SIX CHALLENGES

reaction theory for HEAVY UNSTABLE nuclei

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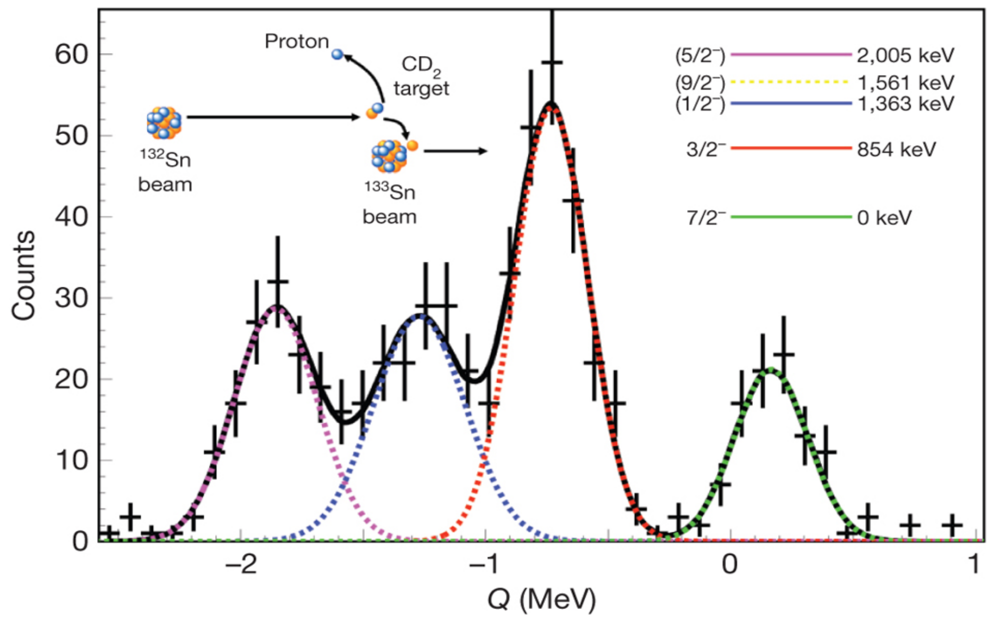
Our starting point

- A complex many-body problem
- Scattering boundary conditions
- Importance of thresholds
- Large Coulomb interactions
- Specific clustering

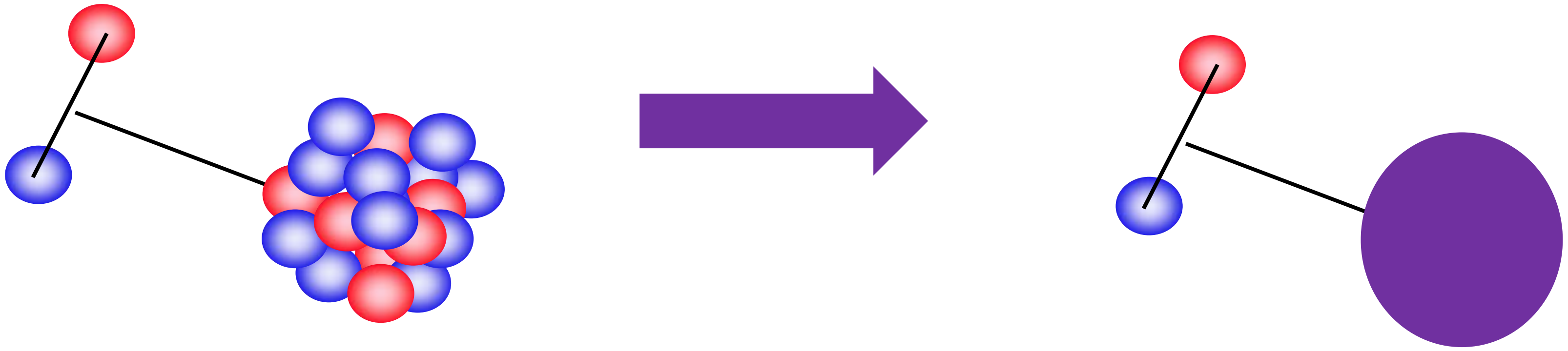
d(^{132}Sn,^{133}Sn)p@5 MeV/u



1st challenge: reduction to few-body

- Reducing the many-body problem to a few-body problem introduces effective interactions.
- How does the original many-body Hamiltonian relate to the few-body Hamiltonian?
- We assume that $\mathcal{H}_{3B} = T_{\mathbf{r}} + T_{\mathbf{R}} + U_{nA} + U_{pA} + V_{np}$
- What are these U_{NA}?

