Dibaryon resonances and three-body forces in large-angle *pd* scattering at intermediate energies

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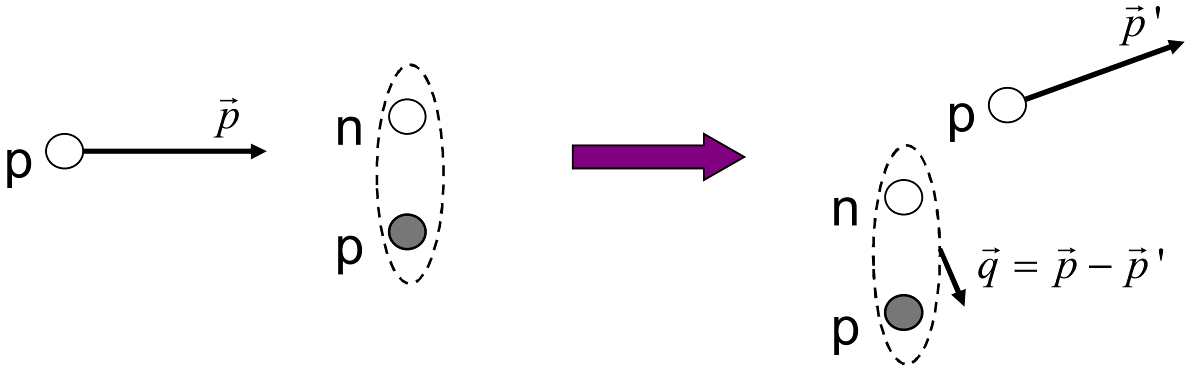
Proton-deuteron scattering at intermediate energies

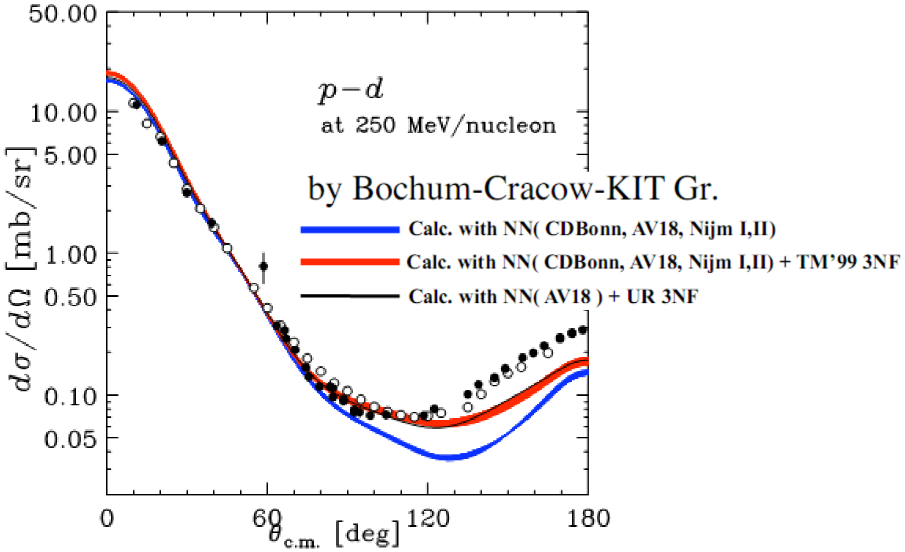


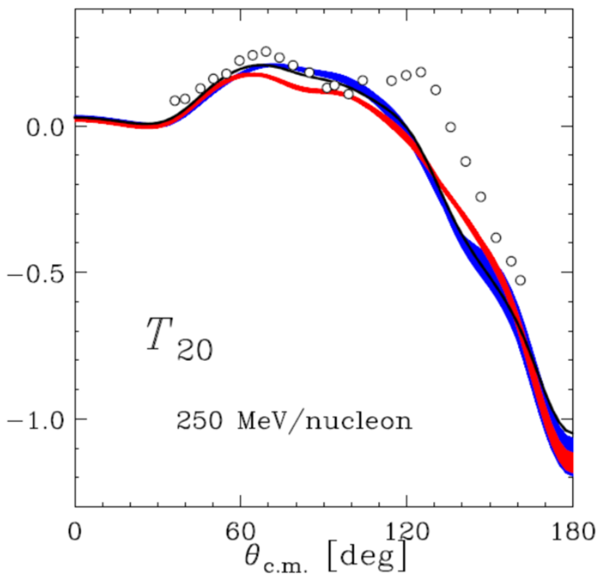
- **Small-angle *pd* scattering:** described perfectly by Faddeev calculations with modern high-precision *NN* potentials (at energies $T_p < 350$ MeV) or Glauber diffraction model (at energies from ~200 MeV to several GeV).

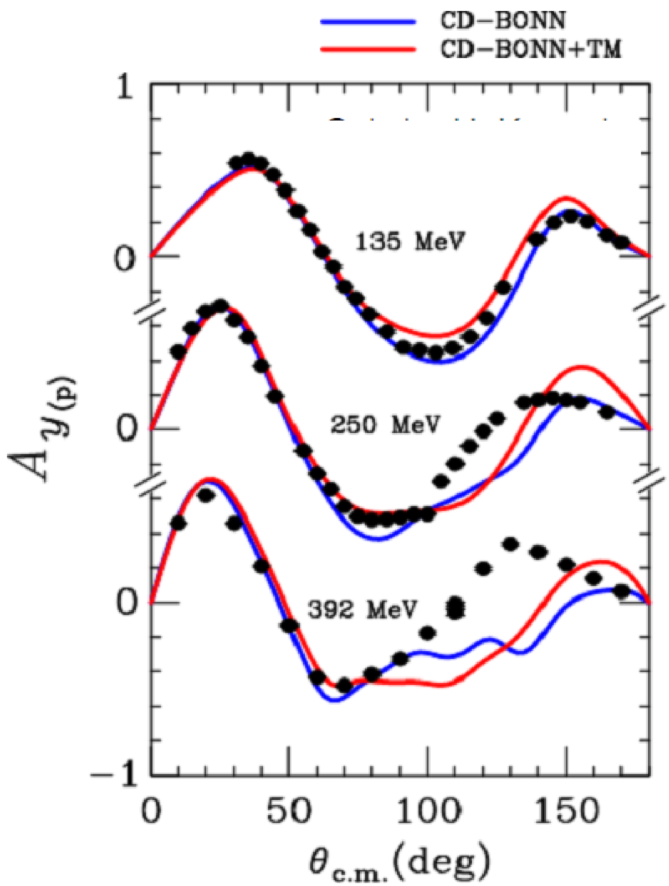
- **Large-angle *pd* scattering: a long-standing puzzle.** No satisfactory explanation by Faddeev calculations with modern 2*N* and 3*N* forces or phenomenological models at $T_p > 200$ MeV.

