Ground-state properties of superheavy ^{7}H

Physics Letters B 829 (2022) 137067

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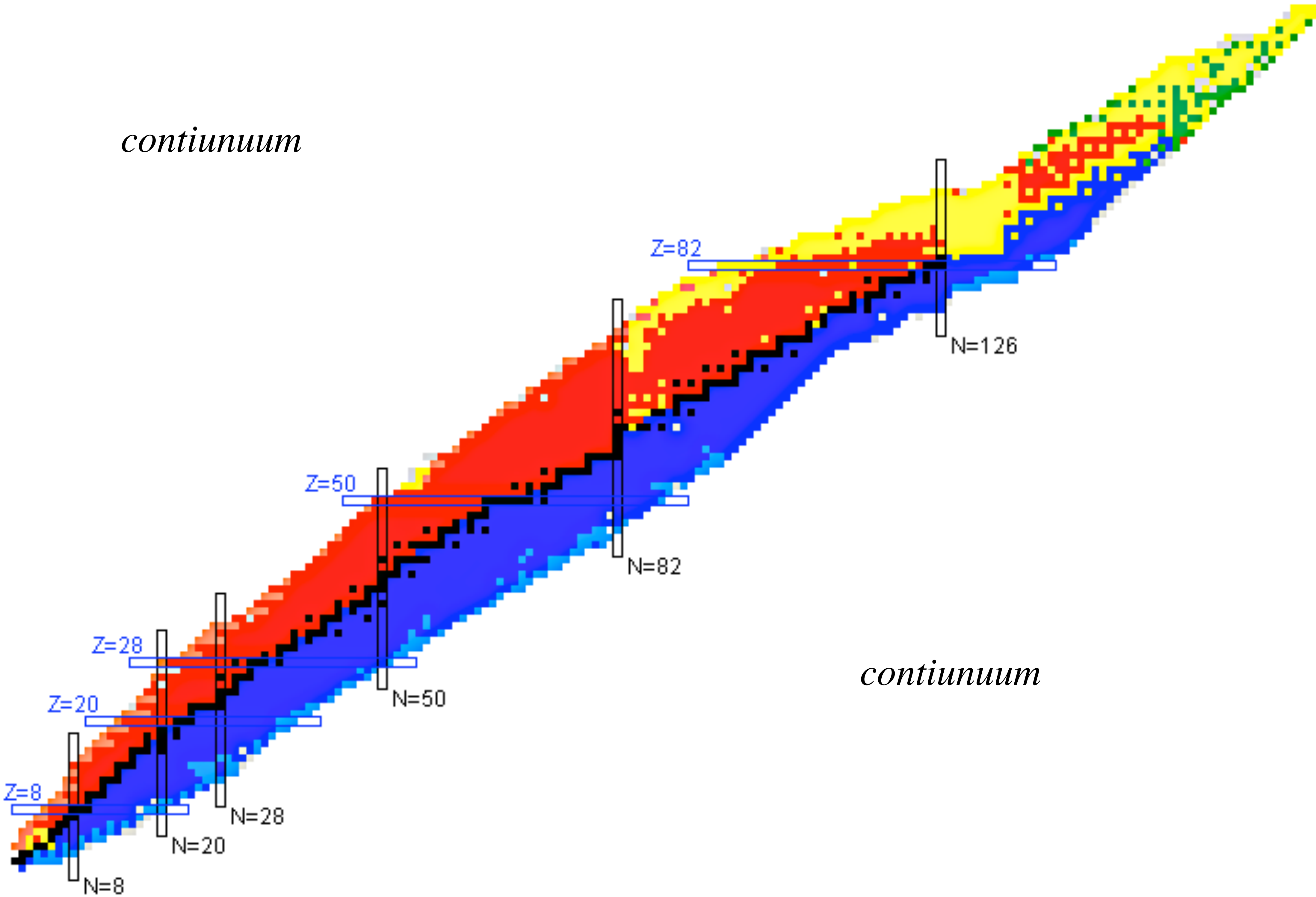
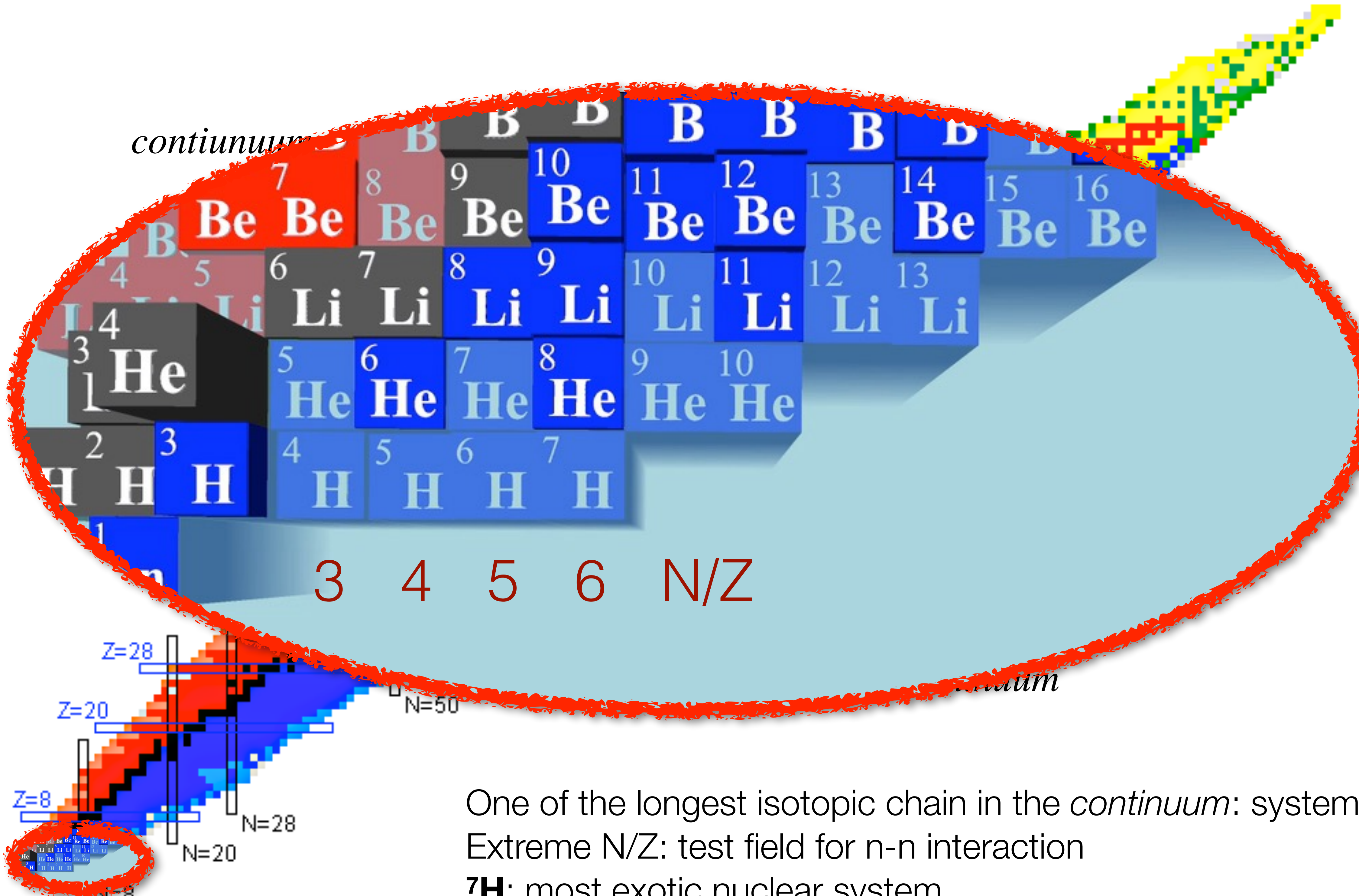


contiunuum
Z=82
N=126
Z=50
N=82
Z=28
N=50
Z=20
Z=8
N=28
N=20
N=8
contiunuum

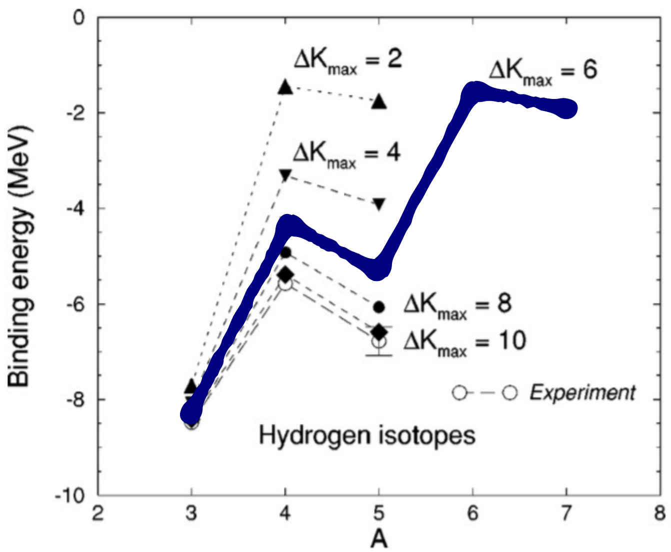


One of the longest isotopic chain in the *continuum*: systematics

Extreme N/Z: test field for n-n interaction

^{7}H: most exotic nuclear system

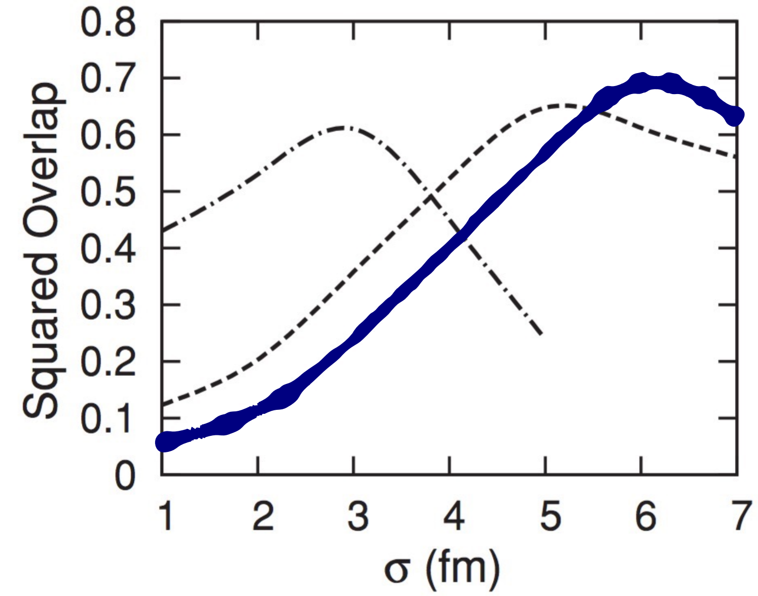
In general, theory goes for a narrow, low-lying, di-neutron system in ^{7}H



N.K. Timofeyuk
PRC 65, 064306 (02)
PRC 69, 034336 (04)

Hyperspherical harmonics
& no-core SM

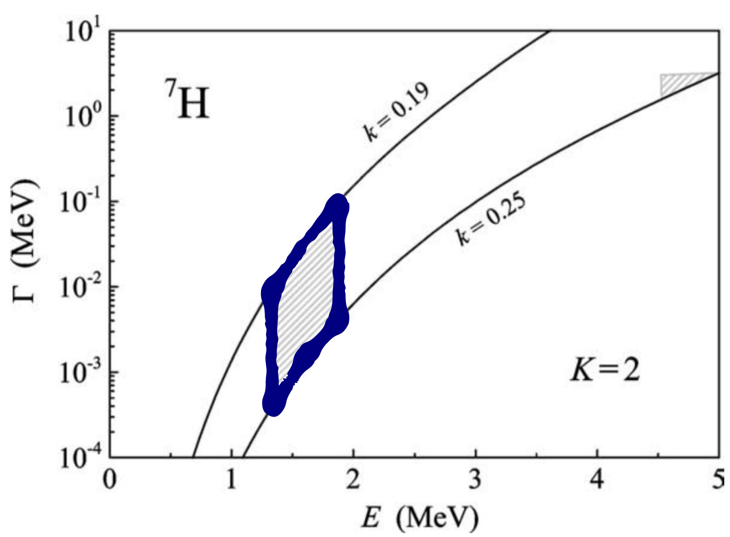
E_R ~0.8–3 MeV
^{8}He-like structure



S. Aoyama, N. Itagaki
PRC 80, 021304(R) (09)

AMD & THRS
boson condensate

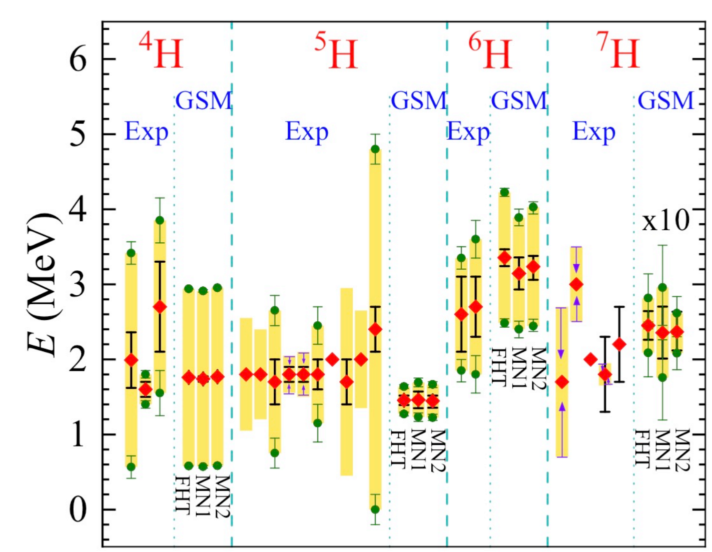
E_R ~3.3 MeV
di-neutron condensate
~4 fm between
^{3}H and n



M.S. Golovkov et al.
PLB 588, 163 (04)

Hyperspherical harmonics
& Gaussian emission

E_R ~1.3–1.8 MeV
Γ ~1–100 keV
simultaneous 5-body emission

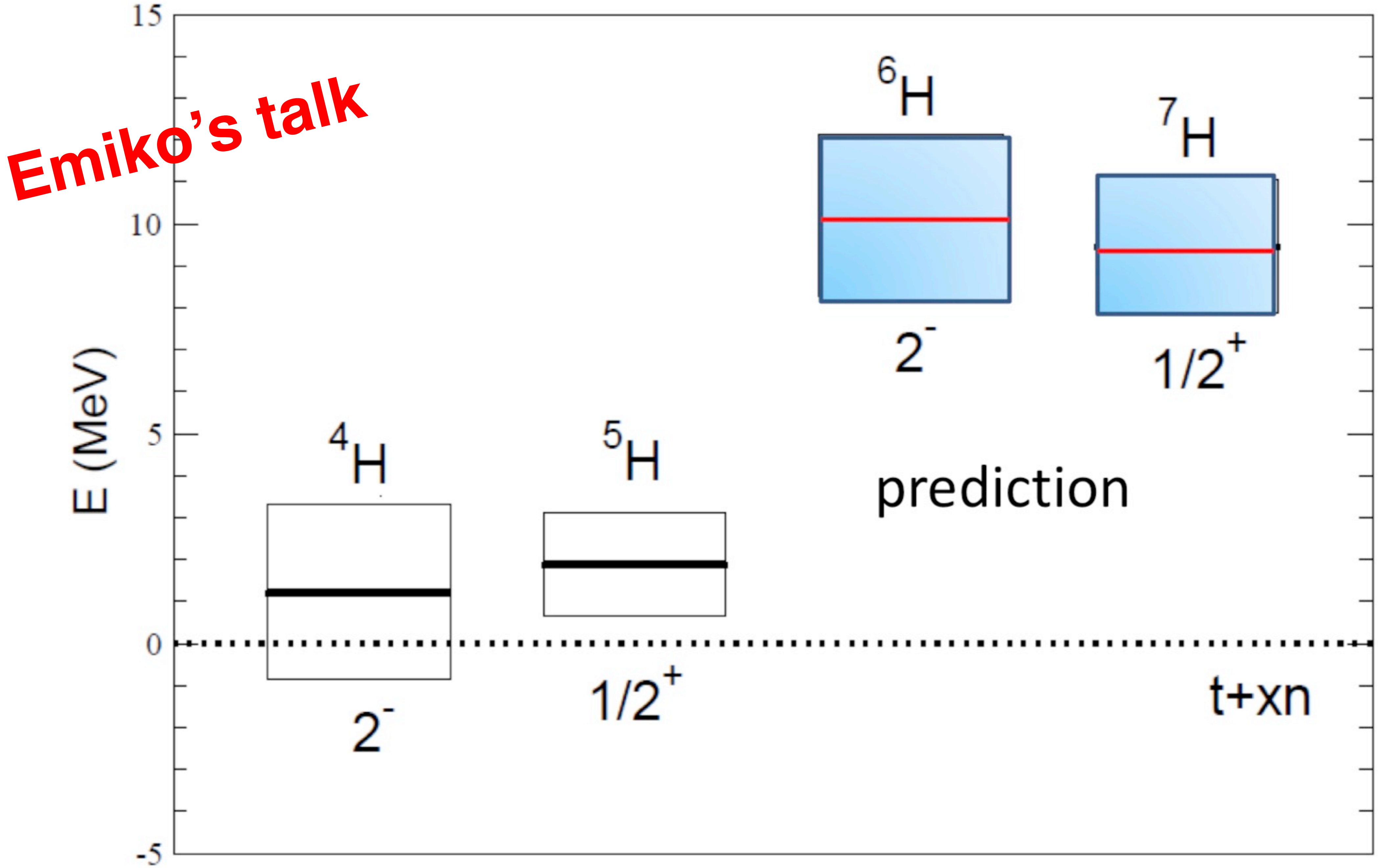


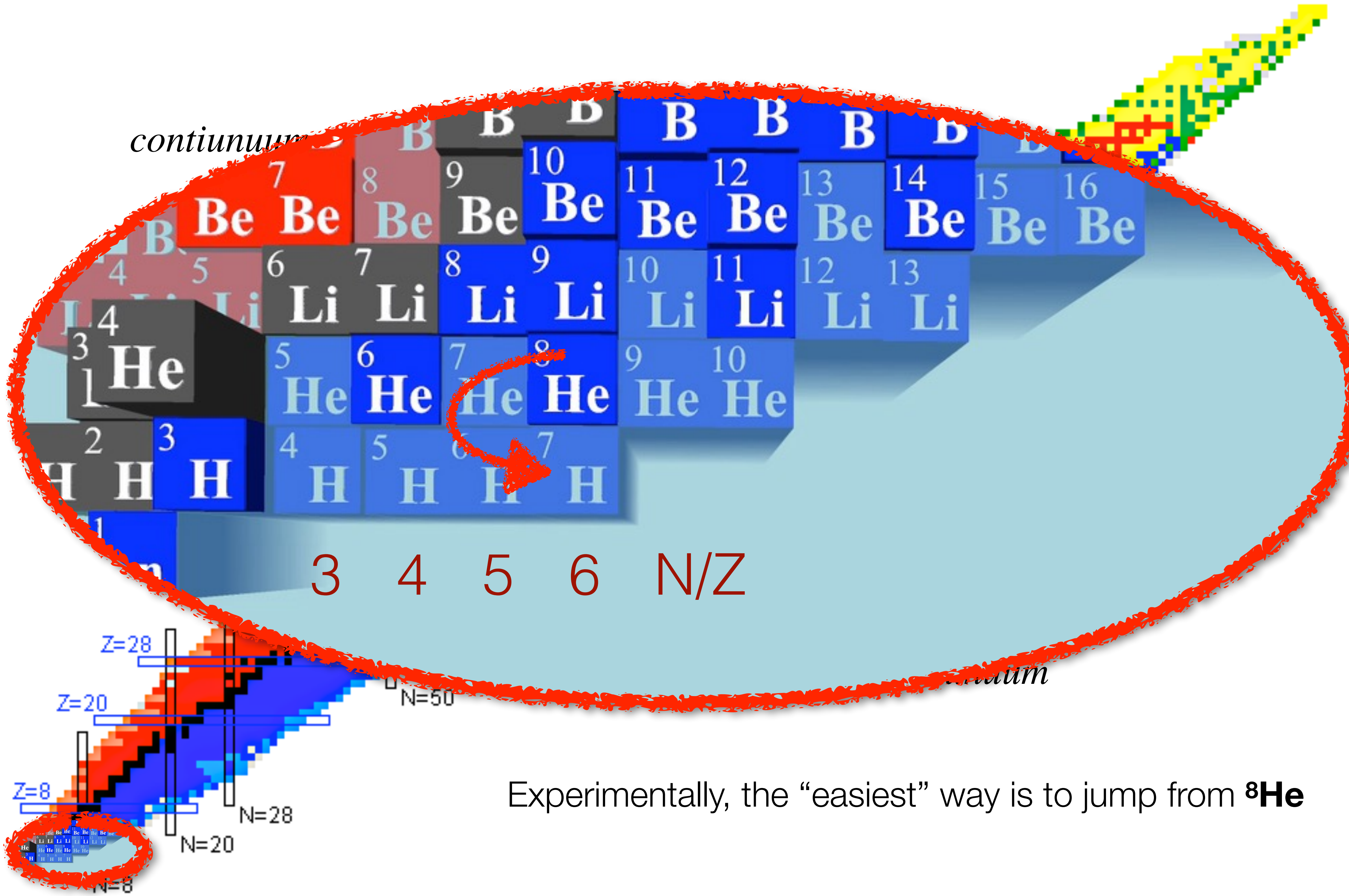
H. H. Li et al.
PRC 1040, L061306 (21)

Gamow Shell Model
WS from experiments

E_R ~2.4 MeV
Γ ~10–240 keV

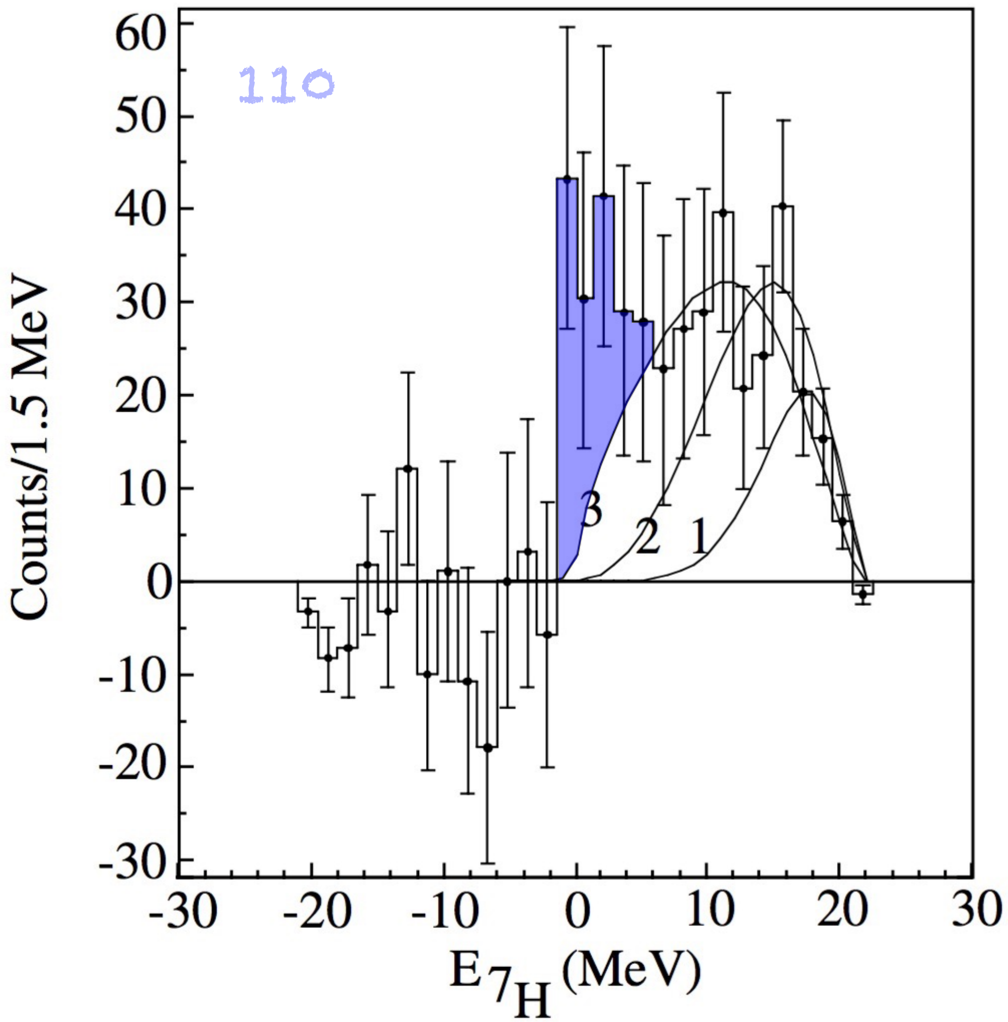
Or not?





