Tetraneutron resonance

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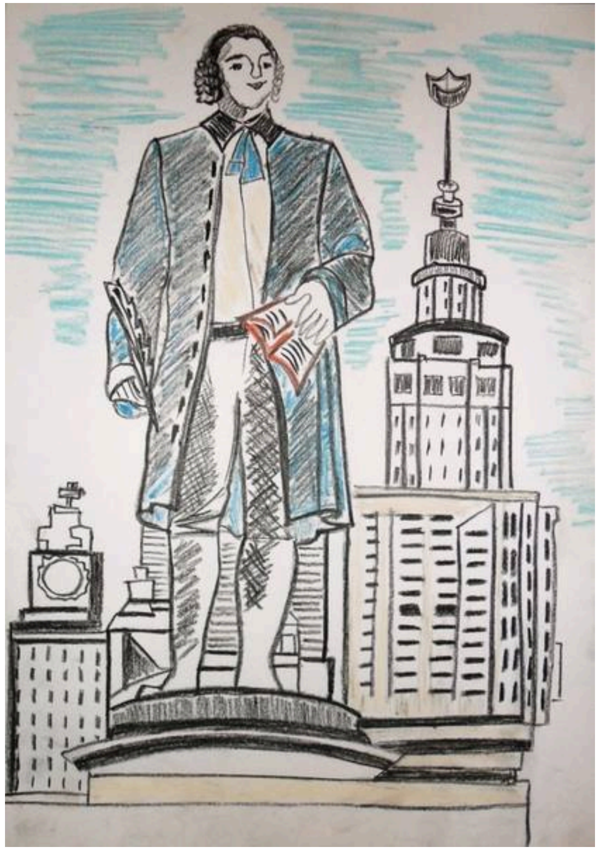

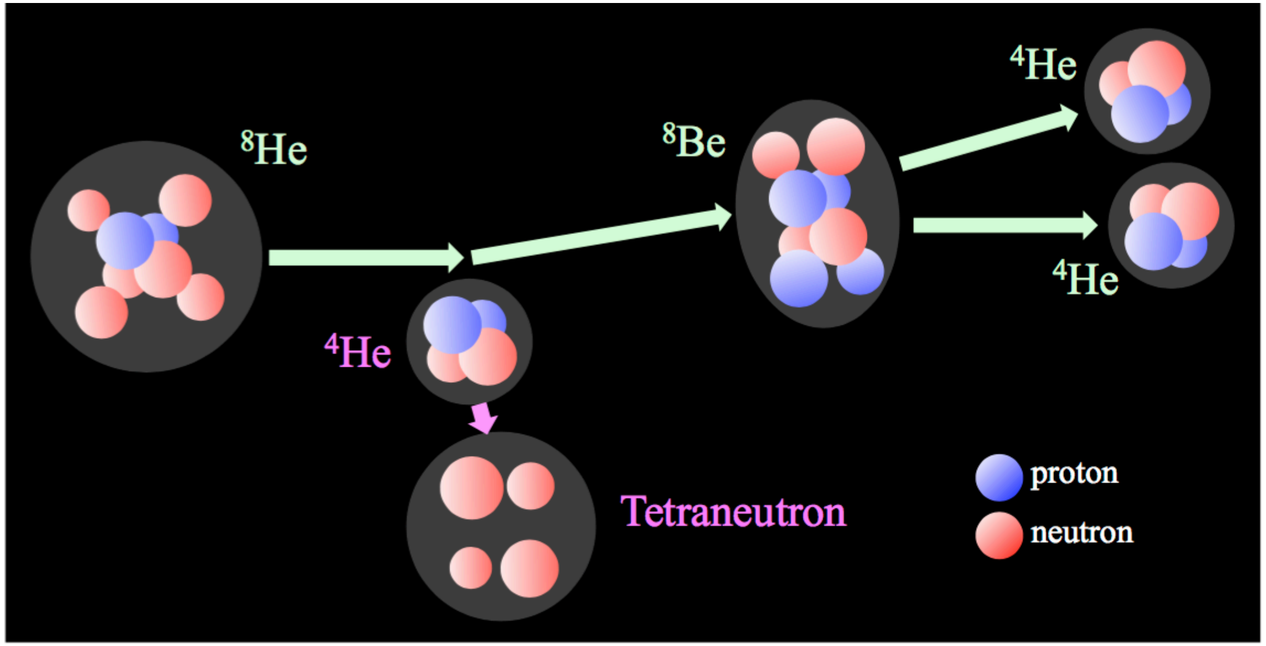

NTSE-2018, Daejeon, November 2, 2018

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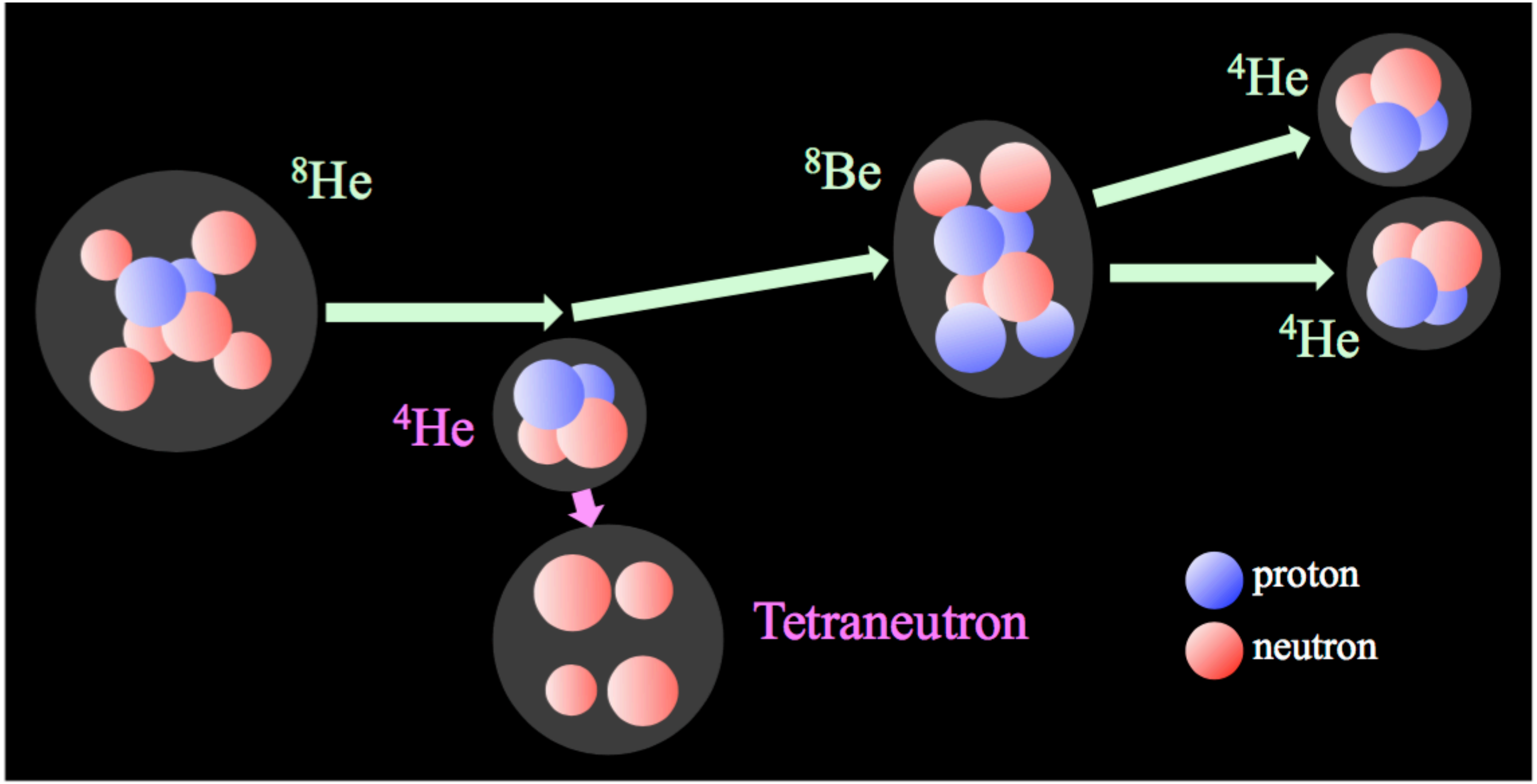
Tetraneutron experiment: history

- More than 50 years of tetraneutron searches
- For historical survey see R. Ya. Kezerashvili, arXiv:1608.00169 [nucl-th] (2016)
- Early studies: ^{4}He$(\pi^-, \pi^+)^4$n reaction – no resonance or bound state
- Later: ^{7}Li(^{11}B,^{14}O)^{4}n; ^{7}Li(^{7}Li,^{10}C)^{4}n – no evidence for ^{4}n
- F. M. Marqués et al., Phys. Rev. C **65**, 044006 (2002): ^{14}Be $\rightarrow$ ^{10}Be + ^{4}n — bound tetraneutron ???

Not confirmed... Experimental program stopped...