Puzzling large-angle *pd* scattering

Exp. data vs. 3-body Faddeev calculations





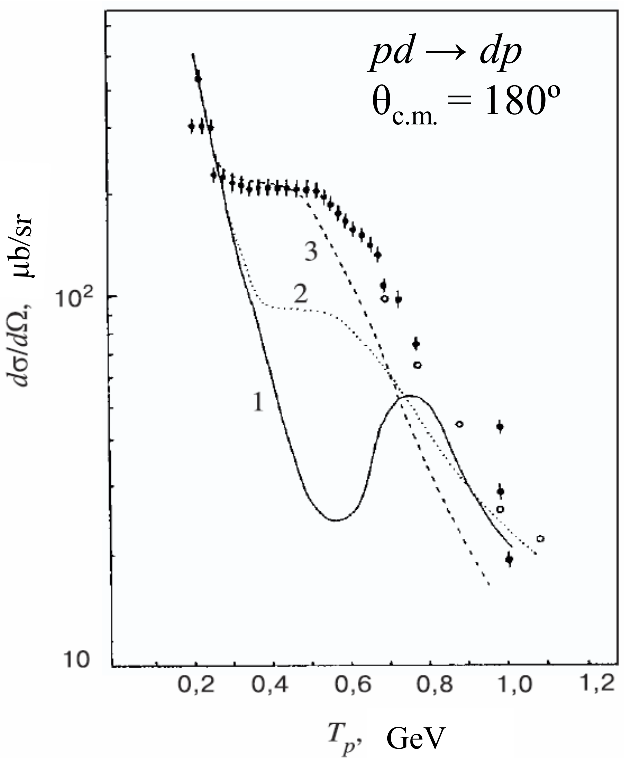


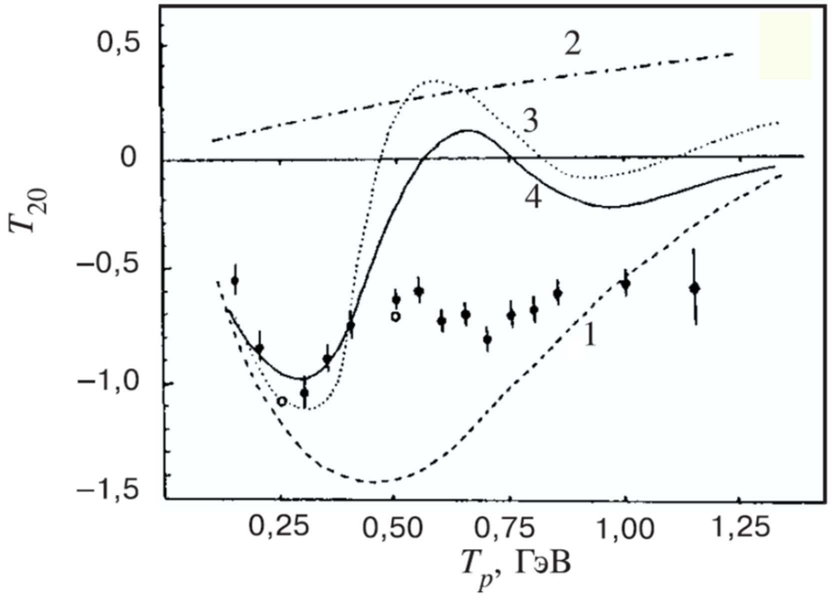
- Similar discrepancies for diff. cross section and polarization observables at T_p > 200 MeV.
- Large-angle discrepancy increases with energy.
- Adding 2π-exchange 3*N* force with intermediate Δ isobar improves description of data only partially.

Figs. from K. Sekiguchi et al., PRC89(2014)064007, talk at FB19 and K. Suda, talk at SPIN2007

Puzzling large-angle *pd* scattering

Energy dependence of *pd* backward cross section and deuteron tensor analyz. power:

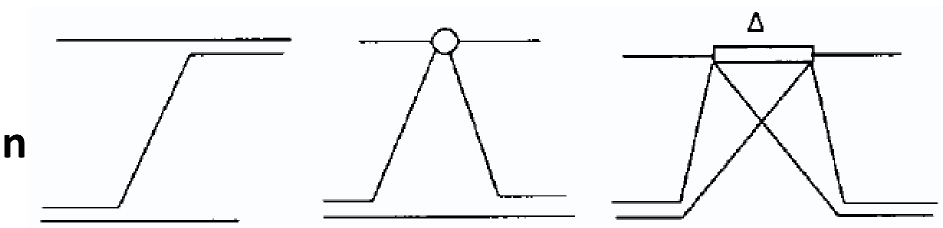




dσ/dΩ: 1,2,3 – different parameterizations of $NN \to N\Delta$ ampl.
T_{20}: 1 – ONE, 2 – Δ, 3 – ONE+SS+Δ, 4 – ONE+SS+Δ+TBR

