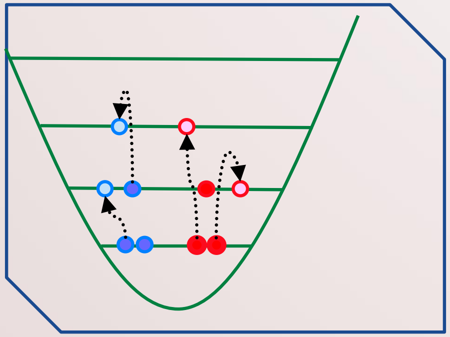
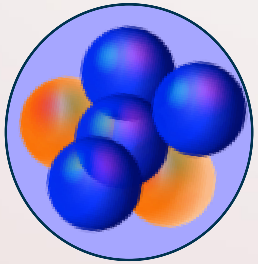
Selected outcomes from ab initio methods for reactions and weakly-bound nuclei

Guillaume Hupin, CNRS IPNO





Collaborators

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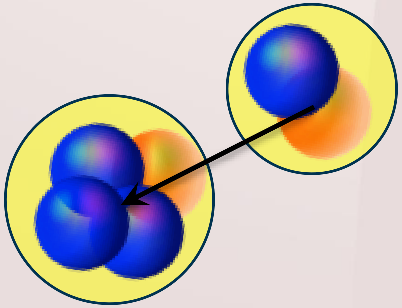
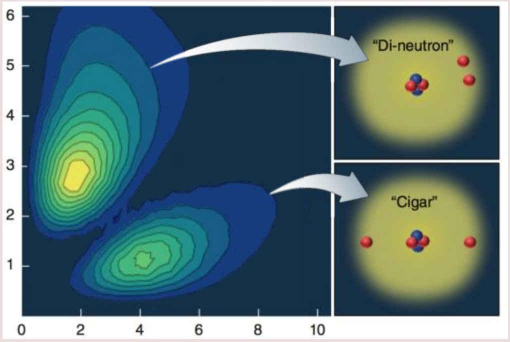
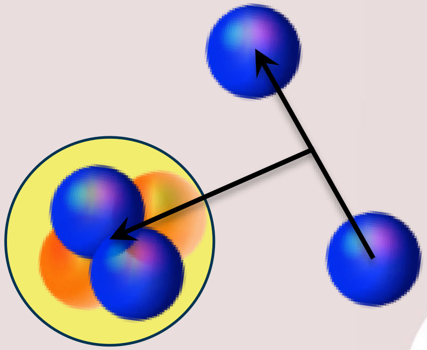


Few slides& inspiration courtesy of

R. Lazauskas (Recent developments in solving few-particle scattering problem by the solution of the Faddeev-Yakubovsky equations; FB22 conference)





Lawrence Livermore National Laboratory

IF YOU ARE INTERESTED IN WEAKLY-BOUND, RESONANT, AND OPEN QUANTUM SYSTEMS PLEASE JOIN US

Réunion groupe de travail n°1 du GdR Resanet

19 nov. 2018 à 12:00 → 21 nov. 2018 à 16:00 Europe/Paris

Salle des conseils; Salle M929; Salle M905Bis (IPN Orsay)

Description GT1: "**Quelle est la structure et la dynamique des systèmes faiblement liés (noyaux exotiques) ?**"

(**Structure and dynamics of weakly bound systems**)

The purpose of this meeting is to review the recent progress and prospect the future of the field.

The organizers have selected seven topics that cover most of the community research. If you feel that item list does not cover your area or that we have missed important are, we strongly encourage you to submit us your suggestion.

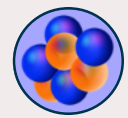
1. Clustering evolution towards the drip-line (i.e. N≠Z), generalized Ikeda conjecture.
2. Evolution of pairing at and along the drip line.
3. Nuclear interaction and shell evolution.
4. Quenching of spectroscopic factors in reactions involving halo/cluster/drip line nuclei.
5. (Broken) Mirror symmetries.
6. Emergence of halo nuclei and Borromean states.
7. Giant or Pigmy modes associated to neutron-rich nuclei.
8. Connection to other open quantum systems or to dilute systems.

- the many body problem can be solved with CI method:

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle$$

Mixing coefficients(unknown)

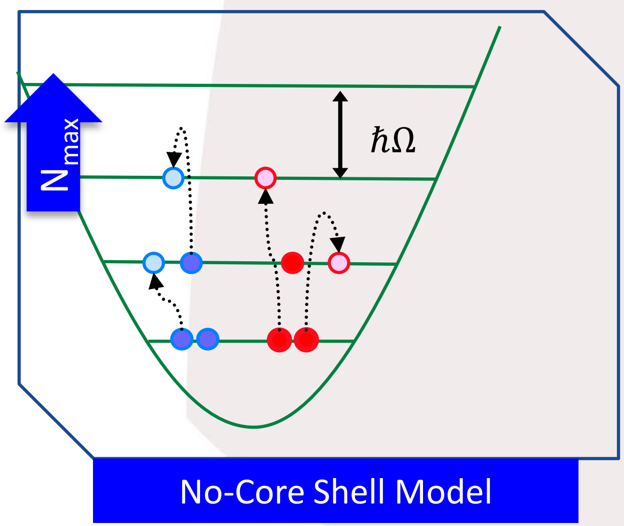
A-body harmonic oscillator states

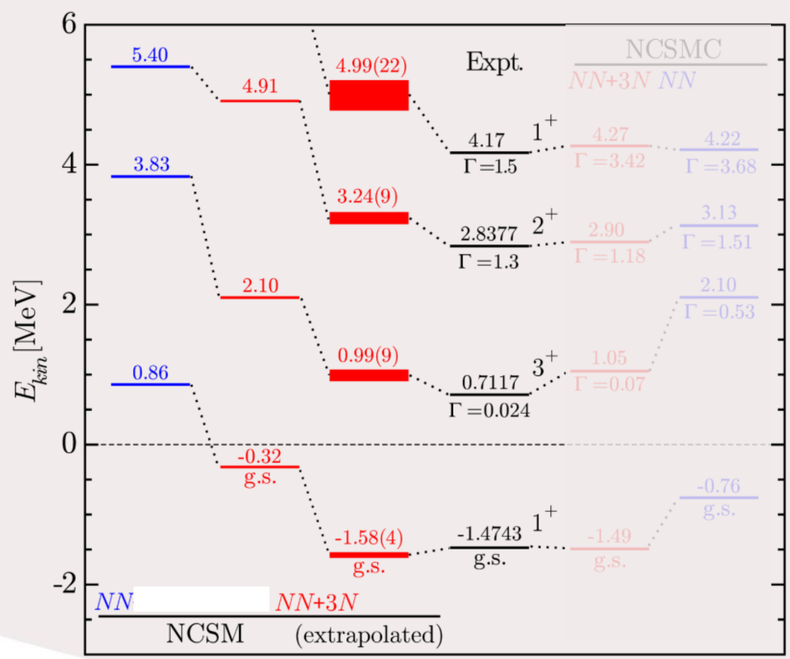


$$|A\lambda J^{\pi} T\rangle_{SD}\, \phi_{00}(\vec{R}^{A}_{c.m.})$$

Second quantization

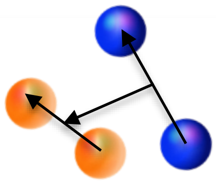
Can address bound and low-lying resonances (short range correlations)

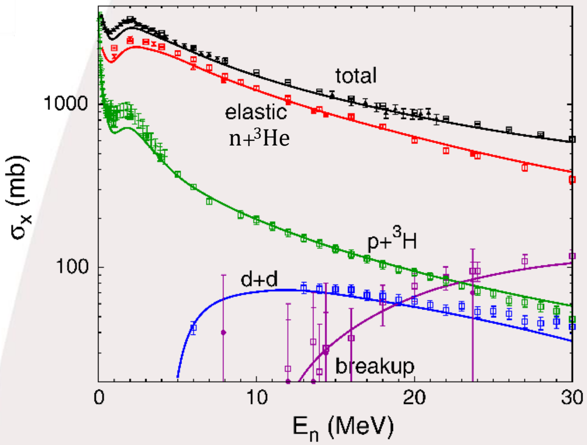


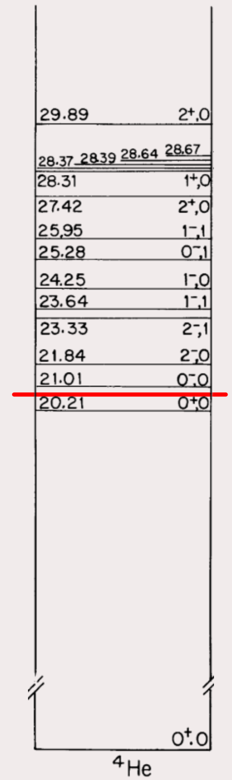


G. Hupin, S. Quaglioni and P. Navrátil PRL**114** (2015)

RECENT PROGRESS IN EXACT METHODS: FOUR-BODY SCATTERING SYSTEMS

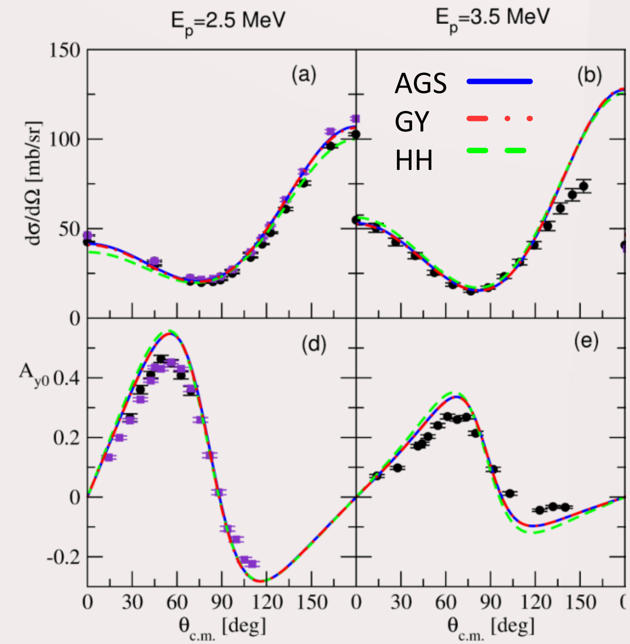




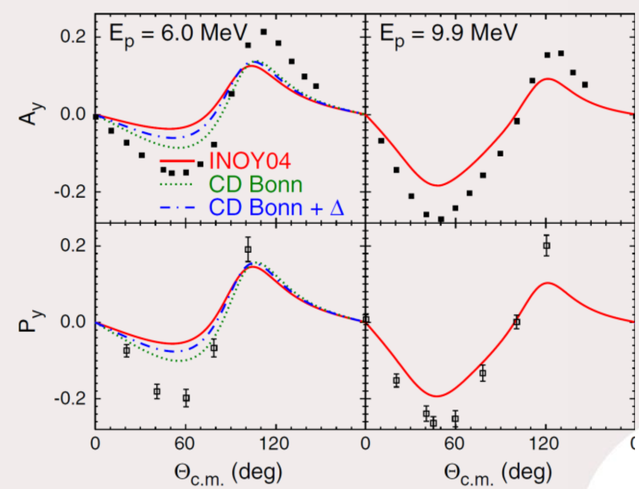


Exact reaction calculations for very light systems
***A*=2, 3 and 4**

- Faddeev-Yacubovsky (FY)
- Alt-Grassberger-Sandhas (AGS)
- Hyperspherical Harmonics (HH)



M. Viviani et al. PRC**95** (2017)

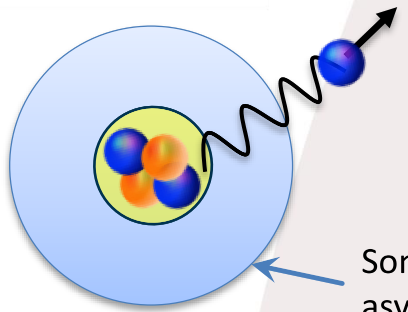


A.C. Fonseca and A. Deltuva FBS**58** (2017)

- All methods agree with each other to a few percent.
- “Significant” discrepancies with expt. are found.
- As observed in A=3, polarization observables are the most sensitive probes.
- Note that there are few measurements (particularly polarization) they are old and maybe inaccurate.

