

The 4th International Conference on Advances in Radioactive Isotope Science (ARIS)
Palais des Papes - Avignon - France, 4-9 June 2023

Observation of a correlated free four-neutron system

Valerii Panin (GSI), Meytal Duer, Thomas Aumann (TU Darmstadt)

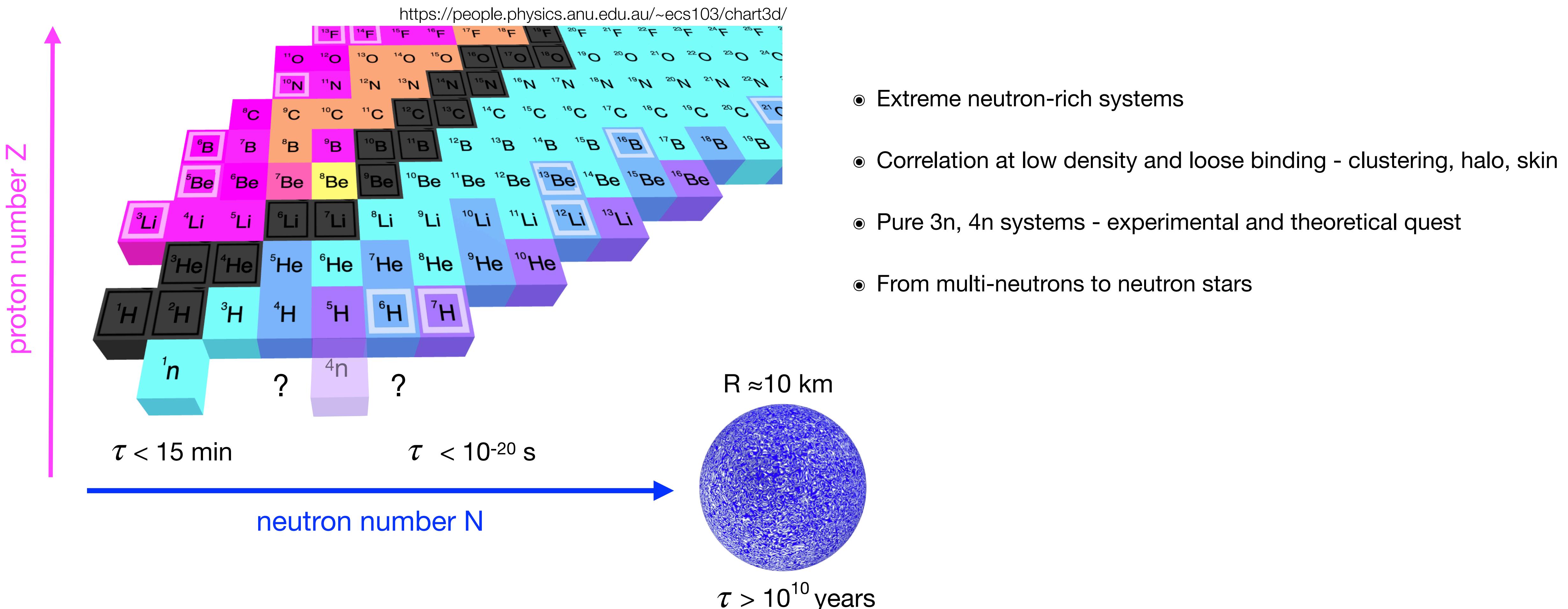
M. Duer et al., Nature 606, 678 (2022)



TECHNISCHE
UNIVERSITÄT
DARMSTADT

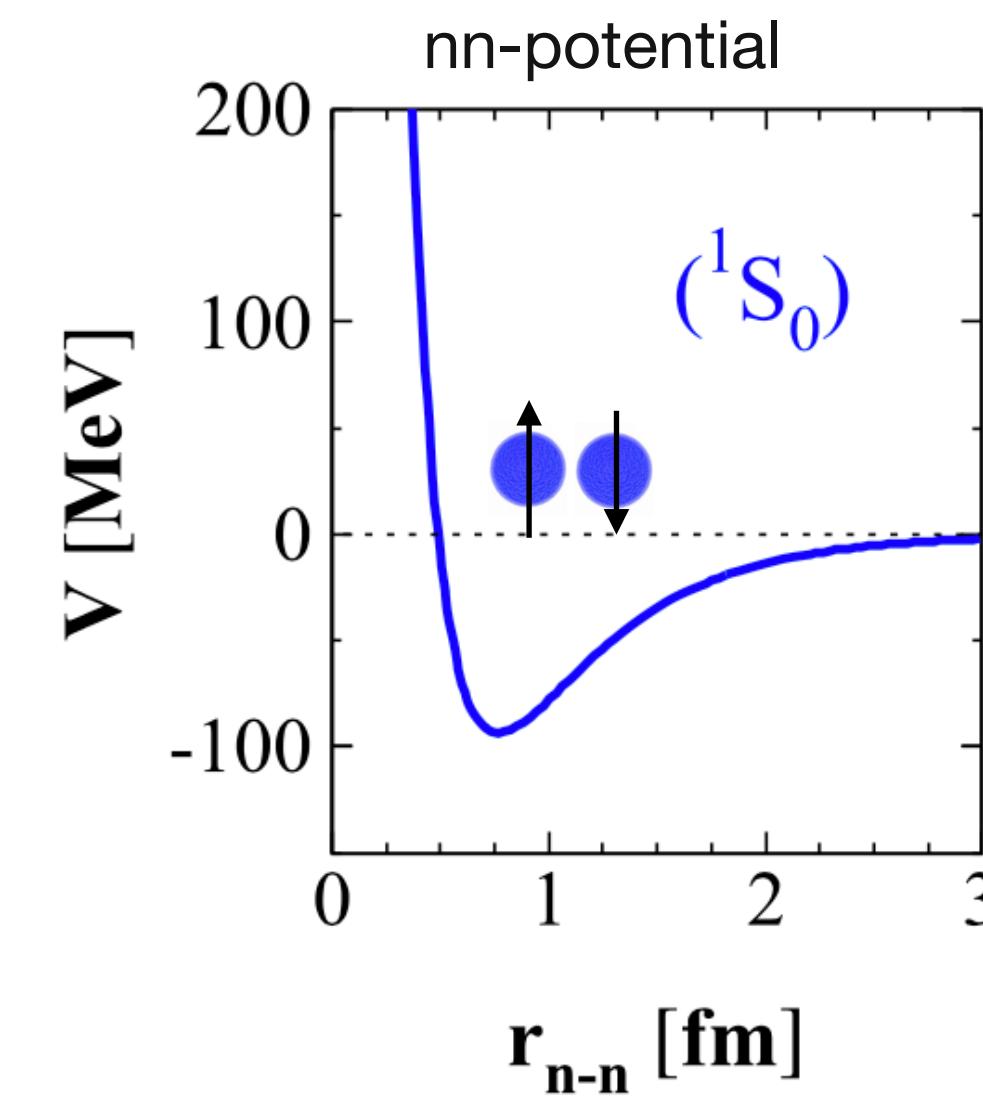
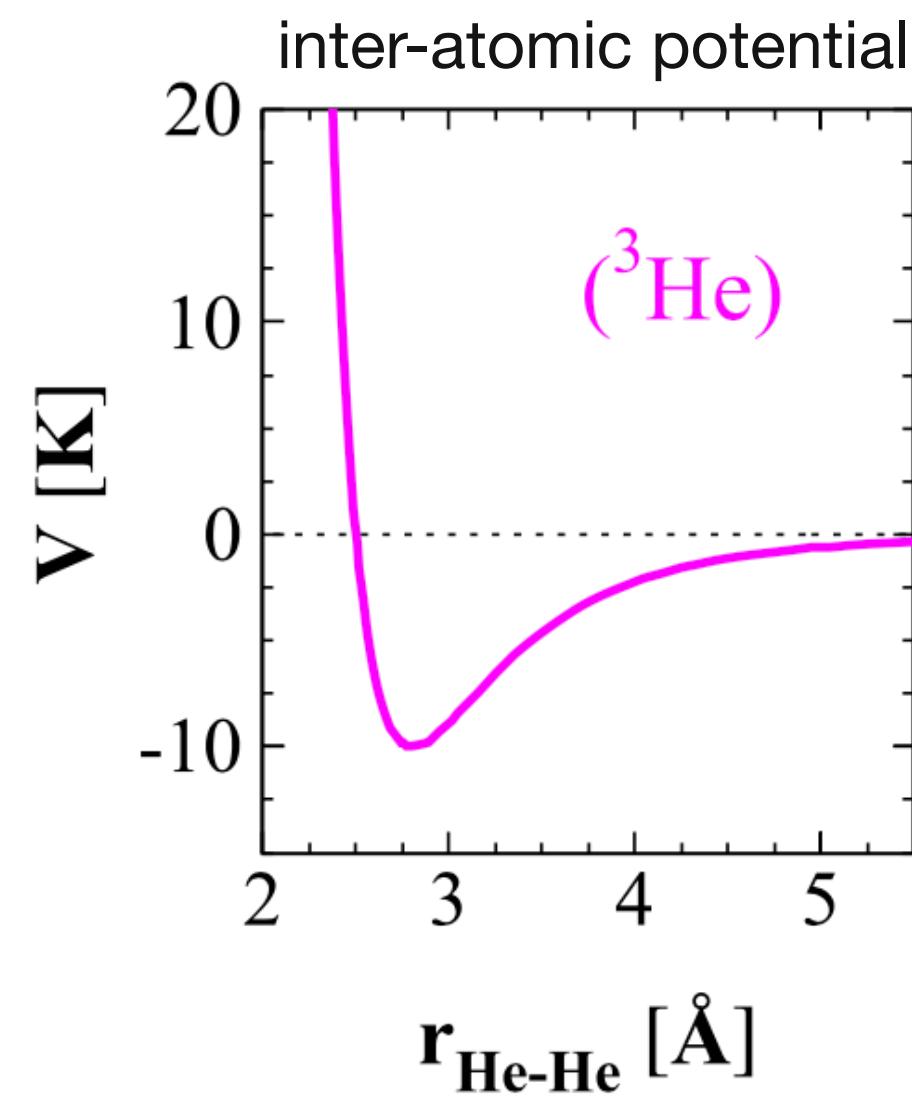


At and beyond the neutron drip-line



Di-neutron correlations

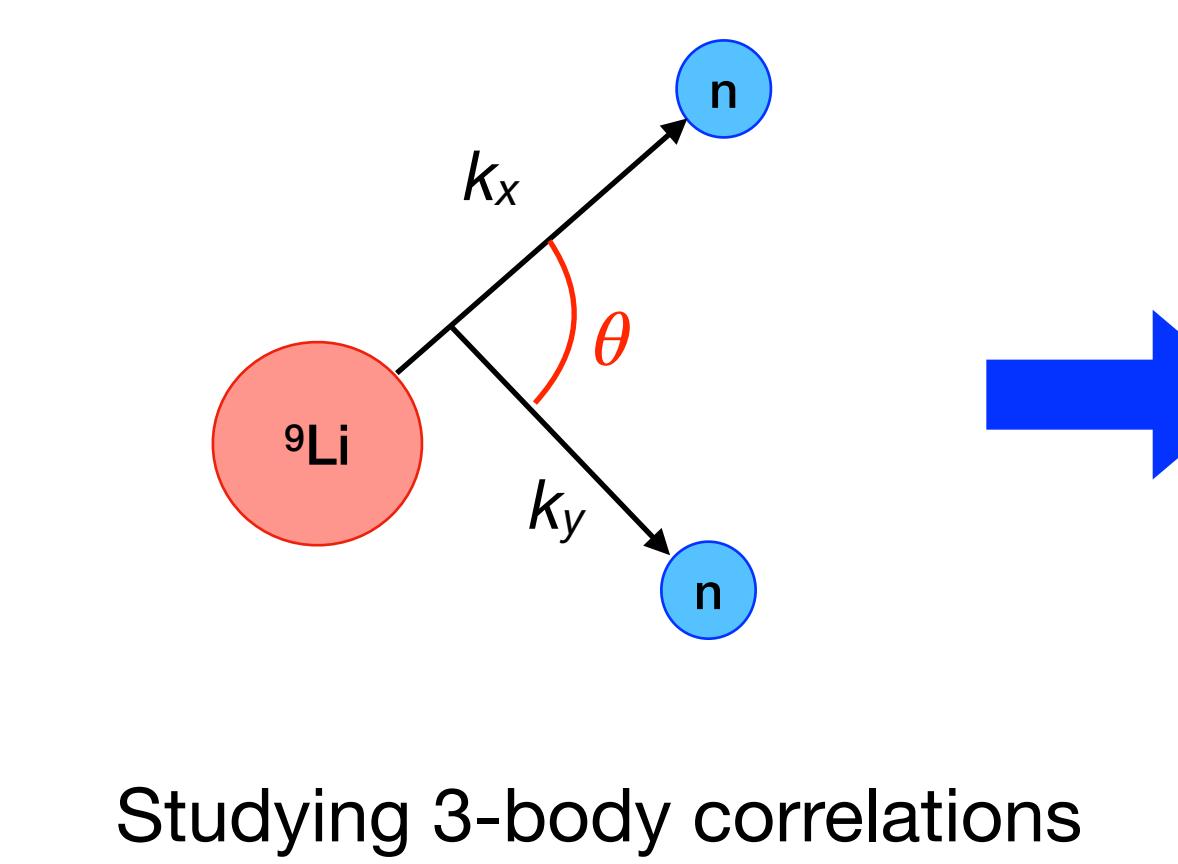
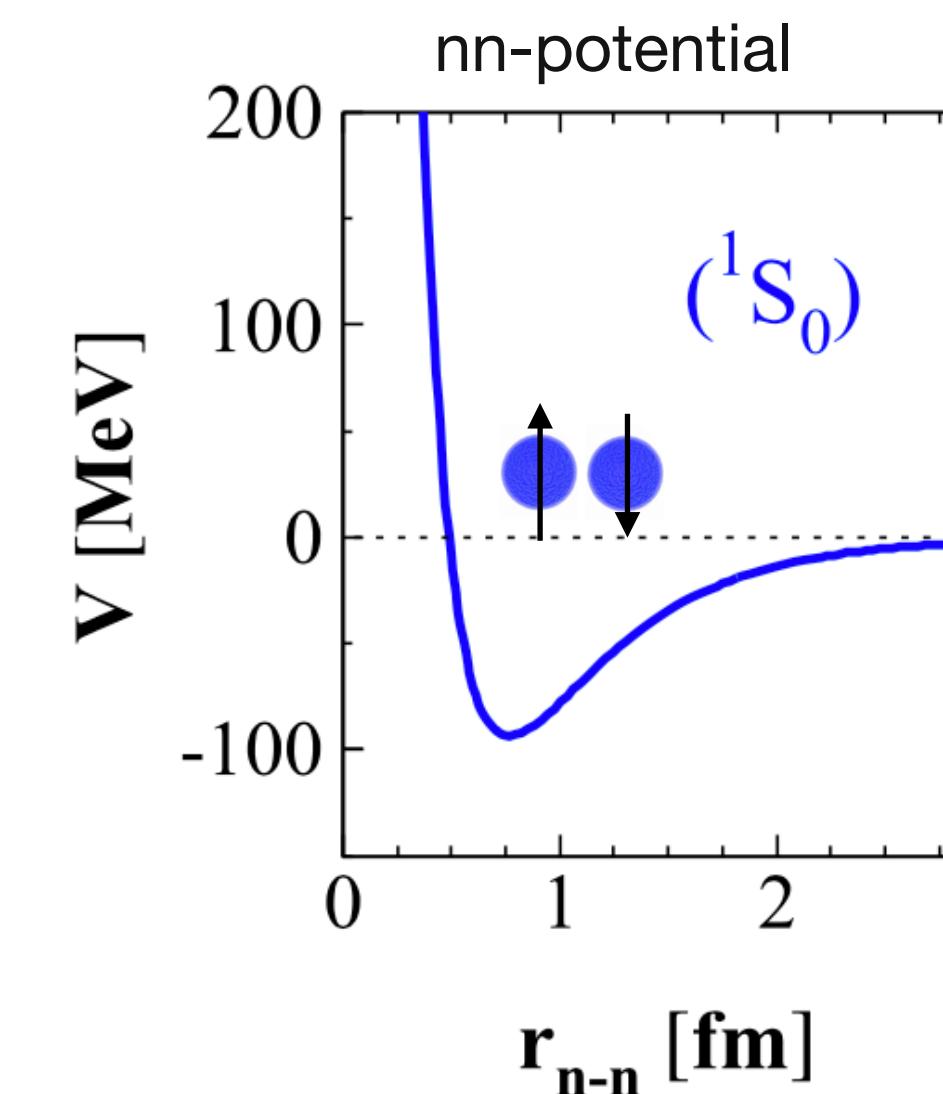
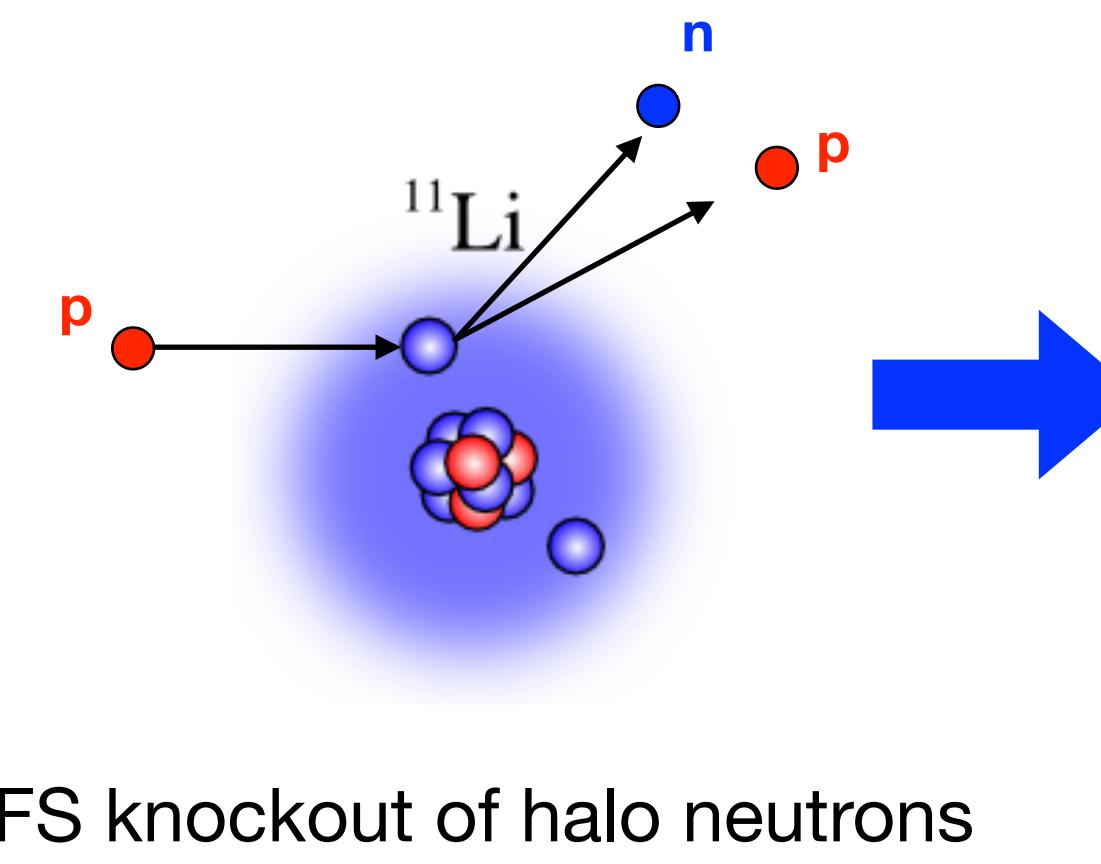
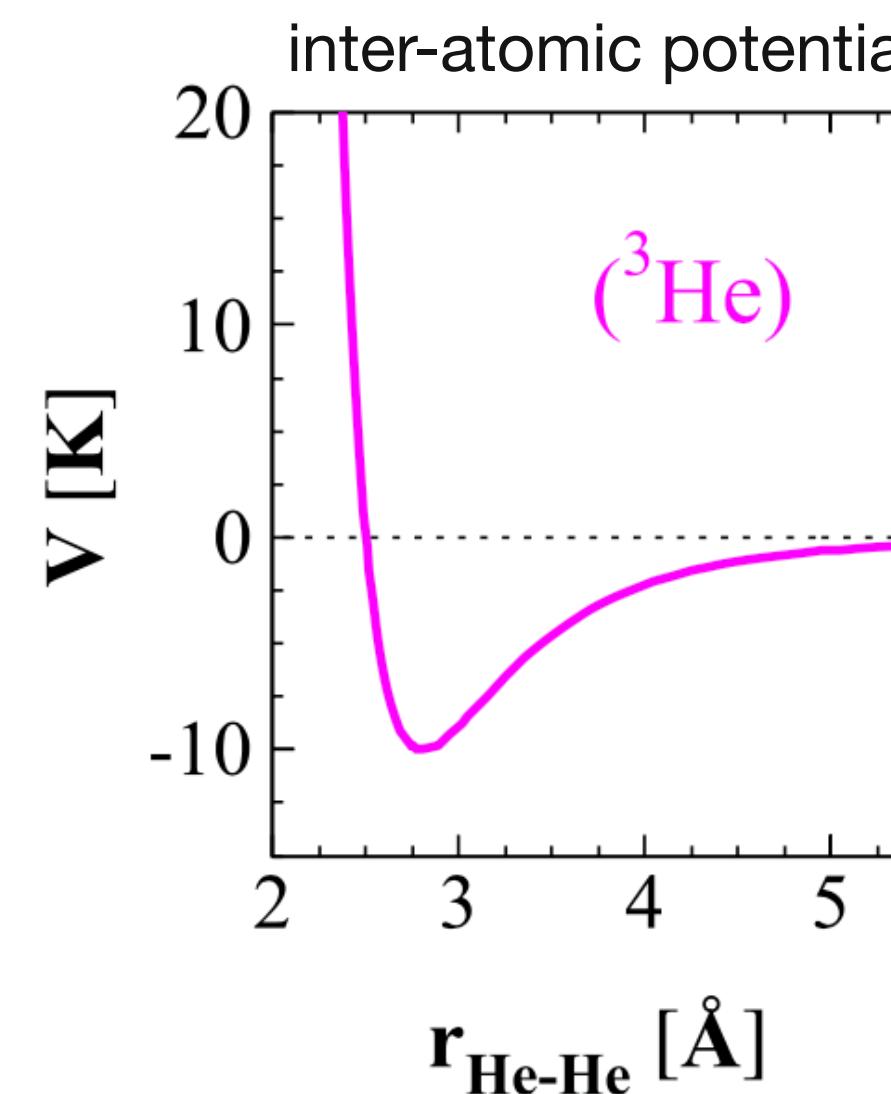
Marqués EPJP (2021) 136



