Search for bound di-neutron by comparing $^3He(e,e'p)D$ and $^3H(e,e'p)X$ measurements

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Hall A/C Collaboration Meeting, June, 2022

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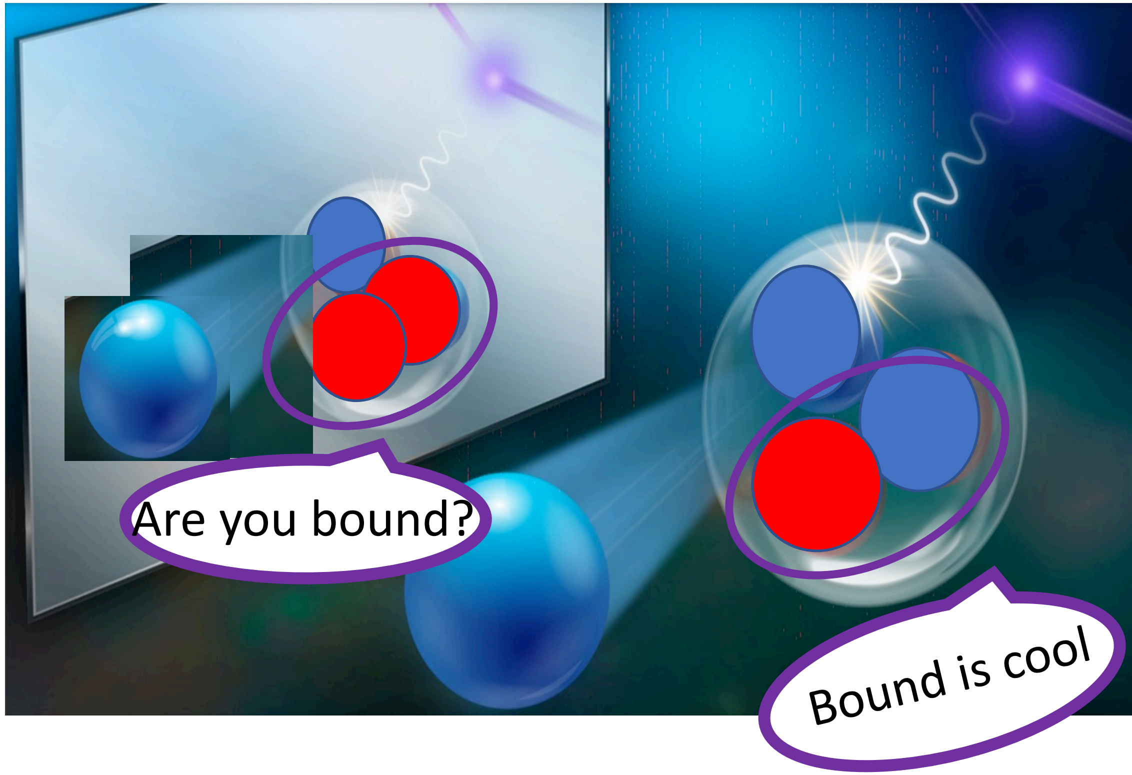
Physics Motivation

(1) Y. L. Sun, et al, Phys. Lett. B 814 (2021) 136072.
(2) Y. Kubota, et al., Phys. Rev. Lett. 125 (2020) 252501.
(3) A. Spyrou, et al., Phys. Rev. Lett. 108 (2012) 102501.
(4) A. Gardestig, J. Phys. G 36 (2009) 053001.
(5) J. P. Kneller, G. C. McLaughlin, Phys. Rev. D 70 (2004) 043512.

- ❑ Deuteron: only known bound di-nucleon pair
- ❑ Evidence for (nn) as part of a larger nucleus
- ❑ Di-neutron could be slightly unbound or slightly bound (~0.1 MeV)



Implication:

- ➢ Nucleon-Nucleon interaction
- ➢ Nucleus structure and More

<u>Goals</u>: Setting the limits on

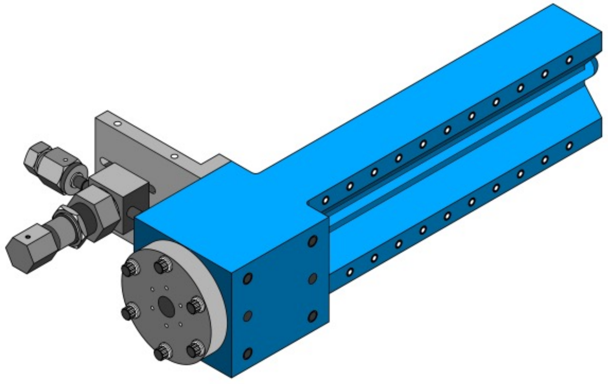
- ❑ $\sigma_{nn}^{3H} / \sigma_{D}^{3He}$: At the same kinematic
- ❑ $S_{nn}^{3H} / S_{3bbu}^{3H}$: nn content of T spectral function

Quasi-elastic ^{3}He / ^{3}H (e,e'p) experiment E12-14-011

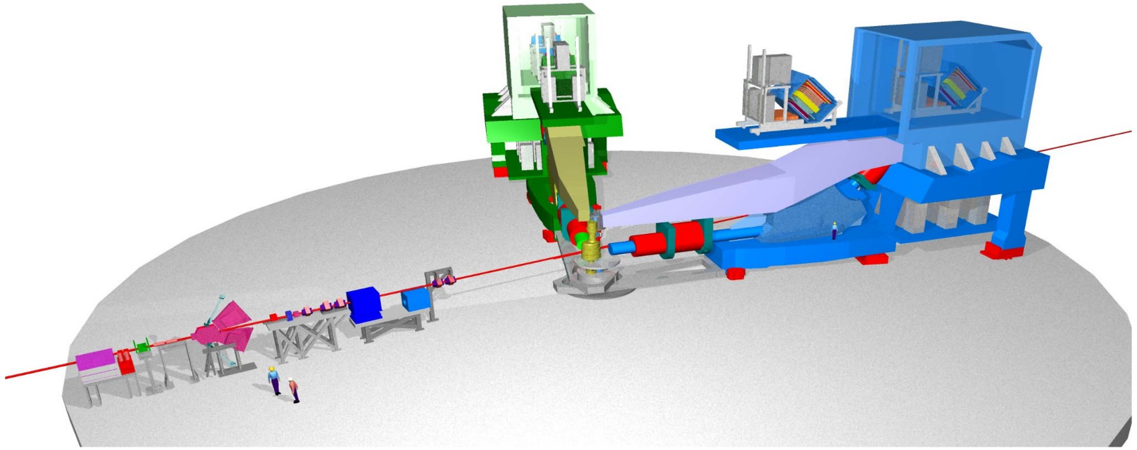
Beam energy = 4.325 GeV

Hall A, Tritium collaboration (2018)

Target	density [mg/cm2]
Hydrogen	70.8 +/- 0.4
Deuterium	142.15 +/- 0.8
Tritium	85.1 +/- 0.8
Helium-3	53.4 +/- 0.6



Kinematics	
LHRS – electrons	RHRS – protons
3.543 [GeV/c]	1.481 [GeV/c]
20.88 [deg]	48.82 [deg]

