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Dibaryon Concept for Short-Range 2*N* and 3*N* Forces: Consequences for Hadronic and Nuclear Physics

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In place of Introduction

In our studies of non-conventional *NN* force models we had to analyze very numerous predictions of the conventional force models and the accurate contributions of three-body force to the observable effects.

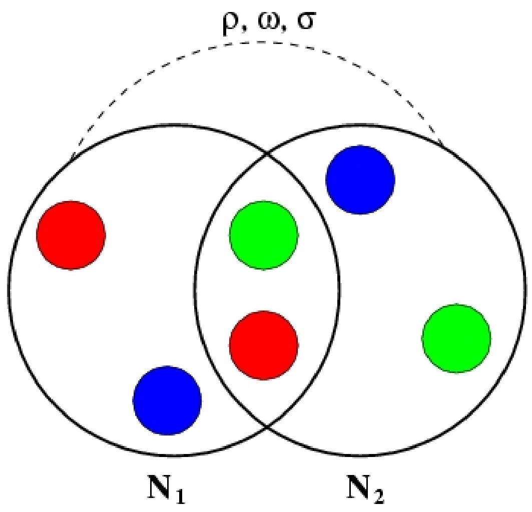
It is my pleasure to claim here that just the very detailed and accurate few-nucleon results of the **Bochum-Cracow group** (*H. Witała, J. Golak, R. Skibinsky, and W. Glöckle*) were the most useful for our studies and that their results stimulated us strongly to looking for new ideas for strong *NN* and 3*N* interactions.

Why dibaryons?

- While the long-range part of nuclear force is well understood now (OBE-like models, ChPT, etc.), the short-range part and respective short-range *NN* and 3*N* correlations in nuclei and nuclear matter are still poorly known and we do not understand the basic interaction mechanisms behind these forces.
- These mechanisms should be intimately interrelated with the fundamental QCD in non-perturbative region. So, we must resort to QCD and QCD-inspired models.

Why dibaryons?

- On the other hand, the short-range *NN* interaction (at r_{NN} < 1 fm) occurs in the area where two nucleons get overlapped because $\langle r_N^q \rangle \sim 0.6$ fm, and their quark cores get also overlapped.



- In such a situation the conception of meson exchange between two isolated nucleons becomes meaningless at all and the mesons from the meson clouds of two nucleons should be moving in the field of the unified six-quark core.

- Thus, the conventional assumption about the mechanism of heavy-meson exchange between two nucleons at distances r_{NN} < 1 fm looks to be completely unjustified theoretically. E.g., the wide-spread idea about existence of a local *NN* repulsive core at r_{NN} < 0.5 fm belongs to such sort of assumptions. (I'll show in the talk how to replace such a repulsive core by non-local repulsive mechanism fully compatible with the quark model.)

Why dibaryons?

- If however we start from the opposite side, i.e., by constructing an effective *NN* potential using quark microscopic model, it leads also to quite disappointing results:

– without an assumption of phenomenological σ-meson exchange between quarks one gets purely repulsive *NN* potential at the distances r_{NN} < 1.4 fm;

– moreover, if to involve phenomenologically *t*-channel σ-meson exchange between quarks taking into account the loops: $\sigma \rightarrow \pi\pi \rightarrow \sigma$..., i.e., the σ-meson width, one gets also purely repulsive *NN* potential.

- Thus, the traditional six-quark model appears to be not leading to correct understanding of the short-range *NN* interaction as well.

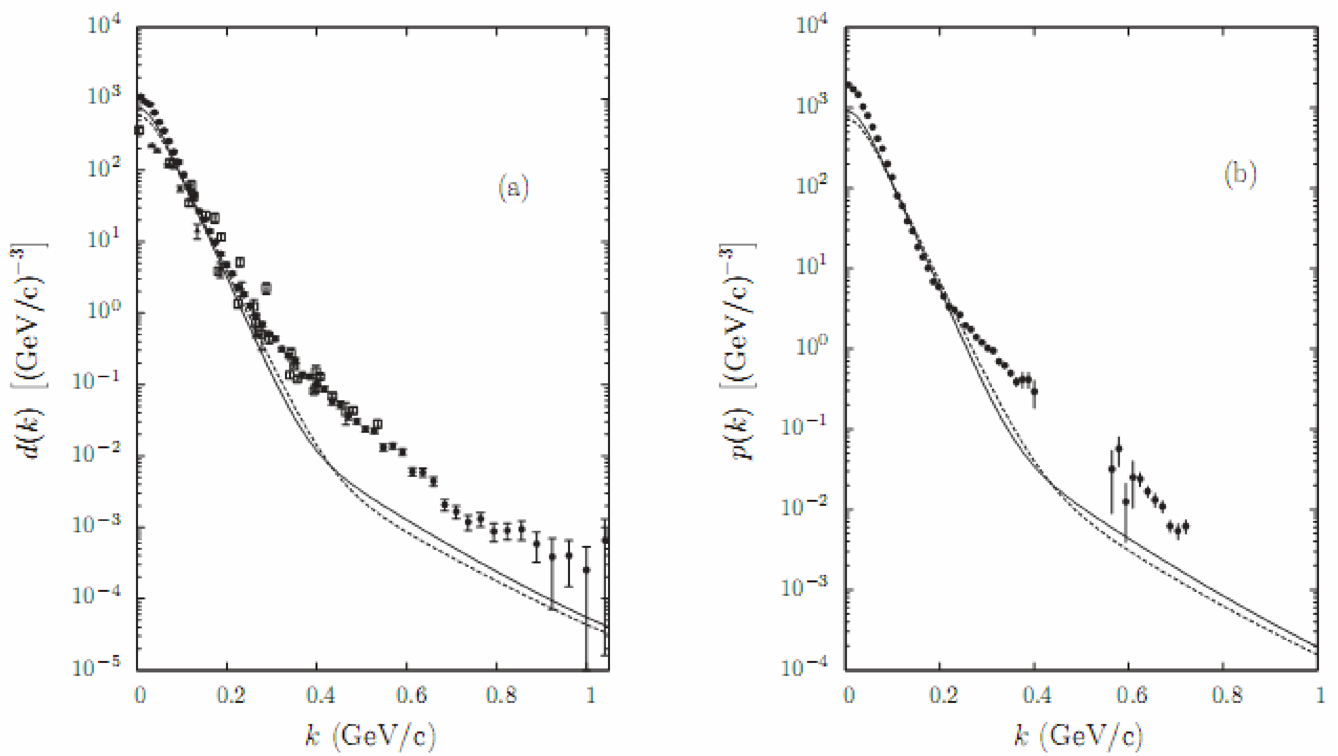
To summarize:

We should look for some principally novel mechanism for short-range *NN* force. In view of the new reliable experimental findings (BNL, WASA@COSY, Mainz, etc.) we should change all the traditional conception for the short-range forces in 2*N* and 3*N* sectors.

Recent experimental results which strongly support the dibaryon concept

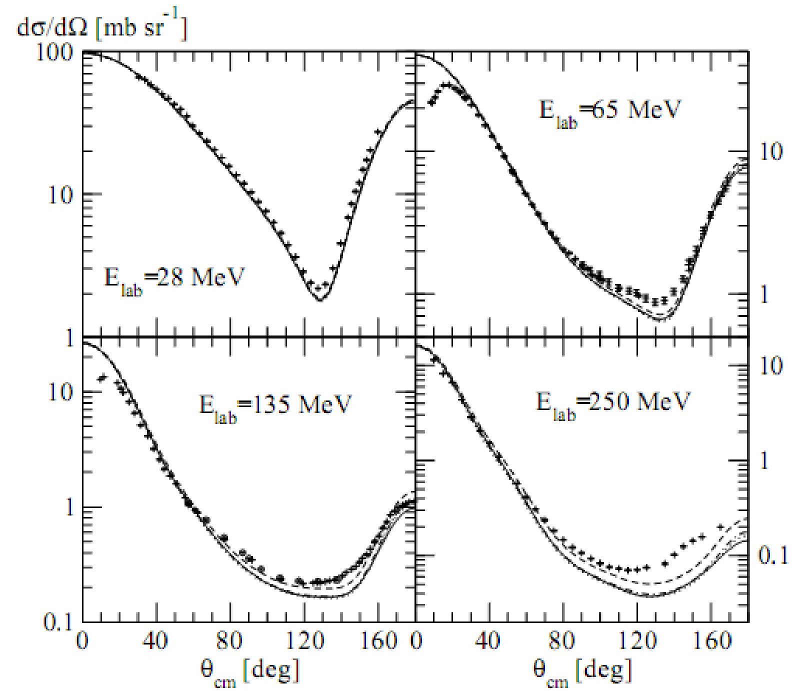
Brief review of modern situation with short-range *NN* and 3*N* interactions

- Numerous experiments demonstrate very clearly the high-momentum correlations of nucleons in all nuclei with momenta p_m > 200 – 300 MeV/*c*, i.e., *well beyond the maximum Fermi-motion nucleon momentum in nuclei.*
- The reliable source for such high-momentum correlations is not fully understood now.

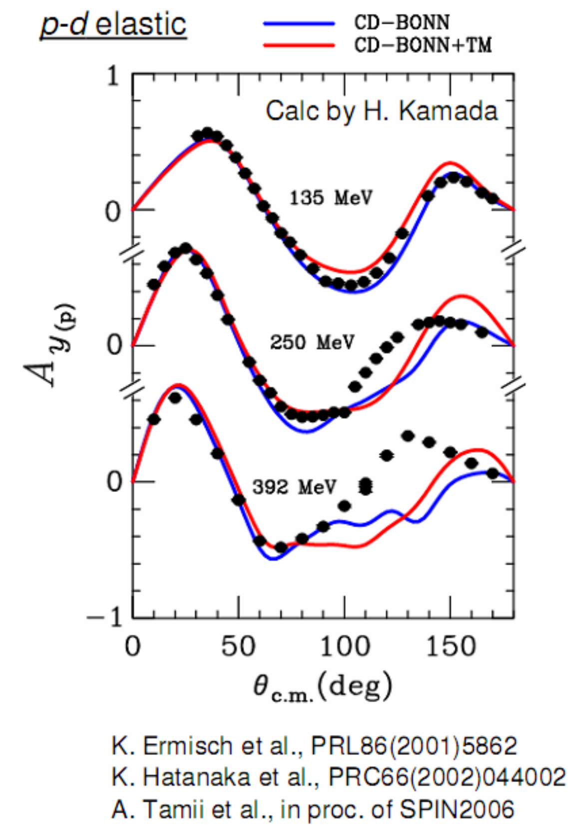


The empirical momentum distribution of the deuterons (a) and the protons (b) in ^{3}He. The solid and dashed lines are calculated with the Paris and CD-Bonn potentials, respectively. [A.Kobushkin, E.Strokovsky, PRC **87**, 024002 (2013)]

- At nucleon momenta in ^{3}He above $k_{max} \approx 250$ MeV/c the experimental cross sections are considerably larger than predictions of theoretical models which make use the traditional *NN* and 3*N* forces. The same story we observe in ^{4}He, etc.
- On the other hand, one can analyze the level of agreement between the traditional 2*N* and 3*N* model predictions and the respective experimental data when the collision energy is rising (in this case we probe the more and more short-distance area).

