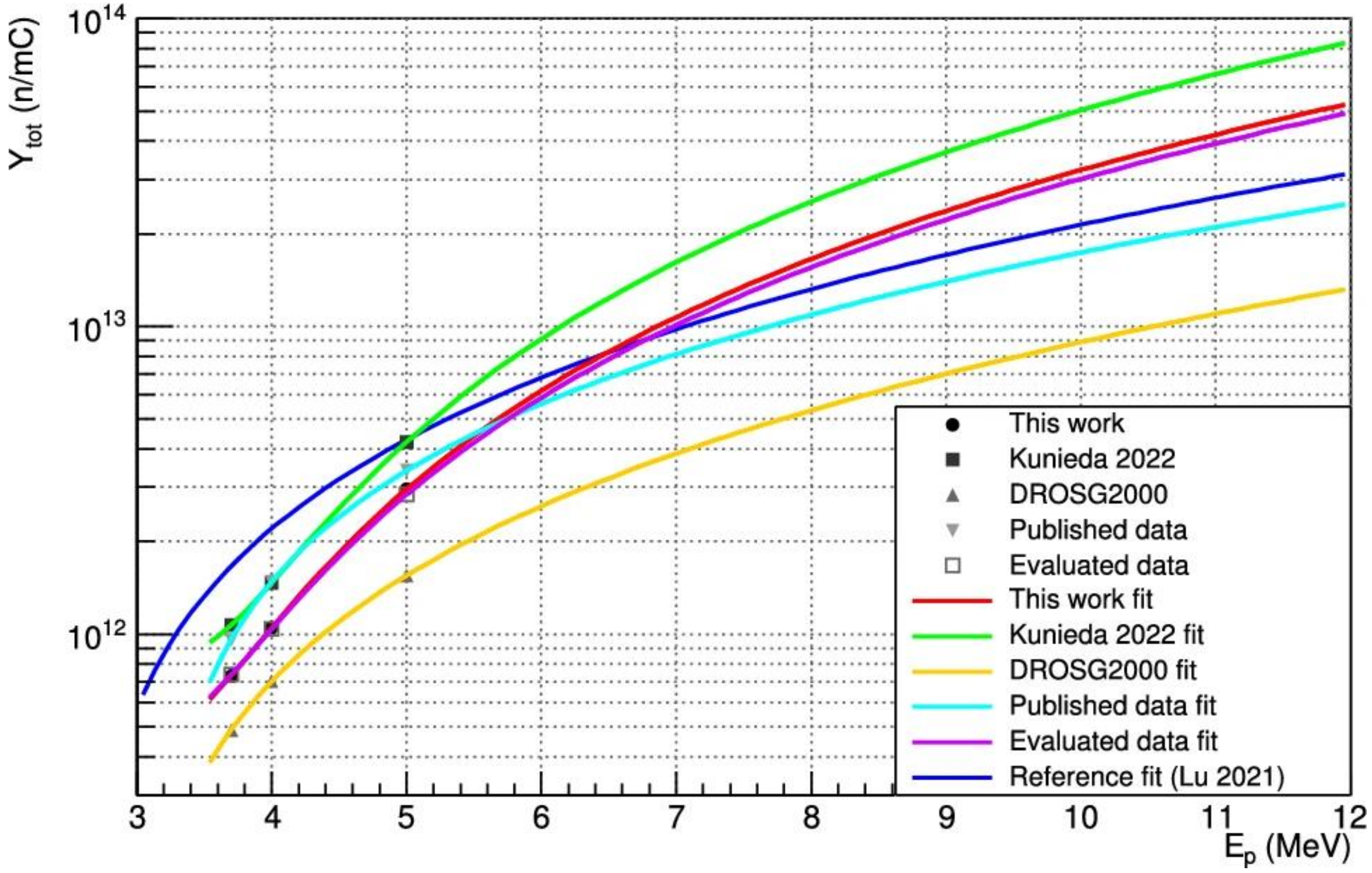
- **Hybrid model for missing (p,p'n) channel.**
- **Improvements** with respect to state-of-art codes.
- **Reassessment of BSA's efficacy** proposed in a previous study [*].

	ϕ_{epi} 10^9 $(\mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	$\frac{\phi_{th}}{\phi_{epi}}$	$\frac{\dot{D}_{Fast}}{\phi_{epi}}$ 10^{-13} $(\mathrm{cm}^2\ \mathrm{Gy})$	$\frac{\dot{D}_{\gamma}}{\phi_{epi}}$ 10^{-13} $(\mathrm{cm}^2\ \mathrm{Gy})$	$\frac{J}{\phi_{epi}}$
IAEA	> 0.5	< 0.05	< 7	< 2	> 0.7
Postuma et al. [*]	1.08 ±0.004%	0.009 ±6.12%	9.50 ±1.07%	4.17 ±1.79%	0.74 ±0.62%
This work	1.02 ±0.001%	0.010 ±2.38%	9.32 ±0.49%	4.18 ±0.78%	0.73 ±0.20%



[*] I. Postuma et al., *A novel approach to design and evaluate BNCT neutron beams combining physical, radiobiological, and dosimetric figures of merit*, Biology 10, 174 (2021).

