Tetra-Neutron from Chiral Interactions

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Motivation

Experiment

- Candidate resonance at $(0.83 \pm 1.89_{\text{tot}})$ MeV and $\Gamma \leq 2.6$ MeV
  Kisamori *et al.*, PRL **116**, 052501 (2016)
- Ongoing Experiments, see talks by Aumann, Shimoura and Marqués

Theory

- Complex scaling and $T = 3/2$ isospin 3-neutron force
  Hiyama, Lazauskas, Carbonell, Kamimura PRC **93**, 044004 (2016)
- HORSE method with JISP16 potential
  $E_\text{r} = 0.8$ MeV $\Gamma = 1.4$ MeV
  Shirokov, Papadimitriou, Mazur, Mazur, Roth, Vary, PRL **117**, 182502 (2016)
- Quantum Monte-Carlo with local chiral interactions
  $E_\text{r} = 2$ MeV $\Gamma =?$ MeV
  Gandolfi, Hammer, Klos, Lynn, Schwenk PRL **118**, 232501 (2017)
- Gamow-NCSM with two-body chiral interactions
  $E_\text{r} = 7.3$ MeV $\Gamma \geq 3.48$ MeV
  Fossez, Rotureau, Michel, and Płoszajczak PRL **119**, 032501 (2017)

Motivation

- Following HORSE method
  - See A. Shirokov's talk this morning
  - Shirokov, Mazur, Mazur, Vary, Phys. Rev. C **94**, 064320 (2016)
    Shirokov et al. PRL **117**, 182502 (2016)
- Relative coordinate / Jacobi-NCSM
- Application to 4n with modern chiral NN+3N interactions
- Model space convergence and SRG effects
- Benchmark of method with ^{4}He+n

HORSE

- Harmonic Oscillator Representation of Scattering Equations

$$\tan(\delta_\ell(k)) = -\frac{j_l(ka) - kaR_l j_l'(ka)}{n_l(ka) - kaR_l n_l'(ka)}$$

$$\tan(\delta_\ell(E)) = -\frac{S_{N\ell}(E) - G^\ell_{NN}(E) S_{N+2,\ell}(E)}{C_{N\ell}(E) - G^\ell_{NN}(E) C_{N+2,\ell}(E)}$$

- Single-State HORSE

$$\tan(\delta_\ell(E_\nu)) = -\frac{S_{N+2,\ell}(E_\nu)}{C_{N+2,\ell}(E_\nu)}$$

- Post processing of NCSM calculation

- Systematic study of N_{max} convergence
- For $N_{\text{max}} \to \infty$ results should be exact

HORSE

- Obtaining phase shift curve:

4n

- Vary model space truncation $N_{\max}$ (range $N_{\max} = 0$ to 26)
- Vary frequency $\hbar\Omega$ (range $\hbar\Omega = 0.5$ to 40 MeV)
- Extract lowest energy eigenvalue for each $(\hbar\Omega, N_{\max})$

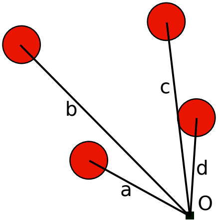
^{4}He+n

- Steps as for 4n for ^{4}He and ^{5}He
- Subtract ^{4}He ground state energy from desired ^{5}He channel with same $\hbar\Omega$ and $N_{\max}$

- Plug into phase shift relation

$$\tan(\delta_\ell(E_\nu)) = -\frac{S_{N+2,\ell}(E_\nu)}{C_{N+2,\ell}(E_\nu)}$$

No-Core Shell Model



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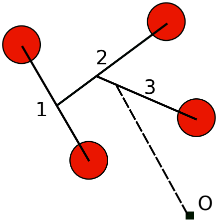