Experimentally, the "easiest" way is to jump from **^{8}He**

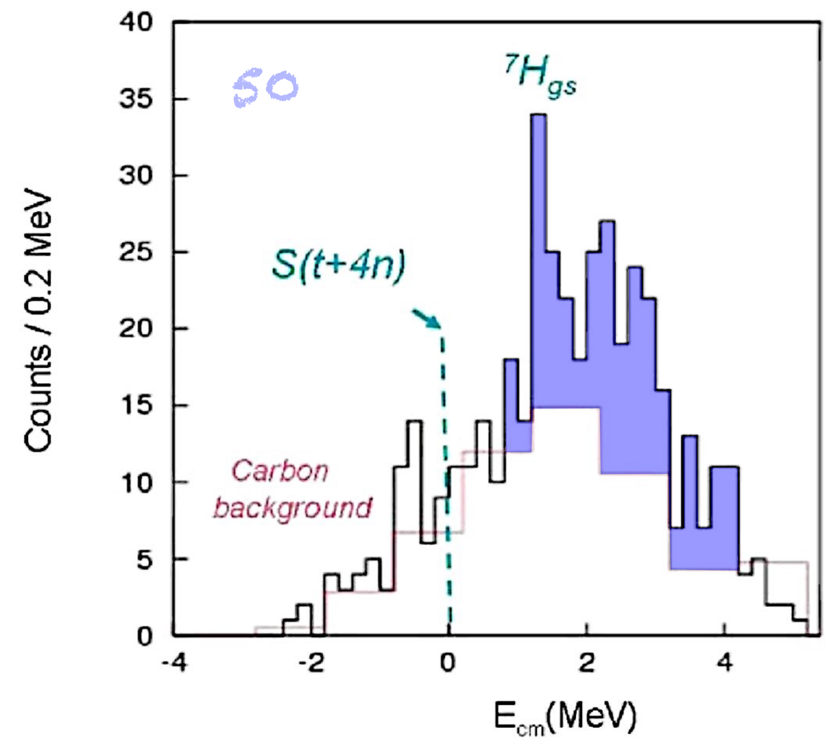
Experimental information is not conclusive but slowly amounting to something…



A.A. Korsheninnikov et al.,
PRL 90, 082501 (03)

p (^{8}He,^{7}H) *pp* at 61.3 AMeV

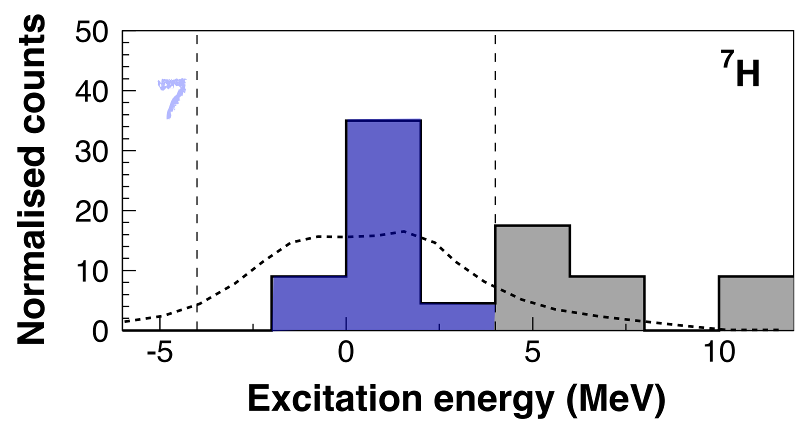
E_{max} ~[0–3 MeV]
FWHM ~[0–2 MeV]
$d\sigma_{(10\text{-}25deg)}$ ~10 μb/sr



S. Fortier et al.,
AIP 912, 2 (07)

d (^{8}He,^{7}H) ^{3}*He*
at 15.3 AMeV

E_{max} ~2(1) MeV
FWHM ~[1–3 MeV]
$d\sigma_{(31.5\text{-}50deg)}$ ~100 μb/sr



M. Caamaño et al.,
PRL 99, 062502 (07)

^{12}C (^{8}He,^{7}H) ^{13}*N*
at 15.4 AMeV

$E_{max} = 0.6^{+0.8}_{-0.3}$ MeV
FWHM = $0.1^{+0.8}_{-0.1}$ MeV
$d\sigma_{(10\text{-}48deg)} = 40^{+58}_{-31}$ μb/sr

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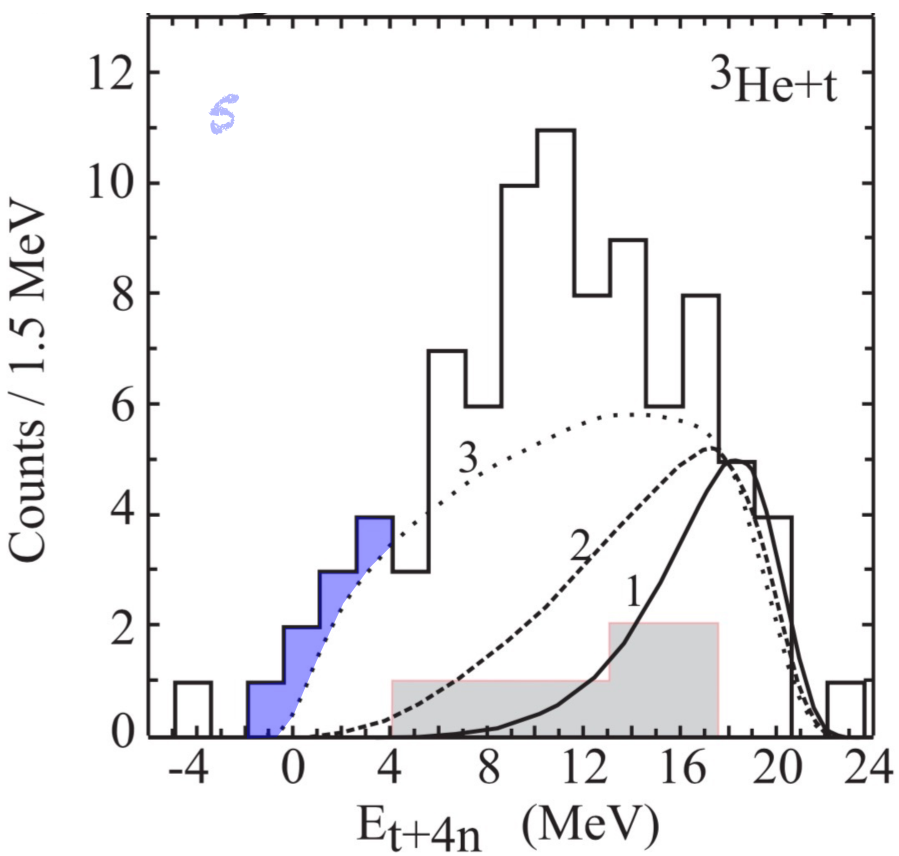
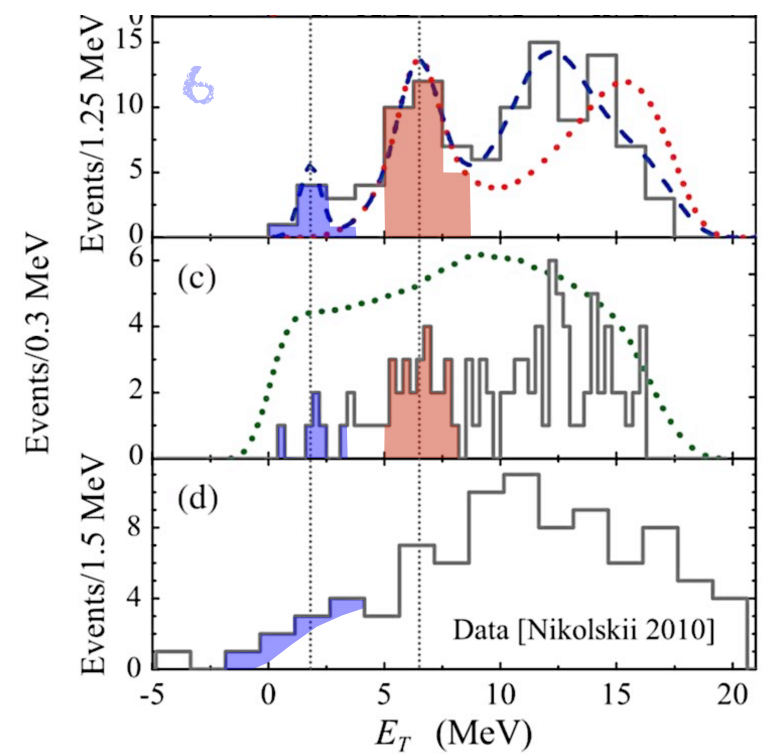


E.Yu. Nikolskii et al.,PRC 81, 064604 (10)

d (^{8}He,^{7}H) ^{3}*He* at 42 AMeV

E_{max} ~2 MeV
FWHM ~[?]
$d\sigma_{(6\text{-}14deg)}$ ~30 μb/sr

Hints of an excited state at 6.5 MeV!!
with $d\sigma_{(10\text{-}45deg)}$ ~ 30 μb/sr



A.A. Bezbakh et al., PRL 124, 022502 (20)

d (^{8}He,^{7}H) ^{3}*He* at 26 AMeV

E_{max} ~1.8(5) MeV
FWHM <0.3 MeV
$d\sigma_{(17\text{-}27deg)}$ ~25 μb/sr

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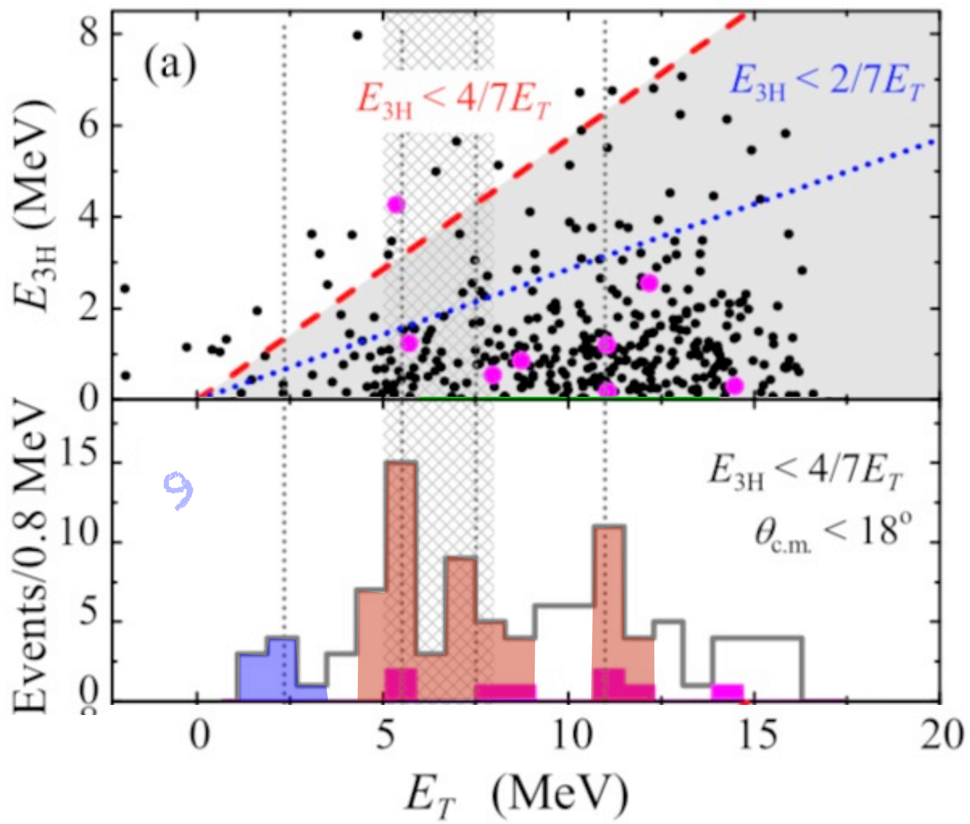


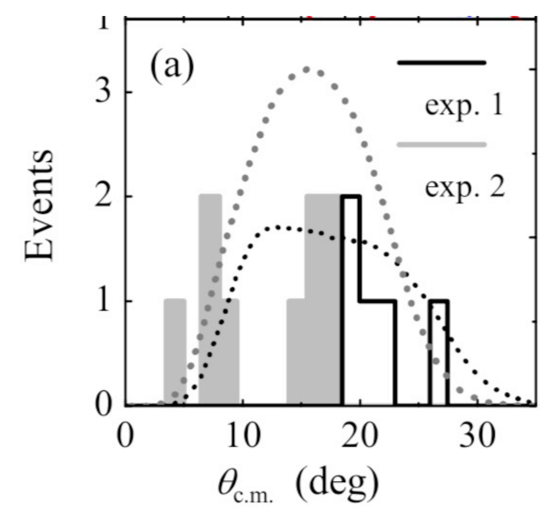
I.A. Muzalevskii et al., PRC 103, 044313 (21)

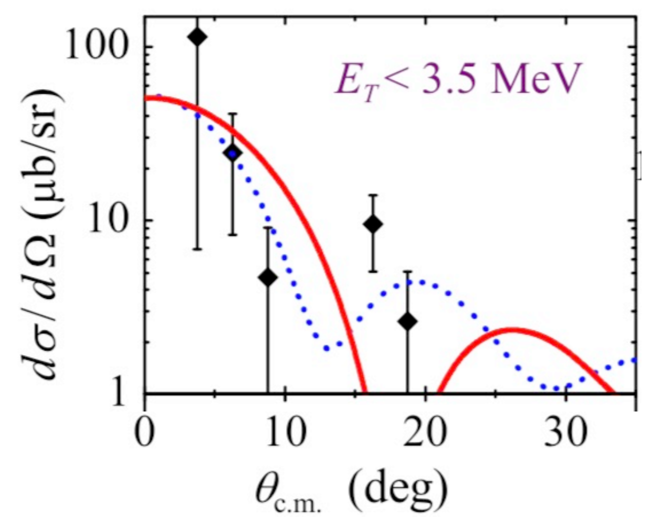
d (^{8}He,^{7}H) ^{3}*He* at 26 AMeV

E_{max} ~2.2(5) MeV
FWHM ~[0 - 0.4] MeV
$d\sigma_{(3\text{-}18deg)}$ ~35 μb/sr

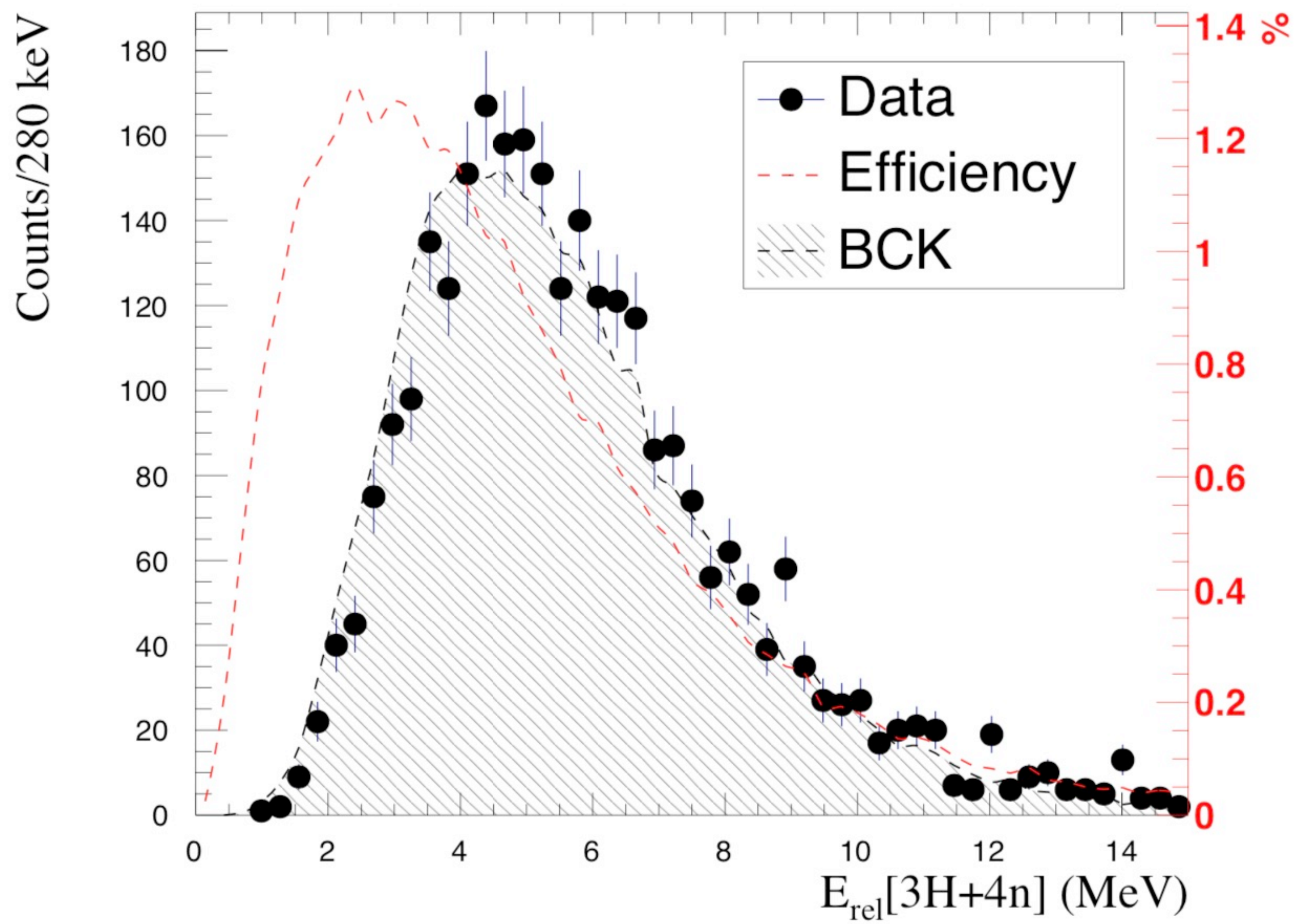
More excited states
at 5.5(3), 7.5(3), 11.0(3) MeV!!

And… a first look at a
possible angular distribution:





Or not?



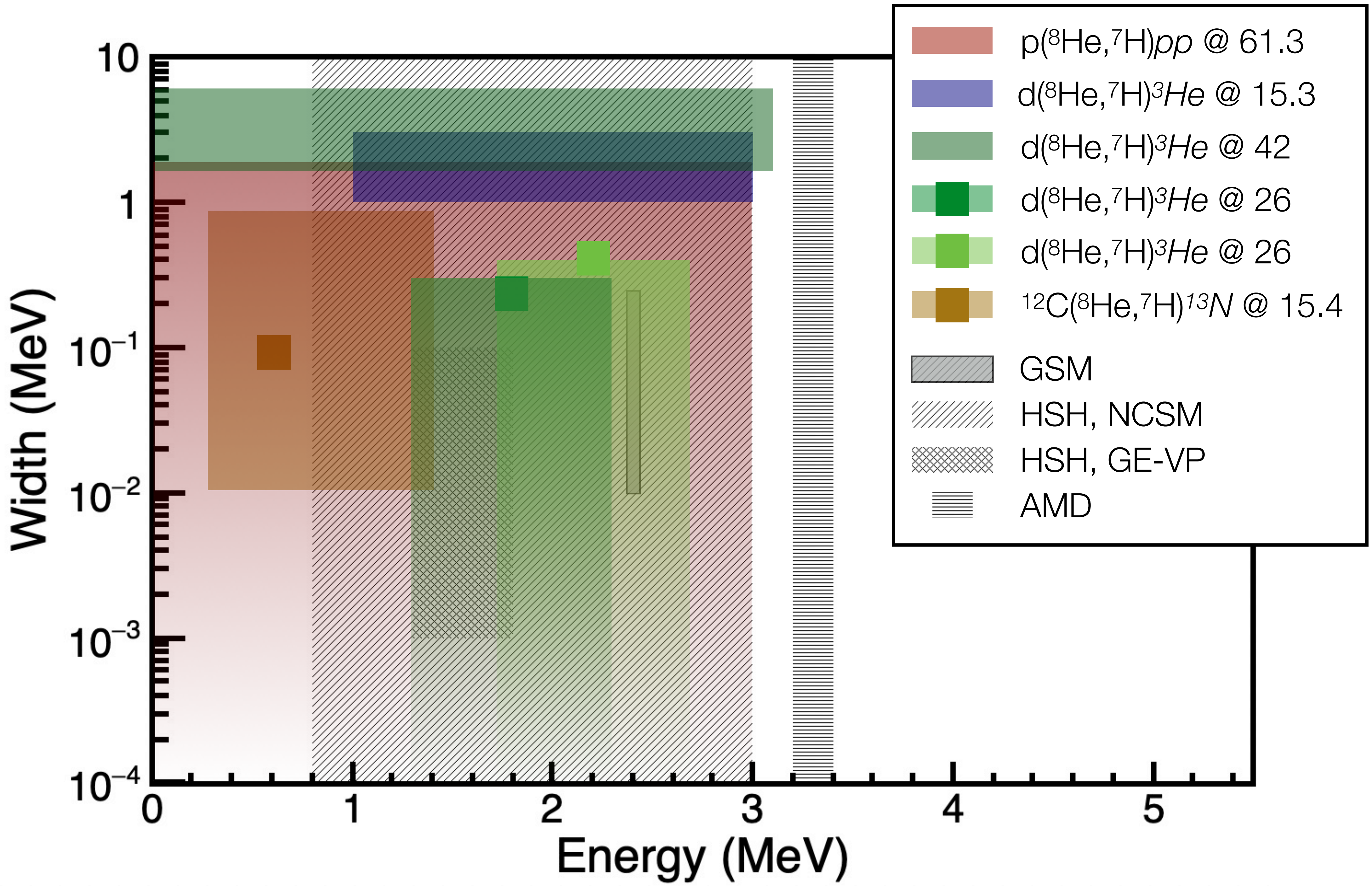
C. Lenain,
PhD U. Caen Normandie
(2021)

Cyril's talk

p (^{8}He,^{7}H) *pp* @ 156 AMeV. Detection of all products.

But no sign of ^{7}H…

Overall, the situation is not yet quite closed:



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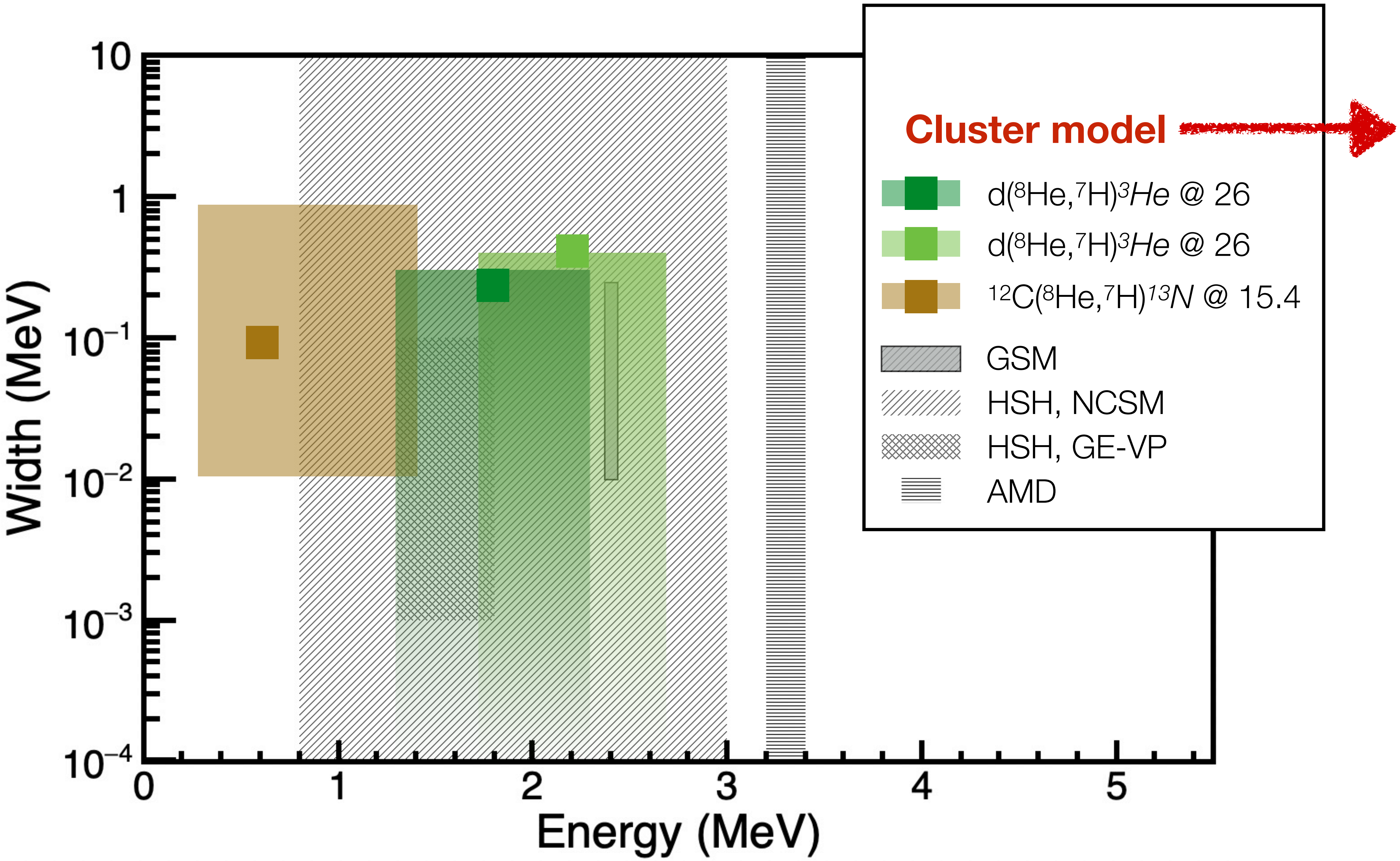
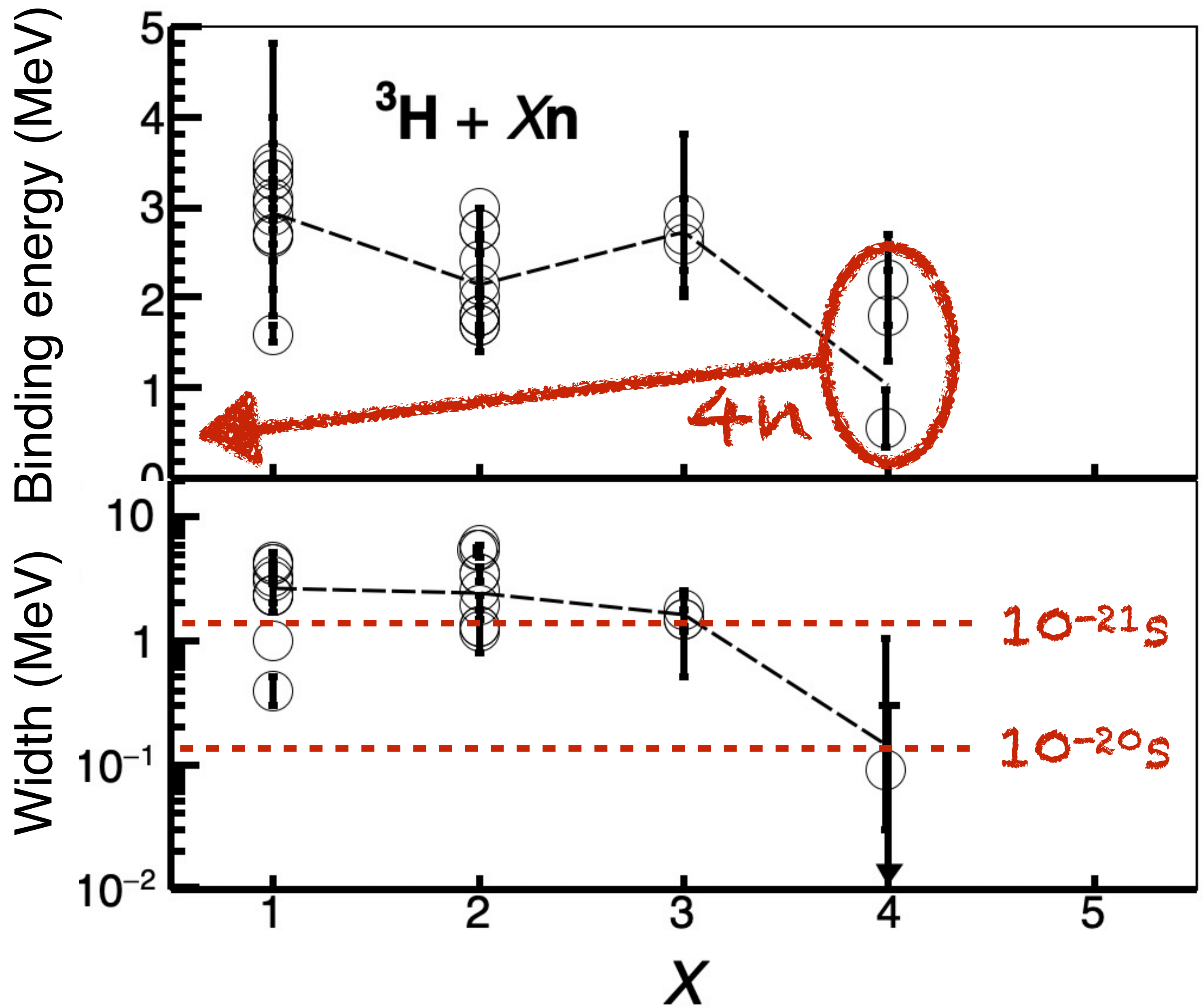
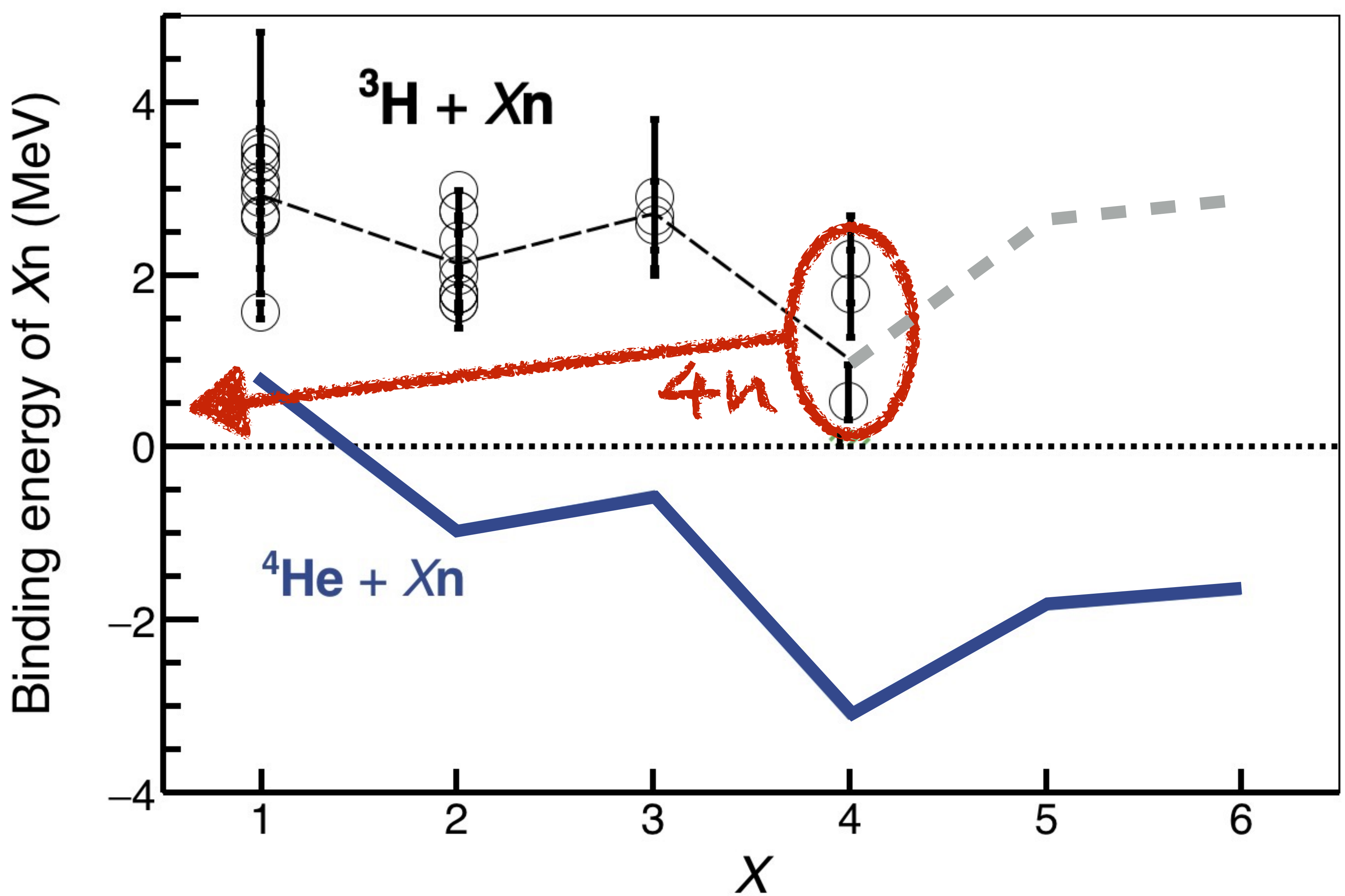


