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Chiral Symmetry Restoration in σ -meson production in hadronic processes

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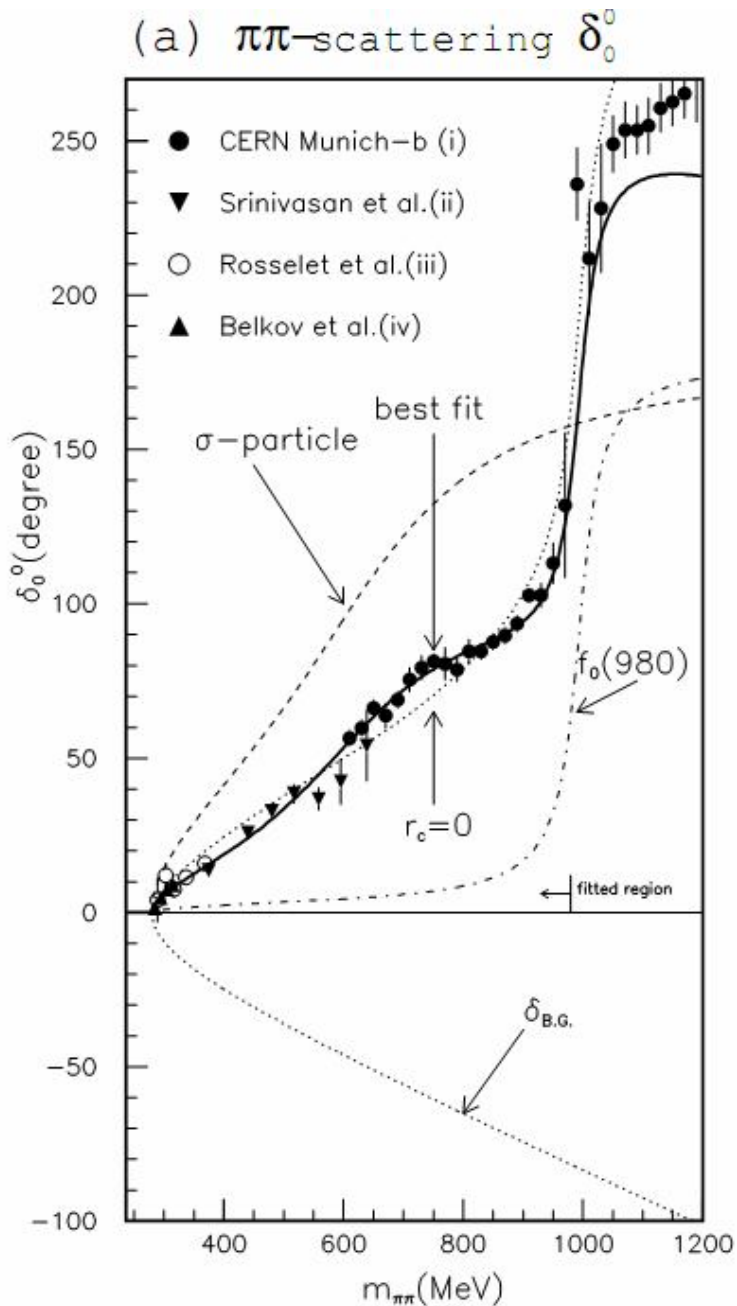
Content

1. The riddle of σ meson.
2. σ meson as a Higgs boson for the strong-interaction physics (**the Higgs particle in QCD**).
3. σ meson and the dibaryon model for nuclear force. The key role of chiral symmetry restoration (χ SR) in short-range nuclear interaction.
4. Roper resonance and σ -meson production in intermediate- and high-energy pp and pn collisions. Can we observe χ SR in these processes?
5. ABC puzzle, dibaryons and χ SR in hadronic systems.

The riddle of σ -meson

- Initially the σ particle, the lightest scalar-isoscalar meson, was predicted (long ago) to exist as a chiral partner of the Nambu-Goldstone π meson, corresponding to the dynamical breaking of *chiral symmetry* (conserving in the massless limit of QCD), with mass $m_\sigma \approx 2m_q$ (m_q is the constituent quark mass).
- This σ meson gives quark constituent masses and thus it plays the role of the Higgs particle in QCD.
- From the other hand, the σ meson was predicted to play a key role in nuclear force at intermediate distances $r_{NN} \leq 1$ fm.
- Just the above light scalar meson exchange between two nucleons should lead inevitably to a strong NN attraction at $r_{NN} \leq 1$ fm, **if such scalar meson exists!**

However, from the $\pi\pi$ phase-shift analysis derived from CERN-Münich experiment of 1974 one observes rather smooth behavior of δ_0^0 phase in $\pi\pi$ scattering up to $E_{\pi\pi} = 1100$ MeV which seems hardly compatible with a well defined scalar resonance.



After subtraction of a rapid contribution of the scalar resonance $f_0(980)$ (180°) the δ_0^0 does not exceed 90° , being insufficient for existence of the $\pi\pi$ resonance around $m = 2m_q = 500 - 600$ MeV.

