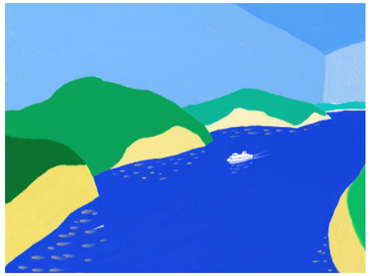

Dibaryon Resonances in Pion Production and Short-Range Nuclear Force

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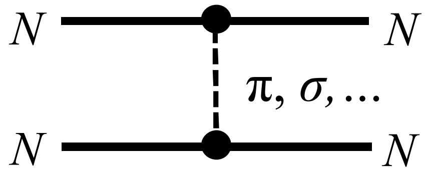
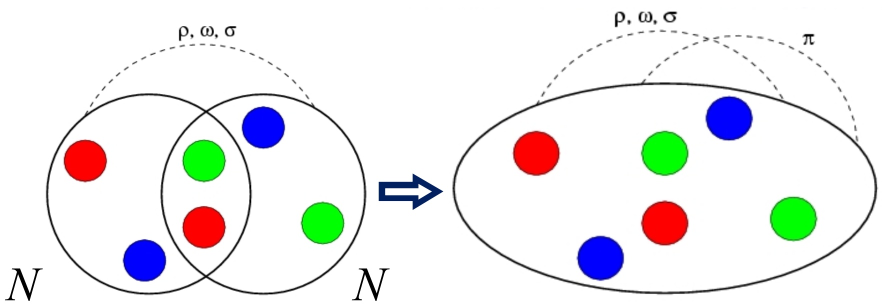
Introduction.
Indications and evidences
for dibaryon (6*q*) states in *NN* system

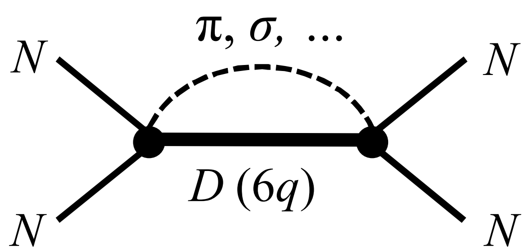
Nature of *NN* interaction

- **r_{NN} > 1 fm**: meson exchange between isolated (point-like) nucleons;
  One-Boson-Exchange (OBE) models for nuclear force



- **r_{NN} < 1 fm**: two nucleons are overlapped with each other →
  their quark structure should be taken into account;
  a six-quark bag (*dibaryon*) dressed with meson fields might be produced;
  such mechanisms are absent in OBE models but predicted in QCD





Do dibaryons really exist in Nature?

First prediction of dibaryon states in *NN* system

- F.J. Dyson and N.-H. Xuong, PRL **13**, 815 (1964):
  Theoretical prediction of 6 zero-strangeness low-lying dibaryons
  (on the basis of SU(6) symmetry)

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:

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

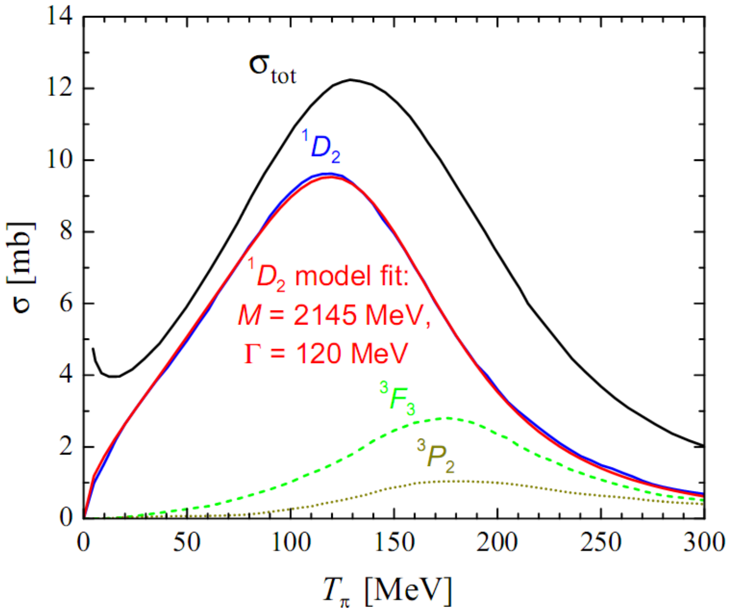
$$M(D_{03}) \approx 2350 \text{ MeV} \approx M(\Delta) + M(\Delta) - 110 \text{ MeV}.$$

Indications of D_{12} and other isovector dibaryons

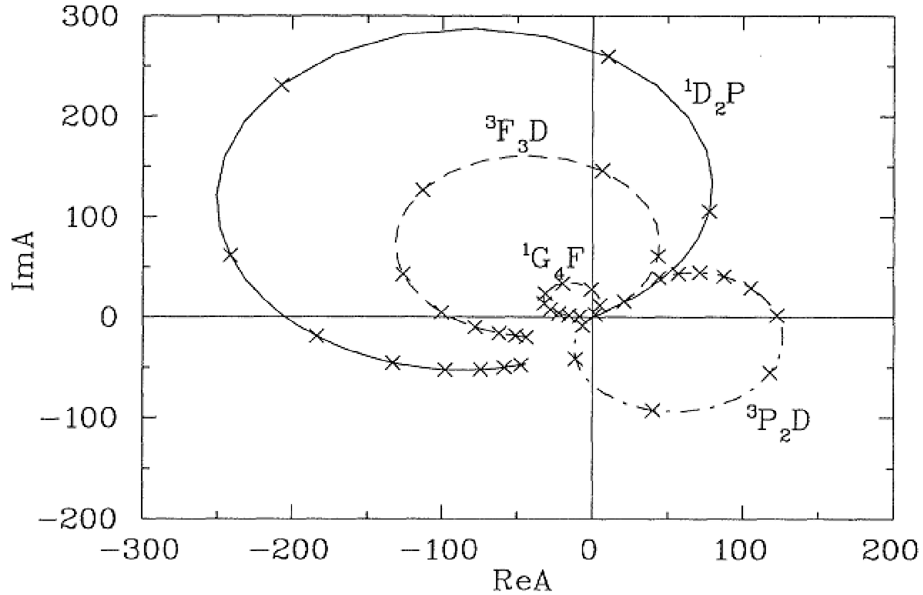
- Experiments on $\vec{p}+\vec{p}$ elastic scattering (I. Auer et al., 1978) and partial wave analyses (PWA) for $pp \to pp$, $\pi^+d \to \pi^+d$ and $\pi^+d \to pp$ (N. Hoshizaki, 1979, 1993; R. Arndt et al., 1981, 1993; etc.) revealed the series of isovector resonances in NN channels ${}^1D_2$, ${}^3F_3$, ${}^1G_4$, etc.
- The lowest (${}^1D_2$) isovector resonance: $I(J^P) = 1(2^+)$,

  $M \approx 2140–2160$ MeV $\approx M(N+\Delta)$ - (10–30 MeV), $\Gamma \approx 100–120$ MeV $\approx \Gamma(\Delta)$.