But it already hints at basic properties of ^7H



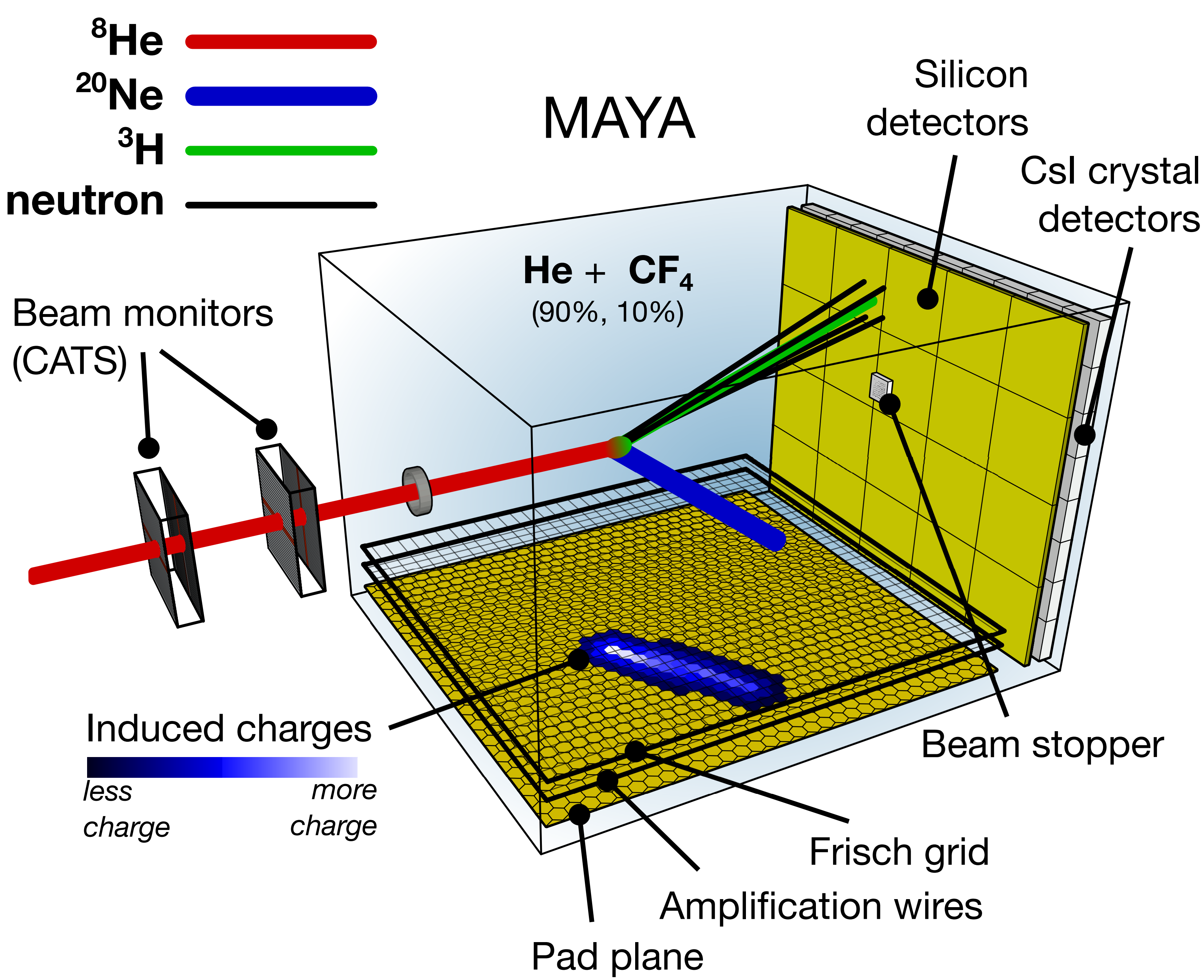
- The **lowest binding energy** of the chain: possible **4n decay** directly to ^3H+4n
- The **smallest width**: longest-lived of the chain

But it already hints at basic properties of ^{7}H



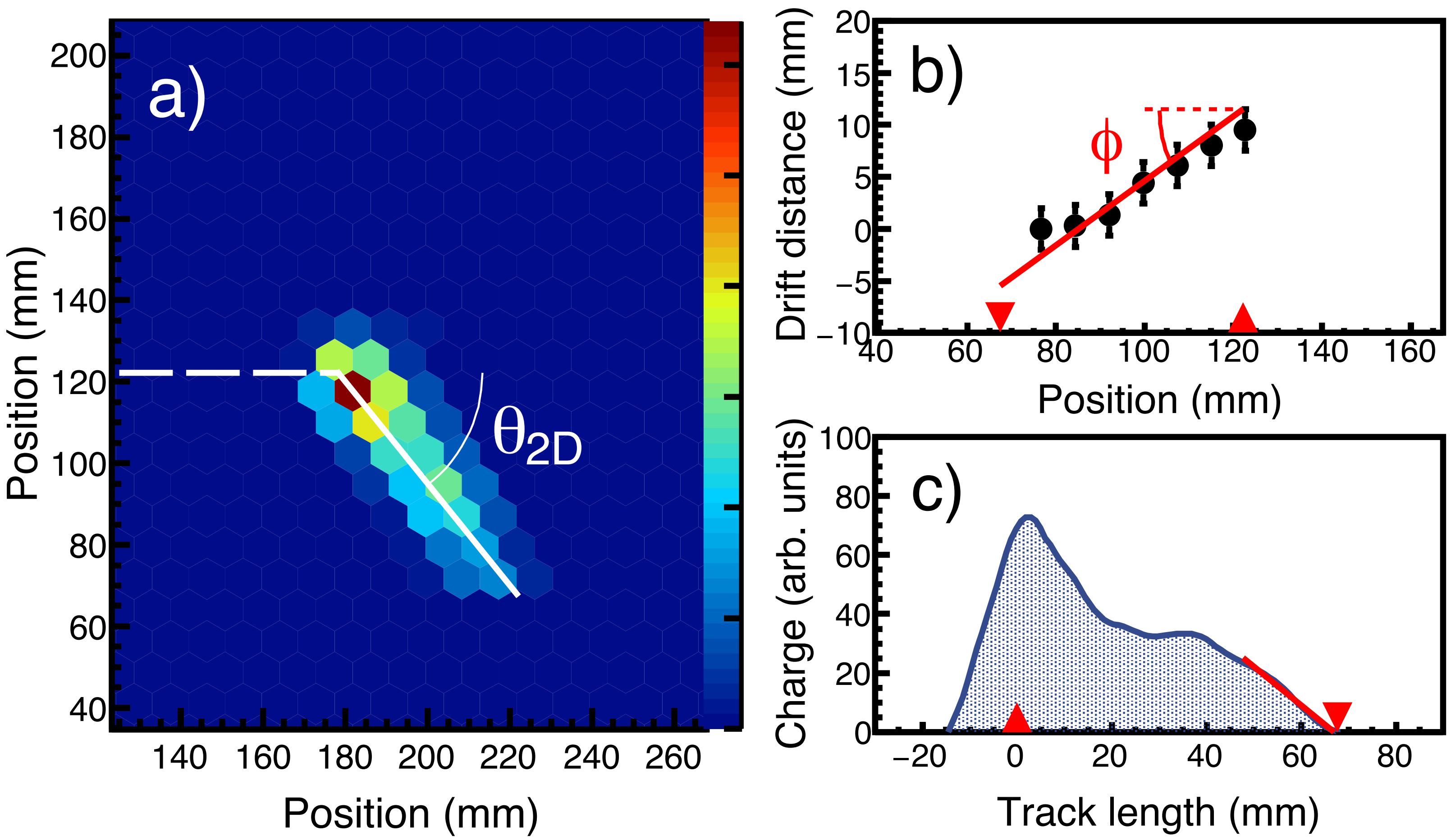
- We can see a similar behaviour in the He chain, driven by neutron pairing.
- If the H chain follows a similar pattern, ^{7}H would be the *least unbound* of the chain.

A new attempt with a (classic) active target

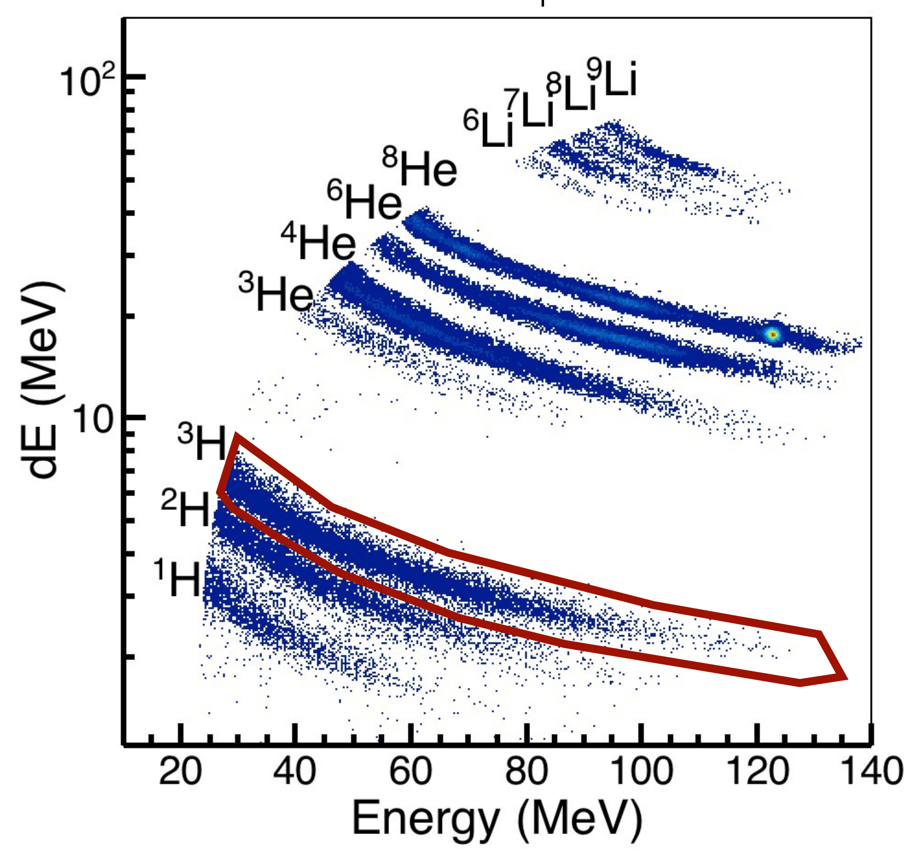


^{19}F (^{8}He,^{7}H) ^{20}*Ne* , ^{12}C (^{8}He,^{7}H) ^{13}*N* at 15.4 AMeV E620S @ GANIL

Target-like recoil analysis with MAYA and event selection



Si - CsI telescope:

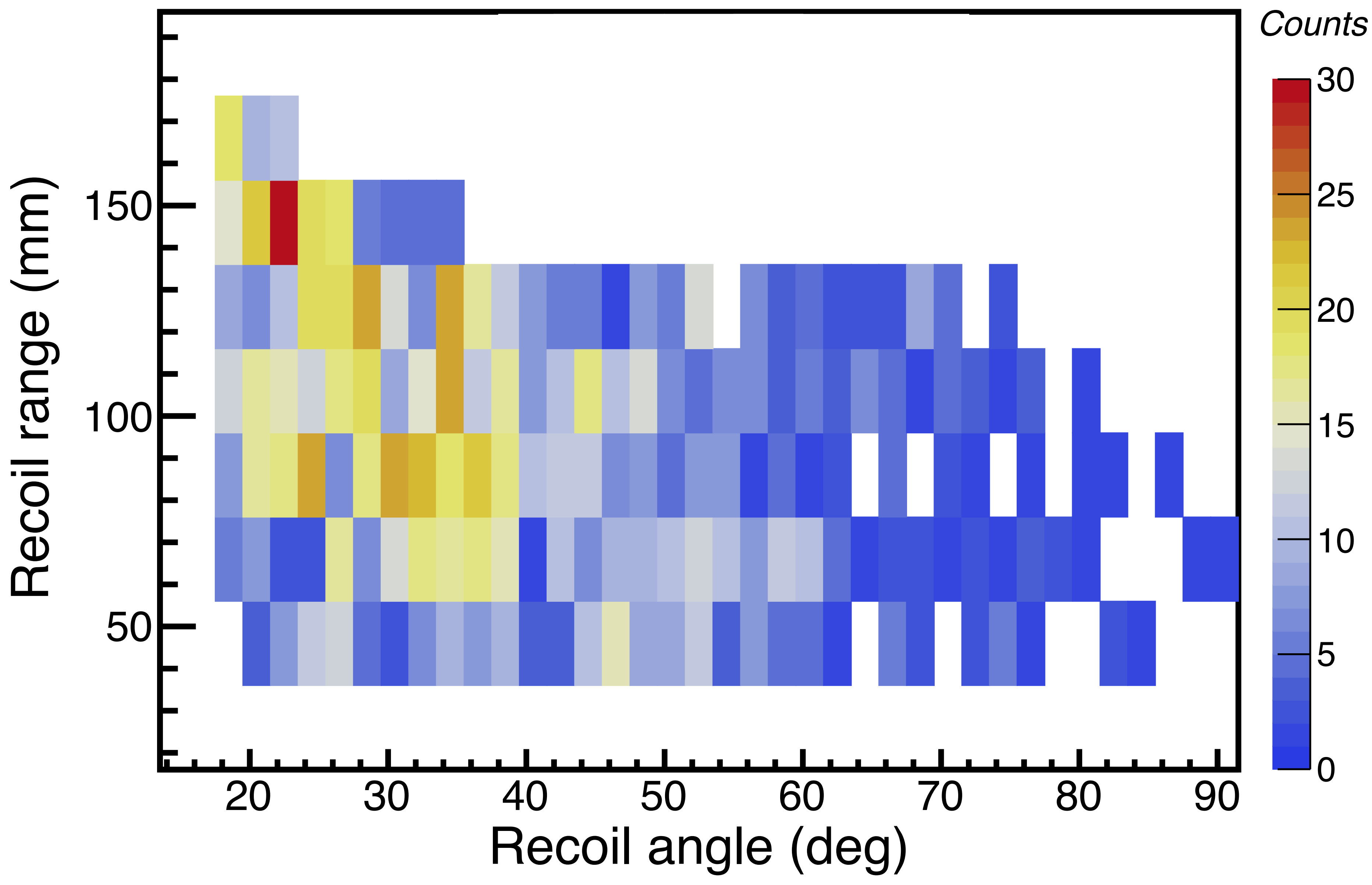


Observables: - **Range** (σ_R~20 mm)
- **Angle** (σ_θ~1.5 deg)
- Reaction plane (σ_Φ~1. deg)
- Charge deposited (σ_Q~30%)

Reconstructed track + Scattered ^{3}H

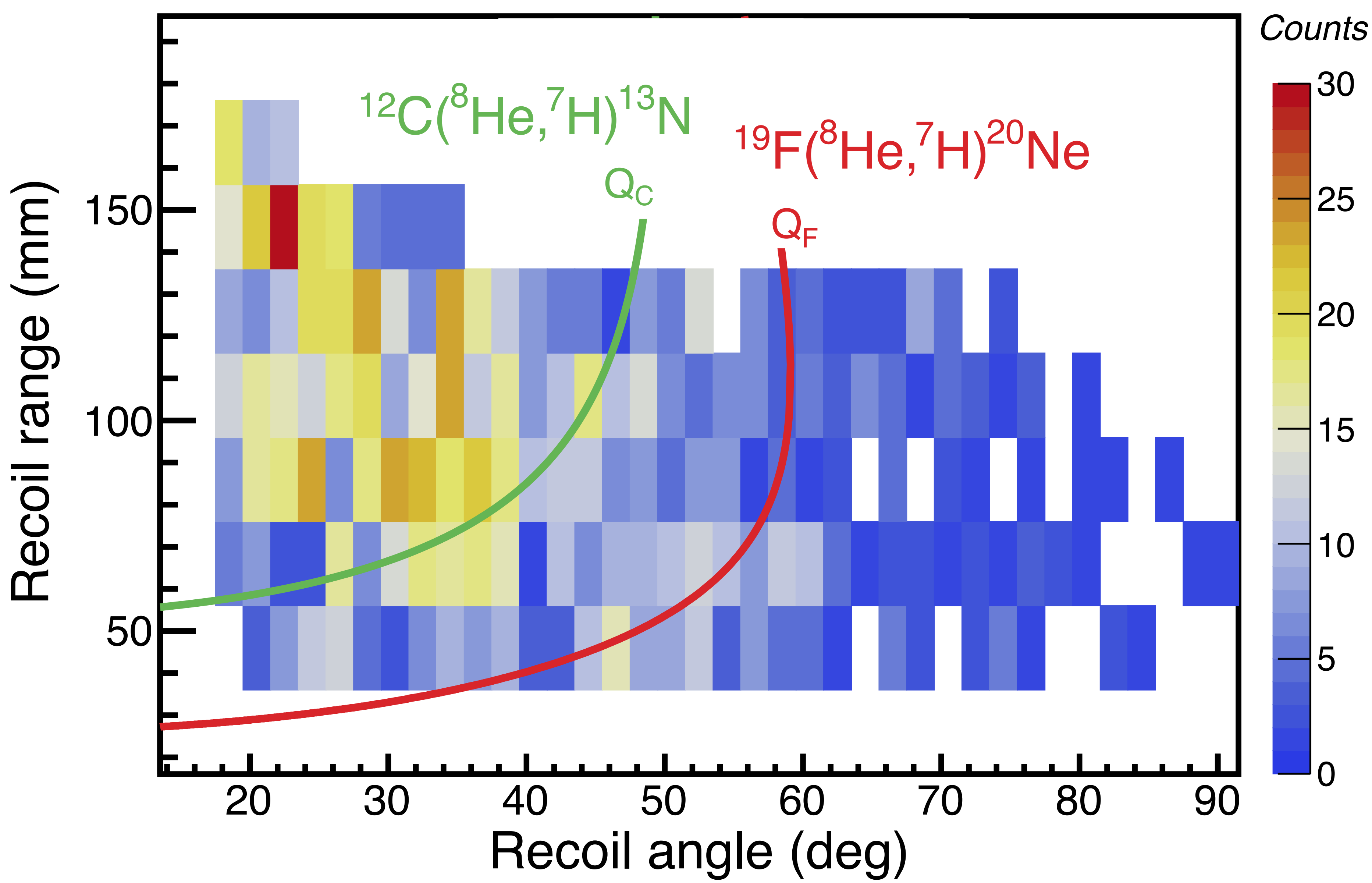
Selects binary-like reactions with a **heavy recoil** (Z>4) and a **^{X}H scattered**.
Other channels are strongly suppressed.

Range - Angle matrix and kinematics



No isotopic identification on the recoil: we must rely on the **Range**
An excess of counts appear along the kinematic line of the one-proton transfer

Range - Angle matrix and kinematics

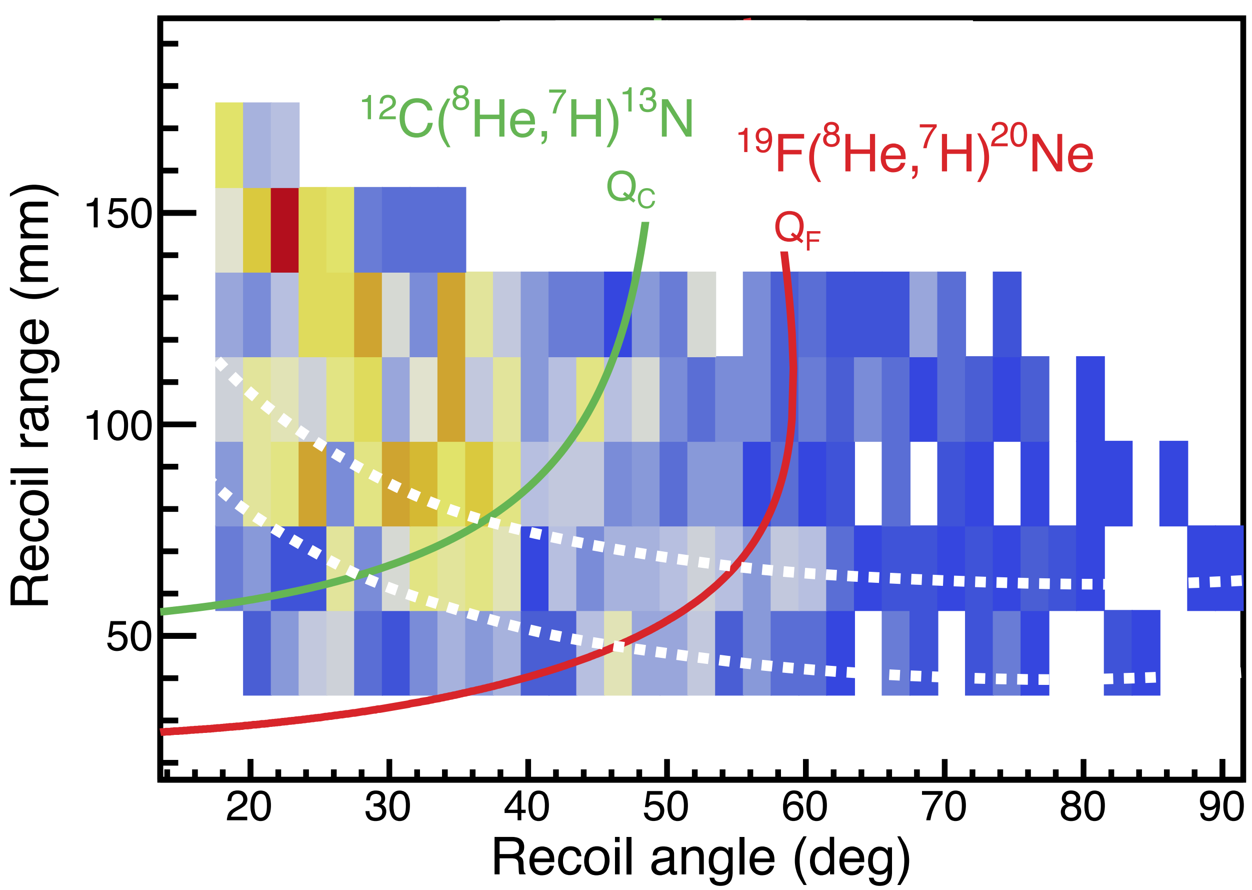


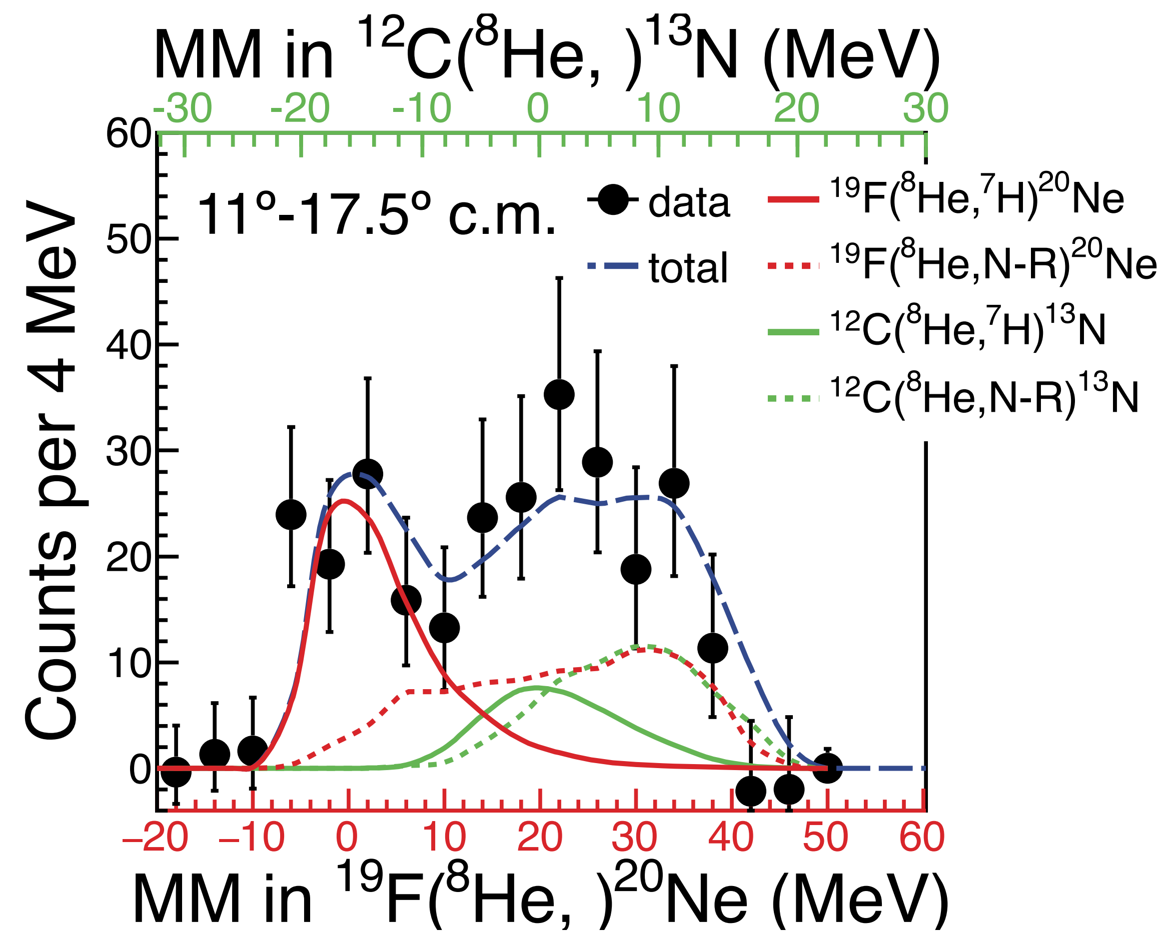
No isotopic identification on the recoil: we must rely on the **Range**

An excess of counts appear along the kinematic line of the one-proton transfer

Simulation and fitting

We produce a simulation with the experimental resolution and constraints applied to the production of the different phase-space components and the resonance