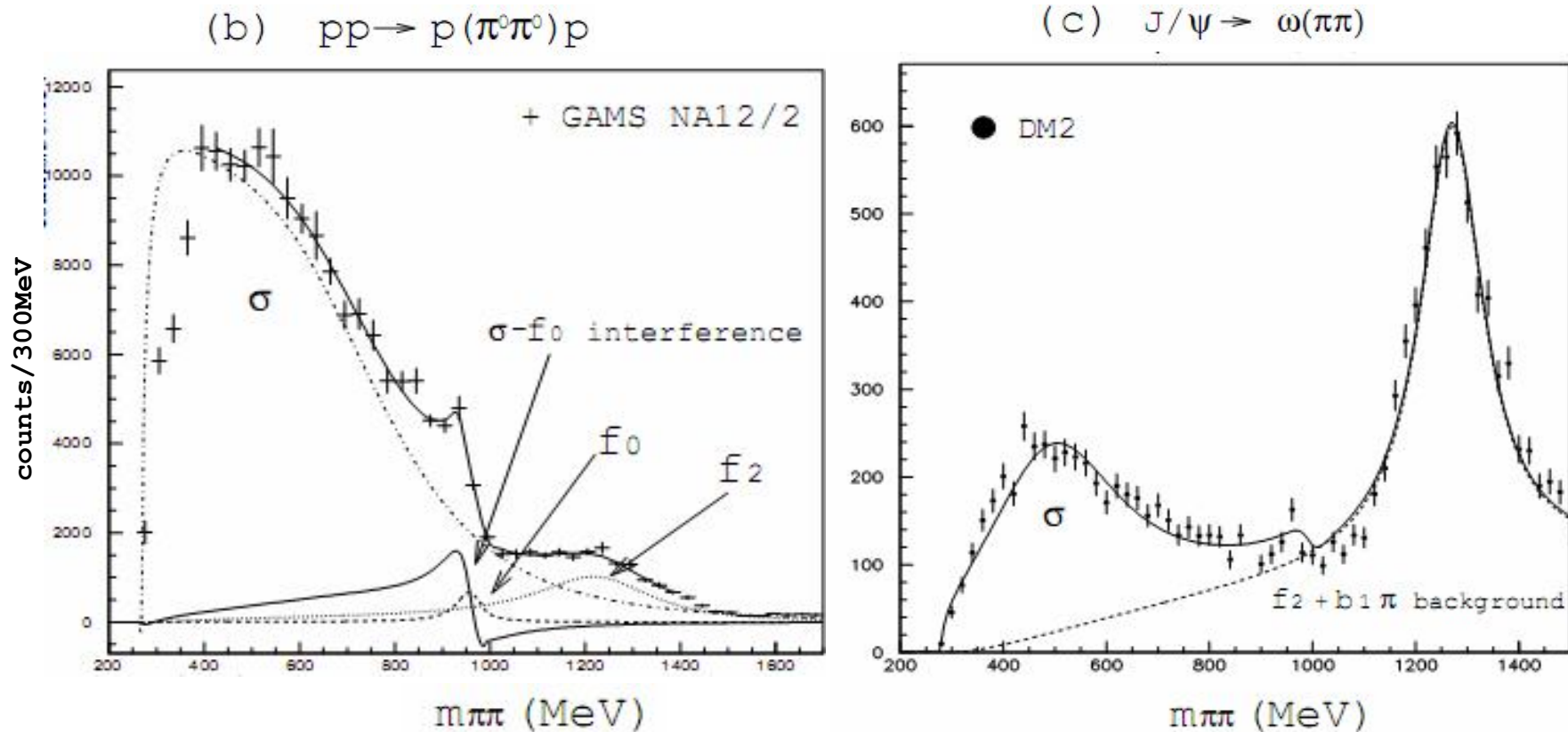
So, most analyses far made on it have yielded conclusions **against** the existence of σ !

(Figure from S. Ishida hep-ph/9712229)

As a result, the light σ particle disappeared from the list of PDG since 1976 edition for more than 20 years! And the direct t -channel σ exchange also disappeared from the current theories of nuclear forces.

However, in many old and recent experiments one still observes a very large event concentration in $I=0$ s -wave $\pi\pi$ channel which cannot be explained as a simple “background” and seems to strongly suggest the existence of σ .

Let's look at the Figures, where a huge accumulation of the low-mass $\pi\pi$ events in high-energy pp collisions (GAMS NA12/2 exp.) and $\pi\pi$ effective mass distribution in $J/\psi \rightarrow \omega(\pi\pi)$ decay are demonstrated:



(Figures from S. Ishida hep-ph/9712229)

Very recently a significant strengthening for the existence of the σ meson (labelled also as $f_0(500)$) has been reached in hadron spectroscopy experiments.

See, e.g.:

- C. Amsler *et al.* (Particle Data Group), Phys. Lett. **B667**, 1 (2008);
- R. Garcia-Martin, J.R. Pelaez, F.J. Yndurain, Phys. Rev. D **76**, 074034 (2007); hep-ph/0701025;
- I. Caprini, G. Colangelo, H. Leutwyler, Phys. Rev. Lett. **96**, 132001 (2006); hep-ph/0512364;
- G. Bonvicini *et al.* (CLEO Coll.), Phys. Rev. D **76**, 012001 (2007); hep-ex/0704.3954

Today one observes very numerous data from the charmonium $\Psi(2S)$, $\Psi(3S)$... and bottomonium $Y(2S)$, $Y(3S)$, $Y(4S)$... decays leading to strong yield of light scalar mesons with a mass in interval $m_\sigma \sim 450 - 550$ MeV, and the width $\Gamma_\sigma \sim 350 - 450$ MeV.

Most of the data have been collected in BESII and BESIII Collaborations experiments on e^+e^- collisions.

The Table (from S. Ishida hep-ph/9712229) demonstrates the typical mass and width values extracted by the Tokyo group (S. Ishida *et al.*) from $\pi\pi$ phase-shift analysis.

	$r_c \neq 0 (\chi^2/N_f = 23.6/30)$	$r_c = 0 (\chi^2/N_f = 163.4/31)$
	$\delta^{\text{tot}} = \delta_{f_0(980)} + [\delta_{\sigma(600)} + \delta_{\text{BG}}]^{\text{pos.}}$	$\delta^{\text{tot}} = \delta_{f_0(980)} + [\delta_{\text{BG}}^{\text{pos.}}]$
	$\sigma(600)$	“ σ ” (equivalent to $\epsilon(900)$ [5])
m_σ	$585 \pm 20 (535 \sim 675)$	920
$\Gamma_\sigma^{(p)}$	385 ± 70	660
$\sqrt{s_{\text{pole}}}/\text{MeV}$	$(602 \pm 26) - i(196 \pm 27)$	970-i320
r_c	$3.03 \pm 0.35 \text{ GeV}^{-1}$ $(0.60 \pm 0.07 \text{ fm})$	- (-)