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 $\pi^+d \to pp$



- True resonances or "pseudoresonances" (intermediate $N+\Delta$ states)?

New evidence for isoscalar D_{03} dibaryon

Experiments on 2π production in $p+n$, $p+d$, $d+d$ collisions and $\vec{p}+\vec{n}$ elastic scattering (CELSIUS/WASA & WASA-at-COSY Collaborations, 2006–2015)

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)

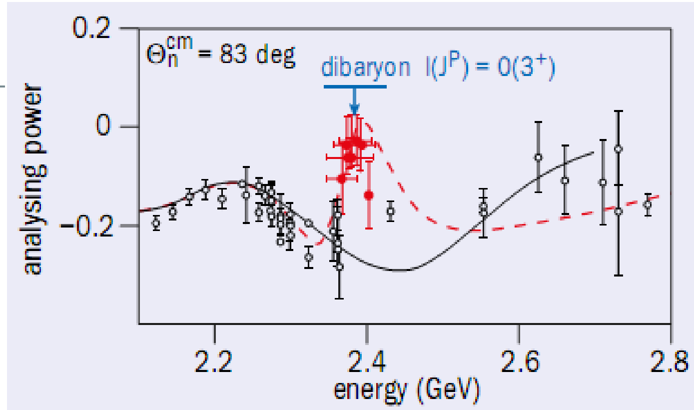
CERN Courier **July/August 2014**

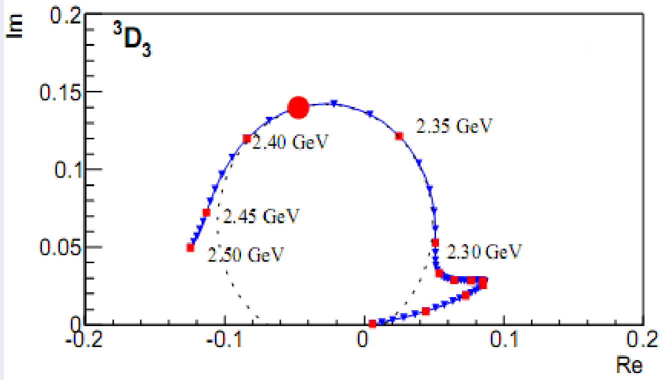
News

NEW PARTICLES

COSY confirms existence of six-quark states

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





SAID SP07 (2007) — new PWA solution (2014)

$D_{03} \approx \Delta\Delta(30\%) + C\bar{C}(70\%)$ [F. Huang et al., nucl-th/1505.05395; see also M. Bashkanov, S. Brodsky, H. Clement, PLB727(2013)438]

- R.m.s. radius $r(D_{03}) \approx 0.7$–0.9 fm (from microscopic quark model calculations)
- Full width $\Gamma(D_{03}) = 70 - 90\ \text{MeV} \ll 2\Gamma(\Delta) = 235\ \text{MeV}$

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

Additional 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:

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

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

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

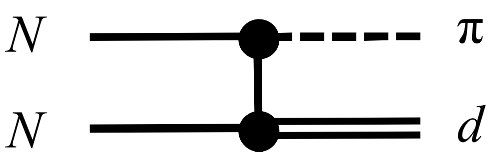
- Very good agreement with Dyson and Xuong predictions as well as with experimental findings.

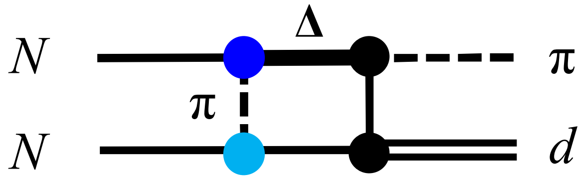
- Cross sections for dibaryon resonance production are generally small compared to the conventional meson exchange processes.
- Manifestation of dibaryon d.o.f. can be tested in processes with high momentum transfers which probe short NN distances, e.g., in *one- and two-pion production.*

Interplay between baryon and dibaryon resonances in the basic one-pion production process $pp \to d\pi^+$

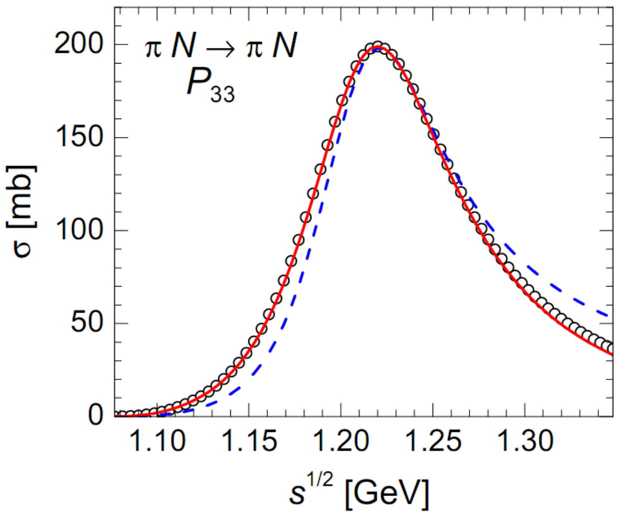
Conventional description for $pp \to d\pi^+$:

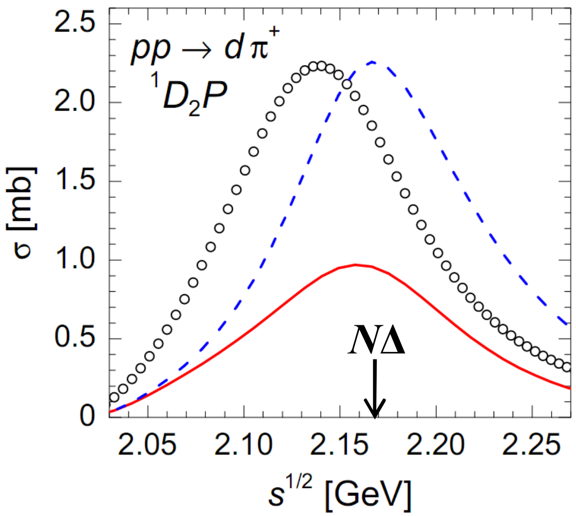
ONE (one-nucleon exchange) **+ $N\Delta$** (N+Δ intermediate state)