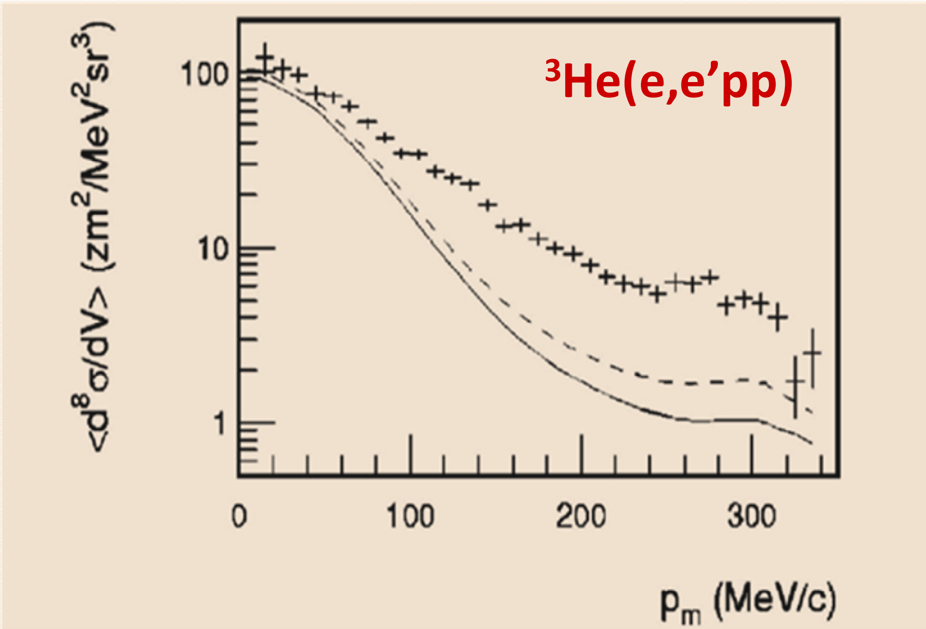


Differential cross sections for *N*d elastic scattering. Solid line – nonrelativistic Faddeev calculation using AV18 potential. Other lines – some relativistic effects added. [H.Witala *et al.*, PRC **71**, 054001 (2005)]

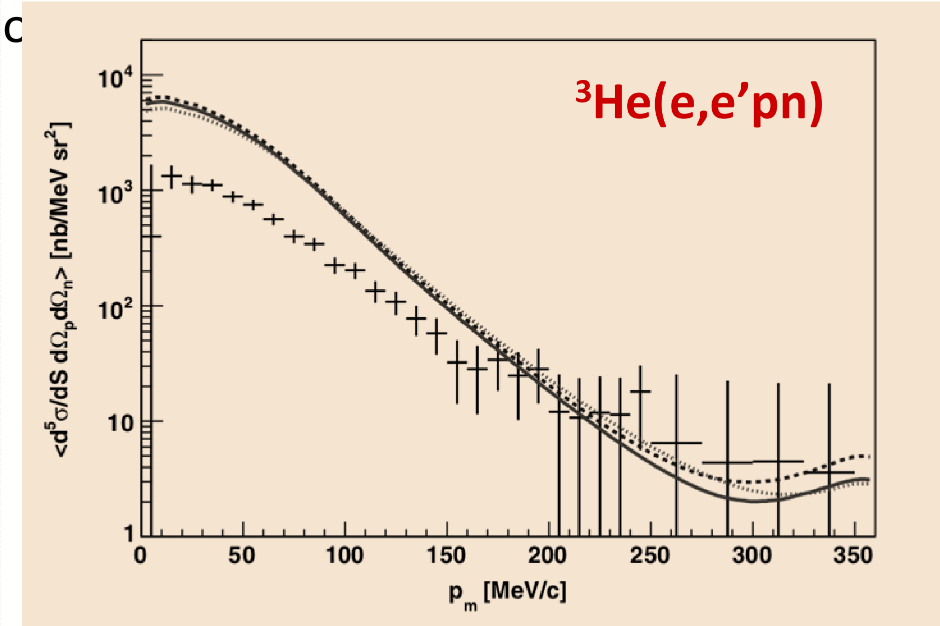


Proton analyzing power in pd elastic scattering.

- In recent years the experimentalists were able to study in detail the pair nucleonic correlations in few-body systems using high-energy electron beams (NIKHEF, Mainz, JLab, etc.) like ^{3}He(e,e'pp), ^{3}He(e,e'pn), etc., at missing momenta p_m > 300 MeV/c.

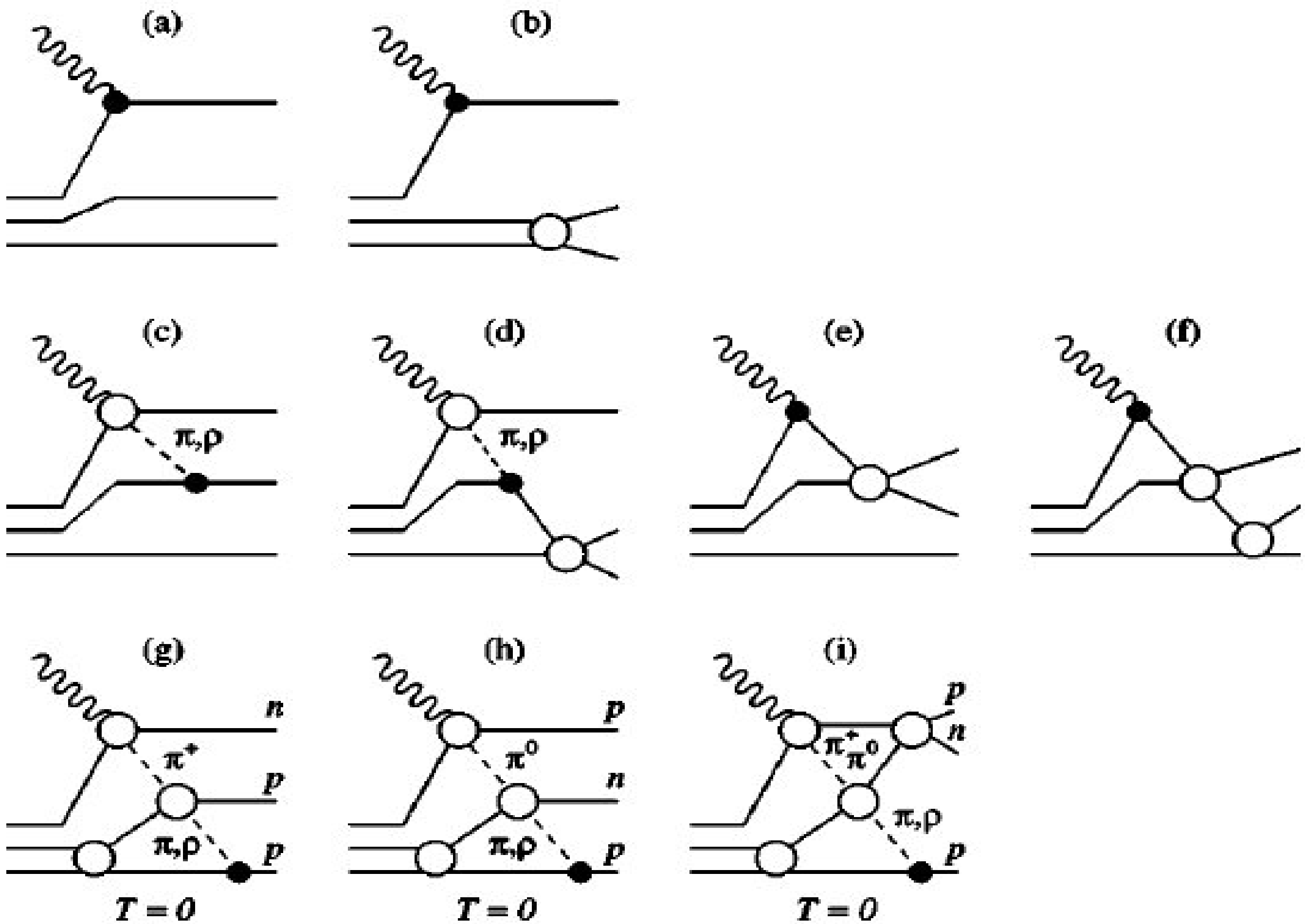


The averaged ^{3}He(e,e'pp) cross section as a function of missing momentum (data of NIKHEF, D.Groep *et al.*, 2000). The theoretical predictions without (solid line) and with (dashed line) pair 2*N* currents are based on full Faddeev 3*N* calculations with three-nucleon force.

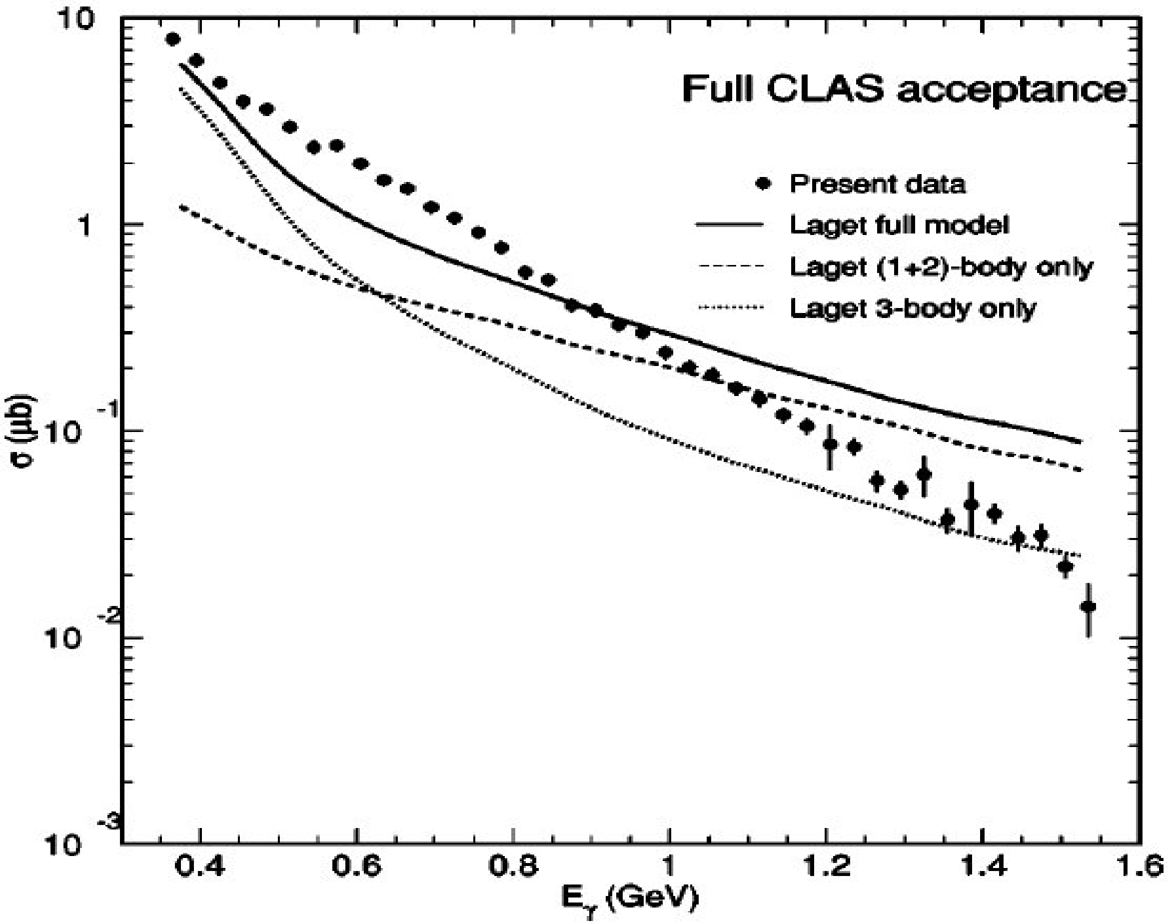


The ^{3}He(e,e'pn) reaction cross section averaged over the experimental acceptance as a function of missing momentum (Data of MAMI, D.Middleton *et al.*, 2009). Solid (dotted) line – theoretical cross section calculated using only a one-body hadronic current operator and the AV18 (Bonn) *NN* potential. Dashed line – for AV18 potential when MECs are also included.