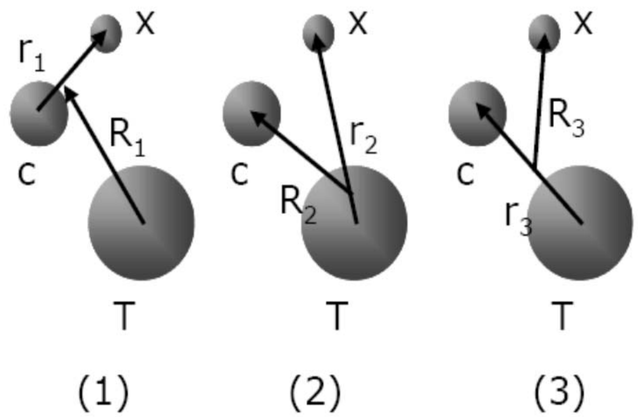
R.C. Johnson, ECT*, November 2015



2^{nd} challenge: solving the few-body

Faddeev Formalism

$$
\begin{aligned}
(E - T_1 - V_{xc})\Psi^{(1)} &= V_{xc}(\Psi^{(2)} + \Psi^{(3)}) \\
(E - T_2 - V_{ct})\Psi^{(2)} &= V_{ct}(\Psi^{(3)} + \Psi^{(1)}) \\
(E - T_3 - V_{tx})\Psi^{(3)} &= V_{tx}(\Psi^{(1)} + \Psi^{(2)})
\end{aligned}
$$



Benchmarking few-body methods

4N bound state

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
CRCGV	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

Method	S wave	P wave	D wave
FY	85.71	0.38	13.91
CRCGV	85.73	0.37	13.90
SVM	85.72	0.368	13.91
HH	85.72	0.369	13.91
NCSM	86.73	0.29	12.98
EIHH	85.73(2)	0.370(1)	13.89(1)

