Course 6: Theory for exploring nuclear reaction experiments

MSU June 2019

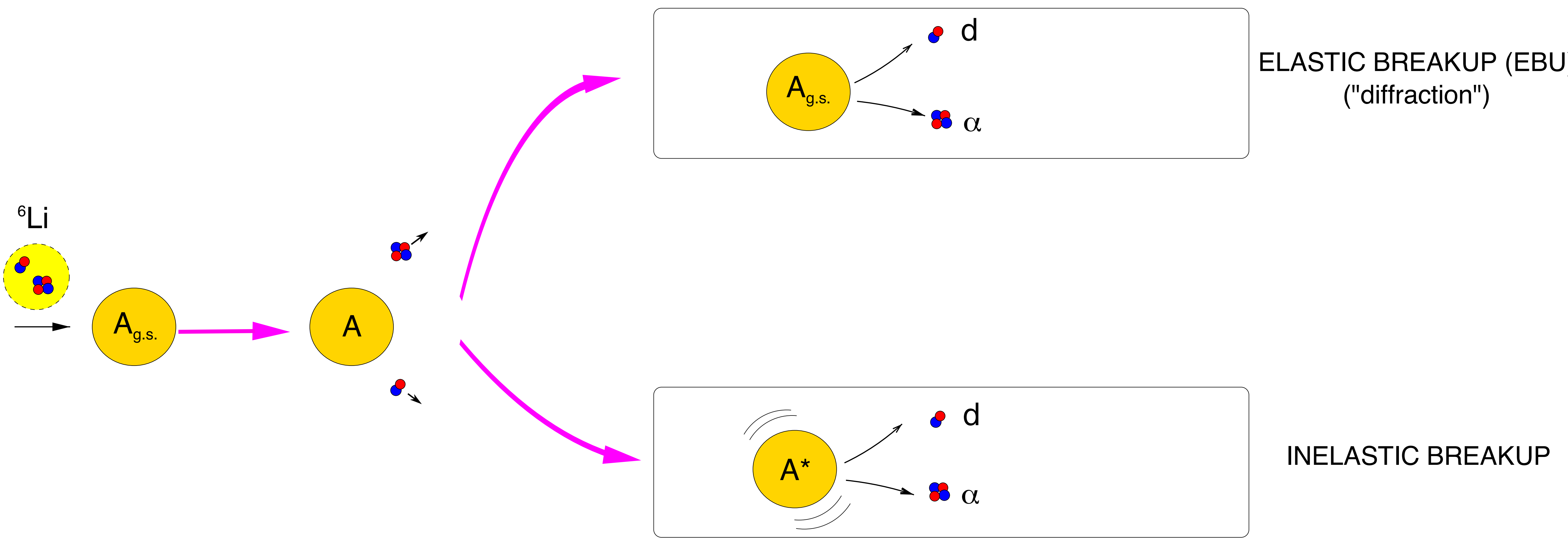
Nuclear reactions in a three body model(ii)