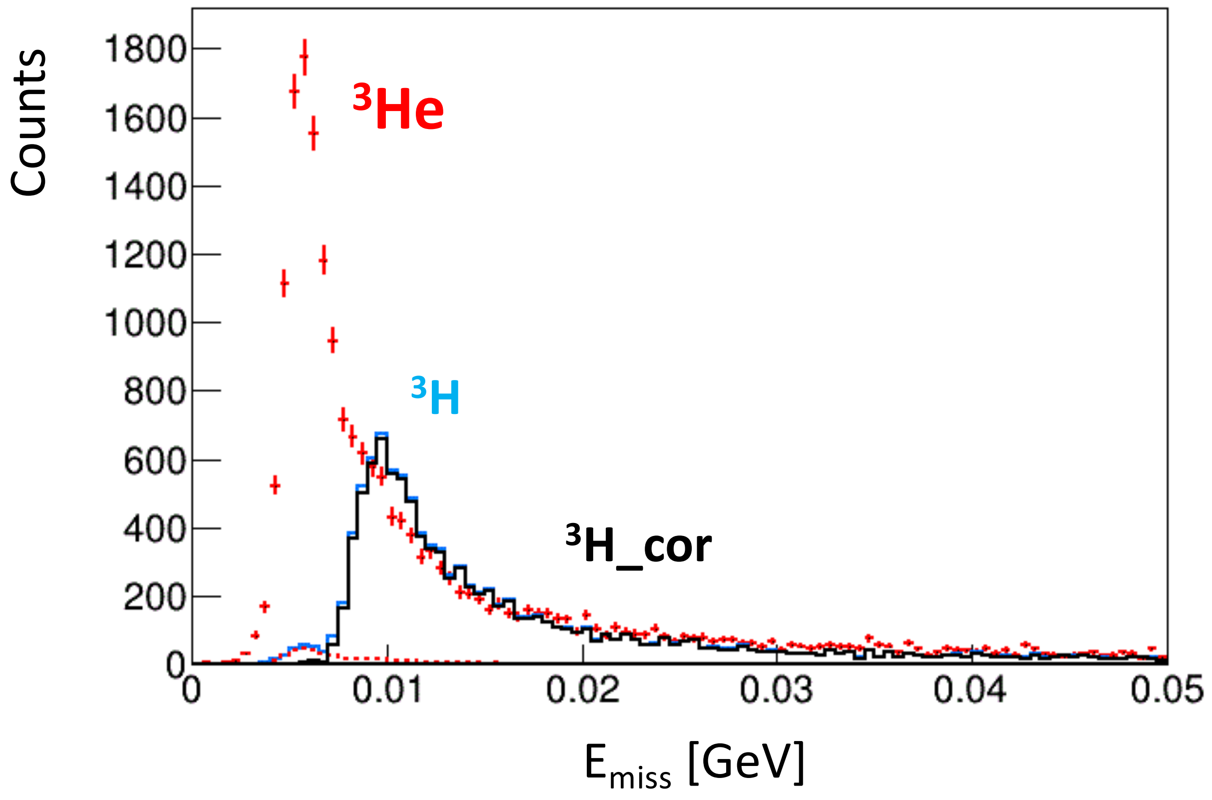


Event selection cuts:

*R. Cruz-Torres, et al., Phys. Rev. Lett. 124 (21) (2020) 212501.
*R. Cruz-Torres, et al., Phys. Lett. B797 (2019) 134890.

***Exactly the same cuts as previous analysis on this data**

- Acceptance
  - -0.04 < **dp** < 0.04 [%]
  - -0.055 < **xptar** < 0.055 [rad]
  - -0.0275 < **yptar** < 0.0275 [rad]
- Vertex
  - -0.095 < **vz** < 0.095 [m]
  - |L_vz – R_vz | < 3σ [m]
- Coinc. time
  - |t1 – t4|/2 < 3σ [ns]
- Particle ID
  - L_prl1+L_prl2/1000/L_mom > 0.5
- Suppression of FSI
  - θrq < 0.654 rad = 37.5 deg



$$E_{miss} = \omega - T_p - T_{A-1}$$

Relationship between cross section and counts

$$\sigma = \frac{N}{\varepsilon\mathcal{L}} = \frac{N}{\varepsilon Q f_{LT} A B}$$

- σ – cross section
- N – measured counts
- ε – detection efficiency
- $\mathcal{L}$ – integrated luminosity, $= Q f_{LT} A B$
- Q – total uncorrected charge
- f_{LT} – live-time fraction
- A – nominal target density (mg/cm^2)
- B – target boiling correction factor

Relationship between cross-section and counts

values and uncertainties (H stands for ^{3}He, T stands for ^{3}H)

- Q_H/Q_T = 0.936 +/- 0.013
- B_H/B_T = 1.041 +/- 0.004
- $f_{LT,H}/f_{LT,T}$ = 1.002 +/- 0.01

Target density is complicated because there is a 2.78% contamination fraction of He-3 inside the tritium cell:

- A_H/A_T = $\frac{53.4}{85.1(1-0.0278)} = 0.645 \pm 0.01$

We define the relative normalization between the two configurations as:

$$n = \frac{Q_T}{Q_H} \cdot \frac{f_{LT,T}}{f_{LT,H}} \cdot \frac{A_T}{A_H} \cdot \frac{B_T}{B_H}$$

$$n = 1.632 \pm 0.041$$

The He-3 contamination factor is

$$x = c\, n$$
$$x = 0.0278\, n$$
$$x = 0.0454 \pm 0.0011$$

* S. N. Santiesteban, et al., Nucl. Instrum. Meth. A940 (2019) 351{358.