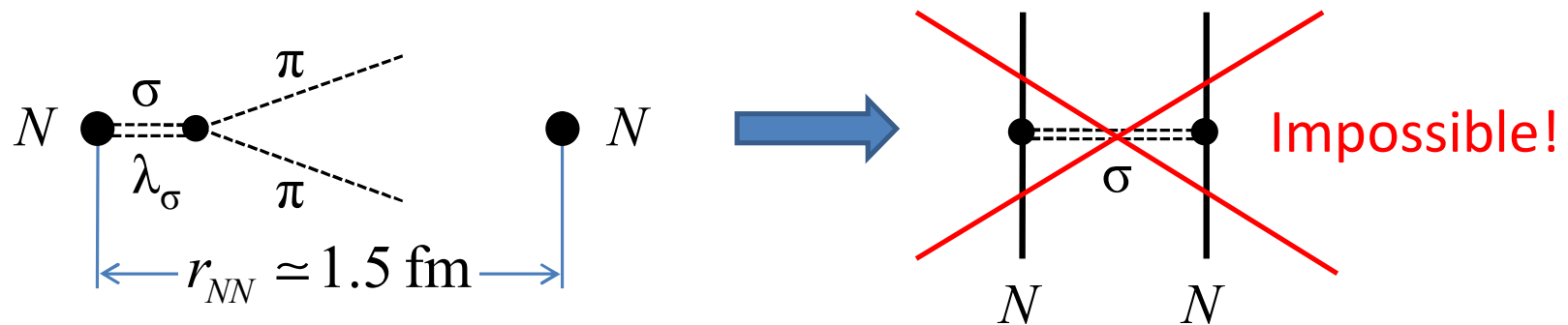
- More recently, I. Caprini, G. Colangelo and H. Leutwyler [PRL **96**, 132001 (2006)], using the subtracted $\pi\pi$ dispersion relations, have found rather accurate **pole position for the σ meson:**

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

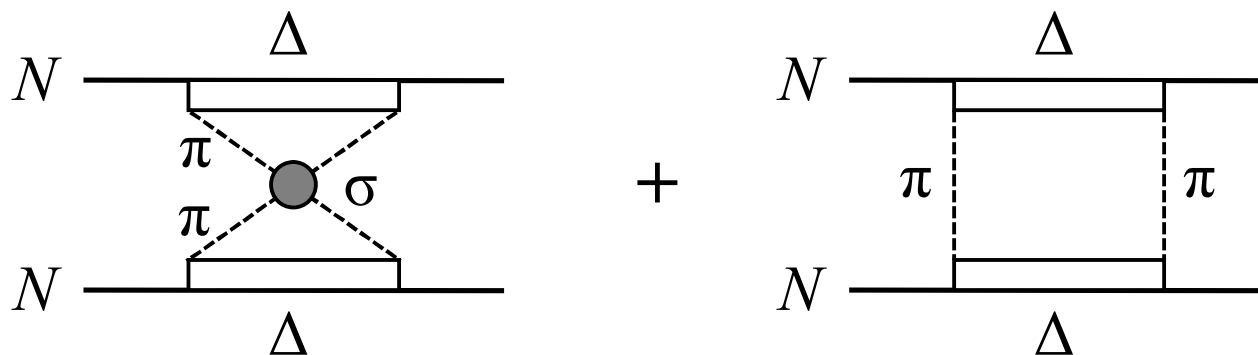
- So, all the different data for m_{σ} and Γ_{σ} are in a general agreement with each other, and also with the $\pi\pi$ PSA data.

- However, the scalar meson with the huge width $\Gamma_\sigma \sim 400 - 550 \text{ MeV}$ is so short-lived that it is absolutely unable to carry a strong intermediate-range attraction between two nucleons postulated in traditional OBE-like models of nuclear force, because its free path should be only $\lambda_\sigma \sim 0.2 \text{ fm}$!

$$\tau_\sigma \approx \hbar / \Gamma_\sigma ; \lambda_\sigma \approx c \cdot \tau \leq 0.2 \text{ fm} - \text{path length for a highly unstable } \sigma\text{-meson}$$

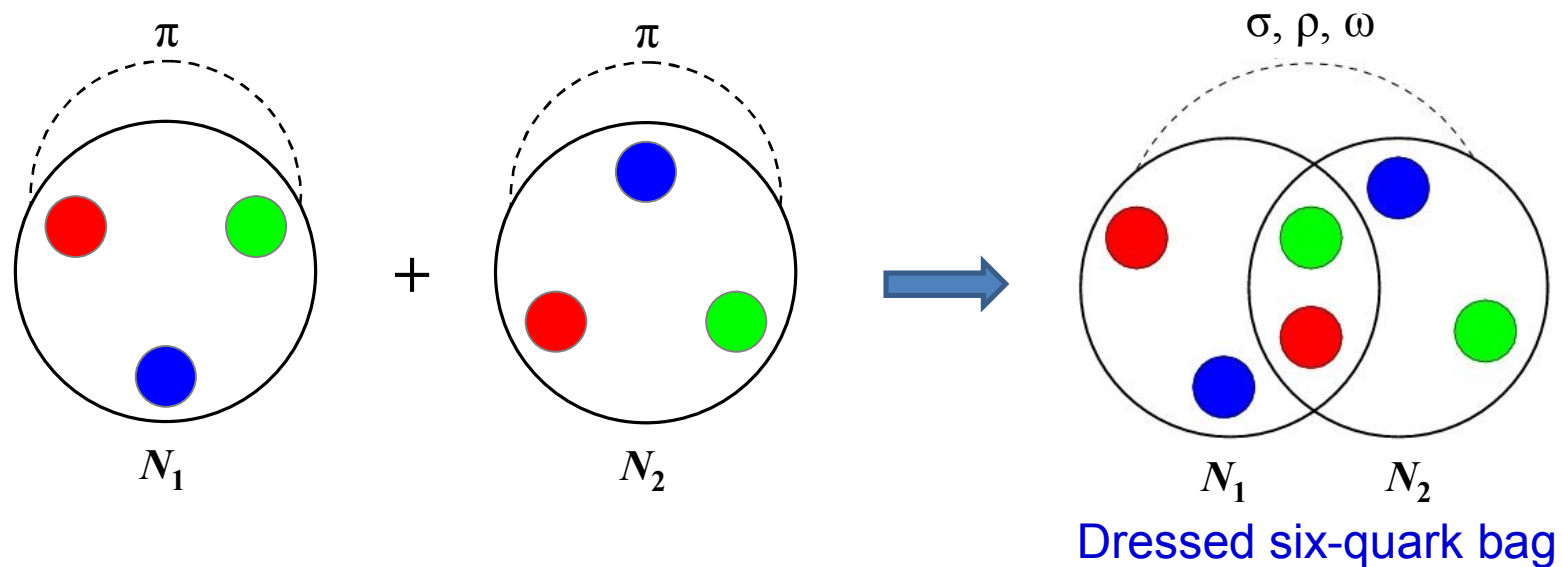


- To avoid this difficulty some authors (Riska, Brown, Dürso) “invented” a meson-exchange mechanism with **two-Delta two-pion exchange**:



- This mechanism with intermediate mass $M_{\Delta\Delta\pi\pi} \approx 2.8 \text{ GeV}$ corresponds to very short distances between two intermediate Δ 's, where they must be strongly overlapped with each other. Thus, one should consider, instead of this 2Δ picture, a generation of intermediate six-quark bag dressed with the 2π -cloud, or the σ -meson cloud.

The dominant contribution to a unified meson cloud of the $6q$ bag comes from σ meson due to its very strong attraction to $6q$ core.



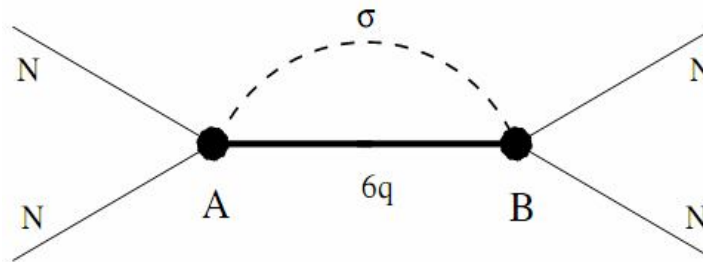
But this is only beginning of the long story...

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]:

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

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 $NN \Rightarrow D$; $g(\mathbf{k})$ is proportional to the overlap of NN wavefunction and six-quark wavefunction with symmetry $|s^4p^2[42] L=0,2; ST\rangle$, 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 $|g_s\rangle$ and $|g_d\rangle$ correspond to the six-quark wavefunctions $|s^4p^2[42] L=0; ST=10\rangle$ and $|s^4p^2[42] L=2; ST=10\rangle$, respectively.

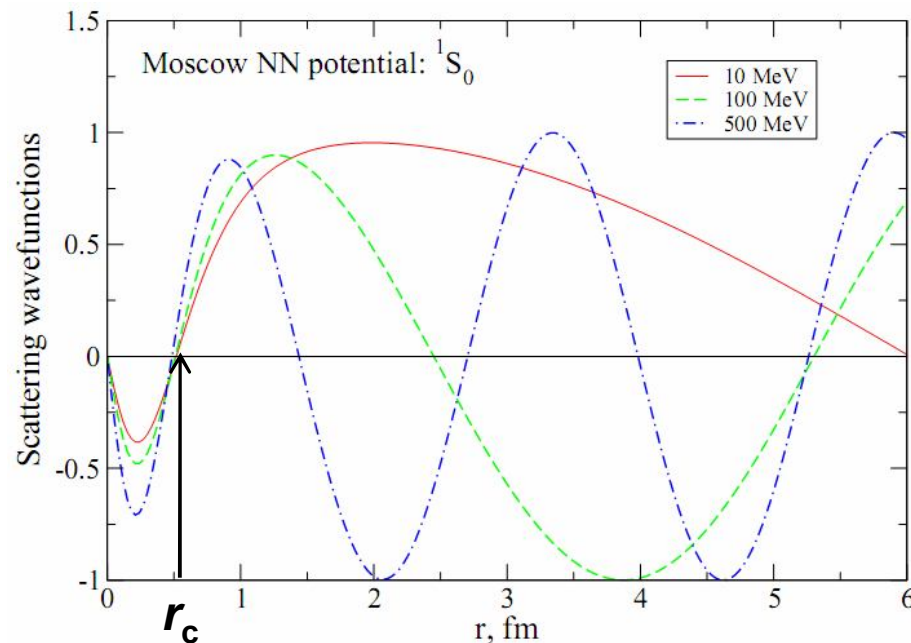
- The consistent **relativistic generalization** of the above dibaryon model has been presented some time ago [[A.Faessler, V.I.Kukulin, M.A.Shikhalev, Ann. Phys. \(N.Y.\) **320**, 71 \(2005\)](#)].

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 $|s^4p^2[42] LST\rangle$ with $2\hbar\omega$ inner excitation.
- So, the projection onto the NN channel:

$$f(r) = \langle NN | s^4 p^2 [42] L=0; ST \rangle$$

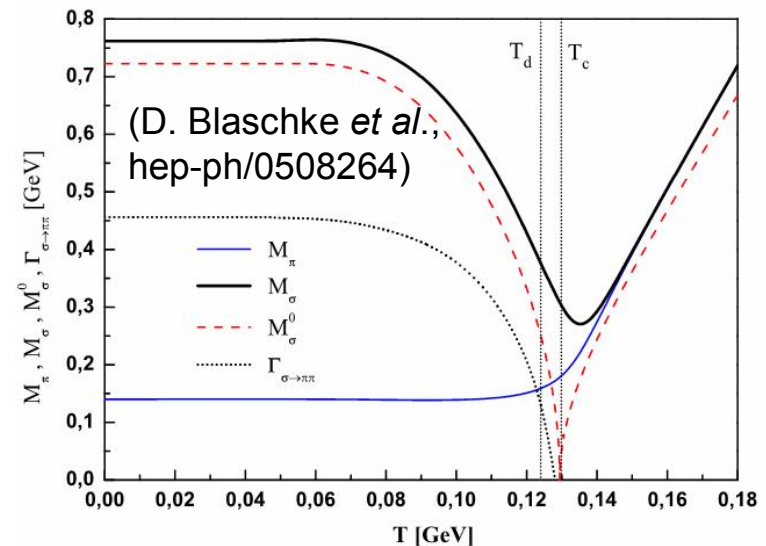
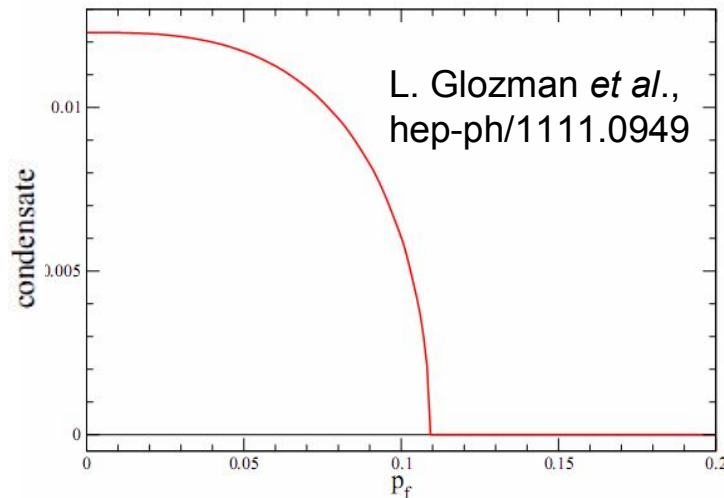
turns out to be a nodal function where the stationary node position at $r_n = r_c$ coincides with the hard core radius $r_c = 0.5$ fm accepted in conventional NN potential models, when we choose the six-quark bag radius $b = 0.55$ fm in a way to reproduce the low-energy spectrum of nucleon excitations.



- It should be stressed that such a dibaryon mechanism with σ loops can be effective only if the mass of intermediate dibaryon dressed with the σ -meson cloud is rather low ($M_D \sim 2.3 - 2.5$ GeV), otherwise the coupling constant $\lambda_{NN \rightarrow D}(E)$ will be small and the probability of dibaryon generation will be insufficient to provide intermediate-range NN attraction!
- However, if one takes the bare mass of the $6q$ bag (~ 2.7 GeV) + bare σ mass (~ 500 MeV), the total mass of the above σ -dressed dibaryon exceeds 3 GeV, and thus **a dibaryon mechanism seems to be ineffective**.
- **To our fortunate, the situation is not so bad due to an effect of **Chiral Symmetry Restoration (χ SR)** in highly excited hadrons proposed by Glzman and others quite recently.**

χ SR in excited hadrons

- The physical origin of χ SR effect is rather simple:
 when the quark kinetic energy inside hadron is rising, the quark condensate is diminishing (it gets “uncoupled” from valence quarks) and thus the quark mass goes down to the bare (current) one.
 So, the chiral symmetry of QCD which is broken at low energy (or zero temperature) gets restored.



- Due to (partial) χ SR effect the masses of six-quark bag and σ mesons surrounding the bag get renormalized strongly, i.e., $M_{6q} \rightarrow 2.2$ GeV, $m_\sigma \rightarrow 300$ MeV. **So, the dressed dibaryon formation can occur with a sufficient probability to yield the effective intermediate-range NN attraction.** [See V.I. Kukulín *et al.*, *Ann. Phys. (N.Y.)* **325**, 1173 (2010)]

χ SR in excited hadrons

- The χ SR effect leads to appearance of **degenerated parity doublets in hadronic spectra**, i.e., the excited states with opposite parities but with the same spins are degenerated, or approximately degenerated (**partial χ SR**).
- The first (approximate) parity doublet in nucleon spectrum is the Roper $N^*_{1/2^+}(1440)$ and $N^*_{1/2^-}(1535)$ states. The puzzle of the Roper resonance state (abnormally low mass of the second positive-parity state) is explained by the χ SR effect.

Spin	Chiral multiplet
1/2	<u>$N_+(1440) - N_-(1535)$</u>
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	$N_+(?) - N_-(2600)$

- The approximate degeneration between the positive and negative parity levels with the same spin in nucleon spectrum can be considered as an indicator for the χ SR effect.

χ SR in excited hadrons

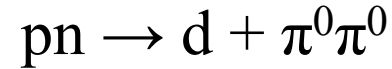
- Some hints of the χ SR phenomenon in generation of the Roper resonance can be found in experiments dedicated to 2π -production in scalar-isoscalar channel, i.e., $(\pi^0\pi^0)_{00}$ or $(\pi^+\pi^-)_{00}$, at intermediate energies:

$pp \rightarrow pp (\pi\pi)_{00}$, $pn \rightarrow d (\pi\pi)_{00}$, $pd \rightarrow {}^3\text{He} (\pi\pi)_{00}$, etc.

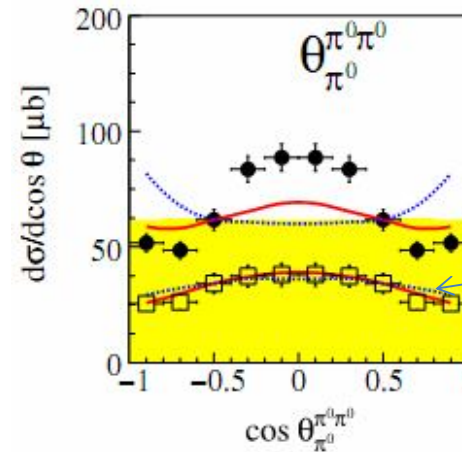
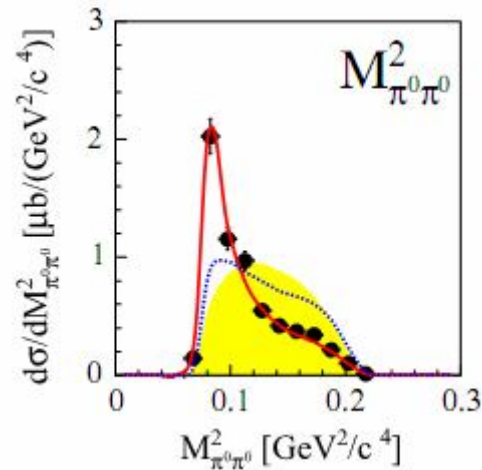
See, e.g.:

- W. Brodowski *et al.*, Phys. Rev. Lett. **88**, 192301 (2002);
 - J. Pätzold *et al.*, Phys. Rev. C **67**, 052202 (2003);
 - T. Skorodko *et al.*, Phys. Lett. **B695**, 115 (2011)
(CELSIUS/WASA Collaboration)
- The issue needs more detailed investigation.