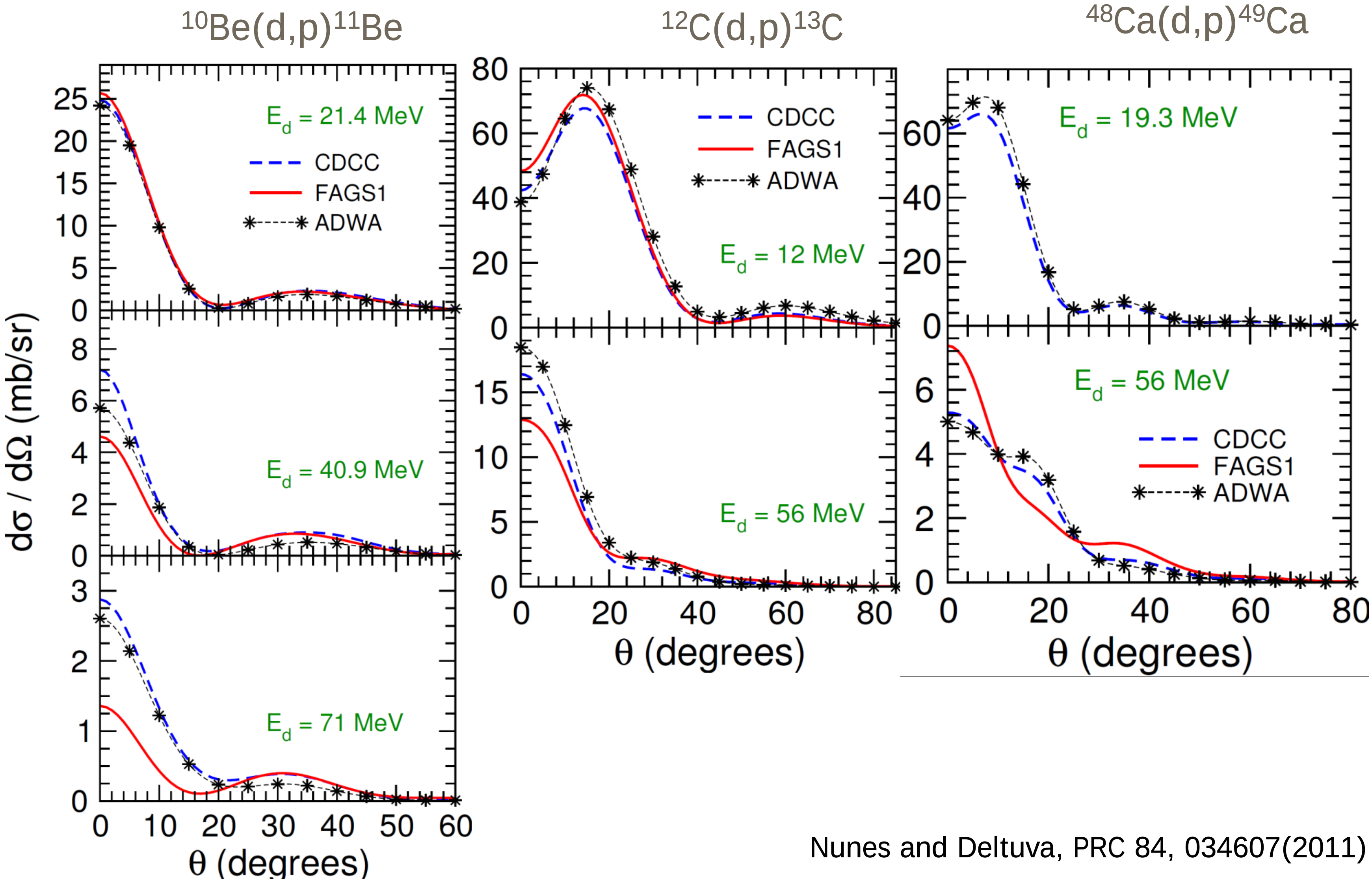
H. Kamada, et al, PRC 64, 044001 (2001)

TABLE III. AV18 n-^{3}H

$E_{c.m.}$	σ (b)	
0.40	1.73	AGS
	1.75	FY
	1.76	HH
0.75	1.79	AGS
	1.78	FY
	1.79	HH
1.50	2.22	AGS
	2.06	FY
	2.06	HH
2.625	2.51	AGS
	2.24	FY
	2.24	HH
3.0	2.48	AGS
	2.21	FY
	2.21	HH

Lazauskas et al., Phys. Rev. C 71, 034004 (2005)

Benchmarking few-body methods



Nunes and Deltuva, PRC 84, 034607(2011)

Upadhyay, Deltuva and Nunes, PRC 85, 054621

2nd challenge: solving the few-body

The problem for a few nucleons (no Coulomb!)

- Scattering is harder than bound states: there are small discrepancies…

When the problem involves intermediate mass systems:

- Approximate methods are often used
- Depending on the observables, different energy region of validity

When the problem involves heavy mass systems:

- No exact methods currently available
- Cannot determine whether approximate methods are suitable
- The goal: to benchmark various methods for reactions with heavy nuclei and at low energy!!

Eremenko and TORUS collaboration, in progress

3rd challenge: determining V_{eff}

Currently our thinking:

- V_{eff} is effective interaction between N-A and should describe elastic scattering (global optical potential)
- V_{eff} is self energy of N+A system and can be extracted from many-body theories (microscopic optical potential)

How do these two approaches compare?

- Study optical potentials for known systems
- Study extrapolations to unknown regions of nuclear chart

Rotureau et al., in progress

Dispersive Optical Model

- Most recent development is a blend of
  - Theory and experiment
  - Structure and reaction
  - Bound and scattering