Data from experiment after selection cuts

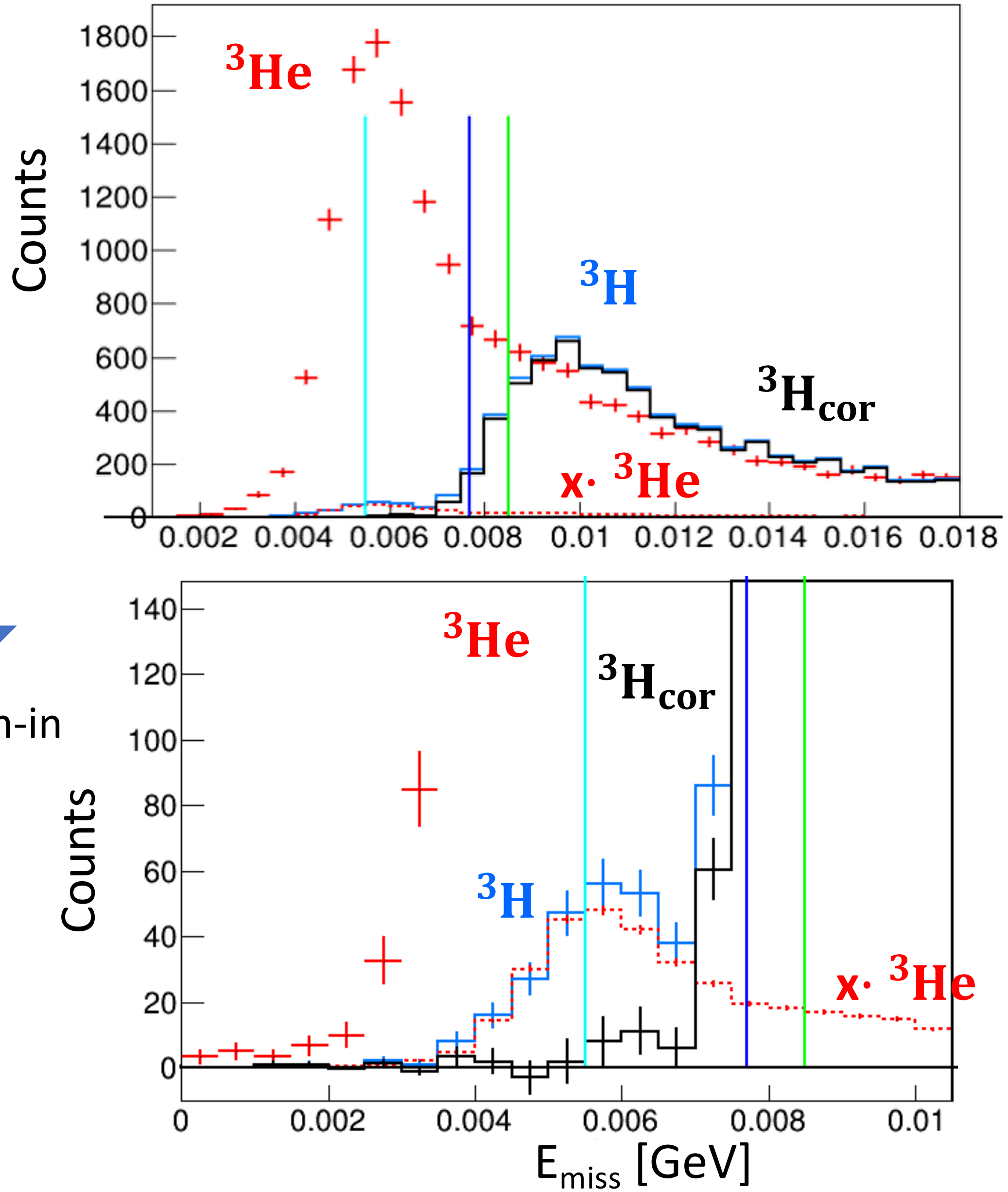
Binding Energies

- Tritium: 8.482 MeV
- He-3: 7.718 MeV
- Deuteron: 2.225 MeV

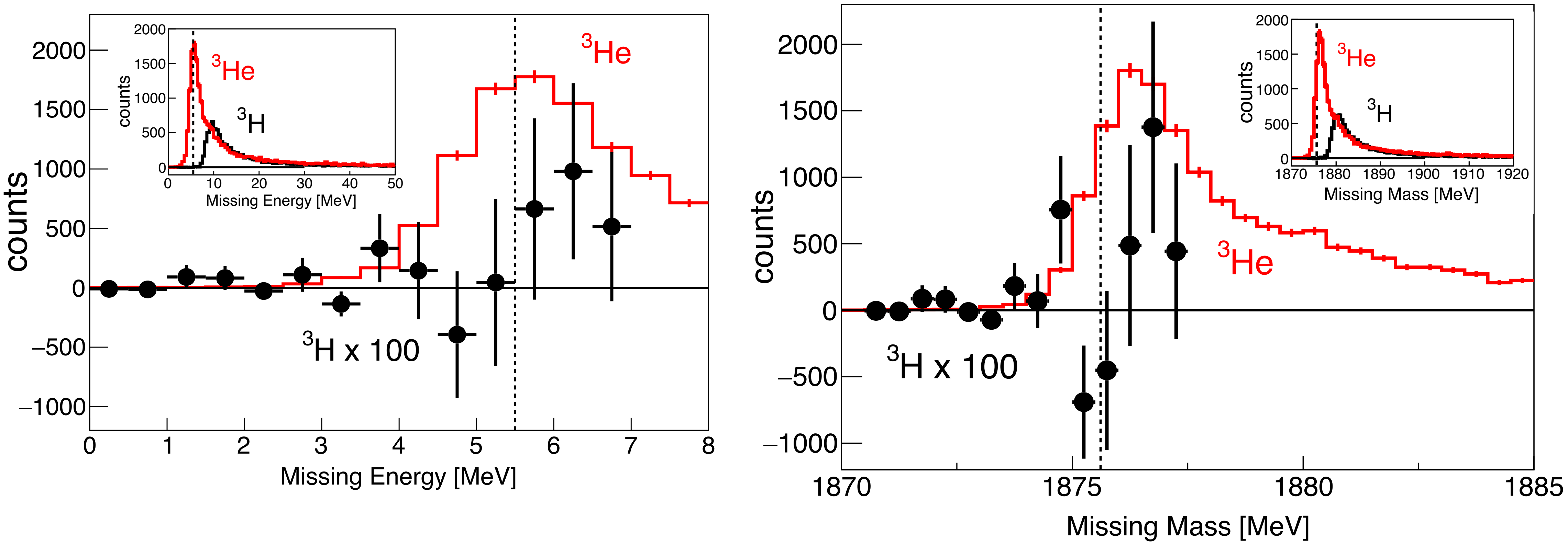
Missing Energies

- He-3:
  - 2-body: 5.5 MeV
  - 3-body threshold: 7.7 MeV
- Tritium
  - 3-body threshold: 8.5 MeV