Tetraneutron



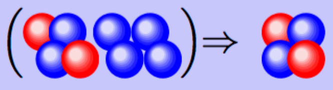
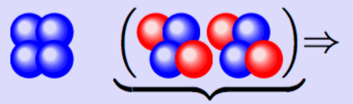
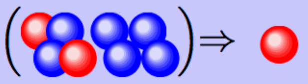
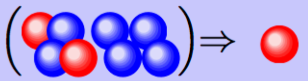
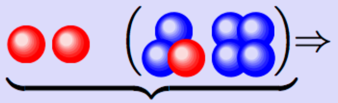
K. Kisamori et al., Phys. Rev. Lett. **116**, 052501 (2016):
E_R = 0.83 ± 0.63(statistical) ± 1.25(systematic) MeV; width $\Gamma \leq 2.6$ MeV

More experimental data are expected
Other experiments are starting

Tetraneutron experiment: future

Tetraneutron context @ RIKEN

- Three experiments : same beam (^{8}**He**) & energy (150–200 MeV/N) ?

reaction	initial state	final state	σ	results
^{4}He (^{8}He, $\alpha\alpha$) ^{4}**n** Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s ^{4}n : E, Γ
^{8}He (p,pα) ^{4}**n** Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s ^{4}n : E, Γ
^{8}He (p,2p) {^{3}**H**+^{4}**n**} FMM/Yang, NP1512-SAMURAI34			**mb**	$N_{evt} \sim$ **10,000** s ^{4}n & ^{7}H : E, Γ, $\boldsymbol{\Omega}$

('16) SHARAQ 2.0 : {DAQ, tracking, calib.} $\Rightarrow$ stat. & res. $\times 5$

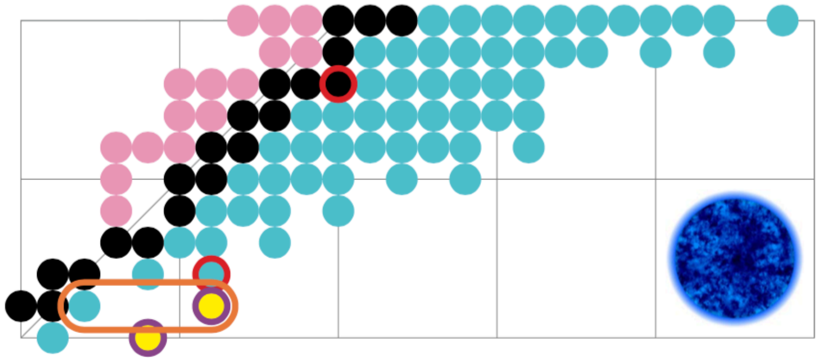
('17) QFS (p,pα) : $\theta_{cm} \lesssim 180°$ $\Rightarrow$ 4n without FSI

('17) 4n decay of ^{7}H $\Rightarrow$ high stat. & res. for any ^{7}H and ^{4}n state

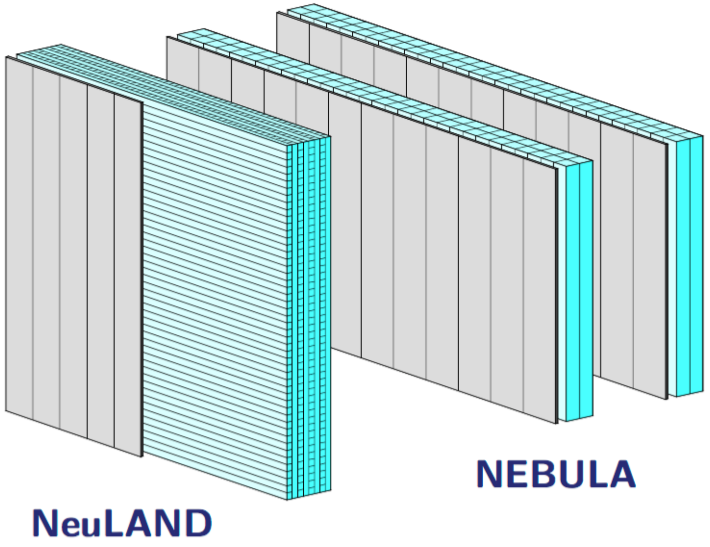
$\Rightarrow$ definitive answer !

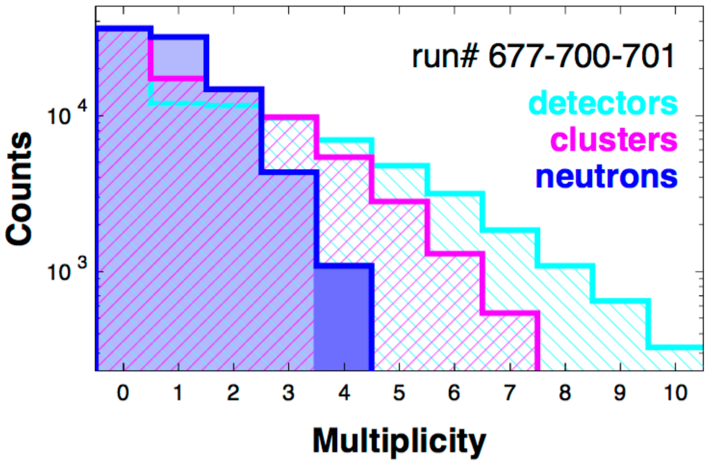
Tetraneutron experiment: future

First online 'results' ...



- Online analysis : $^{8}He(p,2p)$ $^{3}H+^{4}n$
  - ✔ ^{8}He on target
  - ✔ 2p detected
  - ✔ ^{3}H detected
  - → $\geqslant 4$ bars ?





→ complete events : $\approx 8\times10^4$!!!

→ promising results in 1-2 years ...

Tetraneutron theory: history

- For a historical survey see R. Ya. Kezerashvili, arXiv:1608.00169 [nucl-th] (2016)
- There was a lot of theoretical studies of tetraneutron starting from 1970's with various *NN* and *NNN* interactions within various approaches: democratic decay (hyperspherical approach), Faddeev–Yakubovsky equations, Gamow shell model, complex scaling, analytic continuation in the coupling constant, various bound state techniques…
- An undoubtful conclusion: no tetraneutron bound state
- No indication in previous studies of a resonance at low enough energies and narrow enough to be detected experimentally from numerous studies allowing for continuum
- There were, however, some indication on a possible low-lying tetraneutron resonance from some bound-state calculations…

Tetraneutron: an example of
an indication on a possible low-lying tetraneutron resonance from GFMC bound-state calculations

VOLUME 90, NUMBER 25 PHYSICAL REVIEW LETTERS week ending 27 JUNE 2003

Can Modern Nuclear Hamiltonians Tolerate a Bound Tetraneutron?

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(Received 18 February 2003; published 27 June 20

I show that it does not seem possible to change modern nuclear Hamilto without destroying many other successful predictions of those Hamiltonian recent experimental claim of a bound tetraneutron be confirmed, our unde will have to be significantly changed. I also point out some errors in previou problem.

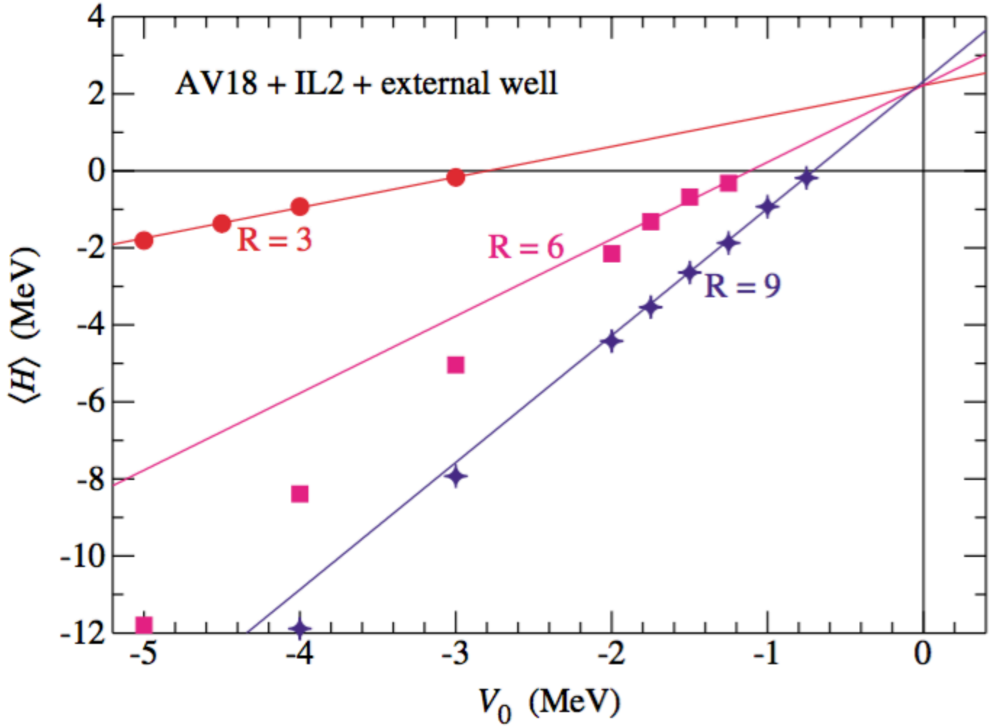

FIG. 1 (color online). Energies of ${}^4n$ in external wells versus the well-depth parameter V_0.

Tetraneutron: an example of a recent study of a possible low-lying tetraneutron resonance

PHYSICAL REVIEW C **93**, 044004 (2016)

Possibility of generating a 4-neutron resonance with a $T = 3/2$ isospin 3-neutron force

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We consider the theoretical possibility of generating a narrow resonance in the 4-neutron system as by a recent experimental result. To that end, a phenomenological $T = 3/2$ 3-neutron force is intr addition to a realistic NN interaction. We inquire what the strength should be of the $3n$ force to gener resonance. The reliability of the 3-neutron force in the $T = 3/2$ channel is examined, by analyzing its c with the low-lying $T = 1$ states of ^{4}H, ^{4}He, and ^{4}Li and the ^{3}H$+n$ scattering. The *ab initio* solution Schrödinger equation is obtained using the complex scaling method with boundary conditions approp four-body resonances. We find that to generate narrow $4n$ resonant states a remarkably attractive $3N$ f $T = 3/2$ channel is required.

To produce resonant tetraneutron states which were situated in the complex energy plane close to the physical axis, and, thus may have an observable impact, we were obliged to introduce strong modifications in the $T = 3/2$ $3N$ force. These modifications were, however, found to be inconsistent with other well-established nuclear properties and low energy scattering data. This result is in line with our previous study of the tetraneutron system [17].

In conclusion, we were not able to validate the recent observation of a ^4n signal [7,8] as related to the existence of resonant $4n$ states.

