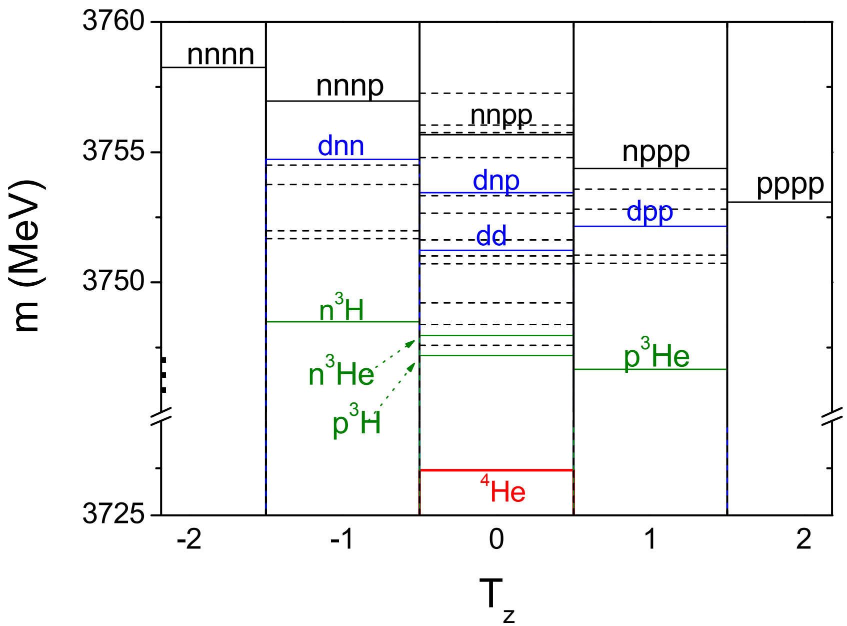
Hadronic resonances in four nucleon systems

In collaboration with **J. Carbonell**, *LPSC Grenoble, France*



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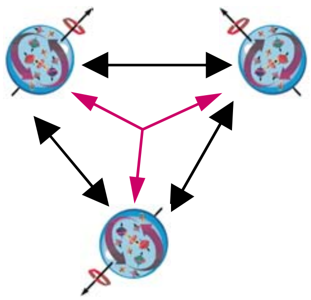
Hadronic resonances in four nucleon systems

Why four-nucleon systems?



- *2N – is made to work (by establishing pot. param.)…*
- *3N – problem starts, requires one more fit (3NF force)…*
  however 3NF does not manifest much in N-d scattering at low en.

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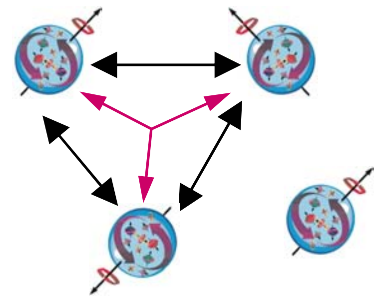
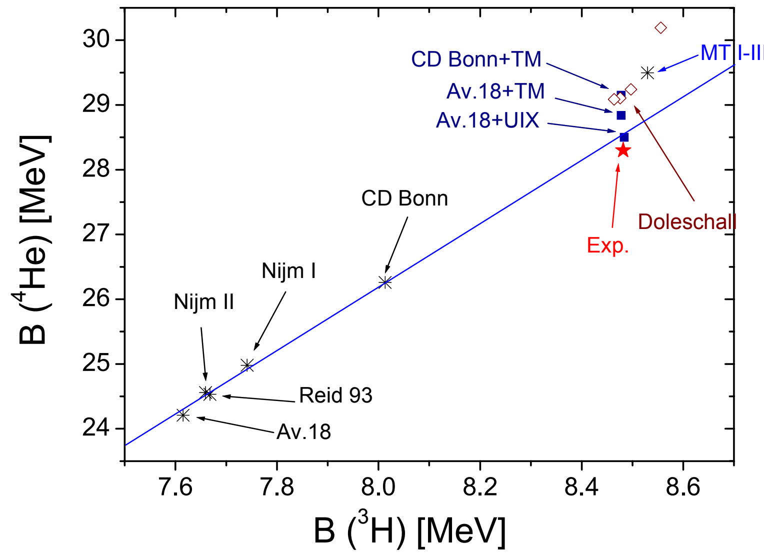


- *2N – is made to work (by establishing pot. param.)…*
- *3N – problem starts, requires one more fit (3NF force)…*
  however 3NF does not manifest much in N-d scattering at low en.
- *Binding energies of heavier nuclei?*
  loss of individuality
  few observables to control
  binding energies are correlated!



A. Nogga et al: Phys.Rev. C65 (2002) 054003

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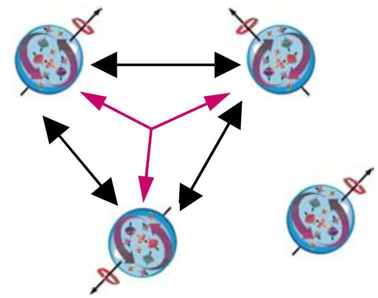
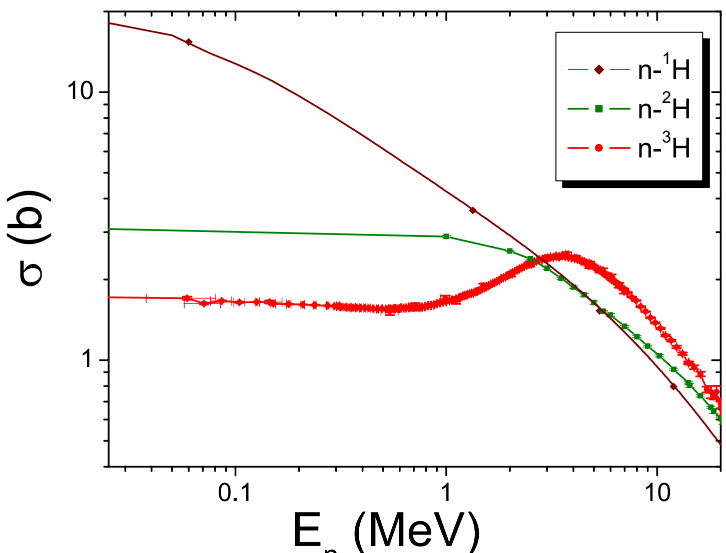
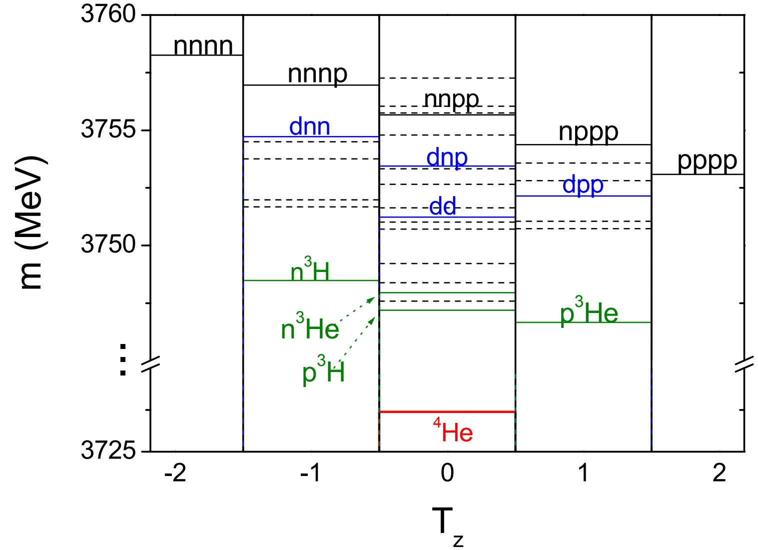


- *2N – is made to work (by establishing pot. param.)…*
- *3N – problem starts, requires one more fit (3NF force)…*

  however 3NF does not manifest much for N-d scattering at low en.
- *Rich structure of 4N continuum.* ***Negative parity resonances!!***