PROPERTIES OF THE RIGOROUS SCATTERING EQ.

Courtesy of R. Lazauskas

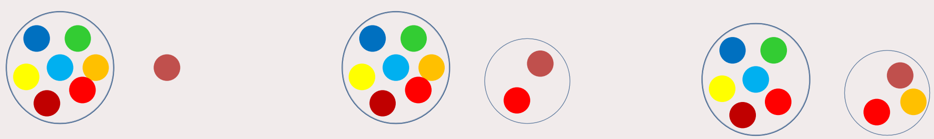


Boundary problem

Sometimes known asymptotic

- Should separate all possible scattering channels to incorporate proper asymptotes! Number of binary channels increases ~2N

$$\Psi_{\mathrm{N}} = \sum_{perm} \Psi_{(N-1)(1)} + \sum_{perm} \Psi_{(N-2)(2)} + \sum_{perm} \Psi_{(N-3)(3)} + \cdots$$

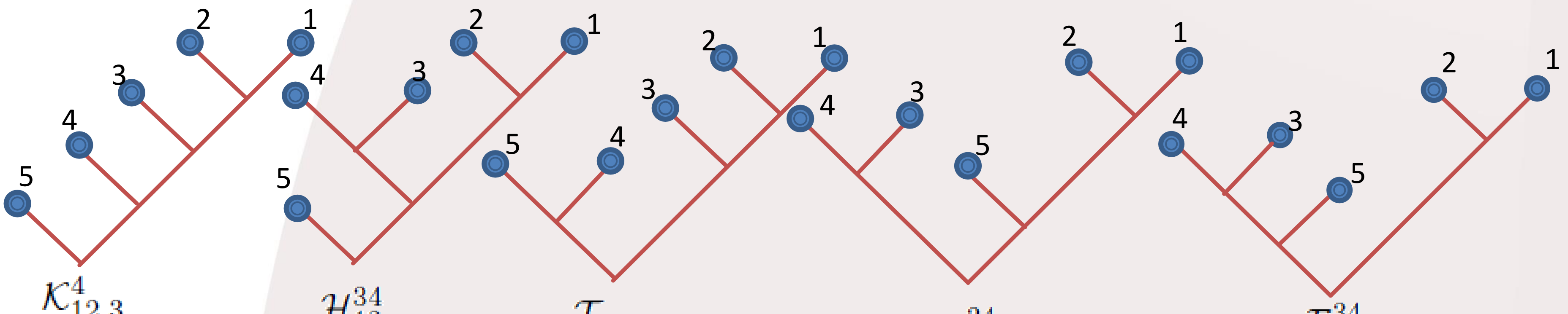


- Should be systematically reducible to smaller subsystems, in order to built proper asymptotic solutions and to be consistent to its subsystems (tree-like structure)

$$\Psi_{(N-i)(i)} = \left(\Psi_{N-i} \bigcup \Psi_i \right)$$

5-BODY FADDEEV-YAKUBOVSKI EQ.

Courtesy of R. Lazauskas

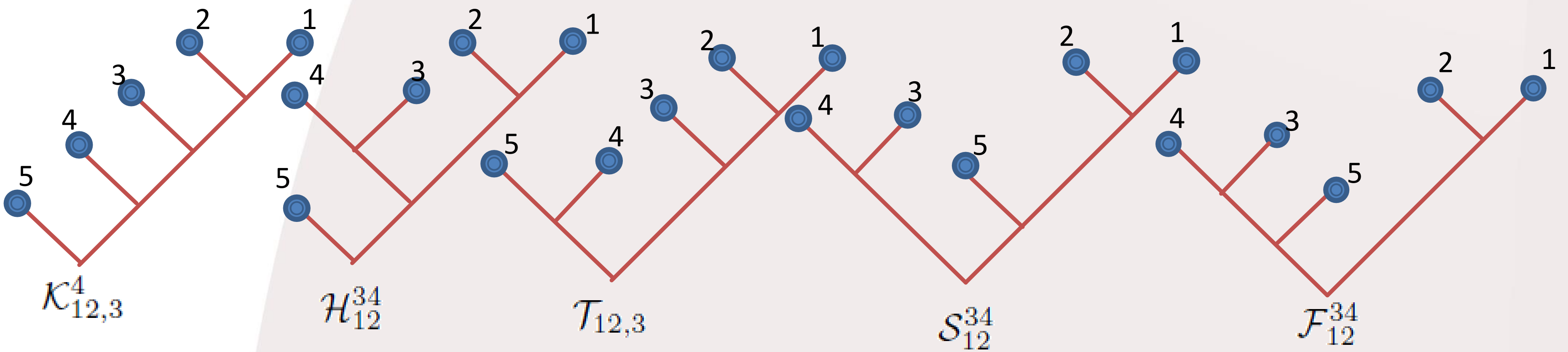


$\mathcal{K}^{4}_{12,3}$ $\mathcal{H}^{34}_{12}$ $\mathcal{T}_{12,3}$ $\mathcal{S}^{34}_{12}$ $\mathcal{F}^{34}_{12}$

$$
\begin{aligned}
(E-H_0-V_{12})\,\mathcal{K}^{4}_{12,3} &= V_{12}\,(\mathcal{K}^{4}_{13,2}+\mathcal{K}^{4}_{23,1}+\mathcal{K}^{5}_{13,4}+\mathcal{K}^{5}_{23,4}+\mathcal{K}^{2}_{13,4}+\mathcal{K}^{1}_{23,4}\\
&\quad +\mathcal{T}_{13,4}+\mathcal{T}_{23,4}\\
&\quad +\mathcal{H}^{24}_{13}+\mathcal{H}^{14}_{23}+\mathcal{S}^{24}_{13}+\mathcal{S}^{14}_{23}+\mathcal{F}^{24}_{13}+\mathcal{F}^{14}_{23})\\
(E-H_0-V_{12})\,\mathcal{H}^{34}_{12} &= V_{12}\,(\mathcal{H}^{12}_{34}+\mathcal{K}^{2}_{34,1}+\mathcal{K}^{1}_{34,2}+\mathcal{K}^{5}_{34,1}+\mathcal{K}^{5}_{34,2}\\
&\quad +\mathcal{T}_{34,1}+\mathcal{T}_{34,2})\\
(E-H_0-V_{12})\,\mathcal{T}_{12,3} &= V_{12}\,(\mathcal{T}_{13,2}+\mathcal{T}_{23,1}\\
&\quad +\mathcal{H}^{45}_{13}+\mathcal{H}^{45}_{23}+\mathcal{S}^{45}_{13}+\mathcal{S}^{45}_{23}+\mathcal{F}^{45}_{13}+\mathcal{F}^{45}_{23})\\
(E-H_0-V_{12})\,\mathcal{S}^{34}_{12} &= V_{12}\,(\mathcal{F}^{12}_{34}+\mathcal{S}^{15}_{34}+\mathcal{S}^{25}_{34}\\
&\quad +\mathcal{F}^{15}_{34}+\mathcal{F}^{25}_{34}\\
&\quad +\mathcal{H}^{15}_{34}+\mathcal{H}^{25}_{34})\\
(E-H_0-V_{12})\,\mathcal{F}^{34}_{12} &= V_{12}\,(\mathcal{S}^{12}_{34}+\mathcal{K}^{1}_{34,5}+\mathcal{K}^{2}_{34,5}+\mathcal{T}_{34,5})
\end{aligned}
$$

5-BODY FADDEEV-YAKUBOVSKI EQ.

Courtesy of R. Lazauskas



Merits:

- ✓ Handling of symmetries
- ✓ Boundary conditions for binary channels
- ✓ Easy reduction to subsystems

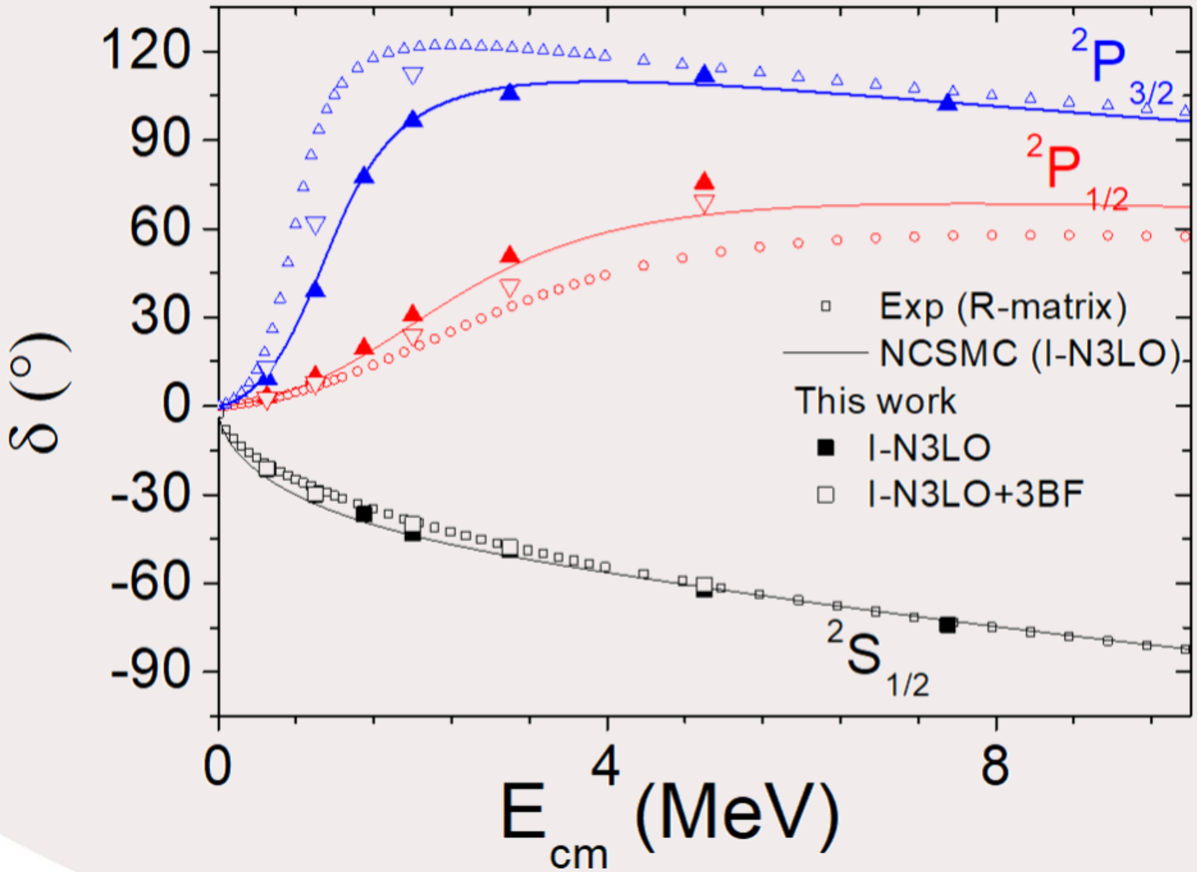
Price

- ✓ Overcomplexity

Problem	Number eq. (identical particles)	Number eq. (different particles)
A=2	1	1
A=3	1	3
A=4	2	18
A=5	5	180
A=6	15	2700
A=N	nint$\left(\frac{2(N-1)!}{(\pi/2)^N}\right)$	$\frac{N!\,(N-1)!}{2^{N-1}}$