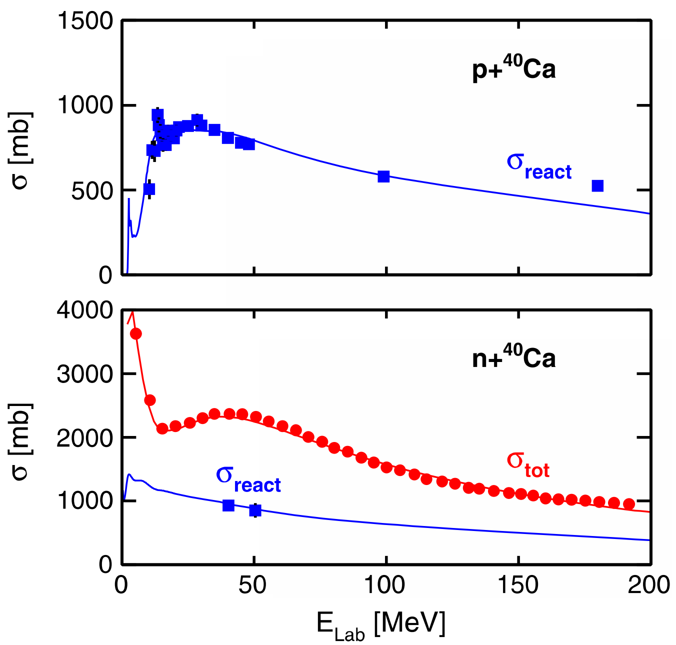


FIG. 2 (color online). Total reaction cross sections are displayed as a function of proton energy while both total and reaction cross sections are shown for neutrons.

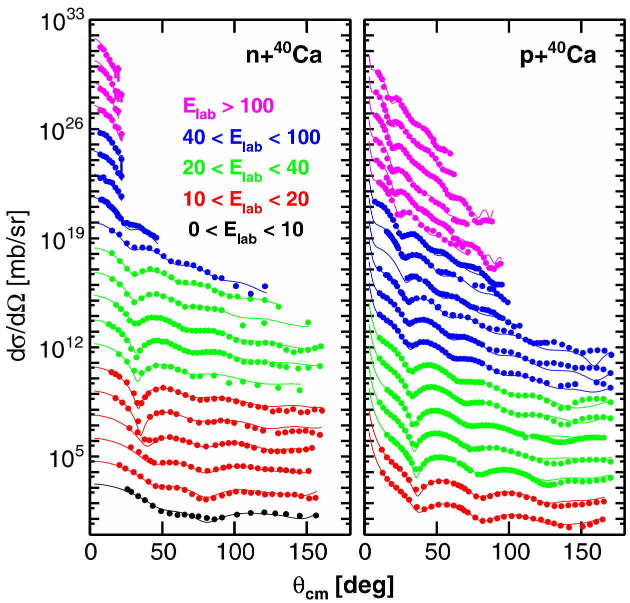


FIG. 1 (color online). Calculated and experimental elastic-scattering angular distributions of the differential cross section $d\sigma/d\Omega$. Panels shows results for $n + {}^{40}$Ca and $p + {}^{40}$Ca. Data for each energy are offset for clarity with the lowest energy at the bottom and highest at the top of each frame. References to the data are given in Ref. [15].

Mahzoon et al, Phys Rev Lett 112, 162503 (2014)

4th challenge: dealing with non-locality

- The optical potential derived from many-body theories is inherently non-local
- The optical potential extractred from data is usually made local

- Effect of non-locality?
- How to deal with non-locality?
- How to pin down non-locality?
- Is this a relevant question?

Titus, Nunes & Johnson, Timofeyuk

Non-locality effect in transfer reactions

- elastic scattering does not constrain non-locality
- effect of non-locality on transfer is very significant
- Unclear how to constrain it experimentally