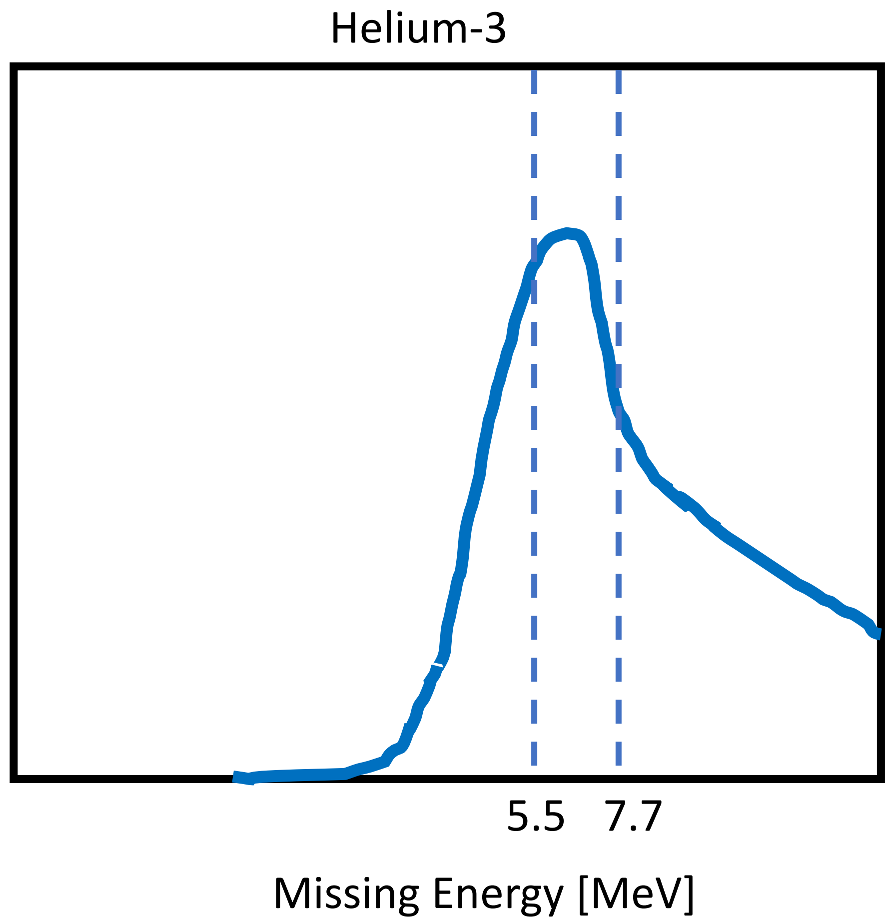
Zoom-in

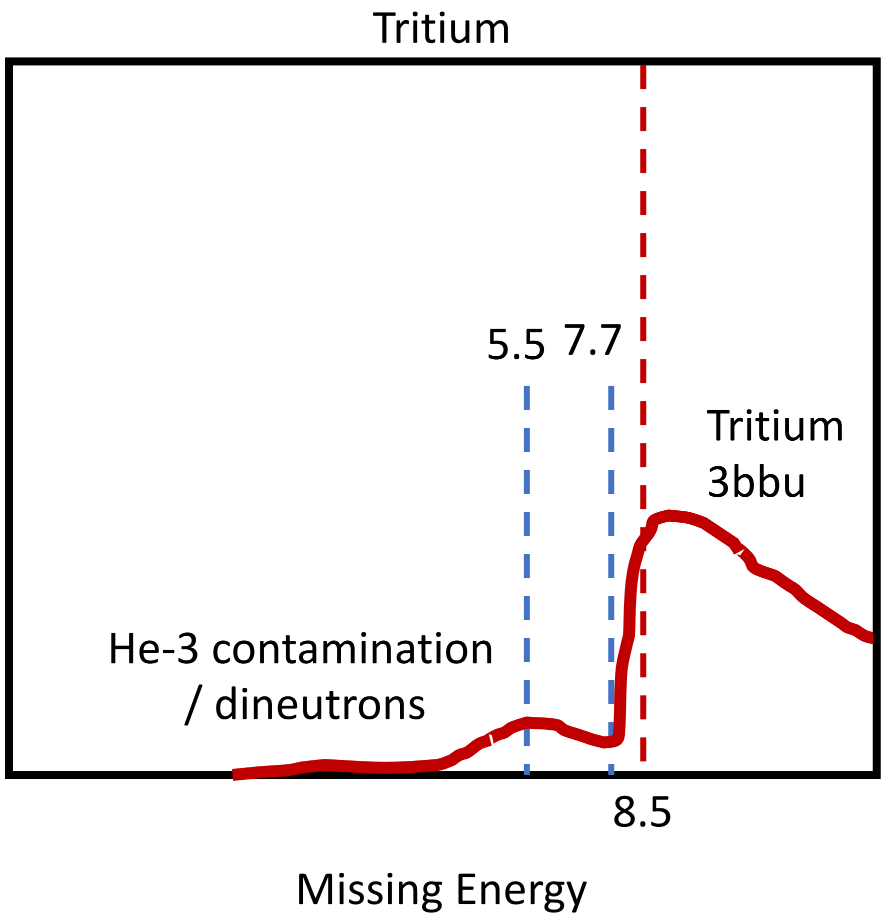


Missing Energy and missing mass



Likelihood Analysis Approaches

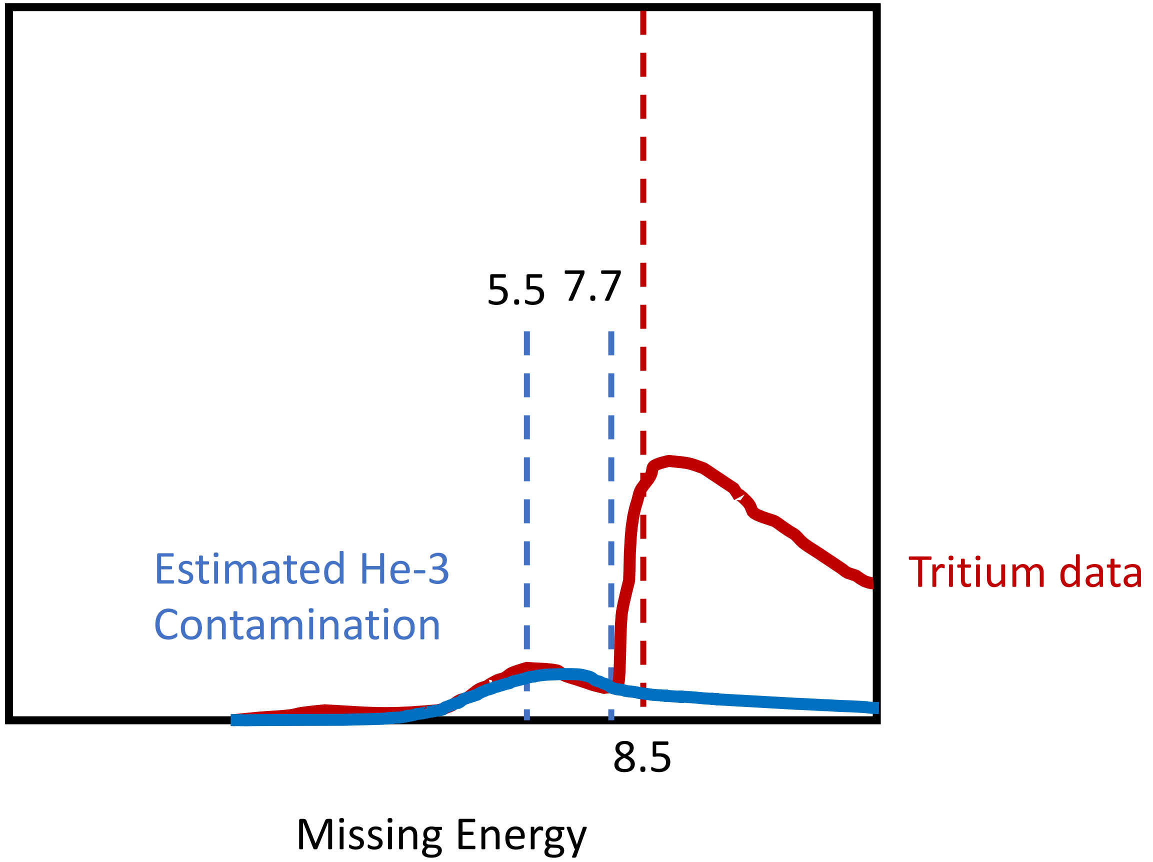




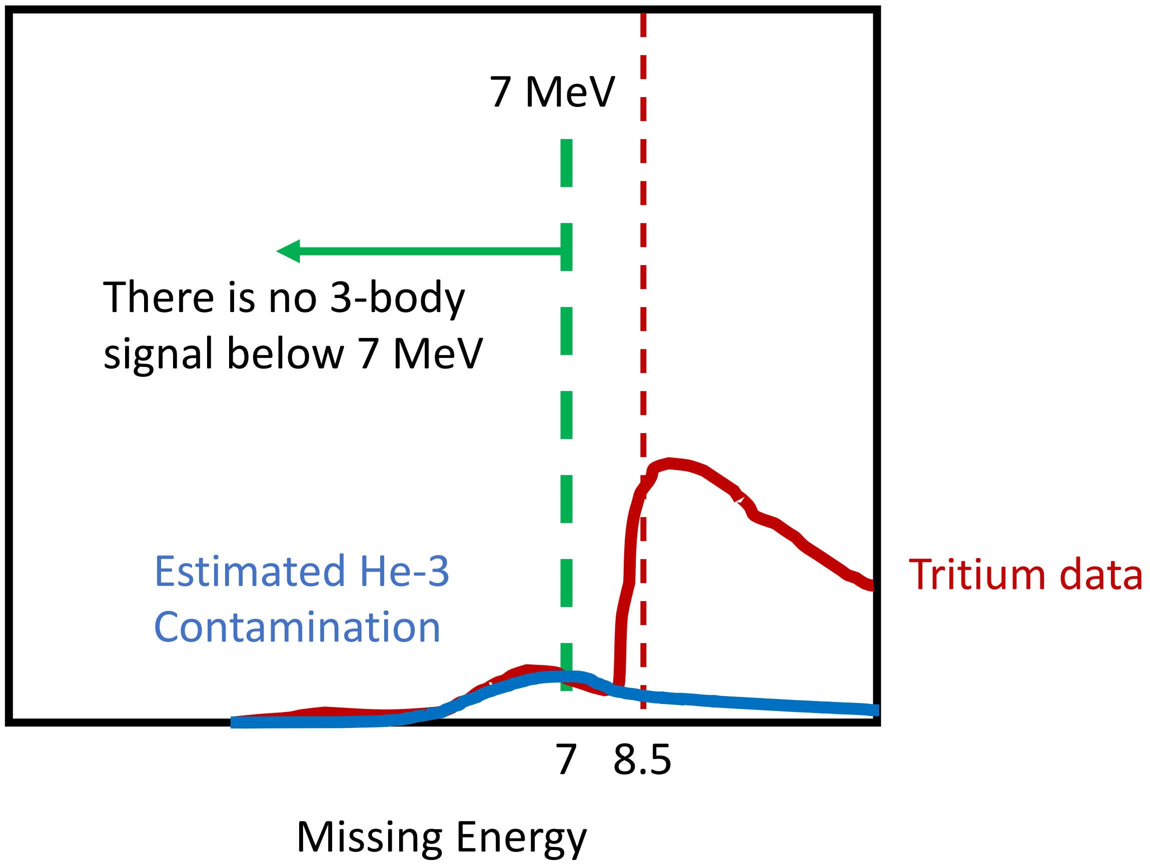
Step 1: Estimating the He-3 contamination

- He-3 contamination =
  - He-3 spectrum * (He-3 contamination fraction) * (H-3 lumi. / He-3 lumi.)