- Especially clear signal of χ SR in hadronic collisions comes from reaction:



studied in detail by the CELSIUS/WASA and WASA@COSY Collaborations.



Data at $T_p = 1.03$ GeV
[M. Bashkanov *et al.*,
PRL **102**, 052301 (2009)]

$$M_{\pi^0\pi^0} < 0.32 \text{ GeV}/c^2$$

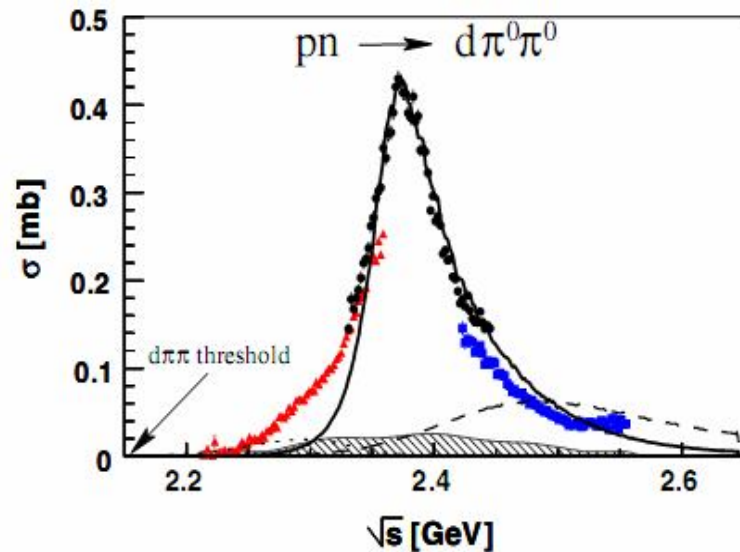
- One observes very clearly a strong enhancement in $M_{\pi^0\pi^0}$ spectrum at $M_{\pi^0\pi^0} \sim 300 \text{ MeV}/c^2$, i.e., very near to 2π -threshold.
- Almost isotropic angular distribution of two pions in their c.m. system in the near-threshold region demonstrates clearly s -wave states of two pions which can be naturally explained by the σ -meson decay into two pions: $\sigma \rightarrow \pi\pi$ ($l=0$). **But where the σ meson comes from?**

The novel 2π -production experiments

- In fact, the novel WASA@COSY experiments on $pn \rightarrow d + (\pi\pi)_0$ reaction are an exclusive version of the old inclusive experiments performed at BNL more than 50 years ago by Abashian, Booth and Crowe who found the famous ABC puzzle in the invariant mass spectrum of two outgoing pions.
- **The ABC puzzle** [A. Abashian, N.E. Booth, K.M. Crowe, PRL5, 258 (1960)] stands for a strong and unexpected 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 theoretical works done for the passed 50 years the puzzle has been explained by the nearby $\Delta\Delta$ threshold. However, the new exclusive experimental data occurred to be incompatible with such a model.
- **But first of all the experimentalists from WASA@COSY Collaboration have found a very clear signal of the dibaryon resonance production.**

The novel 2π -production experiments

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



$$I(J^P) = 0(3^+)$$

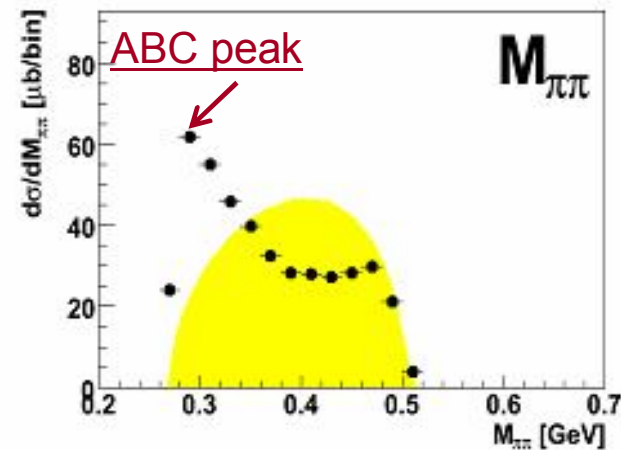
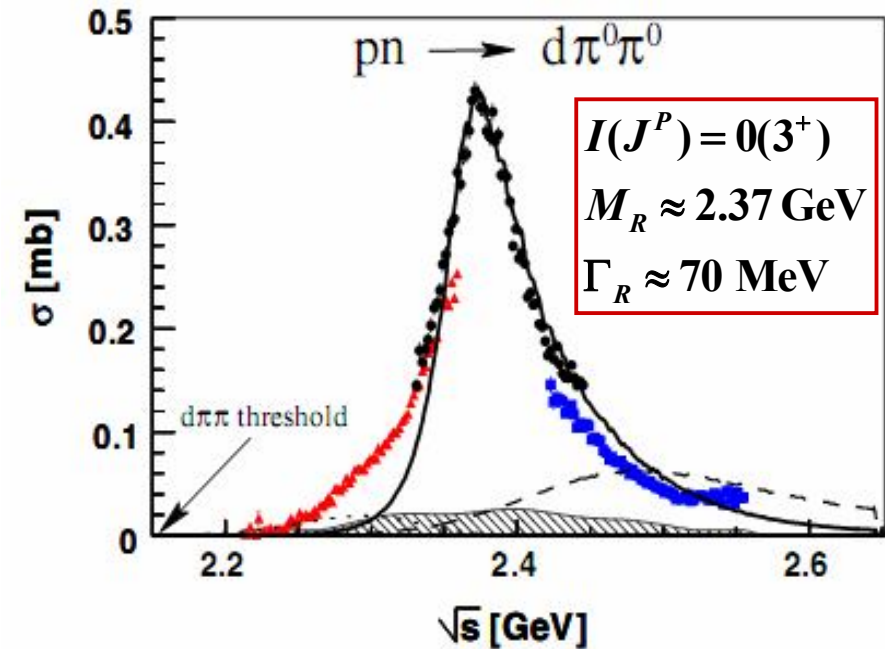
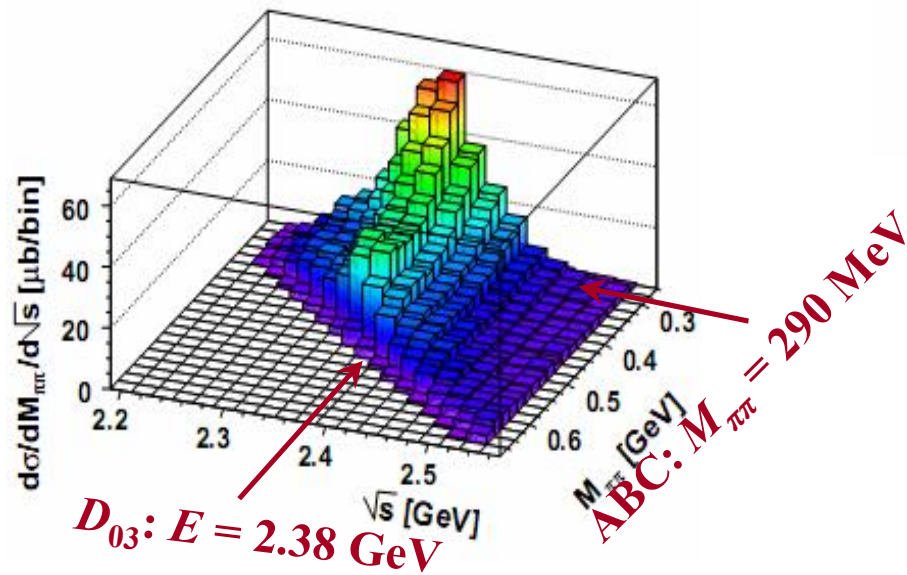
$$M_R \approx 2.37 \text{ GeV}$$