7

FY: n-^{4}HE SCATTERING



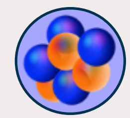
8

RESONATING GROUP METHOD FOR NCSM: LONG-RANGE DYNAMICS AND SCATTERING

S. Quaglioni, P. Navrátil PRL101 (2008).

- Methods develop in this presentation to solve the many body problem

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle \Leftrightarrow$$



$|A\lambda J^{\pi} T\rangle_{SD} \phi_{00}(\vec{R}^{A}_{c.m.})$

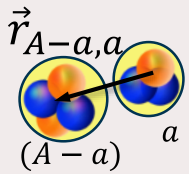
Mixing coefficients(unknown)

A-body harmonic oscillator states

Second quantization

Can address bound and low-lying resonances (short range correlations)

$$\Psi^{(A)}_{RGM} = \sum_{v} \int d\vec{r} \, g_v(\vec{r}) \, \hat{A}_v \left| \Phi^{(A-a,a)}_{v\vec{r}} \right\rangle \Leftrightarrow$$



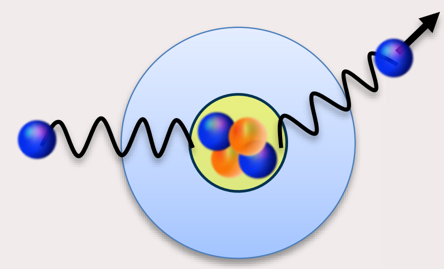
$\psi^{(A-a)}_{\alpha_1} \psi^{(a)}_{\alpha_2} \, \delta(\vec{r} - \vec{r}_{A-a,a})$

Relative wave function (unknown)

Antisymmetrizer

Channel basis

Cluster expansion technique



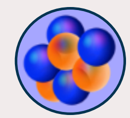
NCSM/RGM
Cluster formalism for elastic/inelastic

EQUAL TREATMENT OF BOUND AND RESONANT STATES: COUPLE NCSM AND NCSM/RGM (NCSMC)

S. Baroni, P. Navrátil and S. Quaglioni PRL110 (2013); PRC93 (2013)

- Methods develop in this presentation to solve the many body problem

$$\Psi^{(A)}_{NCSM} = |A\lambda J^{\pi} T\rangle = \sum_{\alpha} c_{\alpha} \, |A\alpha j_z{}^{\pi} t_z\rangle \Longleftrightarrow |A\lambda J^{\pi} T\rangle_{SD} \phi_{00}(\vec{R}^{A}_{c.m.})$$



Mixing coefficients (unknown)

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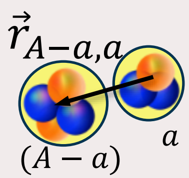
Second quantization

Can address bound and low-lying resonances (short range correlations)

$$\Psi^{(A)}_{RGM} = \sum_{\nu} \int d\vec{r} \, g_{\nu}(\vec{r}) \, \hat{A}_{\nu} \left| \Phi^{(A-a,a)}_{\nu \vec{r}} \right\rangle \Longleftrightarrow \psi^{(A-a)}_{\alpha_1} \psi^{(a)}_{\alpha_2} \, \delta(\vec{r} - \vec{r}_{A-a,a})$$



Relative wave function (unknown)

Antisymmetrizer

Channel basis

Cluster expansion technique

Design to account for scattering states (best for long range correlations)

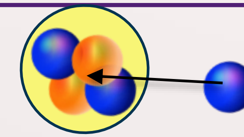
- Our best ansatz combines both wave functions

$$\Psi^{(A)}_{NCSMC} = \sum_{\lambda} c_{\lambda} |A\lambda J^{\pi} T\rangle + \sum_{\nu} \int d\vec{r} \, g_{\nu}(\vec{r}) \, \hat{A}_{\nu} \left| \Phi^{(A-a,a)}_{\nu \vec{r}} \right\rangle$$

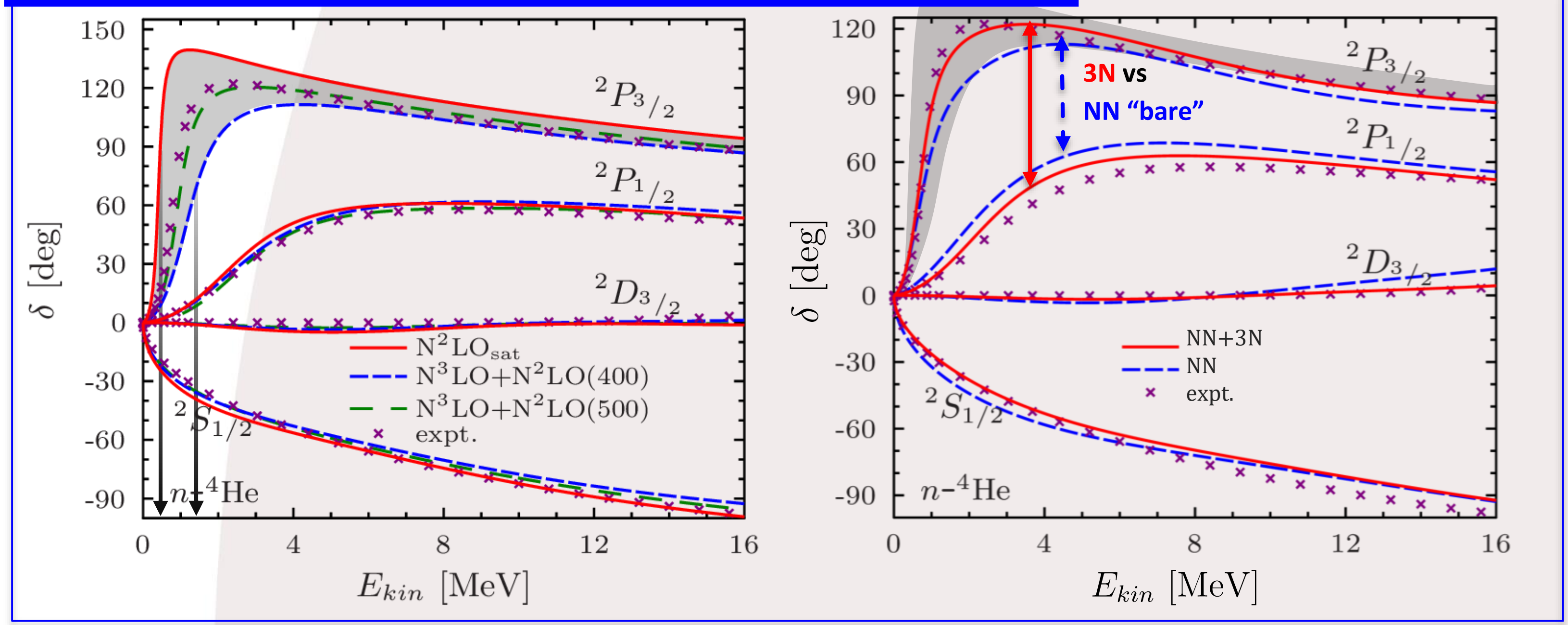
NCSMC

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

DISCLAIMER: ACCURACY OF THE NUCLEAR HAMILTONIAN ?



n-^{4}He scattering phase shifts



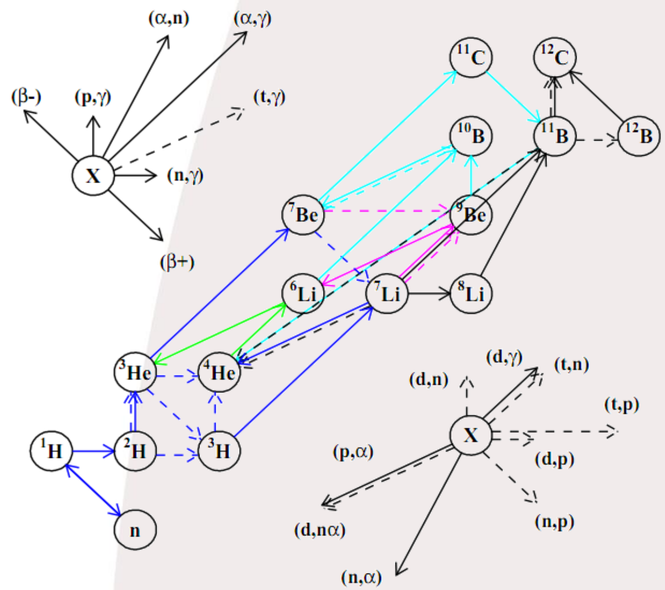
R-matrix results from G. Hale

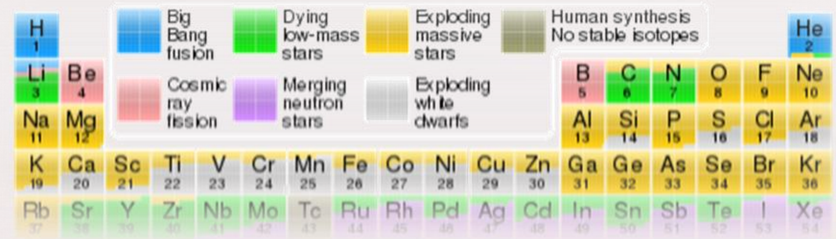
Some of the shortcomings of the nuclear interaction can already be **probed** in *p*-shell nuclei **through reactions**. [known since the work of K. Nollett]

- The 3N interactions **influence** mostly the ***P* waves**.
- Conservative estimate of EFT accuracy is in the range of 3N force effects.

LOW-ENERGY TRANSFER REACTIONS (*d*,*N*)

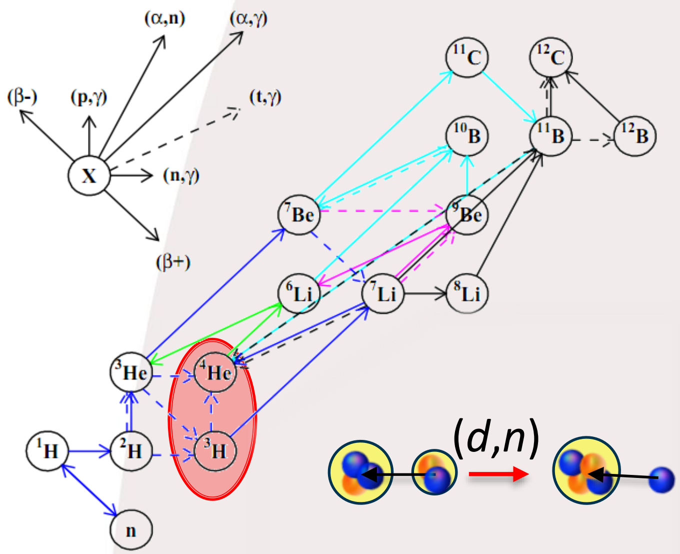
Primordial Nucleosynthesis **(blue)**



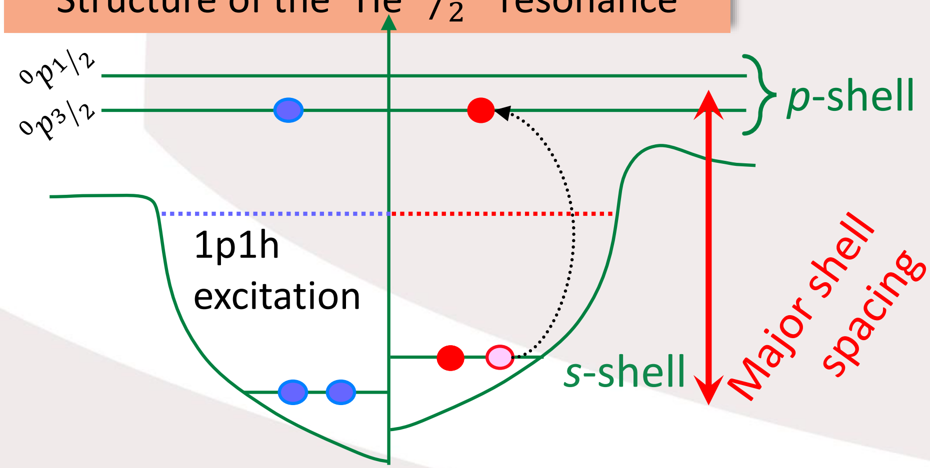


LOW-ENERGY TRANSFER REACTIONS (*d*,*N*)