Results: predictions at higher energies



New paper!

Colombi A., Postuma I., Bortolussi S., Vercesi V. and Fontana A.: *A new hybrid model for accurate double differential neutron yield calculations on 9Be targets for proton-BNCT applications at low energies*. Eur. Phys. J. Plus 140(1142) (2025) https://doi.org/10.1140/epjp/s13360-025-07017-1

Geant4 source definition

We developed an extension of General Particle Source (GPS):

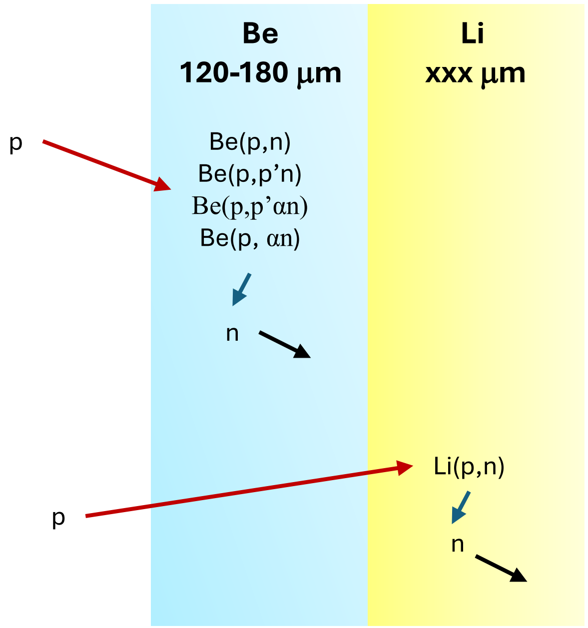
- new class `G4SPSAngEneDistribution`: sampling of 2D correlated angle–energy
- new macro command `/gps/hist2d <filename>` for importing externally generated spectra while preserving native correlations.

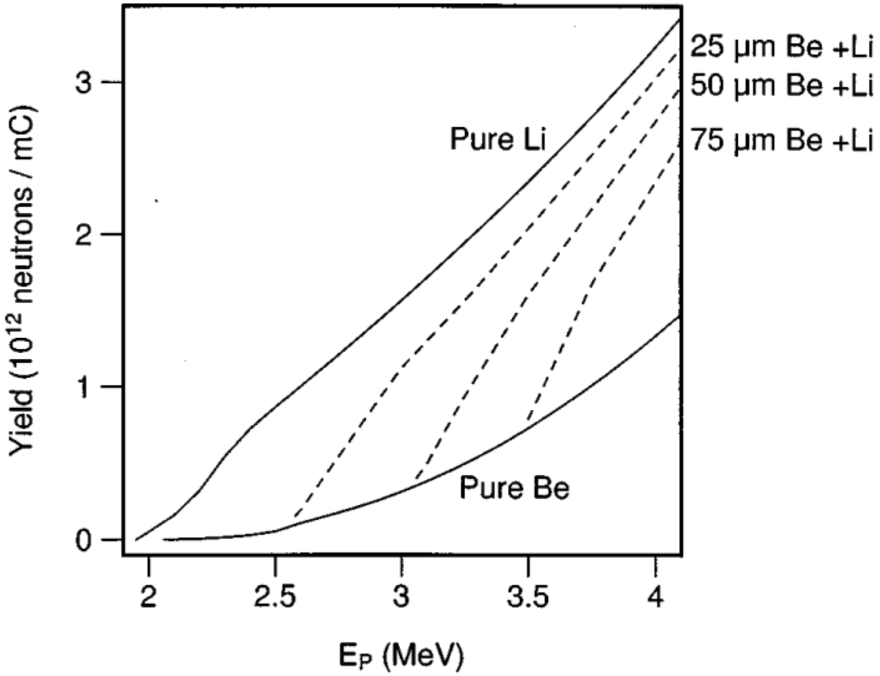
The tool has been **validated** using our **hybrid-model neutron** results and **cosmic-ray** spectra from **EXPACS**, and is planned for inclusion in a future Geant4 release.

Work carried out within the Geant4INFN project.
Testing and manuscript preparation are ongoing.

Composite Beryllium-Lithium target (BeLin)

Study done to assess this impact on Be–Li target performance, keeping Li thick enough to exploit protons to threshold.

