Dibaryon resonances and *NN* interaction

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in collaboration with

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Contents:

1. Dibaryon resonances: predicted many years ago and recently detected.
2. The dressed 6q bag model for NN interaction.
3. Dibaryons in NN scattering.
4. 3N system.
5. Conclusions.

Dibaryon resonances

The first prediction of dibaryon states in *NN* system

F.J. Dyson and N.-H. Xuong, PRL **13**, 815 (1964)

Table I. $Y = 2$ states with zero strangeness predicted by the $\underline{490}$ multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	$\underline{10^*}$	Deuteron	A
D_{10}	1	0	$\underline{27}$	Deuteron singlet state	A
D_{12}	1	2	$\underline{27}$	S-wave N-N^* resonance	$A+6B$
D_{21}	2	1	$\underline{35}$	Charge-3 resonance	$A+6B$
D_{03}	0	3	$\underline{10^*}$	S-wave N^*-N^* resonance	$A+10B$
D_{30}	3	0	$\underline{28}$	Charge-4 resonance	$A+10B$

- The deuteron D_{01}(1876) is the lowest dibaryon state strongly coupled to *NN* *S*-wave channel.
- SU(6) mass formula: $M = A+B[T(T+1)+J(J+1)-2]$
  (A – deuteron mass, $B \approx 47$ MeV)
  Prediction for masses of N-Δ and Δ-Δ *S*-wave resonances:

$$M(D_{12}) \approx 2160 \text{ MeV} \approx M(N) + M(\Delta) - 10 \text{ MeV},$$

$$M(D_{03}) \approx 2350 \text{ MeV} \approx M(\Delta) + M(\Delta) - 110 \text{ MeV}.$$

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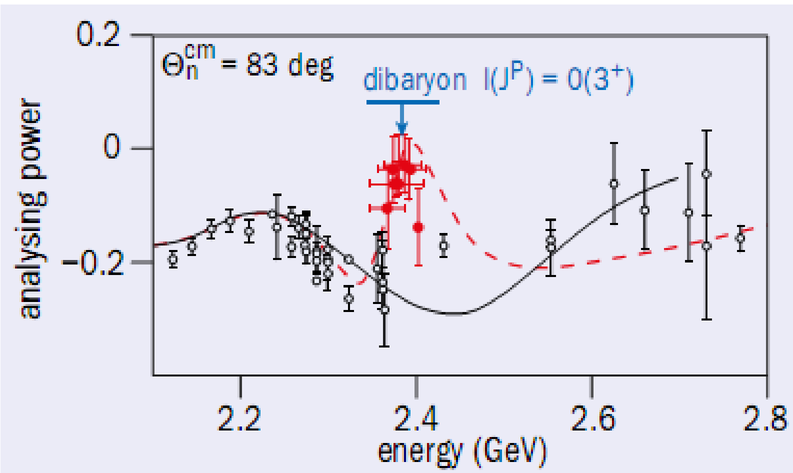
Evidence for D_{03} dibaryon from *n+p* elastic scattering

PRL **112,** 202301 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

(WASA-at-COSY Collaboration) & (SAID Data Analysis Center)



SAID SP07 (2007) new PWA solution (2014)

$$(\sqrt{s})_{\text{pole}} = 2380 \pm 10 - i40 \pm 5 \text{ MeV}$$

$$D_{03} \approx \Delta\Delta(30\%) + C\bar{C}(70\%)$$

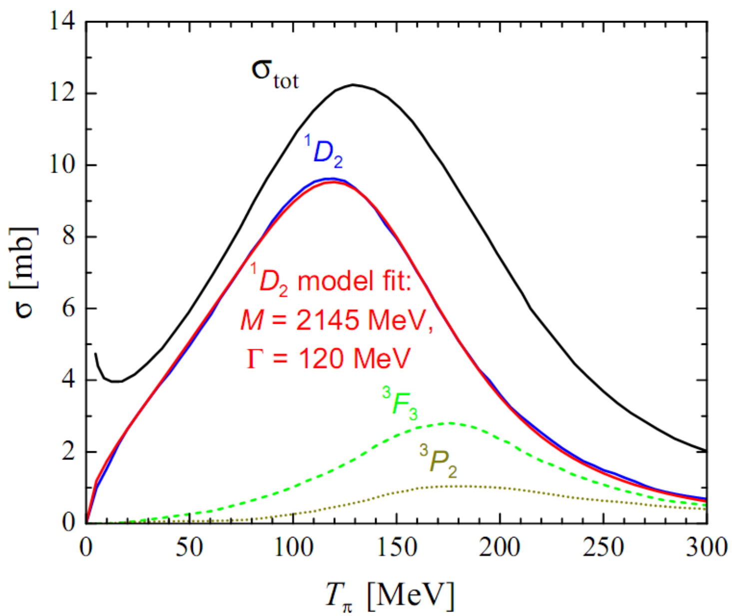
[M. Bashkanov, S. Brodsky, H. Clement, PLB**727**(2013)438]

D_{03} resonance appears to be the *truly dibaryon (6q) state* coupled to $\Delta\Delta$ channel and not only the $\Delta\Delta$ bound state.

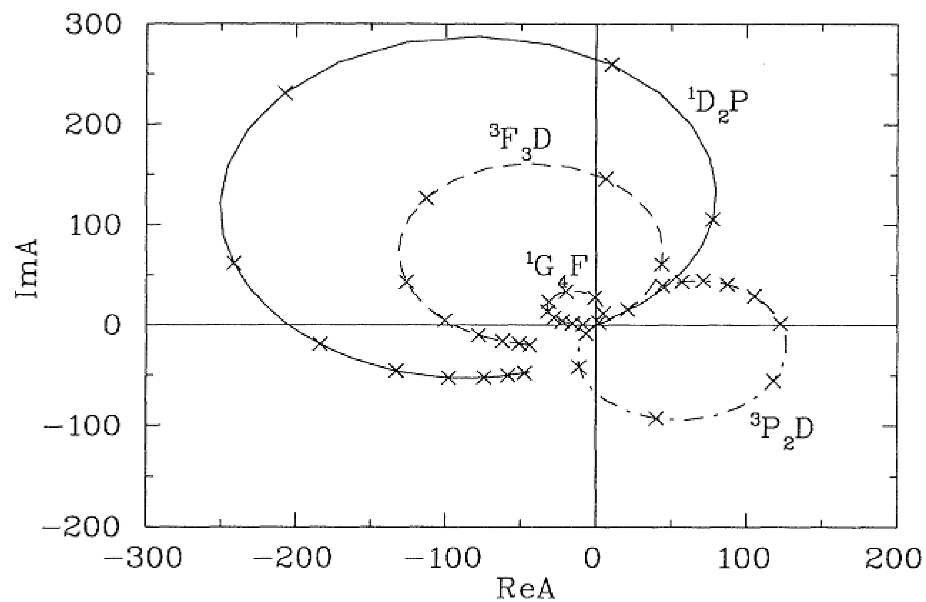
The series of isovector dibaryons

Experiments on $\vec{p} + \vec{p}$ elastic scattering (I. Auer et al., 1978) and partial wave analyses (PWA) for $pp \to pp$, $\pi^+d \to \pi^+d$ and $\pi^+d \to pp$ (by N. Hoshizaki et al., and others) revealed the series of isovector resonances in *NN* channels $^1D_2$, $^3F_3$, $^1G_4$, etc.

Contributions of the dominant ^1D_2P, ^3F_3D and ^3P_2D amplitudes to the $\pi^+d \to pp$ total cross section



Argand plot of the dominant partial-wave amplitudes in $\pi^+d \to pp$



Theoretical confirmation of D_{12} and D_{03} resonances

- From solving exact Faddeev equations for πNN and $\pi N\Delta$ systems the robust dibaryon poles corresponding to D_{12} and D_{03} were found:

$$M(D_{12}) = 2151 \pm 2\ \mathrm{MeV}, \quad \Gamma(D_{12}) = 120 \pm 6\ \mathrm{MeV}$$

$$M(D_{03}) = 2363 \pm 20\ \mathrm{MeV}, \quad \Gamma(D_{03}) = 65 \pm 17\ \mathrm{MeV}$$

[A. Gal, H. Garcilazo, PRL111(2013)172301 & NPA928(2014)73]