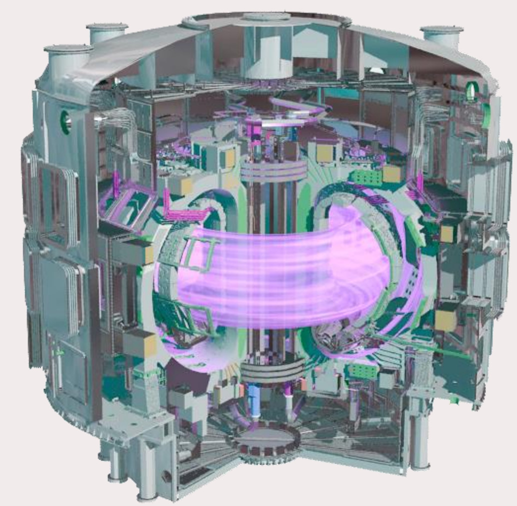
Primordial Nucleosynthesis (blue)



Structure of the ^{5}He $^3/_2{}^+$ resonance



ITER design (Cadarache, France)



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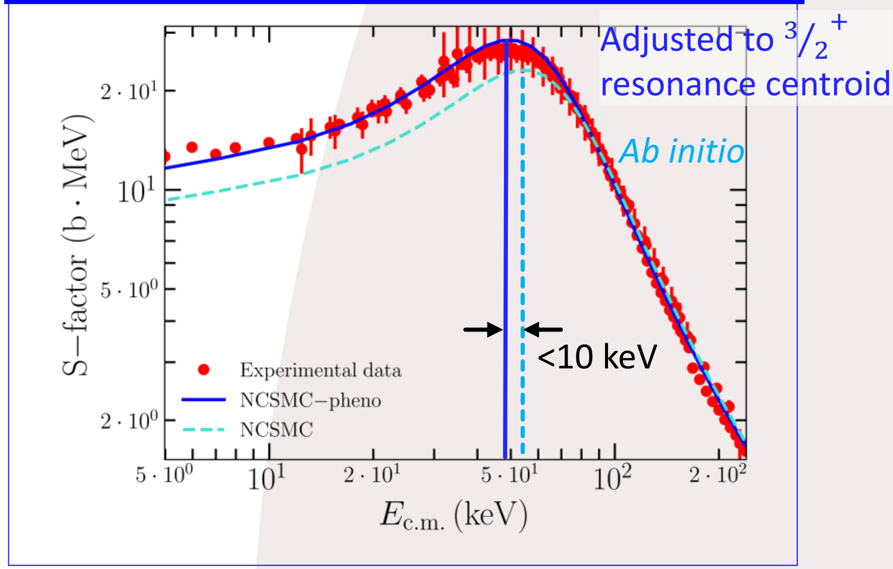
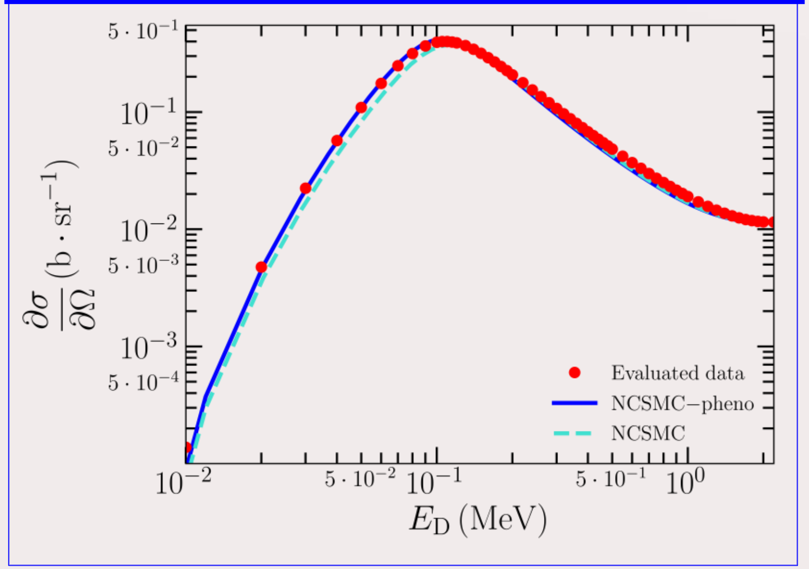
^{3}H(d,n)^{4}He REACTION: COMPARISON TO DATA

S-factor: computed and data



Angular distribution at $\theta = 0^\circ$

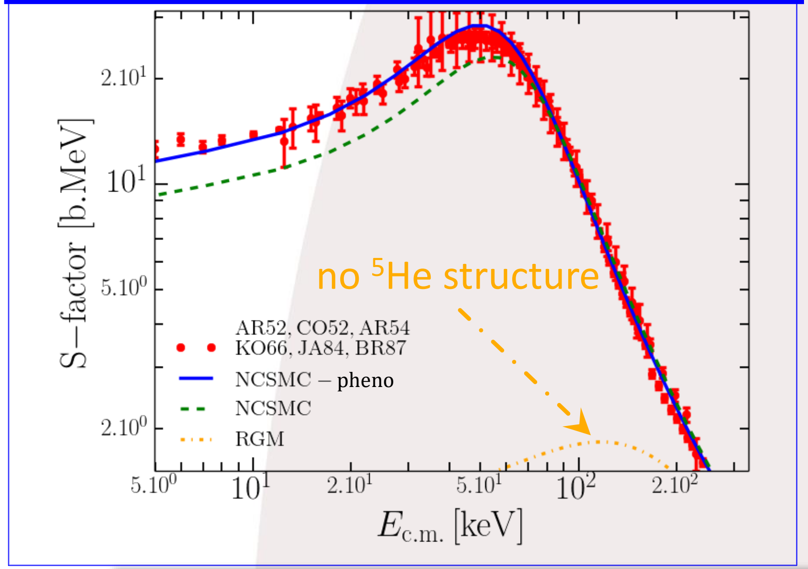


M. Drosg and N. Otuka, INDC(AUS)-0019 (2015).

- The S-factor is globally well reproduced.
- The accurate **reproduction** (of the order of keV) of the **resonance position/width** is **essential**.
- Shape of a the angular distribution **agrees** with recent **evaluation**.

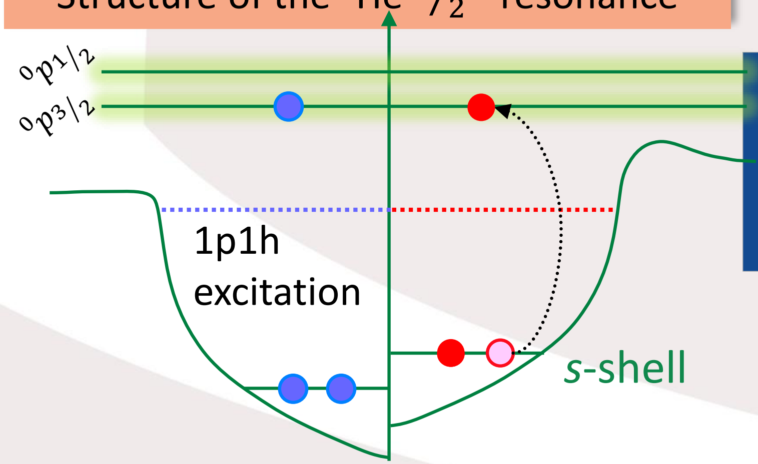
^{3}H(d,n)^{4}He REACTION: IMPACT OF THE RESONANCE STRUCTURE

S-factor: NCSMC vs binary cluster



^{5}He($^4S_{3/2}$)	E_r (keV)	Γ_r (keV)
Cluster basis (D g.s. only)	105	1100
Cluster basis	120	570
NCSMC (D g.s. only)	65	160
NCSMC	55	110
NCSMC-pheno	50	98
R-matrix	48	25

Structure of the ^{5}He $^3/_2{}^+$ resonance



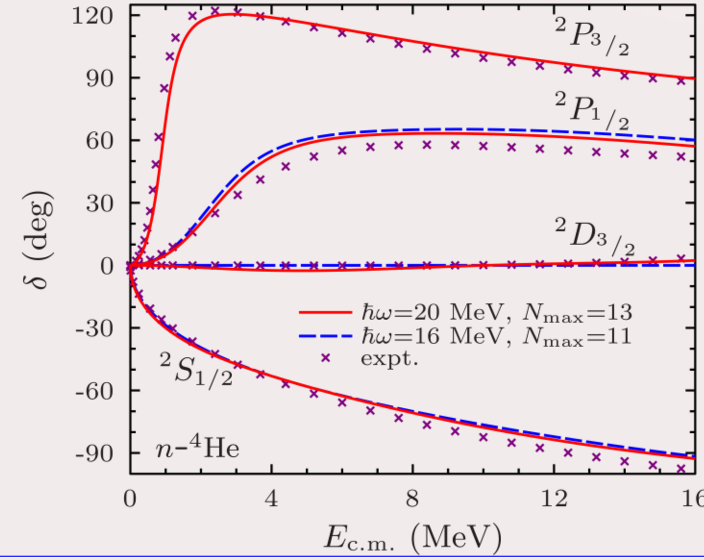
- **Importance** of **structure** of neighboring resonances is magnified in **transfer reactions.**

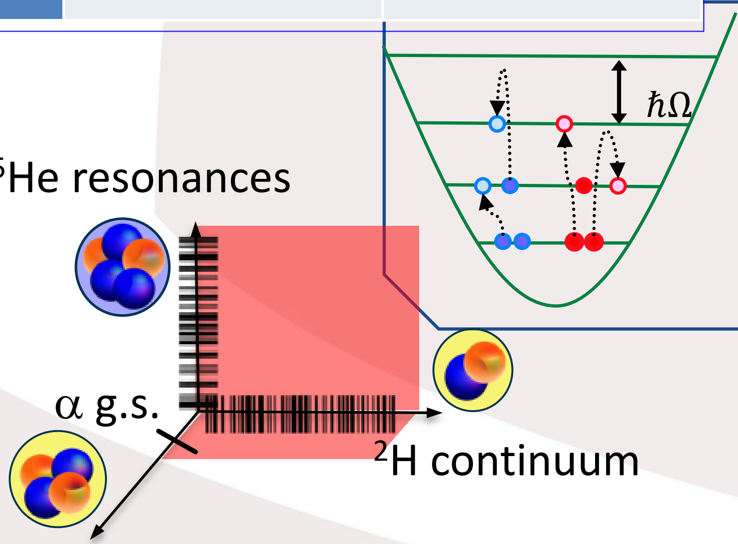
^{3}H(d,n)^{4}He FUSION REACTION: MODEL CONVERGENCE

