Новые горизонты в фундаментальной ядерной физике

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Семинар по ядерной физике
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Short history of relativistic nuclear physics and dibaryon studies

- First experiments by the group of M.G. Mescheryakov at the JINR Synchrocyclotron (Dubna): knock-out of fast deuterons from nuclei A(p,pd) [L.S. Azhgirey et al., JETP 33, 1185 (1957); G.A. Leksin et al., JETP 32, 445 (1957)]: **observation of a large excess of fast deuterons compared to the evaporation model.**

  Proton beam energy T_p = 660 MeV, energy transferred to deuteron $\Delta E_d \approx$ 50-100 MeV (while deuteron binding energy ε_d = 2.2 MeV)

  "*It looks like a flying bullet is reflected from the window glass*"
  - M.G. Mescheryakov.

  For these pioneering results, JINR received its first discovery diploma [L.S. Azhgirey et al., Diploma No. 221, July 1, 1957].

Short history
of relativistic nuclear physics
and dibaryon studies

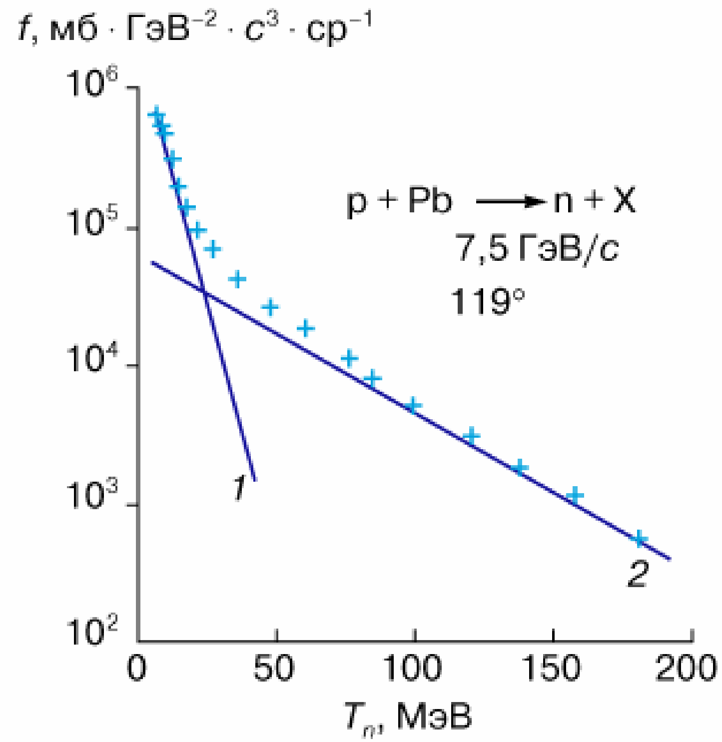
- Discovery of the **nuclear cumulative effect** in particle production processes – V.S. Stavinsky et al., 1973 (first theoretical prediction – A.M. Baldin, 1971).

- These experiments were continued and extended in 1960-1980s by G.A. Leksin et al. at ITEP 8-GeV accelerator and led (together with experiments of Frankel et al. in USA) to a discovery of **nuclear scaling and superscaling phenomena**.

Nuclear collisions at high energies and multibaryons in nuclei

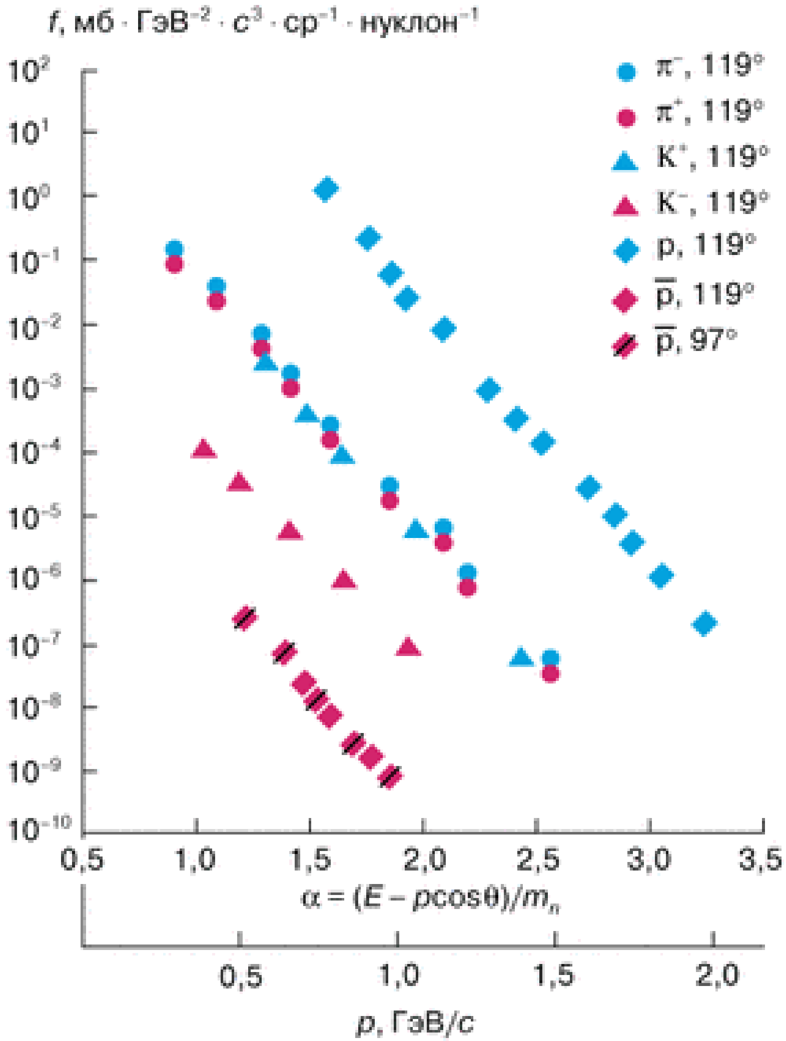
Cumulative processes in high-energy collisions (A.M. Baldin, G.A. Leksin *et al.*)

Scattering of fast particles off nuclei at large angles in lab. system



Dependence of invariant function of cumulative neutrons (proportional to neutron yield) on the neutron kinetic energy: 1 – "evaporating" neutrons, 2 – cumulative neutrons.

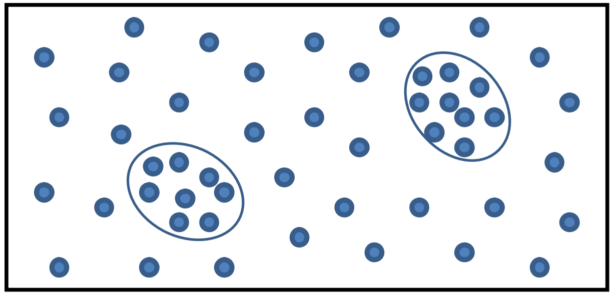
Production of cumulative fast particles at large angles (G.A. Leksin *et al.*)



The dependence of invariant functions for production of different cumulative particles (π-, π+, K-, K+, etc.) on value of α (effective mass of multibaryons in target nucleus which participate in the process).

Short history of relativistic nuclear physics and dibaryon studies

- The first theoretical interpretation of experimental data obtained by M.G. Mescheryakov et al. was the model of fluctons proposed by D.I. Blokhintsev (1957).



- Unfortunately, in late 1950s no clear physical mechanism leading to such strong density fluctuations in nuclear matter was known.
  (The main problem was in finding some physical agents that could bind the nucleons in fluctons.)
- In 1964, the first Gell-Mann’s paper on quark model of hadrons appeared.
- Just a few months after that, Dyson and Xuong published a pioneering work, where 6-quark (dibaryon) states in NN system were predicted on the basis of SU(6) symmetry.

First Prediction of Dibaryon States

- By using SU(6)-symmetry, Dyson and Xuong predicted six zero-strangeness low-lying dibaryons [F.J. Dyson and N.-H. Xuong, PRL **13**, 815 (1964)]:

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	$A+10B$

- From the simple SU(6) mass formula $M = A+B[T(T+1)+J(J+1)-2]$, A being the deuteron mass and $B = 47$ MeV, the masses of $N\Delta$ and $\Delta\Delta$ S-wave resonances were predicted to be

$$M(\boldsymbol{D}_{12}) \approx 2160 \text{ MeV};$$

$$M(\boldsymbol{D}_{03}) \approx 2350 \text{ MeV}.$$

- The deuteron D_{01} was positioned as NN S-wave dibaryon from the same SU(3) multiplet as D_{03}.

Short history
of relativistic nuclear physics
and dibaryon studies

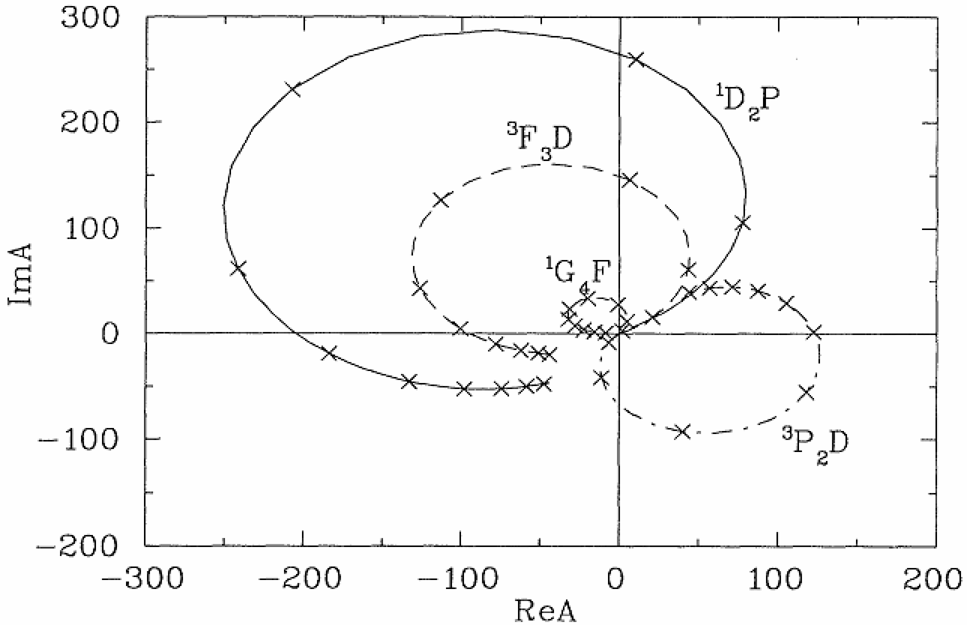
- Interpretation of Blokhintsev's fluctons in terms of multi-quark states was suggested by A.V. Efremov in 1982.
- A.M. Baldin was among the first who understood a key role of dibaryons in nuclear physics (works on "*Condensation of dibaryons in nuclear matter*", Dokl. Acad. Sci. USSR 279, 602 (1984) and others).
- **EMC effect** on deuteron and other nuclei was observed first at CERN in 1983. The effect was interpreted in terms of Bjorken scaling, however, the underlying mechanism was unclear.

  A number of important works on explanation of EMC effect in terms of multi-quark (6q, 9q, 12q) bags were performed in JINR and ITEP.
- 1980s – the beginning of **"dibaryon boom"**. Many dibaryon candidates were discovered, but then most of them were "closed" (since their signals disappeared with increasing statistics of experiments) .

Status of the broad isovector dibaryons

- In 1980s 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 *NΔ* threshold. So, such Argand loops can be related also to opening of the *NΔ* channel.

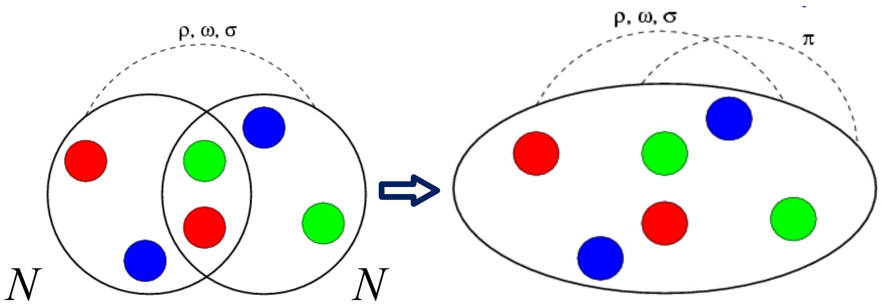
Overall, to the end of XX century, just a few broad dibaryons (discovered in pp elastic scattering in late 1970s) "survived" (however, with a controversial interpretation).

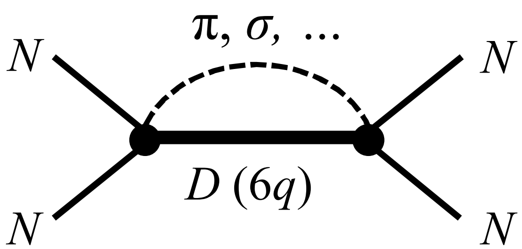
Renaissance of Dibaryon Physics in XXI century

Dibaryons in short-range NN interaction

- Dibaryon model for short-range nuclear force (V.I. Kukulin, Lecture at XXXIII PIYAF Winter School, 1999):

  generation of intermediate dibaryon resonances was considered for the first time as a basic, regular mechanism of NN interaction, rather than multi-quark exotics.

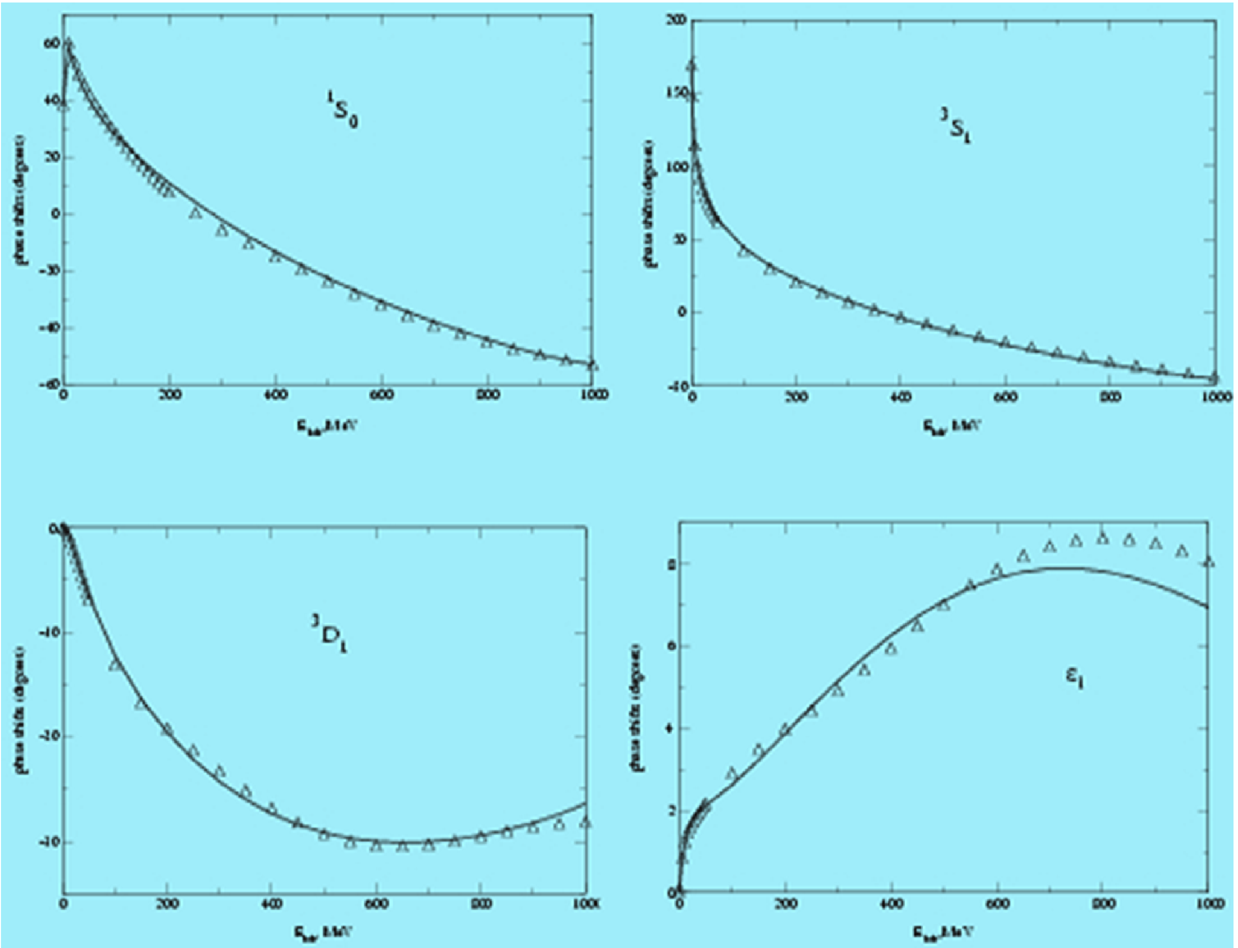




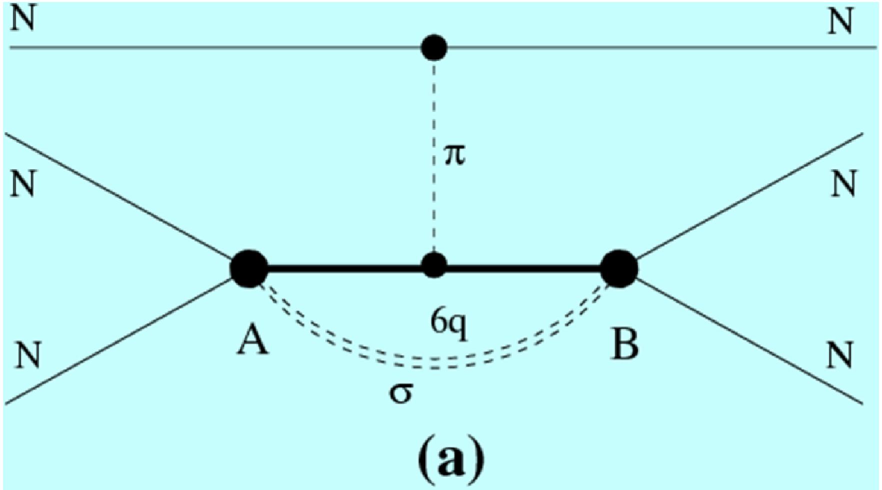
- The development of this new model was motivated by numerous inconsistencies in the basic parameters in meson-baryon vertices traditionally used in OBE-like models for short-range NN and 3N interaction.