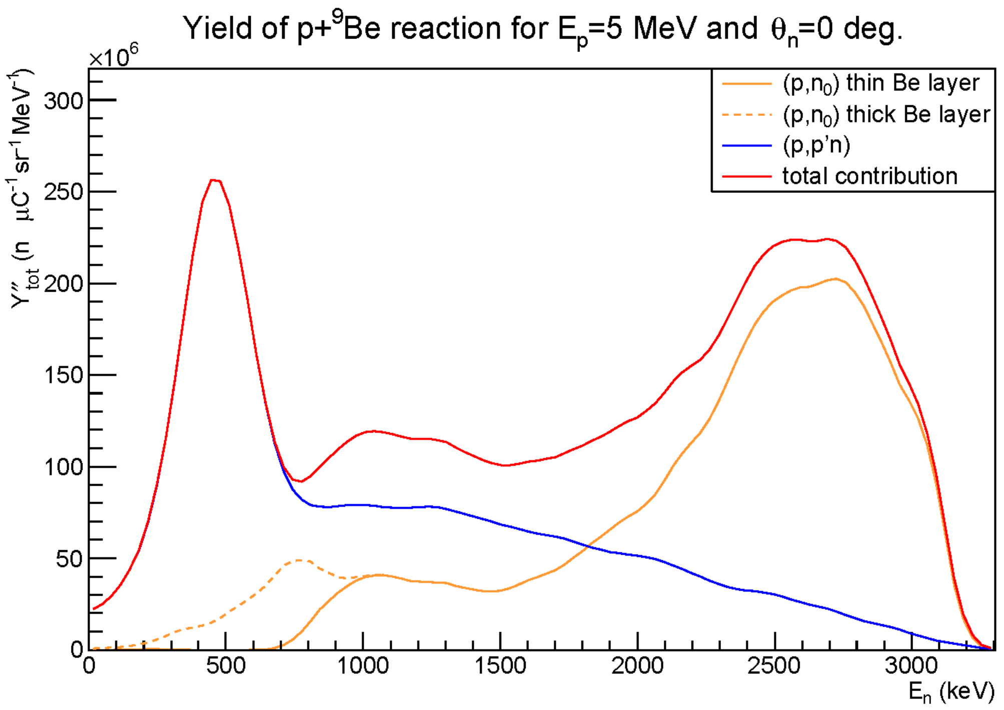


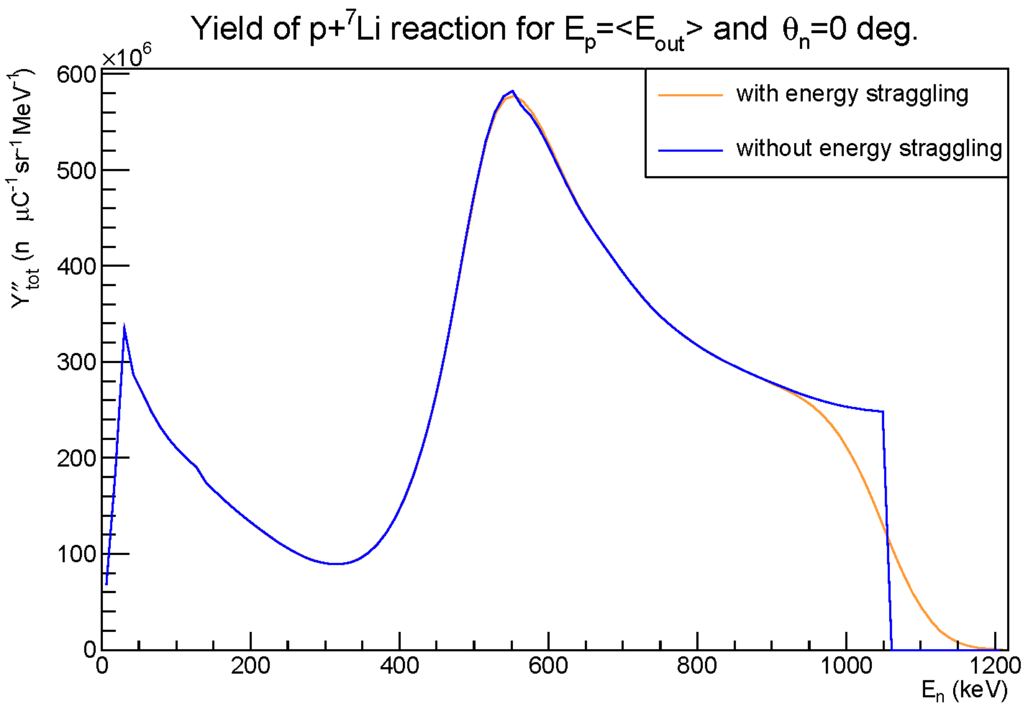


Previous work (@4 MeV with very thin layers):
Randers-Pehrson, G., Brenner, D.: *A practical target system for accelerator-based BNCT which may effectively double the dose rate*. Medical physics 25(6), 894–896 (1998)

BeLin: straggling

- A 150 µm ^{9}Be target leaves protons still above threshold.
- Concept: exiting protons enter a second 150 µm Li layer → extra neutrons.
- Straggling considered at Be exit and Li entrance.



