

Search for multi-neutron correlations

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Unlocking the QCD phase diagram

7.-9. Sept. 2026, Darmstadt Lichtenberg-Haus

celebrating the 80th birthday of Prof. Peter Braun-Munzinger

Method: Population of final states with neutrons using reactions with high-energy neutron-rich beams

Main reaction used: quasi-free scattering: $(p,2p)$, $(p,3p)$, $(p,p\alpha)$

- Multi-neutron correlations in the presence of one charged particle/fragment
- Pure neutron systems (no low-energy Final-State Interaction with remaining charged fragments)

Data discussed here were taken at the RIBF at RIKEN

Physics Programs based on QFS

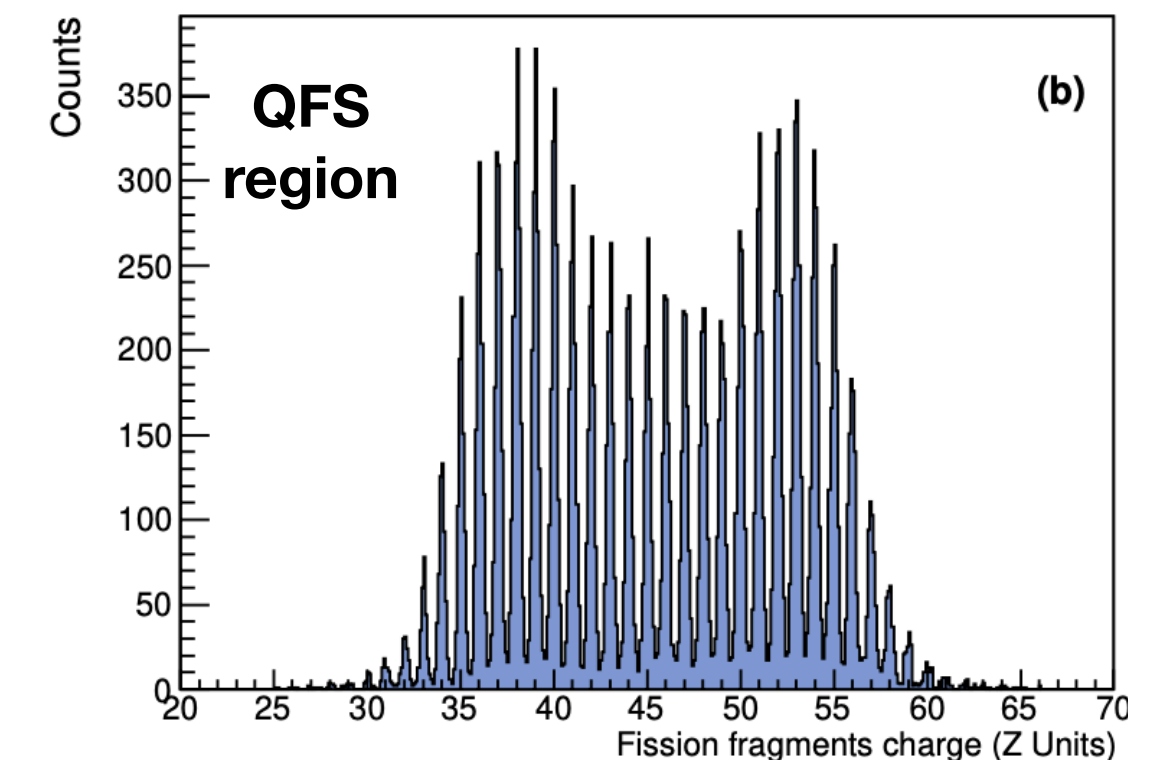
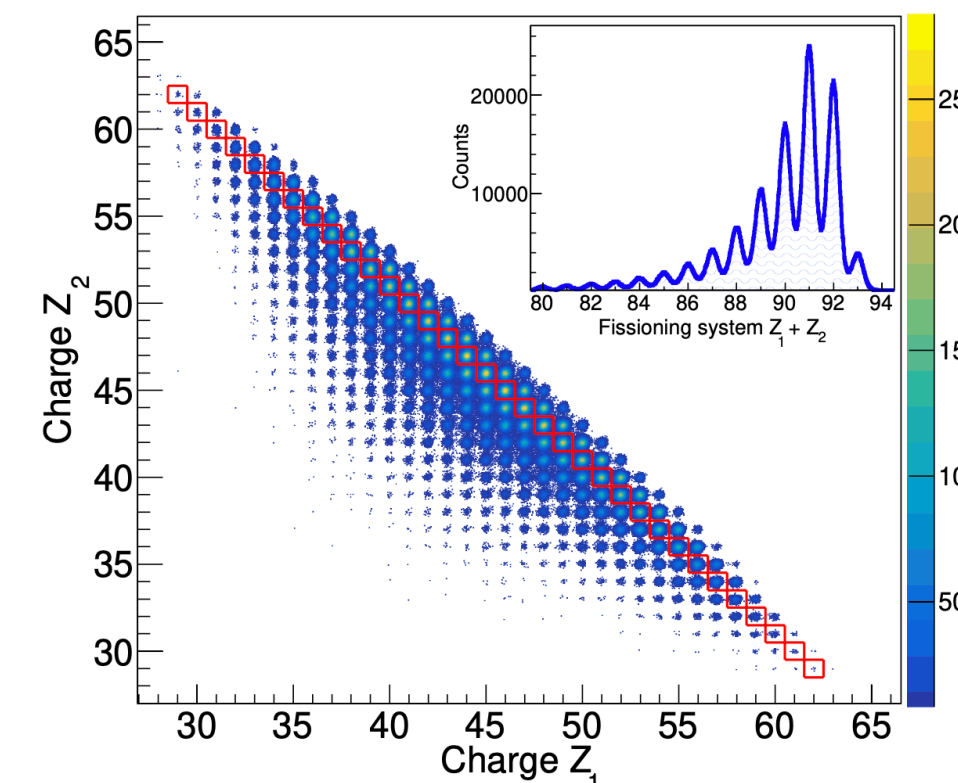
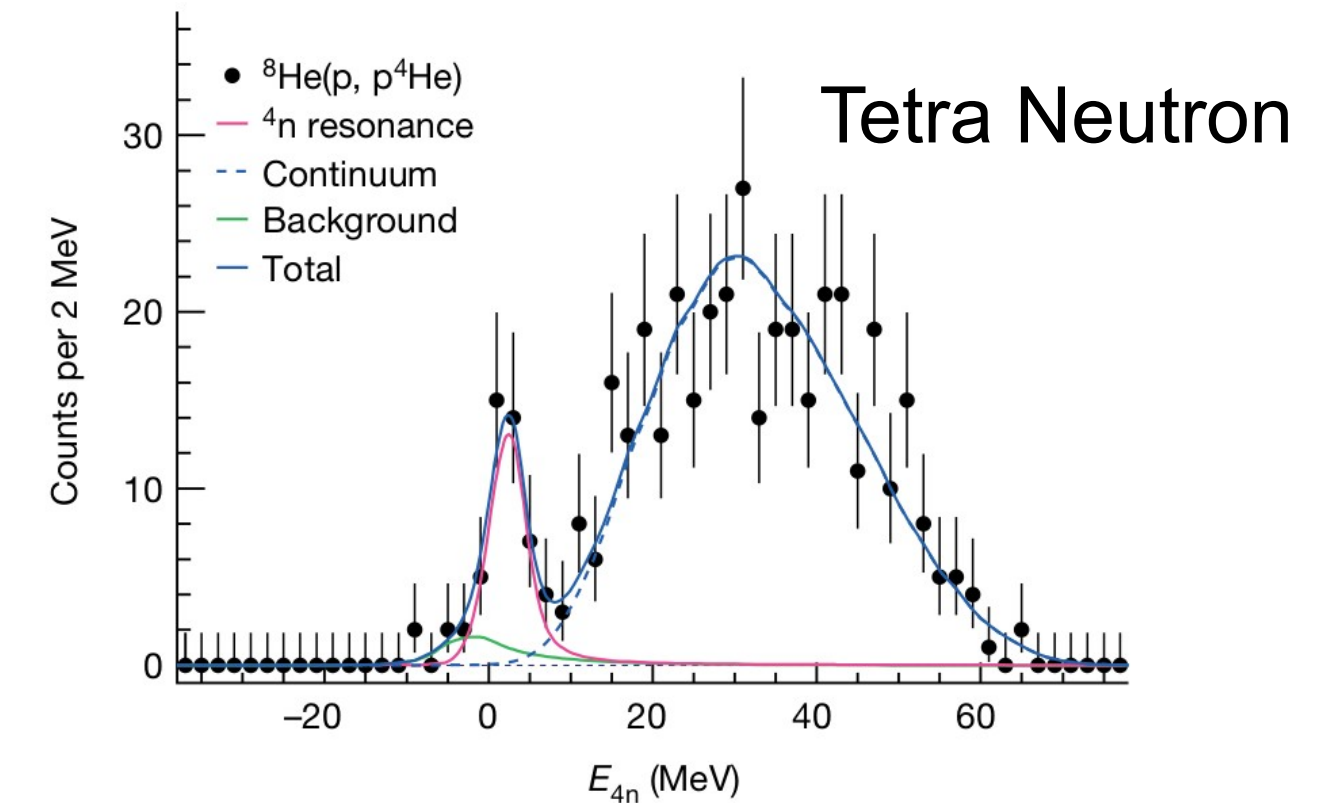
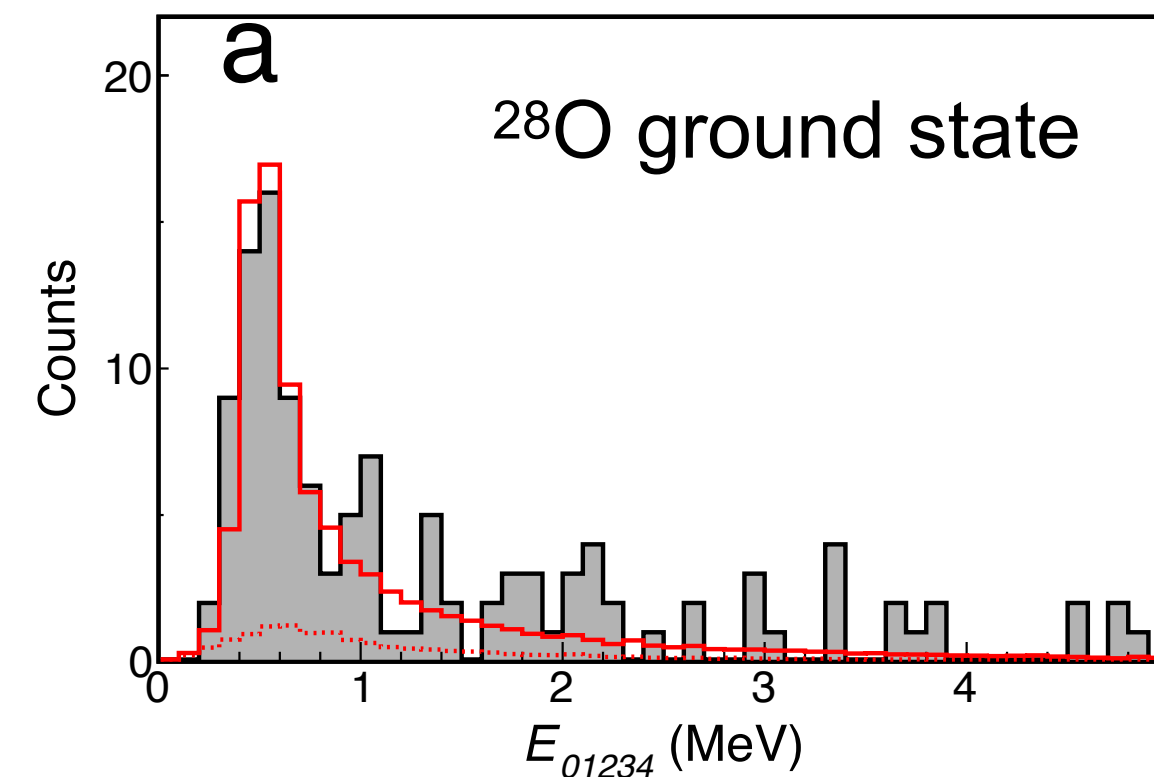
Quasi-free knockout reactions