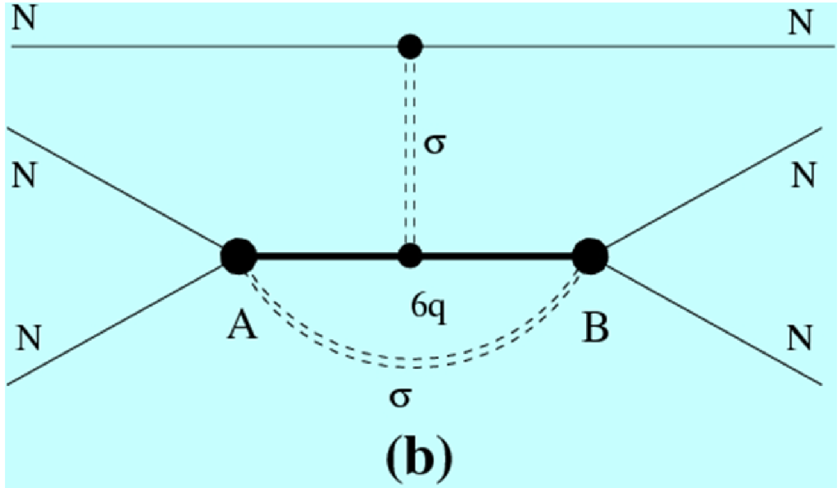
Dibaryon model fit of NN scattering phase shifts

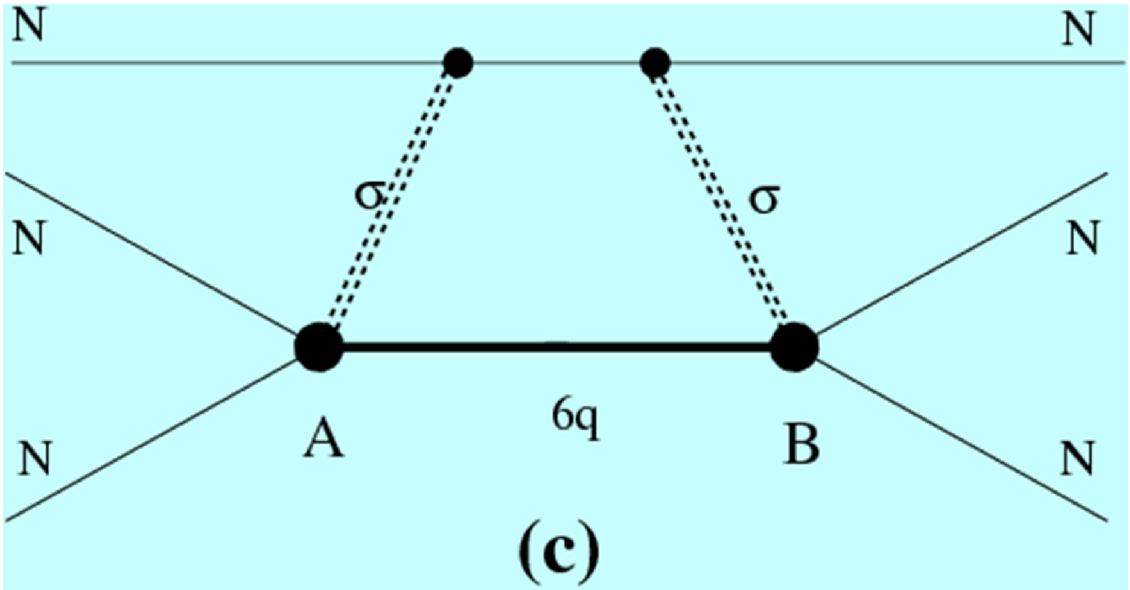
Dibaryon model for NN interaction is able to fit the empirical *NN* phase shifts in low partial waves in the energy range 0–1000 MeV (in contrast to the case of ChPT or conventional OBE models: 0–350 MeV) using only a few basic dibaryon parameters (V.I. Kukulin et al., Int. J. Mod. Phys. E11, 1 (2002)).



New dibaryon-induced 3*N* forces







Results of 3*N* 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

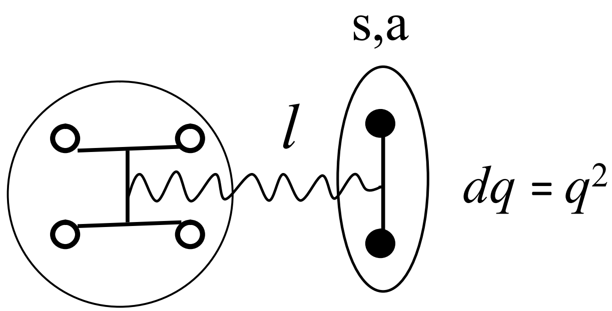
[a] These values of σNN coupling constant in ^{3}H calculations have been chosen to reproduce the exact binding energy of ^{3}H nucleus. The calculations for ^{3}He have been carried out without any free parameters.

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

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

Physical picture behind the dibaryon model

Nijmegen-ITEP dibaryon model:



ST=10,01,00

diquark can be in two states:
scalar (s) and axial (a)

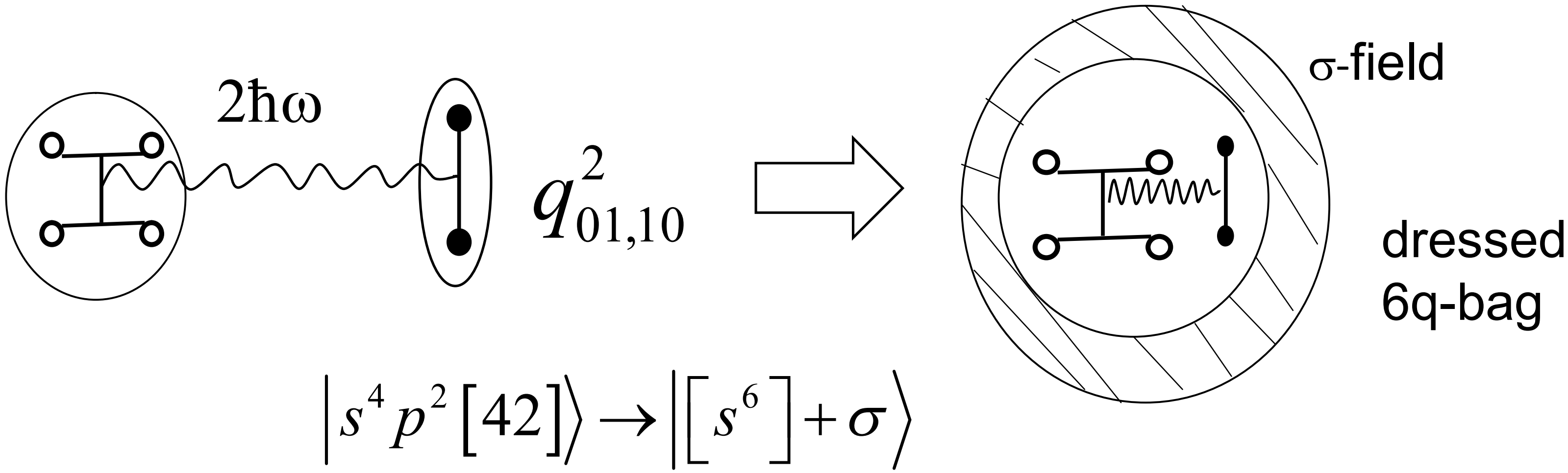
scalar (s) → $S=T=0$

axial (a) → $S=T=1$

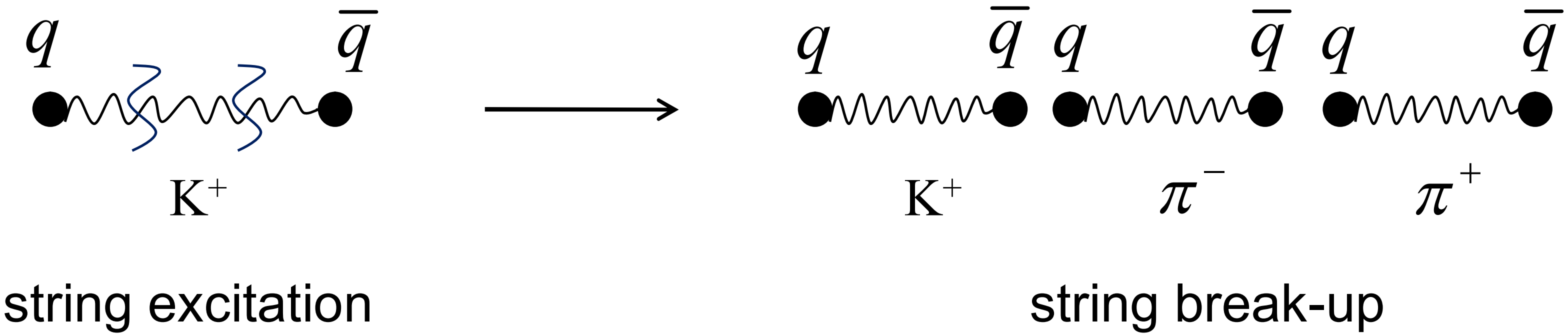
Scalar q^2 corresponds to isoscalar dibaryons (T=0), axial q^2 corresponds to isovector (T=1) dibaryons ($^1D_2$, $^3F_3$, $^1G_4$, …).

Two lowest dibaryons:

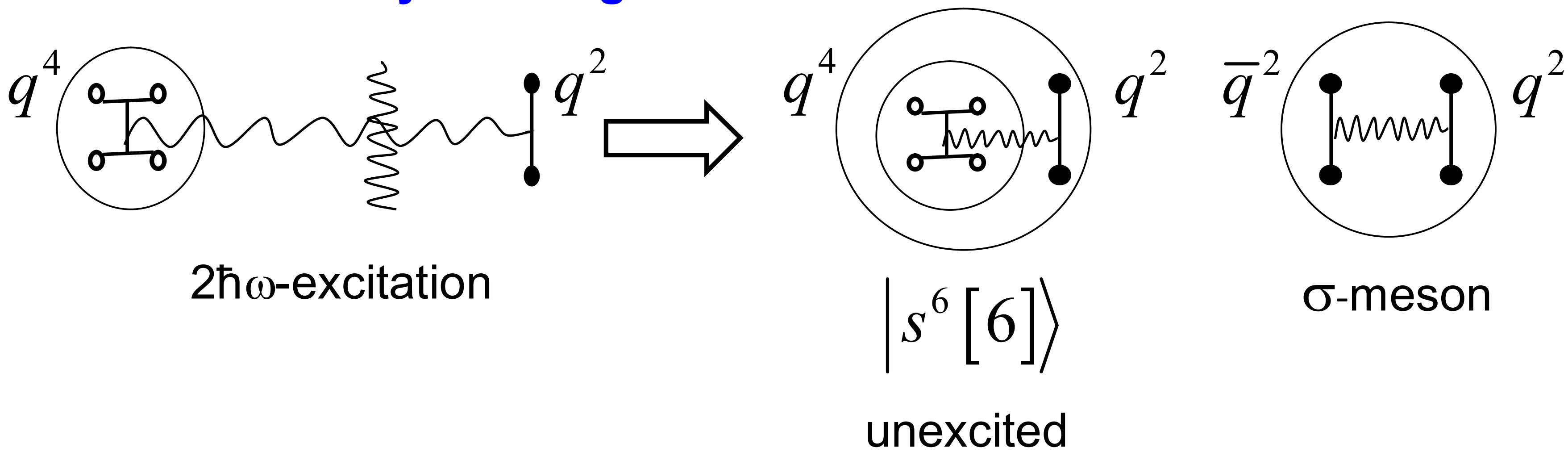
- deuteron ($^3S_1 - {}^3D_1$) - isoscalar,
- “singlet deuteron” ($^1S_0$) - isovector.



This σ-field dressing can be easily illustrated by the **Lund string model**:



For our dibaryon string:



This string picture can be illustrated and confirmed by the experimental data (see, e.g., D. Alde et al., PLB 397(1997)350)

$$pp \rightarrow pp + \pi\pi$$

for pp scattering at high energies $\left(E_p \simeq \ 400 \text{ GeV}\right)$.

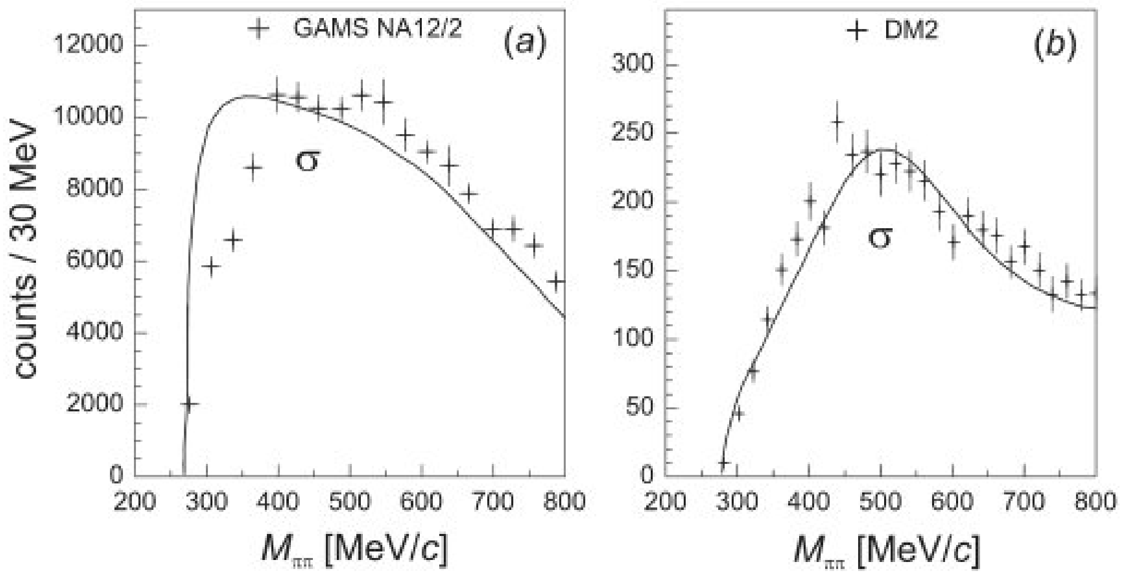


Figure 1. Phenomenological observation of the σ meson in production processes: (a) $\pi^0\pi^0$ invariant-mass distribution in pp central collisions (GAMS NA12/2) and (b) $\pi\pi$ invariant-mass distribution in $J/\psi \to \omega\pi\pi$ decay (DM2).

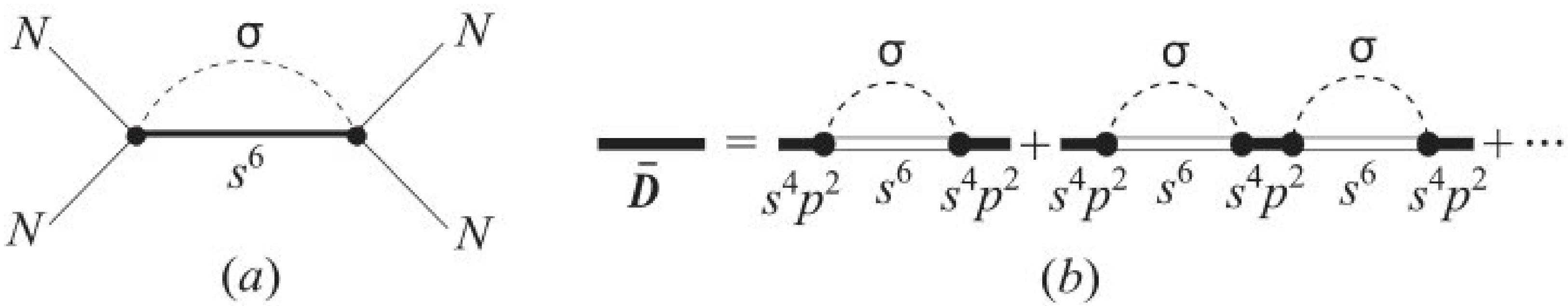
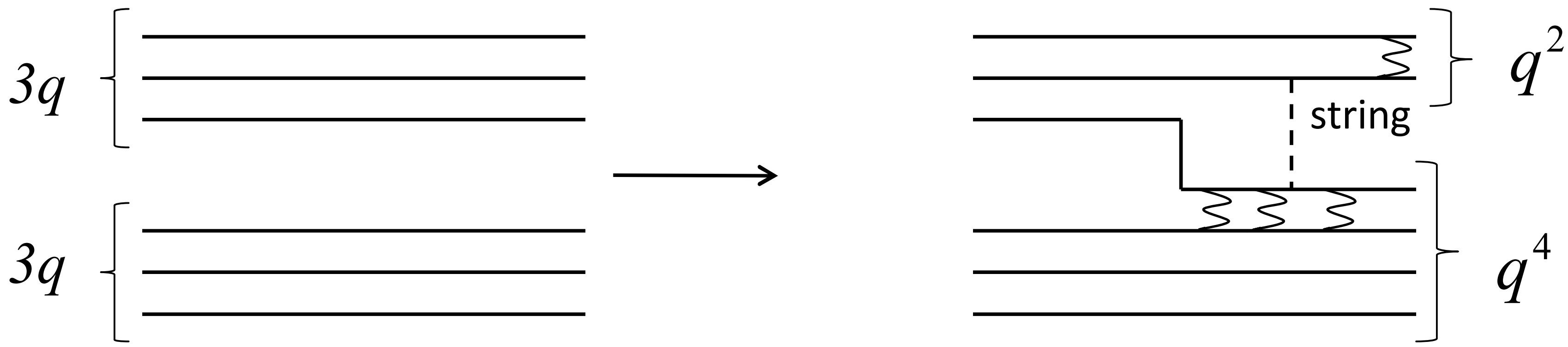


Figure 2. (a) NN potential corresponding to the s-channel σ-dressed dibaryon exchange (the Born term). (b) The σ dressing of the intermediate dibaryon propagator.

According to classical diffraction model of Abramjan, Gribov, Kancheli (Yad. Fiz., 1972) high energy diffraction scattering can be presented by a few quark diagrams:



s.c. planar diagram

So that, the break-up of intermediate string leads immediately to $\pi^+\pi^-$ or σ-meson emission.

Доказательство существования дибарионов

- Первые указания на существование изовекторного $^1D_2$-дибариона были получены Мещеряковым с сотр. в Дубне (Мещеряков М. Г., Неганов Б. С., Докл. АН СССР 100, 677 (1955)) в экспериментах по pp-рассеянию при энергиях $T_p \approx 600$ МэВ.