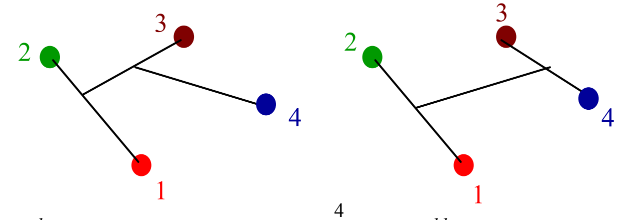


Hadronic resonances in four nucleon systems

- Faddeev-Yakubovski equations in configuration space

$$\boxed{12} \rightarrow (E-\hat{H}_0-V_{12})K^4_{12,3} = V_{12}\left[K^4_{23,1}+K^1_{23,4}+K^4_{13,2}+K^2_{13,4}+H_{13,24}+H_{23,14}\right]$$

$$\boxed{6} \rightarrow (E-\hat{H}_0-V_{12})H_{12,34} = V_{12}\left[K^2_{34,1}+K^1_{34,2}+H_{34,12}\right]$$



$$\Psi(\vec{x},\vec{y},\vec{z}) = \sum_{i<j,k,l=1}^{4} K^{l}_{ij,k}(\vec{x}^{l}_{ij,k},\vec{y}^{l}_{ij,k},\vec{z}^{l}_{ij,k}) + \sum_{i<j,k<l=1}^{4} H^{kl}_{ij}(\vec{x}^{kl}_{ij},\vec{y}^{kl}_{ij},\vec{z}^{kl}_{ij})$$

- Solution is searched by decomposing Faddeev-Yakubovski components in the partial wave basis

$$K_\alpha(\vec{x}_\alpha,\vec{y}_\alpha,\vec{z}_\alpha) = \sum_{LST} \frac{F_{\alpha LST}(x_\alpha,y_\alpha,z_\alpha)}{x_\alpha y_\alpha z_\alpha}\left[L_\alpha(\hat{x}_\alpha,\hat{y}_\alpha,\hat{z}_\alpha)\otimes S_\alpha \otimes T_\alpha\right]$$

$$H_\beta(\vec{x}_\beta,\vec{y}_\beta,\vec{z}_\beta) = \sum_{LST} \frac{F_{\beta LST}(x_\beta,y_\beta,z_\beta)}{x_\beta y_\beta z_\beta}\left[L_\beta(\hat{x}_\beta,\hat{y}_\beta,\hat{z}_\beta)\otimes S_\beta \otimes T_\beta\right]$$

Basis is infinite

- Radial parts of the amplitudes $F_{\alpha LST}(x_\alpha,y_\alpha,z_\alpha)$ are developed in the spline basis, converting differential equations into linear algebra problem.

Hadronic resonances in four nucleon systems

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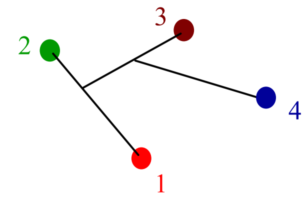

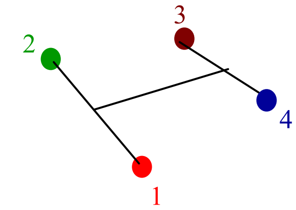

$$\boxed{V_{12}^{Short} + \sum_{i<j=1}^{4} V_{ij}^{Long}} \qquad \boxed{V_{12}^{Short}}$$

- Coulomb? Merkuriev-like decomposition

$$V_{ij}(x) = V_{ij}^{Short}(x,y,z) + V_{ij}^{Long}(x,y,z)$$

Hadronic resonances in four nucleon systems

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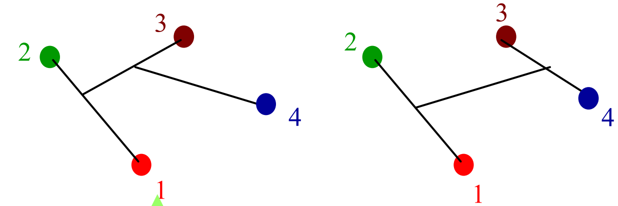
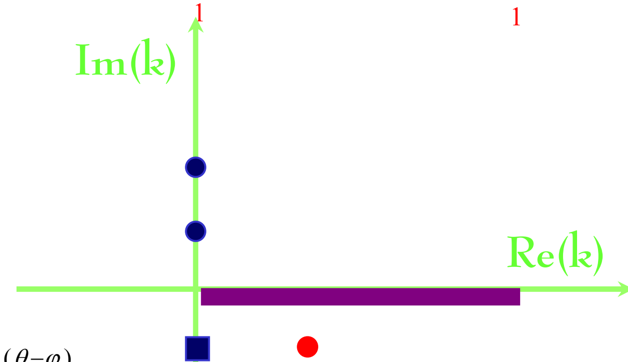


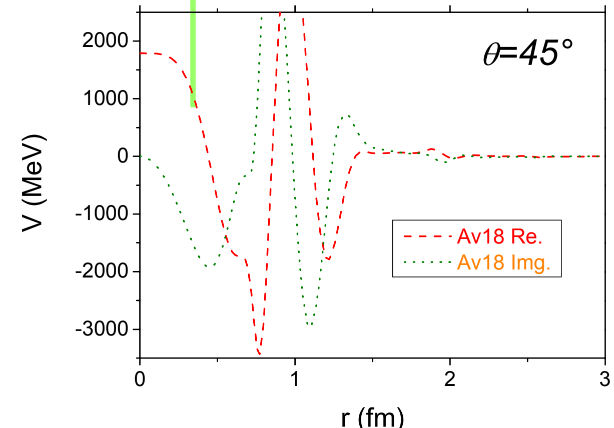
- Coulomb? Merkuriev-like decomposition

- Direct solution for resonant states!

  ✓ Complex scaling method

$$r \rightarrow re^{i\theta} \qquad \Phi(r) \sim e^{ikr} = e^{i|k|e^{-i\varphi}r} \rightarrow e^{i|k|e^{i(\theta-\varphi)}r}$$





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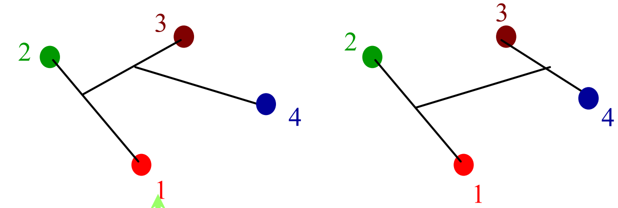

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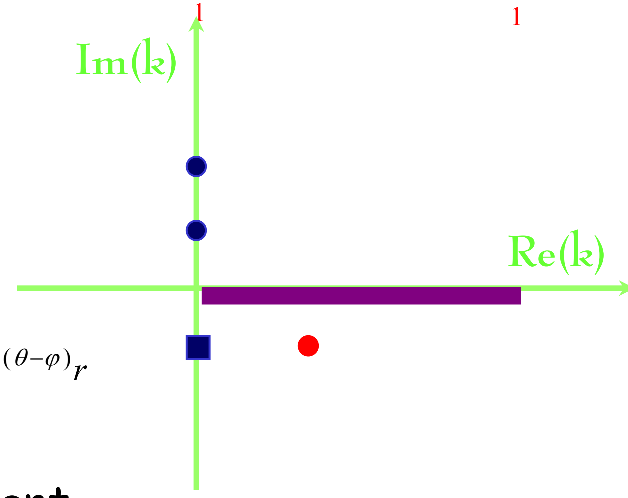


  - ✓ Complex scaling method

$$r \rightarrow re^{i\theta} \qquad \Phi(r) \sim e^{ikr} = e^{i|k|e^{-i\varphi}r} \rightarrow e^{i|k|e^{i(\theta-\varphi)}r}$$