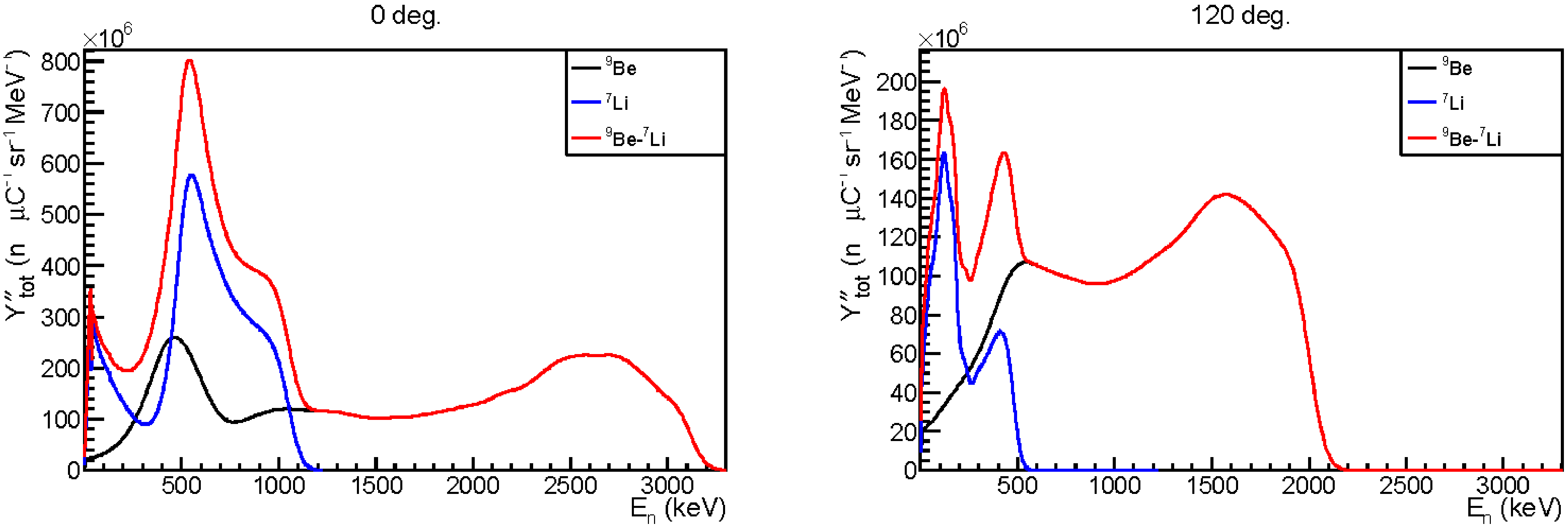


$$\left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^9Be(p,xn)} = \left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^9Be}\left(\frac{1}{2}+\frac{1}{2}\mathrm{erf}\left(\frac{E_p-\langle E_{out}\rangle}{\sqrt{2}\,\sigma}\right)\right)$$

$$\left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^7Li(p,xn)} = \left(\frac{d^2Y_n}{dE_n d\Omega}\right)_{^7Li}\left(\frac{1}{2}-\frac{1}{2}\mathrm{erf}\left(\frac{E_p-\langle E_{out}\rangle}{\sqrt{2}\,\sigma}\right)\right)$$