Tetraneutron theory: history

- So, an undoubtful conclusion: no tetraneutron bound state
- No indication in previous studies of a resonance at low enough energies and narrow enough to be detected experimentally from numerous studies allowing for continuum
- We, however, obtain such a resonance within a newly developed SS-HORSE-NCSM approach with our JISP16 *NN* interaction fitted to *NN* data and properties of light nuclei: AMS et al., Phys. Rev. Lett. **117**, 182502 (2016): E_R = 0.8 MeV; width Γ = 1.4 MeV

Our approach

- Our approach: No-core Shell Model (NCSM) + SS-HORSE technique to calculate *S*-matrix at the NCSM eigenstates (more details in A. Mazur's talk today):

$$\tan\delta(E_\lambda) = \frac{S_{N+1,l}(E_\lambda)}{C_{N+1,l}(E_\lambda)}$$

- Calculating a set of E_λ eigenstates with different $\hbar\Omega$ and N_{max} within the NCSM, we obtain a set of $\delta(E_\lambda)$ values which we can approximate by a smooth curve at low energies; the $\delta(E_\lambda)$ parametrization includes pole terms associated with resonances, etc.
- Specific for tetraneutron is the democratic decay

S-matrix at low energies

Symmetry property:
$$S(-k) = \frac{1}{S(k)}$$
$$S(k) = \exp 2i\delta$$

Hence $$\delta(-k) = -\delta(k), \qquad k \sim \sqrt{E},$$

$$\delta \simeq C\sqrt{E} + D(\sqrt{E})^3 + F(\sqrt{E})^5 + ...$$

As $k \to 0: \quad \delta_\ell \sim k^{2\ell+1} \sim (\sqrt{E})^{2\ell+1}$

Bound state: $$S_b^{(i)}(k) = \frac{k + ik_b^{(i)}}{k - ik_b^{(i)}},$$

$$\delta_0 \simeq \pi - \arctan\sqrt{\frac{E}{|E_b|}} + c\sqrt{E} + d(\sqrt{E})^3 + f(\sqrt{E})^5 ...$$

Resonance: $$S_r^{(i)}(k) = \frac{(k + \kappa_r^{(i)})(k - \kappa_r^{(i)*})}{(k - \kappa_r^{(i)})(k + \kappa_r^{(i)*})}$$

$$\delta_1 \simeq -\arctan\frac{a\sqrt{E}}{E - b^2} + c\sqrt{E} + d(\sqrt{E})^3 + ..., \qquad c = -\frac{a}{b^2}.$$

Tetraneutron

- Democratic decay (no bound subsystems)
- Hyperspherical harmonics:

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, ..., \boldsymbol{r}_A) = \Phi(\rho)\mathcal{Y}_{k\nu}(\Omega), \quad \rho = \sqrt{\sum_{i=1}^{A} (\boldsymbol{r}_i - \boldsymbol{R})^2},$$

$$\Phi_{nK} \equiv \Phi_n^{\mathcal{L}}(\rho) = \rho^{-(3A-4)/2} \varphi_{nK}(\rho), \quad \mathcal{L} = K + \frac{3A-6}{2};$$

$$\frac{\hbar^2}{2m}\left[-\frac{d^2}{d^2\rho} + \frac{\mathcal{L}(\mathcal{L}+1)}{\rho^2}\right]\Phi_n^{\mathcal{L}}(\rho) + \sum_{\mathcal{L}'} V_{\mathcal{L},\mathcal{L}'}\Phi_n^{\mathcal{L}'}(\rho) = E\Phi_n^{\mathcal{L}}(\rho).$$

Approximation:

the only open channel is with $\mathcal{L} = \mathcal{L}_{\min} = K_{\min} + 3 = 5$.

All possible $\mathcal{L}$ (K) values are accounted for in diagonalization of the NCSM Hamiltonian

Tetraneutron

S-matrix: $\quad S = \exp 2i\delta^{\mathcal{L}}$

$$\delta^{\mathcal{L}} = C\sqrt{E} + D(\sqrt{E})^3 + F(\sqrt{E})^5 + \ldots$$

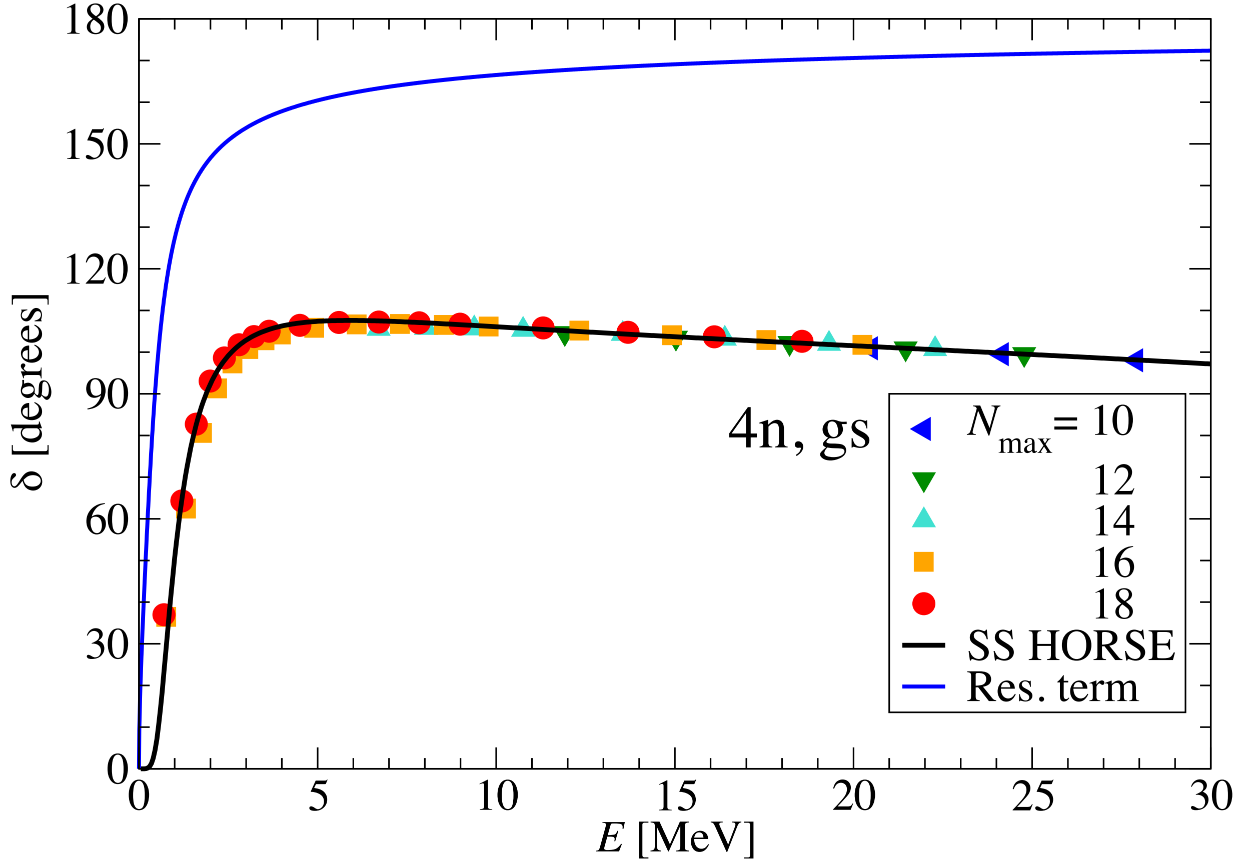
As $E \to 0: \quad \delta^{\mathcal{L}} \sim (\sqrt{E})^{2\mathcal{L}+1} \sim (\sqrt{E})^{11}$ – huge power!

$$\delta = -\arctan \frac{a\sqrt{E}}{E - b^2} - \phi_{3,6}(E),$$

$$\phi_{3,6}(E) = \frac{w_1\sqrt{E} + w_3\left(\sqrt{E}\right)^3 + c\left(\sqrt{E}\right)^5}{1 + w_2 E + w_4 E^2 + w_6 E^3 + dE^4},$$

$$\phi_{3,6}(E) = M_9\left(\sqrt{E}\right) + O\left(\left(\sqrt{E}\right)^{11}\right).$$

Tetraneutron, JISP16



Resonance parameters:
E_r = 186 keV, Γ = 815 keV.