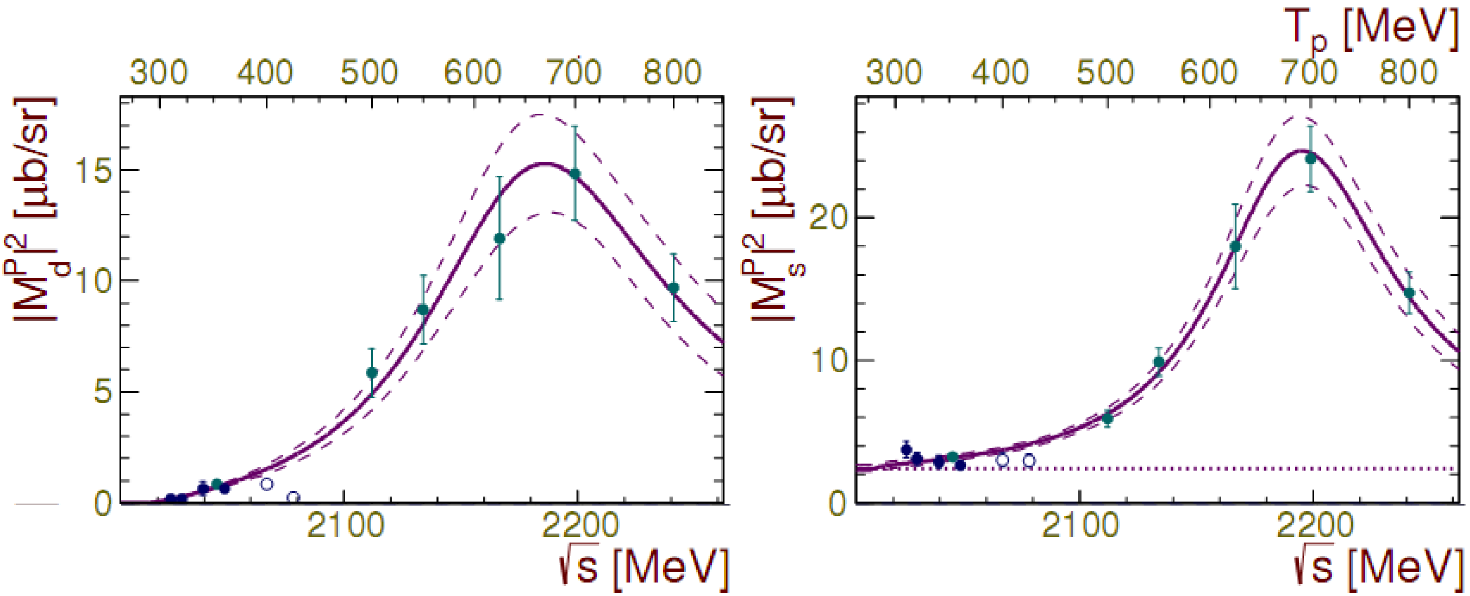
- Very good agreement with Dyson and Xuong predictions as well as with experimental findings!

P-wave isovector dibaryons

V. Komarov et al., Phys. Rev. C 93 (2016) 065206, ANKE

The reaction: $pp \to \{pp\}_s \pi^0$ Two main transitions: ${}^3P_0 \to {}^1S_0 s,\ {}^3P_2 \to {}^1S_0 d$

Partial wave energy dependence

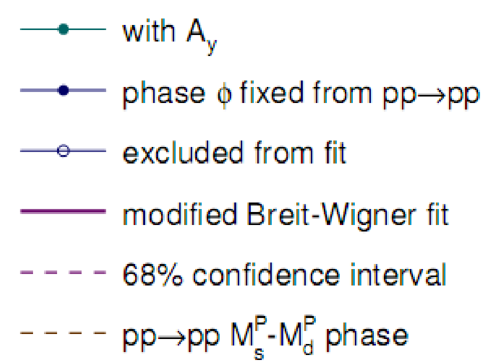


${}^3P_2$ resonance parameters:

E_R=2195 ± 8 MeV, Γ = 134 ± 22 MeV

Indication of ${}^3P_0$ resonance with parameters:

E_R=2199 ± 5 MeV, Γ = 94 ± 11 MeV



Nuclear force model based on the dibaryon mechanism

The dressed bag model with the dibaryon mechanism of NN force:

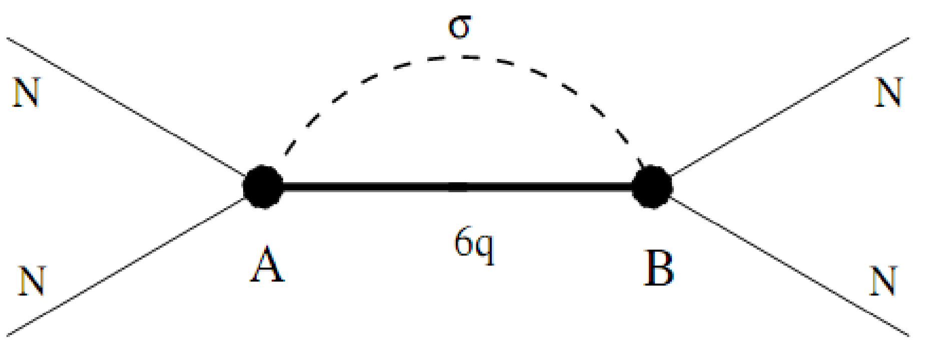
V.I. Kukulin, I.T. Obukhovsky, V.N. Pomerantsev, A. Faessler, *New mechanism for intermediate- and short-range nucleon-nucleon interaction,* J. Phys. G **27**, 1851 (2001).
V. I. Kukulin, I. T. Obukhovsky, V. N. Pomerantsev, A. Faessler, *Two-component dressed-bag model for NN interaction: Deuteron structure and phase shifts up to 1 GeV,* Int. Jour. of Mod. Phys. E **11**, 1 (2002).
V. I. Kukulin, V. N. Pomerantsev, M. Kaskulov, A. Faessler, *The properties of the three-nucleon system with the dressed-bag model for NN interaction: I. New scalar three-body force,* J. Phys. G **30**, 287, (2004).
V. I. Kukulin, V. N. Pomerantsev, A. Faessler, *The properties of the three-nucleon system within the dressed bag model for 2N and 3N forces: II. Coulomb and CSB effects,* J. Phys. G **30**, 309, (2004).
A. Faessler, V.I. Kukulin , M.A. Shikhalev, *Description of intermediate- and short-range NN nuclear force within a covariant effective field theory,* Ann. Phys. **320**, 71 (2005).
V.I. Kukulin et al. Experimental and theoretical indications for an intermediate sigma-dressed dibaryon in the NN interaction, Ann. Phys. **325**, 173 (2010).

Recent results for one- and two-pion production in NN collisions:

M.N. Platonova and V.I. Kukulin, *Hidden dibaryons in one- and two-pion production in NN collisions,* Nucl. Phys. A **946**, 117 (2016).
M.N. Platonova and V.I. Kukulin, *Manifestation of the P-wave diproton resonance in single-pion production in pp collisions,* Phys. Rev. D **94**, 054039 (2016).

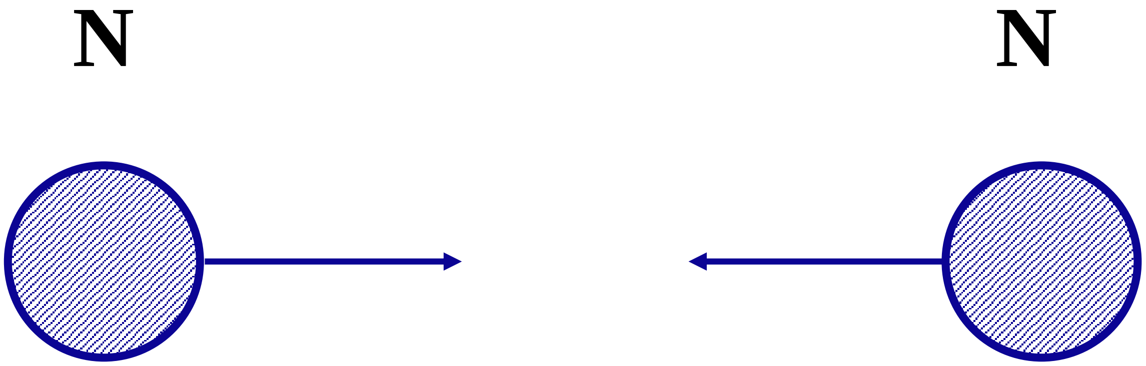
The dibaryon mechanism

The particular short-range mechanism was proposed in 1998 (V.I. Kukulin, in *Proc. XXXIII PIYaF Winter School*, S.-Petersburg, 1998, p.207)



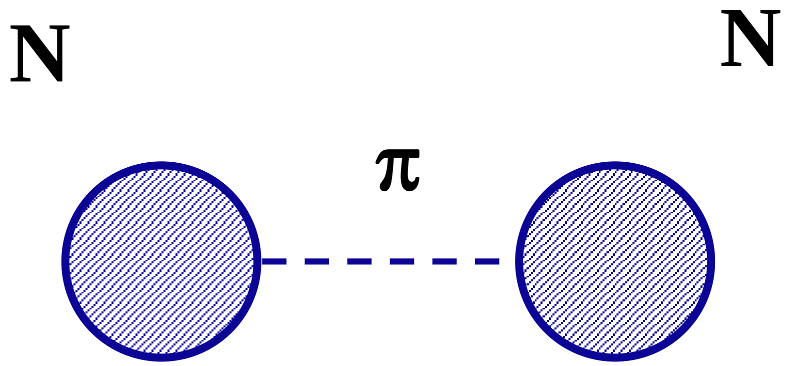
The above mechanism replaces the conventional *t*-channel σ-exchange between two nucleons by the *s*-channel exchange of the σ-dressed six-quark state.