Let's consider the situation with high-energy γ-absorption in ^{3}He.

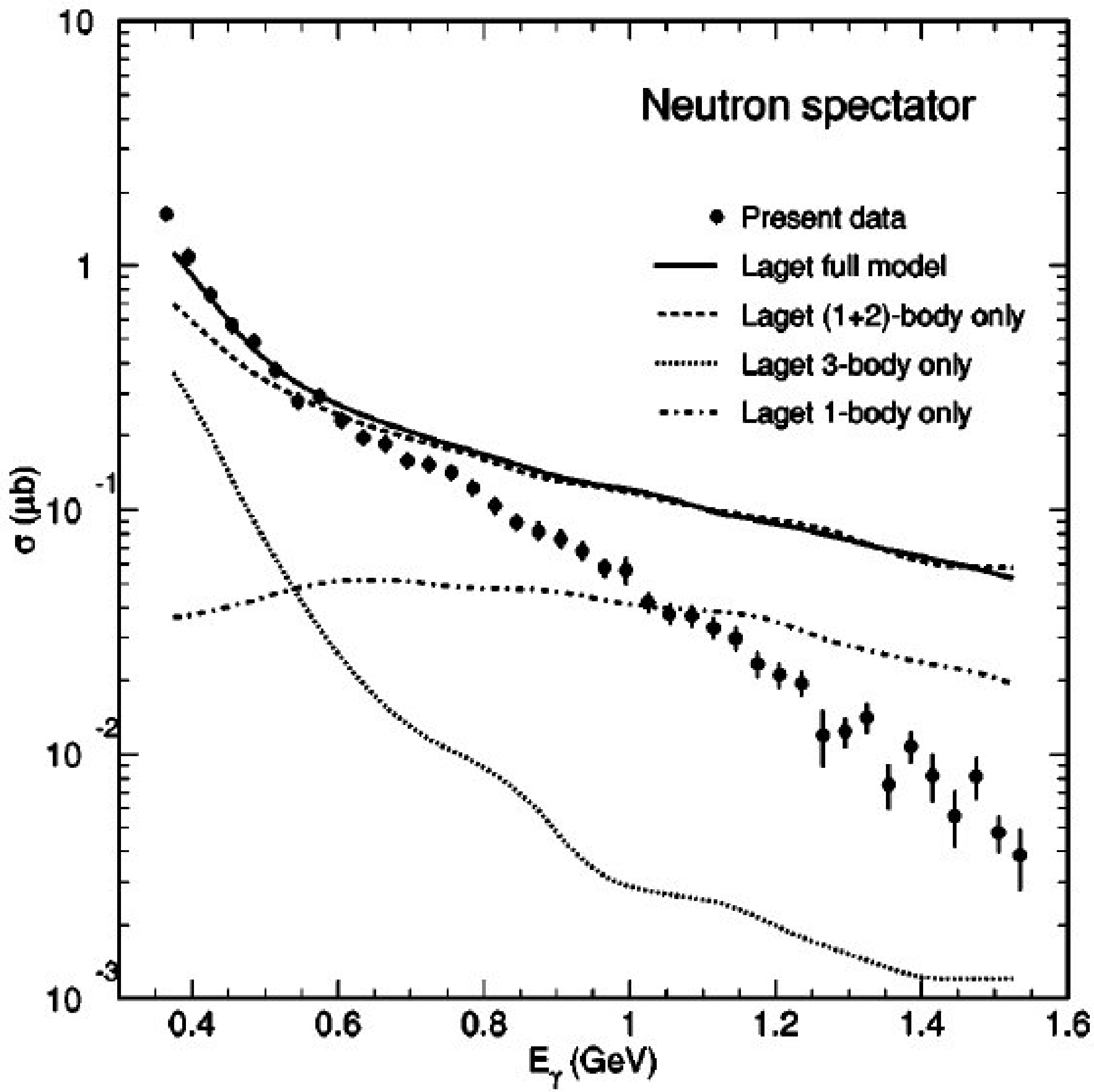


Diagrams used in Laget's model in the calculation of the ^{3}He(γ,pp)n cross sections.



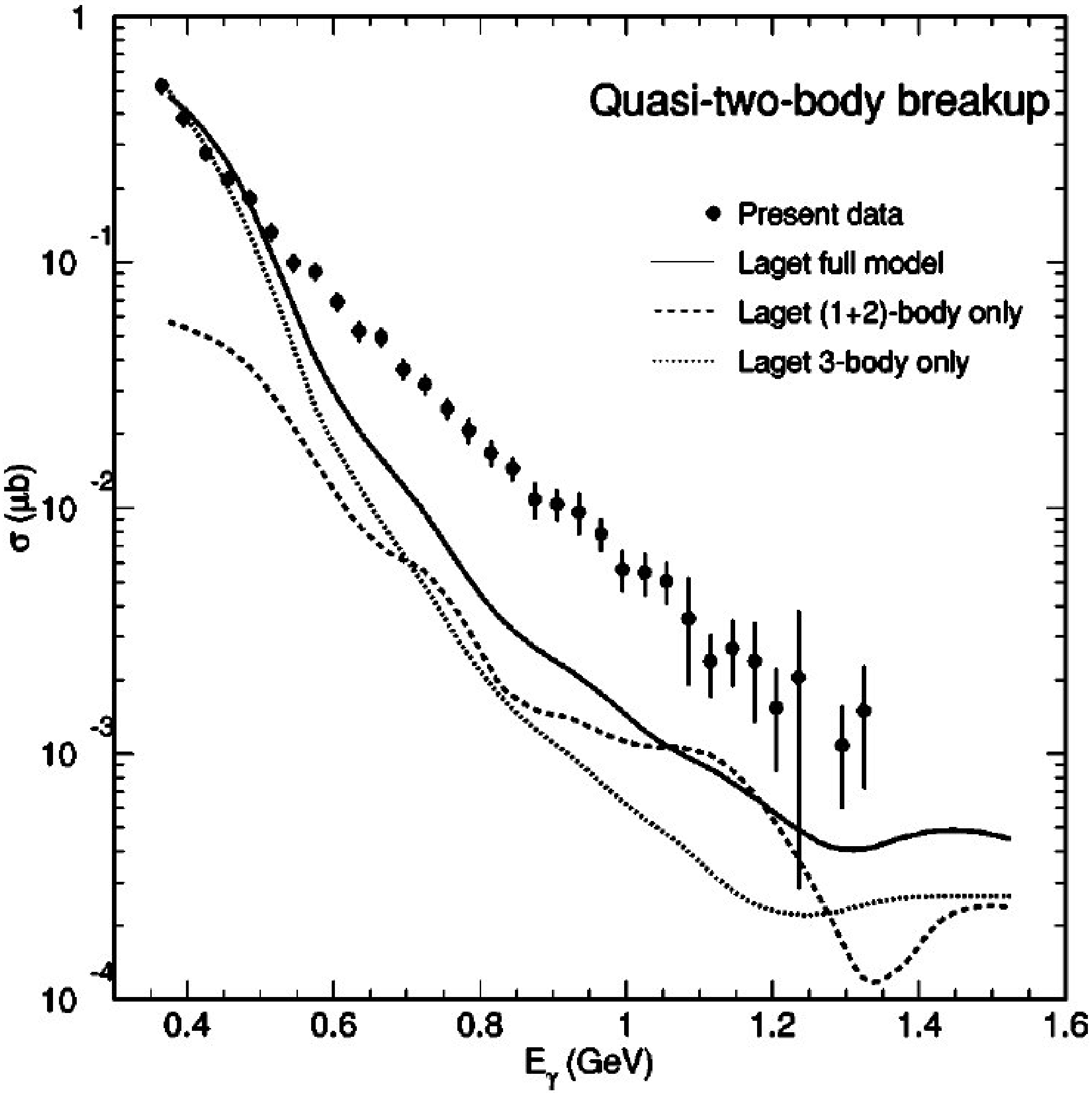
Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Total ppn cross section integrated over the CLAS acceptance plotted as a function of photon energy on a logarithmic scale for the full E_γ range. The ppn cross section (circles) is compared with Laget's full model (solid curve), with the model result without the three-body mechanisms (dashed curve).



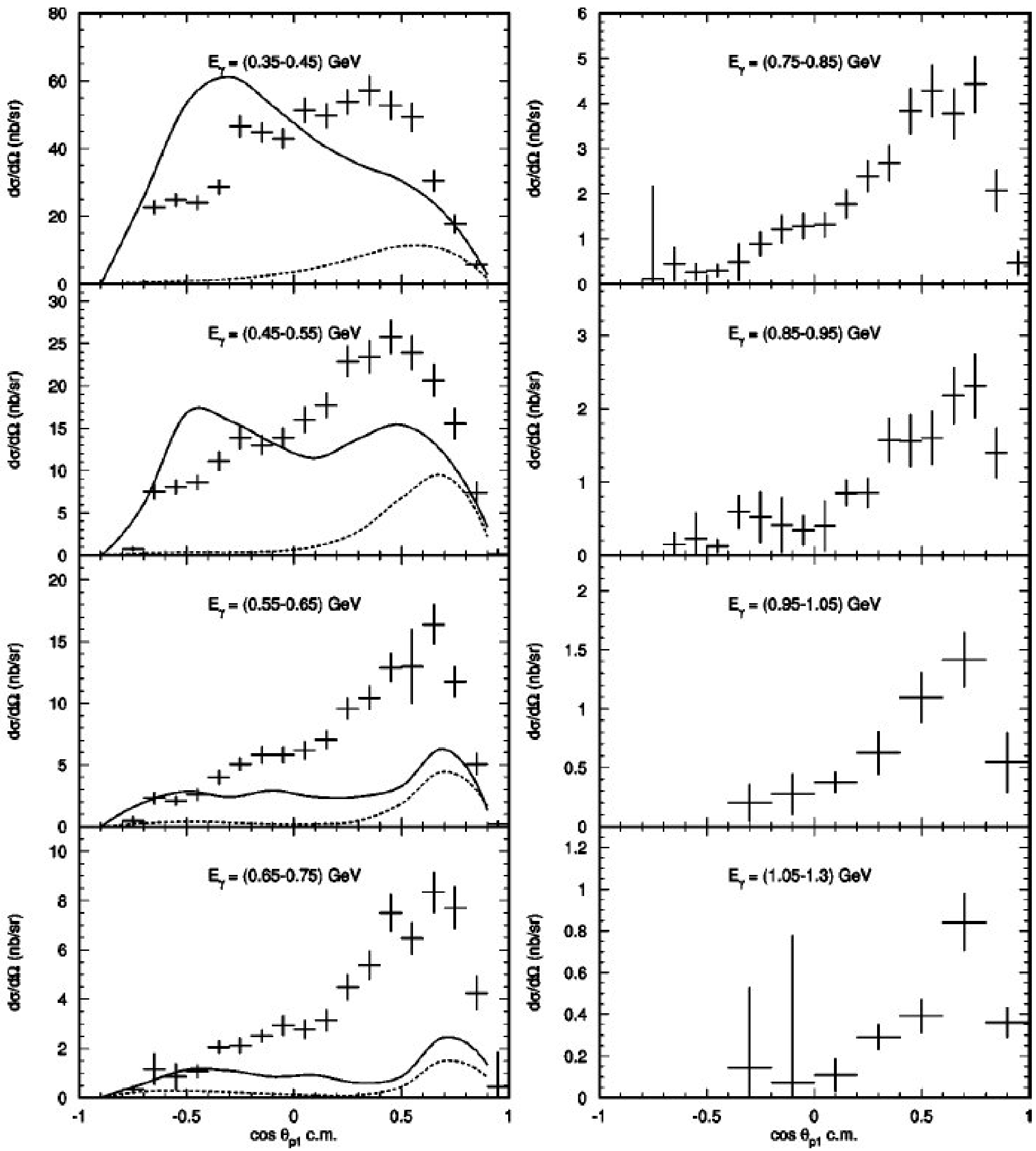
Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Cross sections integrated over the CLAS for the neutron-spectator kinematics plotted as a function of photon energy.