Convergence of $^3/_2{}^+$ resonance

N_{max}	$\hbar\omega$=20 MeV Λ_{SRG}=2.0 fm^{-1}	$\hbar\omega$=16 MeV Λ_{SRG}=1.7 fm^{-1}
7	78.70%	42.29%
9	45.04%	18.85%
11	25.68%	8.41%
13	13.78%	-

n-^{4}He phase shifts

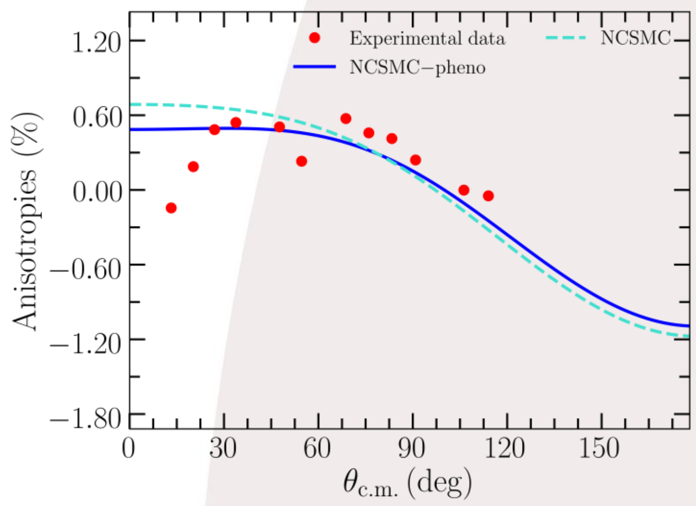




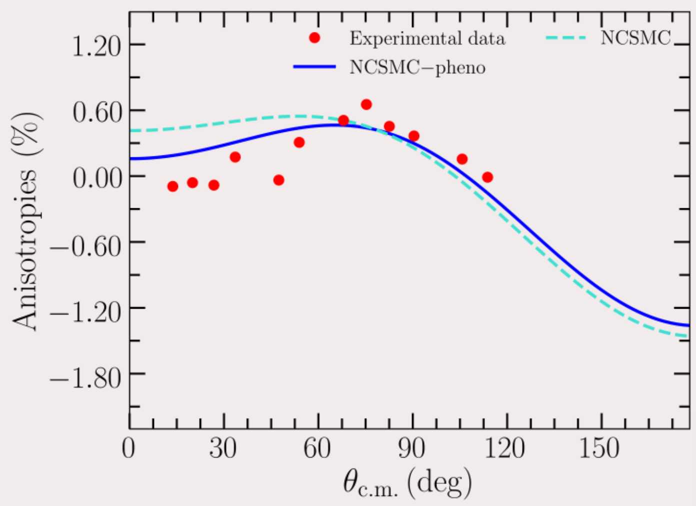
- $^3/_2{}^+$ resonance converges the **fastest** with $\hbar\omega = 16$ MeV, understood from **major shell splitting**.
- n-^{4}He elastic scattering independent of HO frequency and SRG flow.

$^{2}H(t,n)^{4}He$ FUSION REACTION: INFLUENCE $\ell \neq 0$ WAVES

Anisotropies of X-section



Anisotropies of X-section

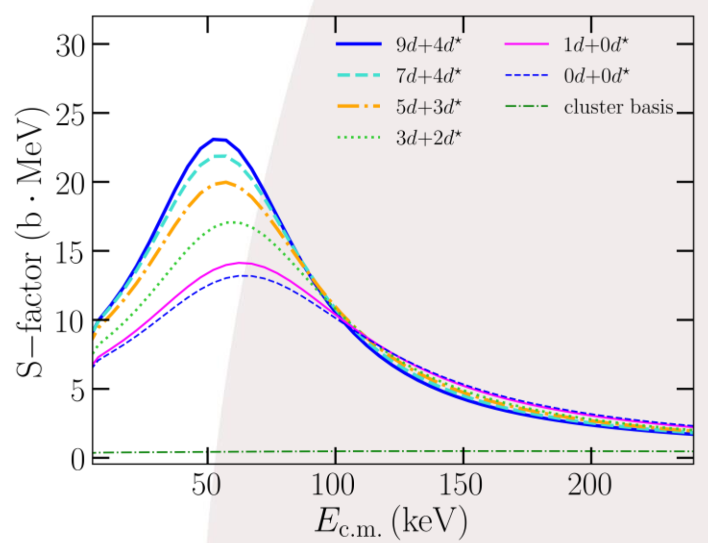


P. Bém *et al.*, Few-Body Syst**22**, 77 (1997).

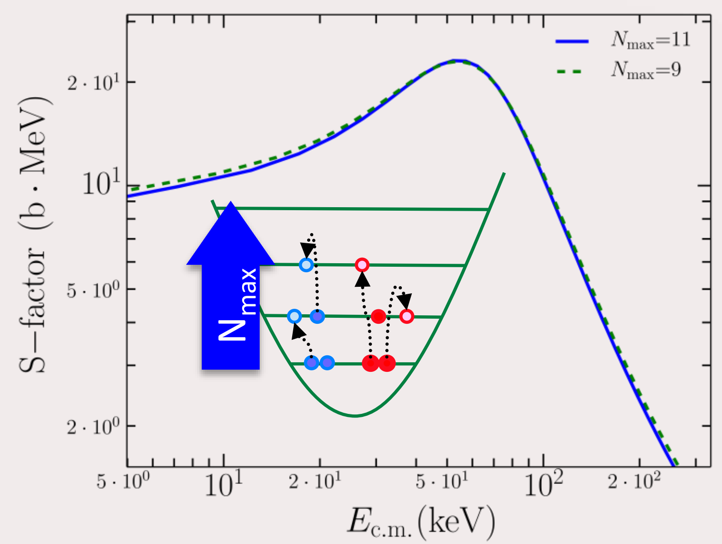
- Influence of *p*- and *d*-waves in the slope and bump of $\partial\sigma_{\mathrm{rel}}/\partial\Omega$, respectively.
- Overall good reproduction of data: **collision matrix** is expected to be **accurate**.

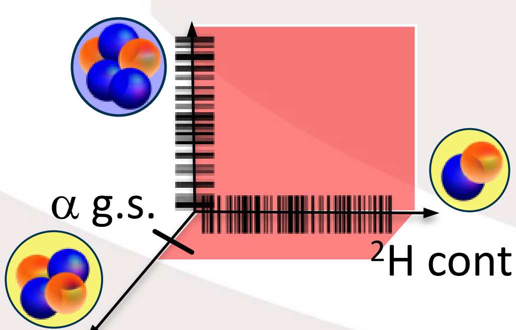
^{2}H(t,n)^{4}He REACTION: MODEL CONVERGENCE

Convergence wrt ^{2}H continuum



Convergence with Nmax

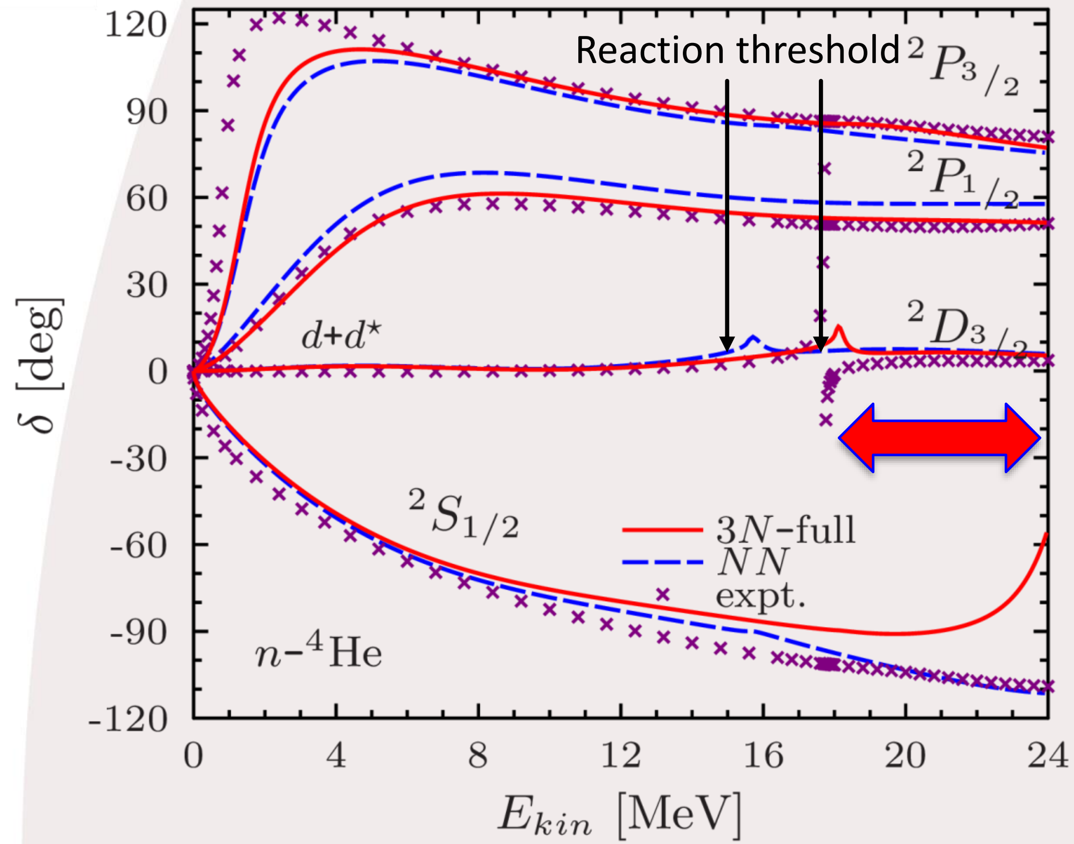


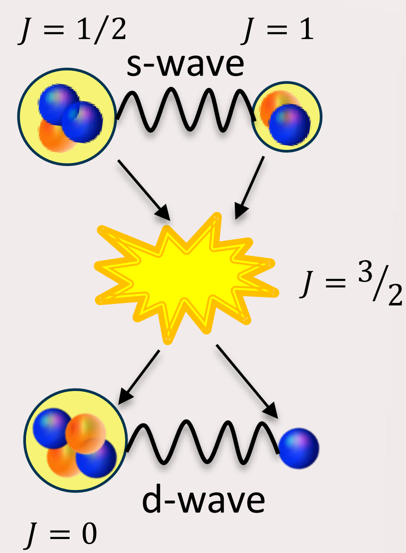


correlated

- Discretization of ^{2}H is **essential** for the reproduction of the S-factor.
- Stable behavior with respect to the number of ^{2}H pseudo states.
- Converged with N_{max}.