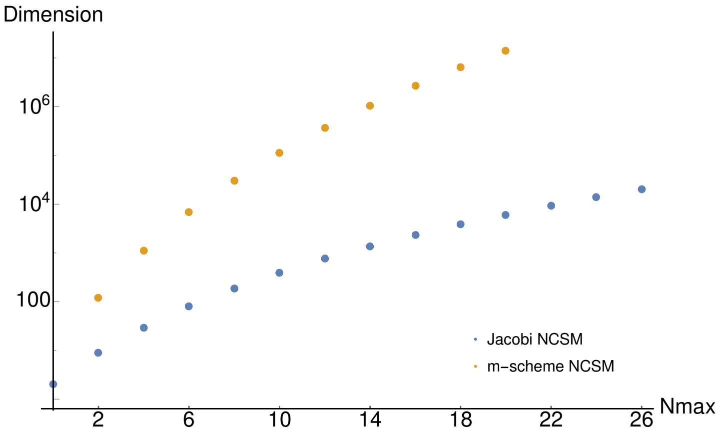
$|123\rangle$

- m-scheme-NCSM
  - A-body Slater determinants from HO states
  - N_{max}: Total A-body excitation quanta $\rightarrow$ Impose N_{max} truncation
- Jacobi-NCSM
  - CoM separation
  - Choice of angular momentum channel
  - HO basis intrinsic Jacobi-coordinate with good J
  - Equivalent N_{max} truncation

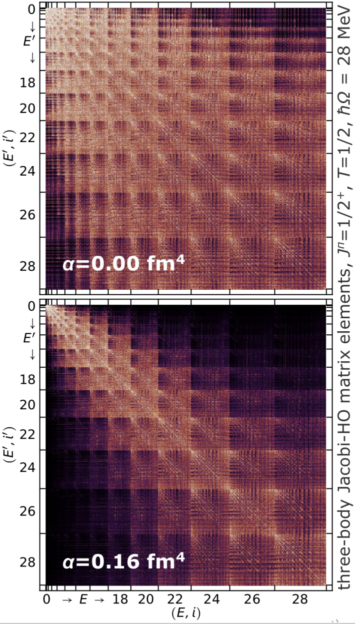
$\Rightarrow$ Diagonalize Hamilton matrix

Jacobi-NCSM

- Allows for larger N_{max} due to smaller basis dimension
- Inclusion of full NN+3N matrix elements



Similarity Renormalization Group



$$\frac{\mathrm{d}}{\mathrm{d}\alpha}\boldsymbol{H}(\alpha) = [\boldsymbol{\eta}(\alpha), \boldsymbol{H}(\alpha)]$$

$$\boldsymbol{\eta}(\alpha) = m_N^2[\boldsymbol{T}_{\text{int}}, \boldsymbol{H}(\alpha)]$$

- Unitary transformation
- Decouples high and low momenta
  ⇒ Improved N_{max} convergence
- BUT: Induced many-body terms
  $\boldsymbol{H}(\alpha) = \boldsymbol{H}_\alpha^{(1)} + \boldsymbol{H}_\alpha^{(2)} + \boldsymbol{H}_\alpha^{(3)} + \boldsymbol{H}_\alpha^{(4)} + \ldots$
  ⇒ Assess via α-dependence

Tetra-Neutron

Interactions

- JISP16
  - NN only

    Shirokov, Vary, Mazur, Weber, PLB **644**, 33 (2007)
- EM/N
  - SRG evolved $\alpha = (0.04, 0.06, 0.08)$ fm^4
  - Cut-off of $\Lambda_{3N} = 400$ and 500 MeV
  - Full 3N and 3N induced

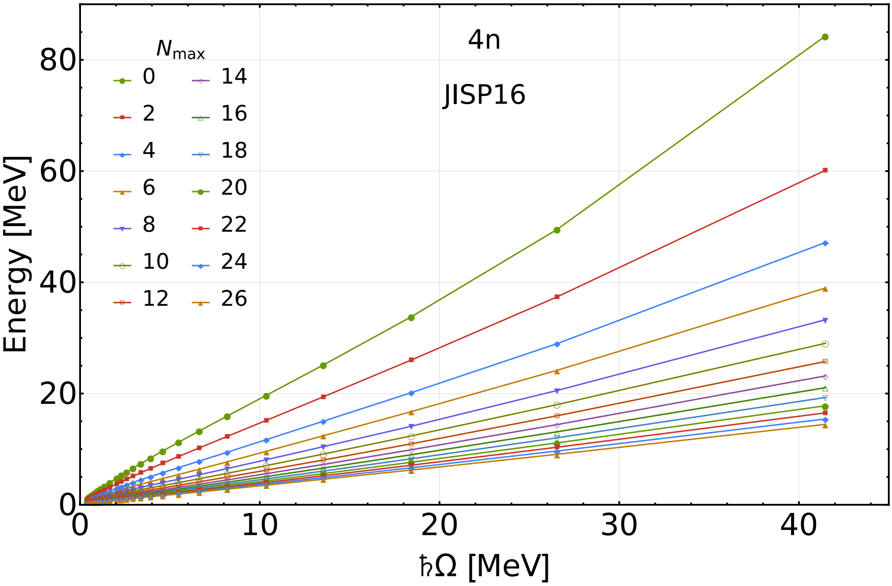
    NN: Entem and Machleidt, PRC **68** , 41001 (2003)