Data of JLab [S. Niccolai *et al*., PRC **70**, 064003 (2004)]

Cross sections integrated over the CLAS for the quasi-two-body breakup plotted as a function of photon energy. The data are compared with the results of the full model (solid curves) and of the (1+2)-body-only model (dashed curves). The full-model calculation agrees quantitatively with the experimental results only up to about 0.55 GeV.



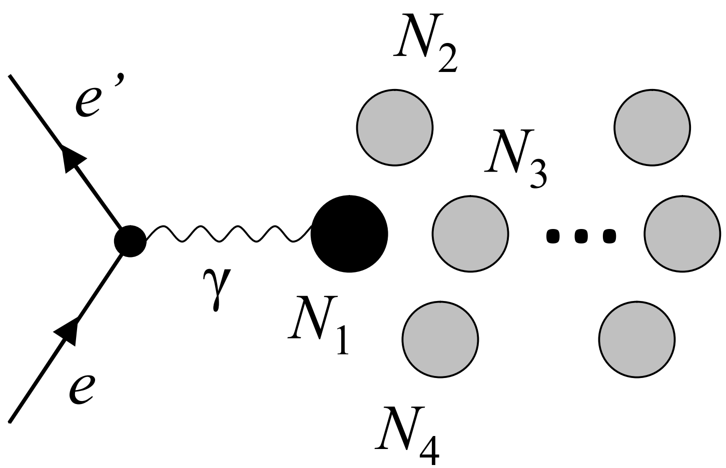
Differential cross sections integrated over the CLAS for the quasi-two-body breakup of the high-energy proton in the center-of-mass frame for photon energies between 0.35 and 1.30 GeV. The data, for $0.35 < E_\gamma < 0.75$ GeV, are compared with the results of the full model (solid curves) and of the (1+2)-body-only model (dashed curves).

Data of JLab [S. Niccolai *et al.*, PRC **70**, 064003 (2004)]

Thus, the modern situation with description of short-range correlations is far from being satisfactory!

- The root of all these problems with description of high-momentum components in basic interaction or in nuclear wavefunctions seems rather evident:

  In traditional picture the fast nucleon (which interacts first with high-energy probe) cannot share effectively (i.e., with a high probability) the high momentum with other nucleons in a nucleus, using the conventional meson-exchange mechanism.



- Failure with description of ^{3}He(e,e'pp), ^{3}He(e,e'pn), etc., demonstrates this very clearly ($3N$ final state rescatterings have been included in theoretical calculations).

- Thus, the short-range $2N$ and $3N$ interactions must be much stronger as compared to the traditional meson-exchange model.

- **The dibaryon mechanism is ideally suited for this because:**

– the color string inside the dibaryon can transmit a huge momentum which is incomparable with a conventional meson exchange;

– dibaryon is not a simple $6q$ bag but some “long-lived” resonance ($\Gamma_D \leq 100$ MeV, while $\Gamma_\Delta = 120$ MeV); using this resonance-like enhancement the color string can transmit a very high momentum (see below).

- There are also some implicit but very clear indications in favor of just dibaryon mechanism for short-range *NN* interaction.

  They are related to the cut-off parameters $\Lambda_{\pi NN}$, $\Lambda_{\pi N\Delta}$, $\Lambda_{\rho NN}$, etc., in form factors of the πNN, $\pi N\Delta$, ρNN, etc., vertices.

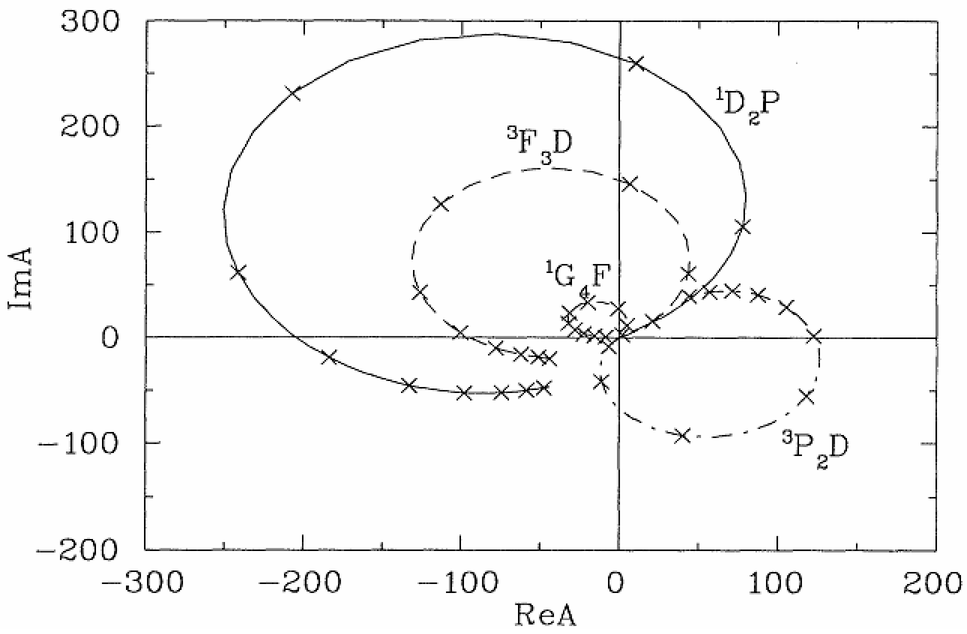
- In OBE-like models one chooses usually these cut-off parameters $\mathbf{\Lambda \sim 1.2 - 1.5}$ **GeV/*c***.

  Such values of Λ's correspond to a very short radius **(*r*** $\sim$ **0.15 fm!)** of the πN, ρN, etc., interactions which contradicts to both fundamental QCD-based approaches and experimental data. So, such very high Λ-values imitate somehow the strong short-range interaction, especially of tensor nature.

Modern experimental status of the dibaryons

- In 80-ies there were numerous experimental indications on diproton states in partial waves $^1D_2$, $^3F_3$, $^1G_4$, etc.

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

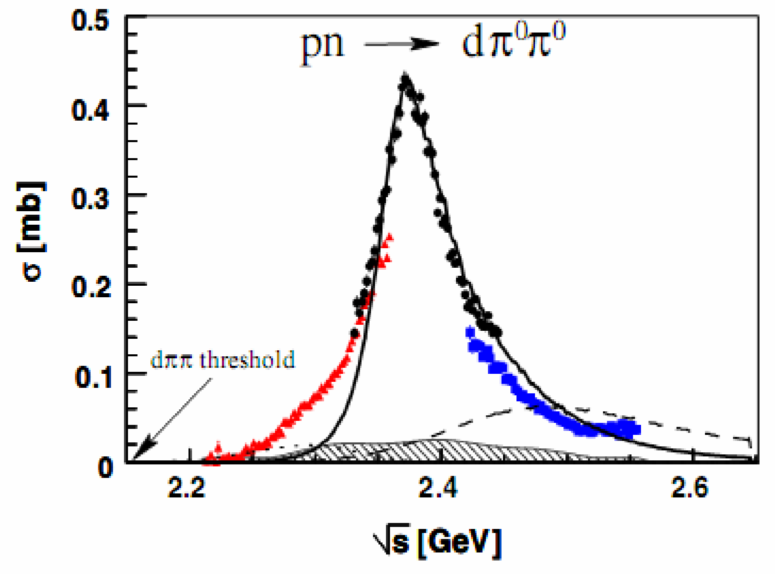


- However, all these diproton states are rather near to the $N\Delta$ threshold. So, such Argand loops can be related also to opening of the $N\Delta$ channel.

Modern experimental status of the dibaryons

- Recently the WASA@COSY Collaboration (Jülich) completed the large series of experiments on 2π-production reactions in p+n, p+d and d+d collisions at intermediate energies (E ~ 0.7–1.7 GeV).

- They found an **unambiguous dibaryon resonance signal** in p+n collisions at $T_p \sim$ 1–1.4 GeV in 2π -production cross section [P. Adlarson *et al*., PRL **106**, 242302 (2011)].



$$I(J^P) = 0(3^+)$$
$$M_R \approx 2.37\ \mathrm{GeV}$$
$$\Gamma_R \approx 70\ \mathrm{MeV}$$

- So, this resonance is located just only 70 MeV below the ΔΔ threshold and can be treated in a model of ΔΔ near-threshold bound state.

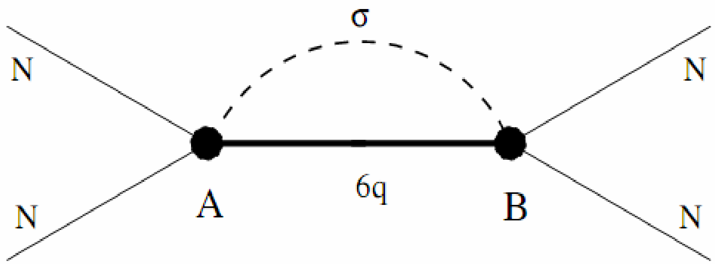
Nuclear force model
based on dibaryon mechanism

- The dibaryon mechanism looks to be ideally suited to describe the short-range *NN* force. It is because the mechanism assumes generation of the intermediate "long-lived" quark-meson states and such a resonance-like state will enhance somehow the short-range *NN* interaction.

- The particular short-range mechanism proposed by us in 1998 [V.I. Kukulin, in *Proc. XXXIII PIYaF Winter School,* S.-Petersburg, 1998, p.207]:

$$N + N \rightarrow |s^4p^2[42]\ L_q = 0{,}2;\ ST> \rightarrow |s^6[6]\ L_q = 0,\ ST + \sigma>,$$

or in graphic form:



- The above mechanism replaces the conventional *t*-channel σ-exchange between two nucleons (which is meaningless at r_{NN} < 1 fm) by the *s*-channel exchange of the σ-dressed dibaryon.