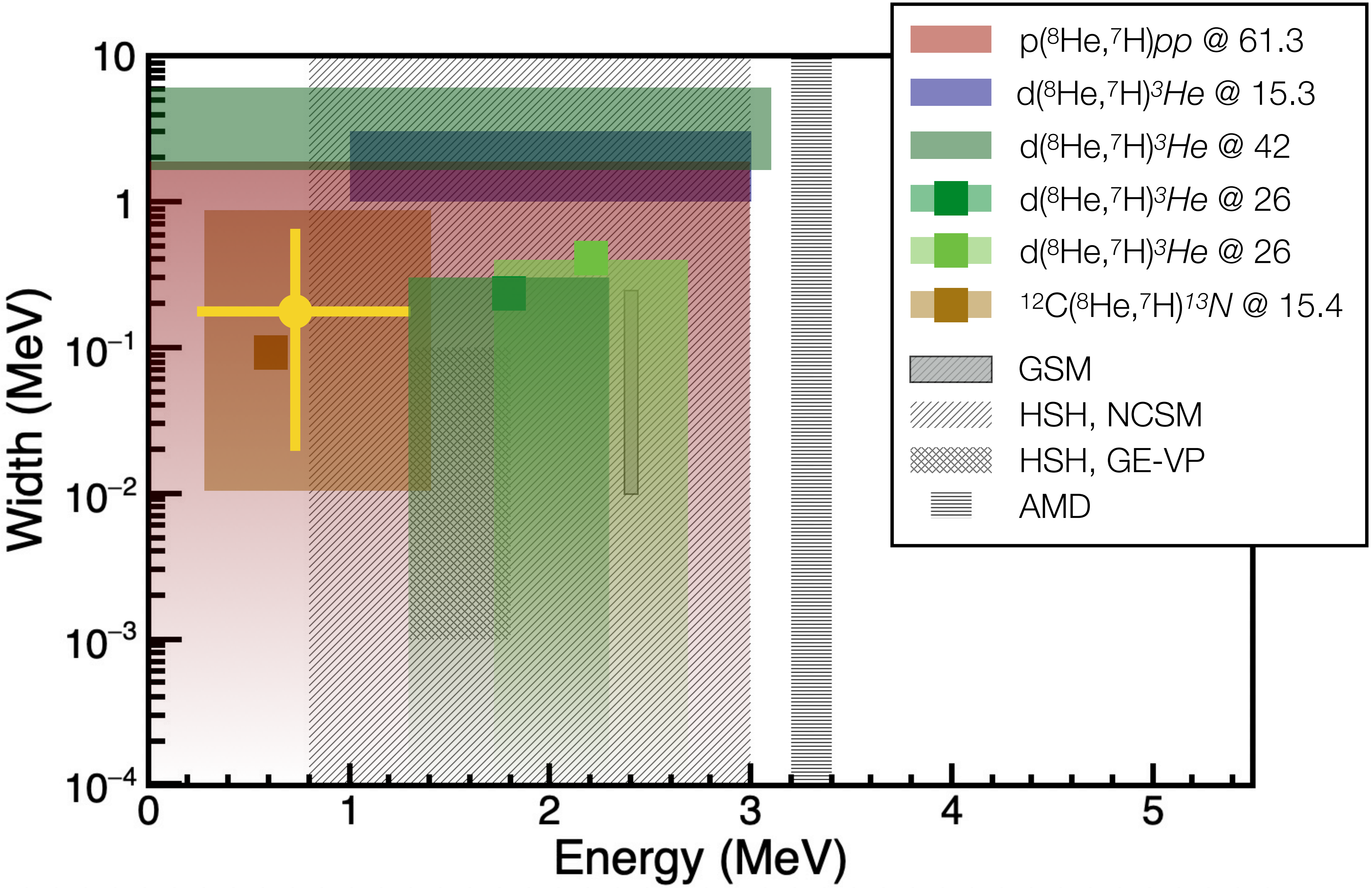




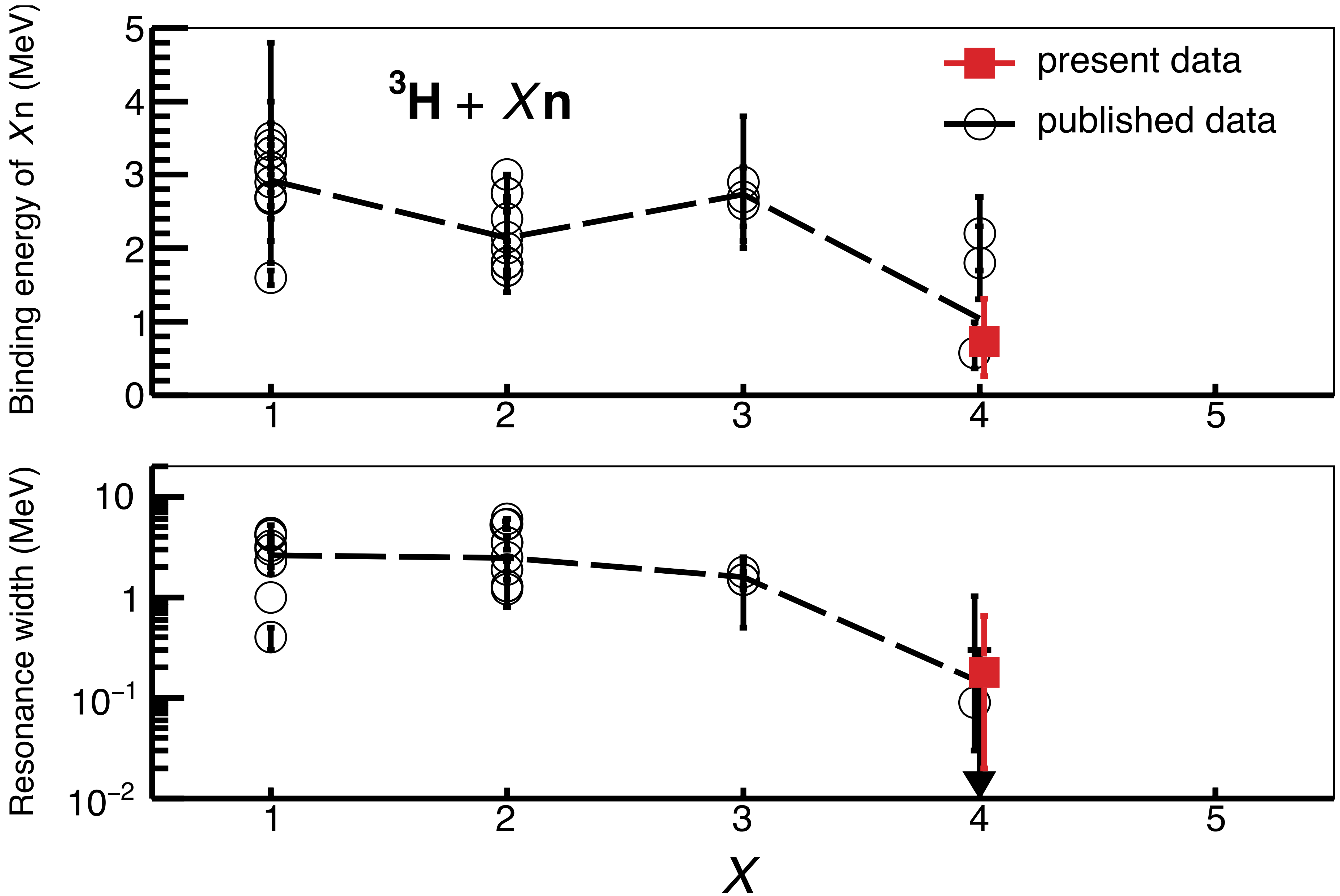
$\mathbf{E_{7H}} = 0.73\ ^{+0.58}_{-0.47}$ MeV $\quad$ $\mathbf{\Gamma_{7H}} = 0.18\ ^{+0.47}_{-0.16}$ MeV

The results depict a low-lying, almost bound resonance with a relatively long half-life

In context:


p(⁸He,⁷H)pp @ 61.3
d(⁸He,⁷H)³He @ 15.3
d(⁸He,⁷H)³He @ 42
d(⁸He,⁷H)³He @ 26
d(⁸He,⁷H)³He @ 26
¹²C(⁸He,⁷H)¹³N @ 15.4
GSM
HSH, NCSM
HSH, GE-VP
AMD
Width (MeV)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
1
2
3
4
5
Energy (MeV)

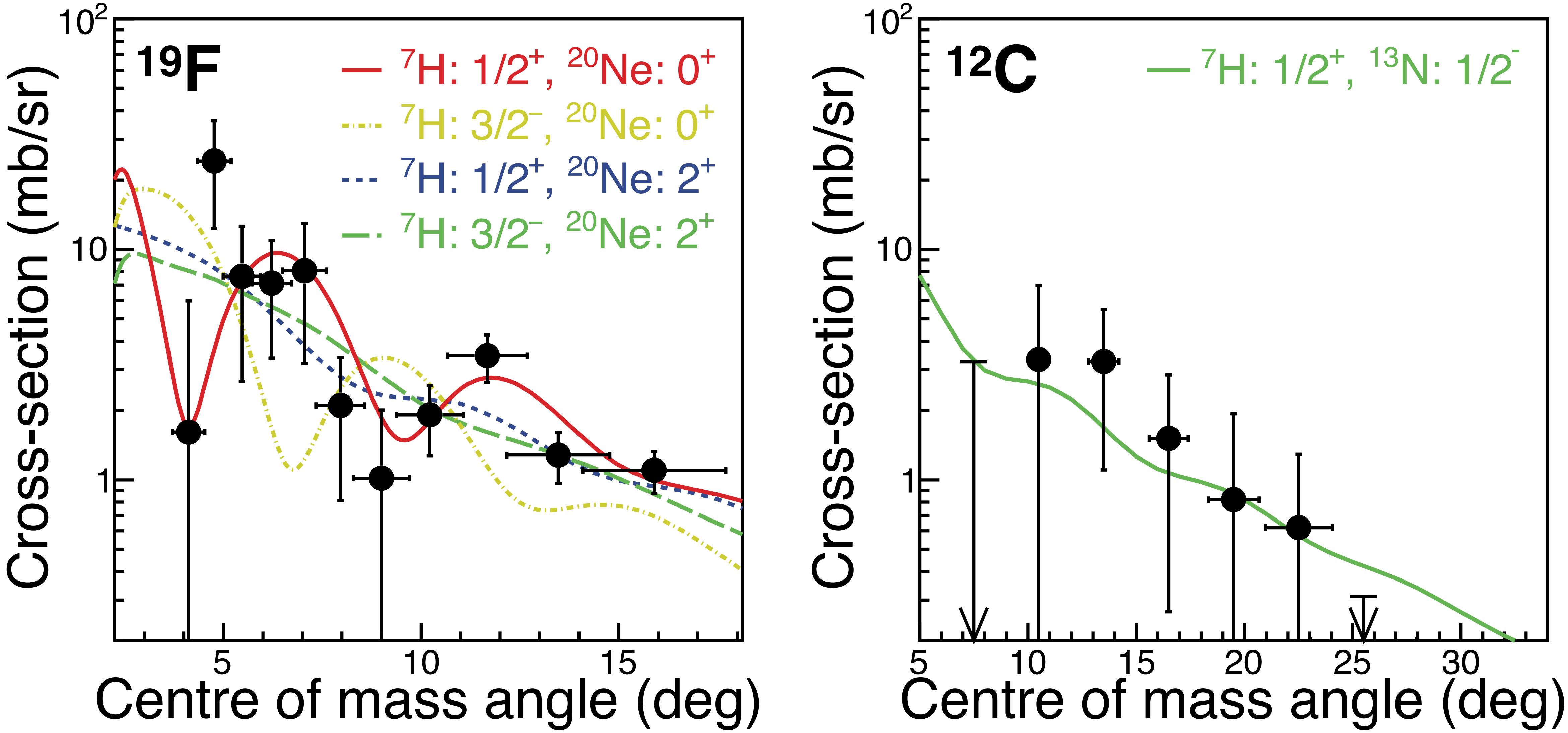
The basic properties of ^7H are confirmed



- The **lowest binding energy** of the chain: possible **4n decay** directly to ^3H+4n
- The **smallest width**: longest-lived of the chain

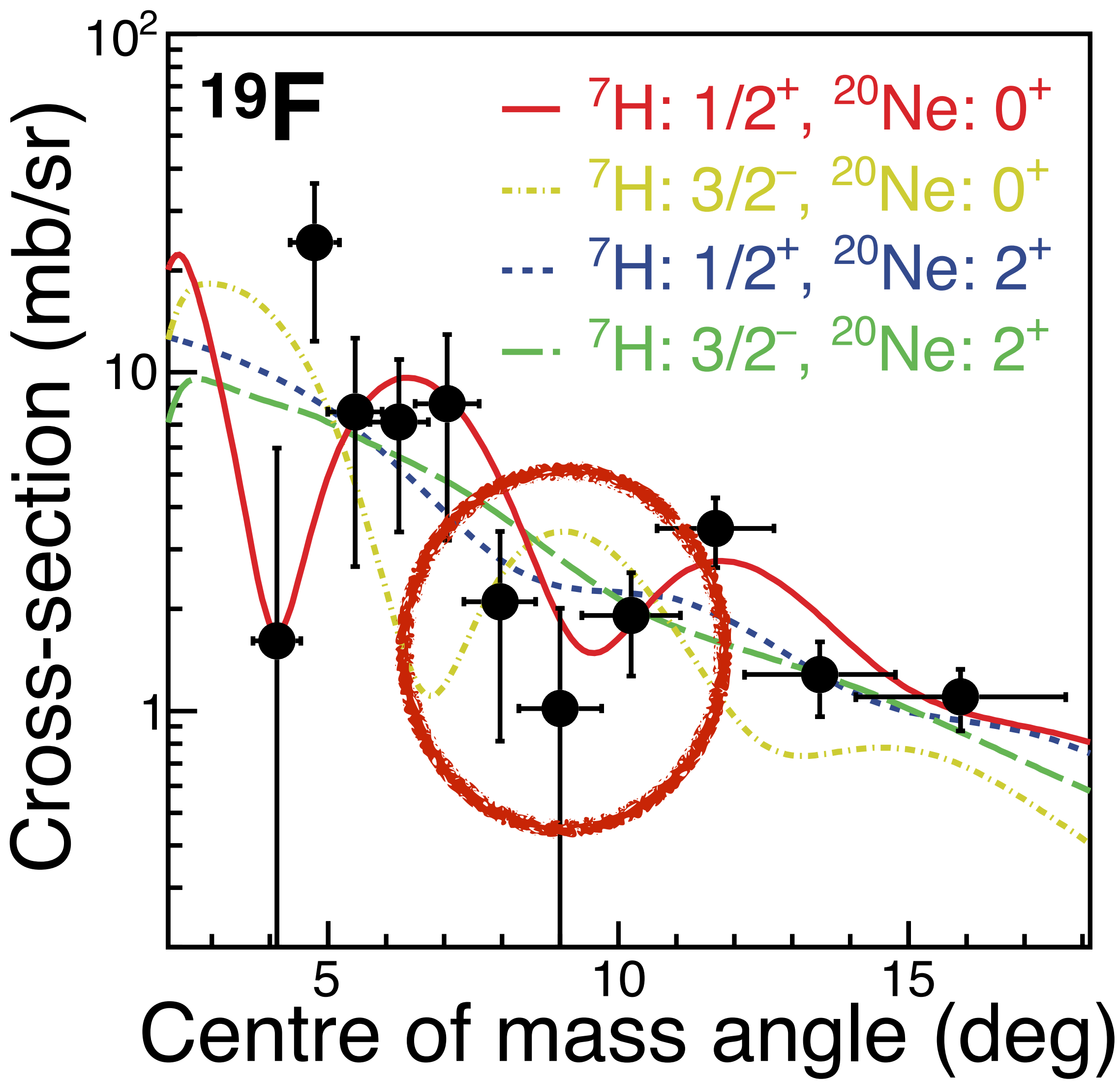
We also have the angular distribution

calculations by
A. Moro (U. Sevilla)
N. Itagaki (U. Kyoto)



- The channel with ^{19}F displays an oscillation pattern, suggesting the formation of a well-defined system.
- Calculations with FRESCO and AMD wave functions with a **$1/2^{+}$ state** reproduce the features of the measured cross section. But they need to be scaled by a factor ~8.

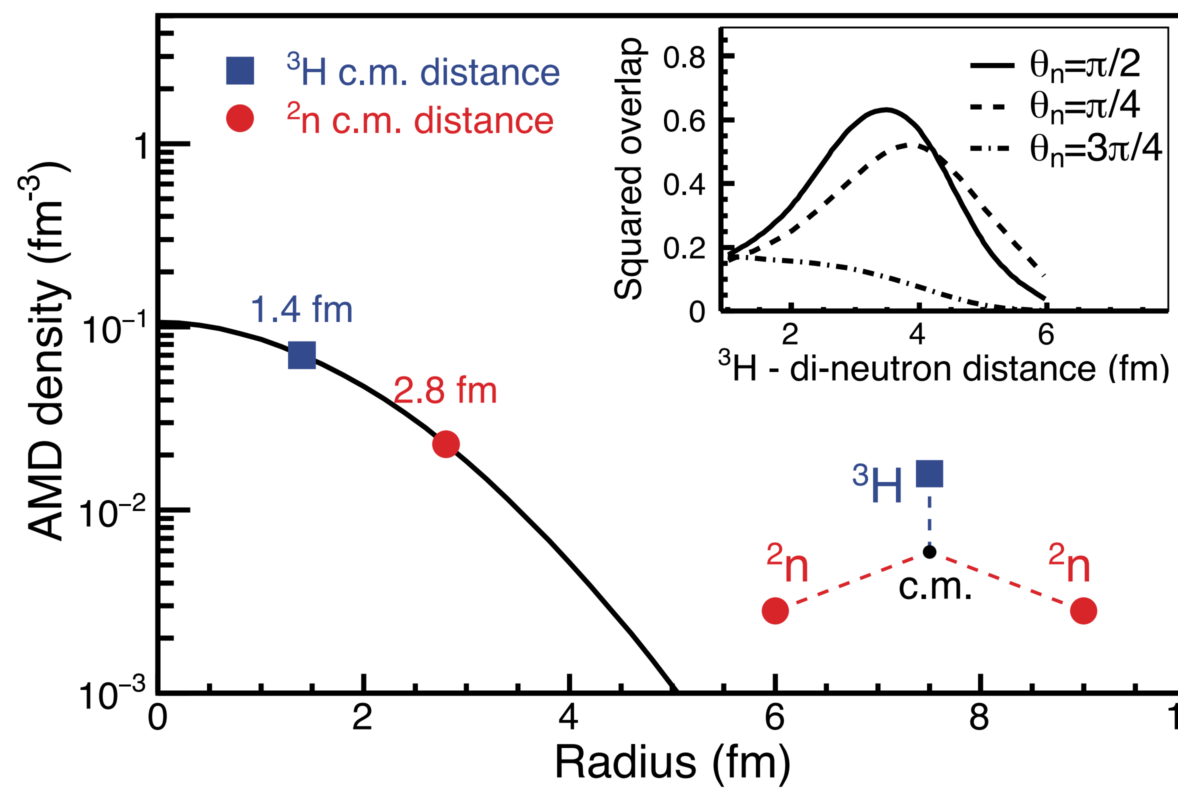
We also have the angular distribution



calculations by

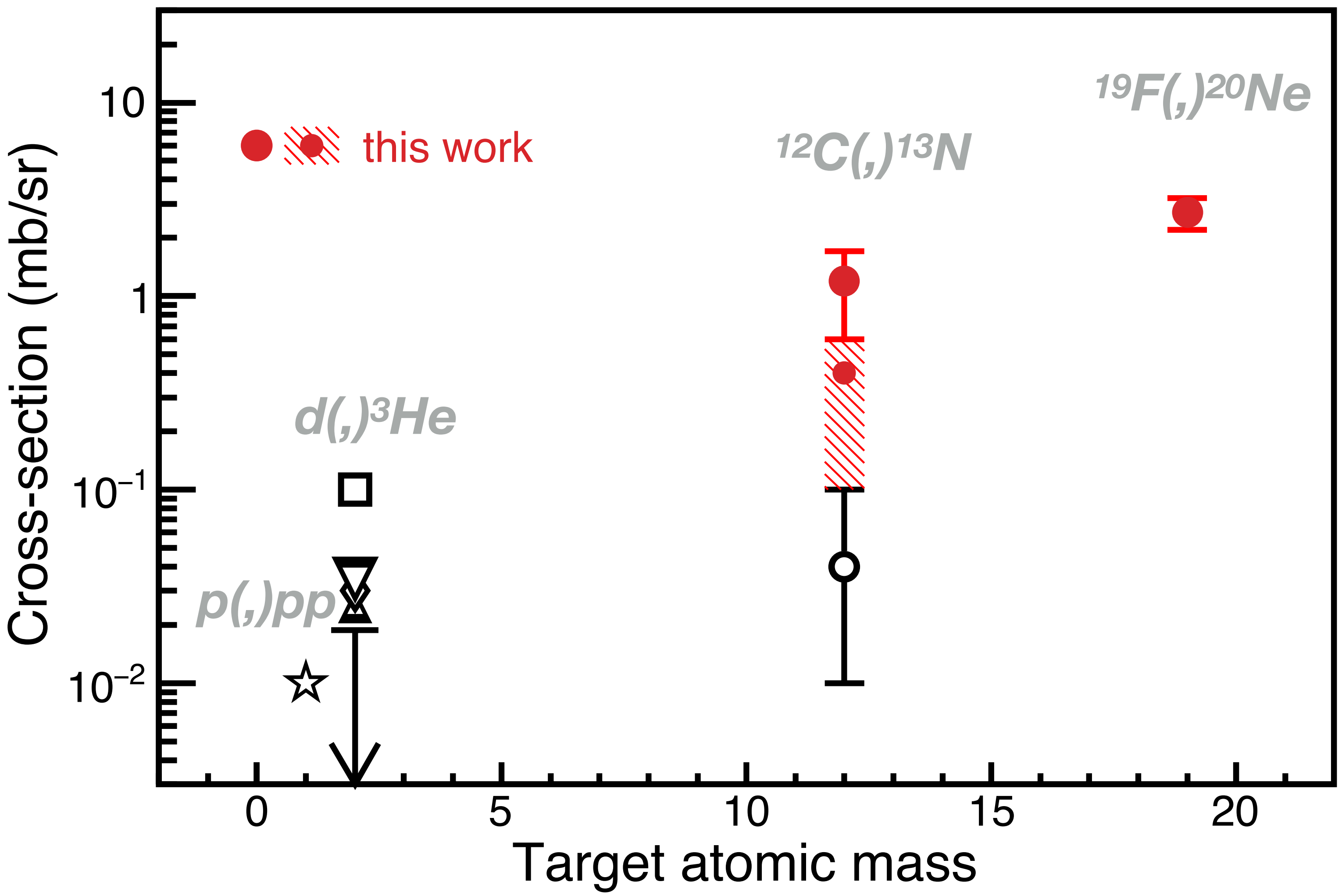
N. Itagaki (U. Kyoto)

PRC 80, 021304(R) (09)



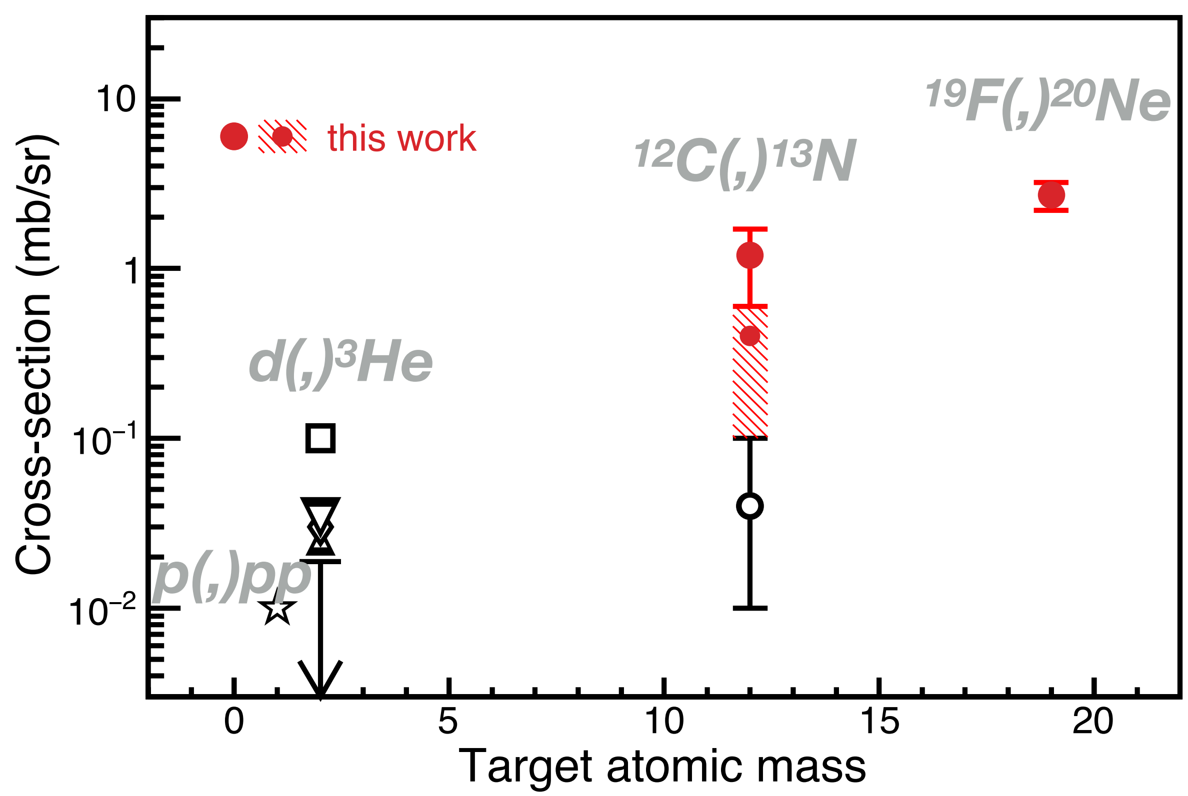
- The slight displacement towards lower angles in c.m. suggests that the size of the resonance might be larger than the predictions by AMD

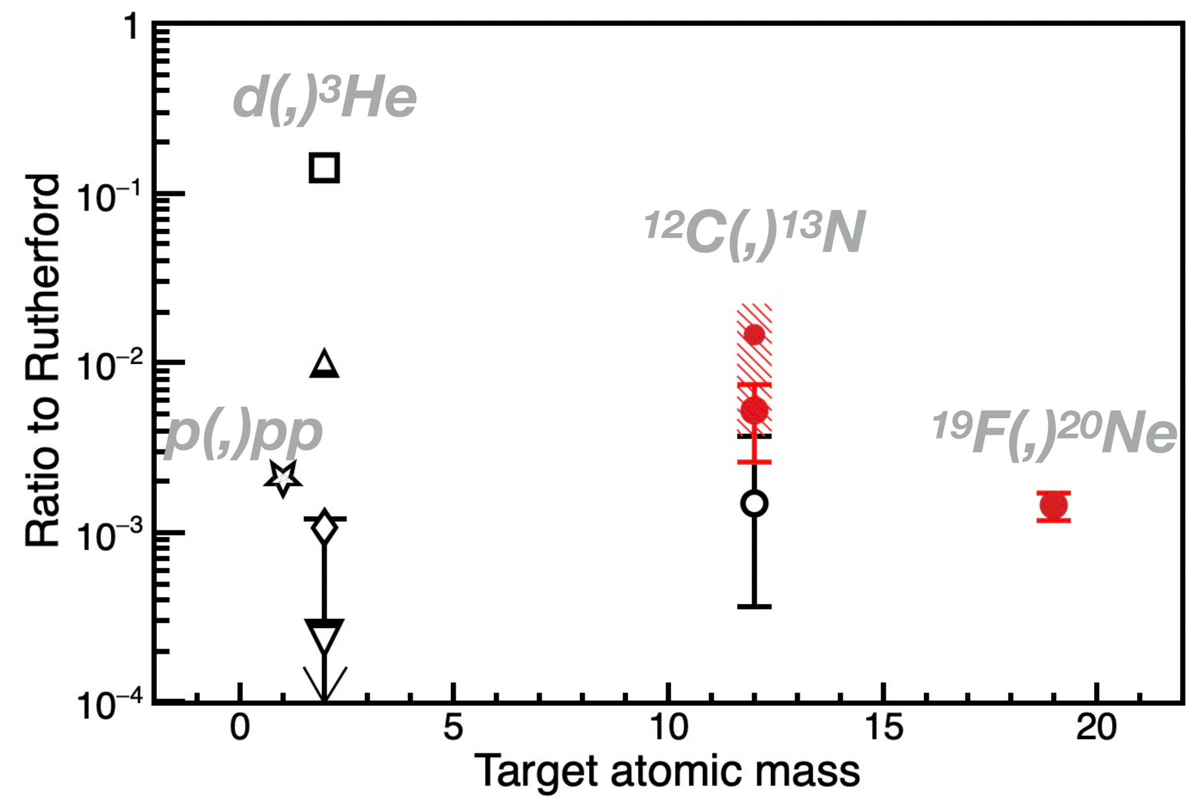
However…



- There is a huge discrepancy between our diff. cross-sections and previous data.
- Although the different experiments cover different angular regions, energies, targets, etc, there seems to be a dependence on the target size.