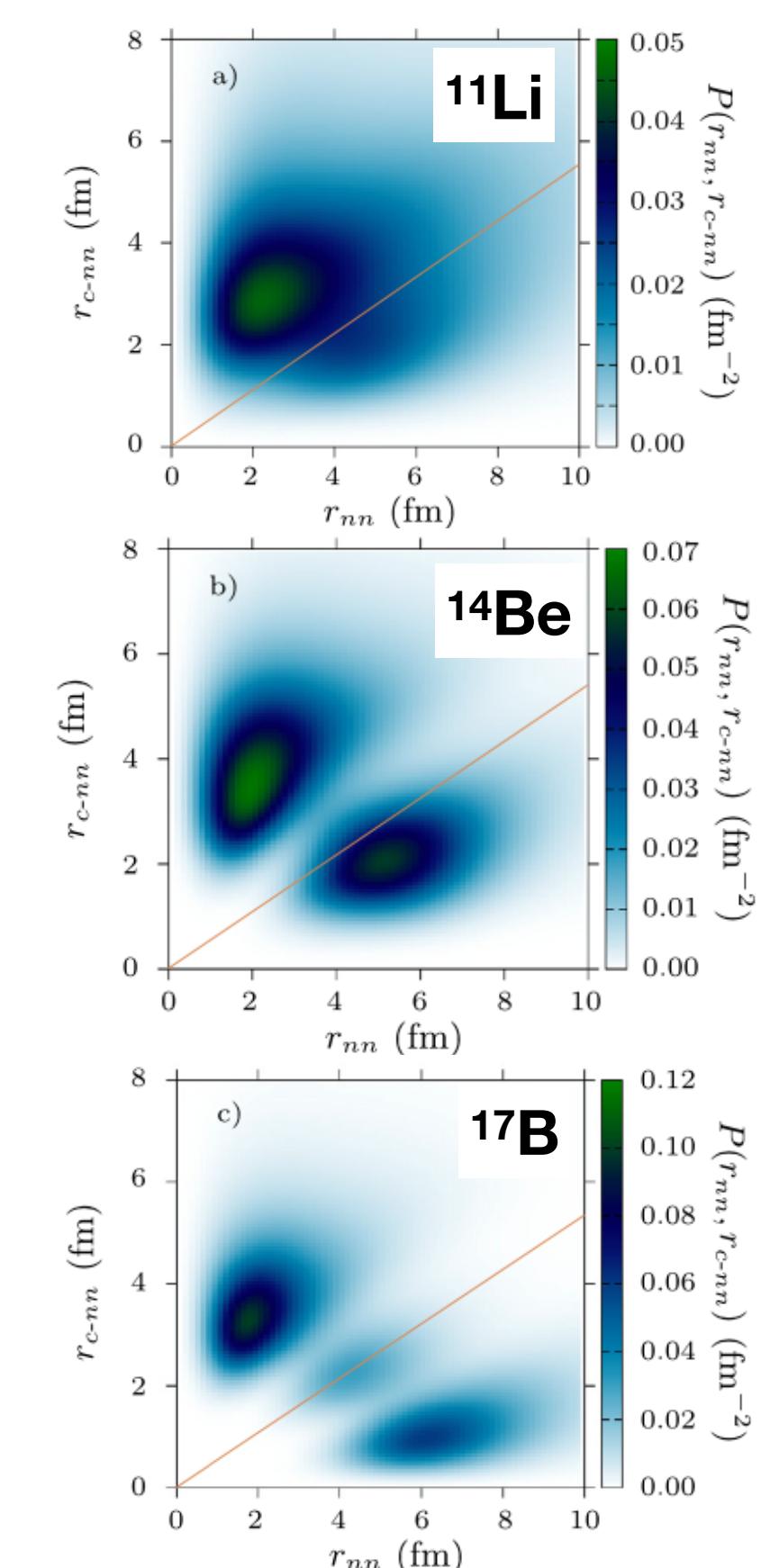
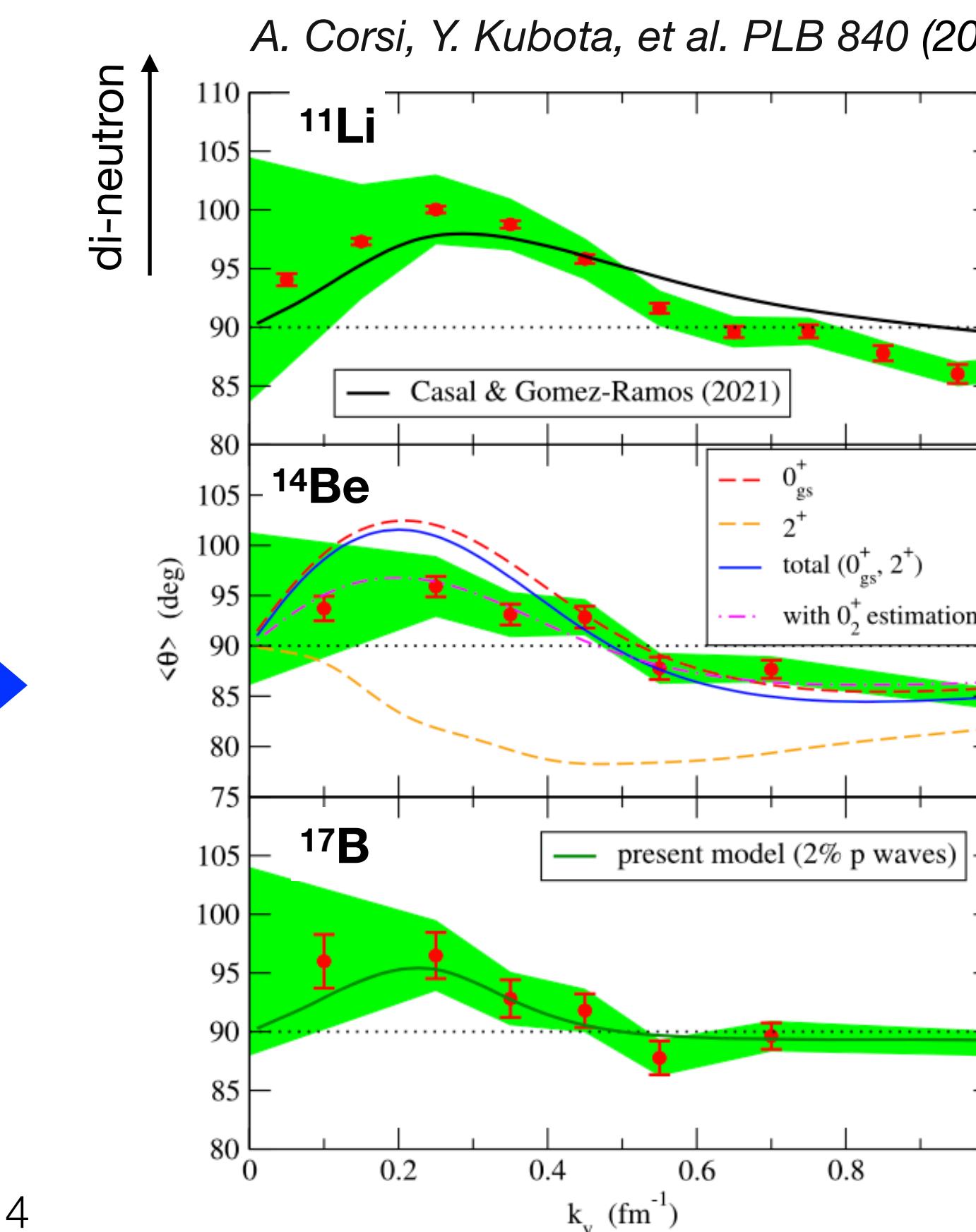
- Free nn-interaction is dominated by an attractive S-wave
- Large scattering length: $a_{\text{nn}} = -18.9(4)$ fm
- Unbound by ~ 100 keV

Di-neutron correlations

Marqués EPJP (2021) 136



- Free nn-interaction is dominated by an attractive S-wave
- Large scattering length: $a_{nn} = -18.9(4) \text{ fm}$
- Unbound by $\sim 100 \text{ keV}$
- **Indication of universality of 2n correlations at low-densities ($10^{-4} < \rho/\rho_0 < 0.5$)**



Modelling multi-neutron systems

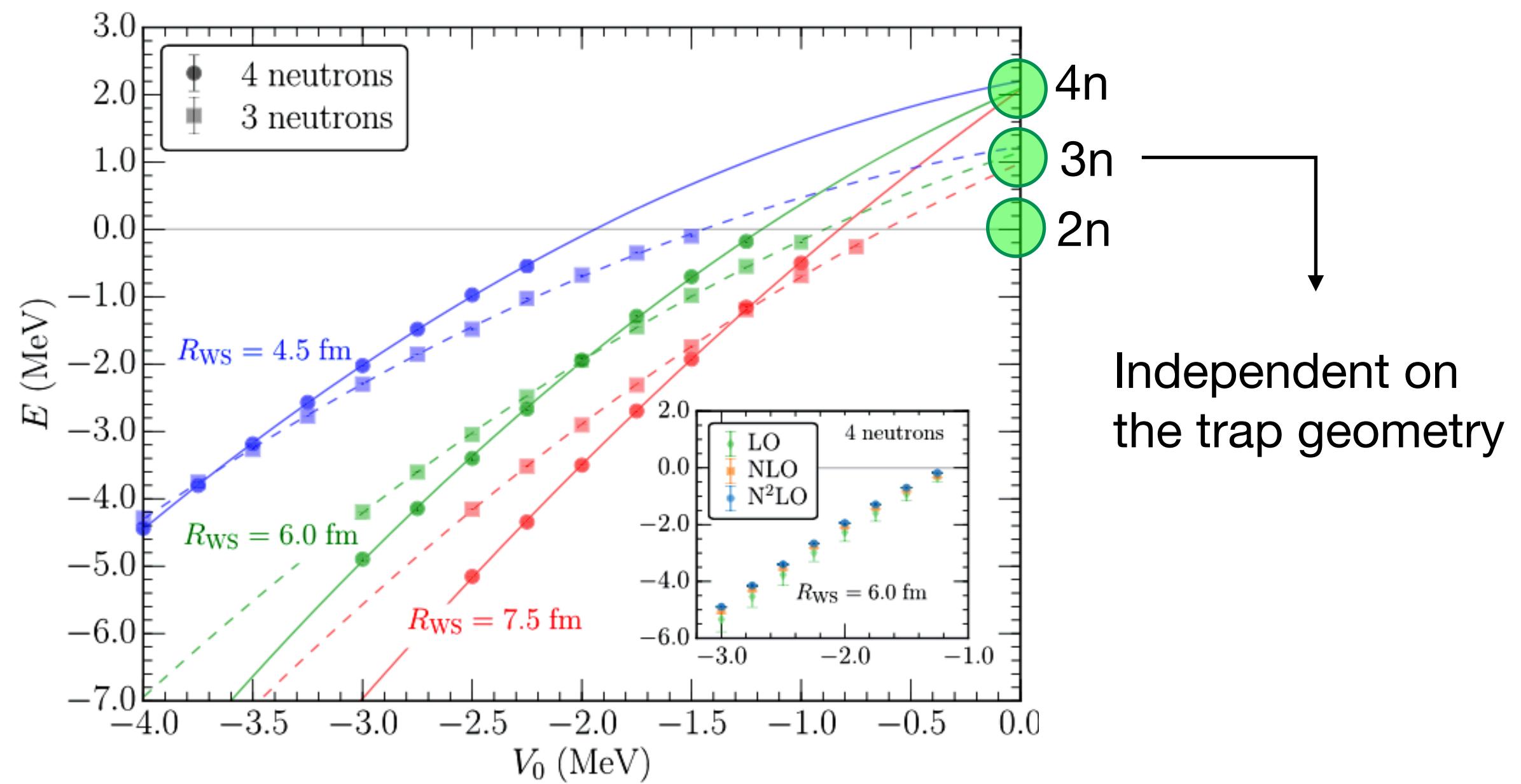
Chiral EFT Woods-Saxon trap

The diagram shows three configurations of blue spheres representing neutrons: a cluster of four spheres, a cluster of three spheres, and a cluster of two spheres. Below these, the Chiral EFT potential is given by:

$$H = - \sum_i \frac{\hbar^2}{2m} \nabla_i^2 + \sum_{i < j} V_{ij} + \sum_{i < j < k} V_{ijk} + \sum_i \frac{-V_0}{1 + \exp\left[\frac{r_i - R_{ws}}{a}\right]}$$

The Woods-Saxon trap potential is shown as a rectangle containing four blue spheres.

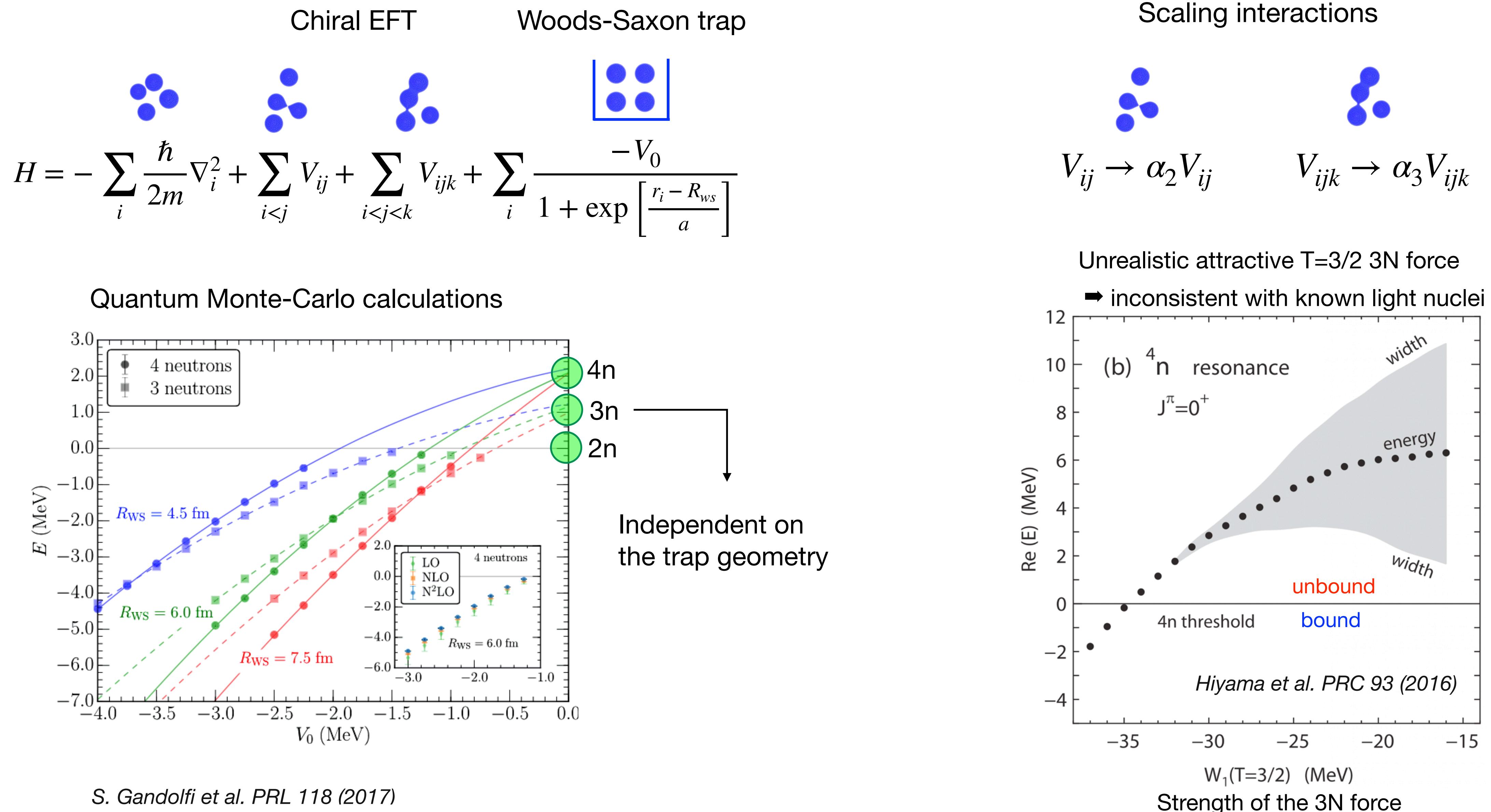
Quantum Monte-Carlo calculations



4n
3n
2n

Independent on
the trap geometry

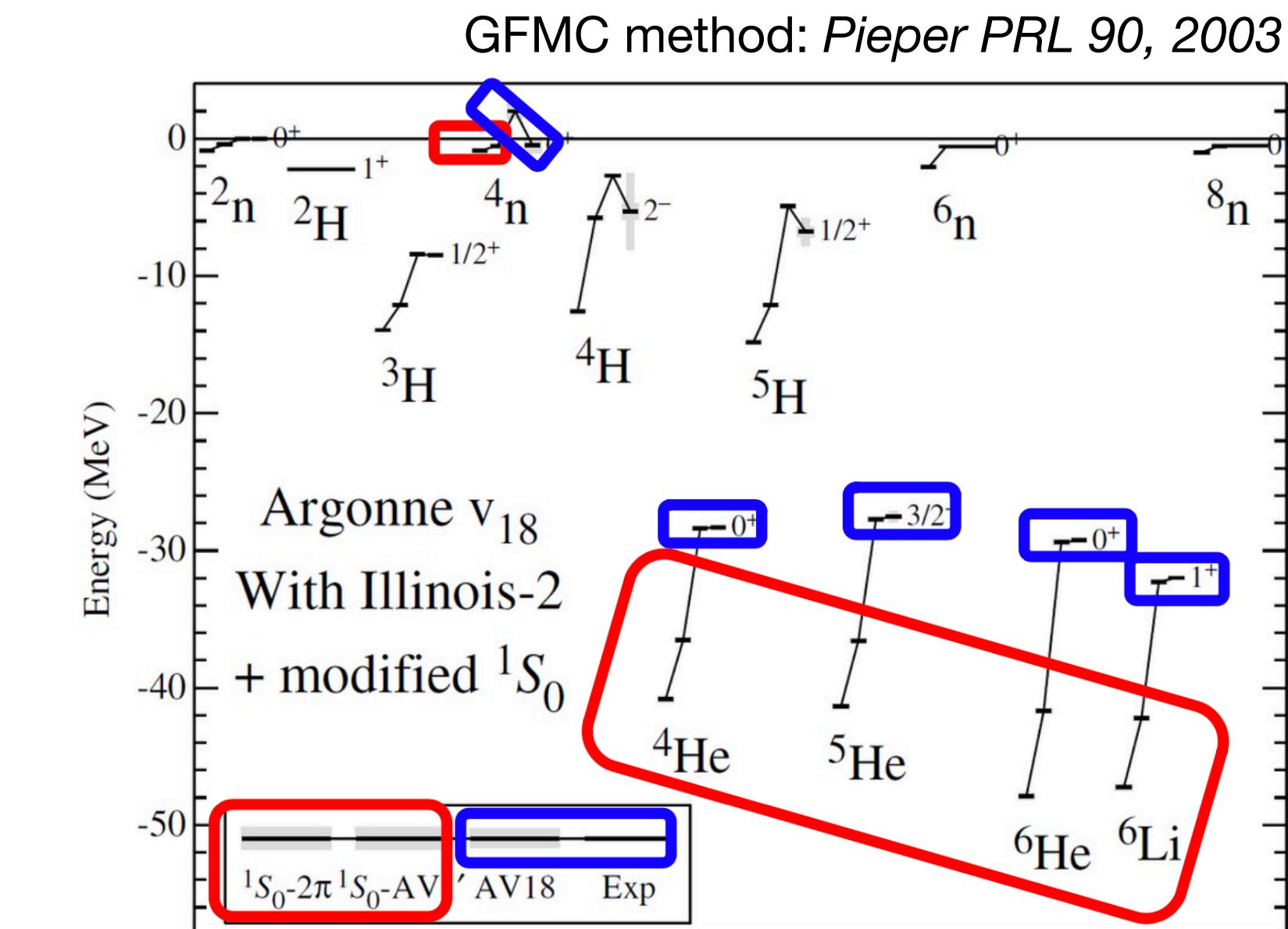
Modelling multi-neutron systems



Modelling multi-neutron systems

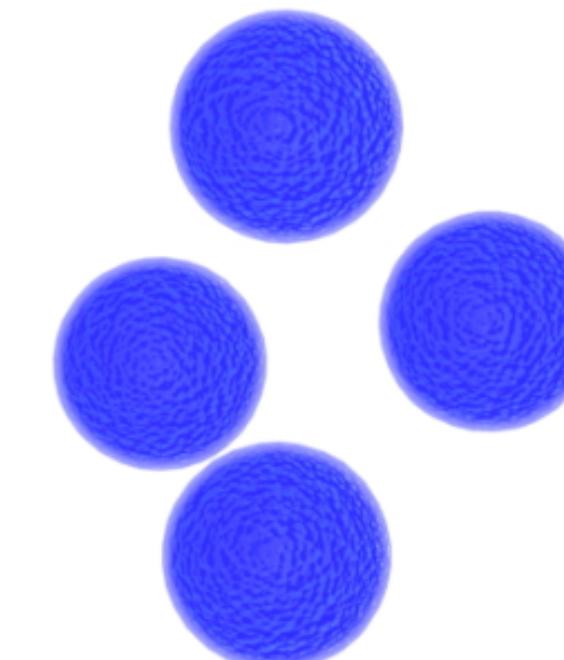
All theoretical studies on 3n and 4n seem to agree on:

- Dominance of V_{nn} (1S_0)
- Negligible contribution of 3N and higher order forces
- Independence on the details of the nn interaction
- Unrealistic modifications of V_{nn} to bind 4n
- Historical consensus: **no bound 3n or 4n**



Contradictory results:

- Near threshold resonances in 3n and 4n systems
- Many-body methods to calculate multi-neutrons
- **Treatment of the continuum**



Search for tetra-neutron - an ongoing quest

XX century

- **Fission of uranium + capture:** $^{14}\text{N}(^4\text{n},\text{n})^{17}\text{N}$ and $^{27}\text{Al}(^4\text{n},\text{t})^{28}\text{Mg}$
Schiffer & Vandenbosch, Phys. Lett. 5 (1963)
- **Activation method by energetic protons**
C. Détraz, Phys. Lett. 66B, 333 (1977)
- **Multi-nucleon transfer reactions:** e.g. $^7\text{Li}(^7\text{Li},^{11}\text{C})3\text{n}$, $^9\text{Be}(^9\text{Be},^{14}\text{O})4\text{n}$
Cerny et al., Phys. Lett. 53B (1974)
- **Double-charge-exchange:** $^4\text{He}(\pi^-, \pi^+)$
Ungar et al., Phys. Lett. B 144 (1984)

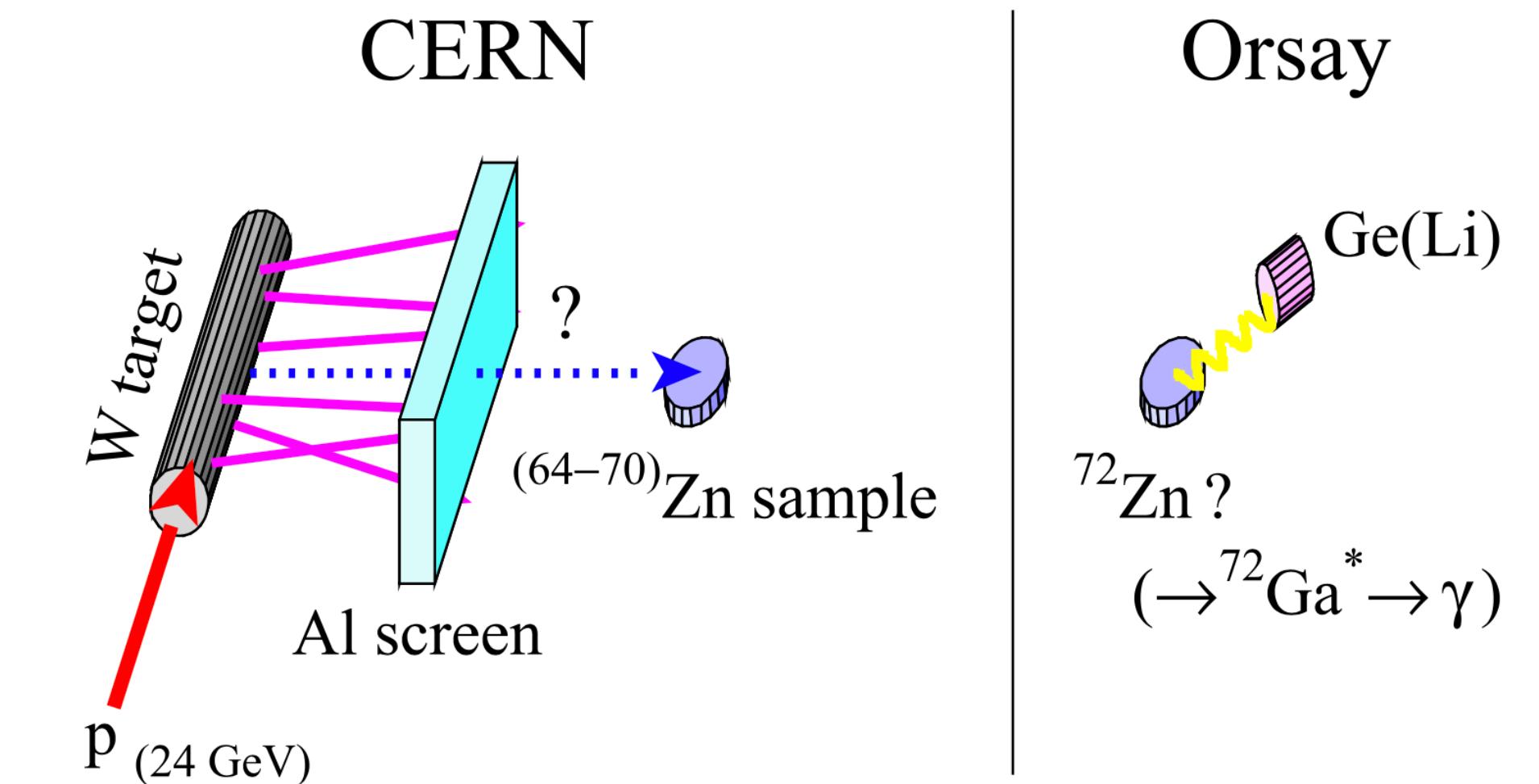


Figure from: F. M. Marqués arXiv:2102.10879 (2021)