- The basic difficulty is the choice of the short-range cut-off parameters Λ and Λ_* in meson-baryon vertices πNN and $\pi N\Delta$ with a virtual pion.





$$F_{\pi N\Delta} = \frac{f_*}{m_\pi}\frac{p_0^2 + \tilde{\Lambda}_*^2}{p^2 + \tilde{\Lambda}_*^2}\Bigg|_{(\text{virtual } \pi)} \simeq \frac{f_*}{m_\pi}\frac{m_\pi^2 - {\Lambda_*}^2}{w_\pi^2 - {\Lambda_*}^2}$$

(p – pion momentum in πN c.m.s.)

$$ {\Lambda_*}^2 \simeq \left(\tilde{\Lambda}_*^2 + \left(\frac{M_\Delta^2 - m^2}{2M_\Delta}\right)^2\right) \Big/ \left(\frac{M_\Delta^2 + m^2}{2M_\Delta^2}\right)$$

○ **PWA (SAID)**

— $\tilde{\Lambda}_* = 0.3$ **GeV** ($\Lambda_* = 0.44$ **GeV**)

-- $\tilde{\Lambda}_* = 0.55$ **GeV** ($\Lambda_* = 0.7$ **GeV**)

- Cut-off parameters describing precisely the πN elastic scattering ➡ conventional mechanisms (ONE+$N\Delta$) give only a half the partial (^1D_2P) $pp \to d\pi^+$ cross section
- Enhancing the $\pi N\Delta$ cut-off value *ad hoc* ➡ the magnitude of the $pp \to d\pi^+$ cross section can be reproduced but with a substantial energy shift
- *An alternative way:* taking the intermediate dibaryon resonances in the NN channels $^1D_2$, $^3F_3$, $^1G_4$, etc., into account

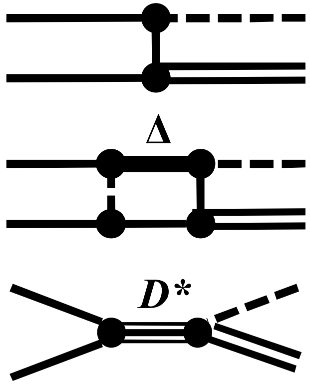
Extended model for $pp \to d\pi^+$:

[M. Platonova, V. Kukulin, nucl-th/1412.4574]

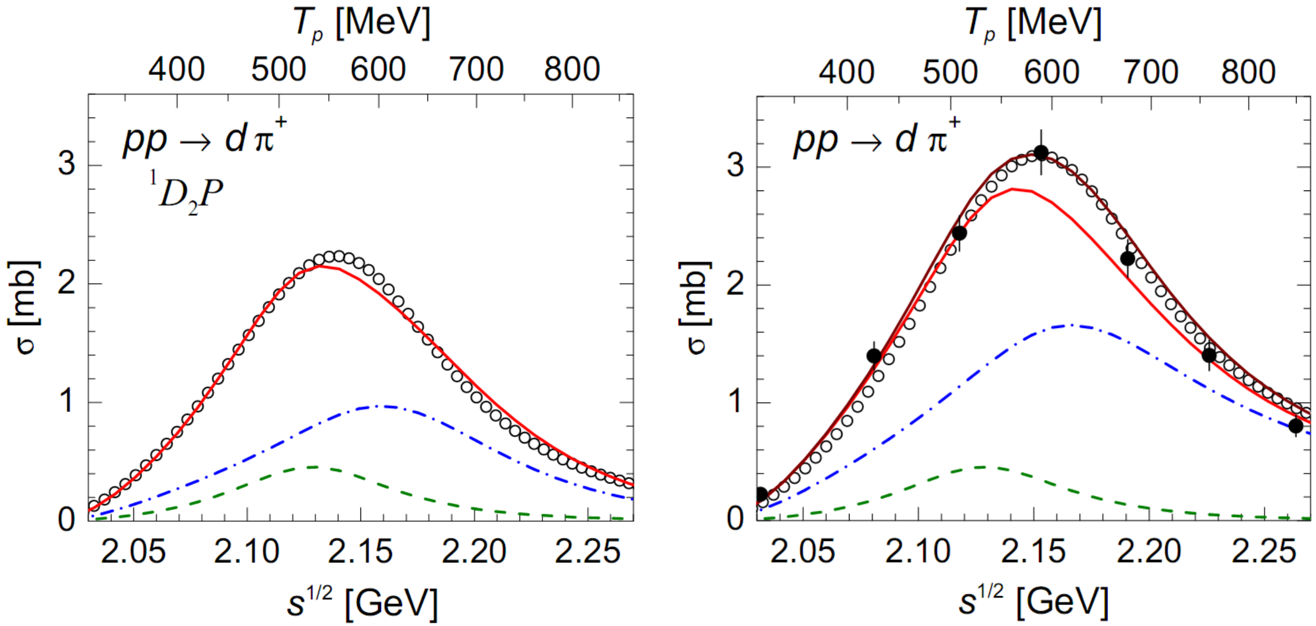
ONE (one-nucleon exchange)

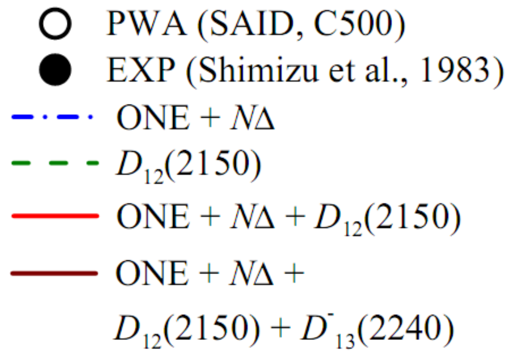
+ $N\Delta$ (N+Δ intermediate state)

+ D^* (dibaryon resonances)



$$A^{(D_{12})} = \frac{16\pi s\sqrt{2\Gamma_{D_{12}\to pp}(s)\Gamma_{D_{12}\to\pi d}(s)/pq}}{s - M^2_{D_{12}} + i\sqrt{s}\Gamma_{D_{12}}(s)}$$