The model: **ONE + Single scattering + Δ excitation**

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

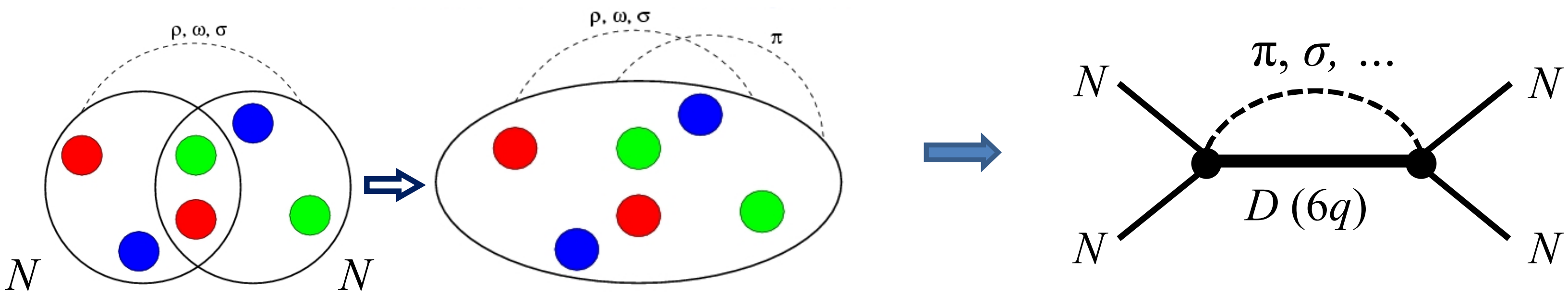


Improvement of data description by the Δ excitation mechanism is significant but strongly model dependent and not satisfactory at T_p > 400 MeV.

Inclusion of double scattering without Δ is also important at large angles, but sizeable discrepancies still remain [N.B. Ladygina, EPJA 52 (2016) 199; 56 (2020) 133].

Short-range *NN* interaction

- *pd* large-angle scattering is accompanied by large momentum transfers to the deuteron -> probes the short-range *NN* interaction.
- At distances r_{NN} < 1 fm two nucleons are overlapped with each other -> their quark structure should be taken into account.
- At short *NN* distances, a 6*q* bag (*dibaryon resonance*) dressed with meson fields might be produced; such mechanisms are absent in OBE models but predicted in QCD.
- A simple and effective way to account for the quark d.o.f. in *NN* interaction: include the 6*q* intermediate state (dressed dibaryon) via *s*-channel exchange mechanism (in addition to the *t*-channel meson exchange at large *NN* distances).



Modern experimental status of dibaryon resonances

- First theoretical prediction of 6 low-lying dibaryon states D_{IJ} on the basis of SU(6) symmetry - F.J. Dyson and N.-H. Xuong, PRL 13 (1964) 815:

  D_{01} and D_{10} near *NN* threshold (deuteron and singlet deuteron),

  D_{12} and D_{21} near *NΔ* threshold,

  D_{03} and D_{30} near *ΔΔ* threshold.

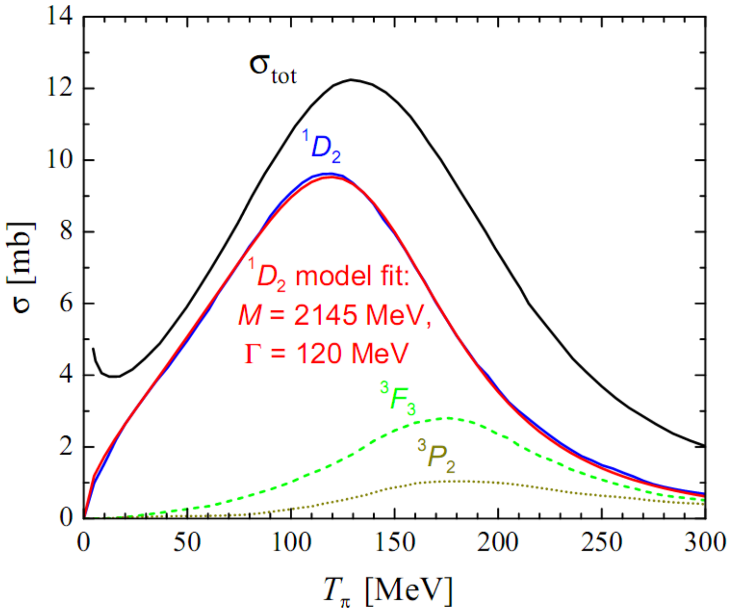
- **Five of them (except for D_{30}) have been now confirmed by experiments.**
- The strongest evidence of the isoscalar state D_{03} (or d*(2380)): pn → d $\pi^0\pi^0$ and other two-pion production reactions, pn elastic scattering: exp. (CELSIUS-WASA and WASA-at-COSY Collab.) + PWA (SAID).
- Isovector state D_{12}: pp and πd elastic scattering, pp ↔ d π^+: exp. + PWA (SAID, Hoshizaki and others), γd → d $\pi^0\pi^0$ (Ishikawa et al., ELPH). Also confirmed by recent Faddeev calculations (Gal & Garcilazo).
- Two more isovector dibaryons in $^3P_2$ and $^3P_0$ pp channels: pp → pp($^1S_0$) π^0 (Komarov et al., ANKE-COSY Collab.).
- Three more isoscalar dibaryon states near *NN**(1520), *NN**(1680) and ηd thresholds: γd → d $\pi^0\pi^0$ and γd → π^0ηd (Ishikawa et al., ELPH).
- And some other states [see reviews H. Clement et al., Prog.Part.Nucl.Phys. 93 (2017) 195, Chin.Phys.C 45 (2021) 022001].