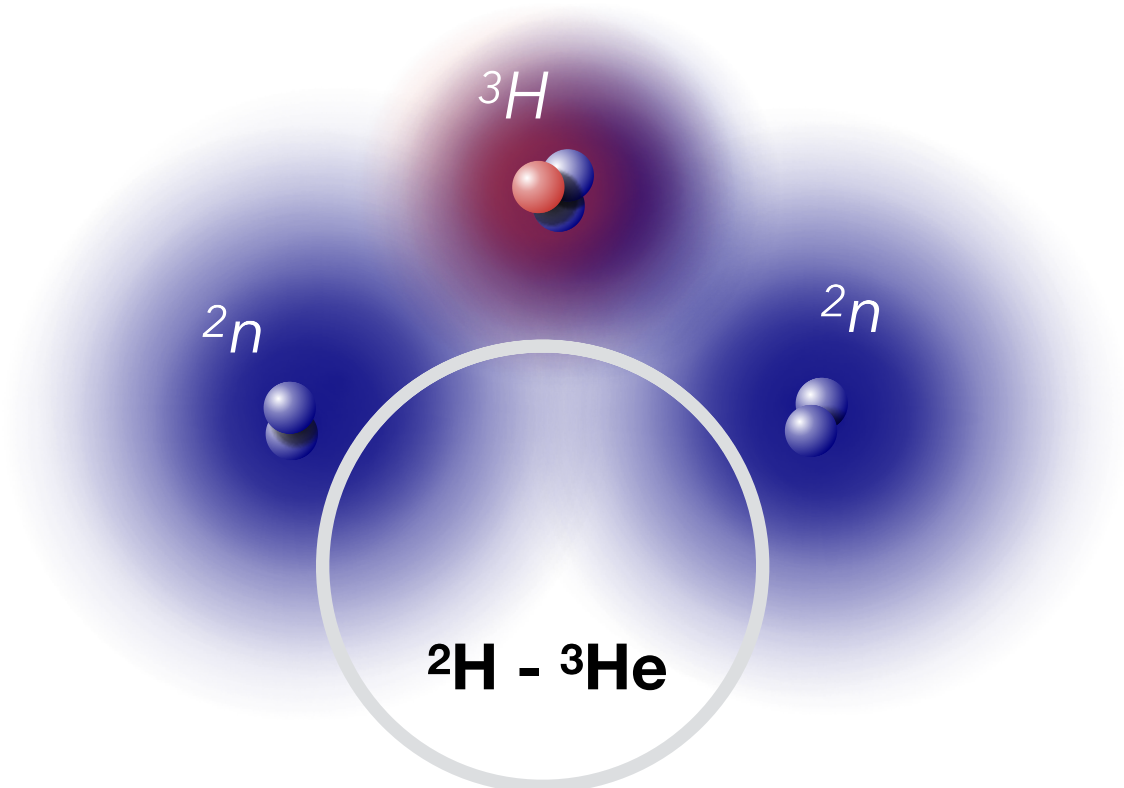
Influence of the target?

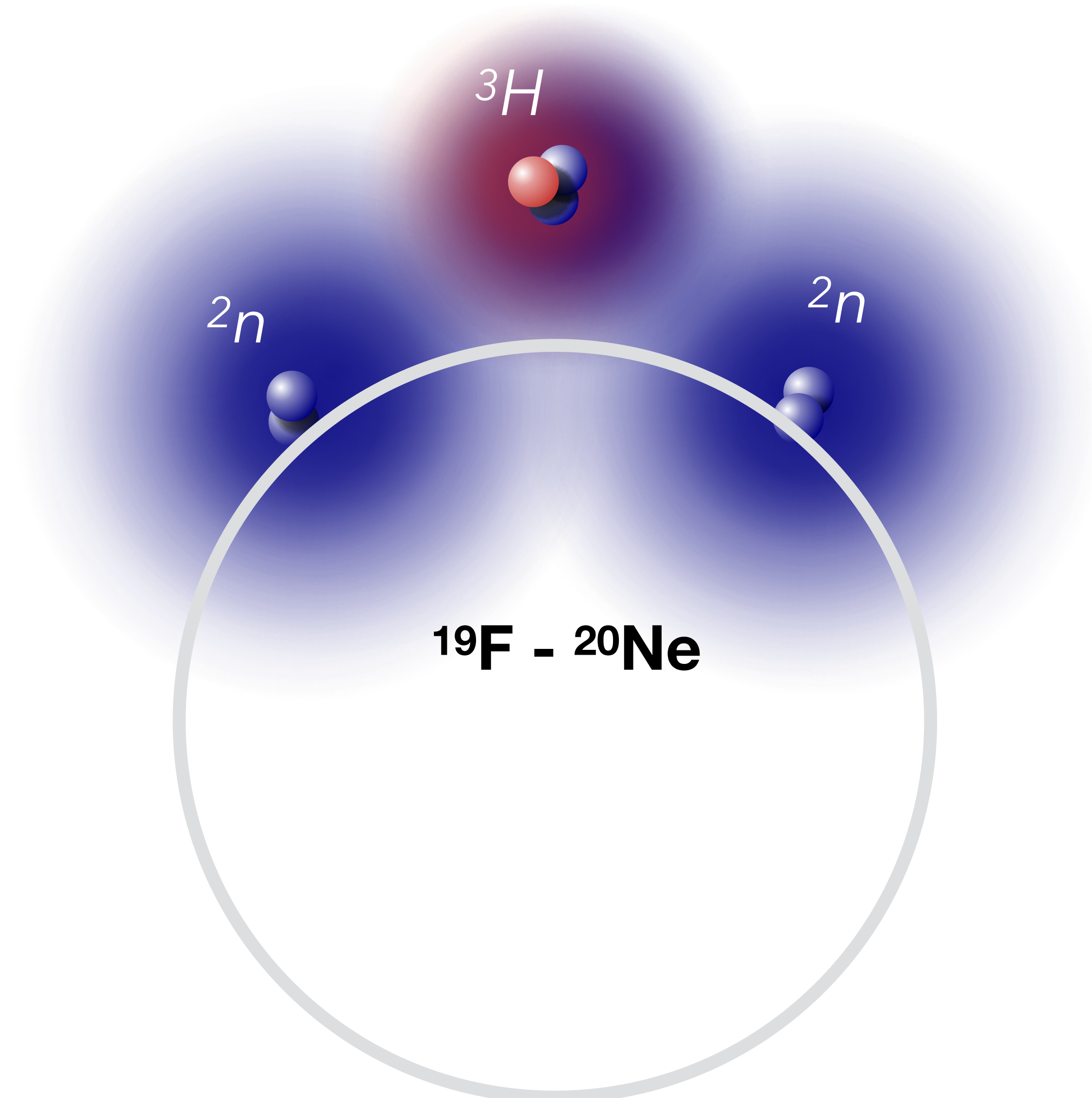




- Weighting each result by its Rutherford cross-section, the dependence on the target mass flattens, but we also see a huge dispersion on the d(,)^{3}He data.

“*In-medium*” effects?

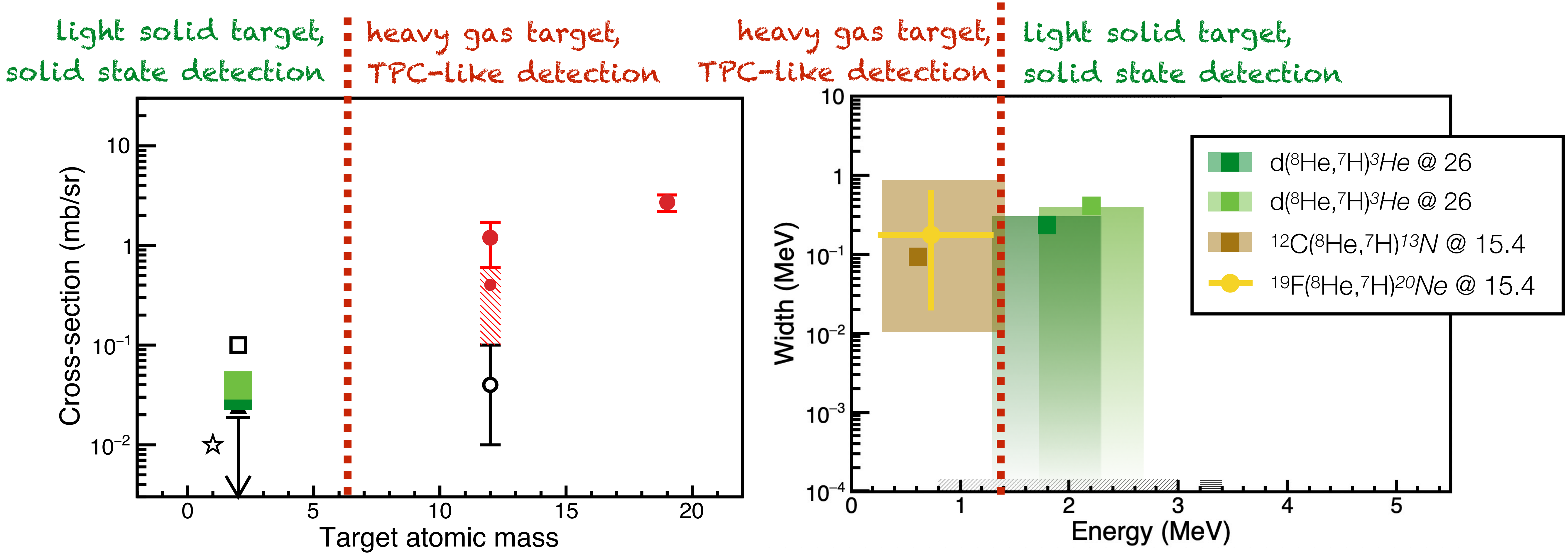




- The overlap between the target and the outer neutrons is much more pronounced in the case of “heavy” targets. Can this help the formation of the resonance?

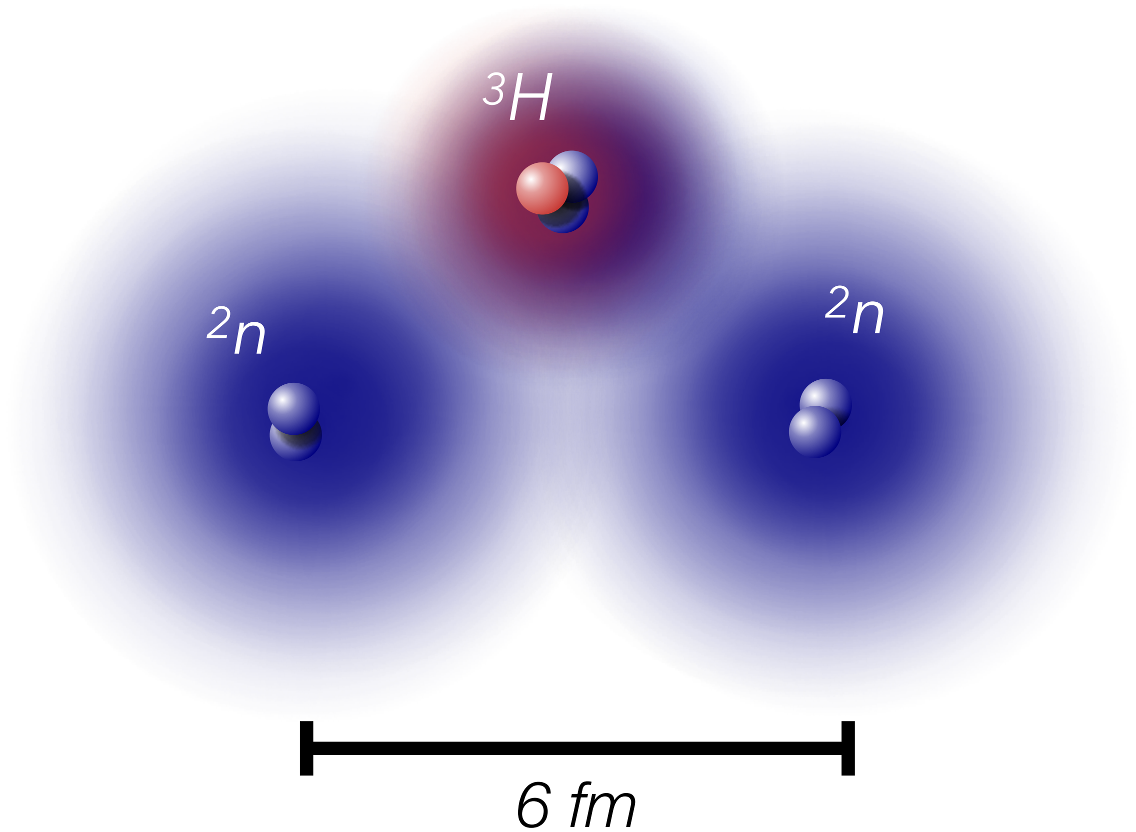
Experimental bias?

A *virtual* resonance?



- The heavy-target channels seem to give higher cross-sections and smaller ^{7}H mass.
- But, coincidentally, they are measured with the same experimental technique.
- —> *cross-technique measurement?*

A *possible* picture of the **most exotic system** of the nuclear chart



- We have an **almost bound**, low-lying system, probably the least unbound of the whole chain
- With the **longest half-life** of the H resonances (?)
- With a unique **4n decay** (probably in the form of $2n^2$ "pseudo-Borromean")
- Built on a **1/2^{+} ^{3}H core** and with an extended **4n halo**
- Theory suggests a dilute di-neutron boson condensate, with a size of ~6 fm

S. Aoyama, N. Itagaki PRC 80, 021304(R) (09)

M. Caamaño [a,*], T. Roger [b], A.M. Moro [c], G.F. Grinyer [b,1], J. Pancin [b], S. Bagchi [d,2], S. Sambi [e], J. Gibelin [f], B. Fernández–Domínguez [a], N. Itagaki [g], J. Benlliure [a], D. Cortina–Gil [a], F. Farget [b,3], B. Jacquot [b], D. Pérez–Loureiro [b,4], B. Pietras [a], R. Raabe [e], D. Ramos [a,5], C. Rodríguez Tajes [b], H. Savajols [b], M. Vandebrouck [h,6]

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[c] *Universidad de Sevilla, E–41080 Sevilla, Spain*
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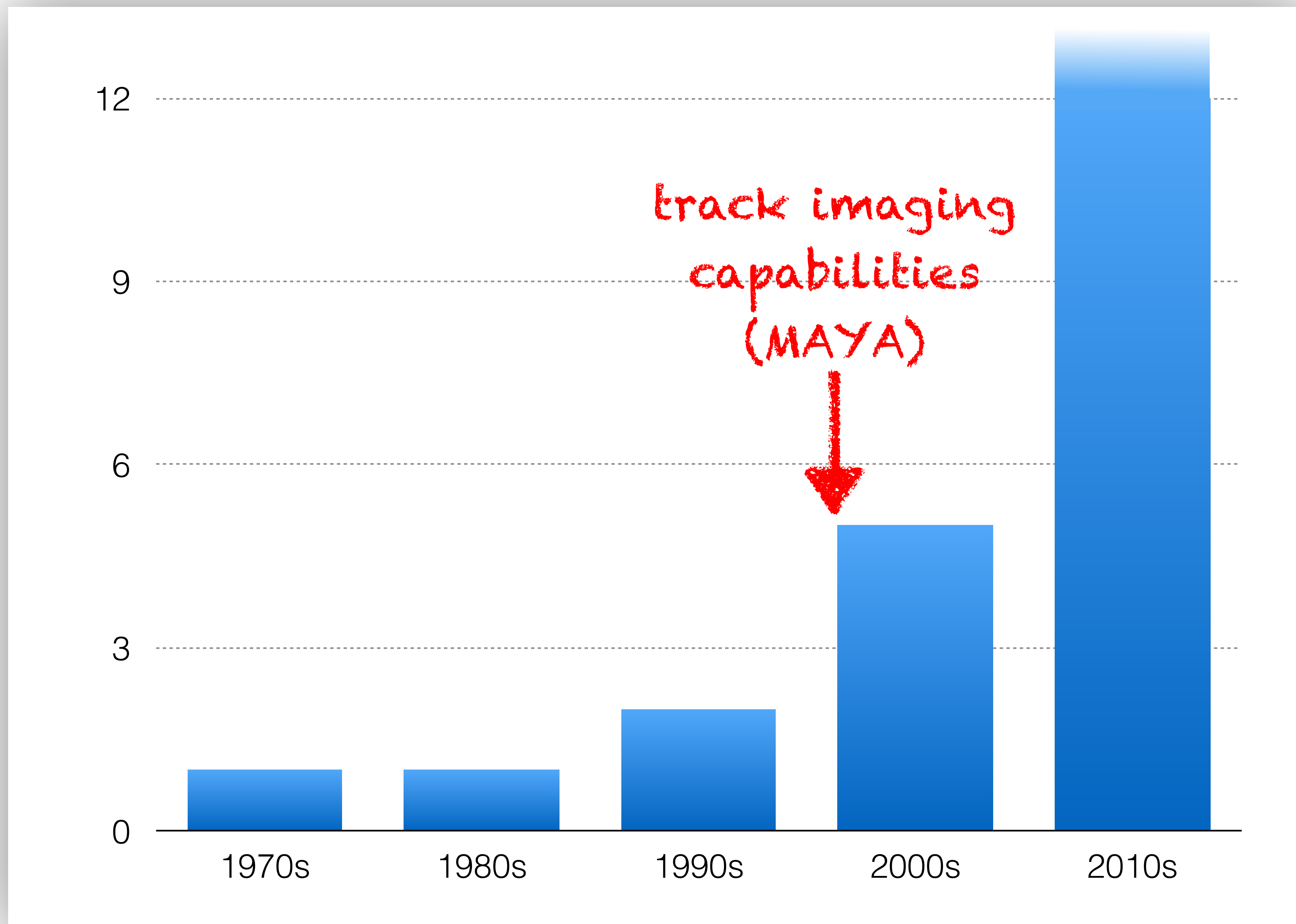
[f] *LPC Caen, Université de Caen Basse–Normandie–ENSICAEN–CNRS/IN2P3, F–14050 Caen Cedex, France*
[g] *Yukawa Institute for Theoretical Physics, Kyoto University, Kitashirakawa Oiwake–Cho, Kyoto 606–8502, Japan*
[h] *IPN Orsay, Université Paris Sud, IN2P3 – CNRS, F–91406 Orsay Cedex, France*

Ground-state properties of superheavy ^{7}H

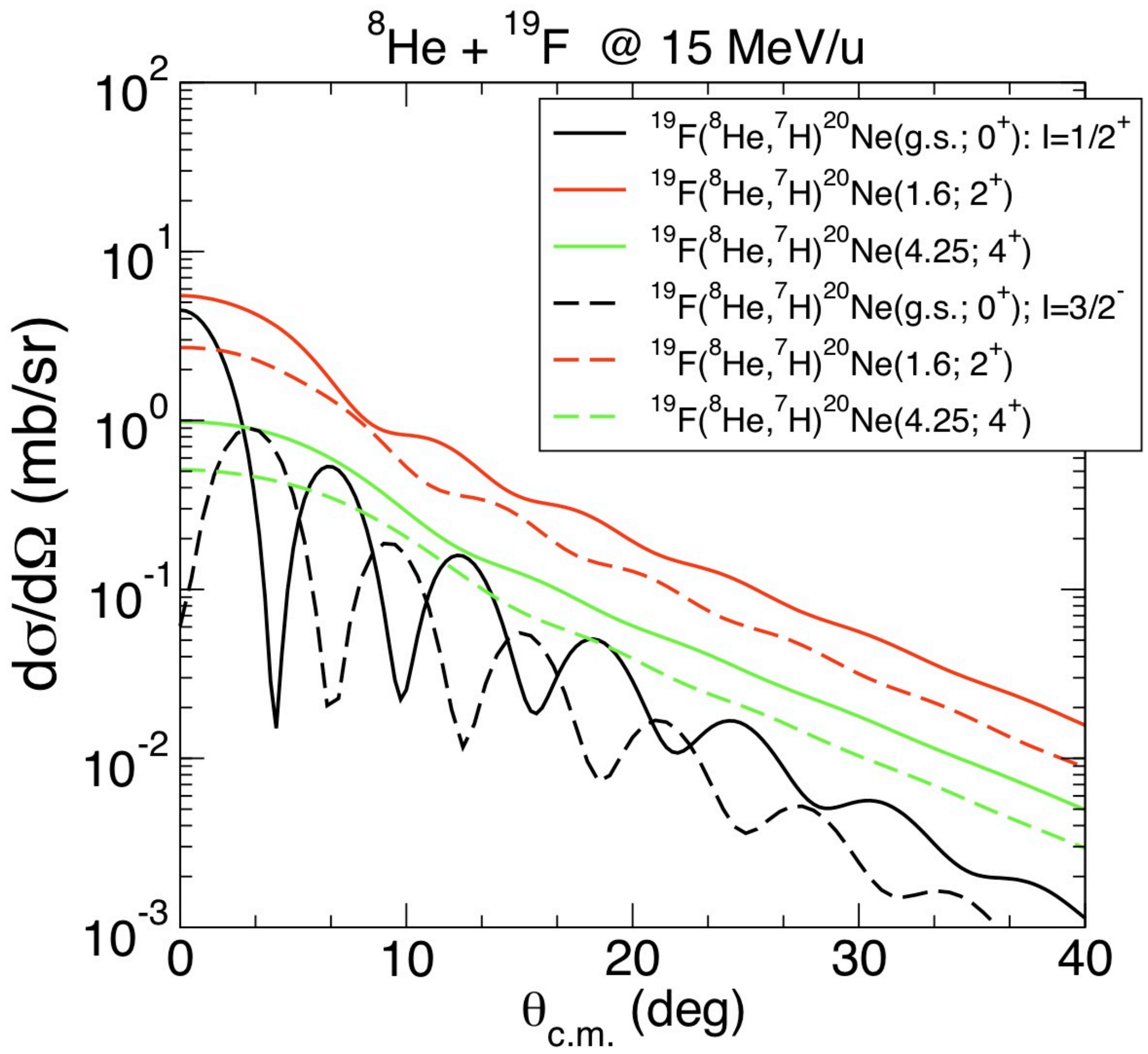
A new attempt with a (classic) active target



^{19}F (^{8}He,^{7}H) ^{20}Ne , ^{12}C (^{8}He,^{7}H) ^{13}N at 15.4 AMeV E620S @ GANIL

The missing channels

We don't see the population of the 1st or 2nd state in ^{20}Ne even though they are expected to be more probable



Simulation and fitting

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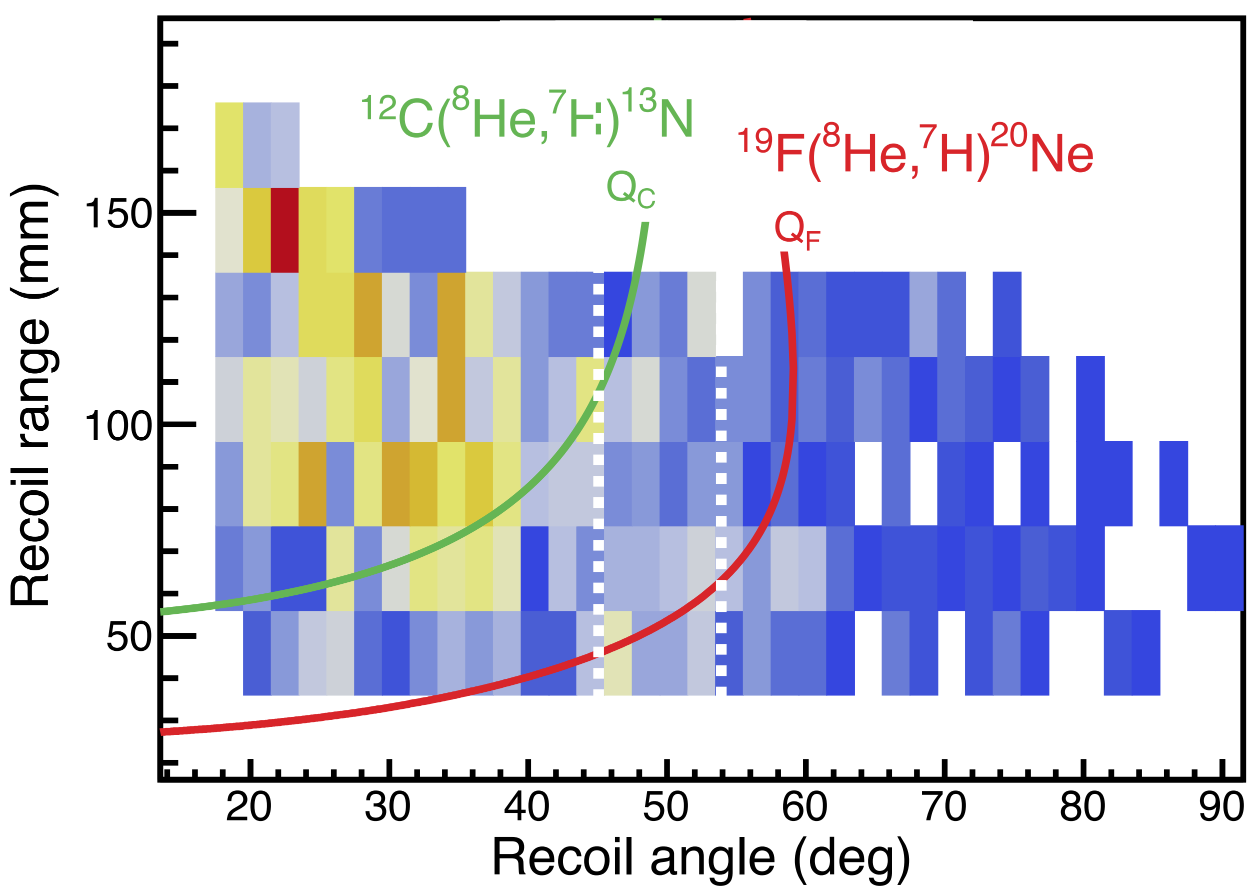
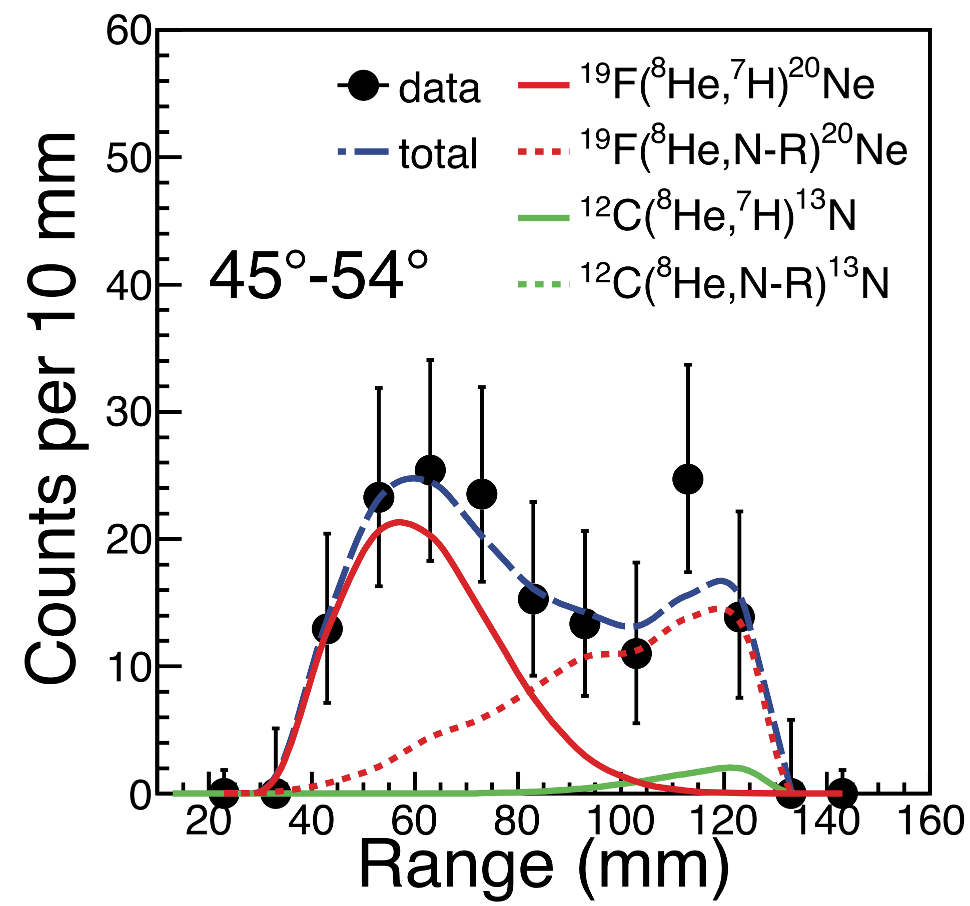


