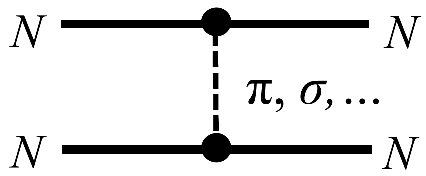
NN and *Nd* scattering with intermediate dibaryons

Maria Platonova, Vladimir Kukulin,
Lomonosov Moscow State University

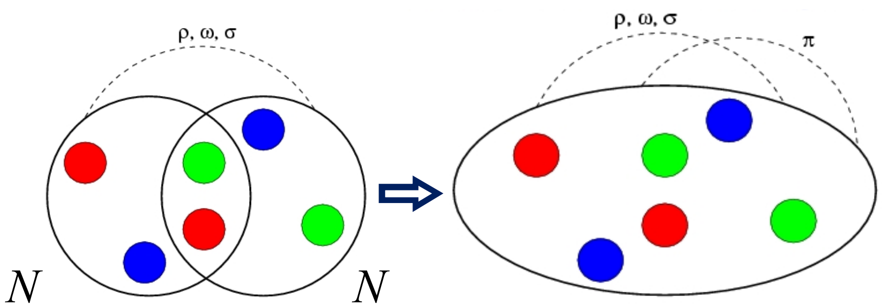
23rd European Conference
on Few-Body Problems in Physics,
August 8 - 12, 2016,
Aarhus University, Denmark

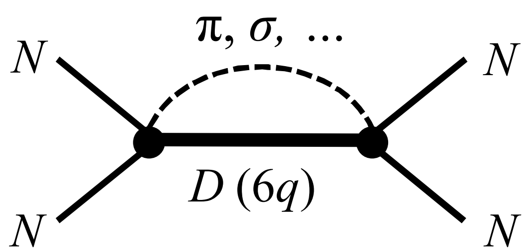
Nature of *NN* interaction

- **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:

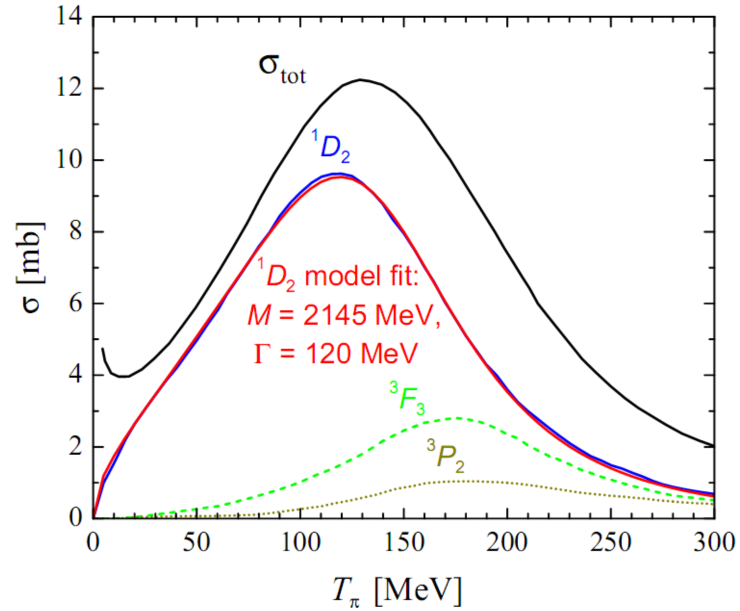
$$M(D_{12}) \approx 2160 \text{ MeV} \approx M(N) + M(\Delta) - 10 \text{ MeV},$$

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

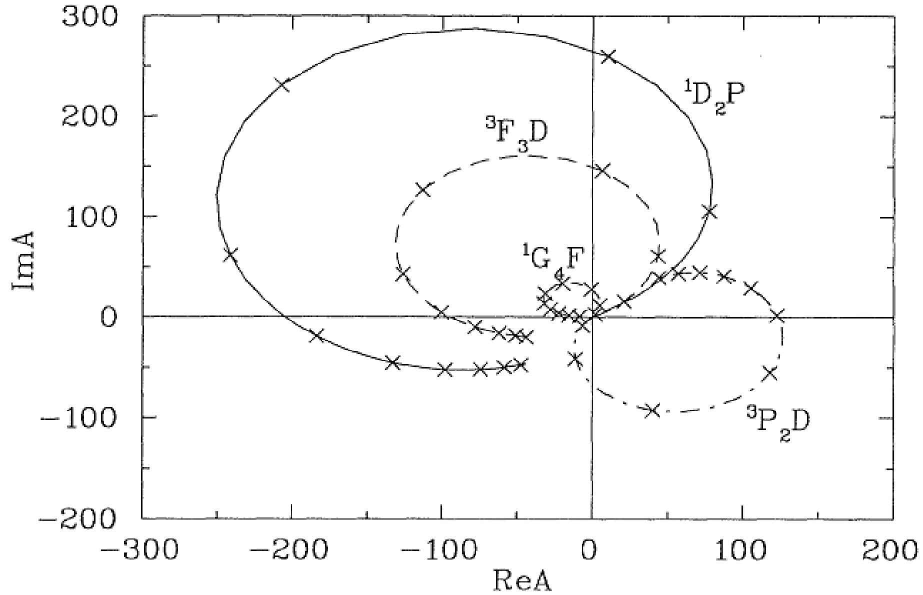
Indications of D_{12} and other isovector dibaryons

- 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 $^1D_2$, $^3F_3$, $^1G_4$, $^3P_2$, etc.
- The lowest ($^1D_2$) isovector resonance with $I(J^P) = 1(2^+)$ is the predicted D_{12} dibaryon: $M \approx 2140–2160$ 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 $\pi^+d \to pp$



R. Arndt et al., PRC48(1993)1926

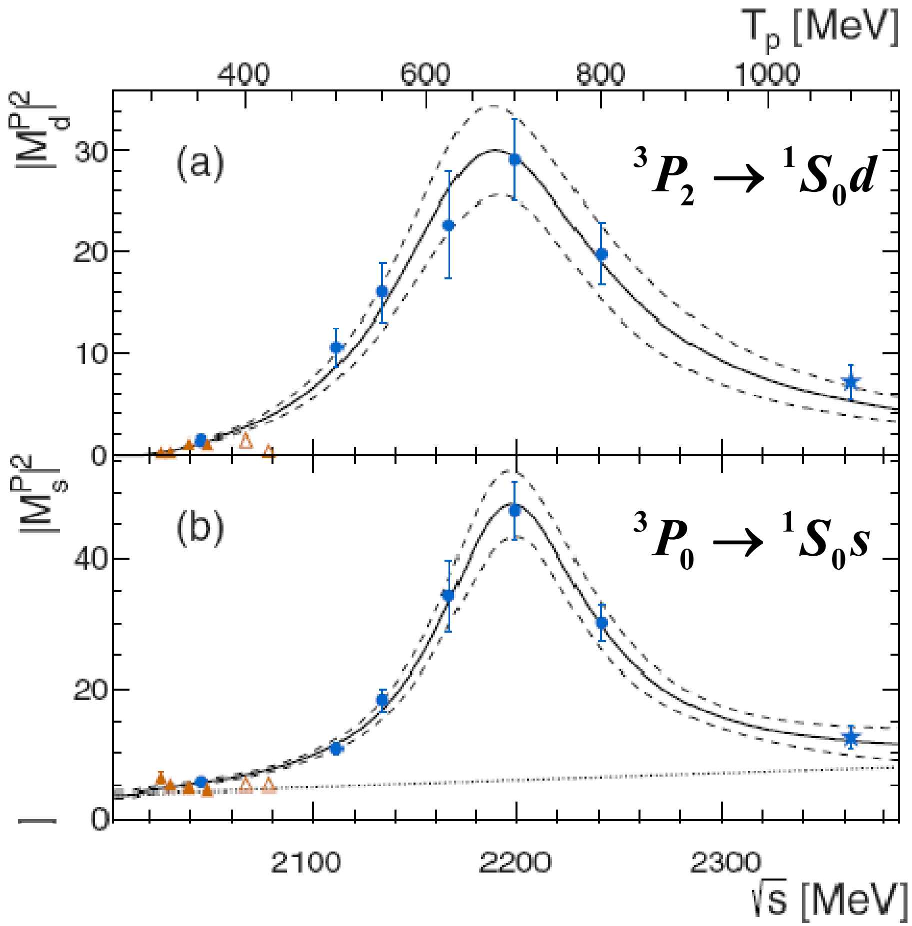
- There might be true resonances or "pseudoresonances" (intermediate $N\Delta$ states).

New evidence for isovector *P*-wave dibaryons

PHYSICAL REVIEW C **93**, 065206 (2016)

Evidence for excitation of two resonance states in the isovector two-baryon system with a mass of 2.2 GeV/ c^2

ANKE/COSY experiment (V. Komarov et al.): $p + p \to pp(^1S_0) + \pi^0$



Resonance parameters:

	E_R [MeV]	Γ_R [MeV]
$^3P_2 d(2^-)$	2197 ± 8	130 ± 21
$^3P_0 s(0^-)$	2201 ± 5	91 ± 12
$^3P_2 d(2^-)$[a]	2207 ± 12	170 ± 32
$^3P_0 s(0^-)$[a]	2204 ± 4	95 ± 9

[a] The results of the global fit

From PWA (SAID) of *pp* elastic scattering (R. Arndt et al., PRD35(1987)128):

State	W_p (MeV)
$^1D_2$	$2148 - i\,63$
$^3F_3$	$2183 - i\,79$
→ $^3P_2$	$2163 - i\,75$
$^3F_2$	$2163 - i\,75$
$^3F_4$	$2210 - i\,78$
$^3H_4$	$2210 - i\,78$

$^3P_0$ resonance was not observed before.