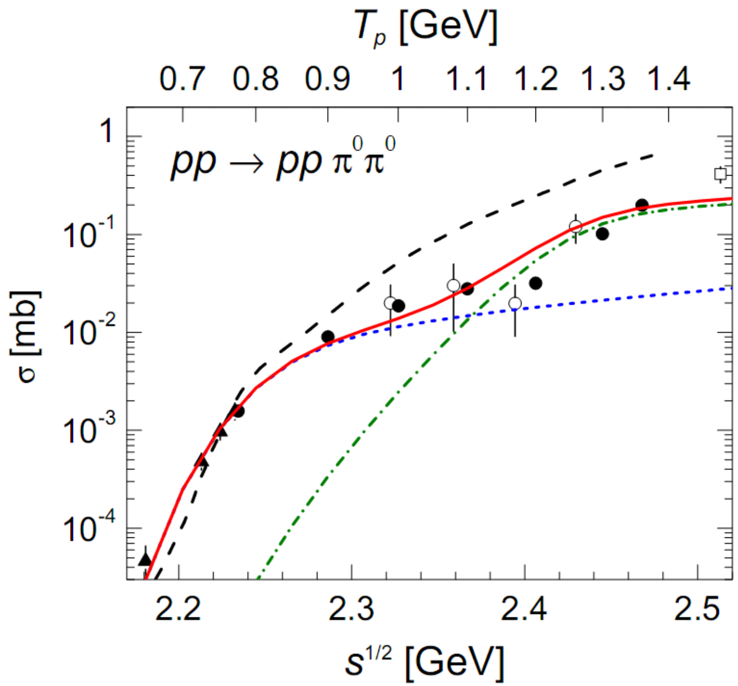


$M(D_{12})$ = 2150 MeV
$\Gamma(D_{12})$ = 110 MeV

D_{12} resonance parameters were chosen consistently with pp and π^+d elastic scattering

- Inclusion of dibaryon resonances improves the description of experimental data without *ad hoc* adjustment of cut-off parameters.
- Accurate description of the total cross section in a broad energy range requires <u>two dibaryon resonances</u>: $D_{12}(2150)$ [$^1D_2$] and $D^-_{13}(2240)$ [$^3F_3$].

Isovector dibaryon signals in reaction *pp* → *pp* + $\pi^0\pi^0$



- - - - - Conventional model (E. Oset et al., 1998):

$$NN^*(1440) + \Delta\Delta \quad (\Lambda_* \simeq 1.3\ \text{GeV!})$$

——— Alternative (dibaryon) model:

$$D_{13}^-(2240)\,[^3F_3] + D_{14}(2430)\,[^1G_4]$$

(blue dotted: $D_{13}^-(2240)$; green dash-dotted: $D_{14}(2430)$)

$$\sigma = \sum_{J=3,4} \frac{\pi(2J+1)}{p^2} \frac{s\Gamma^{(i)}_{D_J}(s)\Gamma^{(f)}_{D_J}(s)}{(s - M^2_{D_J})^2 + s\Gamma_{D_J}(s)^2}$$

- The one- and two-pion production cross sections in *pp* collisions can be qualitatively described with account of intermediate isovector dibaryon resonances;
  however interference with the *resonance-like background* and the *problem of meson-baryon vertex parametrization* complicate unambiguous identification of dibaryon contributions
- It is important to find such processes where dibaryon resonances are manifested more clearly and cannot be “imitated” by *t*-channel meson-exchange mechanisms with enhanced cut-off parameters
- A good candidate for such a process is *two-pion production in pn collisions*

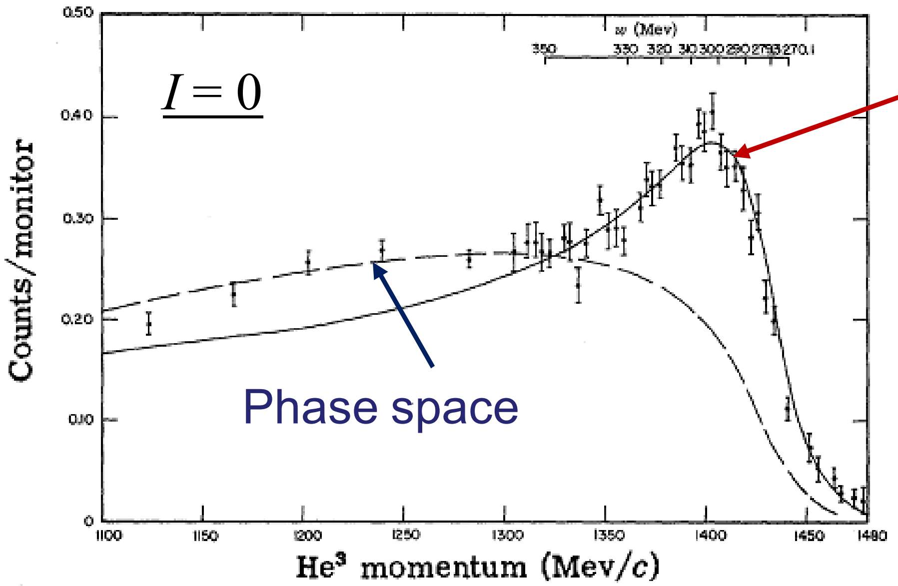
Intermediate dibaryons in two-pion production process $pn \to d(\pi\pi)_0$ and new interpretation of the ABC effect

What is ABC effect?

A. **A**bashian, N.E. **B**ooth, K.M. **C**rowe, PRL **5**, 258 (1960); **7**, 35 (1961):

Inclusive experiment $pd \to {}^3\mathrm{He}\,X$ @ $T_p = 0.743$ GeV

Observation of an <u>anomalous enhancement just above 2π-production threshold</u>



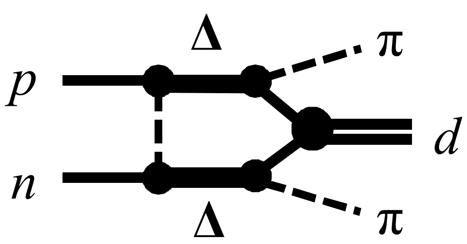
ABC effect: $I(J^P) = 0(0^+)$,
$m_X \approx 300$ MeV $= 2m_{\pi^0} + 30$ MeV

Later on the similar enhancements were observed in reactions

$$pn \to d\,X,$$

$$dd \to {}^4\mathrm{He}\,X$$

<u>Basic reaction</u>: $\boldsymbol{pn \to d + (\pi\pi)_{I=0}}$



Conventional mechanism of 2π production and ABC effect –
t-channel excitation of intermediate ΔΔ state
(T. Risser & M. Shuster, 1973):
qualitative description of some old inclusive data, but
strong disagreement with the new <u>exclusive</u> data.