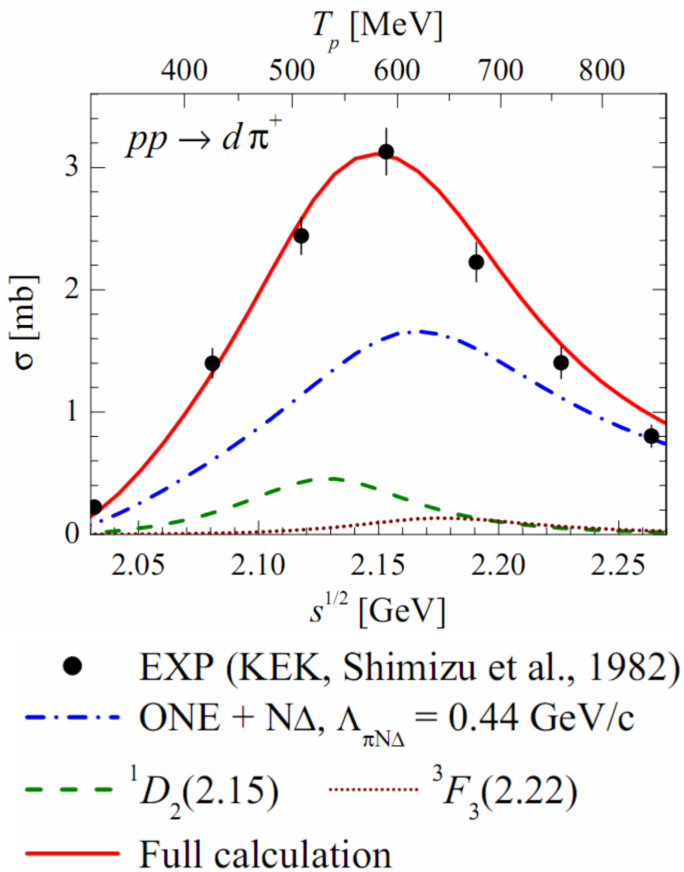
- Дайсон и Ксуонг (F.J. Dyson and N.-H. Xuong, PRL 13, 815 (1964)) использовали найденную в этих работах массу дибариона $M(^1D_2) = 2.16$ ГэВ для предсказания массы изоскалярного $0(3^+)$- (или $^3D_3$-) дибариона и получили значение $M(^3D_3) = 2.35$ ГэВ.

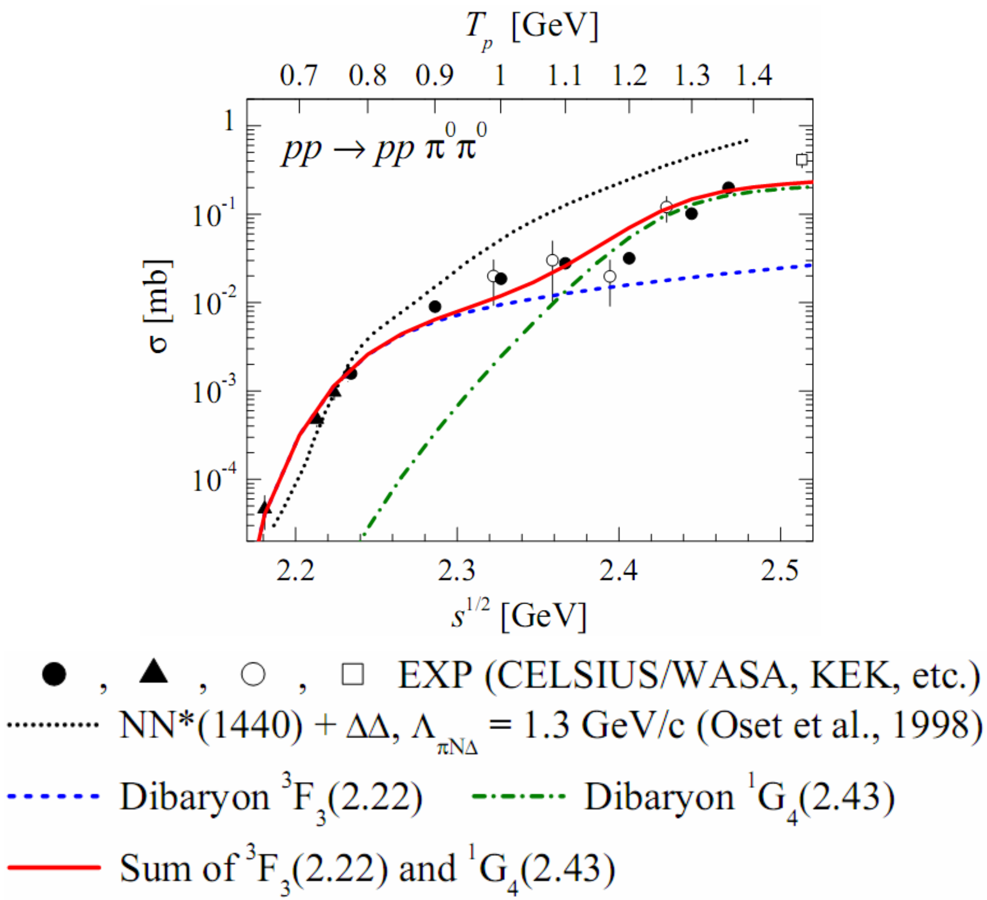
- Дибарион с теми же квантовыми числами был недавно надежно открыт коллаборацией WASA-at-COSY, причем его масса (2.38 ГэВ) оказалась очень близка к предсказанию Дайсона и Ксуонга.

- Совпадение теоретически предсказанных еще в 1964 г. параметров этого изоскалярного дибариона с найденными экспериментально (и затем подтвержденными фазовым анализом SAID упругого np-рассеяния) весьма надежно свидетельствует о существовании как изоскалярного $^3D_3$-, так и изовекторного $^1D_2$-дибарионов.

Isovector dibaryons in one- and two-pion production

[M.N. Platonova, V.I. Kukulin, NPA946, 117(2016)]

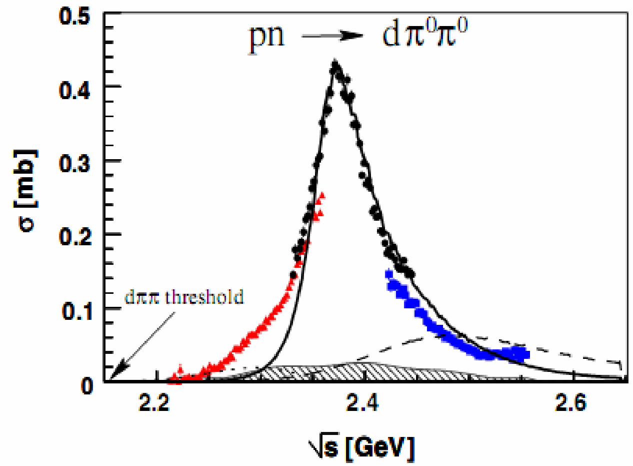




- Inclusion of dibaryon resonances improves the description of experimental data without *ad hoc* adjustment of cut-off parameters.
- However, broad isovector dibaryons are difficult to identify due to interference with “pseudoresonance” background processes.
- **More clear situation with isoscalar dibaryons!**

New evidence for isoscalar D_{03} dibaryon

Exclusive high-statistics 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)

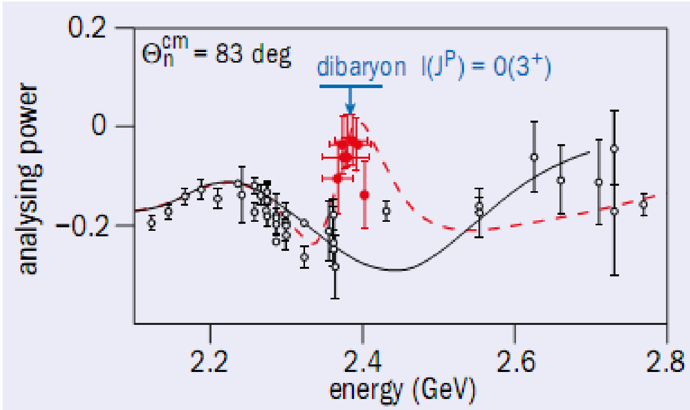
CERN Courier **July/August 2014**

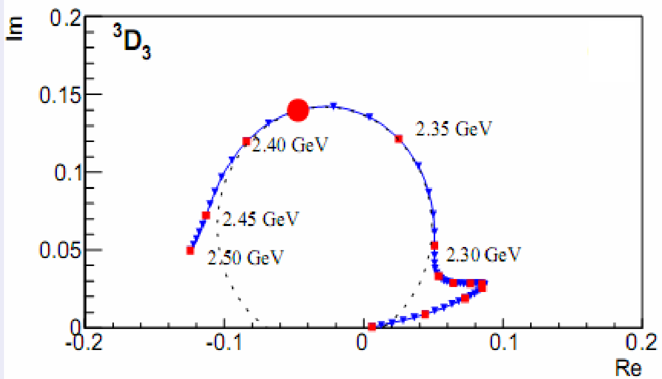
News

NEW PARTICLES

COSY confirms existence of six-quark states

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

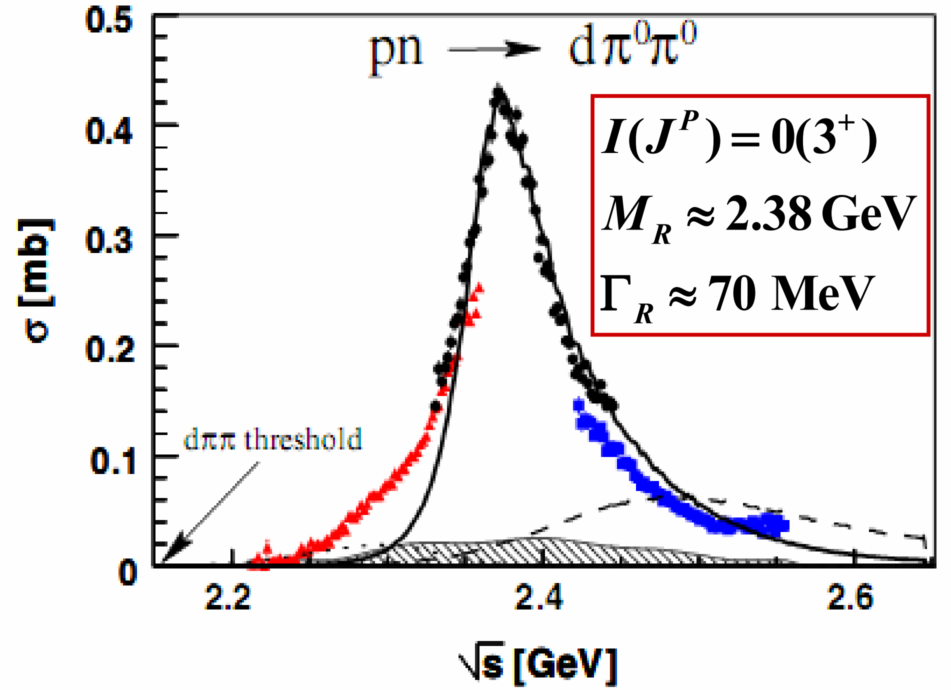


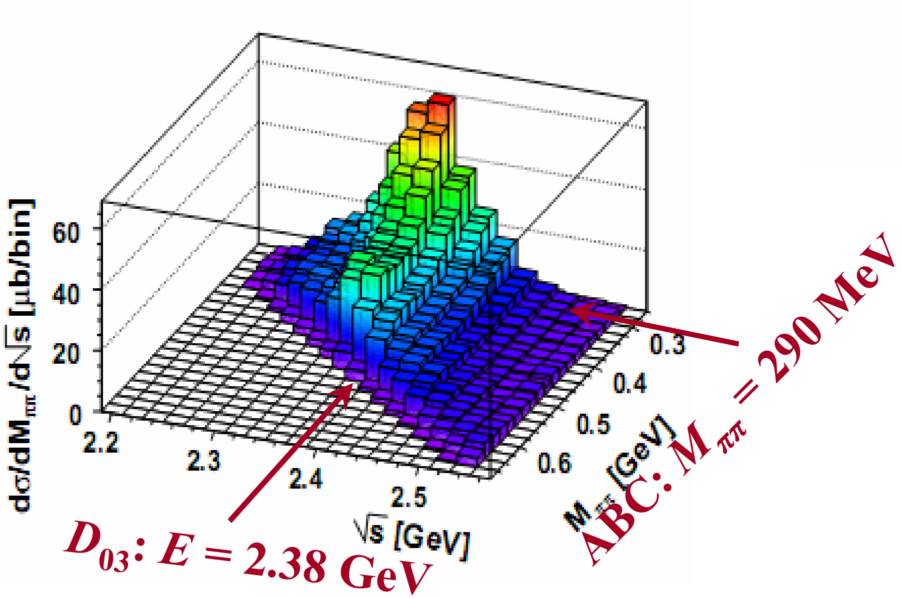


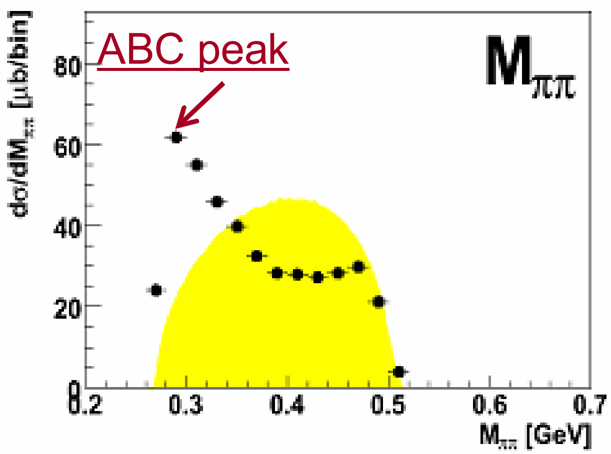
SAID SP07 (2007) — new PWA solution (2014)

Connection with old ABC puzzle

The most interesting feature of the recent experiments of the WASA@COSY Collaboration is a **clear identification of the old ABC-puzzle** [Abashian, Booth & Crowe, PRL5, 258 (1960)] **with 2π emission from the 0(3⁺) dibaryon state.**







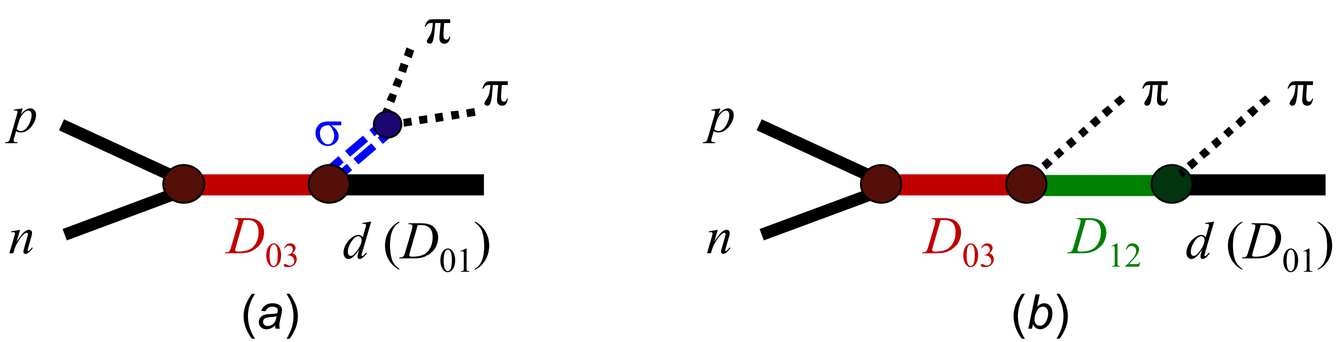
[P. Adlarson *et al*., PRL 106, 242302 (2011)]

Dibaryon model for the ABC puzzle

- The new model [M.N. Platonova, V.I. Kukulin, PRC 87, 025202 (2013)] 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:

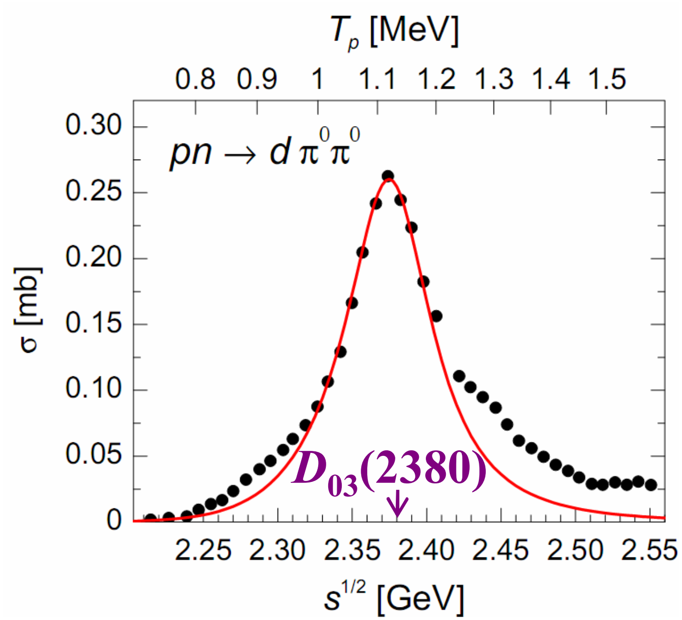
  (*a*) emission of $\pi\pi$ pair from a scalar σ meson produced from dibaryon meson cloud;