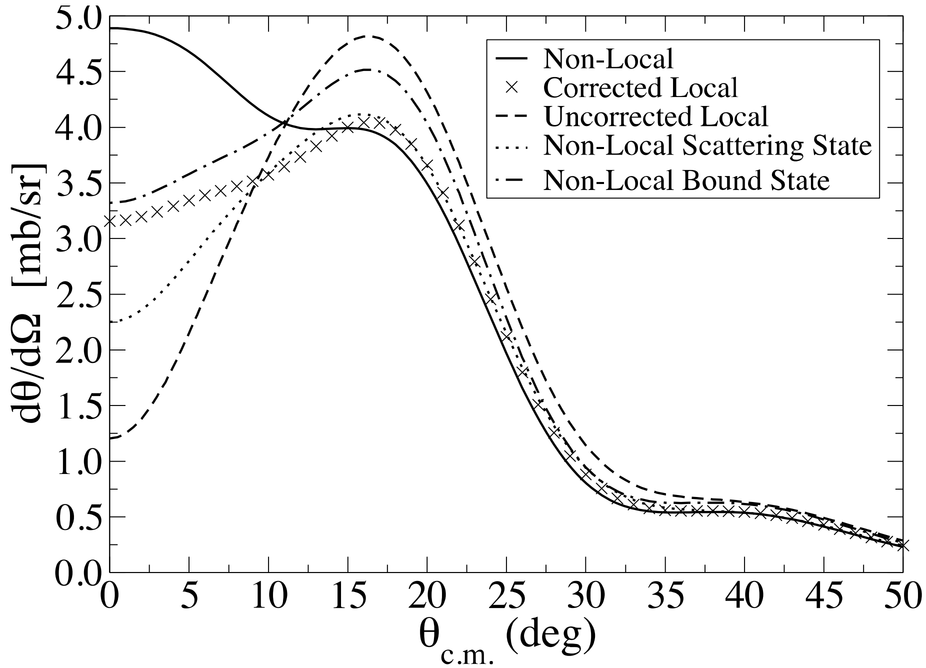
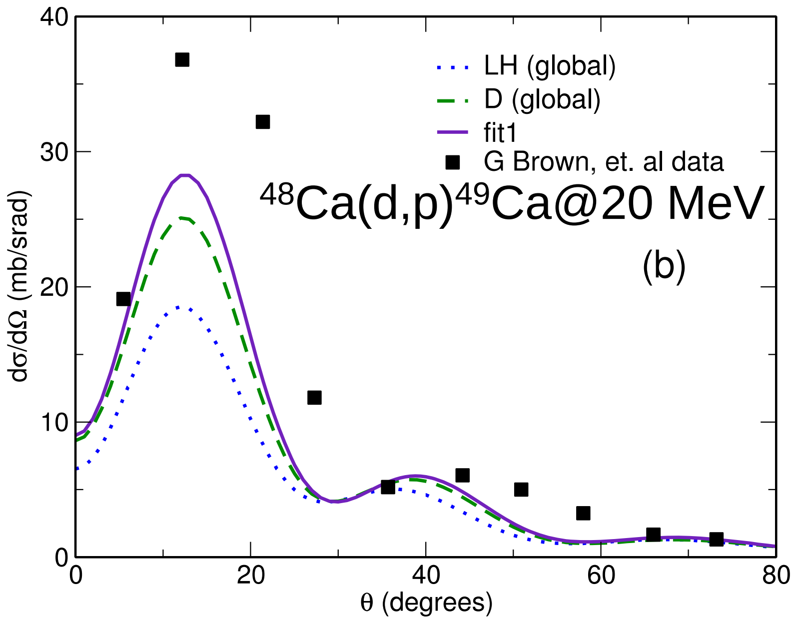


FIG. 5: Angular distributions for $^{49}Ca(p,d)^{48}Ca$ at 50.0 MeV: inclusion of non-locality in both the proton distorted wave and the neutron bound state (solid line), using LEP, then applying the correction factor to both the scattering and bound states (crosses), using the LEP without applying any corrections (dashed line); including non-locality only to the proton distorted wave (dotted line), and including non-locality in the neutron bound state only (dot-dashed line).

Titus and Nunes, PRC 89, 034609 (2014)

5th challenge: uncertainty quantification

- All these challenges introduce uncertainties
- The additional challenge is:
  - to determine those uncertainties
  - to propagate those uncertainties to the observables of interest
  - Situations for stable nuclei



Lovell and Nunes, J Phys G 42, 034014 (2015)