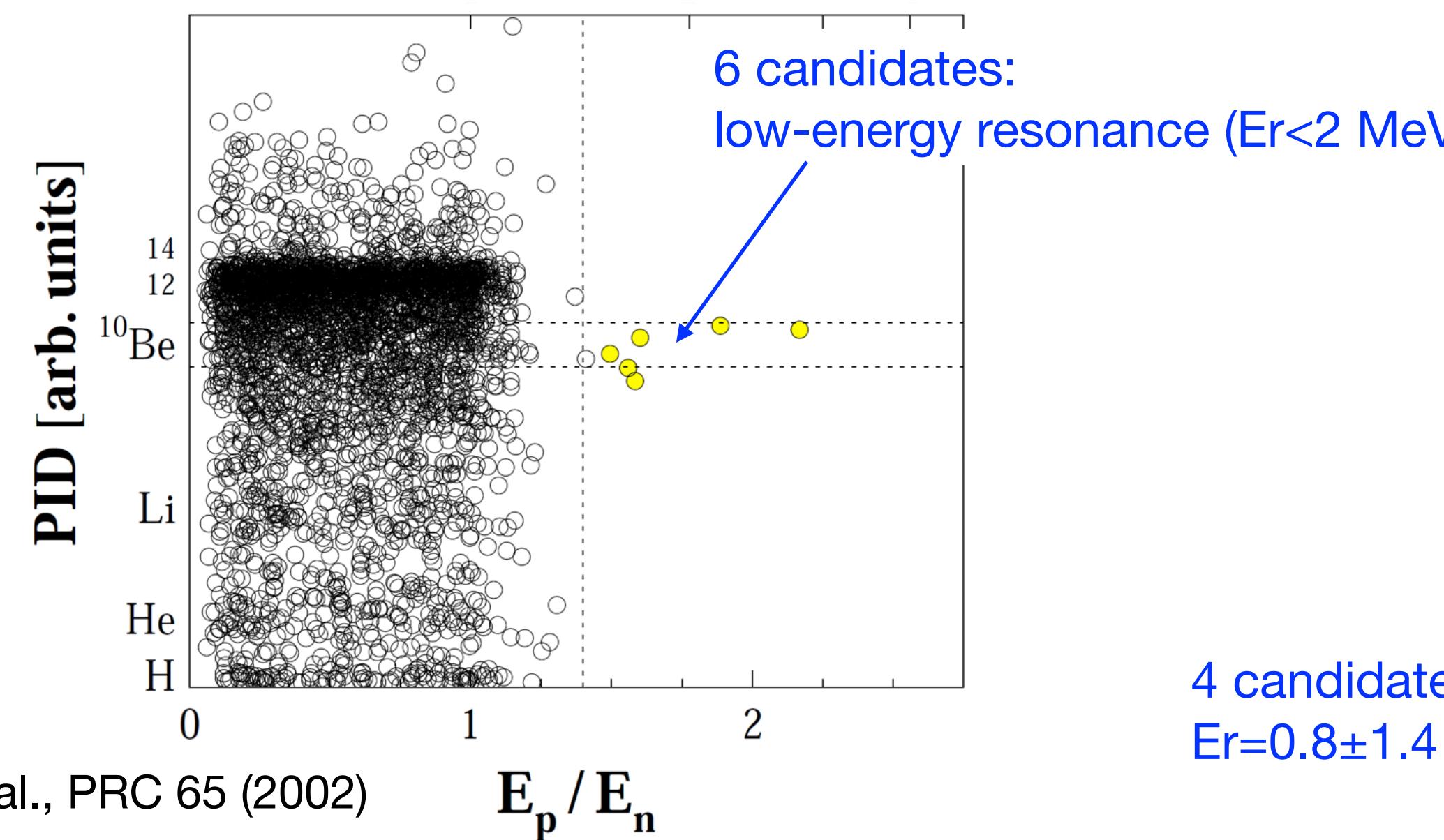
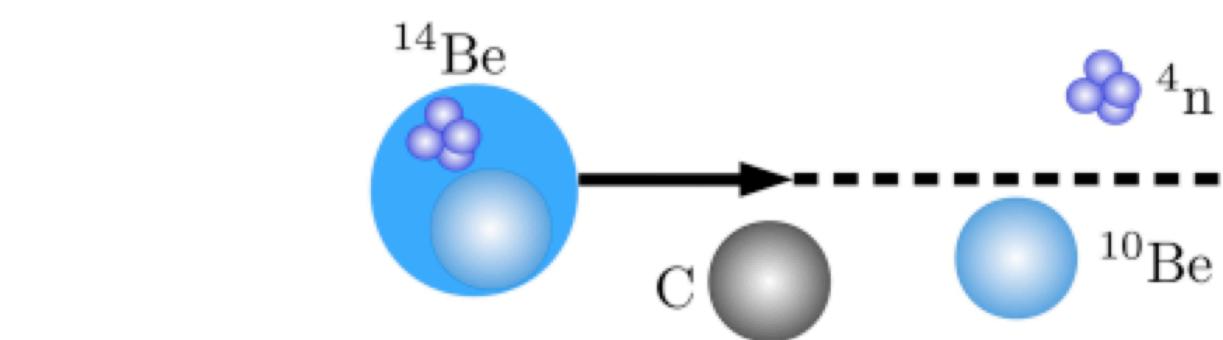
No convincing evidence for a tetra-neutron

Search for tetra-neutron - an ongoing quest

XXI century

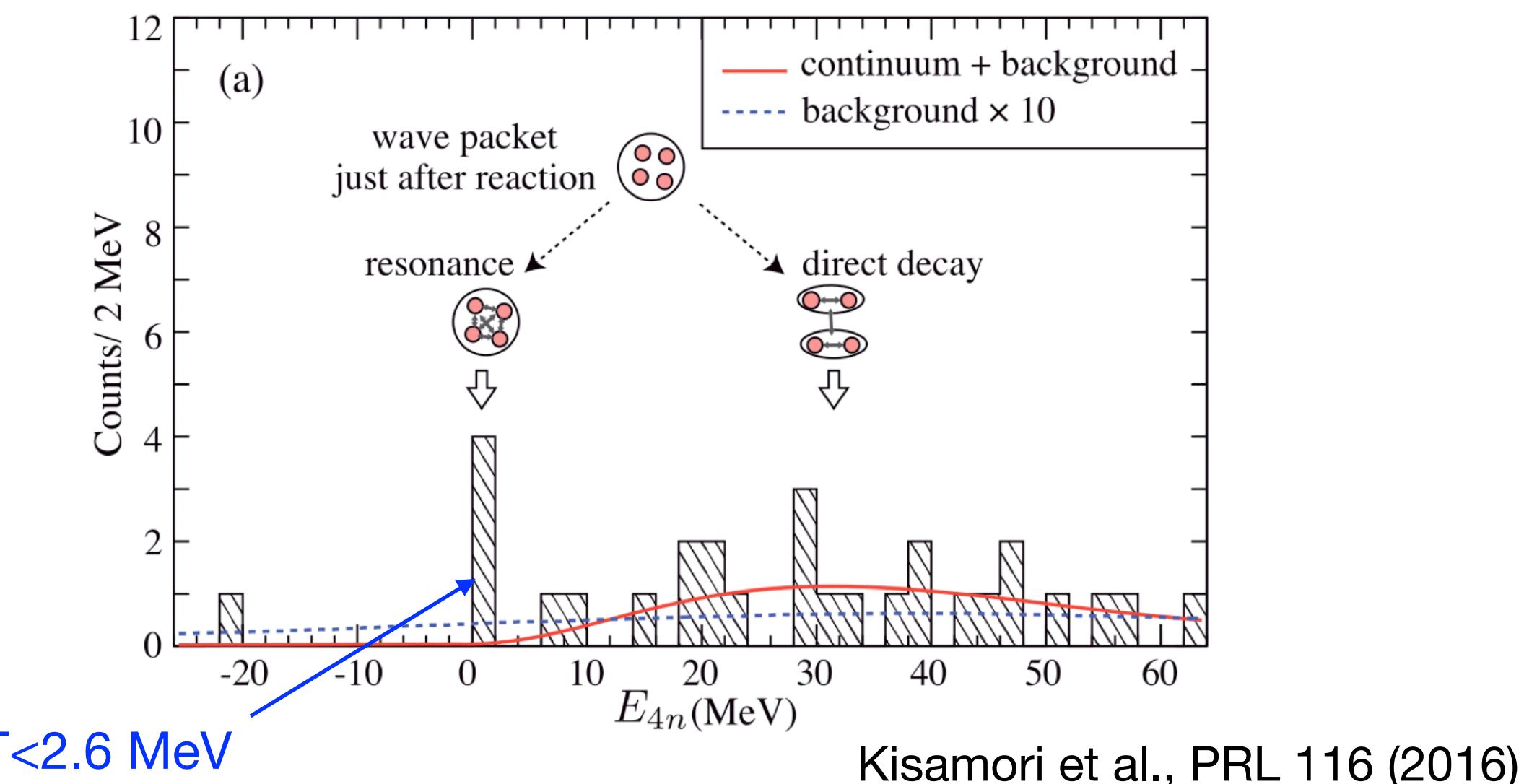
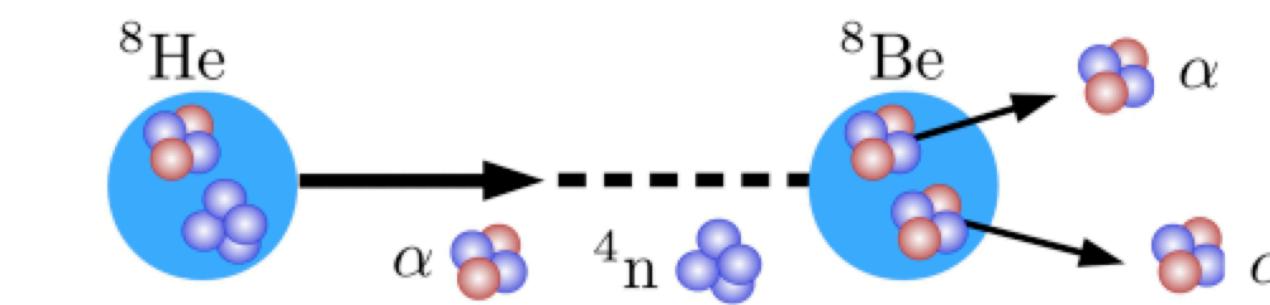
GANIL 2002

breakup @ 35 MeV/u



RIKEN 2016

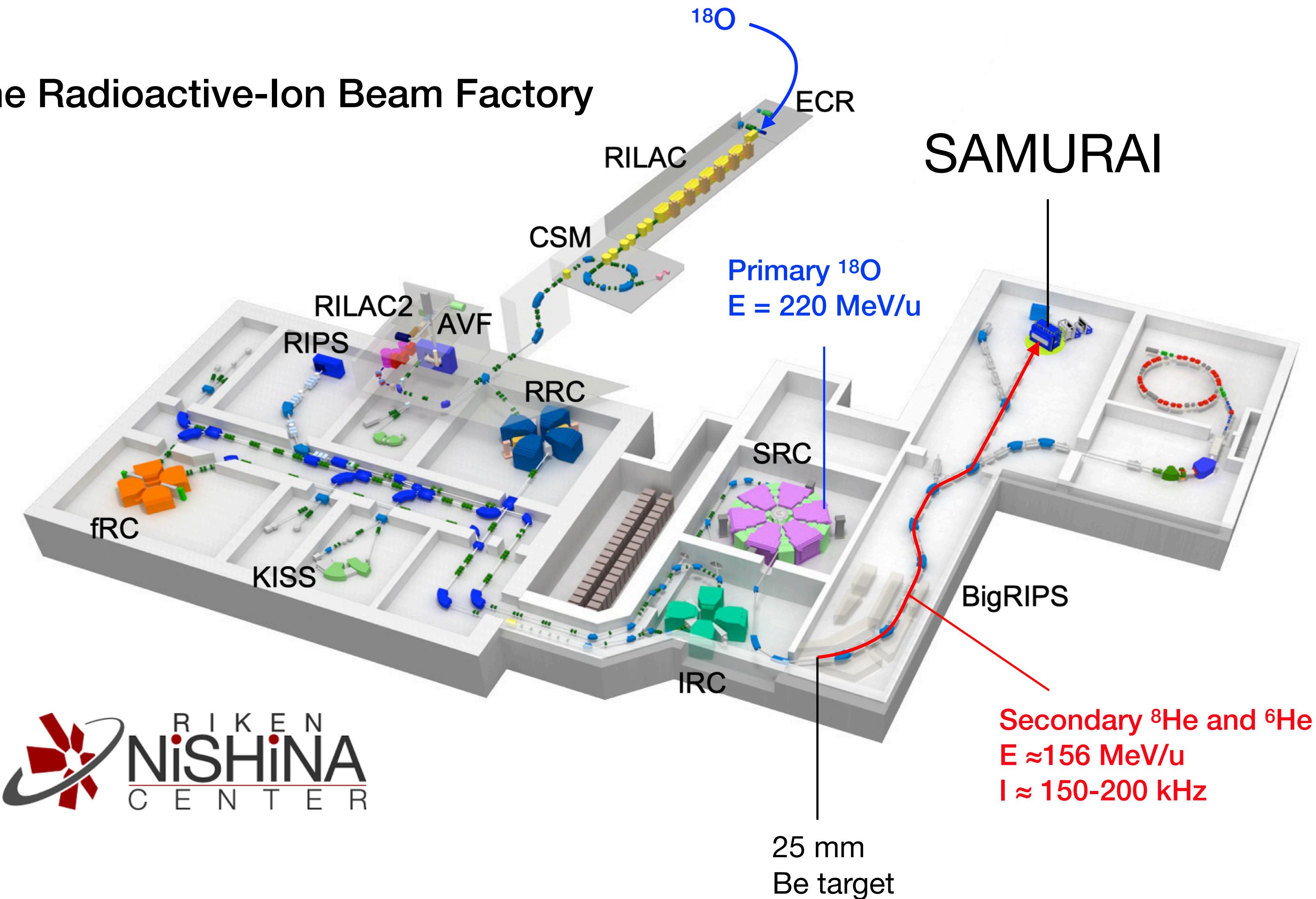
double-charge exchange @ 186 MeV/u



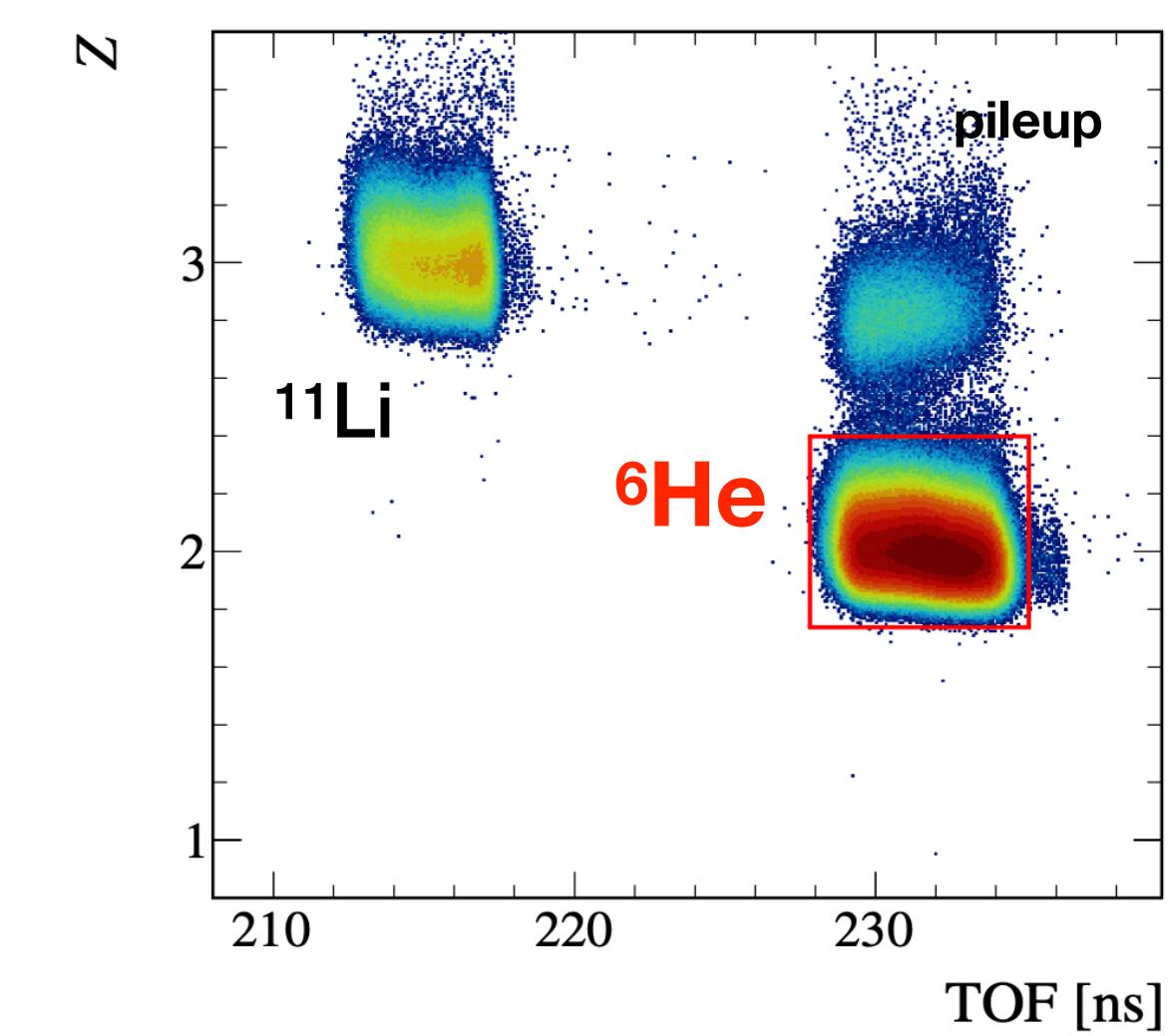
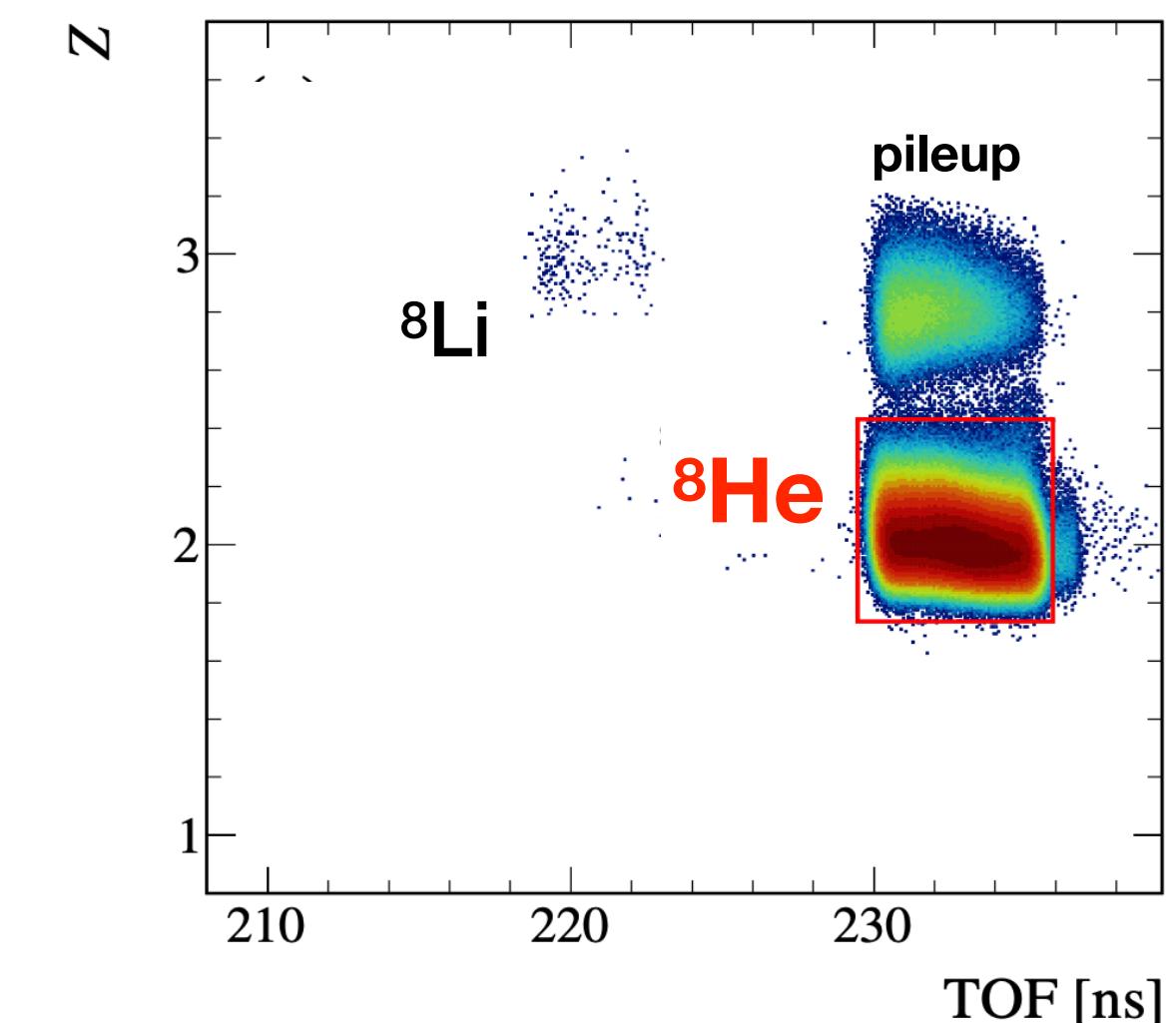
A few positive signals but low statistics

SAMURAI19 experiment in RIKEN (Japan)