$(p,2p)$, (p,pn) , $(p,2pn)$, $(p,p\alpha)$, $(p,2p)$ fission, ...

- Single-particle / Shell structure: spectroscopy
- States beyond the drip-lines
- Nucleon-Nucleon short-range correlations
- Cluster structure of nuclei
- Fission studies, dynamics, fission barriers

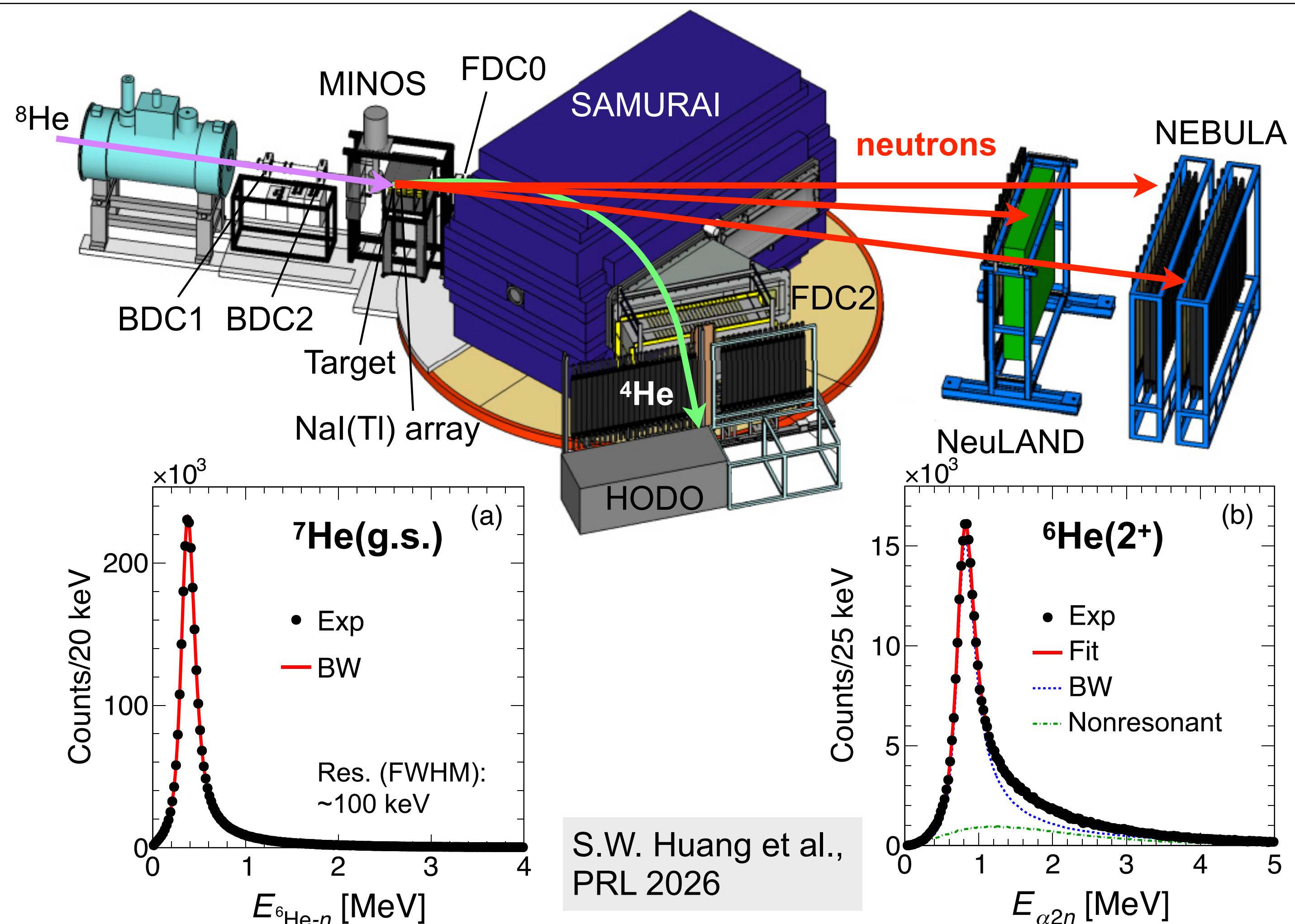
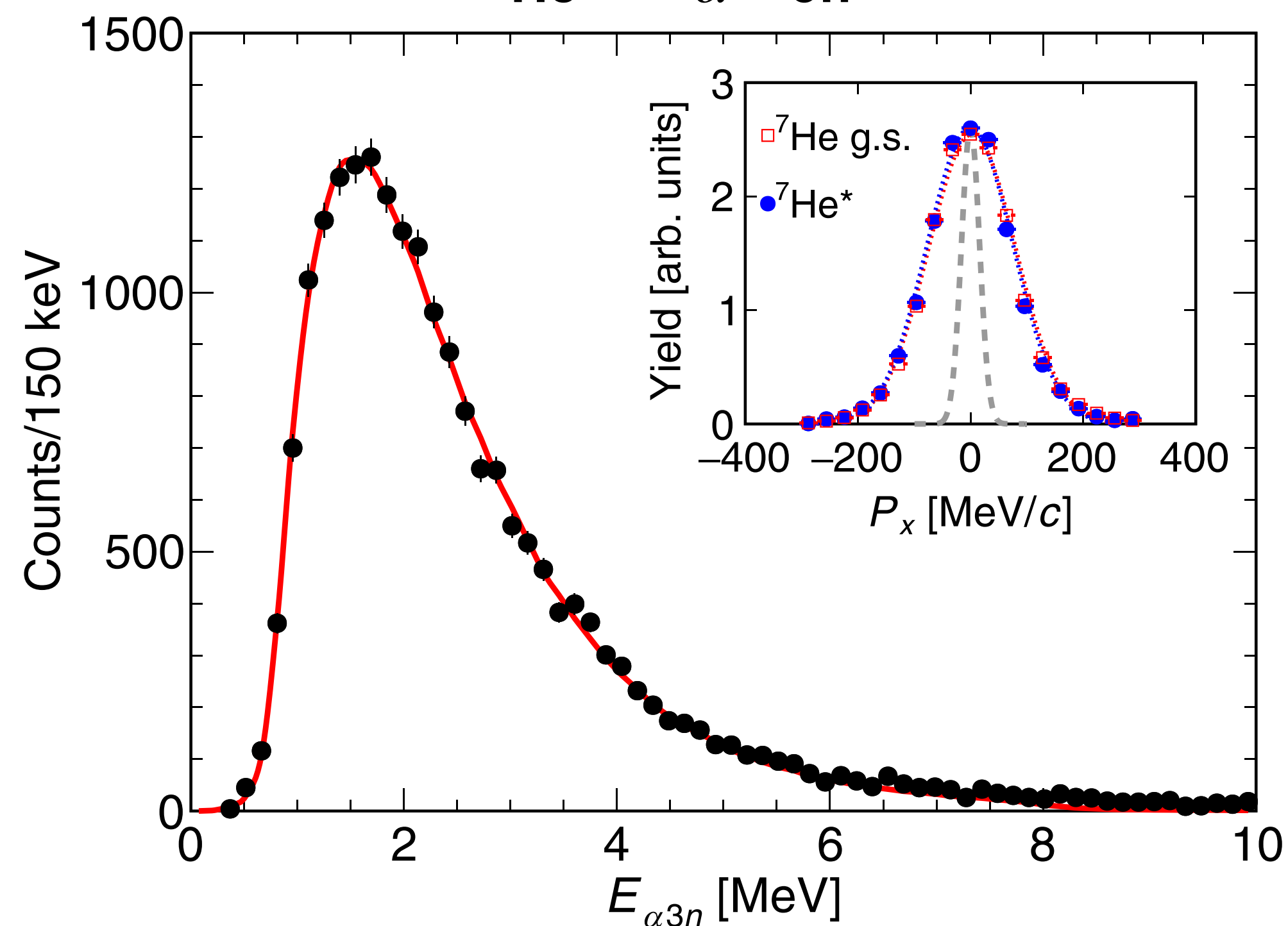
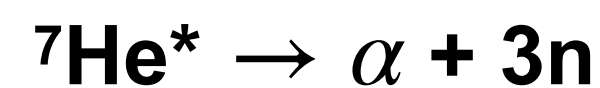
Advantages of using QFS reactions:

- thick liquid hydrogen targets can be used with vertex-tracking to keep the resolution
- measurement of scattered particles + final state in forward direction (fragment(s) including possible decays)
→ almost background-free selection of reaction channel