(0.0278) * (1.6321)



Step 2: Define the tritium integration window



Let: (Di-neutron signal region)

$N_{2bbu}^{^3H}$= tritium counts from $[-\infty, 7]$

$N_{2bbu}^{^3He}$ = he-3 counts from $[-\infty, 6.2]$

Expected background from He-3 contamination is

$x \cdot H$

= 0.045 * H

Step 3: Estimate likelihood.

One Parameter of interest: $R = \sigma_{2bbu}^{^3H} / \sigma_{2bbu}^{^3He}$, the cross section ratio

We can write down the likelihood of the data ($N_{2bbu}^{^3H}, N_{2bbu}^{^3He}, n, c, \epsilon$) given guesses of the parameters ($R, \lambda_{2bbu}^{3He}, n_0, c_0, \epsilon_0$).

$$L = P(N_{2bbu}^{^3\mathrm{He}} | \lambda_{2bbu}^{^3\mathrm{He}}) \cdot P(N_{2bbu}^{^3\mathrm{H}} | n_0 \lambda_{2bbu}^{^3\mathrm{He}} (c_0 + \epsilon_0 R)) \cdot G(n - n_0 | \sigma_n) \cdot G(c - c_0 | \sigma_c) \cdot G(\epsilon - \epsilon_0 | \sigma_\epsilon).$$

From data:

- $N_{2bbu}^{^3H}$: Count in 3H 2bbu (nn) signal region
- $N_{2bbu}^{^3He}$: Count in corresponding 2bbu signal region in 3He
- n : relative normalization factor
- c : contamination factor
- ϵ : relative efficiency for detecting 3H and 3He 2bbu event (Determine by data-driven method)

(This factor is nessesary because the unknown binding energy of di-neutron)

Four nuisance parameters:

- λ_{2bbu}^{3He} : True average count rate for 2bbu on 3He
- n_0, c_0, ϵ_0: True value of n, c, ϵ

$\sigma_{n,c,\epsilon}$: present the uncertainty in different terms

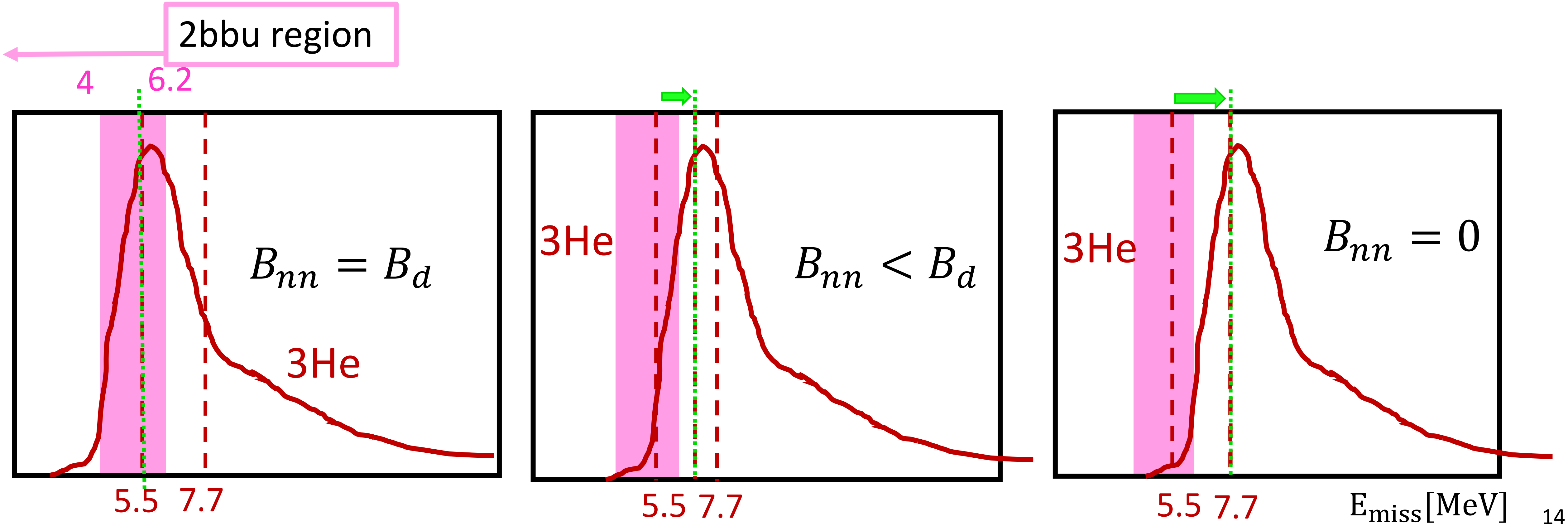
Calculating limits based on change in L

The procedure:

- Step over all possible values of R, the parameter of interest
  - Find the values of the nuisance ($\lambda_{2bbu}^{3He}, n_0 , c_0, \epsilon_0$) parameters for which L is maximized.
- Find the value of R where the conditionally maximized L drops by some significance factor:
  - $\Delta \log(L)$ = 0.5 68% 1σ
  - $\Delta \log(L)$ = 2 95% 2σ
  - $\Delta \log(L)$ = 4.5 99.7% 3σ
  - $\Delta \log(L)$ = 8 99.99% 4σ
  - $\Delta \log(L)$ = 12.5 99.9999% 5σ

Step 4: determining relative efficiency

- Assume shape of 2bbu missing energy spectrum for Helium-3 and Tritium are the same
- Use the 3He spectrum in 2bbu region as a template for the 2bbu 3H spectrum
- Shift this spectrum to simulate different di-neutron binding energies B_{nn}
- Integrate over spectrum in 2bbu region for each binding energy $\propto \varepsilon_{nn}\ (B_{nn})$
- Divide by integral over non-shifted spectrum: $B_d = 2.2\ MeV$ $\propto \varepsilon_d$