The Radioactive-Ion Beam Factory

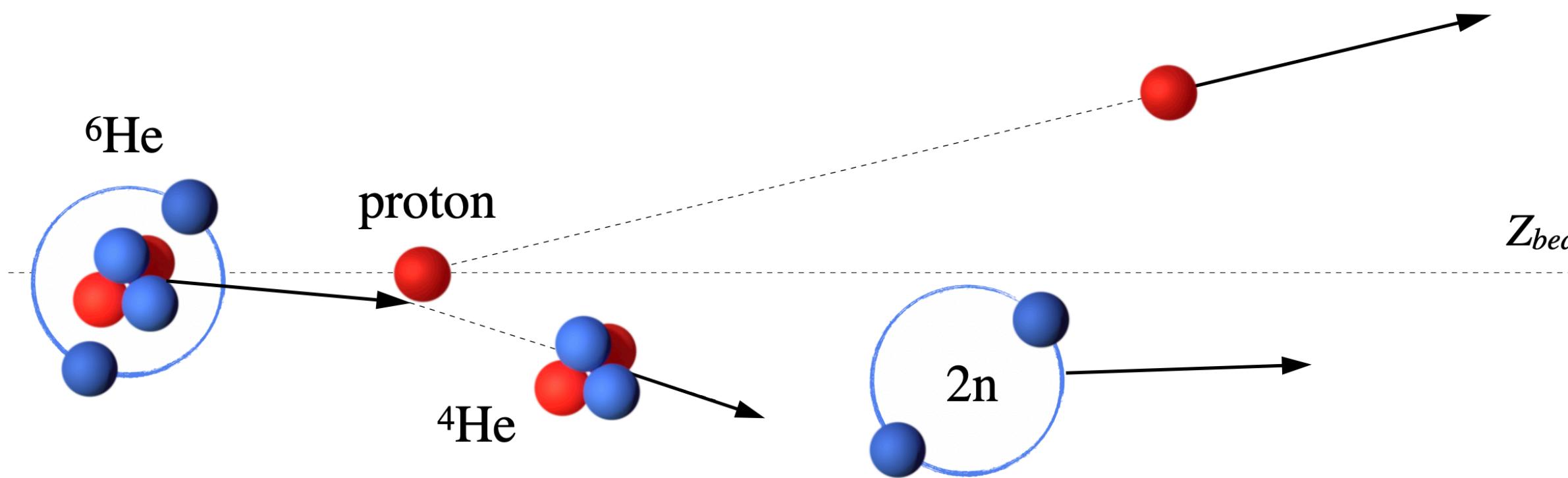


Secondary beam PID

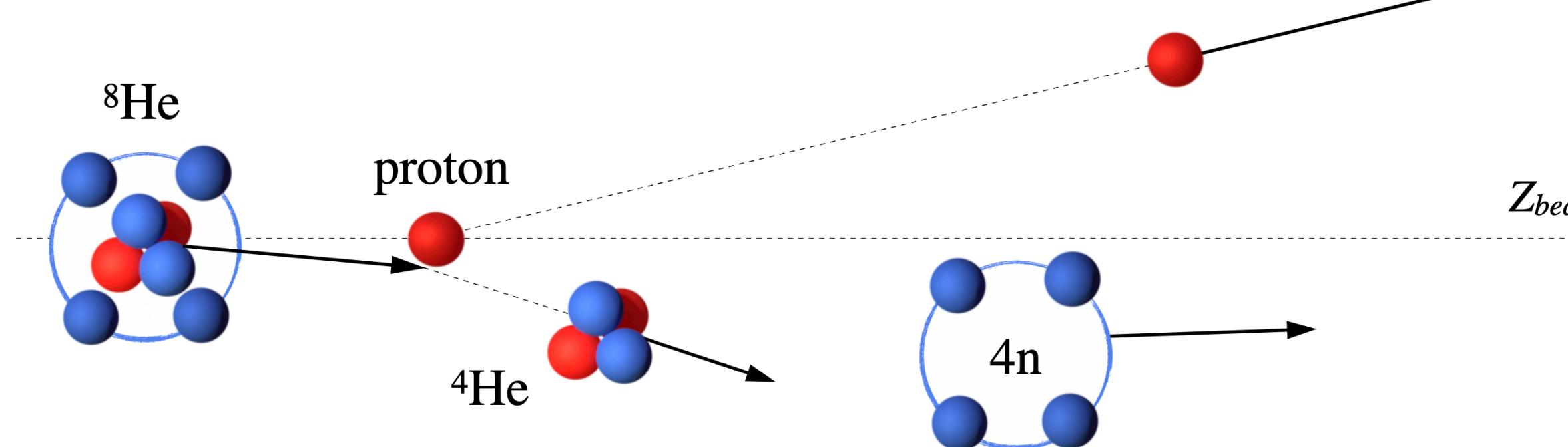


SAMURAI19 experiment in RIKEN (Japan)

di-neutron reference

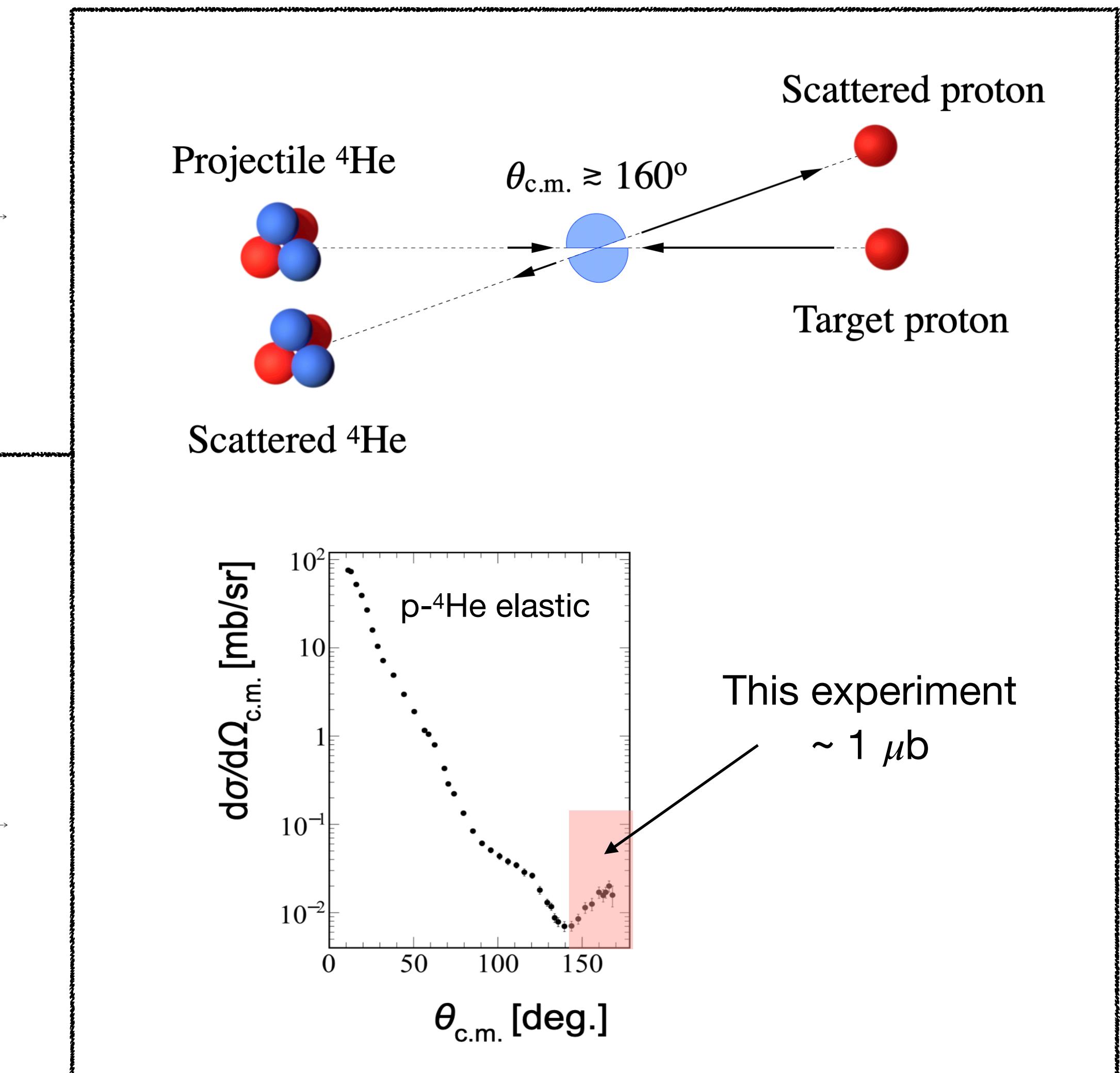


tetraneutron



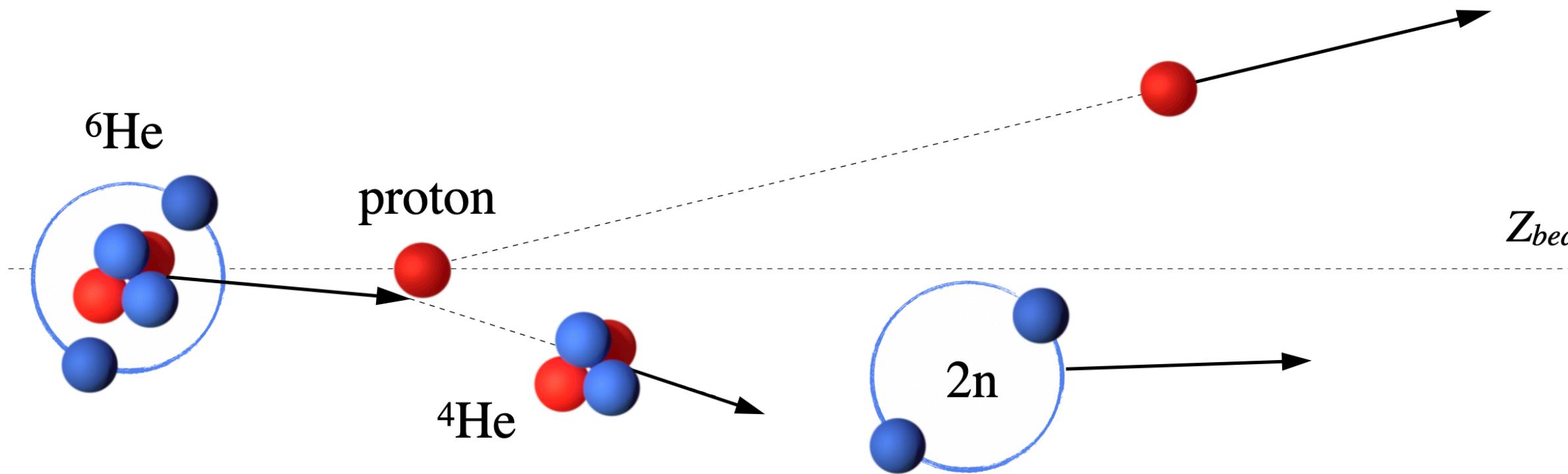
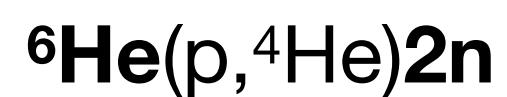
QFS reaction $\text{p}-^4\text{He}$ at large CM angle (max t)

→ minimize FSI

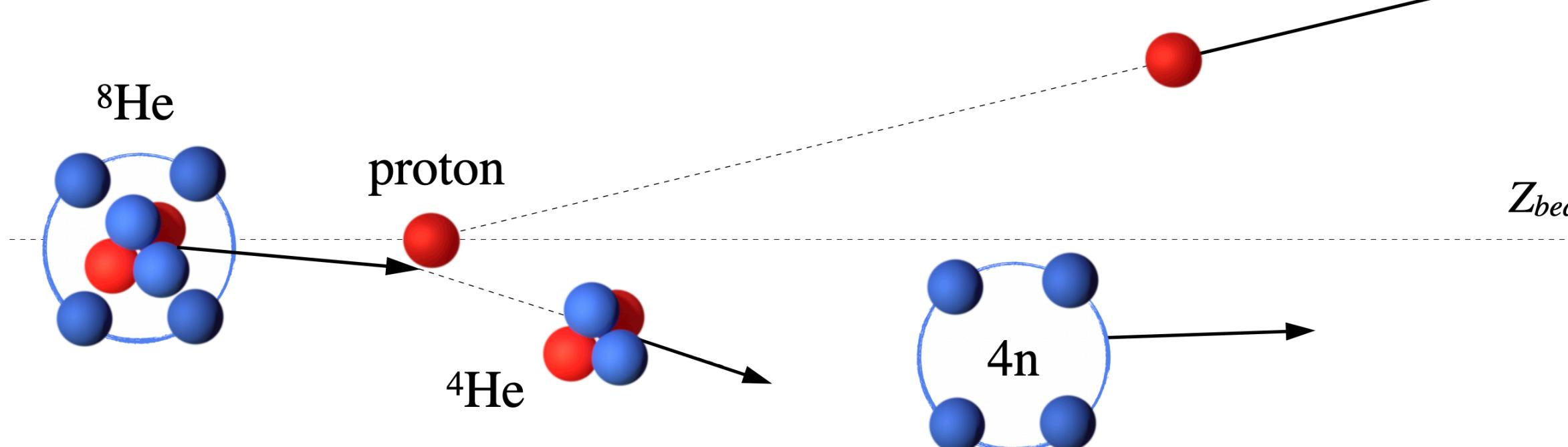


SAMURAI19 experiment in RIKEN (Japan)

di-neutron reference



tetraneutron



QFS reaction $\text{p}-^4\text{He}$ at large CM angle (max t)

→ minimize FSI

Missing 4-momentum:

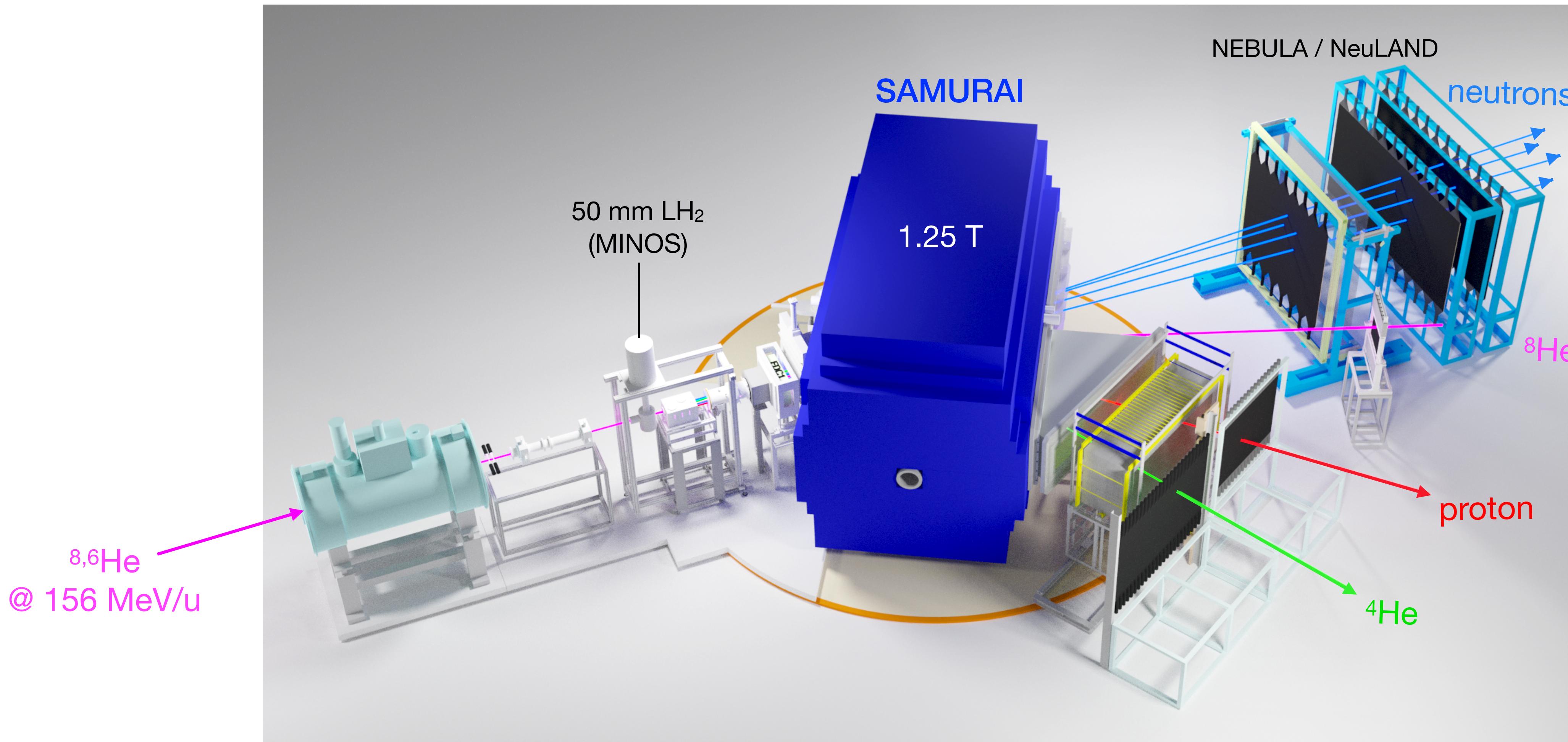
$$\mathbf{P}_{miss} = \mathbf{P}_{p(tgt)} + \mathbf{P}_{^8,^6\text{He}} - \mathbf{P}_{^4\text{He}} - \mathbf{P}_{p(out)}$$

$$E_{2n,4n} = \sqrt{E_{miss}^2 - \mathbf{P}_{miss}^2} - \sum_{n=1}^{2,4} m_n$$

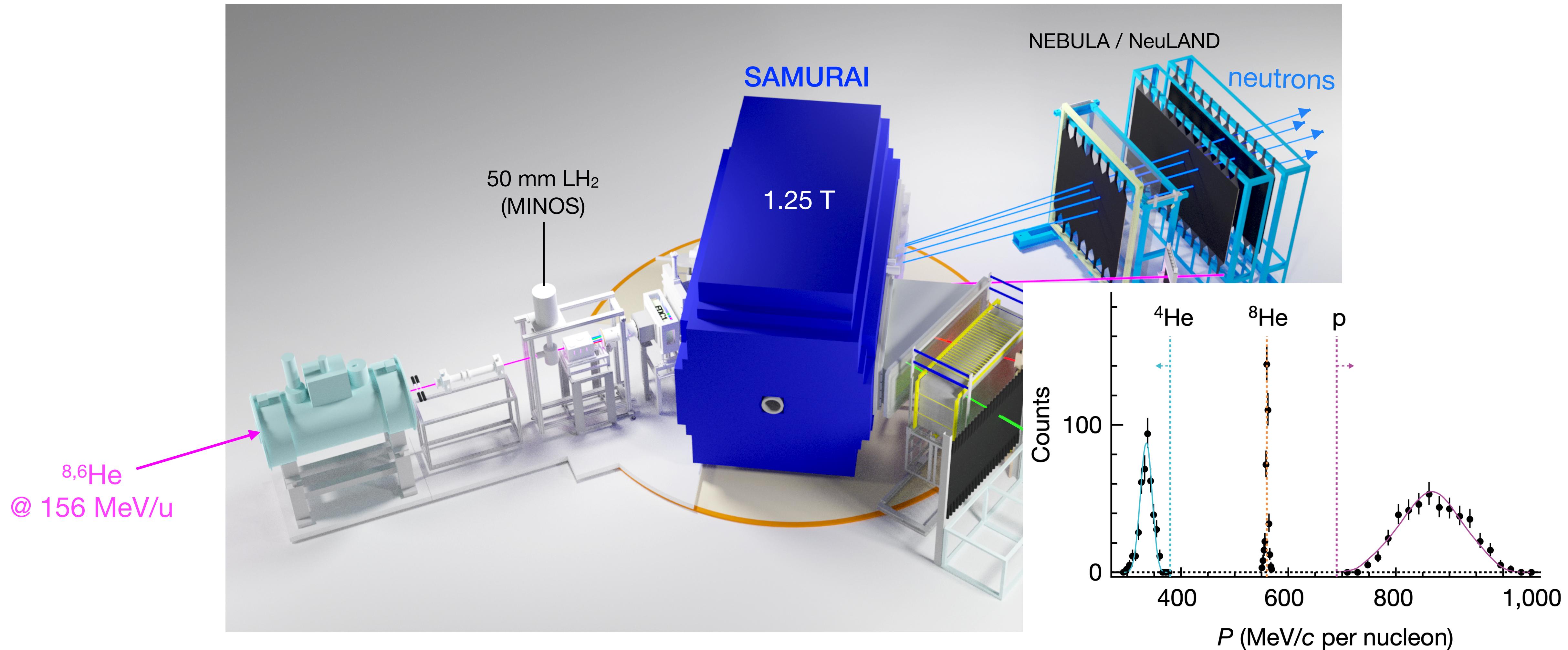
$E_{2n,4n} < 0$ - bound

$E_{2n,4n} > 0$ - unbound

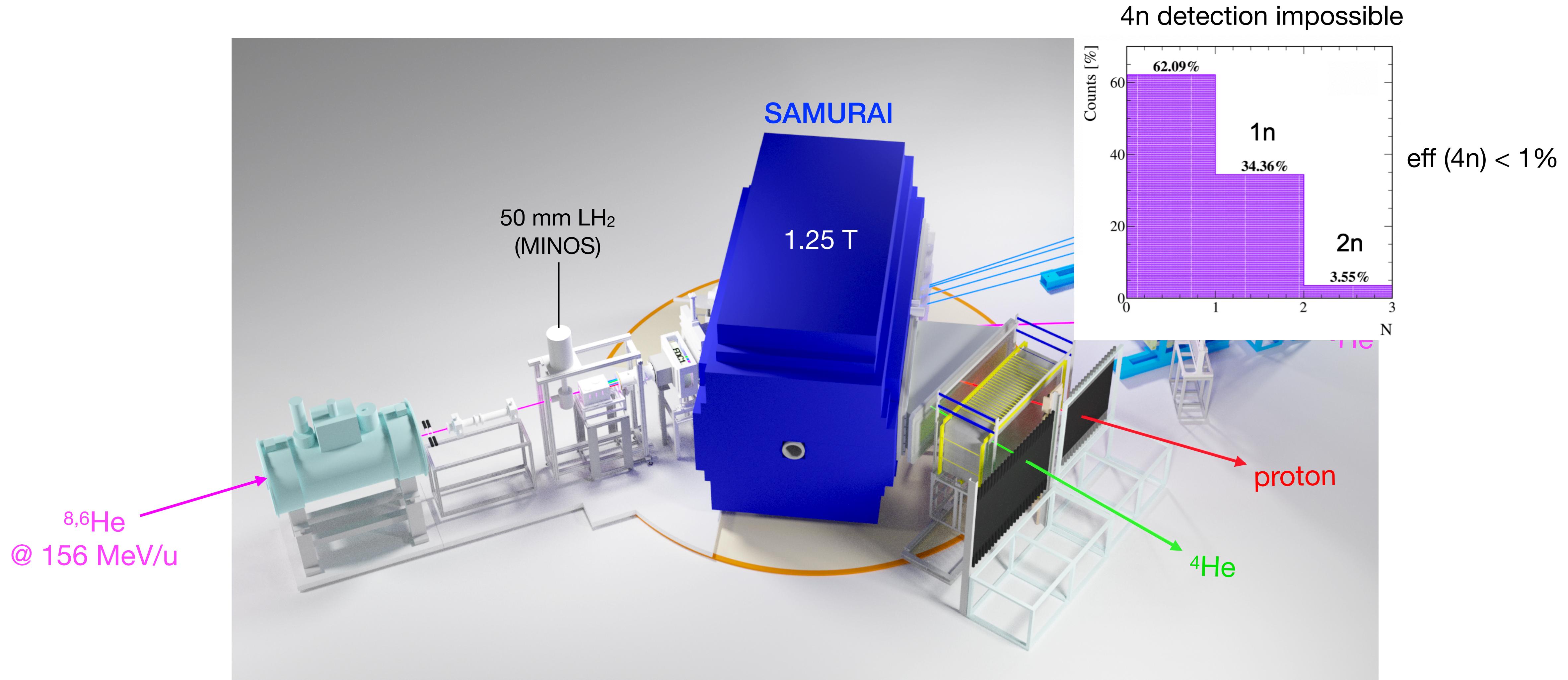
SAMURAI19 experiment in RIKEN (Japan)



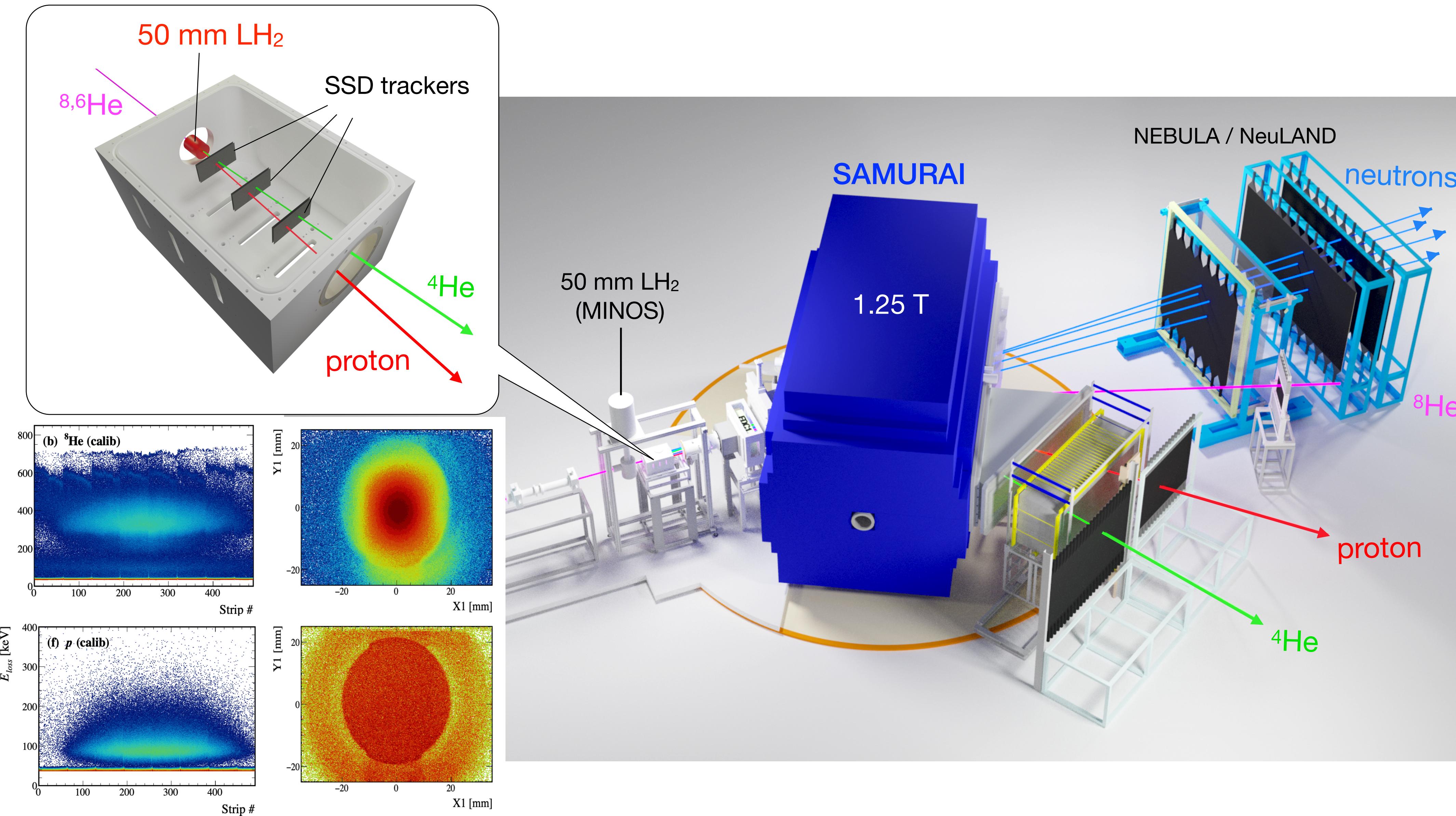
SAMURAI19 experiment in RIKEN (Japan)