BeLin: yield increase

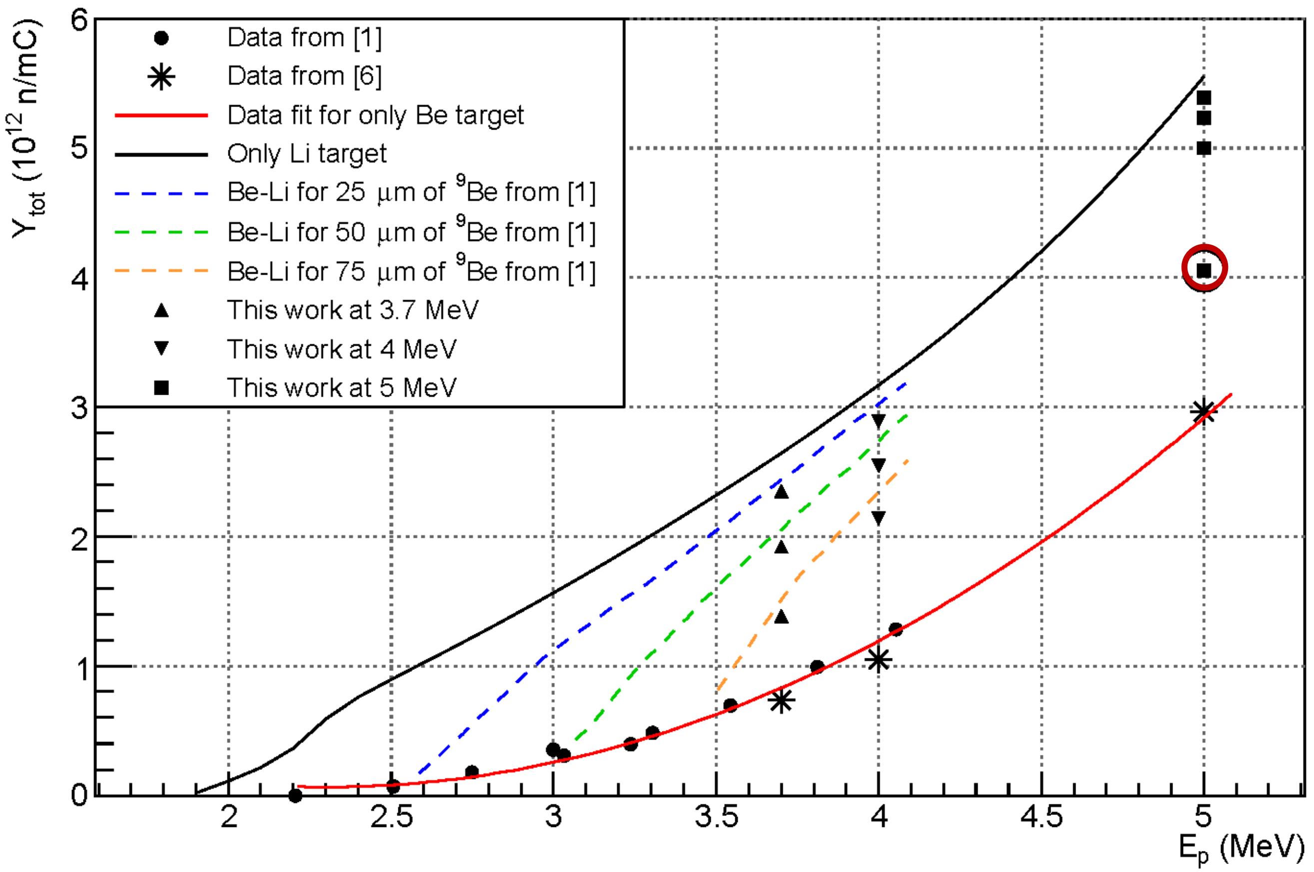
- We have calculated the double differential neutron yield
- Main result: total neutron flux increase of ~50%



BeLin: yield increase

Total neutron yield from $d\Omega$ and dE_n integration.

Target	Y_{tot} (n/mC)
Be	2.82×10^{12}
Li	1.23×10^{12}
Be–Li	4.05×10^{12}



Be–Li target produces an **increase** of:

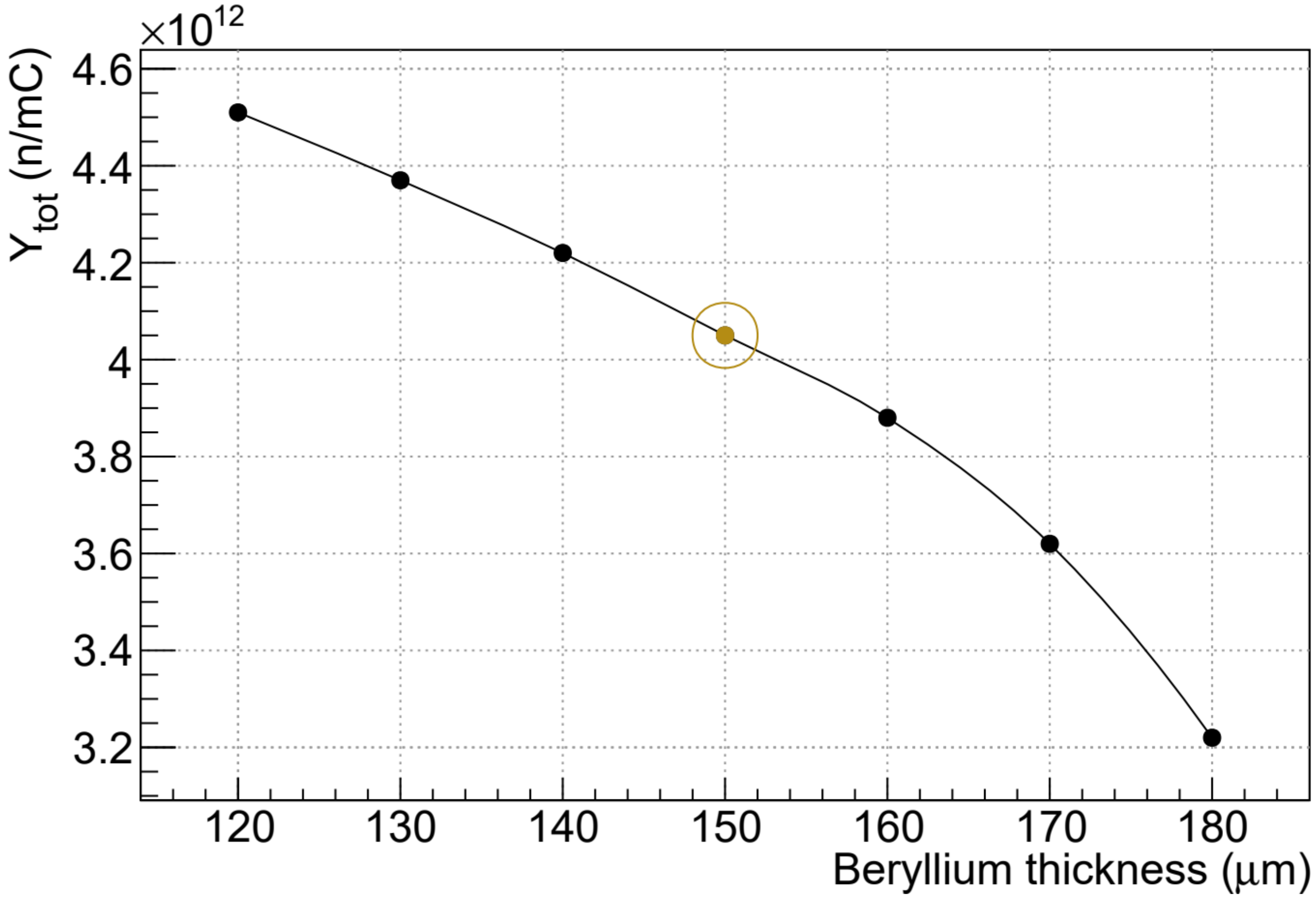
- **~44%** if compared to the **thin** 150µm ^{9}Be layer
- **~37%** if compared to the **thick** 3mm ^{9}Be target

New paper!

Colombi A., Postuma I., Bortolussi S., Vercesi V. and Fontana A.:*Theoretical study of proton induced reactions on a composite Beryllium-Lithium target as a BNCT neutron source*, in press on EPJ