  - ✓ Analytic Continuation in the Coupling Constant

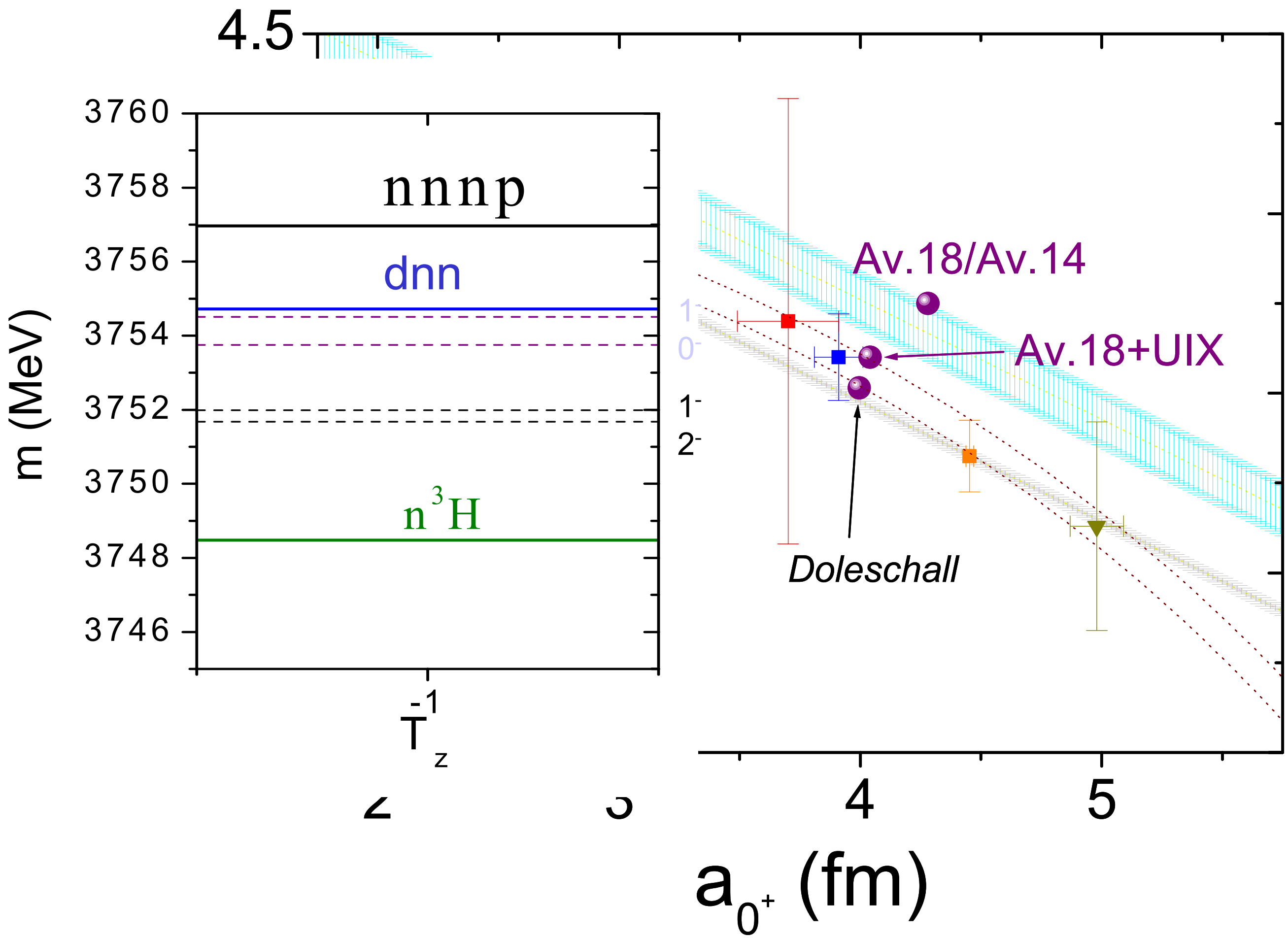
$$\hat{H}' = \hat{H} + \gamma V' \qquad k(\gamma) = if(\gamma-\gamma_0); \quad k(\gamma_0) = 0$$

Hadronic resonances in four nucleon systems

The simplest case: n-^{3}H scattering

$$\sigma_{E=0} = \left(a_{0^+}^2 + 3a_{1^+}^2\right)\pi$$

$$a_c = \frac{a_{0^+} + 3a_{1^+}}{4}$$



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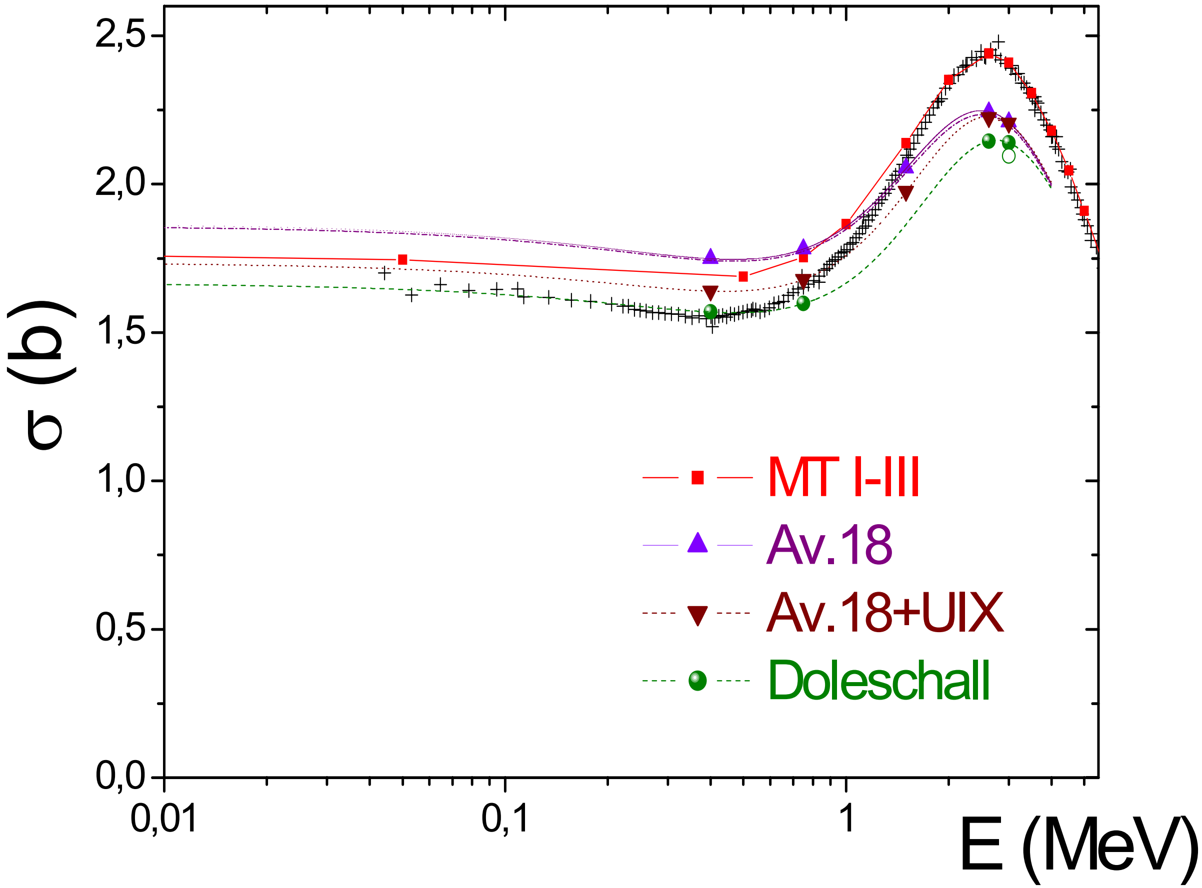
Hadronic resonances in four nucleon systems