Evidence for isoscalar D_{03} dibaryon

Experiments on 2π production in $p+n$, $p+d$, $d+d$ collisions and $\vec{n}+p$ 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)

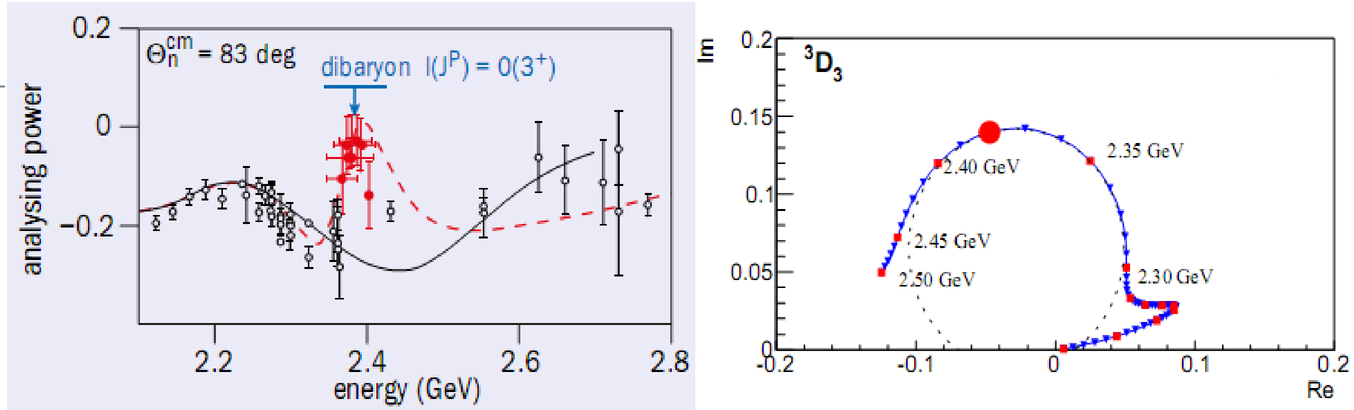
CERN Courier July/August 2014

News

NEW PARTICLES

COSY confirms existence of six-quark states

$$W_{\text{pole}} = 2380 \pm 10 - i40 \pm 5\ \text{MeV}$$



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

$D_{03} \approx \Delta\Delta(30\%) + C\bar{C}(70\%)$ [Y. Dong et al., PRC91(2015)064002; 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:

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

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

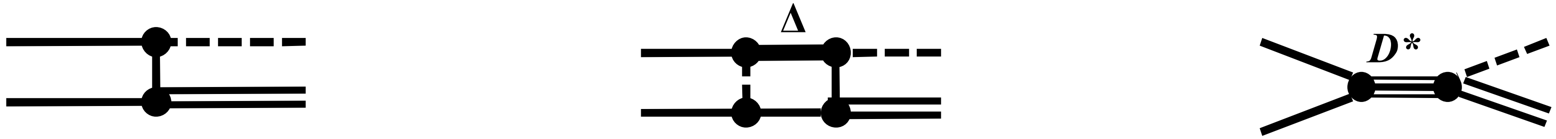
[A. Gal & H. Garcilazo, PRL111(2013)172301; NPA928(2014)73]

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

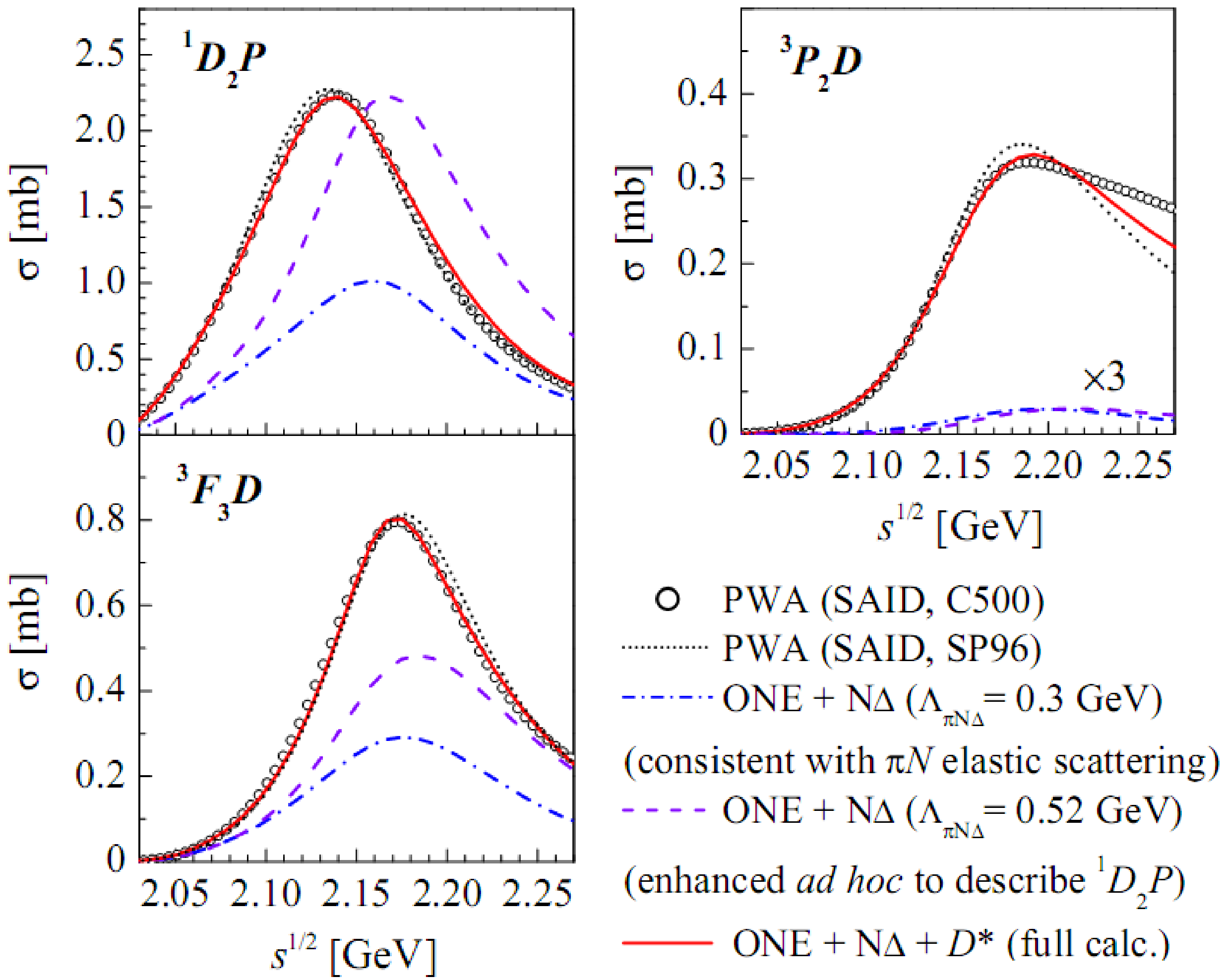
- Cross sections for dibaryon resonance production are generally small compared to the conventional meson exchange processes.
- Manifestation of dibaryon d.o.f. can be tested in processes with high momentum transfers which probe short NN distances, e.g., *inelastic NN and Nd scattering with one- or two-pion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

Dibaryons in $pp \to d\pi^+$ reaction

ONE (one-nucleon exchange) + ***NΔ*** (*N*+Δ intermediate state) + ***D**** (dibaryon resonances)



Partial cross sections for 3 dominant amplitudes:



- Conventional (ONE+NΔ) mechanisms with soft short-range cut-off $\Lambda_{\pi N\Delta}$ in the πNΔ vertex (derived from πN elastic scattering) give 40-50% of the ^1D_2P and ^3F_3D cross sections and only 2.5% of the ^3P_2D cross section.
- Enhancing $\Lambda_{\pi N\Delta}$ *ad hoc* does not help to describe all three amplitudes simultaneously.
- **We found significant contributions of intermediate dibaryons in three dominant resonant amplitudes, *especially in the ^3P_2D one.***

[M.N.P. & V.I.K., NPA946 (2016) 117 and to be published]