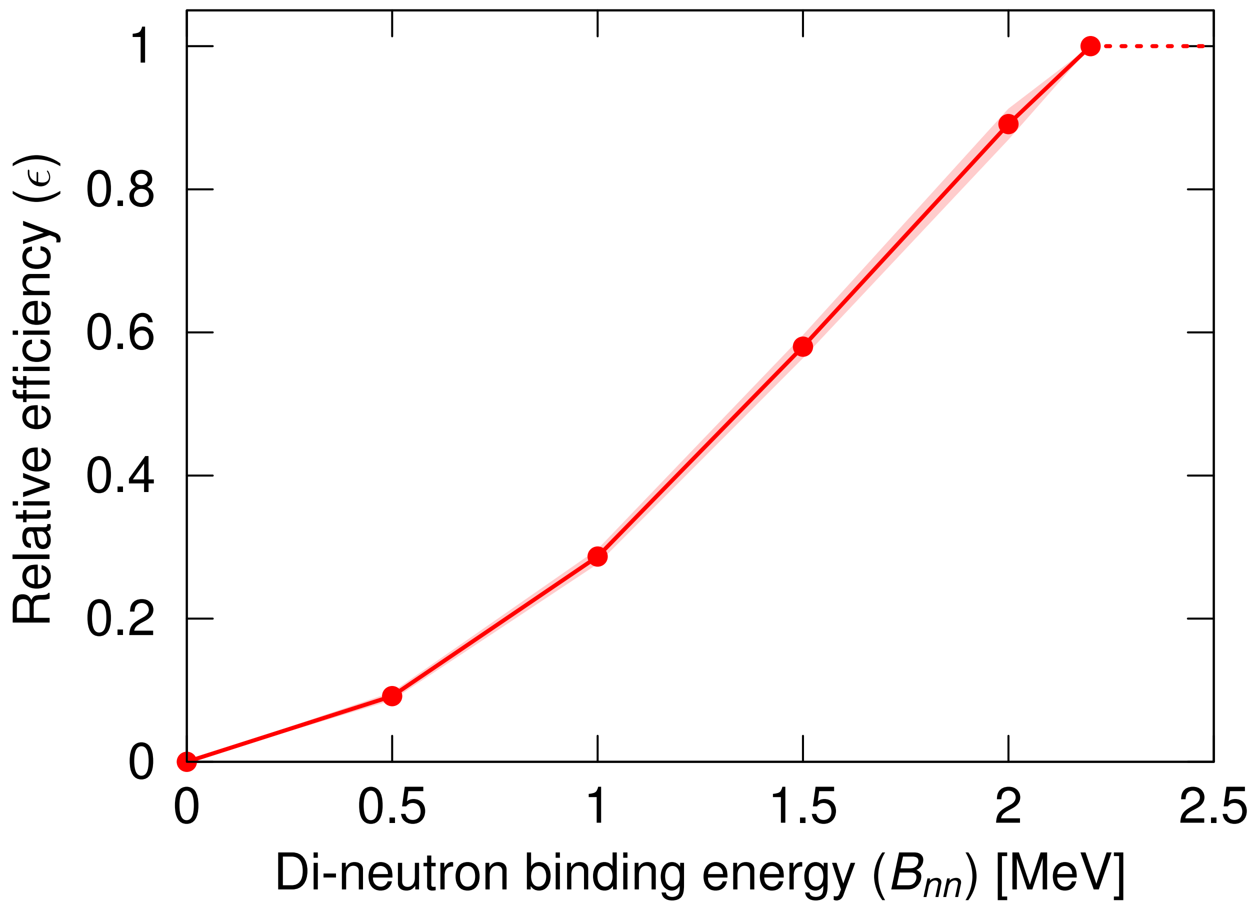


Step 4: determining relative efficiency

We can calculate:

$$\epsilon = \frac{\int_{6.2\text{ MeV}-B_d}^{6.2\text{ MeV}-B_d+B_{nn}} N^{^3\text{He}} dE_m}{\int_{6.2\text{ MeV}-B_d}^{6.2\text{ MeV}} N^{^3\text{He}} dE_m}$$

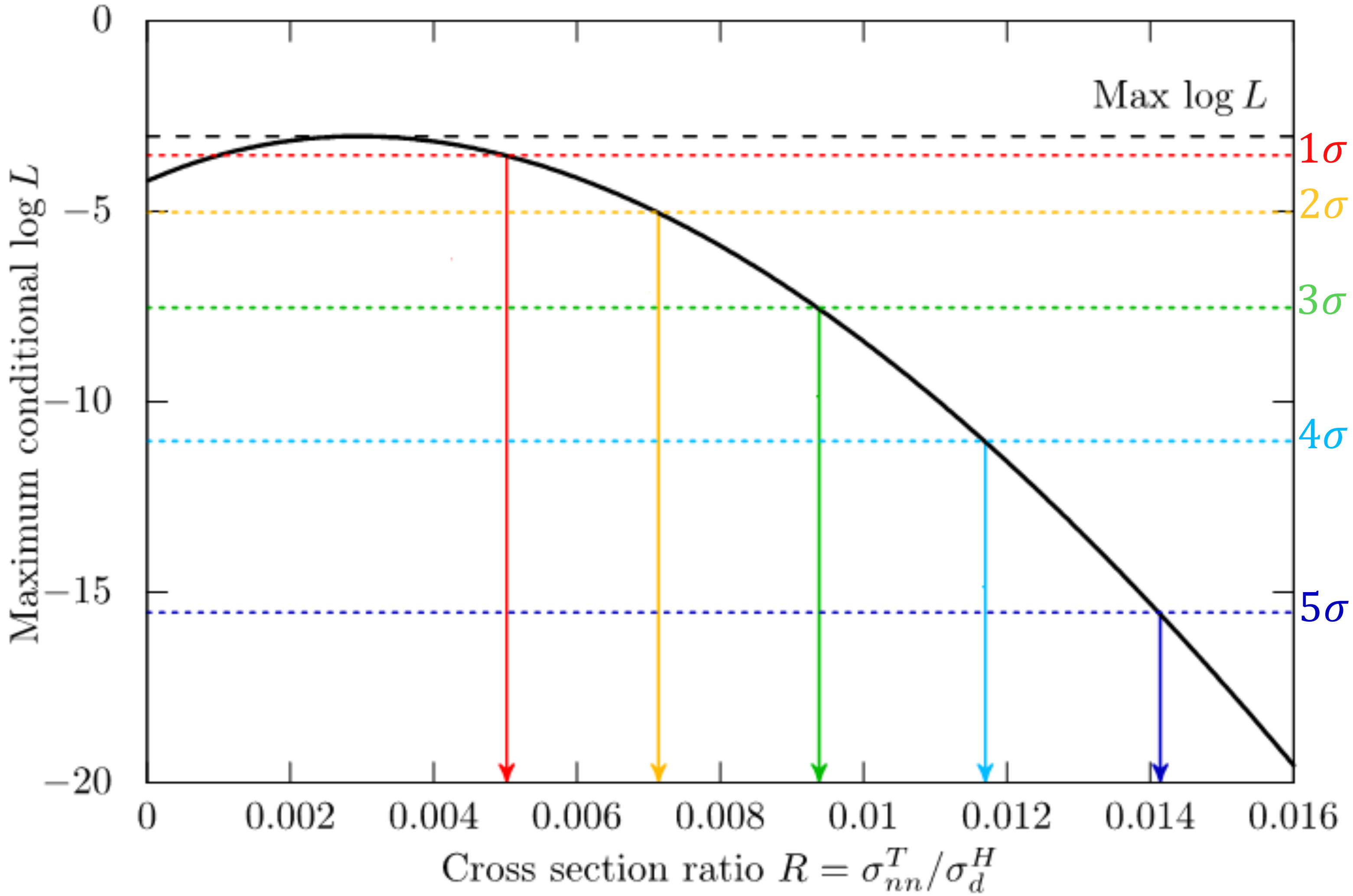
- ~ 100% for di-neutron with binding energy equal to that of D2
- ~0 % for di-neutron with zero binding energy which is indistinguishable in our measurements from 3bbu