- Such a mechanism, in accordance to general rules for the Feynman graphs, corresponds to a separable potential:

$$V_{NqN} \sim \lambda(E) g(\mathbf{k}) g(\mathbf{k'}),$$

where $\sqrt{\lambda(E)}g(\mathbf{k})$ corresponds to a transition vertex *NN* $\Rightarrow$ *D; g*(***k***) is proportional to the overlap of *NN* wavefunction and six-quark wavefunction with symmetry $|s^4p^2[42]\ L=0,2;\ ST>$, and the energy-dependent coupling constant $\lambda(E)$ corresponds to the intermediate dressed dibaryon propagation:

$$\lambda(E) = \int_0^\infty d^3k \frac{g(\mathbf{k}) g(\mathbf{k})^*}{E - m_D - k^2 / m_D - \omega_\sigma(k)}$$

- Thus, to calculate the short-range *NN* potential one needs to know only some basic parameters of the dressed six-quark bag (the mass and radius of the intermediate dibaryon [V.I.Kukulin, I.T.Obukhovsky, V.N. Pomerantsev, A. Faessler, Int. J. Mod. Phys. E **11**, 1 (2002)].

- In case of two channels $^3S_1$-$^3D_1$ coupled by a short-range tensor force (which is originated from one-gluon exchange) one gets the two-channel separable potential (for non-relativistic case):

$$V_{NqN} = \begin{pmatrix} \lambda_{ss} |g_s\rangle\langle g_s| & \lambda_{sd} |g_s\rangle\langle g_d| \\ \lambda_{ds} |g_d\rangle\langle g_s| & \lambda_{dd} |g_d\rangle\langle g_d| \end{pmatrix},$$

where the vertex form factors $|g_s>$ and $|g_d>$ correspond to the six-quark wavefunctions $|s^4p^2[42]$ $L=0;$ $ST=10>$ and $|s^4p^2[42]$ $L=2;$ $ST=10>$, respectively.

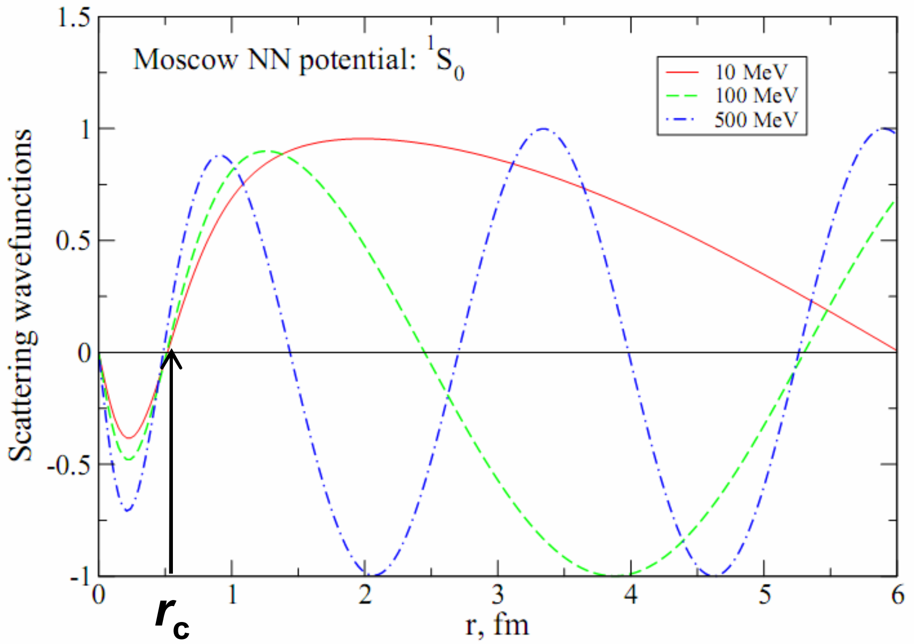
- The consistent relativistic generalization of the above dibaryon model has been presented some time ago [A.Faessler, V.I.Kukulin, M.A.Shikhalev, Ann. Phys. (N.Y.) **320**, 71 (2005)].

How the hard repulsive core effects are reproduced by the dibaryon model

- The above short-range potential V_{NqN} is operating in a six-quark space (to say more accurately, in the space of projections of the six-quark wavefunctions onto the *NN* channel) of mixed symmetry wavefunctions $|s^4p^2[42]\, LST>$ with $2\hbar\omega$ inner excitation.
- So, the projection onto the *NN* channel:

$$f(r) = <NN|s^4p^2[42]\ L{=}0;\ ST>$$

turns out to be a nodal function where the stationary node position at $r_n = r_c$ coincides with the hard core radius $r_c = 0.5$ fm accepted in conventional *NN* potential models when we choose the six-quark bag radius $b = 0.55$ fm in a way to reproduce the low-energy spectrum of nucleon excitations.



How the hard repulsive core effects are reproduced by the dibaryon model

- On the other hand, among many six-quark states which are possible in the *NN* system, the above dibaryon mechanism acts mainly in the mixed symmetry states, while it leads to an effective repulsion for fully symmetric six-quark configurations, like $|s^6[6]\, LST\rangle$, which corresponds to a nodeless wavefunction in the *NN* channel.

- So, one should supplement the short-range *NN* potential V_{NqN} by the projection operator $V_{orth} = \mu|\varphi_0\rangle\langle\varphi_0|$ onto the nodeless *NN* wavefunction with a large positive constant μ (it is the so-called orthogonalizing pseudo-potential – OPP).

- Thus, this strongly repulsive non-local short-range potential V_{orth},which in the dibaryon model leads to appearance of a stationary node at the distance $r = r_c$ in *NN* channel, plays the role of a local repulsive core in the conventional *NN* potential models.

- At larger distances, r_{NN} > 1 fm, the short-range *NN* interaction $(V_{NqN} + V_{\text{orth}})$ should be supplemented by the conventional OPE and TPE potentials.

So that, the total *NN* potential in partial waves $L_{NN} \leq 2$ takes the form:

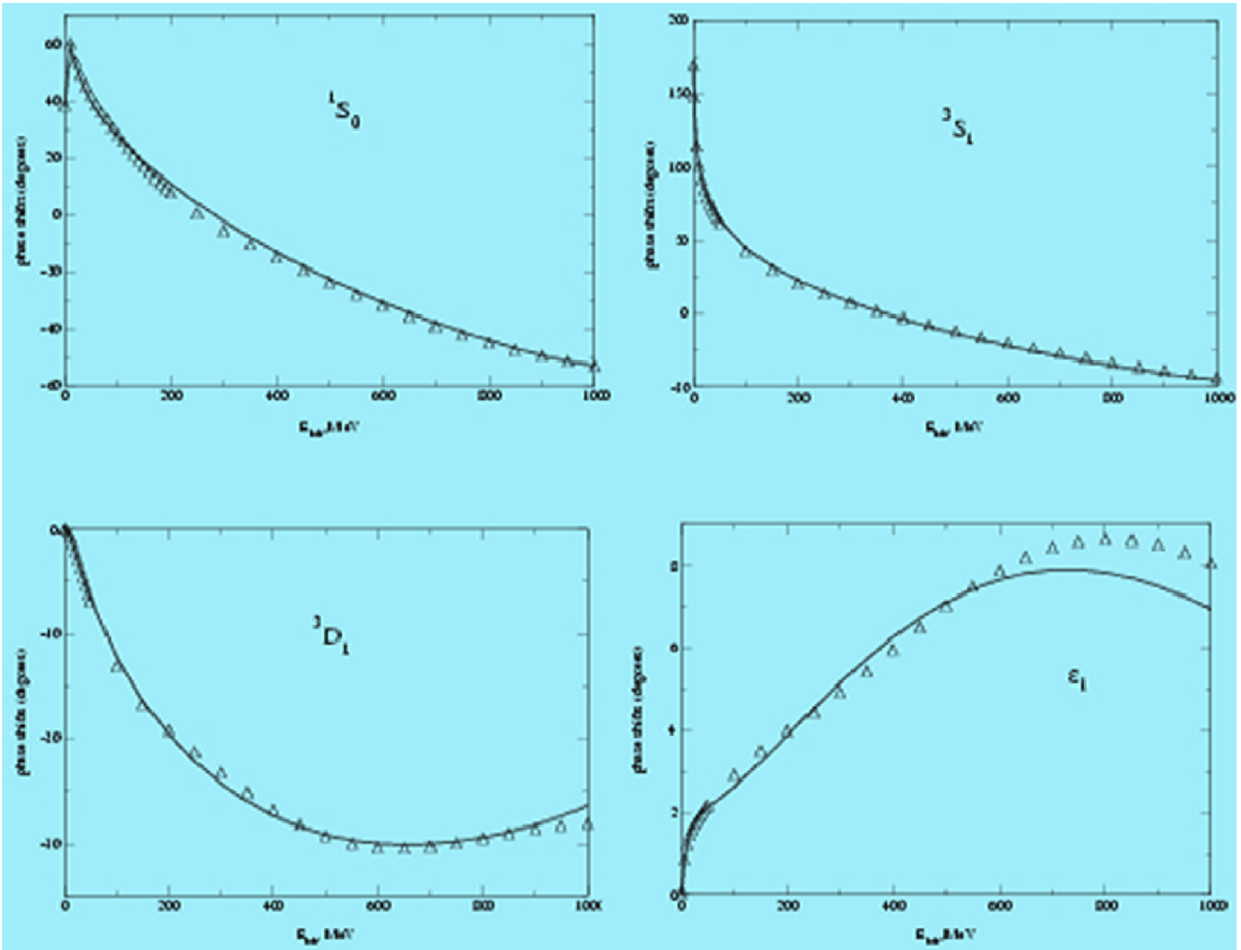
$$V^{\text{total}} = \underbrace{V_{NqN} + V_{\text{orth}}}_{\textit{short-range}} + \underbrace{V^{\text{OPE}} + V^{\text{TPE}}}_{\textit{long-range}}$$

- Now we can improve the long-range components using the potentials derived from the consistent ChPT, or, alternatively, one can replace the very numerous contact terms in ChPt with the dibaryon-model-motivated short-range part $(V_{NqN} + V_{\text{orth}})$.

- It is very plausible that using such a replacement **the energy range**, where theoretical *NN* phase shifts calculated within the hybrid approach (dibaryon model + ChPT) reproduce the empirical *NN* data, **can be extended noticeably** (e.g., until $E \sim 1$ GeV and higher) and that **the number of contact terms or fit parameters can be decreased strongly**.

There is a good evidence to this point:

We have been able to fit our dibaryon-induced potential to empirical *NN* phase shifts in low partial waves in the energy range 0–1000 MeV (in contrast to the case of ChPT or conventional OBE models: 0–350 MeV) using only a few basic dibaryon parameters.



Testing the dibaryon force model in few-body systems

In last few years,

1) we made detailed tests for the dibaryon model;
2) we compared its basic predictions with the experimental data.