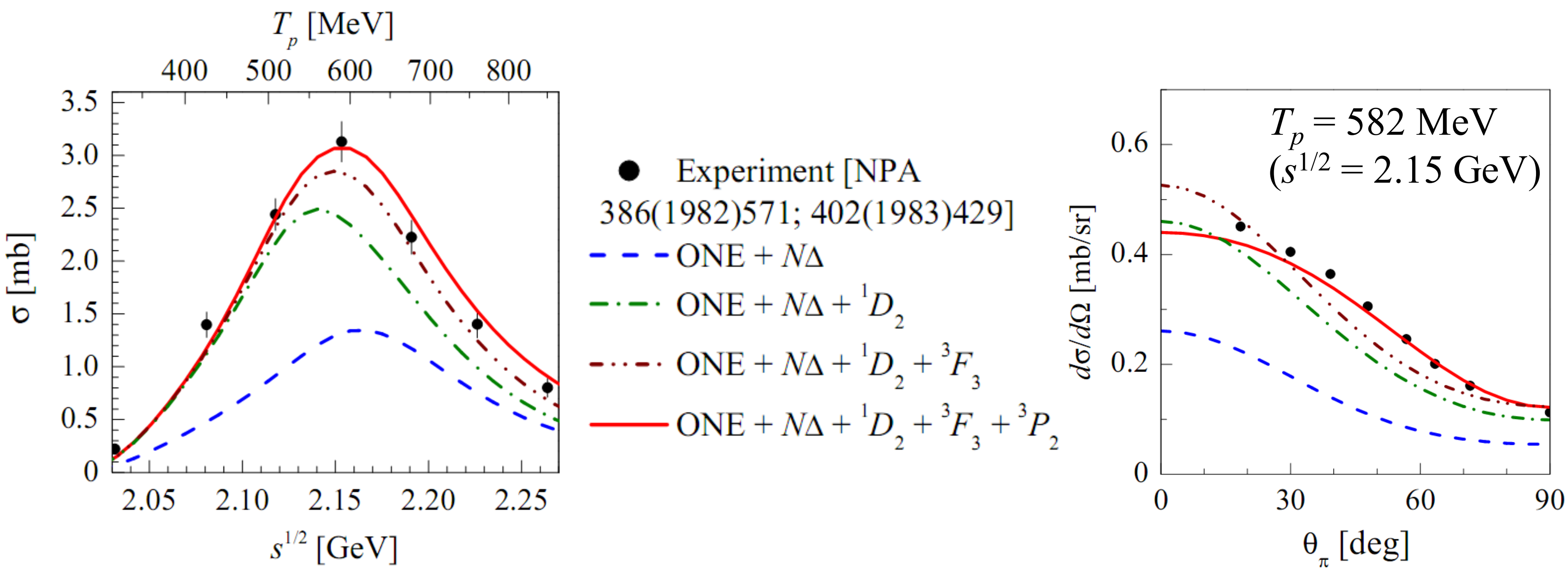
Dibaryons in $pp \to d\pi^+$ reaction

Dibaryon resonance parameters:

(Cf. new ANKE exp. results on $pp \to pp(^1S_0) + \pi^0$ [PRC93(2016)065206] for $^3P_2$ resonance: $M = 2207 \pm 12$ MeV, $\Gamma = 170 \pm 32$ MeV)

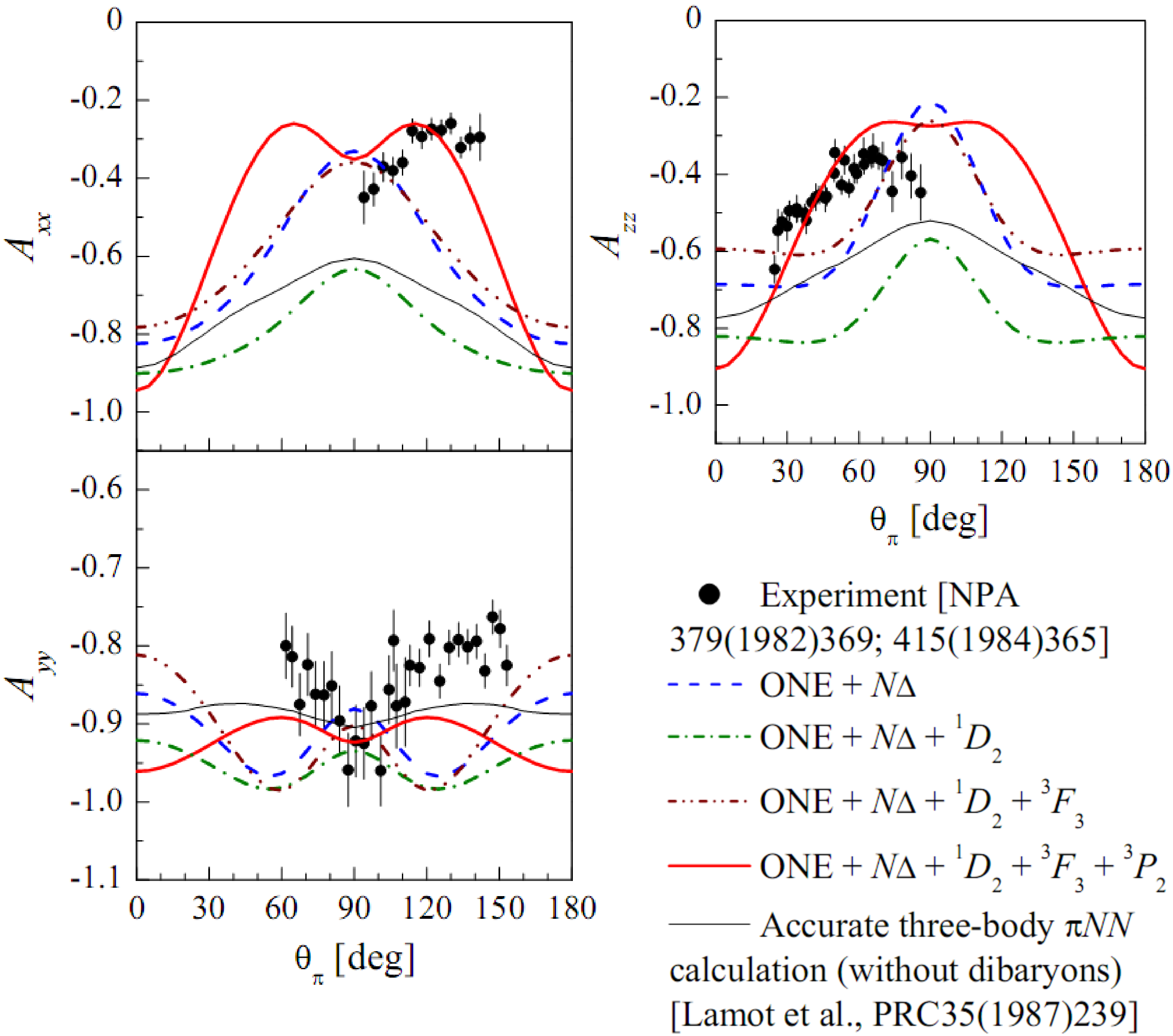
$^{2S+1}L_J$	M_D (MeV)	Γ_D (MeV)
$^1D_2$	2155	101
$^3F_3$	2197	152
$^3P_2$	2211	195

Results for the total and differential cross sections:



For unpolarized cross sections, the proper description of two dominant ^1D_2P and ^3F_3D amplitudes is the most important; the ^3P_2D amplitude gives just a moderate correction.

Results for spin-correlation parameters at T_p = 582 MeV



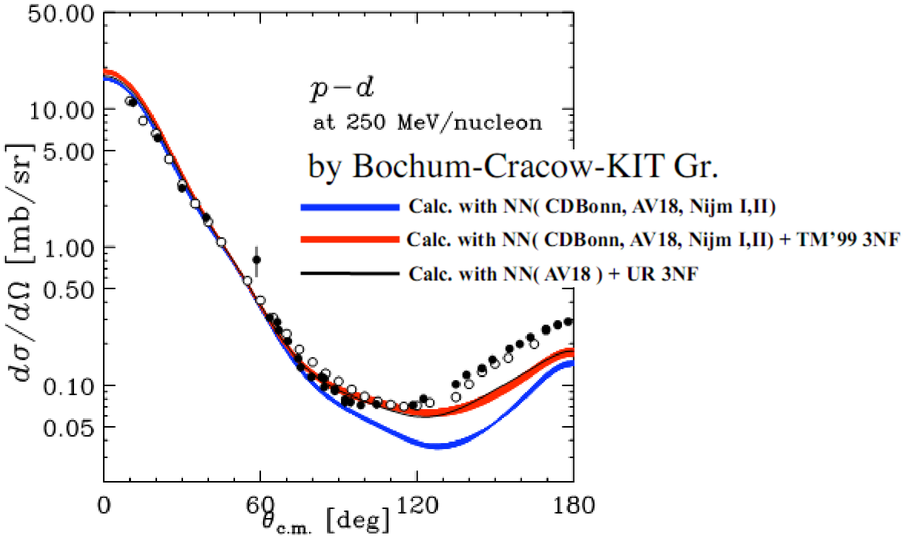
[M.N.P. & V.I.K., to be published]