    3N: Navratil, Few-Body Syst. **41**, 117 (2007)
- N2LO SAT
  - SRG evolved $\alpha = (0.04, 0.08)$ fm^4
  - Cut-off of $\Lambda = 500$ MeV

    Ekström *et al.*, PRC **91**, 051301 (2015)
- EMN 2017
  - Only SRG induced 3N forces
  - SRG evolved $\alpha = (0.04, 0.08)$ fm^4
  - Cut-off of $\Lambda = 500$ MeV
  - Chiral order from N2LO to N4LO

    Entem, Machleidt, Nosyk, PRC **96**, 024004 (2017)

NCSM Data

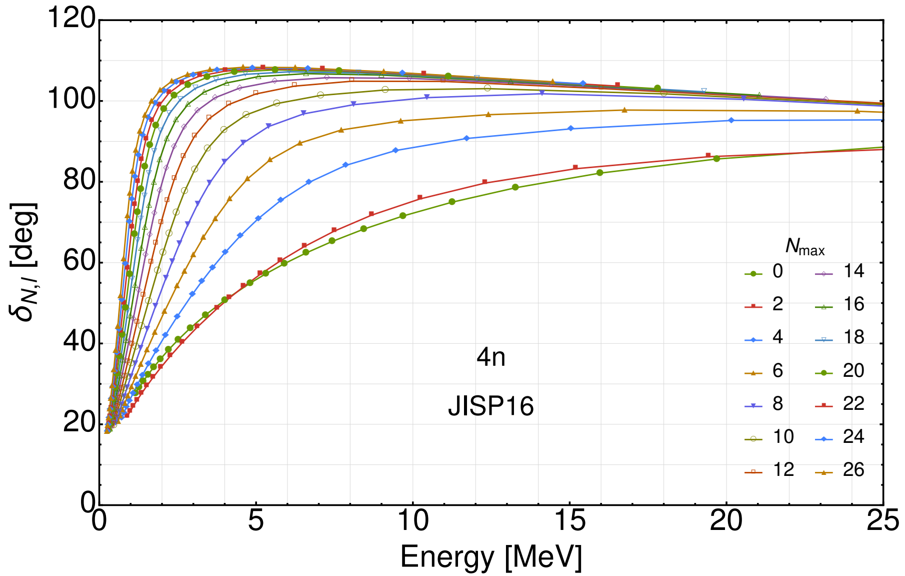


4n
JISP16
N_{max}
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Energy [MeV]
ħΩ [MeV]
0
20
40
60
80
0
10
20
30
40