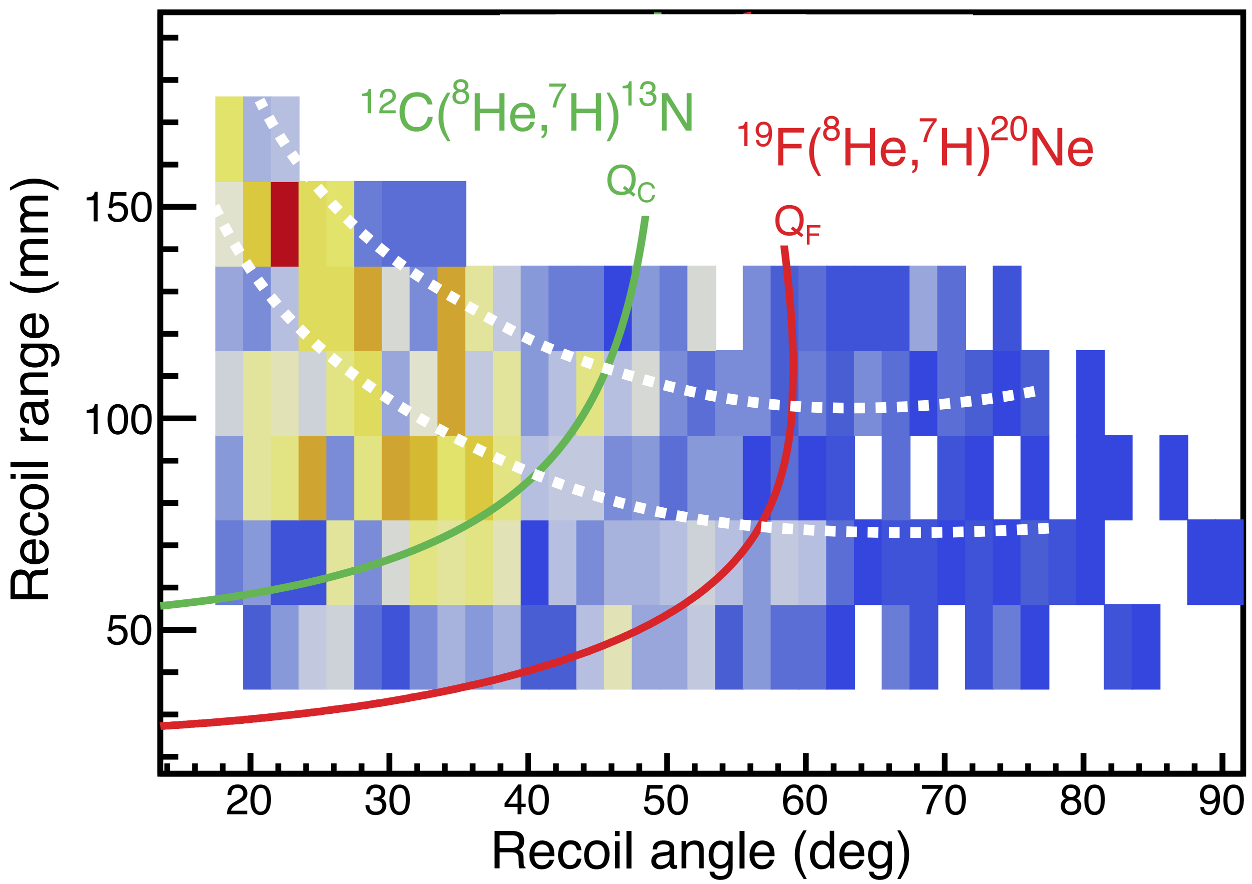


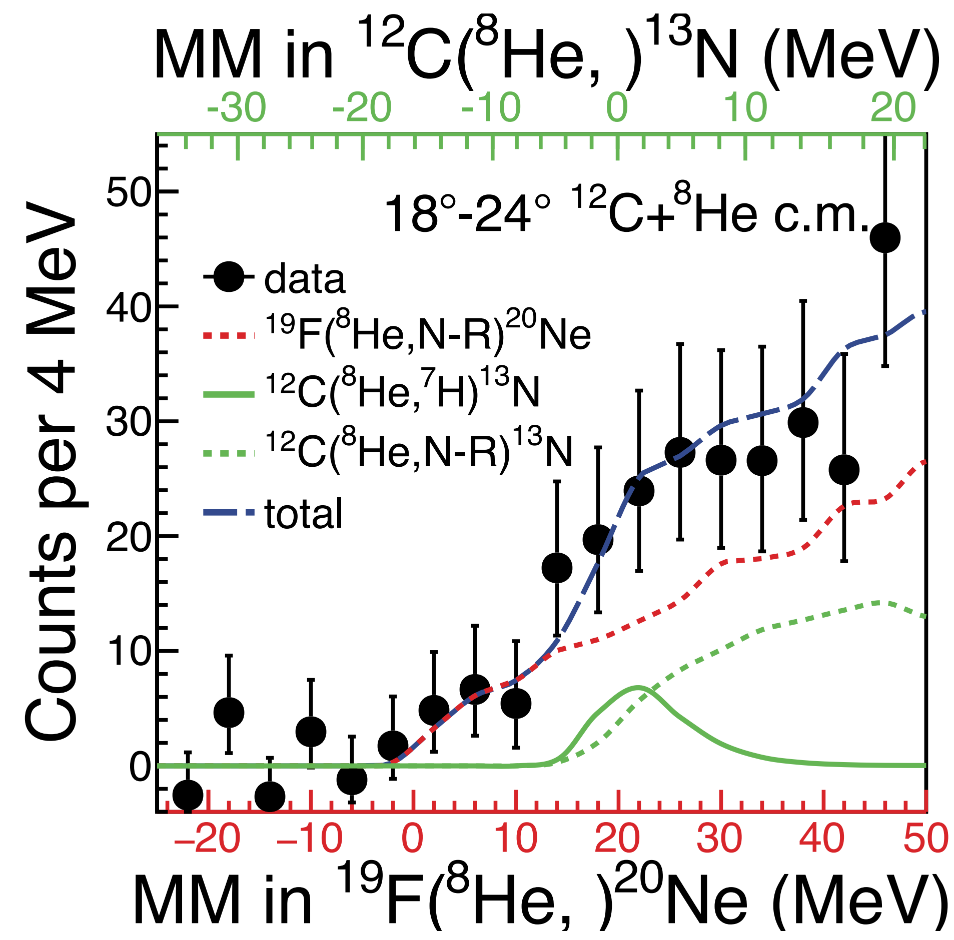
$\mathbf{E_{7H}} = 0.73^{+0.58}_{-0.47}$ MeV $\quad$ $\mathbf{\Gamma_{7H}} = 0.18^{+0.47}_{-0.16}$ MeV

The results depict a low-lying, almost bound resonance with a relatively long half-life

Some checks

The measurement of the scattered light product imposes some limits on binary reactions:

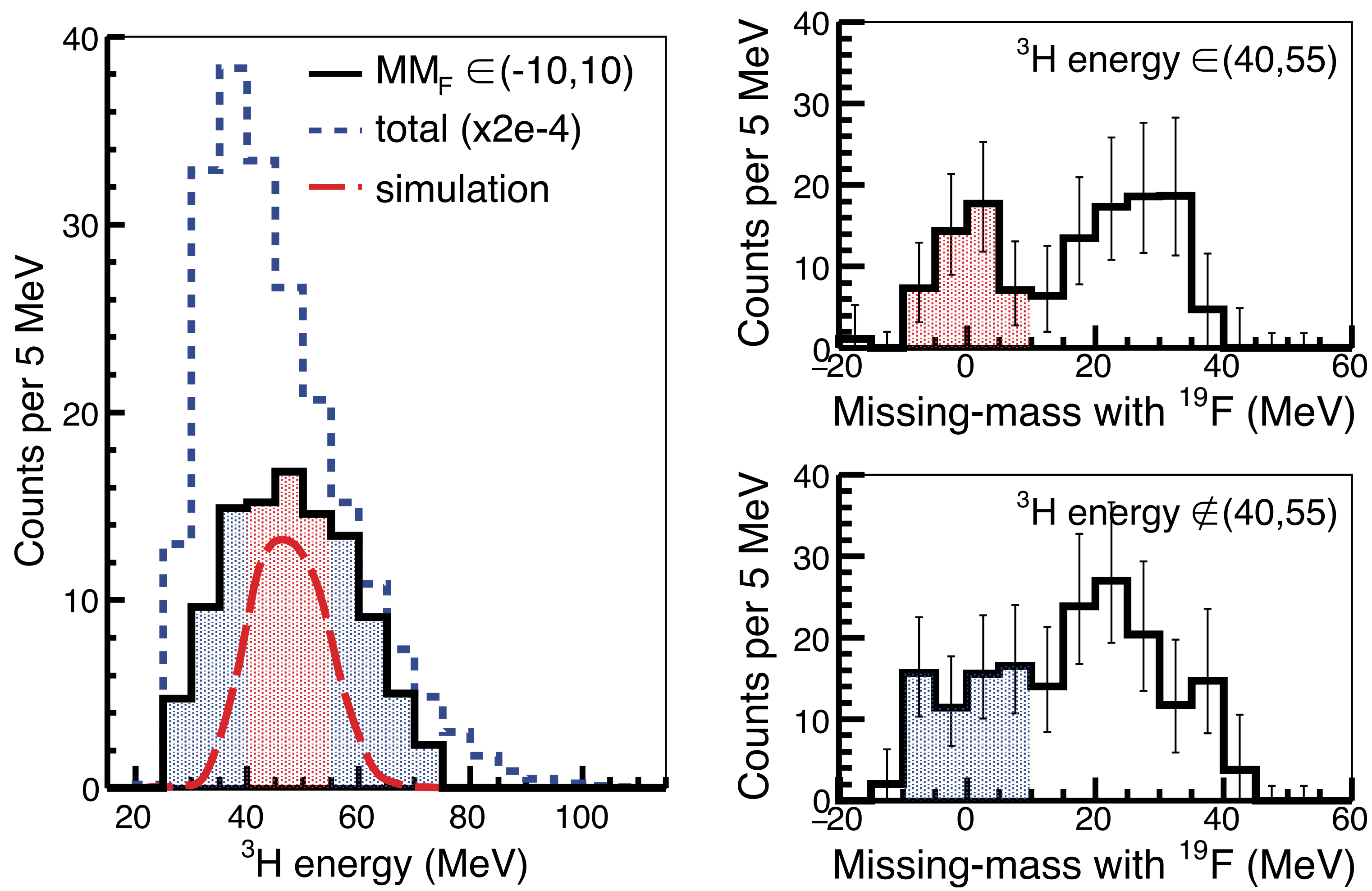




The ^{7}H peak from ^{19}F disappears beyond its kinematic limit, whereas the phase space and the ^{12}C channels are still there.

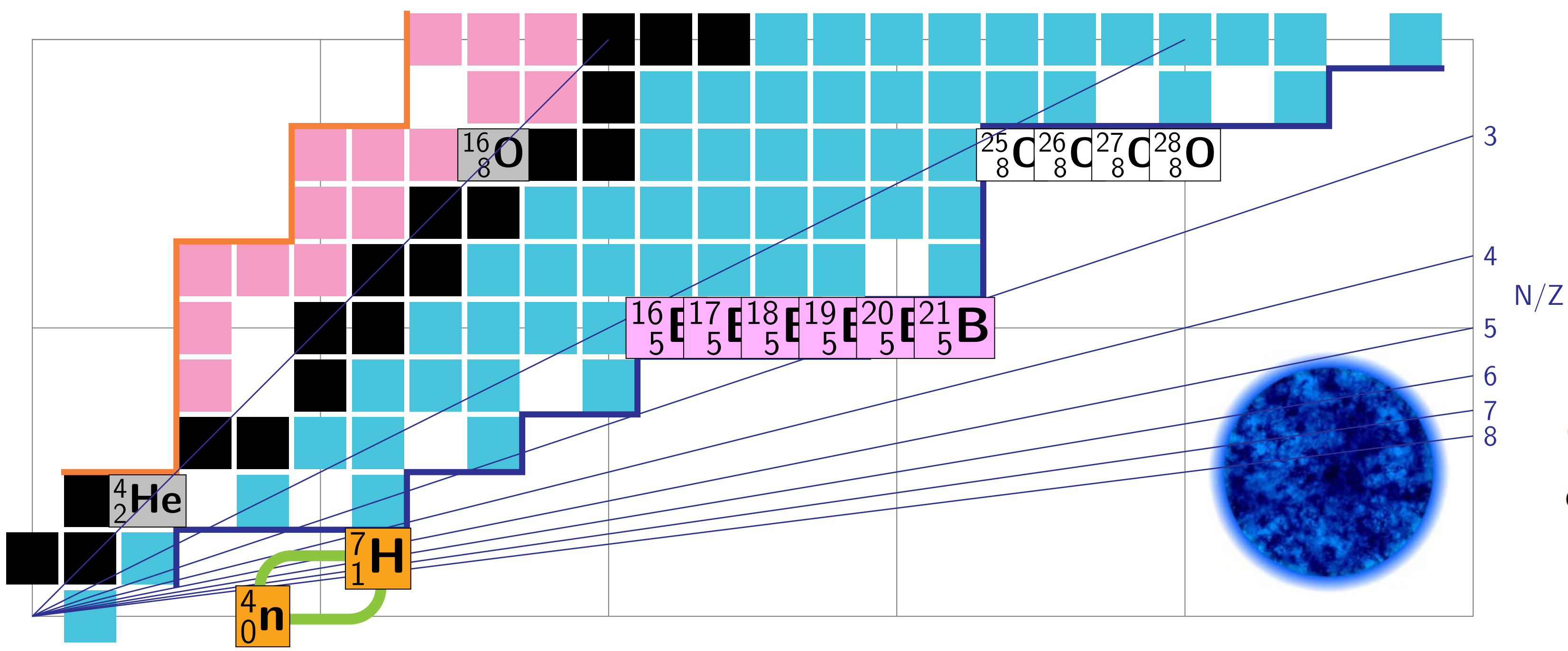
Some checks

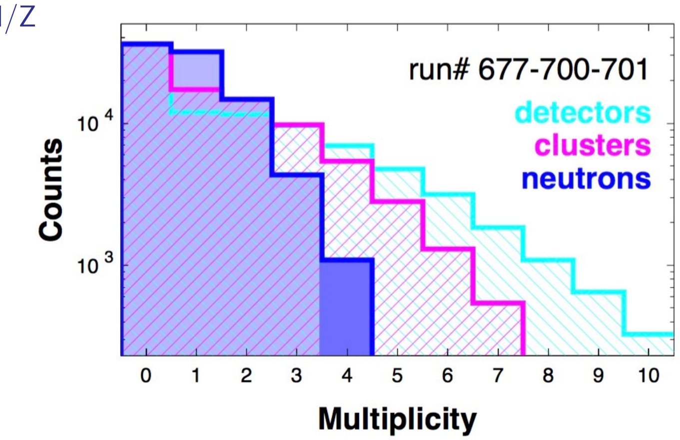
If coming from ^{7}H, the energy of the ^{3}H should have a distribution around 43 MeV

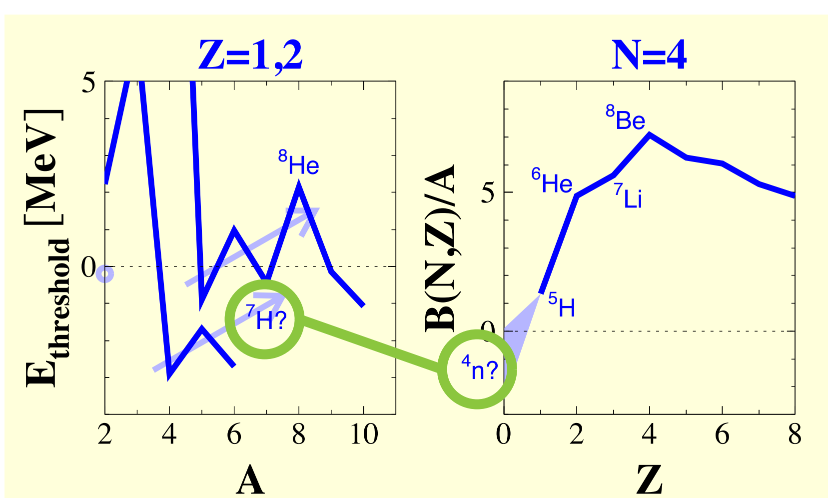


The ^{3}H energy distribution is very consistent with the formation of the ^{7}H peak from ^{19}F targets

Hydrogen 7 & Tetraneutron : tiny 'neutron stars'





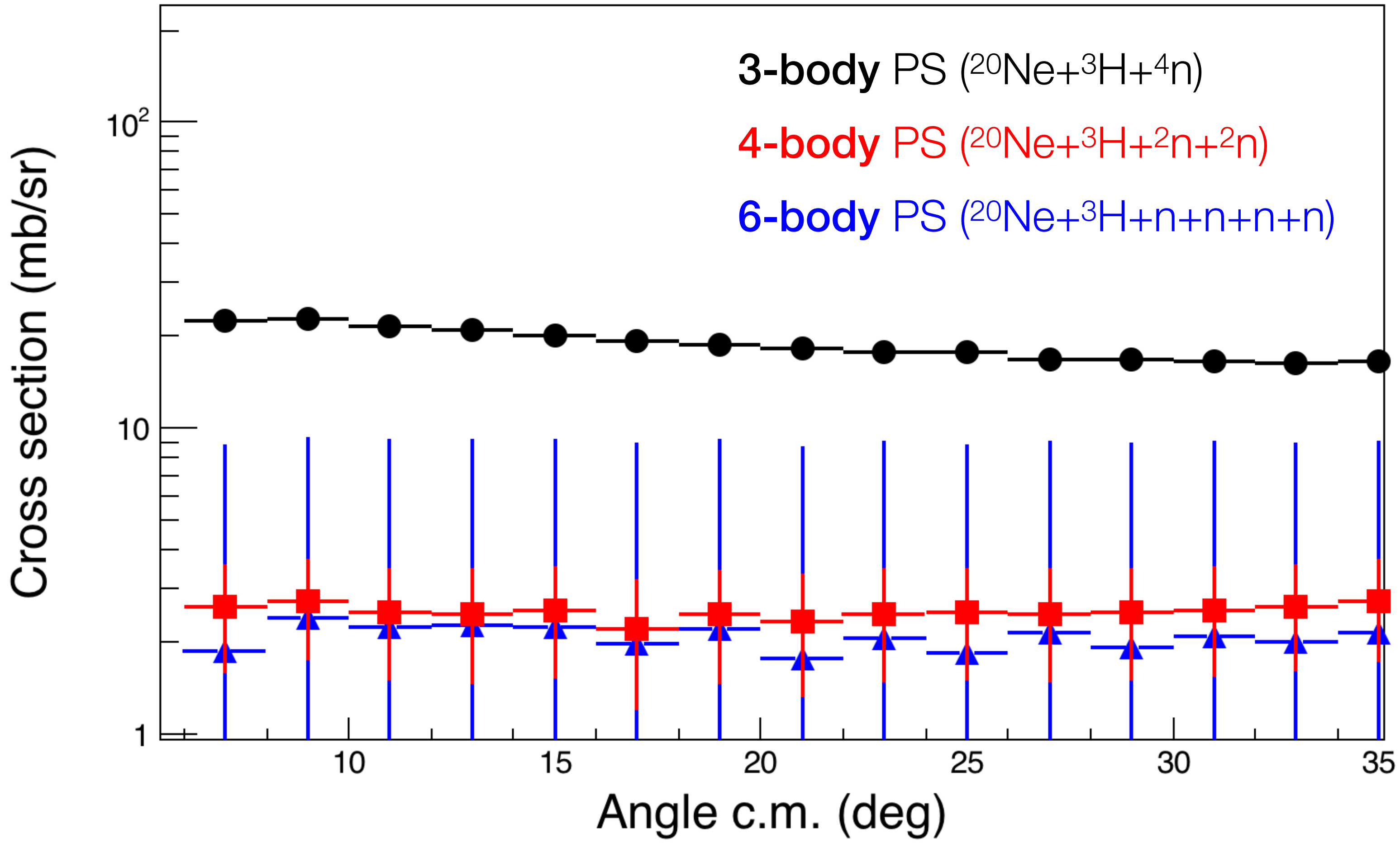


- ▶ Ambiguous and contradictory signals :
  - ✘ low statistics & resolutions
  - ✘ backgrounds (targets, binary channels)
  - ✘ missing mass : no neutron detection

→ total events : ≈ 50k !!!

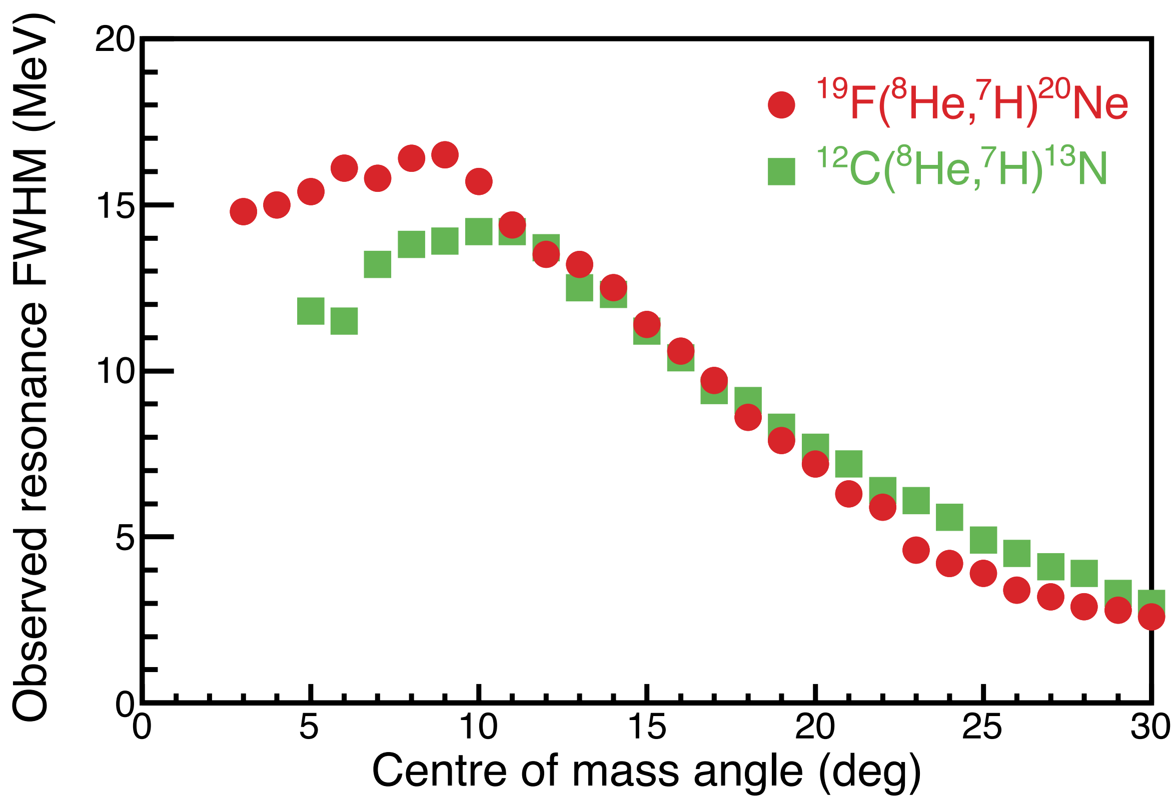
→ still 1–2 years : calibrations ...

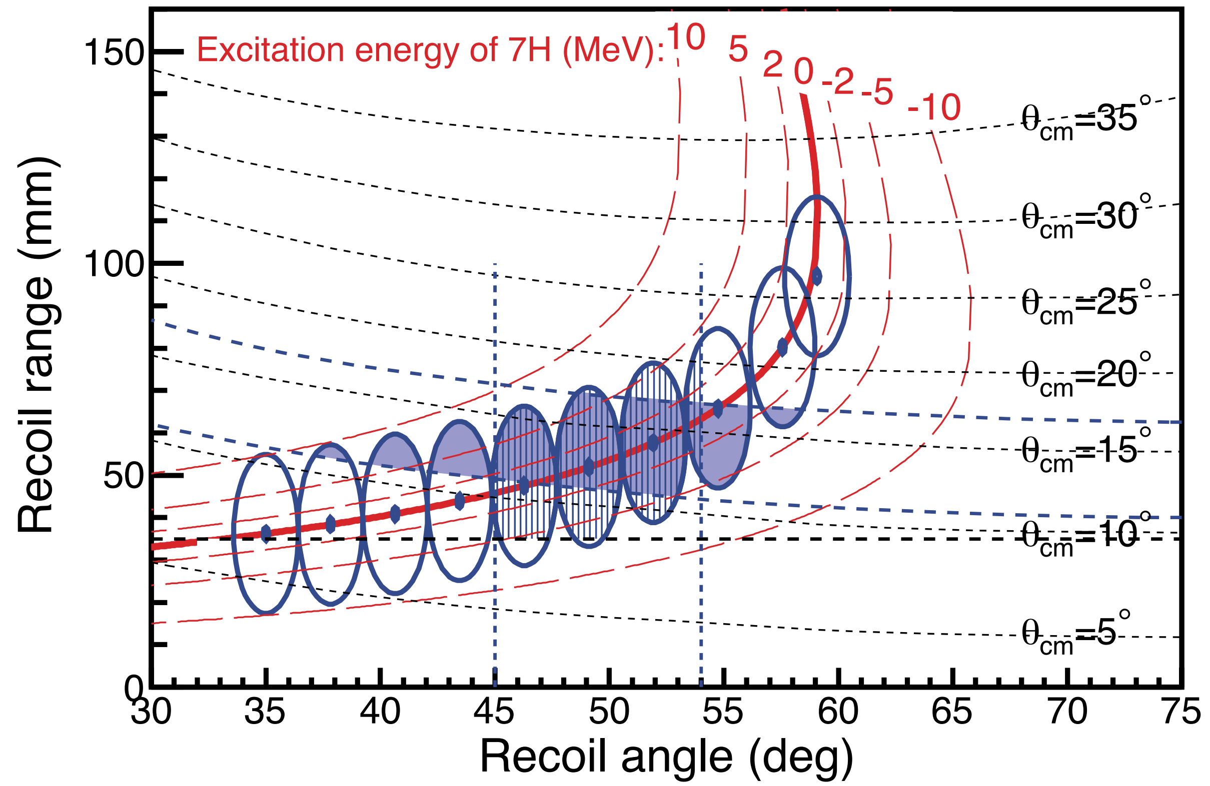
A word about phase-space



- The measured phase space is mostly isotropic and well reproduced by a 3-body partition, with 4 neutrons emitted with a high correlation.