Isovector dibaryons near $N\Delta$ threshold

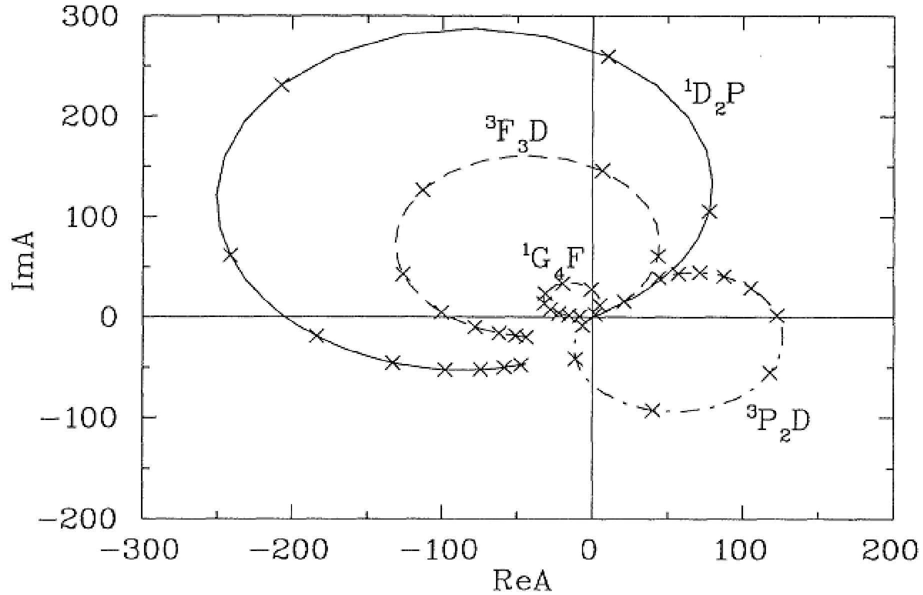
- Experiments on $\vec{p}+\vec{p}$ elastic scattering (I. Auer et al., 1978) and PWA for $pp \to pp$, $\pi^+d \to \pi^+d$ and $\pi^+d \to pp$ (N. Hoshizaki, 1979, 1993; R. Arndt et al., 1981, 1993; etc.) revealed a series of isovector resonances in NN channels ${}^1D_2$, ${}^3F_3$, ${}^1G_4$, ${}^3P_2$, etc.
- The lowest (${}^1D_2$) isovector resonance with $I(J^P) = 1(2^+)$ is the D_{12} dibaryon predicted by Dyson and Xuong: $M(D_{12}) \approx 2140\text{–}2180$ MeV $\approx M(N+\Delta) = 2170$ MeV,

$$\Gamma(D_{12}) \approx 100\text{–}140 \text{ MeV} \approx \Gamma(\Delta) = 117 \text{ MeV}.$$

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



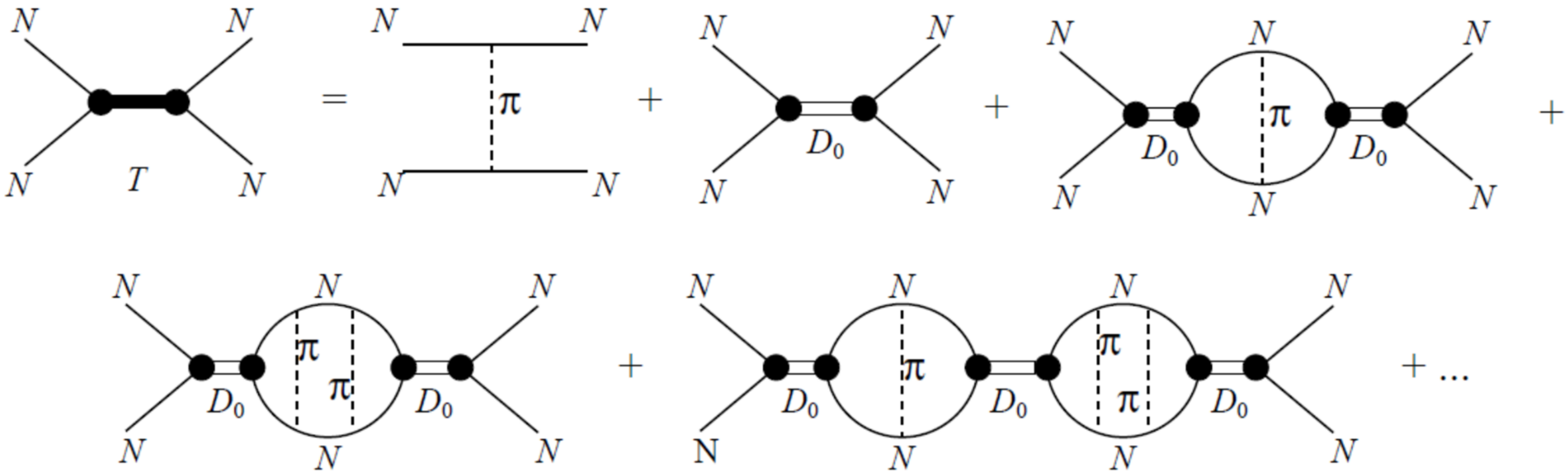
Argand plot of the dominant partial-wave amplitudes in $\pi^+d \to pp$



[R. Arndt et al., PRC 48 (1993) 1926]