The picture of NN interaction at intermediate and short distances



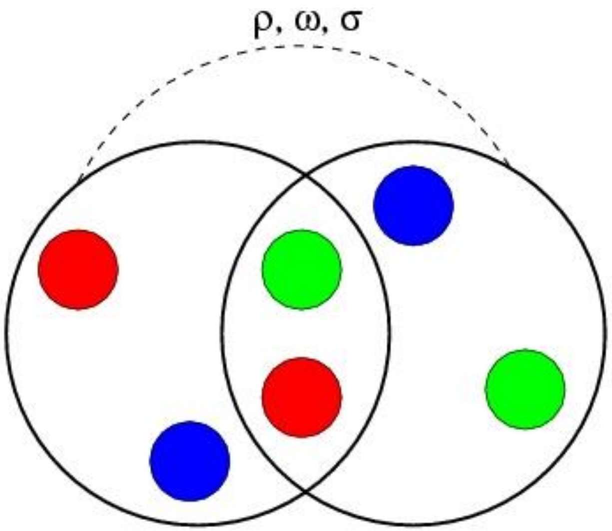
$r_{NN} > 3\,\lambda_\pi$

The picture of NN interaction at intermediate and short distances



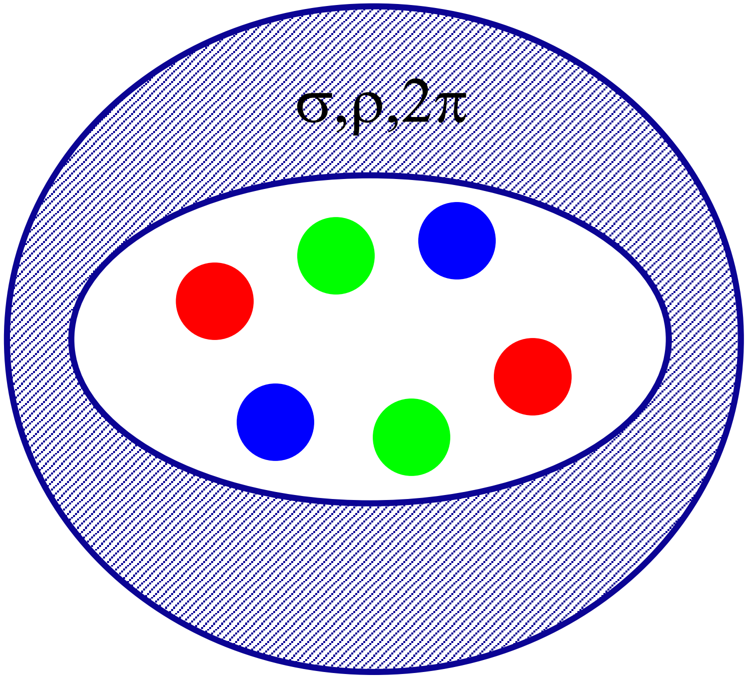
$r_{NN} \sim \lambda_\pi \sim 1.4$ fm

The picture of NN interaction at intermediate and short distances



$\boldsymbol{r}_{NN} < 1$ fm

The picture of NN interaction at intermediate and short distances



$r_{NN} < 1$ fm

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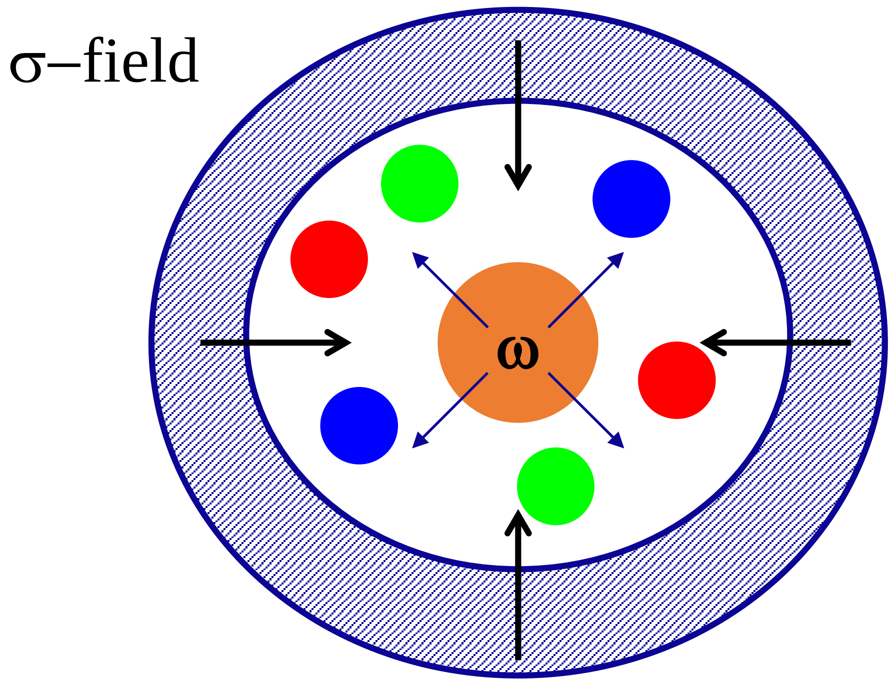
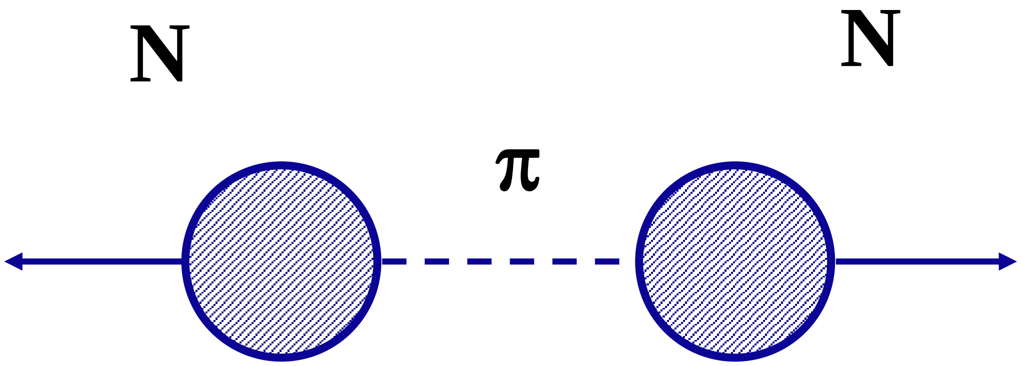


$$r_{NN} < r_{\mathrm{core}} \sim 0.5\ \mathrm{fm}$$

The picture of NN interaction at intermediate and short distances



$r_{NN} \sim \lambda_\pi \sim 1.4$ fm

The picture of NN interaction at intermediate and short distances

$$r_{NN} > 3\,\lambda_\pi$$

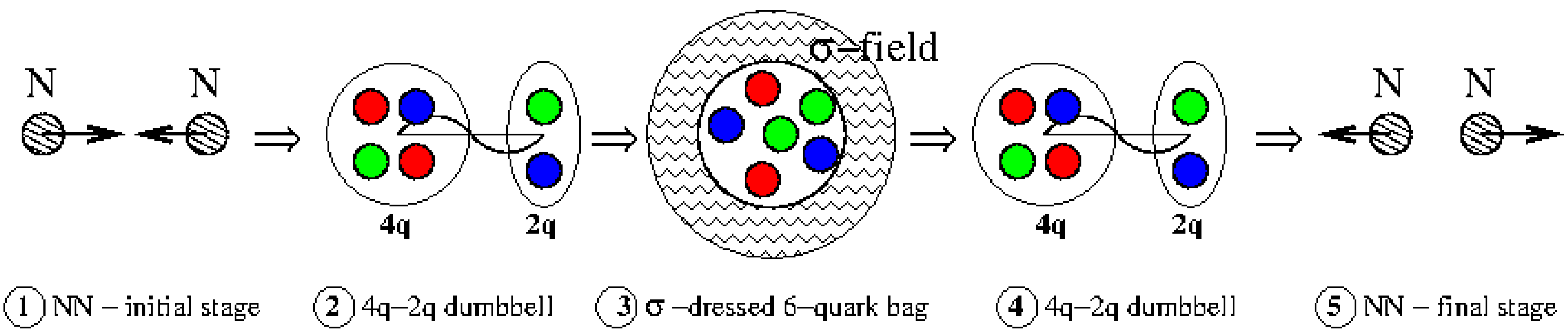
At the QCD level

Two lowest configurations in 6q system:

$$\left| s^6 [6]_x \, L = 0; ST \right\rangle \qquad \left| s^4 p^2 [42]_x \, LST \right\rangle$$

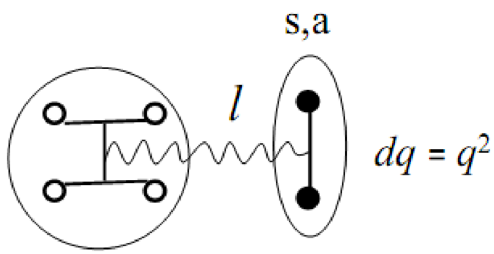
symmetrical config. **mixed symmetry config.**

$$N + N \to D : |s^4p^2[42]\, L_q = 0{,}2;\, ST\rangle \to |s^6[6]\, L_q = 0,\, ST + \sigma\rangle,$$



4q2q configuration has been studied at first in the Nijmegen-ITEP model.