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

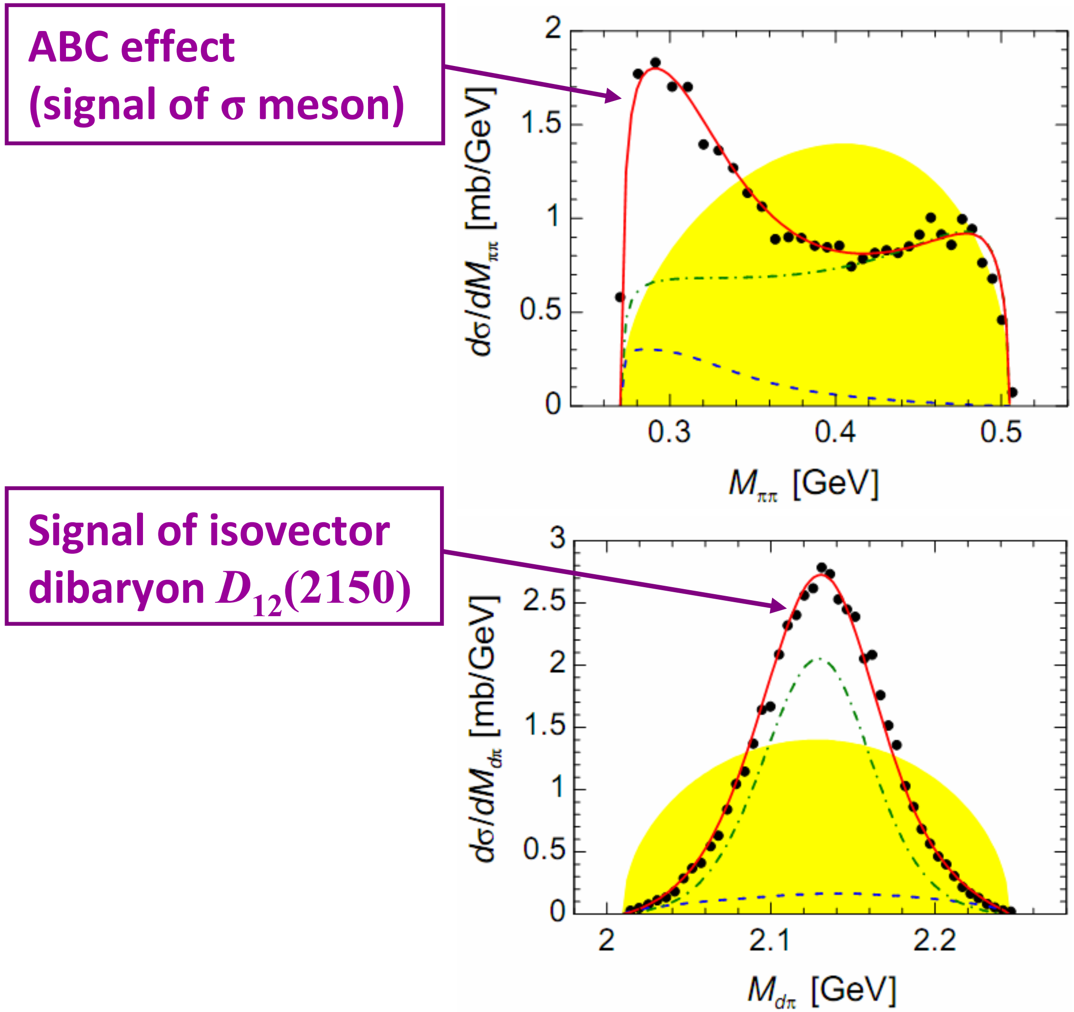


Dibaryon model for the ABC puzzle

I. Total Cross Section



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



- ● **EXP (WASA@COSY, 2011, 2013)**
- yellow solid line: **phase space**
- blue dashed line: $D_{03} \to d + \sigma$
- green dash-dotted line: $D_{03} \to D_{12} + \pi$
- red solid line: **Full calculation**

✓ ABC enhancement appears as a consequence of σ meson production

✓ Peak in $M_{d\pi}$ spectrum reflects production of isovector dibaryon $D_{12}(2150)$

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, PRL96, 132001 (2006)]:

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

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

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

Chiral symmetry restoration in dibaryons and in scalar meson sector

- CSR effects have been predicted by many authors both in dense (or hot) nuclear matter (T. Kunihiro et al., M.K. Volkov et al.) and even in a single hadron when it gets strongly excited (L.Ya. Glozman et al.).
- It should be stressed that the $0(3^+)$ dibaryon with the mass $M_{D*} \approx 2.38$ GeV is in fact *a very dense and 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.
- Just this CSR phenomenon is likely responsible in essence for the basic *NN* attraction at intermediate distances, i.e., for the main component of nuclear force.

Direct experimental evidence for the *s*-channel dibaryon-induced σ-meson production

[arXiv:0406081[hep-ex], Int. Jour. Mod. Phys. A20, 554 (2005)]

Observation of a Structure in $pp \to pp\gamma\gamma$ near the $\pi\pi$ Threshold and its Possible Interpretation by $\gamma\gamma$ Radiation from Chiral Loops in the Mesonic σ Channel

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(Dated: December 23, 2013)

The $pp \to pp\gamma\gamma$ reaction has been measured at CELSIUS using the WASA 4π-detector with hydrogen pellet target. At $T_p = 1.20$ and 1.36 GeV, where most of the statistics has been accumulated, the $\gamma\gamma$ invariant mass spectrum exhibits a narrow structure around the $\pi\pi$ threshold, which possibly may be associated with two-photon radiation of $\pi^+\pi^-$ loops in the mesonic σ channel.

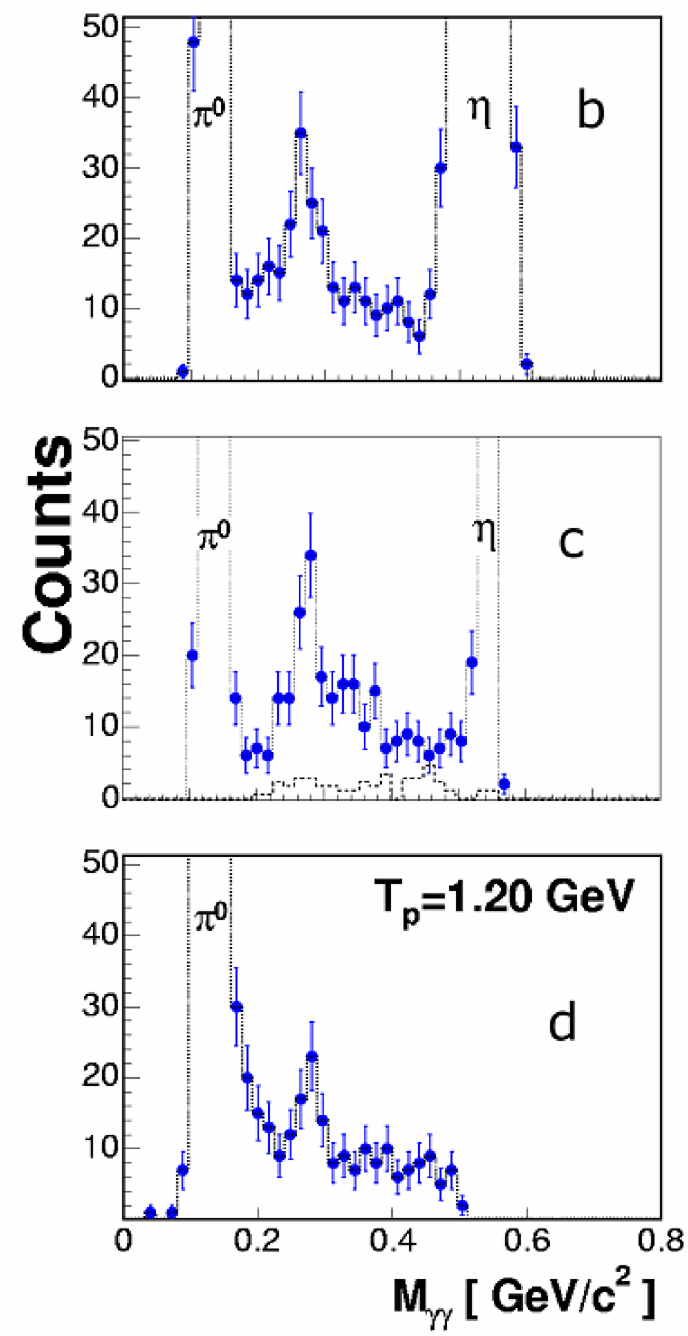

Fig. 1. $M_{\gamma\gamma}$ spectra for the process pp → ppγγ at T_p = 1.36 GeV before (b) and after (c) kinematic fit. The plot (d) is the same as (c) but for T_p = 1.2 GeV.

- The spike around 2π threshold turns out to be very stable against cuts (e.g., increase of the threshold E_γ= 50 MeV to E_γ = 100 MeV has no significant effect on this spike.)
- The model which incorporates very well the γγ events from π^0, η and $\pi^+\pi^-$ production gives practically no events in the intermediate area with $M_{\gamma\gamma}$ ~ 300 – 400 MeV.
- The $\pi^0\pi^0$ production at 1.36 GeV gives about 15% of the observed counts between π^0 and η peaks (dotted histogram in Fig. 1c).

The experimentalists (CELSIUS/WASA) conclude:

"Since none of these simulated processes is able to account for the structure observed near the ππ threshold and also detailed and comprehensive tests of detector performance and event structures have not given any hint for an artefact, we are led to consider seriously the possibility that the observed structure (at $M_{\gamma\gamma} \sim 300 - 400$ MeV) is real and might be due to the process $pp \rightarrow pp\sigma \rightarrow pp\gamma\gamma$, in particular also since $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pp\pi^0\pi^0$ reactions are dominated by σ production."

New γγ-data with high statistics

In experiments done at the Dubna Nuclotron, the authors analyzed the γγ-spectra from pC and dC collisions at 5.5 GeV/c (for protons) and 1.7-3.8 GeV/c per nucleon (for deuterons).

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Resonance structure in the $\gamma\gamma$ invariant mass spectrum in pC and dC interactions

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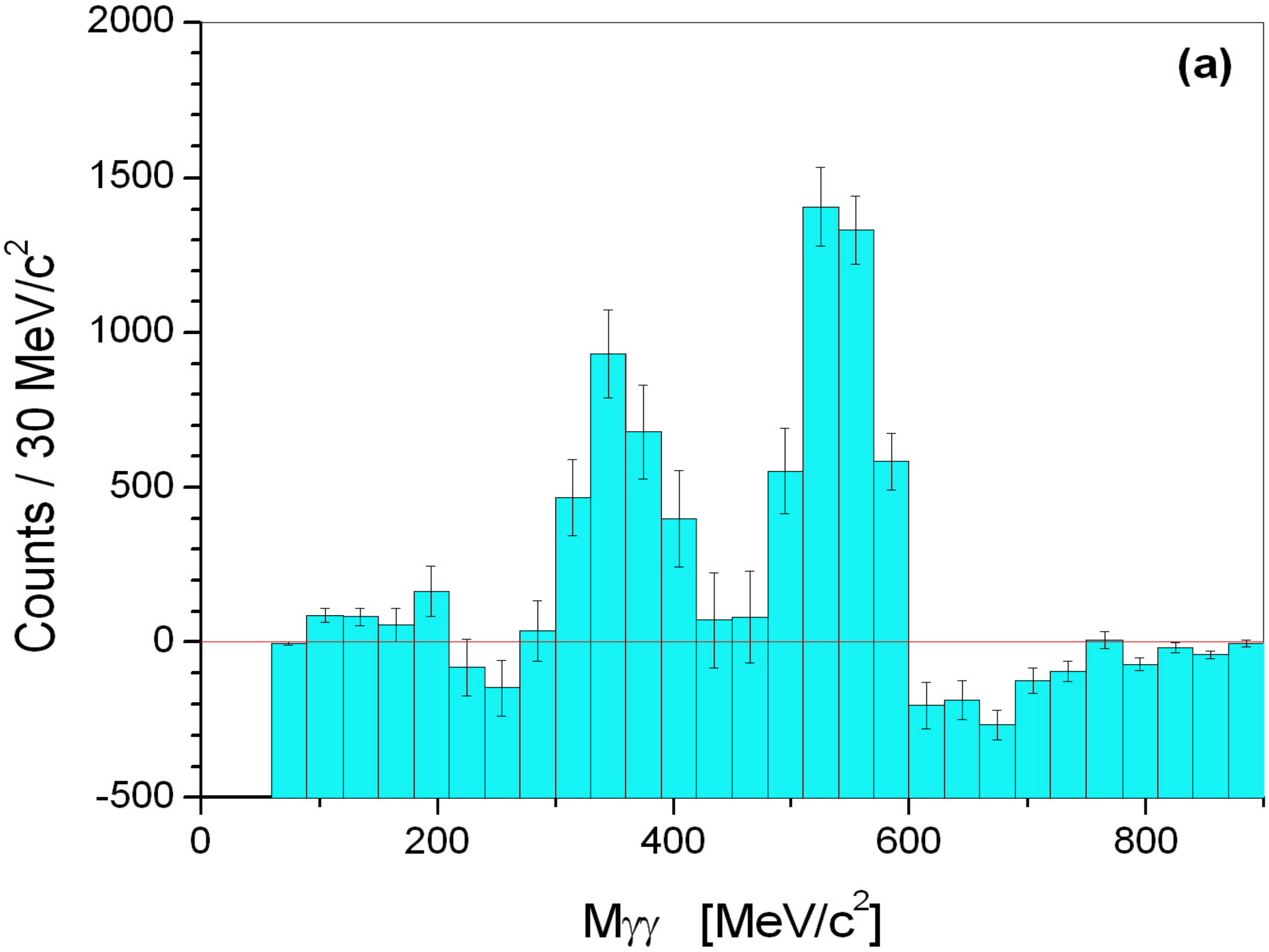
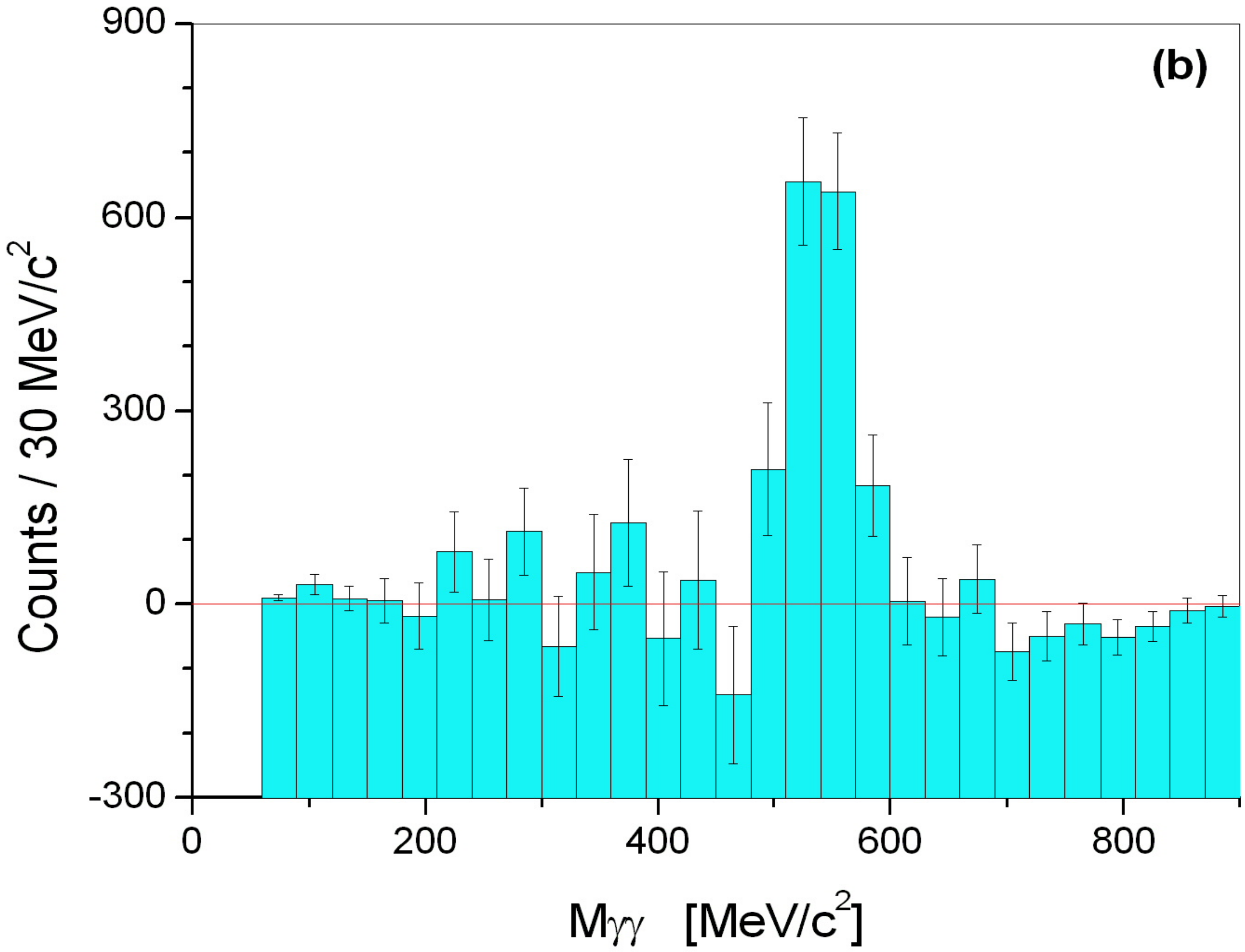
Along with π^0 and η mesons, a resonance structure in the invariant mass spectrum of two photons at $M_{\gamma\gamma} = 360 \pm 7 \pm 9$ MeV is observed in the reaction $d\mathrm{C} \to \gamma + \gamma + X$ at momentum 2.75 GeV/c per nucleon. Estimates of its width and production cross section are $\Gamma = 63.7 \pm 17.8$ MeV and $\sigma_{\gamma\gamma} = 98 \pm 24^{+93}_{-67}$ μb, respectively. The collected statistics amount to 2339 ± 340 events of 1.5×10^6 triggered interactions of a total number $\sim 10^{12}$ of dC interactions. This resonance structure is not observed in pC collisions at the beam momentum 5.5 GeV/c. Possible mechanisms of this ABC-like effect are discussed.