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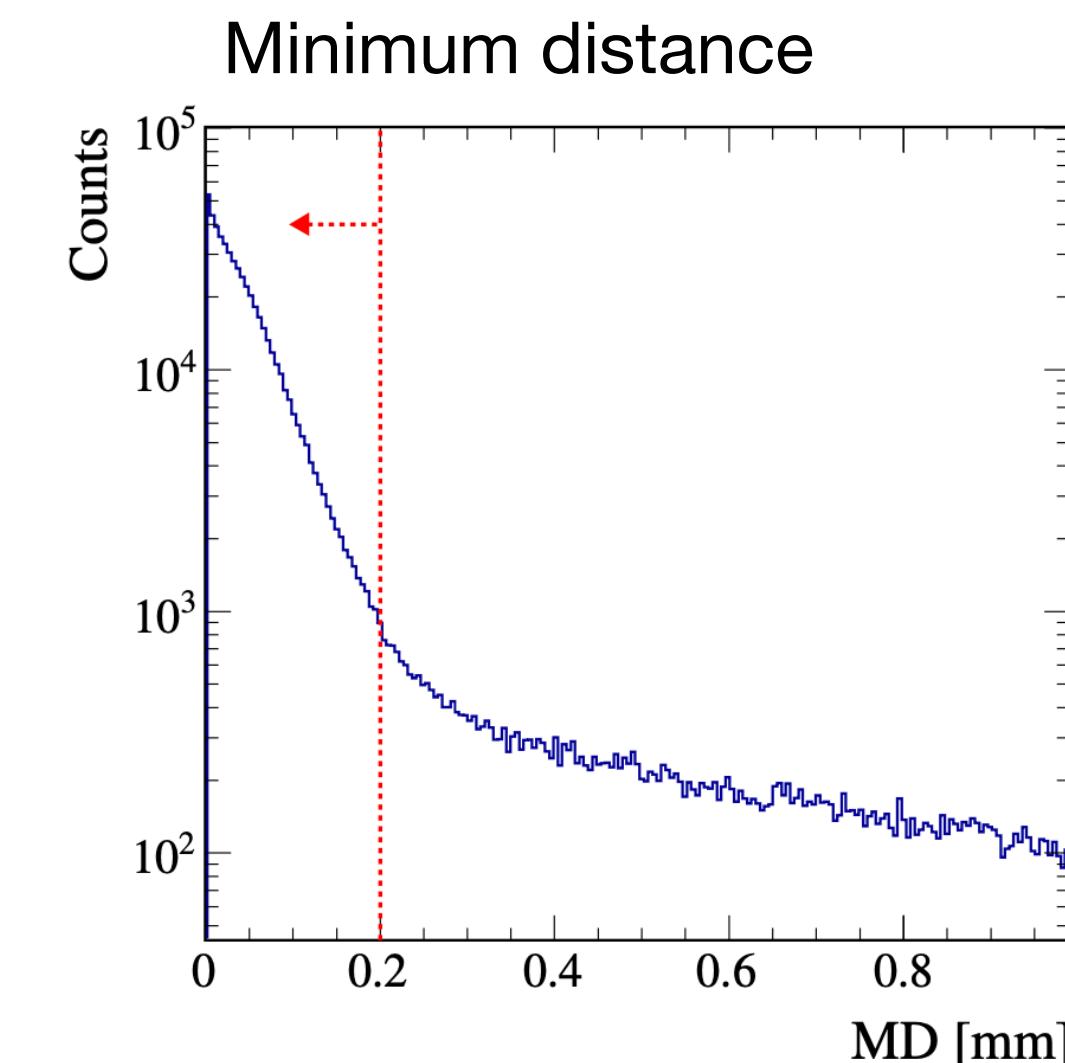
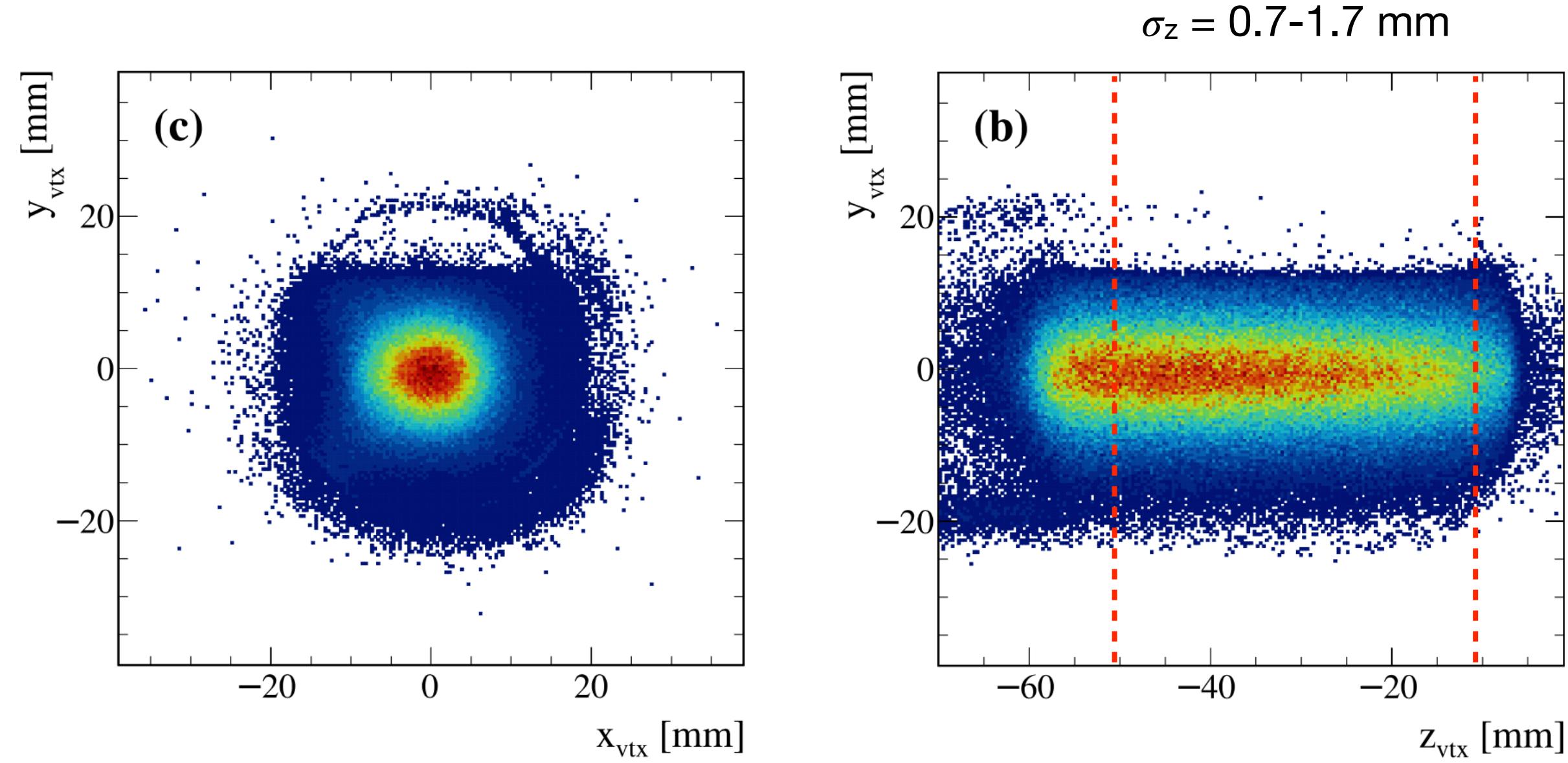


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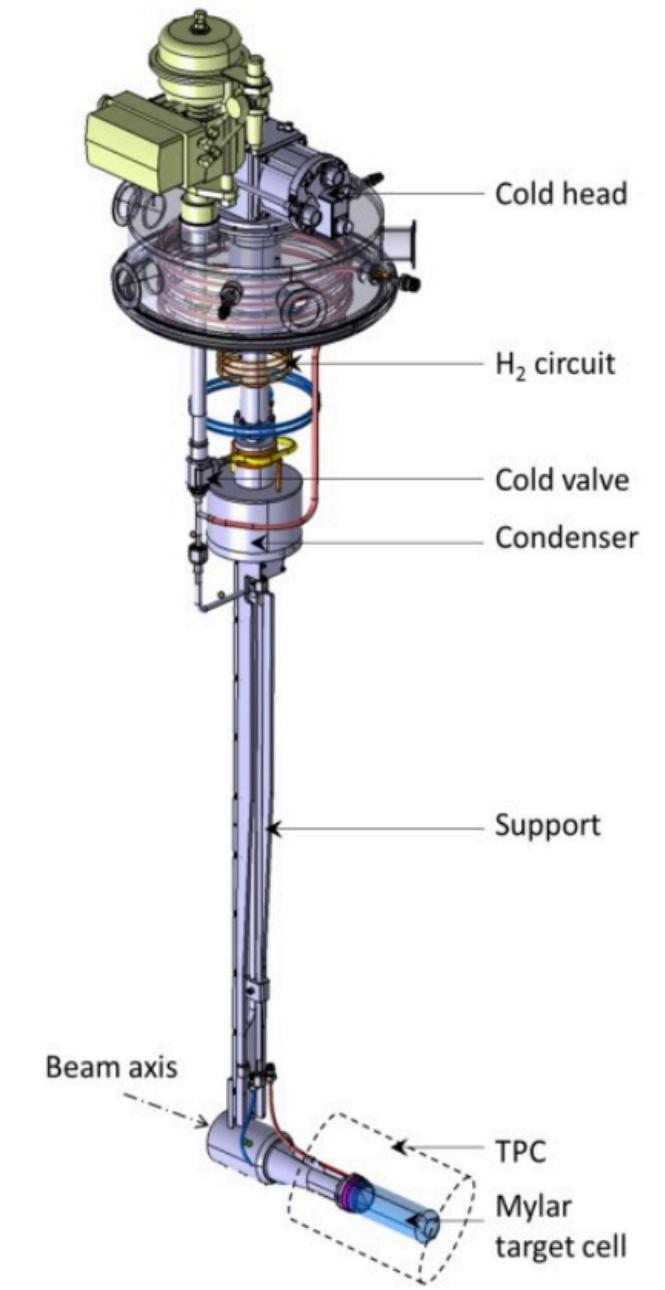


Target vertex reconstruction

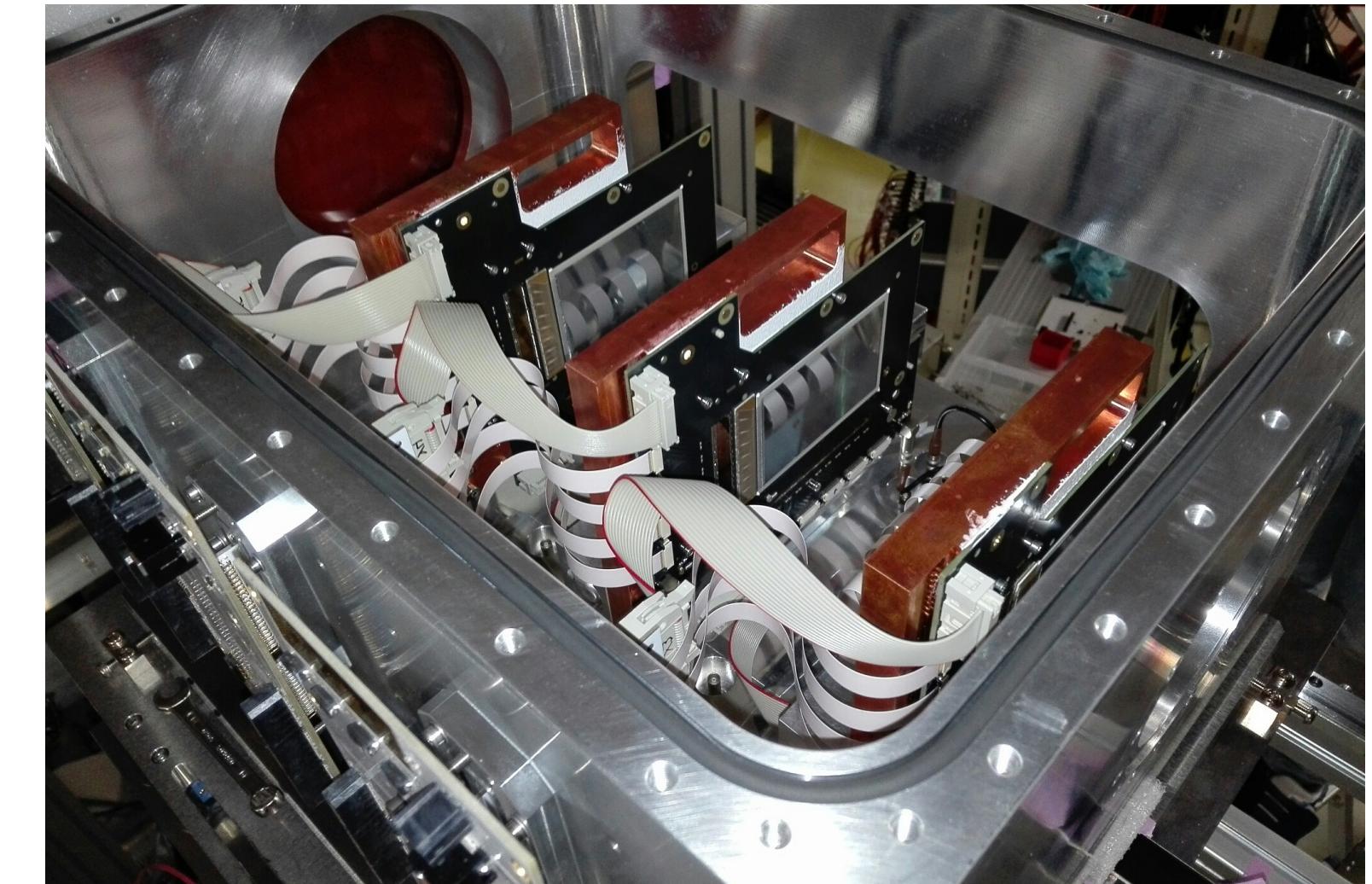
Using events with 2 tracks in SSDs



LH2 target

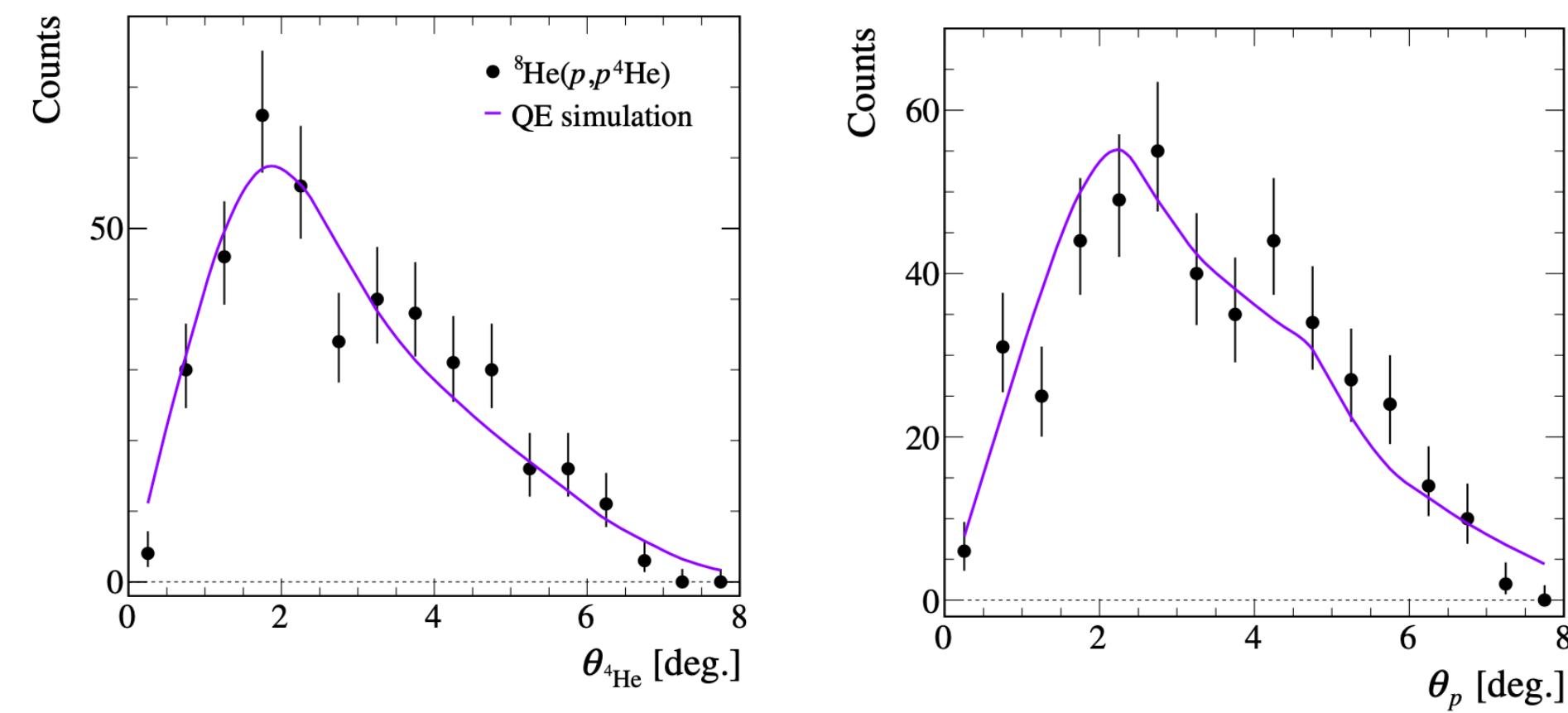


SSD trackers

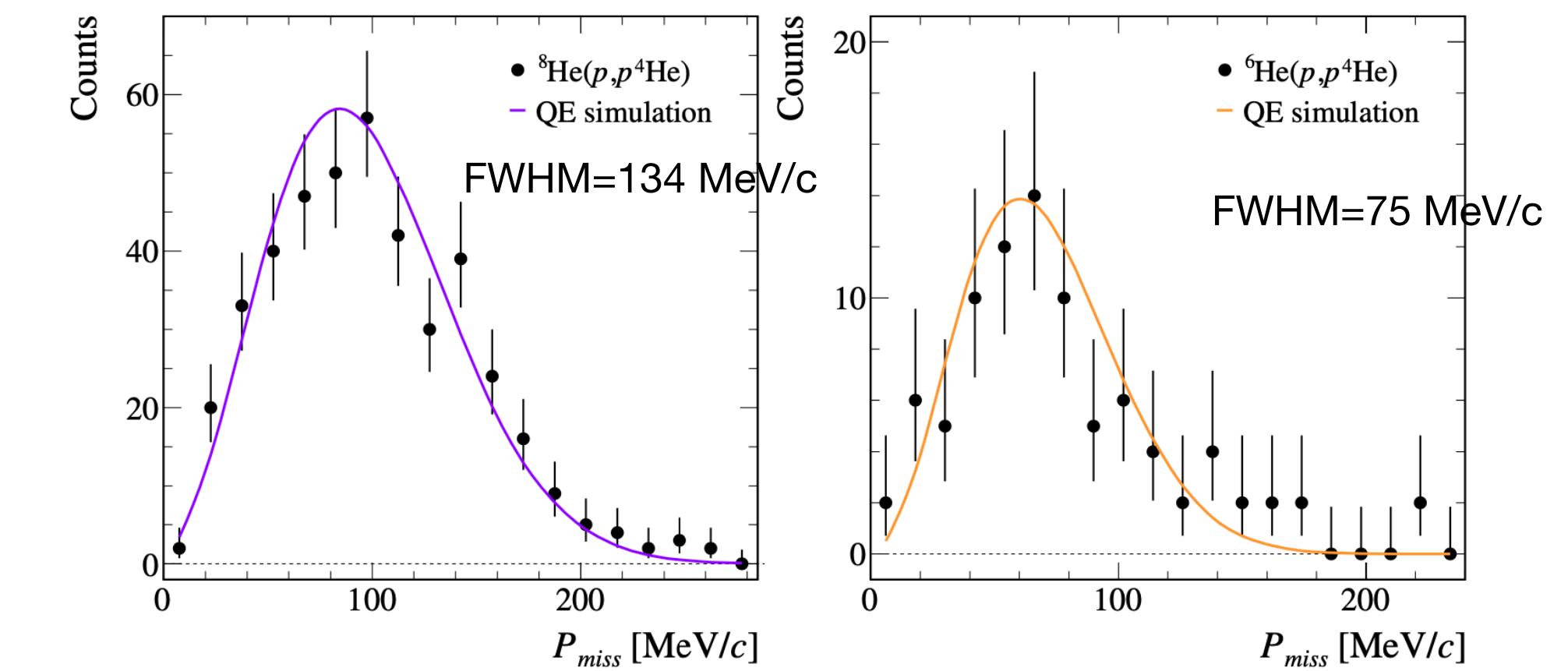


Kinematics of coincident p and ${}^4\text{He}$

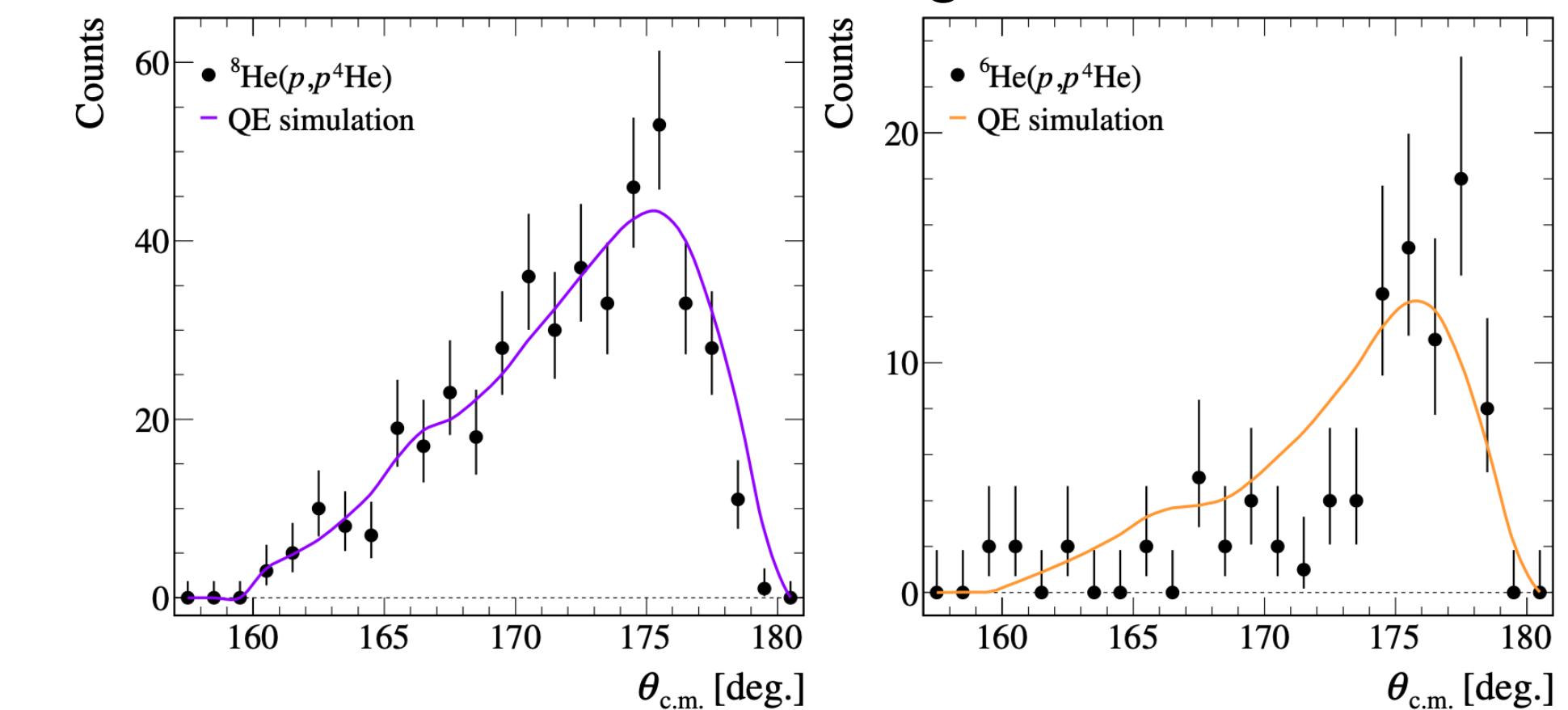
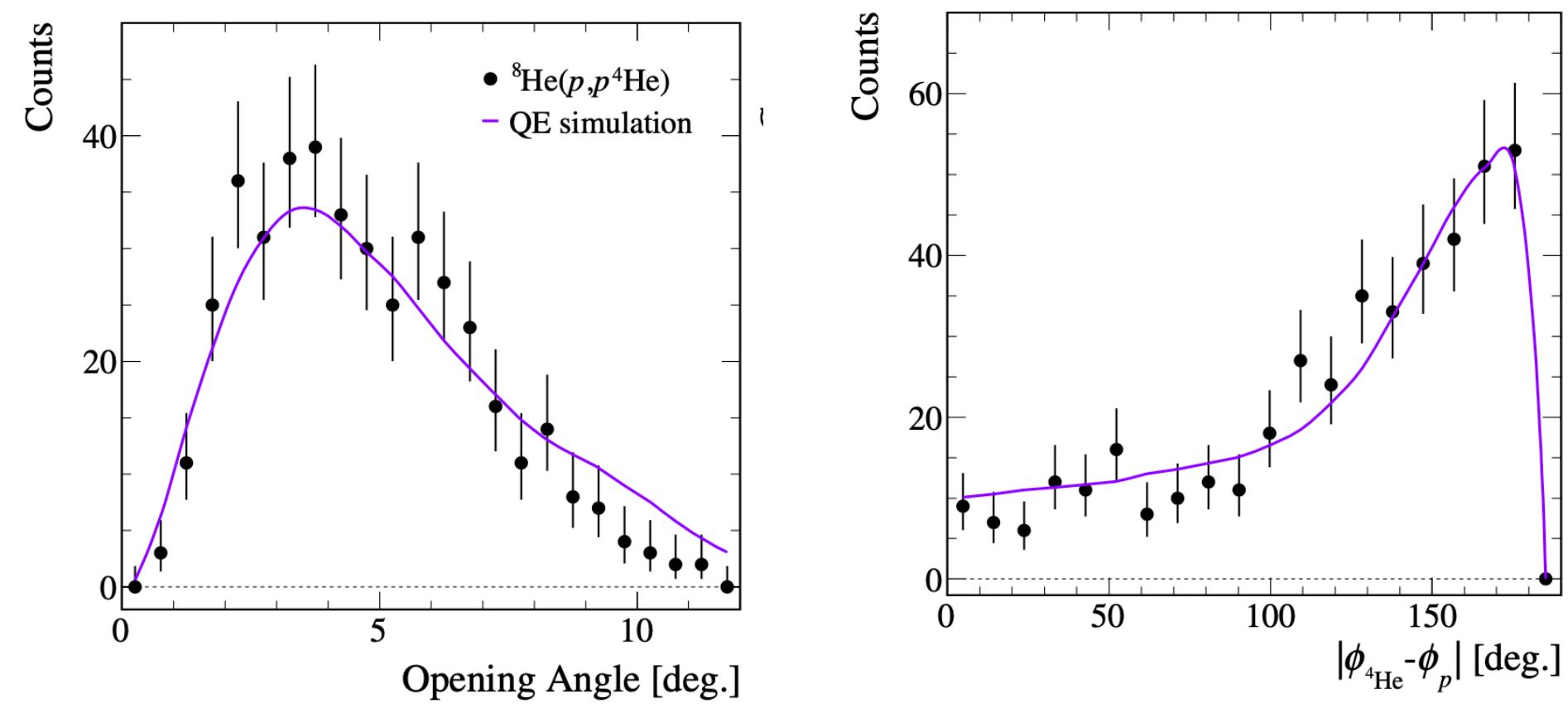
Laboratory angles



