OHIO UNIVERSITY

Investigating core excitation in halo nuclei using halo-EFT

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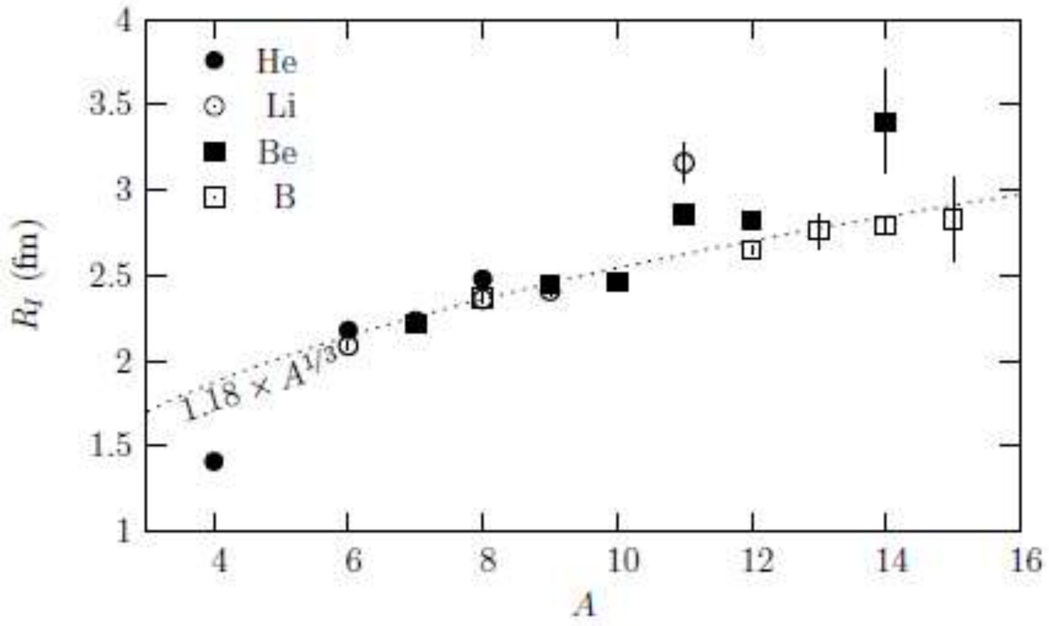
Overview

Unstable nuclei

1985: Measurements of interaction cross sections σ_I of light exotic nuclei
[I. Tanihata PRL 55, 2676 (1985)]
In a simple geometrical model:

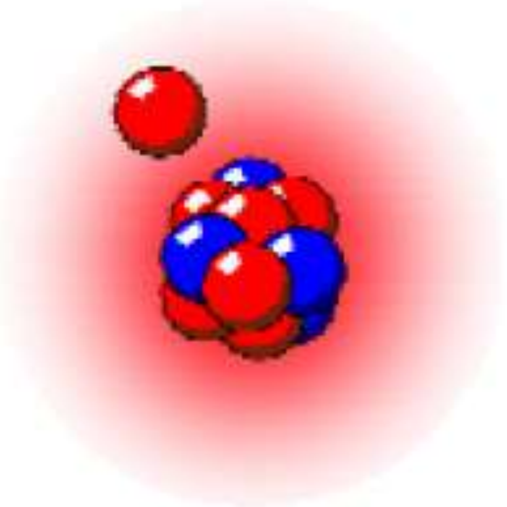
$$\sigma_I = \pi (R_P + R_T)^2$$



Some nuclei deviate from the $A^{1/3}$ trend: ^{6}He, ^{11}Be, ^{11}Li, ^{14}Be...
→ these larger nuclei are: **halo nuclei**

Halo nuclei

- Light, neutron-rich nuclei with large matter radius
- Low $\mathbf{S}_{\mathrm{n}}$ or $\mathbf{S}_{2\mathrm{n}}$: one or two loosely-bound neutrons
- Clusterised structure: neutrons can tunnel far from the core
  $\rightarrow$ halo-nucleus $\equiv$ compact core + valence neutron(s)



- **Our case study** : $^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + \mathrm{n}$
- Short-lived $\rightarrow$ studied via reactions (e.g. **breakup**)
  $\rightarrow$ need of an **effective few-body** model for reaction calculations
  $\rightarrow$ **Halo-EFT**

Halo-EFT description of ^{11}Be

- Halo-structure $\rightarrow$ separation of scales
  $\rightarrow$ small parameter $\eta = \frac{R_{core}}{R_{halo}} \simeq 0.4 < 1$
  $\rightarrow$ expansion of the core-neutron Hamiltonian along η
  [Bertulani, Hammer, van Kolck, NPA 712, 37 (2002)]
  Review: **[Hammer, Ji, Phillips, JPG 44, 103002 (2017)]**

- $^{11}\mathrm{Be} = {}^{10}\mathrm{Be}(0^+) + \mathrm{n}$ [**core has no internal structure**]
  $\rightarrow$ **single-particle description**: $H(\mathbf{r}) = \mathrm{T}_\mathbf{r} + \mathrm{V}_{\mathrm{cn}}(\mathbf{r})$

- Effective Gaussian potentials in each partial wave ℓj @NLO ($\ell \leqslant 1$):

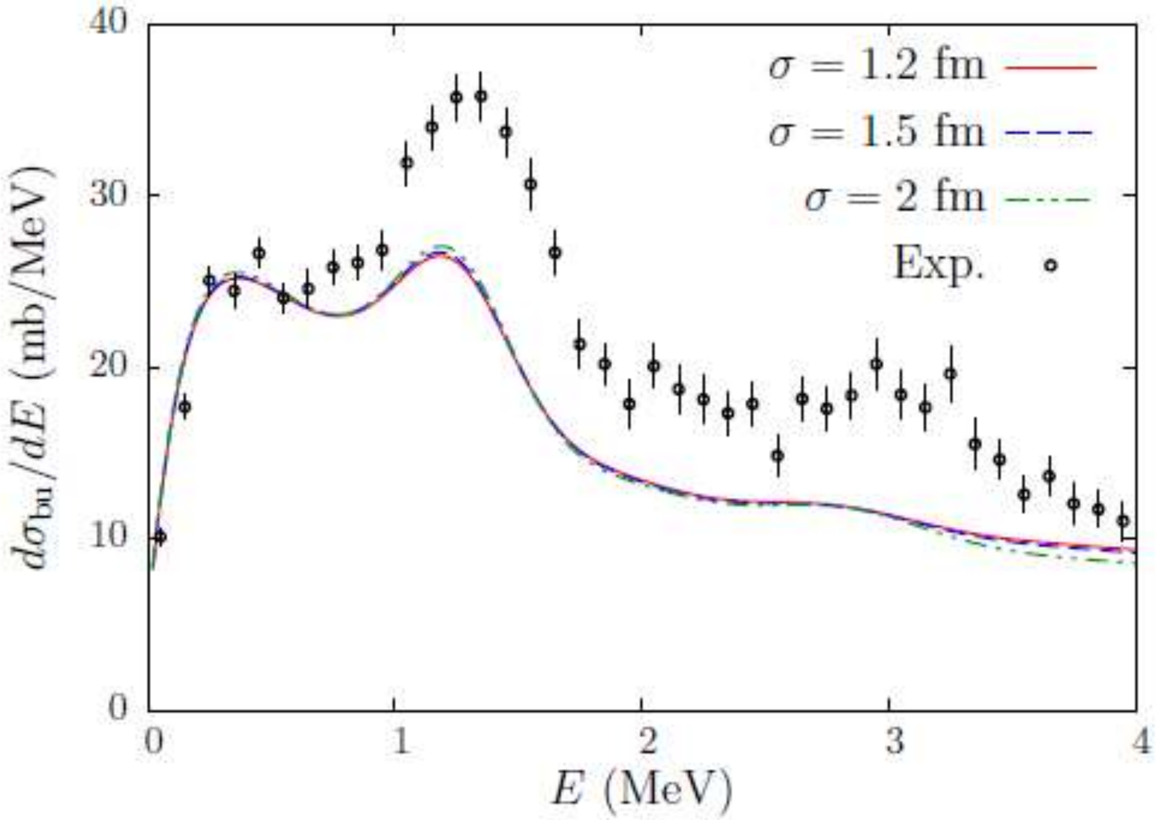
$$\mathrm{V}_{\mathrm{cn}}(\mathrm{r}) = \mathrm{V}^{(0)}_{\ell \mathrm{j}} e^{-\frac{\mathrm{r}^2}{2\sigma^2}} + \mathrm{V}^{(2)}_{\ell \mathrm{j}} \mathrm{r}^2 e^{-\frac{\mathrm{r}^2}{2\sigma^2}}$$