Three-nucleon system within dibaryon model

A $3N$ state Ψ_3 in the full three-body Hilbert space $\mathcal{H}_3 = \mathcal{H}_3^{\text{ex}} \oplus \Sigma_i \mathcal{H}_i^{\text{in}}$ is a four-component column and the total Hamiltonian of the three-body system acting in $\mathcal{H}_3$ can be written as (4×4) matrix:

$$\Psi_3 = \begin{pmatrix} \Psi^{\text{NN}} \\ \Psi_1^{\text{DN}} \\ \Psi_2^{\text{DN}} \\ \Psi_3^{\text{DN}} \end{pmatrix}, \qquad H_3 = \begin{pmatrix} H^{NN} & H_1^{NN\to DN} & H_2^{NN\to DN} & H_3^{NN\to DN} \\ H_1^{DN\to NN} & H_1^{DN} & 0 & 0 \\ H_2^{DN\to NN} & 0 & H_2^{DN} & 0 \\ H_3^{DN\to NN} & 0 & 0 & H_3^{DN} \end{pmatrix}.$$

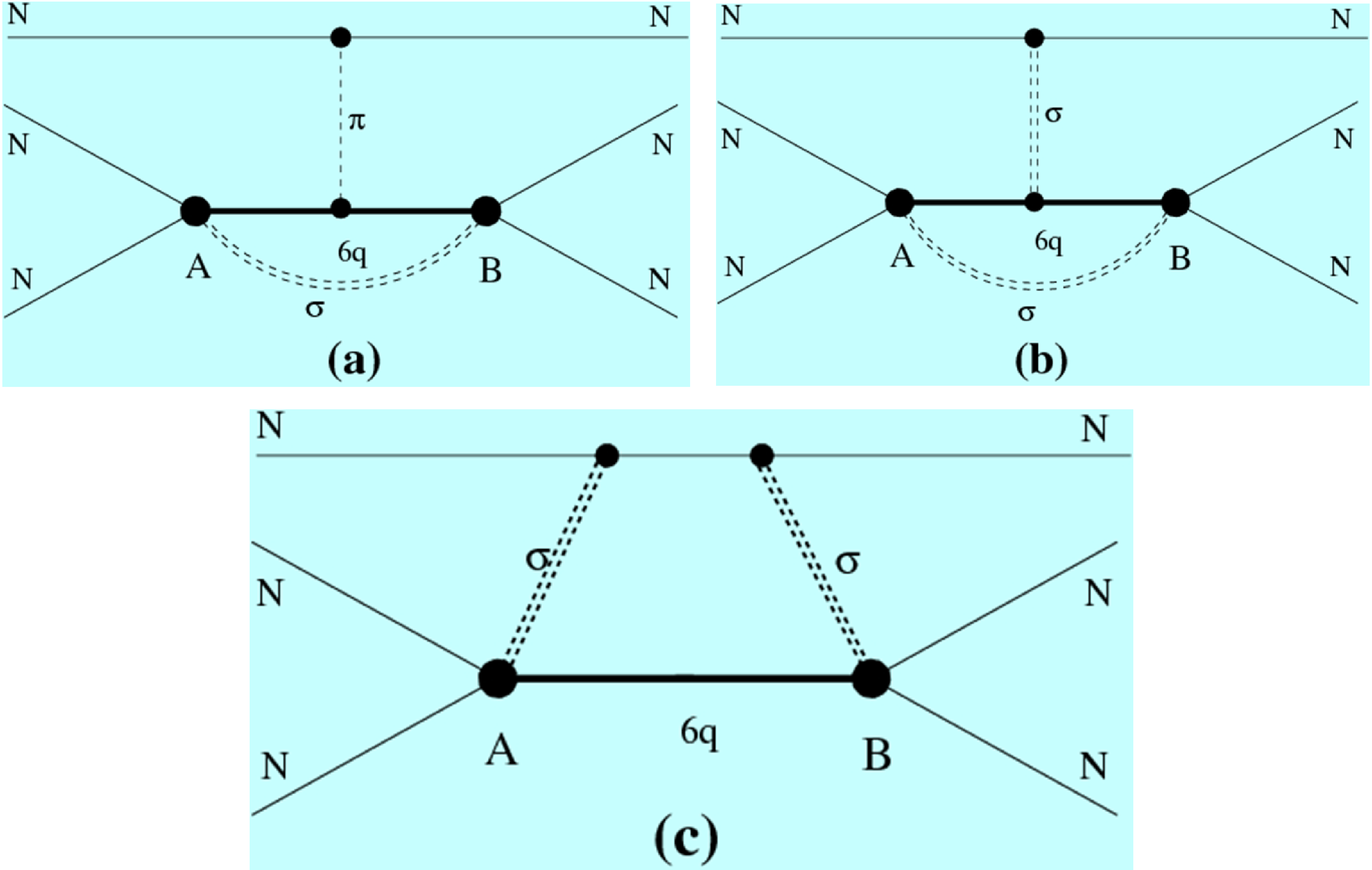
The NN three-body Hamiltonian acts in the external NN space $\mathcal{H}_3^{\text{ex}}$ and includes the total kinetic energy T and the sum of external two-body interactions (OPE + TPE): $H_3^{NN} = T + \Sigma_{i<j} v_{ij}^{\text{OPE+TPE}}$.

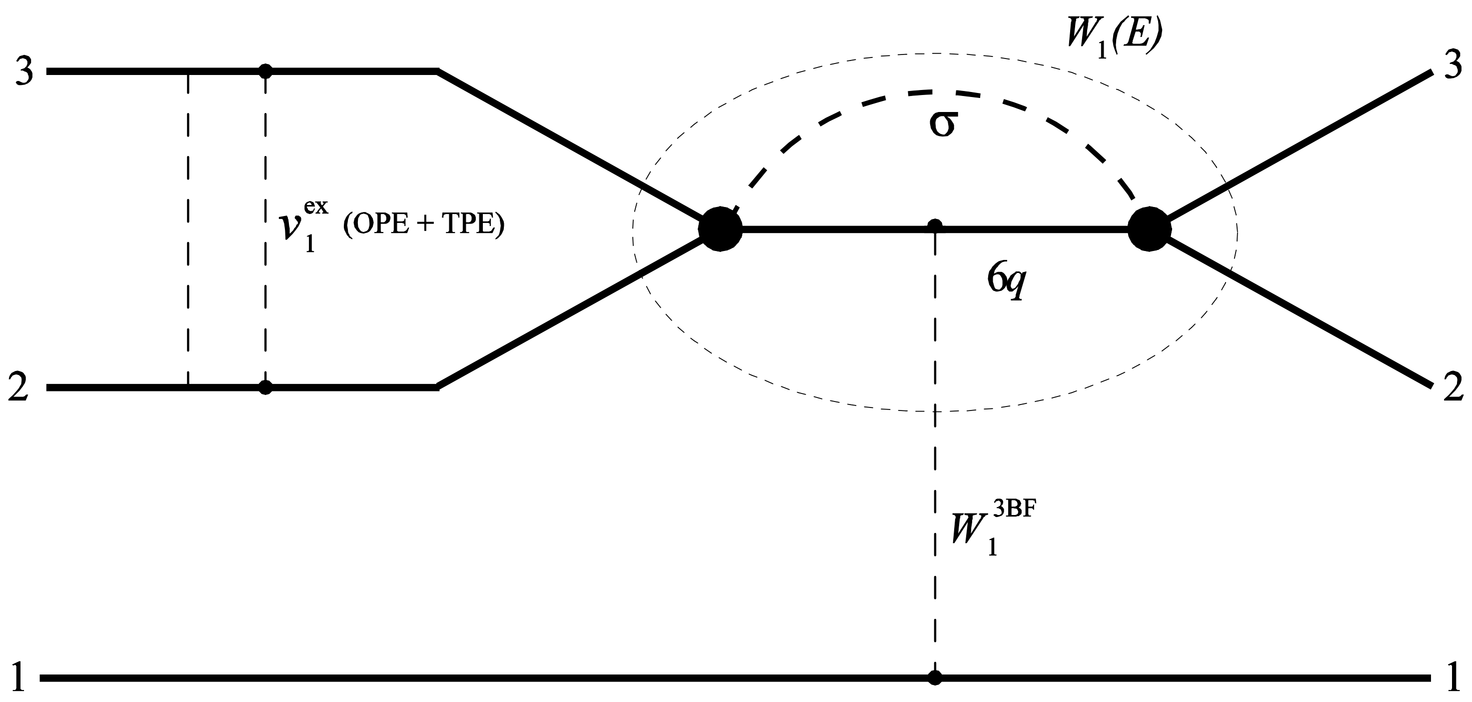
Writing the four-component Schrödinger equation with Hamiltonian H_3: and excluding three dibaryon components, one obtains an effective Schrödinger equation for the NN component of three-body wavefunction Ψ^{NN} with the effective Hamiltonian $H^{\text{eff}}(E)$, which in the dibaryon model has a form:

$$H^{\text{eff}} = T + \sum_{\alpha}\{V_\alpha^{\text{OPE}} + \lambda(E - q^2/(2m))\,|\varphi_\alpha\rangle\langle\varphi_\alpha|\}.$$

But this model leads to appearance of **a new three-body force** in the $3N$ system due to interaction between the dressed bag and third nucleon.

New dibaryon-induced 3*N* force





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

$$W_\alpha^{3BF}(\mathbf{p}_\alpha, \mathbf{p'}_\alpha, \mathbf{q}_\alpha, \mathbf{q}'_\alpha; E) = \varphi(\mathbf{p}_\alpha)\, w^{3BF}(\mathbf{q}_\alpha, \mathbf{q}'_\alpha; E)\, \varphi(\mathbf{p}'_\alpha),$$

where $\mathbf{p}_\alpha$ is the relative momentum of pair nucleons $(\beta\gamma)$, $\mathbf{q}_\alpha$ is momentum of third nucleon in respect to the pair center of mass, and E is the total three-nucleon energy.

Adding these three-body forces to H^{eff} , we get the total effective Hamiltonian in the NN channel:

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

Results of 3N calculations in dibaryon model with 2- and 3-body forces

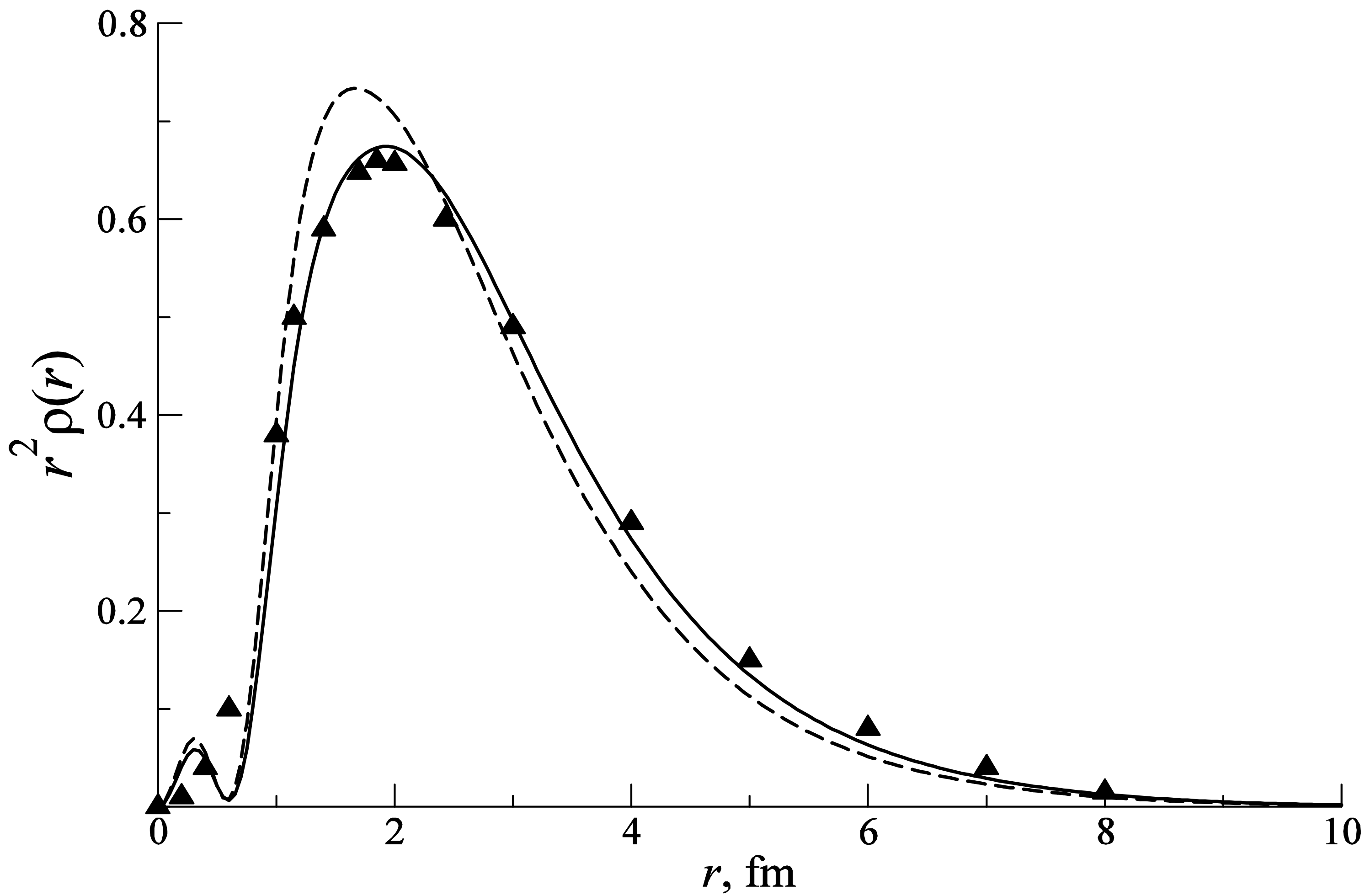
Model	E, MeV	P_D,%	$P_{S'}$,%	P_{6qN},%	Contributions to H, MeV		
					T	$T+V^{(2N)}$	$V^{(3N)}$
			^{3}H				
DBM(I) $g=9.577^{(a)}$	−8.482	6.87	0.67	10.99	112.8	−1.33	−7.15
DBM(II) $g=8.673^{(a)}$	−8.481	7.08	0.68	7.39	112.4	−3.79	−4.69
AV18 + UIX	−8.48	9.3	1.05	–	51.4	−7.27	−1.19
			^{3}He				
DBM(I)	−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	−7.76	9.25	1.24	–	50.6	−6.54	−1.17

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

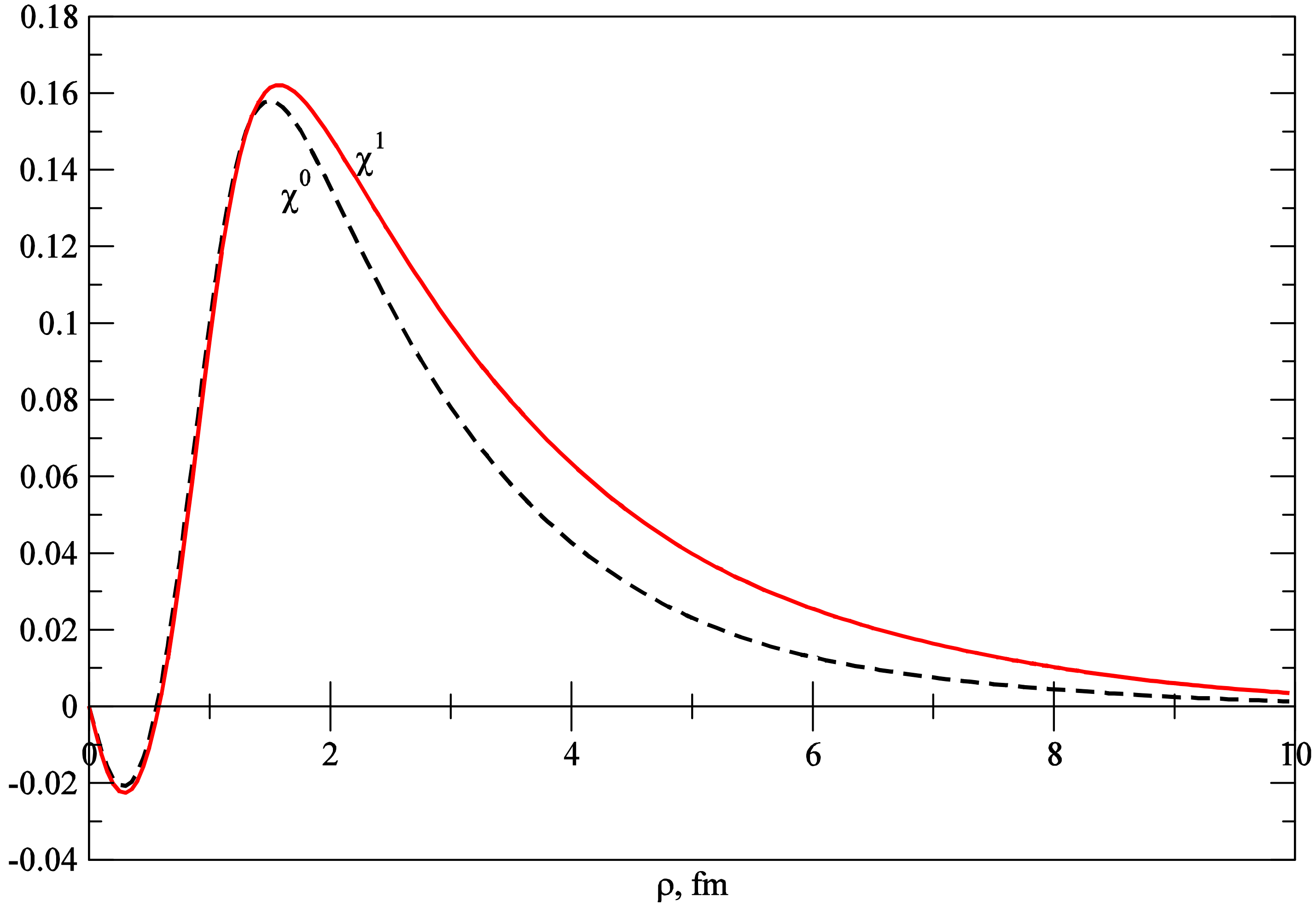
$$\Delta E^{\text{theor}}_{\text{Coul}} = 754 \text{ keV (with no one adjustable parameter)}$$

$$\Delta E^{\text{exp}}_{\text{Coul}} = 764 \text{ keV !}$$

Two-proton density in ^3He (solid line) and two-neutron density in ^3H (dashed line) for dibaryon model vs. two-proton density in ^3He for Bonn *NN* potential (triangles).



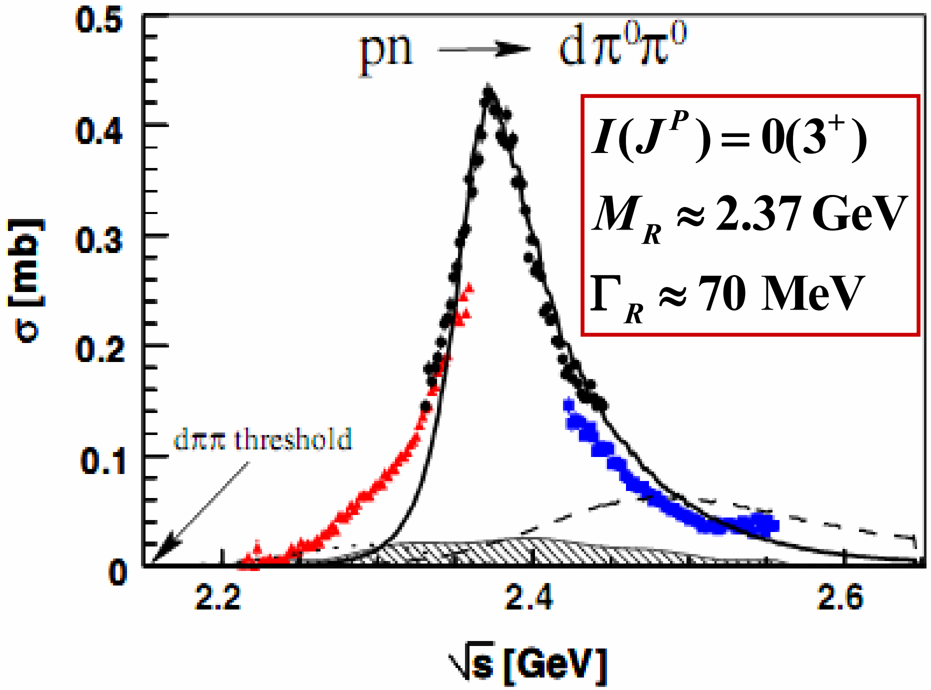
Triplet χ^1 and singlet χ^0 components of ^3H wavefunction in dibaryon-nucleon channel

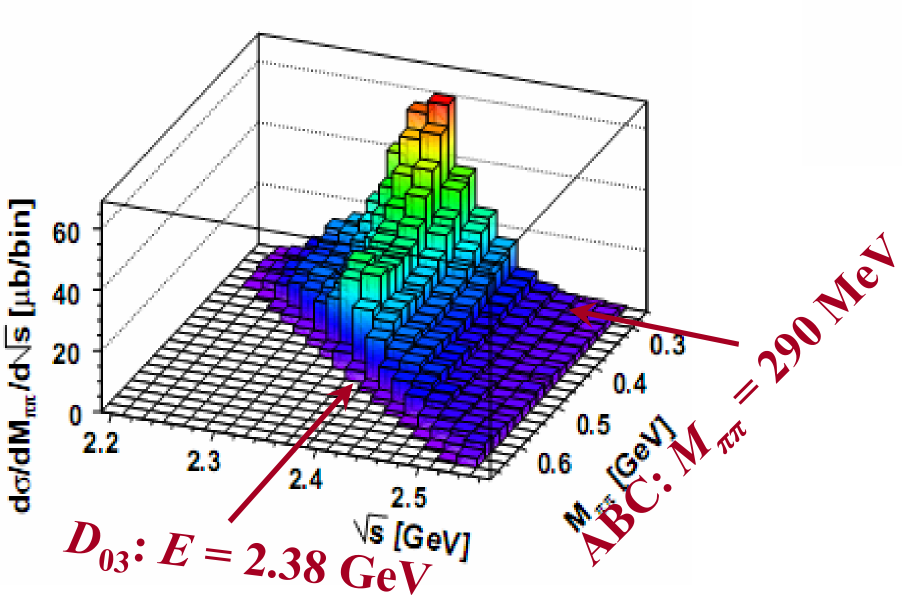


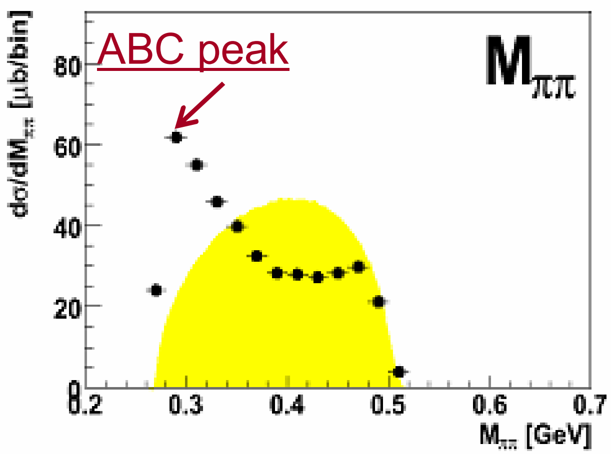
Dibaryon model for the ABC puzzle

The most interesting feature of the recent experiments of the WASA@COSY Collaboration is a clear identification of the old ABC-puzzle with 2π emission from the 3^+0 dibaryon state.