The simplest case: n-^{3}H scattering



Hadronic resonances in four nucleon systems

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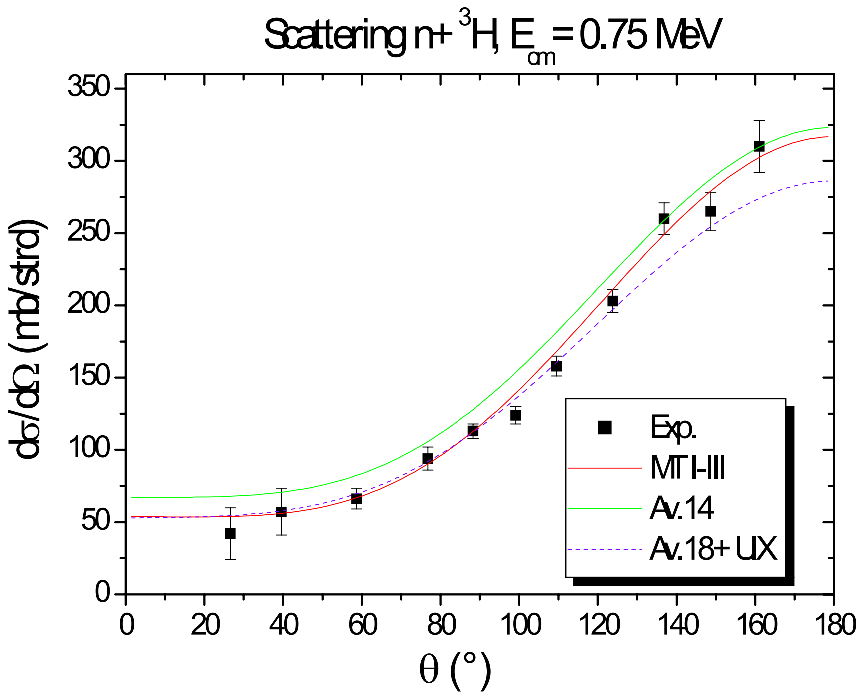
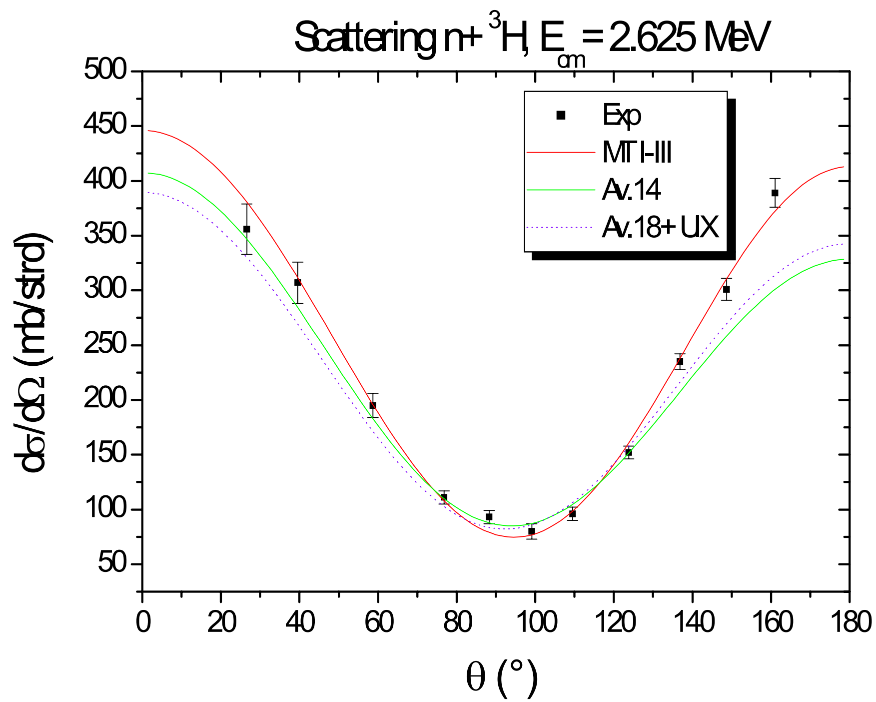
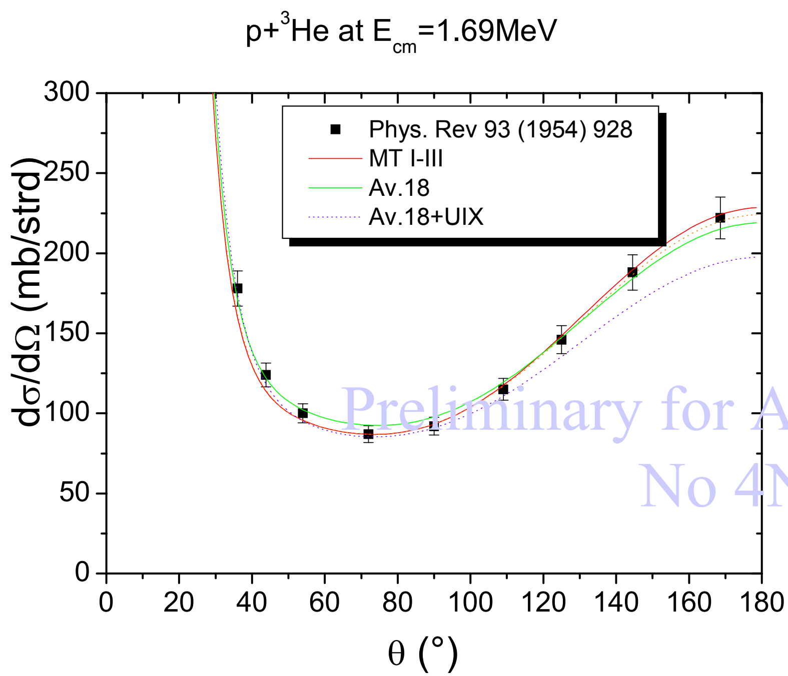
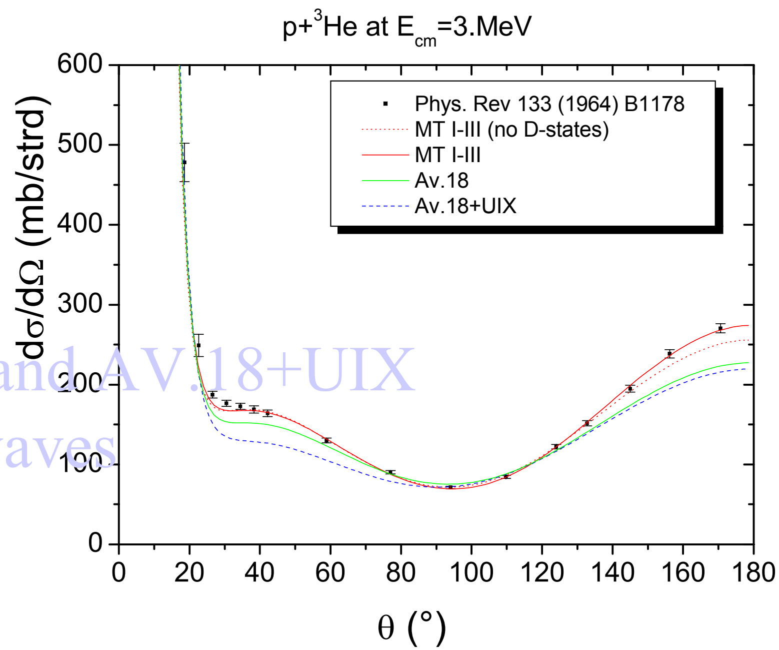