$\mathrm{V}^{(0)}_{\ell \mathrm{j}}$ and $\mathrm{V}^{(2)}_{\ell \mathrm{j}}$ fitted to reproduce:
$\rightarrow$ **S_n** & asymptotic normalization coefficient (**ANC**) for bound states
$\rightarrow$ effective range parameters for continuum states

$\sigma :=$ cut-off $\rightarrow$ evaluates sensitivity to short-range physics

What is the problem ?

- Assumption: ^{10}Be remains in its 0^+ ground state still valid ?
  → Nuclear breakup: ^{11}Be+C → ^{10}Be+n+C



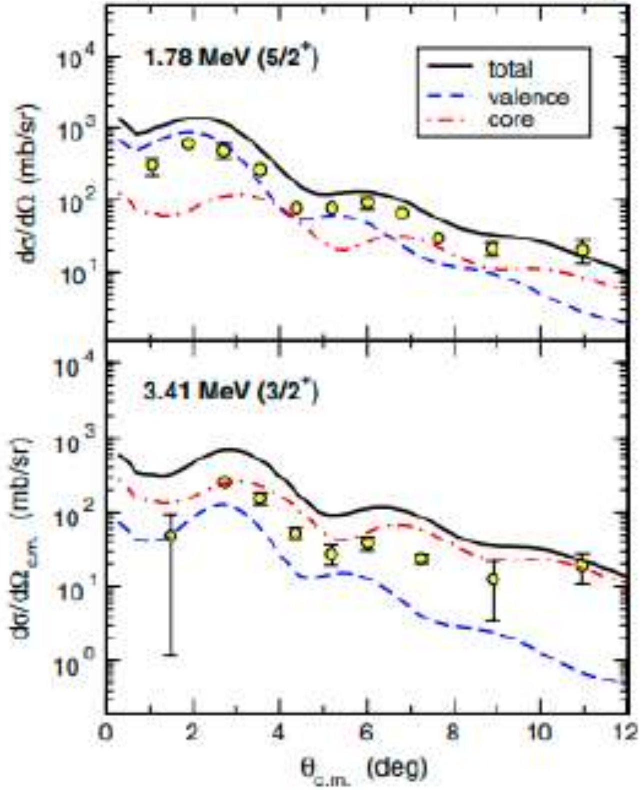
Exp: [Fukuda *et al.* PRC 70, 054606 (2004)]

Th.: **[L.-P. Kubushishi and P. Capel, arXiv:2406.10168 (2024)]**

⇒ Missing peaks at $\frac{5}{2}^+$ and $\frac{3}{2}^+$ resonances → is **s.p.** not enough ?

Nuclear breakup & core excitation

- Origin of these missing strengths ?
  ⇒ missing degree of freedom [^{10}Be(2^+)]
  ⇒ ^{10}Be core can be excited to its first 2^+state
  [Moro & Lay, PRL 109, 232502 (2012)]



- To better understand **structure effects on reaction calculations**
  I develop a **Halo-EFT** few-body model including **core excitation**

Core excitation within Halo-EFT

- **Extension of Halo-EFT to include core excitation:**

$$H(\mathbf{r},\xi) = \mathrm{T}_{\mathbf{r}} + \mathrm{V}_{\mathrm{cn}}(\mathbf{r},\xi) + \mathrm{h}_{\mathrm{core}}(\xi)$$

$\mathrm{h}_{\mathrm{core}}(\xi)$:= intrinsic Hamiltonian of the core with eigenstates $\chi^{\mathrm{c}}_{\mathrm{I}}(\xi)$

- **Halo-EFT particle-rotor model** [Bohr and Mottelson (1975)]:

$$\mathrm{V}_{\mathrm{cn}}(\mathbf{r},\xi) = \mathrm{V}_{\mathrm{cn}}(\mathrm{r}) + \beta\sigma \mathrm{Y}^0_2(\hat{\mathrm{r}})\frac{\mathrm{d}}{\mathrm{d}\sigma}\mathrm{V}_{\mathrm{cn}}(\mathrm{r})$$

- Set of radial **coupled-channel** Schrödinger equations:

$$\left[\mathrm{T}^{\ell}_{\mathrm{r}} + \mathrm{V}_{\alpha\alpha}(\mathrm{r}) + \epsilon_\alpha - \mathrm{E}\right]\psi_\alpha(\mathrm{r}) = -\sum_{\alpha'\neq\alpha}\mathrm{V}_{\alpha\alpha'}(\mathrm{r})\psi_{\alpha'}(\mathrm{r})$$