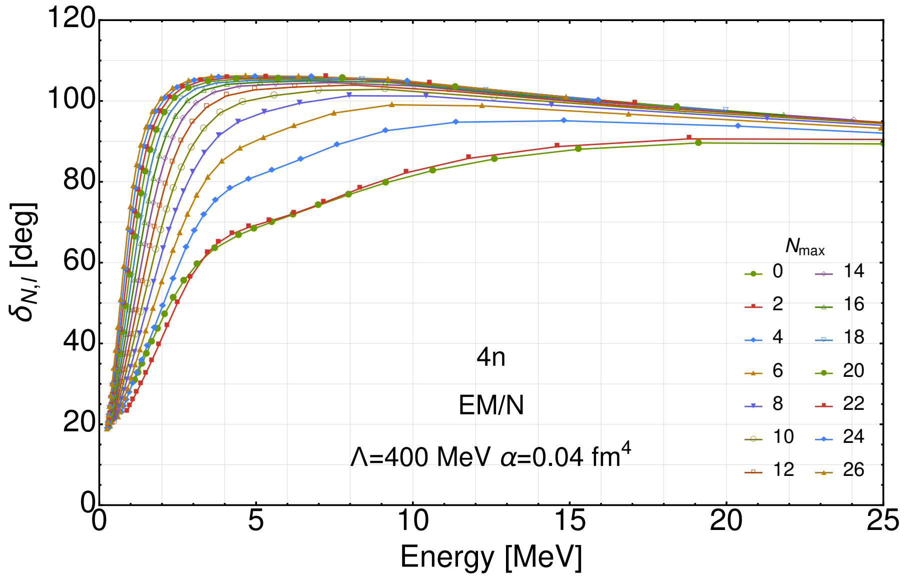
Tetra-Neutron

Model Space Convergence

Phase Shift - Convergence

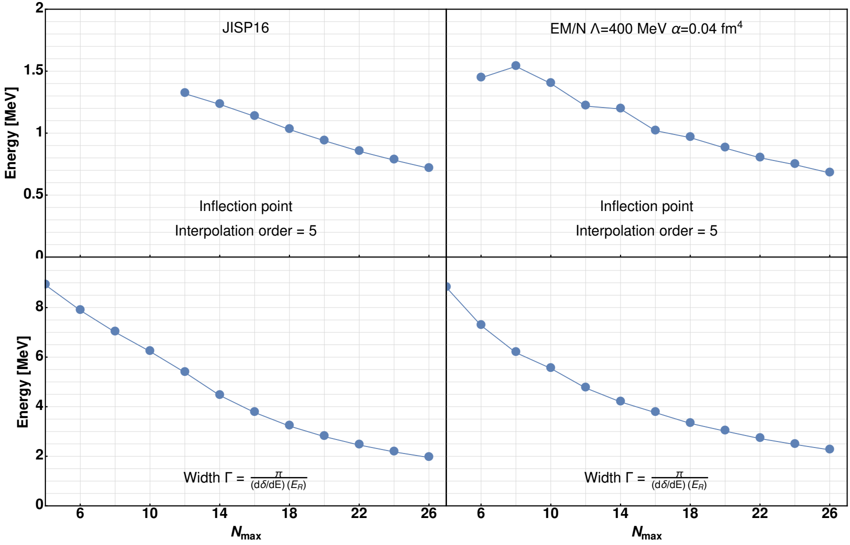


Phase Shift - Convergence



Resonance Parameters

Interpolation of phase shift points



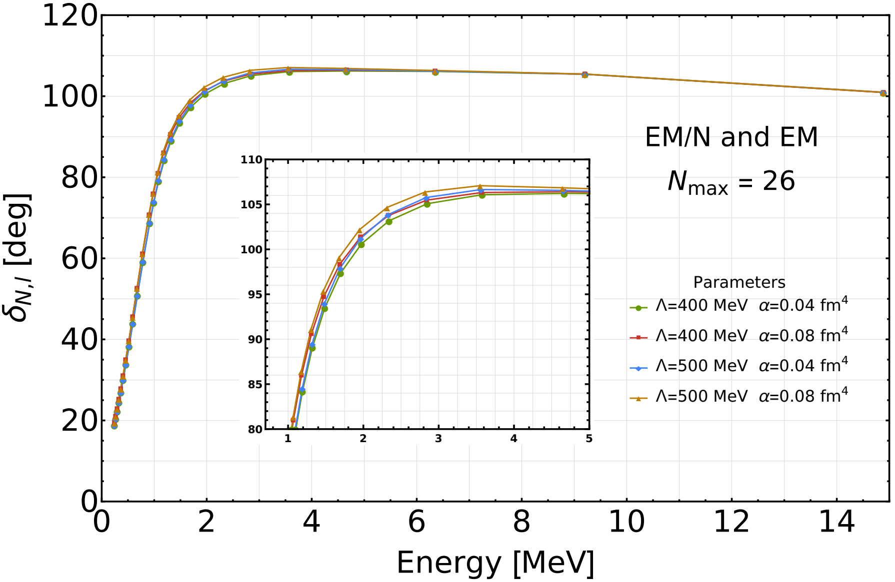
Results -Convergence

- Large model space ($N_{\text{max}} = 26$) due to Jacobi-NCSM
- Phase shift not fully converged
- Inflection point as indicator for resonance energy
- Resonance parameters compatible with experiment