γγ-yield from dC collisions at p=2.75 GeV/cA



γγ-yield from pC collisions at p=5.5 GeV/c



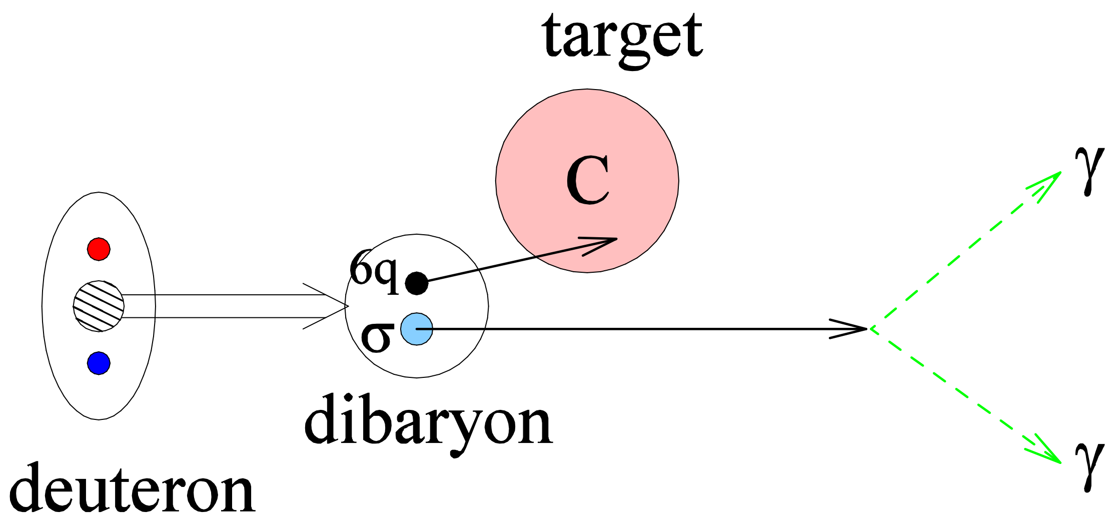
From the authors' conclusion:

"Thus, based on a thorough analysis of experimental data measured at the JINR Nuclotron and record statistics of 2339 ± 340 events of $1.5 \cdot 10^6$ triggered interactions of a total number $2 \cdot 10^{12}$ of dC interactions there was observed a resonance-like enhancement at the mass $M_{\gamma\gamma}$ = 360 ± 7 ± 9 MeV, width Γ= 64 ± 18 MeV … at the momentum of incident deuterons 2.75 GeV/c per nucleon. A structure like this is not observed in the $M_{\gamma\gamma}$ spectrum from pC (5.5 GeV/c) interactions while the η meson is clearly seen in both cases.

…This enhancement at $M_{\gamma\gamma} \sim (2-3)m_\pi$ is similar to the puzzling ABC effect observed for two-pion pairs from nucleon-nucleon and lightest nuclei collisions at the near-threshold energy.

… To understand the origin of the observed structure, several dynamic mechanisms were attempted: production of the hypothetic R resonance (really it is a renormalized σ-meson) in ππ interactions during the evolution of the nuclear collision, formation of the R resonance with participation of photons from the decay, the $\pi^0\pi^0$ interaction effect in the $3\pi^0$ channel of the η decay, a particular decoupled dibaryon mechanism. Unfortunately, none of these mechanisms is able to explain the measured value of the resonance-like enhancement."

Production of two γ-quanta according to dibaryon model



Reduction of the σ-meson mass due to Chiral Symmetry Restoration leads to increasing branching ratio for $\sigma \longrightarrow \gamma\gamma$ decay.

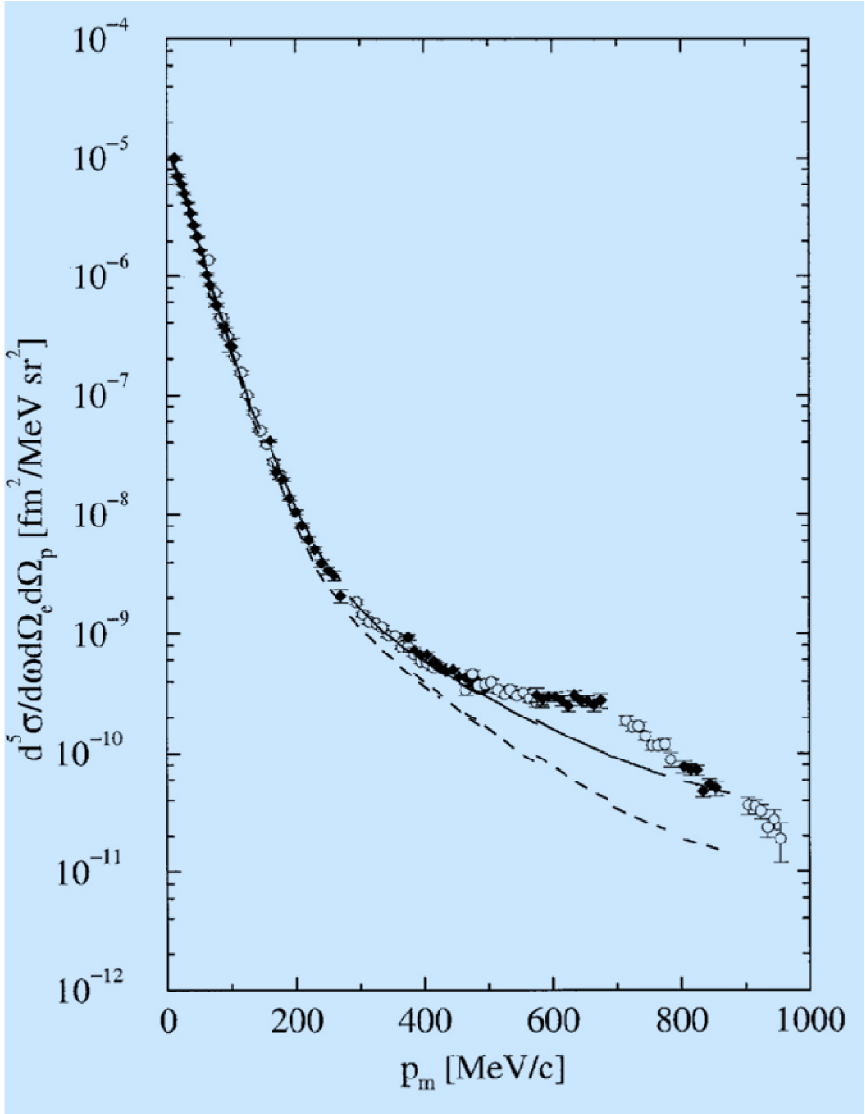
A new possibility of γγ diagnostics of hot/dense nuclear matter and quark-gluon plasma!

Cumulative e.-m. processes at high energy and momentum transfers

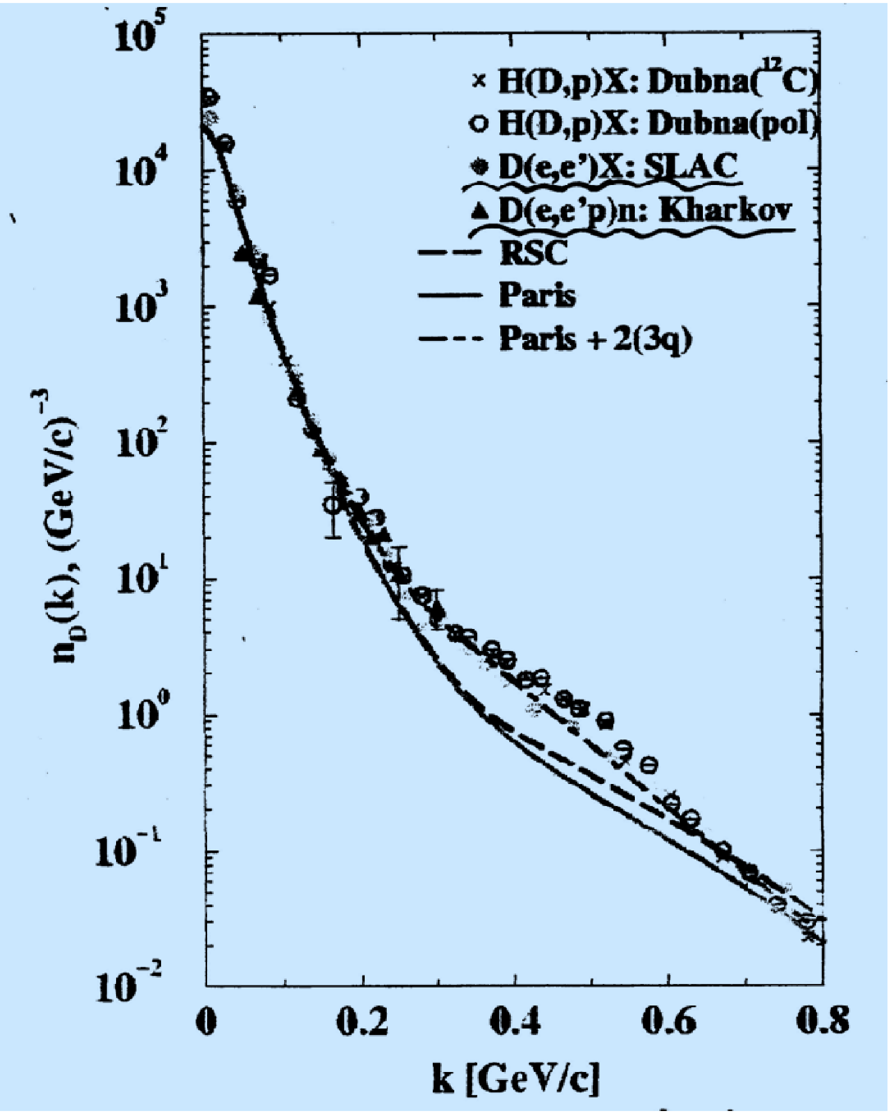
- Cumulative processes have been studied in detail in numerous hadronic works (mainly in JINR, Dubna).

- However, there is very scarce information up to date in the field of cumulative processes in e.-m. physics (at high energy and momentum transfers).

Manifestation of non-nucleonic (quark) d.o.f. in deuteron



D(e,e'p) cross section



Nucleon momentum distribution in deuteron extracted from different experiments

Angular Dependence of Proton Polarization in the Reaction $\gamma d \to pn$ and a Partial-Wave Analysis of Possible Dibaryon Resonances

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(Received 22 March 1979)

The angular dependence of proton polarization in $\gamma d \to pn$ has been measured at photon energies between 400 and 650 MeV. The polarization and differential–cross-section data are consistently explained by introducing a dibaryon resonance $I(J^P) = 0(3^+)$ or $0(1^+)$ at ≈ 2360 MeV.

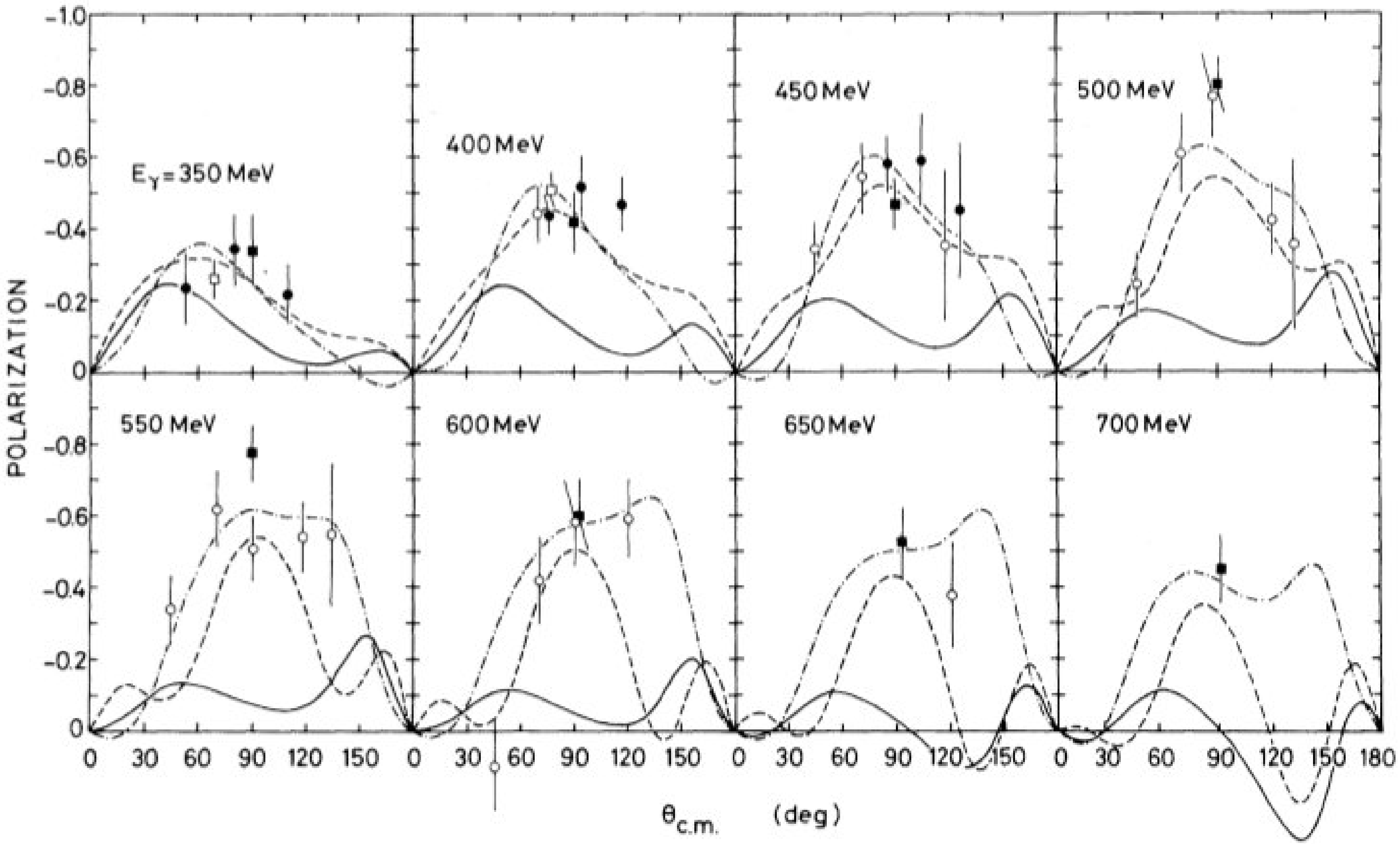


FIG. 1. Angular distributions of the proton polarization. The results of the present experiment (empty circles) are plotted together with the previous data (filled circles, Liu *et al.*, Ref. 12; empty squares, Kose *et al.*, Ref. 12; filled squares, Kamae *et al.*, Ref. 1) used for the χ^2-minimization fits. The dashed curves are the results of the fit including $1(3^-)$ and $0(3^+)$. The dot-dashed curves are the results of the fit including $1(3^-)$ and $0(1^+)$. The solid curves are the calculated results with the nonresonant amplitudes only.

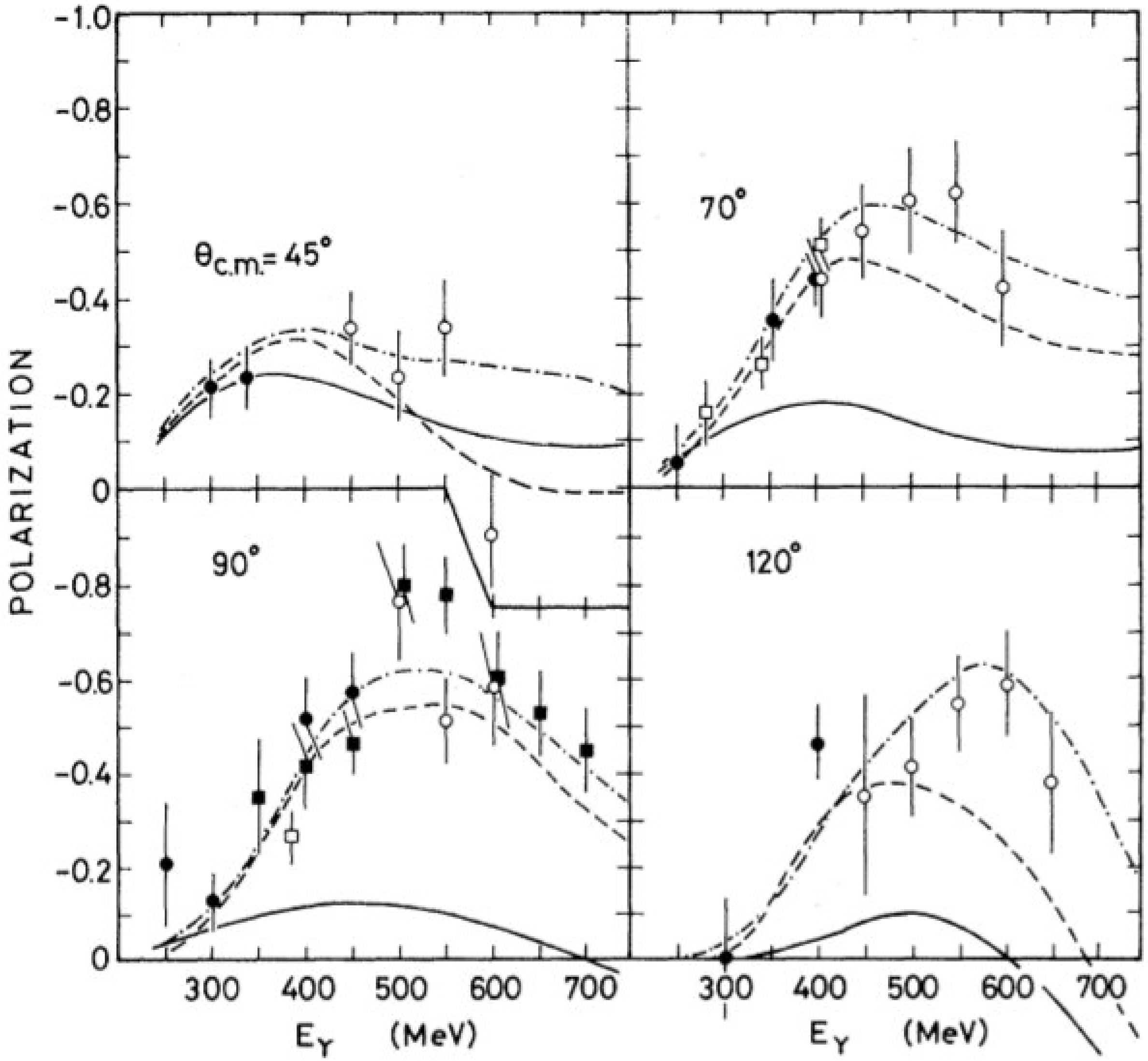
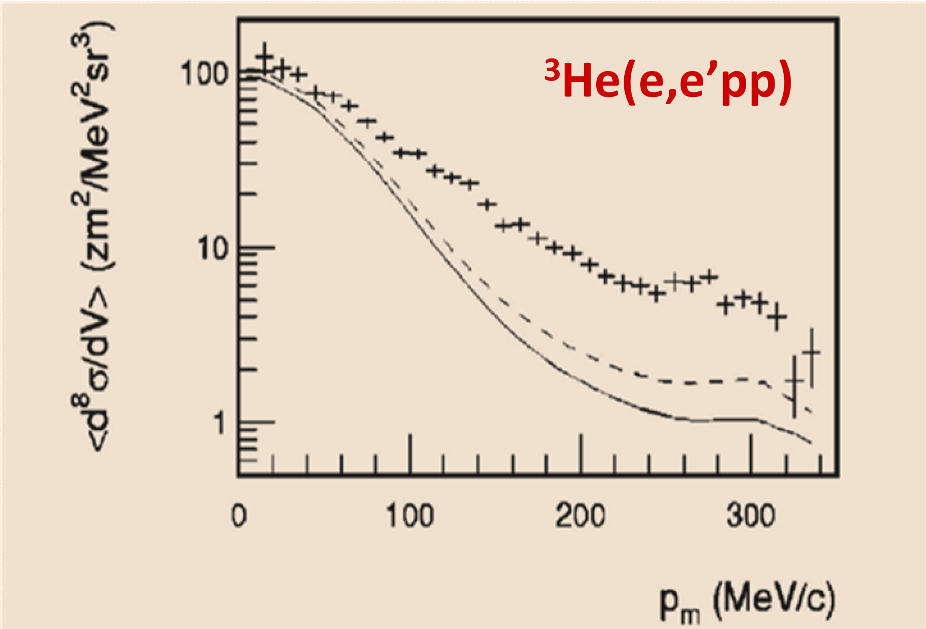