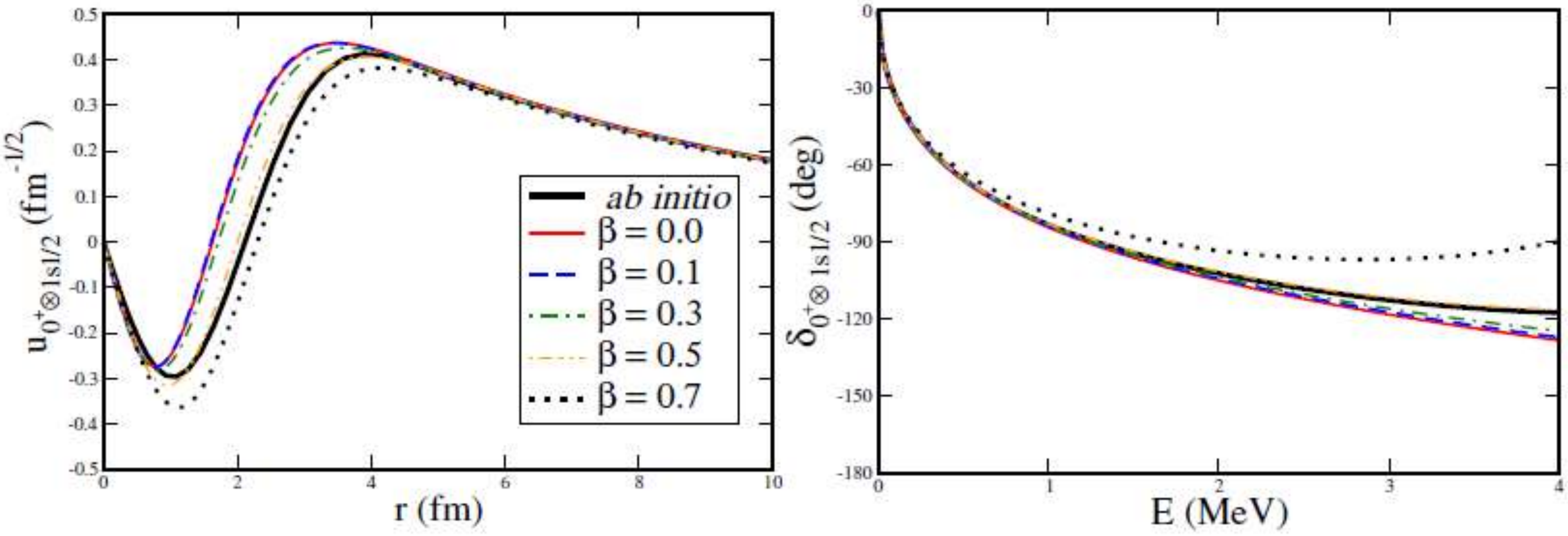
with $\mathrm{V}_{\alpha\alpha'}(\mathrm{r}) = \langle\mathcal{Y}_\alpha(\hat{\mathrm{r}})\chi_\alpha(\xi)|\mathrm{V}_{\mathrm{cn}}(\mathbf{r},\xi)|\mathcal{Y}_{\alpha'}(\hat{\mathrm{r}})\chi_{\alpha'}(\xi)\rangle$, α=$\{\ell,\mathrm{s},\mathrm{j},\mathrm{I}\}$

→ solved within the **R-Matrix method** on a Lagrange mesh
[D. Baye, Physics Reports 565 (2015) 1]
Study impact of core excitation on: ψ_α, δ_α

Ground state: $\frac{1}{2}^+$

Compare to *ab initio* predictions [Calci et al., PRL 117, 242501 (2016)]

- $\Psi_{1/2^+} = \psi_{1s1/2}(\mathbf{r}) \otimes \chi_{0^+}^{^{10}\mathrm{Be}} + \psi_{0d5/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}\mathrm{Be}} + \psi_{0d3/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}\mathrm{Be}}$
- NLO potentials **fitted to** reproduce $\mathbf{S}_n$ and *ab initio* **ANC** for $\neq \beta$



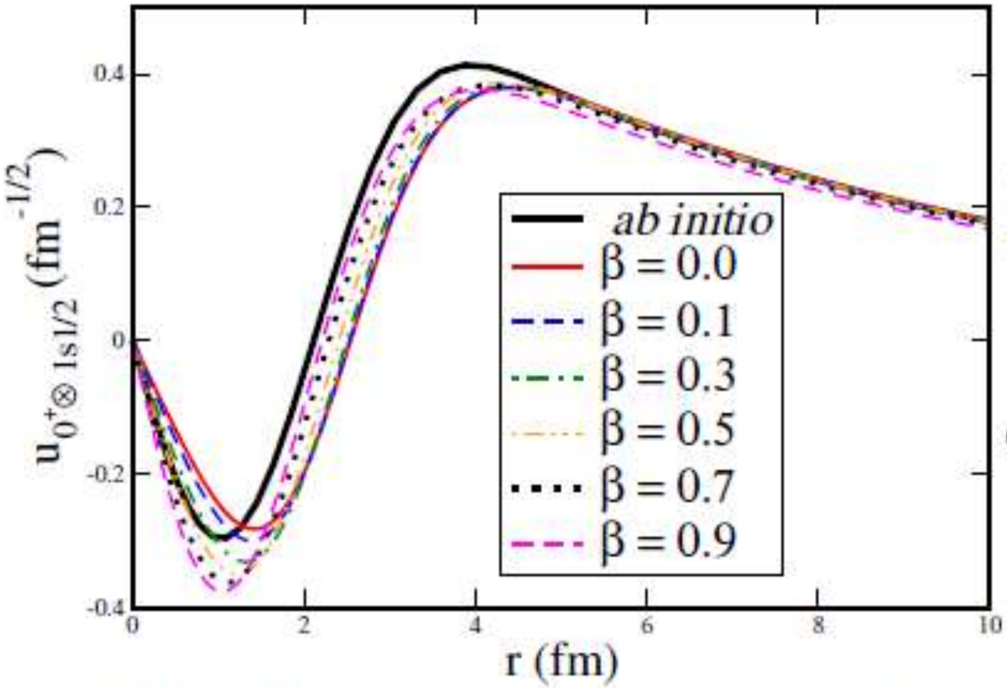
β=**0.5** in excellent agreement with *ab initio* for both ψ_α, δ_α

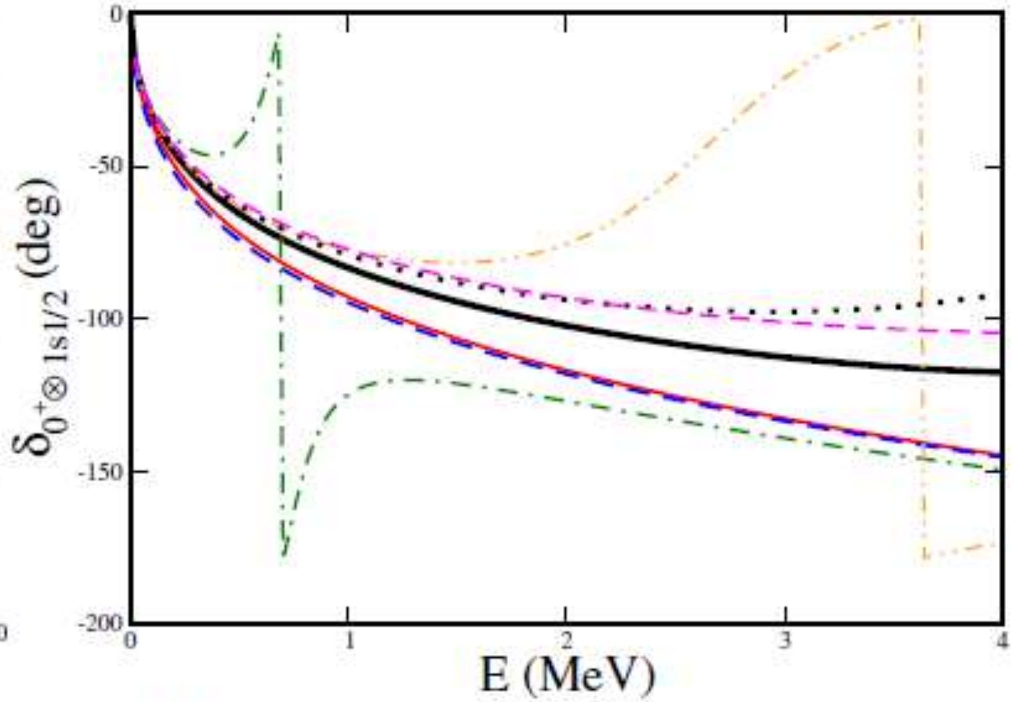
$\Rightarrow$ Including core **dof** improves both ψ_α, δ_α with 1 added parameter: β