Dibaryon model for *NN* interaction

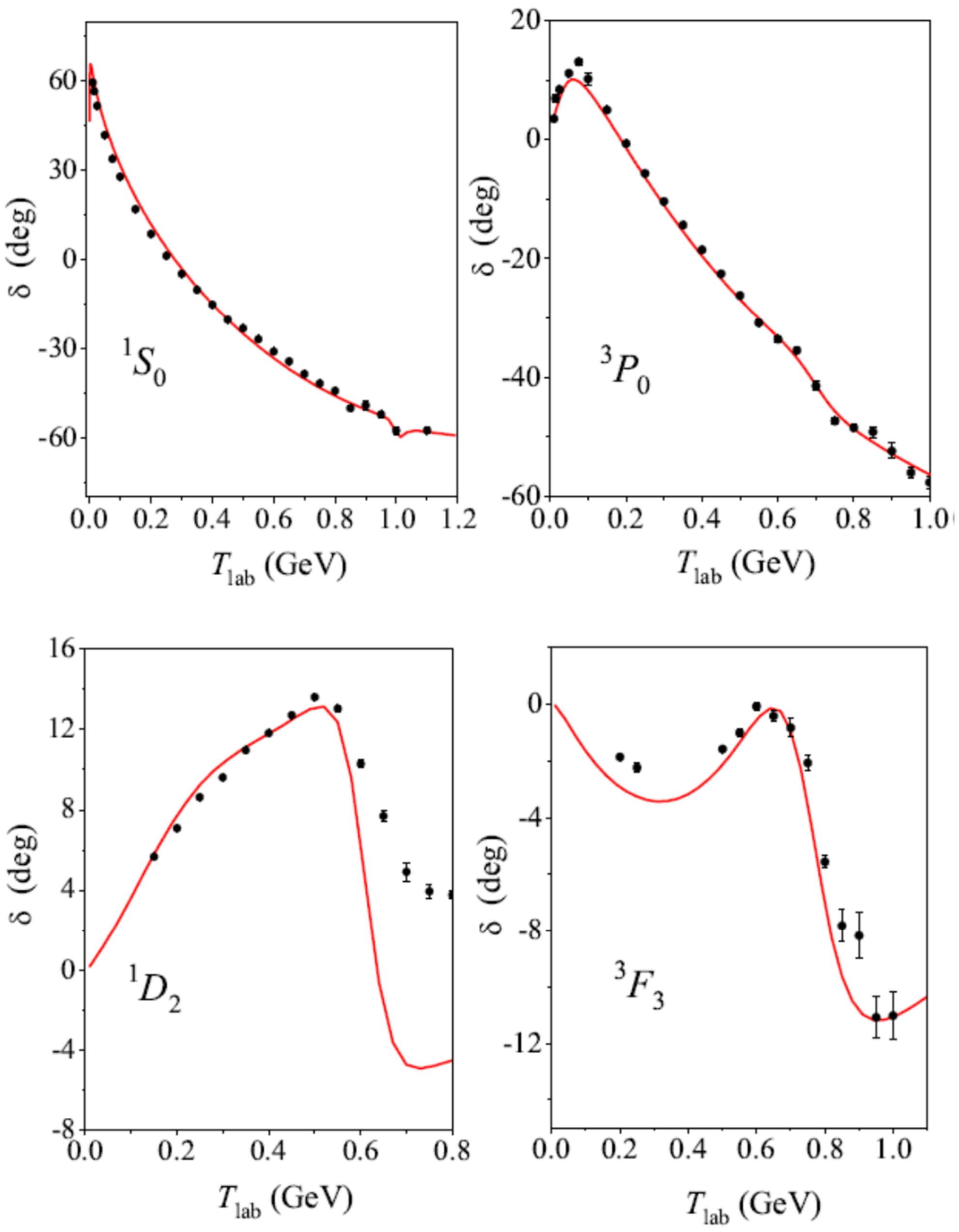
- ***s*-channel dibaryon exchange + *t*-channel pion exchange:**



- Inelastic processes and *NN** intermediate states are treated effectively via the energy-dependent dibaryon width
- 4-5 parameters for the dibaryon potential in each partial wave

Initial version - V. Kukulin et al., JPG 27 (2001) 1851, IJMPE 11 (2002) 1;
updated version - V. Kukulin et al., PLB 801 (2020) 135146, EPJA 56 (2020) 229,
PRD 102 (2020) 114040, PAN 82 (2019) 934.

Dibaryon model for *NN* interaction

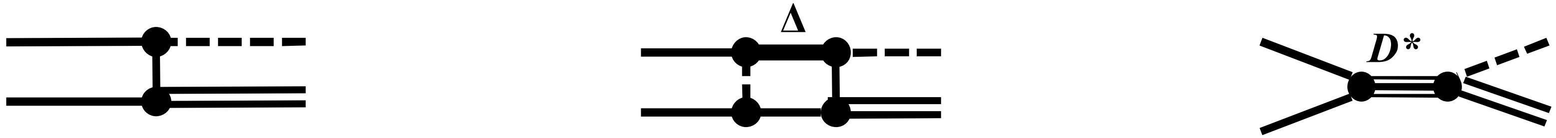


- Very good description of *NN* scattering phase shifts and inelasticities up to T_N = 0.6-1.2 GeV in all *S, P, D, F* partial waves (vs. elastic phase shifts up to 350 MeV only for conventional OBE *NN* potential models).
- Dibaryon masses and widths are consistent with exp. data.