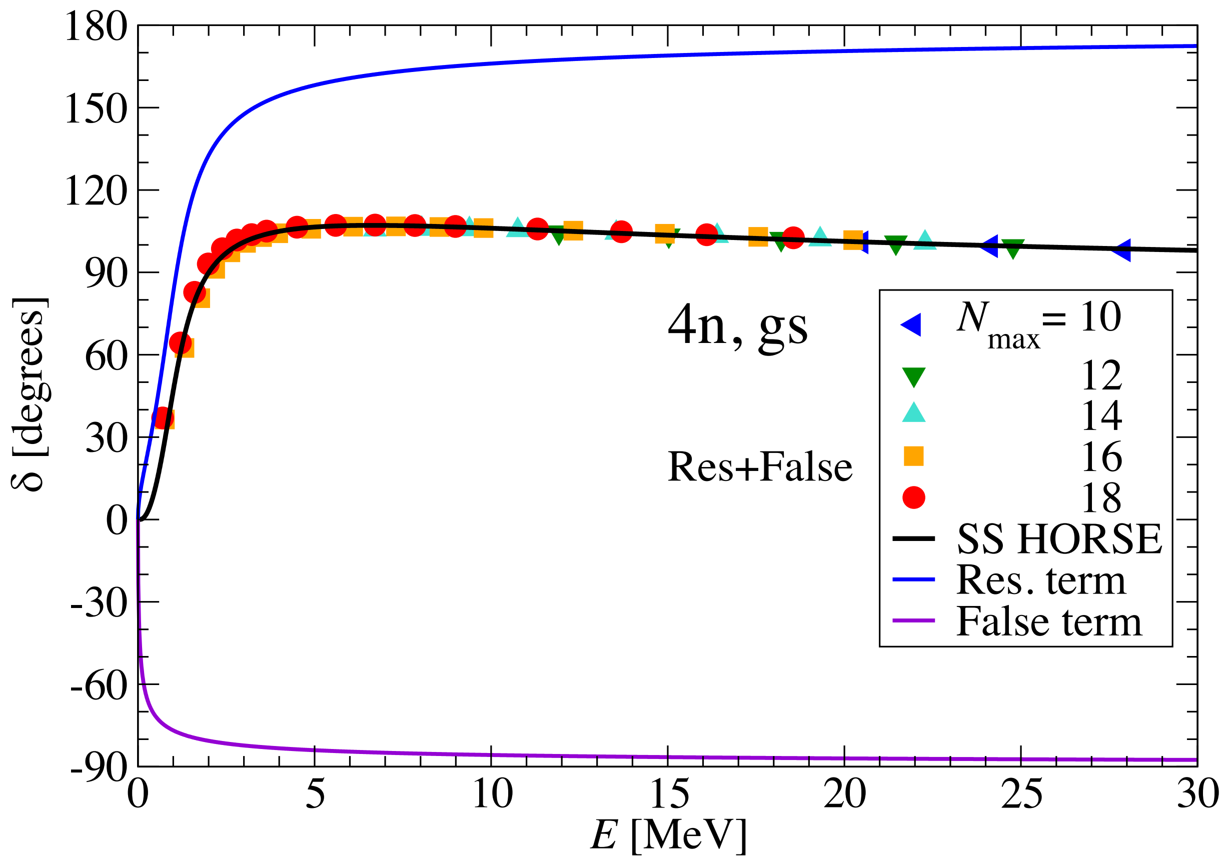
A resonance around E_r = 850 keV with width around Γ = 1.3 MeV is expected!

Can it be a virtual state? No.

Tetraneutron, JISP16

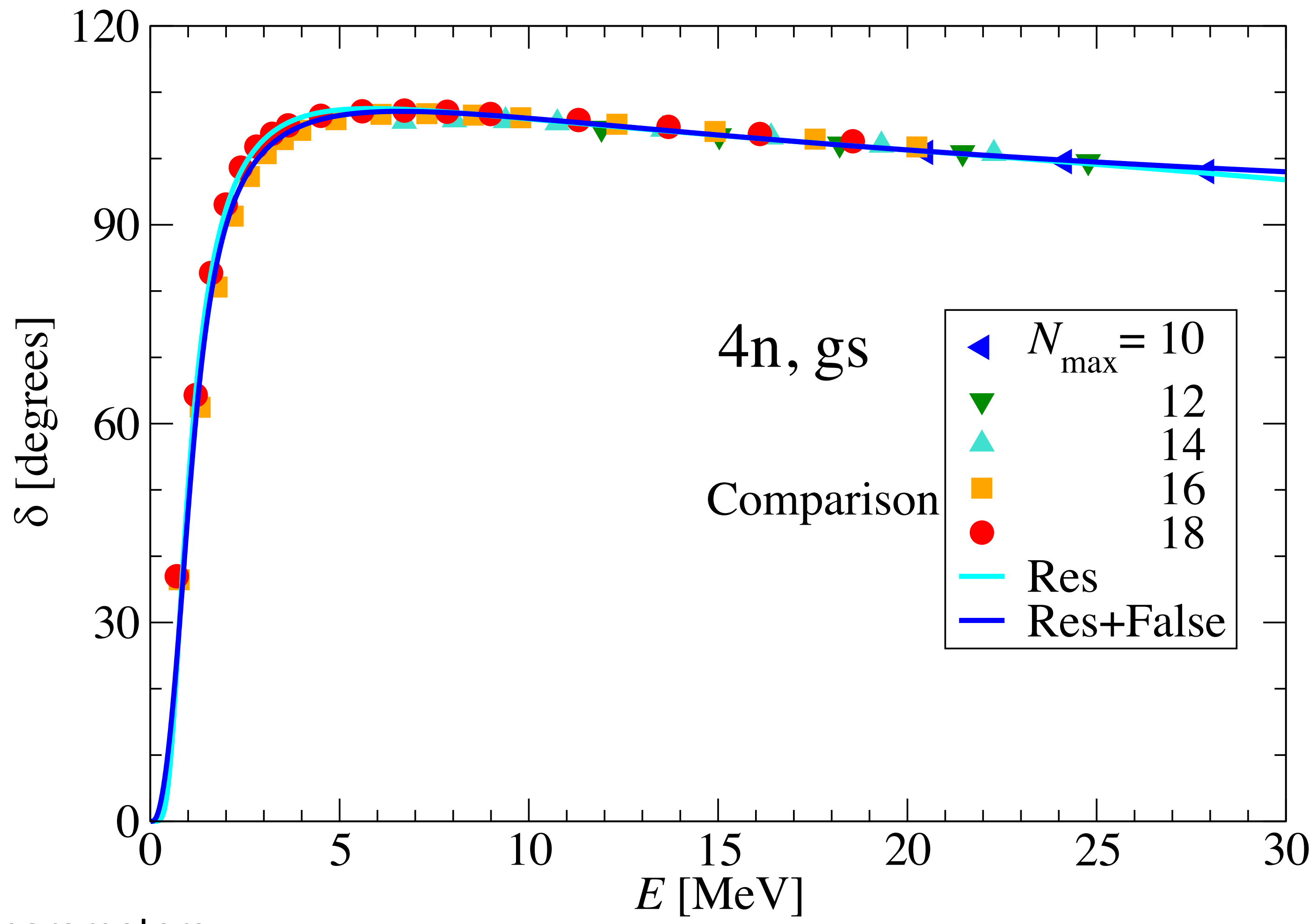
Can it be a combination of a false pole and resonant pole:

$$\delta = -\arctan\frac{a\sqrt{E}}{E-b^2} - \arctan\sqrt{\frac{E}{|E_f|}} - \phi_{3,6}(E)?$$



Yes!
Resonance parameters:
E_r = 844 keV, Γ = 1.378 MeV,
E_{false} = -55 keV.

Tetraneutron, JISP16



Options:

Resonance parameters:

E_r = 844 keV, Γ = 1.378 MeV,

E_{false} = -55 keV.

Or

E_r = 186 keV, Γ = 815 keV ???

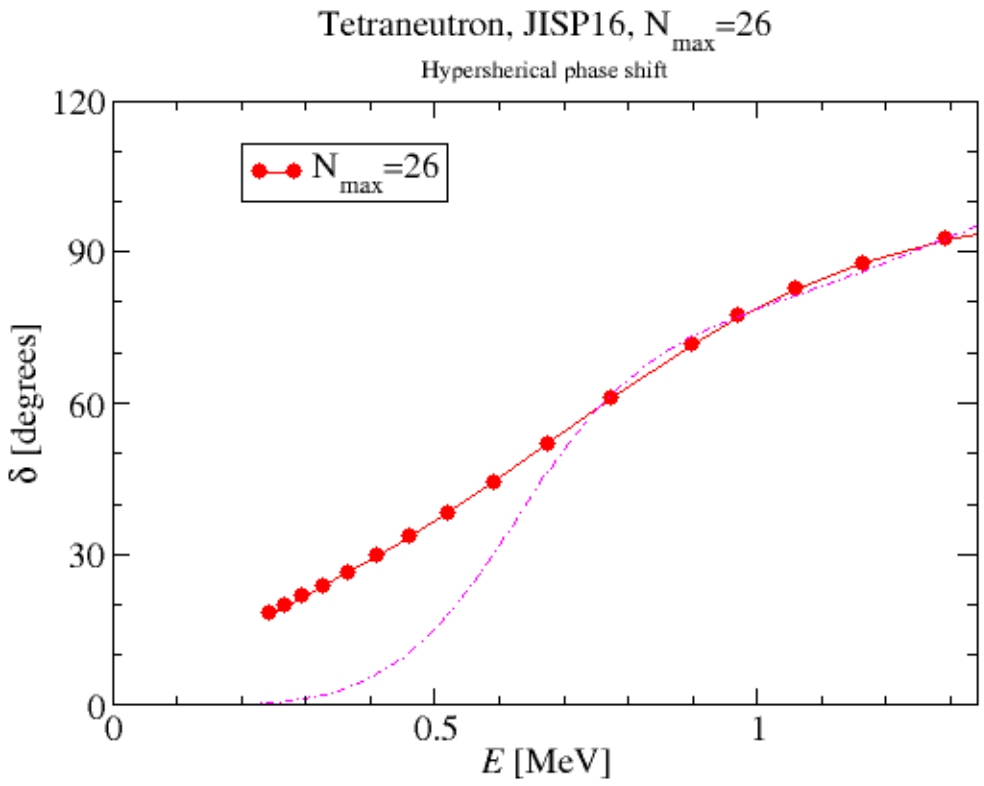
The 2018 development

Larger model spaces (up to $N_{max} = 26$) and smaller $\hbar\Omega$ values:
We get phase shifts at smaller energies and find that it is impossible to fit $\delta \sim k^{11}$ at low energies

Origin:
Hyperspherical potentials are long-ranged: $V \sim \rho^{-3}$ for 3 bodies, for 4 bodies?