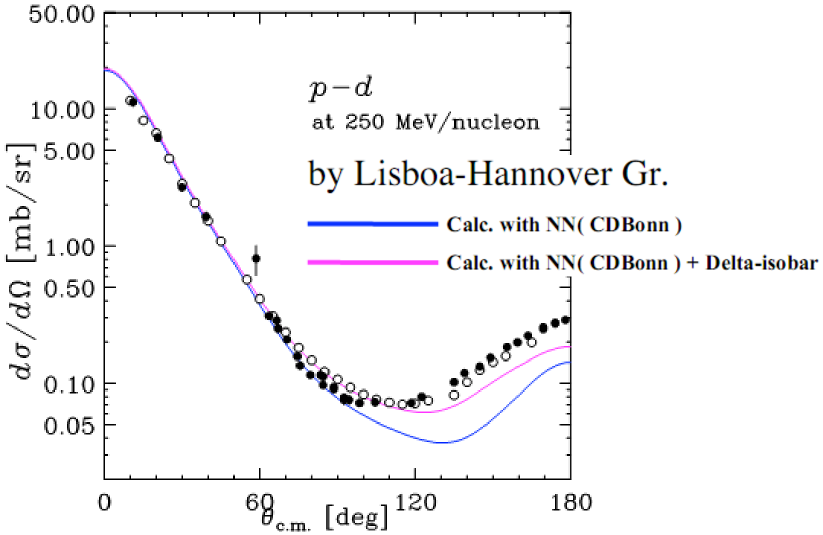
- Very sensitive spin-correlation parameters:
  no satisfactory description by conventional models.
  Adding $^1D_2$ and $^3F_3$ dibaryons does not help either.
- **Just the proper description of the** ***^3P_2D amplitude (dominated by a dibaryon resonance)*** **changes the behavior of these observables, thus turning them into qualitative (or even semiquantitative) agreement with experimental data.**

Puzzling *pd* large-angle scattering

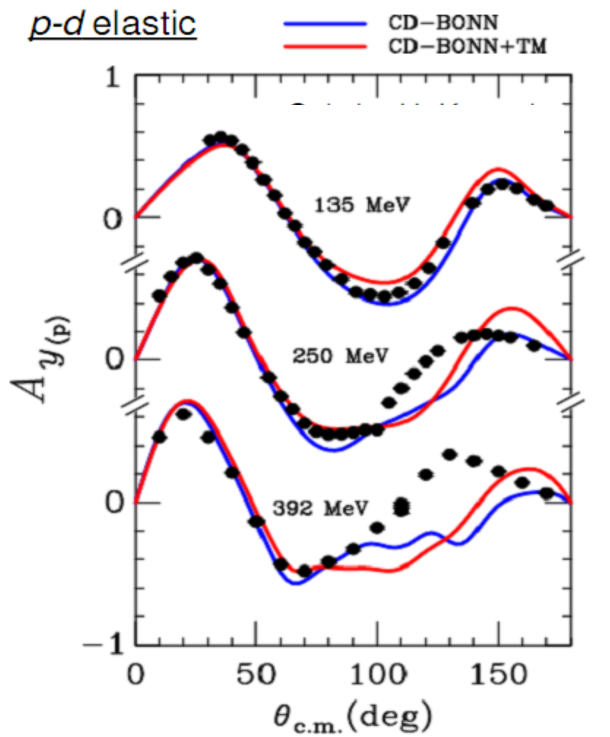
Exp. data vs. 3-body Faddeev calculations

Differential cross section





Proton analyzing power

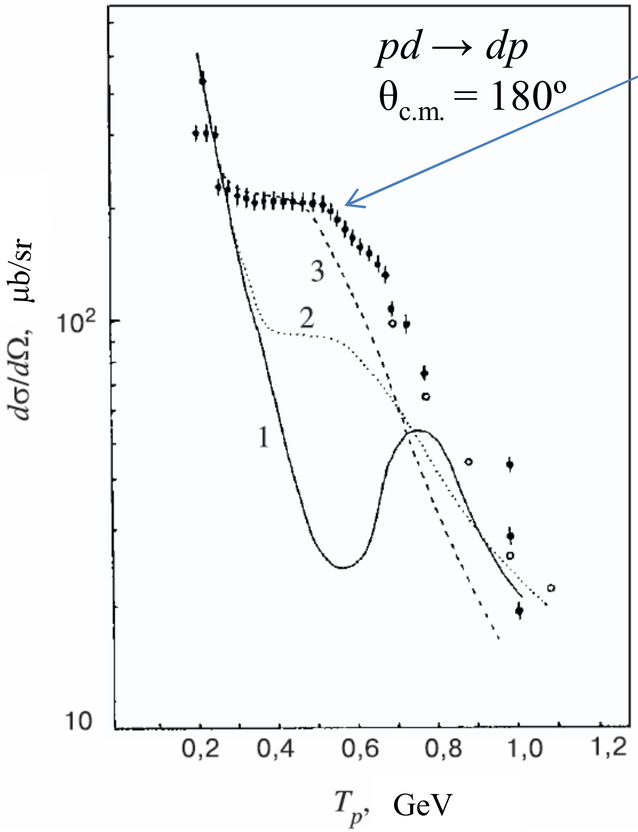


- Similar results for diff. cross section and polarization observables
- Large-angle discrepancy increases with energy
- Adding 2π-exchange 3*N* force with intermediate Δ improves description of data only partially

Exp.: PRL 86 (2001) 5862; PRC 66 (2002) 044002; AIP Conf.Proc. 915 (2007) 765;
Figs. from talks K. Sekiguchi, FB19 and K. Suda, SPIN2007

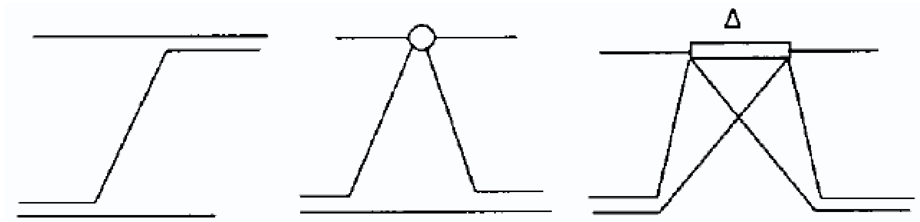
Puzzling *pd* large-angle scattering

Energy dependence of *pd* backward cross section:



Similar "bumps" arise in *d*-fragmentation *d*+A → *p*+X [see, e.g., V. Ableev et al., NPA 393(1983)491]

<u>*The model*</u>: ONE + Single scattering + Δ excitation



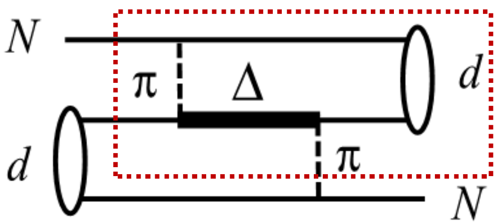
[Yu. Uzikov, Fiz.Elem.Chastits.At.Yadra 29 (1998) 1405]

1,2,3 – different parameterizations of *NN* → *N*Δ ampl.;

3 – fit to pn → pnπ⁺, best fit to *pd* → *dp*.

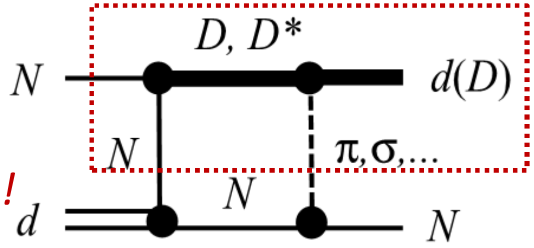
If dibaryons are manifested in *NN* → *d*π & *NN* → *NN*π, they should also contribute to *pd* → *dp* and *dp* → *pnp*.

Conventional 2π-exchange 3N force:



*Both mechanisms include NN → d*π *in the same energy region!*

Additional 3*N* force –
meson exchange between nucleon and dibaryon
(*D* – dibaryon component of the deuteron,
*D** – excited dibaryon (resonance)):

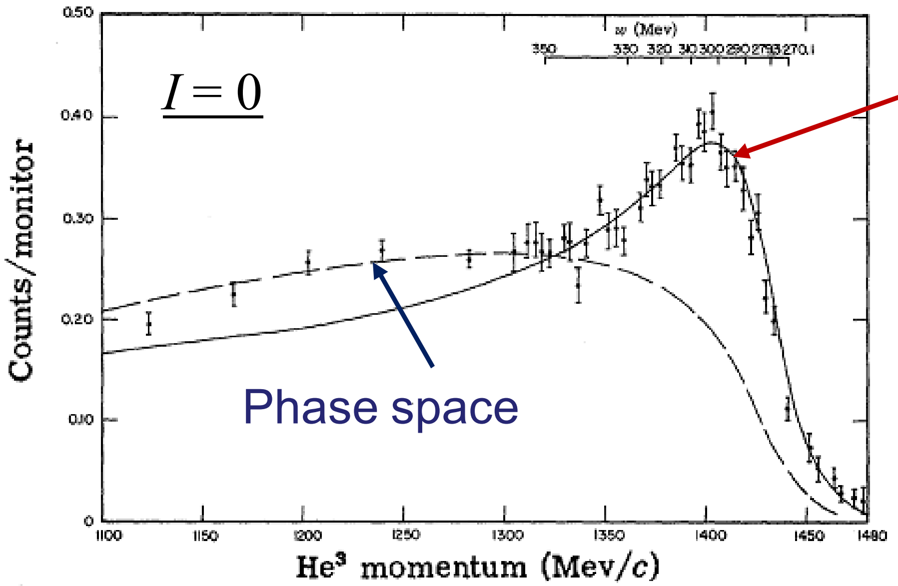


Dibaryons in 2π production and ABC effect

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

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

Observation of an anomalous enhancement just above 2π-production threshold



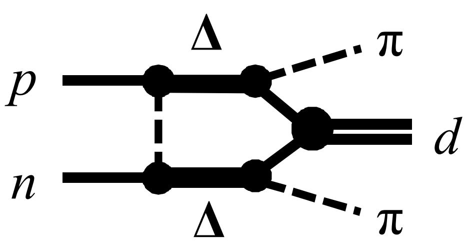
ABC effect: $I(J^P) = 0(0^+)$,
$m_X \approx 300$ MeV $= 2m_{\pi^0} + 30$ MeV

Later on the similar enhancements were observed in reactions

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

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

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



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 exclusive data.