Hadronic resonances in four nucleon systems



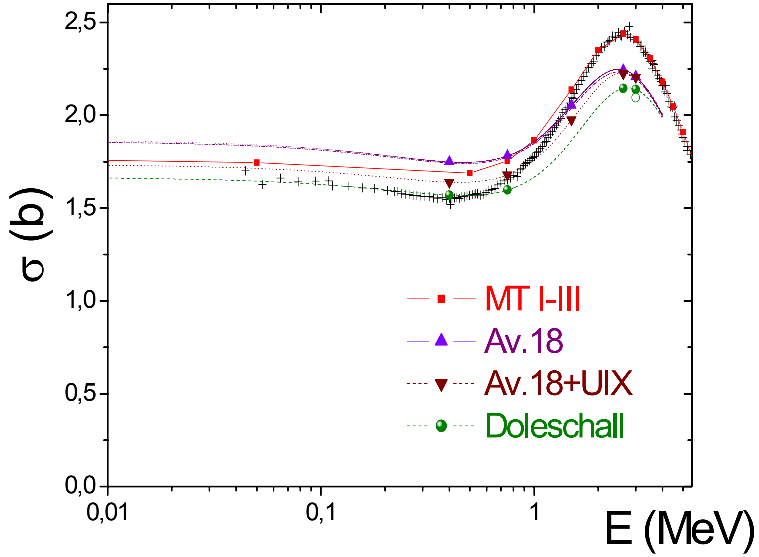


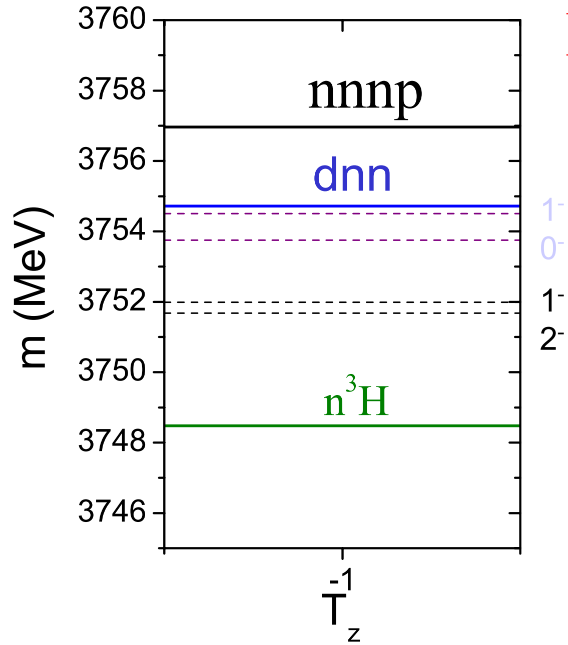
Preliminary for Av.18 and AV.18+UIX
No 4N D-waves

J^{Π}	MT I-III	Av.18+UIX	Av.18+UIX (Viviani et al.*)	Exp.
0^+	11.5	10.9	11.5	10.8±2.6
1^+	9.20	8.70	9.13	8.1±0.5; 10.2 ±1.5

*Phys.Rev.Lett. 81 (1998) 1580-1583

Hadronic resonances in four nucleon systems



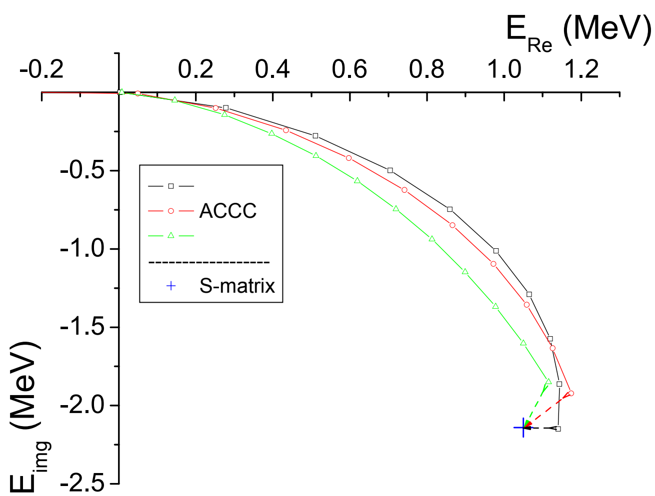


Resonance position?

R-matrix analysis*

J^{π}	E_{res} (MeV)
1^-	6.02-6.50i
0^-	5.27-4.46i
1^-	3.50-3.37i
2^-	3.19-2.71i

*D.R. Tilley et all: Nucl. Phys. A 541 (1992) 1.



S-matrix pole (MT I-III)

S,(L=1)	E_{res} (MeV)
0	0.35 -2.3i
1	1.03 -2.14i

S-matrix pole (Av.18)

J^{π}	E_{res} (MeV)≈
1^-	-0.08 -2.3i
0^-	0.4 -2.8i
1^-	0.80 -2.12i
2^-	1.1 -2.2i

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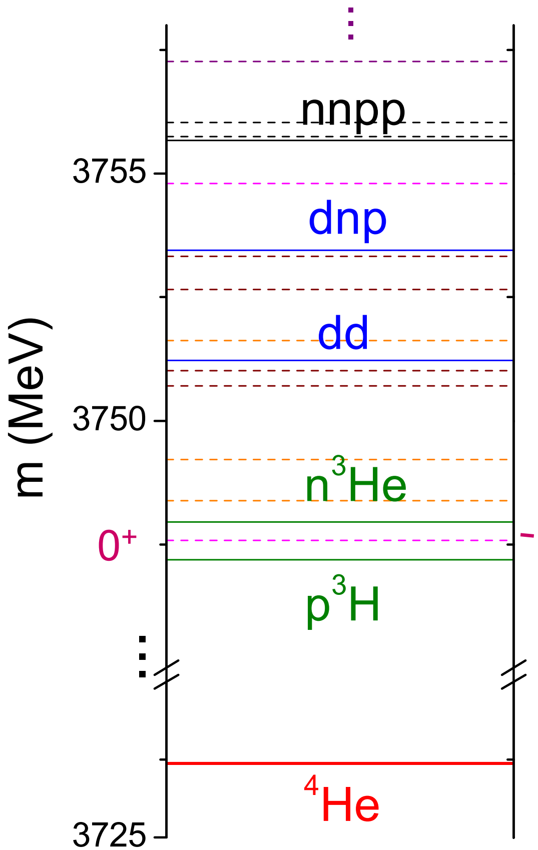
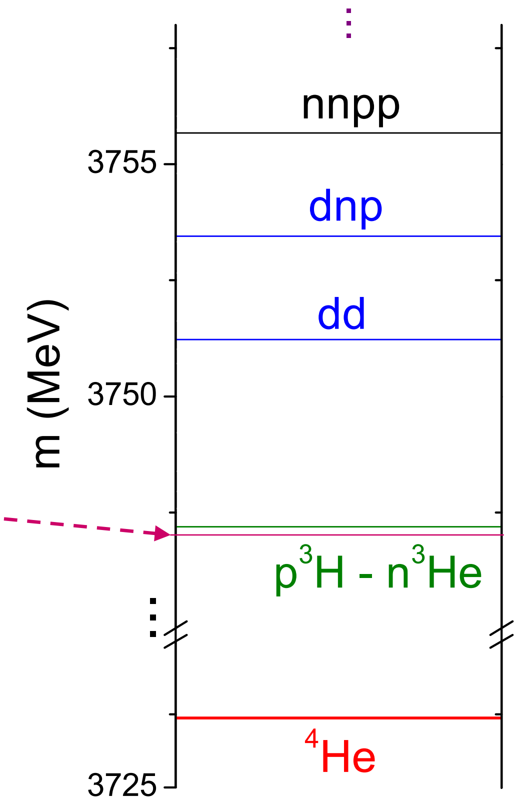