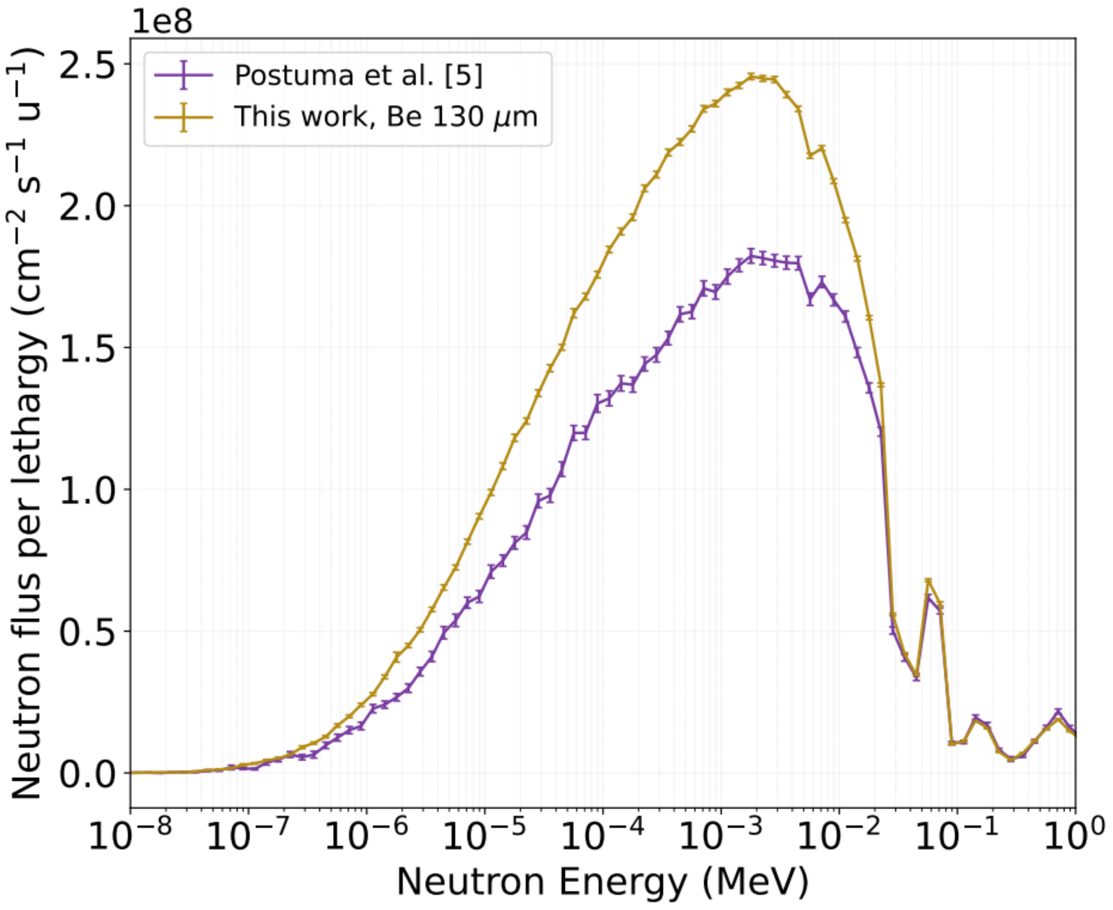
BeLin: beryllium thickness variation

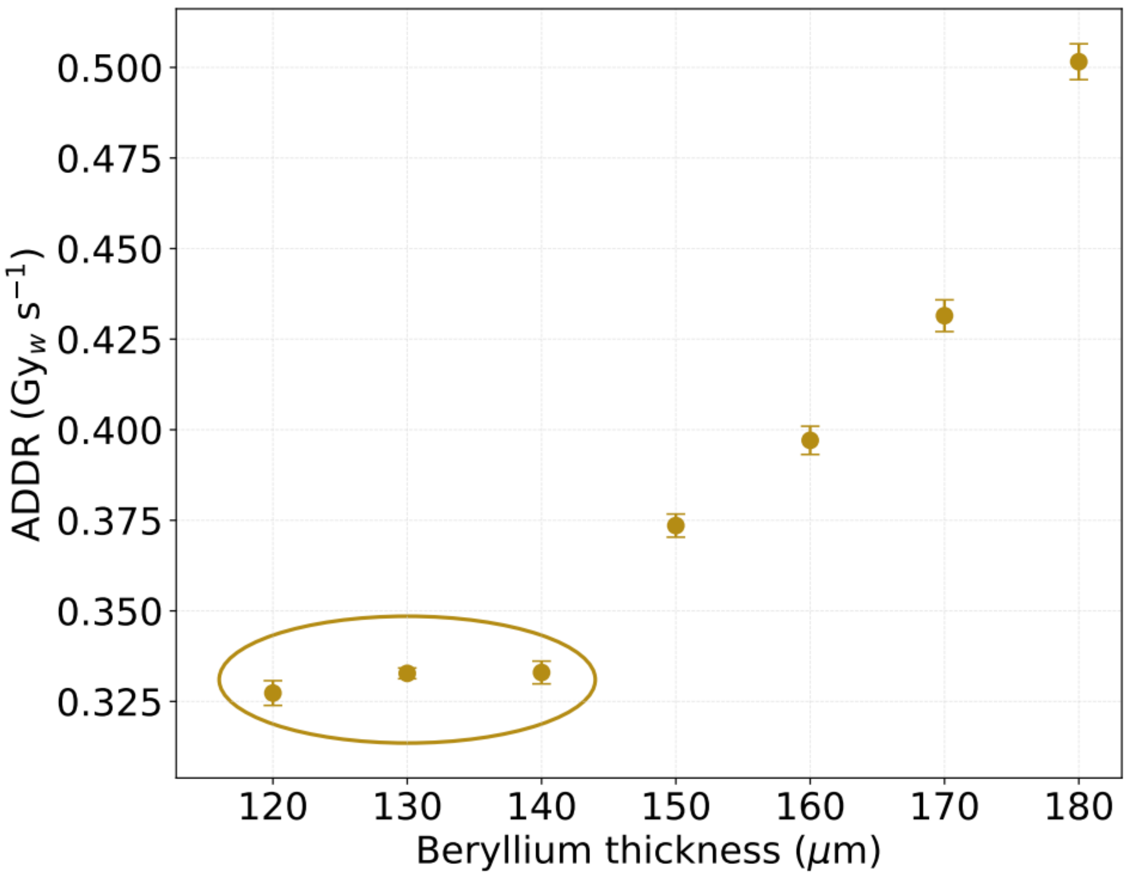
- Be thickness varied around 150 μm (circled point) to reflect realistic fabrication fluctuations (in range 120—180 μm)