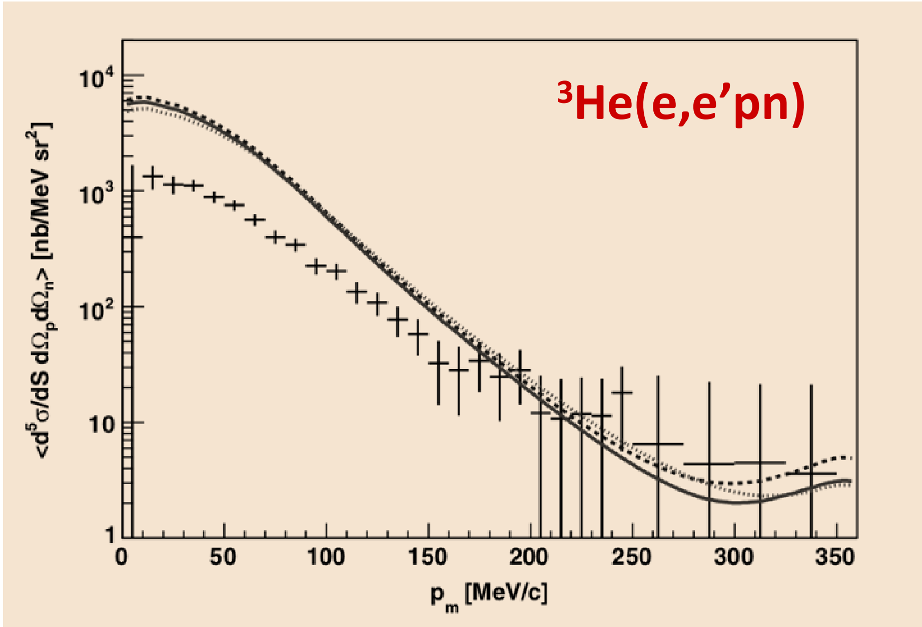
FIG. 2. Proton polarization plotted vs E_γ. The data outside the fitted region are also shown. The curves and symbols are coded as in Fig. 1.

TABLE II. The results of the fits for the two hypotheses giving the smallest χ^2/DF values. The mass and width (in units of MeV) of the $1(3^-)$ resonance are fixed at 2260 and 200, respectively. The coupling parameters a are given for each multipole transition amplitude in the units of $(\mu b)^{1/2}$.

1(3⁻) and 0(1⁺)			1(3⁻) and 0(3⁺)		
$1(3^-)$	$E_3(^3F_3)$	-72 ± 25	$1(3^-)$	$E_3(^3F_3)$	-85 ± 38
	$M_2(^3F_3)$	-246 ± 14		$M_2(^3F_3)$	-260 ± 22
	$M_4(^3F_3)$	63 ± 35		$M_4(^3F_3)$	11 ± 45
$0(1^+)$	W_0	2352 ± 14	$0(3^+)$	W_0	2362 ± 15
	Γ	342 ± 69		Γ	238 ± 48
	$E_2(^3S_1)$	128 ± 28		$E_2(^3D_3)$	31 ± 65
	$E_2(^3D_1)$	63 ± 46		$E_2(^3G_3)$	-203 ± 22
	$M_1(^3S_1)$	11 ± 23		$E_4(^3D_3)$	-113 ± 43
	$M_1(^3D_1)$	-249 ± 15		$E_4(^3G_3)$	-56 ± 146
				$M_3(^3D_3)$	25 ± 62
				$M_3(^3G_3)$	-7 ± 66

E.-m. interactions of hadrons at high momentum transfers





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.

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Knockout of proton-neutron pairs from ^{16}O with electromagnetic probes

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Abstract. After recent improvements to the Pavia model of two-nucleon knockout from ^{16}O with electromagnetic probes the calculated cross-sections are compared to experimental data from such reactions. Comparison with data from a measurement of the ^{16}O(e,e′pn) reaction cross-section shows much better agreement between the experimental data and the results of the theoretical model than was previously observed. In a comparison with recent data from a measurement of the ^{16}O(γ,pn) reaction cross-section the model over-predicts the measured cross-section at low missing momentum.

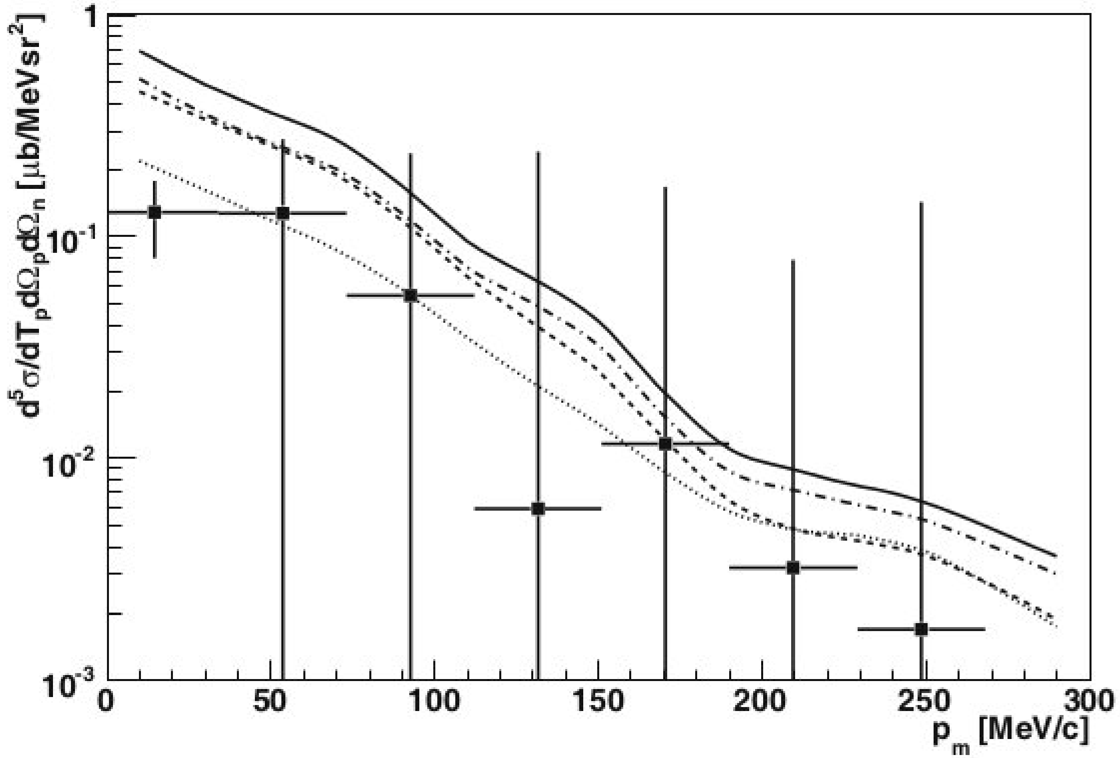
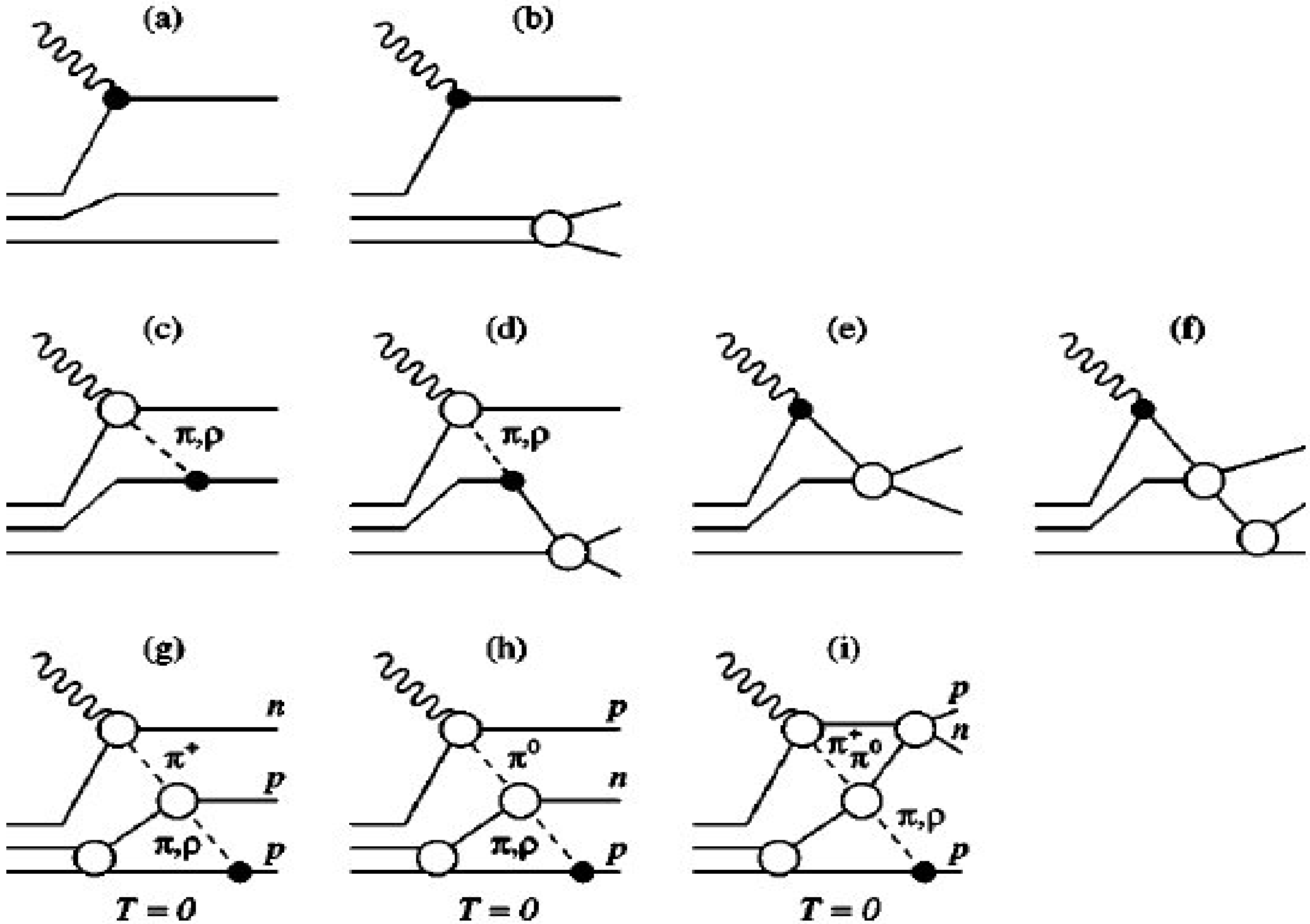


Fig. 4. The $^{16}O(\gamma,pn)^{14}N$ cross-section as a function of the missing momentum for events in the range $2 \leq E_x \leq 10$ MeV. The incident photon energy range was $150 \leq E_\gamma \leq 250$ MeV. The curves show the theoretical cross-section for transitions to the 3.95 MeV (1^+) state. The dashed line is calculated with only one-body currents included; the dotted line also includes the π-seagull term; the dash-dotted line includes the one-body, π-seagull term and pion-in-flight terms and the solid line is for the complete cross-section including contributions from IC.

High-energy γ absorption in ^{3}He



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

PHYSICAL REVIEW C 70, 064003 (2004)

Complete measurement of three-body photodisintegration of ^{3}He for photon energies between 0.35 and 1.55 GeV

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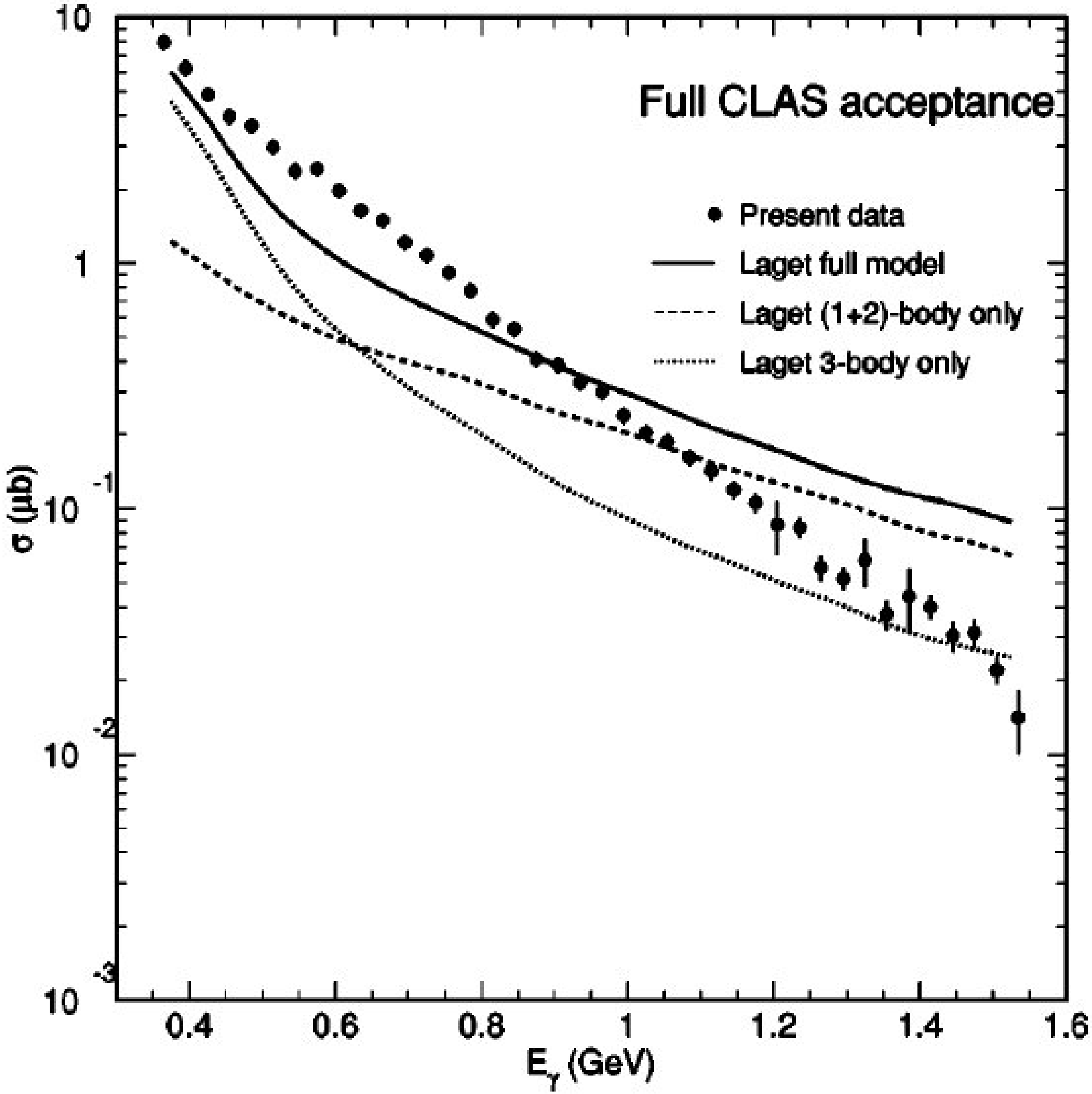
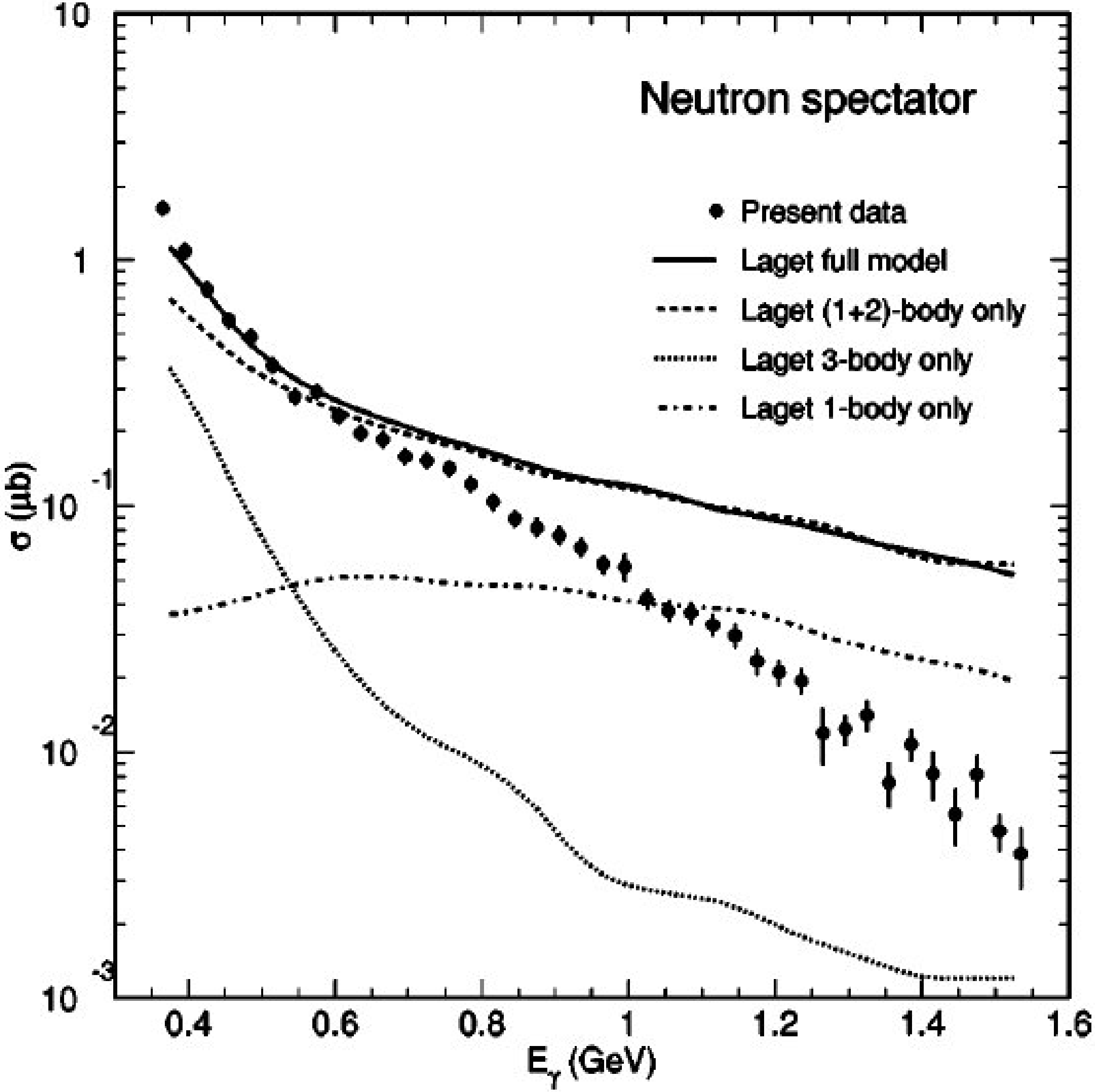
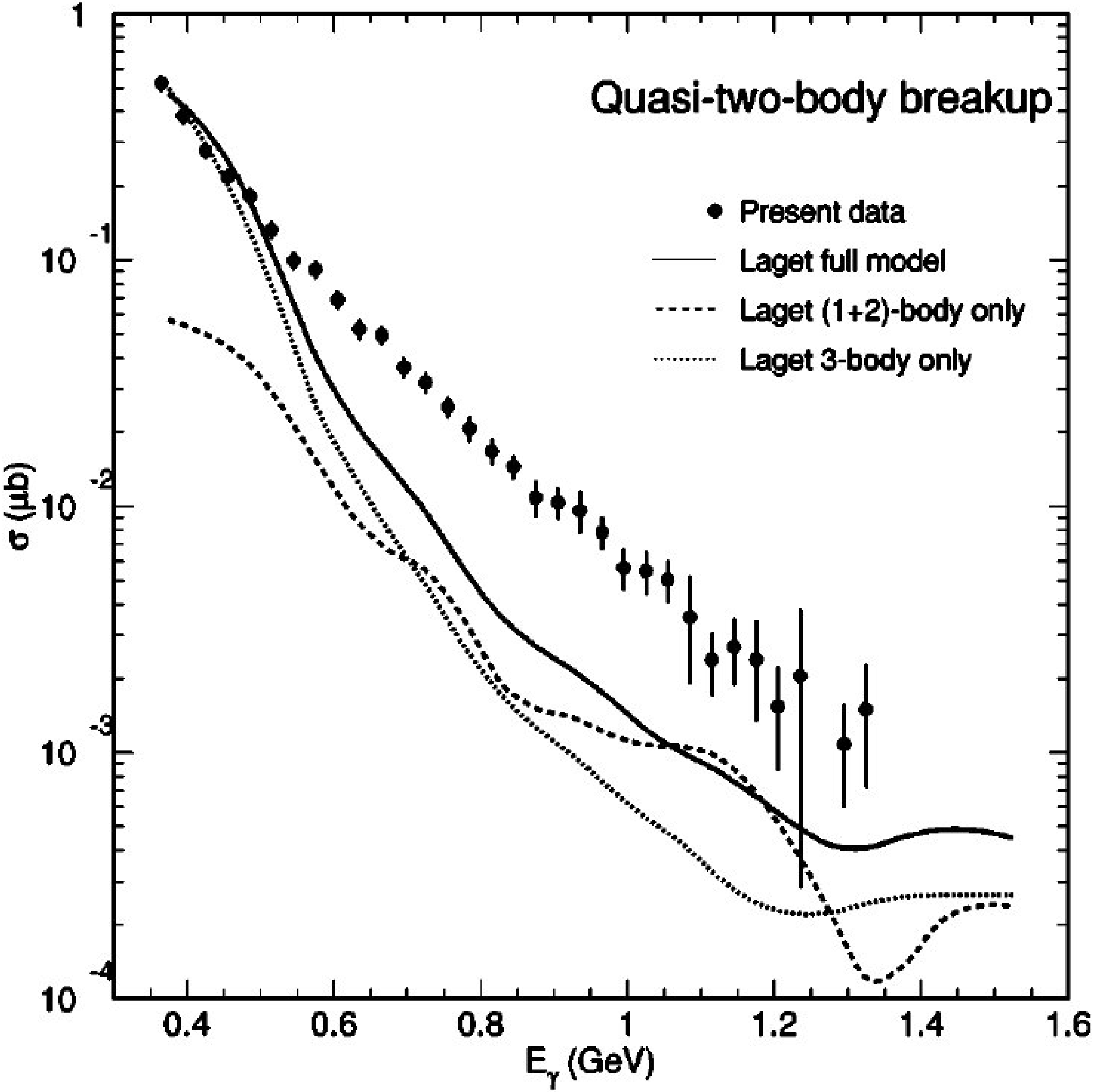