Nijmegen-ITEP dibaryon model:



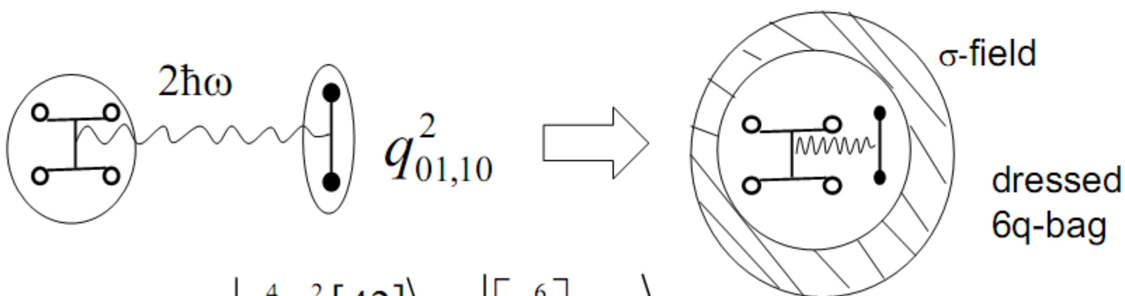
ST=10,01,00

diquark can be in two states:

scalar (s) and axial (a)

scalar (s) → $S=T=0$ → isoscalar dibaryons

axial (a) → $S=T=1$ → isovector dibaryons



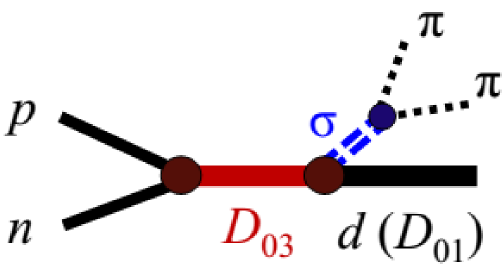
$$\left|s^4 p^2 [42]\right\rangle \rightarrow \left|\left[s^6\right] + \sigma\right\rangle$$

Dibaryon model for the ABC puzzle

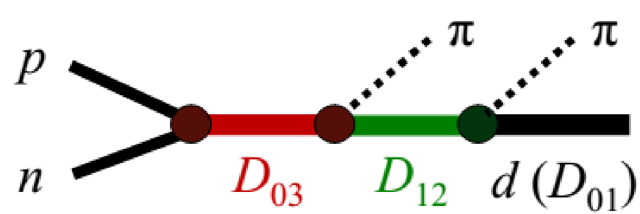
- The new model [M.N. Platonova, V.I. Kukulin, PRC 87, 025202 (2013)] for the reaction $pn \rightarrow d + (\pi\pi)_0$ at energies $T_p = 1$–1.3 GeV ($s^{1/2} = 2.32$–2.44 GeV) includes production of the $D_{03}(2380)$ dibaryon and its subsequent decay into the final deuteron and isoscalar $\pi\pi$ pair via two interfering routes:

  (*a*) emission of $\pi\pi$ pair from a scalar σ meson produced from dibaryon meson cloud;

  (*b*) sequential emission of two pions via an intermediate isovector dibaryon $D_{12}(2150)$.



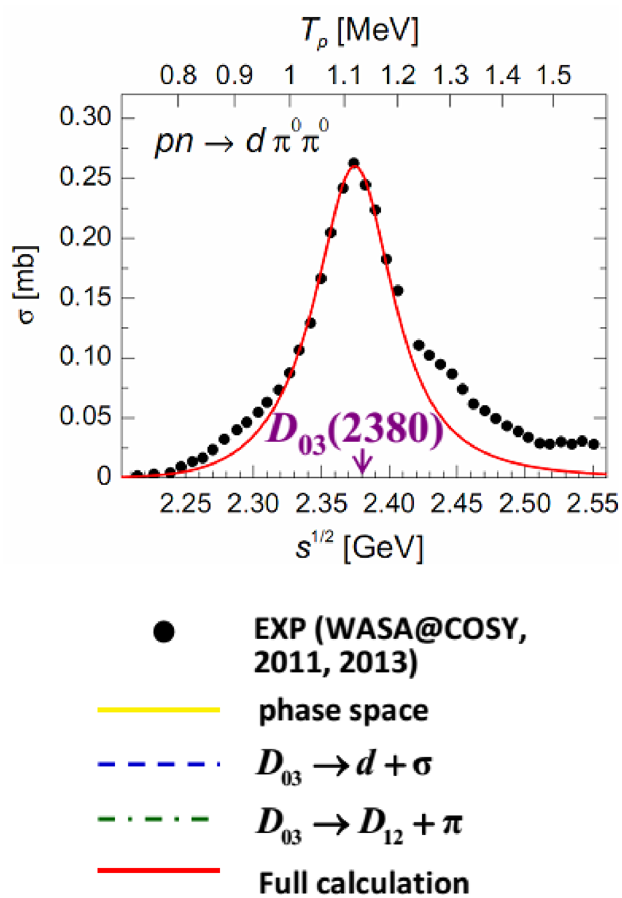
(*a*)



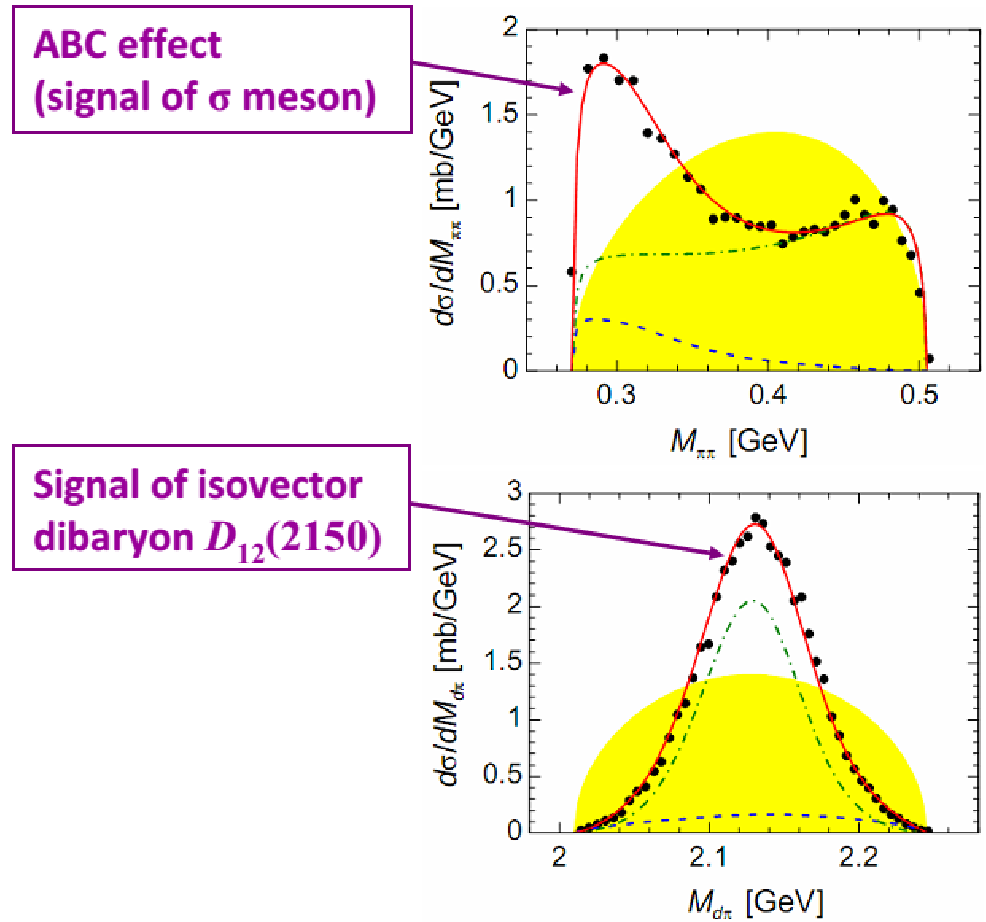
(*b*)

Dibaryon model for the ABC puzzle

I. Total Cross Section



II. Invariant-mass spectra ($s^{1/2} = 2.38$ GeV)



- ✓ ABC enhancement appears as a consequence of σ meson production
- ✓ Peak in $M_{d\pi}$ spectrum reflects production of isovector dibaryon $D_{12}(2150)$

The formalism for NN scattering

A model with external and internal channels

The total Hamiltonian acts in two subspaces of different nature:

$$H = \begin{pmatrix} h^{\mathrm{ex}} & h^{\mathrm{ex,in}} \\ h^{\mathrm{in,ex}} & h^{\mathrm{in}} \end{pmatrix}$$

ex - corresponds to relative motion of particles
in – corresponds to internal degrees of freedom

After an exclusion of internal terms, one gets the effective Hamiltonian in the external subspace:

$$H_{\mathrm{eff}}(E) = h^{\mathrm{ex}} + h^{\mathrm{ex,in}} g^{\mathrm{in}}(E) h^{\mathrm{in,ex}}, \quad g^{\mathrm{in}}(E) = (E - h^{in})^{-1}$$

The mathematical background for the two-channel formalism within the Faddeev approach was given by the Leningrad's group:

Yu.A. Kuperin, K.A. Makarov, S.P. Merkuriev, A.K. Motovilov, and B.S. Pavlov, J. Math. Phys. **31**, 1681 (1990).