Missing momenta

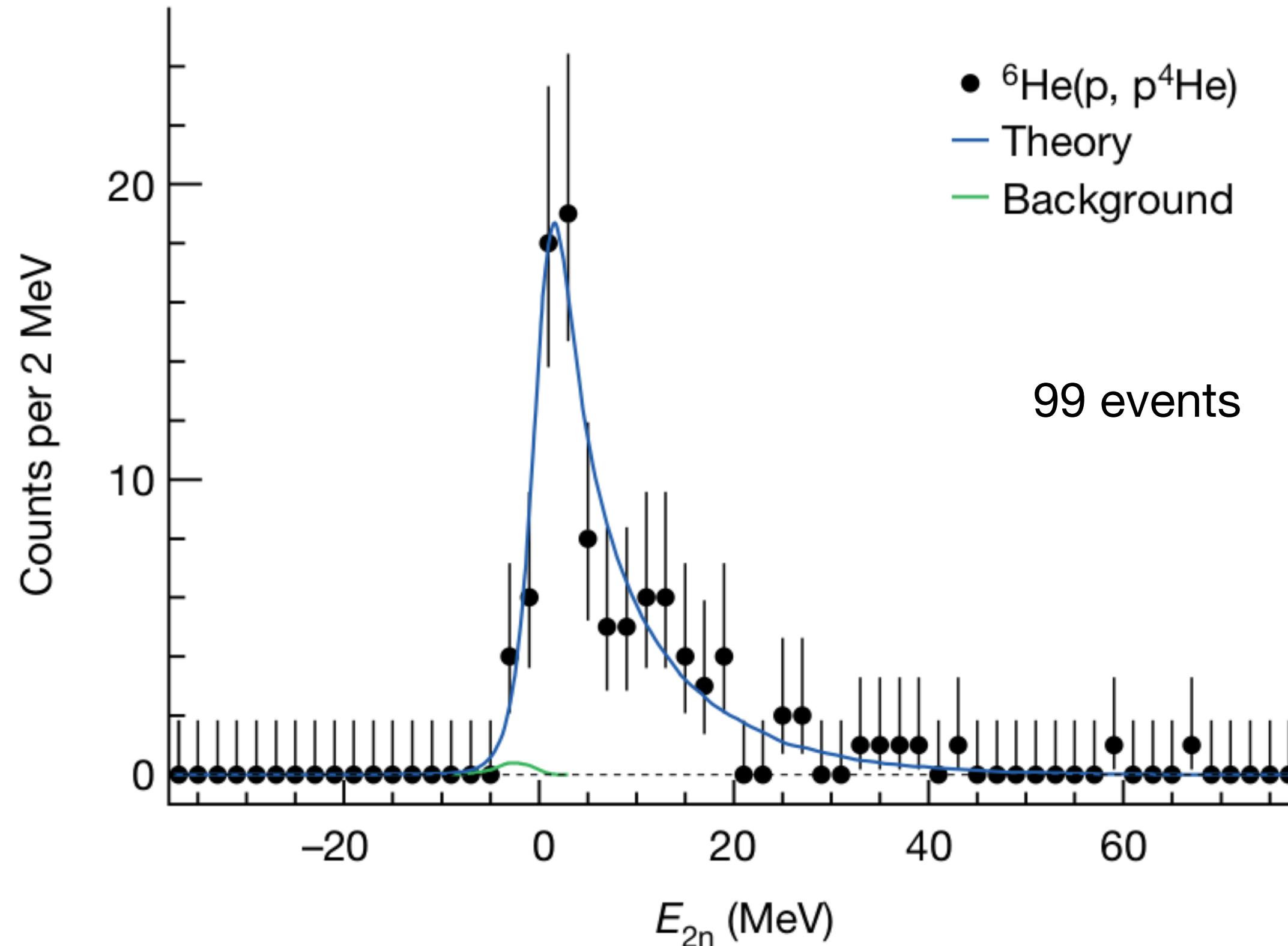


CM angles



Results for 2n

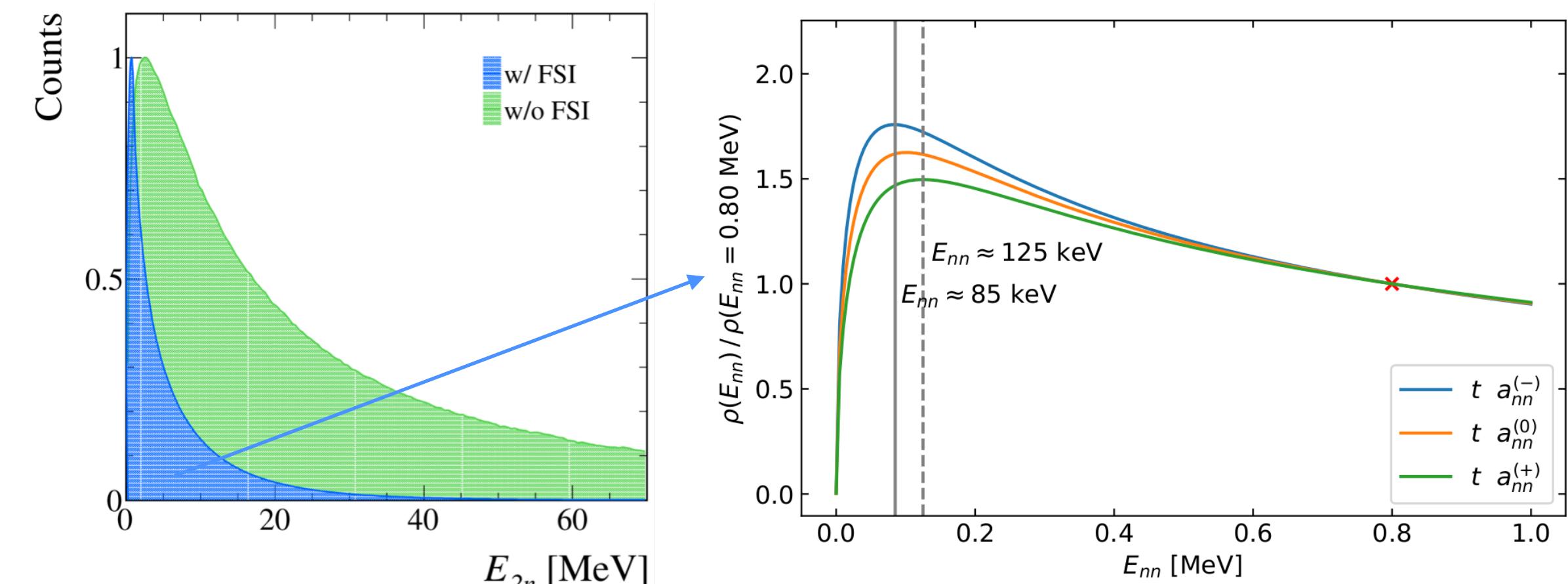
${}^6\text{He}(\text{p}, \text{p}^4\text{He})2\text{n}$



Low-energy peak ~ 100 keV

M. Duer et al., Nature 606, 678 (2022)

Göbel, M. et al. *Phys. Rev. C* **104**, 024001 (2021).

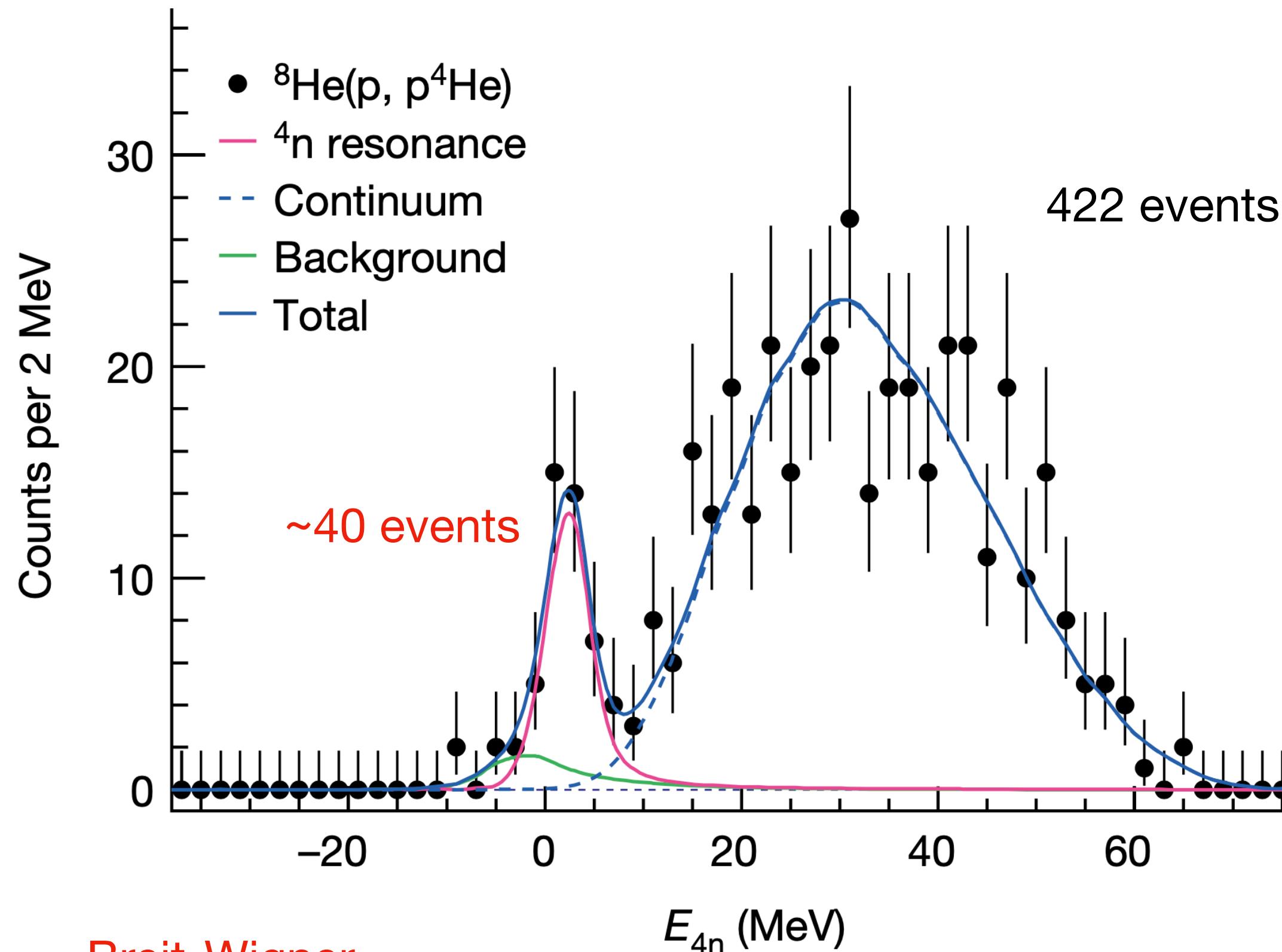


Theory input:

- w/o FSI: Halo EFT 3-body (${}^4\text{He} + \text{n} + \text{n}$) cluster model
 - nn interaction in ${}^1\text{S}_0$ wave
 - na interactions in s-, p-, d-wave
 - phenomenological 3-body force
- w/ FSI: nn final-state interaction
 - nn t-matrix approach

Results for 4n

${}^8\text{He}(\text{p}, \text{p}{}^4\text{He})4\text{n}$



Breit-Wigner

$$E_r = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.}) \text{ MeV}$$

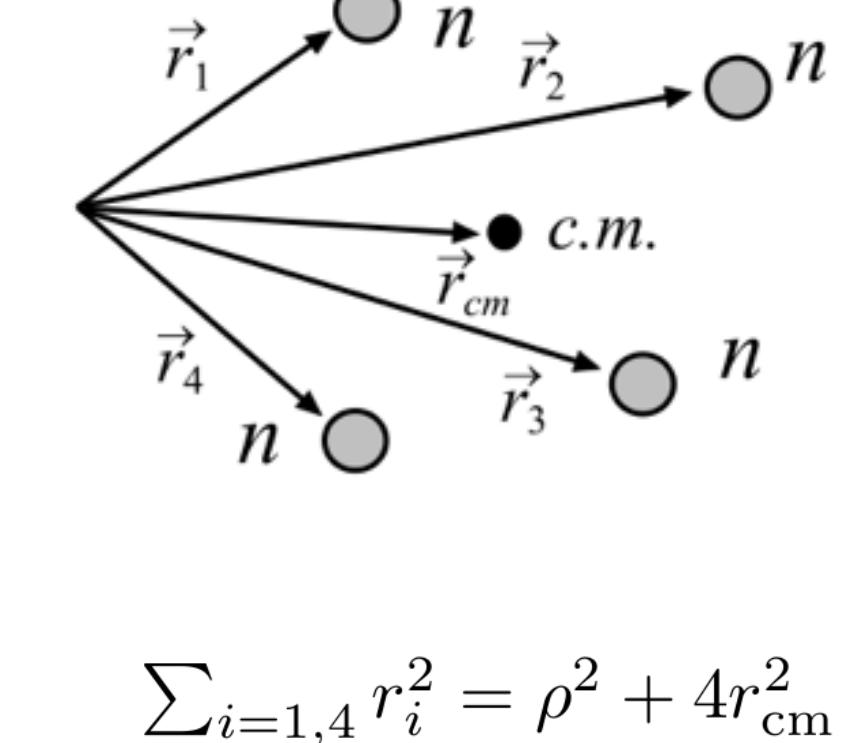
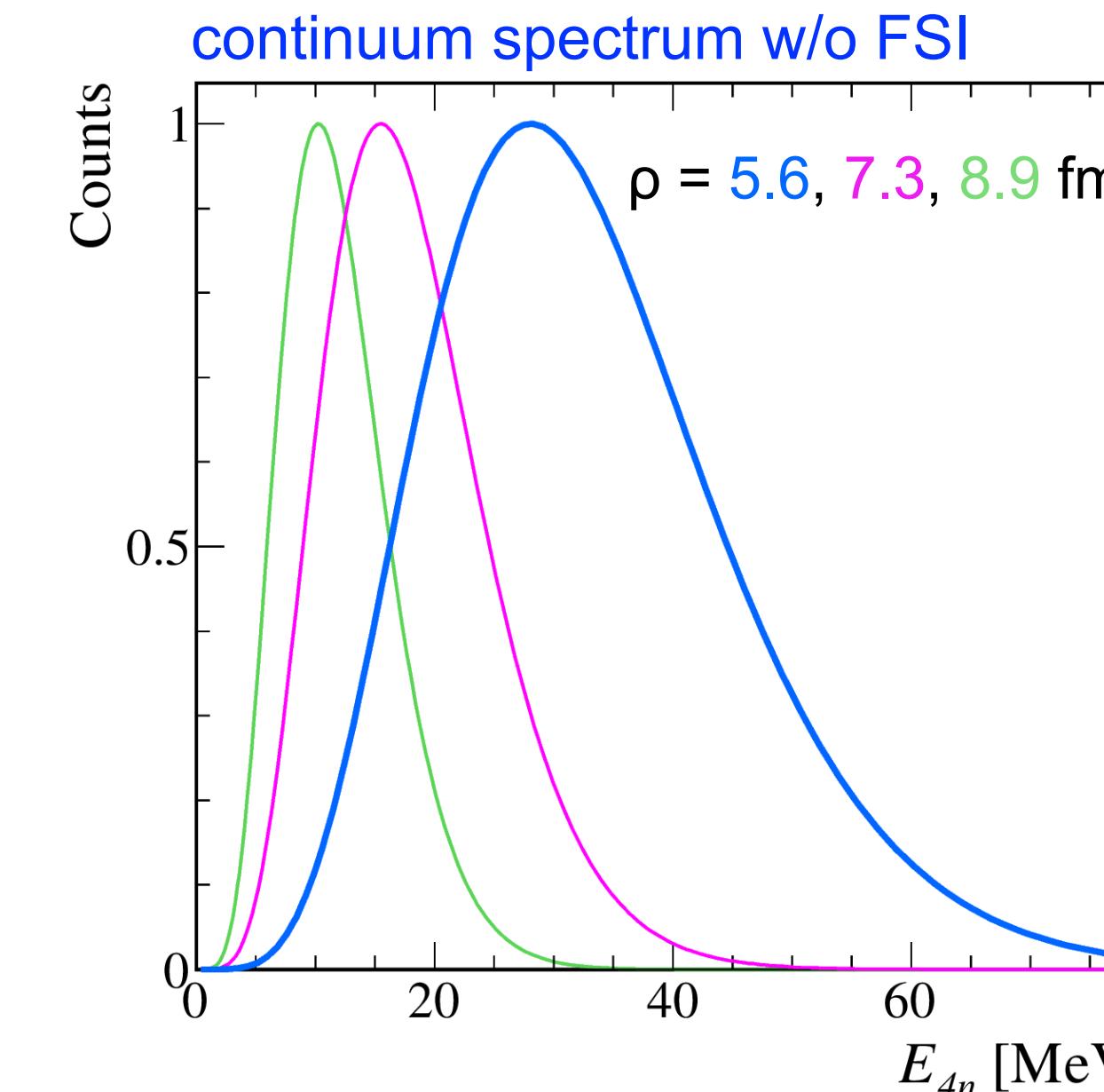
$$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.}) \text{ MeV}$$

$$\tau = (3.8 \pm 0.8) \times 10^{-22} \text{ s}$$

M. Duer et al., Nature 606, 678 (2022)

M .V. Zhukov et al. PRC 50 1994

L. V. Grigorenko et al. Eur. Phys. J. A 19 (2004)

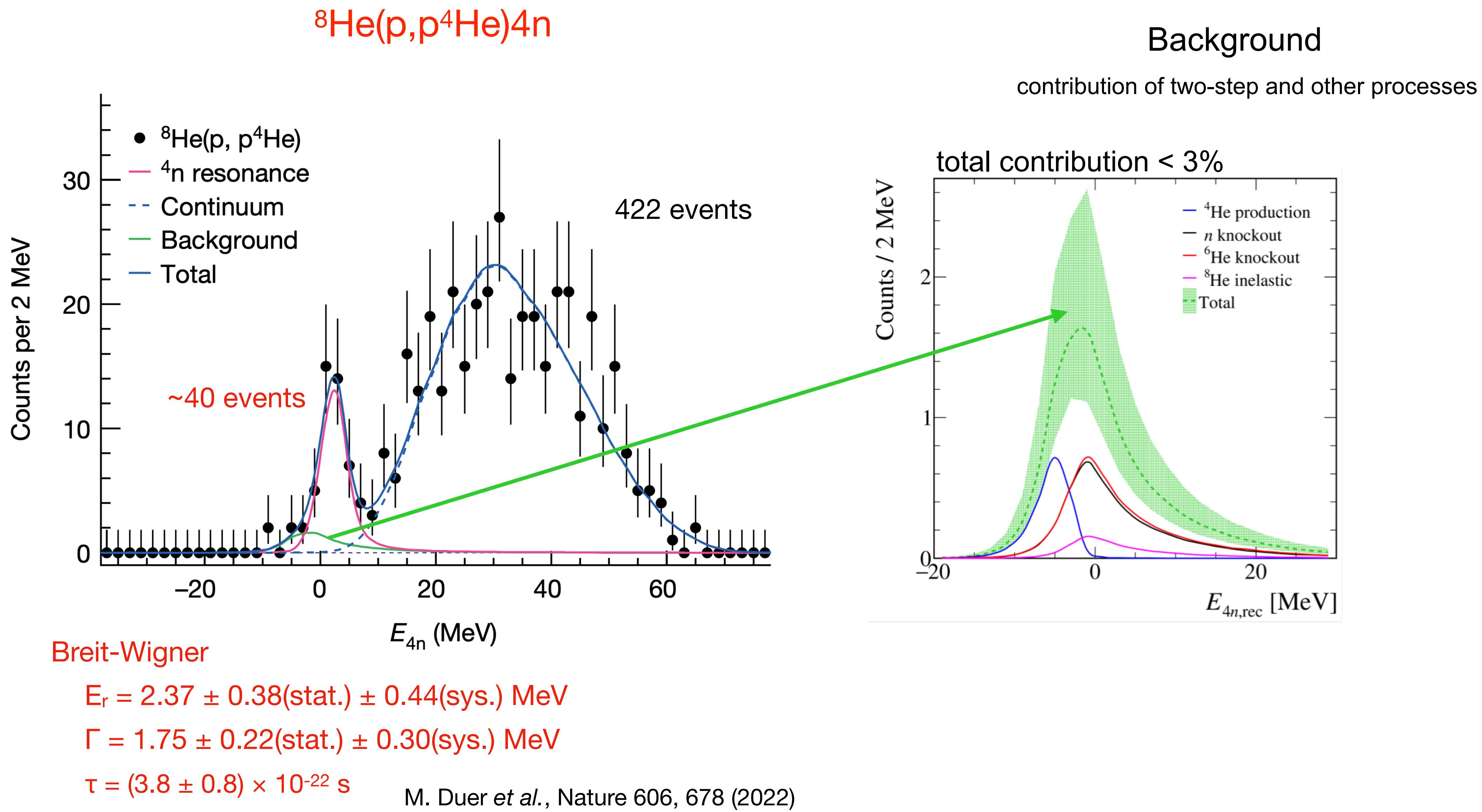


$$\sum_{i=1,4} r_i^2 = \rho^2 + 4r_{cm}^2$$

- COSMA: Five-body (${}^4\text{He} + 4\text{n}$) cluster orbital SM approximation