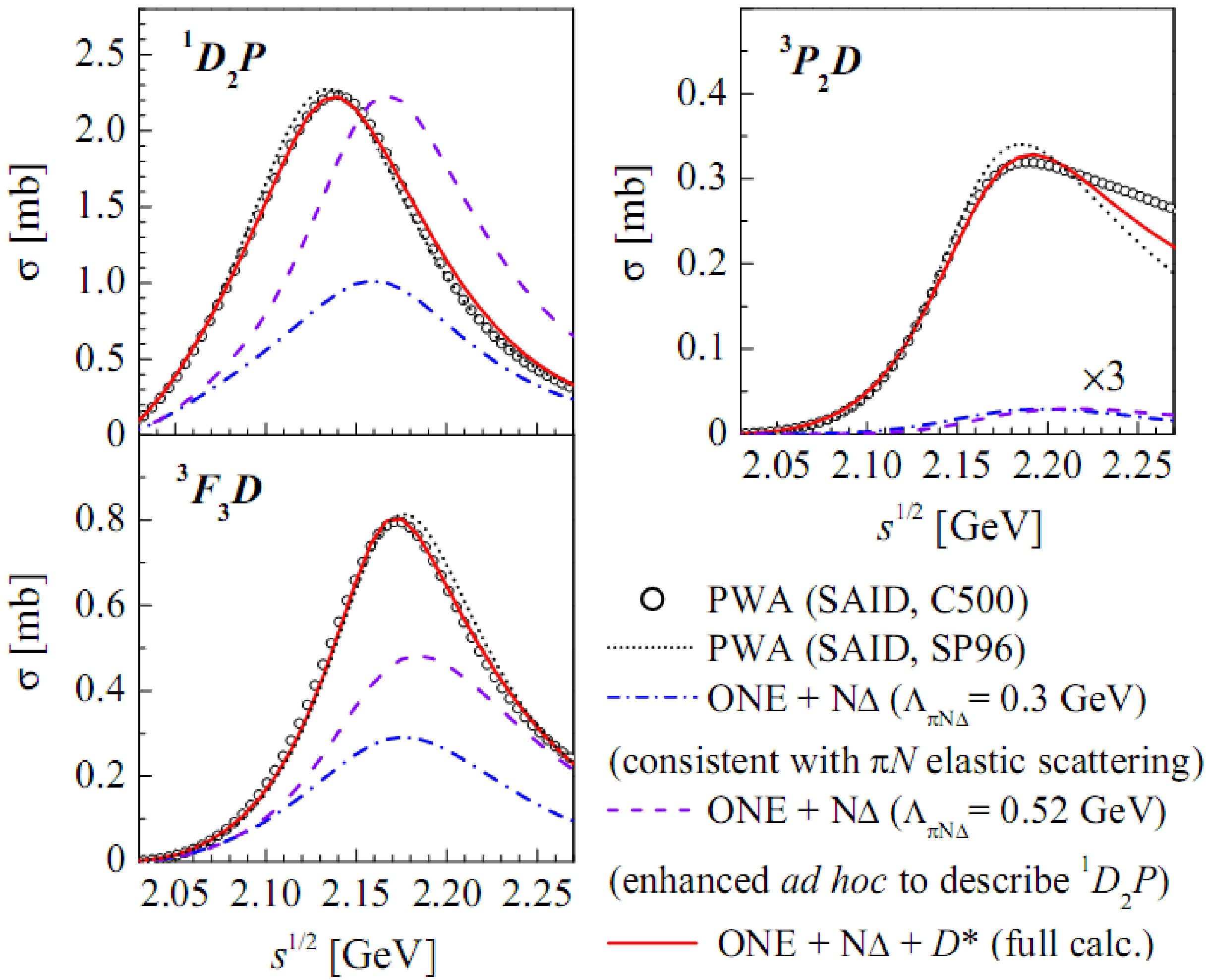
$^{2S+1}L_J$	$T(J^P)$	$M_{\rm th}$	$\Gamma_{\rm th}$	$M_{\rm exp}$	$\Gamma_{\rm exp}$	Ref.
$^1D_2$	$1(2^+)$	2.18	0.14	2.14–2.18	0.05–0.1	[25]
$^3P_0$	$1(0^-)$	2.2	0.99	2.201	0.091	[12]
$^3P_2$-$^3F_2$	$1(2^-)$	2.221	0.17	2.197	0.130	[12]
$^3F_3$	$1(3^-)$	2.23	0.185	2.20–2.26	0.1–0.2	[25]
$^3S_1$-$^3D_1$	$0(1^+)$	2.31	0.16	2.315	0.15	[69]
$^1S_0$	$1(0^+)$	2.33	0.05	2.32	0.15	[69]
$^3D_3$-$^3G_3$	$0(3^+)$	2.376	0.084	2.38	0.08	[54]

Dibaryon model for $pp \to d\pi^+$ reaction

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



Partial cross sections for 3 dominant amplitudes:

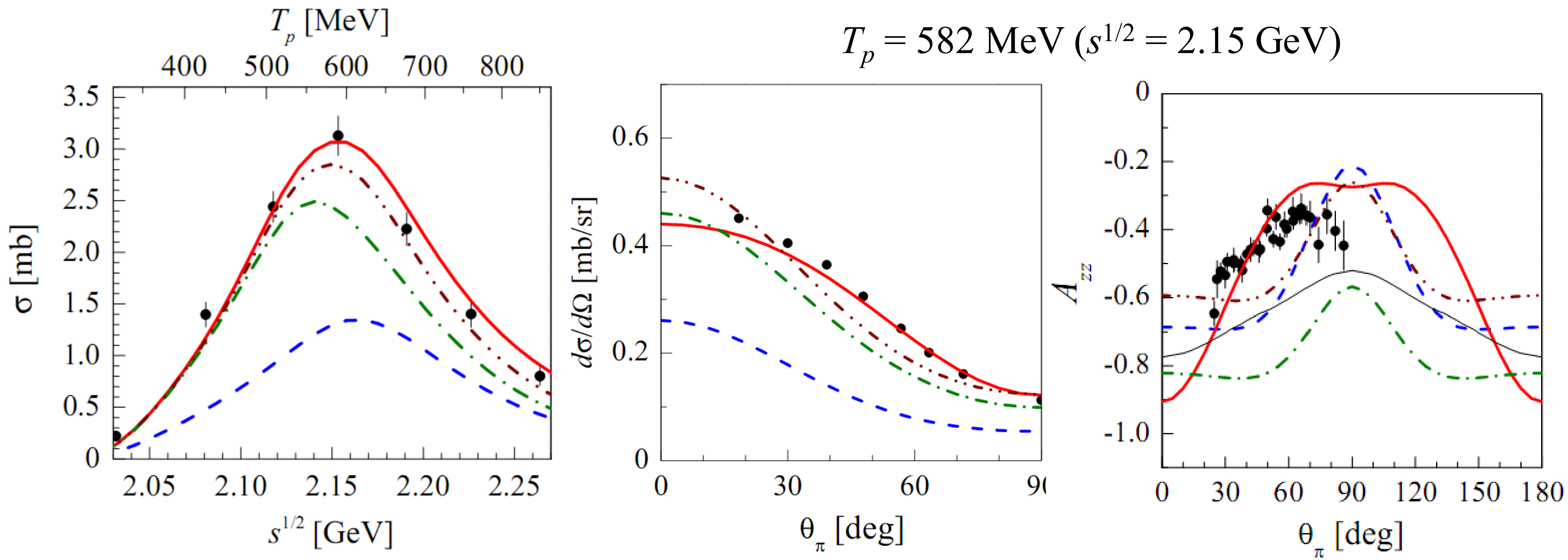


- Conventional (ONE+NΔ) mechanisms with soft short-range cut-off $\Lambda_{\pi N\Delta}$ in the πNΔ vertex (consistent with πN elastic scattering) give 40-50% of the ^1D_2P and ^3F_3D cross sections and only 2.5% of the ^3P_2D cross section.
- **Significant contributions of intermediate dibaryons in three dominant resonant amplitudes**
- **Dibaryon parameters consistent with exp. data and the model for *NN* elastic scattering**

[M.N. Platonova & V.I. Kukulin, PRD 94 (2016) 054039]

Dibaryon model for $pp \rightarrow d\pi^+$ reaction

Total and diff. cross sections, *pp* spin correlation parameter:



● Experiment [NPA 379(1982)369; 415(1984)365]

- - - ONE + $N\Delta$

-·-·- ONE + $N\Delta$ + $^1D_2$

-··-·· ONE + $N\Delta$ + $^1D_2$ + $^3F_3$

—— ONE + $N\Delta$ + $^1D_2$ + $^3F_3$ + $^3P_2$

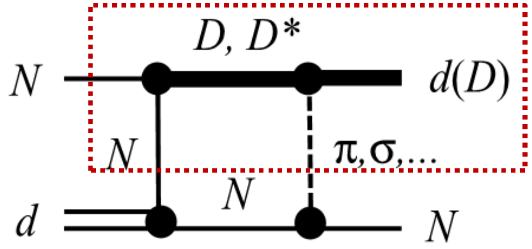
—— Accurate three-body πNN calculation (without dibaryons) [Lamot et al., PRC35(1987)239]

Dibaryon parameters:

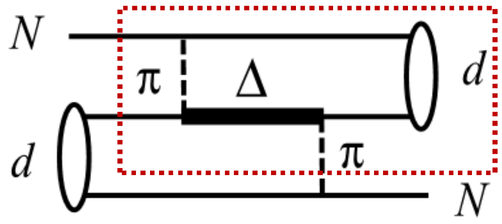
$^{2S+1}L_J$	M_D (MeV)	Γ_D (MeV)
$^1D_2$	2155	101
$^3F_3$	2197	152
$^3P_2$	2211	195

pd large-angle scattering with intermediate dibaryon resonances

- Dibaryon model for *NN* and 3*N* interaction gives a new 3*N* force – meson exchange between the nucleon and dibaryon
- The following mechanism with 3*N* force and intermediate dibaryon resonance arises from Faddeev (AGS) equations for *pd* scattering amplitude:



Cf. conventional 2π-exchange 3*N* force with Δ-isobar excitation:



(*D* – dibaryon component of the deuteron,
*D** – excited dibaryon (resonance)):

- Connection between *pd* elastic scattering and *NN* → *d*π reaction was first suggested by Cragie & Wilkin in 1969 (without detailed treatment of *NN* → *d*π reaction mechanism)

If dibaryons near *N*Δ threshold contribute to *NN* → *d*π, they should also contribute to *pd* → *dp*.

pd backward scattering with D_{12} dibaryon

- The initial simple model: one-nucleon-exchange (ONE) – the background + D_{12} resonance excitation.

- Rescattering processes give a small contribution to *pd* backward (180°) scattering (though it rises with decreasing scattering angle).

- N+Δ intermediate state is treated effectively as a part of D_{12} (like in the present version of dibaryon model for *NN* interaction).