A model with internal and external channels

The total Hamiltonian in the dibaryon model:

$$H = \begin{pmatrix} h_{NN} & \lambda|\varphi\rangle\langle B| \\ \lambda|B\rangle\langle\varphi| & h^{\text{in}} \end{pmatrix}$$

h_{NN} is the Hamiltonian which acts in the *NN* relative momentum space.
The internal space corresponds to the 6q degrees of freedom.

In the simplest case, this space is spanned with a single state:

$$h^{\text{in}} = E_D|B\rangle\langle B|$$

The energy-dependent effective Hamiltonian:

$$H_{\text{eff}}(E) = h_{NN} + \frac{\lambda^2}{E - E_D}|\varphi\rangle\langle\varphi|$$

The external Hamiltonian

The Hamiltonian in the external channel:

$$h_{NN} = t_{NN} + V_{OPE} + V_{\text{orth}}$$

One pion exchange (OPE) potential:

$$V_{OPE}(\mathbf{p},\mathbf{p}') = -\frac{f_\pi^2}{m_\pi^2}(\boldsymbol{\tau}_1\boldsymbol{\tau}_2)\frac{(\boldsymbol{\sigma}_1\mathbf{q})(\boldsymbol{\sigma}_2\mathbf{q})}{q^2+m_\pi^2}\left(\frac{\Lambda_{\pi NN}^2 - m_\pi^2}{\Lambda_{\pi NN}^2 + q^2}\right)^2, \mathbf{q} = \mathbf{p} - \mathbf{p}'$$

V_{orth} is related to the orthogonality condition and plays the same role as the repulsive core in conventional models.

The repulsive core effects

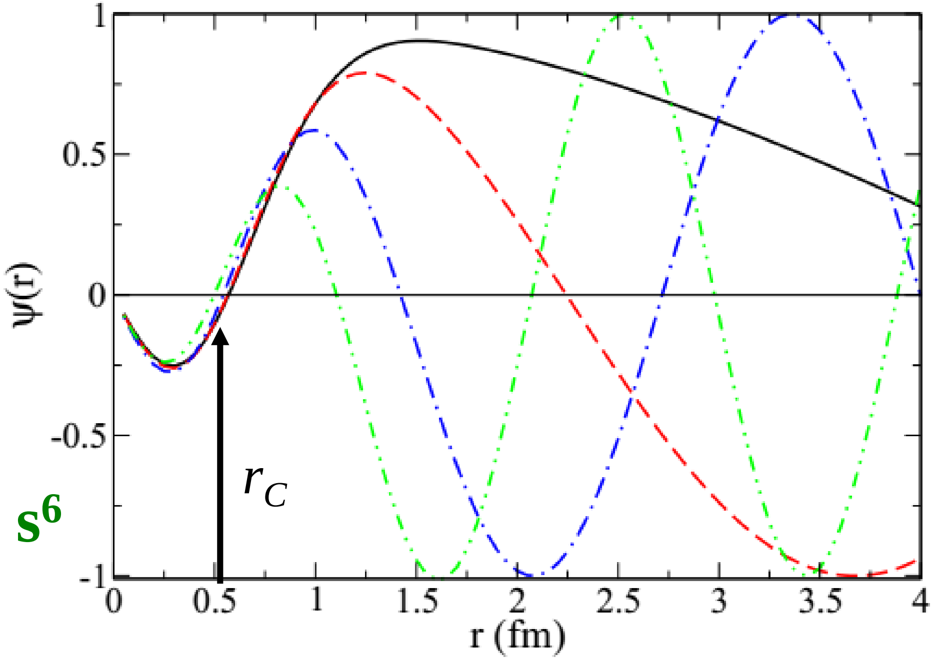
6q configurations: $\left| s^4 p^2 [42]_x \, LST \right\rangle$ $\left| s^6 [6]_x \, L=0; ST \right\rangle$

The NN relative momentum space corresponds to the mixed symmetry 6q configuration s^4p^2 . Its projection onto NN channel has a stationary node (see e.g. F. Stancu et al., PRC **56**, 2779 (1997)).

To reproduce this behaviour, one should add the orthogonalizing pseudo-potential in a form:

$$V_{\mathrm{orth}} = \lambda_0 \left| \varphi_0 \right\rangle \left\langle \varphi_0 \right|, \; \lambda_0 \to \infty$$

projection onto the symmetrical config. s^6



NN scattering wave functions in $^1S_0$ channel.
Different colors correspond to different energies.

The node position is close to the repulsive core range r_C.

The effective Hamiltonian

$$H_{\text{eff}}(E) = t_{NN} + V_{OPE} + V_{\text{orth}} + \frac{\lambda^2}{E - E_D} |\varphi\rangle\langle\varphi|$$

Further, one may consider a complex pole: $E_D = E_0 - \mathrm{i}\Gamma(E)/2$

$\Gamma(E)$ takes into account decays of the dibaryon state into all inelastic channels (such as NΔ, $\Delta\Delta$, etc.) except the NN channel.
For example, the decay width for the $D \to \pi$NN process:

$$\Gamma_D(\sqrt{s}) = \begin{cases} 0, & \sqrt{s} \le E_{\text{thr}}; \\ \Gamma_0 \dfrac{F(\sqrt{s})}{F(M_0)}, & \sqrt{s} > E_{\text{thr}} \end{cases}, \qquad E_{\text{thr}} = 2m + m_\pi$$

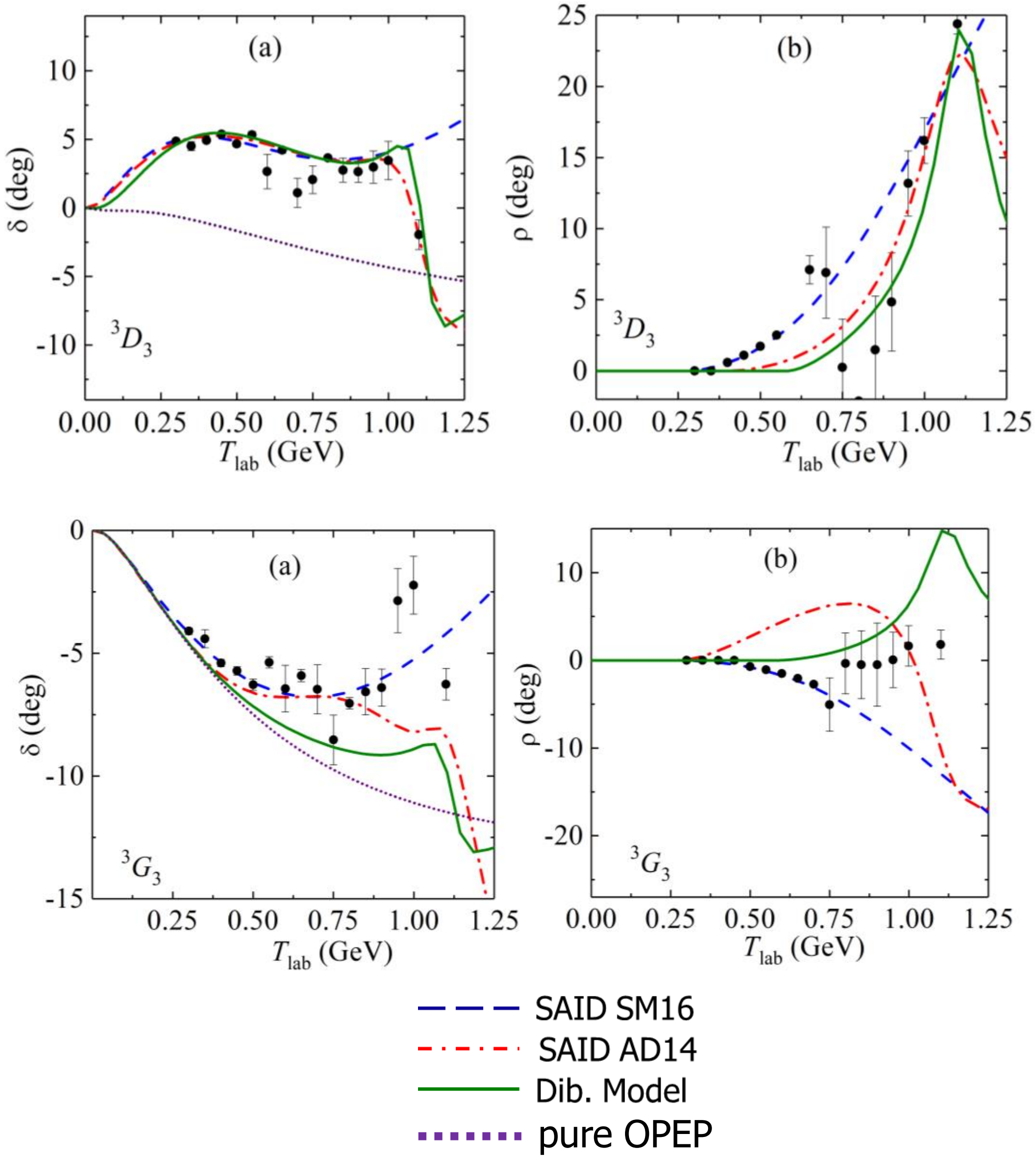
$$F(\sqrt{s}) = \frac{1}{s} \int_{2m}^{\sqrt{s}-m_\pi} dM_{NN} \frac{q^{2l_\pi+1} k^{2L_{NN}+1}}{(q^2+\Lambda^2)^{l_\pi+1}(k^2+\Lambda^2)^{L_{NN}+1}},$$