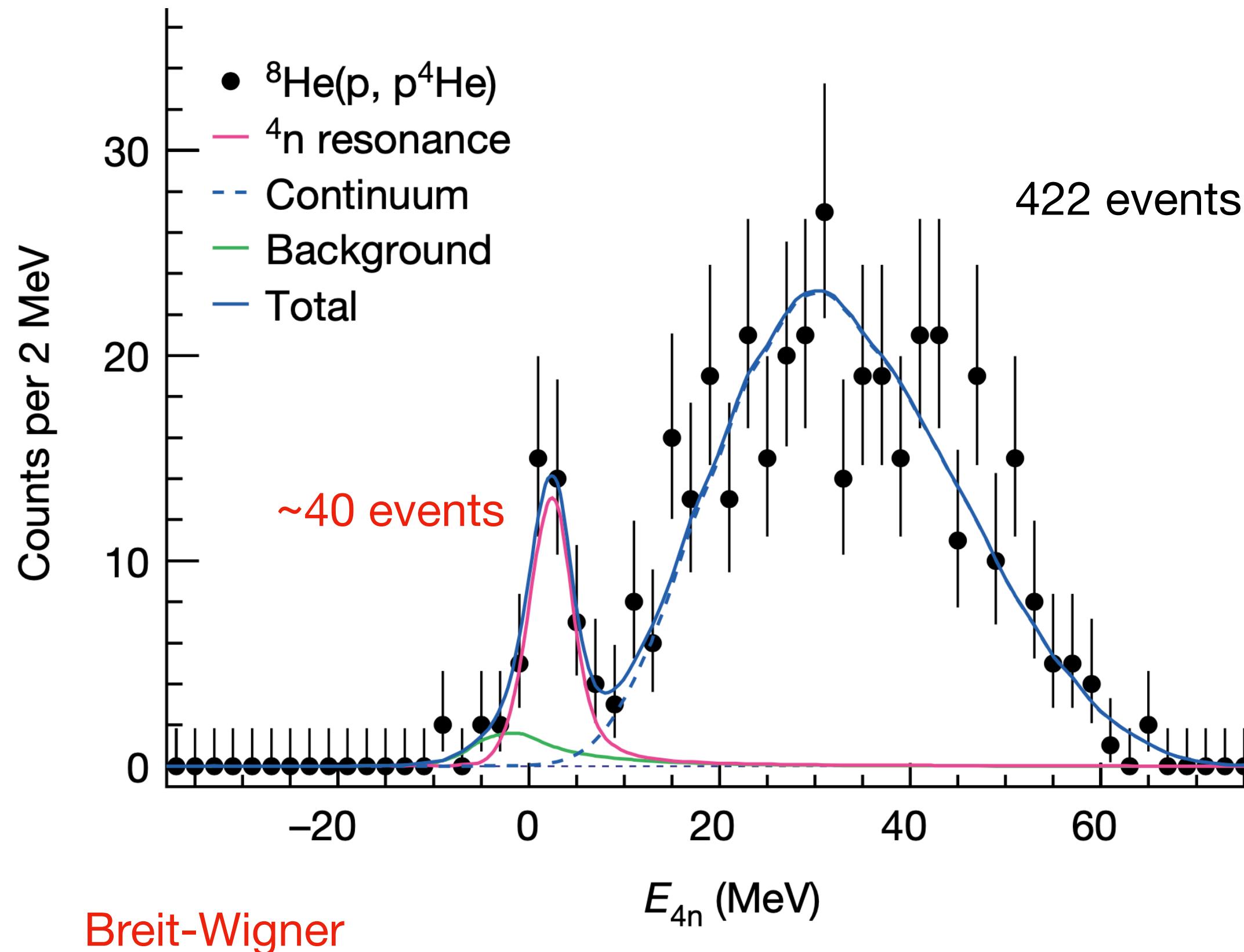
- A source term for the reaction mechanism: structure of ${}^8\text{He}$
- Sensitive to the hyper radius of the source
- $\rho = 5.6 \text{ fm}$ reproduces experimental ${}^8\text{He}$ radius

Results for 4n



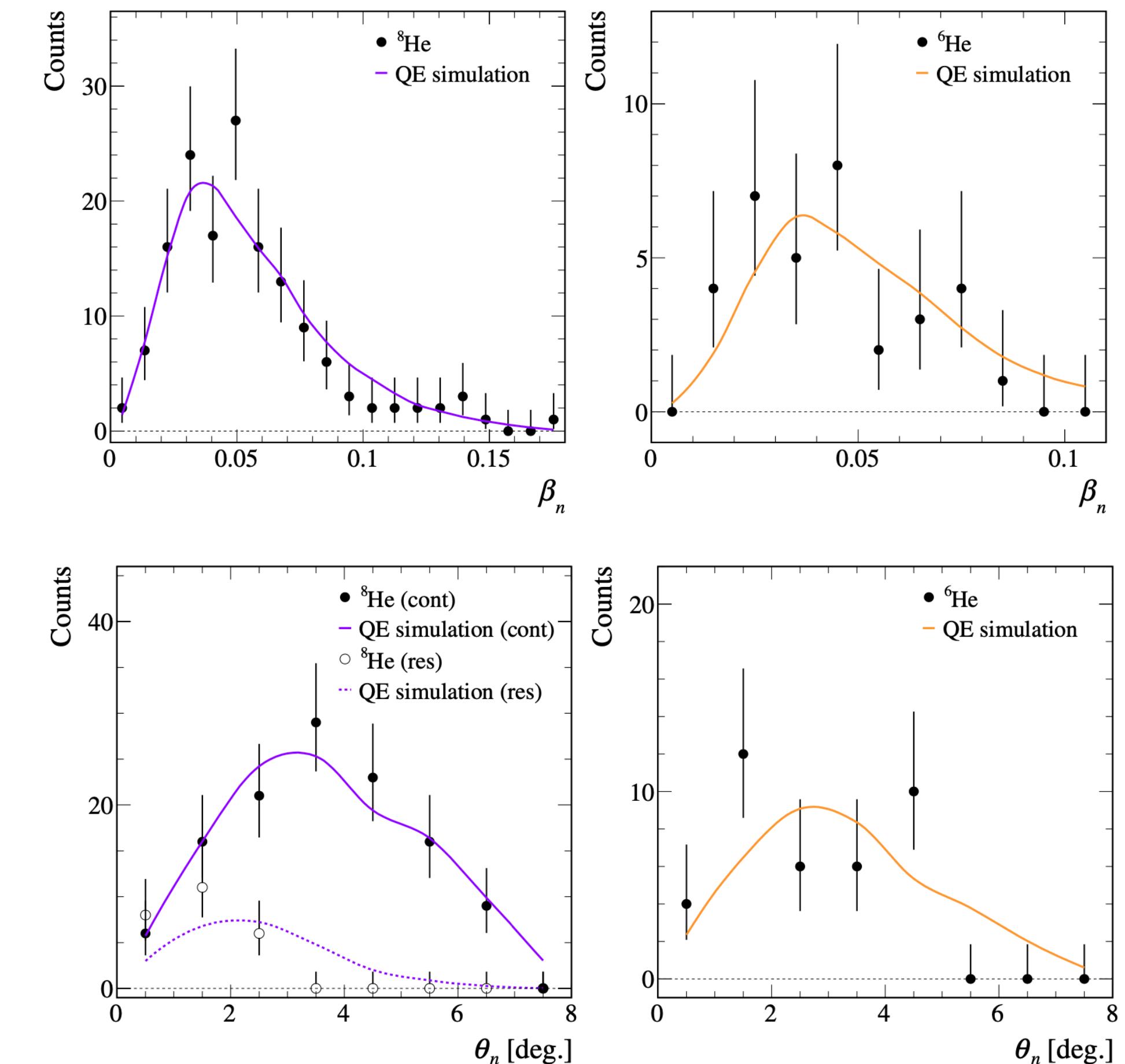
Results for 4n

${}^8\text{He}(\text{p}, \text{p}{}^4\text{He})4\text{n}$

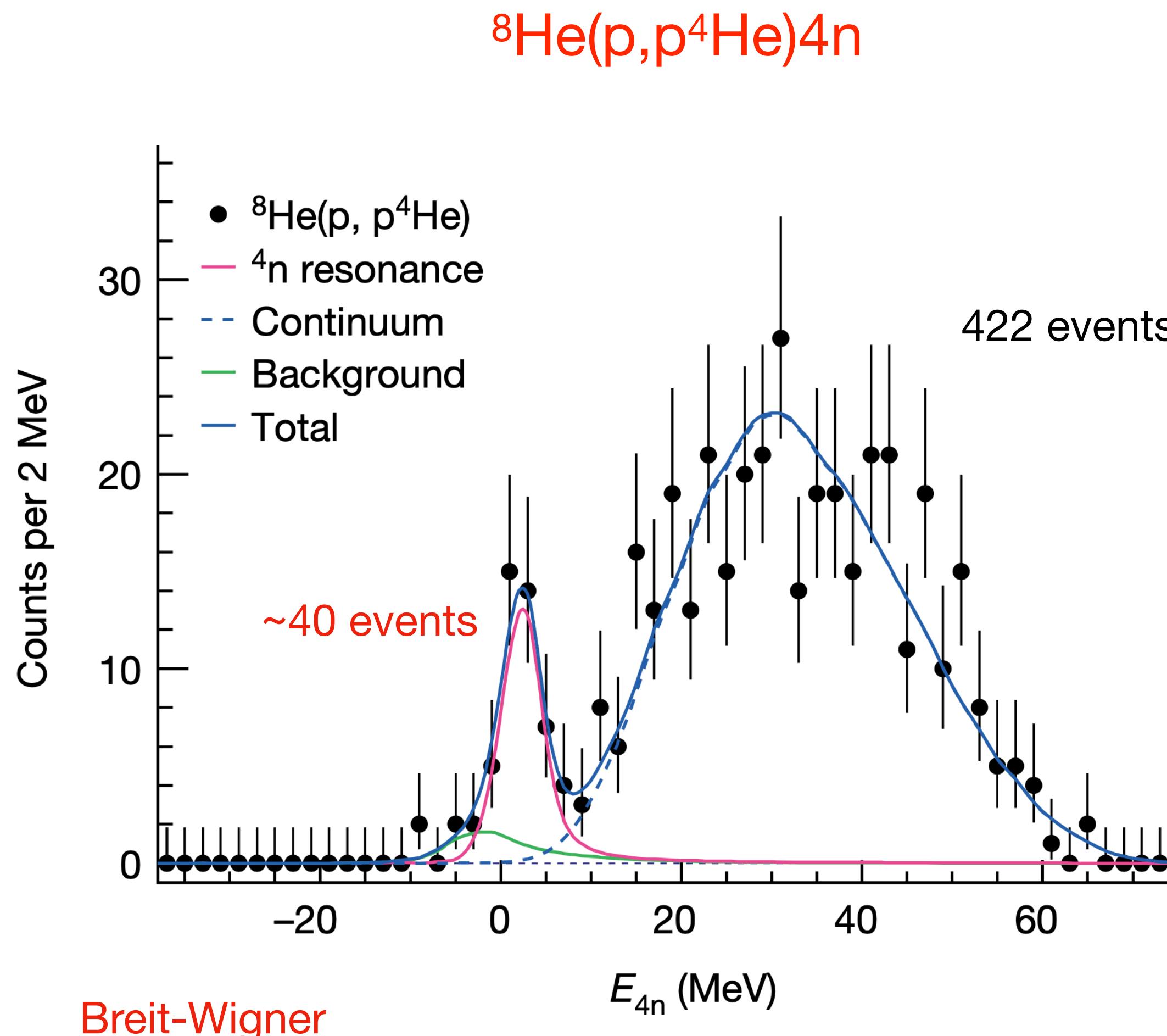


M. Duer *et al.*, Nature 606, 678 (2022)

Consistency check with one detected neutron in coincidence



Results for 4n



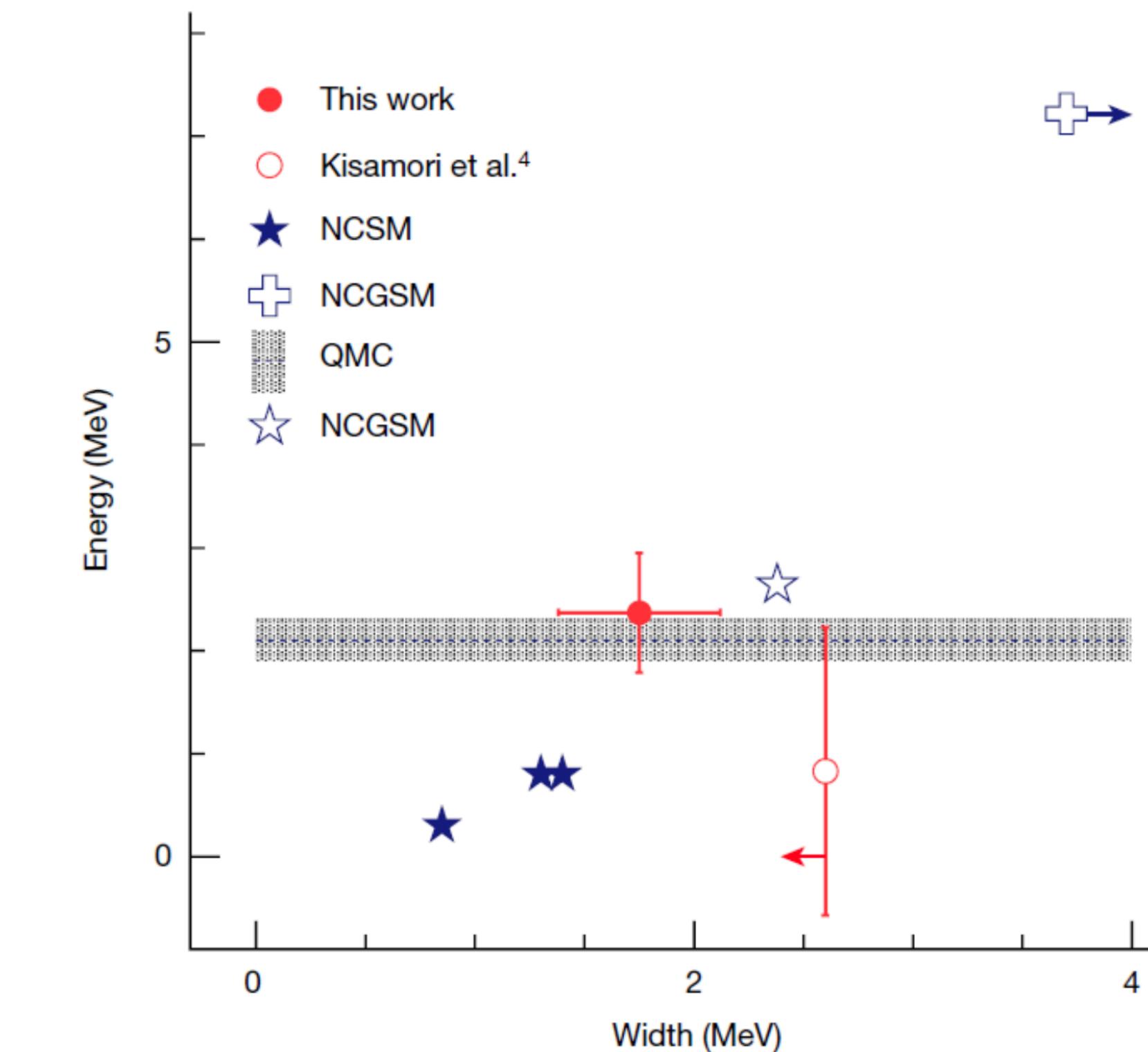
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Comparison with literature

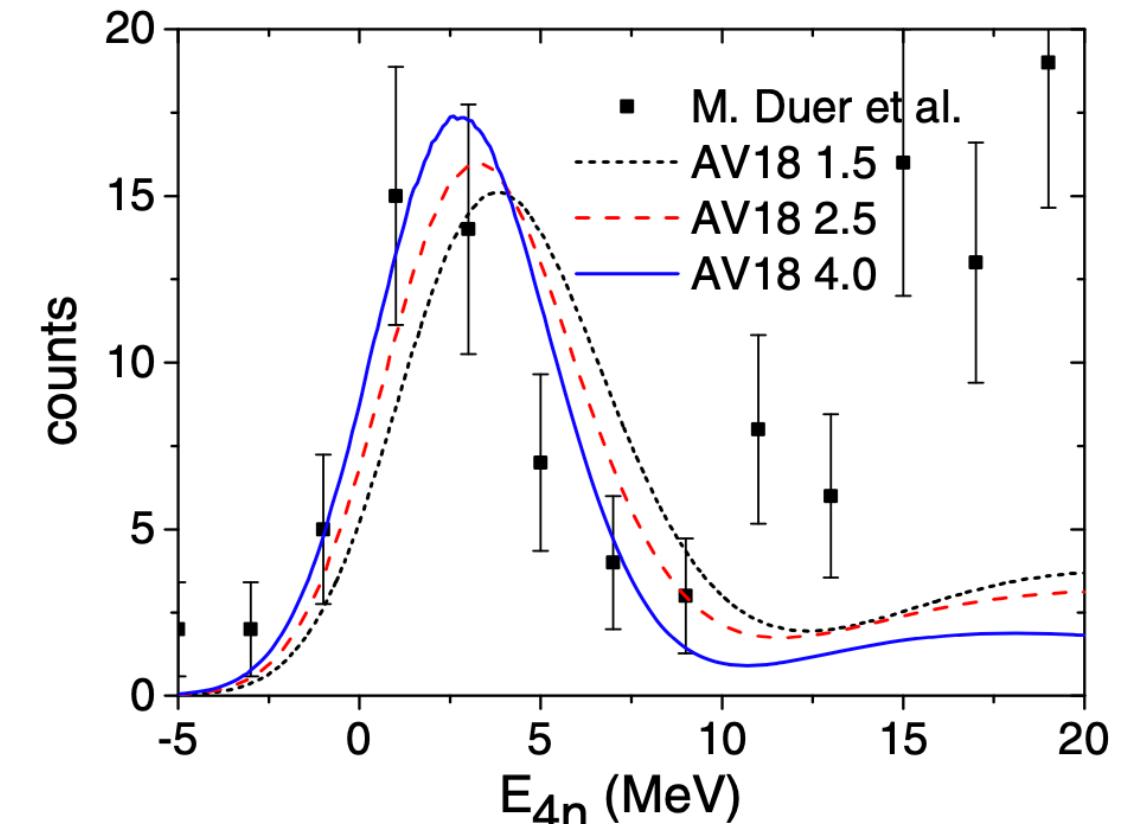


★ Shirokov PRL 117 (2016); ■ Gandolfi PRL 118 (2017);
 + Fossez PRL 119 (2017); ☆ Li PRC 100 (2019);

Theoretical interpretations

2n - 2n FSI correlations?

Laszauskas, Hiyama & Carbonell PRL 130, 102501 (2023)



$$H_i = H_0 + \lambda \sum_{i=1}^N |\psi_\alpha(r_i)\rangle\langle\psi_\alpha(r_i)| + \sum_{i<j=1}^N V_{nn}(r_{ij}) + \sum_{i=1}^N V(r_{iG}) + \sum_{i<j=1}^N W_{ij}(\rho, r_{ijG}),$$

Pauli n-n mean-field n-n-a

$$A \equiv \langle {}^4\text{He} \Phi_{4n}(E) | \hat{O} | {}^8\text{He} \rangle = \langle \Phi_f | \hat{O} | \Psi_i \rangle$$

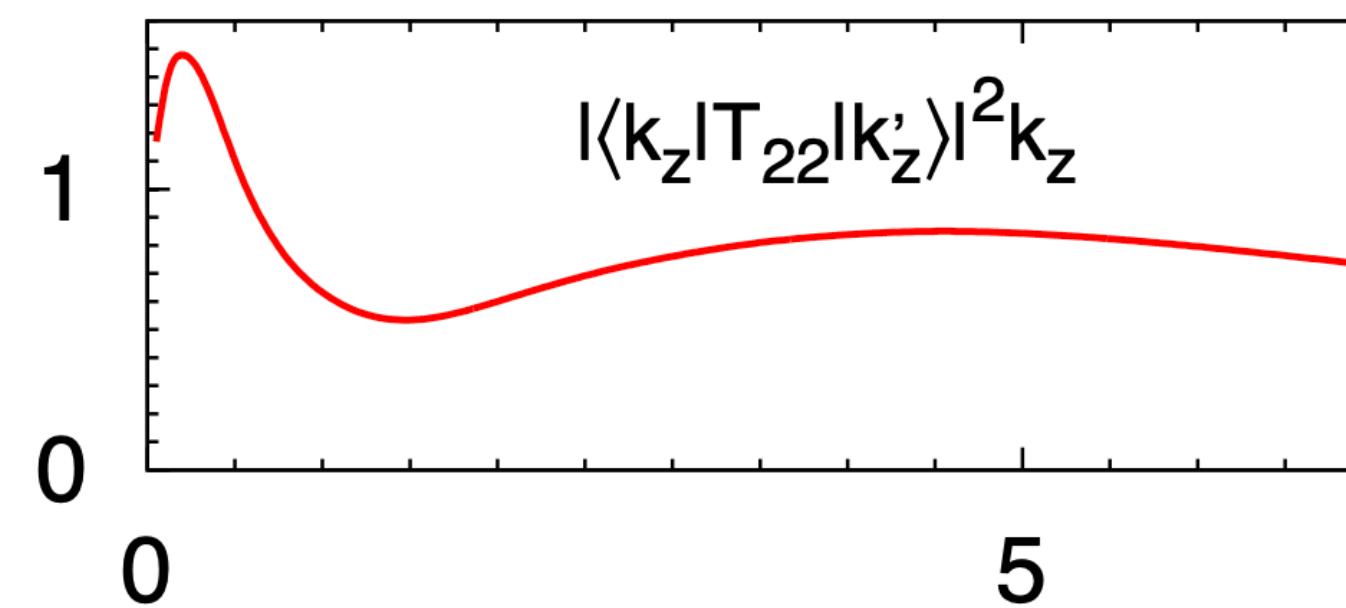
“..., we propose a natural explanation for the low energy structure:

it emerges as a consequence of the final state interaction among the 4n and the important presence of four neutrons in the periphery of the ${}^8\text{He}$ projectile.”

No resonance with exact continuum treatment!

(complex-scaled Fadeev-Yakobovsky equations)

Deltuva, PLB 782 (2018) 238–241



Despite that no observable 4n resonance is predicted, matrix elements of transition operators acquire large absolute values at low energies

Summary

- (p,pa) reactions with $^{8,6}\text{He}$ beams @ 156 MeV/u to study 2n and 4n systems
- 2n spectrum benchmark: very good agreement with the theory
- 4n spectrum: low-lying resonance-like structure at $E \approx 2.4$ MeV + continuum
- FSI between neutrons drive the 2n and 4n low-energy spectra
- 4n peak needs further investigations

Outlook

- Measure correlations between neutrons in the final state (+ invariant mass)
- Explore different kinematic ranges of (p,p ^4He) or different reactions mechanisms, i.e. (p, ^3He), (p,3p)
- Probe larger systems 5n, 6n, etc - multi-neutron program at SAMURAI

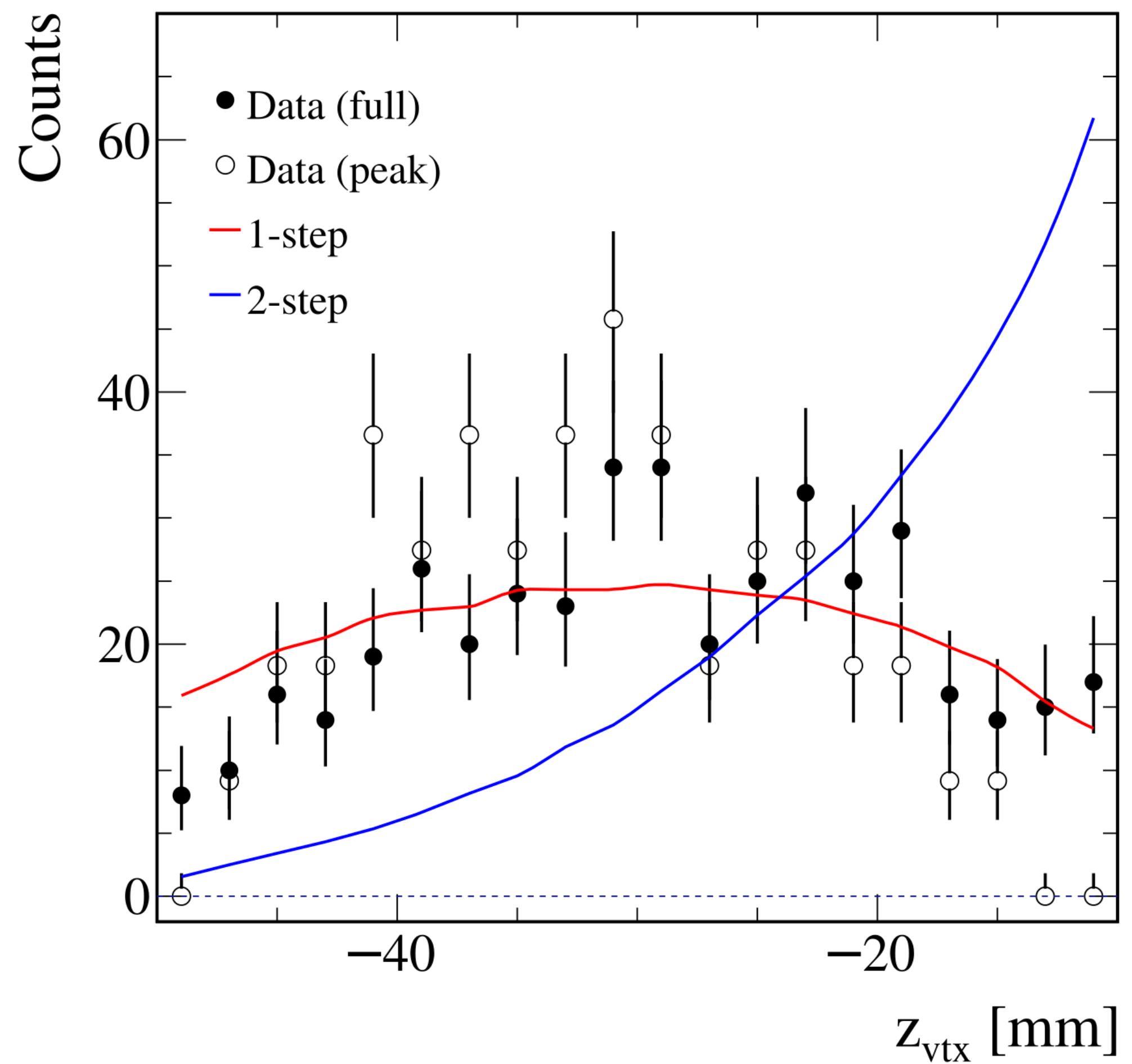
SAMURAI19 collaboration

M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H. Baba, C. A. Bertulani, M. Böhmer, K. Boretzky, C. Caesar, N. Chiga, A. Corsi, D. Cortina-Gil, C. A. Douma, F. Dufter, Z. Elekes, J. Feng, B. Fernández-Domínguez, U. Forsberg, N. Fukuda, I. Gasparic, Z. Ge, J. M. Gheller, J. Gibelin, A. Gillibert, K. I. Hahn, Z. Halász, M. N. Harakeh, A. Hirayama, M. Holl, N. Inabe, T. Isobe, J. Kahlbow, N. Kalantar-Nayestanaki, D. Kim, S. Kim, T. Kobayashi, Y. Kondo, D. Körper, P. Koseoglou, Y. Kubota, I. Kuti, P. J. Li, C. Lehr, S. Lindberg, Y. Liu, F. M. Marqués, S. Masuoka, M. Matsumoto, J. Mayer, K. Miki, B. Monteagudo, T. Nakamura, T. Nilsson, A. Obertelli, N. A. Orr, H. Otsu, S. Y. Park, M. Parlog, P. M. Potlog, S. Reichert, A. Revel, A. T. Saito, M. Sasano, H. Scheit, F. Schindler, S. Shimoura, H. Simon, L. Stuhl, H. Suzuki, D. Symochko, H. Takeda, J. Tanaka, Y. Togano, T. Tomai, H. T. Törnqvist, J. Tscheuschner, T. Uesaka, V. Wagner, H. Yamada, B. Yang, L. Yang, Z. H. Yang, M. Yasuda, K. Yoneda, L. Zanetti, J. Zenihiro, and M. V. Zhukov.