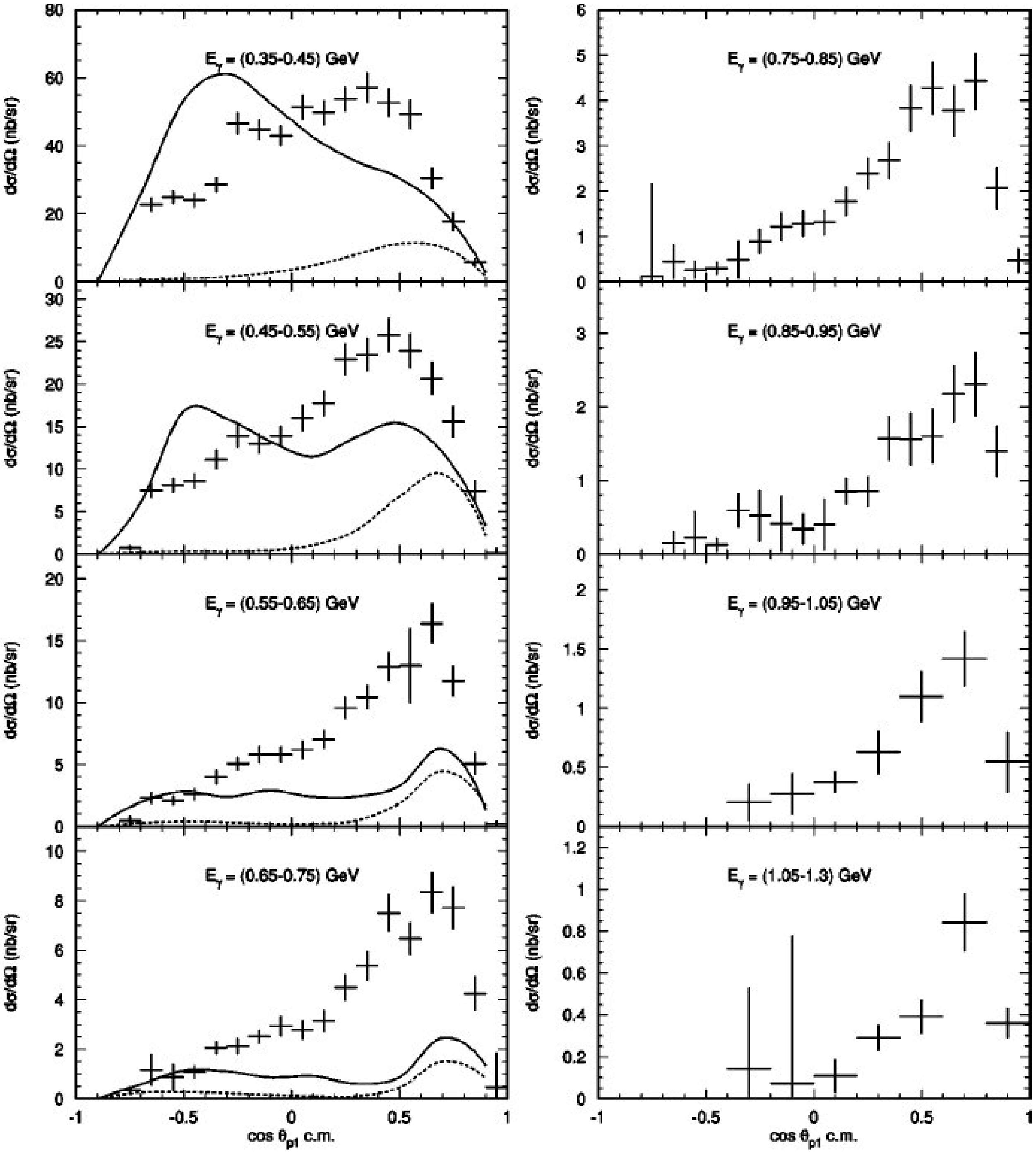
Total ppn cross section integrated over the CLAS acceptance plotted as a function of photon energy for the full E_γ range. The ppn cross section (circles) is compared with Laget's full model (solid curve) and with the model result without the three-body mechanisms (dashed curve).



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



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 $E_\gamma \approx 0.55$ 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).

The forward peak is very remarkable here!

Hard Two-Body Photodisintegration of ^{3}He

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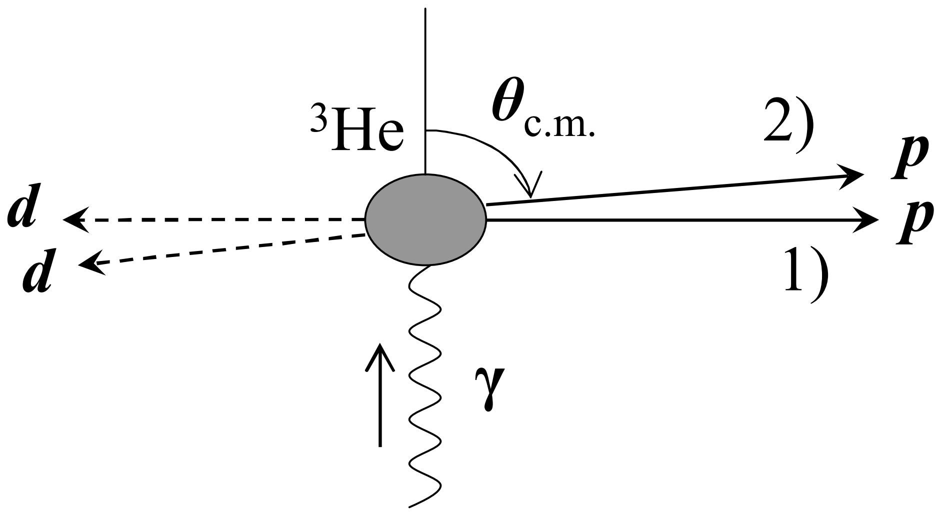
(CLAS and Hall-A Collaborations)

Experimental setting



$^{3}\mathrm{He}(\boldsymbol{\gamma}, \boldsymbol{pd})$

$\boldsymbol{E_\gamma} = \mathbf{1.656}$ GeV

1) $\boldsymbol{\theta}_{\mathrm{c.m.}} = \mathbf{90°}$; 2) $\boldsymbol{\theta}_{\mathrm{c.m.}} = \mathbf{85°}$

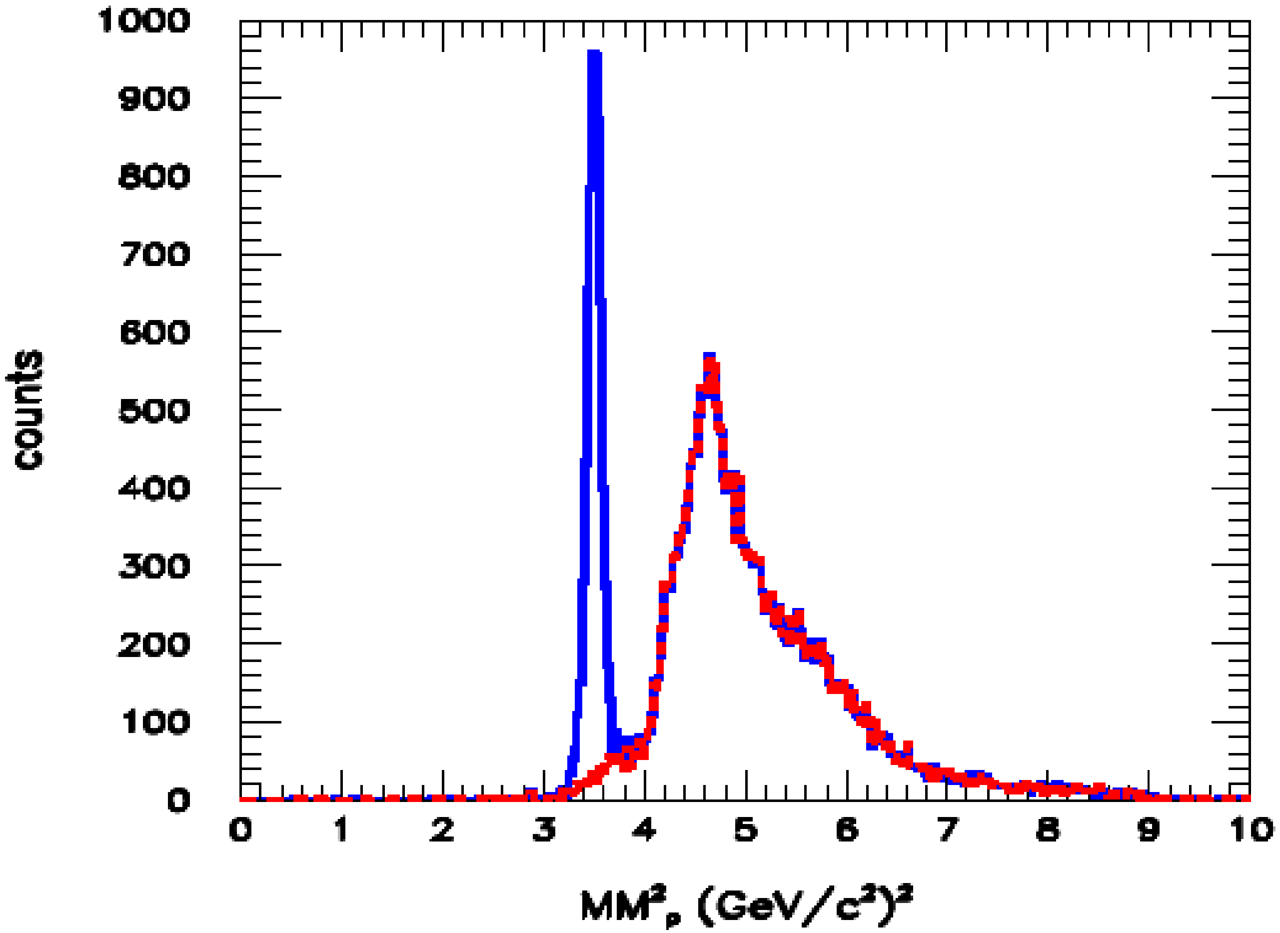


FIG. 2. (Color online) Event distributions measured by CLAS, of the missing-mass of the proton, MM_p^2 for proton c.m. angle of 90°, with (dashed red line) and without (blue solid line) the kinematic cuts, are shown. Events from the pd final state are clearly identified in the peak. Accidental and multipion events give rise to the background. The background distribution (events rejected by the kinematic cuts) exhibits smooth behavior under the deuteron peak and reproduces nicely the background shape outside of the peak.

Dimensional scaling

$$\frac{d\sigma}{dt} \sim s^{2-n_i-n_f} = s^{-n},$$

where n_i and n_f are total number of elementary fields in initial and final states that carry a finite fraction of particle momentum, e.g., n=3 for nucleon.

For $\gamma + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{d}$ reaction n_i = 10 (9+1), n_f = 9, so that, n = 17 and thus

$$\frac{d\sigma}{dt} \sim s^{-17}.$$

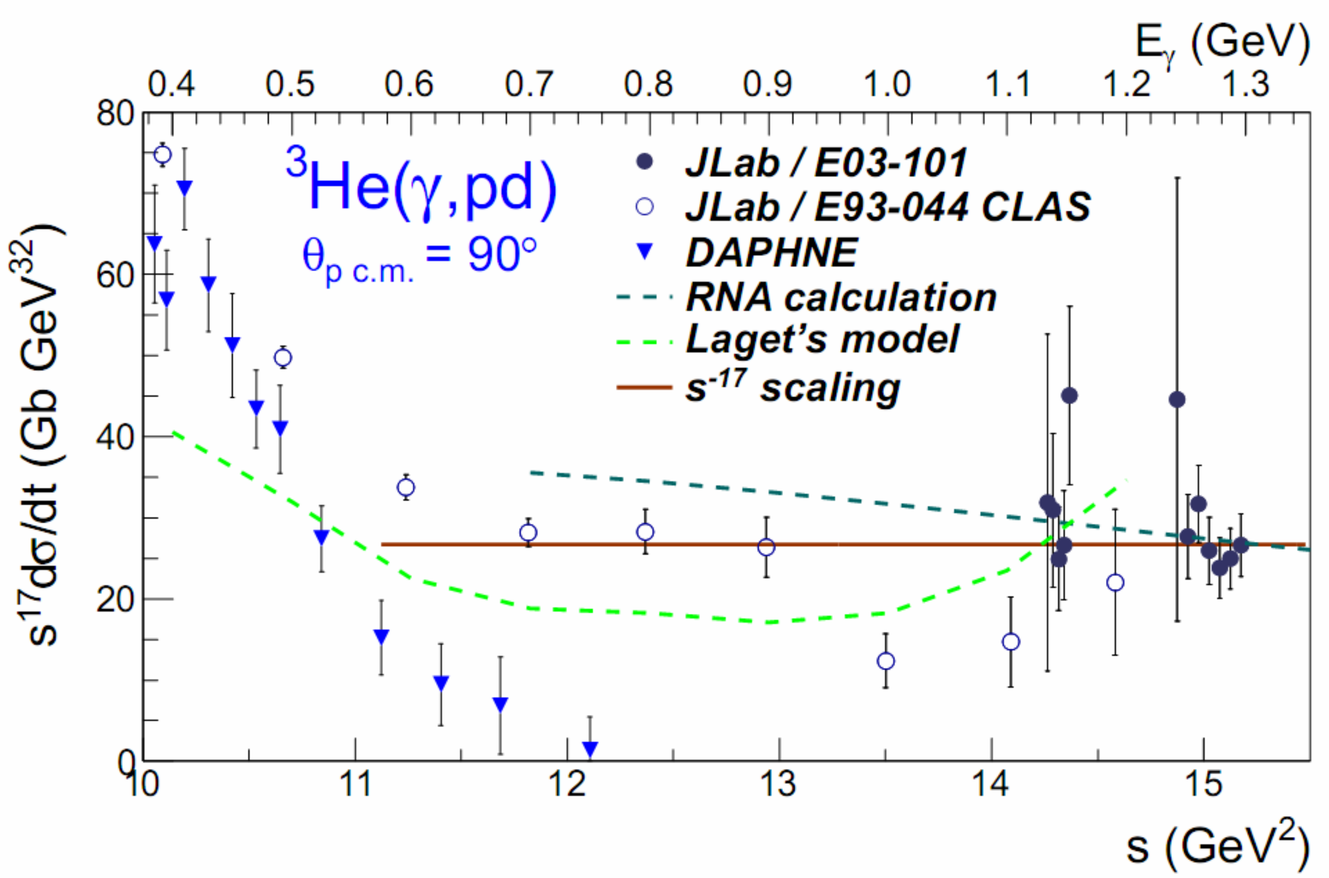
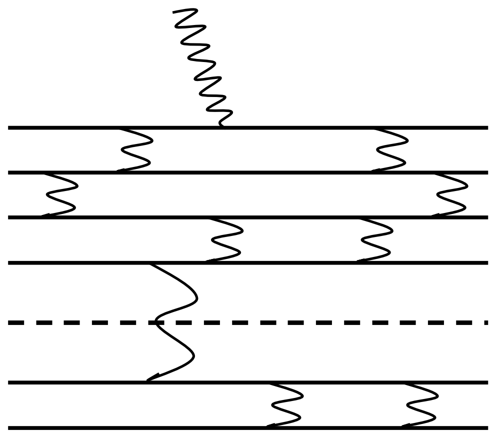


FIG. 3. The invariant cross section $d\sigma/dt$ multiplied by s^{17} to remove the expected energy dependence. The DAPHNE data is taken from [37]. The RNA [17] calculation is normalized to our highest energy data point from JLab/E03-101.