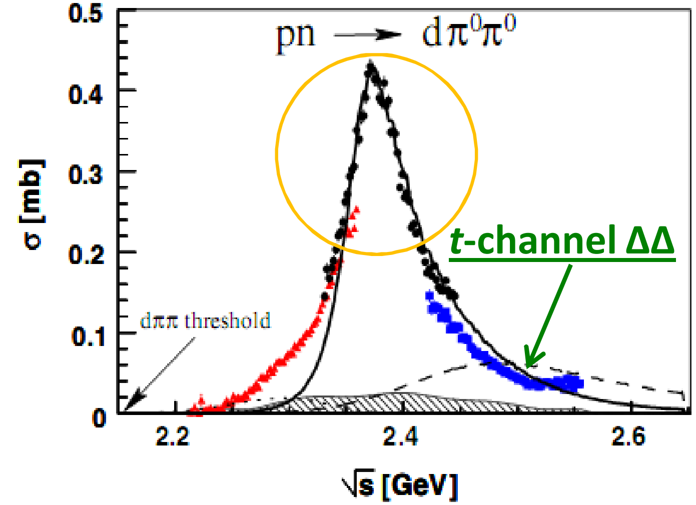
New exclusive experiments of the WASA@COSY Collaboration

First exclusive high-statistics experiments in full 4π geometry

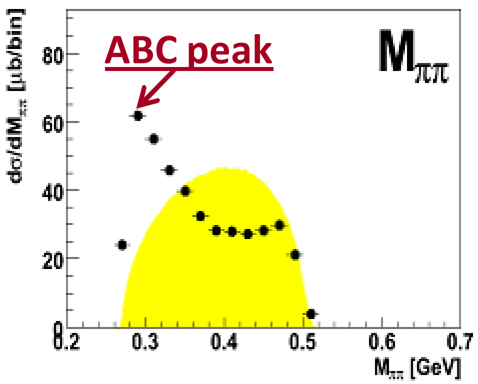
$$p + d \to p_{\text{spectator}} + d + \pi^0\pi^0, \quad T_p = 1.0 - 1.4 \text{ GeV}$$

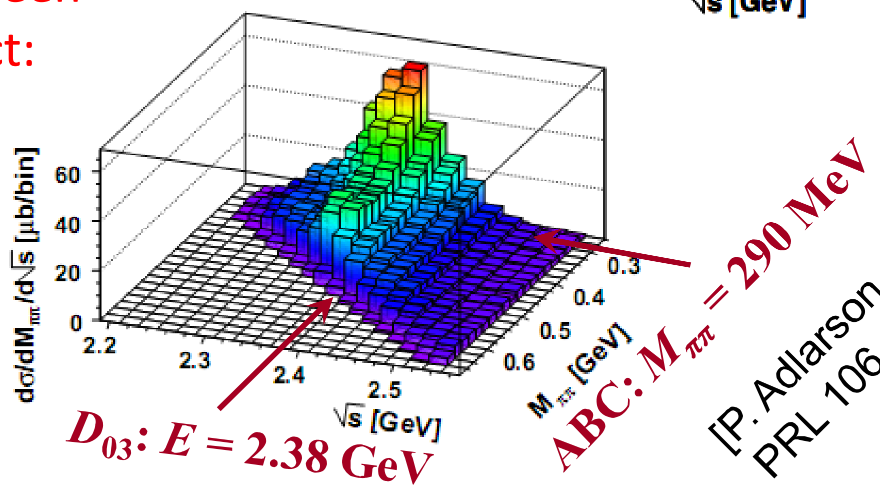
Experimental data have clearly shown production of isoscalar dibaryon resonance D_{03} with parameters:

$$I(J^P) = 0(3^+)$$
$$M \approx 2380 \text{ MeV} = 2M_\Delta - 80 \text{ MeV}$$
$$\Gamma \approx 70 \text{ MeV} \ll 2\Gamma_\Delta = 235 \text{ MeV}$$



and direct interrelation between this resonance and ABC effect:

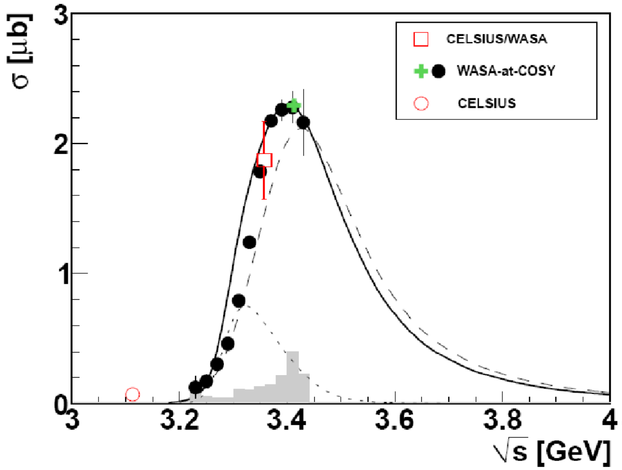


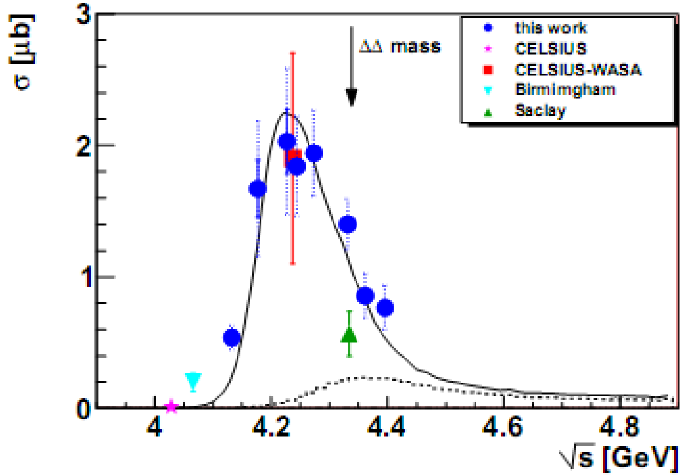


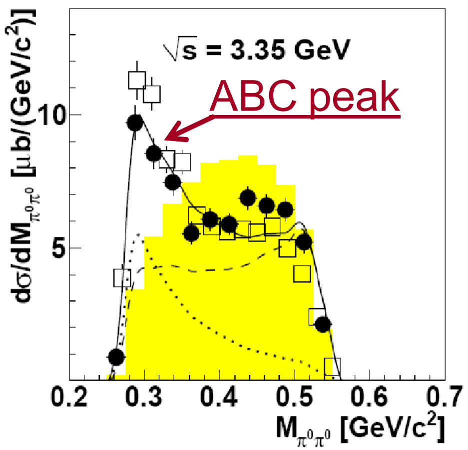
[P. Adlarson et al., PRL 106 (2011) 242302]

New exclusive experiments of the WASA@COSY Collaboration

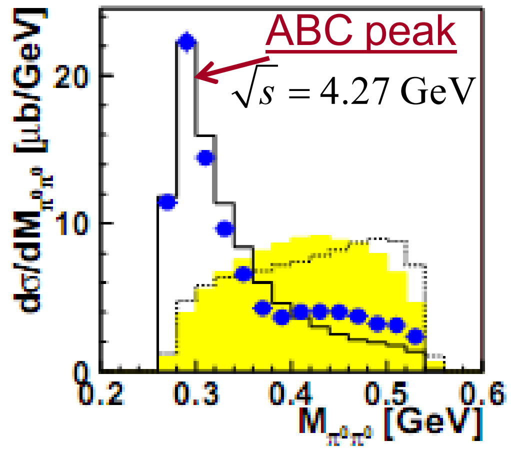
The same isoscalar resonance along with ABC enhancement were then observed also in $pd \rightarrow {}^3\text{He} + \pi^0\pi^0$ and $dd \rightarrow {}^4\text{He} + \pi^0\pi^0$ [P. Adlarson et al., PRC 91 (2015) 015201; 86 (2012) 032201].







"That way the ABC effect in the double-pionic fusion to nuclei is traced back to a ***pn* resonance**, which obviously is strong enough to survive even in the nuclear medium." – P. Adlarson *et al.*, PRC 86 (2012) 032201



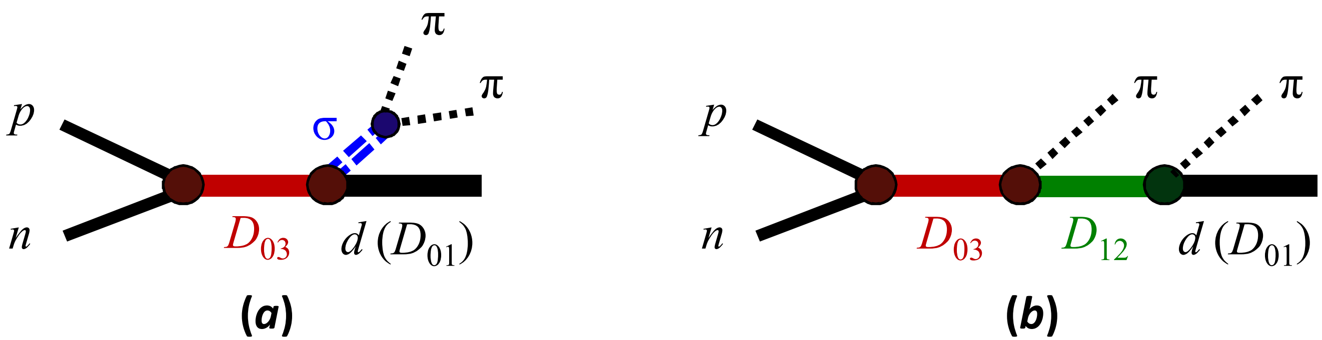
What mechanism of the D_{03}-resonance decay leads to ABC enhancement?