[P. Adlarson *et al*., PRL **106**, 242302 (2011)]





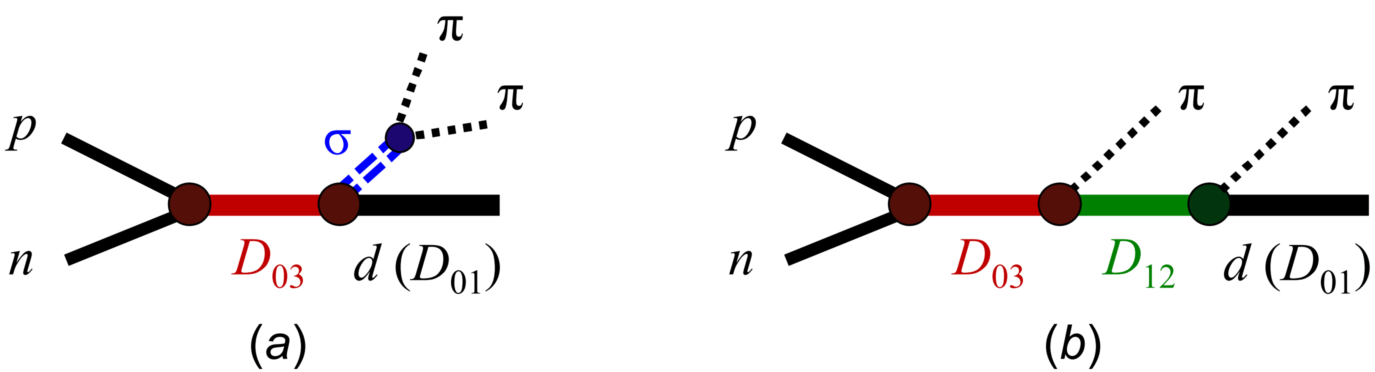


Dibaryon model for the ABC puzzle

- The ABC puzzle [A. Abashian, N.E. Booth, K.M. Crowe, PRL**5**, 258 (1960)] was a strange enhancement of 2π production very near to the 2π threshold ($2m_\pi \approx 280$ MeV) in scalar-isoscalar channel, i.e., $\pi^0\pi^0$ or $(\pi^+\pi^-)_0$ in p+n, p+d and d+d fusion reactions.
- In the most of theoretical works done for the passed 50 years the puzzle has been explained by the nearby ΔΔ threshold. However, the new WASA@COSY experimental results occurred to be <u>incompatible with such a model</u>.
- So, the experimentalists suggested a new model for the ABC puzzle based on idea of the ΔΔ bound state. Unfortunately, their model includes a non-realistic very soft form factor for ΔΔ bound state and thus looks to be not quite consistent.

Dibaryon model for the ABC puzzle

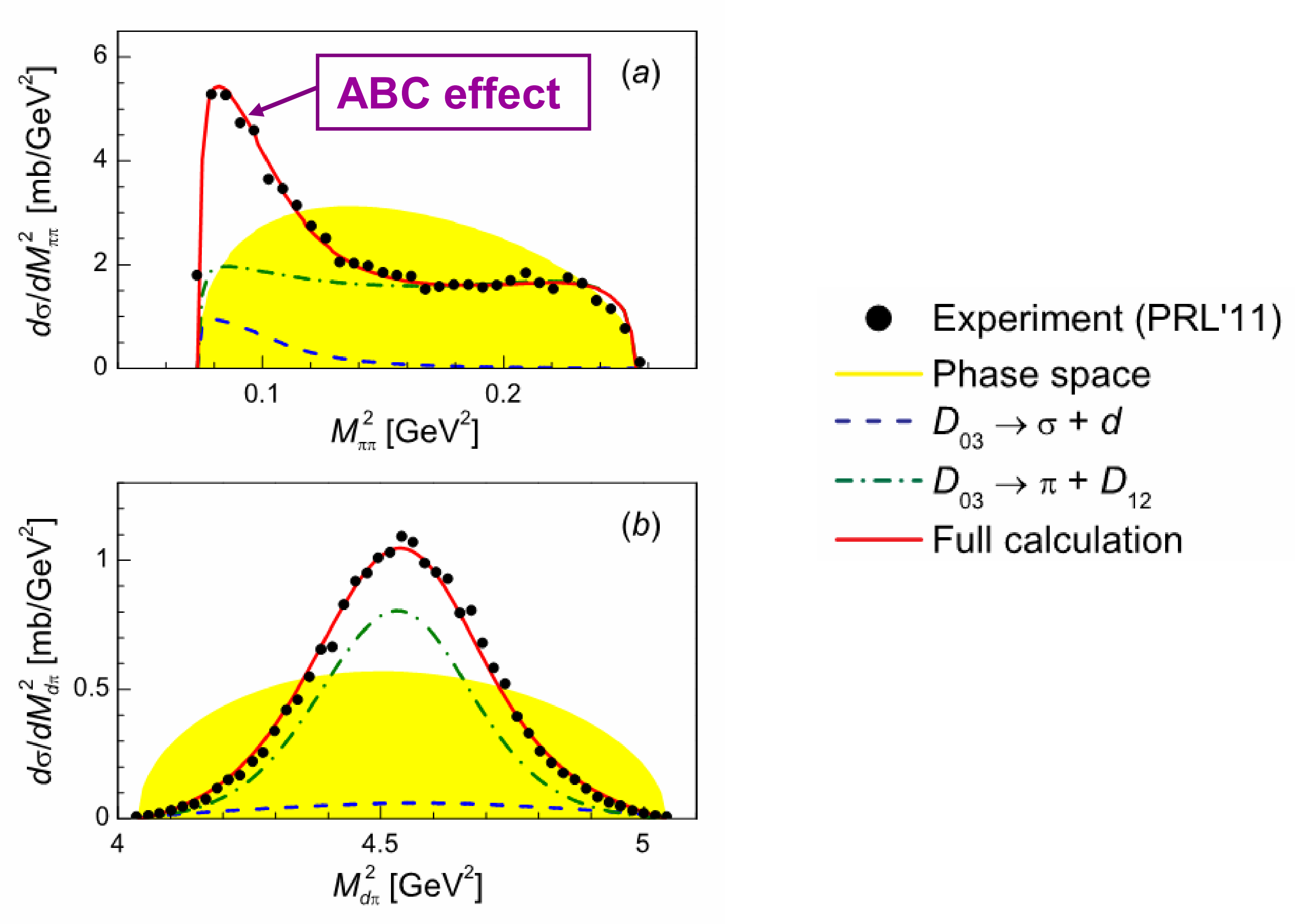
- We reanalyzed the new WASA@COSY experimental data in terms of the dibaryon model [M.N. Platonova, V.I. Kukulin, PRC **87**, 025202 (2013)]. Our model includes two basic mechanisms for the two-pion production in p+n fusion to deuteron at $T_p \sim$ 1–1.4 GeV:



- The mechanism (*a*) corresponds to the near-threshold emission of the lightest scalar meson σ, while the mechanism (*b*) describes the consequent emission of two pions via an intermediate $2^{+}1$ isovector dibaryon.

Dibaryon model for the ABC puzzle

Using the above two mechanisms, we were able to fit the new WASA@COSY experimental data almost perfectly.



Chiral symmetry restoration in dibaryons and in scalar meson sector

- However, the experimental data can be fitted very well only by taking the σ-meson mass and width which are strongly reduced as compared to their values extracted from ππ dispersion relations [I. Caprini, G. Colangelo, H. Leutwyler, PRL**96**, 132001 (2006)]:

$$\boxed{m_\sigma^{\mathrm{ABC}} \simeq 300\ \mathrm{MeV}, \quad \Gamma_\sigma^{\mathrm{ABC}} \simeq 100\ \mathrm{MeV}}$$

$$\boxed{m_\sigma^{\pi\pi} = 441_{-8}^{+16}\ \mathrm{MeV}, \quad \Gamma_\sigma^{\pi\pi} = 544_{-25}^{+18}\ \mathrm{MeV}}$$

- Such a reduction for the σ-meson parameters means the partial **Chiral Symmetry Restoration (CSR)** effect in 3^+0 dibaryon state.

- The riddle of the σ-meson is interrelated very closely with the CSR phenomenon in QCD.

Chiral symmetry restoration in dibaryons

- CSR effects have been predicted by many authors both in dense (or hot) nuclear matter and even in a single hadron when it gets strongly excited.
- It should be stressed here that the 3^+0 dibaryon with the mass $M_{D*} \approx 2.37$ GeV is in fact *a strongly excited hadron* (with the excitation energy $E^* \approx 500$ MeV) and the CSR phenomenon is predicted for such states rather reliably.
- Thus, the σ mesons which dress the dibaryon must be much lighter and narrower as compared to the bare σ mesons in ππ scattering in free space.
- So, just this CSR phenomenon is responsible in essence for the basic *NN* attraction at intermediate distances, i.e., for the main component of nuclear force.

- Fully similar CSR effects can be studied also in the Roper resonance state $N^*(1440)$.

  In this case the positive parity ($2\hbar\omega$-excited) state $N^*(1440)$ is located well below the lowest negative parity ($1\hbar\omega$-excited) nucleon resonance $N^*(1535)$. It is possible if the $N^*(1535)$ state is on its normal place in the nucleon spectrum while the Roper resonance is <u>strongly shifted downwards</u>.

- Many hadronic models suggested to explain CSR effects in hadronic spectra predict the appearance of parity doublets in nucleonic spectra as a manifestation of CSR phenomenon.

Spin	Chiral multiplet
1/2	$N_+(1440) - N_-(1535)$
1/2	$N_+(1710) - N_-(1650)$
3/2	$N_+(1720) - N_-(1700)$
5/2	$N_+(1680) - N_-(1675)$
7/2	$N_+(?) - N_-(2190)$
9/2	$N_+(2220) - N_-(2250)$
11/2	$N_+(?) - N_-(2600)$

- Thus, the approximate degeneration between the positive and negative parity levels with the same J in nucleon spectrum can be treated as an indicator for the CSR effect.

So, our prediction for the CSR phenomenon in dibaryon states, and thus as a driving QCD mechanism for short-range nuclear force, can help establish a fundamental QCD origin for nuclear physics at all.

"It is only by the collective analysis of all of these that we can hope to solve the riddle of the σ. It is a puzzle worth solving, since the nature and properties of the σ lie at the heart of the QCD vacuum."

– M.R. Pennington, hep-ph/9905241

Conclusions

1. The dibaryon mechanism based, in essence, on the CSR phenomenon should be responsible for short-range nuclear force.
2. We derived a potential model (both in non-relativistic and relativistic formulations) on the basis of mainly symmetry considerations of a $6q$ system, which describes the empirical NN phase shifts reasonably well in a wide energy range 0–1000 MeV. (From the model we can also derive the imaginary parts of phase shifts related to single and double pion emission.)
3. We tested successfully the model in $3N$ calculations (for ^{3}He and ^{3}H bound states).
4. The model predicts inevitably very strong $3N$ force (with central and spin-orbit components) in all nuclei induced by the scalar meson exchange.

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Thank You
For Your Attention!