$\Rightarrow$ Results are σ-**independent**

Ground state: $\frac{1}{2}^{+}$- Type 2 solution

- $\Psi_{1/2^+} = \psi_{1s1/2}(\mathbf{r}) \otimes \chi_{0^+}^{^{10}\mathrm{Be}} + \psi_{0d5/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}\mathrm{Be}} + \psi_{0d3/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}\mathrm{Be}}$
- Another type of solutions can be found:
  → when potential hosts a 0d **bound state** (expected in shell model)





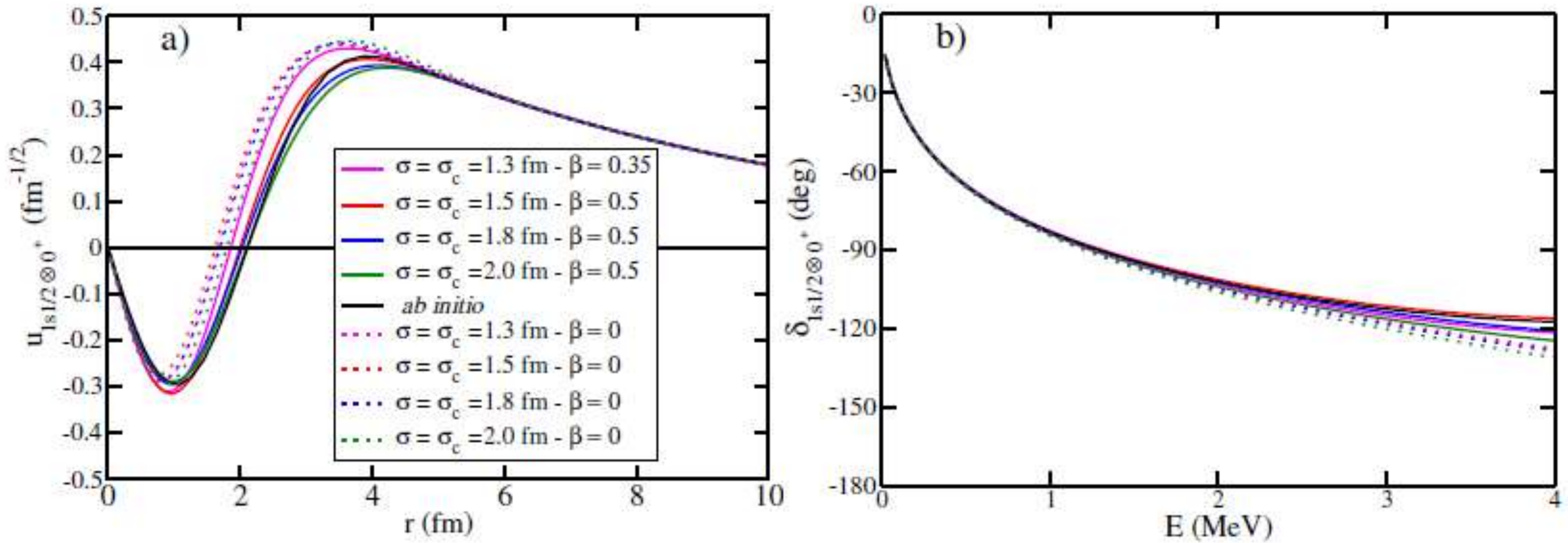
- Results less good than calculations without core excitation
  → this solution is rejected

Ground state and σ-dependency

Q1: In the spirit of the Halo-EFT, are our calculations σ-independent ?

Q2: Does adding a new degree of freedom lessen σ-dependency ?

Idea: compare coupled-channel [**Type 1 solution**] to s.p. NLO results

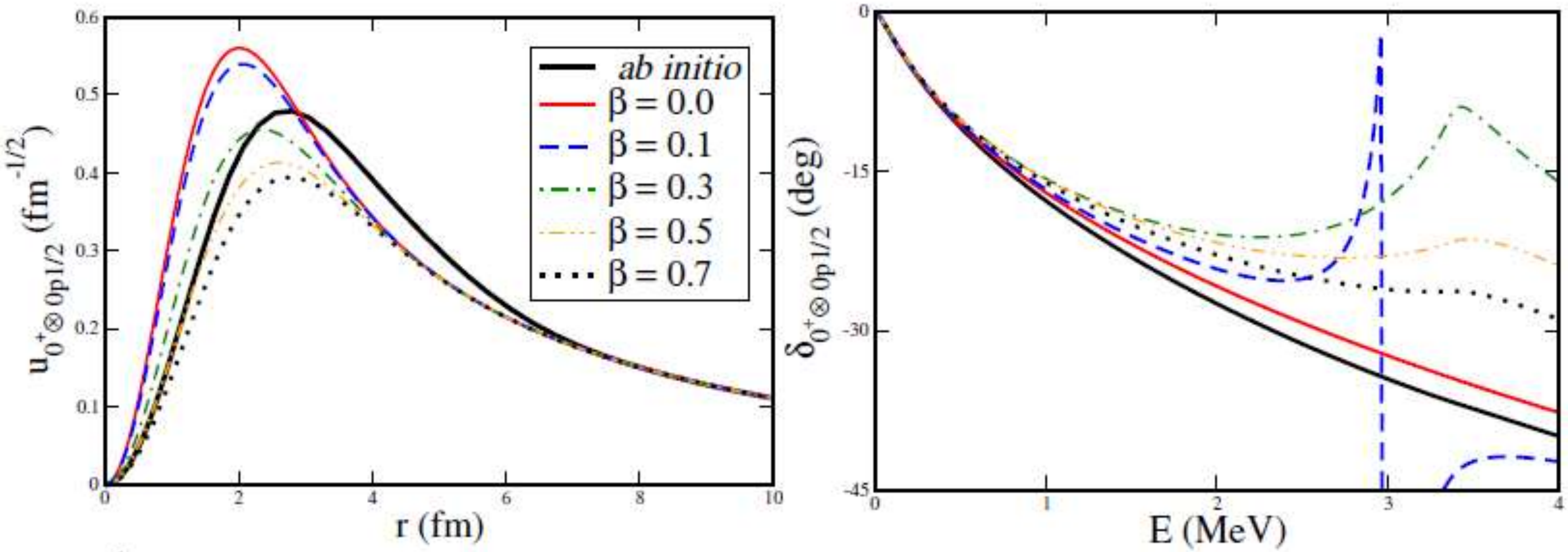


Coupled-channel calculations reduce σ-dependency for both ψ_α and δ_α

$\rightarrow$ **new degree of freedom decreases σ-dependency**

First bound excited state: $\frac{1}{2}^+$

- $\Psi_{1/2^-} = \psi_{0p1/2}(\mathbf{r}) \otimes \chi_{0^+}^{^{10}Be} + \psi_{0p3/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}Be} + \psi_{0f5/2}(\mathbf{r}) \otimes \chi_{2^+}^{^{10}Be}$
- NLO potentials **fitted to** reproduce $\mathbf{S_n}$ and *ab initio* **ANC** for $\neq \beta$