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

- Dibaryon 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 $D_{12}(2150)$

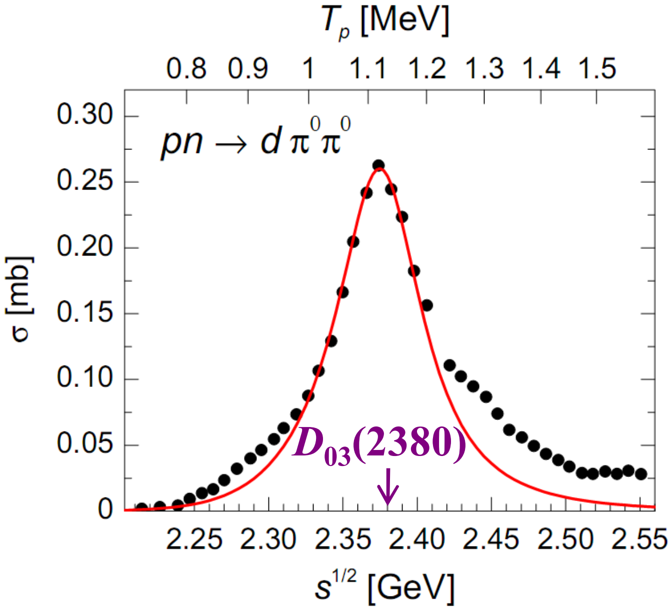


- Transitions between different dibaryon states are considered *for the first time*, similarly to the known transitions between baryons (cf. the Roper resonance decay routes: $N^*(1440) \to N + \sigma \to N + \pi\pi$ and $N^*(1440) \to \Delta(1232) + \pi \to N + \pi\pi$).
- Invariant mass distribution: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

[M.N.P. & V.I.K., PRC 87 (2013) 025202]

Results of the model calculations

I. Total Cross Section



● **Experiment WASA@COSY** [PRL106(2011)242302, renorm. in PLB721(2013)229]

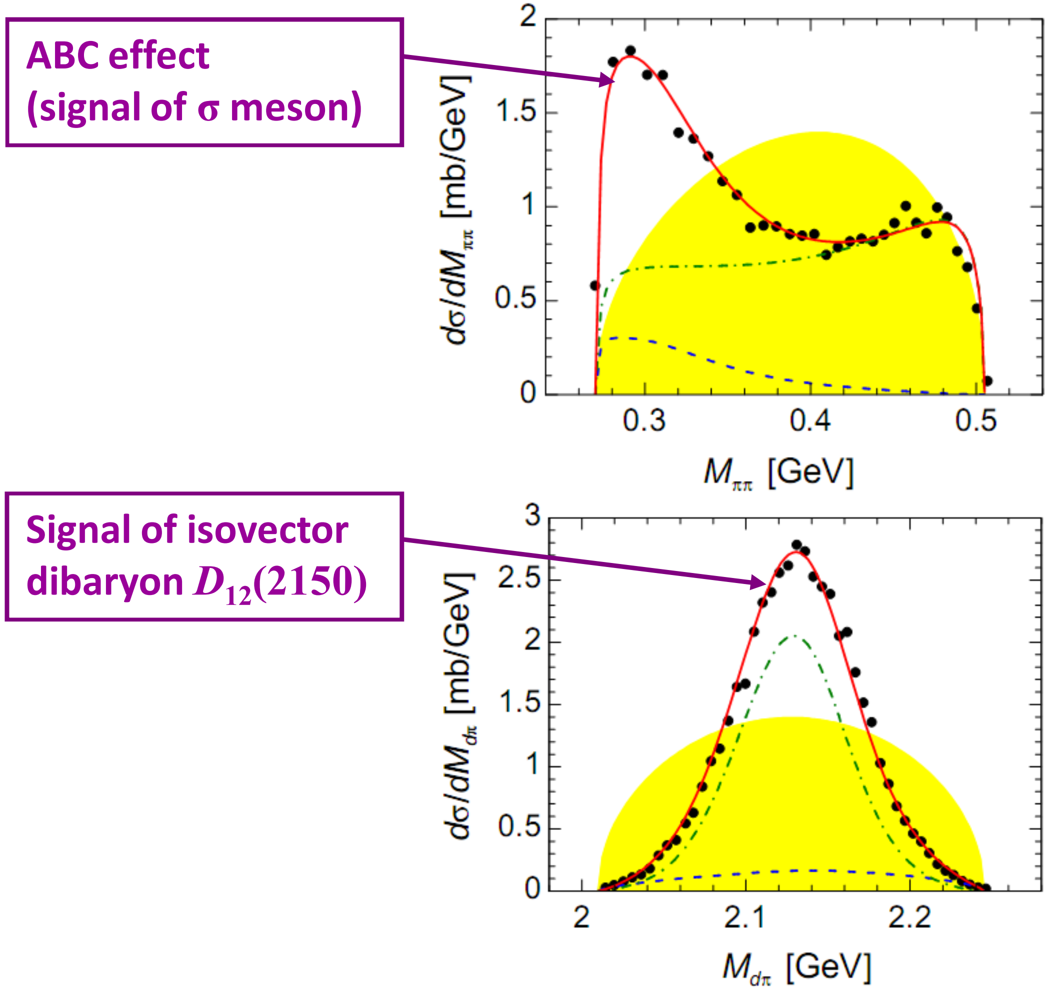
phase space

$D_{03} \to d + \sigma$

$D_{03} \to D_{12} + \pi$

Full calculation

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



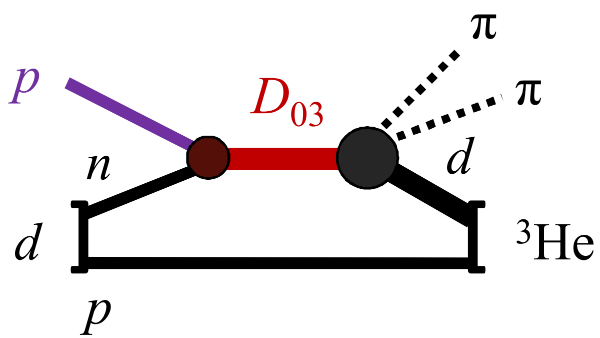
- ✓ ABC enhancement appears as a consequence of σ meson production.
- ✓ Peak in $M_{d\pi}$ spectrum reflects production of isovector dibaryon $D_{12}(2150)$.
- ✓ Other isovector dibaryons should also contribute, but would be less intensive and further suppressed by an angular momentum barrier (d-wave pions).

Extension to $pd \to {}^3\text{He} + (\pi\pi)_0$

- At the experimental total cross section peak in $pd \to {}^3\text{He} + \pi^0\pi^0$:

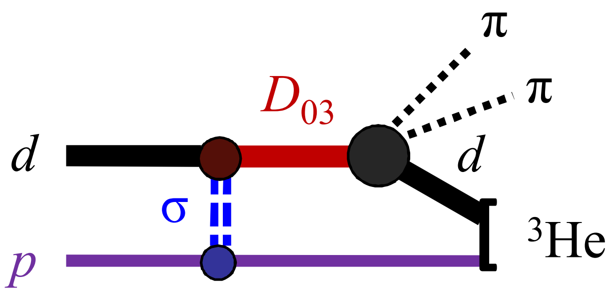
$$\left(\sqrt{s}\right)_{pd} = 3.35\,\text{GeV},\, T_p = 0.88\,\text{GeV} \Rightarrow \left(\sqrt{s}\right)_{pn} \approx 2.28\,\text{GeV}$$

- One possible mechanism – the same as in $pn \to d + \pi^0\pi^0$ (WASA@COSY):



$$E^*_{pn} \approx 400\,\text{MeV}\ (\approx 500 \pm 35\ \text{MeV needed for } D_{03})$$

- We propose also a different mechanism – **D_{03} excitation from the deuteron as a whole (i.e., from its short-range dibaryon component) by, e.g., σ exchange**



$$E^*_{pd} = 530\,\text{MeV}$$

- Relative contributions of different mechanisms to *pd* double-pionic fusion need more detailed investigation. Calculations in progress…

Parameters of the σ meson

- From our 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 (2013) 025202]

- 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 (2006) 132001]

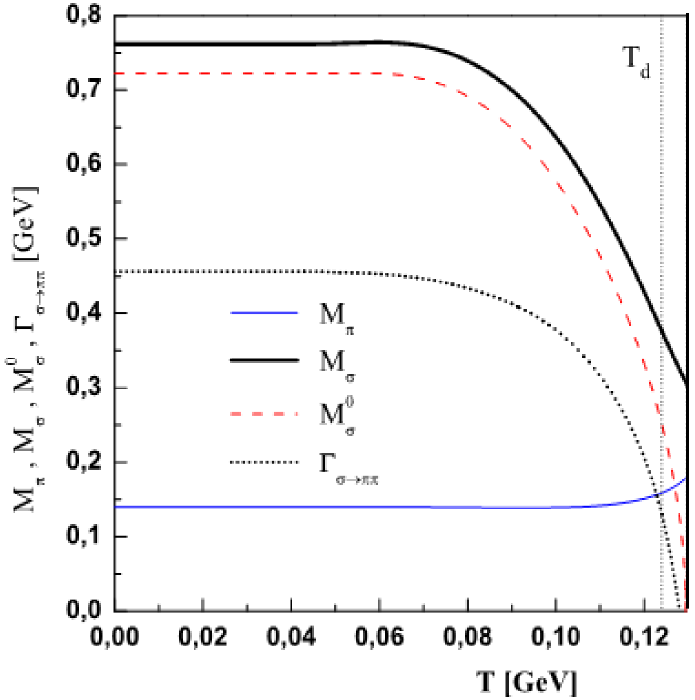
Is there a real contradiction?