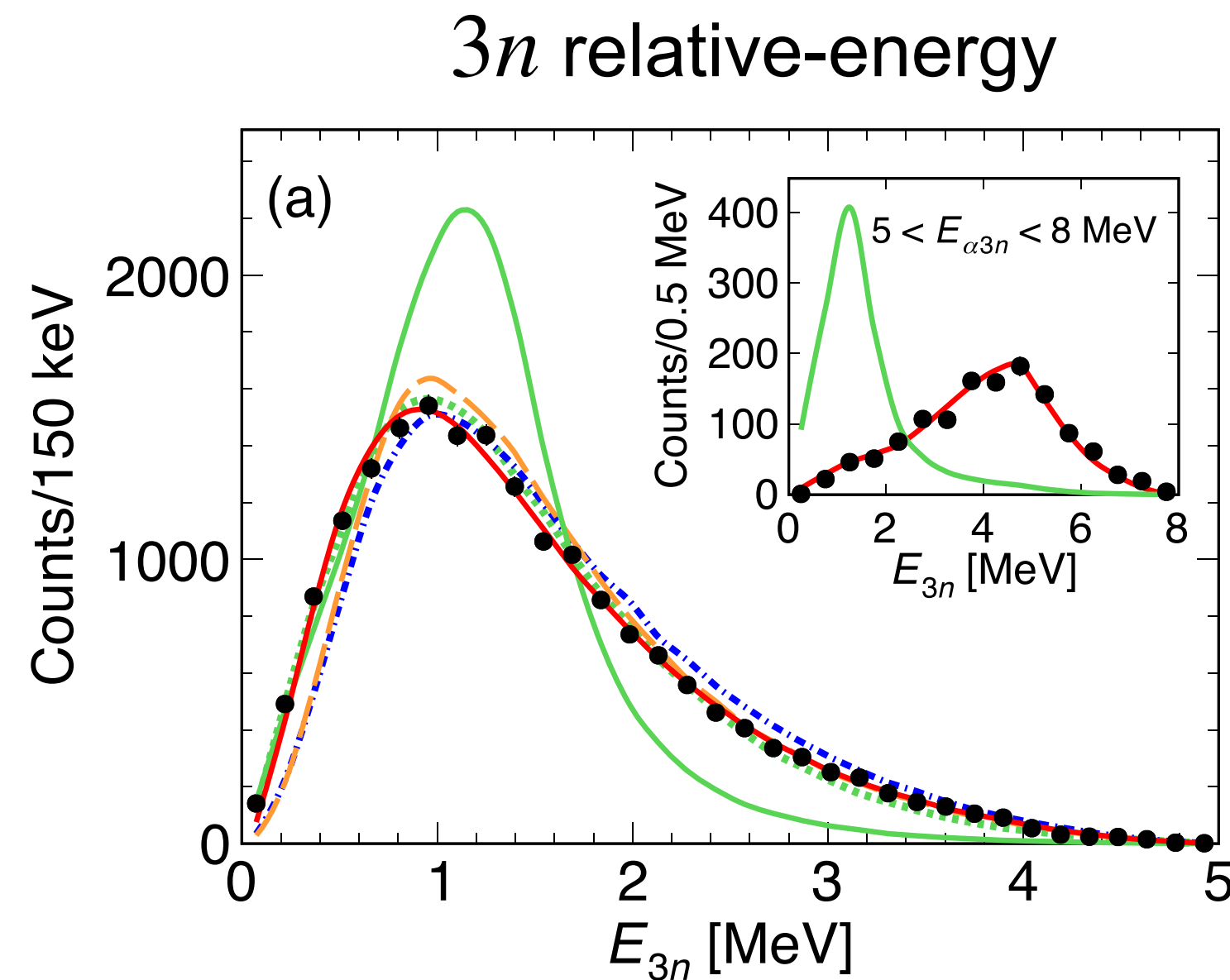


Correlations in the three-neutron decay of ${}^7\text{He}^*$

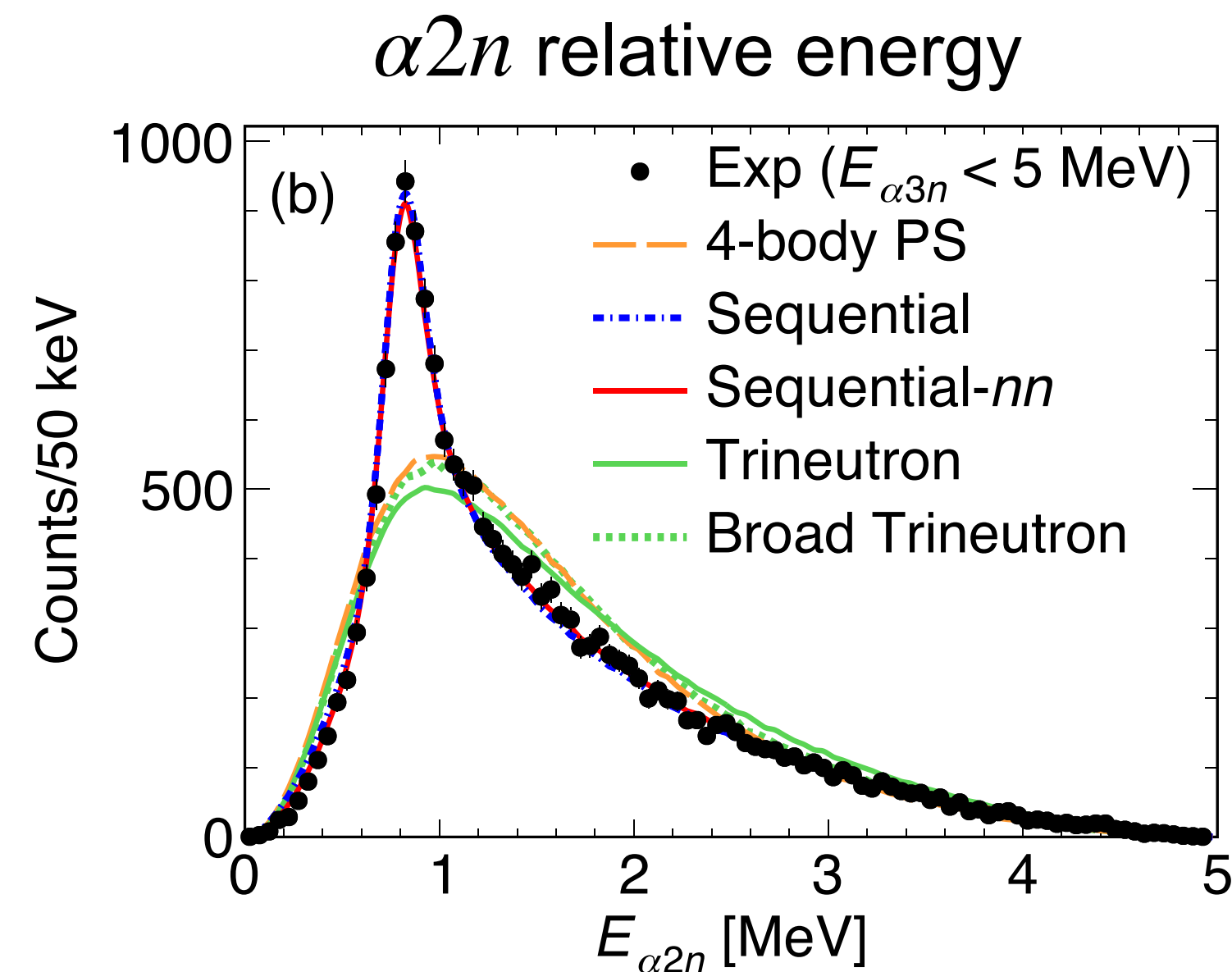
- Experiment was performed at the RIBF at the RIKEN Nishina Center using the SAMURAI facility
- ${}^{18}\text{O}$ beam (220 MeV/u) $\rightarrow$ BigRIPS $\rightarrow$ ${}^8\text{He}$ (156 MeV/u)
- Reaction ${}^8\text{He}(p,pn){}^7\text{He}$ in a thick (15 cm) LH2 target (MINOS)



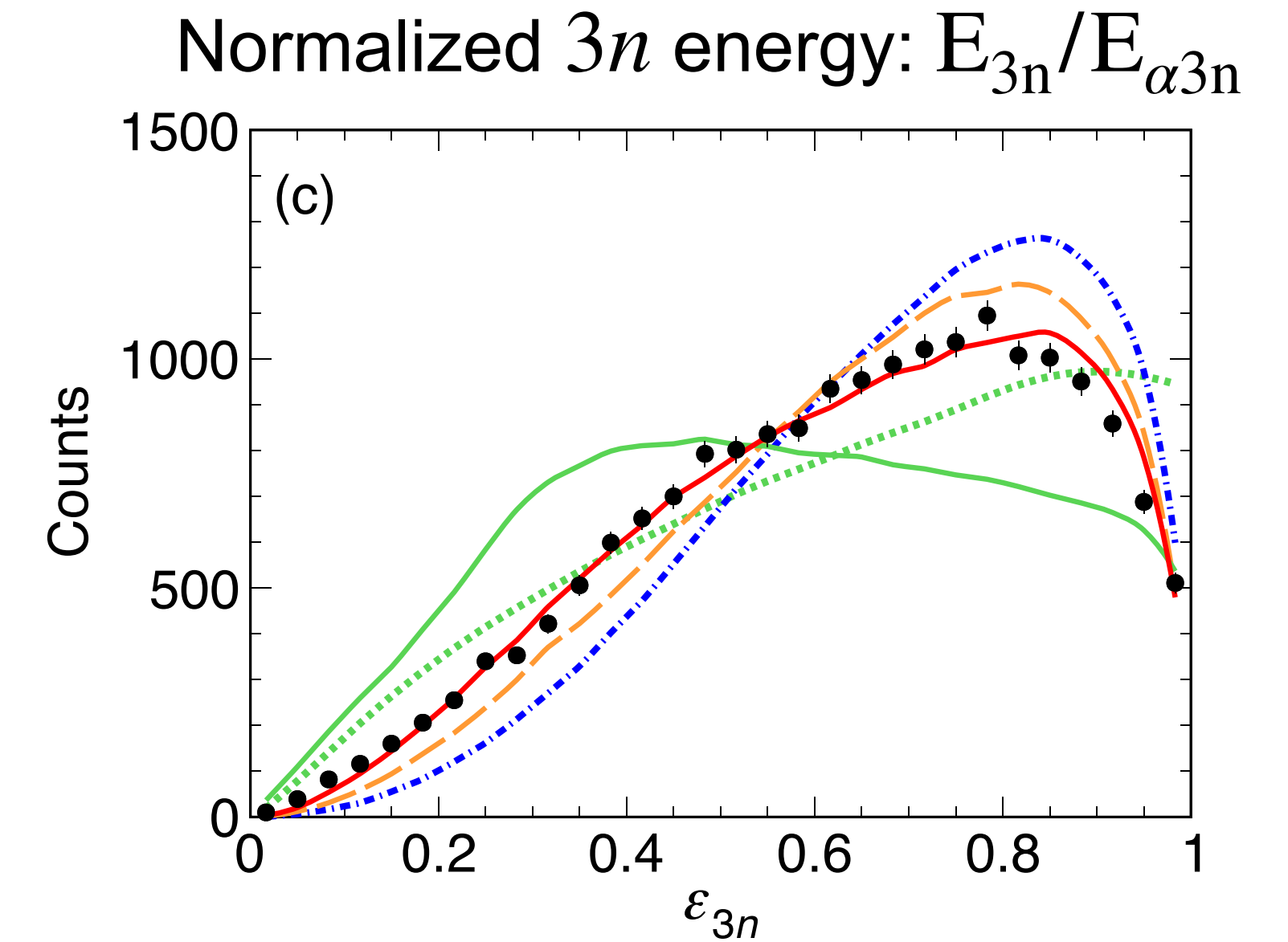
Results: ${}^7\text{He} \rightarrow \alpha + 3n$