New experiments of the WASA@COSY Collaboration

First exclusive high-statistics experiments in full 4π geometry

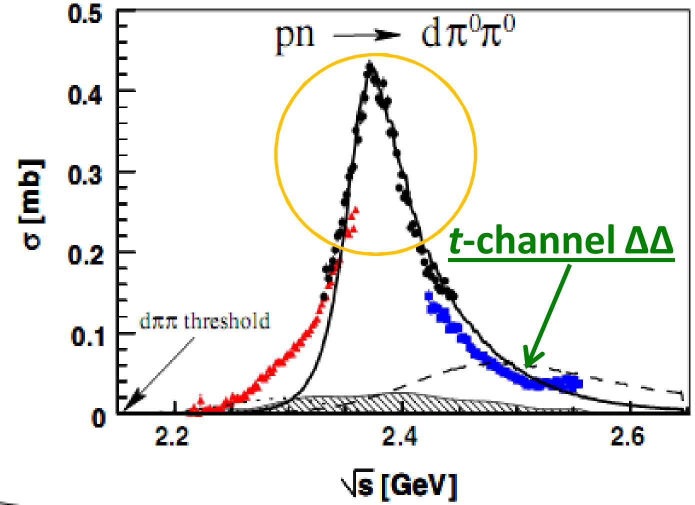
$$p + d \to p_{\text{spectator}} + d + \pi^0\pi^0, \quad T_p = 1.0 - 1.4 \text{ GeV}$$

Experimental data have clearly shown production of isoscalar dibaryon resonance D_{03} with parameters:

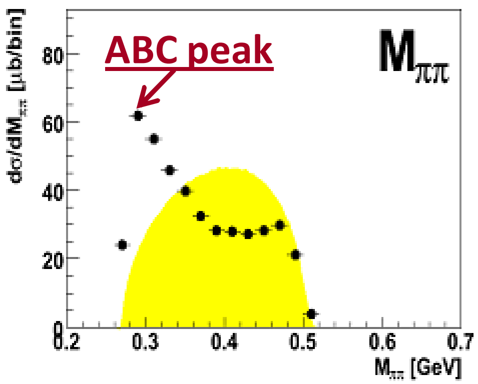
$$I(J^P) = 0(3^+)$$

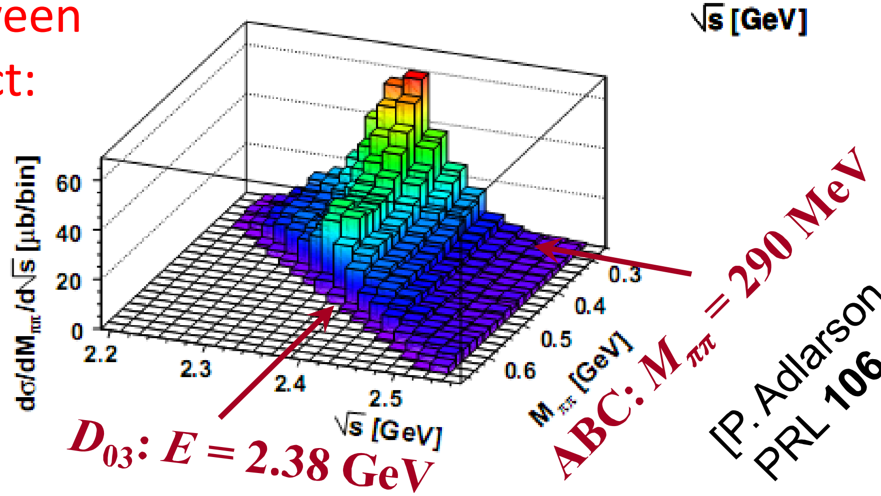
$$M \approx 2380 \text{ MeV} = 2M_\Delta - 80 \text{ MeV}$$

$$\Gamma \approx 70 \text{ MeV} \ll 2\Gamma_\Delta = 235 \text{ MeV}$$



and direct interrelation between this resonance and ABC effect:





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

What mechanism of the D_{03}-resonance decay leads to ABC enhancement?

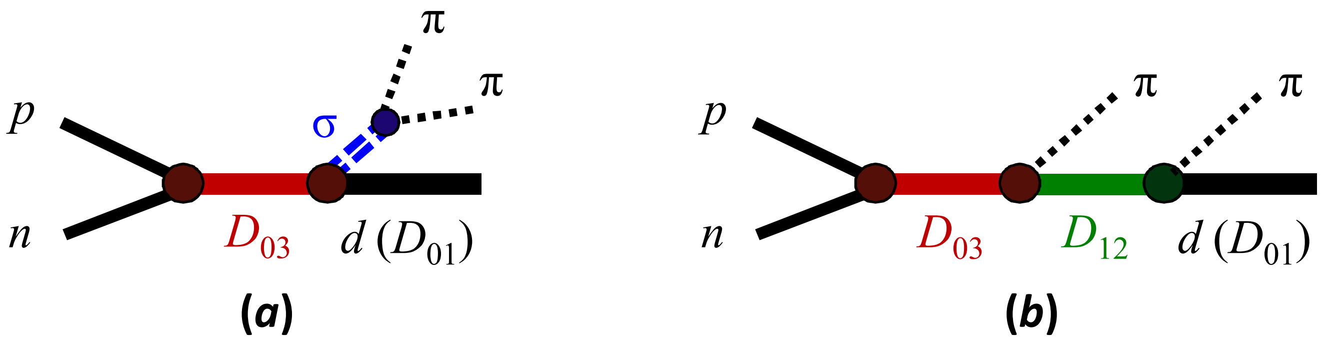
Dibaryon model for the reaction $pn \to d + (\pi\pi)_0$ in the ABC region

[M. Platonova, V. Kukulin, PRC **87**, 025202 (2013)]

- The new model for the reaction $pn \to d + (\pi\pi)_0$ at energies $T_p = 1\text{–}1.3$ GeV ($s^{1/2} = 2.32\text{–}2.44$ 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;

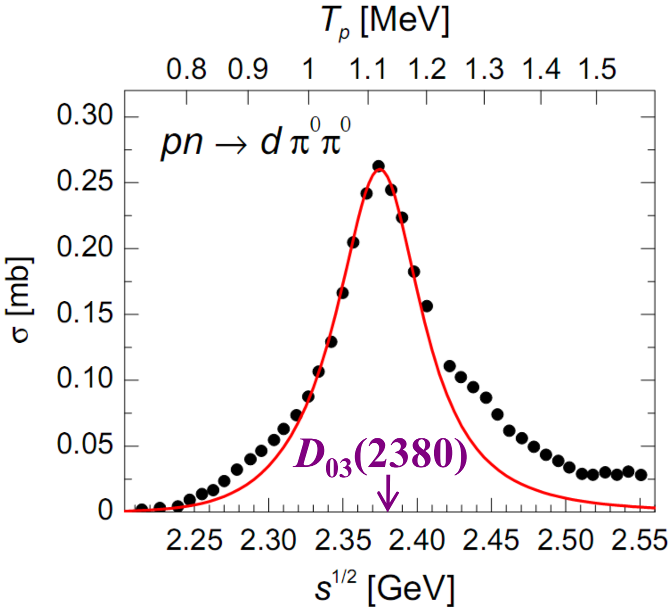
  (*b*) sequential emission of two pions via an intermediate isovector dibaryon $D_{12}(2150)$