Chiral Symmetry Restoration (χSR)

- Two basic phenomena of nonperturbative QCD:
  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.

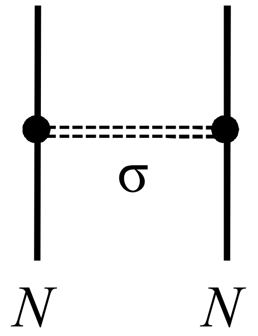
  This can be visible in parameters of σ mesons produced from dibaryons.

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

Basic *NN* attraction in nuclei and scalar σ meson

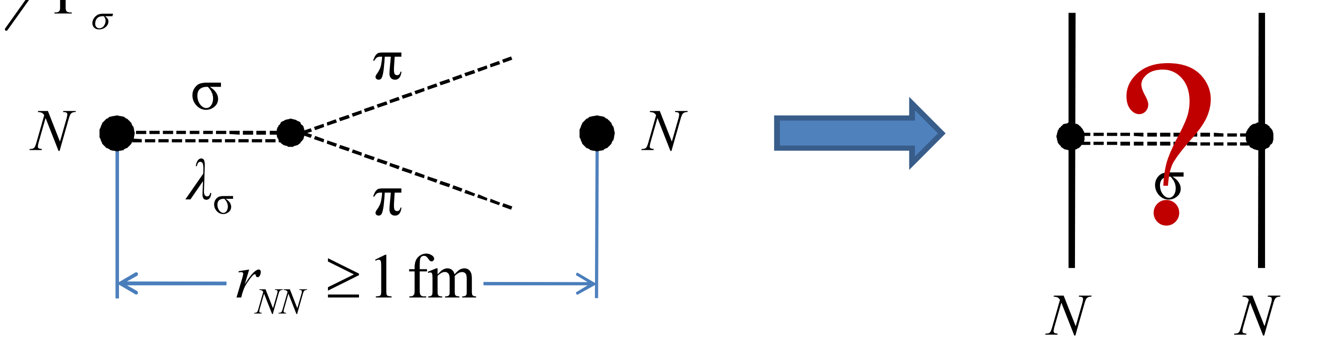
- Light scalar meson σ (or $f_0(500)$), $I(J^P) = 0(0^+)$, plays a fundamental role
  - in QCD (provides hadron masses through chiral symmetry breaking; is sometimes called the "*Higgs boson of strong interaction*" [M. Schumacher, Eur.Phys.J.C67(2010)283]),
  - in nuclear physics (responsible for the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

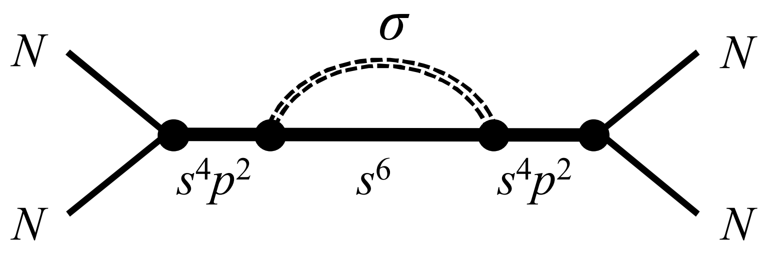
- $\tau \simeq \hbar / \Gamma_\sigma$; $\lambda_\sigma \simeq c \cdot \tau \simeq 0.4$ fm — path length for an unstable σ-meson



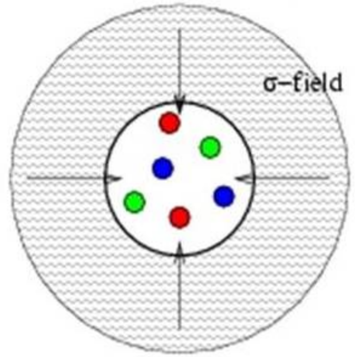
- **Such highly unstable σ meson can hardly bind the nucleons in nuclei! Need some physical mechanism to stabilize the scalar σ field.**

The σ-dressed dibaryon model for short-range *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. G 27 (2001) 1851]



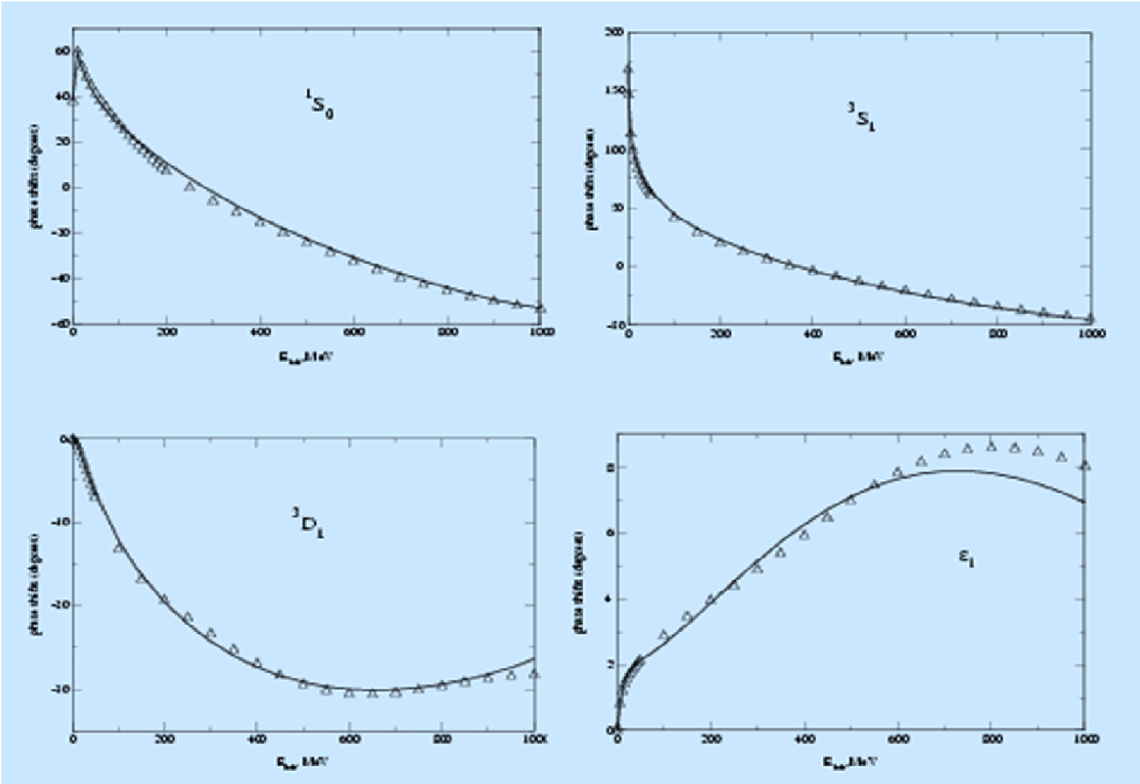
- Scalar σ field arises within a transition from the dominant ($2\hbar\omega$-excited) mixed-symmetry $6q$ configuration s^4p^2 to a fully symmetric one s^6:

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

- 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 partial *χ*SR in excited 6*q* bag).

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. E 11 (2002) 1]

- If this picture is realized in Nature, dibaryon states should be produced *in all NN partial waves* (however, with different probabilities).
- Further tests of the model in few-nucleon systems and nuclear matter are needed.

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

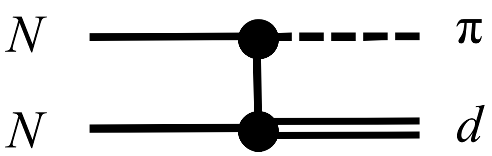
- Concept of σ-dressed dibaryon combined with idea of chiral symmetry restoration in dense and excited quark matter provides a new explanation for the long-standing ABC puzzle and has important consequences for treatment of short-range nuclear force.

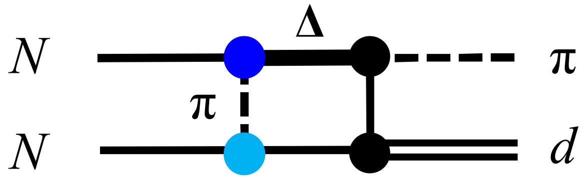
- One can suggest the dibaryon resonances to be not only “multiquark exotics” but also a manifestation of fundamental properties of nonperturbative QCD which govern short-range *NN* interaction and correlations in nuclei.

Thank You!