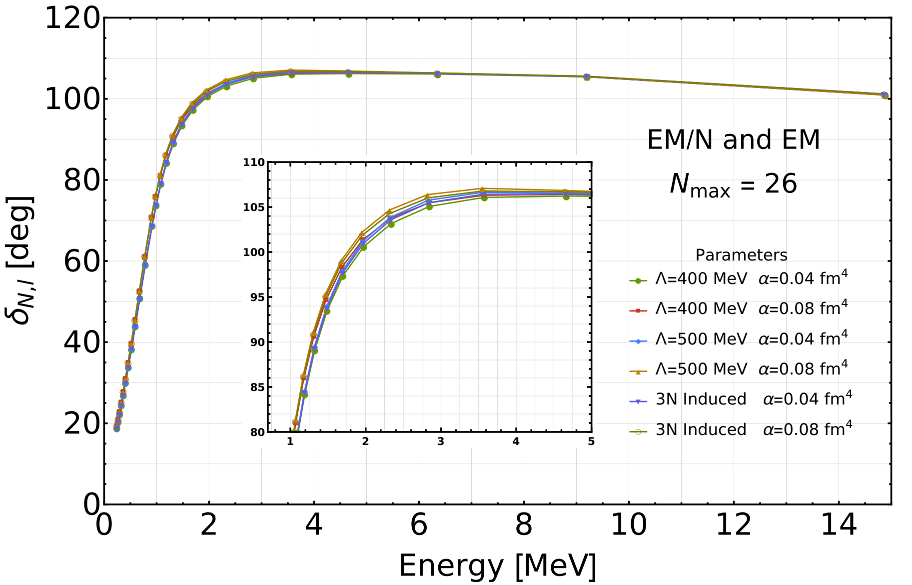
Tetra-Neutron

Interaction effects, influence of SRG and cut-off

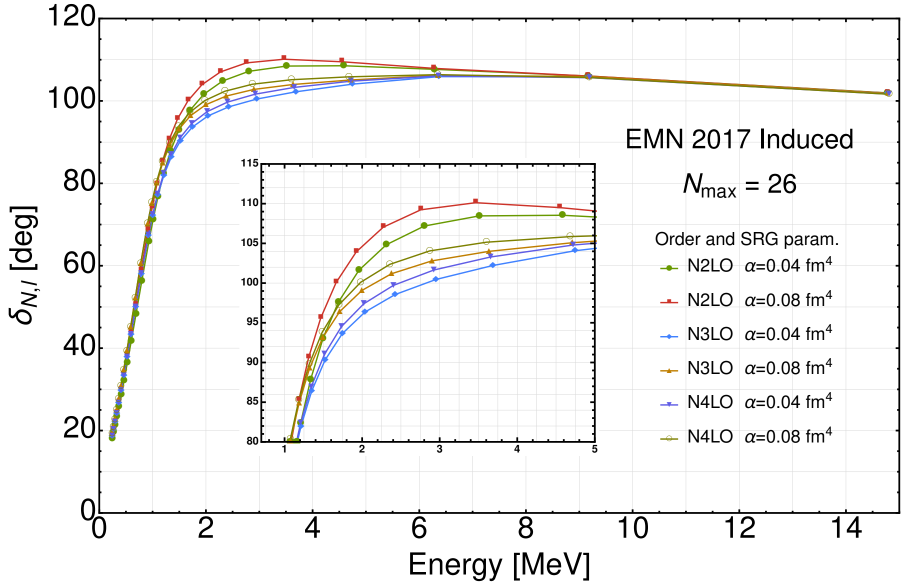
Interaction effects



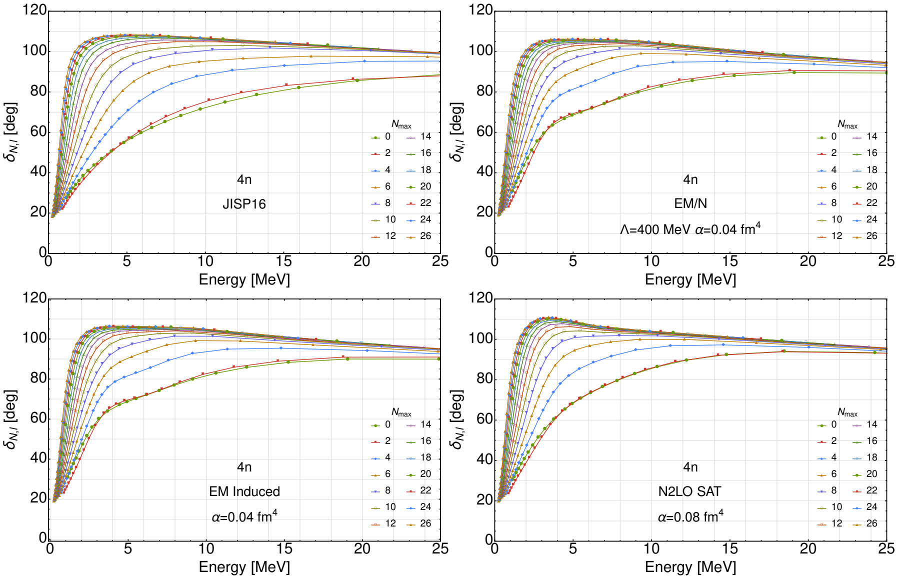
Interaction effects



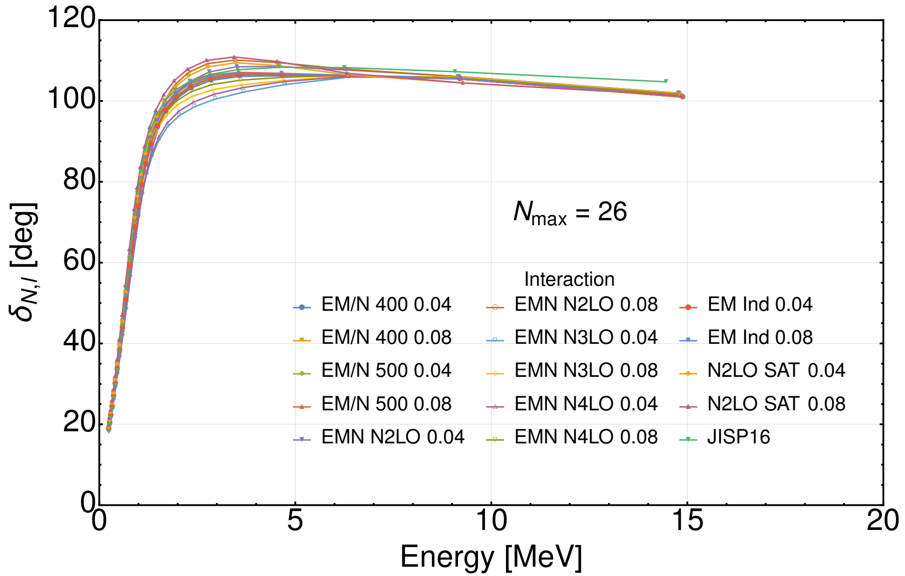
Interaction effects



Interaction effects

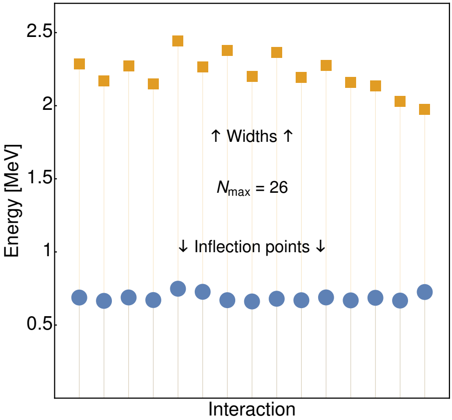


Interaction effects



Interaction effects

- Resonance parameters robust w.r.t to interactions
- REMINDER:
  - $N_{\text{max}} = 26$ not fully converged
  - Inflection point only indicators of resonance energy