Jin Lei

Ohio University

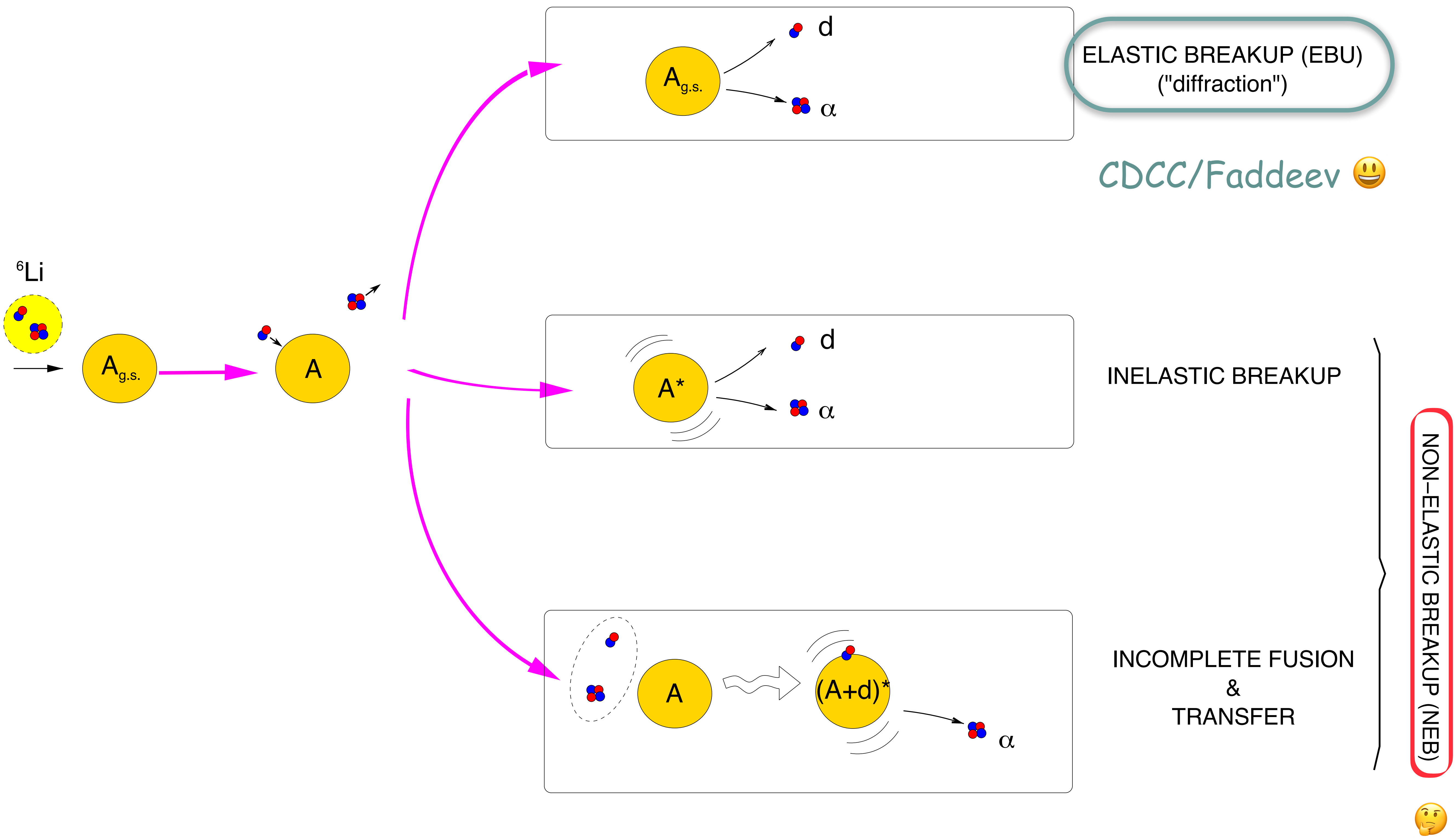
Exclusive measurement

- Take ^{6}Li as example



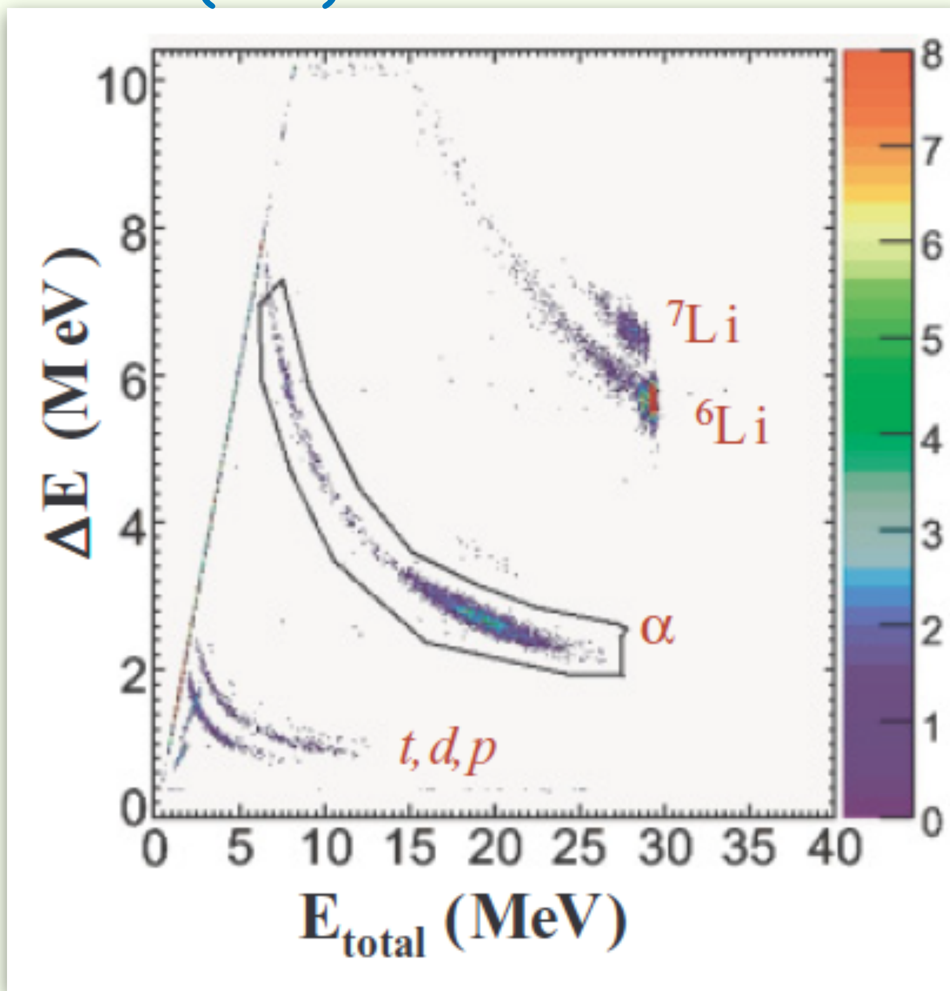
Inclusive measurement

- Take ^{6}Li as example



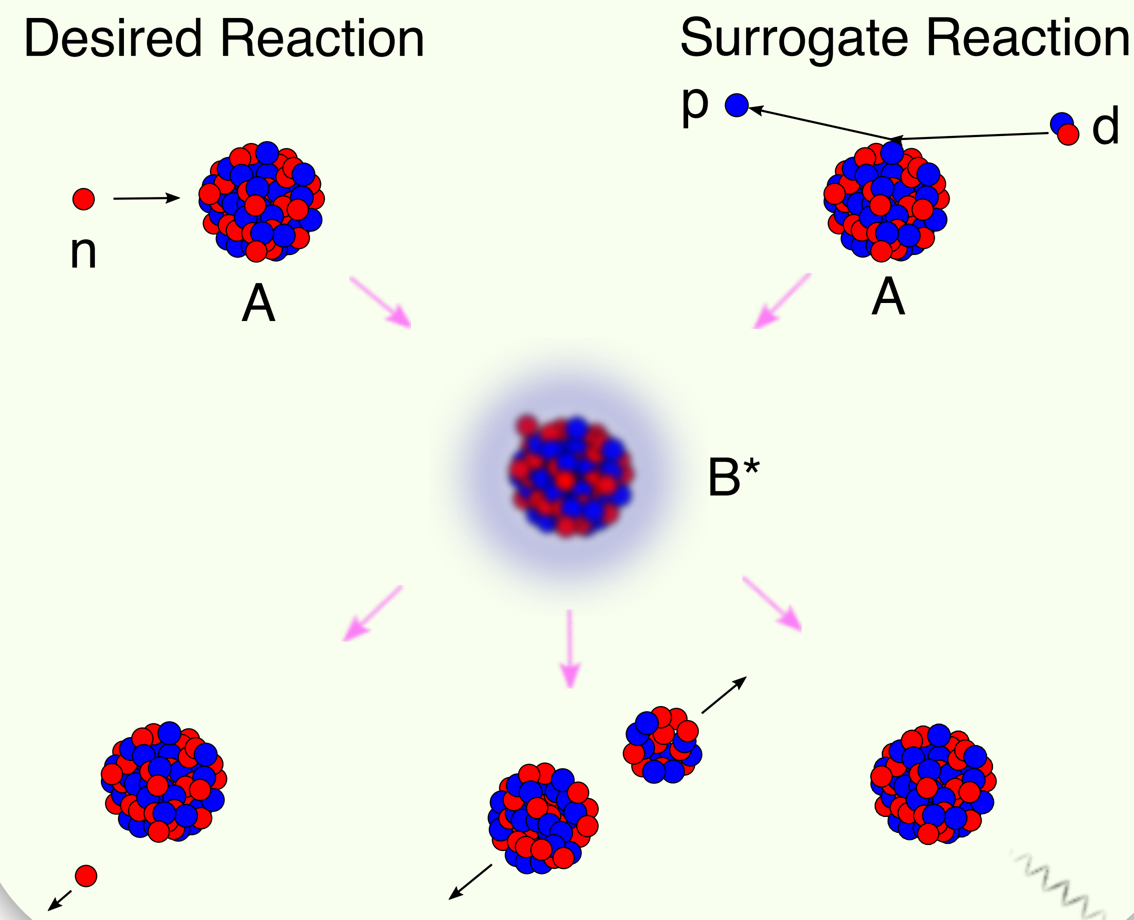
Experimental examples

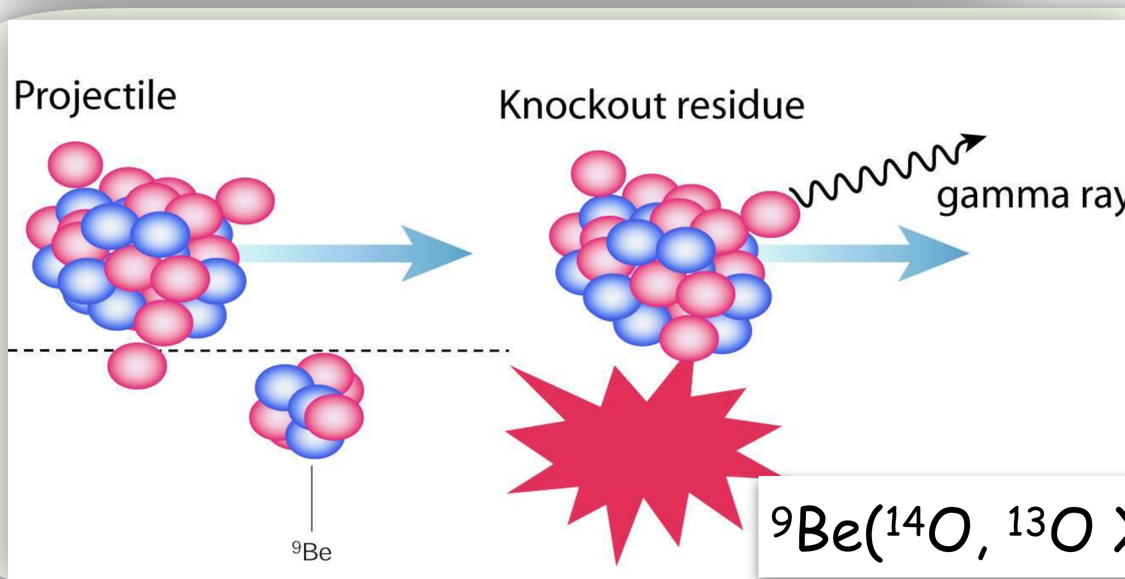
^{6}Li(d+α) induced reaction



S. Santra et al, Phys. Rev. C 85, 014612 (2012)

Surrogate reaction





^{9}Be(^{14}O, ^{13}O X)

- Knockout reaction
- Study the Spectroscopic factor
- Current theory based on eikonal approximation (semi-classical)
- Fully quantum model is needed

Theoretical models for inclusive (nonelastic) breakup

- Requires inclusion of all possible processes through which the breakup fragment can interact with the target. Impractical in most cases.