$^3H(d,n)^4He$ REACTION: MASSES & Q-VALUES AND TENSOR FORCE

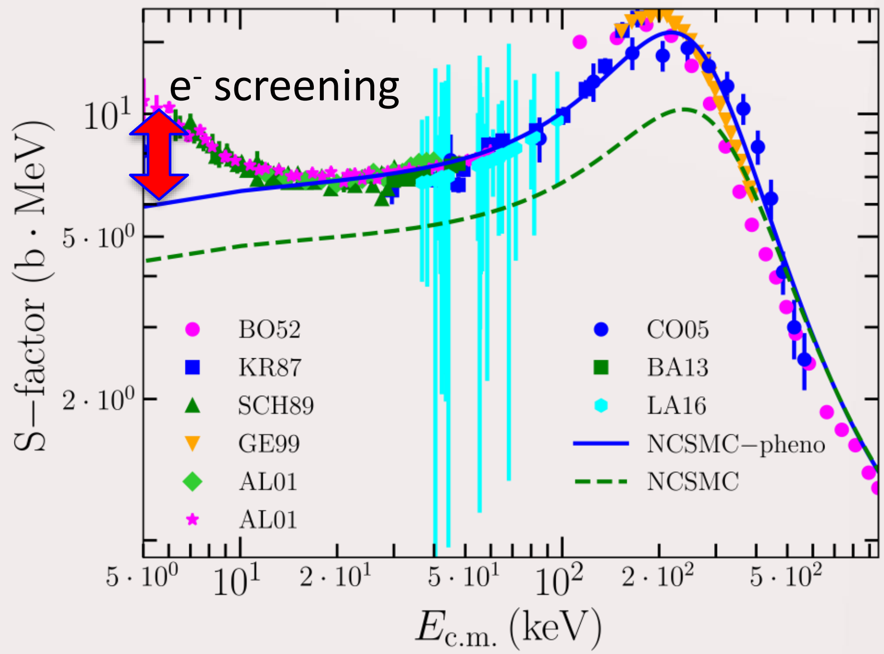


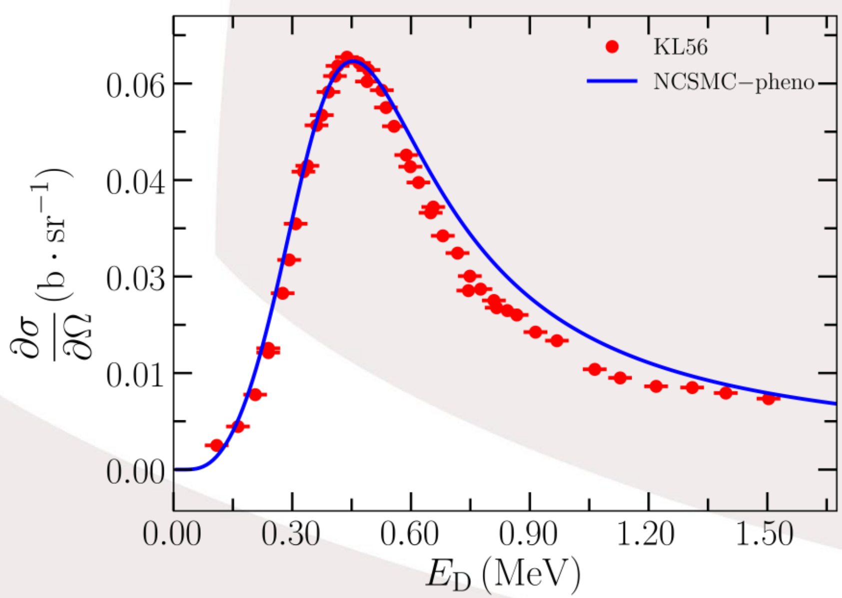


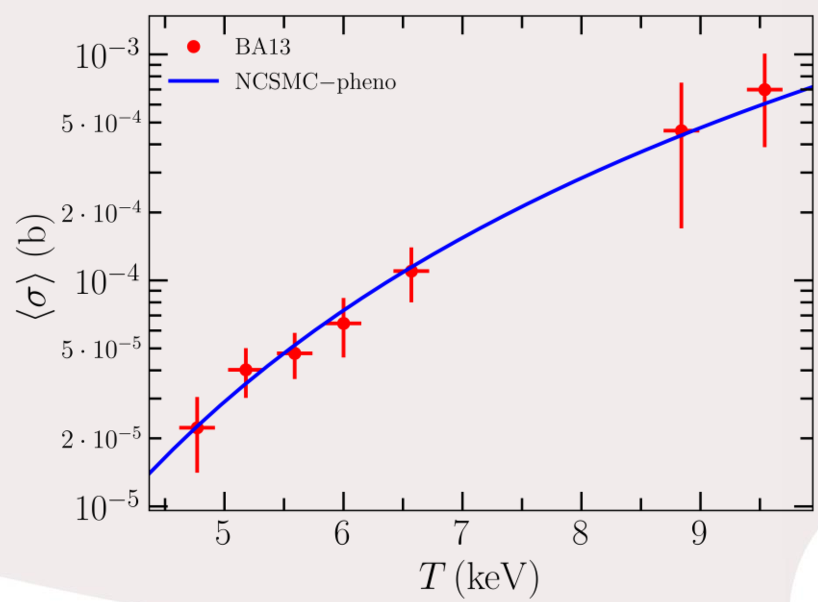
- 3N force impacts:
  - The threshold position.
  - The **positions and splitting** between the $^3/_2{}^+$ and $^1/_2{}^+$ resonances.
- **Tensor force** is essential to model the $^3H(d,n)^4He$ transfer reaction.

$^{3}He(d,p)^{4}He$ FUSION REACTION: GLOBALLY SIMILAR TO DT

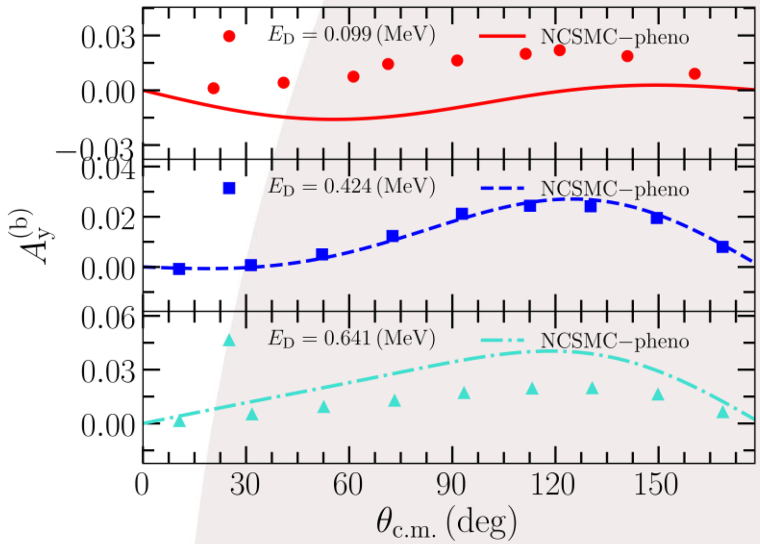
- The S-factor is globally well reproduced.
- However, there are **discrepancies** between data sets around the peak of the S-factor.
- Influence of *p*- and *d*-waves in agreement with data.

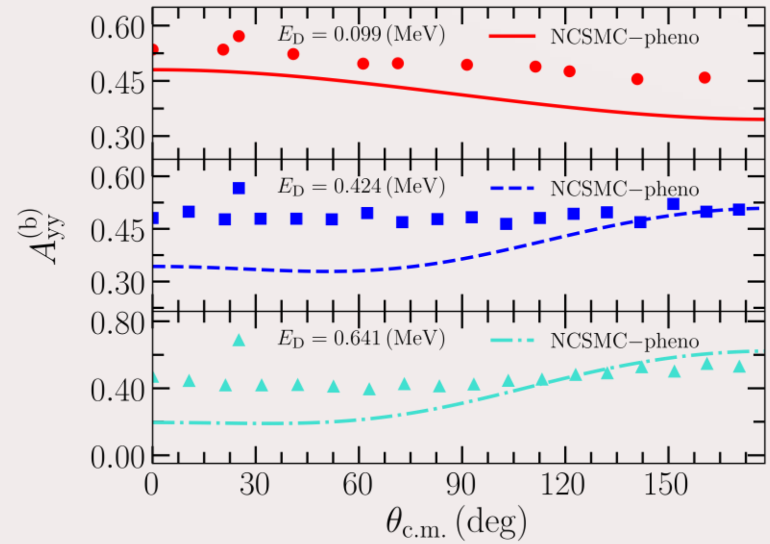


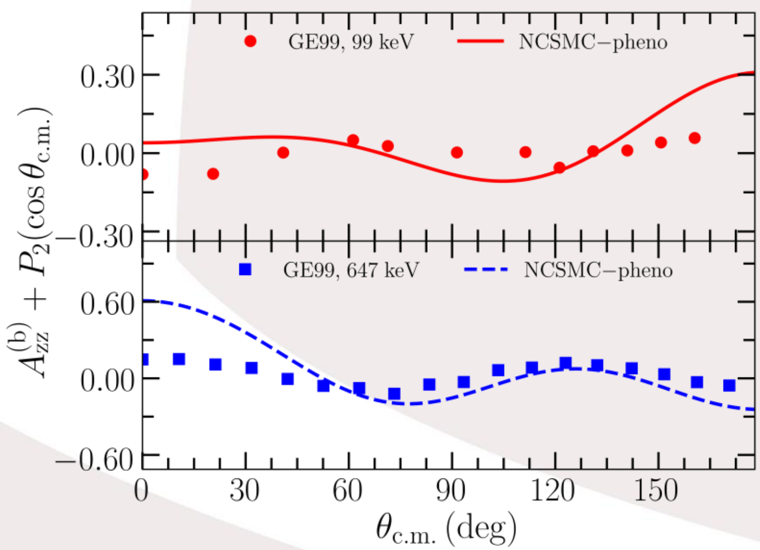




^{3}He($\vec{d}$,p)^{4}He REACTION

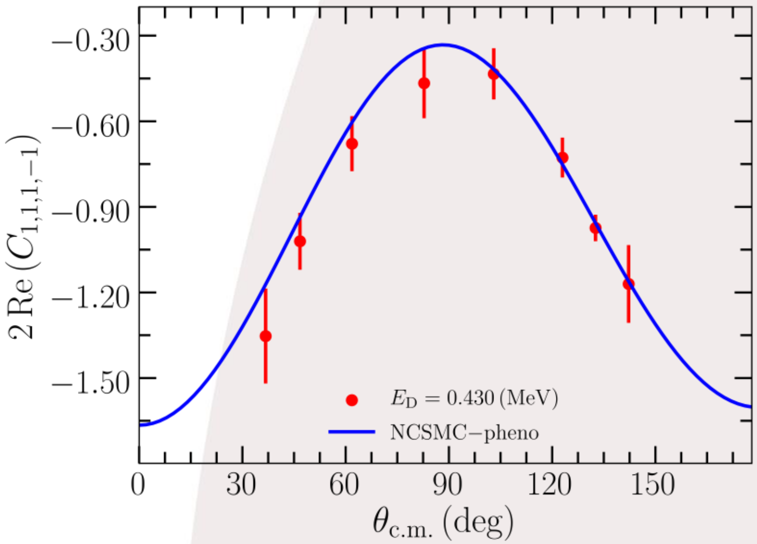


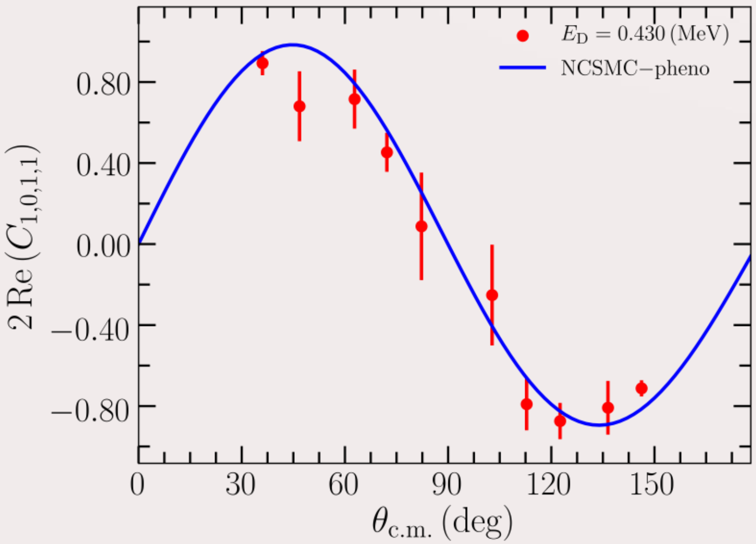


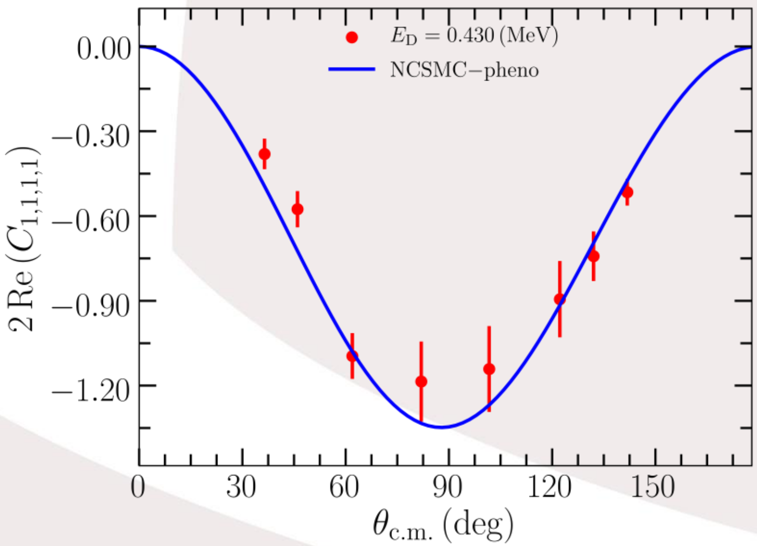


Deviations from a pure *s*-wave of the analyzing tensors are globally reproduced in shape but their **amplitude is not**.