1 broad peak at 1 MeV close to predicted 3n resonance (Gamow no-core shell model) but much wider



$\alpha 2n$ shows a clear peak structure at 0.8 MeV arising from the decay of the ${}^6\text{He}(2^+)$ state
Direct Trineutron decay cannot describe the spectrum (resonance or phase space)

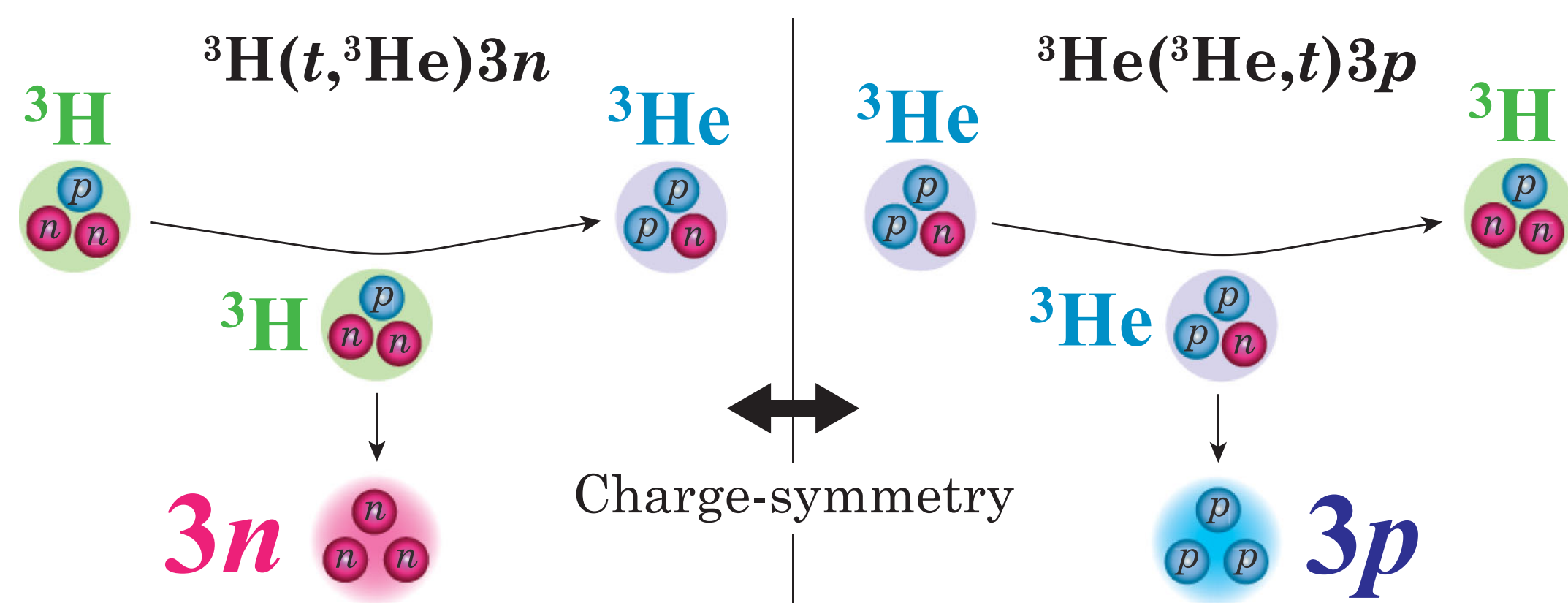


Best description of normalized 3n spectrum by sequential-decay assumption

S.W. Huang et al., PRL 2026

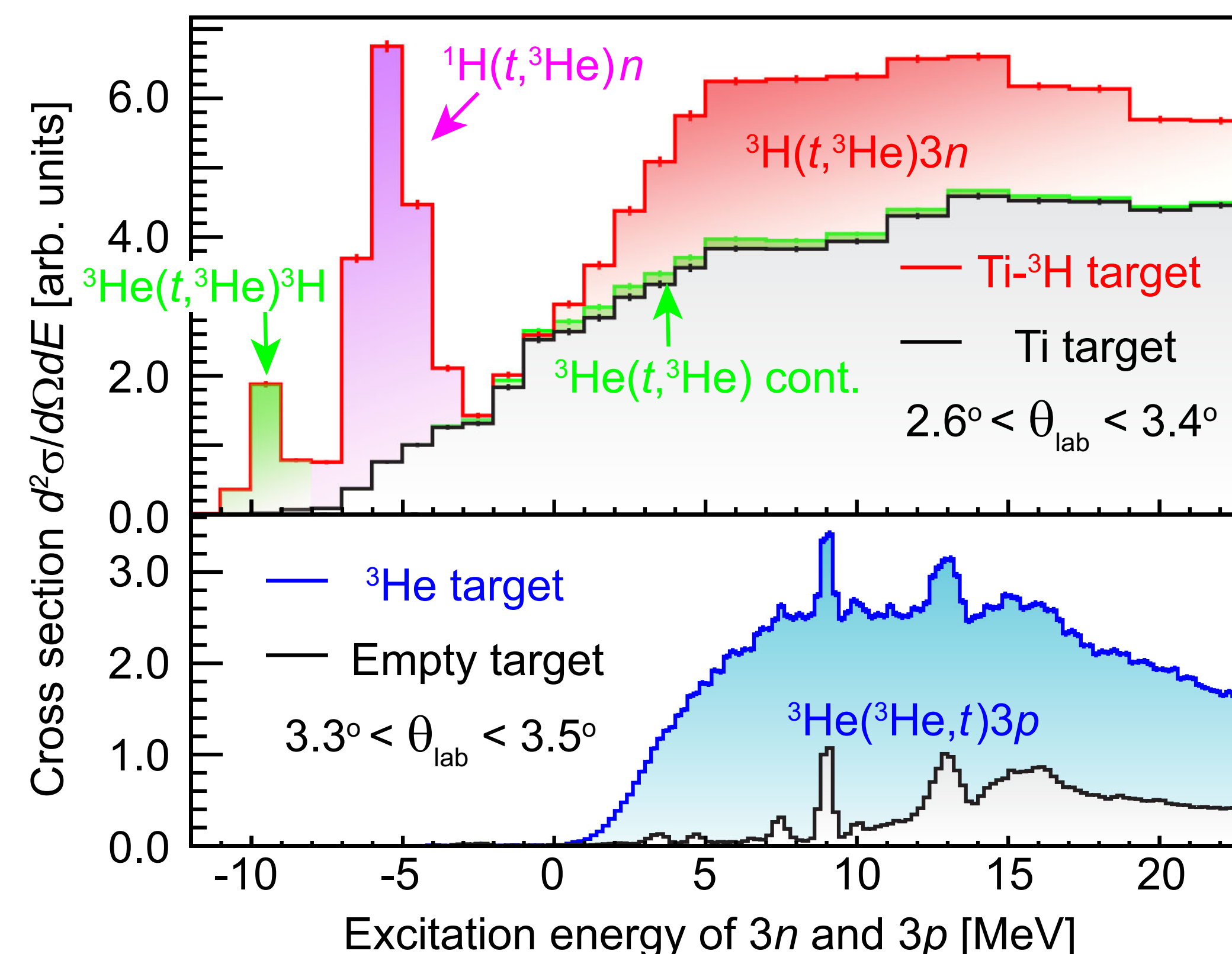
- No evidence for a 3n resonance or non-resonant 3n correlation
- Decaying final state well understood as sequential decay of ${}^7\text{He}^*$ via the ${}^6\text{He}(2^+)$ state + nn FSI