Resolution





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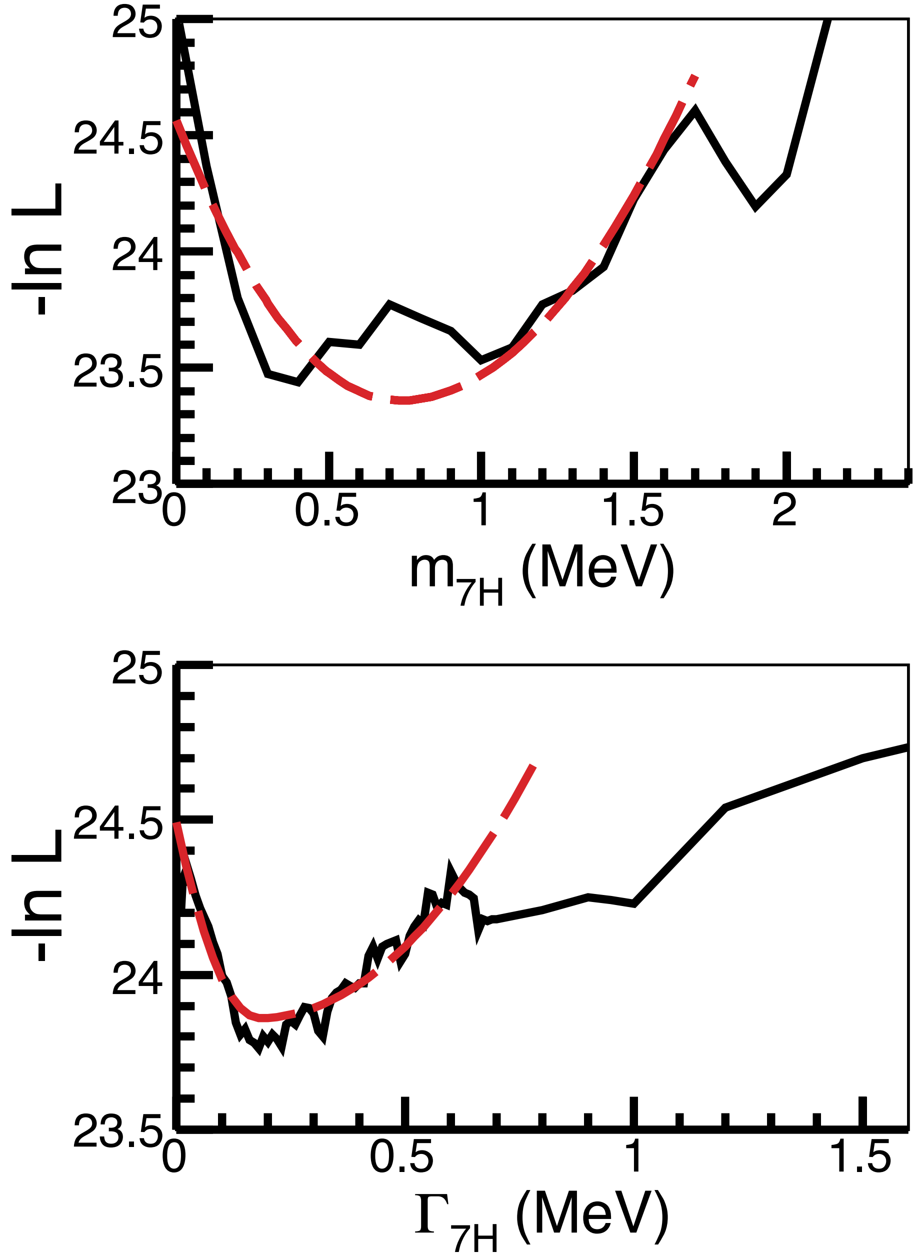
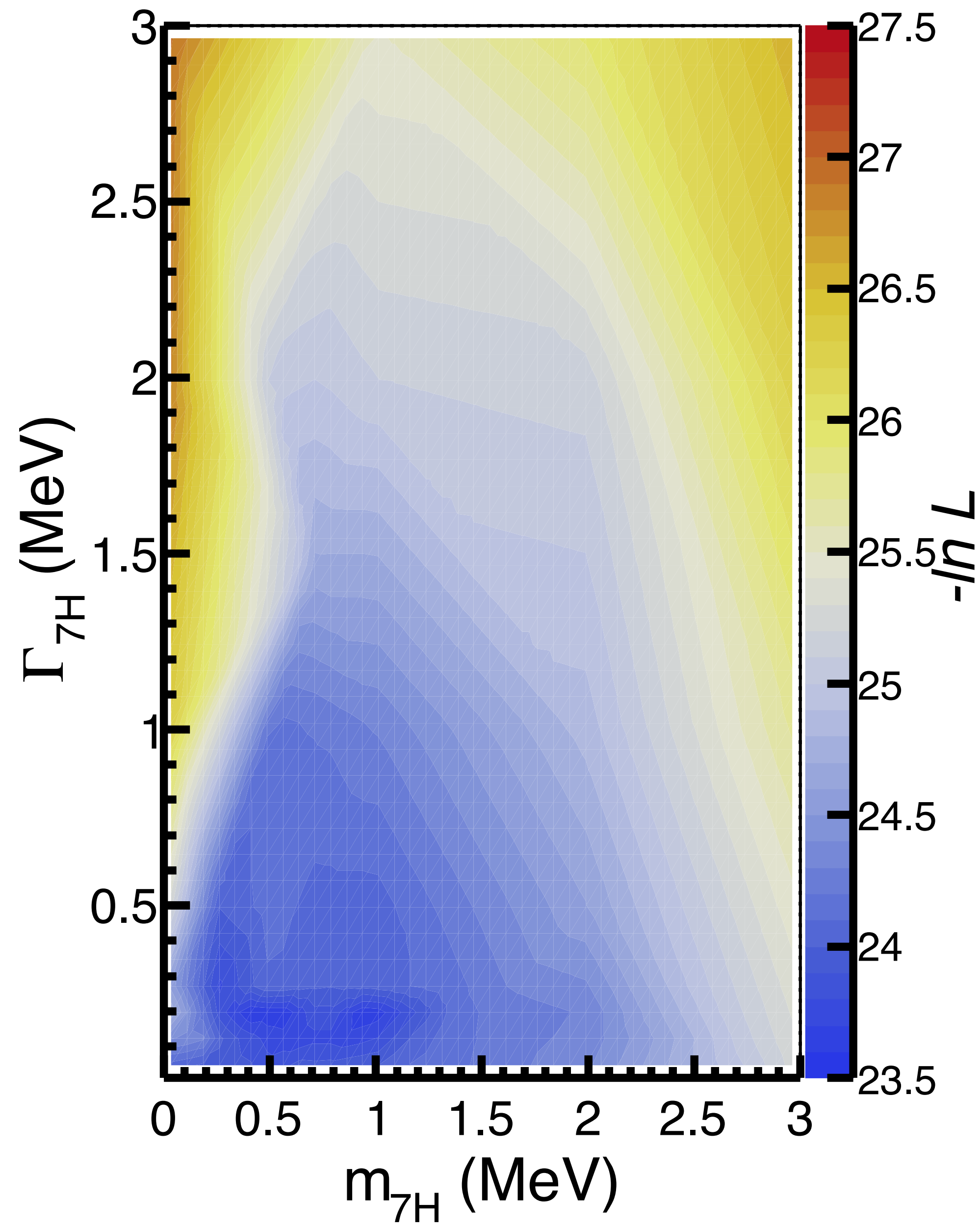
Fitting





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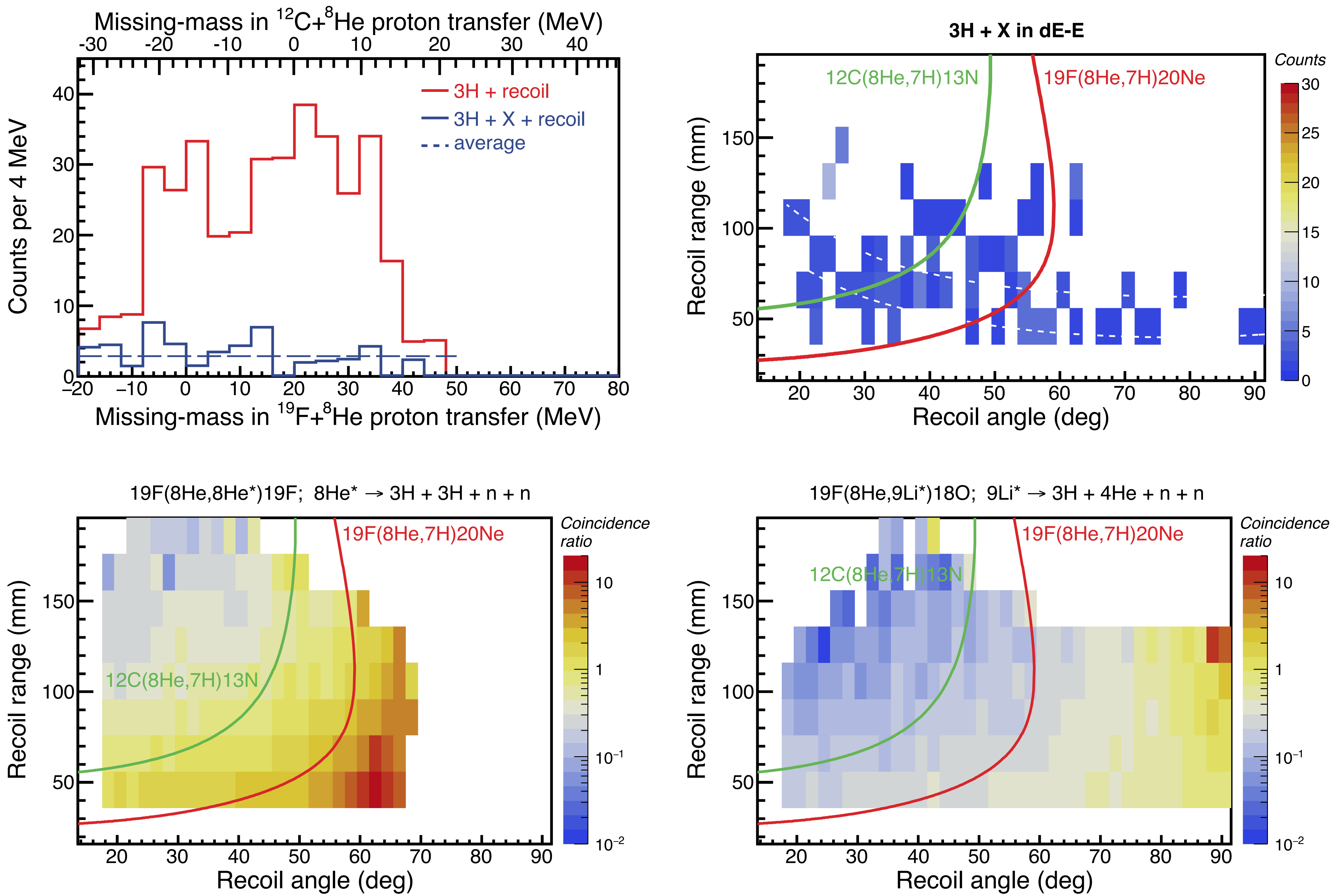
Contaminants



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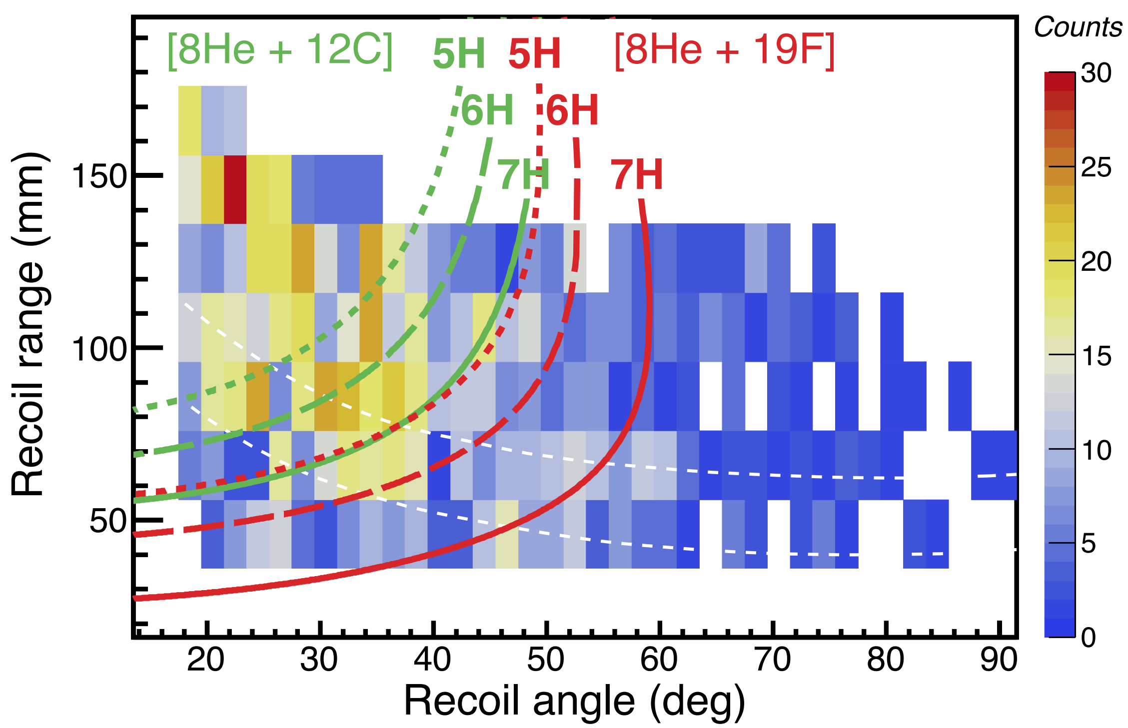
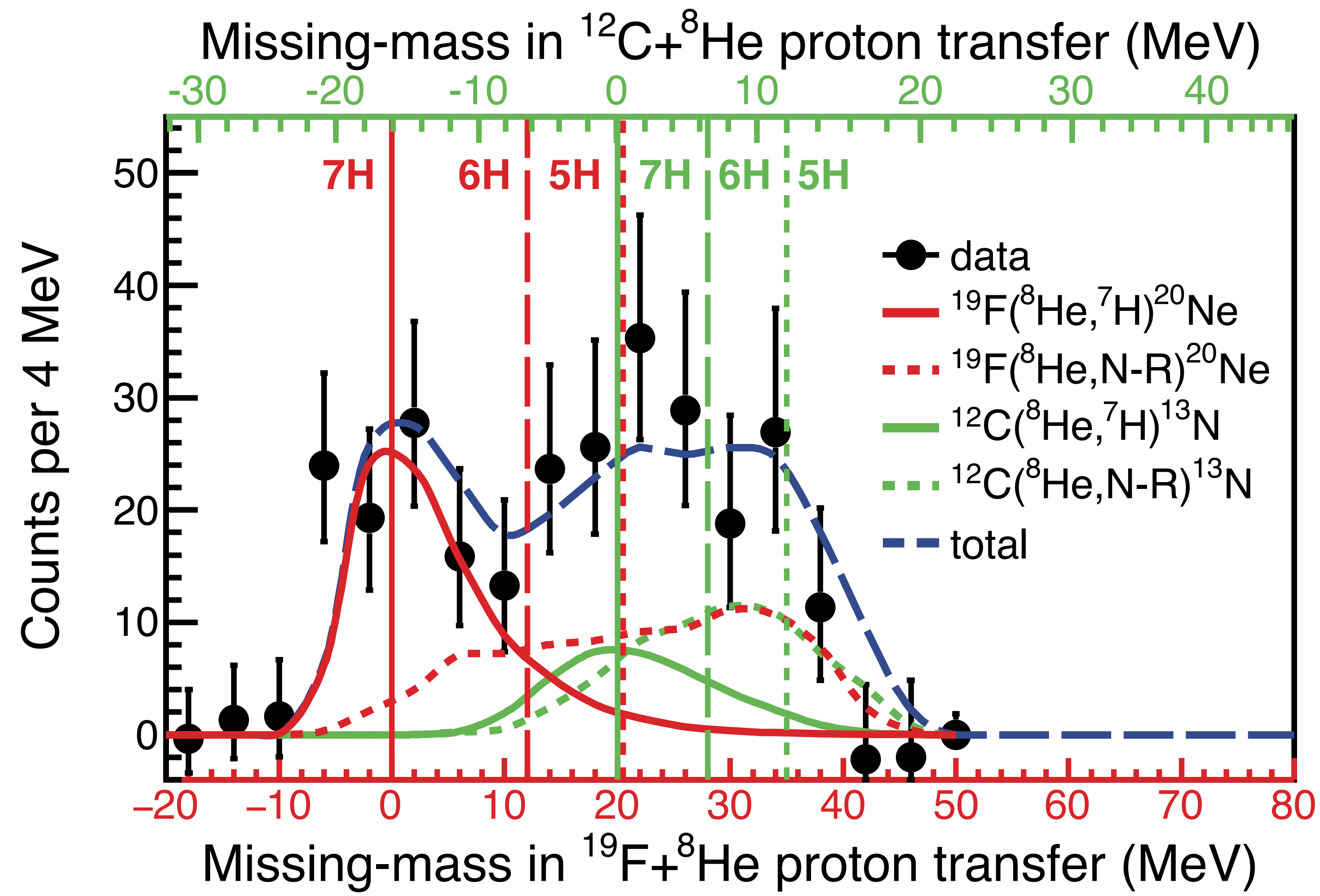
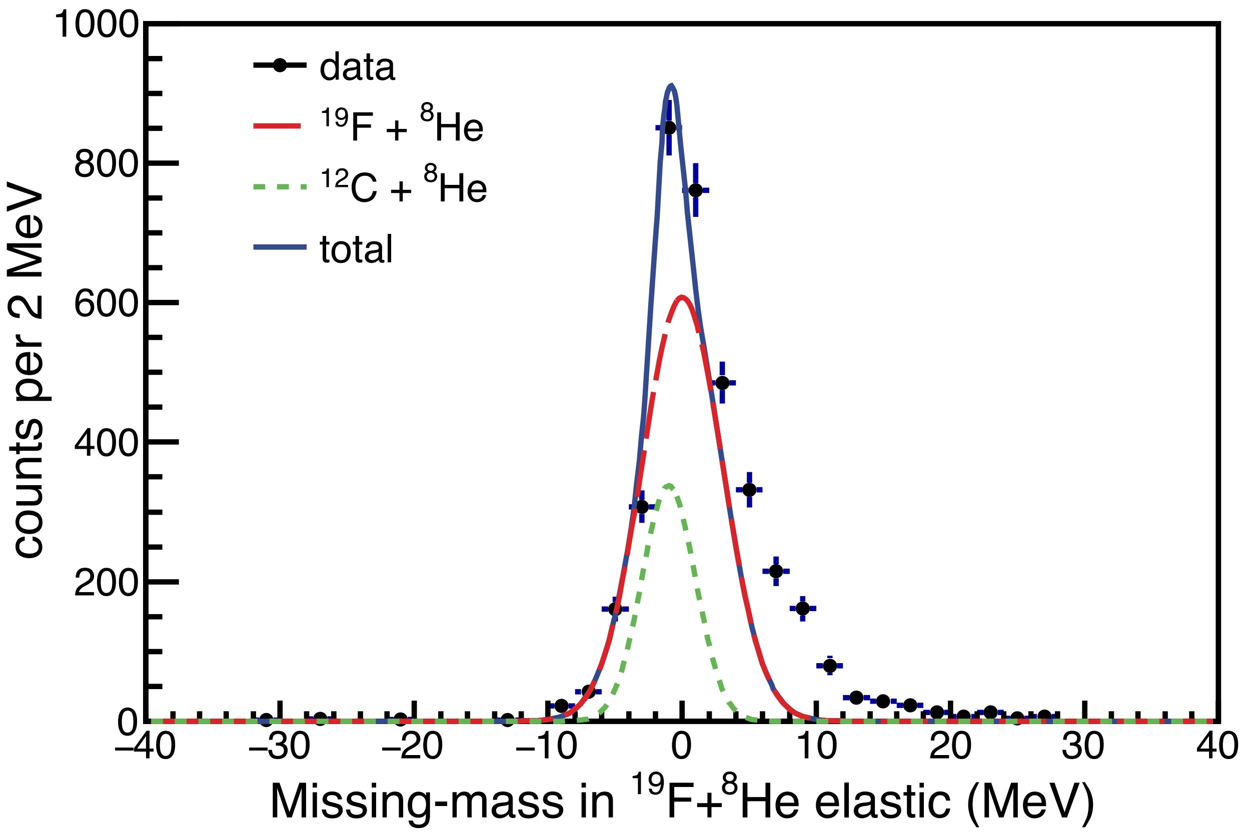
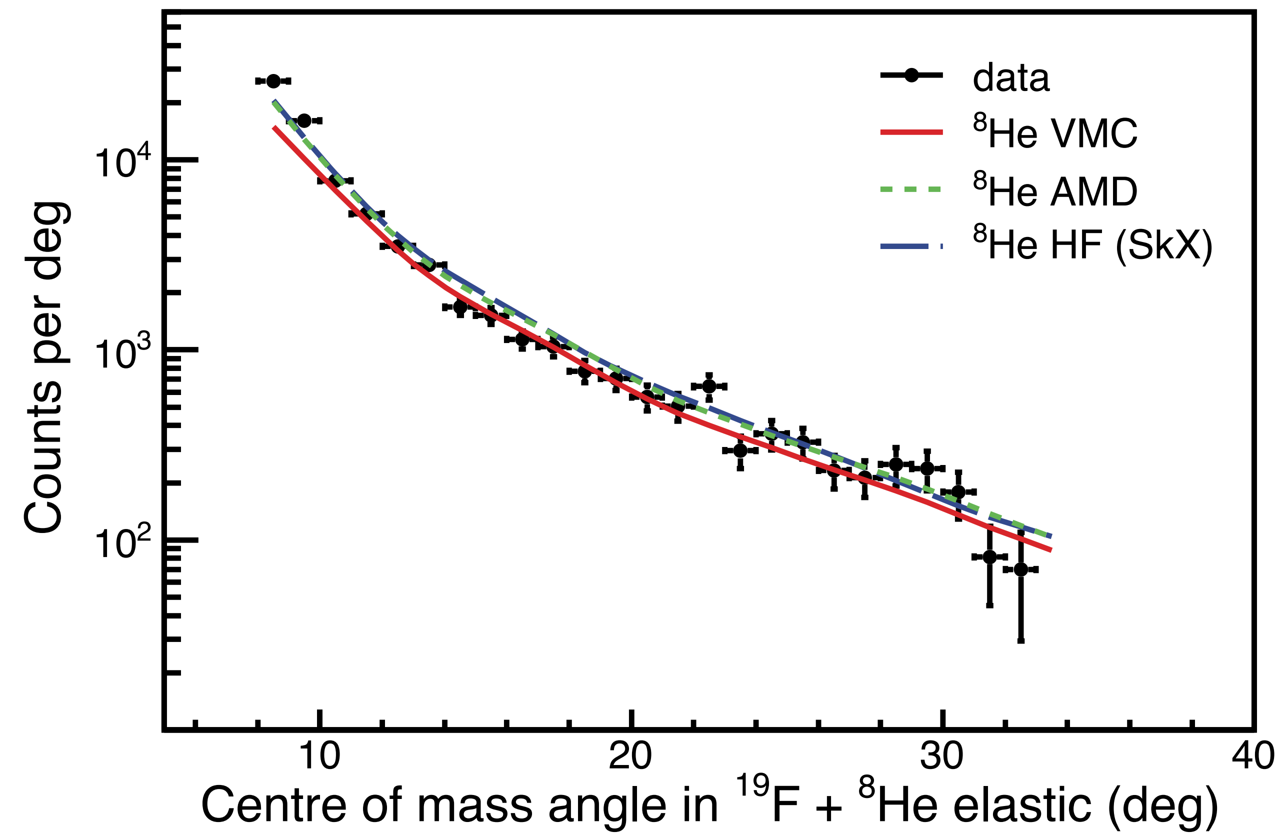
Other H channels





About elastic scattering





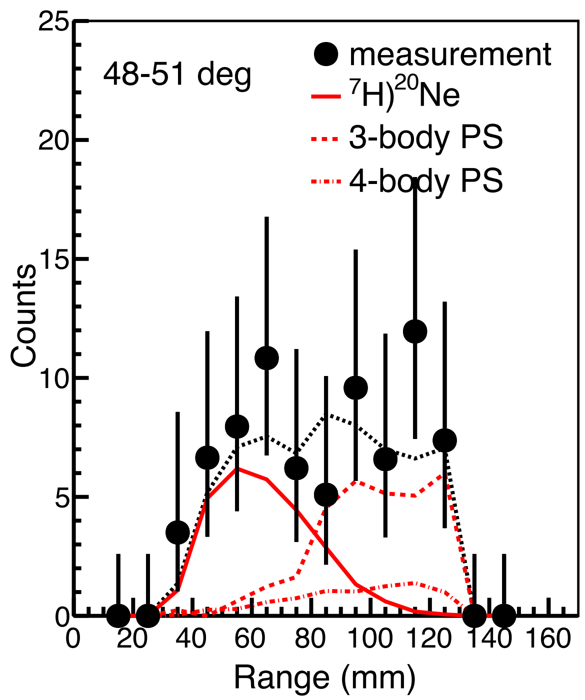
- The measured elastic scattering is strongly affected by the experimental resolution, and both ^{12}C and ^{19}F channels are mixed.

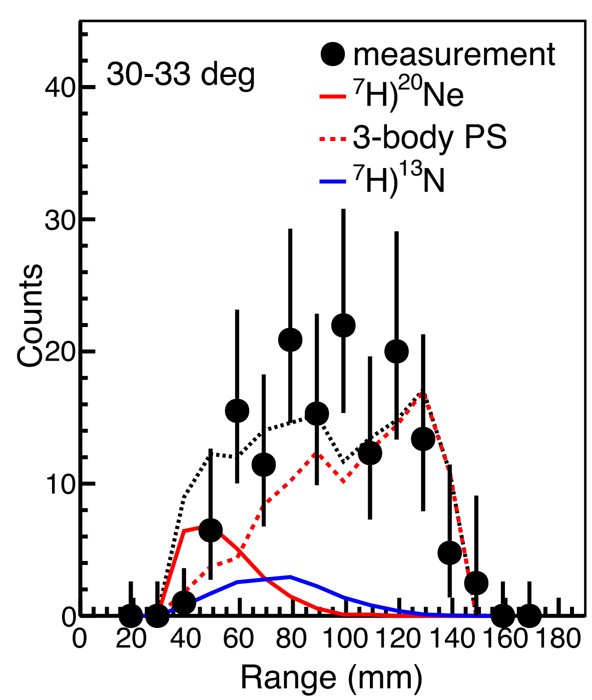
- However, FRESCO calculations for both channels need a similar factor of **0.9±0.1** to match the experimental data.

Simulation and fitting

We produce a simulation with the experimental resolution and constraints where we calculate the production of the different phase-space and the resonance as:

$$\sigma_{7\mathrm{H}}(E) = \sigma_0 \frac{\Gamma_{7\mathrm{H}}\sqrt{\frac{E}{E_{7\mathrm{H}}}}}{(E_{7\mathrm{H}} - E)^2 + \frac{1}{4}\left(\Gamma_{7\mathrm{H}}\sqrt{\frac{E}{E_{7\mathrm{H}}}}\right)^2}$$





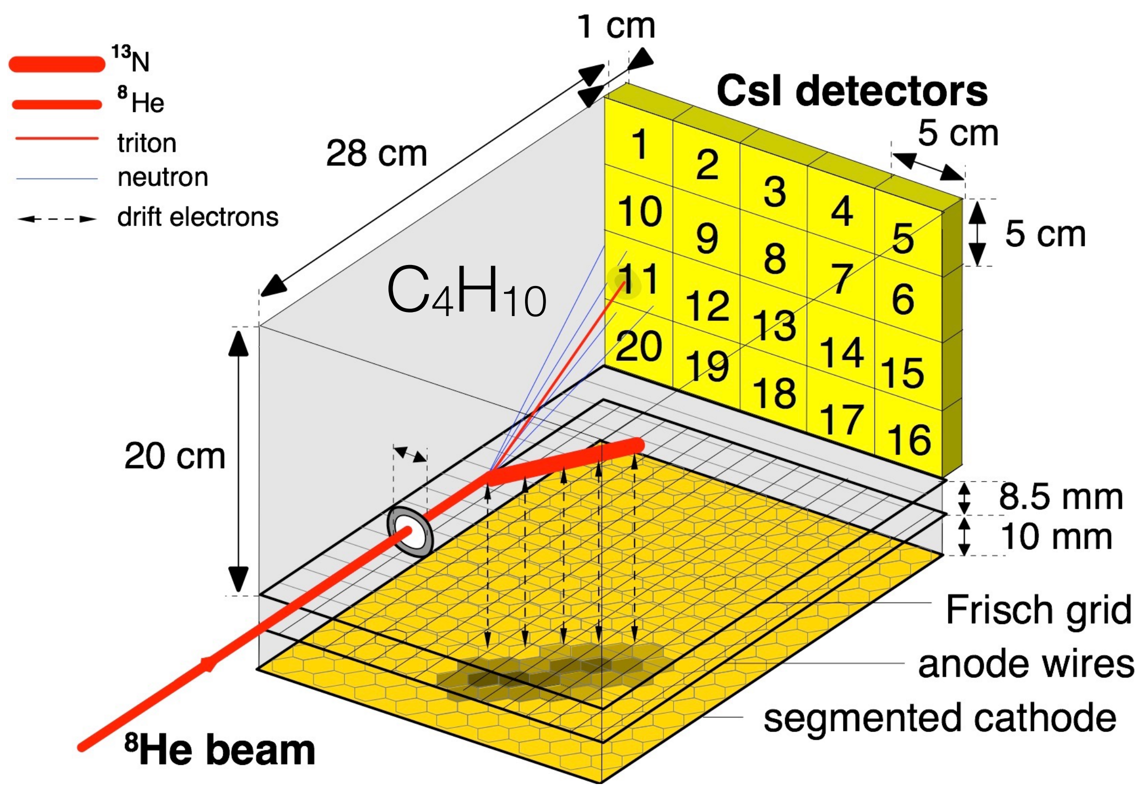
Multi-step process:

1 - Fit E_R and Γ for $45<\theta<54$
Also varying bin offset.

2 - Check for systematic dependences

3 - Calculate E_R and Γ considering uncertainties and covariance.

4 - Fix E_R and Γ and fit the contributions of each channel for $18<\theta<57$.
Also varying bin offset.