- Transitions between different dibaryon states are considered *for the first time*, similarly to the known transitions between baryons (cf. the Roper resonance decay routes: $N^*(1440) \to N + \sigma \to N + \pi\pi$ and $N^*(1440) \to \Delta(1232) + \pi \to N + \pi\pi$)
- <u>Invariant mass distribution</u>: $d\sigma / dM_{\pi\pi} = (\text{phase space}) \times \iint d\Omega_d^{\text{c.m.}} d\Omega_\pi^{\pi\pi} \sum_{\text{spin}} \left| A^{(a)} + A^{(b)} \right|^2$
- <u>3 model parameters</u>: M_σ, Γ_σ and the relative weight of the amplitudes $A^{(a)}/A^{(b)}$.

Results of the model calculations

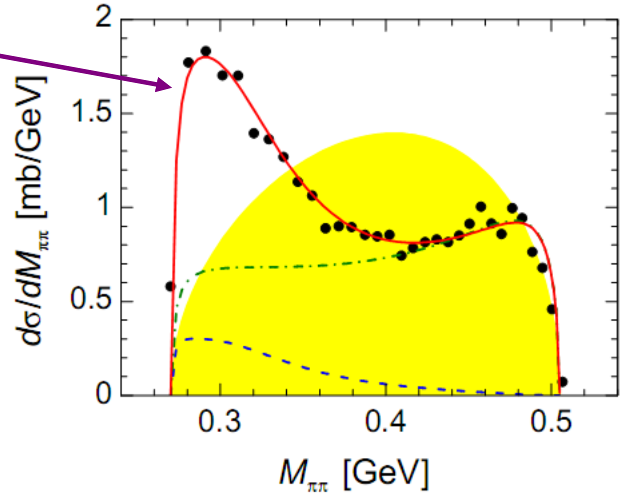
I. Total Cross Section



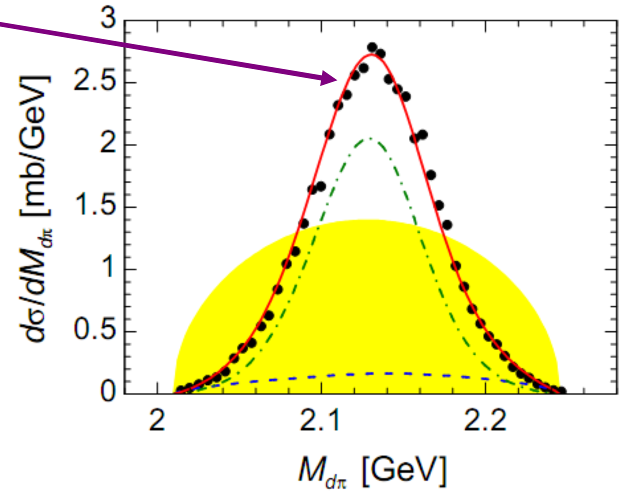
- ● **Experiment WASA@COSY** [PRL106(2011)242302, renorm. in PLB721(2013)229]
- (yellow line) **phase space**
- (blue dashed line) $D_{03} \to d + \sigma$
- (green dash-dotted line) $D_{03} \to D_{12} + \pi$
- (red line) **Full calculation**

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

ABC effect (signal of σ meson)



Signal of isovector dibaryon $D_{12}(2150)$



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

Parameters of the σ meson

- From the model description of the ABC peak

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

[M. Platonova, V. Kukulin, PRC **87**, 025202 (2013)]

- From $\pi\pi$ elastic scattering in free space:

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

[I. Caprini, G. Colangelo, H. Leutwyler, PRL **96**, 132001 (2006)]

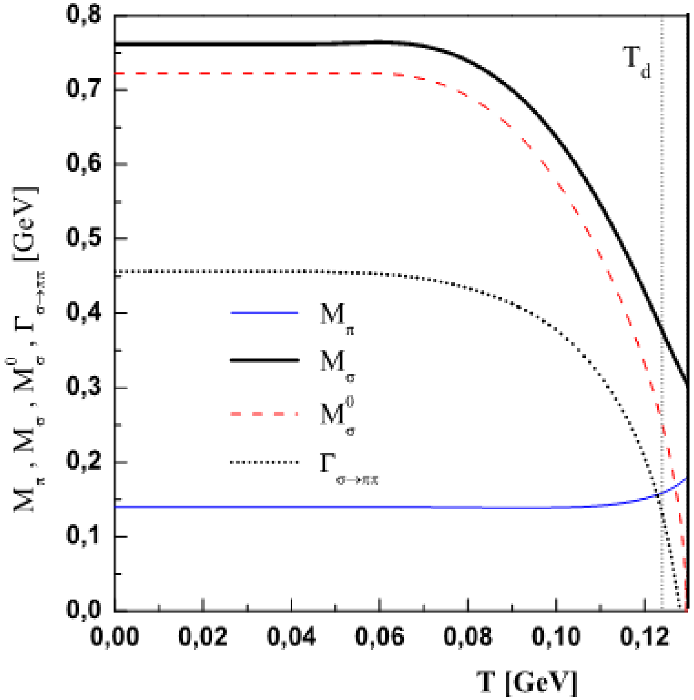
Is there a real contradiction?

Chiral Symmetry Restoration (χSR)

- <u>Two basic phenomena of nonperturbative QCD:</u>
  confinement & chiral symmetry breaking
  Prediction at very high energies:
  deconfinement & chiral symmetry restoration

- **Partial χSR** can occur already in
- – isolated excited hadrons at $E^* \geq 500$ MeV
  [L. Glozman, PLB475(2000)329, PRL99(2007)191602],
- – nuclear matter at finite density ($\rho \geq \rho_0$) and/or temperature ($T \geq 100$ MeV)
  [T. Hatsuda, T. Kunihiro, H. Shimizu, PRL82(1999)2840;
  M. Volkov et al., PLB424(1998)235];

  is manifested in reduction of scalar
  σ-meson mass and $\sigma \to \pi\pi$ decay width



D. Blaschke et al., hep-ph/0508264

- Dibaryon $D_{03}(2380)$:
  high density ($r \approx 0.7$–0.9 fm; $\rho \approx 6$–$8\ \rho_0$)
  + excitation energy ($E^* \approx 500$ MeV)