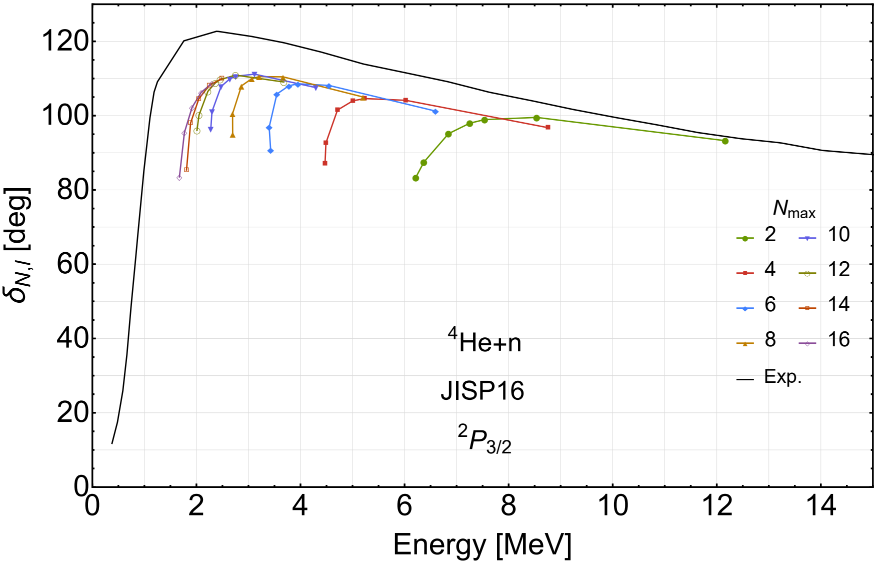


Benchmark

^{4}He+n scattering

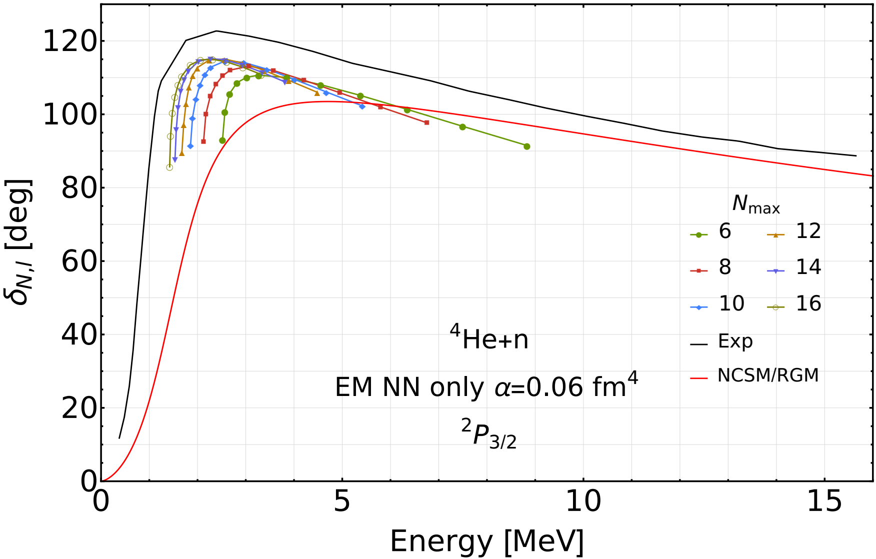
W.I.P.

Benchmark: ^{4}He+n scattering



Data: Navratil, Roth, Quaglioni, Phys. Rev. C **82** , 034609 (2010)

Benchmark: ^{4}He+n scattering



Data: Navratil, Roth, Quaglioni, Phys. Rev. C **82** , 034609 (2010)

Summary

Summary

- HORSE method enables phase shift extraction from NCSM
- Relative coordinate NCSM allows for large N_{max}
- Phase shift convergence w.r.t to N_{max} not fully reached
- **Results compatible with experiment**
- **Little sensitivity to interactions**

Outlook

- Uncertainty quantification
- Resonance parameter extraction
- Full HORSE technically possible with Jacobi-NCSM
- Complementary Gamow-NCSM
- Results of experiments
- Tri-neutron

Epilog

- **Thanks to my group & collaborators**
  - D. Derr, E. Gebrerufael, A. Geißel, **T. Hüther**, **R. Roth**, S. Schulz, C. Stumpf, A. Tichai, K. Vobig, R. Wirth

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- **Thank you for your attention!**