$^3\overrightarrow{He}(\vec{d},p)^4$He REACTION

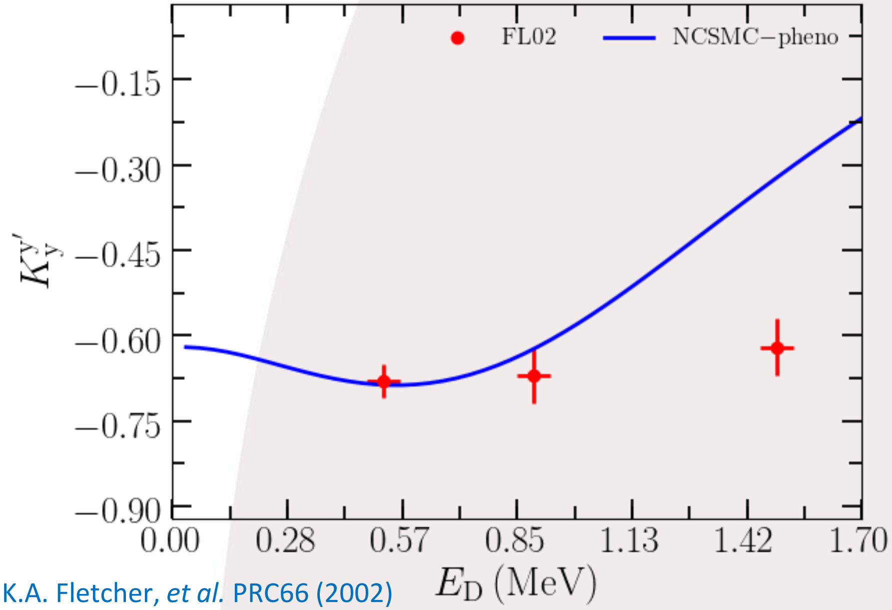






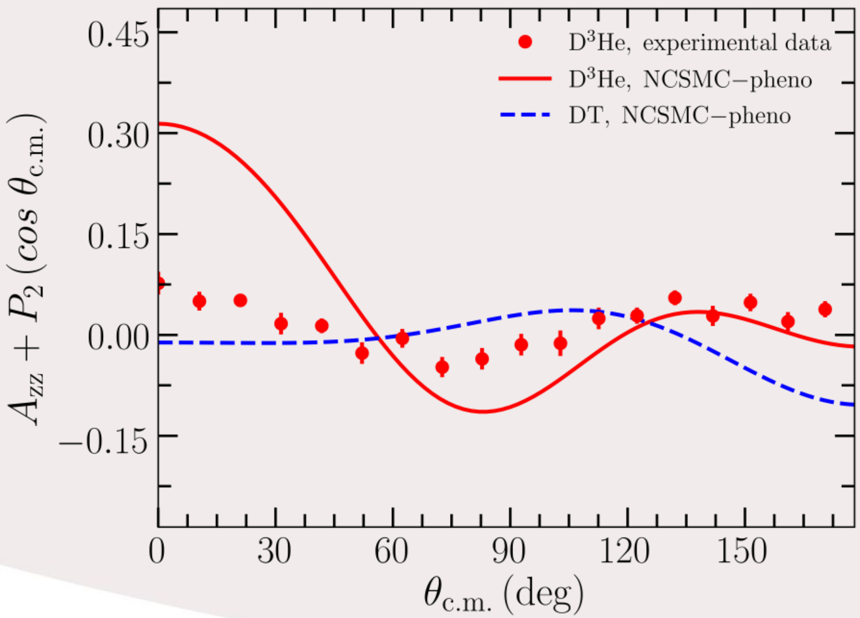
Deviations from a pure *s*-wave of the analyzing tensors are globally reproduced in shape but their **amplitude is not**.

$^3He(d,p)^4He$ REACTION



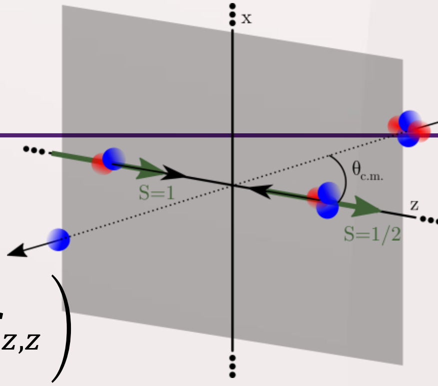
K.A. Fletcher, *et al.* PRC66 (2002)

Polarization transfer is in agreement with data around the fusion peak but disagree at higher energies.
[as is the differential cross-section]



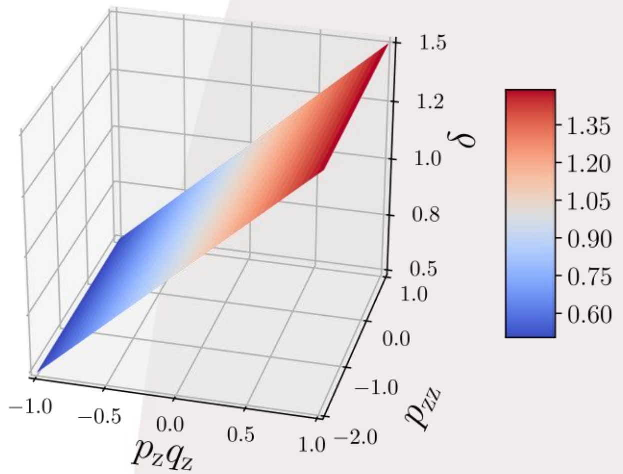
Caution: analyzing tensors cannot be deduced straightforwardly from mirror reaction.

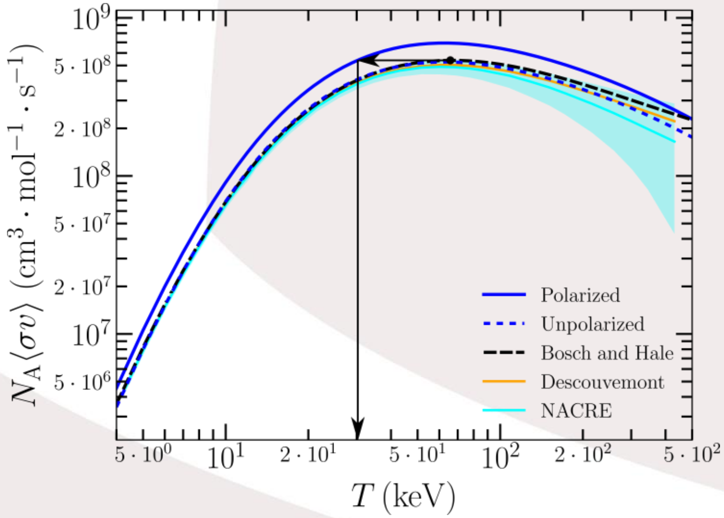
DT POLARIZED



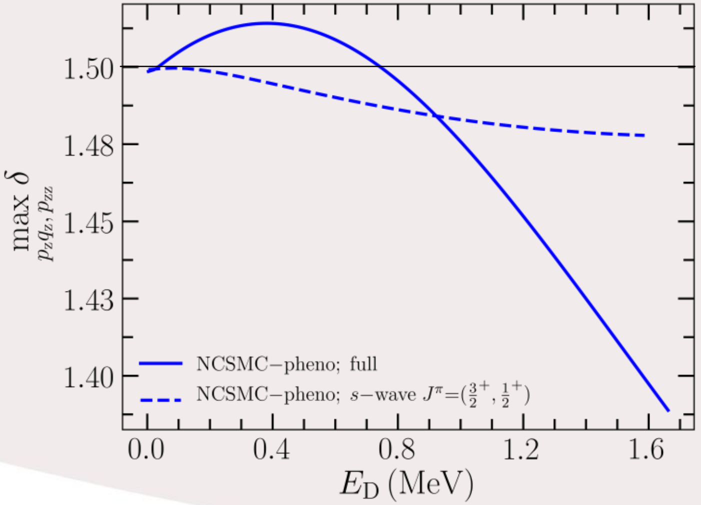
$$\sigma^{\text{polar}}(\theta) = \sigma(\theta)\left(1 + \frac{1}{2}p_{zz}A_{zz} + \frac{3}{2}p_z q_z C_{z,z}\right)$$

Enhancement factor and reaction rate



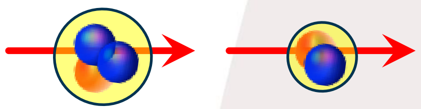


- **Predictions** for polarized $^3\vec{\mathrm{H}}(\vec{d},n)^4\mathrm{He}$ enhancement factor and reaction rate.
- **Confirmation** of maximum enhancement ($\delta = 1.5$) scenario.
- *Ab initio* calculation shows that $\delta = 1.38$ can be achieved in lab.

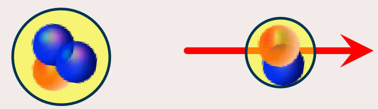


ANISOTROPIES IN POLARIZED REACTION

Angular distribution in different polarization scenarios

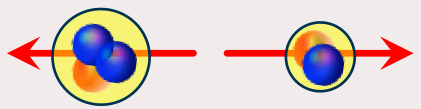


Total cross section increased

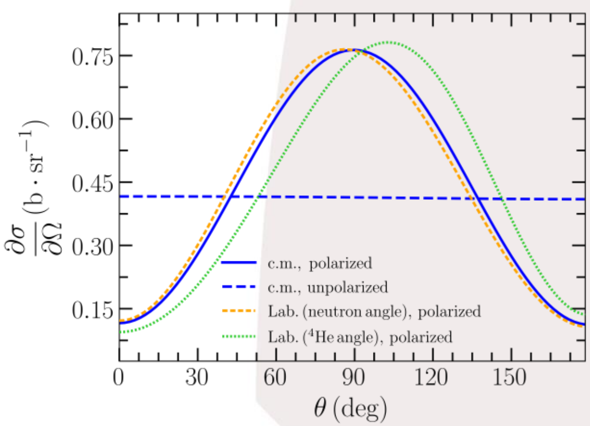


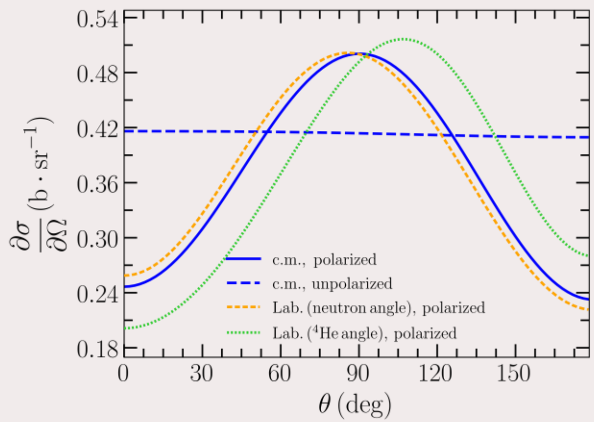
on average no effects

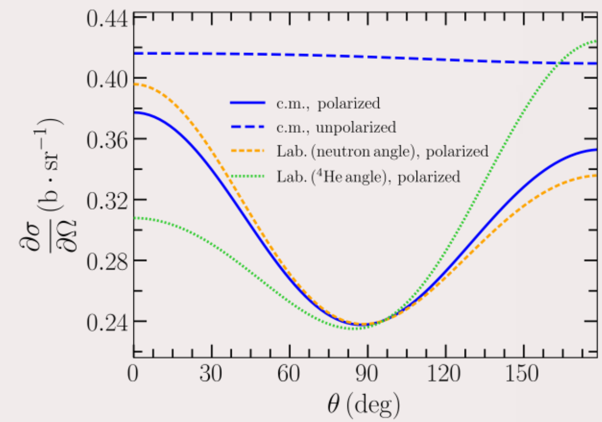
$J = 1/2$ $J_z = -1/2$ $J = 1$ $J_z = 1$