No Coulomb



B=]0.04-0.26[MeV

Hadronic resonances in four nucleon systems

$$Exp.: \quad a_{0^+} \approx [-16,-20]\ fm$$

<u>Theory without Coulomb:</u>

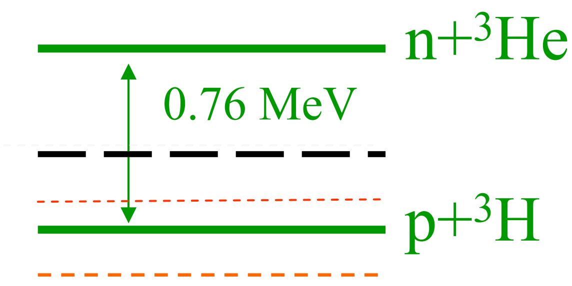
MT I-III: $a_{0^+} = 9.4\ fm$

<u>With Coulomb:</u>

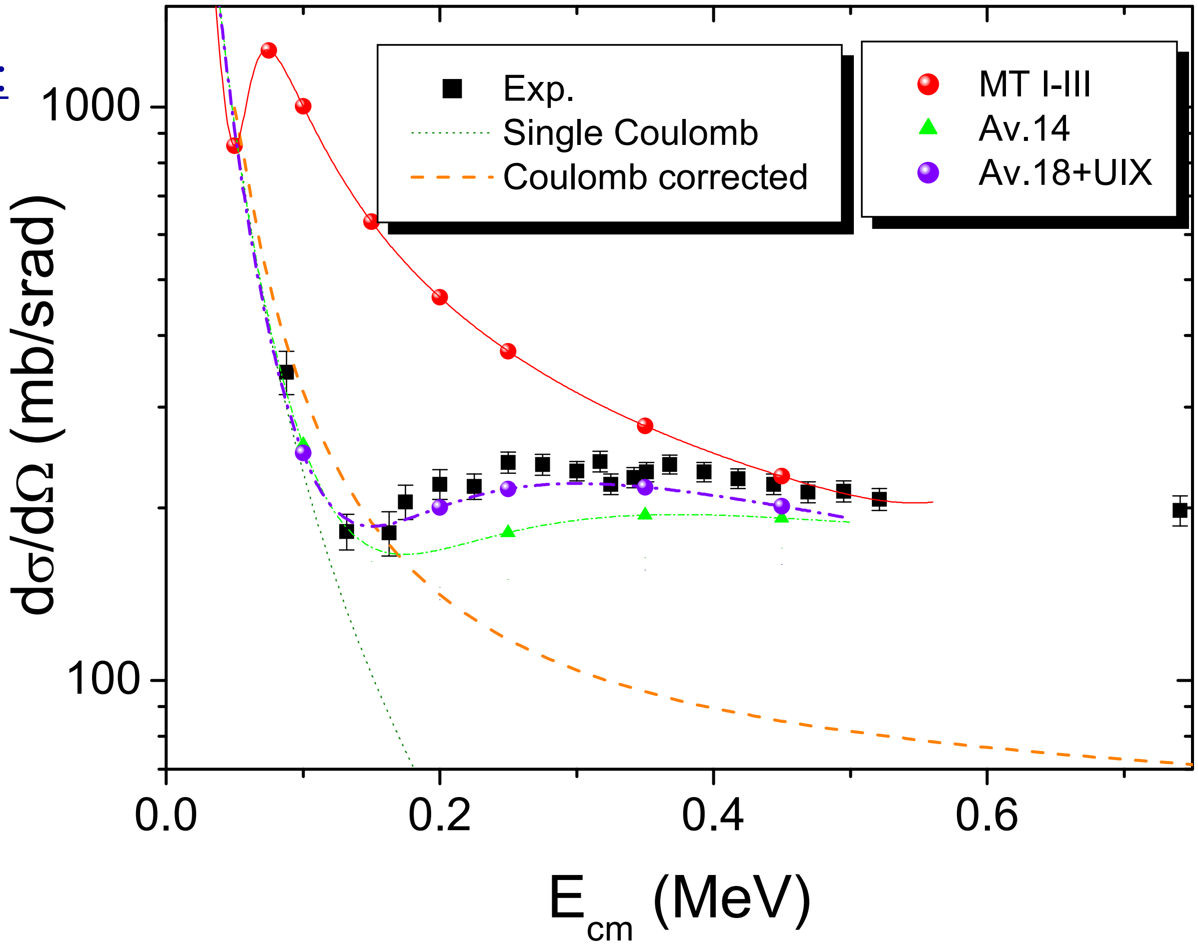
MT I-III: $a_{0^+} = -63\ fm$

AV14: $a_{0^+} = -13.9\ fm$

AV18+UIX: $a_{0^+} = -16.5\ fm$



Scattering p+³H, α=120°



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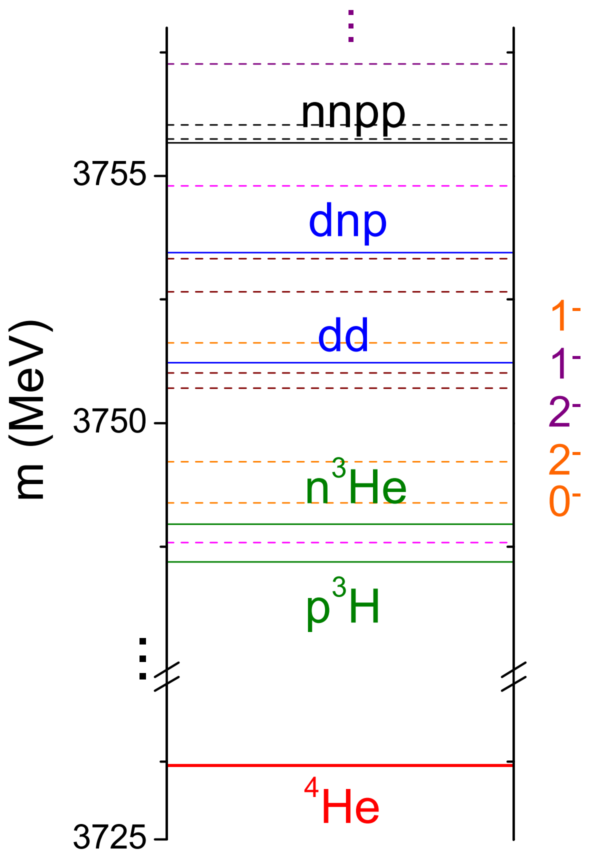

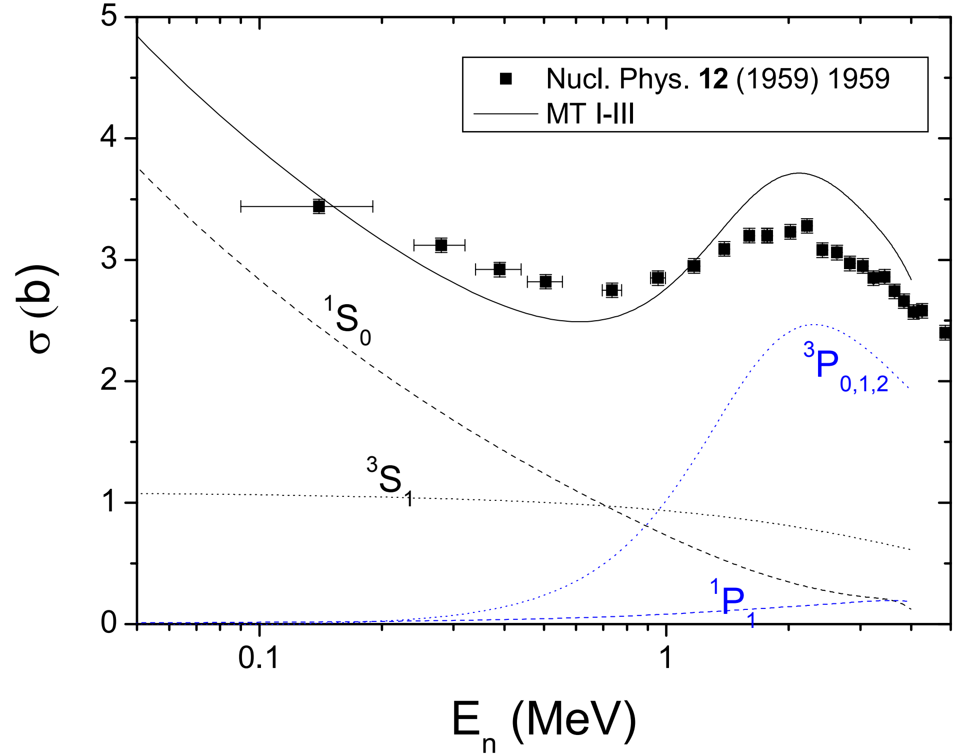

J^{Π}	MT I-III	Av.18+UIX (Hofmann et al.*)	Exp.
0^+	8.00 -2.90*i*	7.62 -4.07*i*	7.37 -4.448*i*
1^+	3.34 -0.0083*i*	3.333 -0.0052*i*	3.278 -0.001*i*