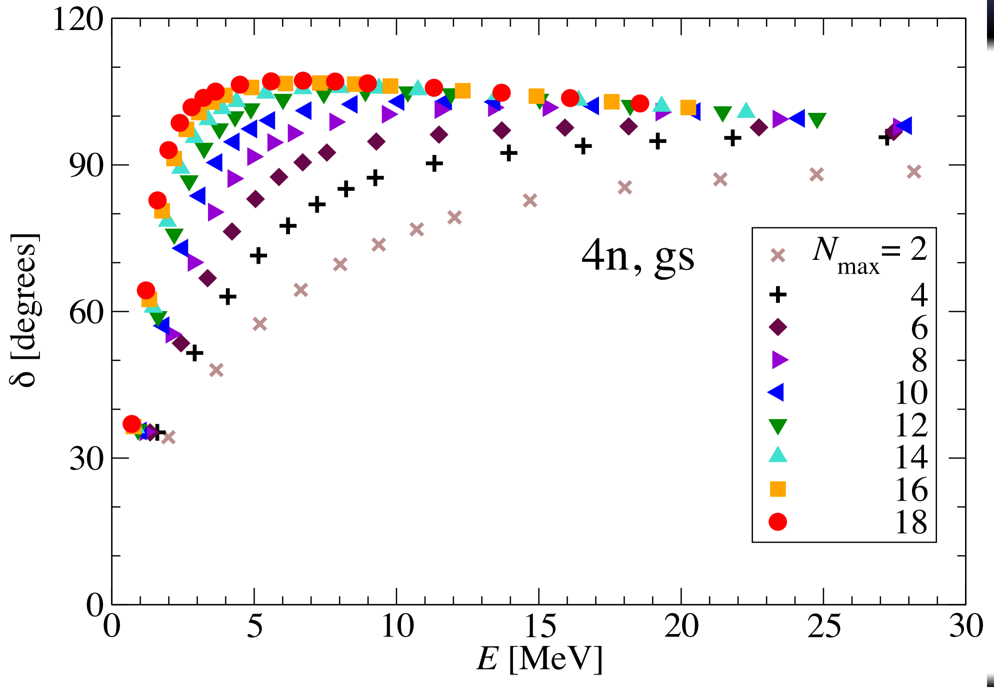
Such a slow decrease of the interaction spoils the phase shifts at low energies

The long-range $V \sim \rho^{-3}$ (?) behavior of hyperspherical potentials spoils the phase shifts at low energies and results in convergence problems at large $N_{\max}$

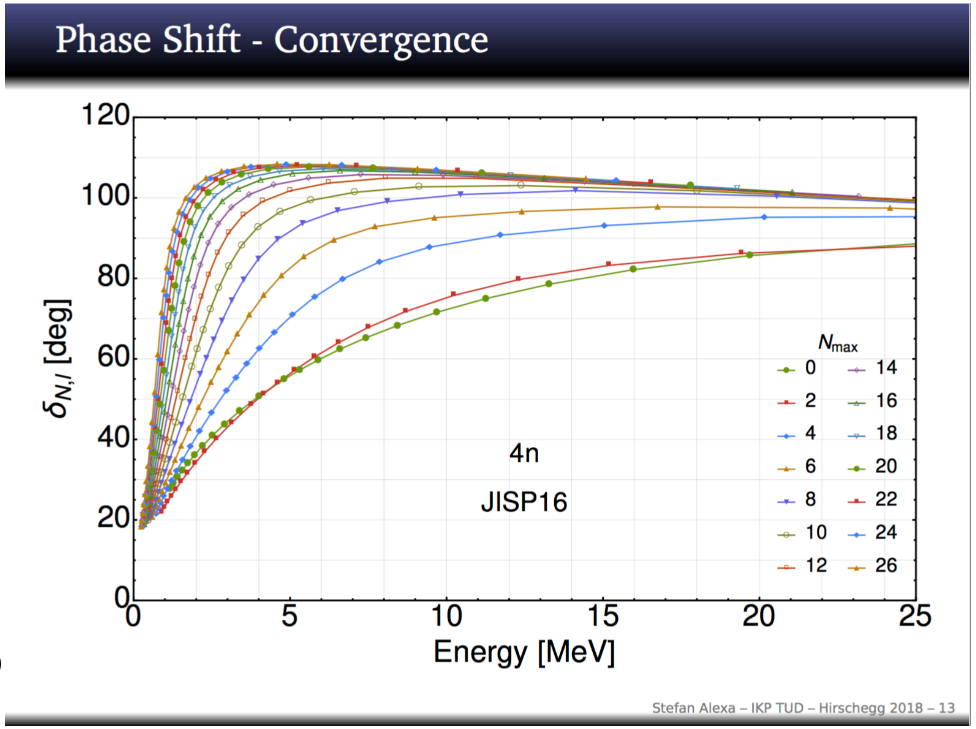


The 2018 results with JISP16

Before 2018: convergence seems to be achieved at $N_{\max} \leq 18$

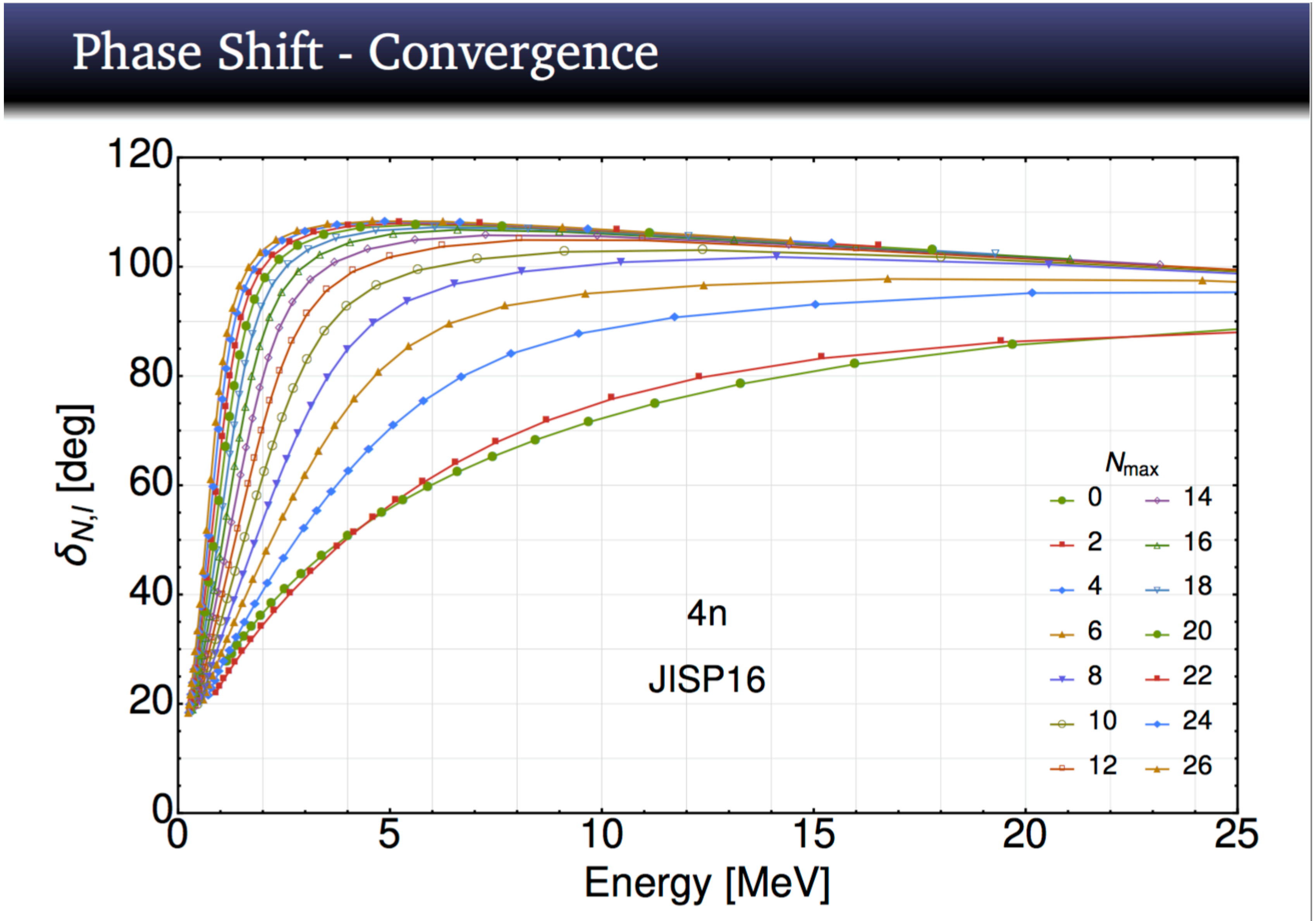


At 2018: convergence seems to be not achieved when larger $N_{\max}$ were calculated