- $\frac{1}{2}^-$:= **core excitation does not improve the model**:
  → wfs: no improvement in the **"pre-asymptotic" region (4-6 fm)**
  → phaseshifts: less good than without core excitation
- **No "type 2" solution** because $E_{0p3/2}$ not at the right energy

Electric dipole transition probability: B(E1)

$$\mathcal{B}(E\lambda; J \to J') = \frac{2J'+1}{2J+1} \left| \langle J' \| \mathcal{M}(E\lambda) \| J \rangle \right|^2$$

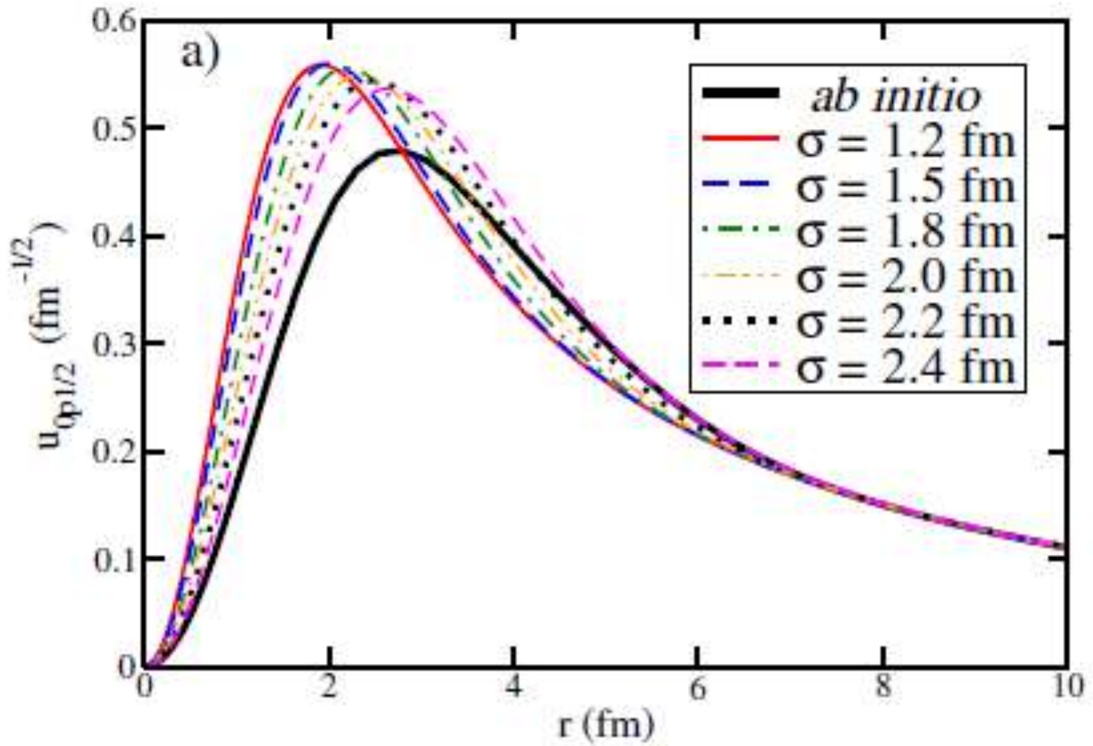
$$\mathcal{B}(E1; \tfrac{1}{2}^{+} \to \tfrac{1}{2}^{-})$$

Different models/experiments	B(E1)[e^2fm^2]
Exp. (1983) from Ref. [114]	0.116(12)
Exp. (2007) from Ref. [113]	0.105(12)
Exp. (2014) from Ref. [112]	0.102(2)
Th. - F.M. Nunes (1996) - CC mean-field - from Ref. [70]	0.150
Th. - N.C. Summers (2014) - XCDCC - from Ref. [112]	0.098(4)
Th.- Calci *et al.* (2016) - "NCSMC" *ab initio* - from Ref. [22]	0.117
This work - CC (σ=σ_c=1.3 - β_2=0.35)	0.104
This work - CC (σ=σ_c=1.5 - β_2=0.50)	0.106
This work - CC (σ=σ_c=1.8 - β_2=0.50)	0.109
This work - CC (σ=σ_c=2.0 - β_2=0.50)	0.110

- Excellent agreement with experimental data BUT small discrepancies with *ab initio value*
- *Ab initio* B(E1) overestimates the data → due to their ½⁻ state (see A. Moro's talk)

Excited state and σ-dependency: s.p. analysis @NLO

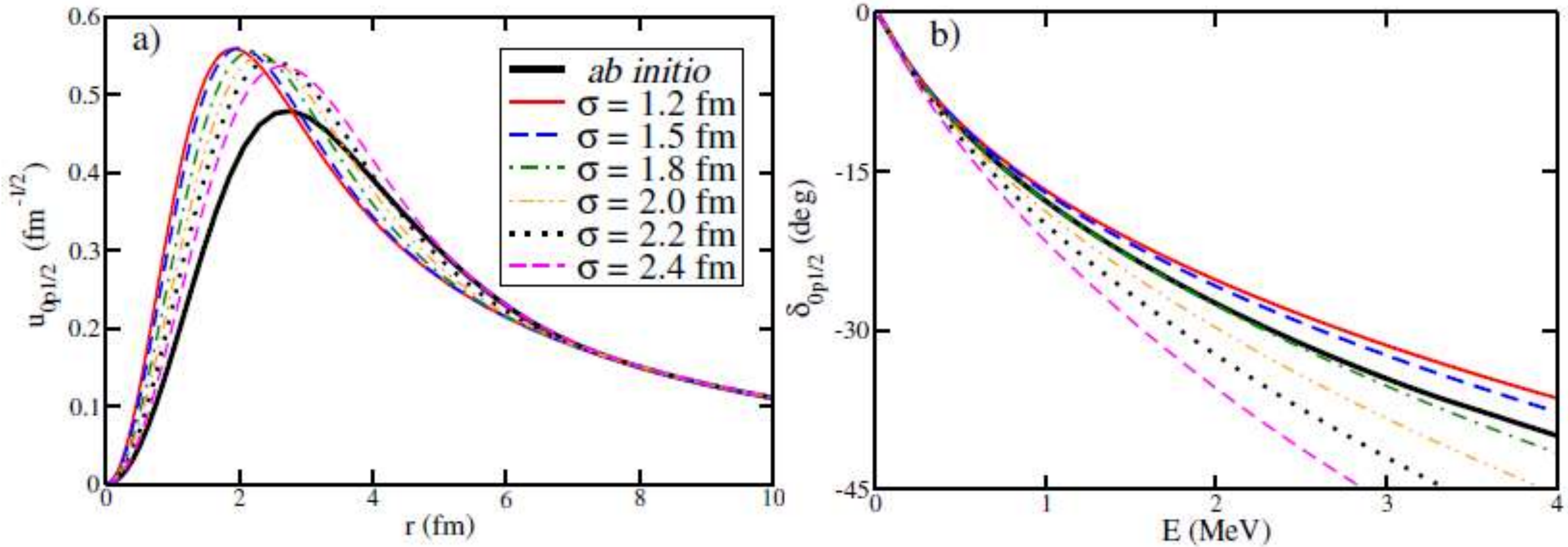
σ-dependency already visible in s.p. NLO results:



- Pre-asymptotic region only reproduced with large cut-off [$\sigma = 2.4$ fm]
  $\rightarrow \frac{1}{2}^{-}$ **state:= mean-field state**

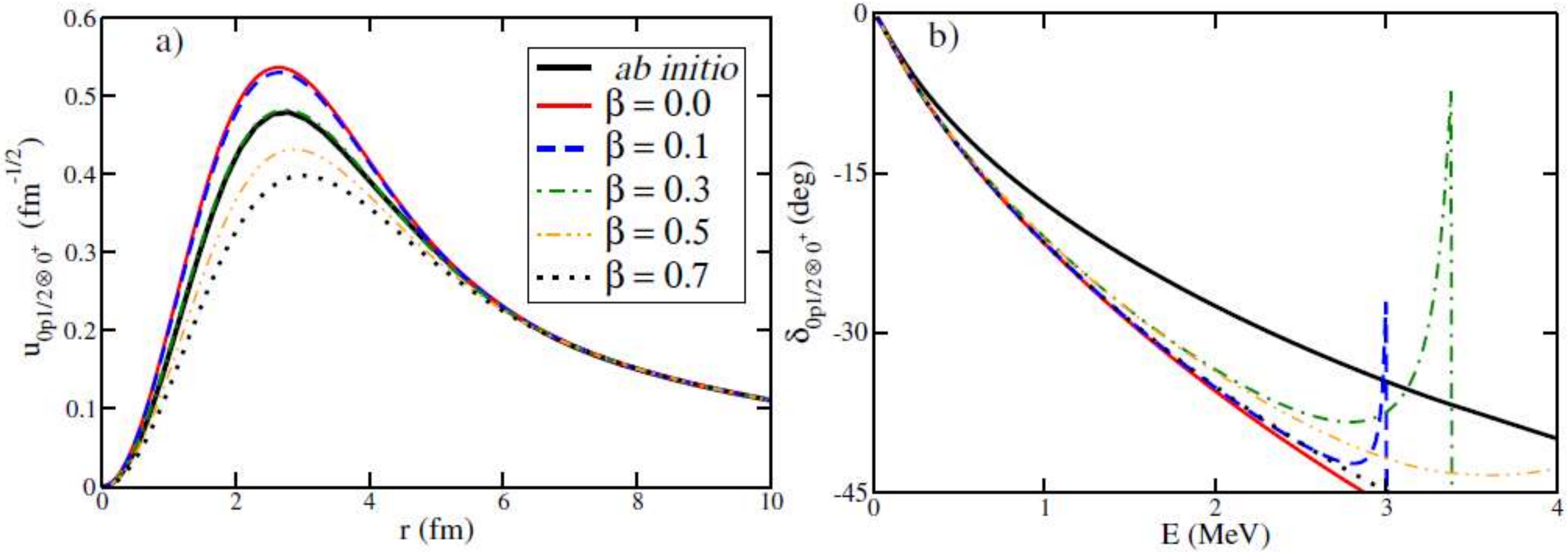
Excited state and σ-dependency: s.p. analysis @NLO

σ-dependency already visible in s.p. NLO results:



- Pre-asymptotic region only reproduced with large cut-off [$\sigma = 2.4$ fm]
  $\rightarrow \frac{1}{2}^-$ **state:= mean-field state**
- Phaseshifts: clear σ-dependency [best δ_α for $\sigma = 1.8$ fm]
  $\rightarrow$ need of N^2LO **structure** and **breakup** calculations

First bound excited state: $\frac{1}{2}^+$ - large σ=2.4fm



β=0.3:

→ reproduces the *ab initio* wf very well [SF=0.86 vs 0.85 for *ab initio*]

→ yields B(E1) in very good agreement with the *ab initio* prediction

→ (and all βs) reproduces poorly the *ab initio* phaseshift

$\frac{1}{2}^+$ - large σ=2.4fm → my B(E1) vs *ab initio* B(E1)

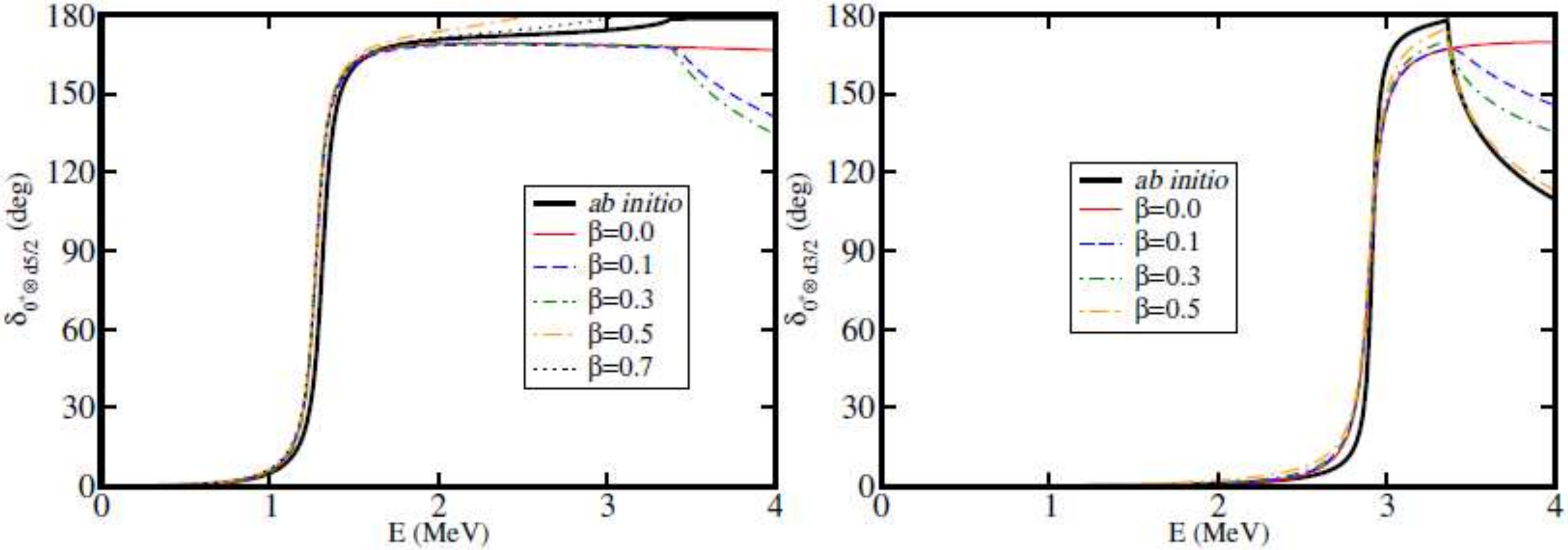
g.s	e.s	
$\sigma=\sigma_c$ [fm]	$\sigma=\sigma_c$ [fm]	$\mathcal{B}(E1)$ [e^2fm^2]
1.3 - β_2=0.35	1.3 - β_2=0.35	0.104
1.5 - β_2=0.50	1.5 - β_2=0.50	0.106
1.8 - β_2=0.50	1.8 - β_2=0.50	0.109
2.0 - β_2=0.50	2.0 - β_2=0.50	0.110
1.3 - β_2=0.35	2.4 - β_2=0.30	0.115
1.5 - β_2=0.50	2.4 - β_2=0.30	0.114
1.8 - β_2=0.50	2.4 - β_2=0.30	0.114
2.0 - β_2=0.50	2.4 - β_2=0.30	0.113
ab initio from Ref. [22]	/	0.117
Exp. from Ref. [113]	/	0.105(12)
Exp. from Ref. [114]	/	0.116(12)
Exp. from Ref. [112]	/	0.102(2)