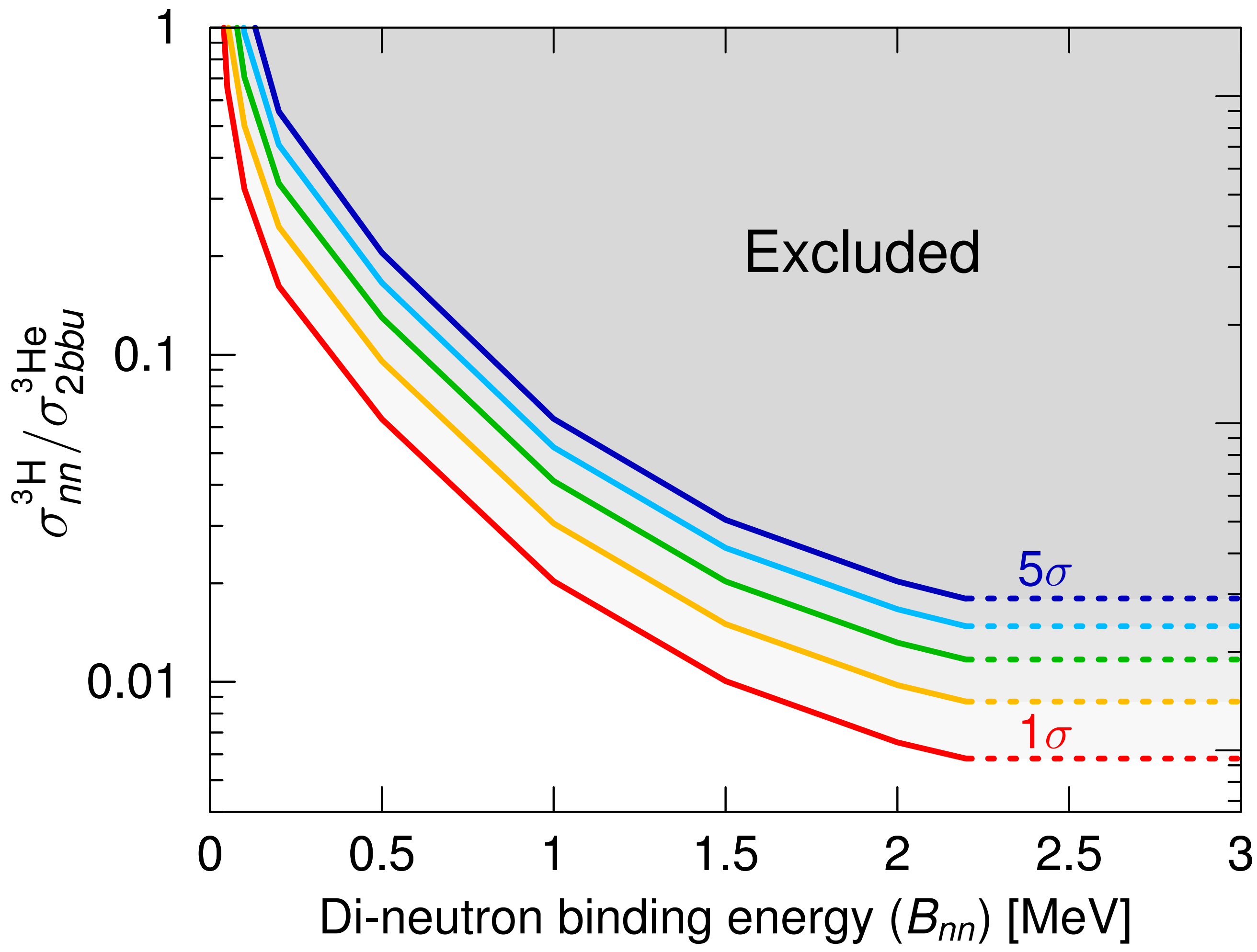
- We can not estimate relative efficiency for detecting di-neutron bound by more than 2.2 MeV since there is unavoidable contamination of 3bbu, we can set lower bound as dashed line.

For each di-neutron binding energy the value of R at each confidence level gives the exclusion limits

example for $B_{nn} = 2.2\ MeV$



Exclusion limit on $R = \sigma_{2bbu}^{^3H} / \sigma_{2bbu}^{^3He}$



Step 5: Implications for ^{3}H ground state

Let S represent the integral of the spectral function over p_m, E_m.

$$S_{nn}^{^3\mathrm{H}} = \int d^3 p_{miss} S^{^3\mathrm{H}}(E_{miss}^{nn}, \vec{p}_{miss})$$

$$S_{3bbu}^{^3\mathrm{H}} = \int d^3 p_{miss} \int_{E_{3bbu}}^{\infty} dE_{miss} S^{^3\mathrm{H}}(E_{miss}, \vec{p}_{miss}).$$

Type equation here.We aim to place exclusion limits on ratio:

$$\frac{S_{nn}^{^3\mathrm{H}}}{S_{3bbu}^{^3\mathrm{H}}} = \left[\frac{\sigma_{nn}^{^3\mathrm{H}}}{\sigma_{2bbu}^{^3\mathrm{He}}}\right] \cdot \left(\left[\frac{\sigma_{2bbu}^{^3\mathrm{He}}}{\sigma_{3bbu}^{^3\mathrm{He}}}\right] \cdot \left[\frac{\sigma_{3bbu}^{^3\mathrm{He}}}{\sigma_{3bbu}^{^3\mathrm{H}}}\right] \cdot \left[\frac{S_{nn}^{^3\mathrm{H}}}{S_{3bbu}^{^3\mathrm{H}}} \frac{\sigma_{3bbu}^{^3\mathrm{H}}}{\sigma_{nn}^{^3\mathrm{H}}}\right]\right)$$

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The ratio R we just put a limit on.

Measured He-3 2-body to 3-body ratio in our kinematics

Measured He-3 to tritium 3-body cross section ratio in our kinematics.

Correction factor for going from cross sections to spectral functions in our kinematics. we argue that this factor is the same for Helium-3 and Tritium.

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$$\frac{S^{^3\mathrm{H}}_{nn}}{S^{^3\mathrm{H}}_{3bbu}} = \left[\frac{\sigma^{^3\mathrm{H}}_{nn}}{\sigma^{^3\mathrm{He}}_{2bbu}}\right] \cdot \left(\left[\frac{\sigma^{^3\mathrm{He}}_{2bbu}}{\sigma^{^3\mathrm{He}}_{3bbu}}\right] \cdot \left[\frac{\sigma^{^3\mathrm{He}}_{3bbu}}{\sigma^{^3\mathrm{H}}_{3bbu}}\right] \cdot \left[\frac{S^{^3\mathrm{H}}_{nn}}{S^{^3\mathrm{H}}_{3bbu}} \frac{\sigma^{^3\mathrm{H}}_{3bbu}}{\sigma^{^3\mathrm{H}}_{nn}}\right]\right)$$

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$$\left[\frac{S_d^{3He}}{S_{3bbu}^{3He}} \cdot \frac{\sigma_{3bbu}^{3He}}{\sigma_d^{3He}}\right] = \frac{2.077}{1.673} = 1.24$$

c. Ciofi and Katari spectral function

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$$\frac{S^{^3\mathrm{H}}_{nn}}{S^{^3\mathrm{H}}_{3bbu}} = \left[\frac{\sigma^{^3\mathrm{H}}_{nn}}{\sigma^{^3\mathrm{He}}_{2bbu}}\right] \cdot \left(\left[\frac{\sigma^{^3\mathrm{He}}_{2bbu}}{\sigma^{^3\mathrm{He}}_{3bbu}}\right] \cdot \left[\frac{\sigma^{^3\mathrm{He}}_{3bbu}}{\sigma^{^3\mathrm{H}}_{3bbu}}\right] \cdot \left[\frac{S^{^3\mathrm{H}}_{nn}}{S^{^3\mathrm{H}}_{3bbu}} \frac{\sigma^{^3\mathrm{H}}_{3bbu}}{\sigma^{^3\mathrm{H}}_{nn}}\right]\right)$$

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$\frac{\sigma^H_{3bbu}}{\sigma^T_{3bbu}} \sim \frac{N^H_{3bbu}}{N^T_{3bbu}}$ *n ~0.78

Correction factor for going from cross sections to spectral functions in our kinematics. We argue that this factor is the same for Helium-3 and Tritium.