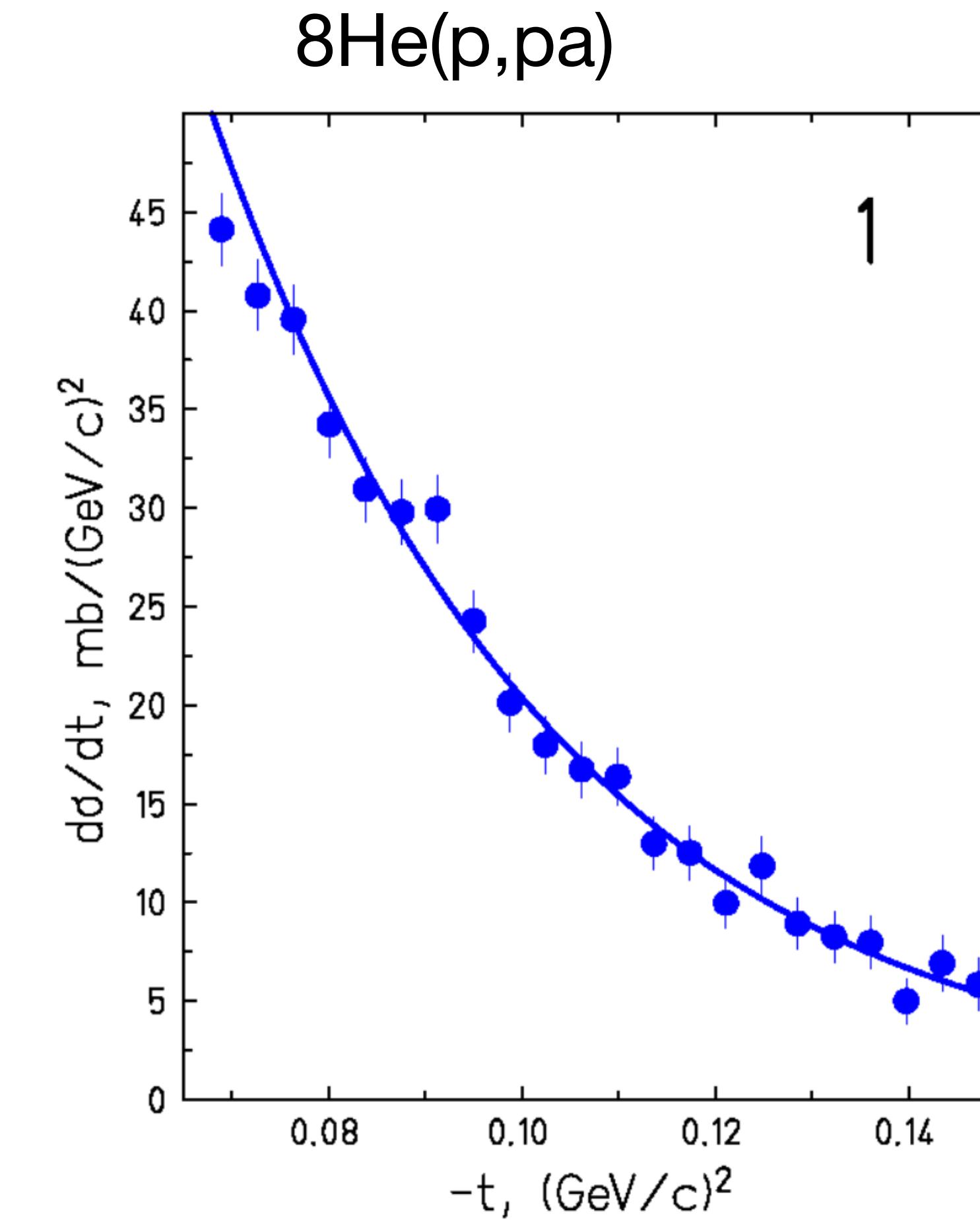
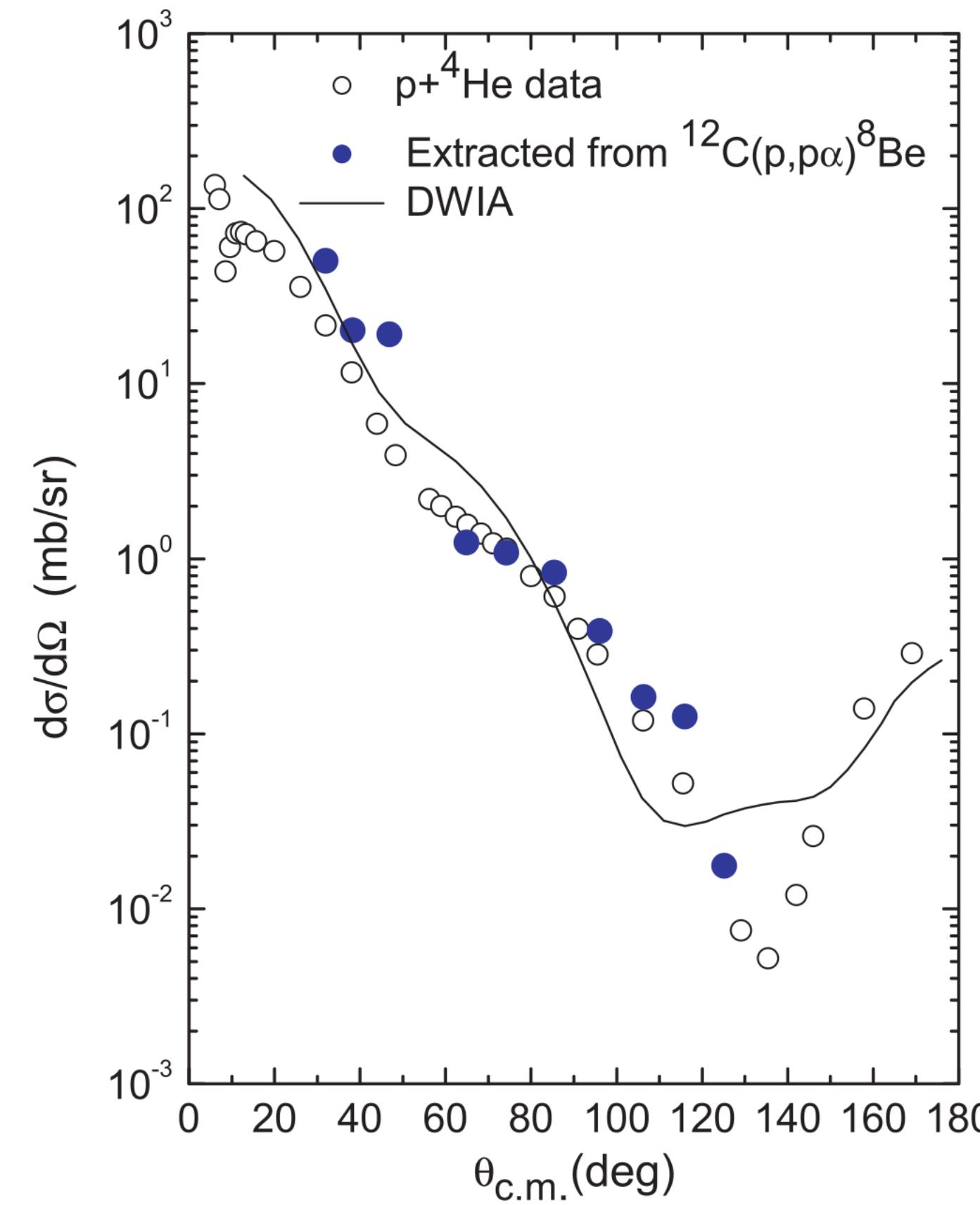


Thank you!

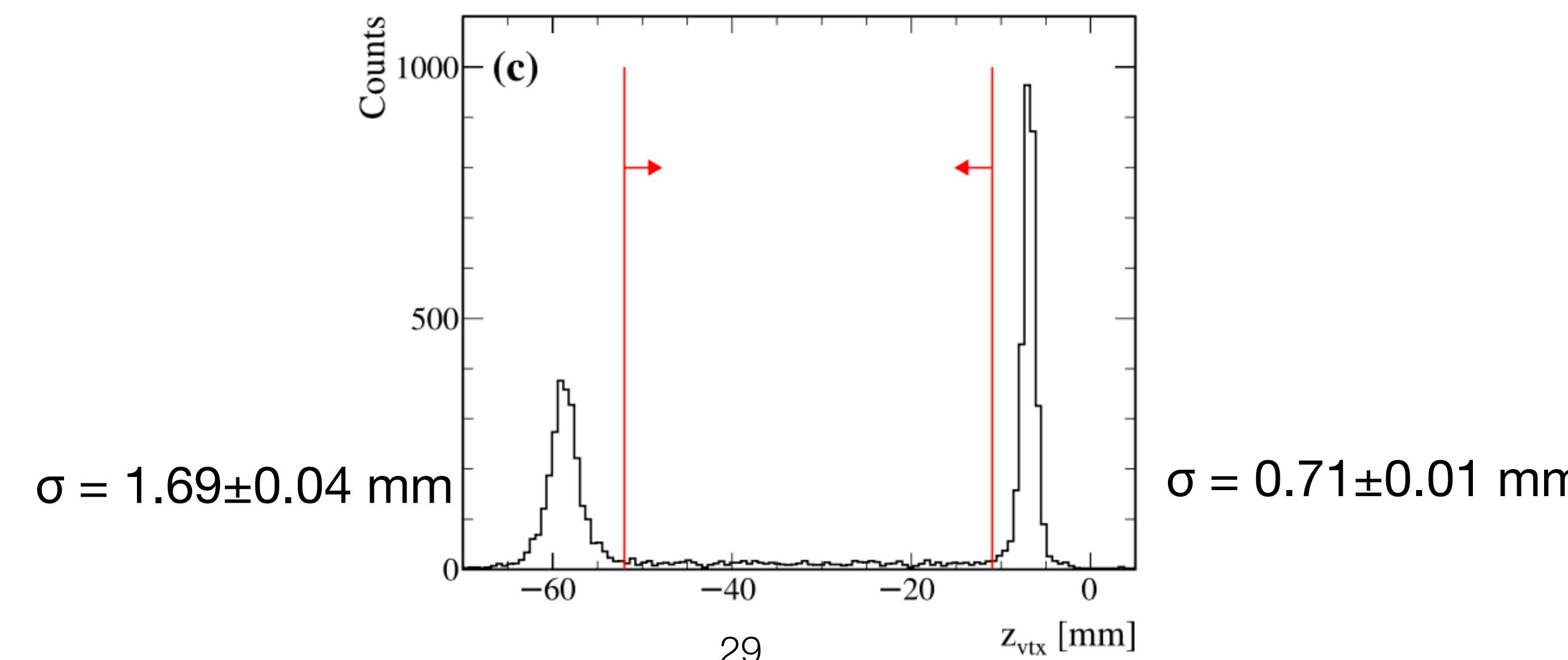
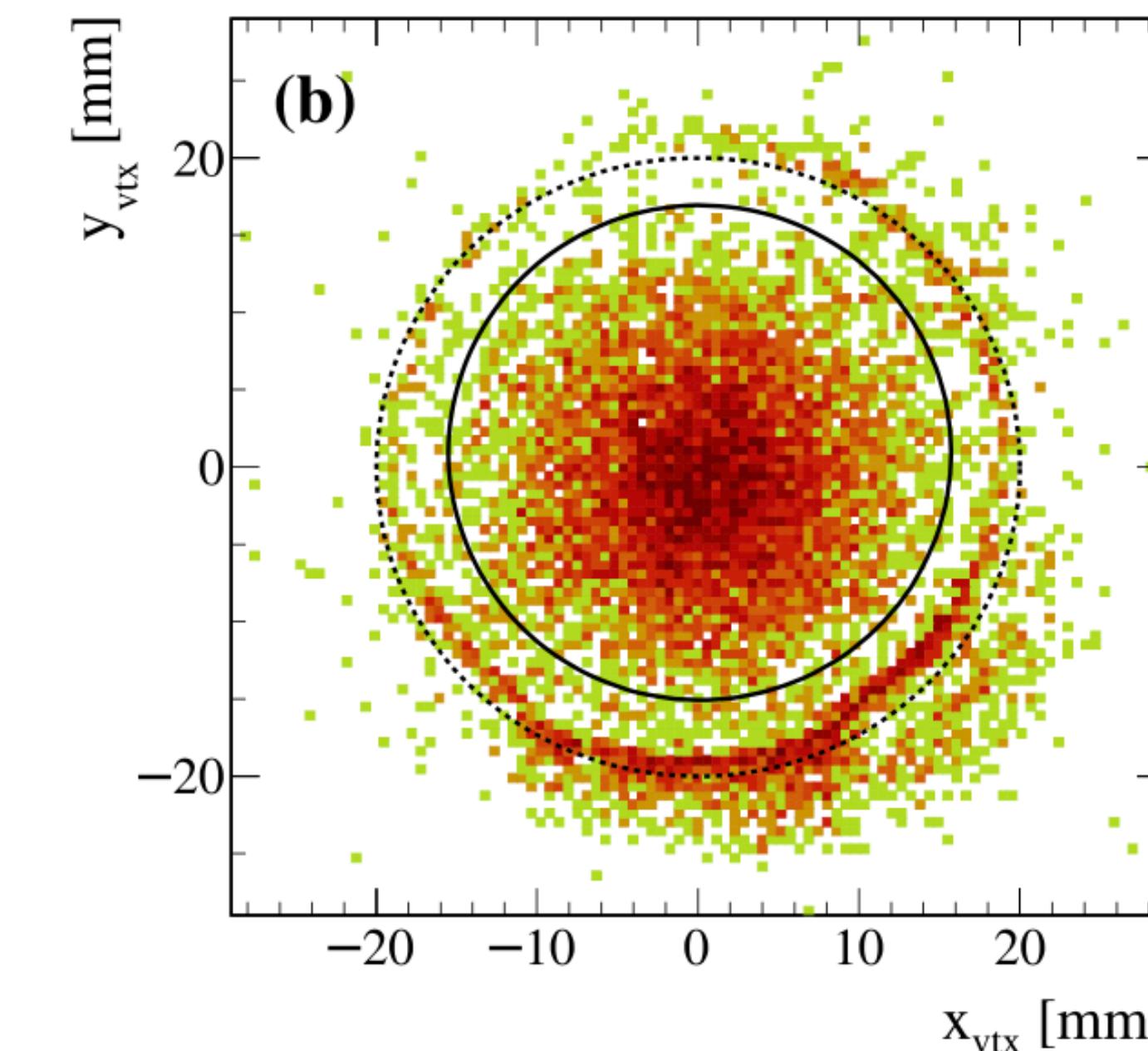
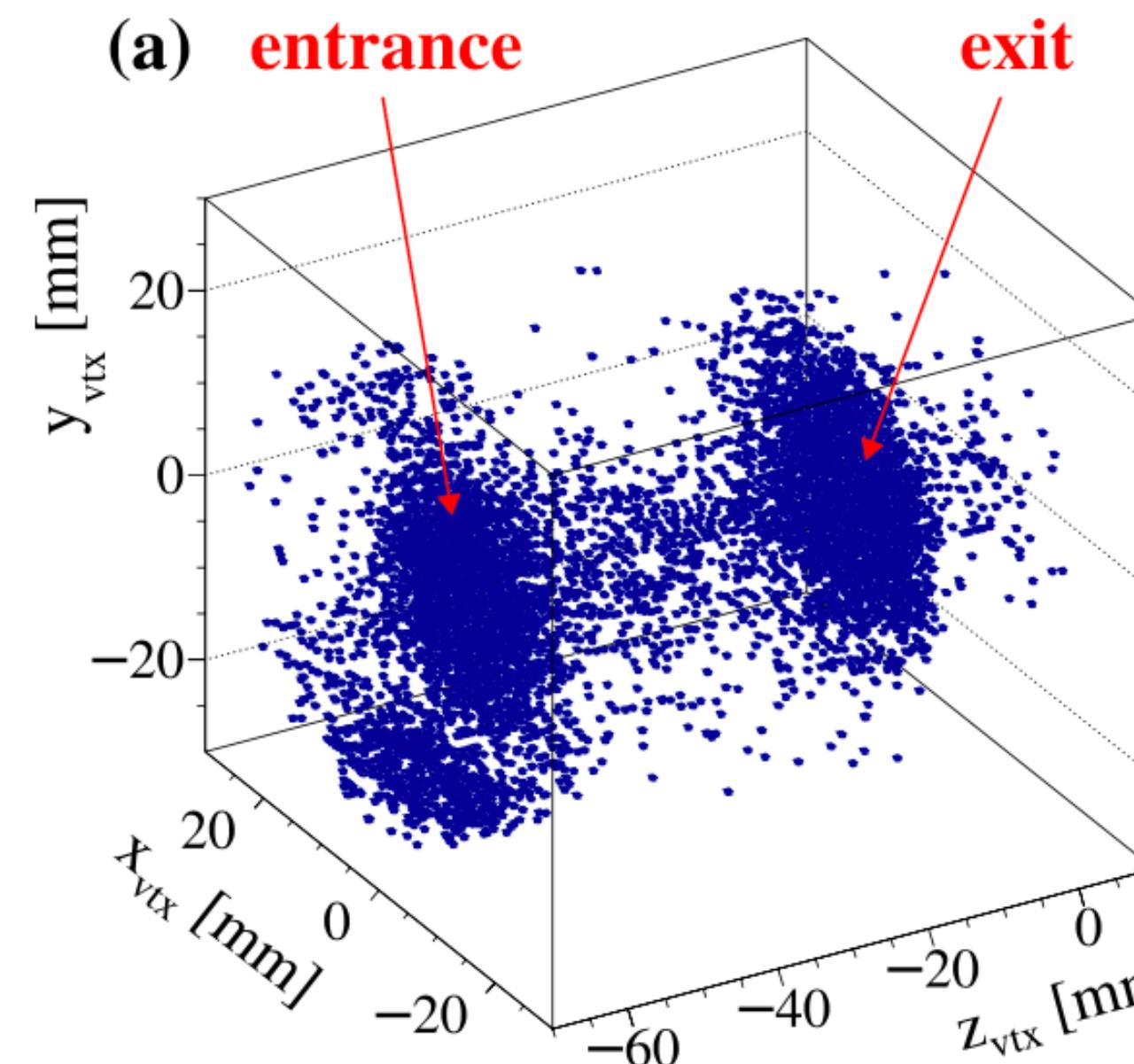
Target vertex



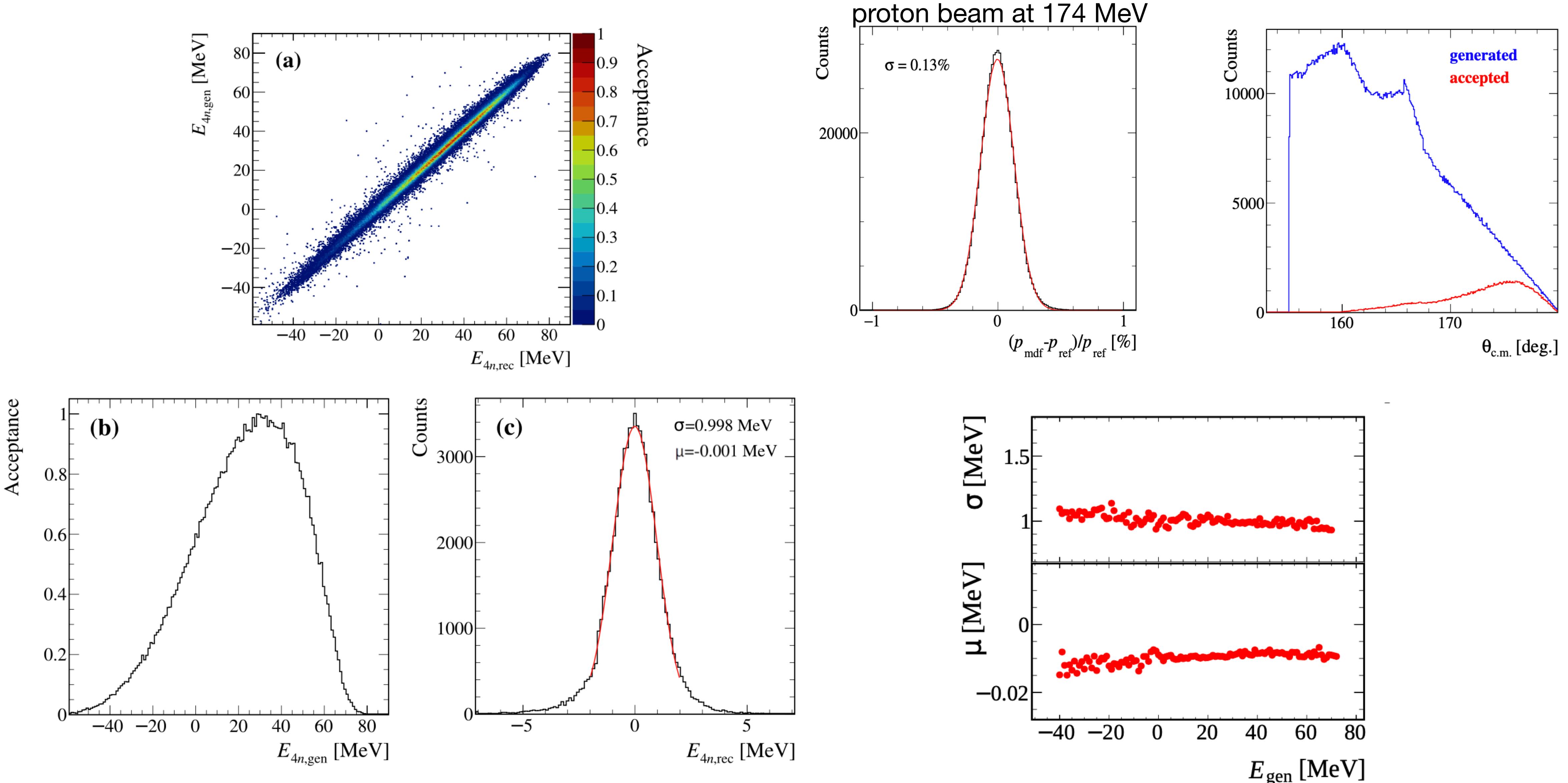
QFS (p,pa) in other experiments



Vertex resolution (empty target)



Acceptance, resolution



Identification of protons and ${}^4\text{He}$ behind SAMURAI