*Phys.Rev. C68 (2003) 021002

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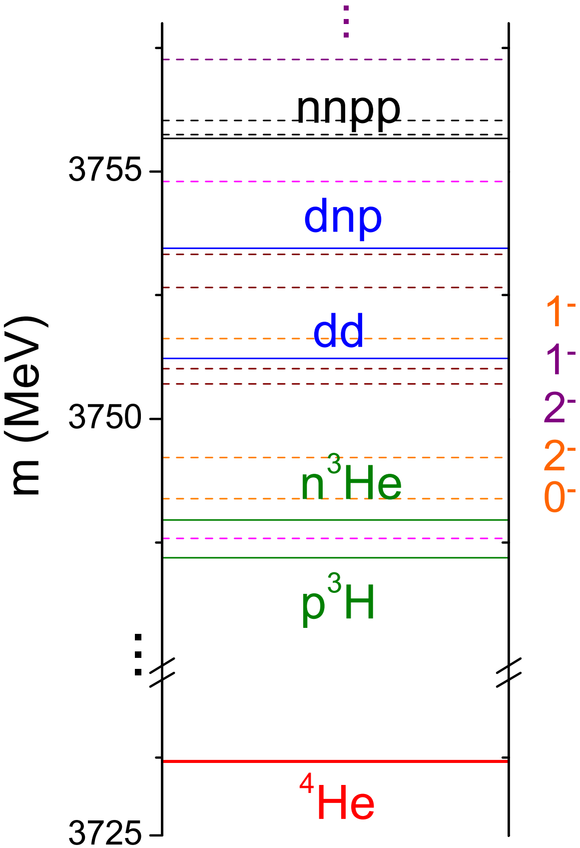
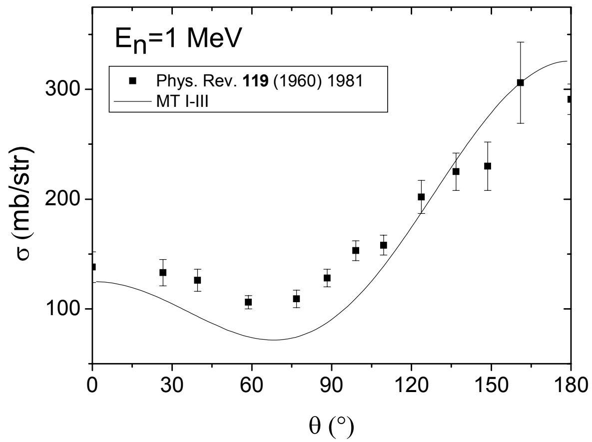
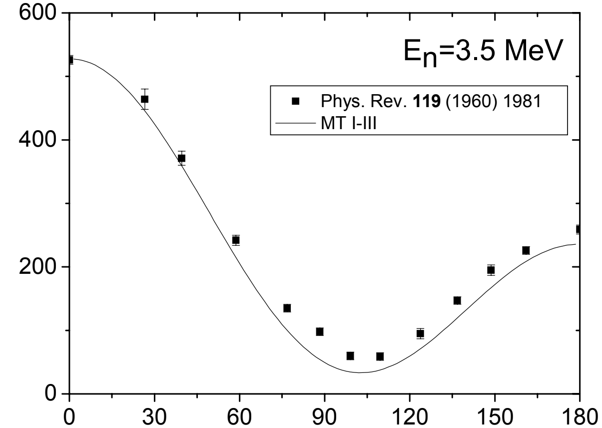
Hadronic resonances in four nucleon systems







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Hadronic resonances in four nucleon systems

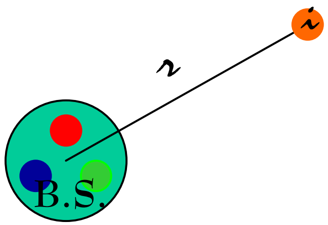
- To what the phaseshifts are sensible?

In bound state we calculate mean values: $\frac{\langle \Psi | V | \Psi \rangle}{\langle \Psi || \Psi \rangle}$.

But scattering wave functions diverge!

- Integral representation of phaseshifts:

$$\sin\delta = -\frac{m}{\hbar^2}\int \Phi_\alpha^{B.S.}(\vec{R}_{B.S.})\hat{j}_l(kr)\left(\sum_{k\neq i} V_{ik}\right)\Psi\left(\vec{R}_{B.S.},\vec{r}\right)dV$$



J^π E(MeV)	$^1S_0$	$^3SD_1$	$^3P_0$	$^3P_1$	$^3P_2$	$^1P_1$
0^+ 0.0	76.0	21.4	-1.30	1.94	-0.81	3.60
0^+ 3.0	79.8	17.9	-1.05	1.91	-0.58	3.41
0^- 3.0	64.2	28.2	32.8	-29.7	2.31	-0.38
2^- 3.0	39.8	51.7	1.06	-6.90	14.3	-0.16

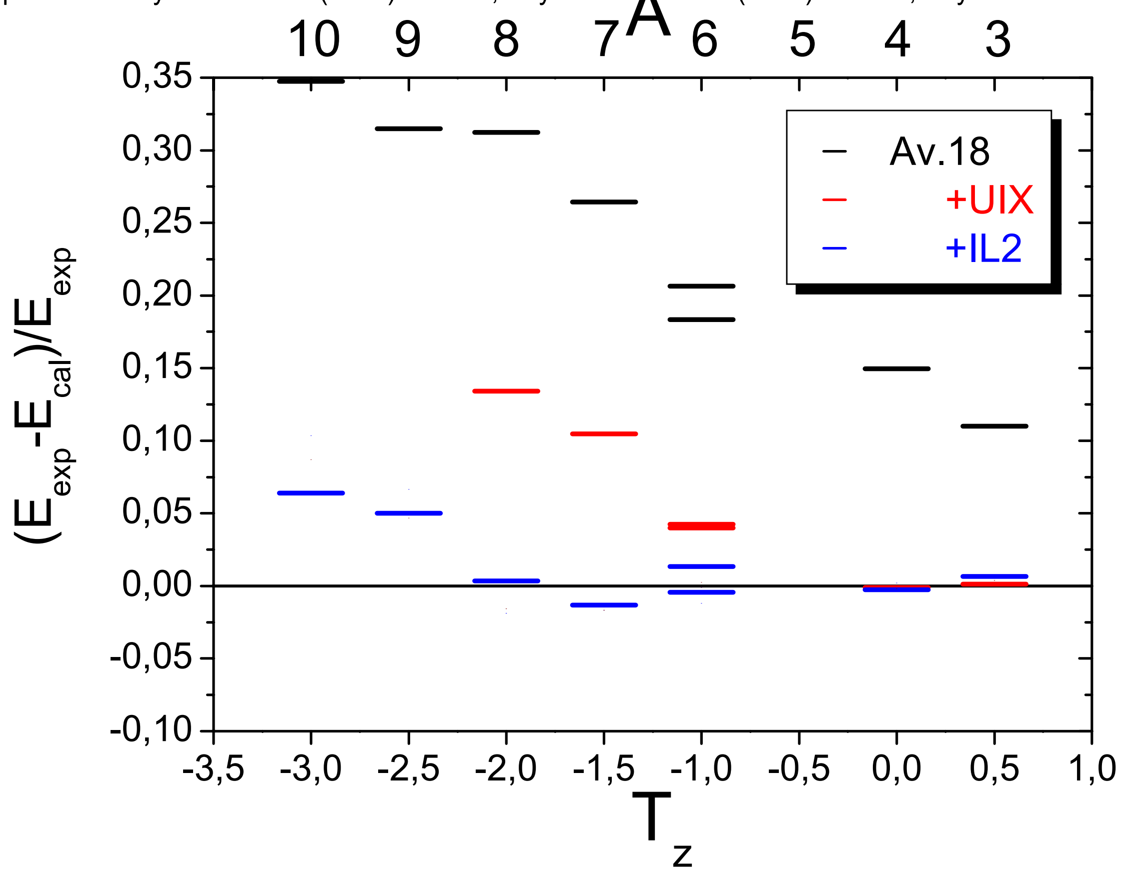
Hadronic resonances in four nucleon systems

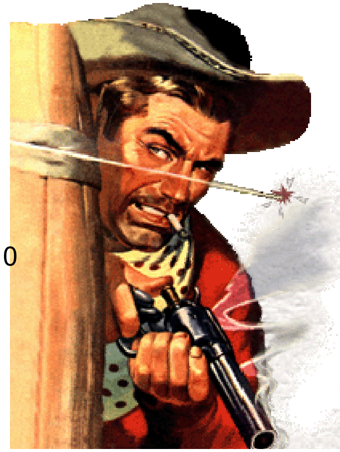
✓ A_y and tensor analyzing power…

A. Kievsky et al., Phys. Rev. C 57 (1998) 555; H. Witała et al. Nucl. Phys.A 528 (1991) 48

✓ Binding energies…

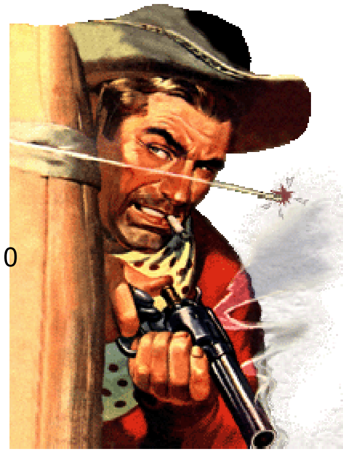
C. Pieper et al.: Phys. Rev. C 64 (2001) 014001; Phys. Rev. Lett. 89 (2002) 182501; Phys. Rev. C 66 (2002) 044310





What is wrong?