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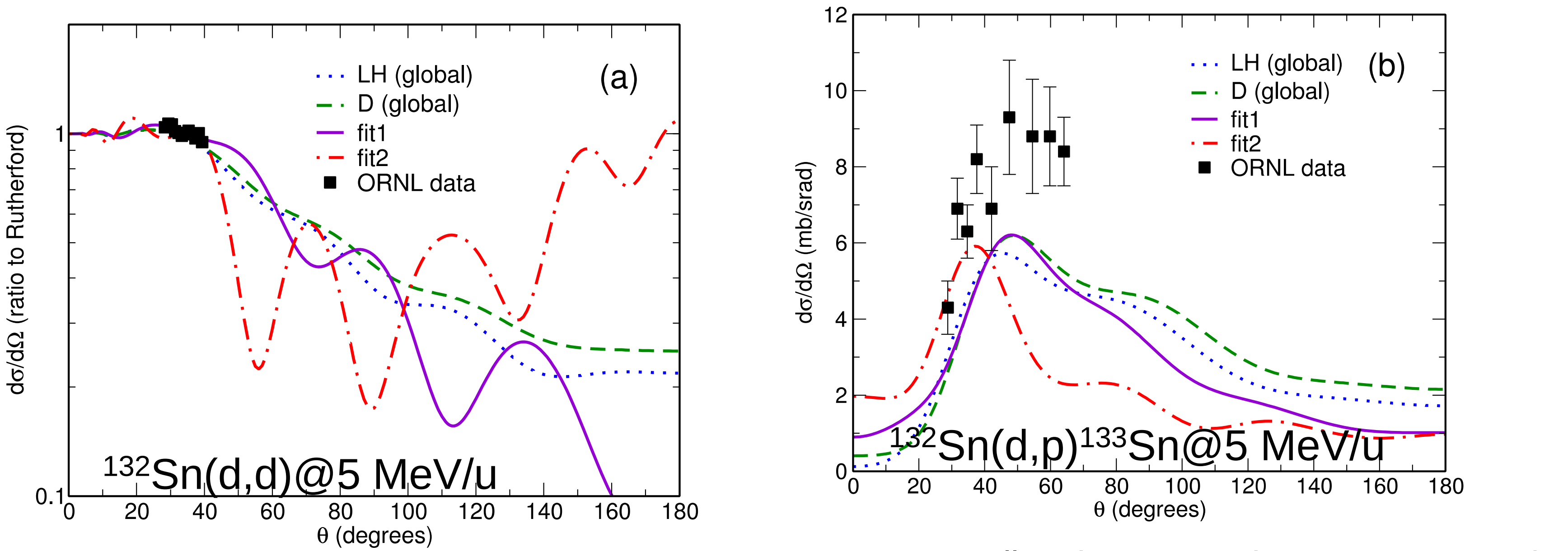
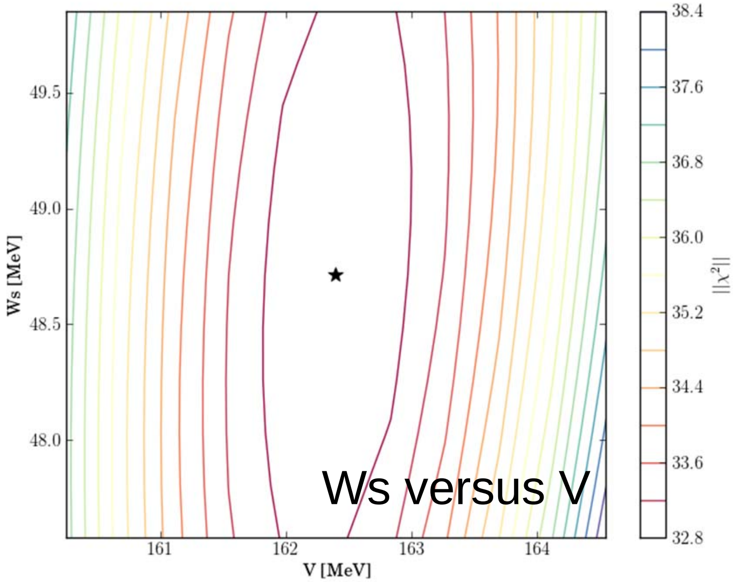
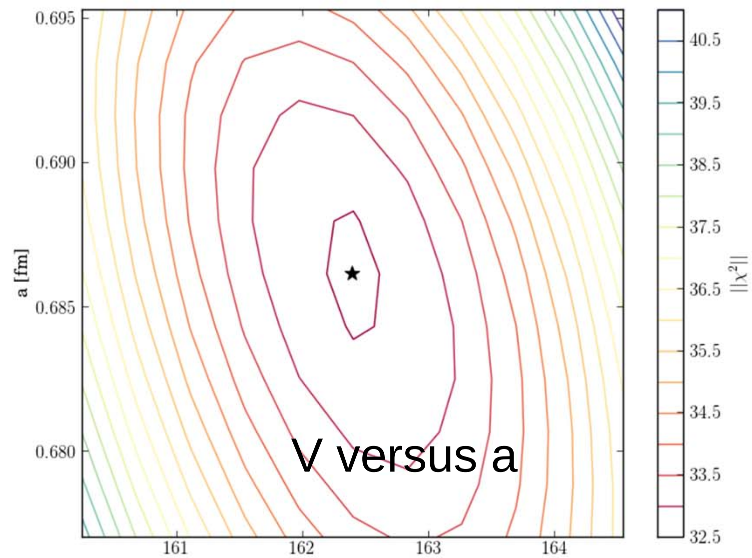