The 2018 results with JISP16

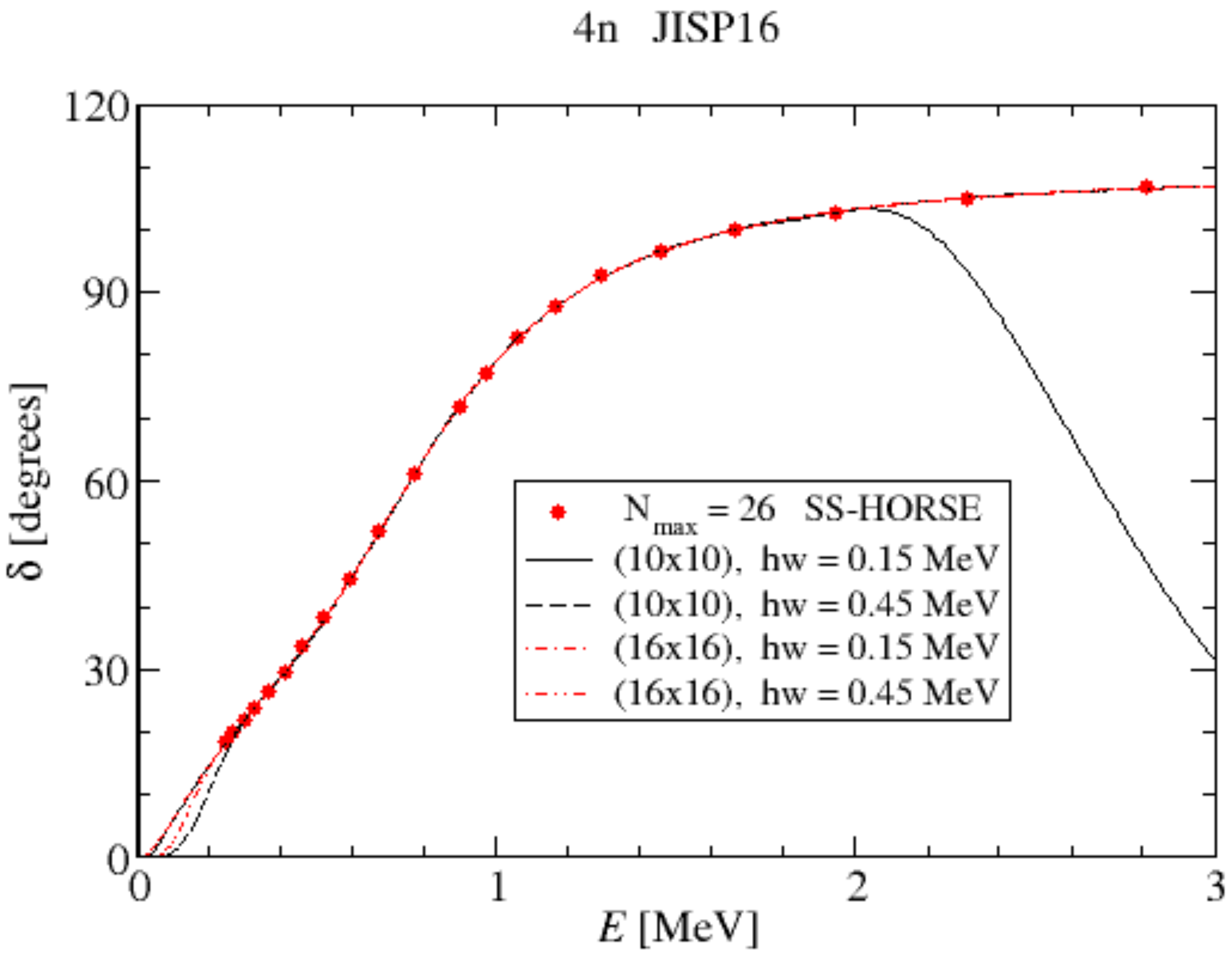
At 2018: however, the convergence seems to be achieved at the smallest energies



The 2018 development

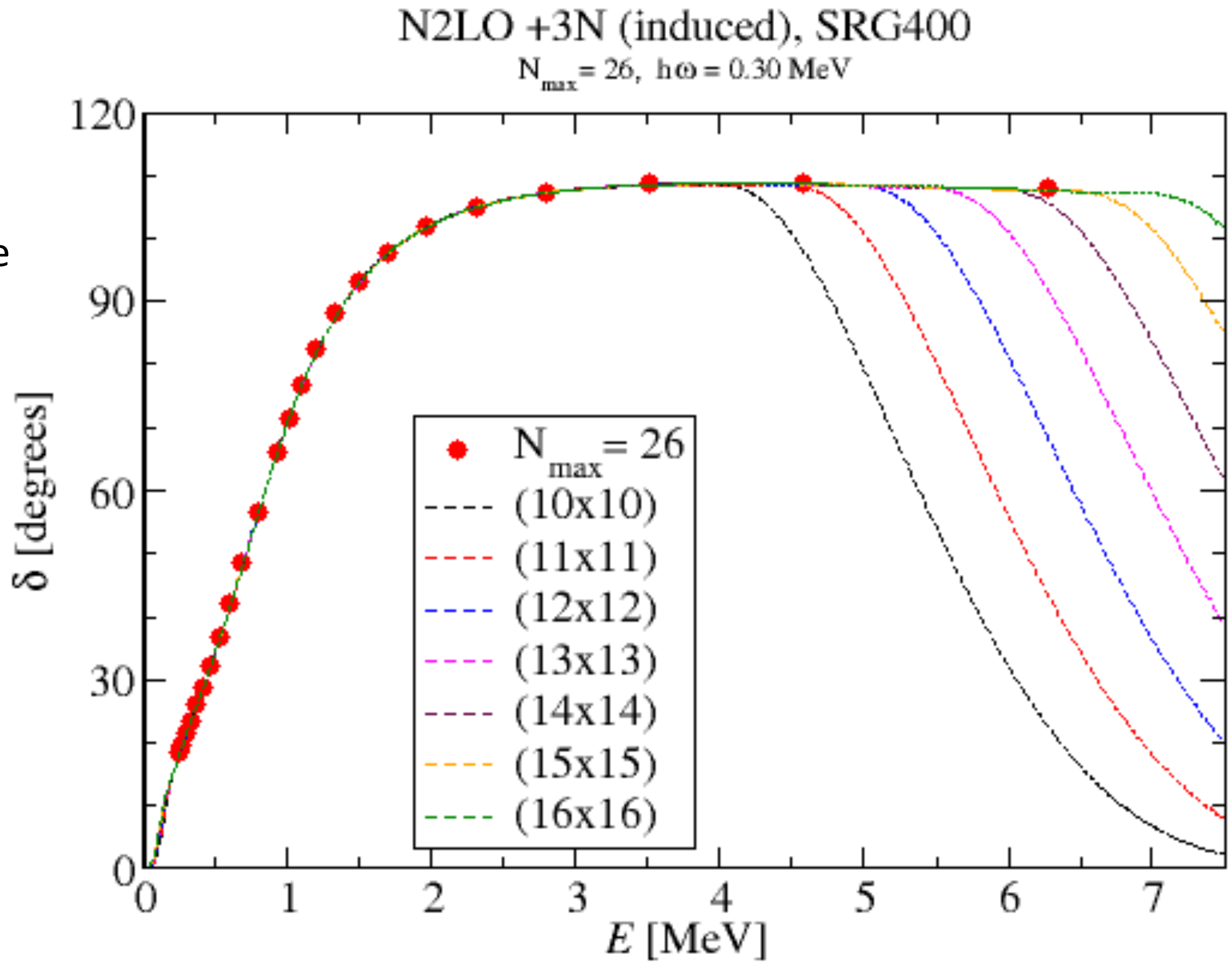
- To resolve this problem we use the *J*-matrix inverse scattering approach (S. A. Zaytsev, Theor. Math. Phys. **115**, 575 (1998); AMS *et al*, PRC **70**, 044005 (2004); PRC **79**, 014610 (2009)); i.e., we construct an interaction as a finite tridiagonal matrix in the oscillator basis describing our SS-HORSE hyperspherical phase shifts obtained with some $N_{\max}$ value and search numerically for the *S*-matrix poles.
- Ideally we need to construct the infinite potential matrix to guarantee the description of the long-range ρ^{-3} interaction tail, but ...
- So, we construct a set of interaction matrices of increasing rank *N*, obtain the poles and extrapolate the resonant energies and widths supposing their exponential convergence with *N.*