Tri-neutron search: Isolated $3n$ system in final state using charge-exchange reaction



Measurement of $3n$ and $3p$ for comparison

- $3p$ experiment at the RCNP Grand Raiden spectrometer
- $3n$ experiment at the RIBF SHARAQ spectrometer
 - Newly developed thick (3 mg/cm^2) Ti-triton target: 1.6 TBq in titanium foil
- Raw spectra look similar and structureless for $3n$ and $3p$ after background subtraction



Ken Miki et al, PRL 2024

3n and 3p correlations

Comparison of 3n and 3p spectra

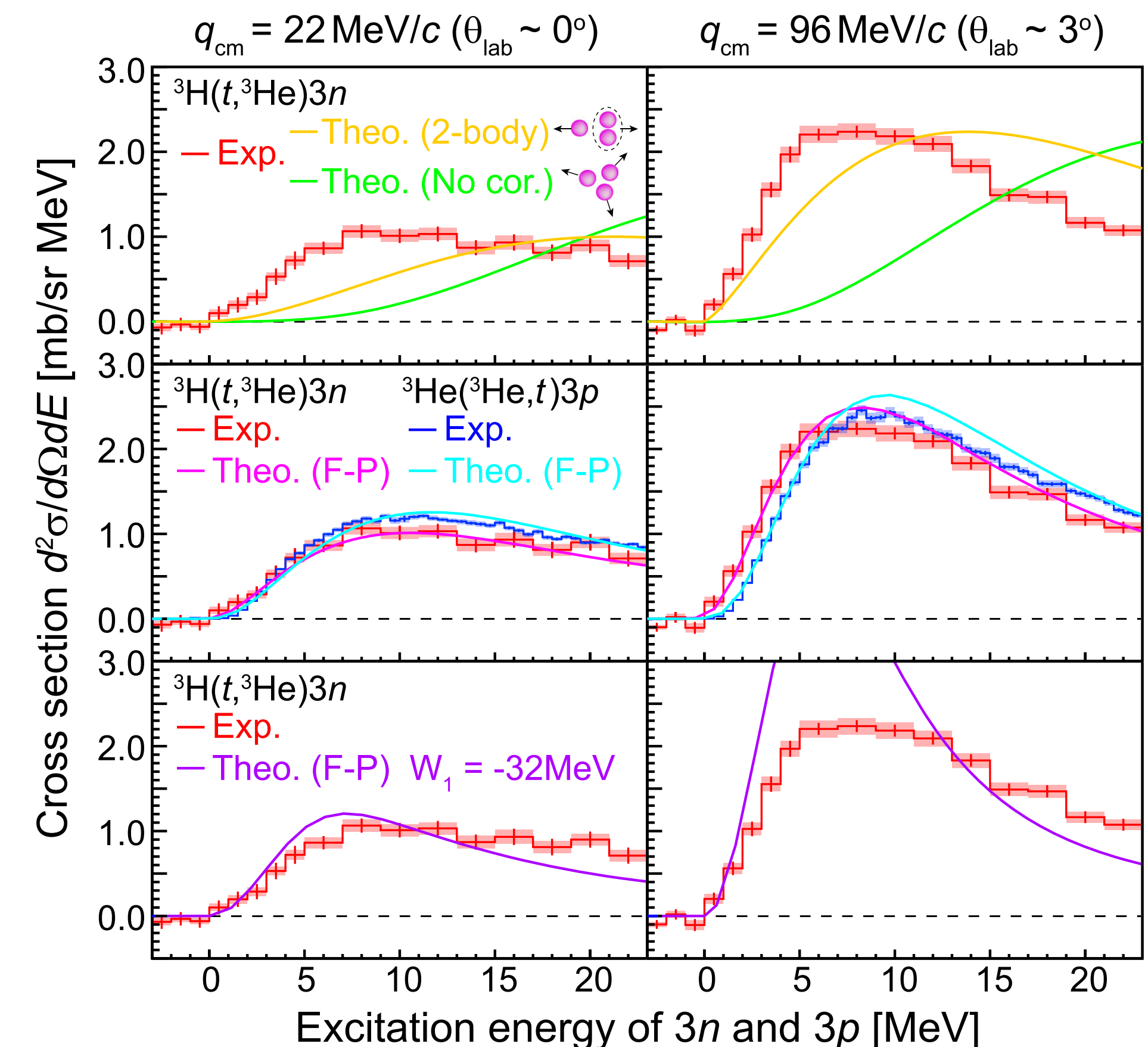
Both spectra look similar and structureless at different momentum transfers except some slight shift due to Coulomb repulsion

Spectra cannot be explained by no or only two-body correlations

Theory: F-P: Faddeev formulation using realistic interaction (AV18) including three-body correlations and Coulomb
Same calculation does not have resonance pole for 3n system

→ ab initio theory reproduces measured spectra well

Arbitrary enhancing 3b-force to a very large value (to reproduce a 4n resonance at the position seen in the 4n experiments) cannot describe the 3n data



Ken Miki et al, PRL 2024

Tetra-neutron correlations

Two experiments producing isolated $4n$ -system in the final state

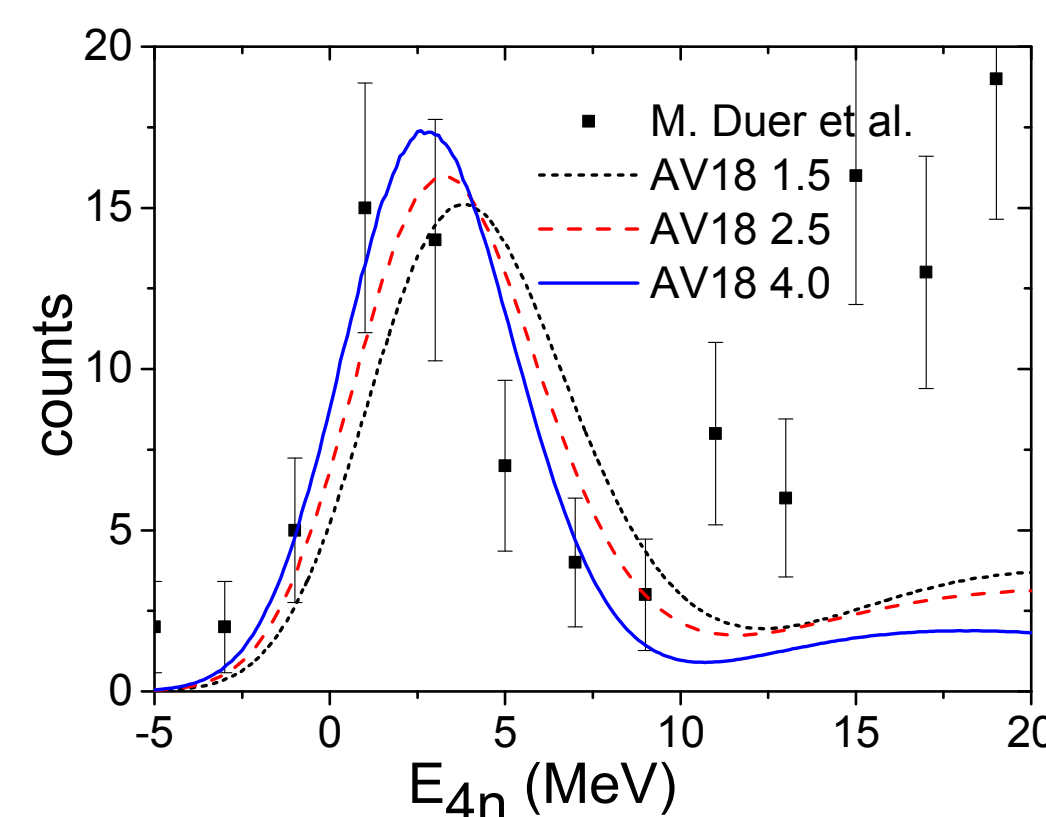
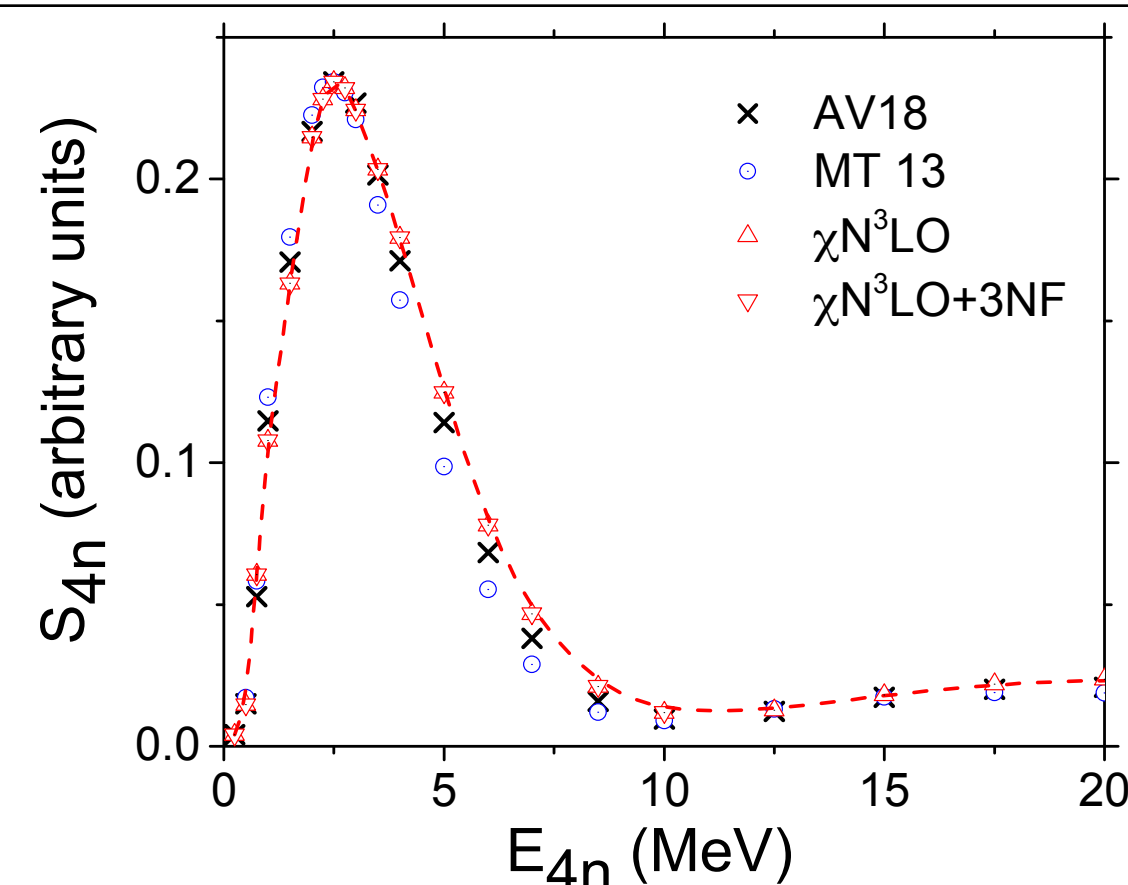
(without charged fragment interaction) using very different reactions:

- 1) ^4He double charge exchange to $4n$
- 2) ^8He alpha knockout to $4n$

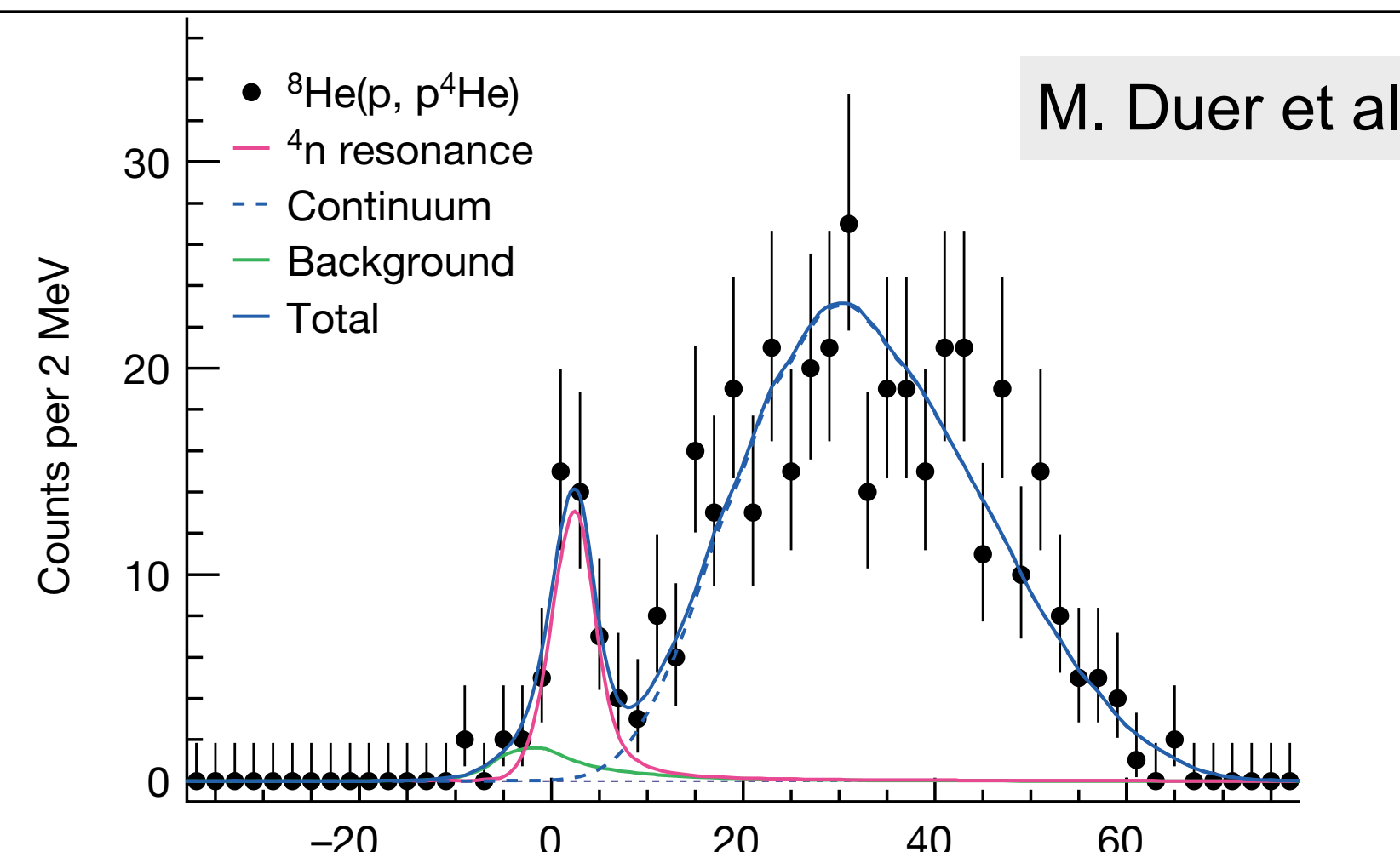
→ consistent result !

Resonance or non-resonant correlation due to two-body nn FSI + preformation in the initial state ^8He ?