→ e.s. with large σ=2.4fm → ab initio B(E1) reproduced with max. 4% error !

Resonances @NLO: $\frac{5}{2}^+, \frac{3}{2}^-, \frac{3}{2}^+$

Compare to *ab initio* predictions [Calci et al., PRL 117, 242501 (2016)]

- NLO potentials **fitted to** reproduce exp. $\mathbf{E}_{\rm res}$ and $\Gamma_{\rm res}$ for $\neq \beta$

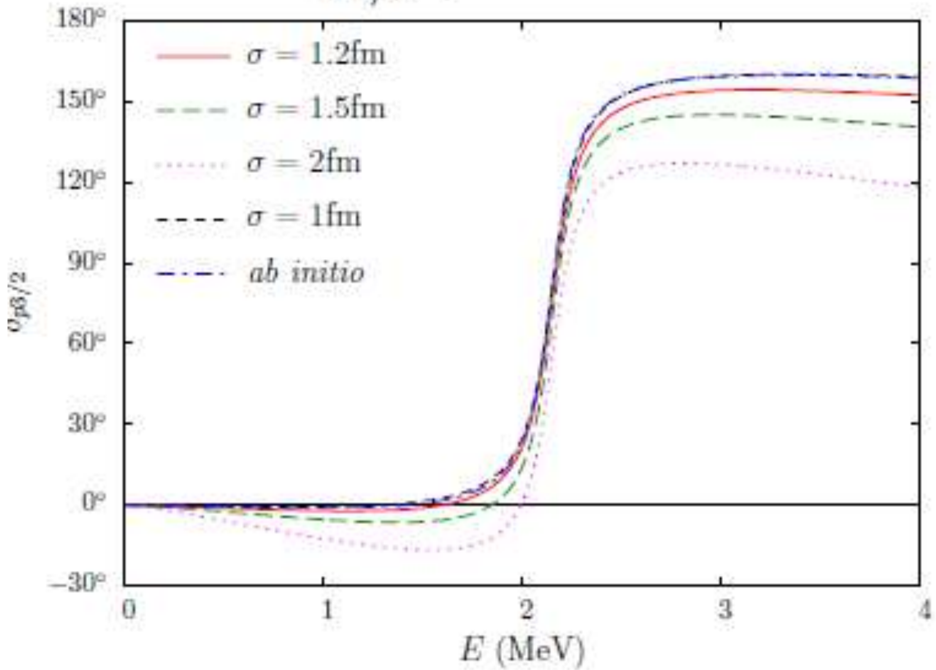


- Very good agreement for resonances too!
  → allows probing the **nature of resonances**
- Direct access to scattering wf, phaseshifts
  → $\frac{dB(E1)}{dE}$, cross sections for breakup, Coulomb excitation, transfer,...

s.p. @NLO: σ-dependency in p-waves

Sensitivity already seen in NLO calculations:
[Capel, Phillips, Hammer, PRC 98, 034610 (2018)]