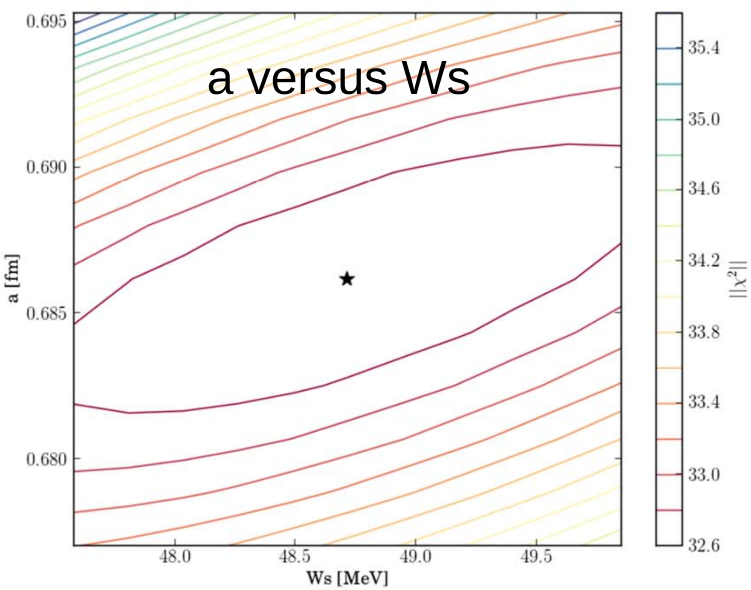
Lovell and Nunes, J Phys G 42, 034014 (2015)

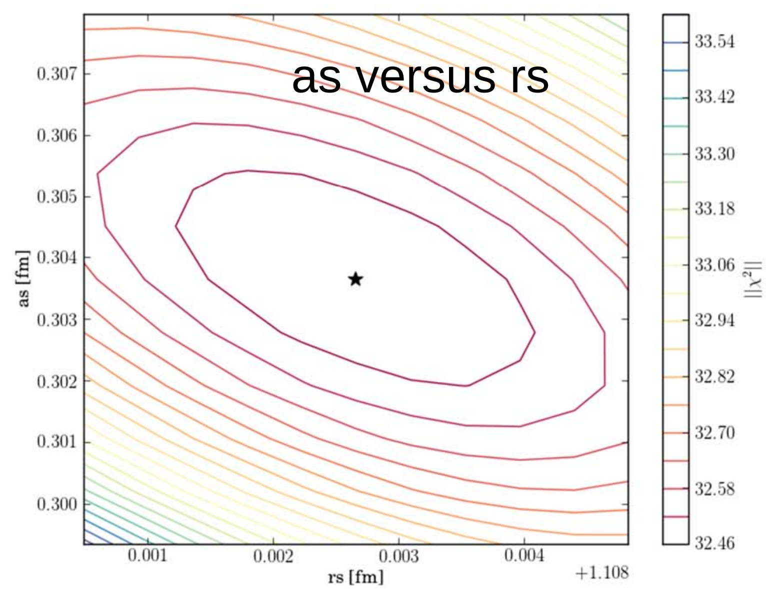
Lovell, Nunes, Sarich, Wild, in progress

Analysing the correlations between fitting parameters









6th challenge: who's going to do the work?