Total cross section decreased



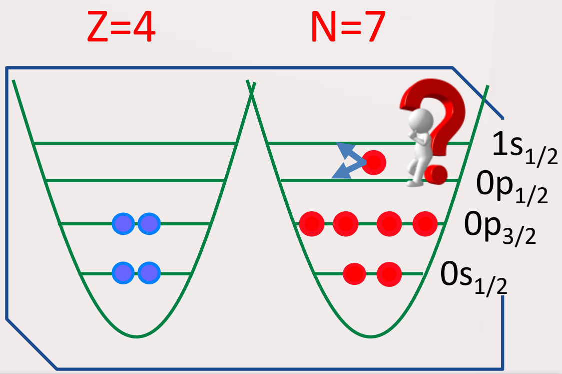




Spin tensor properties of the deuteron give the angular shape.
(Same as in $^3\overrightarrow{\mathrm{He}}(\vec{d},p)^4\mathrm{He}$)

ν-RICH HALO NUCLEUS ^{11}Be

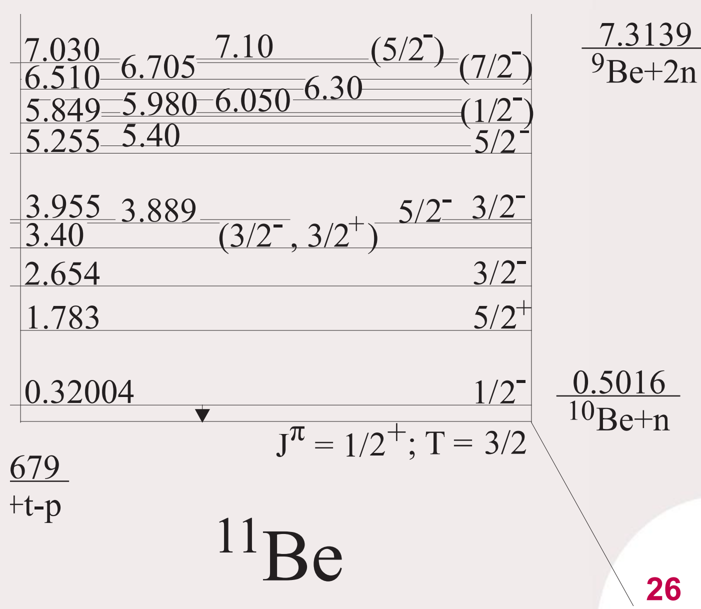
- In a shell model picture, the g.s. expected to be $J^{\pi} = 1/2^{-}$.
- In reality, ^{11}Be g.s. is $J^{\pi} = 1/2^{+}$ -- parity inversion.
- Very weakly bound: E_{th}=-0.5 MeV Halo state -- dominated by n-^{10}Be in a S-wave.
- The $1/2^{-}$ state also bound -- only by 180 keV.



Single particle interpretation using nuclear shell model

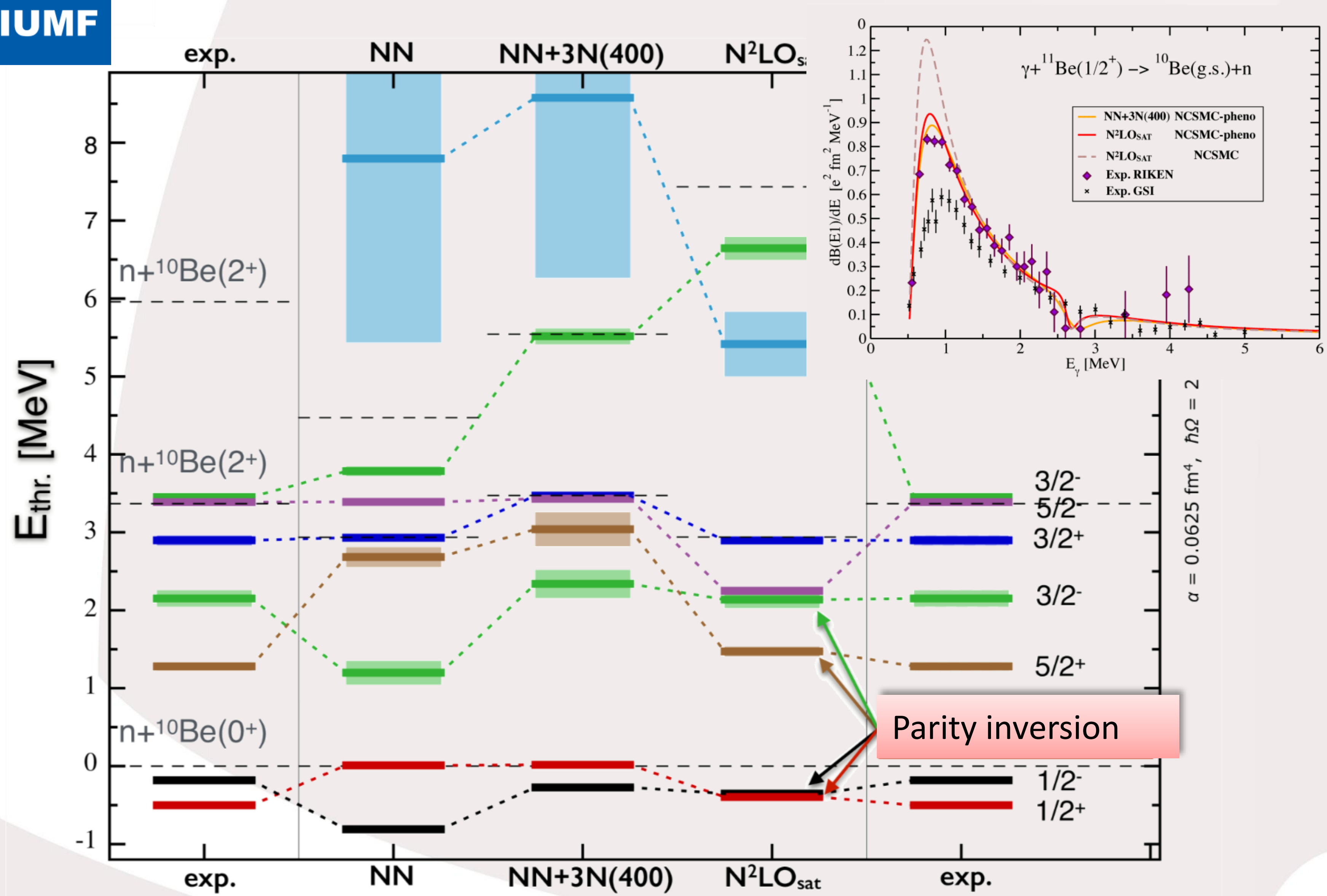
Can we describe ^{11}Be in *ab initio* calculations?

- Continuum must be included.
- Does the 3N interaction play a role in the parity inversion?



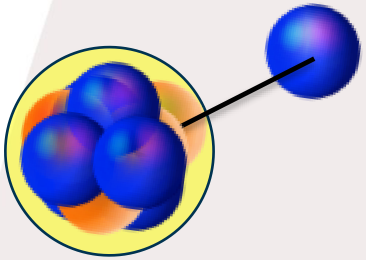
^{11}Be WITHIN NCSMC: DISCRIMINATION AMONG CHIRAL NUCLEAR FORCES

A. Calci et al. PRL117 (2016)



BEYOND AB INITIO: HYBRID METHOD

P. Capel, D.R. Phillips, H.-W. Hammer PRC09 034610 (2018)

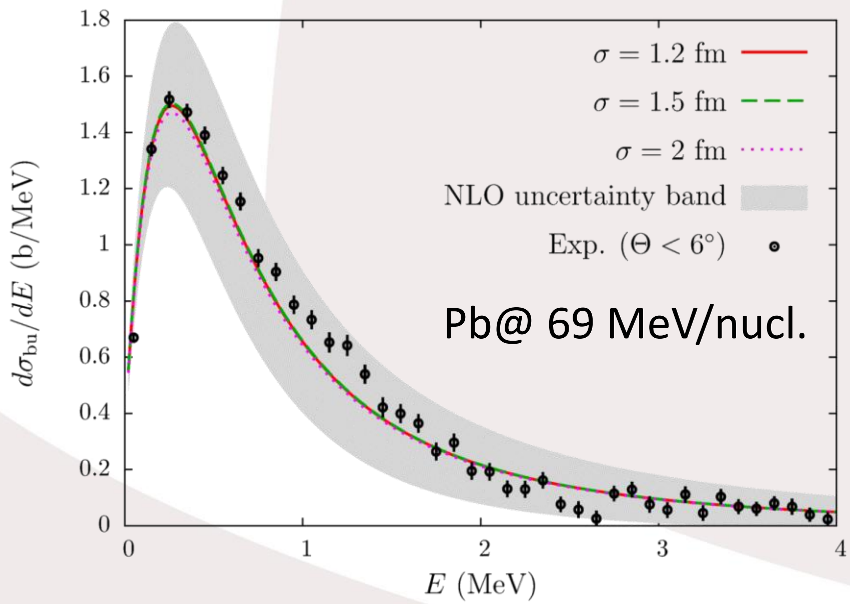


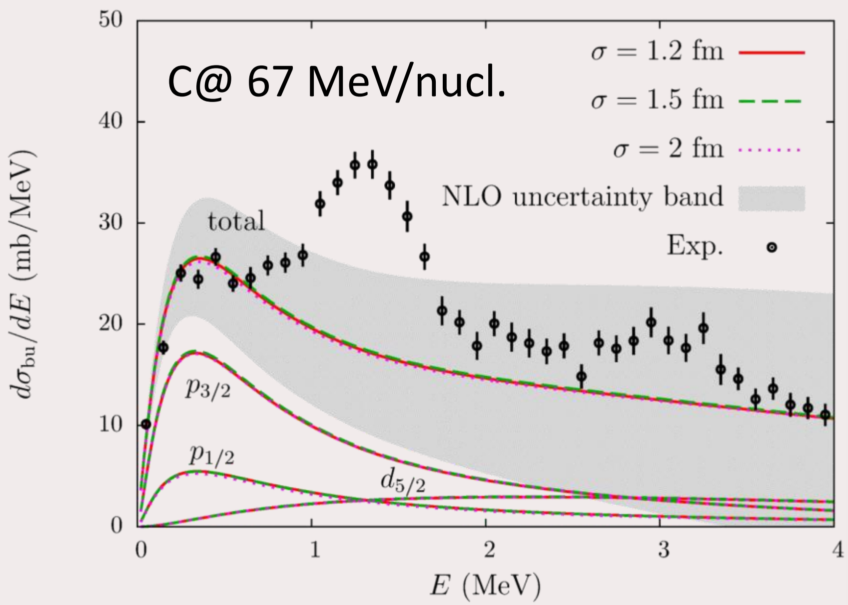
Inputs:

- Ab initio ANC for s- and p-wave bound states.
- Experimental S_n.

Methods:

- Response function and ^{10}Be-n potential from Halo EFT.
- Optical potential for target interactions.





IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

THANK YOU !

Summary:

- *Ab initio* reaction model is reasonably accurate.
- Continued evidence that 3N force is essential to *p*-shell physics.
- Surprisingly good postdiction of DT and D^3He fusion reaction.
- Confirmation of a 50 year old idea suggested for plasma application.