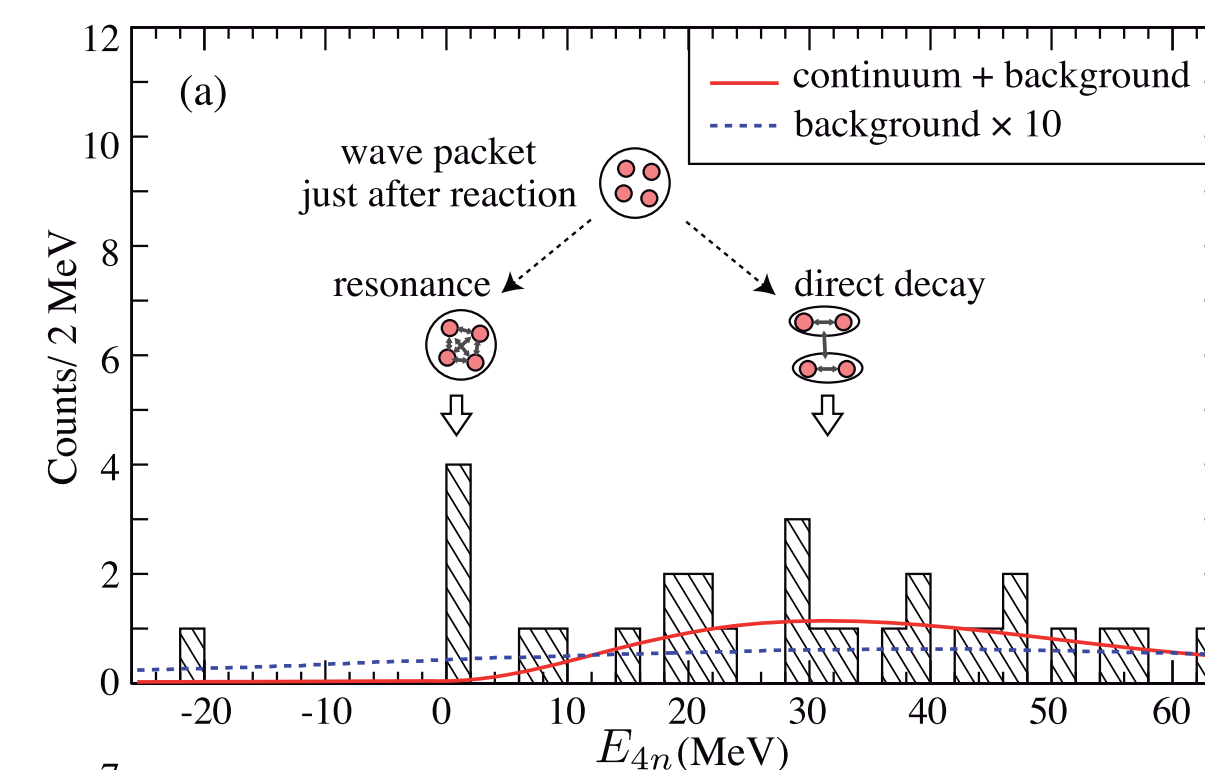
Theory: $^8\text{He}(p, p\alpha)4n$ reaction explained by nn - nn correlations (Lazauskas et al.), effect of three-body correlations negligible.



Theory: Lazauskas, Hiyama, Carbonnel, PRL 2023



M. Duer et al

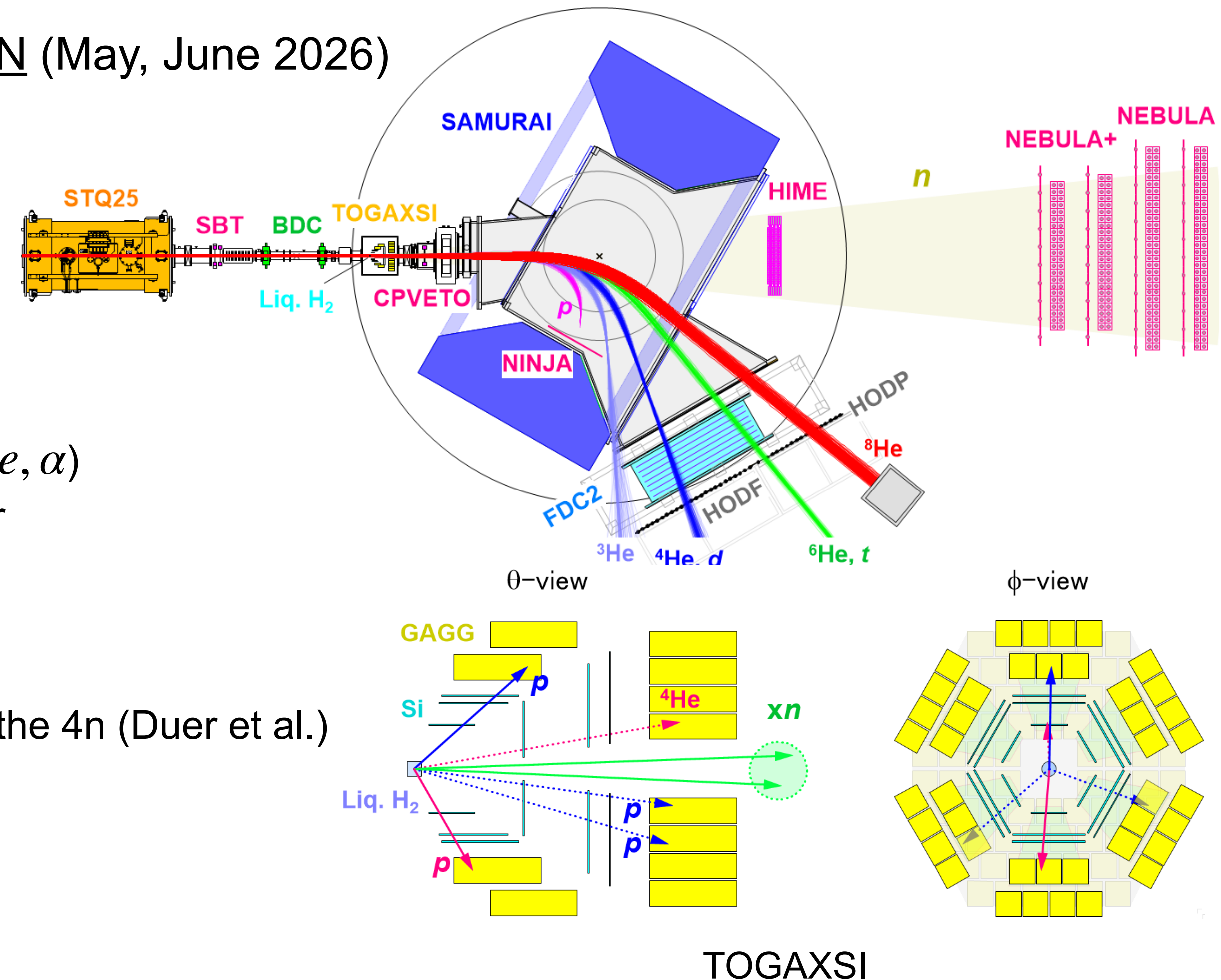


K. Kisamori et al.

What's next ?

New experimental campaign with SAMURAI at RIBF in RIKEN (May, June 2026)

- Beams used: p, d, t, ^6He , ^8He
- Large-acceptance setup to cover all channels produced with the different beams
- New detectors: TOGAXSI (RIKEN development), Si tracking+GAGG:Ce Scintillator optimized for detection of cluster knockout ($d, t, ^3\text{He}, \alpha$)
HIME (Darmstadt), high-resolution neutron detector
- Main aims and reaction channels
 - $t(p, 2p)2n$, $^6\text{He}(p, p\alpha)2n \rightarrow nn$ scattering length
 - $^8\text{He}(p, p\alpha)4n \rightarrow$ four neutron correlations (nn-nn?); detection of the 4n (Duer et al.)
 - $^6\text{He}(p, 3p)4n \rightarrow$ test initial-state dependency (Duer, Miki et al.)
 - $^8\text{He}(p, 3p)6n \rightarrow$ 6n correlations (Miki et al.)
 - Plus many side-channels (Uesaka et al.)



Conclusion multi-neutron systems

- $2n$
well understood; systematic differences between two type of experiments beyond uncertainty
→ unknown systemic uncertainty
→ new experiment with RI beams: $t(p,2p)2n$, ${}^6\text{He}(p,p\alpha)2n$ (performed June 2026)
- $3n$
well understood with ab initio calculations using realistic 2b- and 3b-interactions, only small deviations
 $3n$ decay of ${}^7\text{He}$ dominated by sequential decay
- $4n$
experiments show strong $4n$ correlations (two different reaction mechanisms and initial states)
one result explainable by initial state + nn - nn correlations in the final scattering state
→ new experiment measuring correlation of $4n$ in the final state + ${}^6\text{He}(p,3p)4n$ to test IS dependance (performed June 2026)
- $6n$
new experiment ${}^8\text{He}(p,3p)6n$ (performed June 2026)
- **New results in about 2 years ! Stay tuned**

Thank you
for your attention