The 2018 results:
inverse scattering phase shifts

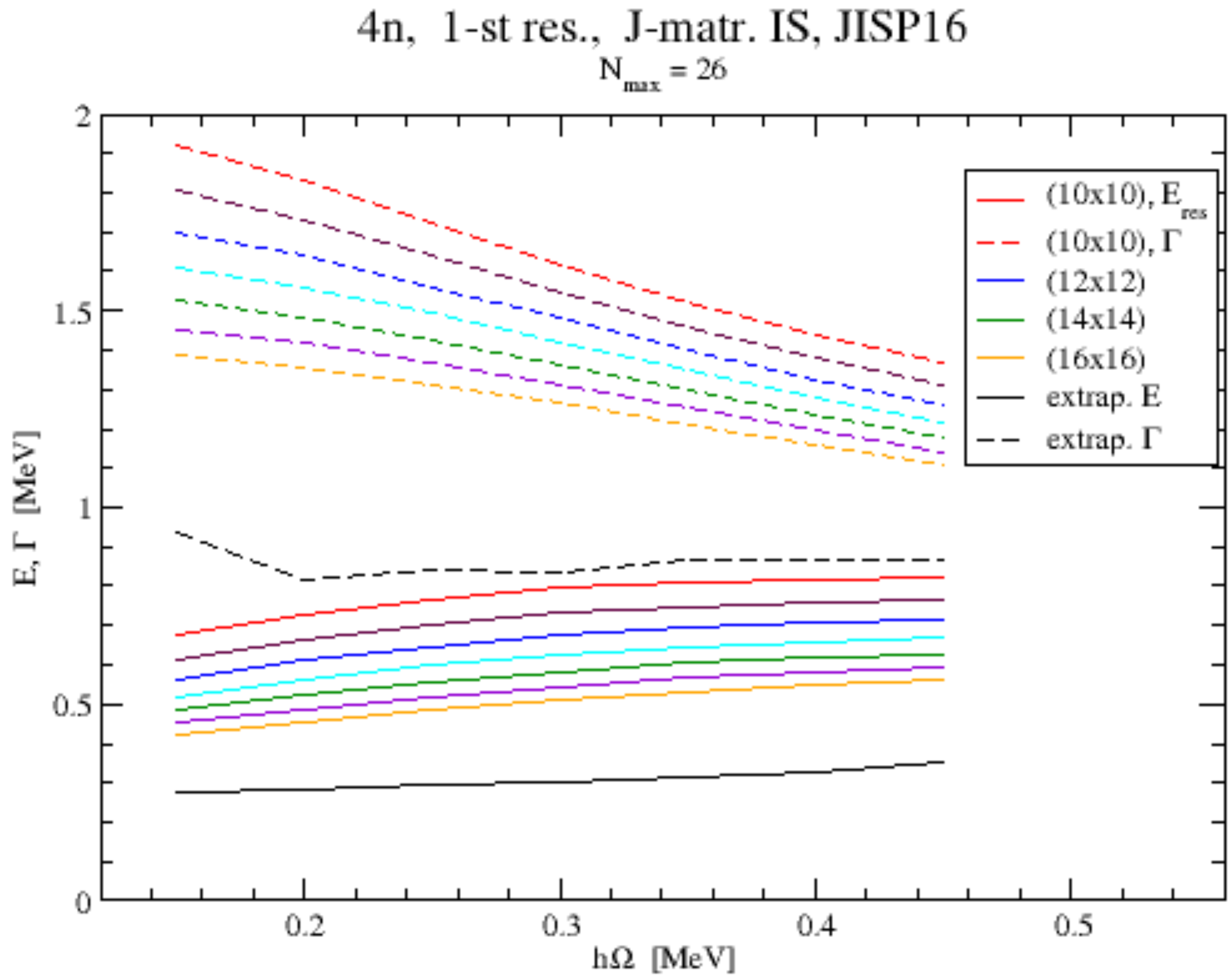


The 2018 results: inverse scattering phase shifts

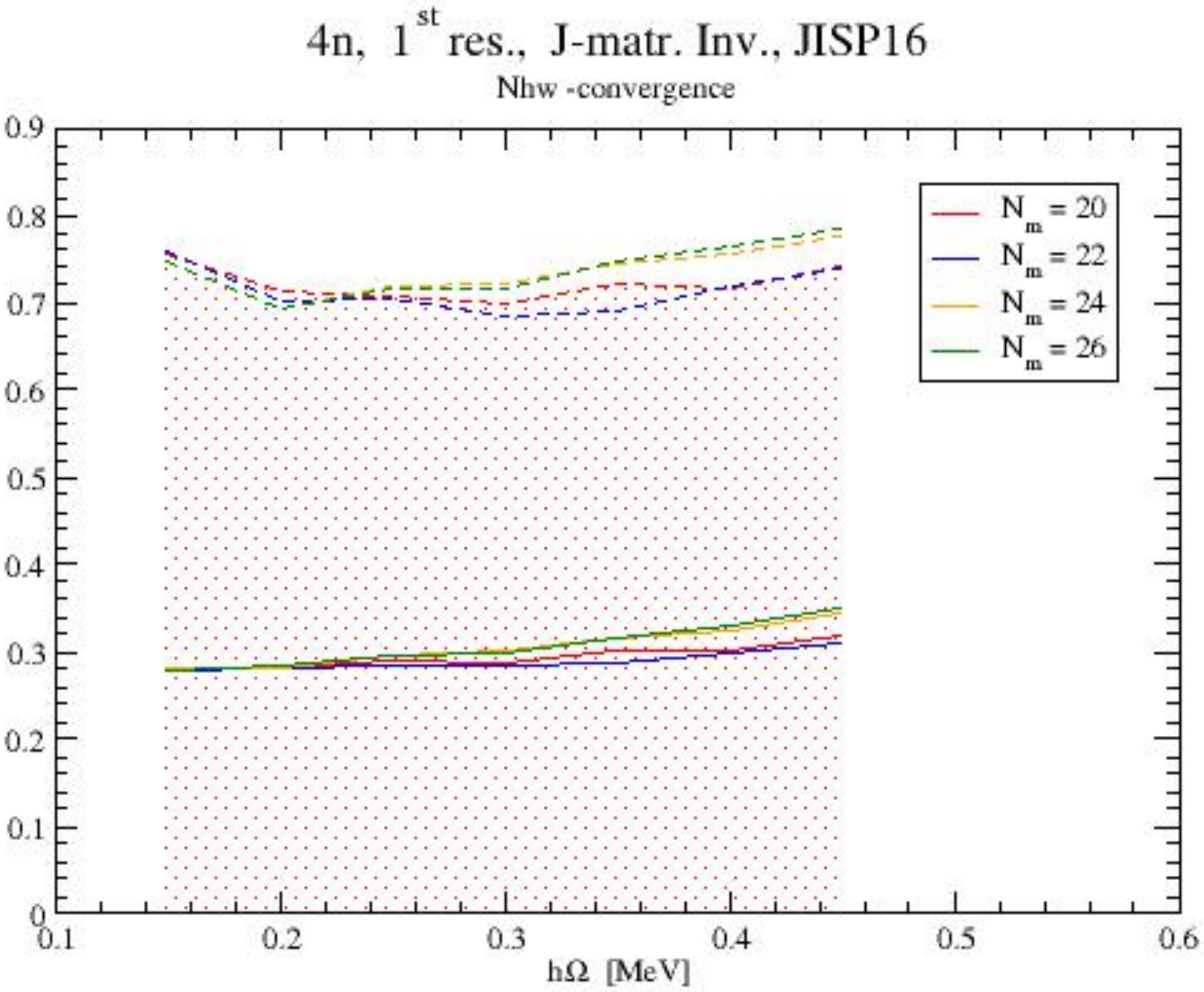
With larger matrix of the inverse scattering potential (and larger $\hbar\Omega$ value) we describe phase shifts in a larger energy interval



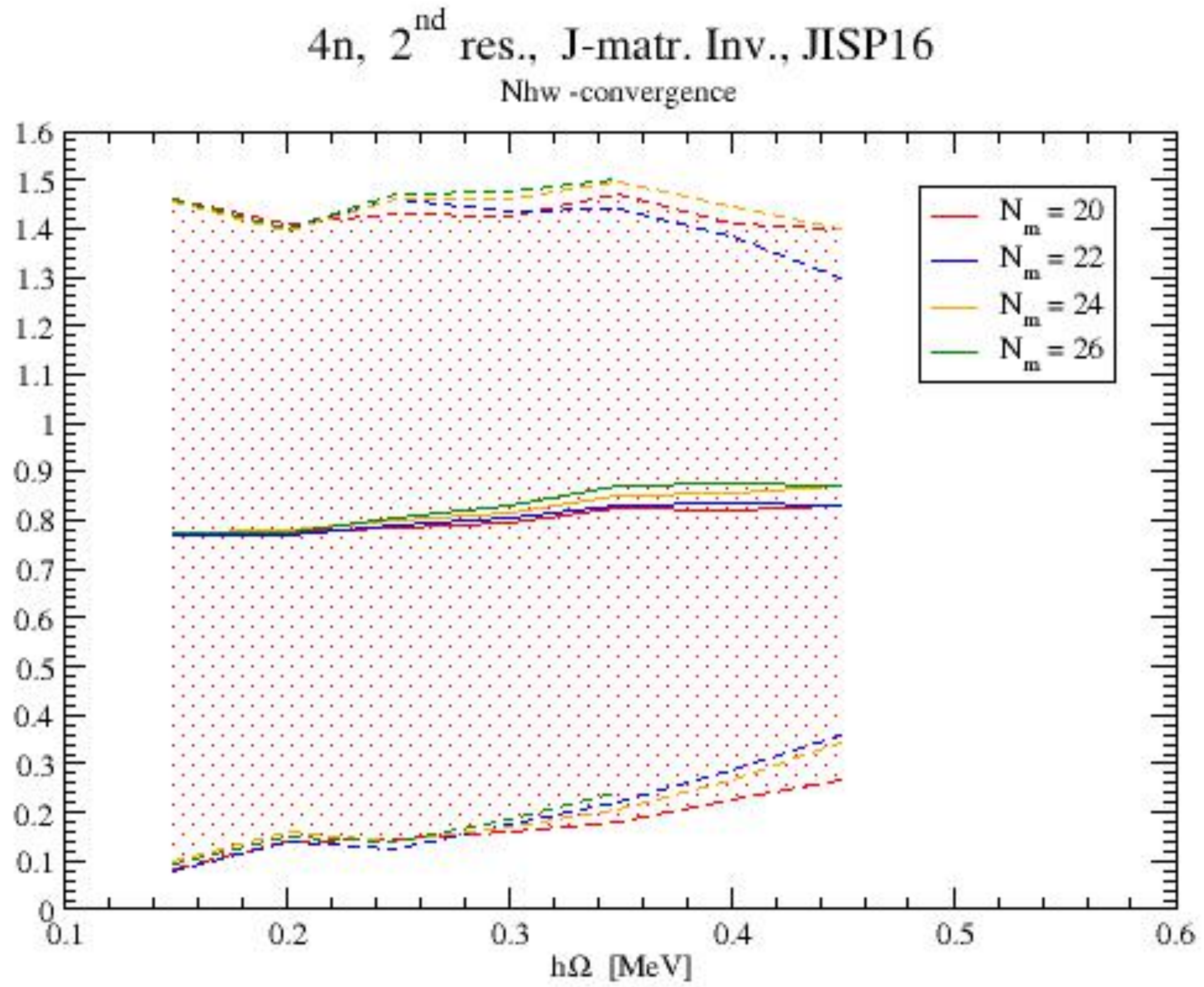
The 2018 results: resonance energy and width for $N_{\max} = 26$