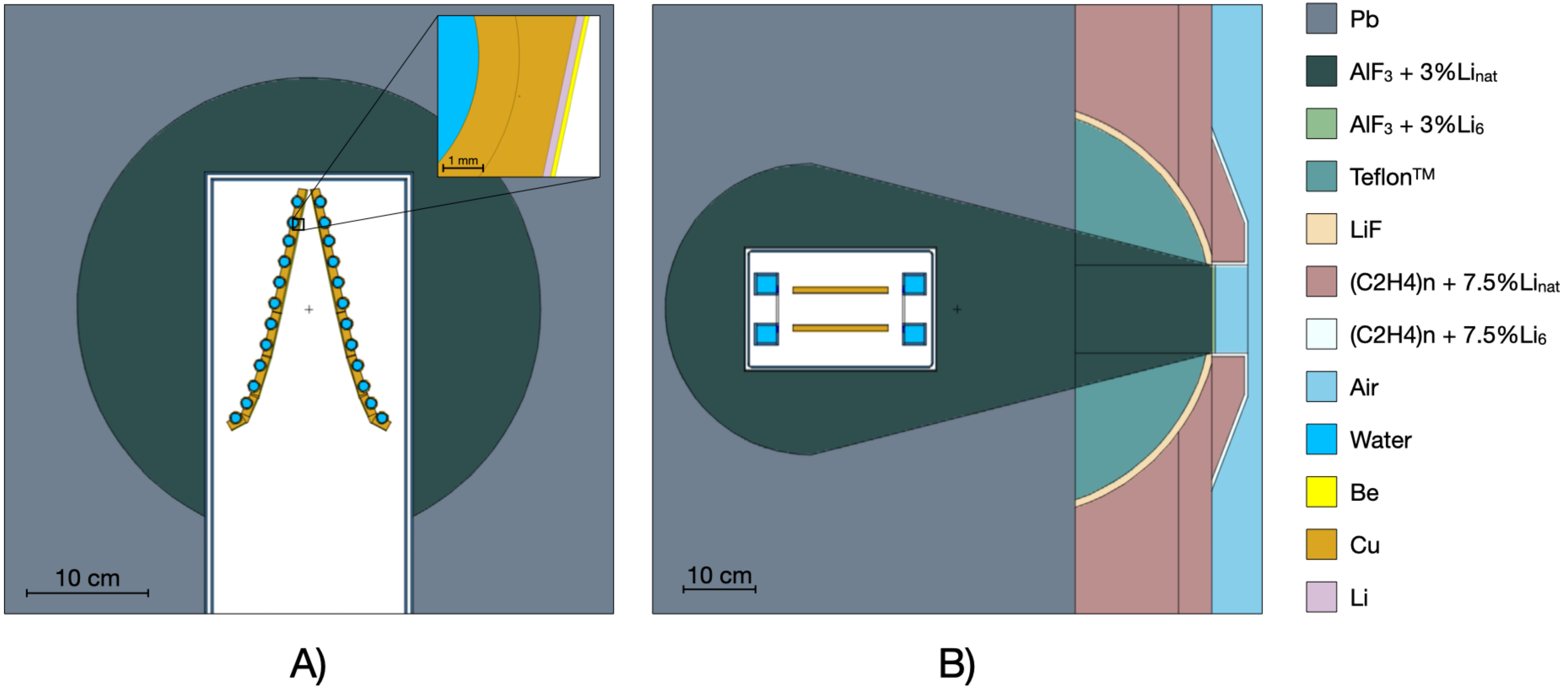
BeLin: BSA performances

- Fast-neutron contribution remains stable between 120 μm and 140 μm, the most relevant contribution for normal-tissue dosimetry (bottom right, circled region).
- A bilayer target enhances BNCT robustness against thickness variations while maintaining competitive clinical performances.





BeLin: target and BSA geometry



Colors indicate the different materials composing the BSA; (A) and (B) show orthogonal cross-sections of the assembly and target region, with a **zoom** on thin layered structure of the target, **highlighting Be and Li**.

Conclusions and outlook

- **Two new publications** for the neutron source of ANTHEM!

- **Hybrid model**:
    1. new data at 5 MeV will be useful for validation and further refinements
    2. new data at higher energies (e.g. 8-10 MeV) could be of interest for the community

- **Composite Be+Li target**:
    - Only a theoretical idea at the moment
    - Many technical issues require further mechanical/thermal studies
    - Very **promising result**: 50% yield increase and dosimetric robustness could be used as a guideline to **motivate further studies** in the Be-Li target construction.

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Thank you!