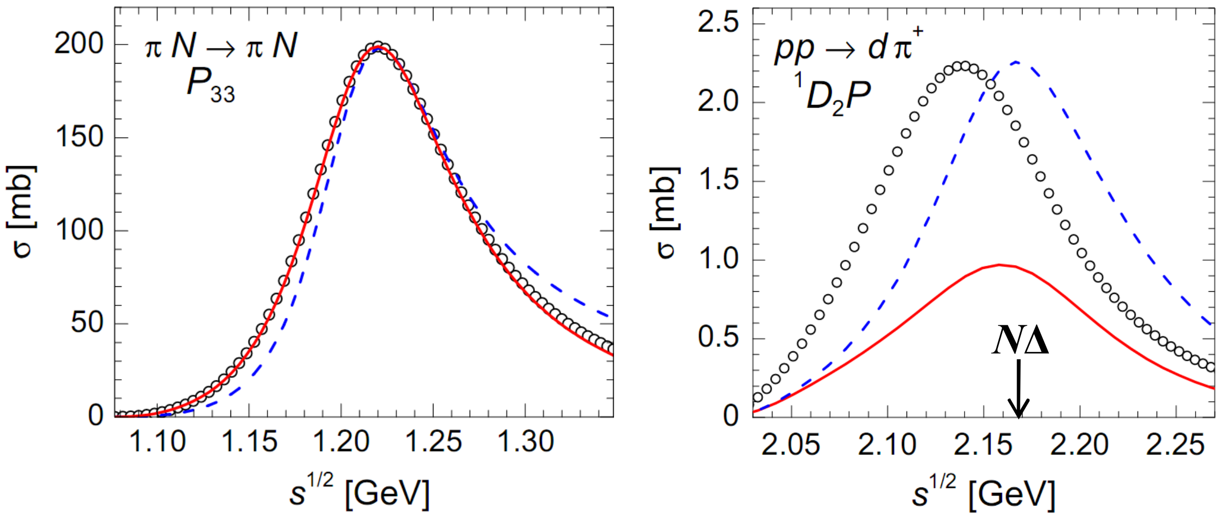
Conventional description for $pp \to d\pi^+$:

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.)

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

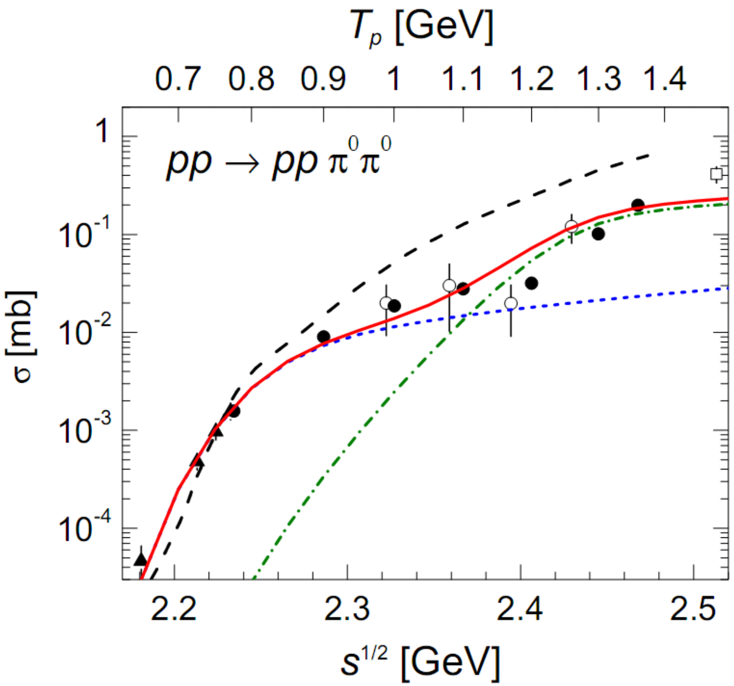
○ **PWA (SAID)**

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

- - - **$\tilde{\Lambda}_* = 0.52$ GeV ($\Lambda_* = 0.68$ GeV)** (blue dashed)

- 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.
- The magnitude of the $pp \to d\pi^+$ cross section can be approximately reproduced by enhancing the $\pi N\Delta$ cut-off value. However, this way is fully *ad hoc*.
- *An alternative way:* taking the intermediate dibaryon resonances in the NN channels $^1D_2$, $^3F_3$, $^3P_2$, etc., into account.

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



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

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

——— Alternative (dibaryon) model:

$$D^-_{13}(2220)\,[^3F_3] + D_{14}(2430)\,[^1G_4]$$

(dotted blue: D^-_{13}; dash-dotted green: D_{14})

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

- 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.*

The deuteron in dibaryon model

- The deuteron wave function (d.w.f.) in dibaryon model is described as a two-component Fock column:

$$\Psi_d = \begin{pmatrix} \Psi_{NN} \\ \Psi_{6q+\sigma} \end{pmatrix}$$

- The second component of the deuteron $\Psi_{6q+\sigma}$ is a 6q bag surrounded by σ-meson cloud, in the same way that the nucleon is a 3q bag dressed with pion cloud.
- However, closeness to *NN* threshold makes this "elementary deuteron" to be coupled strongly to *NN* channel. As a result, the quark-meson component $\Psi_{6q+\sigma}$ gives just a small contribution (~ 2–3%) to the total d.w.f. normalization, however it is still dominant at short *NN* distances, i.e., when two nucleons are overlapped with each other.
- Analogously, the D_{12} and D_{03} states may be considered as dressed dibaryons coupled to *N*Δ and ΔΔ channels, respectively.
- We claim that D_{12} and D_{03} resonances may be treated as excited states of the deuteron D_{01}, in the same way that nucleon resonances Δ, *N**(1440), etc., are treated as excited nucleon states.

The role of the σ meson in heavy-ion collisions at ultra-relativistic energies

A. Andronic, P. Braun-Munzinger, J. Stachel
Phys. Lett. B673(2009)142; nucl-th/0812.1186

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

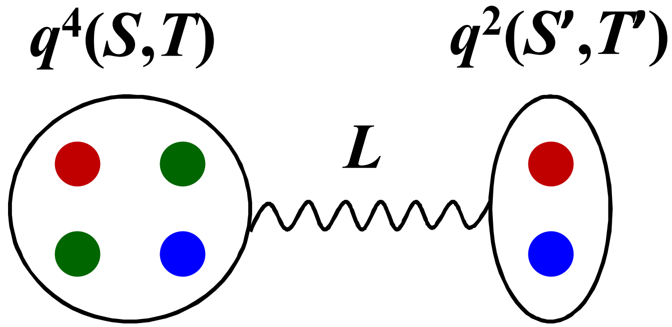
"In summary, we have demonstrated that by inclusion of the σ meson and many higher mass resonances into the resonance spectrum employed in the statistical model calculations an improved description is obtained of hadron production in central nucleus-nucleus collisions at ultra-relativistic energies."

"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."

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)



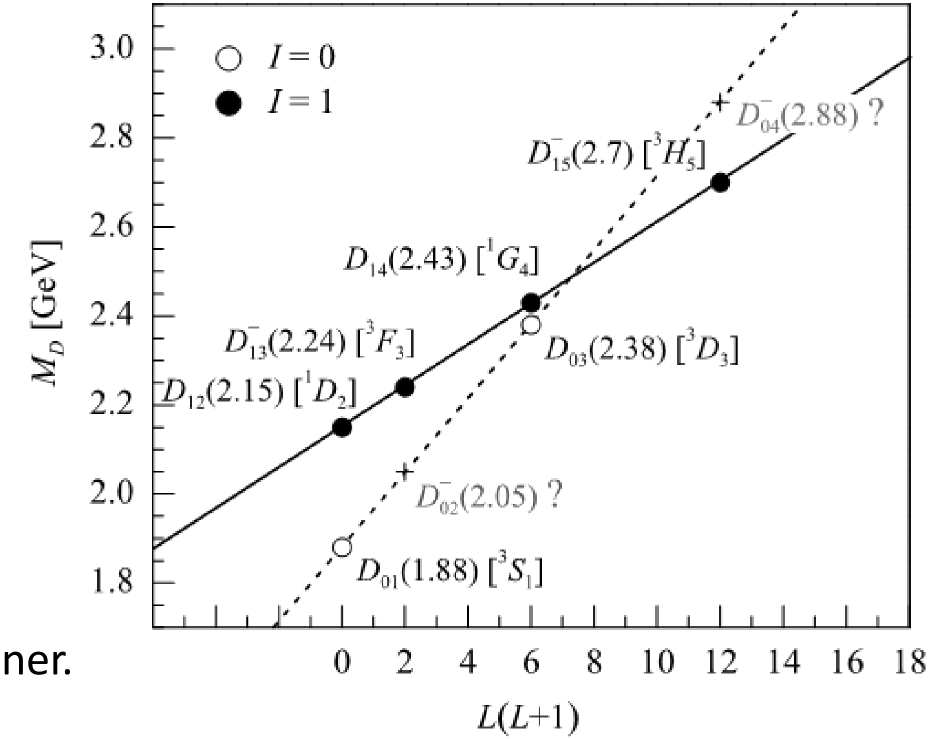
- For the lowest states $(\Delta M \ll M_0)$:
  non-relativistic rigid-rotor model

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

  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…

[M.N.P. & V.I.K., NPA 946 (2016) 117]