In 1980s

- Ichimura, Austern, and Vincent developed a spectator-participant model (post-form) — Phys. Rev. C 23, 1847 (1981); Phys. Rev. C 32, 431 (1985)
- Udagawa and Tamura suggested a breakup-fusion model (prior-form) — Phys. Rev. C 24, 1348 (1981); Phys. Lett. B 135, 333(1984)
- Hussein and McVoy adopted a spectator model with the Feshbach projection method — Nucl. Phys. A 445, 124 (1985)
- Three different approaches with different predictions

Goals

- Find a suitable model for inclusive breakup
- Explore relations between these models

Challenges

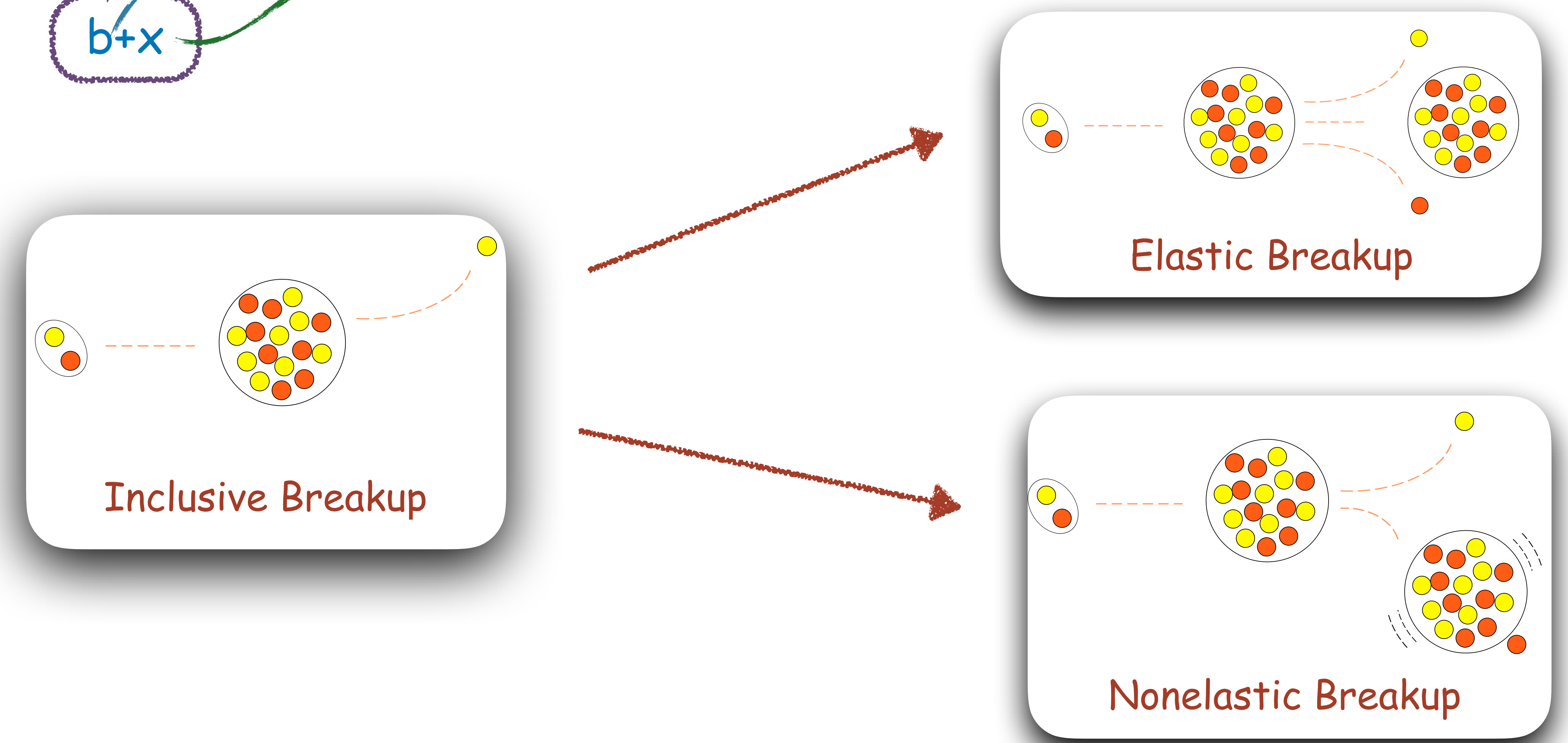
- Numerically difficult
- No numerical implementation in 1980s-2000s even for Finite Range DWBA

The Ichimura, Austern, Vincent (IAV) model

- Inclusive breakup :
  - a + A ⟶ b + anything ⟶ (x+A)*

b+x

Any possible states between x and A (including all nucleons degree of freedom)



- Project all degrees of freedom into three body model space

$$\left.\frac{d^2\sigma}{dE_b d\Omega_b}\right|_{NEB} = -\frac{2}{\hbar v_a}\rho_b(E_b)\langle \varphi_x(\vec{k}_b)\,|\,W_x\,|\,\varphi_x(\vec{k}_b)\rangle$$

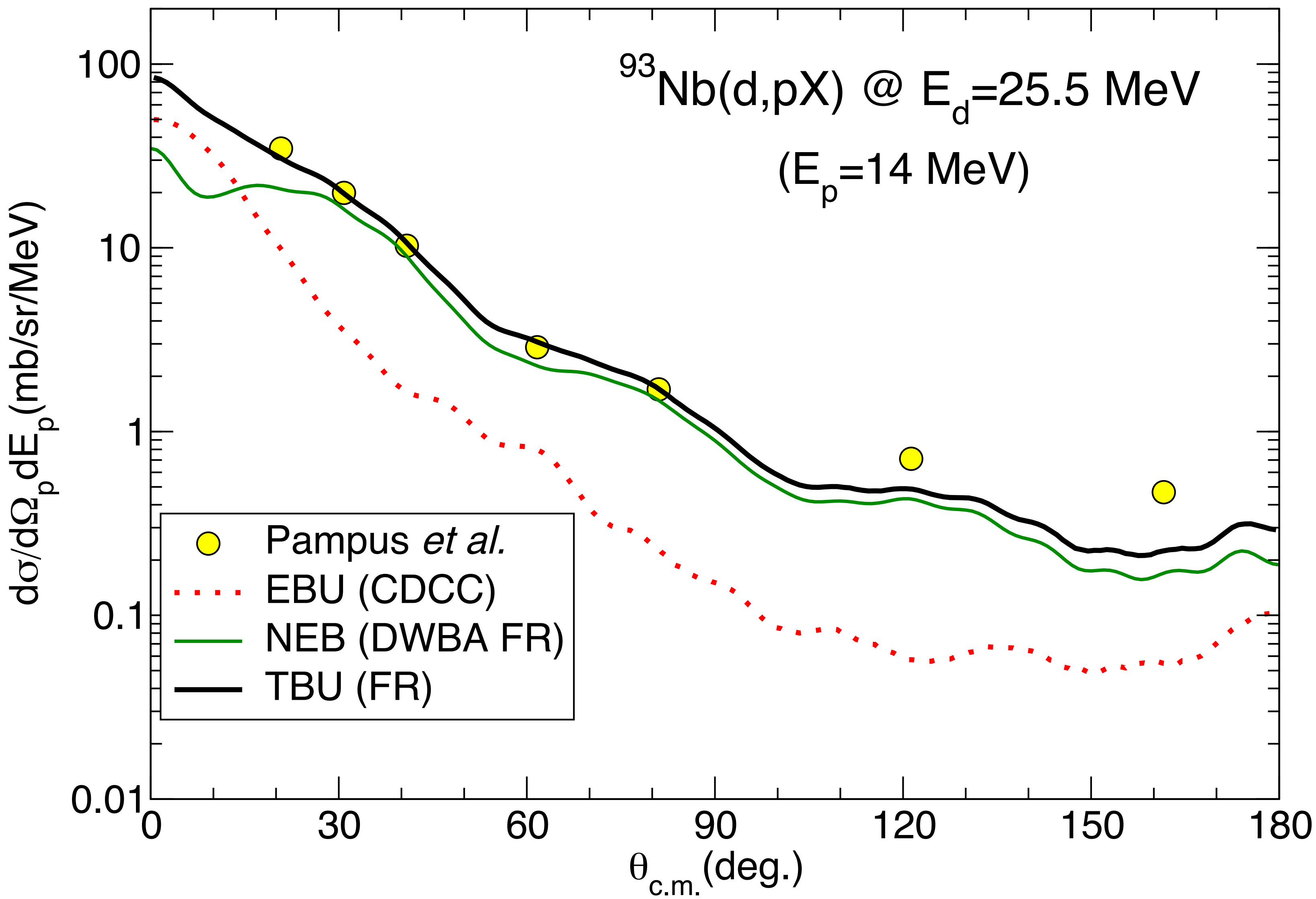
Imaginary part of x-A effective interaction