$$\Gamma_R \approx 70 \text{ MeV}$$

- Since this resonance is located only 70 MeV below the $\Delta\Delta$ threshold, it can be treated in a model of $\Delta\Delta$ near-threshold bound state.
- So, the experimentalists suggested a new model for the ABC puzzle based on the idea of the $\Delta\Delta$ bound state. Unfortunately, their model includes a non-realistic very soft form factor for $\Delta\Delta$ bound state and thus looks to be not quite consistent.

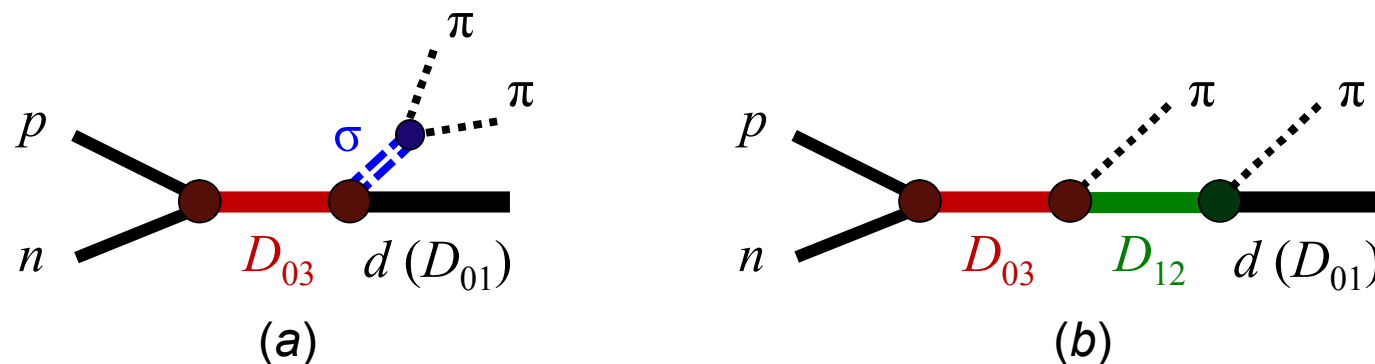
The novel 2π -production experiments

Still the most intriguing feature of the novel WASA@COSY experiments is a clear identification of the ABC puzzle with 2π emission from the 3^+0 dibaryon state.