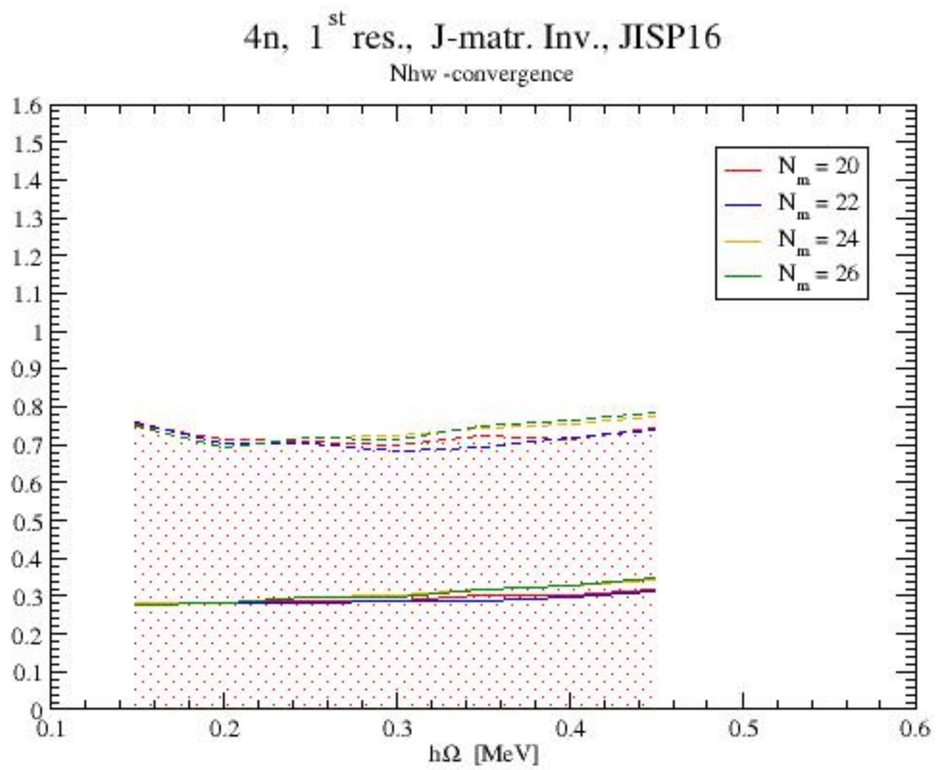
The 2018 results: resonance energy and width for various $N_{\max}$

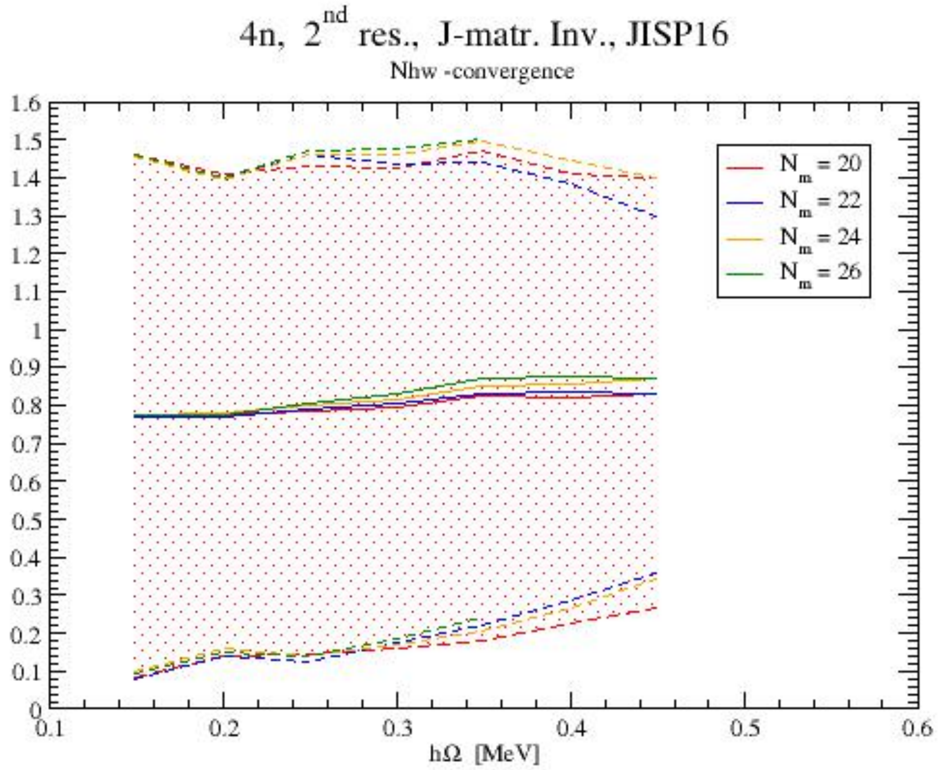


The 2018 results: surprisingly, we have two resonances



The 2018 JISP16 results: extrapolated resonance energies and widths





$E \approx 0.29\ \mathrm{MeV}, \Gamma \approx 0.85\ \mathrm{MeV}$

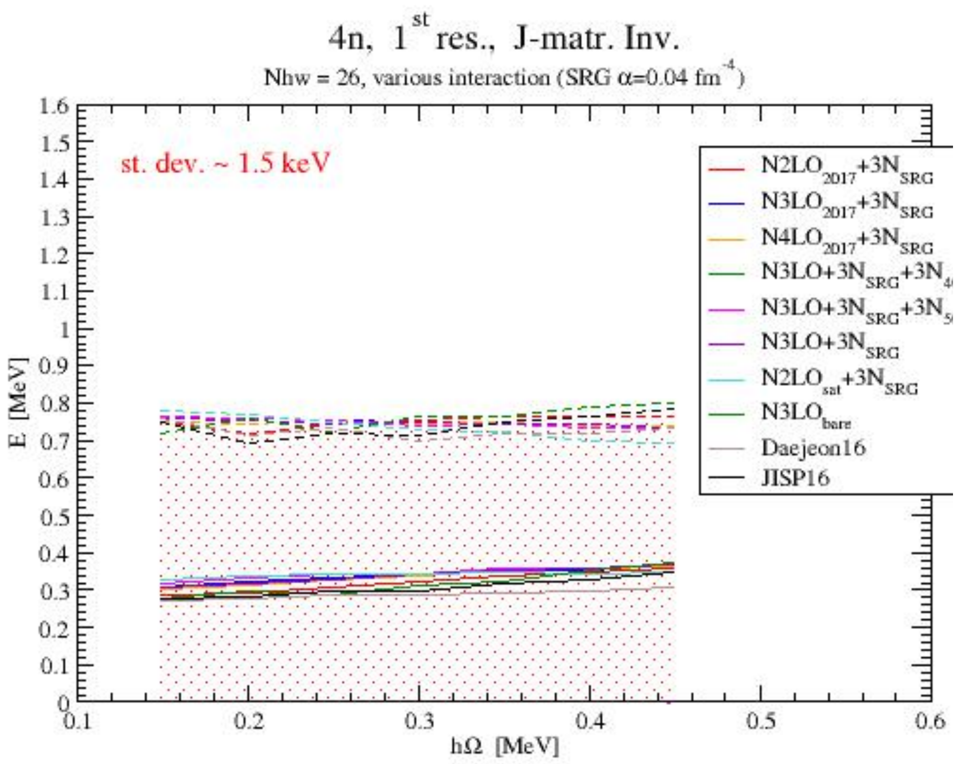
$E \approx 0.8\ \mathrm{MeV}, \Gamma \approx 1.3\ \mathrm{MeV}$

Before we had:

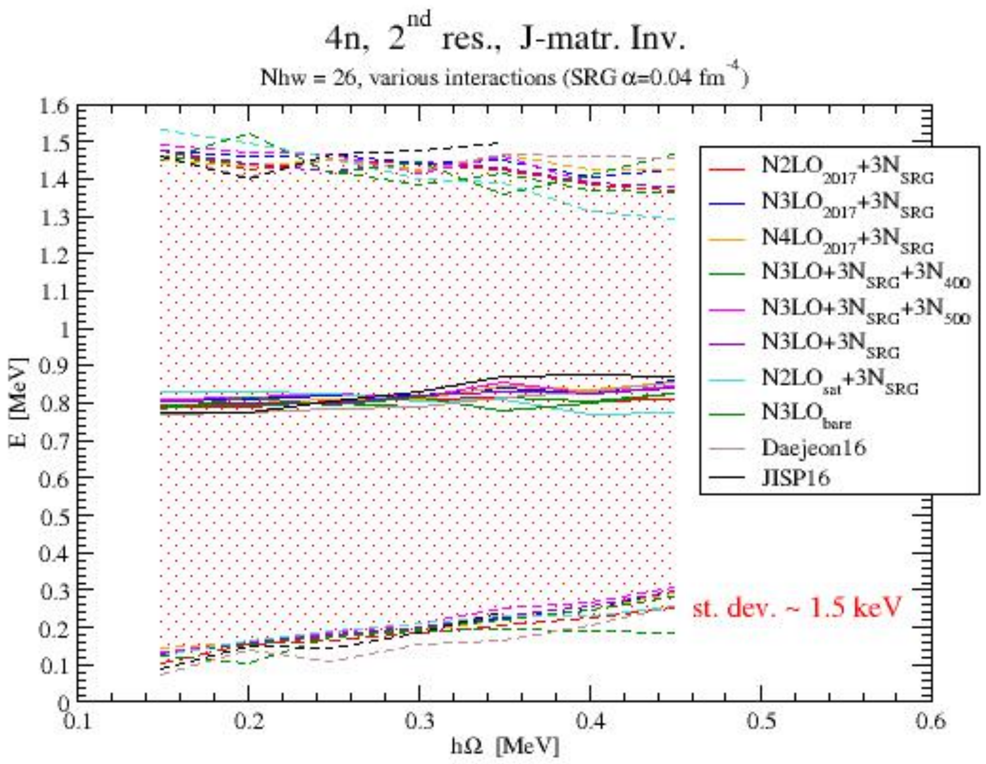
E_r = 186 keV, Γ = 815 keV

E_r = 844 keV, Γ = 1.378 MeV,
E_{false} = -55 keV

The 2018: extrapolated resonance energies and widths with various interactions



$E \approx 0.3$ MeV, $\Gamma \approx 0.85$ MeV



$E \approx 0.8$ MeV, $\Gamma \approx 1.3$ MeV

Before we had with JISP16:

E_r = 186 keV, Γ = 815 keV

E_r = 844 keV, Γ = 1.378 MeV,
E_{false} = -55 keV

Conclusions

- We obtain two low-lying narrow enough resonances in tetraneutron with various modern interactions in the minimal democratic approximation
- We plan to include more HH with $K = K_{\min}$, $K = K_{\min} + 2$, $K = K_{\min} + 4$, etc., to verify the validity of the minimal democratic approximation
- Clearly, more experimental information is desired and awaited
- Unfortunately, experimentalists don not measure *S*-matrix poles but cross sections; reaction mechanism may be very important

- Thank you!