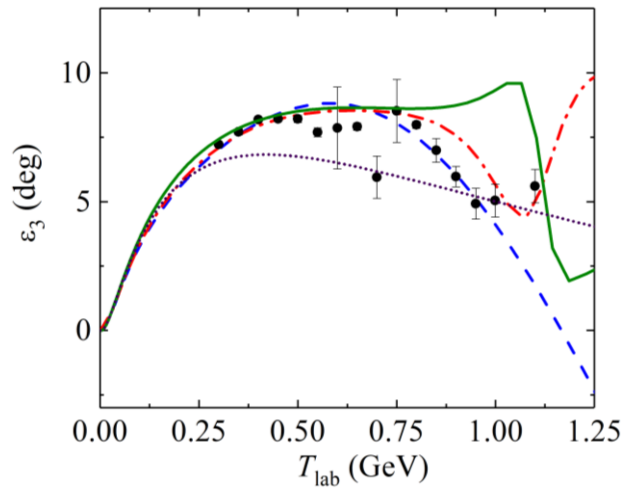
$q = \sqrt{(s - m_\pi^2 - M_{NN}^2)^2 - 4m_\pi^2 M_{NN}^2} \Big/ 2\sqrt{s}$ - momentum of the pion in total c.m. frame

$k = \dfrac{1}{2}\sqrt{M_{NN}^2 - 4m^2}$ - nucleon momentum in the NN c.m. frame

Partial NN phase shifts

Coupled channels $^3D_3$-$^3G_3$





The parameters of the resonance found within our model:

M_{th}=2.376 GeV, Γ_{th}=0.084 GeV.

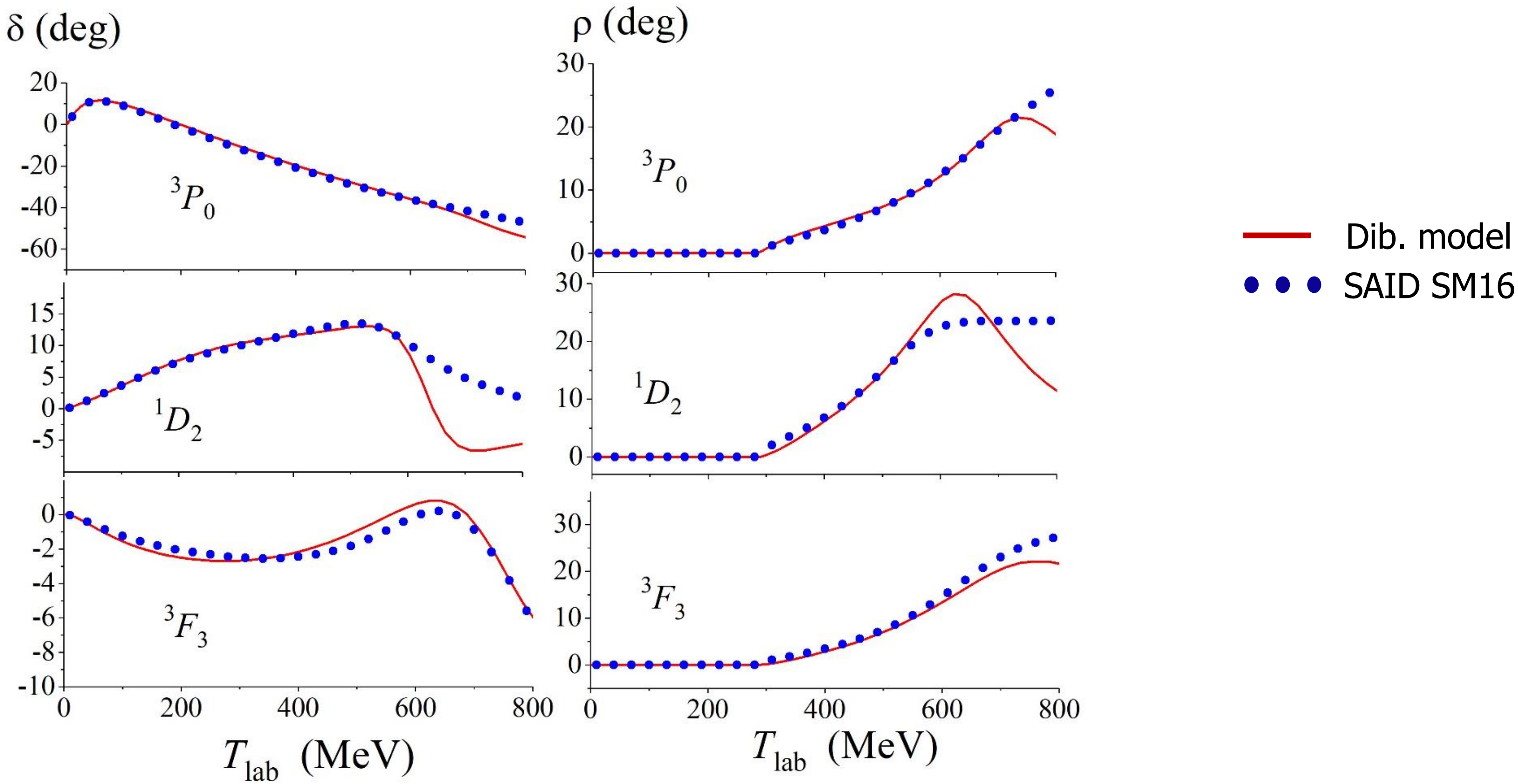
Experimental values:

M_{exp}(d*)=2.38 GeV,

Γ_{exp}(d*)=0.08±0.01 GeV.

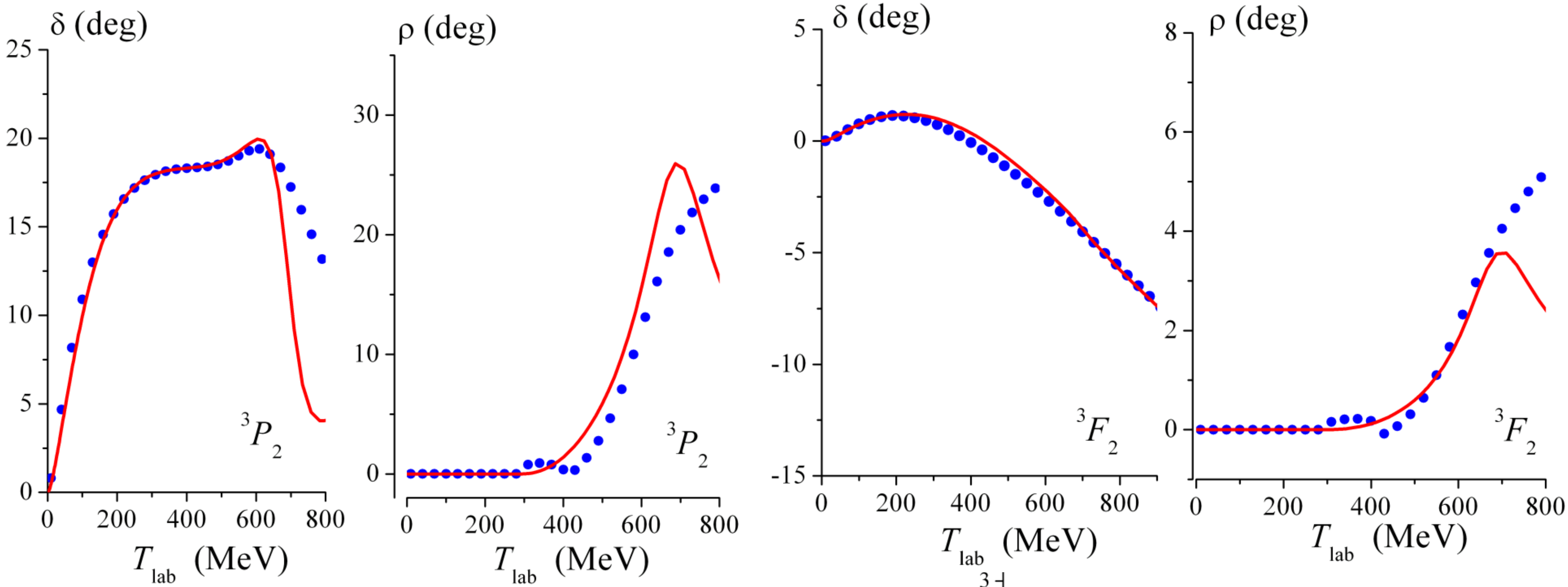
Isovector channels

(V.N. Pomerantsev et al., FBS 2019)