The non-scaled cross section in the energy interval s = 11.5-15 GeV^2 falls by two orders of magnitude!

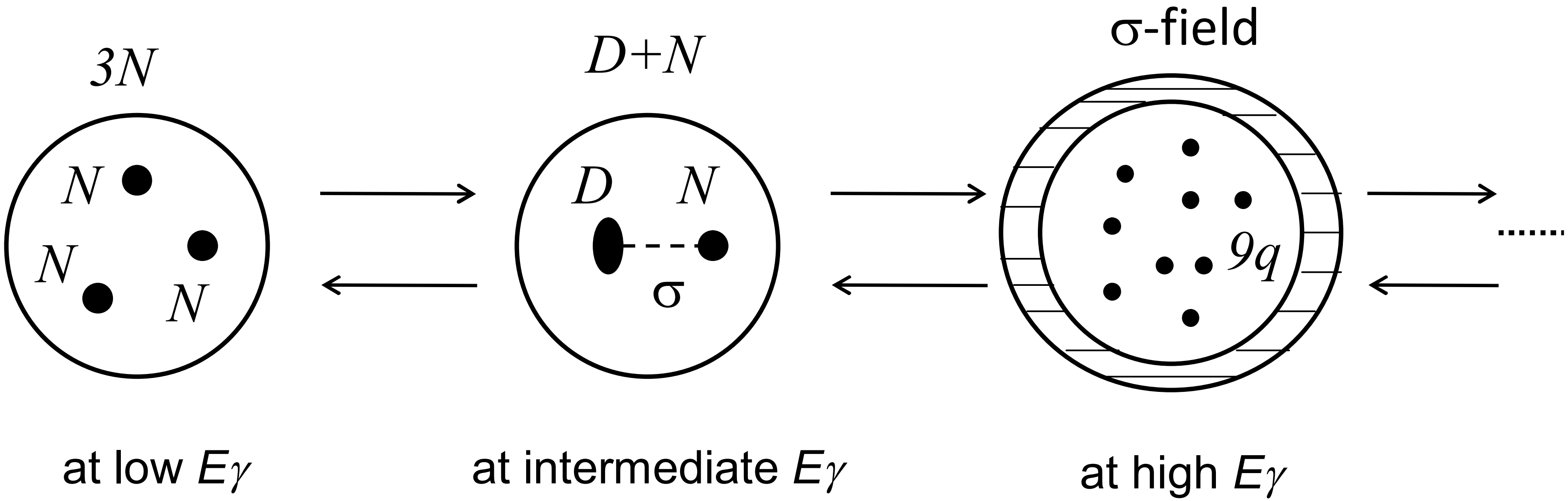
Origin of dimensional scaling (quark counting rule)



Initial high energy of γ is shared more or less homogeneously among all n elementary constituents (quarks).

Thus, physically, dimensional scaling for $\gamma + {}^3He$ means that the high-energy γ-probe is interacting with a 9-quark object! (at $E\gamma > 0.7$ GeV).

So that, the ^{3}He nucleus looks at different scales like:



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Yordanka Ilieva · The CLAS Collaboration

Recent Results from CLAS on Baryon Structure and Interactions

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Abstract The understanding of baryon structure and interactions from Quantum Chromodynamics is one of the main objectives of modern hadron physics. Of particular interest is the regime of confinement where perturbative methods are not applicable to derive testable predictions. Understanding the transition from hadronic to partonic degrees of freedom, the hyperon-nucleon interaction, and nuclei in terms of quarks and gluons are some of the key problems. Here we present results of photoproduction experiments on light nuclear targets from Jefferson Lab Hall B. Our observation of onset of dimensional scaling in the cross section of two-body photodisintegration of ^{3}He at energy and momentum transfer well below 1 GeV suggests that quarks and gluons may be relevant degrees of freedom for the description of nuclear dynamics at energies lower than previously considered. Our program to study lambda-nucleon scattering via a large set of polarization observables for final-state interactions in exclusive hyperon photoproduction off the deuteron has produced preliminary results for single-polarization observables. The beam-spin asymmetry shows interesting features at large lambda polar angles and large kaon momenta.

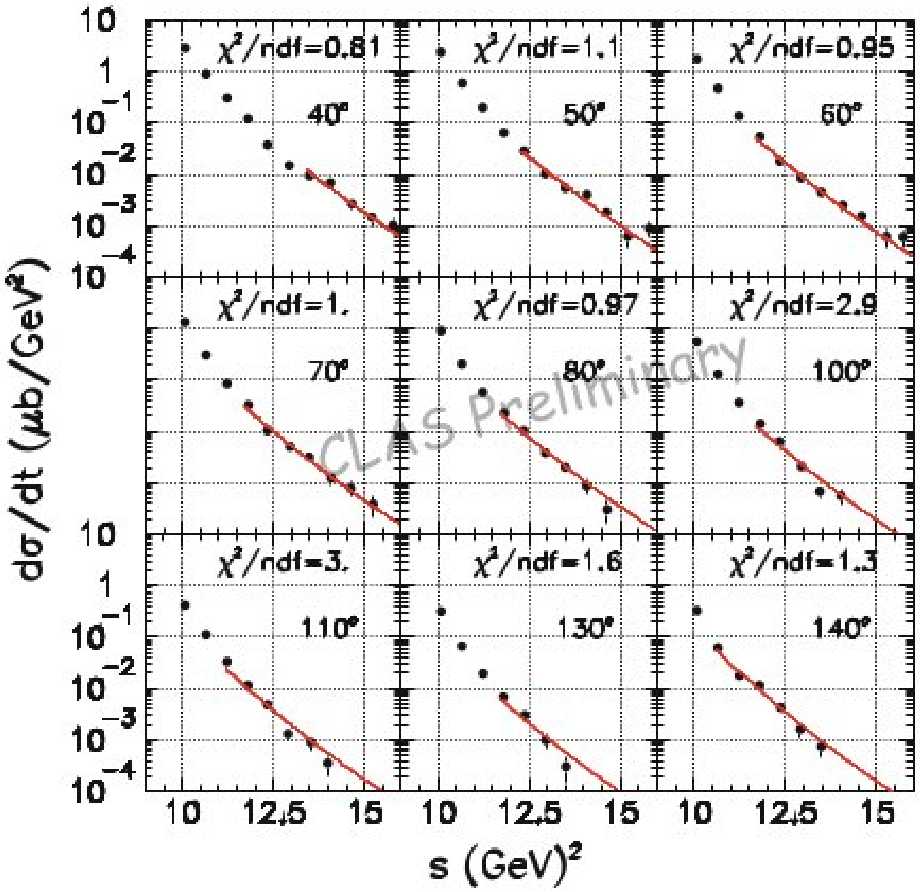

Fig. 2 Preliminary CLAS differential cross sections of the reaction γ^3He $\rightarrow$ pd as a function of s for different proton c.m. angles (shown in each plot). The *solid lines* show fits to the cross sections with the function $d\sigma/dt = As^{-17}$, where A is a fit parameter. The quality of the fits is shown through the χ^2/ndf, where ndf labels the number of degrees of freedom in the fit, shown at the *top* of each plot.

Excellent confirmation for the dimensional scaling in ^{3}He!

Phase transition in dense nuclear matter

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Interaction of a dense fermion medium with a scalar-meson field*

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The interaction between a dense fermion medium and a scalar-meson field is studied. It is shown that in the quasiclassical approximation, independently of the details of the theory, at low fermion density the lowest energy state is normal (i.e., effective fermion mass $m_{\text{eff}} \cong$ free mass), but at high density the state is abnormal (i.e., $m_{\text{eff}} \cong 0$). The nature of the transition is analyzed at zero and low temperatures. Our main concern is to examine the problem of quantum fluctuation. Both the one- and two-loop diagrams are calculated. By developing a variational formalism involving only two-line irreducible diagrams, we derive a suitable high-density expansion for the energy. The quasiclassical solution emerges as the lowest-order term in this expansion. Therefore, when the expansion is valid, the overall description of the transition given by the quasiclassical solution remains correct with the inclusion of quantum corrections.

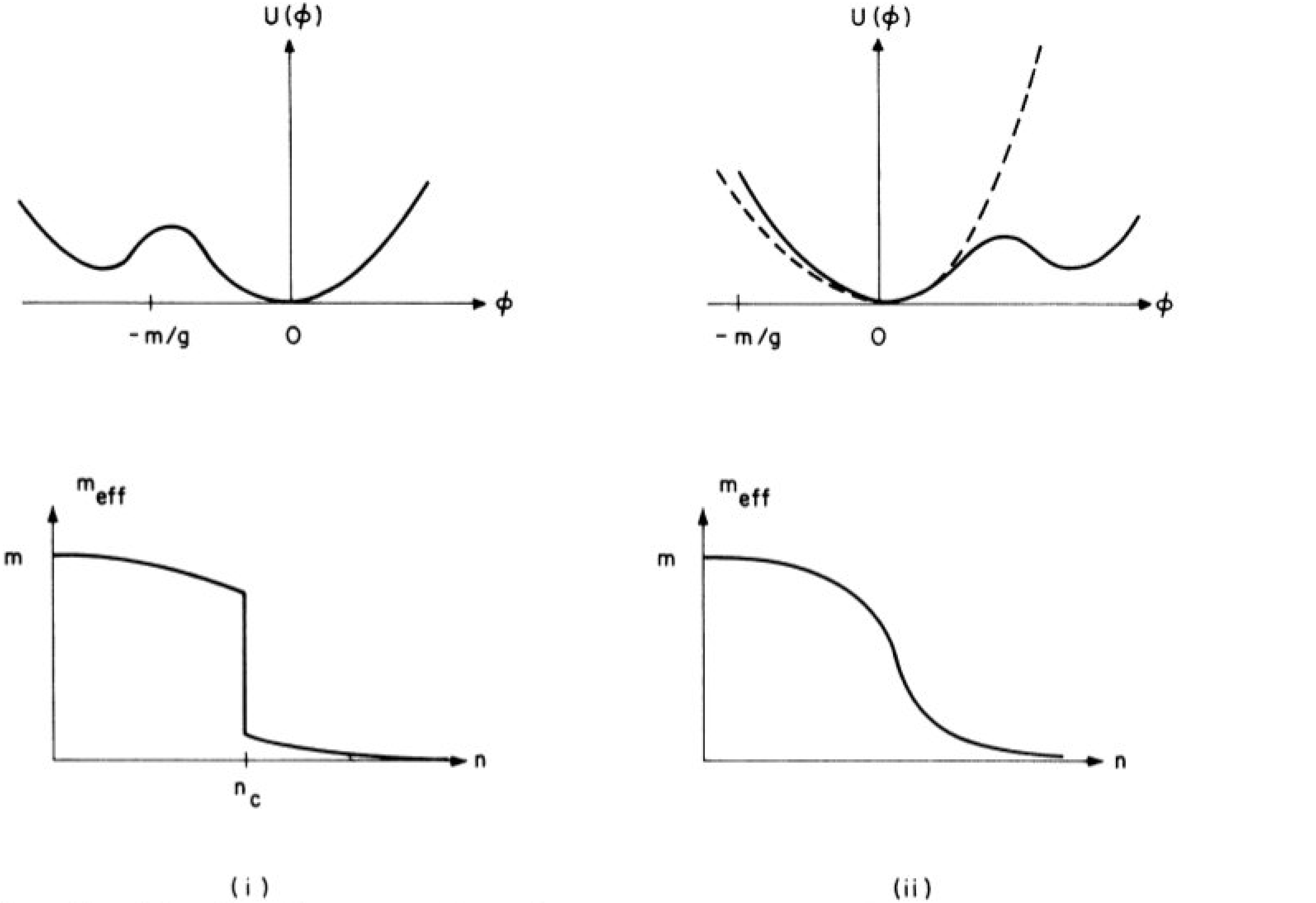
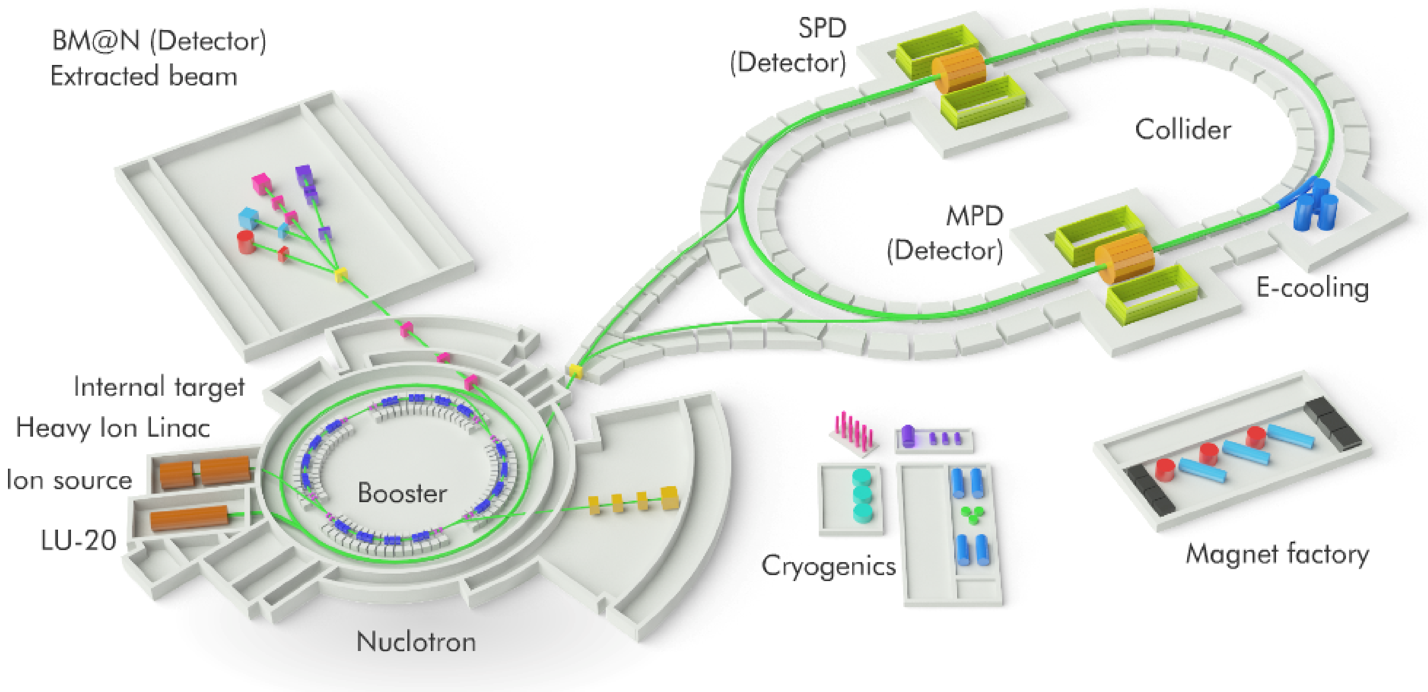


FIG. 1. Examples of (i) a discontinuous transition and (ii) a continuous transition between the normal state (m_{eff} $\cong$ free fermion mass m) and the abnormal state ($m_{eff} \cong 0$). The necessary conditions for a discontinous transition [i.e., case (i)] are $b^2 > 2ac$ and b of the same sign as g; both conditions are satisfied in the σ model. In case (ii), the function $U(\phi)$ can have either two minima (solid curve), or only one minimum (dashed curve).

NICA at JINR



One of the main goals of NICA will be the search for signs of the phase transition between hadronic matter and quark-gluon plasma and search for new phases of baryonic matter.

Dibaryons (and multibaryons) in cold matter can be considered as precursors of phase transition to quark-meson-gluon plasma state through the intermediate mixed-phase state.

Conclusion

- Nucleus is a very complicated dynamical system with many d.o.f. at different scales of momentum and energy.
- Nuclear force is dominated by very complicated QCD mechanisms including phase transition (chiral symmetry restoration) and has the Yukawa meson-exchange character only in the peripheral region.
- At higher density, nuclear matter likely undergoes the QCD phase transition to abnormal matter with zero nucleon mass and of Bose-condensate character.
- The cold abnormal matter is a good candidate for dark matter in the Universe.

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