Apply to inclusive deuteron breakup

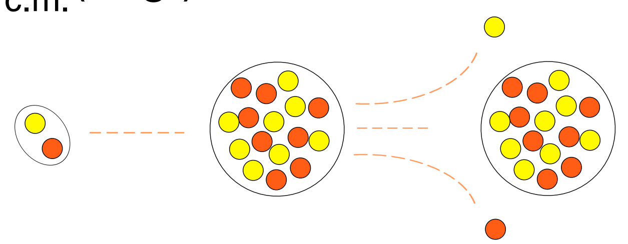
- $d \Rightarrow (n + p)$, S_p=2.224 MeV
- Only proton is detected
- EBU : CDCC (FRESCO)
- NEB : IAV model
- Total Breakup (TBU)=EBU+NEB

- Dominated by NEB
- EBU has large contributions at small angles
- Supports IAV model

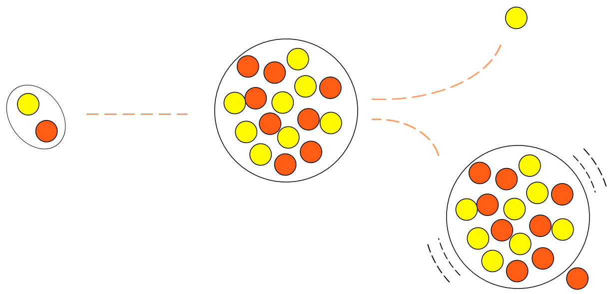
JL and A. M. Moro,
Phys. Rev. C 92, 044616 (2015)



EBU: Elastic Breakup

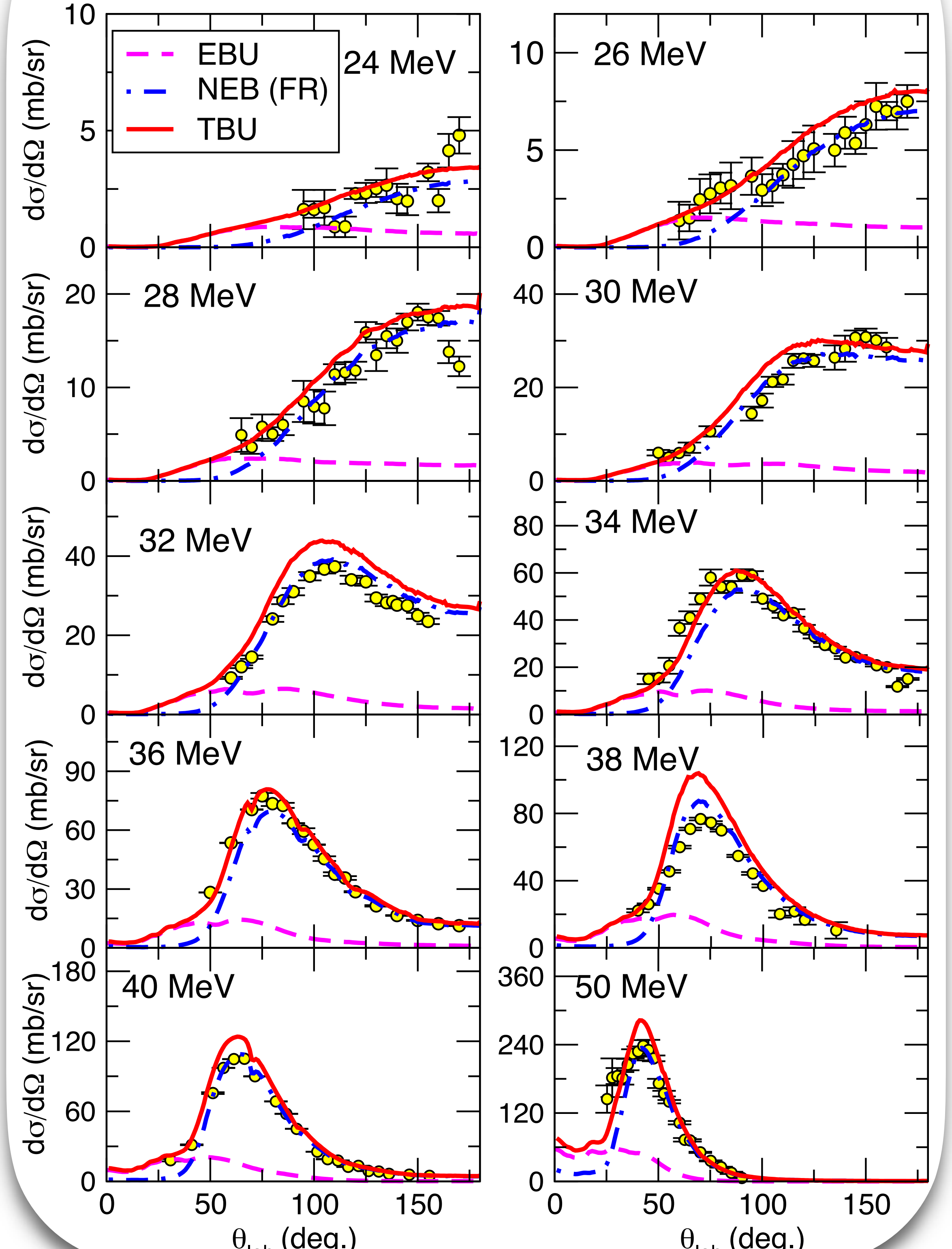


NEB: Nonelastic Breakup

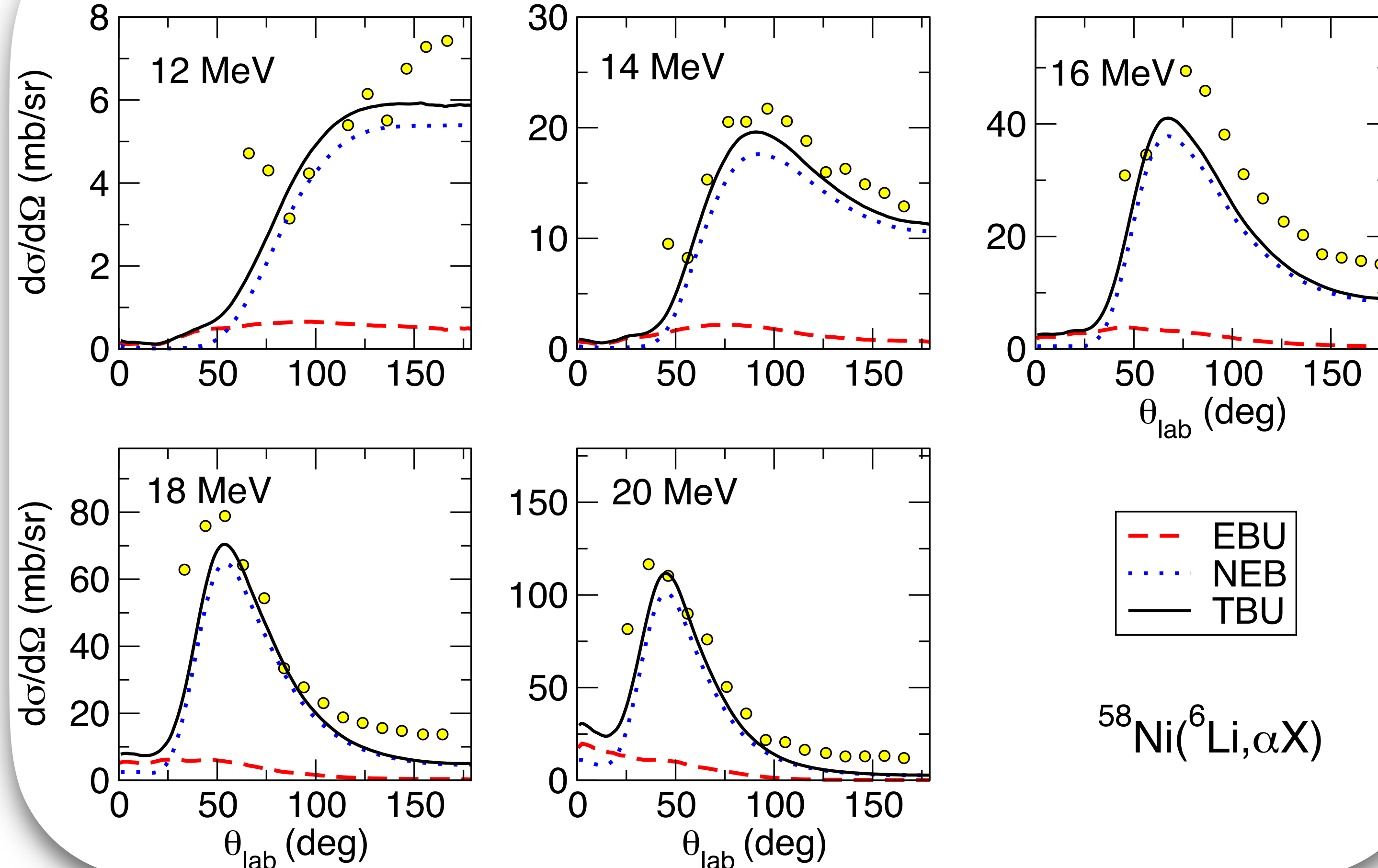


Apply to inclusive A(^{6}Li,αX)