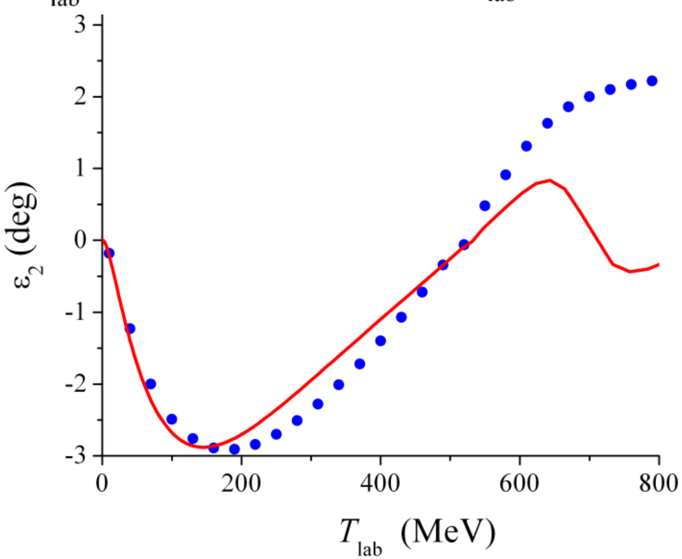


$^{2S+1}L_J$	$M_{\rm th}$	$\Gamma_{\rm th}$	$M_{\rm exp}$	$\Gamma_{\rm exp}$
$^3P_0$	2.21	0.1	2.20(5)	0.091(12)
$^1D_2$	2.18	0.11	2.14–2.18	0.05–0.1
$^3F_3$	2.22	0.17	2.20–2.26	0.1–0.2

Coupled channels $^3P_2$-$^3F_2$



E_{th}=2216 MeV, Γ_{th}=144 MeV

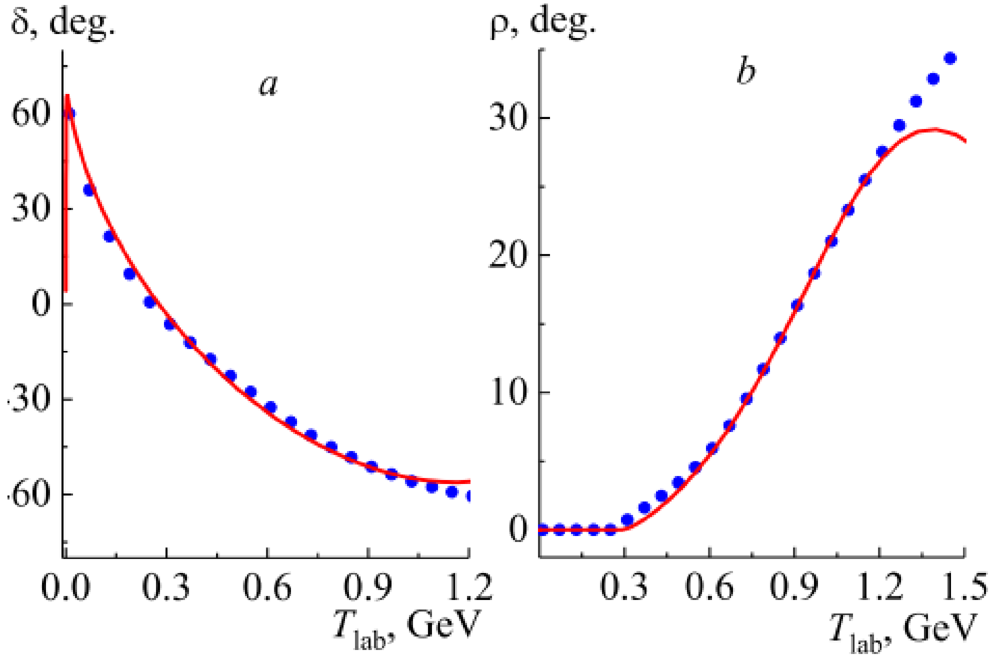


Exp. values:

E_R=2195 ± 8 MeV, Γ = 134 ± 22 MeV

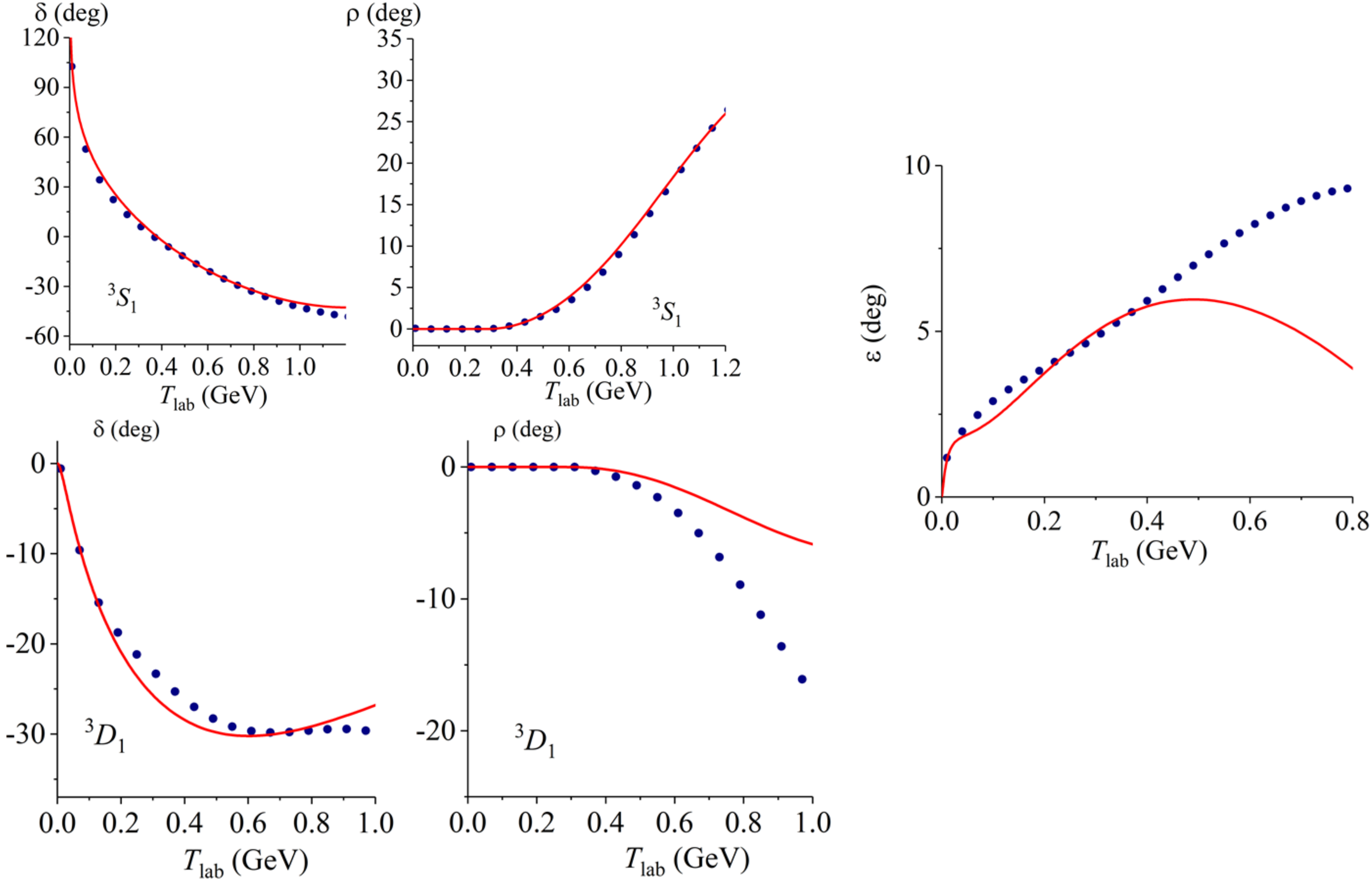
$^1S_0$ channel

V.I. Kukulin et al., Phys. At. Nucl. 2019; arXiv:1908.10551v1 [nucl-th]



The additional broad resonance: E_{th}=2.6 GeV, Γ_{th}=0.6 GeV

Coupled channels $^3S_1$-$^3D_1$



3N system

Three-nucleon system within the dibaryon model

(V.N. Pomerantsev et al., FBS 19)

The total space consists of 4 components:

$$\hat{\Psi} = \begin{pmatrix} \Psi^0 \\ \Psi^1 \\ \Psi^2 \\ \Psi^3 \end{pmatrix}, \quad \mathbb{H} = \begin{pmatrix} H^0 & H^{01} & H^{02} & H^{03} \\ H^{10} & H^1 & 0 & 0 \\ H^{20} & 0 & H^2 & 0 \\ H^{30} & 0 & 0 & H^3 \end{pmatrix},$$