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$$\frac{S_{nn}^{^3H}}{S_{3bbu}^{^3H}} = \left[\frac{\sigma_{nn}^{^3H}}{\sigma_{2bbu}^{^3He}}\right] \cdot \left(\left[\frac{\sigma_{2bbu}^{^3He}}{\sigma_{3bbu}^{^3He}}\right] \cdot \left[\frac{\sigma_{3bbu}^{^3He}}{\sigma_{3bbu}^{^3H}}\right] \cdot \left[\frac{S_{nn}^{^3H}}{S_{3bbu}^{^3H}} \frac{\sigma_{3bbu}^{^3H}}{\sigma_{nn}^{^3H}}\right]\right)$$

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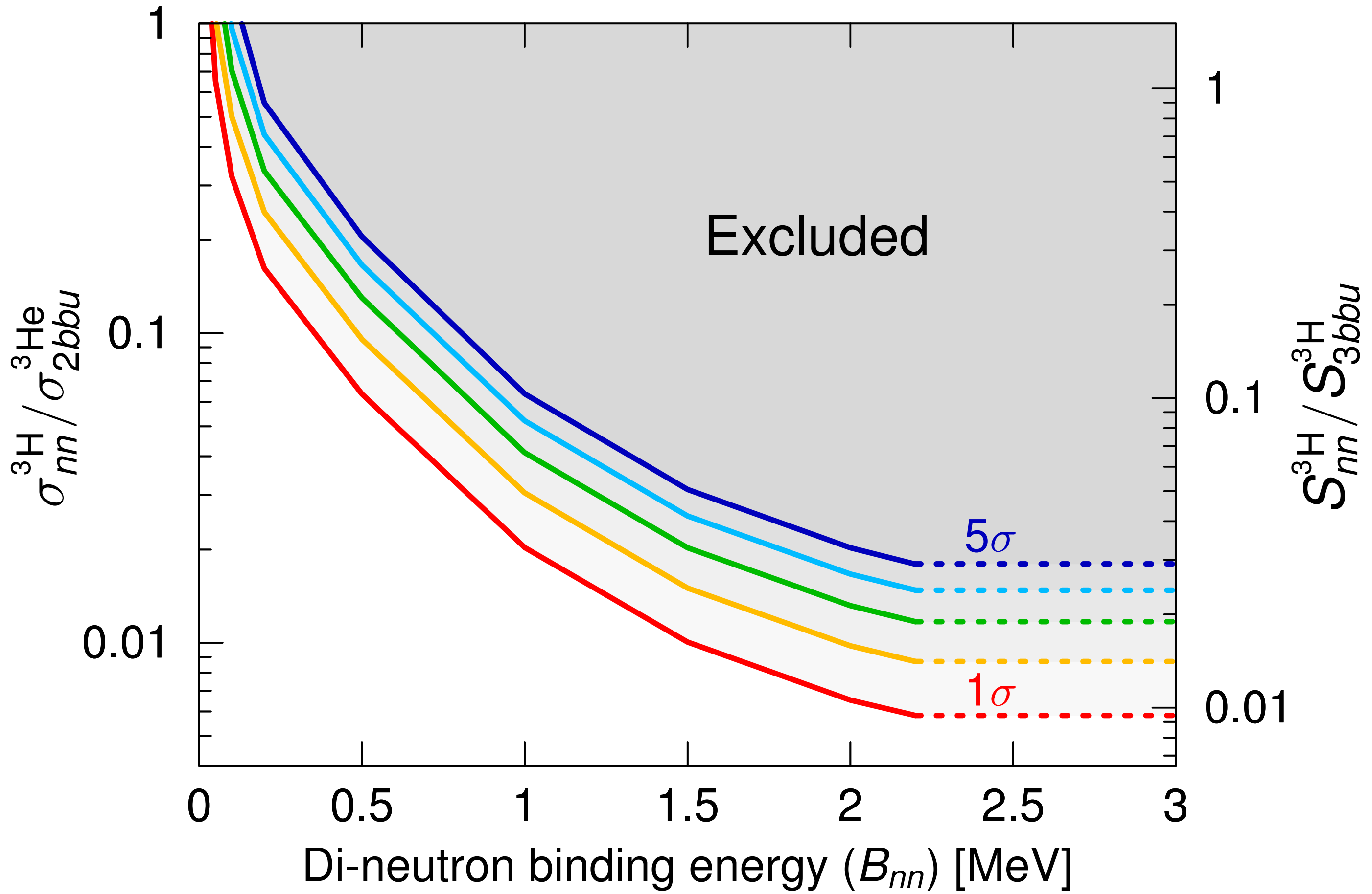
Using 2bbu and 3bbu XS fitting to determine

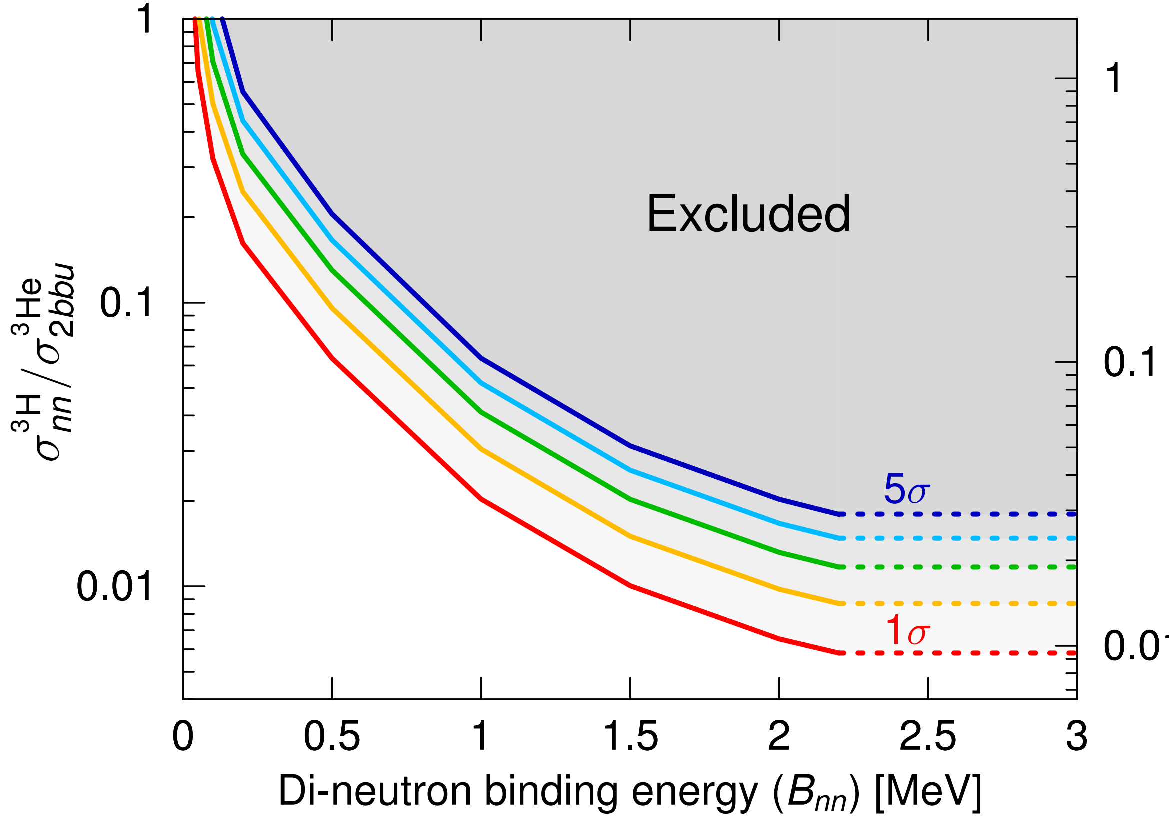
Results: Put all together



- ❑ $\sigma_{nn}^{3H} / \sigma_{2bbu}^{3He} < 0.9$ % at the same kinematic at 95% confidence level
- ❑ $S_{nn}^{T} / S_{3bbu}^{T} < 1.5$ % at 95% confidence level

Summary

- We search for a bound di-neutron system using the 3He and 3H mirror nuclei.
- We found no evidence of such a state and establish an upper limit.
- Our sensitivity degrades rapidly as the di-neutron binding energy decreases.
- Dedicated QE experiments with better resolution can be more sensitive to a near threshold nn resonance or bound system.



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