^{6}Li+^{209}Bi



^{6}Li+^{58}Ni



- Dominated by NEB
- Supports IAV model

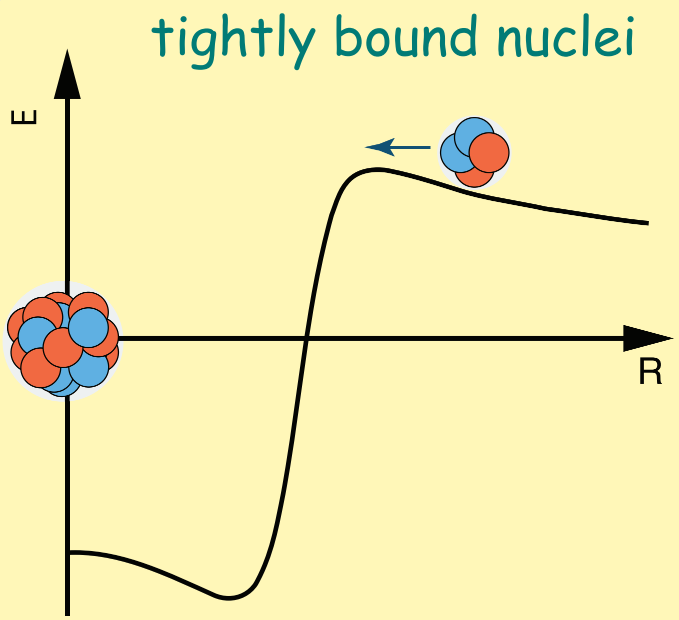
JL and A. M. Moro,
Phys. Rev. C 92, 044616 (2015)
Phys. Rev. C 95, 044605 (2017)

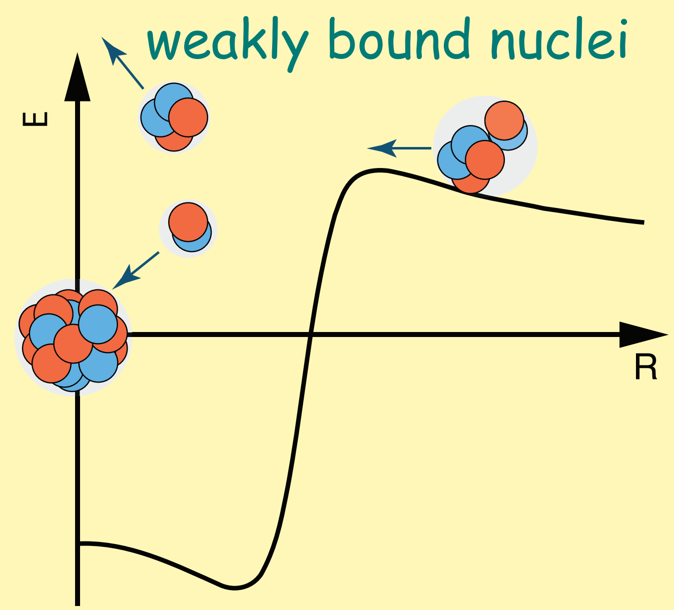
We also studied the relations between different inclusive models

JL and A.M. Moro
Phys. Rev. C 97, 011601 (R) (2018)
Phys. Rev. C 92, 061602 (R) (2015)

Breakup and fusion

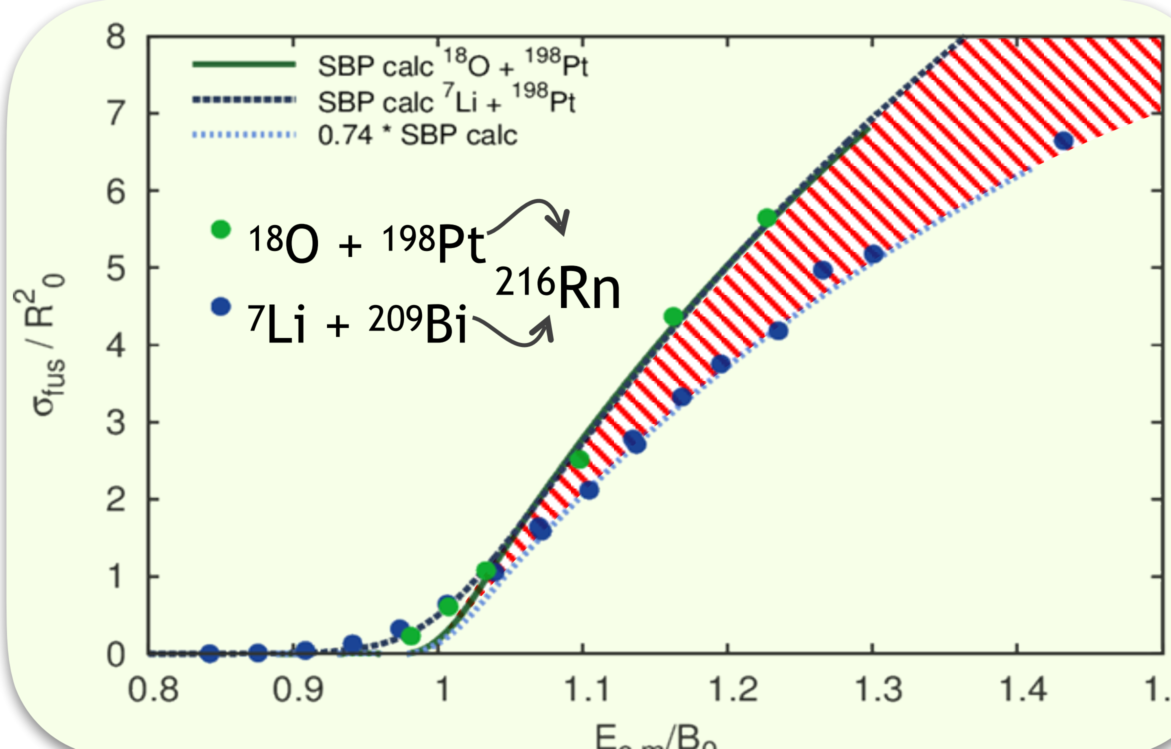
- From the barrier penetration picture





- **Complete fusion**: total charge of the projectile is absorbed by the target
- **Incomplete fusion**: part of the projectile is absorbed by the target