0 – an external momentum space
1,2,3 – internal subspaces
for each Jacobi set

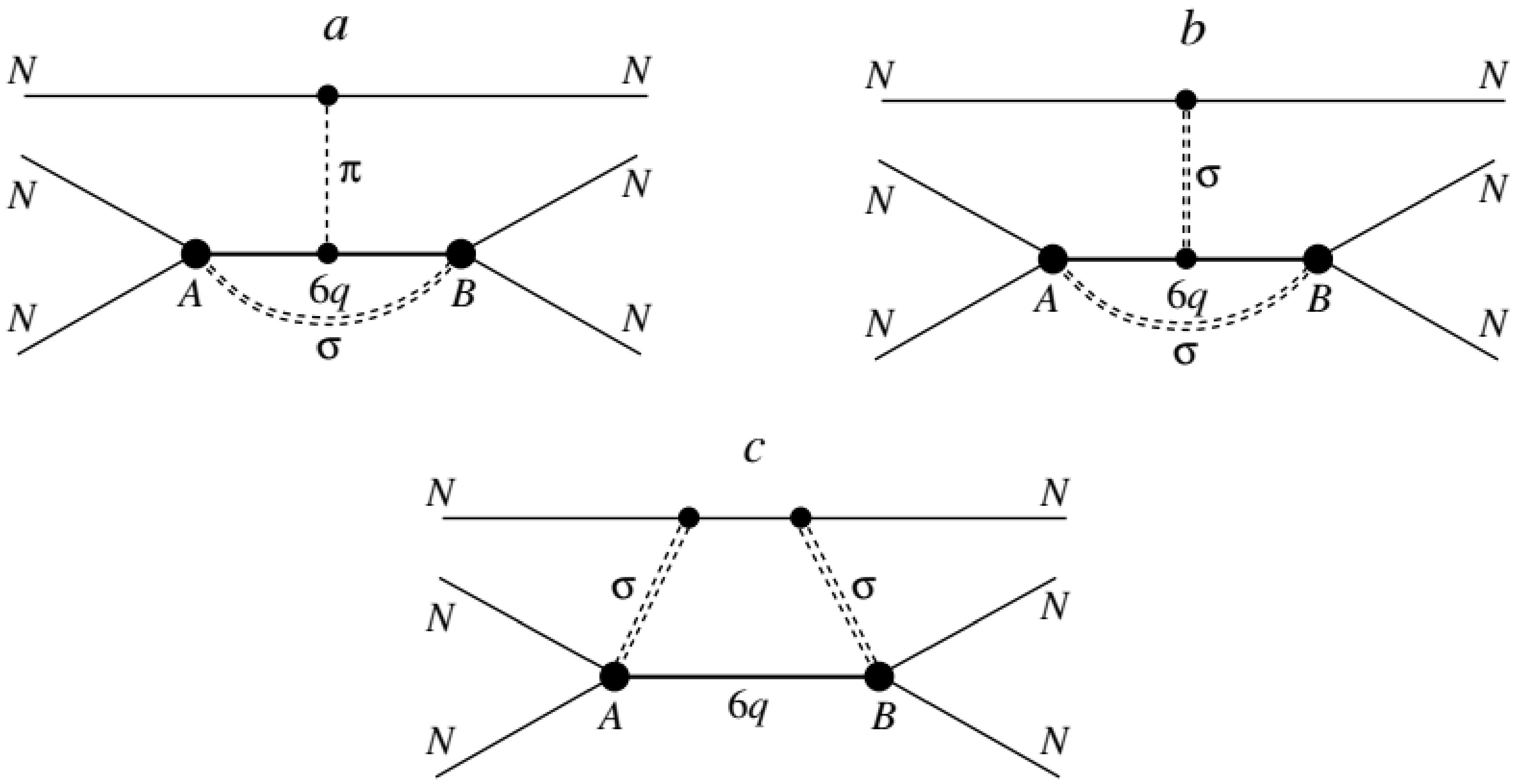
The effective Hamiltonian:

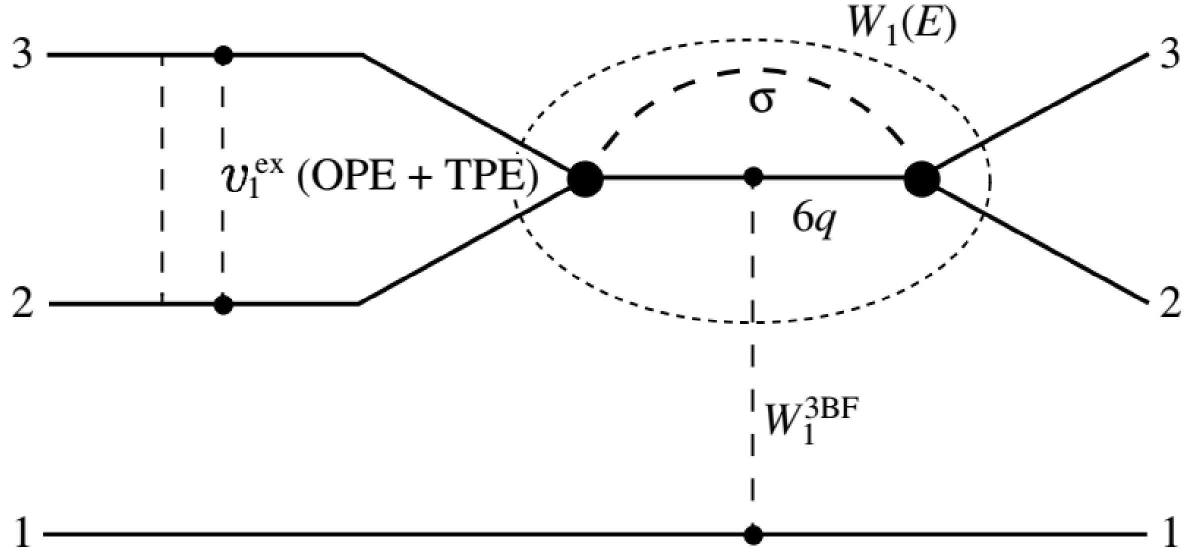
$$H^{\text{eff}}(E)\Psi^0 = E\Psi^0,$$

$$H^{\text{eff}}(E) = H^0 + \sum_i H^{0i} G^i(E) H^{i0} = T + \sum_i \left[V_i + W_i(E - t_i) \right]$$

The Hamiltonian should be supplemented with the dibaryon 3N force.

Dibaryon-induced 3*N* force





These three-body forces are expressed in momentum representation by integral operators with factorized kernel like:

$$W_1^{3BF}(\mathbf{p_1},\mathbf{q_1},\mathbf{p_1^{'}},\mathbf{q_1^{'}};E)=\varphi(\mathbf{p_1})w(\mathbf{q_1},\mathbf{q_1^{'}};E)\varphi(\mathbf{p_1^{'}})$$

The total Hamiltonian:

$$H^{\mathrm{tot}}(E)=H_{\mathrm{eff}}(E)+\sum_{\alpha}W_{\alpha}^{3BF}(E)$$

Properties of ^{3}H and ^{3}He from 3N calculations with the dibaryon model

V.N. Pomerantsev et al., Phys. At. Nucl. **68**, 1453 (2005)

Model	E, MeV	P_D, %	$P_{S'}$, %	$P_{6qN}(P_{\text{in}})$, %	Contributions to H, MeV		
					T	$T+V^{(2N)}$	$V^{(3N)}$
				^{3}H			
DBM(I) $g = 9.577$[a)]	−8.482	6.87	0.67	10.99	112.8	−1.33	−7.15
DBM(II) $g = 8.673$[a)]	−8.481	7.08	0.68	7.39	112.4	−3.79	−4.69
AV18 + UIX[b)]	−8.48	9.3	1.05	–	51.4	−7.27	−1.19
				^{3}He			
DBM(I)	−7.772	6.85	0.74	10.80	110.2	−0.90	−6.88
DBM(II)	−7.789	7.06	0.75	7.26	109.9	−3.28	−4.51
AV18 + UIX[(b)]	−7.76	9.25	1.24	–	50.6	−6.54	−1.17

a) These values of the σNN coupling constant in ^{3}H calculations have been chosen to reproduce the exact binding energy of the ^{3}H nucleus. The calculations for ^{3}H have been carried out without any free parameters.

b) S. C. Pieper et al., Phys. Rev. C **64**, 014001 (2001).

$$\Delta E_{\text{Coul}} = 754 \text{ keV} \quad \left(\Delta E_{\text{Coul}}^{\text{exp}} = 764 \text{ keV}\right)$$

Conclusions:

- Attraction in partial NN channels can be explained by the suggested s-channel dibaryon mechanism.
- The parameters of the found dressed dibaryon states are in good agreement with experimental data.
- These results supplement other achievements of the dibaryon model, such as an accurate description of one-pion and two-pion production in NN collisions .

Further development:

- Explicit account of inelastic channels such as NΔ, ΔΔ etc.
- Scattering in 3N system…
- Nuclear matter calculations: study of short-range correlations, pairing etc.
- …

Thank you for your attention!

Properties of the deuteron:

V.N. Pomerantsev et al., Phys. At. Nucl. **68**, 1453 (2005)

Model	E_d, MeV	P_D, %	r_m, fm	Q_d, fm^2	μ_d, n.m.	A_S, fm$^{-1/2}$	$\eta(D/S)$
RSC	2.22461	6.47	1.957	0.2796	0.8429	0.8776	0.0262
Moscow 99	2.22452	5.52	1.966	0.2722	0.8483	0.8844	0.0255
Bonn 2001	2.224575	4.85	1.966	0.270	0.8521	0.8846	0.0256
DBM(I) $P_{6q} = 3.66\%$	2.22454	5.22	1.9715	0.2754	0.8548	0.8864	0.02588
DBM(II) $P_{6q} = 2.5\%$	2.22459	5.31	1.970	0.2768	0.8538	0.8866	0.0263
Experiment	2.224575	–	1.971	0.2859	0.8574	0.8846	0.0263[a)]