  ⇒ partial χSR can occur in dibaryon states

  This can be visible in parameters of σ mesons produced from dibaryons

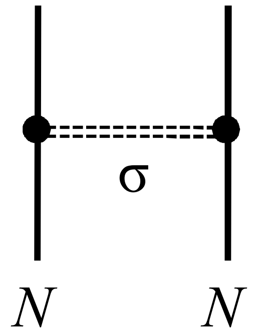
ABC effect may be considered as a first experimental indication of this prediction

Role of 6*q* states and light scalar mesons in short-range nuclear force

Basic *NN* attraction in nuclei and scalar σ meson

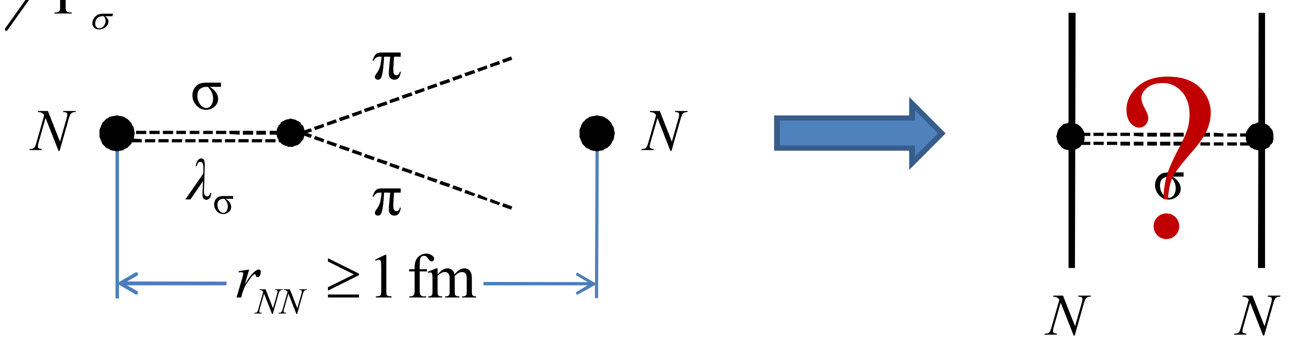
- Light scalar meson σ (or $f_0(500)$), $I(J^P) = 0(0^+)$, plays a fundamental role
  - in QCD (provides hadron masses through chiral symmetry breaking; is sometimes called the "*Higgs boson of strong interaction*" [M. Schumacher, Eur.Phys.J.C67(2010)283]),
  - in nuclear physics (responsible for the basic *NN* attraction in nuclei)

- Conventional mechanism of the basic *NN* attraction ($r_{NN} \sim 1$ fm): *t*-channel σ exchange; no width for σ meson is assumed!



- $\pi + \pi \rightleftarrows \sigma$ — very broad resonance in ππ scattering: $\Gamma_\sigma \simeq 500$ MeV

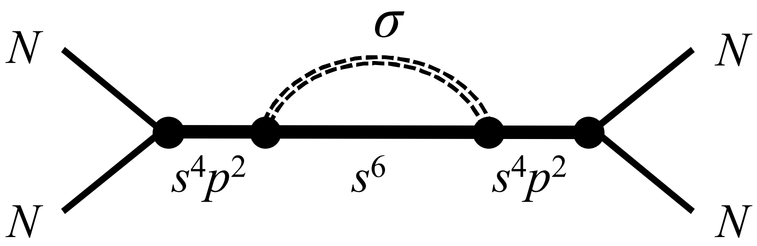
- $\tau \simeq \hbar / \Gamma_\sigma$; $\lambda_\sigma \simeq c \cdot \tau \simeq 0.4$ fm — path length for an unstable σ-meson



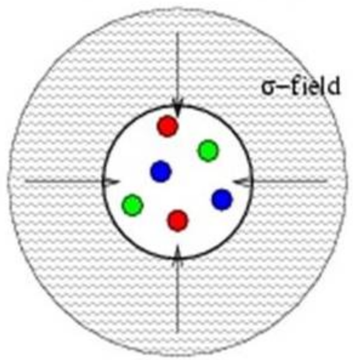
- **Such highly unstable σ meson cannot bind the nucleons in nuclei!**

The σ-dressed dibaryons in *NN* interaction

- The basic mechanism of short-range *NN* interaction in the dibaryon model for nuclear force – instead of *t*-channel σ exchange:



V. Kukulin et al., J.Phys.G27(2001)1851



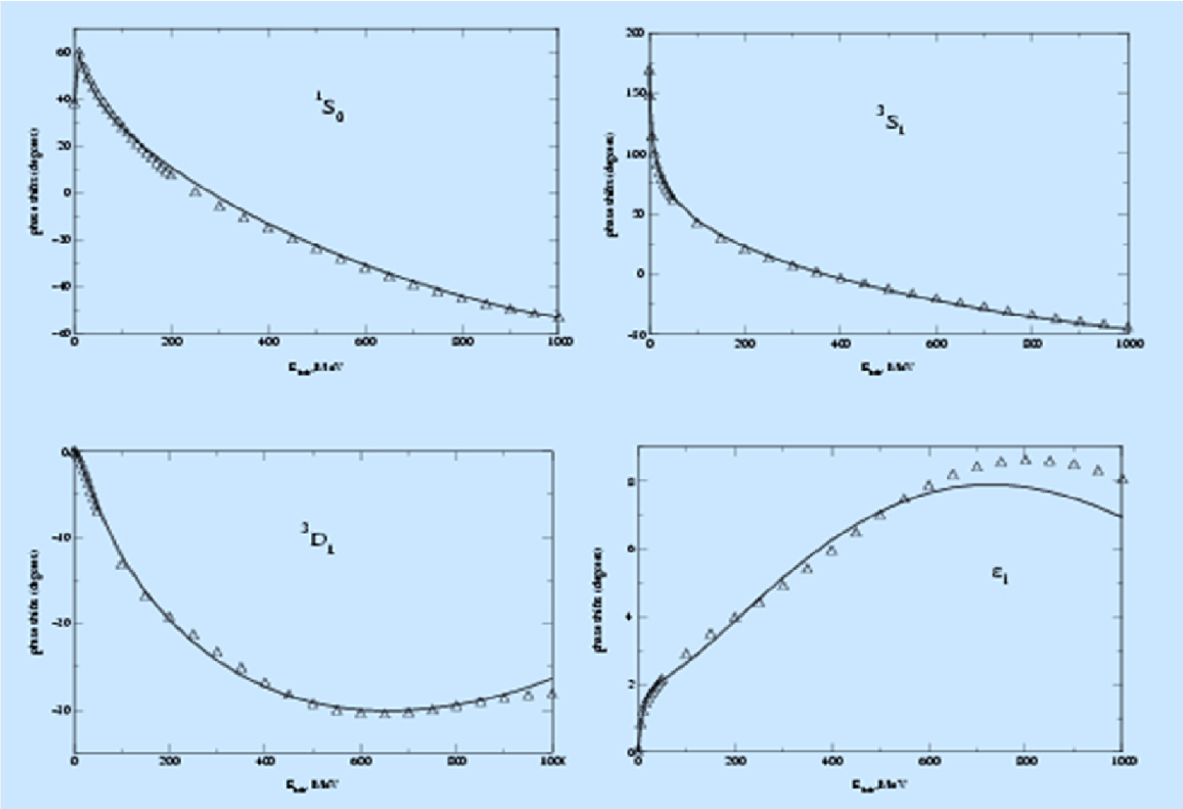
- Scalar σ field arises within a transition from the dominant mixed-symmetry $6q$ configuration s^4p^2 to a fully symmetric one s^6:

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

- The σ field stabilizes the $6q$ bag and shifts its bare mass from ~ 3 GeV to ~2.2 GeV.
- The σ field itself is also stabilized (its mass and width are shifted downwards due to the effect of partial χSR).
- The $2\hbar\omega$ excitation of the s^4p^2 $6q$ configuration above s^6 one strengthens partial χSR effects.

The σ-dressed dibaryons in *NN* interaction

- Within the dibaryon model, a very good description of *NN*-scattering phase shifts up to $T_N = 1$ GeV and also of the lightest nuclei properties was achieved with only a few basic parameters and $m_\sigma \approx 300–400$ MeV (not 500–600 MeV as in conventional OBE *NN*-force models).



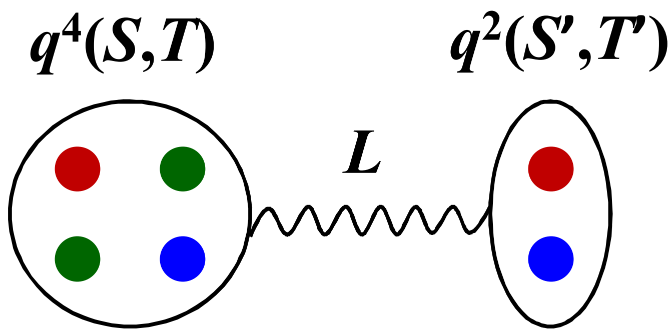
V. Kukulin et al., Int.J.Mod.Phys.E11(2002)1

- If this picture is realized in Nature, dibaryon states should be produced *in all NN partial waves* (however, with different probability) .

Dibaryon Spectroscopy

- **Nijmegen & ITEP model**
  [P. Mulders et al., PRD21(1980)2653;
  L. Kondratyuk et al., Sov.J.Nucl.Phys.45(1987)776]

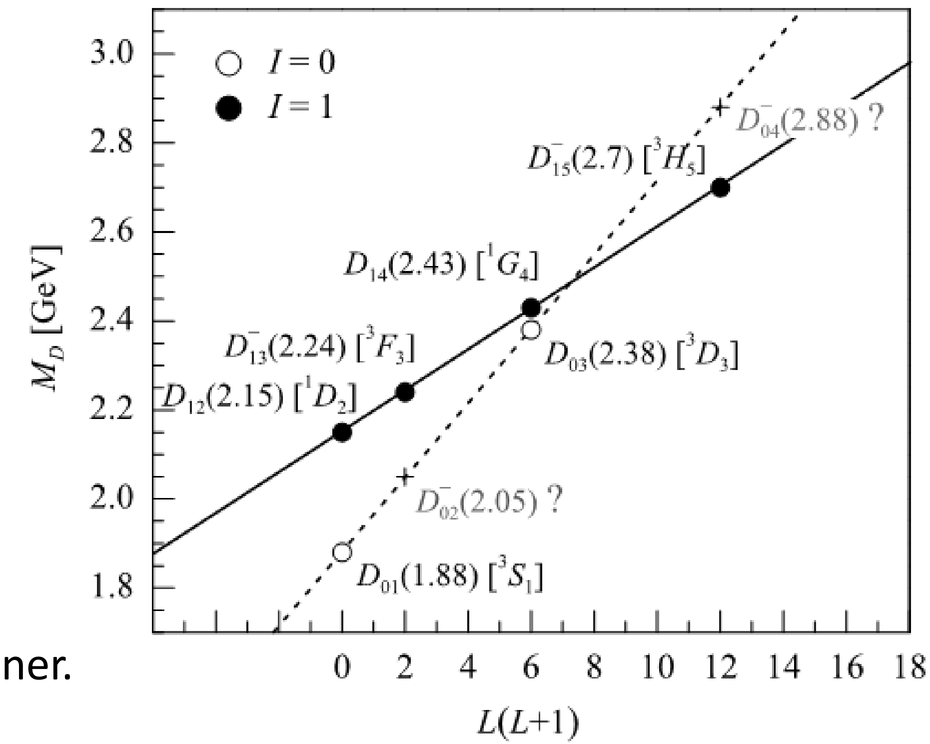
  Dibaryons as orbital excitations
  of two-cluster system q^4-q^2;
  Regge trajectory on (J,M^2)



- For the lowest states $(\Delta M \ll M_0)$:
  non-relativistic rigid-rotor model

$$M(L) \simeq M_0 + \frac{\hbar^2}{2\mathcal{I}} L(L+1)$$

  Almost straight line on $(L(L+1),M)$!



- Tetraquark q^4 $(S=1,T=0)$;
  Diquark q^2:
  scalar (S′=T′=0) for $I=0$ dibaryons,
  axial (S′=T′=1) for $I=1$ dibaryons

  Each $I=1$ dibaryon should have an $I=0$ partner.

Are there additional $I=0$ states? Are there another dibaryon trajectories?

More questions to be answered…

Conclusions

- Due to significant progress of experimental technique, new quite convincing evidences for existence of dibaryon (6*q*) states in *NN* system have been found, 50 years after their first theoretical prediction.

- Taking the intermediate isovector and isoscalar dibaryon resonances into account allows to consistently describe a number of processes accompanied with high momentum transfers, e.g., one- and two-pion production in *NN* collisions.

- Concept of σ-dressed dibaryon combined with idea of chiral symmetry restoration in dense and excited quark matter provides a new explanation for the long-standing ABC puzzle and has important consequences for treatment of short-range nuclear force.

- One can suggest the dibaryon resonances to be not only “multiquark exotics” but also a manifestation of fundamental properties of nonperturbative QCD which govern short-range *NN* interaction and correlations in nuclei.

Thank You

For Your Attention!