- Complete Fusion is suppressed due to weak binding of the projectile

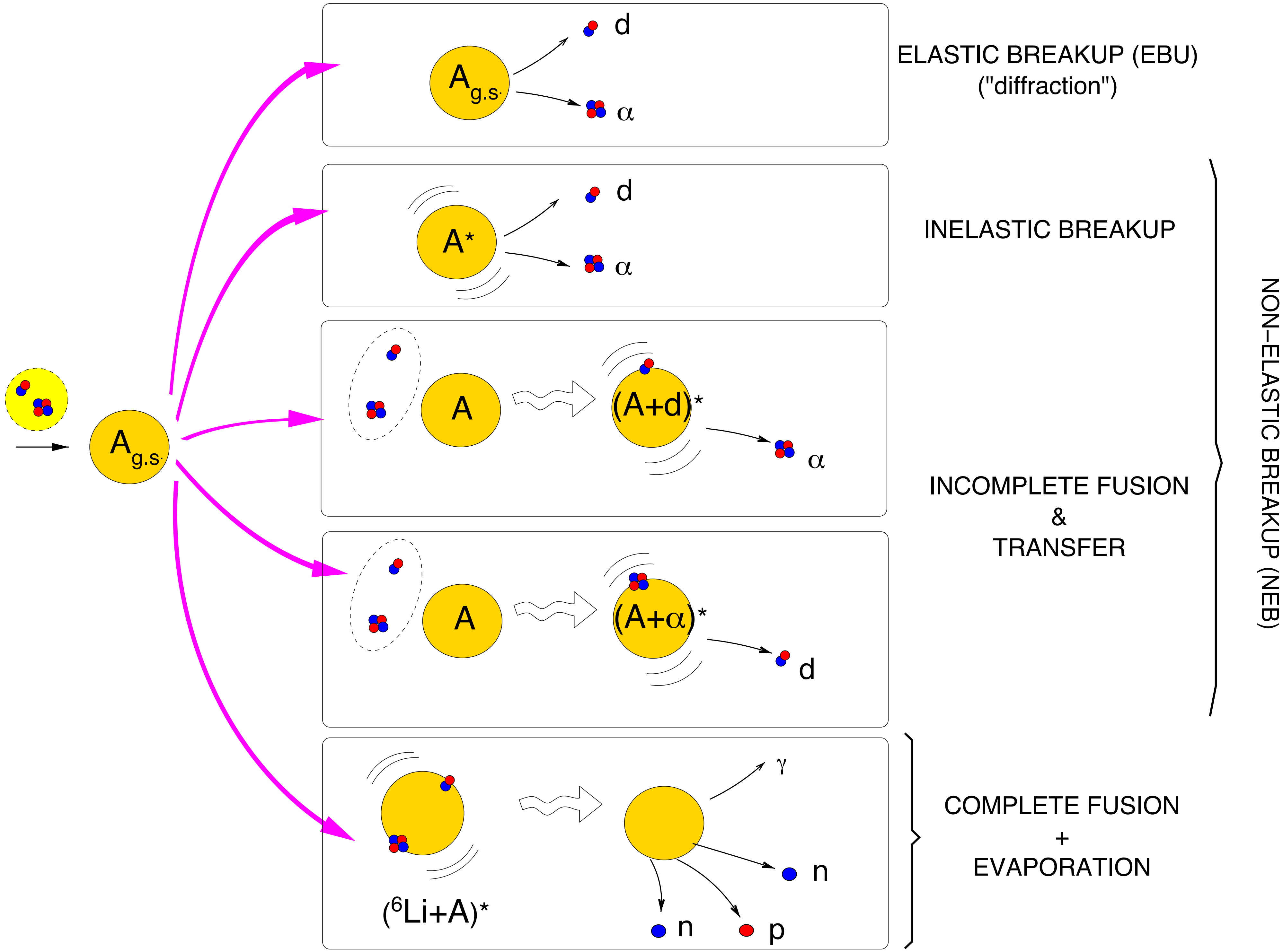


Challenges

- To correctly understand fusion suppression (not only from semi-classical picture) and simultaneously predict the complete fusion cross section
- To study incomplete fusion is breakup-fusion (two-step) or transfer to continuum (one-step)

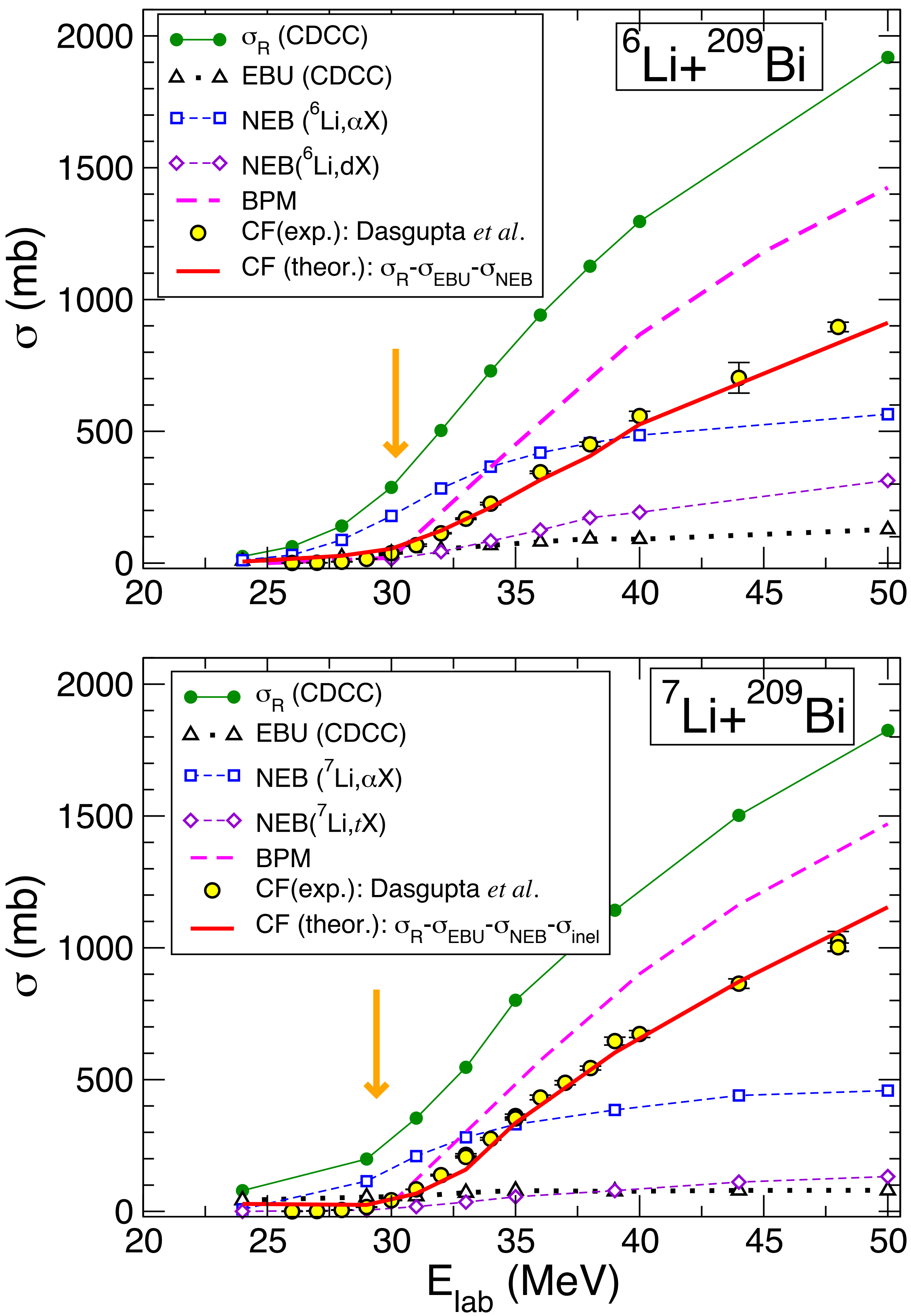
Study the fusion cross section through a three body model

- Take ^{6}Li+A as an example



$$\sigma_R \approx \sigma_{\mathrm{CF}} + \sigma_{\mathrm{EBU}} + \sigma_{\mathrm{NEB}}^{(b)} + \sigma_{\mathrm{NEB}}^{(x)}$$

Study the fusion cross section through a three body model



Data: M. Dasgupta et al., Phys. Rev. C 70, 024606 (2004)

$$\sigma_{\rm CF} \approx \sigma_R - \sigma_{\rm EBU} - \sigma^{(b)}_{\rm NEB} - \sigma^{(x)}_{\rm NEB}$$

- Apply the above relation to ^{6,7}Li+209Bi reaction around the Coulomb barrier
- Compare calculated fusion cross section with experiment