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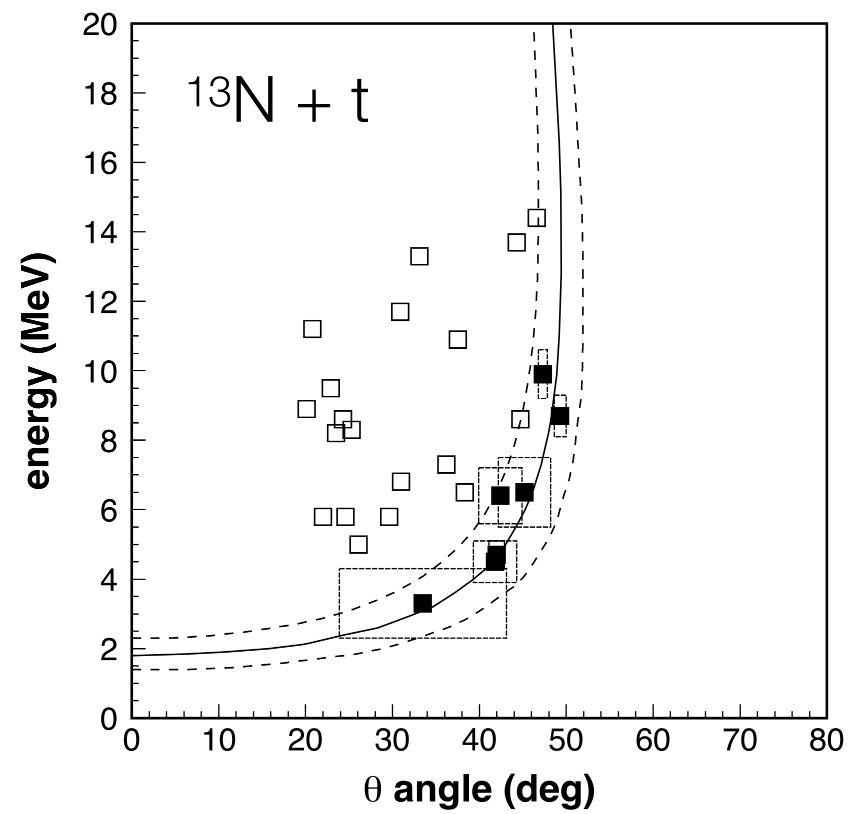
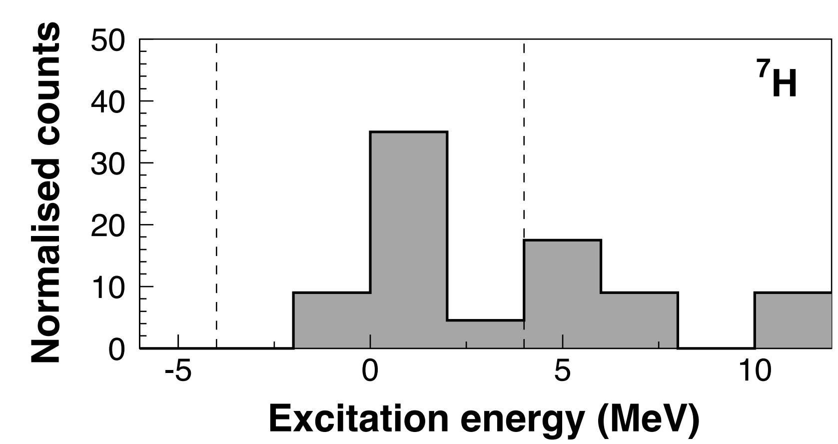




$^{12}C\ (^{8}He,^{7}H)\ ^{13}N$ at 15.4 AMeV

$E_R = 0.6^{+0.4}_{-0.2}$ MeV

$\Gamma = 0.1^{+0.9}_{-0.1}$ MeV

$\mathbf{E_{max}} = 0.6^{+0.4}_{-0.3}$ MeV

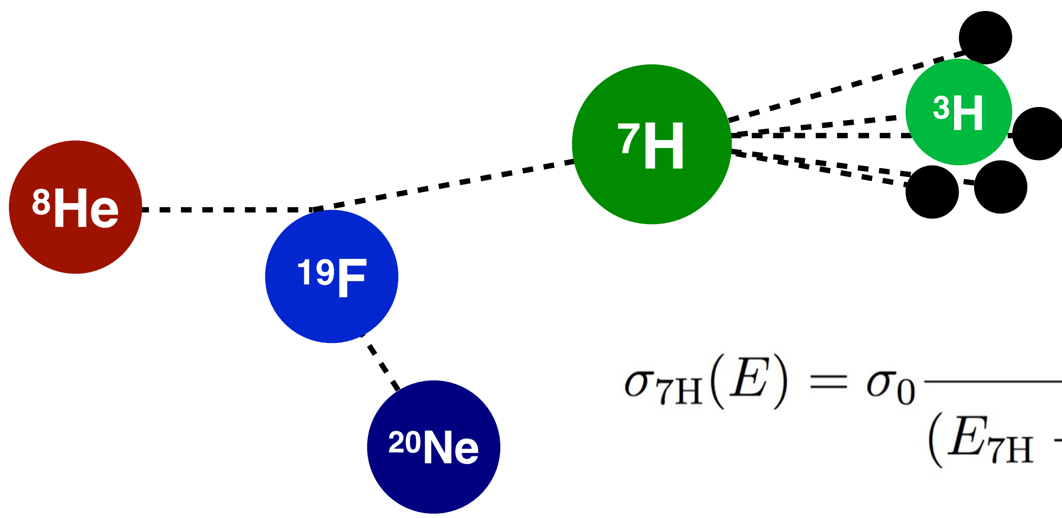
FWHM $= 0.1^{+0.8}_{-0.1}$ MeV

$d\sigma_{(10\text{-}48deg)} = 40^{+58}_{-31}\ \mu b/sr$

Simulation and fitting

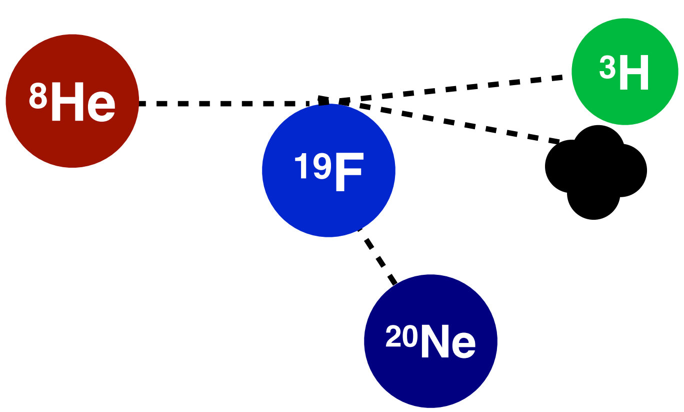
We produce a simulation with the experimental resolution and constraints applied to the production of the different phase-space components and the resonance

2-body (^{7}H+^{20}Ne)

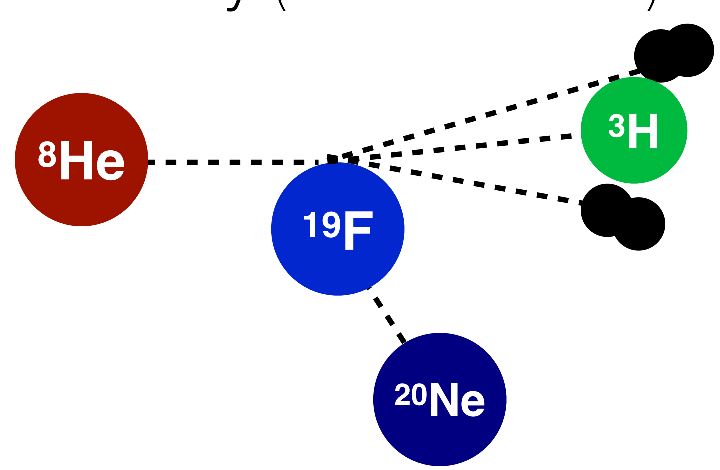


$$\sigma_{7\mathrm{H}}(E) = \sigma_0 \frac{\Gamma_{7\mathrm{H}}\sqrt{\frac{E}{E_{7\mathrm{H}}}}}{(E_{7\mathrm{H}} - E)^2 + \frac{1}{4}\left(\Gamma_{7\mathrm{H}}\sqrt{\frac{E}{E_{7\mathrm{H}}}}\right)^2}$$

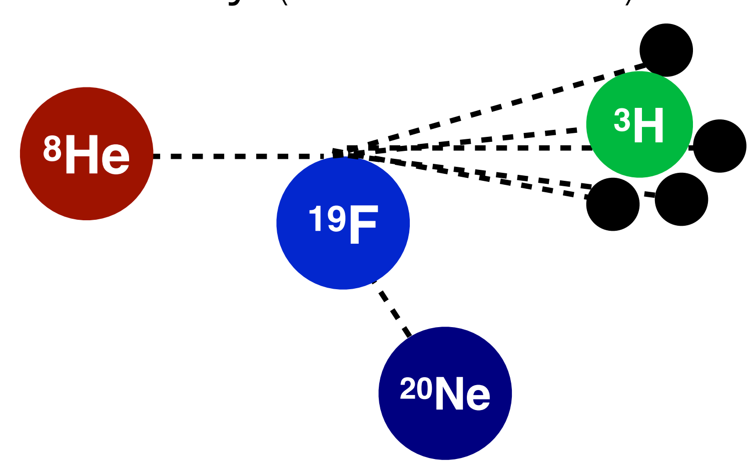
3-body (^{3}H+^{20}Ne+n^{4})



4-body (^{3}H+^{20}Ne+2n^{2})



6-body (^{3}H+^{20}Ne+4n)



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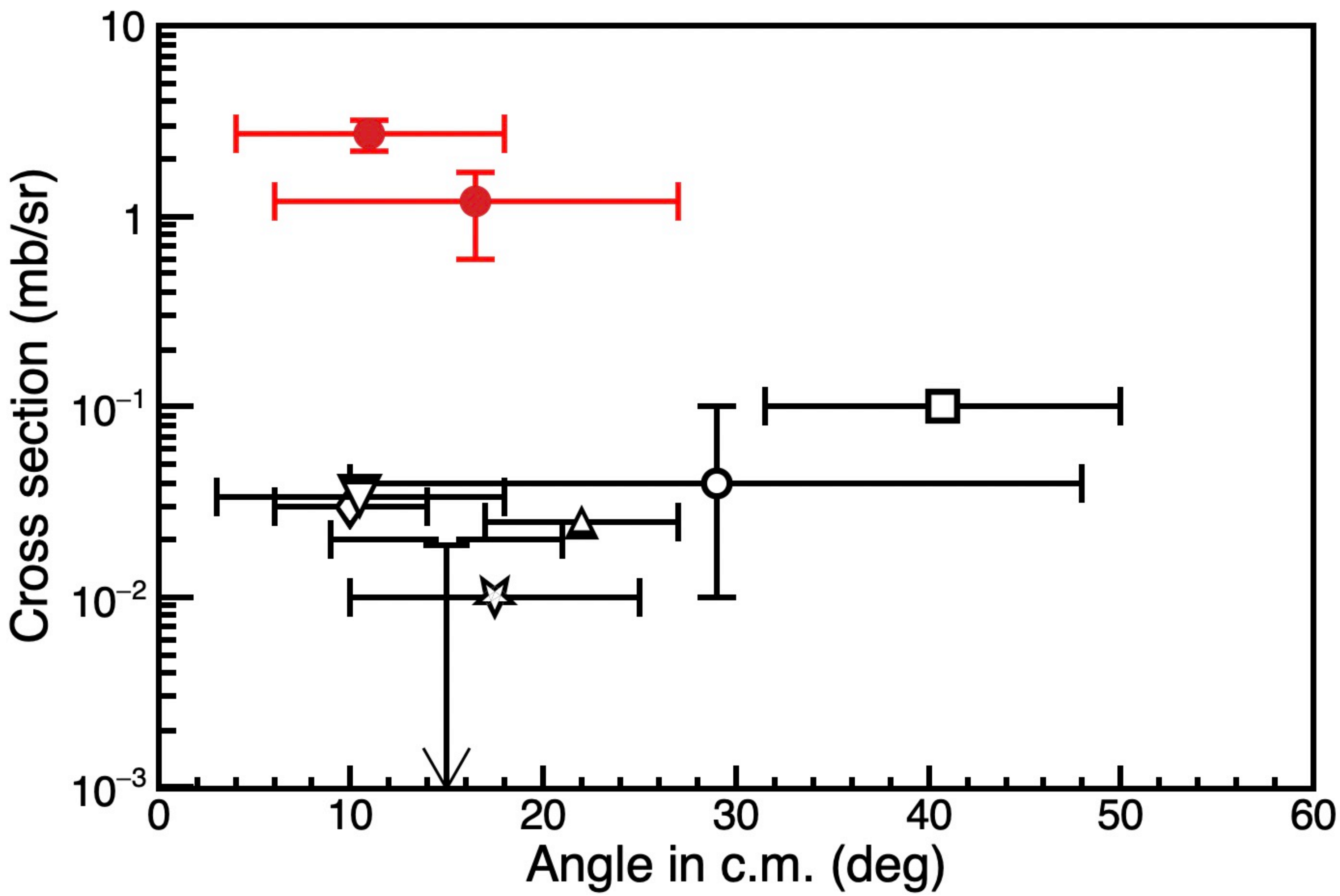
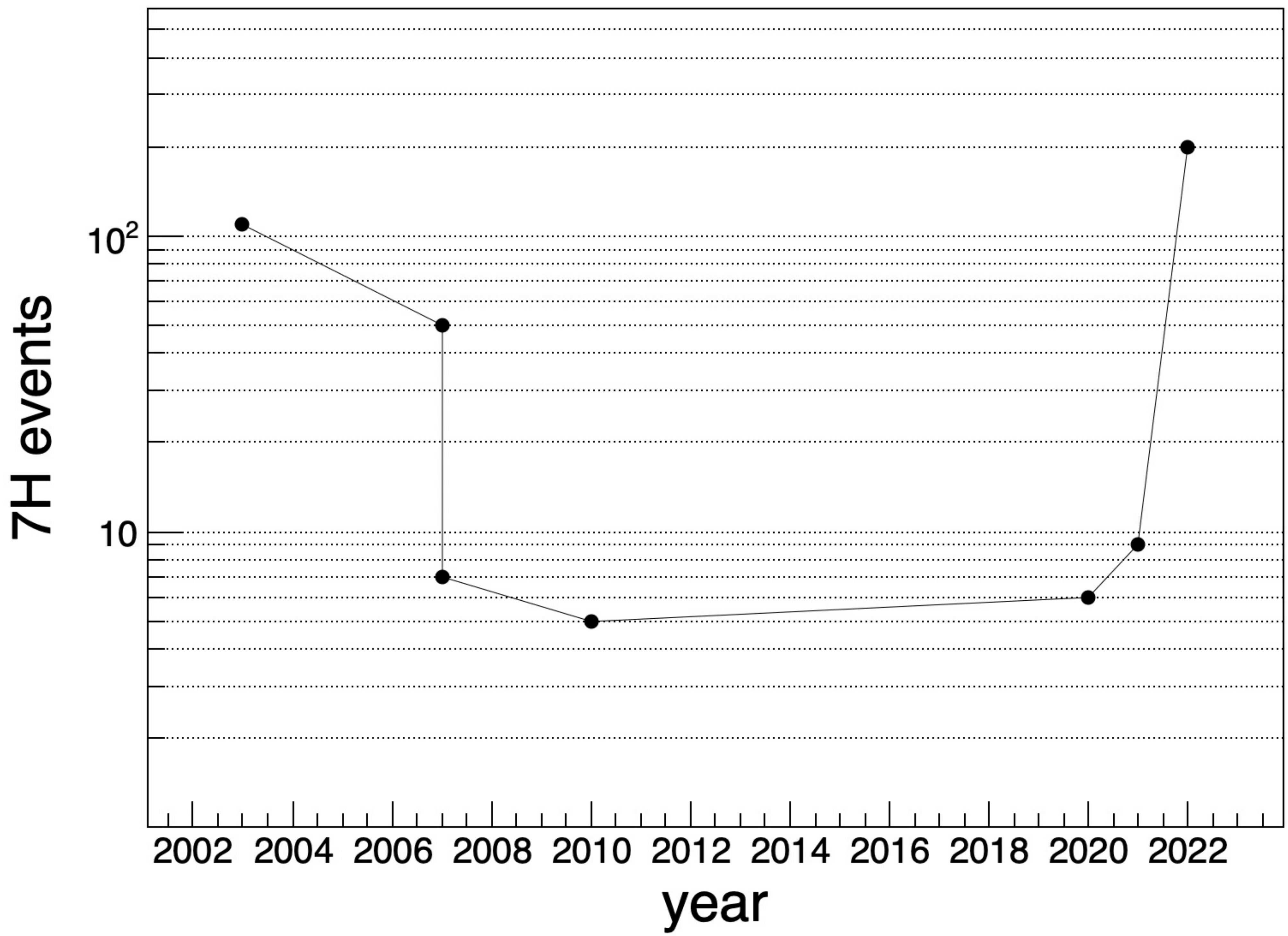
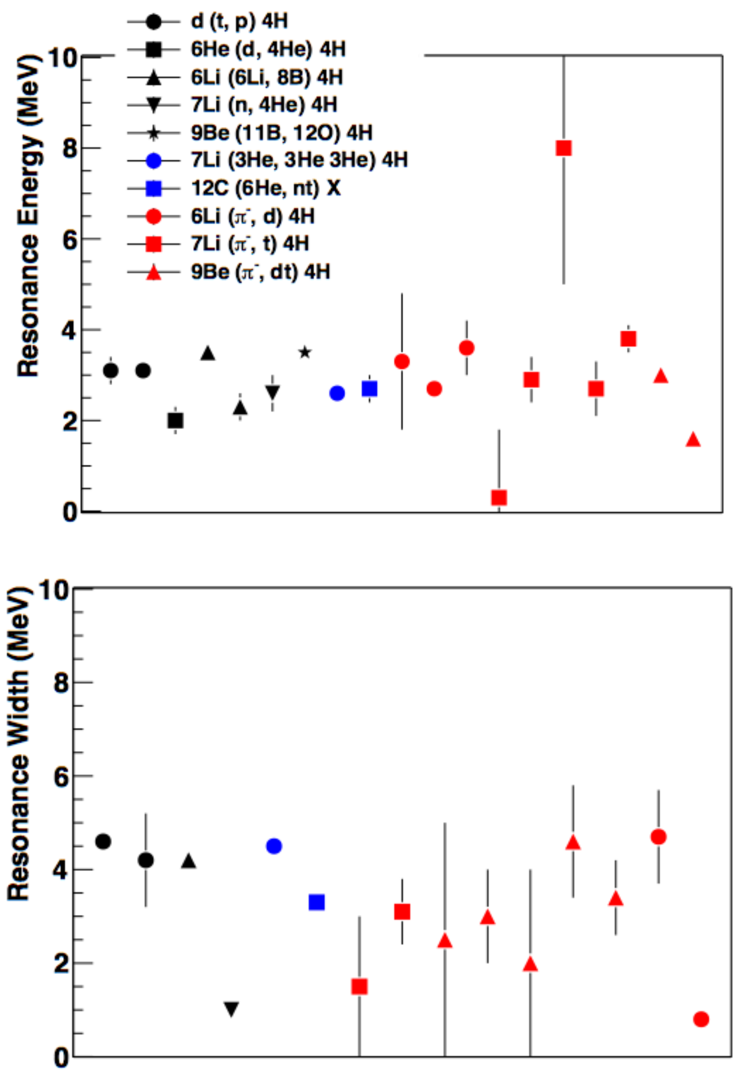


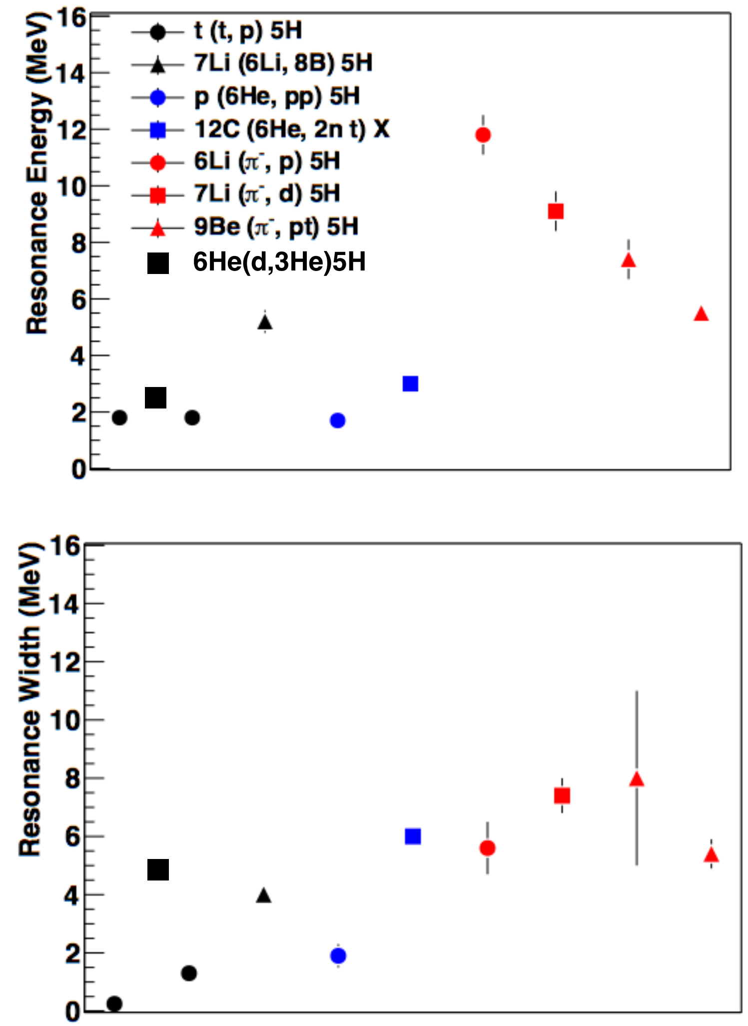
10
1
10⁻¹
10⁻²
10⁻³
Cross section (mb/sr)
0
10
20
30
40
50
60
Angle in c.m. (deg)


7H events
10^2
10
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
year

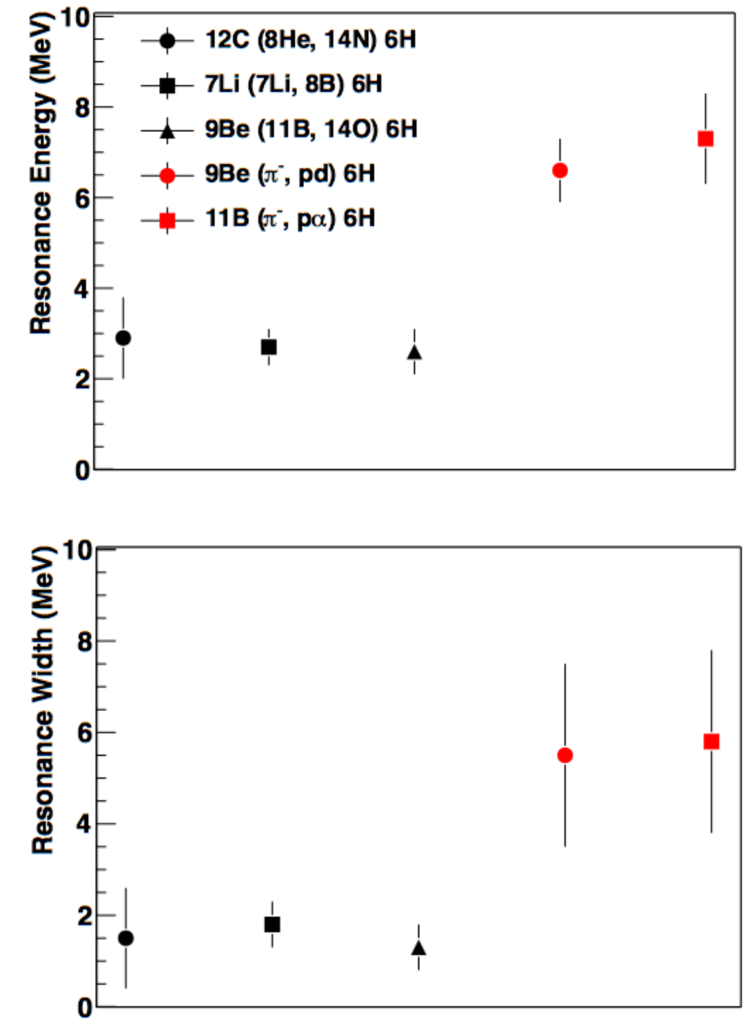
^{4}H



^{5}H



^{6}H



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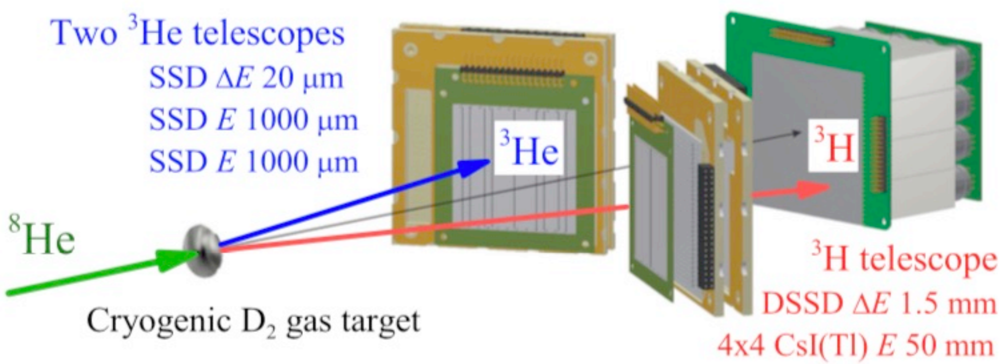

FIG. 3. Charged particle detector telescopes used in experiment 1.

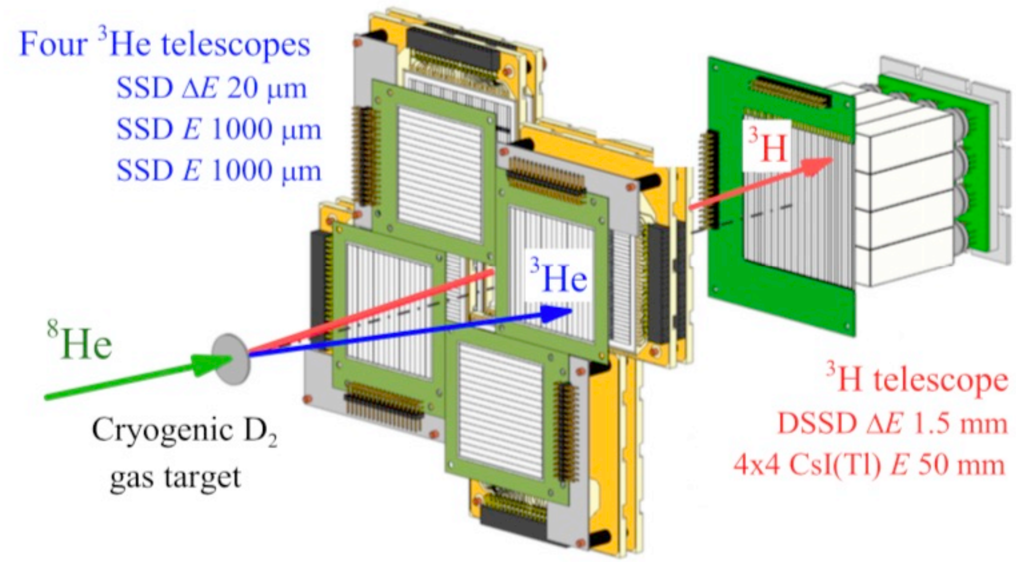

FIG. 4. Charged particle detector telescopes used in experiment 2.

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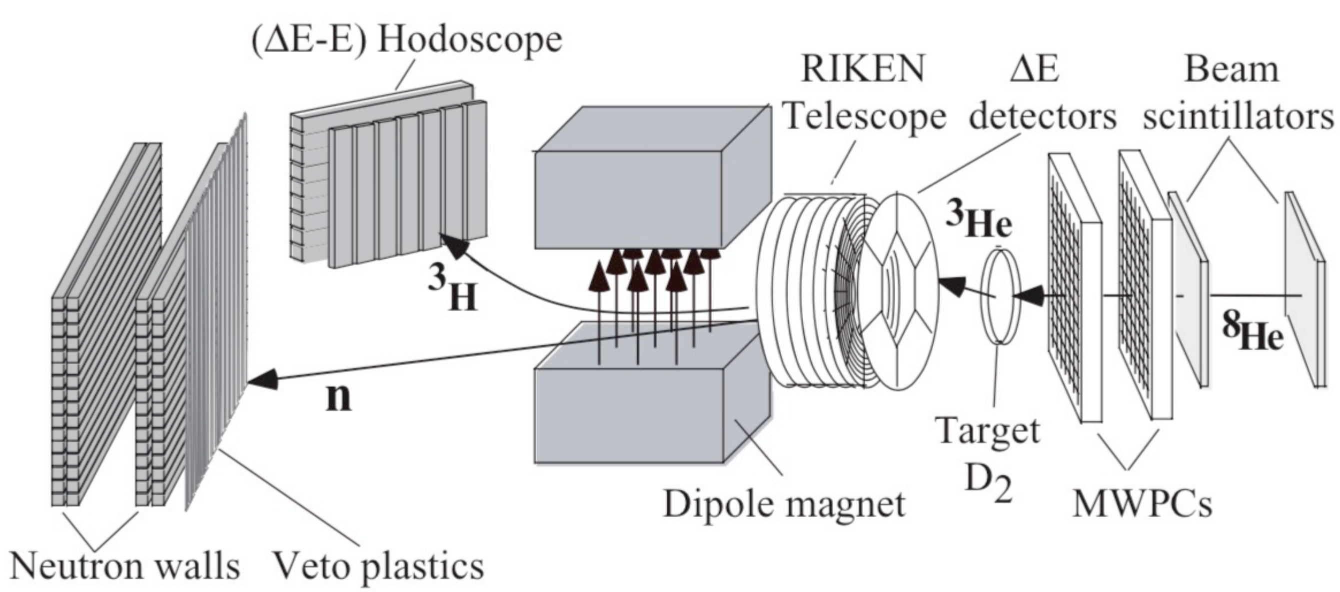

FIG. 1. Experimental setup.