$\delta_{p_{3/2}}$ phaseshifts

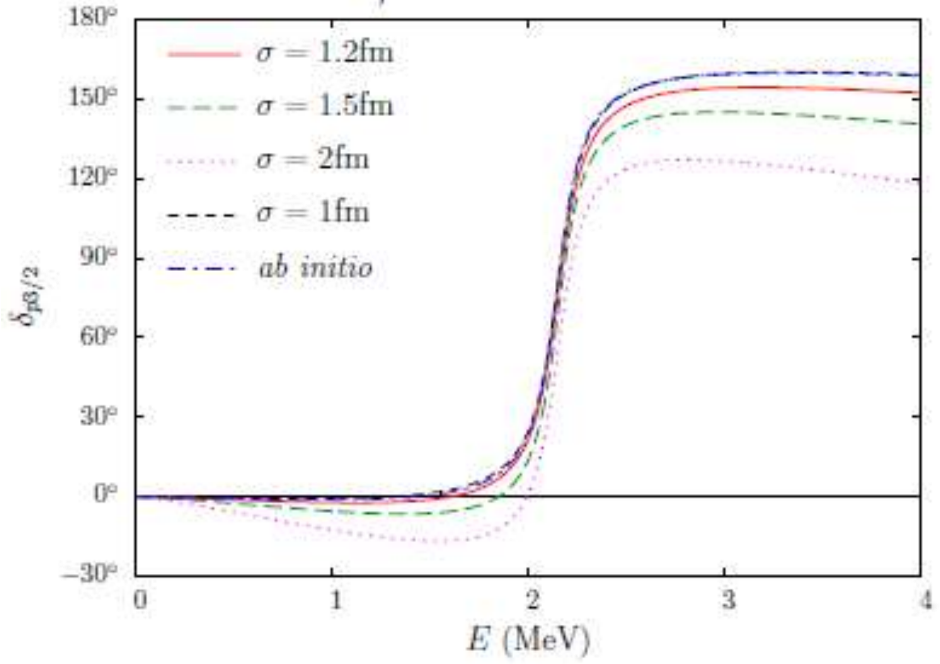


- @NLO: σ-dependency in δ

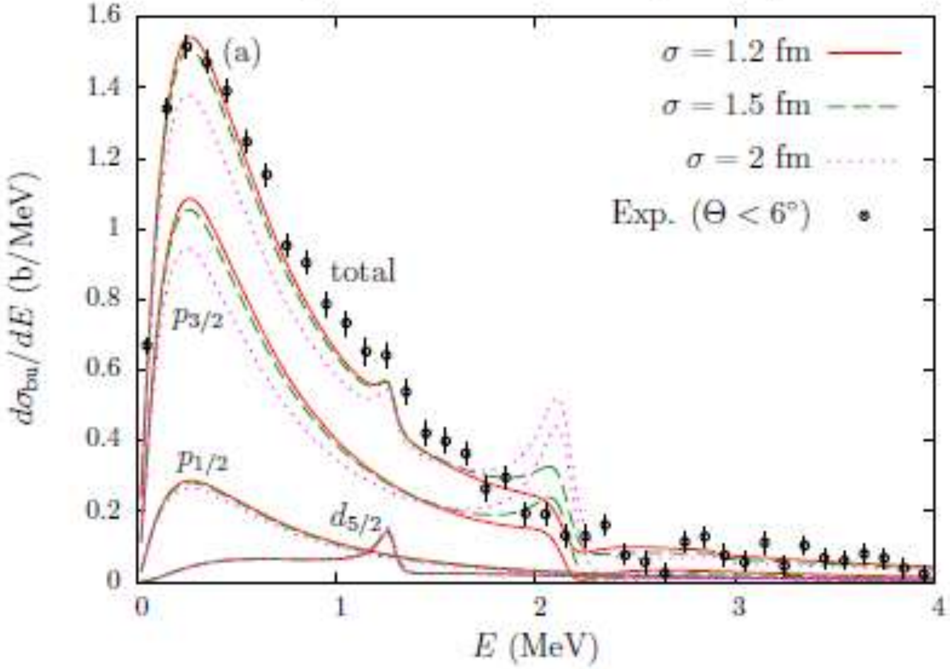
s.p. @NLO: σ-dependency in p-waves

Sensitivity already seen in NLO calculations:
[Capel, Phillips, Hammer, PRC 98, 034610 (2018)]

$\delta_{p_{3/2}}$ phaseshifts



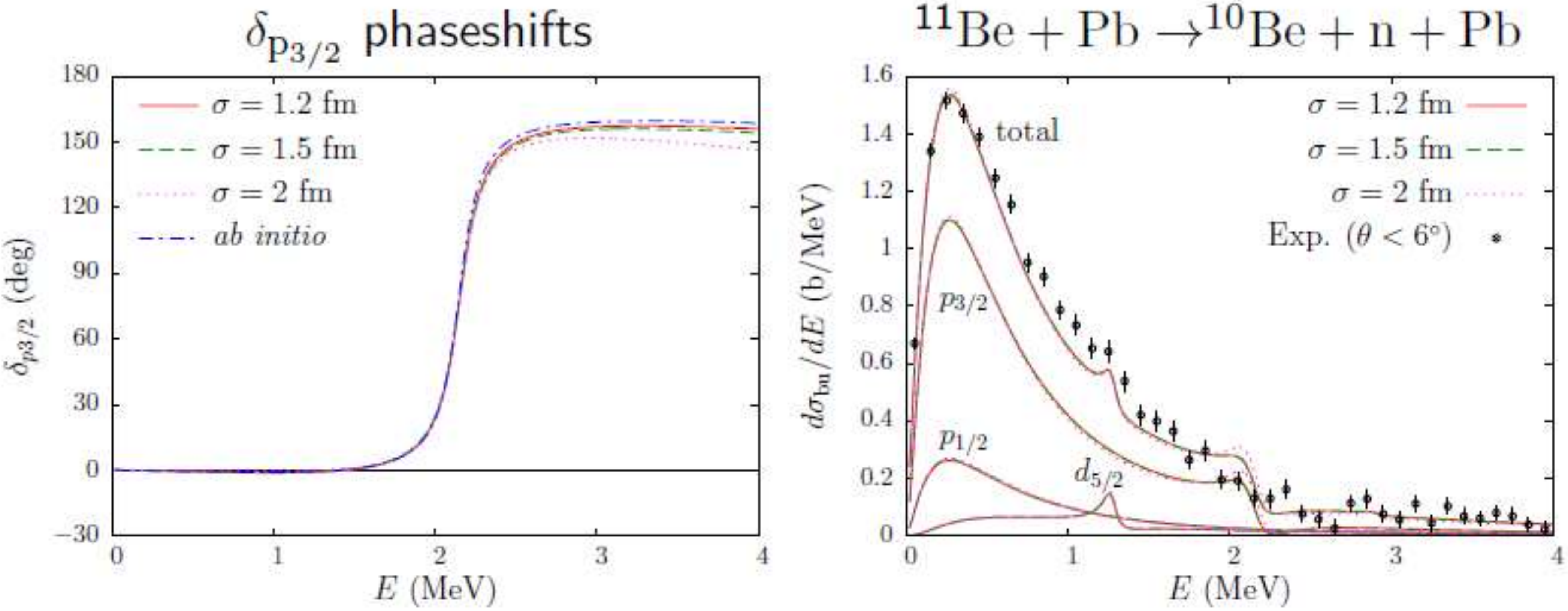
^{11}Be + Pb $\rightarrow$ ^{10}Be + n + Pb



- @NLO: σ-dependency in δ leads to σ-dependency on cross sections
- @N^{2}LO: strong reduction of the σ-dependency in $\delta_{p_{1/2}}$ and $\delta_{p_{3/2}}$?
  $\rightarrow$ Impact of N^{2}LO structure model on reaction observables ?

s.p. @N²LO: σ-dependency in p-waves

Description of ^{11}Be @N^{2}LO:



- Suppression σ-dependency in p-waves phaseshifts
  → same cross sections for all σ

[L.-P. Kubushishi and P. Capel, arXiv:2406.10168 (2024)]

Conclusion/outlook

I want to study reactions involving **one-neutron halo nuclei** :

- need of a **realistic few-body** model for reaction calculations
  $\rightarrow$ Halo-EFT

My model of one-neutron halo nuclei provides:

- perturbative inclusion of **core excitation within Halo-EFT**
- $\frac{1}{2}^{+}$ **state:** core excitation improves its few-body description
  $\rightarrow$ both wavefunction and phaseshift
- $\frac{1}{2}^{-}$ **state:** core excitation does not improve its few-body description

[L.-P. Kubushishi and P. Capel, (2024), (in preparation)]

Going @N^{2}LO in **s.p.** description:

- removes σ-dependency in $\delta_{\mathrm{p}_{1/2}}$ and $\delta_{\mathrm{p}_{3/2}}$ phaseshifts/cross sections

[L.-P. Kubushishi and P. Capel, arXiv:2406.10168 (2024)]

Outlook:

- same formalism to study heavier haloes: ^{19}C, ^{31}Ne, ^{37}Mg, ^{34}Na
- include our model in reaction codes (**breakup**, Coulomb excitation,...)

Thank you!