Hadronic resonances in four nucleon systems



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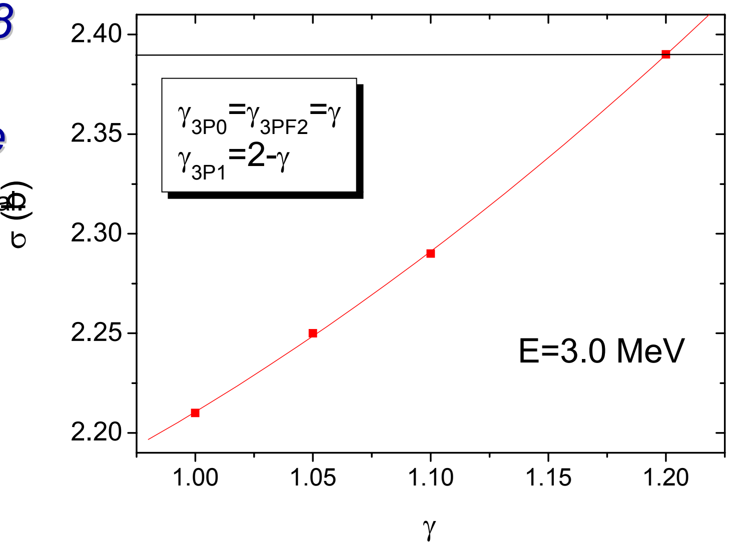
- ***Can we improve n-t cross sections?***

✓ *If NN P-waves should be modified: AV18 nn P-waves should be changed by ~20%*

✓ *Compare to ~6-8% neccesary to improve A_y in n-d* (A. Kievsky et al., Phys. Rev. C 57 (1998) 555; H. Witała et al. Nucl. Phys.A 528 (1991) 48)

✓ *One needs still strong, isospin breaking 3NF… n- ^{3}H puzzle???*



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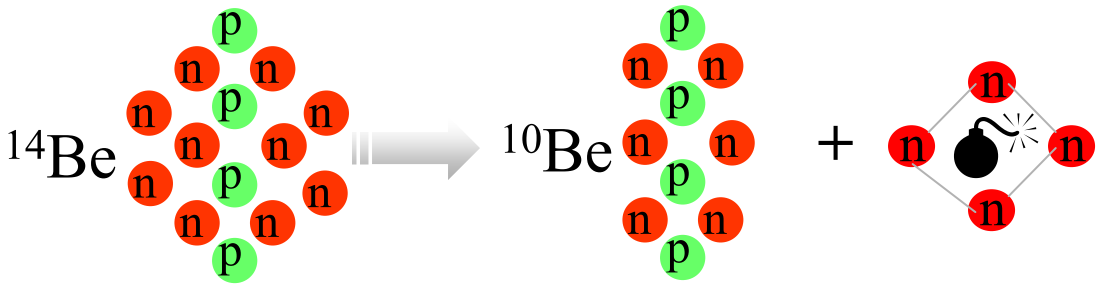
What is wrong?

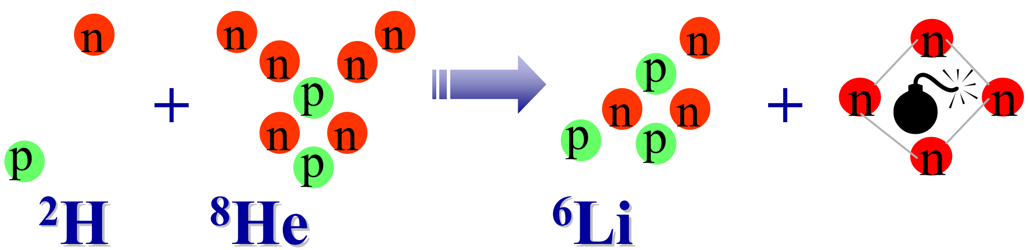
Hadronic resonances in four nucleon systems

Recent experiments in GANIL

F.M. Marqués et al: Phys. Rev. C 65 (2002) 044006 et arxiv:nucl-ex/0504009

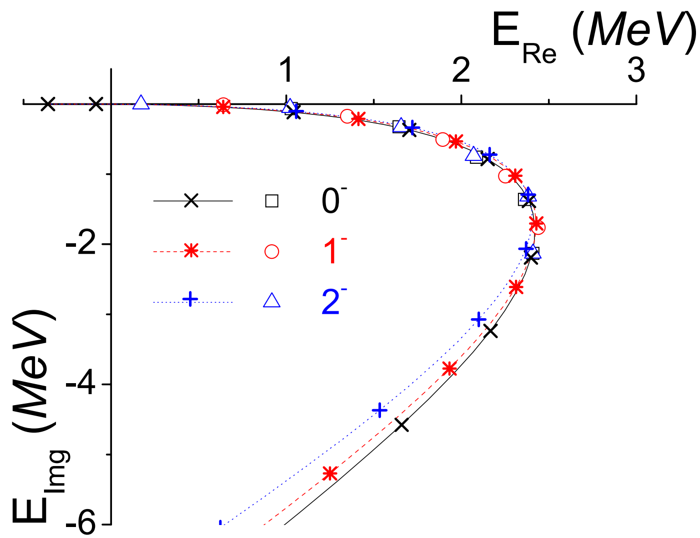


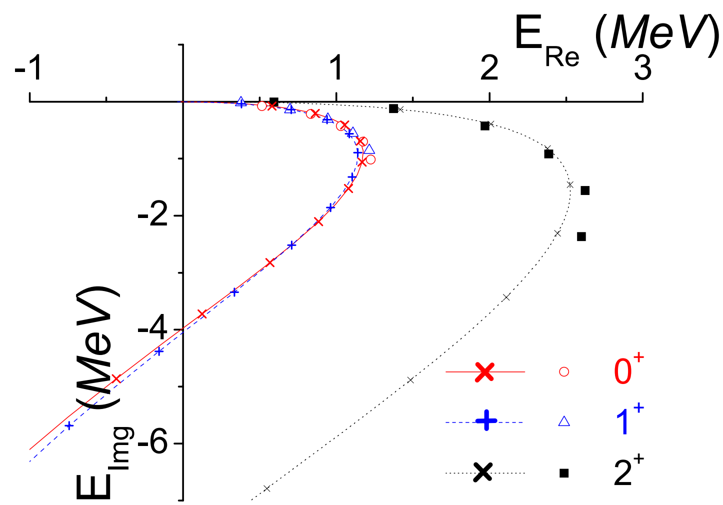
E. Rich et al: proceedings Exxon conference 2004



Hadronic resonances in four nucleon systems

✓ ^3n and ^4n resonances are explored using realistic *NN* interaction Reid93 in conjunction with additional attractive force:





All the resonance trajectories end up in III-rd energy quadrant, with $|E_{img}|>6$ MeV

Hadronic resonances in four nucleon systems

4N is a mine of surprises and disappointments: A=4 continuum test other dynamical aspects of NN potentials than A=2,3 and bring new, yet not solved, problems. *Realistic potentials 'still' do well at the difficult (p+t) and fail at 'rather simple' (n+t)*

- Problem with negative parity states prior to A_y or break-up: modified P-waves and/or 3NF with strong CIB needed?

n-t scattering puzzle?

^3n and ^4n are non-resonant!!