JURECA — LOEWE-CSC — LICHTENBERG

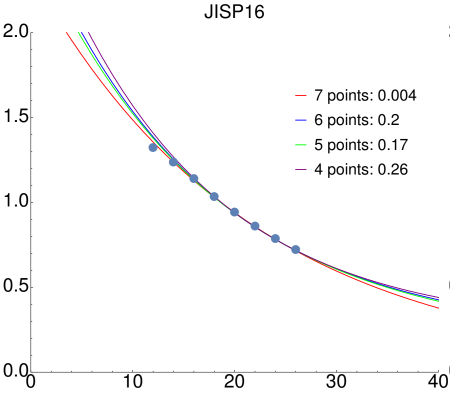
COMPUTING TIME

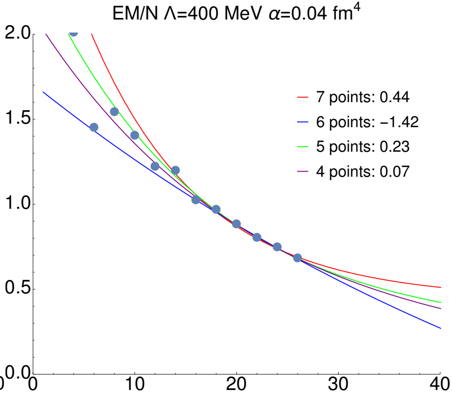
BACKUP

BACKUP

Results - Convergence

- Exponential fit
- Variation in number of points considered in fit





Obtaining resonance parameters

- Parametrize phase shift

$$\delta_\ell(E) = \delta_R(E) + \phi(E)$$

- Resonant part

$$\delta_R(E) = -\tan^{-1}\left(\frac{a\sqrt{E}}{E-b^2}\right)$$

- Resonance energy

$$E_R = b^2 - \frac{a^2}{2}$$

- Resonance width

$$\Gamma = 2a\sqrt{b^2 - \frac{a^2}{4}}$$

Obtaining resonance parameters

- Background
  - Taylor expansion

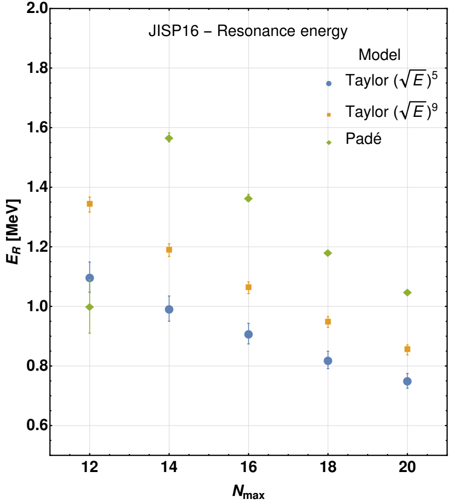
$$\phi_1(E) = c\sqrt{E} + d\sqrt{E}^3 + f\sqrt{E}^5$$

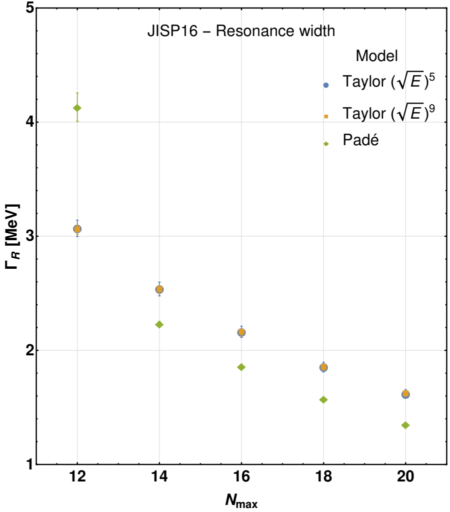
$$\phi_2(E) = c\sqrt{E} + .. + h\sqrt{E}^9$$

  - Padé expansion

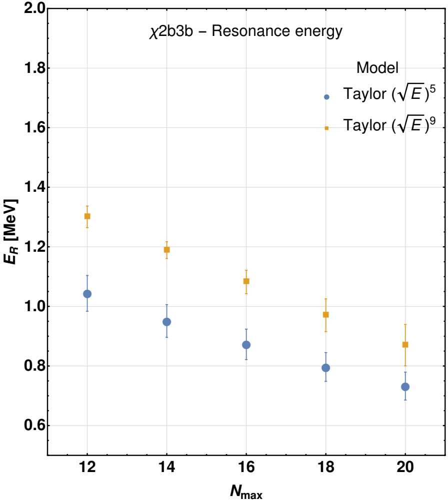
$$\phi_3(E) = \frac{w_1\sqrt{E} + w_3\sqrt{E}^3 + c\sqrt{E}^5}{1 + w_2E + w_4E^2 + w_6E^3 + dE^4}$$

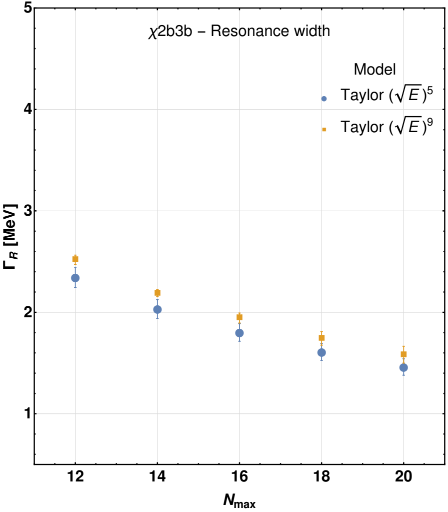
Results - Resonance energy and width





Results - Resonance energy and width





Results - Resonance energy and width