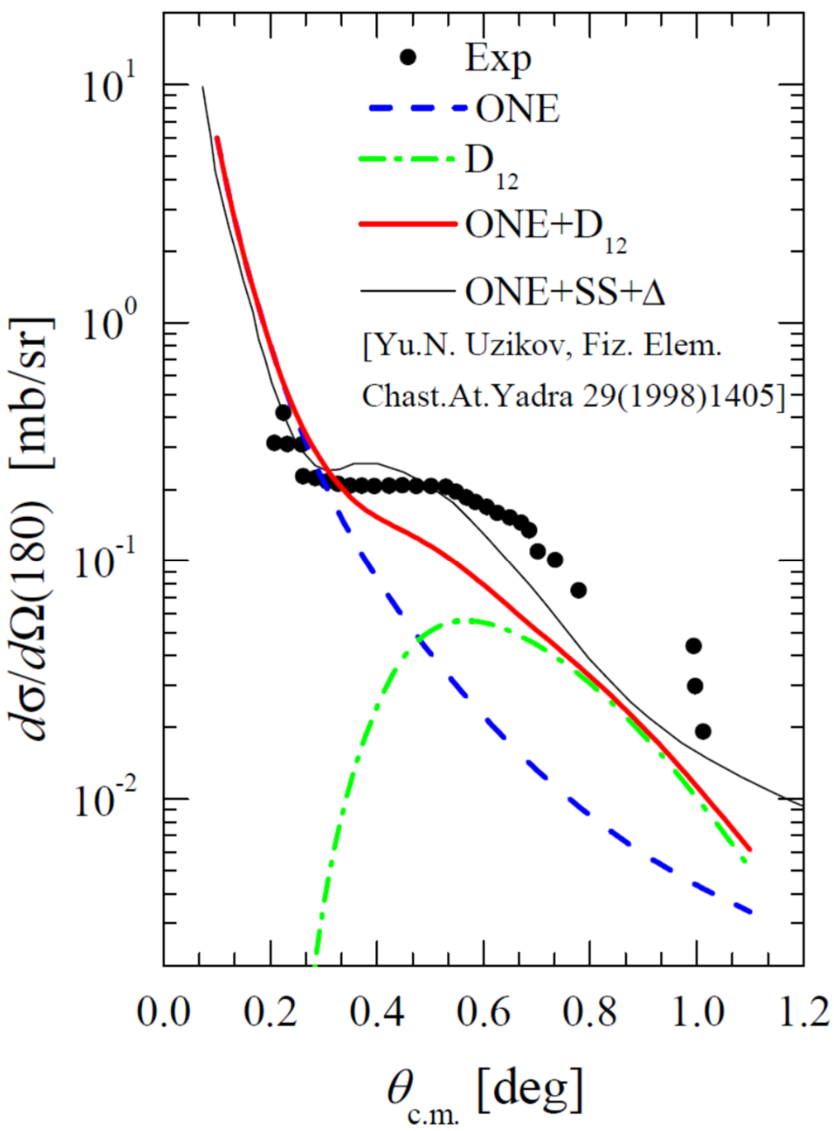
- Parameters of D_{12} (mass, total and partial widths) were adjusted to fit the $pp \to d\,\pi^+$ partial cross section in the ${}^1D_2P$ partial wave:

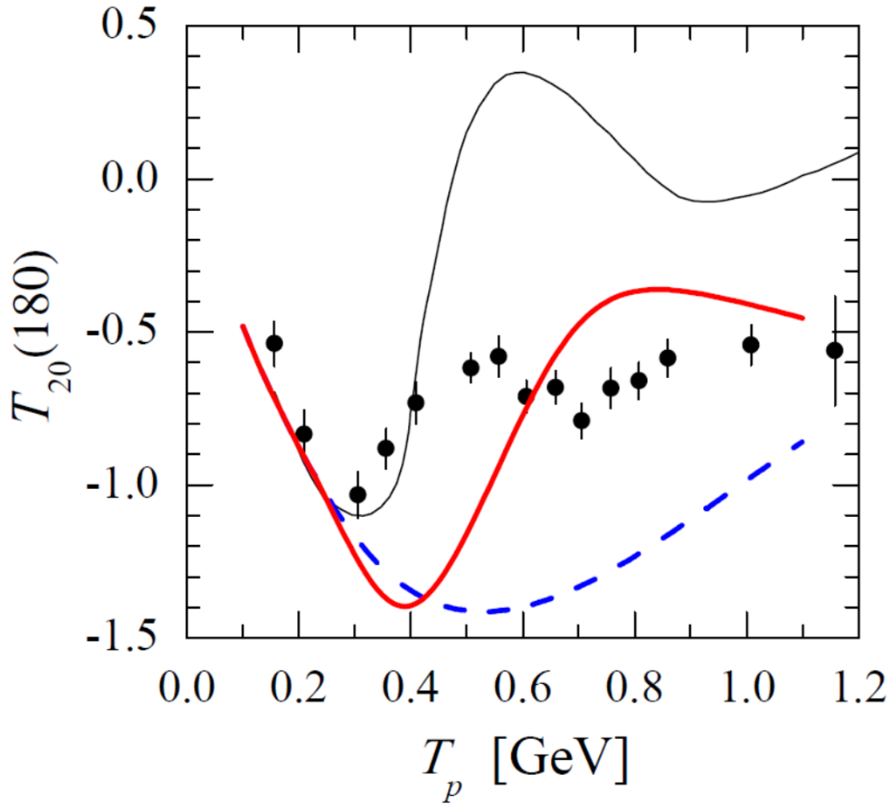
  $$M(D_{12}) = 2145 \text{ MeV}, \; \Gamma(D_{12}) = 120 \text{ MeV},$$

  $$\text{BR}(D_{12} \to \text{NN}) = 16\%, \; \text{BR}(D_{12} \to \pi d) = 30\%.$$

  These values are consistent with D_{12} parameters found from SAID PWA of $pp \to pp$, $\pi^+ d \to \pi^+ d$ and $\pi^+ d \to pp$.

pd backward scattering with D_{12} dibaryon





- **Sizeable effect of the D_{12} resonance comparable to that of the Δ at T_p > 300 MeV**
- Other dibaryon resonances (at least, $^3F_3$ and $^3P_2$) should be included
- Accurate treatment of t-channel Δ excitation is needed

Conclusions

- Existence of dibaryon resonances and their important role in *NN* elastic and inelastic scattering have been now confirmed by experiments.

- A new mechanism for puzzling *pd* large-angle scattering including the intermediate dibaryon formation and the corresponding three-body force is proposed.

- A sizeable effect of the *N*Δ *S*-wave resonance $D_{12}(2150)$ (with parameters derived from the $pp \to d\,\pi^+$ reaction) in *pd* backward scattering at 300 MeV < T_p < 1.2 GeV is found.

- Inclusion of other known dibaryon resonances as well as accurate treatment of the *t*-channel Δ excitation is needed to improve agreement with the data.

- Consistent theoretical treatment of *pd* scattering on the basis of Faddeev equations and dibaryon model for *NN* and 3*N* interactions is planned.

Thank You!