CF: complete fusion

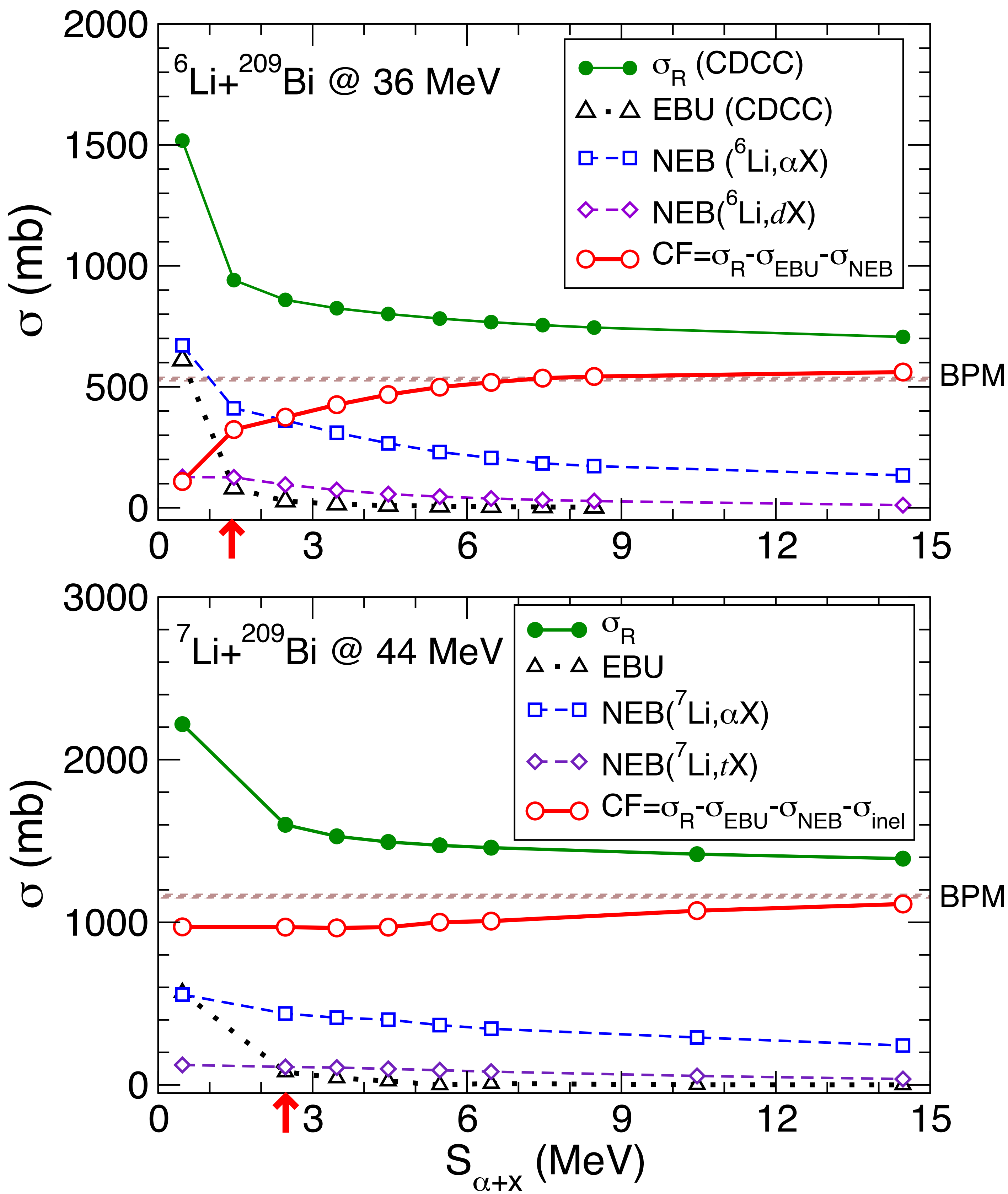
NEB: nonelastic breakup

EBU: elastic breakup

- EBU mechanism plays a minor role
- Dominant breakup mechanism in both reactions is alpha production due to ($^{6;7}$Li,αX) NEB.

JL and Antonio M. Moro,
Phys. Rev. Lett. 122, 042503 (2019)

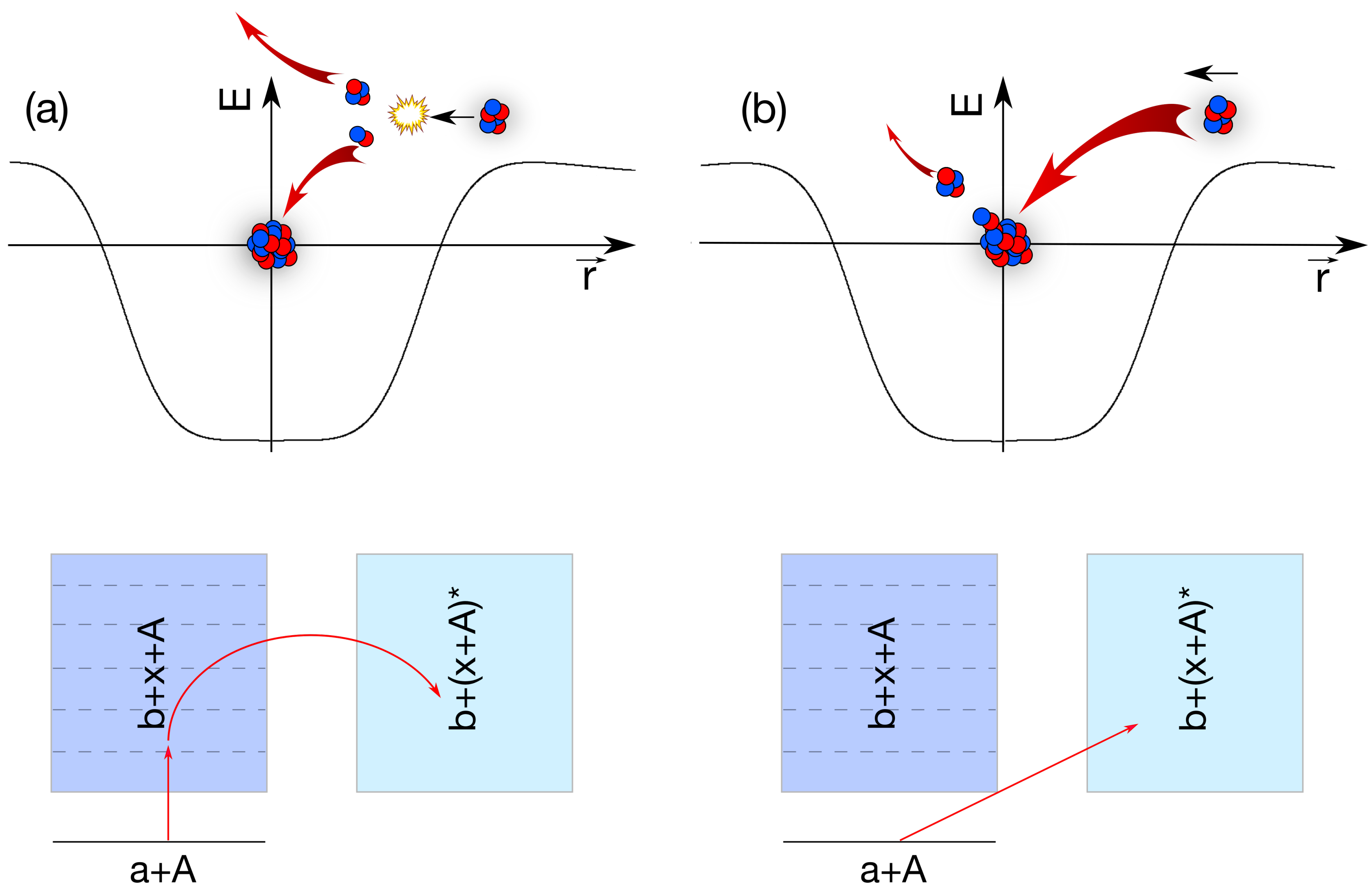
Unraveling the mechanisms leading to fusion suppression



- Use a toy model to study effects of separation energy
  - vary the binding energy of ^{7}Li(α+t) and ^{6}Li(α+d) in the projectile.
- When the binding energy becomes larger, the calculated cross section approaches the barrier penetration model (BPM)

JL and Antonio M. Moro, Phys. Rev. Lett. 122, 042503 (2019)

Exploring the reaction path for incomplete fusion



Incomplete fusion: part of the projectile absorbed by the target

Two-step: projectile is inelastically excited into its continuum and then fuses with the target

One-step: fragment fuses with the target directly from its ground state

Resolve this puzzle by studying nonelastic breakup (incomplete fusion is a part)

Use CDCC wave-function in the IAV model:

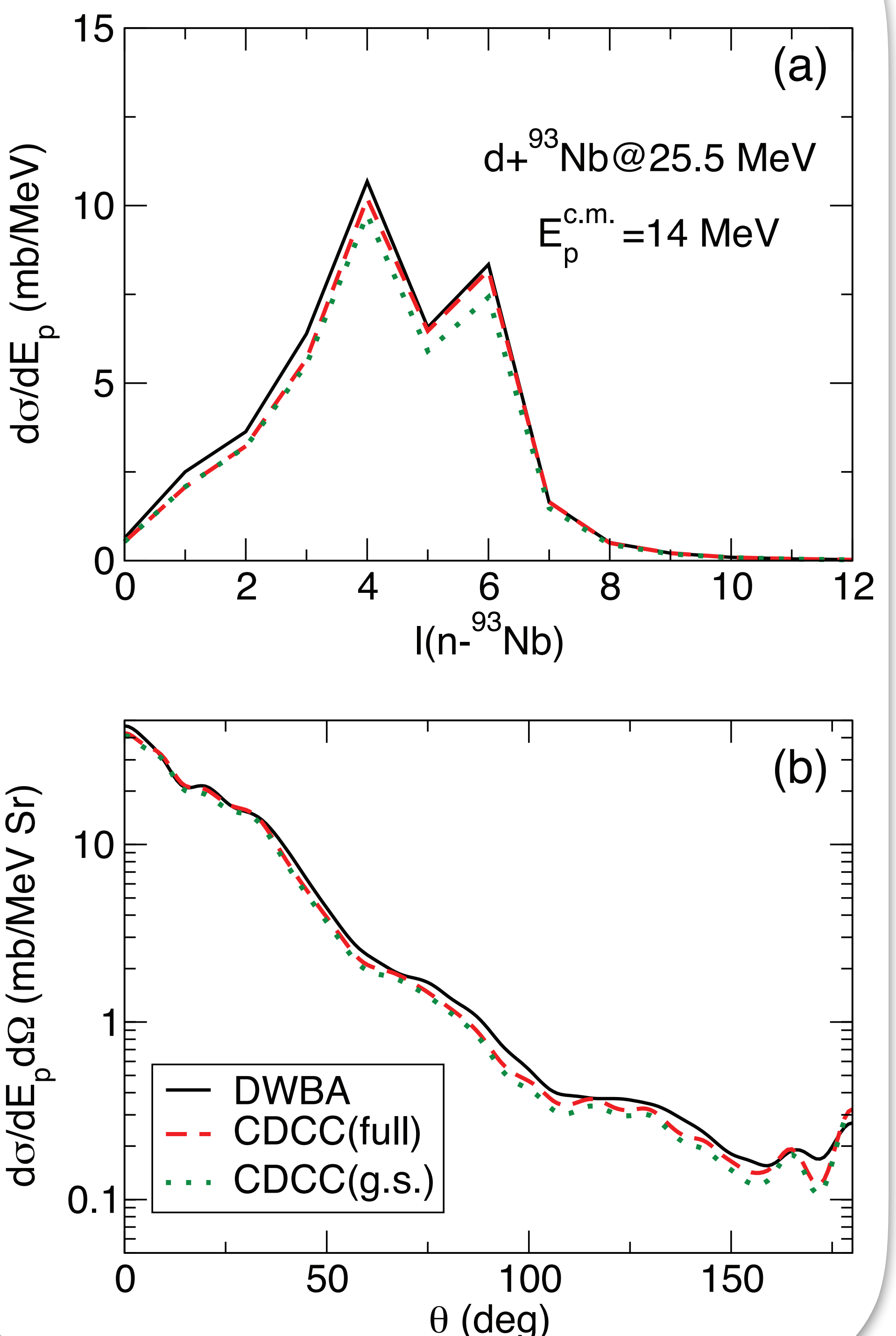
$$\varphi_x(\mathbf{k}_b, \mathbf{r}_x) = \int G_x(\mathbf{r}_x, \mathbf{r}'_x)\langle \mathbf{r}'_x \chi_b^{(-)} | V_{post} | \Psi^{\mathrm{CDCC}(+)} \rangle d\mathbf{r}'_x$$

$$\Psi^{\mathrm{CDCC}(+)}(\mathbf{r}_a, \mathbf{r}_{bx}) = \sum_b \phi_a^b(\mathbf{r}_{bx})\chi_a^{b(+)}(\mathbf{r}_a) + \int d\mathbf{k}\phi_a^{\mathbf{k}}(\mathbf{r}_{bx})\chi_a^{\mathbf{k}(+)}(\mathbf{r}_a)$$

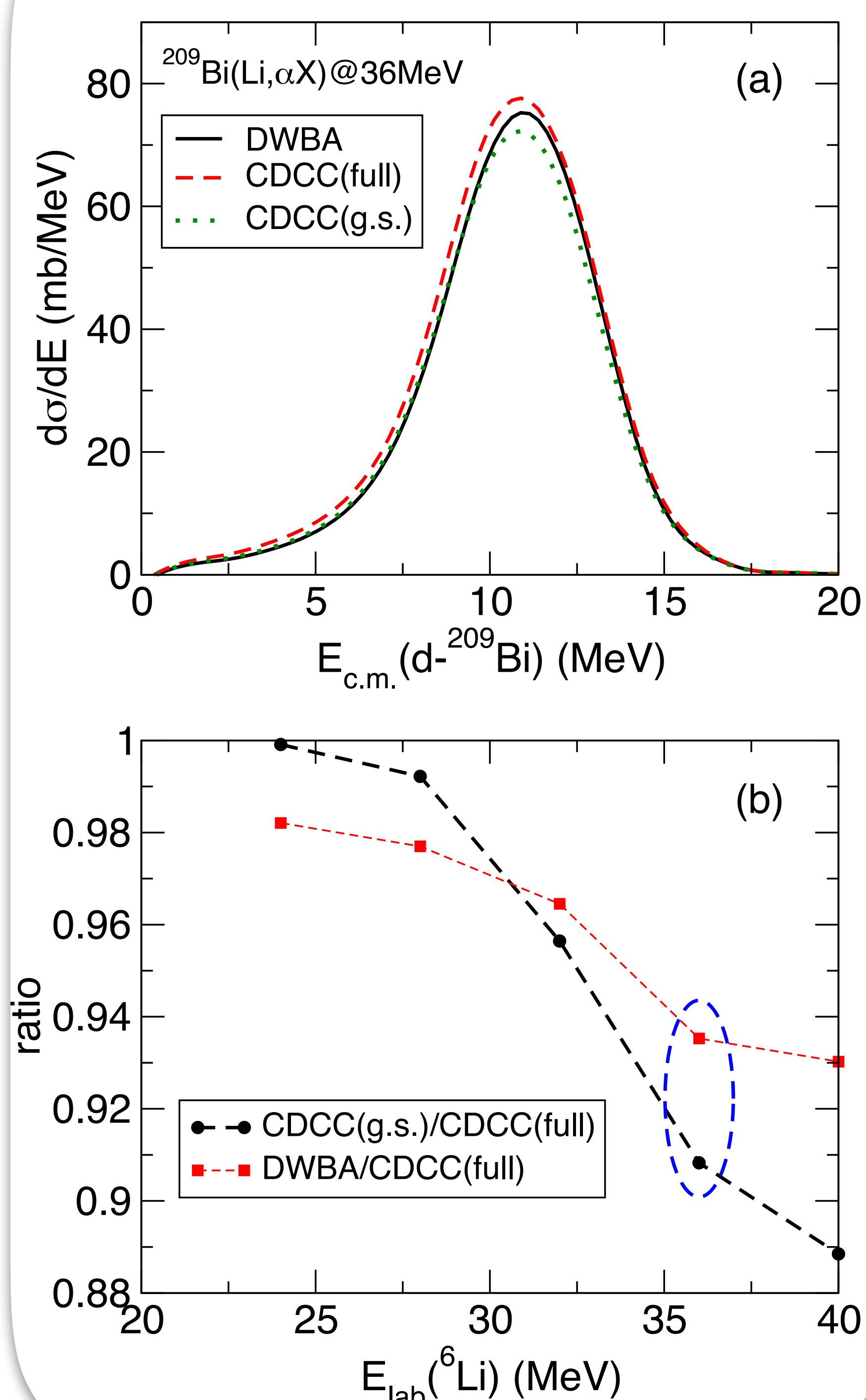
- Continuum and ground states are separated
- Allows to study continuum effects on the NEB
- Test validity of DWBA

Apply to deuteron and ^{6}Li induced reaction

deuteron case



^{6}Li case



- DWBA is a good approximation compared to CDCC
- Nonelastic breakup (incomplete fusion) is mixture of one-step (>90%) and two-step (<10%) processes