Dibaryon model for the ABC puzzle

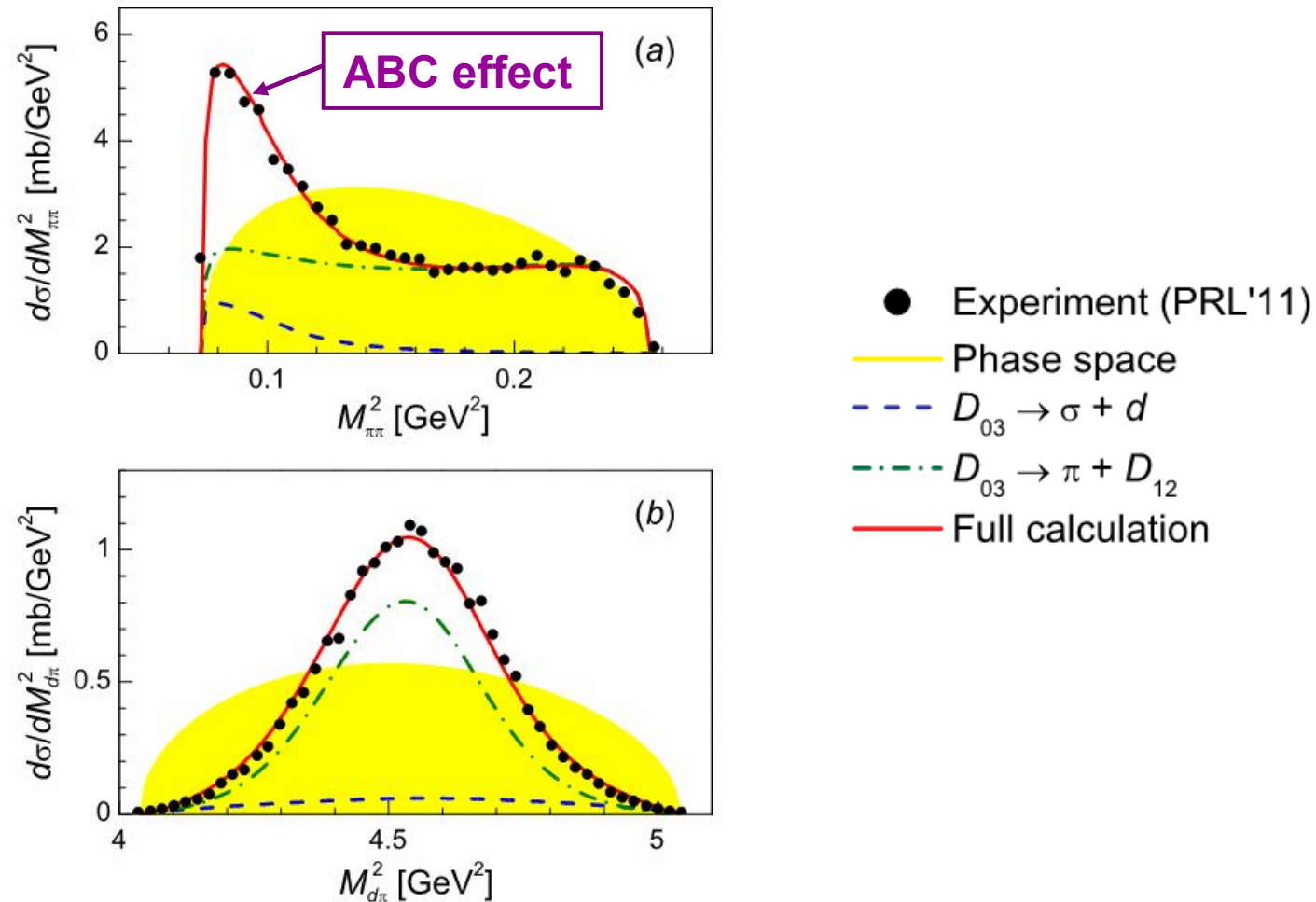
- We reanalyzed the new WASA@COSY experimental data in terms of the dibaryon model [M.N. Platonova, V.I. Kukulín, PRC **87**, 025202 (2013)]. Our model includes two basic mechanisms for the two-pion production in p+n fusion to deuteron at $T_p \sim 1\text{--}1.4$ GeV:



- The mechanism (a) corresponds to the near-threshold emission of the σ meson (amplitude $M^{(a)}$), while the mechanism (b) describes the consequent emission of two pions via an intermediate 2^+1 isovector dibaryon (amplitude $M^{(b)}$).
- Then one assumes $d\sigma / dM_{\pi\pi} = (\text{phase space}) \times \iint d\Omega_d^{\text{c.m.}} d\Omega_\pi^{\pi\pi} \sum_{\text{spin}} |M^{(a)} + M^{(b)}|^2$,
i.e., we add coherently two above amplitudes.

Dibaryon model for the ABC puzzle

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



χ SR in dibaryons and in scalar meson sector

- However we found that the experimental data can be fitted very well only by taking the σ -meson mass and width with strongly reduced values as compared to their free-space values extracted from $\pi\pi$ dispersion relations [I. Caprini, G. Colangelo, H. Leutwyler, PRL96, 132001 (2006)]:

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

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

- Such a reduction for the σ -meson parameters may indicate the partial χ SR effect in the 3^+0 dibaryon state.
- The riddle of the σ meson is interrelated very closely with the χ SR phenomenon in QCD.

χ SR in short-range nuclear force induced by intermediate dibaryons

- The χ SR effects have been studied by many authors both in dense (or hot) nuclear matter and in a single hadron when it gets strongly excited.
- It should be stressed that the 3^+0 dibaryon (which has been discovered in pn collisions at $T_p \sim 1$ GeV) with the mass $M_{D_{03}} \approx 2.37$ GeV is in fact a *strongly excited hadron* (with the excitation energy $E^* \approx 500$ MeV) and the χ SR phenomenon is predicted for such states rather reliably.
- According to our model for the ABC puzzle, just this χ SR phenomenon is seen in the near-threshold two-pion enhancement observed in ABC-type experiments.
- We emphasize simultaneously that the low-lying dibaryons which drive the short-range nuclear force in our approach also correspond to χ SR due to their inner excitation.
- Thus, the σ mesons which dress the dibaryons must be lighter and narrower as compared to the bare σ mesons in $\pi\pi$ scattering in free space.

As summary, we can suggest that the nature of short-range nuclear force is based on Chiral Symmetry Restoration.

So, our prediction for the χ SR 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

The (unexpected) role of σ meson in heavy-ion collisions at ultra-relativistic energies

A. Andronic, P. Braun-Munzinger, J. Stachel

Phys. Lett. B**673**, 142 (2009); nucl-th/0812.1186

“Thermal hadron production in relativistic nuclear collisions: the hadron mass spectrum, the horn, and the QCD phase transition”

“In summary, we have demonstrated that by inclusion of the σ meson and many higher mass resonances into the resonance spectrum employed in the statistical model calculations an improved description is obtained of hadron production in central nucleus-nucleus collisions at ultra-relativistic energies.”

“It is interesting to note that central questions in hadron spectroscopy such as the existence (and nature) of the σ meson apparently play an important role in quark-gluon plasma physics. Our results strongly imply that hadronic observables near and above the horn structure at a beam energy of 30 AGeV provide a link to the QCD phase transition.”

Conclusions

1. Numerous experimental results and general arguments in favor of **chiral symmetry restoration (χ SR)** in excited hadrons, especially for the Roper resonance structure and decay modes, are presented.
2. The novel mechanism for intermediate- and short-range nuclear interactions through the **intermediate dibaryon production** is presented. The dibaryon properties are governed by the χ SR phenomenon and symmetries of QCD.
3. The new model for the famous ABC puzzle, based on dibaryon production with strongly renormalized σ field, is developed. The model allowed to see the mechanism of χ SR for σ meson inside the strongly excited hadrons (e.g., dibaryons).
4. All these results may put the cornerstone to the future nuclear physics based on QCD.

***Thank You
For Your Attention!***